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A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV

The ATLAS Collaboration

The coupling constant of the strong force is determined from the transverse-momentum distribution of Z bosons produced in 8 TeV proton–proton collisions at the LHC and recorded by the ATLAS experiment. The Z-boson cross sections are measured in the full phase space of the decay leptons using 15.3 million electron and muon pairs, in a dataset collected in 2012 and corresponding to an integrated luminosity of 20.2 fb^{-1}. The analysis is based on predictions evaluated at third order in perturbative QCD, supplemented by the resummation of logarithmically enhanced contributions in the low transverse-momentum region of the lepton pairs. The determined value of the strong coupling at the reference scale corresponding to the Z-boson mass is $\alpha_s(m_Z) = 0.1183 \pm 0.0009$. This is the most precise experimental determination of $\alpha_s(m_Z)$ achieved so far.

1 Introduction

The coupling constant of the strong interaction is one of the fundamental parameters of the Standard Model, yet remains the least precisely determined of the four fundamental couplings in nature. The strong interaction is described theoretically by quantum chromodynamics (QCD), a gauge field theory with symmetry group SU(3) [1, 2]. The free parameters of QCD include the six quark masses and the running coupling constant $\alpha_{\mathrm{s}}(Q)$, which runs with the energy scale Q characterising the interaction. While the running of the coupling constant is fully predicted by theory, its value at a reference scale needs to be determined experimentally. The latest world-average value of experimental determinations and QCD lattice calculations of the strong-coupling constant at the scale of the Z-boson mass is calculated to be $\alpha_{\mathrm{s}}(Q = m_Z) = 0.1179 \pm 0.0009$, with a relative uncertainty of 0.8% [3]. This uncertainty is orders of magnitude larger than that of the couplings of the other three fundamental interactions: the electromagnetic, weak, and gravitational forces.

Our knowledge of the strong-coupling constant has improved over the years, from the significant uncertainties in the first determinations in the mid 1980s [4], to the present uncertainty at the percent level. Further improvement in the precision of α_{s} is important in order to reduce the associated theoretical uncertainty which enters all cross-section calculations for processes at the LHC and affects several key observables at e^+e^- colliders. As an example, in the global fit of the electroweak sector of the Standard Model, the value of $\alpha_{\mathrm{s}}(m_Z)$ is the leading source of uncertainty in the computation of the total and partial hadronic decay widths of the Z boson [5–7]. A precise determination of $\alpha_{\mathrm{s}}(m_Z)$ is required to fully exploit the sensitivity to new physics expected from high-precision measurements of such observables at future e^+e^- colliders. The value of $\alpha_{\mathrm{s}}(m_Z)$ and its energy evolution also have far-reaching implications for the stability of the electroweak vacuum [8] and the convergence of the couplings of the strong, weak and electromagnetic forces at an energy close to the Planck scale, which might signal the onset of a grand unification of these forces.

Various different determinations of $\alpha_{\mathrm{s}}(m_Z)$ contribute to the current world average, and are categorised according to their methodological approach [9]. The most precise determinations are based on lattice QCD analysis of hadron spectroscopy, resulting in $\alpha_{\mathrm{s}}(m_Z) = 0.1184 \pm 0.0008$ [10], and hadronic τ-lepton decays, resulting in $\alpha_{\mathrm{s}}(m_Z) = 0.1177 \pm 0.0019$ [3, 11–16]. Arguably the cleaner determinations are those from global fits of the electroweak observables, which exploit the sensitivity of total and partial hadronic decay widths of the Z boson, as in Ref. [6], yielding $\alpha_{\mathrm{s}}(m_Z) = 0.1194 \pm 0.0029$. These determinations have been performed at next-to-next-to-next-to-leading order (N^{3}LO) in QCD and are currently limited by experimental uncertainties. In hadron-induced collisions, the strong-coupling constant has been determined from final states with jets [17–20], from inclusive top-quark pair production [21, 22], and from inclusive W- and Z-boson production [23]. The high-momentum region of the Z-boson transverse-momentum (p_{T}) distribution measured at the LHC [24–26] was included in the determination of parton distribution functions (PDFs) [27], and contributed to the simultaneous determination of PDFs and the strong-coupling constant in Refs. [28–30].

Further improvement in our knowledge of $\alpha_{\mathrm{s}}(m_Z)$ is limited by two important sources of theoretical uncertainty: the accuracy of the perturbative predictions and the size of non-perturbative effects. In this context, it is highly desirable to investigate alternative determinations of $\alpha_{\mathrm{s}}(m_Z)$ based on the most sensitive observables and state-of-the-art theory predictions.

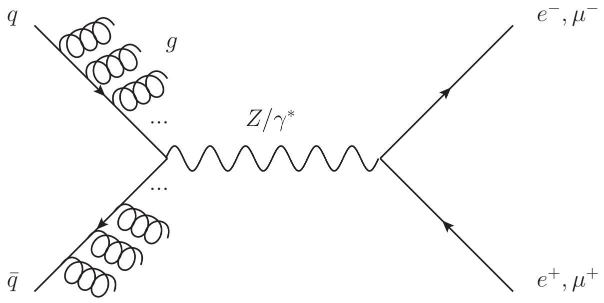

Figure 1: Leading-order Feynman diagram for the production of a massive electron or muon pair through the Drell–Yan process, including soft gluon radiation from the initial-state quarks.

This article presents a precise determination of $\alpha_s(m_Z)$ from a semi-inclusive observable,[1] namely the low-momentum Sudakov region[2] of the transverse-momentum distribution of Z bosons produced via the Drell–Yan process [34], which refers to the production of a massive lepton-pair in hadron–hadron collisions at high energies. The strong force is responsible for the radiation from the initial-state partons, and for the subsequent recoil of the Z bosons which acquire non-zero transverse momentum with respect to the incoming proton beam axis. The hardness of the transverse-momentum distribution is a measure of the strength of the recoil of the Z bosons, which in turn is proportional to the strong coupling. In contrast to most other determinations of $\alpha_s(m_Z)$ at hadron colliders, which analyse observables based on QCD final-state radiative objects, this analysis uses QCD initial-state radiative processes to determine the strong coupling. In the Drell–Yan process, the final-state particles are not subject to the strong interaction, which reduces theoretical complications and uncertainties. The energy scale at which the strong-coupling constant is perturbatively expanded is unambiguously fixed to the Z-boson mass. This methodology was tested in Ref. [35] using proton–antiproton collision data at the Tevatron, and is applied here for the first time at the LHC.

Figure 1 depicts the leading-order Feynman diagram of the Drell–Yan process, with a schematic representation of soft gluon radiation from the initial-state quarks. Figure 2 shows the Z-boson transverse-momentum distribution for three different values of $\alpha_s(m_Z)$.

Compared to other determinations of $\alpha_s(m_Z)$ at hadron colliders, based on either exclusive or inclusive observables, this determination gathers the desirable features for high precision: large observable sensitivity to $\alpha_s(m_Z)$ relative to the experimental precision, and high perturbative accuracy of the theoretical predictions [38–40], enabled by the computation of some perturbative corrections in QCD at four- or five-loop level [41–45].

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[1] Semi-inclusive observables are those with more than one kinematic momentum scale in the perturbative regime, where the semi-inclusive region is close to the boundary of the phase space allowed by the kinematics. In such a limit, the associated parton radiation is strongly inhibited and large logarithmic corrections appear in the perturbative computation [31, 32].

[2] The low-energy region of the transverse-momentum distribution of Z bosons is characterised by very high probabilities of gluon emissions with vanishingly small momenta. Rather than calculate each of these, it is theoretically simpler to model them as a single factor quantifying the probability of no emission, known as the Sudakov form factor [33].

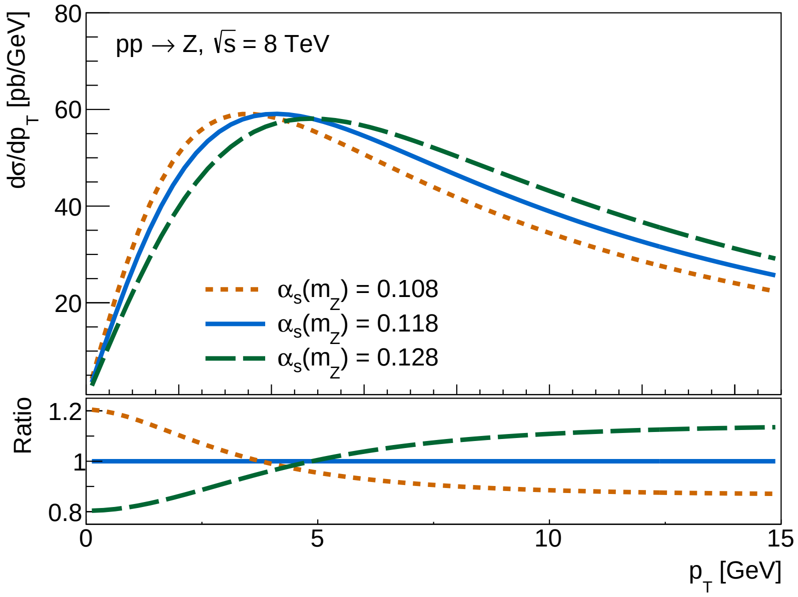

Figure 2: Transverse-momentum distribution of Z bosons predicted with `DYTurbo` [36] at different values of $\alpha_s(m_Z)$, using the MSHT20 PDF set [37]. The impact of changing $\alpha_s(m_Z)$ on the PDFs is included.

2 ATLAS detector and data sample

The ATLAS experiment [46] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[3] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision chambers for tracking and fast detectors for triggering. A three-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate of at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted event rate to 400 Hz on average depending on the data-taking conditions during 2012. An extensive software suite [47] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment. The data were collected by the ATLAS detector in 2012 at a centre-of-mass

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[3] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

energy of $\sqrt{s} = 8$ TeV, and correspond to an integrated luminosity of 20.2 fb^{-1}. The mean number of additional pp interactions per bunch crossing (pile-up events) in the dataset is approximately 20.

3 Cross-section measurement

The Z-boson transverse-momentum distribution is measured in the electron and muon decay channels, which provide a clear signature with low background rates and a high-precision measurement of the momentum, as presented in Ref. [48]. The double-differential cross sections as functions of transverse momentum (p_{T}) and rapidity (y) of the Z boson are measured in the pole region, defined as $80 < m_{\ell\ell} < 100$ GeV, where $m_{\ell\ell}$ is the invariant mass of the dilepton system. The combination of 6.2 million electron pairs and 7.8 million muon pairs in the central region, with pseudorapidity $|\eta| < 2.4$, is complemented by 1.3 million electron pairs with one electron in the forward region of the detector, $2.5 < |\eta| < 4.9$, and one electron in the central region.

Events with two 'central' electrons were collected using either a dielectron trigger, requiring two electron candidates to each have $p_{\mathrm{T}} > 12$ GeV, or two high-p_{T} single-electron triggers, the main one having a p_{T} threshold of 24 GeV. Events with two central muons were collected with either a dimuon trigger requiring two muon candidates with $p_{\mathrm{T}} > 18$ GeV and 8 GeV, respectively, or two high-p_{T} single-muon triggers, the main one having a p_{T} threshold of 24 GeV. Events with one central electron and one forward electron were collected using the two high-p_{T} single-electron triggers described above. Electron candidates in the central region are required in the offline analysis to have either $p_{\mathrm{T}} > 20$ GeV when paired with another central electron candidate or $p_{\mathrm{T}} > 25$ GeV when paired with a forward electron candidate. Muon candidates are required offline to have $p_{\mathrm{T}} > 20$ GeV. Electron candidates in the forward region are required offline to have $p_{\mathrm{T}} > 20$ GeV.

The cross-section measurement relies on the decomposition of the leptons' $\cos\theta$ and ϕ angular distributions in the Collins–Soper frame[4] into nine spherical harmonic polynomials, multiplied by angular coefficients [50]. The cross sections in the full lepton phase space, i.e. without kinematic requirements on the transverse momenta and pseudorapidity of the leptons, are extracted from the data by fitting templates of the spherical harmonic polynomials to the reconstructed angular distributions in $(\cos\theta, \phi)$. The decomposition into nine spherical harmonics is based on a simple and model-independent ansatz, namely the spin-one nature of the intermediate boson and spin-half nature of the decay leptons, and on the assumption of angular momentum conservation and quantisation. By measuring the cross sections in the full lepton phase space there is no longer a requirement for predictions to model the polarisation and decay of the Z boson; only its production properties are of interest for comparison with the measurements, thus enabling a determination of the strong-coupling constant not affected by theoretical uncertainties and ambiguities related to spin correlations.

The double-differential cross sections are measured in eight rapidity regions in the range $|y| < 3.6$. The region of Z-boson transverse momentum $p_{\mathrm{T}} < 29$ GeV is considered for the determination of $\alpha_{\mathrm{s}}(m_Z)$, corresponding to nine bins of transverse momentum. The choice of bin boundaries in p_{T} is the result of an optimisation with respect to the limited resolution of the measurements at low p_{T}. The background rates from other QCD and electroweak processes are at the level of 0.3% for central electron and muon

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[4] The Collins–Soper frame is the rest frame of the Z boson in which the z-axis bisects the angle between the momentum vector of one proton and the negative momentum vector of the other proton, the x-axis is fixed by the transverse momentum of the Z boson, and the y-axis completes a right-handed coordinate system [49].

pairs, and 1.1% for events with one central electron and one forward electron. The total uncertainties in the measurements are dominated by the statistical uncertainties of the data and, to a lesser extent, those of the simulation samples. Apart from the luminosity uncertainty of 1.8% [51], the total uncertainties are below 1% for $|y| < 2.0$, and below 10% for $2.0 < |y| < 3.6$ [48].

4 Theoretical framework and statistical analysis

The theoretical predictions are computed with the public numerical program `DYTurbo` [36], which implements the resummation of logarithmically enhanced contributions in the low-p_T region of the lepton pairs at approximate next-to-next-to-next-to-next-to-leading-logarithm accuracy (N^{4}LLa) [52], combined with the hard-collinear contributions at N^{3}LO in powers of the QCD coupling [38], and matched to fixed order, namely to N^{3}LO. The resummation is carried out in impact-parameter space b, which is the Fourier-transform variable conjugate to p_T [53–55]. The resummed cross section is given by the convolution of the leading-order (LO) cross section, the hard-collinear contributions, and the universal (process-independent) Sudakov form factor. The hard-collinear contributions are expanded in powers of α_s, whereas the Sudakov form factor contains all the terms that order-by-order in α_s are logarithmically divergent as $p_\mathrm{T} \rightarrow 0$. A unitarity constraint is imposed in the matching to fixed order of the p_T-resummed prediction so as to exactly recover the N^{3}LO finite-order result when integrating the full lepton-phase-space resummed cross section over p_T. The $O(\alpha_\mathrm{s}^3)$ coefficient of the Z+jet cross-section predictions, required for the matching to fixed order, was computed with MCFM [40, 56], using a lower cut-off of $p_\mathrm{T} = 5$ GeV. The corresponding matching corrections were interpolated with their known quadratic dependence on the ratio of p_T/m_Z [57] and extrapolated to $p_\mathrm{T} = 0$. The Sudakov form factor is singular in the region of transverse momenta of the order of the QCD coupling scale Λ_QCD. This signals that a truly non-perturbative region is approached and perturbative results are not reliable. Non-perturbative QCD effects are included with a corresponding form factor [53, 58], which depends on a set of parameters which are either left free in the fit for the determination of $\alpha_\mathrm{s}(m_Z)$ or varied when assessing non-perturbative uncertainties.

The predicted cross sections depend on three unphysical QCD scales: the renormalisation scale μ_r, which refers to the characteristic energy scale at which the running coupling constant is evaluated, the factorisation scale μ_f, which separates long-distance and short-distance physics in a scattering process, and the resummation scale Q, which parameterises the arbitrariness in the resummation procedure. The central value of each scale is set to the quadratic sum of $m_{\ell\ell}$ and p_T of the Z boson.

The PDF set used in the predictions is the approximate N^{3}LO MSHT20 PDF set [59], which is the only PDF set currently available at this order. The PDFs are interpolated with LHAPDF [60] at the factorisation scale μ_f, and evolved backwards using the N^{3}LO solution of the evolution equation. The number of active flavours is set to five in all the coefficients entering the calculation, and in the evolution of the PDFs. The charm- and bottom-quark PDFs are asymptotically switched off in the backward evolution when approaching their corresponding thresholds.

The effect of initial-state radiation of photons on the transverse-momentum distribution's shape is estimated at leading-logarithm accuracy with Pythia 8 [61] and the AZ set of tuned parton shower parameters [24], and applied as a bin-by-bin multiplicative correction factor. A computation of initial-state radiation of photons at next-to-leading-logarithm accuracy [62] is used to validate the Pythia 8 predictions. Higher-order effects on the cross-section normalisation from QED initial-state radiation and from electroweak virtual corrections are considered at next-to-leading order. These are directly computed using the code from Ref. [63], and are in agreement with the results from other calculations benchmarked by the LHC

EW working group. At the Z pole, the virtual effects decrease the predicted cross sections by 0.8%, while the QED initial-state effects increase them by 0.4%. These corrections are found to be independent of rapidity. Higher-order electroweak corrections are expected to be very small at the Z-boson pole, and are neglected.[5]

The statistical analysis for the determination of $\alpha_s(m_Z)$ is performed in the xFitter framework [64]. The value of $\alpha_s(m_Z)$ is determined by minimising a χ^2 function which includes both the experimental uncertainties and the theoretical uncertainties arising from PDF variations:

$$\begin{aligned}\chi^2(\beta_{\text{exp}}, \beta_{\text{th}}) = \\ &\sum_{i=1}^{N_{\text{data}}} \frac{\left(\sigma_i^{\text{exp}} + \sum_j \Gamma_{ij}^{\text{exp}} \beta_{j,\text{exp}} - \sigma_i^{\text{th}} - \sum_k \Gamma_{ik}^{\text{th}} \beta_{k,\text{th}}\right)^2}{\Delta_i^2} \\ &+ \sum_j \beta_{j,\text{exp}}^2 + \sum_k \beta_{k,\text{th}}^2 \,. \end{aligned} \tag{1}$$

The correlated experimental and theoretical uncertainties are included by using the nuisance parameter vectors β_{exp} and β_{th}, respectively. Their influence on the data and theory predictions is described by the Γ_{ij}^{exp} and Γ_{ik}^{th} matrices. The index i runs over all $N_{\text{data}} = 72$ data points of the double-differential Z-boson p_{T} and y distribution, whereas the indices j and k correspond to the experimental and theoretical uncertainty nuisance parameters respectively. The measurements and the uncorrelated experimental uncertainties are given by σ_i^{exp} and Δ_i , respectively, and the theory predictions are σ_i^{th}. The matrices Γ_{ij}^{exp} encode all the information in the experimental covariance matrix of the measured double-differential cross sections as functions of the transverse momentum and rapidity of the Z boson. The matrices Γ_{ik}^{th} cover the nuisance parameters of the PDF Hessian uncertainties, and parameters of the non-perturbative form factor, which are left free in the fit by allowing unconstrained variations.

Determinations of $\alpha_s(m_Z)$ at hadron colliders are usually affected by significant correlations between $\alpha_s(m_Z)$ and the PDFs, especially the gluon PDF [65]. The dependence of the PDFs on the value of $\alpha_s(m_Z)$ is accounted for by using corresponding α_s-series of PDF sets, which are provided for seven fixed values of $\alpha_s(m_Z)$ in the range $0.114 < \alpha_s(m_Z) < 0.120$. At each value of $\alpha_s(m_Z)$, the PDF uncertainties are Hessian profiled and the χ^2 function is minimised by solving a system of linear equations, according to Eq. (1) [66], whereas the different values of χ^2 as a function of $\alpha_s(m_Z)$ are minimised through a polynomial interpolation to determine $\alpha_s(m_Z)$.

A validation of the statistical analysis, as well as an estimate of the sensitivity of the measured Z-boson cross sections to $\alpha_s(m_Z)$, is provided by a pseudo-fit. Identical theory predictions are used as central values for both data and theory in Eq. (1), including all statistical and systematic experimental uncertainties, without theoretical uncertainties, and with fixed values of the non-perturbative QCD parameters. The input value is set to $\alpha_s(m_Z) = 0.118$, and the pseudo-fit yields $\alpha_s(m_Z) = 0.11801 \pm 0.00006$. The closure of the method is thus found to be accurate to 0.01% and the relative uncertainty in $\alpha_s(m_Z)$ is estimated to be 0.05% before including the theoretical uncertainties discussed in the following.

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[5] The electroweak parameters are set according to the G_μ scheme, in which the Fermi coupling constant G_{F}, the W-boson mass m_W, and the Z-boson mass m_Z are set to the input values $G_{\text{F}} = 1.1663787 \cdot 10^{-5}$ GeV^{-2}, $m_W = 80.385$ GeV, and $m_Z = 91.1876$ GeV [16], whereas the weak-mixing angle and the QED coupling are calculated at tree level.

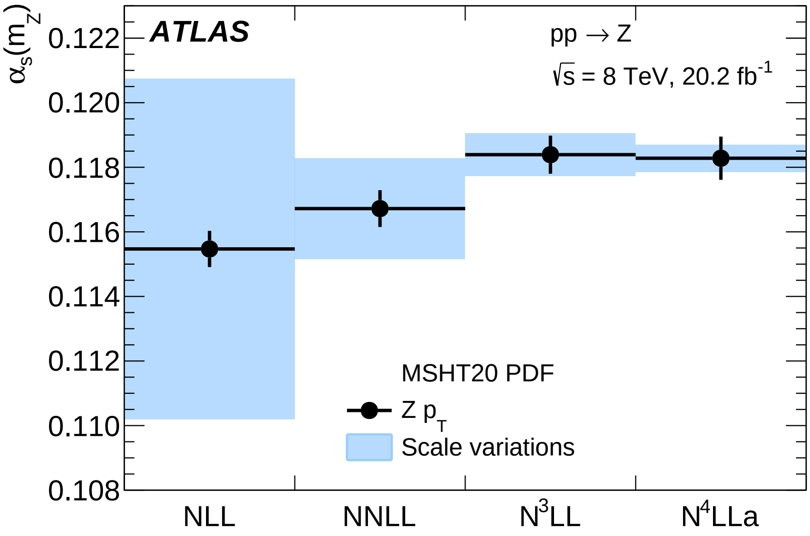

Figure 3: Determination of $\alpha_\mathrm{s}(m_Z)$ at various different orders in the QCD perturbative expansion, using the MSHT20 PDF set. The filled area represents missing higher-order uncertainties estimated through scale variations, and the vertical error bars include experimental and PDF uncertainties.

5 Determination of $\alpha_\mathrm{s}(m_Z)$

The determination of $\alpha_\mathrm{s}(m_Z)$ with central values of the QCD scales and using Eq. (1) yields $\alpha_\mathrm{s}(m_Z) = 0.11847 \pm 0.00067$, with contributions to the fit uncertainty from the experimental sources and from the PDFs estimated as ± 0.00044 and ± 0.00051 respectively.[6] Uncertainties arising from missing higher orders, due to truncation of the perturbative series, are estimated through independent variations of μ_r, μ_f and Q in the range $0.5 \cdot \sqrt{m_{\ell\ell}^2 + p_\mathrm{T}^2} \leq \{\mu_\mathrm{r}, \mu_\mathrm{f}, Q\} \leq 2 \cdot \sqrt{m_{\ell\ell}^2 + p_\mathrm{T}^2}$ with the constraints $0.5 \leq \{\mu_\mathrm{f}/\mu_\mathrm{r}, Q/\mu_\mathrm{r}, Q/\mu_\mathrm{f}\} \leq 2$, leading to 14 variations.

The fit is repeated for each scale variation, and the determined values of $\alpha_\mathrm{s}(m_Z)$ range from a minimum of 0.11786 to a maximum of 0.11870. The midpoint of this range of $\alpha_\mathrm{s}(m_Z)$ values, $\alpha_\mathrm{s}(m_Z) = 0.11828$, is taken as the nominal result, and the range's envelope of ± 0.00042 is used as an estimate of the uncertainties due to missing higher orders, henceforth referred to as 'missing higher-order uncertainties'.

The procedure is repeated at lower orders, starting from next-to-leading-logarithm accuracy matched to next-to-leading order (NLL+NLO). The MSHT20 PDF set is used throughout, and the order of the PDFs is matched to the order required by the logarithmic terms included in the p_T-resummation, i.e. NNLO at $\mathrm{N^3LL}$ and NLO at NNLL.[7] The results are shown in Figure 3. At every order, the estimate of missing higher-order uncertainties obtained from the scale variations overlaps with determinations of $\alpha_\mathrm{s}(m_Z)$ at higher orders, giving confidence in the robustness and gradual convergence of these estimates.

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[6] The non-perturbative QCD parameters are left free in the fit, and, due to their correlation with $\alpha_\mathrm{s}(m_Z)$, the experimental uncertainties are significantly larger here than in the pseudo-fit, where they are kept fixed to assess the experimental sensitivity to $\alpha_\mathrm{s}(m_Z)$.

[7] At NLL the NLO PDF set is used because the LO PDF set does not have $\alpha_\mathrm{s}(m_Z)$ variations.

Table 1: Summary of the uncertainties in the determination of $\alpha_s(m_Z)$, in units of 10^{-3}.

Experimental uncertainty	±0.44	
PDF uncertainty	±0.51	
Scale variation uncertainties	±0.42	
Matching to fixed order	0	−0.08
Non-perturbative model	+0.12	−0.20
Flavour model	+0.40	−0.29
QED ISR	±0.14	
N^4LL approximation	±0.04	
Total	+0.91	−0.88

Fits without the $O(\alpha_s^3)$ matching corrections yield an $\alpha_s(m_Z)$ central value which is 0.00024 lower, and the half envelope due to the scale variations increases from ±0.00042 to ±0.00062, which is consistent with the observed shift. Uncertainties in the matching to fixed order are estimated with fits in which the unitarity constraint is not applied. For these fits, the midpoint and half envelope of $\alpha_s(m_Z)$ values from the scale variations yield $\alpha_s(m_Z) = 0.11820 \pm 0.00037$. The difference between this set of fits and the nominal set of fits is taken as a one-sided matching uncertainty of −0.00008.

Additional uncertainties in the modelling of the non-perturbative form factor are estimated with variations of corresponding parameters, leading to an estimate of $^{+0.00012}_{-0.00020}$, as described in Section 7. The effect of charm- and bottom-quark masses and thresholds are estimated with various alternative fits, such as by including variable-flavour number either in the evolution of the PDFs (−0.00029) or in the running of α_s [67] in the Sudakov form factor (+0.00021), by varying the charm threshold μ_c by a factor of 2 (+0.00007), by varying the bottom threshold μ_b by a factor of 0.5 (−0.00029), or by including the effect of final-state gluon-splitting into massive bottom-quark (+0.00040) and charm-quark (+0.00001) pairs. The largest excursions are taken as an estimated uncertainty of $^{+0.00040}_{-0.00029}$ associated with the flavour model.

The inclusion of initial-state radiation of photons at leading-logarithm accuracy shifts the value of $\alpha_s(m_Z)$ by −0.00028. Half of this shift is assigned as an uncertainty associated with missing higher-order corrections for the initial-state radiation of photons. Initial-state radiation of photons at next-to-leading-logarithm accuracy [62] shifts the value of $\alpha_s(m_Z)$ by +0.00007, which is well within the assigned uncertainty. The inclusion of NLO electroweak corrections shifts the value of $\alpha_s(m_Z)$ by +0.00006, and uncertainties related to missing electroweak higher orders are considered negligible.

Uncertainties related to the numerical approximation or our incomplete knowledge of some of the coefficients required for N^4LL accuracy of p_T-resummation are estimated to contribute at the level of ±0.00004, with the largest contribution coming from the numerical approximation of the *cusp* anomalous dimension at five loops [42], and from our incomplete knowledge of the hard-collinear contributions at four loops [45]. Uncertainties due to the numerical approximation of the four-loop splitting functions are already included in the MSHT20 PDF uncertainties.

A summary of the uncertainties in the determination of $\alpha_s(m_Z)$ is shown in Table 1.

The goodness of fit is assessed by computing the value of the χ^2 function with the theory predictions evaluated at the measured value of $\alpha_s(m_Z)$ and with the best-fit values of the non-perturbative parameters and the QCD scales. In addition to the PDF uncertainties included in Eq. (1), all theory uncertainties considered in the analysis are added as theory nuisance parameters. The computed χ^2 value is 82 for 72 data points, corresponding to a p-value of 0.2.

The upper end of the fit range is varied to test the stability of the results with respect to missing higher-order corrections in the matching to fixed order. Lowering the upper end from 29 GeV to 22 GeV shifts the $\alpha_\mathrm{s}(m_Z)$ value by -0.00017 and increases the estimated missing higher-order uncertainties from 0.00042 to 0.00050. Raising the upper end to 40.4 GeV shifts the $\alpha_\mathrm{s}(m_Z)$ value by $+0.00028$ and increases the estimated missing higher-order uncertainties to 0.00088. The shifts in the central value are compatible with the increase in the missing higher-order uncertainties.

The fit range is also varied by excluding the low transverse-momentum region. The range is narrowed to $5 < p_\mathrm{T} < 29$ GeV, with a spread in the values of $\alpha_\mathrm{s}(m_Z)$ at the level of $^{+0.00017}_{-0.00010}$, compatible with the increase in the uncertainty of the fit, from 0.00067 to 0.00071. Since the low transverse-momentum region of $p_\mathrm{T} < 5$ GeV is the most sensitive to the non-perturbative and quark-flavour effects, this test provides a strong validation of the modelling of these corrections.

The post-fit predictions are compared with the measured Z-boson transverse-momentum distribution in Figure 4. The overall change in the normalisation is accounted for by a pull of the 1.8% luminosity uncertainty by +1.3 standard deviations.

The determination of $\alpha_\mathrm{s}(m_Z)$ is repeated at a lower order, N^{3}LL+N^{3}LO, with the MSHT20, CT18A, NNPDF4.0 and HERAPDF2.0 NNLO PDF sets. The spread of the fitted values of $\alpha_\mathrm{s}(m_Z)$ is ± 0.00102, driven by the difference between CT18A and NNPDF4.0. While these PDF sets are not appropriate for the present measurement given their lower theoretical accuracy, this study provides a conservative estimate of the residual PDF model dependence of the result, demonstrating that the achievable accuracy is excellent compared to that of other methods of extracting $\alpha_\mathrm{s}(m_Z)$. At this order, in addition to the Hessian profiling approach, a simultaneous PDF-fit determination is performed through the numerical minimisation of the χ^2 in the full multidimensional parameter space of PDFs, the non-perturbative parameters, and $\alpha_\mathrm{s}(m_Z)$. The combined neutral- and charged-current deep inelastic scattering (DIS) cross-section data from the H1 and ZEUS experiments at the HERA collider [65] are included in the fit, with a minimum squared four-momentum transfer Q^2 of 10 GeV^2, together with the measured Z-boson transverse-momentum distribution. The value of $\alpha_\mathrm{s}(m_Z)$ determined from this fit is 0.11866 ± 0.00064, where the quoted uncertainty is the uncertainty from the fit, which includes experimental and PDF uncertainties. The determined value of $\alpha_\mathrm{s}(m_Z)$ is in agreement with corresponding determinations using the Hessian profiling approach at this order, and the uncertainty is comparable to the uncertainty of the nominal fit. At N^{3}LL+N^{3}LO, missing higher-order uncertainties estimated with scale variations amount to ± 0.00066. Considering all the other relevant uncertainties listed in Table 1, the result of this determination is $\alpha_\mathrm{s}(m_Z) = 0.1187 \pm 0.0010$.

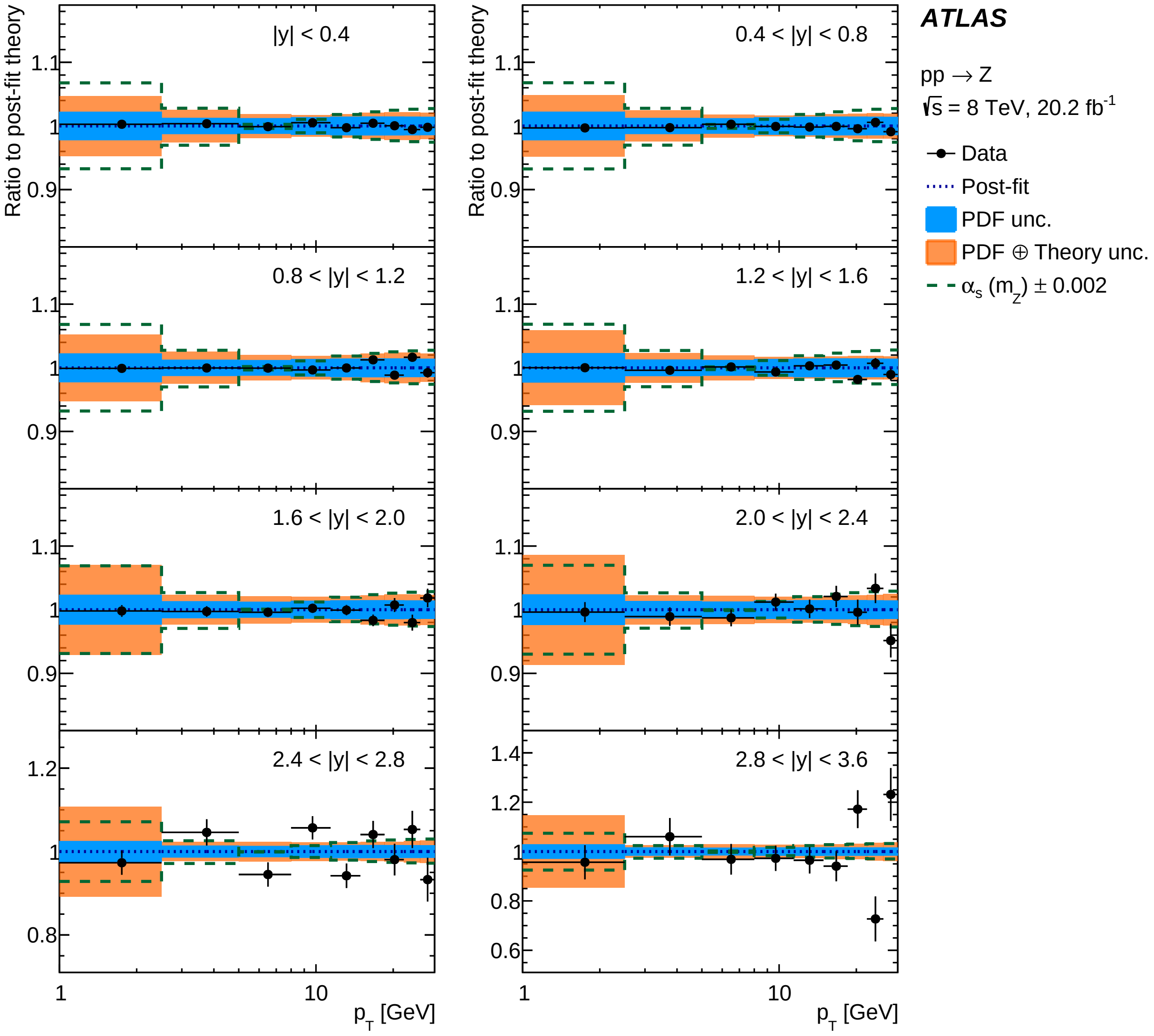

Figure 4: Ratios of the measured double-differential cross sections to the post-fit predictions, both as functions of the transverse momentum and rapidity of the Z boson. The blue inner band shows the PDF uncertainties of the predictions pulled and constrained by the fit, and the orange band shows the PDF and all other unconstrained theoretical uncertainties added in quadrature. The measured cross sections are corrected by the post-fit pull of the luminosity uncertainty. The vertical error bars show the experimental uncertainties of the measurement. The dashed lines show post-fit predictions in which $\alpha_s(m_Z)$ is varied by ±0.002 and all other parameters are kept fixed.

6 Outlook

The coupling constant of the strong force is determined from a measurement of the transverse-momentum distribution of Z bosons produced at the LHC in 20.2 fb^{-1} of 8 TeV proton–proton collisions and recorded by the ATLAS experiment. The analysis is based on a semi-inclusive observable at hadron–hadron colliders, and employs QCD resummed theory predictions. In contrast to other hadron collider observables, the Z-boson transverse-momentum distribution in the Sudakov region is not included in PDF fits, thus largely removing the issue of correlation between this $\alpha_\text{s}(m_Z)$ determination and simultaneous determinations of PDFs and the strong-coupling constant. The measured value of $\alpha_\text{s}(m_Z) = 0.1183 \pm 0.0009$ is compatible with other determinations and with the world-average value, as illustrated in Figure 5.

Among experimental determinations, this is the most precise to date and the first based on $\text{N}^4\text{LLa}+\text{N}^3\text{LO}$ predictions in perturbative QCD. This result marks the start of a new era in precision studies of QCD with the Drell–Yan process. Using this approach, the strong-coupling constant can be investigated with higher precision and in higher energy regimes with future larger datasets.

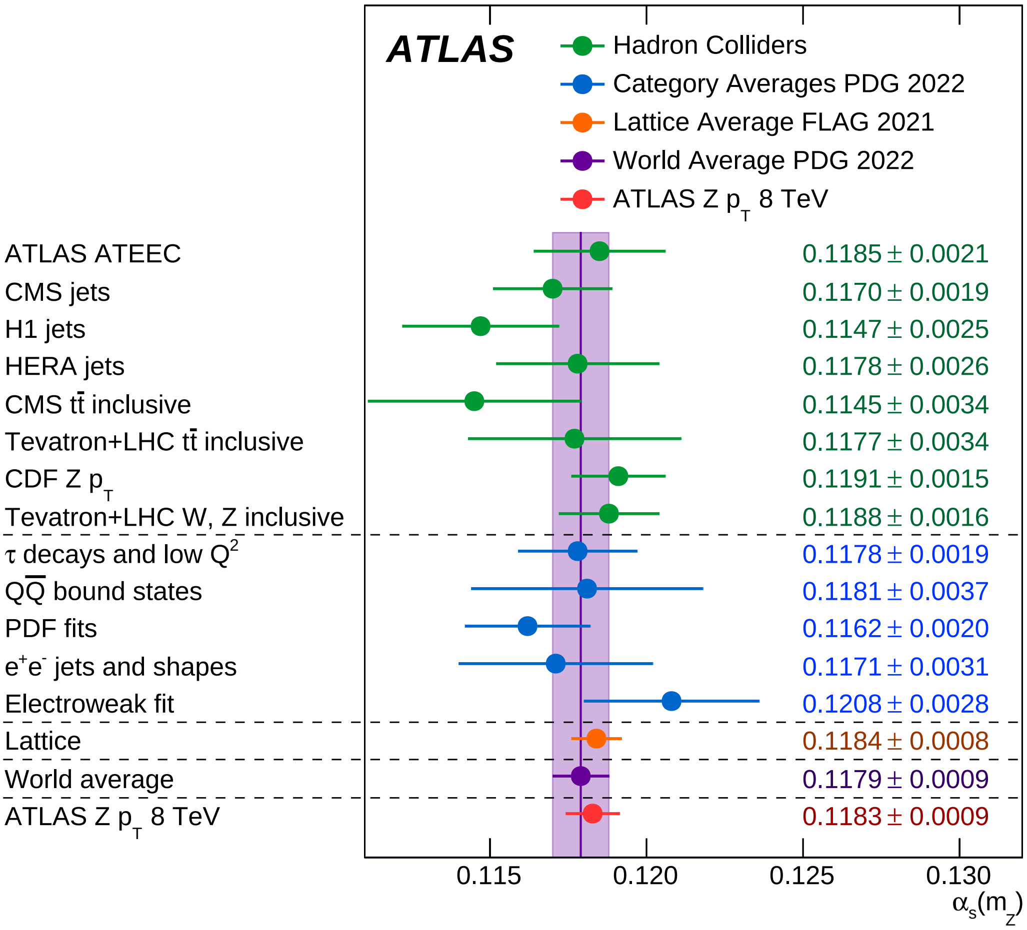

Figure 5: Comparison of the determination of $\alpha_s(m_Z)$ from the Z-boson transverse-momentum distribution (ATLAS Z p_T 8 TeV) with other determinations at hadron colliders [17–23, 35], with the PDG category averages [3], with the lattice QCD determination [10], and with the PDG world average [3].

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7 Methods

Modelling of non-perturbative effects. Determinations of $\alpha_s(m_Z)$ are affected by non-perturbative power corrections of the type $\Lambda^p_{\text{QCD}}/Q^p$, where Λ_{QCD} is the non-perturbative scale of QCD and Q is the order of magnitude of the momentum transfer in the process. Their impact strongly depends on the value of the power p for the given process used to determine $\alpha_s(m_Z)$. Non-perturbative QCD effects [53, 58, 69–77], are expected to be quadratically suppressed for the Drell–Yan p_T distribution at large p_T, or, equivalently, in the limit of small b [78], thanks to the azimuthal symmetry of the intrinsic transverse-momentum smearing of partons [79, 80]. In the small p_T region the non-perturbative corrections are expected to become linear below a given scale [58, 81], which is estimated of the order of 1 GeV in Ref. [82].

In the case of the Z-boson p_T-resummed predictions used in this analysis, the Sudakov form factor is singular in the region of transverse momenta of the order of the QCD scale Λ_{QCD}. The singular behaviour of the perturbative form factor is removed by using the so-called b_* [53, 83] regularisation procedure, in which the dependence of the Sudakov form factor on the impact parameter b is frozen before reaching the singular point by performing the replacement $b^2 \to b_*^2 = b^2 b^2_{\text{lim}}/(b^2 + b^2_{\text{lim}})$. A default value of $b_{\text{lim}} = 2$ GeV^{-1} is used in the calculation. Non-perturbative QCD effects are included in this analysis with a non-perturbative form factor [53, 58]:

$$S_{\text{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m^2_{\ell\ell}}{Q_0^2}\right] \tag{2}$$

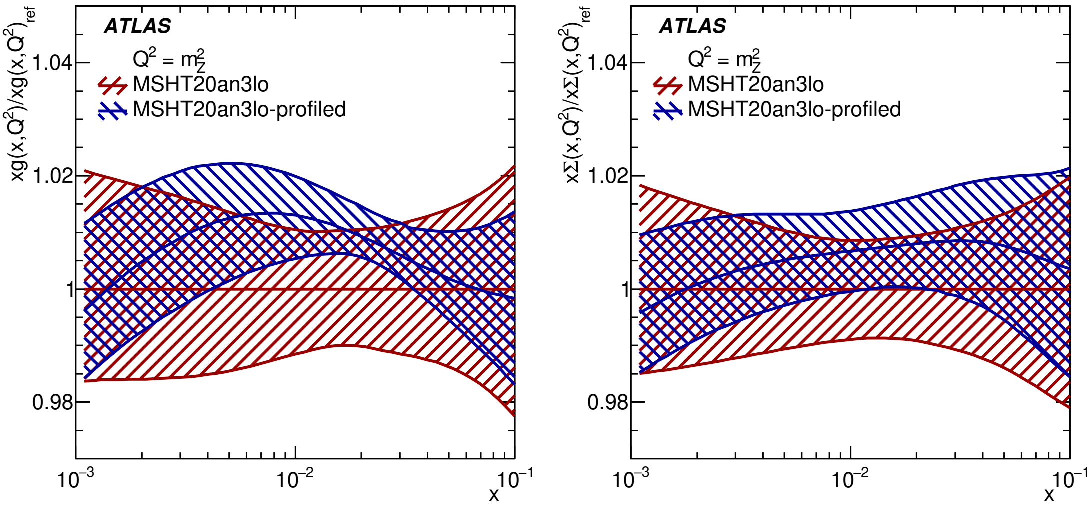
with

$$g_j(b) = \frac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \text{sign}(q)\left(1 - \exp\left[-|q|\,b^4\right]\right) \tag{3}$$

$$g_K(b) = g_0\left(1 - \exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\,b^2_{\text{lim}}}\right]\right), \tag{4}$$

where $b_0 = 2\mathrm{e}^{-\gamma_E}$, and γ_E is the Euler number. The g and q parameters represent the leading quadratic and quartic terms which are dominant in the region of moderate p_T of 4–10 GeV, where the sensitivity to $\alpha_s(m_Z)$ is maximal, and they are left free in the fit. The parameter λ controls the scale of transition from quadratic (Gaussian) to linear (exponential) behaviour of the non-perturbative primordial k_T. It is set to 1 GeV^2 and varied when assessing uncertainties of the non-perturbative model. The parameter g_0 controls the asymptotic behaviour of the non-perturbative form factor at very small p_T, in a region where the measured cross section and the determined value of $\alpha_s(m_Z)$ have very little sensitivity. It is set to 0.3 [58] and varied when assessing uncertainties of the non-perturbative model. The parameters b_{lim} and Q_0 represent respectively the scale at which the running of α_s is frozen, and the starting scale at which the non-perturbative form factor is parameterised by the function $g_j(b)$. Changes in these parameters should be completely reabsorbed by changes in the functions $g_K(b)$ and $g_j(b)$, provided they are flexible enough. Variations of b_{lim} and of Q_0 are performed to assess the uncertainty related to the choice of parameterisation in Eqs. (2)–(4).

The value of g determined in the nominal fit is $g = 0.54 \pm 0.04$ GeV^2 and its correlation with $\alpha_s(m_Z)$ is -0.6. The value of q determined in the fit is $q = -0.06 \pm 0.04$ GeV^4 and its correlation with $\alpha_s(m_Z)$ is $+0.4$. The correlation between g and q is -0.7. Uncertainties in the modelling of the non-perturbative form factor are estimated with variations of the parameters b_{lim}, Q_0, g_0, and λ. Variations of b_{lim} in the range



(a) (b)

Figure 6: Ratios of the profiled (a) gluon and (b) sea-quark PDFs to their initial values, at the scale $q^2 = m_Z^2$. The error bands represent the 68% confidence level.

Table 2: Summary of N^{3}LL fits with NNLO PDFs.

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
MSHT20 [37]	0.11839	0.00040	0.44	−0.07
NNPDF4.0 [84]	0.11779	0.00024	0.50	−0.08
CT18A [29]	0.11982	0.00050	0.36	−0.03
HERAPDF2.0 [65]	0.11890	0.00027	0.40	−0.04

1.5–2.5 GeV^{-1} yield $\alpha_s(m_Z)$ variations of $^{+0.00012}_{-0.00020}$. Variations of Q_0 in the range 0.5–2 GeV yield $\alpha_s(m_Z)$ variations of $^{+0.00006}_{-0.00002}$. Variations of g_0 in the range 0.1–0.5 yield $\alpha_s(m_Z)$ variations which are at the level of ± 0.00002. Variations of λ in the range 0.5–2 GeV^2 yield $\alpha_s(m_Z)$ variations of $^{+0.00011}_{-0.00019}$. The envelope of these variations is $^{+0.00012}_{-0.00020}$, which is used as an estimate of the uncertainty in the non-perturbative model.

PDF profiling. Pulls and constraints on the nuisance parameters associated with the PDF uncertainties in Eq. (1) can be reinterpreted in the PDF space through a Hessian profiling procedure [66]. Such a reinterpretation provides valuable information about the sensitivity of the measured cross sections to the PDFs. The largest observed effects are on the gluon and sea-quark PDFs, which are shown in Figure 6.

Fits with NNLO PDFs. At order N^{4}LLa+N^{3}LO, only one N^{3}LO PDF set is currently available, namely the MSHT20aN^{3}LO [59] PDF set. In order to study the dependence of the results on the choice of PDF set, fits are performed at a lower order, N^{3}LL+N^{3}LO, using NNLO PDF sets. Table 2 shows results of fits with various PDF sets. At this order, the spread observed in the values of $\alpha_s(m_Z)$ extracted with different PDF sets is ± 0.00102, which is driven by the difference between the NNPDF4.0 and CT18A PDF sets.

The determination of $\alpha_s(m_Z)$ from the transverse-momentum distribution of Z bosons is particularly sensitive to the gluon PDF. The PDF determinations at NNLO are affected by significant tension between the low-x and high-x gluon PDFs, which is ascribed to tensions between observables sensitive to the gluon PDF, such as those for inclusive deep inelastic scattering (DIS) at the HERA collider, hadron-collider jet measurements, top-quark pair production, and Z-boson p_T measurements in the high transverse-momentum region.

In order to investigate the effect of these tensions on the determination of $\alpha_\mathrm{s}(m_Z)$ at N^{3}LL, fits are performed which also include the combined neutral- and charged-current DIS cross-section data from the H1 and ZEUS experiments at the HERA collider [65], with a minimum Q^2 value of 10 GeV^2, together with the measured Z-boson transverse-momentum cross sections. The HERA data are already included in all PDF fits, they are included again here for the purpose of lessening the impact of other datasets on the gluon PDF. After the inclusion of HERA data in the fit, all PDF sets yield values of $\alpha_\mathrm{s}(m_Z)$ consistent with the initial results, except for CT18A, which is shifted by -0.00166 compared to a PDF uncertainty of ± 0.00050, and the half-envelope of $\alpha_\mathrm{s}(m_Z)$ values for the PDF sets considered is reduced to ± 0.00016.

The approximate N^{3}LO PDF fit of MSHT20, which is used for the nominal result, largely removes the tension in the gluon PDF, as indicated by the significant improvement in the χ^2 associated with the Z-boson p_T measurement in the high transverse-momentum region and with inclusive DIS at the HERA collider, compared to the NNLO fit [59]. These observations suggest that the spread in $\alpha_\mathrm{s}(m_Z)$ when using different PDF sets at NNLO is not representative of the true PDF uncertainty at N^{3}LO. However, further studies to verify the robustness of the estimate of the PDF uncertainties at N^{3}LO in the MSHT20 analysis will be possible when other PDF determinations at this order become available.

Combined fits of $\alpha_\mathrm{s}(m_Z)$ and PDFs. Determinations of $\alpha_\mathrm{s}(m_Z)$ at hadron colliders are exposed to possible biases unless the PDFs are determined simultaneously along with $\alpha_\mathrm{s}(m_Z)$ [85]. The Hessian profiling employed in this analysis provides an approximation to a PDF determination which relies on the accuracy of the quadratic approximation around the minimum [86]. In the nominal fit of $\alpha_\mathrm{s}(m_Z)$ at N^{4}LLa+N^{3}LO, pulls and constraints on the nuisance parameters associated with the PDF uncertainties are below one standard deviation and 30%, respectively, indicating that the new minimum of the profiled PDFs is close to the original minimum, which gives confidence in the validity of the quadratic approximation.

A simultaneous determination of $\alpha_\mathrm{s}(m_Z)$, the PDFs, and the non-perturbative parameters through the numerical minimisation of the χ^2 in the full multidimensional parameters space [87] is performed at N^{3}LL+N^{3}LO, with PDFs evolved at NNLO. The combined neutral- and charged-current DIS cross-section data from the H1 and ZEUS experiments at the HERA collider [65] are included, with a minimum squared four-momentum transfer Q^2 of 10 GeV^2, corresponding to 1016 data points, together with the measured Z-boson transverse-momentum cross sections.

The light-quark coefficient functions of the DIS cross sections are calculated in the $\overline{MS}$ scheme [88], and with the renormalisation and factorisation scales set to the squared four-momentum transfers Q^2. The heavy quarks c and b are generated dynamically, and the corresponding coefficient functions for the neutral-current processes with γ^* exchange are calculated in the general-mass variable-flavour-number scheme [89–91], with up to five active quark flavours. The charm-quark mass is set to $m_c = 1.43$ GeV, and the bottom-quark mass to $m_b = 4.50$ GeV [65]. For the charged-current processes, the heavy quarks are treated as massless.

The PDFs for the gluon, valence u- and d-quark, and $\bar{u}$- and $\bar{d}$-quark densities are parameterised at the input scale $Q_0^2 = 1.9$ GeV^2 with the parameterisation in Ref. [92]. The contribution of the s-quark density is taken to be proportional to the $\bar{d}$-quark density by setting $x\bar{s}(x) = r_s x\bar{d}(x)$, with $r_s = 0.67$.

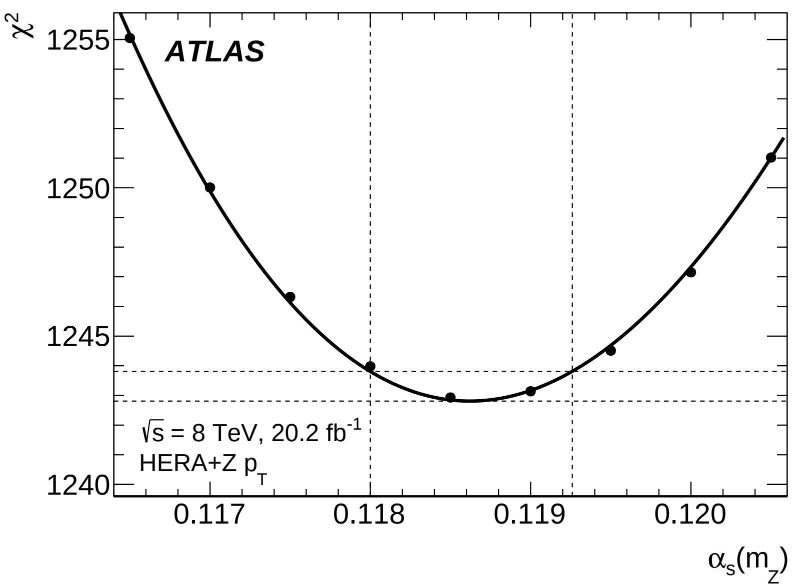


Figure 7: Values of the χ^2 function for the determination of $\alpha_s(m_Z)$ from a simultaneous fit of PDFs and non-perturbative parameters at N^{3}LL+N^{3}LO, with PDFs evolved at NNLO. The horizontal dashed lines indicate the minimum value of the χ^2 and the minimum χ^2 plus one. The vertical dashed lines show the intersections of the line at the minimum χ^2 plus one with the χ^2 function, which correspond to the $\alpha_s(m_Z)$ uncertainties from the fit.

Fits are performed at fixed values of $\alpha_s(m_Z)$, and the fitted value of $\alpha_s(m_Z)$ is determined from a quadratic interpolation of the χ^2 as a function of $\alpha_s(m_Z)$, as shown in Figure 7. The determined value of $\alpha_s(m_Z)$ is 0.11866 ± 0.00064, where the quoted uncertainty is the uncertainty from the fit, which includes experimental and PDF uncertainties. The value of $\alpha_s(m_Z)$ is in agreement with corresponding determinations using the Hessian profiling approach at this order, as shown in Table 2, and the uncertainty is comparable to the uncertainty of ±0.00067 in the nominal fit. The dependence of $\alpha_s(m_Z)$ on the minimum squared four-momentum transfer Q^2 of the HERA data is studied in the range from 2.5 GeV^2 to 25 GeV^2, as shown in Figure 8. No significant dependence is observed above 5 GeV^2.

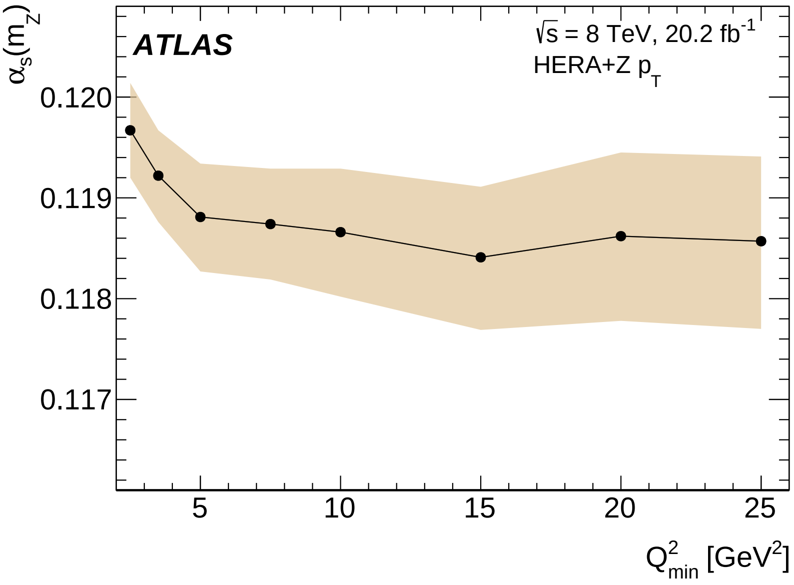


Figure 8: Dependence of $\alpha_s(m_Z)$ on the minimum squared four-momentum transfer Q^2 of the HERA data from a simultaneous fit of PDFs and non-perturbative parameters at N^{3}LL+N^{3}LO, with PDFs evolved at NNLO. The shaded area shows the uncertainty from the fit

Sudakov subleading higher-order corrections. Additional fits are performed which differ from the nominal fit for subleading higher-order corrections in the Sudakov form factor. In Ref. [93], different procedures for the computation of the Sudakov form factor are discussed, including analytic and numerical solutions. Subleading corrections in the definition of the Sudakov form factor and in the running of α_s are tested with fits where the Sudakov form factor is evaluated with a numerical integration, and $\alpha_s(Q)$ in the Sudakov form factor is obtained from the exact numerical renormalisation-group-equation invariant solution for the running of α_s. The effects of scale variations are estimated with the methodology proposed in Ref. [94]. For these fits, the midpoint and half envelope of the $\alpha_s(m_Z)$ values from the scale variations yield $\alpha_s(m_Z) = 0.11832 \pm 0.00029$. Fits where the hard-collinear coefficients are evolved according to the CSS scheme [53] yield a value of $\alpha_s(m_Z) = 0.11872$ for the central value of the scales. In all the cases considered, the inclusion of subleading higher-order corrections is covered by the estimate of missing higher-order corrections based on scale variations, so no additional uncertainty is considered.

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Sciandra[136], G. Sciolla[26], F. Scuri[74a], C.D. Sebastiani[92], K. Sedlaczek[115], P. Seema[18], S.C. Seidel[112], A. Seiden[136], B.D. Seidlitz[41], C. Seitz[48], J.M. Seixas[83b], G. Sekhniaidze[72a], S.J. Sekula[44], L. Selem[60], N. Semprini-Cesari[23b,23a], D. Sengupta[56], V. Senthilkumar[163], L. Serin[66], L. Serkin[69a,69b], M. Sessa[76a,76b], H. Severini[120], F. Sforza[57b,57a], A. Sfyrla[56], E. Shabalina[55], R. Shaheen[144], J.D. Shahinian[128], D. Shaked Renous[169], L.Y. Shan[14a], M. Shapiro[17a], A. Sharma[36], A.S. Sharma[164], P. Sharma[80], S. Sharma[48], P.B. Shatalov[37], K. Shaw[146], S.M. Shaw[101], A. Shcherbakova[37], Q. Shen[62c,5], P. Sherwood[96], L. Shi[96], X. Shi[14a], C.O. Shimmin[172], Y. Shimogama[168], J.D. Shinner[95], I.P.J. Shipsey[126], S. Shirabe[56,i], M. Shiyakova[38,ab], J. Shlomi[169], M.J. Shochet[39], J. Shojaii[105], D.R. Shope[125], B. Shrestha[120], S. Shrestha[119,as], E.M. Shrif[33g], M.J. Shroff[165], P. Sicho[131], A.M. Sickles[162], E. Sideras Haddad[33g], A. Sidoti[23b], F. Siegert[50], Dj. Sijacki[15], R. Sikora[86a], F. Sili[90], J.M. Silva[20], M.V. Silva Oliveira[29], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[36], E.L. Simpson[59], H. Simpson[146], L.R. Simpson[106], N.D. Simpson[98], S. Simsek[82], S. Sindhu[55], P. Sinervo[155], S. Singh[155], S. Sinha[48], S. Sinha[101], M. Sioli[23b,23a], I. Siral[36], E. Sitnikova[48], S.Yu. Sivoklokov[37,*], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[20,am], P. Skubic[120], M. Slawinska[87], V. Smakhtin[169], B.H. Smart[134], J. Smiesko[36], S.Yu. Smirnov[37], Y. Smirnov[37], L.N. Smirnova[37,a], O. Smirnova[98], A.C. Smith[41], E.A. Smith[39], H.A. Smith[126], J.L. Smith[92], R. Smith[143], M. Smizanska[91], K. Smolek[132], A.A. Snesarev[37], S.R. Snider[155], H.L. Snoek[114], S. Snyder[29], R. Sobie[165,ad], A. Soffer[151], C.A. Solans Sanchez[36], E.Yu. Soldatov[37], U. Soldevila[163], A.A. Solodkov[37], S. Solomon[26], A. Soloshenko[38], K. Solovieva[54], O.V. Solovyanov[40], V. Solovyev[37], P. Sommer[36], A. Sonay[13], W.Y. Song[156b], J.M. Sonneveld[114], A. Sopczak[132], A.L. Sopio[96], F. Sopkova[28b], V. Sothilingam[63a], S. Sottocornola[68], R. Soualah[116b], Z. Soumaimi[35e], D. South[48], S. Spagnolo[70a,70b], M. Spalla[110], D. Sperlich[54], G. Spigo[36], M. Spina[146], S. Spinali[91], D.P. Spiteri[59], M. Spousta[133], E.J. Staats[34], A. Stabile[71a,71b], R. Stamen[63a], M. Stamenkovic[114], A. Stampekis[20], M. Standke[24], E. Stanecka[87], M.V. Stange[50], B. Stanislaus[17a], M.M. Stanitzki[48], B. Stapf[48], E.A. Starchenko[37], G.H. Stark[136], J. Stark[102,aj], D.M. Starko[156b], P. Staroba[131], P. Starovoitov[63a], S. Stärz[104], R. Staszewski[87], G. Stavropoulos[46], J. Steentoft[161], P. Steinberg[29], B. Stelzer[142,156a], H.J. Stelzer[129], O. Stelzer-Chilton[156a], H. Stenzel[58], T.J. Stevenson[146], G.A. Stewart[36], J.R. Stewart[121], M.C. Stockton[36], G. Stoicea[27b], M. Stolarski[130a], S. Stonjek[110], A. Straessner[50], J. Strandberg[144], S. Strandberg[47a,47b], M. Strauss[120], T. Strebler[102], P. Strizenec[28b], R. Ströhmer[166], D.M. Strom[123], L.R. Strom[48], R. Stroynowski[44], A. Strubig[47a,47b], S.A. Stucci[29], B. Stugu[16], J. Stupak[120], N.A. Styles[48], D. Su[143], S. Su[62a], W. Su[62d], X. Su[62a,66], K. Sugizaki[153], V.V. Sulin[37], M.J. Sullivan[92], D.M.S. Sultan[78a,78b], L. Sultanaliyeva[37], S. Sultansoy[3b], T. Sumida[88], S. Sun[106], S. Sun[170], O. Sunneborn Gudnadottir[161], N. Sur[102], M.R. Sutton[146], H. Suzuki[157], M. Svatos[131], M. Swiatlowski[156a], T. Swirski[166], I. Sykora[28a], M. Sykora[133], T. Sykora[133], D. Ta[100], K. Tackmann[48,aa], A. Taffard[160], R. Tafirout[156a], J.S. Tafoya Vargas[66], E.P. Takeva[52], Y. Takubo[84], M. Talby[102], A.A. Talyshev[37], K.C. Tam[64b], N.M. Tamir[151], A. Tanaka[153], J. Tanaka[153], R. Tanaka[66], M. Tanasini[57b,57a], Z. Tao[164], S. Tapia Araya[137f], S. Tapprogge[100], A. Tarek Abouelfadl Mohamed[107], S. Tarem[150], K. Tariq[14a], G. Tarna[102,27b], G.F. Tartarelli[71a], P. Tas[133], M. Tasevsky[131], E. Tassi[43b,43a], A.C. Tate[162], G. Tateno[153], Y. Tayalati[35e,ac], G.N. Taylor[105], W. Taylor[156b], H. Teagle[92], A.S. Tee[170], R. Teixeira De Lima[143], P. Teixeira-Dias[95], J.J. Teoh[155], K. Terashi[153], J. Terron[99], S. Terzo[13], M. Testa[53], R.J. Teuscher[155,ad], A. Thaler[79], O. Theiner[56], N. Themistokleous[52], T. Theveneaux-Pelzer[102], O. Thielmann[171], D.W. Thomas[95], J.P. Thomas[20], E.A. Thompson[17a], P.D. Thompson[20], E. Thomson[128], Y. Tian[55], V. Tikhomirov[37,a], Yu.A. Tikhonov[37], S. Timoshenko[37], D. Timoshyn[133], E.X.L. Ting[1], P. Tipton[172], S.H. Tlou[33g], A. Tnourji[40], K. Todome[23b,23a], S. Todorova-Nova[133], S. Todt[50], M. Togawa[84], J. Tojo[89], S. Tokár[28a], K. Tokushuku[84], O. Toldaiev[68], R. Tombs[32], M. Tomoto[84,111], L. Tompkins[143,s], K.W. Topolnicki[86b], E. Torrence[123], H. Torres[102,aj], E. Torró Pastor[163], M. Toscani[30], C. Tosciri[39], M. Tost[11], D.R. Tovey[139], A. Traeet[16], I.S. Trandafir[27b], T. Trefzger[166], A. Tricoli[29], I.M. Trigger[156a], S. Trincaz-Duvoid[127], D.A. Trischuk[26], B. Trocmé[60], C. Troncon[71a], L. Truong[33c], M. Trzebinski[87], A. Trzupek[87], F. Tsai[145], M. Tsai[106], A. Tsiamis[152,f], P.V. Tsiareshka[37], S. Tsigaridas[156a], A. Tsirigotis[152,y], V. Tsiskaridze[155], E.G. Tskhadadze[149a], M. Tsopoulou[152,f], Y. Tsujikawa[88], I.I. Tsukerman[37], V. Tsulaia[17a], S. Tsuno[84], O. Tsur[150], K. Tsuri[118], D. Tsybychev[145], Y. Tu[64b], A. Tudorache[27b], V. Tudorache[27b], A.N. Tuna[36], S. Turchikhin[38], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[38,ae], P.M. Tuts[41], S. Tzamarias[152,f], P. Tzanis[10], E. Tzovara[100], K. Uchida[153], F. Ukegawa[157], P.A. Ulloa Poblete[137c,137b], E.N. Umaka[29], G. Unal[36], M. Unal[11], A. Undrus[29], G. Unel[160], J. Urban[28b], P. Urquijo[105], G. Usai[8], R. Ushioda[154], M. Usman[108], Z. Uysal[21b], L. Vacavant[102], V. Vacek[132], B. Vachon[104], K.O.H. Vadla[125], T. Vafeiadis[36], A. Vaitkus[96], C. Valderanis[109], E. Valdes Santurio[47a,47b], M. Valente[156a], S. Valentinetti[23b,23a], A. Valero[163], E. Valiente Moreno[163], A. Vallier[102,aj], J.A. Valls Ferrer[163], D.R. Van Arneman[114], T.R. Van Daalen[138], A. Van Der Graaf[49], P. Van Gemmeren[6], M. Van Rijnbach[125,36], S. Van Stroud[96], I. Van Vulpen[114], M. Vanadia[76a,76b], W. Vandelli[36], M. Vandenbroucke[135], E.R. Vandewall[121], D. Vannicola[151], L. Vannoli[57b,57a], R. Vari[75a], E.W. Varnes[7], C. Varni[17b], T. Varol[148], D. Varouchas[66], L. Varriale[163], K.E. Varvell[147], M.E. Vasile[27b], L. Vaslin[40], G.A. Vasquez[165], F. Vazeille[40], T. Vazquez Schroeder[36], J. Veatch[31], V. Vecchio[101], M.J. Veen[103], I. Veliscek[126], L.M. Veloce[155], F. Veloso[130a,130c], S. Veneziano[75a], A. Ventura[70a,70b], A. Verbytskyi[110], M. Verducci[74a,74b], C. Vergis[24], M. Verissimo De Araujo[83b], W. Verkerke[114], J.C. Vermeulen[114], C. Vernieri[143], M. Vessella[103], M.C. Vetterli[142,ap], A. Vgenopoulos[152,f], N. Viaux Maira[137f], T. Vickey[139], O.E. Vickey Boeriu[139], G.H.A. Viehhauser[126], L. Vigani[63b], M. Villa[23b,23a], M. Villaplana Perez[163], E.M. Villhauer[52], E. Vilucchi[53], M.G. Vincter[34], G.S. Virdee[20], A. Vishwakarma[52], A. Visibile[114], C. Vittori[36], I. Vivarelli[146], V. Vladimirov[167], E. Voevodina[110], F. Vogel[109], P. Vokac[132], J. Von Ahnen[48], E. Von Toerne[24], B. Vormwald[36], V. Vorobel[133], K. Vorobev[37], M. Vos[163], K. Voss[141], J.H. Vossebeld[92], M. Vozak[114], L. Vozdecky[94], N. Vranjes[15], M. Vranjes Milosavljevic[15], M. Vreeswijk[114], R. Vuillermet[36], O. Vujinovic[100], I. Vukotic[39], S. Wada[157], C. Wagner[103], J.M. Wagner[17a], W. Wagner[171], S. Wahdan[171], H. Wahlberg[90], R. Wakasa[157], M. Wakida[111], J. Walder[134], R. Walker[109], W. Walkowiak[141], A. 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J. Weingarten[49], M. Weirich[100], C. Weiser[54], C.J. Wells[48], T. Wenaus[29], B. Wendland[49], T. Wengler[36], N.S. Wenke[110], N. Wermes[24], M. Wessels[63a], K. Whalen[123], A.M. Wharton[91], A.S. White[61], A. White[8], M.J. White[1], D. Whiteson[160], L. Wickremasinghe[124], W. Wiedenmann[170], C. Wiel[50], M. Wielers[134], C. Wiglesworth[42], D.J. Wilbern[120], H.G. Wilkens[36], D.M. Williams[41], H.H. Williams[128], S. Williams[32], S. Willocq[103], B.J. Wilson[101], P.J. Windischhofer[39], F.I. Winkel[30], F. Winklmeier[123], B.T. Winter[54], J.K. Winter[101], M. Wittgen[143], M. Wobisch[97], Z. Wolffs[114], R. Wölker[126], J. Wollrath[160], M.W. Wolter[87], H. Wolters[130a,130c], A.F. Wongel[48], S.D. Worm[48], B.K. Wosiek[87], K.W. Woźniak[87], S. Wozniewski[55], K. Wraight[59], C. Wu[20], J. Wu[14a,14e], M. Wu[64a], M. Wu[113], S.L. Wu[170], X. Wu[56], Y. Wu[62a], Z. Wu[135], J. Wuerzinger[110,an], T.R. Wyatt[101], B.M. Wynne[52], S. Xella[42], L. Xia[14c], M. Xia[14b], J. Xiang[64c], X. Xiao[106], M. Xie[62a], X. Xie[62a], S. Xin[14a,14e], J. Xiong[17a], D. Xu[14a], H. Xu[62a], L. Xu[62a], R. Xu[128], T. Xu[106], Y. Xu[14b], Z. Xu[52], Z. Xu[14a], B. Yabsley[147], S. Yacoob[33a], N. Yamaguchi[89], Y. Yamaguchi[154], E. Yamashita[153], H. Yamauchi[157], T. Yamazaki[17a], Y. Yamazaki[85], J. Yan[62c], S. Yan[126], Z. Yan[25], H.J. Yang[62c,62d], H.T. Yang[62a], S. Yang[62a], T. Yang[64c], X. Yang[62a], X. Yang[14a], Y. Yang[44], Y. Yang[62a], Z. Yang[62a], W-M. Yao[17a], Y.C. Yap[48], H. Ye[14c], H. Ye[55], J. Ye[44], S. Ye[29], X. Ye[62a], Y. Yeh[96], I. Yeletskikh[38], B.K. Yeo[17b], M.R. Yexley[96], P. Yin[41], K. Yorita[168], S. Younas[27b], C.J.S. Young[36], C. Young[143], Y. Yu[62a], M. Yuan[106], R. Yuan[62b,l], L. Yue[96], M. Zaazoua[62a], B. Zabinski[87], E. Zaid[52], T. Zakareishvili[149b], N. Zakharchuk[34], S. Zambito[56], J.A. Zamora Saa[137d,137b], J. Zang[153], D. Zanzi[54], O. Zaplatilek[132], C. Zeitnitz[171], H. Zeng[14a], J.C. Zeng[162], D.T. Zenger Jr[26], O. Zenin[37], T. Ženiš[28a], S. Zenz[94], S. Zerradi[35a], D. Zerwas[66], M. Zhai[14a,14e], B. Zhang[14c], D.F. Zhang[139], J. Zhang[62b], J. Zhang[6], K. Zhang[14a,14e], L. Zhang[14c], P. Zhang[14a,14e], R. Zhang[170], S. Zhang[106], T. Zhang[153], X. Zhang[62c], X. Zhang[62b], Y. Zhang[62c,5], Y. Zhang[96], Z. Zhang[17a], Z. Zhang[66], H. Zhao[138], P. Zhao[51], T. Zhao[62b], Y. Zhao[136], Z. Zhao[62a], A. Zhemchugov[38], K. Zheng[162], X. Zheng[62a], Z. Zheng[143], D. Zhong[162], B. Zhou[106], H. Zhou[7], N. Zhou[62c], Y. Zhou[7], C.G. Zhu[62b], J. Zhu[106], Y. Zhu[62c], Y. Zhu[62a], X. Zhuang[14a], K. Zhukov[37], V. Zhulanov[37], N.I. Zimine[38], J. Zinsser[63b], M. Ziolkowski[141], L. Živković[15], A. Zoccoli[23b,23a], K. Zoch[56], T.G. Zorbas[139], O. Zormpa[46], W. Zou[41], L. Zwalinski[36].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.
[2]Department of Physics, University of Alberta, Edmonton AB; Canada.
[3](a)Department of Physics, Ankara University, Ankara;(b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.
[4]LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
[5]APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
[6]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10]Physics Department, National Technical University of Athens, Zografou; Greece.
[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[14](a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;(b)Physics Department,

Tsinghua University, Beijing;(c)Department of Physics, Nanjing University, Nanjing;(d)School of Science, Shenzhen Campus of Sun Yat-sen University;(e)University of Chinese Academy of Science (UCAS), Beijing; China.
[15]Institute of Physics, University of Belgrade, Belgrade; Serbia.
[16]Department for Physics and Technology, University of Bergen, Bergen; Norway.
[17](a)Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;(b)University of California, Berkeley CA; United States of America.
[18]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[19]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[20]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[21](a)Department of Physics, Bogazici University, Istanbul;(b)Department of Physics Engineering, Gaziantep University, Gaziantep;(c)Department of Physics, Istanbul University, Istanbul; Türkiye.
[22](a)Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;(b)Departamento de Física, Universidad Nacional de Colombia, Bogotá;(c)Pontificia Universidad Javeriana, Bogota; Colombia.
[23](a)Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;(b)INFN Sezione di Bologna; Italy.
[24]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[25]Department of Physics, Boston University, Boston MA; United States of America.
[26]Department of Physics, Brandeis University, Waltham MA; United States of America.
[27](a)Transilvania University of Brasov, Brasov;(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;(e)University Politehnica Bucharest, Bucharest;(f)West University in Timisoara, Timisoara;(g)Faculty of Physics, University of Bucharest, Bucharest; Romania.
[28](a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[29]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[30]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
[31]California State University, CA; United States of America.
[32]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[33](a)Department of Physics, University of Cape Town, Cape Town;(b)iThemba Labs, Western Cape;(c)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;(d)National Institute of Physics, University of the Philippines Diliman (Philippines);(e)University of South Africa, Department of Physics, Pretoria;(f)University of Zululand, KwaDlangezwa;(g)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[34]Department of Physics, Carleton University, Ottawa ON; Canada.
[35](a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;(b)Faculté des Sciences, Université Ibn-Tofail, Kénitra;(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;(d)LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;(e)Faculté des sciences, Université Mohammed V, Rabat;(f)Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[36]CERN, Geneva; Switzerland.
[37]Affiliated with an institute covered by a cooperation agreement with CERN.

[38]Affiliated with an international laboratory covered by a cooperation agreement with CERN.
[39]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[40]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[41]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[42]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[43][(a)]Dipartimento di Fisica, Università della Calabria, Rende;[(b)]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[44]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[45]Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
[46]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[47][(a)]Department of Physics, Stockholm University;[(b)]Oskar Klein Centre, Stockholm; Sweden.
[48]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[49]Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.
[50]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[51]Department of Physics, Duke University, Durham NC; United States of America.
[52]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[53]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[54]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[55]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[56]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[57][(a)]Dipartimento di Fisica, Università di Genova, Genova;[(b)]INFN Sezione di Genova; Italy.
[58]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[59]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[60]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[61]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[62][(a)]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;[(b)]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;[(c)]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;[(d)]Tsung-Dao Lee Institute, Shanghai; China.
[63][(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;[(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[64][(a)]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;[(b)]Department of Physics, University of Hong Kong, Hong Kong;[(c)]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
[65]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[66]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
[67]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
[68]Department of Physics, Indiana University, Bloomington IN; United States of America.
[69][(a)]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;[(b)]ICTP, Trieste;[(c)]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
[70][(a)]INFN Sezione di Lecce;[(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[71][(a)]INFN Sezione di Milano;[(b)]Dipartimento di Fisica, Università di Milano, Milano; Italy.
[72][(a)]INFN Sezione di Napoli;[(b)]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[73][(a)]INFN Sezione di Pavia;[(b)]Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[74][(a)]INFN Sezione di Pisa;[(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

[75](a)INFN Sezione di Roma;(b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[76](a)INFN Sezione di Roma Tor Vergata;(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[77](a)INFN Sezione di Roma Tre;(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[78](a)INFN-TIFPA;(b)Università degli Studi di Trento, Trento; Italy.
[79]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
[80]University of Iowa, Iowa City IA; United States of America.
[81]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[82]Istinye University, Sariyer, Istanbul; Türkiye.
[83](a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(c)Instituto de Física, Universidade de São Paulo, São Paulo;(d)Rio de Janeiro State University, Rio de Janeiro; Brazil.
[84]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[85]Graduate School of Science, Kobe University, Kobe; Japan.
[86](a)AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[87]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[88]Faculty of Science, Kyoto University, Kyoto; Japan.
[89]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[90]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[91]Physics Department, Lancaster University, Lancaster; United Kingdom.
[92]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[93]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[94]School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[95]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[96]Department of Physics and Astronomy, University College London, London; United Kingdom.
[97]Louisiana Tech University, Ruston LA; United States of America.
[98]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[99]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[100]Institut für Physik, Universität Mainz, Mainz; Germany.
[101]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[102]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[103]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[104]Department of Physics, McGill University, Montreal QC; Canada.
[105]School of Physics, University of Melbourne, Victoria; Australia.
[106]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[107]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[108]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[109]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[110]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[111]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[112]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.

[113]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
[114]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[115]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[116(a)]New York University Abu Dhabi, Abu Dhabi;[(b)]University of Sharjah, Sharjah; United Arab Emirates.
[117]Department of Physics, New York University, New York NY; United States of America.
[118]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[119]Ohio State University, Columbus OH; United States of America.
[120]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[121]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[122]Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
[123]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
[124]Graduate School of Science, Osaka University, Osaka; Japan.
[125]Department of Physics, University of Oslo, Oslo; Norway.
[126]Department of Physics, Oxford University, Oxford; United Kingdom.
[127]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
[128]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[129]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[130(a)]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;[(b)]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;[(c)]Departamento de Física, Universidade de Coimbra, Coimbra;[(d)]Centro de Física Nuclear da Universidade de Lisboa, Lisboa;[(e)]Departamento de Física, Universidade do Minho, Braga;[(f)]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);[(g)]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
[131]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
[132]Czech Technical University in Prague, Prague; Czech Republic.
[133]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[134]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[135]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[136]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[137(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;[(b)]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;[(c)]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;[(d)]Universidad Andres Bello, Department of Physics, Santiago;[(e)]Instituto de Alta Investigación, Universidad de Tarapacá, Arica;[(f)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
[138]Department of Physics, University of Washington, Seattle WA; United States of America.
[139]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[140]Department of Physics, Shinshu University, Nagano; Japan.
[141]Department Physik, Universität Siegen, Siegen; Germany.
[142]Department of Physics, Simon Fraser University, Burnaby BC; Canada.
[143]SLAC National Accelerator Laboratory, Stanford CA; United States of America.

[144]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
[145]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[146]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[147]School of Physics, University of Sydney, Sydney; Australia.
[148]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[149](a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;(b)High Energy Physics Institute, Tbilisi State University, Tbilisi;(c)University of Georgia, Tbilisi; Georgia.
[150]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[151]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[152]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[153]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[154]Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
[155]Department of Physics, University of Toronto, Toronto ON; Canada.
[156](a)TRIUMF, Vancouver BC;(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
[157]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[158]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[159]United Arab Emirates University, Al Ain; United Arab Emirates.
[160]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
[161]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[162]Department of Physics, University of Illinois, Urbana IL; United States of America.
[163]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[164]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[165]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[166]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[167]Department of Physics, University of Warwick, Coventry; United Kingdom.
[168]Waseda University, Tokyo; Japan.
[169]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
[170]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[171]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[172]Department of Physics, Yale University, New Haven CT; United States of America.
[a] Also Affiliated with an institute covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
[d] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[e] Also at Center for High Energy Physics, Peking University; China.
[f] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[g] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[h] Also at CERN, Geneva; Switzerland.
[i] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[j] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.

[k] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[l] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[m] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[n] Also at Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[o] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[p] Also at Department of Physics, California State University, Sacramento; United States of America.
[q] Also at Department of Physics, King's College London, London; United Kingdom.
[r] Also at Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[s] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[t] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[u] Also at Department of Physics, University of Thessaly; Greece.
[v] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[w] Associated at Dipartimento di Fisica, Università di Milano, Milano; Italy.
[x] Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[y] Also at Hellenic Open University, Patras; Greece.
[z] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[aa] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[ab] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[ac] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[ad] Also at Institute of Particle Physics (IPP); Canada.
[ae] Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
[af] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ag] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ah] Associated at Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[ai] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[aj] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[ak] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[al] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[am] Also at School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[an] Also at Technical University of Munich, Munich; Germany.
[ao] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ap] Also at TRIUMF, Vancouver BC; Canada.
[aq] Also at Università di Napoli Parthenope, Napoli; Italy.
[ar] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[as] Also at Washington College, Chestertown, MD; United States of America.
[at] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased