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### Title

Search for narrow resonances lighter than Y mesons

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<https://escholarship.org/uc/item/9ph0415g>

### Journal

European Physical Journal C, 62(2)

### ISSN

1434-6044

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### Publication Date

2009-07-01

### DOI

10.1140/epjc/s10052-009-1057-4

Peer reviewed

## Search for narrow resonances lighter than $\Upsilon$ mesons

CDF Collaboration

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Received: 15 April 2009 / Revised: 19 April 2009 / Published online: 28 May 2009

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**Abstract** We report a search for narrow resonances, produced in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV, that decay into muon pairs with invariant mass between 6.3 and 9.0 GeV/ $c^2$ . The data, collected with the CDF II detector at the Fermilab Tevatron collider, correspond to an integrated luminosity of 630 pb $^{-1}$ . We use the dimuon invariant mass distribution to set 90% upper credible limits of about 1% to the ratio of the production cross section times muonic branching fraction of possible narrow resonances to that of the  $\Upsilon(1S)$  meson.

## 1 Introduction

Searches for narrow resonances at SPEAR have set upper bounds on  $\Gamma_l$ , the leptonic width of possible resonances, of about 100 eV in the cms energy region  $5.7 \leq E_{\text{cm}} \leq 6.4$  GeV and of approximately 60 eV in the region  $7.0 \leq E_{\text{cm}} \leq 7.4$  GeV [1–3]. These limits do not exclude bound states of charge  $-1/3$  and spin 0 light quarks, the existence of which is required by supersymmetric theories. The leptonic width of  $\mathcal{E}$  mesons,  $1^{--}$  bound states of charge  $-1/3$

scalar quarks, has been evaluated in Ref. [4] using potential models of ordinary heavy quarks [5, 6]. Because of the p-wave suppression of the fermion contribution, the leptonic width is estimated to be approximately 18 (6) eV for a resonance with a 6 (10) GeV/ $c^2$  mass. A more recent study [7] has set an average 90% upper credible limit of  $\Gamma_l \simeq 8$  eV to the existence of narrow resonances in the invariant mass range 6.3–9 GeV/ $c^2$  by using a dimuon sample corresponding to a luminosity of approximately 110 pb $^{-1}$  collected with the CDF detector during the 1992–1995 Tevatron collider run. Because of statistical fluctuations, that study does not rule out the existence of  $\mathcal{E}$  states over the full mass range. In particular, at a mass of 7.2 GeV/ $c^2$ , that study returns an upper credible limit that is consistent with what is expected if an  $\mathcal{E}$  state is produced.

In this study, we repeat the analysis in Ref. [7] and take advantage of a higher statistics data sample that corresponds to an integrated luminosity of 630 pb $^{-1}$  collected with the CDF II detector after May 2006. At that time, the CDF II trigger system was upgraded and made capable of acquiring events containing muon pairs with invariant mass larger than 6 GeV/ $c^2$  and a kinematic acceptance comparable to that of the Run I trigger system. Section 2 describes the detector systems relevant to this analysis. The data sample and analysis method are described in Sect. 3. In Sect. 4, we fit the dimuon invariant mass distribution and derive 90% upper credible limits to  $\Gamma_l$  as a function of the resonance mass. Our conclusions are summarized in Sect. 5.

## 2 CDF II detector and trigger system

CDF II is a multipurpose detector, equipped with a charged particle spectrometer and a finely segmented calorimeter. In this section, we briefly describe the detector components that are relevant to this analysis. A detailed description of these subsystems can be found in Refs. [8–17]. Two devices inside the 1.4 T solenoid are used for measuring the momentum of charged particles: the silicon vertex detector (SVXII and ISL) and the central tracking chamber (COT). The SVXII detector consists of microstrip sensors arranged in six cylindrical shells with radii between 1.5 and 10.6 cm, and with a total  $z$  coverage<sup>1</sup> of 90 cm. The first SVXII layer, also referred to as the L00 detector, is made of single-sided sensors mounted on the beryllium beam pipe. The remaining five SVXII layers are made of double-sided sensors and are divided into three contiguous five-layer sections

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<sup>1</sup>In the CDF coordinate system,  $\theta$  and  $\phi$  are the polar and azimuthal angles of a track, respectively, defined with respect to the proton beam direction,  $z$ . The pseudorapidity  $\eta$  is defined as  $-\ln \tan(\theta/2)$ . The transverse momentum of a particle is  $p_T = p \sin(\theta)$ . The rapidity is defined as  $y = 1/2 \cdot \ln((E + p_z)/(E - p_z))$ , where  $E$  and  $p_z$  are the energy and longitudinal momentum of the particle associated with the track, respectively.



along the beam direction  $z$ . The two additional silicon layers of the ISL help to link tracks in the COT to hits in the SVXII. The COT is a cylindrical drift chamber containing 96 sense wire layers grouped into eight alternating superlayers of axial and stereo wires. Its active volume covers  $|z| \leq 155$  cm and 40 to 140 cm in radius. The transverse momentum resolution of tracks reconstructed using COT hits is  $\sigma(p_T)/p_T^2 \simeq 0.0017$  [GeV/c] $^{-1}$ .

The central muon detector (CMU) is located around the central electromagnetic and hadronic calorimeters, which have a thickness of 5.5 interaction lengths at normal incidence. The CMU detector covers a nominal pseudorapidity range  $|\eta| \leq 0.63$  relative to the center of the detector, and is segmented into two barrels of 24 modules, each covering  $15^\circ$  in  $\phi$ . Every module is further segmented into three submodules, each covering  $4.2^\circ$  in  $\phi$  and consisting of four layers of drift chambers. The smallest drift unit, called a stack, covers a  $1.2^\circ$  angle in  $\phi$ . Adjacent pairs of stacks are combined together into a tower. A track segment (hits in two out of four layers of a stack) detected in a tower is referred to as a CMU stub. A second set of muon drift chambers (CMP) is located behind an additional steel absorber of 3.3 interaction lengths. The chambers are 640 cm long and are arranged axially to form a box around the central detector. The CMP detector covers a nominal pseudorapidity range  $|\eta| \leq 0.54$  relative to the center of the detector. Muons that produce a stub in both CMU and CMP systems are called CMUP muons. The CMX muon detector consists of eight drift chamber layers and scintillation counters positioned behind the hadron calorimeter. The CMX detector extends the muon coverage to  $|\eta| \leq 1$ .

The luminosity is measured using gaseous Cherenkov counters (CLC) that monitor the rate of inelastic  $p\bar{p}$  collisions. The inelastic  $p\bar{p}$  cross section at  $\sqrt{s} = 1960$  GeV is scaled from measurements at  $\sqrt{s} = 1800$  GeV using the calculations in Ref. [18]. The integrated luminosity is determined with a 6% systematic uncertainty [19].

CDF uses a three-level trigger system. At Level 1 (L1), data from every beam crossing are stored in a pipeline capable of buffering data from 42 beam crossings. The L1 trigger either rejects events or copies them into one of the four Level 2 (L2) buffers. Events that pass the L1 and L2 selection criteria are sent to the Level 3 (L3) trigger, a cluster of computers running speed-optimized reconstruction code. For this study, we select events with two muon candidates identified by the L1 and L2 triggers. The L1 trigger uses tracks with  $p_T \geq 1.5$  GeV/c found by a fast track processor (XFT). The XFT examines COT hits from the four axial superlayers and uses the  $r$ - $\phi$  information to find tracks with  $p_T \geq 1.5$  GeV/c in azimuthal sections of  $1.25^\circ$ . The XFT passes the tracks to a set of extrapolation units that determine the CMU (CMX) towers in which a CMU (CMX) stub should be found if the track is a muon. If a stub is found, a L1

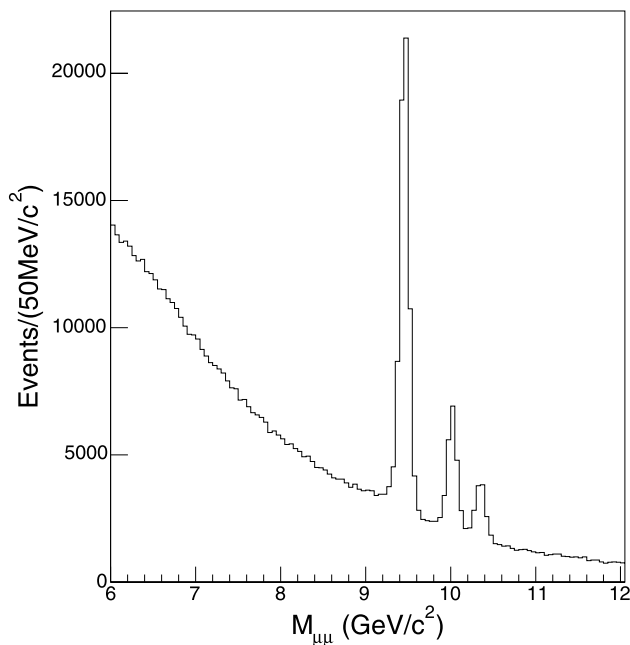
CMU (CMX) primitive is generated. The L1 dimuon trigger requires one CMU primitive and an additional CMU or CMX primitive. The L2 trigger additionally requires that at least one of the muons has a CMUP stub matched to an XFT track with  $p_T \geq 3$  GeV/c and that additional CMU (CMX) stubs are matched to XFT tracks with  $p_T \geq 1.5$  (2) GeV/c. The L2 trigger is dynamically prescaled as a function of the Tevatron luminosity in order to optimize the data acquisition performance. The L3 trigger selects muon pairs with invariant mass larger than 5 GeV/ $c^2$ , and  $|\delta z_0| \leq 5$  cm, where  $z_0$  is the  $z$  coordinate of the muon track at its point of closest approach to the beam line in the  $r$ - $\phi$  plane. These requirements define the dimuon trigger used in this analysis.

### 3 Dimuon data sample

In this analysis, we select events acquired with the dimuon trigger and which contain two and only two muons with opposite charge. Events are reconstructed offline taking advantage of more refined calibration constants and reconstruction algorithms. COT tracks are extrapolated into the SVXII detector, and refitted adding silicon hits consistent with the track extrapolation into the microvertex detector. We require that at least one muon has stubs reconstructed in both the CMU and CMP detectors and is matched to a track with  $p_T \geq 3$  GeV/c. A track is identified as a CMUP muon if  $\Delta r\phi$ , the distance in the  $r$ - $\phi$  plane between the track projected to the CMU (CMP) chambers and a CMU (CMP) stub, is less than 30 (40) cm. The additional muon is accepted if a stub reconstructed in the CMU or CMX detectors is matched to a track with  $p_T \geq 2$  GeV/c. A track is identified as a CMU (CMX) muon if  $\Delta r\phi$  is less than 30 (50) cm. We require that muon-candidate stubs correspond to L1 primitives, and correct the muon momentum for energy losses in the detector.

Previous measurements of the  $B$  hadron mixing probability [20] and of the  $b\bar{b}$  correlated production [21] have used similarly selected dimuon data samples. Those studies show that 70–75% of these dimuon pairs are contributed by  $b\bar{b}$  and  $c\bar{c}$  production. Following the procedure pioneered in Ref. [7], we reject muons arising from the decay of hadrons with heavy flavor with the following requirements:

1. Isolation. The isolation,  $I$ , is defined as the scalar sum of the transverse momenta of all the tracks in a cone of radius  $R = \sqrt{\delta\phi^2 + \delta\eta^2} = 0.4$  around the muon direction. We require that both muons have isolation  $I \leq 4$  GeV/c.
2. Promptness. In contrast to  $b$  and  $c$  hadrons, the  $\Upsilon(1S)$  and  $\mathcal{E}$  mesons have a negligible lifetime. We evaluate the invariant mass of each muon pair by constraining the two muon tracks to originate from a common point in the three-dimensional space (vertex constraint). We reject muon pairs if the probability of the vertex-constrained



**Fig. 1** Invariant mass distribution of the selected muon pairs

fit is smaller than 0.001. We also reject muon pairs if  $L_{xy}/\sigma_{L_{xy}} \geq 3$ , where  $L_{xy}$  is the displacement of the dimuon-candidate vertex with respect to the  $p\bar{p}$  event vertex projected onto the dimuon transverse momentum vector, and  $\sigma_{L_{xy}}$  is its uncertainty.

The invariant mass distribution of the muon pairs passing these selection requirements<sup>2</sup> is shown in Fig. 1.

#### 4 Search for narrow resonances

As in Ref. [7], we limit our search for narrow resonances to the mass region above  $6.3 \text{ GeV}/c^2$ , where the kinematic acceptance becomes independent of the  $\mathcal{E}$ -candidate transverse momentum. The number of  $\Upsilon$  mesons in the data is derived by fitting the invariant mass distribution in Fig. 1 with a binned maximum likelihood method [22]. We use a fifth-order polynomial to model the continuum in the invariant mass region  $6\text{--}12 \text{ GeV}/c^2$  and Gaussian functions to model the  $\Upsilon$  contributions.<sup>3</sup> The best fit, which has 114 dof and a 60% probability, returns  $52700 \pm 350 \Upsilon(1S)$  meson events. The fit returns  $M_{\Upsilon(1S)} = 9459 \pm 1 \text{ MeV}/c^2$  and yields a rms mass resolution of  $52 \pm 1 \text{ MeV}/c^2$ . This mass

<sup>2</sup>As in Ref. [7], the isolation and promptness requirements retain more than 90% of the  $\Upsilon$  signal and reduce the number of remaining events by more than a factor of three.

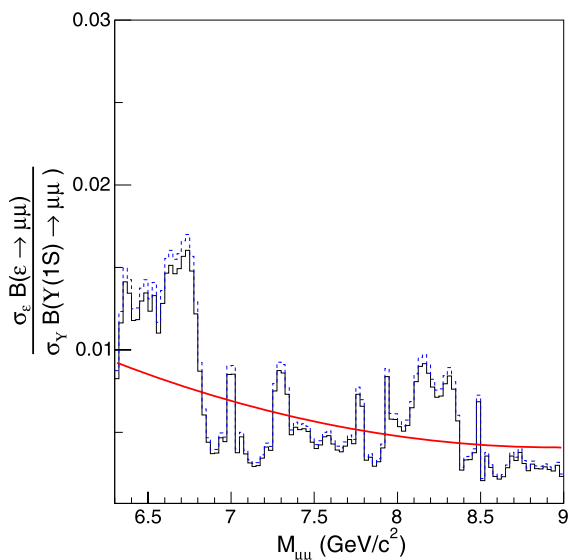
<sup>3</sup>Two Gaussian functions with the same peak are required to model each  $\Upsilon(1S)$  or  $\Upsilon(2S)$  signal, whereas a single Gaussian function is sufficient to describe the  $\Upsilon(3S)$  signal.

resolution is well modeled by a simulation of the process  $p\bar{p} \rightarrow \Upsilon(1S)X$ . In the simulation, the event generator produces unpolarized  $\Upsilon(1S)$  mesons with the transverse momentum distribution of the data [23, 24] and a flat rapidity distribution for  $|y| \leq 1$ . The generated events are processed with the CDF II detector simulation that in turn is based on the GEANT simulation package [25, 26]. Events are then required to pass the same trigger requirements, analysis selection, and reconstruction criteria imposed on the data. The same simulation<sup>4</sup> predicts an invariant mass resolution that increases from  $32 \text{ MeV}/c^2$  for an  $\mathcal{E}$  state with a mass of  $6.3 \text{ GeV}/c^2$  to  $50 \text{ MeV}/c^2$  for  $m_{\mathcal{E}} = 9 \text{ GeV}/c^2$ .

The invariant mass distribution in Fig. 1 does not exhibit any significant narrow bump in the mass range  $6.3\text{--}9.0 \text{ GeV}/c^2$ . We set limits to  $R = [\sigma_{\mathcal{E}}BR(\mathcal{E} \rightarrow \mu\mu)]/[\sigma_{\Upsilon(1S)}BR(\Upsilon(1S) \rightarrow \mu\mu)]$ , the ratio of the production cross sections times the muonic branching fractions, under the assumptions that  $\mathcal{E}$  states have negligible widths with respect to the experimental resolution and are produced unpolarized. We also assume that the efficiency of the isolation requirement, used to suppress the heavy flavor contribution, does not depend on the  $\mathcal{E}$  mass and is equal to that for  $\Upsilon(1S)$  mesons. Limits on the existence of narrow  $\mathcal{E}$  states are set by adding a Gaussian term to the likelihood function used to fit the data in the  $6\text{--}12 \text{ GeV}/c^2$  mass interval. We perform 108 fits in which we change the position of the Gaussian peak in steps of  $25 \text{ MeV}/c^2$  from  $6.3$  to  $9.0 \text{ GeV}/c^2$ . In each fit, we force the Gaussian width to the rms mass resolution predicted by the detector simulation for that mass. The usage of only one Gaussian function to estimate the number of  $\mathcal{E}$  events introduces a 4.5% systematic uncertainty. The uncertainty is estimated as the difference between the number of  $\Upsilon(1S)$  events returned by fits that use one or two Gaussian functions to estimate the  $\Upsilon(1S)$  signal. For each  $\mathcal{E}$  mass value, we use the integral of the Gaussian function and its error returned by the best fit to derive  $N_{ul}$ , the 90% credibility upper limit to the number of events contributed by a narrow resonance.<sup>5</sup> We evaluate the ratio of the geometric and kinematic acceptance for an  $\mathcal{E}$  resonance to that for the  $\Upsilon(1S)$  meson with the previously described Monte Carlo simulation. The geometric and kinematic acceptance

<sup>4</sup>When simulating  $\mathcal{E}$  states, the transverse momentum distribution is rescaled from that of the  $\Upsilon(1S)$  data so that  $\langle p_T^{\mathcal{E}} \rangle / \langle p_T^{\Upsilon(1S)} \rangle = m_{\mathcal{E}}/m_{\Upsilon(1S)}$ . For  $J/\psi$  mesons, this rescaling procedure predicts a  $d\sigma/dp_T$  distribution that decreases more rapidly with increasing momenta than the distribution of the data. However, a poor modeling of the transverse momentum distribution is not a cause of significant error because the kinematic acceptance does not depend on the  $\mathcal{E}$  transverse momentum within a couple of percent.

<sup>5</sup>The integral of the fit likelihood from  $N_{ul}$  to infinity is 10% of the integral of the fit likelihood from 0 to infinity. The justification for this procedure is Bayesian with a prior that is zero for negative resonance cross sections and flat for positive ones.

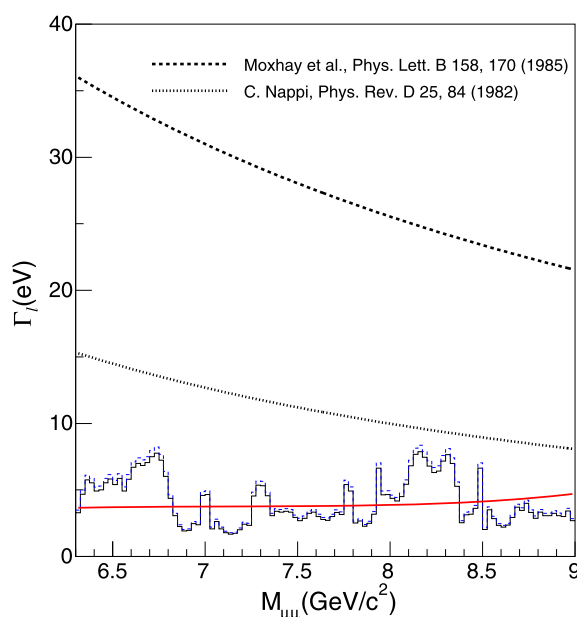


**Fig. 2** Bayesian 90% upper credible limits (*histogram*) to  $\frac{\sigma_{\mathcal{E}} BR(\mathcal{E} \rightarrow \mu\mu)}{\sigma_{\Upsilon(1S)} BR(\Upsilon(1S) \rightarrow \mu\mu)}$  as a function of the dimuon invariant mass. The *dashed histogram* represents limits that include the 6% systematic uncertainty. The *solid line* represents the limits expected when fits return no  $\mathcal{E}$  events

depends on the resonance mass and increases from 65.5% of that of the  $\Upsilon(1S)$  meson for  $m_{\mathcal{E}} = 6.3 \text{ GeV}/c^2$  to 97.4% for  $m_{\mathcal{E}} = 9.0 \text{ GeV}/c^2$ . Small data-to-simulation correction factors for the trigger and reconstruction efficiency [21, 27] depend little on the muon  $p_T$  and are neglected as in the study in Ref. [7]. The kinematic acceptance for  $\Upsilon(1S)$  mesons depends on their polarization. If  $\Upsilon(1S)$  mesons are produced longitudinally polarized, the acceptance increases by 5%, whereas it decreases by 3% if  $\Upsilon(1S)$  mesons are produced transversely polarized. The current knowledge of the polarization of  $\Upsilon(1S)$  mesons produced at the Tevatron [28, 29] yields an additional 3% systematic uncertainty on the ratio of the  $\mathcal{E}$  to  $\Upsilon(1S)$  production cross sections. The total systematic uncertainty on the ratio (6%) is added in quadrature to the statistical errors returned by the fits.

The 90% credibility upper limit to  $R$  is given by the ratio of  $N_{ul}$  to the number of observed  $\Upsilon(1S)$  mesons, corrected for the relative acceptance. These limits are shown in Fig. 2 as a function of the  $\mathcal{E}$  mass. Figure 3 shows the 90% upper credible limits to  $\Gamma_l^{\mathcal{E}}$ . The latter limits are derived under the assumption<sup>6</sup> that  $\sigma_{\mathcal{E}} BR(\mathcal{E} \rightarrow \mu\mu) = \sigma_{\Upsilon(1S)} BR(\Upsilon(1S) \rightarrow \mu\mu) \times (m_{\Upsilon(1S)}/m_{\mathcal{E}})^3 \times \Gamma_{\mu}^{\mathcal{E}}/\Gamma_{\mu}^{\Upsilon(1S)}$  [7].

<sup>6</sup>As noted in Ref. [7], this equation tends to underestimate the production cross section of states lighter than the  $\Upsilon(1S)$  meson. If this were the case, the  $\Gamma_l^{\mathcal{E}}$  limits set by our study would be correspondingly smaller than those indicated in Fig. 3.



**Fig. 3** Bayesian 90% upper limits to  $\Gamma_l^{\mathcal{E}}$  (*histogram*). The *dashed histogram* represents limits that include the 6% systematic uncertainty. The *solid line* represents the limits expected when fits return no  $\mathcal{E}$  events. The *dashed and dotted lines* represent the leptonic widths of  $1^{--}$  bound states of scalar quarks predicted in Refs. [4] and [30], respectively

### 5 Conclusions

We present a study of the invariant mass spectrum of oppositely-charged muon pairs produced at the Fermilab Tevatron collider and collected by the CDF experiment. This study improves previous limits to the existence of narrow resonances  $\mathcal{E}$ , possible bound states of charge  $-1/3$  scalar quarks, in the invariant mass range 6.3–9.0  $\text{GeV}/c^2$ . Under the reasonable assumption that  $\Upsilon(1S)$  and  $\mathcal{E}$  mesons have analogous production mechanisms, we derive 90% upper credible limits to  $R$ , the ratio of the production cross section times muonic branching fraction of possible narrow resonances to that of the  $\Upsilon(1S)$  meson, of the order of 1%. Assuming that  $\sigma_{\mathcal{E}} BR(\mathcal{E} \rightarrow \mu\mu) = \sigma_{\Upsilon(1S)} BR(\Upsilon(1S) \rightarrow \mu\mu) \times (m_{\Upsilon(1S)}/m_{\mathcal{E}})^3 \times \Gamma_{\mu}^{\mathcal{E}}/\Gamma_{\mu}^{\Upsilon(1S)}$ , these limits correspond to 90% upper credible limits smaller than 10 eV to the leptonic width of possible narrow resonances.

**Acknowledgements** 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 Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique



des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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