# Search for high-mass states with one lepton plus missing transverse momentum in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector ☆

ATLAS Collaboration ★

**A B S T R A C T**

The ATLAS detector is used to search for high-mass states, such as heavy charged gauge bosons ($W'$, $W^*$), decaying to a charged lepton (electron or muon) and a neutrino. Results are presented based on the analysis of $pp$ collisions at a center-of-mass energy of 7 TeV corresponding to an integrated luminosity of 36 pb$^{-1}$. No excess beyond standard model expectations is observed. A $W'$ with sequential standard model couplings is excluded at 95% confidence level for masses below 1.49 TeV, and a $W^*$ (charged chiral boson) for masses below 1.35 TeV.

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Although the standard model (SM) of strong and electroweak interactions is remarkably consistent with particle physics observations to date, the high-energy collisions at the CERN Large Hadron Collider provide new opportunities to search for physics beyond it. One extension common to many models is the existence of additional heavy gauge bosons [1], the charged ones commonly denoted $W'$. Such particles are most easily searched for in their decay to a charged lepton (either electron or muon) and a neutrino.

In this Letter, 7 TeV $pp$ collision data collected with the ATLAS detector during 2010 and corresponding to a total integrated luminosity of 36 pb$^{-1}$ are used to supplement current limits [2–6] on $\sigma B$ (cross section times branching fraction) as a function of $W'$ mass. A lower limit on the mass of a $W'$ boson in the sequential standard model (SSM) [7] is also reported. In this model, the $W'$ has the same couplings to fermions as the SM $W$ boson and thus a width which increases linearly with $W'$ mass.

Limits are also established for $W^*$, the charged partner of the chiral bosons described in [8]. Theoretical motivation for such bosons is provided in [9]. The anomalous (magnetic-moment type) coupling of the $W^*$ leads to kinematic distributions significantly different from those of the $W'$. To fix the coupling strength, a model with total and partial decay widths equal to those of the SSM $W'$ with the same mass is adopted [10].

The analysis presented here identifies candidates in the electron and muon channels, sets separate limits for $W'/W^* \to e\nu$ and

$W'/W^* \to \mu\nu$, and derives combined limits assuming the same branching fraction for both channels. The kinematic variable used to identify the $W'/W^*$ is the transverse mass

$$m_T = \sqrt{2p_T E_T^{\mathrm{miss}}(1 - \cos\varphi_{l\nu})} \tag{1}$$

which displays a Jacobian peak that, for $W' \to \ell\nu$, falls sharply above the resonance mass. Here $p_T$ is the lepton transverse momentum, $E_T^{\mathrm{miss}}$ is the magnitude of the missing transverse momentum (missing $E_T$), and $\varphi_{l\nu}$ is the angle between the $p_T$ and missing $E_T$ vectors. Throughout this Letter, transverse refers to the plane perpendicular to the colliding beams, longitudinal means parallel to the beams, $\theta$ and $\varphi$ are the polar and azimuthal angles with respect to the longitudinal direction, and pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$.

The main background to the $W'$ and $W^*$ signals comes from the high-$m_T$ tail of SM $W \to \ell\nu$ decay. Other backgrounds are $Z$ bosons decaying into two leptons where one lepton is not reconstructed, $W$ or $Z$ decaying to $\tau$-leptons where the $\tau$ subsequently decays to an electron or muon, and diboson production. These are collectively referred to as the electroweak (EW) background. In addition, there is a background contribution from $t\bar{t}$ production which is most important for the lowest $W'/W^*$ masses considered here where it constitutes about 20% of the background after final selection. Other background sources, where a light or heavy hadron decays semileptonically or a jet is misidentified as an electron, are estimated to be at most 3% of the total background (with the uncertainty on this estimate less than 10% of the total background level). These are called QCD background in the following.

The ATLAS detector [11] has three major components: the inner (tracking) detector, the calorimeter and the muon spectrometer.

Charged particle tracks and vertices are reconstructed with silicon pixel and silicon strip detectors covering $|\eta| < 2.5$ and transition radiation detectors covering $|\eta| < 2.0$, all immersed in a homogeneous 2 T magnetic field provided by a superconducting solenoid. This tracking detector is surrounded by a finely-segmented, hermetic calorimeter system that covers $|\eta| < 4.9$ and provides three-dimensional reconstruction of particle showers. It uses liquid argon for the inner electromagnetic compartment followed by a hadronic compartment based on scintillating tiles in the central region ($|\eta| < 1.7$) and additional liquid argon for higher $|\eta|$. Outside the calorimeter, there is a muon spectrometer with air-core toroids providing a magnetic field, whose integral averages about 3 Tm. Three stations of drift tubes and cathode strip chambers provide precision measurements and resistive-plate and thin-gap chambers provide muon triggering capability and measurement of the $\varphi$ coordinate.

Most of the data were recorded with highly efficient triggers requiring the presence of an electron or muon candidate with $p_T > 20$ GeV. Lower thresholds were used for the early data.

Each energy cluster reconstructed in the electromagnetic compartment of the calorimeter with $E_T > 20$ GeV and $|\eta| < 2.47$ is considered as an electron candidate if it loosely matches with an inner detector track. The electron direction is defined as that of the reconstructed track and its energy as that of the cluster. The intrinsic resolution of the energy measurement is about 2% at 50 GeV, improving to approximately 1% at 200 GeV. Electron candidates with clusters containing cells overlapping with the few problematic regions of the calorimeter readout are removed. This reduces the acceptance by 8%.

Electrons are further identified based on lateral shower shapes in the first two layers of the electromagnetic part of the calorimeter and the fraction of energy leaking into the hadronic compartment. A hit in the first pixel layer is also required to reduce background from photon conversions in the inner detector material. These requirements give about 89% identification efficiency for electrons with $E_T > 25$ GeV and a 1/5000 probability to falsely identify jets as electrons before isolation requirements are imposed [12].

Muon tracks can be reconstructed independently in both the inner detector and muon spectrometer, and the muons used in this study are required to have matching tracks in both systems. The high-$p_T$ resolution of the inner detector and muon spectrometer systems is sensitive to detector alignment. The muons used for this analysis are restricted to those which pass through the barrel part of the muon spectrometer, $|\eta| < 1.05$, where the muon spectrometer alignment is best understood, in particular using high-energy cosmic rays [13]. The momentum of the muon is obtained from the muon spectrometer and the average momentum resolution is currently about 20% at $p_T = 1$ TeV. Muons are required to have hits in all three muon stations to ensure this precise measurement of the momentum. About 80% of the muons in the barrel are reconstructed, with most of the loss coming from regions with limited detector coverage.

For the electron channel, the missing $E_T$ is obtained from a vector sum over calorimeter cells associated with topological clusters [14]:

$$\mathbf{E}_T^{\text{miss}} = \mathbf{E}_{T\,\text{calo}}^{\text{miss}} = -\sum_{\text{topo}} \mathbf{E}_T^{\text{clus}}. \qquad (2)$$

In the muon channel, most of the muon energy is not deposited in the calorimeter and the missing $E_T$ is obtained from

$$\mathbf{E}_T^{\text{miss}} = \mathbf{E}_{T\,\text{calo}}^{\text{miss}} - \mathbf{p}_T^{\mu} + \mathbf{E}_T^{\mu,\text{loss}}, \qquad (3)$$

where the second term in this vector sum subtracts the muon transverse momentum and the last corrects for the transverse

**Table 1**

Calculated values of $\sigma B$ for $W'$, $W^*$ and the leading backgrounds. The value for $t\bar{t} \to \ell X$ includes all final states with at least one lepton ($e$, $\mu$ or $\tau$). The others are exclusive and are used for both $\ell = e$ and $\ell = \mu$.

| Process | Order | Mass [GeV] | $\sigma B$ [pb] |
|---|---|---|---|
| $W' \to \ell \nu$ | NNLO | 500 | 17.25 |
| | | 750 | 3.20 |
| | | 1000 | 0.837 |
| | | 1250 | 0.261 |
| | | 1500 | 0.0887 |
| | | 1750 | 0.0325 |
| $W^* \to \ell \nu$ | LO | 500 | 12.6 |
| | | 750 | 2.34 |
| | | 1000 | 0.610 |
| | | 1250 | 0.188 |
| | | 1500 | 0.0636 |
| | | 1750 | 0.0226 |
| $W \to \ell \nu$ | NNLO | | 10 460 |
| $Z/\gamma^* \to \ell\ell$ | NNLO | | 989 |
| ($m_{Z/\gamma^*} > 60$ GeV) | | | |
| $t\bar{t} \to \ell X$ | Near-NNLO | | 89.4 |

component of the energy deposited in the calorimeter by the muon which is included in both of the first two terms. The energy loss is estimated by integrating the amount of material traversed and applying a calibrated conversion from path length to energy for each material type.

This analysis makes use of all the $\sqrt{s} = 7$ TeV data collected in 2010 that satisfy data quality requirements which guarantee the relevant detector systems were operating properly. The integrated luminosity for the data used in this study is 36 pb$^{-1}$ for each channel. The uncertainty on this estimate is 11% [15].

The $W'$ signal and the $W/Z$ boson backgrounds are generated with Pythia 6.421 [16] using MRST LO* [17] parton distribution functions (PDFs). The $t\bar{t}$ background is generated with Mc@nlo 3.41 [18]. $W^* \to \ell\nu$ events are generated with CompHEP [19] using CTEQ6L1 [20] PDFs followed by Pythia for parton showering and underlying event generation. For all samples, final-state photon radiation is handled by Photos [21] and the propagation of particles and response of the detector are evaluated using ATLAS full detector simulation [22] based on Geant4 [23].

The Pythia signal model for $W'$ has $V\text{–}A$ SM couplings but does not include interference between $W$ and $W'$. Decays to channels other than $e\nu$ and $\mu\nu$, including $\tau\nu$, $ud$, $sc$ and $tb$, are included in the calculation of the $W'$ and $W^*$ widths but are not explicitly included as signal or background.

The $W' \to \ell\nu$, $W \to \ell\nu$ and $Z \to \ell\ell$ cross sections are calculated at next-to-next-to-leading order QCD (NNLO) using FEWZ [24,25] with MSTW2008 PDFs [26]. For the $W$ and $Z$, higher-order electroweak corrections (beyond the photon radiation included in the simulation) are calculated using Horace [27,28]. In the high-mass region of interest, the electroweak corrections reduce the cross sections, with the reduction increasing with mass. For $m_T > 750$ GeV, the electroweak corrections reduce the $W \to \ell\nu$ cross section by 6%. Electroweak corrections beyond final-state radiation are not included for $W'$ because the calculation for the SM $W$ cannot be applied directly. The $t\bar{t}$ cross section is calculated at near-NNLO using the results from Ref. [29] and assuming a top-quark mass of 172.5 GeV. The signal and most important background cross sections are listed in Table 1. Cross-section uncertainties for $W' \to \ell\nu$ and the $W/Z$ [12] and $t\bar{t}$ [30] backgrounds are estimated from PDF error sets, the difference between MSTW and CTEQ PDF sets, and standard variations of renormalization and factorization scales. The uncertainties for the LO $W^* \to \ell\nu$ cross sections include only the contributions from the PDFs.
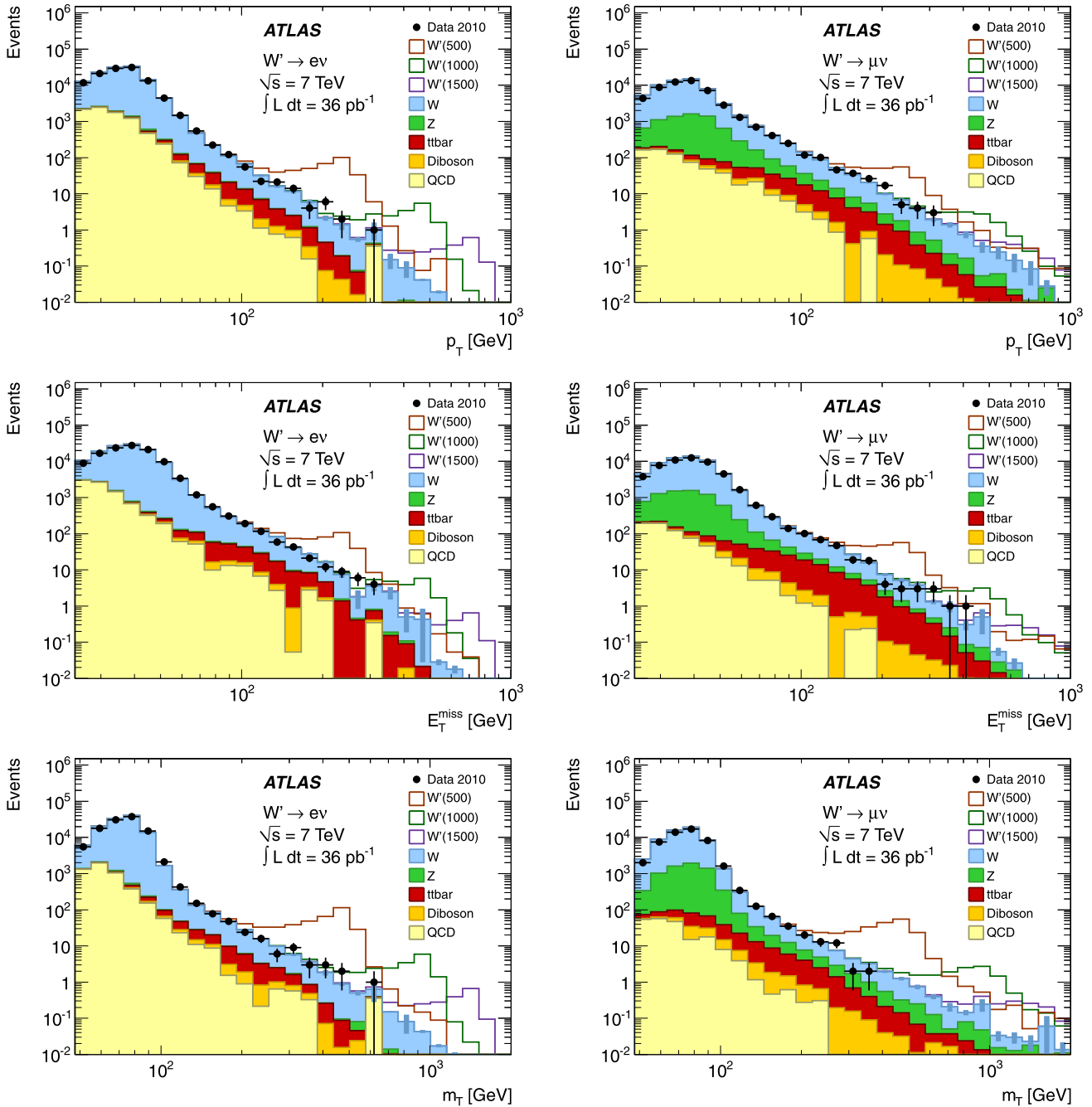
**Fig. 1.** Spectra of $p_T$ (top), missing $E_T$ (center) and $m_T$ (bottom) for the electron (left) and muon (right) channels after final event selection. The points represent ATLAS data and the filled histograms show the stacked backgrounds. Both direct production of leptons and indirect from $\tau$-leptons are included. Open histograms are $W'$ signals added to the background with masses in GeV indicated in parentheses in the legend. The QCD background is estimated from data. The signal and other background samples are normalized using the integrated luminosity of the data and the NNLO (near-NNLO for $t\bar{t}$) cross sections listed in Table 1.

Except for QCD and cosmic-ray contamination, expected signal and background levels are evaluated with simulated samples and normalized using the aforementioned cross sections and the integrated luminosity of the data. The same reconstruction and event selection are applied to both data and simulated samples.

Events are required to have a primary vertex reconstructed from at least three tracks with $p_T > 150$ MeV and longitudinal distance less than 150 mm from the center of the collision region. Spurious tails in missing $E_T$ arising from calorimeter noise and other detector problems are suppressed by checking the quality of each reconstructed jet and discarding events where any jet

has a shape indicating such problems (following Ref. [31]). Events are required to have exactly one candidate electron or one candidate muon, defined as follows. A candidate electron is one reconstructed with $E_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.40$. A muon is considered a candidate if it has $p_T > 25$ GeV, $|\eta| < 1.05$ and has matching tracks in the inner detector and muon spectrometer. In addition, the inner detector track associated with the electron or muon is required to be compatible with originating from the primary vertex, specifically with transverse distance of closest approach $|r_0| < 1$ mm and longitudinal distance at this point $|z_0| < 5$ mm.

**Table 2**

Expected number of events from the various background sources in both decay channels for $m_T > 750$ GeV, the region used to search for $W'/W^*$ with a mass of 1500 GeV. The $W \to \ell\nu$ and $Z \to \ell\ell$ entries include the expected contributions from the $\tau$-lepton. The uncertainties are statistical.

|  | $e\nu$ | $\mu\nu$ |
|---|---|---|
| $W \to \ell\nu$ | $0.145 \pm 0.001$ | $0.43 \pm 0.10$ |
| $Z \to \ell\ell$ | $0.0001 \pm 0.0001$ | $0.11 \pm 0.02$ |
| Diboson | $0.011 \pm 0.001$ | $0.01 \pm 0.01$ |
| $t\bar{t}$ | $0.003 \pm 0.003$ | $0.05 \pm 0.02$ |
| QCD | $0.001^{+0.004}_{-0.001}$ | $0.02^{+0.05}_{-0.01}$ |
| Cosmic ray |  | $0.006 \pm 0.003$ |
| Total | $0.159 \pm 0.005$ | $0.62 \pm 0.11$ |

The above requirements constitute the event preselection criteria. To suppress the QCD background, the lepton is required to be isolated. In the electron channel, the isolation energy is measured with the calorimeter in a cone $\Delta R < 0.4$ ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$) around the electron track and the requirement is $\sum E_T < 10$ GeV, where the sum excludes the core energy deposited by the electron and is corrected to account for leakage of the electron energy outside this core. In the muon channel, the isolation energy is measured using inner detector tracks with $p_T^{trk} > 1$ GeV in a cone $\Delta R < 0.3$ around the muon track. The isolation requirement is $\sum p_T^{trk} < 0.05 p_T$, where the muon track is excluded from the sum. The scaling of the threshold with the muon $p_T$ reduces efficiency losses due to radiation from the muon at high $p_T$.

Finally, a missing $E_T$ threshold is applied to further suppress the QCD background. In both channels, a fixed threshold is applied: $E_T^{miss} > 25$ GeV. In the electron channel, where QCD jets may be misidentified as electrons, a scaled threshold is also applied: $E_T^{miss} > 0.6 E_T$. Taken together, all the above constitute the final selection requirements.

Fig. 1 shows the $p_T$, missing $E_T$, and $m_T$ spectra in both channels after final selection for the data, for the expected background, and for three examples of $W'$ signals at different masses. The agreement between the data and expected background is good. Table 2 shows as an example how different sources contribute to the background for $m_T > 750$ GeV, which is the region used to search for a $W'$ or $W^*$ with a mass of 1500 GeV. There are significant differences between the background levels in the electron and muon channels. The background from $W \to \ell\nu$ and $t\bar{t}$ is higher in the muon channel because of the worse momentum resolution for high-$p_T$ muons. The difference is even larger for the $Z \to \ell\ell$ background because there is additionally a much larger chance that one lepton is lost due to the restricted acceptance in $\eta$. The QCD background in the electron channel is less than that in the muon channel because of the tighter electron selection criteria: an isolation threshold that is not scaled with $p_T$ and the addition of a scaled missing $E_T$ threshold.

In the electron channel, four techniques are used to estimate the QCD background level from data through the use of subsidiary samples which are disjoint from the analysis region. In the "Inverted identification" technique, the distributions of the QCD background as a function of $p_T$, missing $E_T$, or $m_T$ are estimated from events which pass relaxed identification criteria but fail the normal selection. The normalization is obtained by fitting the missing $E_T$ distribution plus the estimates for EW and $t\bar{t}$ to the observed data. The other techniques are described elsewhere: "Isolation templates" [12], "Three control regions" [32], "Matrix" [33,30]. Fig. 2 shows the estimates obtained from all four techniques after final selection as a function of $m_T$ along with the power-law fit to all four sets of results and its $1\sigma$ uncertainty band. The extrapolation of this fit and uncertainty band provides the estimate of the
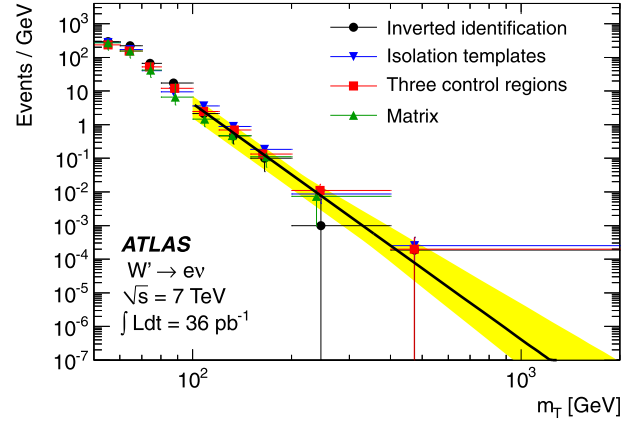


**Fig. 2.** Estimated QCD background as a function of $m_T$ in the electron channel after final selection as obtained from the four data-driven methods (see text). The power-law fit to all four sets of results and its $1\sigma$ uncertainty band are also shown.
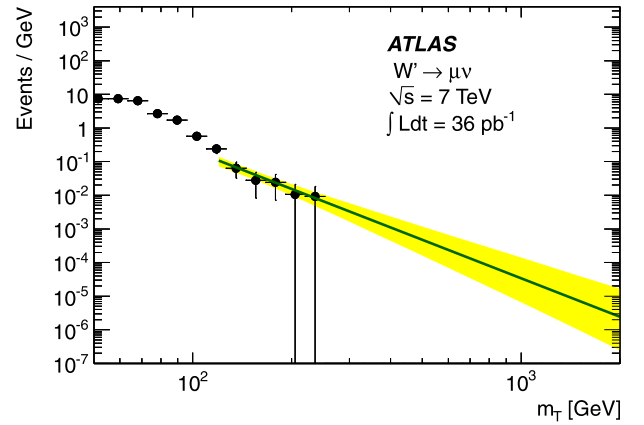


**Fig. 3.** Estimated QCD background as a function of $m_T$ in the muon channel after final selection as obtained from the data-driven method (see text). The unbinned power-law fit to the data and its $1\sigma$ uncertainty band are also shown.

QCD background level and uncertainty in the high-$m_T$ region used for the limit calculations.

The shape of the QCD background for the muon channel is evaluated by starting with the muon preselection and replacing the isolation threshold with a range of values in the non-isolated region: $0.2 < \sum p_T^{trk}/p_T < 0.4$. The normalization of the QCD background is determined by fitting the resulting missing $E_T$ spectrum plus the EW and $t\bar{t}$ predictions from simulation to the data after final selection, excluding the missing $E_T$ threshold. The isolation range used to determine the shape is varied to determine the uncertainty in the prediction for the QCD background level. Fig. 3 shows the predicted background level after final selection as a function of $m_T$ along with the unbinned power-law fit and its $1\sigma$ uncertainty band. The range of $m_T$ used for the fit is the one which gives largest values for the upper end of this band. The lower end of the uncertainty band corresponds to a negligible background level for all fits. The extrapolation of the fit and uncertainty band provides the QCD background level and uncertainty in the high-$m_T$ region used for the limit calculations.

Cosmic rays can mimic the signal in the muon channel if the muon is only reconstructed on one side of the detector. Most of this background is rejected by the requirement that the muon pass close to the primary vertex and the remainder is estimated by looking at the rate away from the vertex. The measured rate after final selection is less than 2% of the total background for any $m_T$ threshold relevant to this analysis.

The data show no evidence for any excess above SM expectations and are used to set limits on $\sigma B$ for $W'$ and $W^*$ production with the masses listed in Table 1. The limits are evaluated using a single-bin likelihood analysis, i.e. by counting events with $m_T > 0.5 m_{W'/W^*}$. The expected number of events in each channel is

$$N_{exp} = \varepsilon_{sig} L_{int} \sigma B + N_{bg}, \tag{4}$$

where $L_{int}$ is the integrated luminosity of the data sample and $\varepsilon_{sig}$ is the event selection efficiency, i.e. the fraction of events that pass final event selection criteria and have $m_T$ above threshold. $N_{bg}$ is the expected number of background events. Using Poisson statistics, the likelihood to observe $N_{obs}$ events is:

$$\mathcal{L}(\sigma B) = \frac{(L_{int}\varepsilon_{sig}\sigma B + N_{bg})^{N_{obs}} e^{-(L_{int}\varepsilon_{sig}\sigma B + N_{bg})}}{N_{obs}!} \tag{5}$$

and this expression is used to set limits on $\sigma B$. Uncertainties are handled by introducing nuisance parameters and multiplying by the probability density function (pdf) characterizing that uncertainty:

$$\mathcal{L}(\sigma B, \theta_1, \ldots, \theta_N) = \mathcal{L}(\sigma B) \prod g_i(\theta_i), \tag{6}$$

where $g_i(\theta_i)$ is the Gaussian pdf for nuisance parameter $\theta_i$. The nuisance parameters are taken to be the explicit dependencies: $L_{int}$, $\varepsilon_{sig}$ and $N_{bg}$. Correlations between these are neglected. This is justified by the small effect that the nuisance parameters themselves have on the limits, as demonstrated below.

The fraction of fully simulated signal events that pass final selection and are above $m_T$ threshold provides an initial estimate of the expected numbers of events for each mass. Small corrections are made to account for differences between the kinematical distributions at NNLO (obtained from FEWZ) and those in the LO simulation. The largest correction is around 4%. Contributions from $W' \to \tau\nu$ with the $\tau$-lepton decaying leptonically have been neglected and would increase the $W'$ selection efficiencies by 3–4%.

The EW and $t\bar{t}$ background predictions are also obtained from full simulation, normalized to the integrated luminosity of the data. For the EW background, small corrections are again made to account for differences between kinematical distributions in LO simulation and higher order calculations, now using NLO MCFM [34] because the present version of FEWZ does not provide reliable values far from the resonance peak. The background level for each mass is obtained by adding the small QCD and cosmic-ray contributions to these values.

The uncertainties on $\varepsilon_{sig}$ and $N_{bg}$ account for experimental and theoretical systematic effects as well as the statistics of the simulation samples. The experimental systematic uncertainties include efficiencies for lepton trigger, reconstruction, impact parameter and isolation as well as event vertex reconstruction. Lepton momentum and missing $E_T$ response, characterized by scale and resolution, are also included. Most of these performance metrics are measured at relatively low $p_T$ and their values are extrapolated to the high-$p_T$ regime relevant to this analysis. The uncertainties due to these extrapolations are included but are too small to significantly affect the $W'/W^*$ limits. The uncertainties on the QCD and cosmic-ray background estimates also contribute to $N_{bg}$. Theoretical systematic uncertainties arise from the calculation of cross sections and their kinematical distributions, lepton isolation, and the distribution of the ratio of neutrino to lepton $p_T$ which affects the scaled missing $E_T$ selection efficiency.

Table 3 summarizes the uncertainties on the event-selection efficiencies and background levels for a $W'$ signal with $m_{W'} = 1500$ GeV (i.e. for $m_T > 750$ GeV).

**Table 3**

Relative uncertainties on the event-selection efficiency and background level for a $W'$ with a mass of 1500 GeV. The most important uncertainties are indicated in bold. The last row gives the total uncertainties.

| Source | $\varepsilon_{sig}$ | | $N_{bg}$ | |
|---|---|---|---|---|
| | $e\nu$ | $\mu\nu$ | $e\nu$ | $\mu\nu$ |
| Missing $E_T$ scale | 0.1% | 0.1% | 1.1% | **3.4%** |
| Trigger efficiency | **1.0%** | **0.7%** | 1.0% | 0.7% |
| Reco. and id. efficiency | **3.6%** | **1.6%** | 3.6% | 1.3% |
| Isolation leakage | **2.7%** | | **3.4%** | |
| Energy/momentum resolution | 0.1% | 0.4% | 2.4% | **3.1%** |
| Energy/momentum scale | **0.8%** | 0.1% | **6.6%** | 0.1% |
| Correlated misalignment | | 0.6% | | **3.3%** |
| QCD background | | | 2.2% | **7.7%** |
| Monte Carlo statistics | **1.7%** | **1.6%** | 2.2% | **16.6%** |
| Cross section (shape/level) | **0.7%** | **0.7%** | **8.5%** | **7.7%** |
| Isolation | **1.5%** | **1.5%** | 1.0% | 1.0% |
| Other | 0.2% | 0.4% | 0.4% | 0.9% |
| All | 5.3% | 3.0% | 12.6% | 20.7% |

For $\varepsilon_{sig}$, most of the uncertainty in the electron channel comes from electron identification except for the higher masses where the isolation leakage is also important. The total is less than 6% for all $W'/W^*$ masses and has a negligible effect on the limit evaluation. The signal uncertainties are even smaller in the muon channel. For $N_{bg}$, the dominant uncertainties in the electron channel come from the electron energy scale and the cross-section calculation. For the muon channel, the simulation statistics followed by the uncertainties on the QCD background and cross-section calculation dominate. The first is large because momentum smearing pushes events with low $m_T$, and hence higher cross section, into the high-$m_T$ bins used in the limit evaluation. The cross-section uncertainties are large (around 8% in Table 3) because it is the high-mass tail that is relevant to this analysis.

Limits for 95% CL (confidence level) exclusion on $\sigma B$ for each $W'$ and $W^*$ mass and decay channel are set using the likelihood function in Eq. (6) as input to the estimator $CL_s = CL_{s+b}/CL_b$ [35]. The inputs for the limit calculation are $L_{int}$, $\varepsilon_{sig}$, $N_{bg}$, $N_{obs}$ and the uncertainties on the first three. Except for $L_{int}$ and its uncertainty, these inputs are all listed in Table 4. The table also lists the predicted numbers of signal events, $N_{sig}$, with their uncertainty including both that of $\varepsilon_{sig}$ and the cross-section calculation. The uncertainties on $\varepsilon_{sig}$, $N_{bg}$ and $N_{sig}$ account for all relevant experimental and theoretical effects except for integrated luminosity which is included separately to allow for the correlation between signal and background. The numbers of observed events are in good agreement with the expected numbers of background events for all mass bins in the electron channel and for the lowest bin ($m_T > 250$ GeV) in the muon channel. A discrepancy is observed in the muon channel for $m_T > 375$ GeV where 5.48 muon events are predicted and none are observed, a result for which the Poisson probability is only 0.4%. However, the muon $p_T$ spectrum in Fig. 1 shows no evidence of any discrepancy between data and predicted background at high $p_T$, confirming that, as expected, the muon efficiency remains stable at high $p_T$.

Table 5 and Fig. 4 show the $W'$ and $W^*$ observed limits on $\sigma B$ for both decay channels and their combination. The figure also shows the expected limits and the theoretical $\sigma B$. The intersection between the central theoretical prediction and the observed limits provides the 95% CL lower limit on the mass. Table 6 presents the $W'$ and $W^*$ expected and observed mass limits for the electron and muon decay channels and for the combination of both channels. These limits increase by 5–10 GeV if the uncertainties on $\varepsilon_{sig}$, $N_{bg}$ and $L_{int}$ are neglected. For both channels, the effect of the $\varepsilon_{sig}$ and $N_{bg}$ uncertainties on the limits is small for the lowest-$m_T$ bin and negligible for the others.

**Table 4**
Inputs for the $W'/W^* \to \ell\nu \ \sigma B$ limit calculations for an integrated luminosity of 36 pb$^{-1}$. The first two columns are the $W'/W^*$ mass and decay mode. The next four are the corrected signal selection efficiency, $\varepsilon_{\text{sig}}$, and the prediction for the number of signal events, $N_{\text{sig}}$, obtained with this efficiency. The last two columns are the expected number of background events, $N_{\text{bg}}$, and the number of events observed in data, $N_{\text{obs}}$. The uncertainties for $N_{\text{sig}}$ and $N_{\text{bg}}$ include contributions from the uncertainties in the cross sections but not from the integrated luminosity.

| $m$ [GeV] | Decay | $\varepsilon_{\text{sig}}$ | | $N_{\text{sig}}$ | | $N_{\text{bg}}$ | $N_{\text{obs}}$ |
|---|---|---|---|---|---|---|---|
| | | $W'$ | $W^*$ | $W'$ | $W^*$ | | |
| 500 | $e\nu$ | $0.556 \pm 0.024$ | $0.455 \pm 0.019$ | $349 \pm 30$ | $208 \pm 18$ | $21.5 \pm 2.0$ | 24 |
| | $\mu\nu$ | $0.339 \pm 0.008$ | $0.228 \pm 0.004$ | $212 \pm 17$ | $104 \pm 8$ | $20.3 \pm 1.1$ | 16 |
| 750 | $e\nu$ | $0.565 \pm 0.025$ | $0.466 \pm 0.020$ | $65.8 \pm 4.8$ | $39.6 \pm 3.5$ | $4.05 \pm 0.35$ | 6 |
| | $\mu\nu$ | $0.362 \pm 0.009$ | $0.230 \pm 0.005$ | $42.1 \pm 2.7$ | $19.6 \pm 1.5$ | $5.48 \pm 0.44$ | 0 |
| 1000 | $e\nu$ | $0.562 \pm 0.025$ | $0.473 \pm 0.021$ | $17.1 \pm 1.4$ | $10.5 \pm 1.0$ | $1.11 \pm 0.11$ | 1 |
| | $\mu\nu$ | $0.381 \pm 0.010$ | $0.242 \pm 0.005$ | $11.6 \pm 0.9$ | $5.4 \pm 0.5$ | $2.05 \pm 0.25$ | 0 |
| 1250 | $e\nu$ | $0.552 \pm 0.026$ | $0.469 \pm 0.021$ | $5.23 \pm 0.51$ | $3.22 \pm 0.42$ | $0.400 \pm 0.054$ | 0 |
| | $\mu\nu$ | $0.386 \pm 0.011$ | $0.237 \pm 0.005$ | $3.66 \pm 0.33$ | $1.63 \pm 0.20$ | $1.01 \pm 0.17$ | 0 |
| 1500 | $e\nu$ | $0.530 \pm 0.028$ | $0.457 \pm 0.023$ | $1.71 \pm 0.21$ | $1.06 \pm 0.17$ | $0.159 \pm 0.020$ | 0 |
| | $\mu\nu$ | $0.383 \pm 0.012$ | $0.235 \pm 0.006$ | $1.24 \pm 0.14$ | $0.54 \pm 0.08$ | $0.62 \pm 0.13$ | 0 |
| 1750 | $e\nu$ | $0.503 \pm 0.027$ | $0.454 \pm 0.027$ | $0.59 \pm 0.09$ | $0.37 \pm 0.07$ | $0.069 \pm 0.009$ | 0 |
| | $\mu\nu$ | $0.360 \pm 0.012$ | $0.239 \pm 0.006$ | $0.43 \pm 0.06$ | $0.20 \pm 0.04$ | $0.47 \pm 0.09$ | 0 |

**Table 5**
Upper limits on $W'$ and $W^* \ \sigma B$. The first two columns are the mass and decay channel and the following are the 95% CL limits with headers indicating the nuisance parameters for which uncertainties are included: S for the event selection efficiency ($\varepsilon_{\text{sig}}$), B for the background level ($N_{\text{bg}}$), and L for the integrated luminosity ($L_{\text{int}}$). Columns labeled SBL include all uncertainties and are used to evaluate mass limits. Results are given for the electron and muon channels and the combination of the two.

| $m$ [GeV] | | 95% CL limit on $\sigma B$ [fb] | | | | | |
|---|---|---|---|---|---|---|---|
| | | $W'$ | | | | $W^*$ | |
| | | none | S | SB | SBL | none | SBL |
| 500 | $e\nu$ | 647 | 649 | 682 | 795 | 791 | 973 |
| | $\mu\nu$ | 625 | 625 | 640 | 786 | 931 | 1172 |
| | both | 413 | 416 | 444 | 583 | 551 | 764 |
| 750 | $e\nu$ | 390 | 391 | 393 | 416 | 473 | 504 |
| | $\mu\nu$ | 227 | 228 | 228 | 248 | 357 | 391 |
| | both | 186 | 184 | 188 | 208 | 259 | 289 |
| 1000 | $e\nu$ | 199 | 200 | 200 | 207 | 237 | 246 |
| | $\mu\nu$ | 216 | 216 | 216 | 226 | 349 | 356 |
| | both | 108 | 109 | 109 | 115 | 146 | 154 |
| 1250 | $e\nu$ | 149 | 150 | 150 | 153 | 175 | 180 |
| | $\mu\nu$ | 213 | 214 | 213 | 220 | 347 | 359 |
| | both | 88 | 88 | 88 | 91 | 117 | 121 |
| 1500 | $e\nu$ | 155 | 156 | 156 | 159 | 180 | 185 |
| | $\mu\nu$ | 215 | 215 | 215 | 221 | 349 | 359 |
| | both | 90 | 90 | 90 | 93 | 119 | 122 |
| 1750 | $e\nu$ | 164 | 163 | 164 | 168 | 181 | 186 |
| | $\mu\nu$ | 229 | 229 | 229 | 235 | 344 | 353 |
| | both | 95 | 96 | 96 | 98 | 119 | 122 |

**Table 6**
Lower limits on $W'$ and $W^*$ masses. The first column is the decay channel ($e\nu$, $\mu\nu$ or both combined) and the following give the expected (Exp.) and observed (Obs.) mass limits.

| Decay | Mass limit [GeV] | | | |
|---|---|---|---|---|
| | $W'$ | | $W^*$ | |
| | Exp. | Obs. | Exp. | Obs. |
| $e\nu$ | 1370 | 1370 | 1260 | 1260 |
| $\mu\nu$ | 1210 | 1290 | 1020 | 1120 |
| both | 1450 | 1490 | 1320 | 1350 |

limit of 1580 GeV. Fig. 5 compares the result presented here with the $W' \to e\nu$ result from CDF and the combination from CMS. The comparison is made using the ratio of the limit to the calculated value of $\sigma B$, a quantity that is proportional to the square of the coupling strength. The NNLO cross sections in Table 1 are used for both the ATLAS and CMS points.

In conclusion, the ATLAS detector has been used to search for new high-mass states decaying to a lepton plus missing $E_{\text{T}}$ in $pp$ collisions at $\sqrt{s} = 7$ TeV using 36 pb$^{-1}$ of integrated luminosity. No excess beyond SM expectations is observed. Limits on $\sigma B$ are shown in Figs. 4 and 5. A $W'$ with SSM couplings is excluded for masses below 1490 GeV at 95% CL. The exclusion for $W^*$ with couplings set in accordance with Ref. [10] is 1350 GeV. These are the first direct limits on $W^*$ production.

### Acknowledgements

Limits on $W' \to \ell\nu$ have been reported in many other experiments [1–6]. Prior to this Letter and the recent $W' \to \mu\nu$ results from CMS [6], the best limits in the high-mass region were reported by CDF [4] and CMS [5], both for $W' \to e\nu$. The CDF measurement was made with $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 5.3 fb$^{-1}$. Both CMS results were obtained at the same collision energy ($\sqrt{s} = 7$ TeV) and during the same run period as those reported here. The CMS limits were set using a Bayesian approach. Ref. [6] also reports a combination of the CMS results in the two decay channels with an SSM $W'$ mass

**Fig. 4.** Limits at 95% CL for $W'$ (left) and $W^*$ (right) production in the decay channels $W'/W^* \to e\nu$ (top), $W'/W^* \to \mu\nu$ (center), and the combination of these (bottom). The solid lines show the observed limits with all uncertainties. The expected limit is indicated with dashed lines surrounded by $1\sigma$ and $2\sigma$ shaded bands. Dashed lines show the theory predictions (NNLO for $W'$, LO for $W^*$) between solid lines indicating their uncertainties. The $W'$ $\sigma B$ uncertainties are obtained by varying renormalization and factorization scales and by varying PDFs. Only the latter are included for $W^*$.

**Fig. 5.** Normalized cross-section limits ($\sigma_{\text{limit}}/\sigma_{\text{theory}}$) for $W'$ as a function of mass for this measurement and those from CDF and CMS. The cross-section calculations assume the $W'$ has the same couplings as the standard model $W$ boson. The region above each curve is excluded at 95% CL.

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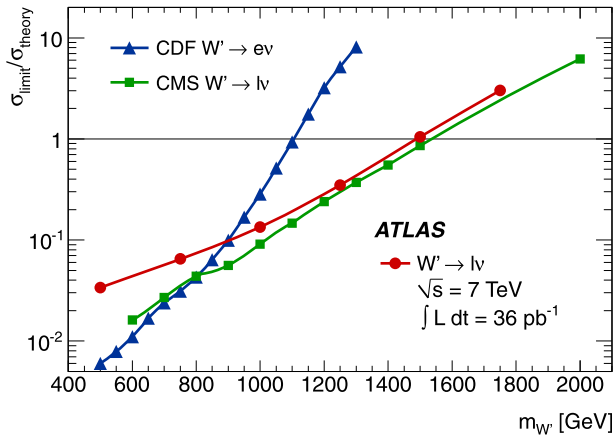[1] K. Nakamura, et al., Particle Data Group, J. Phys. G 37 (2010) 075021.
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Shabalina [54], M. Shamim [114], L.Y. Shan [32a], J.T. Shank [21], Q.T. Shao [86], M. Shapiro [14], P.B. Shatalov [95], L. Shaver [6], C. Shaw [53],

K. Shaw [164a,164c], D. Sherman [175], P. Sherwood [77], A. Shibata [108], S. Shimizu [29], M. Shimojima [100], T. Shin [56], A. Shmeleva [94], M.J. Shochet [30], D. Short [118], M.A. Shupe [6], P. Sicho [125], A. Sidoti [15], A. Siebel [174], F. Siegert [48], J. Siegrist [14], Dj. Sijacki [12a], O. Silbert [171], J. Silva [124a,b], Y. Silver [153], D. Silverstein [143], S.B. Silverstein [146a], V. Simak [127], O. Simard [136], Lj. Simic [12a], S. Simion [115], B. Simmons [77], M. Simonyan [35], P. Sinervo [158], N.B. Sinev [114], V. Sipica [141], G. Siragusa [81], A.N. Sisakyan [65], S.Yu. Sivoklokov [97], J. Sjölin [146a,146b], T.B. Sjursen [13], L.A. Skinnari [14], K. Skovpen [107], P. Skubic [111], N. Skvorodnev [22], M. Slater [17], T. Slavicek [127], K. Sliwa [161], T.J. Sloan [71], J. Sloper [29], V. Smakhtin [171], S.Yu. Smirnov [96], L.N. Smirnova [97], O. Smirnova [79], B.C. Smith [57], D. Smith [143], K.M. Smith [53], M. Smizanska [71], K. Smolek [127], A.A. Snesarev [94], S.W. Snow [82], J. Snow [111], J. Snuverink [105], S. Snyder [24], M. Soares [124a], R. Sobie [169,i], J. Sodomka [127], A. Soffer [153], C.A. Solans [167], M. Solar [127], J. Solc [127], E. Soldatov [96], U. Soldevila [167], E. Solfaroli Camillocci [132a,132b], A.A. Solodkov [128], O.V. Solovyanov [128], J. Sondericker [24], N. Soni [2], V. Sopko [127], B. Sopko [127], M. Sorbi [89a,89b], M. Sosebee [7], A. Soukharev [107], S. Spagnolo [72a,72b], F. Spanò [34], R. Spighi [19a], G. Spigo [29], F. Spila [132a,132b], E. Spiriti [134a], R. Spiwoks [29], M. Spousta [126], T. Spreitzer [158], B. Spurlock [7], R.D. St. Denis [53], T. Stahl [141], J. Stahlman [120], R. Stamen [58a], E. Stanecka [29], R.W. Stanek [5], C. Stanescu [134a], S. Stapnes [117], E.A. Starchenko [128], J. Stark [55], P. Staroba [125], P. Starovoitov [91], A. Staude [98], P. Stavina [144a], G. Stavropoulos [14], G. Steele [53], P. Steinbach [43], P. Steinberg [24], I. Stekl [127], B. Stelzer [142], H.J. Stelzer [41], O. Stelzer-Chilton [159a], H. Stenzel [52], K. Stevenson [75], G.A. Stewart [53], J.A. Stillings [20], T. Stockmanns [20], M.C. Stockton [29], K. Stoerig [48], G. Stoicea [25a], S. Stonjek [99], P. Strachota [126], A.R. Stradling [7], A. Straessner [43], J. Strandberg [87], S. Strandberg [146a,146b], A. Strandlie [117], M. Strang [109], E. Strauss [143], M. Strauss [111], P. Strizenec [144b], R. Ströhmer [173], D.M. Strom [114], J.A. Strong [76,*], R. Stroynowski [39], J. Strube [129], B. Stugu [13], I. Stumer [24,*], J. Stupak [148], P. Sturm [174], D.A. Soh [151,o], D. Su [143], HS. Subramania [2], Y. Sugaya [116], T. Sugimoto [101], C. Suhr [106], K. Suita [67], M. Suk [126], V.V. Sulin [94], S. Sultansoy [3d], T. Sumida [29], X. Sun [55], J.E. Sundermann [48], K. Suruliz [164a,164b], S. Sushkov [11], G. Susinno [36a,36b], M.R. Sutton [139], Y. Suzuki [66], Yu.M. Sviridov [128], S. Swedish [168], I. Sykora [144a], T. Sykora [126], B. Szeless [29], J. Sánchez [167], D. Ta [105], K. Tackmann [29], A. Taffard [163], R. Tafirout [159a], A. Taga [117], N. Taiblum [153], Y. Takahashi [101], H. Takai [24], R. Takashima [69], H. Takeda [67], T. Takeshita [140], M. Talby [83], A. Talyshev [107], M.C. Tamsett [24], J. Tanaka [155], R. Tanaka [115], S. Tanaka [131], S. Tanaka [66], Y. Tanaka [100], K. Tani [67], N. Tannoury [83], G.P. Tappern [29], S. Tapprogge [81], D. Tardif [158], S. Tarem [152], F. Tarrade [24], G.F. Tartarelli [89a], P. Tas [126], M. Tasevsky [125], E. Tassi [36a,36b], M. Tatarkhanov [14], C. Taylor [77], F.E. Taylor [92], G.N. Taylor [86], W. Taylor [159b], M. Teixeira Dias Castanheira [75], P. Teixeira-Dias [76], K.K. Temming [48], H. Ten Kate [29], P.K. Teng [151], S. Terada [66], K. Terashi [155], J. Terron [80], M. Terwort [41,m], M. Testa [47], R.J. Teuscher [158,i], C.M. Tevlin [82], J. Thadome [174], J. Therhaag [20], T. Theveneaux-Pelzer [78], M. Thioye [175], S. Thoma [48], J.P. Thomas [17], E.N. Thompson [84], P.D. 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P. van Gemmeren [5], Z. van Kesteren [105], I. van Vulpen [105], W. Vandelli [29], G. Vandoni [29], A. Vaniachine [5], P. Vankov [41], F. Vannucci [78], F. Varela Rodriguez [29], R. Vari [132a], E.W. Varnes [6], D. Varouchas [14], A. Vartapetian [7], K.E. Varvell [150], V.I. Vassilakopoulos [56], F. Vazeille [33], G. Vegni [89a,89b], J.J. Veillet [115], C. Vellidis [8], F. Veloso [124a], R. Veness [29], S. Veneziano [132a], A. Ventura [72a,72b], D. Ventura [138], M. Venturi [48], N. Venturi [16], V. Vercesi [119a], M. Verducci [138], W. Verkerke [105], J.C. Vermeulen [105], A. Vest [43], M.C. Vetterli [142,d], I. Vichou [165], T. Vickey [145b,y], G.H.A. Viehhauser [118], S. Viel [168], M. Villa [19a,19b], M. Villaplana Perez [167], E. Vilucchi [47], M.G. Vincter [28], E. Vinek [29], V.B. Vinogradov [65], M. Virchaux [136,*], S. Viret [33], J. Virzi [14], A. Vitale [19a,19b], O. Vitells [171], M. Viti [41], I. Vivarelli [48], F. Vives Vaque [11], S. Vlachos [9], M. Vlasak [127], N. Vlasov [20], A. Vogel [20], P. Vokac [127], G. Volpi [47], M. Volpi [11], G. Volpini [89a], H. von der Schmitt [99], J. von Loeben [99], H. von Radziewski [48], E. von Toerne [20], V. Vorobel [126], A.P. Vorobiev [128], V. Vorwerk [11], M. Vos [167], R. Voss [29], T.T. Voss [174], J.H. Vossebeld [73], A.S. Vovenko [128], N. Vranjes [12a], M. Vranjes Milosavljevic [12a], V. Vrba [125], M. Vreeswijk [105], T. Vu Anh [81], R. Vuillermet [29], I. Vukotic [115], W. Wagner [174], P. Wagner [120], H. Wahlen [174], J. Wakabayashi [101], J. Walbersloh [42], S. Walch [87], J. Walder [71], R. Walker [98], W. Walkowiak [141], R. Wall [175], P. Waller [73], C. Wang [44], H. Wang [172], J. Wang [151], J. Wang [32d], J.C. Wang [138], R. Wang [103], S.M. Wang [151], A. Warburton [85], C.P. Ward [27], M. Warsinsky [48], P.M. Watkins [17], A.T. Watson [17], M.F. Watson [17], G. Watts [138], S. Watts [82], A.T. Waugh [150], B.M. Waugh [77], J. Weber [42], M. Weber [129], M.S. Weber [16], P. Weber [54], A.R. Weidberg [118], P. Weigell [99], J. Weingarten [54], C. Weiser [48], H. Wellenstein [22], P.S. Wells [29], M. Wen [47], T. Wenaus [24], S. Wendler [123], Z. Weng [151,o], T. Wengler [29], S. Wenig [29], N. Wermes [20], M. Werner [48], P. Werner [29], M. Werth [163], M. Wessels [58a], K. Whalen [28], S.J. Wheeler-Ellis [163], S.P. Whitaker [21], A. White [7], M.J. White [86], S. White [24], S.R. Whitehead [118], D. Whiteson [163], D. Whittington [61], F. Wicek [115], D. Wicke [174], F.J. Wickens [129], W. Wiedenmann [172], M. Wielers [129], P. Wienemann [20], C. Wiglesworth [73], L.A.M. Wiik [48], P.A. Wijeratne [77], A. Wildauer [167], M.A. Wildt [41,m], I. Wilhelm [126], H.G. Wilkens [29], J.Z. Will [98], E. Williams [34], H.H. Williams [120], W. Willis [34], S. Willocq [84], J.A. Wilson [17], M.G. Wilson [143], A. Wilson [87], I. Wingerter-Seez [4], S. Winkelmann [48], F. Winklmeier [29], M. Wittgen [143], M.W. Wolter [38], H. Wolters [124a,g], G. Wooden [118], B.K. Wosiek [38], J. Wotschack [29], M.J. Woudstra [84], K. Wraight [53], C. Wright [53], B. Wrona [73], S.L. Wu [172], X. Wu [49], Y. Wu [32b], E. Wulf [34], R. Wunstorf [42], B.M. Wynne [45], L. Xaplanteris [9], S. Xella [35], S. Xie [48], Y. Xie [32a], C. Xu [32b], D. Xu [139], G. Xu [32a], B. Yabsley [150], M. Yamada [66], A. Yamamoto [66], K. Yamamoto [64], S. Yamamoto [155], T. Yamamura [155], J. Yamaoka [44], T. Yamazaki [155], Y. Yamazaki [67], Z. Yan [21], H. Yang [87], U.K. Yang [82], Y. Yang [61], Y. Yang [32a], Z. Yang [146a,146b], S. Yanush [91], W.-M. Yao [14], Y. Yao [14], Y. Yasu [66], G.V. Ybeles Smit [130], J. Ye [39], S. Ye [24], M. Yilmaz [3c], R. Yoosoofmiya [123], K. Yorita [170], R. Yoshida [5], C. Young [143], S. Youssef [21], D. Yu [24], J. Yu [7], J. Yu [32c,z], L. Yuan [32a,aa], A. Yurkewicz [148], V.G. Zaets [128], R. Zaidan [63], A.M. Zaitsev [128], Z. Zajacova [29], Yo.K. Zalite [121], L. Zanello [132a,132b], P. Zarzhitsky [39], A. Zaytsev [107], C. Zeitnitz [174], M. Zeller [175], P.F. Zema [29], A. Zemla [38], C. Zendler [20], A.V. Zenin [128], O. Zenin [128], T. Ženiš [144a], Z. Zenonos [122a,122b], S. Zenz [14], D. Zerwas [115], G. Zevi della Porta [57], Z. Zhan [32d], D. Zhang [32b], H. Zhang [88], J. Zhang [5], X. Zhang [32d], Z. Zhang [115], L. Zhao [108], T. Zhao [138], Z. Zhao [32b], A. Zhemchugov [65], S. Zheng [32a], J. Zhong [151,ab], B. Zhou [87], N. Zhou [163], Y. Zhou [151], C.G. Zhu [32d], H. Zhu [41], Y. Zhu [172], X. Zhuang [98], V. Zhuravlov [99], D. Zieminska [61], B. Zilka [144a], R. Zimmermann [20], S. Zimmermann [20], S. Zimmermann [48], M. Ziolkowski [141], R. Zitoun [4], L. Živković [34], V.V. Zmouchko [128,*], G. Zobernig [172], A. Zoccoli [19a,19b], Y. Zolnierowski [4], A. Zsenei [29], M. zur Nedden [15], V. Zutshi [106], L. Zwalinski [29].

[16] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[17] *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[18] [a] *Department of Physics, Bogazici University, Istanbul;* [b] *Division of Physics, Dogus University, Istanbul;* [c] *Department of Physics Engineering, Gaziantep University, Gaziantep;* [d] *Department of Physics, Istanbul Technical University, Istanbul, Turkey*
[19] [a] *INFN Sezione di Bologna;* [b] *Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[20] *Physikalisches Institut, University of Bonn, Bonn, Germany*
[21] *Department of Physics, Boston University, Boston, MA, United States*
[22] *Department of Physics, Brandeis University, Waltham, MA, United States*
[23] [a] *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* [b] *Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[24] *Physics Department, Brookhaven National Laboratory, Upton, NY, United States*
[25] [a] *National Institute of Physics and Nuclear Engineering, Bucharest;* [b] *University Politehnica Bucharest, Bucharest;* [c] *West University in Timisoara, Timisoara, Romania*
[26] *Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[27] *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[28] *Department of Physics, Carleton University, Ottawa, ON, Canada*
[29] *CERN, Geneva, Switzerland*
[30] *Enrico Fermi Institute, University of Chicago, Chicago, IL, United States*
[31] [a] *Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago;* [b] *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[32] [a] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* [b] *Department of Modern Physics, University of Science and Technology of China, Anhui;* [c] *Department of Physics, Nanjing University, Jiangsu;* [d] *High Energy Physics Group, Shandong University, Shandong, China*
[33] *Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France*
[34] *Nevis Laboratory, Columbia University, Irvington, NY, United States*
[35] *Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[36] [a] *INFN Gruppo Collegato di Cosenza;* [b] *Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy*
[37] *Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland*
[38] *The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[39] *Physics Department, Southern Methodist University, Dallas, TX, United States*
[40] *Physics Department, University of Texas at Dallas, Richardson, TX, United States*
[41] *DESY, Hamburg and Zeuthen, Germany*
[42] *Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[43] *Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany*
[44] *Department of Physics, Duke University, Durham, NC, United States*
[45] *SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[46] *Fachhochschule Wiener Neustadt, Wiener Neustadt, Austria*
[47] *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[48] *Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany*
[49] *Section de Physique, Université de Genève, Geneva, Switzerland*
[50] [a] *INFN Sezione di Genova;* [b] *Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51] *Institute of Physics and HEP Institute, Georgian Academy of Sciences and Tbilisi State University, Tbilisi, Georgia*
[52] *II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[53] *SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[54] *II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
[55] *Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France*
[56] *Department of Physics, Hampton University, Hampton, VA, United States*
[57] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States*
[58] [a] *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [b] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [c] *ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*
[59] *Faculty of Science, Hiroshima University, Hiroshima, Japan*
[60] *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
[61] *Department of Physics, Indiana University, Bloomington, IN, United States*
[62] *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[63] *University of Iowa, Iowa City, IA, United States*
[64] *Department of Physics and Astronomy, Iowa State University, Ames, IA, United States*
[65] *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
[66] *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[67] *Graduate School of Science, Kobe University, Kobe, Japan*
[68] *Faculty of Science, Kyoto University, Kyoto, Japan*
[69] *Kyoto University of Education, Kyoto, Japan*
[70] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[71] *Physics Department, Lancaster University, Lancaster, United Kingdom*
[72] [a] *INFN Sezione di Lecce;* [b] *Dipartimento di Fisica, Università del Salento, Lecce, Italy*
[73] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[74] *Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
[75] *Department of Physics, Queen Mary University of London, London, United Kingdom*
[76] *Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
[77] *Department of Physics and Astronomy, University College London, London, United Kingdom*
[78] *Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[79] *Fysiska Institutionen, Lunds universitet, Lund, Sweden*
[80] *Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*
[81] *Institut für Physik, Universität Mainz, Mainz, Germany*
[82] *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[83] *CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*
[84] *Department of Physics, University of Massachusetts, Amherst, MA, United States*
[85] *Department of Physics, McGill University, Montreal, QC, Canada*
[86] *School of Physics, University of Melbourne, Victoria, Australia*
[87] *Department of Physics, The University of Michigan, Ann Arbor, MI, United States*
[88] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States*
[89] [a] *INFN Sezione di Milano;* [b] *Dipartimento di Fisica, Università di Milano, Milano, Italy*
[90] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus*
[91] *National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus*

[92] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States*
[93] *Group of Particle Physics, University of Montreal, Montreal, QC, Canada*
[94] *P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[95] *Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[96] *Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
[97] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[98] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[99] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[100] *Nagasaki Institute of Applied Science, Nagasaki, Japan*
[101] *Graduate School of Science, Nagoya University, Nagoya, Japan*
[102] *[a] INFN Sezione di Napoli; [b] Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
[103] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States*
[104] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[105] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[106] *Department of Physics, Northern Illinois University, DeKalb, IL, United States*
[107] *Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia*
[108] *Department of Physics, New York University, New York, NY, United States*
[109] *Ohio State University, Columbus, OH, United States*
[110] *Faculty of Science, Okayama University, Okayama, Japan*
[111] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States*
[112] *Department of Physics, Oklahoma State University, Stillwater, OK, United States*
[113] *Palacký University, RCPTM, Olomouc, Czech Republic*
[114] *Center for High Energy Physics, University of Oregon, Eugene, OR, United States*
[115] *LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France*
[116] *Graduate School of Science, Osaka University, Osaka, Japan*
[117] *Department of Physics, University of Oslo, Oslo, Norway*
[118] *Department of Physics, Oxford University, Oxford, United Kingdom*
[119] *[a] INFN Sezione di Pavia; [b] Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy*
[120] *Department of Physics, University of Pennsylvania, Philadelphia, PA, United States*
[121] *Petersburg Nuclear Physics Institute, Gatchina, Russia*
[122] *[a] INFN Sezione di Pisa; [b] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[123] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States*
[124] *[a] Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal; [b] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
[125] *Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[126] *Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[127] *Czech Technical University in Prague, Praha, Czech Republic*
[128] *State Research Center Institute for High Energy Physics, Protvino, Russia*
[129] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[130] *Physics Department, University of Regina, Regina, SK, Canada*
[131] *Ritsumeikan University, Kusatsu, Shiga, Japan*
[132] *[a] INFN Sezione di Roma I; [b] Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[133] *[a] INFN Sezione di Roma Tor Vergata; [b] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[134] *[a] INFN Sezione di Roma Tre; [b] Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
[135] *[a] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; [b] Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [c] Université Cadi Ayyad, Faculté des Sciences Semlalia, Département de Physique, B.P. 2390, Marrakech 40000; [d] Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [e] Faculté des Sciences, Université Mohammed V, Rabat, Morocco*
[136] *DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France*
[137] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States*
[138] *Department of Physics, University of Washington, Seattle, WA, United States*
[139] *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[140] *Department of Physics, Shinshu University, Nagano, Japan*
[141] *Fachbereich Physik, Universität Siegen, Siegen, Germany*
[142] *Department of Physics, Simon Fraser University, Burnaby, BC, Canada*
[143] *SLAC National Accelerator Laboratory, Stanford, CA, United States*
[144] *[a] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [b] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[145] *[a] Department of Physics, University of Johannesburg, Johannesburg; [b] School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[146] *[a] Department of Physics, Stockholm University; [b] The Oskar Klein Centre, Stockholm, Sweden*
[147] *Physics Department, Royal Institute of Technology, Stockholm, Sweden*
[148] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States*
[149] *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[150] *School of Physics, University of Sydney, Sydney, Australia*
[151] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[152] *Department of Physics, Technion – Israel Inst. of Technology, Haifa, Israel*
[153] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[154] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[155] *International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*
[156] *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[157] *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[158] *Department of Physics, University of Toronto, Toronto, ON, Canada*
[159] *[a] TRIUMF, Vancouver, BC; [b] Department of Physics and Astronomy, York University, Toronto, ON, Canada*
[160] *Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan*
[161] *Science and Technology Center, Tufts University, Medford, MA, United States*
[162] *Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[163] *Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States*
[164] *[a] INFN Gruppo Collegato di Udine; [b] ICTP, Trieste; [c] Dipartimento di Fisica, Università di Udine, Udine, Italy*
[165] *Department of Physics, University of Illinois, Urbana, IL, United States*
[166] *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*

[167] *Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB–CNM), University of Valencia and CSIC, Valencia, Spain*
[168] *Department of Physics, University of British Columbia, Vancouver, BC, Canada*
[169] *Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada*
[170] *Waseda University, Tokyo, Japan*
[171] *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*
[172] *Department of Physics, University of Wisconsin, Madison, WI, United States*
[173] *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
[174] *Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[175] *Department of Physics, Yale University, New Haven, CT, United States*
[176] *Yerevan Physics Institute, Yerevan, Armenia*
[177] *Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France*

[a] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas – LIP, Lisboa, Portugal.
[b] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
[c] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[d] Also at TRIUMF, Vancouver, BC, Canada.
[e] Also at Department of Physics, California State University, Fresno, CA, United States.
[f] Also at Faculty of Physics and Applied Computer Science, AGH – University of Science and Technology, Krakow, Poland.
[g] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[h] Also at Università di Napoli Parthenope, Napoli, Italy.
[i] Also at Institute of Particle Physics (IPP), Canada.
[j] Also at Louisiana Tech University, Ruston, LA, United States.
[k] Also at Group of Particle Physics, University of Montreal, Montreal, QC, Canada.
[l] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[m] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[n] Also at Manhattan College, New York, NY, United States.
[o] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[p] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[q] Also at High Energy Physics Group, Shandong University, Shandong, China.
[r] Also at California Institute of Technology, Pasadena, CA, United States.
[s] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
[t] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[u] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[v] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.
[w] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[x] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[y] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[z] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France.
[aa] Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
[ab] Also at Department of Physics, Nanjing University, Jiangsu, China.
[*] Deceased.