



Search for scalar leptoquarks produced via τ -lepton-quark scattering in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract

The first search for scalar leptoquarks produced in τ -lepton-quark collisions is presented. It is based on a set of proton-proton collision data recorded with the CMS detector at the LHC at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 138 fb^{-1} . The reconstructed final state consists of a jet, significant missing transverse momentum, and a τ lepton reconstructed through its hadronic or leptonic decays. Limits are set on the product of the leptoquark production cross section and branching fraction and interpreted as exclusions in the plane of the leptoquark mass and the leptoquark- τ -quark coupling strength.

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Leptoquarks (LQs) are hypothetical color-triplet bosons carrying both baryon and lepton numbers and having fractional electric charge [1–6]. Mechanisms involving LQs coupled to third-generation quarks and leptons could explain the deviations from standard model (SM) predictions observed in several measurements of B meson decays, as explained in Refs. [7–10] and references therein.

At the CERN LHC, LQs can be produced singly through quark-gluon fusion, in pairs through gluon fusion or quark-antiquark annihilation, as part of the nonresonant production of two leptons in the t -channel, or from lepton-quark collisions. While the ATLAS and CMS Collaborations have performed searches for LQs targeting the first three production mechanisms [11–17], the last production mode has never been explored at the LHC. Recent theoretical progress in the determination of the lepton and photon density functions in the proton [18], based on the LUX approach [19, 20], has shown that a significant LQ production cross section can be expected in proton-proton (pp) collisions [21–24].

Lepton-induced production of LQs proceeds via the collision of a lepton and a quark, where the lepton is produced through a photon via quantum fluctuations in the proton. A leading-order (LO) Feynman diagram for this process is shown in Fig. 1. After the decay of the LQ, the final state consists of a high transverse momentum (p_T) centrally-produced lepton from the LQ decay, a same-flavor opposite-sign forward lepton from the photon decay, and a high- p_T centrally-produced jet from the LQ decay. The forward lepton in this production mode usually has p_T below reconstruction threshold and differs from other production modes, which typically have two high- p_T leptons. This Letter presents the first search for scalar LQs produced in τq collisions. For the strongest experimental sensitivity, we consider couplings to light-flavor (u, d, and s) and b quarks. The search is based on pp collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector in 2016–2018 corresponding to an integrated luminosity of 138 fb^{-1} . Three different decay modes of the τ lepton are studied, resulting in the $\tau_h + \text{jet}$, $e + \text{jet}$, and $\mu + \text{jet}$ final states, where τ_h denotes a τ lepton decaying hadronically. Tabulated results are provided in the HEPData record for this analysis [25].

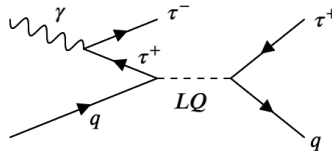


Figure 1: Feynman diagram of the lepton-induced LQ production.

The CMS apparatus [26] is a multipurpose, nearly hermetic detector, designed to trigger on [27, 28] and identify electrons, muons, photons, and both charged and neutral hadrons [29–31]. A global “particle-flow” (PF) algorithm [32] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic, and a brass and scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build τ leptons, jets, and missing transverse momentum (\vec{p}_T^{miss}) [33–36].

The signal and some of the background contributions are estimated using simulations. Signal samples for scalar LQs in the s -channel single LQ production are generated at next-to-LO (NLO) with POWHEG interfaced with HERWIG [37] for the showering, using the models and LUXLEP lepton PDFs described in Refs. [18, 21]. The LUXLEP PDF set results from the combination of the NNPDF3.1LUXQED set [38] and the lepton PDFs of Ref. [18], which are obtained with a framework similar to that used to determine the PDFs of the photon in the proton using

electron-proton scattering data [19, 20]. The signal samples are generated for $b\tau$ ($u\tau$) couplings, for LQ masses m_{LQ} between 0.6 and 2.0 (0.6 and 3.0) TeV, an absolute electric charge of $2/3e$ ($1/3e$), and a Yukawa coupling at the LQ-lepton-quark vertex, λ , between 0.5 and 3.0 (0.2 and 2.0). Charge conjugate pairs are simulated together. The analysis acceptance and efficiency, determined from simulation, are similar for couplings to any light-flavor quark, and the samples with LQ- u - τ couplings are also used to extract results on LQ- d - τ and LQ- s - τ couplings. Results on LQ- c - τ couplings cannot be extracted from the same simulation because events with such couplings have a different efficiency for the requirement on the identification of jets originating from b quarks, which is used to build analysis categories as described later.

The cross sections for all coupling hypotheses are computed at NLO [23, 24]. The MADGRAPH5_aMC@NLO 2.6.5 event generator [39] is used to generate events originating from $Z + \text{jets}$ and $W + \text{jets}$ processes. They are simulated at NLO with the FxFx jet matching and merging [40]. The vector boson p_T distribution is corrected to match a calculation at next-to-NLO (NNLO) for strong interactions and NLO with the next-to-leading logarithmic Sudakov approximation for electroweak interactions [41]. The MADGRAPH5_aMC@NLO generator is also used for the simulation of diboson production, while POWHEG 2.0 [42–46] is used for $t\bar{t}$ and single top quark production. The generators are interfaced with PYTHIA 8.240 [47] to model the parton showering, fragmentation, and hadronization, as well as the decay of the τ leptons. The PYTHIA parameters affecting the description of the underlying event are set to the CP5 tune [48]. The NNPDF3.1 parton distribution function (PDF) set [49–51] at NNLO precision is used for background simulations. Additional pp interactions per bunch crossing are added to the simulated samples with the frequency distribution matching that observed in data. Generated events are processed through a GEANT4 [52] simulation of the CMS detector.

Electrons are reconstructed from energy deposits in the calorimeters and tracks in the tracking system, and identified with a cut-based discriminant [29]. Muons are reconstructed from tracks and hits in the tracker and muon systems [30, 53]. Jets are clustered from PF candidates using the anti- k_T FASTJET algorithm with a distance parameter R of 0.4 [54, 55]. Their energy is corrected on an event-by-event basis [56]. Jets originating from b quarks are identified with the medium working point of the DEEPIET algorithm [57, 58]. The decay products of τ leptons decaying hadronically are reconstructed with the hadrons-plus-strips algorithm [33]. Quark and gluon jets, electrons, and muons misidentified as τ_h candidates are reduced with deep neural network discriminants [36]. The tight working point is used to separate τ_h candidates from jets; its efficiency is about 75% for τ_h with $p_T > 100$ GeV [36]. The loosest working point, used in the background estimation procedure, has an efficiency above 98%. The vector \vec{p}_T^{miss} is defined as the projection onto the plane perpendicular to the beam axis of the negative vector momentum sum of all reconstructed PF objects in an event. Its magnitude is referred to as p_T^{miss} .

The selection of events in the $\tau_h + \text{jet}$ final state relies either on a single τ_h trigger with online thresholds ranging from 140 to 180 GeV, depending on the data-taking year, or on a trigger requiring the scalar p_T sum of jets in the event with $p_T > 40$ GeV to be above 900–1050 GeV. Events are selected in the $e + \text{jet}$ final state using a single isolated electron trigger with online thresholds in the range of 27–35 GeV complemented with a photon trigger for $p_T > 175 - 200$ GeV. In the $\mu + \text{jet}$ final state, single muon triggers with online thresholds between 24 and 50 GeV are used. Depending on whether the jet is tagged as originating from a b quark [57, 58], the event is classified to be in a “btag” or “no-btag” category. A significant \vec{p}_T^{miss} satisfying $|\Delta\phi(\ell, \vec{p}_T^{\text{miss}})| < 0.2\text{--}0.3$ is required, where ℓ stands for the visible decay products of the τ lepton, as expected from the presence of one or more neutrinos in the τ lepton decay. The offline selection criteria for the lepton, leading jet, and \vec{p}_T^{miss} are presented in Table 1. They differ slightly for final states with leptonically and hadronically decaying τ leptons because of

Table 1: Selection criteria per final state.

Variable	$\tau_h + \text{jet}$	e + jet	$\mu + \text{jet}$
p_T^ℓ (GeV)	>200	>100	>100
$ \eta^\ell $	<2.1	<2.1	<2.1
p_T^{jet} (GeV)	>300	>200	>200
$ \eta^{\text{jet}} $	<2.4	<2.4	<2.4
p_T^{miss} (GeV)	>100	>150	>150
$p_T(\vec{\ell} + \vec{p}_T^{\text{miss}})$ (GeV)	>100	>100	>100
$ \Delta\phi(\ell, \vec{p}_T^{\text{miss}}) $ (radians)	<0.3	<0.2	<0.2
$\Delta R(\ell, \text{jet})$	>0.5	>0.5	>0.5

the different background contributions, triggers, and fractions of visible τ lepton momentum. To select the LQ production mechanism targeted in this analysis, events are discarded if a second well-identified and isolated electron, muon, or τ_h candidate with $p_T > 50$ GeV and absolute pseudorapidity, $|\eta|$, less than 2.1 is found. This additional lepton veto removes about 5% of the signal events in simulation. With this veto, other LQ production modes contribute less than 1% to the signal yield and are neglected.

As an estimation of m_{LQ} at reconstruction level, we calculate the collinear mass, defined as $m_{\text{coll}} = m_{\text{vis}}(\tau, \text{jet}) / \sqrt{x_{\text{vis}}}$, where $m_{\text{vis}}(\tau, \text{jet})$ is the invariant mass of the visible τ decay products and the jet, $x_{\text{vis}} = p_T^{\text{vis}}(\tau) / (p_T^{\text{vis}}(\tau) + p_T^{\text{invis}}(\tau))$, and $p_T^{\text{invis}}(\tau)$ is the component of \vec{p}_T^{miss} in the direction of the visible τ decay products. This calculation assumes that the neutrinos from τ lepton decays are the only source of \vec{p}_T^{miss} and have the same η as the visible τ decay products. The experimental resolution on m_{coll} is about 5–10%, depending on the final state and m_{LQ} , and for $\lambda \lesssim 1$ the natural width of the signal is negligible by comparison. In simulated events, the m_{coll} distribution peaks at the generated m_{LQ} values.

Background events with a prompt lepton in the final state ($W + \text{jets}$, Drell–Yan, diboson, single top quark, and $t\bar{t}$ production events) are estimated from simulation and normalized to their theoretical cross sections [59–64], with the exception of the normalization of $W + \text{jets}$ events in the btag categories. Because of the lack of a precise prediction for the cross section of $W + \text{jets}$ in association with heavy-flavor jets, the latter is extracted from data in control regions (CRs) in the e + jet and $\mu + \text{jet}$ final states with $0.2 < |\Delta\phi(\ell, \vec{p}_T^{\text{miss}})| < 0.4$, where ϕ is the azimuthal angle in radians. The variable N_{jets} , defined as the number of jets with $p_T > 30$ GeV and $|\eta| < 2.4$, and separated by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.5$ from the selected lepton, is used as an observable to separate $W + \text{jets}$ from $t\bar{t}$ events, which on average have a higher number of jets. After the maximum likelihood fit including the signal regions (SRs), described later, the cross section for the $W + \text{jets}$ background in the btag categories is measured to be $1.04_{-0.06}^{+0.07}$ times the prediction from simulation, using the inclusive $W + \text{jets}$ cross section at NNLO [59].

The backgrounds with a jet misidentified as a τ_h candidate (an electron or muon), dominated by quantum chromodynamics (QCD) multijet events, constitute about 50 (10)% of the total background and are estimated from data. The probability for jets selected with the loosest working point of the τ_h discriminator to pass the tighter identification requirements in the SR, called the misidentification factor (MF), is measured as a function of $p_T(\tau_h)$, N_{jets} , $|\eta|$, and jet p_T . It is in the range 0.10–0.25. This measurement is performed in a CR with a selection identical to that in the SR, except that the p_T^{miss} requirement is inverted. A multiplicative correction for the extrapolation to higher p_T^{miss} values in the SR is applied. The MF for electrons is measured

as a function of the electron p_T because the trigger requirements are p_T -dependent, while the muon MF is measured as a function of p_T^{miss} , since the relative fraction of QCD multijet and $W + \text{jets}$ backgrounds varies with p_T^{miss} . The observed p_T^{miss} linear dependence is extrapolated to the SR for $150 < p_T^{\text{miss}} < 300 \text{ GeV}$ and is assumed constant above 300 GeV. Events that pass the SR selection with the exception of the τ_h , electron, or muon identification, depending on the final state, are reweighted using the MFs to estimate the background with misidentified jets. Contributions from prompt τ_h candidates, electrons, or muons in this region are estimated from simulation and subtracted to avoid double-counting events containing genuine leptons.

After the application of the selection criteria shown in Table 1, boosted decision trees (BDTs) are trained with the TMVA package [65] for each final state to improve the separation between the signal and background. The input variables, chosen to have a limited dependence on m_{LQ} , are the following: $|\Delta\phi|$ between pairs of analysis objects (electrons, muons, τ_h , jets, \vec{p}_T^{miss}), the ratio of the objects' p_T to m_{coll} or to each other's p_T , the ΔR separation between the jet and the reconstructed τ lepton, and N_{jets} . The BDTs are trained with a mixture of all signal samples with various m_{LQ} and λ , against background events coming from $W + \text{jets}$ production and either processes with misidentified jets in the $\tau_h + \text{jet}$ channel, or $t\bar{t}$ events in the $e + \text{jet}$ and $\mu + \text{jet}$ channels. The BDT training is performed once for each final state, and is used in the btag and no-btag categories, for all data-taking years and m_{LQ} hypotheses. The BDT output distribution is verified to be well predicted in a validation region where the requirement on $|\Delta\phi(\ell, \vec{p}_T^{\text{miss}})|$ is inverted.

Events in the no-btag (btag) category are further split into 4 (3) subcategories on the basis of their BDT output. In the btag subcategories, events with $N_{\text{jets}} > 2$ are vetoed to reduce the contribution from the $t\bar{t}$ background. The discriminating observable is m_{coll} in all subcategories and final states.

Uncertainties in the reconstruction, identification, and isolation of τ_h candidates (electrons, muons) are determined via the “tag-and-probe” method [66] and can be as high as 15 (2, 2)%. The b tagging uncertainties for heavy-flavor jets and mistagging uncertainties for light-flavor quark and gluon jets are included with partial correlations between the data-taking years. They are in the range 6–9% in the btag category for LQs coupled to b quarks. The uncertainty in the efficiency of the τ_h (electron, muon) trigger ranges up to 11 (2, 2)%. The uncertainty in the energy scale of τ_h candidates is below the percent level for all τ_h decay modes, and is propagated to the m_{coll} distributions. The impact of uncertainties in the energy scale and resolution of jets, and in the measurement of \vec{p}_T^{miss} , is smaller by comparison. The uncertainties in the energy scale of electrons and muons are negligible as compared with the uncertainties mentioned above.

The uncertainties in the $t\bar{t}$, diboson, and single top quark production cross sections are 5.2, 2.5, and 3.7%, respectively [61–64]. The uncertainties in the NNLO cross sections of the $Z + \text{jets}$ and $W + \text{jets}$ backgrounds are 2 and 3%, respectively [59, 60]. In the btag category, the $Z + \text{jets}$ background normalization uncertainty is increased to 20% on the basis of the agreement observed in a CR with 2 τ_h candidates and 1 b tagged jet, while the normalization of the $W + \text{jets}$ background is left floating in the fit, resulting in an uncertainty of 7% as detailed above. The acceptance uncertainties in the renormalization and factorization scales, PDFs, and parton showering for these simulated processes are also included. For the signal, uncertainties in the renormalization and factorization scales, and in the PDFs are included. They affect the m_{coll} distributions and have a normalization effect in the ranges 3–4 (4–6)% (scales) and 2–3 (2–4)% (PDFs), respectively, for LQs with $u\tau$ ($b\tau$) couplings, in the mass ranges considered in the analysis [23]. The uncertainty in the integrated luminosity is 1.6% [67–69].

Different uncertainties affecting the m_{coll} distributions are considered for the background with jets misidentified as τ_h candidates: 10% uncertainty per detector region (barrel or endcaps), 10% uncertainty per N_{jets} bin, 30% uncertainty for events with $p_T(\tau_h) > 600$ GeV, 10% uncertainty in the leading jet p_T correction, and the p_T^{miss} correction uncertainty described earlier. The uncertainty in the MFs for electrons and muons originates from the limited number of events in the measurement and from the choice of observables and selection criteria. It results in a 20% normalization uncertainty for backgrounds with misidentified electrons or muons, uncorrelated between the data-taking years. In the $\mu + \text{jet}$ channel, an uncertainty in the p_T^{miss} dependence is included.

A maximum likelihood fit is performed with the signal normalization as a free parameter, and the systematic uncertainties described above as nuisance parameters. The m_{coll} distributions in the different subcategories and final states are fitted simultaneously, together with the N_{jets} distributions in the CRs that control the normalization of the background from $W + \text{jets}$ with a b tagged jet. Those with the highest BDT output requirement, selecting the most signal-like events, are shown in Fig. 2. The btag subcategory with the highest BDT output requirement contains about 70 (41, 56)% of the LQ events with $m_{\text{LQ}} = 2$ TeV and $\lambda_{b\tau} = 1.0$ entering the btag category, and about 9.8 (5.6, 12)% of the total background in the $\tau_h + \text{jet}$ ($e + \text{jet}$, $\mu + \text{jet}$) final state. The no-btag subcategory with the highest BDT output requirement contains about 55 (30, 33)% of the LQ events with $m_{\text{LQ}} = 3$ TeV and $\lambda_{u\tau} = 1.0$ entering the no-btag category, and about 0.86 (1.1, 1.9)% of the total background in the no-btag category in the $\tau_h + \text{jet}$ ($e + \text{jet}$, $\mu + \text{jet}$) final state.

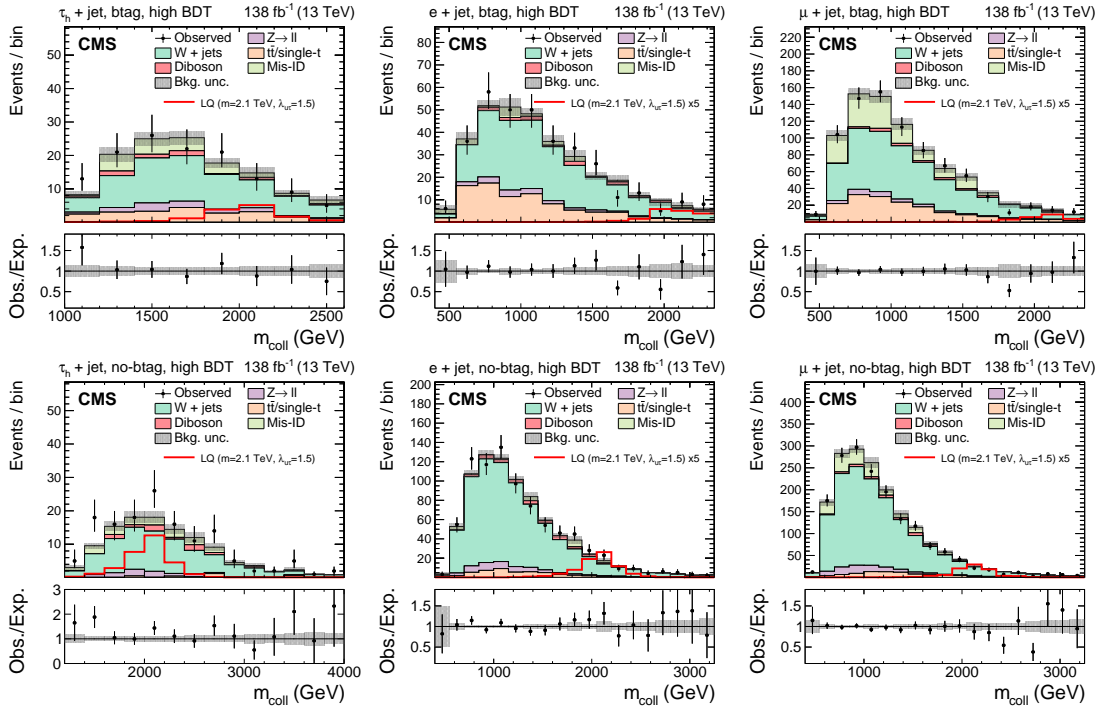


Figure 2: Observed and expected distributions of m_{coll} in the $\tau_h + \text{jet}$ (left), $e + \text{jet}$ (center), and $\mu + \text{jet}$ (right) channels for the btag (upper) and no-btag (lower) subcategories with the BDT requirements selecting the most signal-like events. The bands include statistical and systematic uncertainties. The background distributions are the results of the maximum likelihood fit. For clarity, the signal distributions in the $e + \text{jet}$ and $\mu + \text{jet}$ final states are multiplied by a factor of 5.

No statistically significant excess above the SM backgrounds is observed. Upper limits at 95%

confidence level (CL) are set on the product of the LQ production cross section and the branching fraction for different coupling hypotheses, using the CL_s method [70, 71] in the asymptotic approximation [72]. Because of the trigger requirements, the signal acceptance in the $\tau_h + \text{jet}$ final state is low for $m_{LQ} = 600 \text{ GeV}$ and the limits for this mass point are derived from the distributions in the $e + \text{jet}$ and $\mu + \text{jet}$ final states only. The 95% CL limits are in the range $0.34\text{--}0.0018$ ($0.15\text{--}0.0030$) pb for masses between 0.6 and 3.0 (0.6 and 2.0) TeV for $\lambda_{u\tau} = 1.5$ ($\lambda_{b\tau} = 1.5$), as shown in Fig. 3. The limits are translated into exclusion regions in the m_{LQ} - λ plane, as shown in Fig. 4, assuming the branching fraction of the LQs to a quark and a τ lepton to be 100% for the considered quark flavor. The observed limits on LQs coupling to b quarks and τ leptons extend existing constraints from searches in other production modes at high m_{LQ} [12]. Leptoquarks coupling to light-flavor quarks and τ leptons can be excluded at masses above the previously existing limit of 1.3 TeV [17], for $\lambda_{u\tau}$ ($\lambda_{d\tau}$, $\lambda_{s\tau}$) above 0.6 (0.8, 1.9).

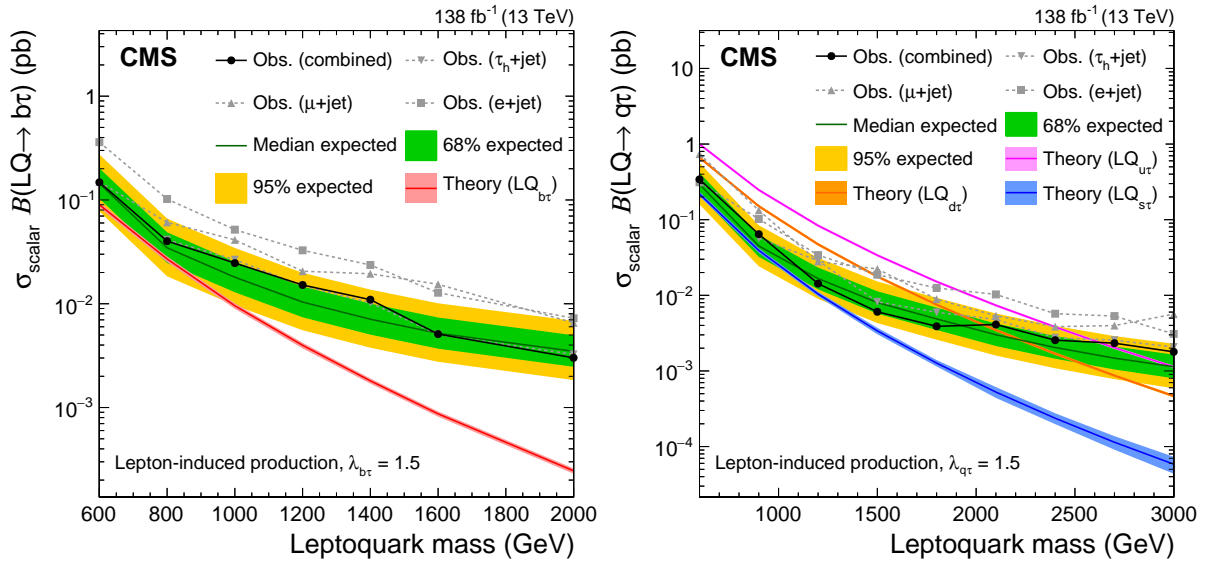


Figure 3: Expected and observed upper limits at 95% CL on the product of the scalar lepton-induced LQ production cross section and the branching fraction for a LQ coupled to b quarks and τ leptons (left), or to light-flavor quarks and τ leptons (right), using $\lambda = 1.5$. The theoretical cross sections correspond to the calculations of Refs. [23, 24]. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The filled circles show the observed limits for the combination of final states, while the other markers indicate the observed results per final state.

In summary, a search for leptoquarks produced in lepton-quark collisions and coupled to τ leptons has been performed for the first time, using data collected with the CMS detector in 2016–2018. These limits are complementary to those set using other production modes at high mass and coupling values for $b\tau$ couplings, while the limits on the couplings of leptoquarks to light-flavor quarks extend the mass range excluded by previous searches in other production modes.

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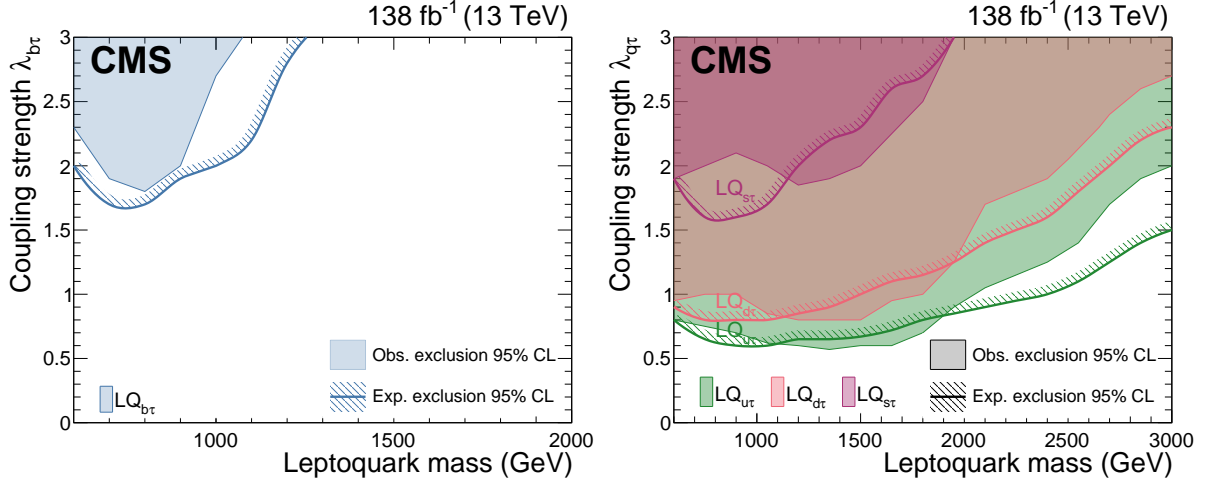


Figure 4: Upper limit at 95% CL on the coupling strength λ of a scalar LQ to b quarks and τ leptons (left), and to light-flavor quarks and τ leptons (right). Regions above the hatched lines correspond to the expected exclusions.

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References

- [1] J. C. Pati and A. Salam, “Lepton number as the fourth color”, *Phys. Rev. D* **10** (1974) 275, doi:10.1103/PhysRevD.10.275.
- [2] H. Georgi and S. L. Glashow, “Unity of all elementary-particle forces”, *Phys. Rev. Lett.* **32** (1974) 438, doi:10.1103/PhysRevLett.32.438.
- [3] S. Dimopoulos and L. Susskind, “Mass without scalars”, *Nucl. Phys. B* **155** (1979) 237, doi:10.1016/0550-3213(79)90364-X.
- [4] S. Dimopoulos, “Technicoloured signatures”, *Nucl. Phys. B* **168** (1980) 69, doi:10.1016/0550-3213(80)90277-1.
- [5] B. Schrempp and F. Schrempp, “Light leptoquarks”, *Phys. Lett. B* **153** (1985) 101, doi:10.1016/0370-2693(85)91450-9.
- [6] W. Buchmüller and D. Wyler, “Constraints on SU(5)-type leptoquarks”, *Phys. Lett. B* **177** (1986) 377, doi:10.1016/0370-2693(86)90771-9.
- [7] B. Dumont, K. Nishiwaki, and R. Watanabe, “LHC constraints and prospects for S_1 scalar leptoquark explaining the $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$ anomaly”, *Phys. Rev. D* **94** (2016) 034001, doi:10.1103/PhysRevD.94.034001, arXiv:1603.05248.
- [8] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, “B-physics anomalies: a guide to combined explanations”, *JHEP* **11** (2017) 044, doi:10.1007/JHEP11(2017)044, arXiv:1706.07808.
- [9] J. Kumar, D. London, and R. Watanabe, “Combined explanations of the $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow c\tau^-\bar{\nu}$ anomalies: a general model analysis”, *Phys. Rev. D* **99** (2019) 015007, doi:10.1103/PhysRevD.99.015007, arXiv:1806.07403.
- [10] A. Angelescu et al., “Single leptoquark solutions to the B-physics anomalies”, *Phys. Rev. D* **104** (2021) 055017, doi:10.1103/PhysRevD.104.055017, arXiv:2103.12504.
- [11] ATLAS Collaboration, “Search for new phenomena in pp collisions in final states with tau leptons, b-jets, and missing transverse momentum with the ATLAS detector”, *Phys. Rev. D* **104** (2021) 112005, doi:10.1103/PhysRevD.104.112005, arXiv:2108.07665.
- [12] CMS Collaboration, “Search for a singly produced third-generation scalar leptoquark decaying to a τ lepton and a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 115, doi:10.1007/JHEP07(2018)115, arXiv:1806.03472.
- [13] CMS Collaboration, “Search for singly and pair-produced leptoquarks coupling to third-generation fermions in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **819** (2021) 136446, doi:10.1016/j.physletb.2021.136446, arXiv:2012.04178.
- [14] ATLAS Collaboration, “Search for pair production of third-generation scalar leptoquarks decaying into a top quark and a τ -lepton in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **06** (2021) 179, doi:10.1007/JHEP06(2021)179, arXiv:2101.11582.
- [15] CMS Collaboration, “Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2023) 073, doi:10.1007/JHEP07(2023)073, arXiv:2208.02717.

- [16] CMS Collaboration, “Search for new physics in the τ lepton plus missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **09** (2023) 051, doi:10.1007/JHEP09(2023)051, arXiv:2212.12604.
- [17] ATLAS Collaboration, “Search for excited τ -leptons and leptoquarks in the final state with τ -leptons and jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **06** (2023) 199, doi:10.1007/JHEP06(2023)199, arXiv:2303.09444.
- [18] L. Buonocore, P. Nason, F. Tramontano, and G. Zanderighi, “Leptons in the proton”, *JHEP* **08** (2020) 019, doi:10.1007/JHEP08(2020)019, arXiv:2005.06477.
- [19] A. Manohar, P. Nason, G. P. Salam, and G. Zanderighi, “How bright is the proton? A precise determination of the photon parton distribution function”, *Phys. Rev. Lett.* **117** (2016) 242002, doi:10.1103/PhysRevLett.117.242002, arXiv:1607.04266.
- [20] A. V. Manohar, P. Nason, G. P. Salam, and G. Zanderighi, “The photon content of the proton”, *JHEP* **12** (2017) 046, doi:10.1007/JHEP12(2017)046, arXiv:1708.01256.
- [21] L. Buonocore et al., “Lepton-quark collisions at the Large Hadron Collider”, *Phys. Rev. Lett.* **125** (2020) 231804, doi:10.1103/PhysRevLett.125.231804, arXiv:2005.06475.
- [22] U. Haisch and G. Polesello, “Resonant third-generation leptoquark signatures at the Large Hadron Collider”, *JHEP* **05** (2021) 057, doi:10.1007/JHEP05(2021)057, arXiv:2012.11474.
- [23] A. Greljo and N. Selimovic, “Lepton-quark fusion at hadron colliders, precisely”, *JHEP* **03** (2021) 279, doi:10.1007/JHEP03(2021)279, arXiv:2012.02092.
- [24] L. Buonocore et al., “Resonant leptoquark at NLO with POWHEG”, *JHEP* **11** (2022) 129, doi:10.1007/JHEP11(2022)129, arXiv:2209.02599.
- [25] HEPData record for this analysis, 2023. doi:10.17182/hepdata.141335.
- [26] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [27] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [28] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [29] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [30] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [31] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.


-
- [32] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [33] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
- [34] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [35] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [36] CMS Collaboration, “Identification of hadronic tau lepton decays using a deep neural network”, *JINST* **17** (2022) P07023, doi:10.1088/1748-0221/17/07/P07023, arXiv:2201.08458.
- [37] M. Bahr et al., “Herwig++ physics and manual”, *Eur. Phys. J. C* **58** (2008) 639, doi:10.1140/epjc/s10052-008-0798-9, arXiv:0803.0883.
- [38] NNPDF Collaboration, “Illuminating the photon content of the proton within a global PDF analysis”, *SciPost Phys.* **5** (2018) 008, doi:10.21468/SciPostPhys.5.1.008, arXiv:1712.07053.
- [39] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [40] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [41] J. M. Lindert et al., “Precise predictions for V + jets dark matter backgrounds”, *Eur. Phys. J. C* **77** (2017) 829, doi:10.1140/epjc/s10052-017-5389-1, arXiv:1705.04664.
- [42] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [43] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [44] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [45] S. Alioli et al., “Jet pair production in POWHEG”, *JHEP* **04** (2011) 081, doi:10.1007/JHEP04(2011)081, arXiv:1012.3380.
- [46] S. Alioli, P. Nason, C. Oleari, and E. Re, “NLO Higgs boson production via gluon fusion matched with shower in POWHEG”, *JHEP* **04** (2009) 002, doi:10.1088/1126-6708/2009/04/002, arXiv:0812.0578.

- [47] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [48] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [49] R. D. Ball et al., “Unbiased global determination of parton distributions and their uncertainties at NNLO and at LO”, *Nucl. Phys. B* **855** (2012) 153, doi:10.1016/j.nuclphysb.2011.09.024, arXiv:1107.2652.
- [50] NNPDF Collaboration, “Parton distributions with QED corrections”, *Nucl. Phys. B* **877** (2013) 290, doi:10.1016/j.nuclphysb.2013.10.010, arXiv:1308.0598.
- [51] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [52] GEANT4 Collaboration, “GEANT4 — a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [53] CMS Collaboration, “Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P02027, doi:10.1088/1748-0221/15/02/P02027, arXiv:1912.03516.
- [54] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [55] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, CERN, Geneva, Switzerland, 2017.
- [56] CMS Collaboration, “Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016-2018”, CMS Detector Performance Summary CMS-DP-2020-019, CERN, Geneva, Switzerland, 2020.
- [57] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [58] E. Bols et al., “Jet flavour classification using DeepJet”, *JINST* **15** (2020) P12012, doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [59] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, “W physics at the LHC with FEWZ 2.1”, *Comput. Phys. Commun.* **184** (2013) 208, doi:10.1016/j.cpc.2012.09.005, arXiv:1201.5896.
- [60] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, “FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order”, *Comput. Phys. Commun.* **182** (2011) 2388, doi:10.1016/j.cpc.2011.06.008, arXiv:1011.3540.
- [61] M. Czakon and A. Mitov, “Top++: A program for the calculation of the top-pair cross-section at hadron colliders”, *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.



















- [62] T. Gehrmann et al., “ W^+W^- production at hadron colliders in next-to-next-to-leading order QCD”, *Phys. Rev. Lett.* **113** (2014) 212001, doi:10.1103/PhysRevLett.113.212001, arXiv:1408.5243.
- [63] J. Campbell, T. Neumann, and Z. Sullivan, “Single-top-quark production in the t -channel at NNLO”, *JHEP* **02** (2021) 040, doi:10.1007/JHEP02(2021)040, arXiv:2012.01574.
- [64] N. Kidonakis and N. Yamanaka, “Higher-order corrections for tW production at high-energy hadron colliders”, *JHEP* **05** (2021) 278, doi:10.1007/JHEP05(2021)278, arXiv:2102.11300.
- [65] A. Hoecker et al., “TMVA4 — Toolkit for multivariate data analysis with ROOT. Users guide”, 2007. arXiv:physics/0703039.
- [66] CMS Collaboration, “Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.
- [67] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [68] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, CERN, Geneva, Switzerland, 2018.
- [69] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, CERN, Geneva, Switzerland, 2019.
- [70] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [71] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [72] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

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


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
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






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





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

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


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





















































































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









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






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









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








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





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


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

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


























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























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















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














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

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






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






















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






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


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


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


































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D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler , D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , F. Fallavollita⁶¹ , L. Forthomme , G. Franzoni , W. Funk , S. Giani , D. Gigi , K. Gill , F. Glege , L. Gouskos , M. Haranko , J. Hegeman , B. Huber , V. Innocente , T. James , P. Janot , J. Kieseler , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , M. Matthewman , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Moortgat , M. Mulders , S. Orfanelli , F. Pantaleo , M. Peruzzi , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , H. Qu , D. Rabadý , G. Reales Gutiérrez , M. Rovere , H. Sakulin , S. Scarfi , M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁶² , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , A. Tsiros , D. Walter , J. Wanczyk⁶³ , K.A. Wozniak⁶⁴ , P. Zehetner , P. Zejdl , W.D. Zeuner 



















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





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










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

















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





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
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R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 


















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









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














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











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












































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















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












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M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁹ , F. Ravera , A. Reinsvold Hall⁹⁰ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






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

















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





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

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











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





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


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

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


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

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







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











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

















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













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











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









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












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


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





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
















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