Physics Letters B 698 (2011) 21–39

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for a heavy gauge boson W′ in the final state with an electron and large missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ARTICLE INFO

Article history:
Received 29 December 2010
Received in revised form 8 February 2011
Accepted 19 February 2011
Available online 24 February 2011
Editor: M. Doser

Keywords:
CMS
Physics
Particle physics
LHC

ABSTRACT

A search for a heavy gauge boson W′ has been conducted by the CMS experiment at the LHC in the decay channel with an electron and large transverse energy imbalance $E_{\mathrm{T}}^{\mathrm{miss}}$, using proton–proton collision data corresponding to an integrated luminosity of 36 pb^{-1}. No excess above standard model expectations is seen in the transverse mass distribution of the electron-$E_{\mathrm{T}}^{\mathrm{miss}}$ system. Assuming standard-model-like couplings and decay branching fractions, a W′ boson with a mass less than 1.36 TeV/c^2 is excluded at 95% confidence level.

This Letter describes a search for a heavy analogue of the standard model W gauge boson, W′, where the particle decays leptonically to an electron and a neutrino ($\mathrm{W}' \to \mathrm{e}\nu$). Heavy partners of gauge bosons are predicted in many extensions to the standard model (SM), such as left–right symmetric models and supersymmetric grand unified theories [1–3]. The sensitivity to searches of new heavy bosons is usually explored using a reference model from Ref. [4], in which the W′ is a copy of the W boson with the same left-handed fermionic couplings. Interactions with the SM gauge bosons are excluded, as are interactions with other heavy gauge bosons such as a Z′. Thus, the W′ decay modes and branching fractions are similar to those of the W boson, with the notable exception of the $\mathrm{t\bar{b}}$ channel, which opens for W′ masses beyond 180 GeV/c^2. The leptonic branching fraction is $\mathcal{B}(\mathrm{W}' \to \mathrm{e}\nu) = 8.5\%$ for all masses considered. In searches directly comparable to this one, the CDF and D0 experiments at the Fermilab Tevatron have excluded masses below 1.1 TeV/c^2 [5,6]. Here we report the result of a W′ search using 36.1 ± 4.0 pb^{-1} of data collected between March and October 2010 in pp collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV with the Compact Muon Solenoid (CMS) experiment at the CERN Large Hadron Collider (LHC).

A detailed description of the CMS detector can be found elsewhere [7]. We use a cylindrical coordinate system about the beam axis in which θ is the polar angle with respect to the counterclockwise beam direction, ϕ is the azimuthal angle, and $\eta \equiv -\ln\tan(\theta/2)$. The transverse energy is $E_{\mathrm{T}} \equiv E\sin\theta$, where E is defined as energy measured by the calorimeters. The detectors used for this analysis include the pixel and silicon strip trackers. They provide coverage in the region $|\eta| < 2.5$ and are immersed in a 3.8 T magnetic field to allow momentum determination of charged particles. The electromagnetic and hadron calorimeters are used to detect energy deposits from electrons in the range $|\eta| < 2.5$ as well as to provide an estimate of missing transverse energy due to escaping particles. The electromagnetic calorimeter has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The energy resolution is 3% or better for the range of electron energies relevant for this analysis.

Signal events would be characterized by the presence of a high-energy electron and a large energy imbalance due to the undetected escaping neutrino. To acquire the data, we employ a collection of single-electron triggers with several trigger thresholds, which were changing frequently because of the evolving beam conditions during 2010. The bulk of the data were collected with a trigger requiring an electron with $E_{\mathrm{T}}^{\mathrm{ele}} > 22$ GeV. An electron is reconstructed as an energy deposit in the electromagnetic calorimeter (referred to as a "super-cluster") with a track pointing towards it. The electron track reconstruction is based on a Gaussian sum filter algorithm [8] which takes into account bremsstrahlung emissions along the electron trajectory. Electron tracks pointing towards the transition region between the barrel and endcap detectors in the electromagnetic calorimeter are rejected. Other requirements include matching criteria in η and ϕ between the super-cluster and the track, and the consistency of the transverse shape of the

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doi:10.1016/j.physletb.2011.02.048

energy deposit with that expected for an electron. The electrons must have a transverse energy greater than 30 GeV, and should be isolated in a cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ around the electron candidate direction, both in the tracker and in the calorimeter. In the tracker, the sum of the p_T of the tracks, excluding tracks within an inner cone of 0.04, is required to be less than 7 (15) GeV for electron candidates reconstructed within the barrel (endcap) acceptance. For the isolation using calorimeters, the total transverse energy in the barrel, excluding deposits associated to the electron, should be less than $0.03 \cdot E_T^{ele} + 2.0$ GeV. In the endcap, the isolation exploits the segmentation of the hadron calorimeter to minimize contamination from the multi-jet background. For electrons in the endcap with $E_T^{ele} > 50$ GeV, the sum of E_T of deposits in the electromagnetic and the first segment of the hadron calorimeter, not associated to the electron itself, must be less than $0.03 \cdot (E_T^{ele} - 50) + 2.5$ GeV. For endcap electrons of less than 50 GeV the sum of E_T should be below 2.5 GeV. The E_T of deposits in the second segment of the hadron calorimeter must be less than 0.5 GeV [9]. These selections are designed to ensure high efficiency for electrons and a high rejection of misreconstructed electrons from multi-jet backgrounds. Since the amount of background from multi-jet events differs in the central and the forward region, the selections described are optimized for high energy electrons separately in the two regions [9].

To account for the energy imbalance due to the escaping neutrino, we use a particle flow technique, which reconstructs a complete list of particles in an event using all the available information [10]. Muons, electrons, photons, and charged and neutral hadrons are reconstructed individually. We denote the negative vector sum of the energy of all reconstructed particles in the event projected on the transverse plane as E_T^{miss}. It represents an estimate of the vector sum of the transverse momentum of all escaping neutral particles, such as neutrinos.

Since we are searching for a two-body decay which reconstructs to a high mass, the energy of the neutrino and electron are expected to be mostly balanced in the transverse plane, both in direction and in magnitude. We therefore require $0.4 < E_T^{ele}/E_T^{miss} < 1.5$. For the same reason, we require that the angle between the electron and the E_T^{miss} be close to π radians: $\Delta\phi_{e E_T^{miss}} > 2.5$ rad.

The primary discriminating variable is the transverse mass M_T. The transverse mass is the equivalent of the invariant mass of a four-vector computed with only the transverse components of those four-vectors: $M_T = \sqrt{2 \cdot E_T^{ele} \cdot E_T^{miss} \cdot (1 - \cos\Delta\phi_{e E_T^{miss}})/c^2}$. As with a W, we expect the M_T distribution of W′ events to exhibit a characteristic Jacobian edge at the value of the mass of the decaying particle.

After applying these event selection criteria, the main background consists of $W \to e\nu$ decays in the tails of the SM W mass distribution. Given the high transverse mass of a potential signal, multi-jet production constitutes a background when one jet is misreconstructed and the E_T^{miss} is a result of this misreconstruction. Further contributions are due to $W \to \tau\nu$ decays where the tau–lepton subsequently decays to an electron and neutrinos. Since these electrons result from several preceding decays, their energies are rather low and do not spread much into the signal region. Electrons from semi-leptonic decays of $t\bar{t}$ events may also constitute a background primarily at low energies. Small contributions are caused by Drell–Yan Z/γ production followed by decays into e^+e^- pairs where one electron is not detected, diboson production and other QCD backgrounds such as γ + jet. All backgrounds are summarized in Table 1.

Estimates of the M_T distribution for all backgrounds except for the two backgrounds, $W \to e\nu$ and multi-jet events,

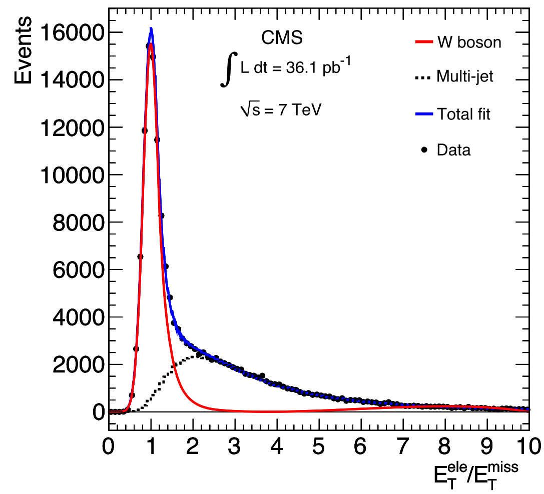

Fig. 1. Distributions of the variable E_T^{ele}/E_T^{miss}. The curves show the result of a simultaneous fit of the normalizations of multi-jet and W background shapes to the data, after subtraction of the contribution of the other backgrounds.

are obtained using Monte Carlo simulations, with a combination of PYTHIA v6.422 [11] and MADGRAPH [12] event generators. The geometric and kinematic acceptances are calculated using a GEANT-based simulation of the CMS detector [13]. The CTEQ6L1 parton distribution functions are used to model the momentum distribution of the initial-state partons [14]. For the signal sample, the PYTHIA event generator with its implementation of the reference model [4] is used at varying mass points up to $M_{W'} = 2.0$ TeV/c^2. A mass-dependent K-factor of about 1.3 approximating the next-to-next-to-leading-order (NNLO) cross sections is applied [15,16], varying between 1.26 (for $M_{W'} = 2$ TeV/c^2) and 1.32 (for $M_{W'} = 0.6$ TeV/c^2). After the final event selections, the product of geometric acceptance and efficiency for the W′ signal is greater than 64%, independent of mass, for the range $M_{W'} = 0.9$–2.0 TeV/c^2. The electron identification efficiency is measured with the tag-and-probe method in data and simulation using a clean sample of $Z \to e^+e^-$. In this method one lepton candidate, called the "tag", satisfies certain selection criteria while the other lepton candidate, called the "probe", is required to pass specific criteria which define the particular efficiency under study. This method measured the electron identification efficiency to be about 2% lower in data than in Monte Carlo simulations and therefore a correction factor was applied to the simulation.

The W and multi-jet background estimates are derived from a combination of experimental data and Monte Carlo simulations. For the $W \to e\nu$ background, we obtain an initial estimate of the M_T shape from simulations using the PYTHIA event generator. Differences in the E_T^{miss} resolution between the data and simulations are corrected using a technique based on the measurement of E_T^{miss} in $Z \to e^+e^-$ events [17]. The absolute normalizations of the multi-jet and W backgrounds are obtained using the E_T^{ele}/E_T^{miss} distribution. A Crystal Ball [18] function is used to describe the distribution for W bosons and an empirical shape is used for the multi-jet background, while for all other backgrounds the distributions and the normalisations are fixed to the standard model predictions. After subtraction of the latter backgrounds, a simultaneous fit to the E_T^{ele}/E_T^{miss} distribution in the data provides the multi-jet and W normalizations. Fig. 1 shows the result of this fit.

Table 1 shows the resulting number of predicted background and observed events. The background estimate models the number of observed events well, including the low transverse mass region ($M_T > 45$ GeV/c^2), which contains most of the W-boson sample and provides a validation of the background model. For $M_T > 400$ GeV/c^2 the total expected background amounts to

Table 1
Standard model background predictions and observed event counts, as a function of minimum M_T requirement, in units of GeV/c^2. The errors include statistical and systematic uncertainties, but not the uncertainty on the luminosity normalization.

Sample	> 45	> 200	> 300	> 400	> 500	> 600
$W \to e\nu$	75609 ± 319	33.7 ± 2.7	7.19 ± 0.91	2.52 ± 0.48	0.88 ± 0.28	0.57 ± 0.21
Multi-jet	7083 ± 3546	6.3 ± 3.3	1.64 ± 0.93	0.47 ± 0.33	0.23 ± 0.20	0.23 ± 0.20
$W \to \tau\nu$	1083 ± 80	1.1 ± 0.3	0.21 ± 0.19	< 0.13	< 0.08	< 0.08
$t\bar{t}$	60 ± 23	4.1 ± 1.7	0.64 ± 0.29	0.15 ± 0.09	0.03 ± 0.03	0.01 ± 0.02
Other bkg	359 ± 73	2.0 ± 0.4	0.56 ± 0.14	0.15 ± 0.05	0.06 ± 0.03	0.04 ± 0.03
Total bkg	84194 ± 3563	47.2 ± 4.7	10.24 ± 1.35	3.29 ± 0.61	1.21 ± 0.35	0.85 ± 0.30
Data	84468	38	8	2	0	0

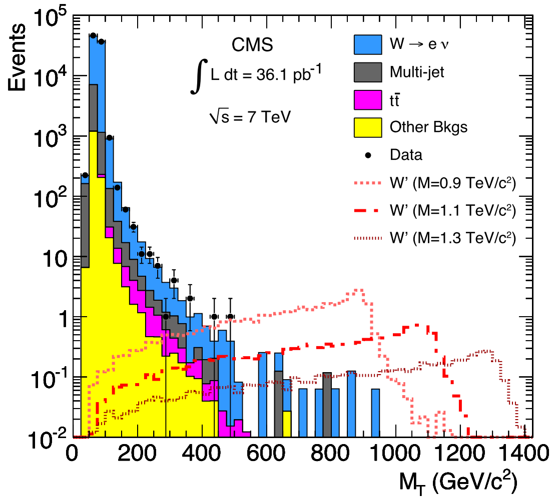

Fig. 2. Transverse mass distributions for all estimated standard model backgrounds and for CMS data. Here, other backgrounds also includes $W \to \tau\nu$, in addition to the combined "other" backgrounds in Table 1. The hashed lines represent the expected M_T distributions for a W′ signal with three different W′ masses.

3.29 ± 0.61 events, out of which 75% are caused by W bosons and 15% by QCD. No $W \to \tau\nu$ event is expected and a 68% confidence limit (C.L.) upper limit is given in Table 1. Contributions caused by $t\bar{t}$ are extremely small as well, of the same order as other backgrounds, which include Drell–Yan, dibosons and γ + jets.

In evaluating the systematic uncertainties, we consider estimates of the acceptance and efficiency for reconstructing electrons (for the W′ signal yield) as well as the uncertainty associated with the background. For those backgrounds that are not derived from data, an uncertainty on the absolute value of the integrated luminosity is included, taken as 11% [19], along with uncertainties on the cross sections ranging from 5% for diboson and $Z \to \ell^+\ell^-$ to 39% for $t\bar{t}$ [20] using the CMS measurement for the latter. With respect to electrons, reconstruction and identification efficiency uncertainties of 1.9 and 1.5%, respectively, are included for signal and backgrounds as determined in an analysis of $Z \to e^+e^-$ events. For the electron energy scale an uncertainty of 1% in the central section and 3% for electrons in the endcaps of the electromagnetic calorimeter [21] is included. For the E_T^{miss} resolution we assume an uncertainty of 10% [22], applied as an extra smearing to the reconstructed E_T^{miss} in the simulation. The impact on the number of events from all backgrounds is below 1%. A similar approach is used to evaluate the impact of the E_T^{miss} scale. A shift of 5% is applied event by event to the E_T^{miss} scale [23] and the impact on the event count for $M_T > 200$ GeV/c^2 is found to be smaller than 10% for all backgrounds considered. For the $W \to e\nu$ background, the E_T^{miss} and its associated uncertainty are derived using the hadronic recoil correction. If we examine a region $M_T > 200$ GeV/c^2, the resulting uncertainty on the predicted number of event counts is 8% for the main background $W \to e\nu$ (dominated by the uncertainties on the shape of the M_T distribution due to the energy scale uncertainty) and 50% for the sub-dominant multi-jet background (studied by inverting the isolation requirement and analyzing the multi-jet template in bins of M_T). The uncertainty on the number of signal events, shown in Table 2, is dominated by the luminosity uncertainty (11%) unlike the number of background events which is dominated by the electron and E_T^{miss} scale and resolution uncertainties (in total 28.7%). The limits reported in the same table are relatively insensitive to systematic uncertainties.

With all background estimates in hand, we examine the data for evidence of non-SM events. Fig. 2 shows the CMS data overlaid with background expectations. Since no excess is observed in the data beyond the SM background prediction, we set a lower bound on the mass of the W′ boson in the reference model. For each mass point, we choose a minimum M_T requirement that provides the best *a priori* limit and use the M_T region above this threshold as the search window.

The resultant minimum M_T requirement ranges from 400 to 675 GeV/c^2 across the W′ mass range and is shown in Table 2 along with the corresponding number of potential signal and background events. The errors include all systematic uncertainties. The number of events found in data is also shown. The highest transverse mass event we observe has $M_T = 493$ GeV/c^2 and is shown in Fig. 3.

We use a Bayesian technique to determine an upper limit on the cross section as a function of the W′ boson mass with a C.L. of 95%, following the method described in [24]. We assume a flat prior probability distribution for the cross section. To incorporate the systematic uncertainties described above, we treat them as nuisance parameters and use a log-normal distribution to integrate over these parameters. Fig. 4 shows both the expected and the observed limit. The uncertainty on the theoretical cross section was determined by re-weighting each event using all the eigenvectors of the CTEQ6 PDF set. We exclude the existence of W′ bosons with standard model-like couplings and branching fractions with masses up to 1.36 TeV/c^2 at 95% C.L. using the central value of the theoretical cross section.

In summary, we have performed a search for a heavy gauge boson W′ in the decay channel with an electron and large transverse energy imbalance. We observe no excess over the background. A new W boson-like gauge particle with standard-model-like couplings and branching fractions up to a mass of 1.36 TeV/c^2 is excluded by the data, the most stringent limit to date.

Acknowledgements

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China);

Table 2
Lower M_T requirement as a function of W′ mass and expected and observed data counts. The entries n_s, n_b and n_d correspond to the expected signal and background counts and the observed data counts, respectively. The cross sections σ_t, σ_e and σ_o correspond to the theoretical W′ production cross section and the expected and observed limits, respectively. The errors include all systematic uncertainties.

$M_{W'}$ (TeV/c^2)	min M_T (TeV/c^2)	n_s	n_b	n_d	σ_t (pb)	σ_e (pb)	σ_o (pb)
0.6	0.400	129.38 ± 20.16	3.29 ± 0.61	2	8.290	0.379	0.289
0.7	0.500	60.77 ± 9.61	1.21 ± 0.35	0	4.264	0.314	0.215
0.8	0.500	39.54 ± 6.08	1.21 ± 0.35	0	2.426	0.274	0.188
0.9	0.500	25.24 ± 3.85	1.21 ± 0.35	0	1.389	0.246	0.168
1.0	0.500	16.10 ± 2.45	1.21 ± 0.35	0	0.838	0.232	0.159
1.1	0.500	10.06 ± 1.53	1.21 ± 0.35	0	0.516	0.229	0.157
1.2	0.650	6.02 ± 0.92	0.60 ± 0.24	0	0.334	0.215	0.170
1.3	0.675	3.92 ± 0.60	0.51 ± 0.21	0	0.215	0.207	0.168
1.4	0.675	2.52 ± 0.38	0.51 ± 0.21	0	0.136	0.203	0.164
1.5	0.675	1.89 ± 0.29	0.51 ± 0.21	0	0.099	0.196	0.159
2.0	0.675	0.27 ± 0.04	0.51 ± 0.21	0	0.014	0.206	0.167

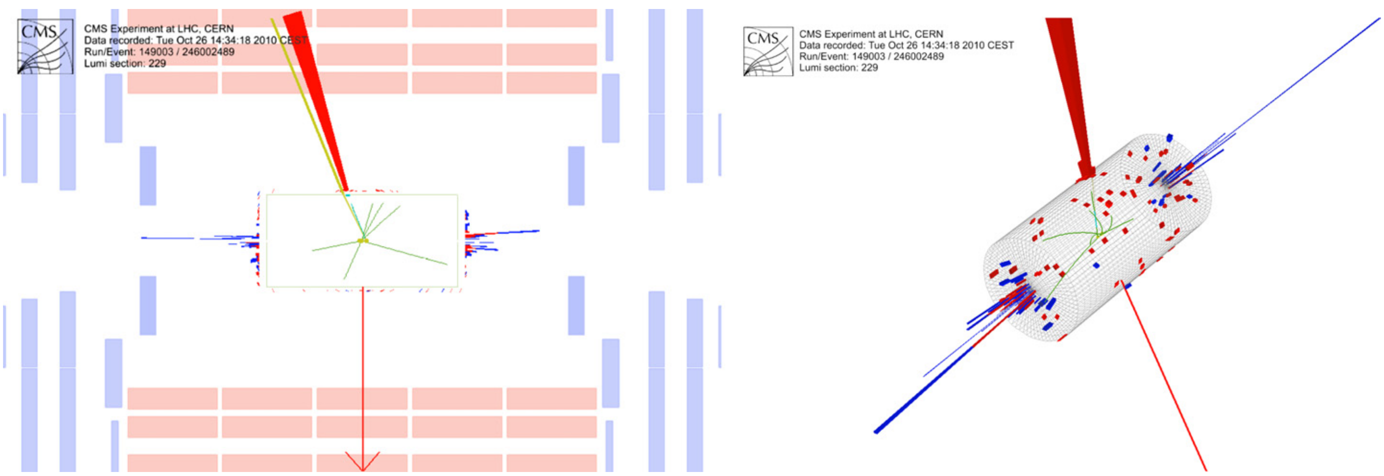

Fig. 3. Displays of the highest M_T event. The projection on the left shows the envelope of the inner tracking detector along with the electromagnetic and hadron calorimeters, and part of the muon system. The 3D view on the right shows an enlarged view of the inner region. Charged particle tracks as well as the deposited energy per calorimeter cell are displayed. The electron energy and E_T^{miss} are shown in red, with the amount of energy represented graphically by the length of the bar. For scale, the largest tower in the electromagnetic calorimeter has an energy of 258 GeV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

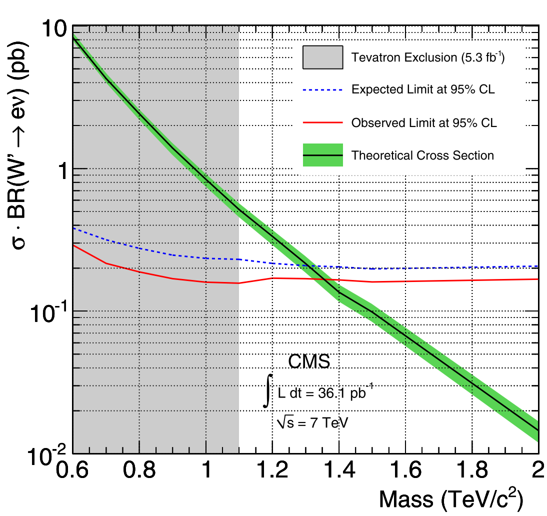

Fig. 4. Limit using a Bayesian technique with a counting experiment in the search window, for the reference model. The intersection of the cross section limit curve and the central value of the theoretical cross section yields a lower limit of $M_{W'} > 1.36$ TeV/c^2 at 95% C.L. for the assumed $\sigma \times \mathcal{B}(W' \to e\nu)$.

COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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