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Evidence for the collective nature of radial flow in Pb+Pb collisions with the ATLAS detector

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Anisotropic flow and radial flow are two key probes of the expansion dynamics and properties of the quark-gluon plasma (QGP). While anisotropic flow has been extensively studied, radial flow, which governs the system's radial expansion, has received less attention. Notably, experimental evidence for the global and collective nature of radial flow has been lacking. This Letter presents the first measurement of transverse momentum (p_{T}) dependence of radial flow fluctuations ($v_0(p_{\mathrm{T}})$) over $0.5 < p_{\mathrm{T}} < 10$ GeV, using a two-particle correlation method in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data reveal three key features supporting the collective nature of radial flow: long-range correlation in pseudorapidity, factorization in p_{T}, and centrality-independent shape in p_{T}. The comparison with a hydrodynamic model demonstrates the sensitivity of $v_0(p_{\mathrm{T}})$ to bulk viscosity, a crucial transport property of the QGP. These findings establish a new, powerful tool for probing collective dynamics and properties of the QGP.

Introduction. Heavy-ion collisions at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) provide unique conditions for creating and studying the quark–gluon plasma (QGP). The spacetime evolution of the QGP is well described by relativistic hydrodynamics [1, 2], where the system, driven by pressure gradients, expands collectively and cools until hadronization. This gradient-driven expansion turns geometric anisotropies and size variations in the initial state into two distinct final-state collective phenomena: anisotropic flow (v_n, $n = 1, 2, \cdots$) and radial flow (v_0), respectively. Anisotropic flow quantifies azimuthal momentum anisotropy, while radial flow characterizes the radial boost of the system, which influences the average transverse momentum of particles $[p_{\mathrm{T}}]$ in each event [3].

Extensive measurements of anisotropic flow, particularly differential studies of $v_n(p_{\mathrm{T}})$ and their event-by-event (EbE) fluctuations [4–11], provided crucial insights into the initial conditions and transport properties of the QGP. In contrast, studies of radial flow have been comparatively limited, focusing primarily on the moments of $[p_{\mathrm{T}}]$ distribution over an event ensemble, such as the mean, $\langle[p_{\mathrm{T}}]\rangle$ [12], and the scaled variance, $v_0 = \sqrt{\langle(\delta[p_{\mathrm{T}}])^2\rangle}/\langle[p_{\mathrm{T}}]\rangle$ [13–17], where $\delta[p_{\mathrm{T}}] = [p_{\mathrm{T}}] - \langle[p_{\mathrm{T}}]\rangle$. The v_0 observable characterizes the global EbE radial flow fluctuations [18, 19], and scales with the square root of the charged-particle multiplicity [16].

Anisotropic and radial flow originate from single-particle distributions and exhibit long-range correlations in pseudorapidity (η). For anisotropic flow, these two features have been verified by the approximate factorization of the coefficients of two-particle azimuthal correlation into single-particle coefficients: $V_{n\Delta}(p_{\mathrm{T1}}, p_{\mathrm{T2}}) \approx v_n(p_{\mathrm{T1}})v_n(p_{\mathrm{T2}})$ [6, 20] and $V_{n\Delta}(\eta_1, \eta_2) \approx v_n(\eta_1)v_n(\eta_2)$ [21–23]. Furthermore, $v_n(p_{\mathrm{T}})$ divided by the integrated flow v_n exhibits a near-universal behavior across centralities [24]. This universality arises because the magnitude of $v_n(p_{\mathrm{T}})$ scales with initial state eccentricity, while its shape characterized by $k_n(p_{\mathrm{T}}) = v_n(p_{\mathrm{T}})/v_n$ reflects the hydrodynamic response, which is nearly independent of centrality [25]. While this factorization and centrality-independent scaling hold at $p_{\mathrm{T}} \lesssim 4$ GeV in central to midcentral Pb+Pb collisions, deviations are observed in peripheral collisions or at higher p_{T}, attributable to non-flow correlations such as resonance decays or jet fragmentation.

In contrast to anisotropic flow, the collective nature of radial flow has not yet been directly established due to a lack of p_{T}-differential measurements. A new observable, $v_0(p_{\mathrm{T}})$, was proposed recently [26] to fill this gap. Unlike anisotropic flow, which is more sensitive to shear viscosity, $v_0(p_{\mathrm{T}})$ is more sensitive to bulk viscosity [26, 27], which is not as well constrained. A precision measurement of $v_0(p_{\mathrm{T}})$, including factorization and scaling checks, thus offers valuable opportunities to constrain the properties of the QGP [28, 29].

The $v_0(p_{\mathrm{T}})$ observable is defined based on the correlation between particle spectra in narrow p_{T} ranges, $N(p_{\mathrm{T}})$, and $[p_{\mathrm{T}}]$ [26, 27] (see Figure 1). To avoid fluctuations in the total multiplicity and capture only shape variations, the fractional spectrum $n(p_{\mathrm{T}}) = N(p_{\mathrm{T}})/\int N(p_{\mathrm{T}})dp_{\mathrm{T}}$ in each event is used. Events with a larger (smaller) radial flow feature a flatter (steeper) distribution of $n(p_{\mathrm{T}})$ and a correspondingly higher (lower) $[p_{\mathrm{T}}]$. The resulting fluctuations in the spectrum, $\delta n(p_{\mathrm{T}}) = n(p_{\mathrm{T}}) - \langle n(p_{\mathrm{T}})\rangle$, and in $\delta[p_{\mathrm{T}}]$ are correlated in a characteristic pattern: negative correlation at $p_{\mathrm{T}} \lesssim \langle[p_{\mathrm{T}}]\rangle$ and positive at $p_{\mathrm{T}} \gtrsim \langle[p_{\mathrm{T}}]\rangle$. By assuming a factorization of the normalized covariance [26, 27]:

$$\frac{\langle\delta n(p_{\mathrm{T}})\delta[p_{\mathrm{T}}]\rangle}{\langle n(p_{\mathrm{T}})\rangle\,\langle[p_{\mathrm{T}}]\rangle} = v_0(p_{\mathrm{T}})v_0\,, \tag{1}$$

$v_0(p_{\mathrm{T}})$ can be calculated from the data. The normalization reduces sensitivity to the particle reconstruction

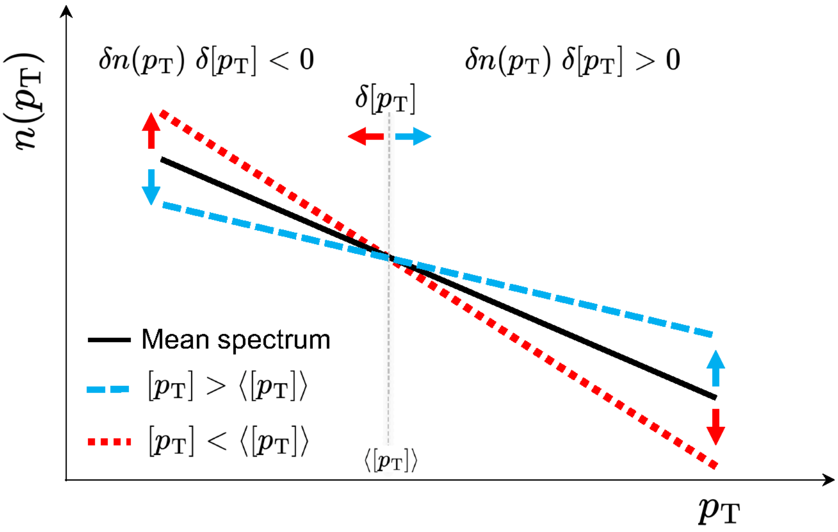

Figure 1: Schematic illustration of how radial flow fluctuations lead to correlations between the EbE p_T-differential yield $n(p_\mathrm{T})$ and the EbE average transverse momentum $[p_\mathrm{T}]$. The blue curve represents an event with larger-than-average radial flow, the red curve an event with smaller-than-average radial flow, and the black curve the ensemble-averaged spectrum. Events with larger radial flow have flatter spectra, resulting in a positive covariance ($\langle\delta n(p_\mathrm{T})\delta[p_\mathrm{T}]\rangle > 0$) at $p_\mathrm{T} \gtrsim \langle[p_\mathrm{T}]\rangle$ and a negative covariance ($\langle\delta n(p_\mathrm{T})\delta[p_\mathrm{T}]\rangle < 0$) at $p_\mathrm{T} \lesssim \langle[p_\mathrm{T}]\rangle$ [27]. The zero-crossing point, $p_\mathrm{T} \approx \langle[p_\mathrm{T}]\rangle$, depends on the p_T range used for $v_0(p_\mathrm{T})$ measurement, which is 0.5–10 GeV in this analysis, but does not depend on $p_\mathrm{T}^{\mathrm{ref}}$ (Eqs. (1) and (2) and associated discussion).

efficiency. If radial flow is collective, v_0 is related to $v_0(p_\mathrm{T})$ by an approximate sum rule [26]:

$$v_0 \equiv \frac{\sqrt{\left\langle(\delta[p_\mathrm{T}])^2\right\rangle_A}}{\langle[p_\mathrm{T}]\rangle_A} \approx \frac{\int_{p_\mathrm{T}\in A}(p_\mathrm{T}-\langle[p_\mathrm{T}]\rangle_A)\langle n(p_\mathrm{T})\rangle v_0(p_\mathrm{T})dp_\mathrm{T}}{\int_{p_\mathrm{T}\in A} p_\mathrm{T}\,\langle n(p_\mathrm{T})\rangle\, dp_\mathrm{T}}, \quad (2)$$

where "A" denotes the reference-p_T ($p_\mathrm{T}^{\mathrm{ref}}$) range for integration and calculating v_0. The measured $v_0(p_\mathrm{T})$ is expected to be independent of $p_\mathrm{T}^{\mathrm{ref}}$ and exhibit centrality-independent scaling. However, this factorization and scaling can be broken in the presence of significant non-flow correlations.

This Letter presents measurements of $v_0(p_\mathrm{T})$ using 470 μb^{-1} of Pb+Pb collision data at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV from 2015. Results are obtained for several $p_\mathrm{T}^{\mathrm{ref}}$ and various centrality ranges. Comparison with a hydrodynamic model further reveals the impact of QGP viscosities, particularly bulk viscosity, on radial flow fluctuations. This analysis closely follows a previous ATLAS analysis that measured v_0 and its centrality scaling properties [16].

ATLAS detector and data selection. The measurements are performed using the ATLAS inner detector (ID), forward calorimeter (FCal), and zero-degree calorimeters (ZDCs) along with the trigger and data acquisition systems [30–32]. The ID detects charged particles within $|\eta| < 2.5$ [1] using a combination of silicon pixel and microstrip detectors, along with a straw-tube transition-radiation tracker, all immersed in a 2 T axial magnetic field [31]. The FCal consists of three sampling layers, covering $3.2 < |\eta| < 4.9$. The

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η=-ln tan $\theta/2$.

ZDCs are positioned at ±140 m from the interaction point and detect neutrons with $|\eta| > 8.3$. The ATLAS trigger system [32] consists of a hardware-based level-one (L1) and software-based high-level triggers. A software suite [33] is used in data simulation, in the reconstruction and analysis of real and simulated data, in the detector operations, and in the trigger and data acquisition systems.

Pb+Pb events are selected by requiring the total transverse energy deposited in calorimeters over $|\eta| < 4.9$ at L1 to exceed 50 GeV. Additionally, dedicated central collision triggers enhance the number of events with large FCal transverse energy [11].

Charged-particle tracks are reconstructed from hits in the ID using a procedure optimized for heavy-ion collisions [34]. The distance of the closest approach of the track to the primary vertex must be within 1.25 mm in both the transverse and longitudinal directions. More details of the track selection are found in Ref. [24]. Tracks used in this analysis have $0.5 < p_{\mathrm{T}} < 10$ GeV and $|\eta| < 2.5$. This p_{T} range spans the regime predominantly influenced by radial flow as well as the transition region where jet-quenching effects become significant. The total number of such tracks is denoted by $N_{\mathrm{ch}}^{\mathrm{rec}}$. Events containing multiple inelastic collisions (pileup) are suppressed by exploiting the correlation between $N_{\mathrm{ch}}^{\mathrm{rec}}$ and the transverse energy measured in the FCal, $E_{\mathrm{T}}^{\mathrm{FCal}}$, as well as between the energy deposited in the ZDCs and $E_{\mathrm{T}}^{\mathrm{FCal}}$. The residual pileup probability is 0.17% among all selected events, but is smaller than 0.01% in central collisions [16, 35].

Events are categorized into centrality ranges using a parametrization of the $E_{\mathrm{T}}^{\mathrm{FCal}}$ distribution [11] based on a Glauber model [36], starting at 0% for the most central collisions with the highest $E_{\mathrm{T}}^{\mathrm{FCal}}$ value and ending at 70%. Events in this centrality range are fully efficient against the L1 event selection criteria.

Analysis. The track reconstruction efficiency, $\epsilon\left(p_{\mathrm{T}}, \eta, N_{\mathrm{ch}}^{\mathrm{rec}}\right)$, is evaluated using Monte Carlo (MC) simulated events for Pb+Pb collisions generated with Hijing [37] and charged particles definition according to Ref. [34]. The detector response is simulated using Geant4 [38, 39], and events are reconstructed with the same algorithms as used for the data. The HIJING spectra have been reweighted to match the data. In central Pb+Pb collisions, the efficiency ranges from 71% at $\eta \approx 0$ to about 40% for $|\eta| > 2$ at $p_{\mathrm{T}} > 0.8$ GeV, and it decreases by 12% from 0.8 to 0.5 GeV in p_{T}. In peripheral collisions, the efficiency is up to 4% higher. The rate of falsely reconstructed ("fake") tracks, $f\left(p_{\mathrm{T}}, \eta, N_{\mathrm{ch}}^{\mathrm{rec}}\right)$, is significant for $p_{\mathrm{T}} < 1$ GeV in central collisions, ranging from 2% for $|\eta| < 1$ to 8% at larger $|\eta|$. The fake-track rate drops rapidly for higher p_{T} and more peripheral collisions.

The observables in this analysis are obtained using a two-subevent method [40, 41], in which the particles are taken from two η regions labeled a and b: $-2.5 < \eta_a < -\frac{\eta_{\mathrm{gap}}}{2}$ and $\frac{\eta_{\mathrm{gap}}}{2} < \eta_b < 2.5$. Such subevent method was first used to measure the v_0 at RHIC in Ref. [17]. Four choices of gaps, $\eta_{\mathrm{gap}} = 0, 1, 2$, and 3, are used to evaluate the effects of short-range non-flow correlations as well as possible longitudinal radial flow decorrelations [42]. Each reconstructed charged track i is assigned a weight w_i to correct for reconstruction efficiency ϵ_i and fake rate f_i : $w_i \equiv (1 - f_i)/\epsilon_i$ [43]. The charged-particle multiplicity, corrected for detector effects, in $0.5 < p_{\mathrm{T}} < 5$ GeV and $|\eta| < 2.5$ is obtained as $N_{\mathrm{ch}} = \Sigma_i w_i$.

For each collision subevent, the following quantities are calculated: $[p_{\mathrm{T}}] = \Sigma_i w_i p_{\mathrm{T},i}/\Sigma_i w_i$, $\delta[p_{\mathrm{T}}] = \Sigma_i w_i \delta p_{\mathrm{T},i}/\Sigma_i w_i$ with $\delta p_{\mathrm{T},i} \equiv p_{\mathrm{T},i} - \langle [p_{\mathrm{T}}]\rangle$, and $n(p_{\mathrm{T}}) = \Sigma_i^{p_{\mathrm{T}}} w_i/\Sigma_i w_i$, where $\Sigma_i^{p_{\mathrm{T}}}$ represents the sum over all tracks in a narrow p_{T} range. The two-particle observables are calculated in narrow N_{ch} ranges as: $\left\langle(\delta[p_{\mathrm{T}}])^2\right\rangle = \langle\delta[p_{\mathrm{T}}]_a\delta[p_{\mathrm{T}}]_b\rangle$, $\langle\delta n(p_{\mathrm{T}})\delta[p_{\mathrm{T}}]\rangle = \frac{1}{2}\langle\delta n_a(p_{\mathrm{T}})\delta[p_{\mathrm{T}}]_b + \delta n_b(p_{\mathrm{T}})\delta[p_{\mathrm{T}}]_a\rangle$. The measurements are performed for three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, 0.5–2, 0.5–5, and 1–5 GeV; according to Eq. (1), v_0 can only be calculated in fairly wide $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, motivating the partial overlap in their choices. Statistical uncertainties for all observables are computed using a standard Poisson bootstrap method.

Systematic uncertainties stem from track selection, reconstruction efficiency, residual pileup, centrality definition, and MC closure test of the analysis procedure. These uncertainties obtained in $0.5 < p_{\mathrm{T}}^{\mathrm{ref}} < 2$ GeV and $\eta_{\mathrm{gap}} = 1$ are summarized below for v_0 and for $v_0(p_{\mathrm{T}})$ at a low p_{T} (0.5–0.8 GeV) and a high p_{T} region (2–3 GeV).

Track selection uncertainties are assessed by comparing nominal results with those obtained under looser or stricter criteria. This results in a deviation of 0.5–5% for v_0, and 1–8% at low p_{T} and 0.5–1.5% at high p_{T} for $v_0(p_{\mathrm{T}})$. The $v_0(p_{\mathrm{T}})$ as defined in Eq. (1) is insensitive to the track reconstruction efficiency. Indeed, repeating the analysis without track weights leads to variations in $v_0(p_{\mathrm{T}})$ smaller than uncertainties due to track selection. Uncertainties in the efficiency, mainly due to modeling of the detector material in Geant4, can be as large as 4%. Their impacts are within 0.5–1% for v_0 and 2–3% at low p_{T} and 0.5–1% at high p_{T} for $v_0(p_{\mathrm{T}})$. The impact of the azimuthal efficiency variation is assessed by including it in the track weight; no observable changes are found in the results. Residual pileup effects are estimated by adjusting the pileup rejection criteria, leading to uncertainties less than 0.5% for all observables. Centrality definition uncertainties, assessed by varying the Glauber model parameters, are relevant only when results are presented in centrality ranges and are below 3% for all observables.

The Hijing MC samples are used to evaluate the consistency of calculated observables, obtained using truth particles or the reconstructed tracks with the same correction procedures as for the real data applied [11]. This check also accounts for the smearing of measured $[p_{\mathrm{T}}]$ and $n(p_{\mathrm{T}})$ from their true values. The differences are about 1% for v_0 and 2% for $v_0(p_{\mathrm{T}})$.

The full systematic uncertainties for each observable are obtained by adding contributions from individual sources in quadrature. Track selection is the dominant source of systematic uncertainty, particularly in midcentral and central collisions. The total uncertainties are 1.5–5% for v_0, and 3–8.5% for $v_0(p_{\mathrm{T}})$ at low p_{T} and 2–3.5% at high p_{T}. The uncertainties are largest in central collisions and reduce to less than half the size in peripheral collisions. The uncertainties are generally smaller for the other two $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, and are somewhat larger for bigger η_{gap}. The total uncertainties for each data point are obtained by combining statistical and systematic uncertainties, which are then shown alongside the statistical uncertainties when presenting the results.

Results. Figure 2a shows the centrality dependence of v_0 computed in three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges. The magnitude of v_0 depends on the choice of $p_{\mathrm{T}}^{\mathrm{ref}}$, and shows a characteristic decrease toward central collisions as observed in Ref. [16]. It is largest for the widest $p_{\mathrm{T}}^{\mathrm{ref}}$ range, as expected from Eq. (2). However, when dividing v_0 by its value in the 0–5% centrality range, $v_0/v_0^{0-5\%}$, the trend in centrality is nearly the same across all $p_{\mathrm{T}}^{\mathrm{ref}}$ selections, as shown in Figure 2b. Hence, v_0 captures EbE fluctuations in the overall spectral shape, consistent with a collective nature of radial flow fluctuations.

To quantify this collective nature, the factorization of the covariance into a product of $v_0(p_{\mathrm{T}})$ and v_0 from Eq. (1) is examined in Figures 2c and 2d for two representative centralities (0–5% and 50–60%). While the normalized covariance varies substantially with $p_{\mathrm{T}}^{\mathrm{ref}}$, the extracted $v_0(p_{\mathrm{T}})$ remains nearly $p_{\mathrm{T}}^{\mathrm{ref}}$-independent up to $p_{\mathrm{T}} \approx 3$ GeV. This factorization, akin to what is observed for anisotropic flow, further supports the collective nature of radial flow. The $v_0(p_{\mathrm{T}})$ data for the three $p_{\mathrm{T}}^{\mathrm{ref}}$ cross zero at $p_{\mathrm{T}} \approx 1$ GeV, approximately the $\langle [p_{\mathrm{T}}] \rangle$ for the 0.5–10 GeV range. The $v_0(p_{\mathrm{T}})$ data are also found to satisfy the sum rule in Eq. (2) within 4%. Above $p_{\mathrm{T}} \approx 3$ GeV and in more peripheral collisions, the data become dependent on $p_{\mathrm{T}}^{\mathrm{ref}}$ due to larger non-flow contributions. Among the three reference ranges, results for $p_{\mathrm{T}}^{\mathrm{ref}} \in 0.5$–2 GeV are least affected by non-flow correlations, as suggested by the trend of $v_0(p_{\mathrm{T}})$ at high p_{T}.

In central collisions, $v_0(p_{\mathrm{T}})$ shows a decrease above $p_{\mathrm{T}} \approx 4$ GeV, similar to anisotropic flow, which might be associated with a transition from a flow-dominated regime to a jet-quenching dominated regime [26],

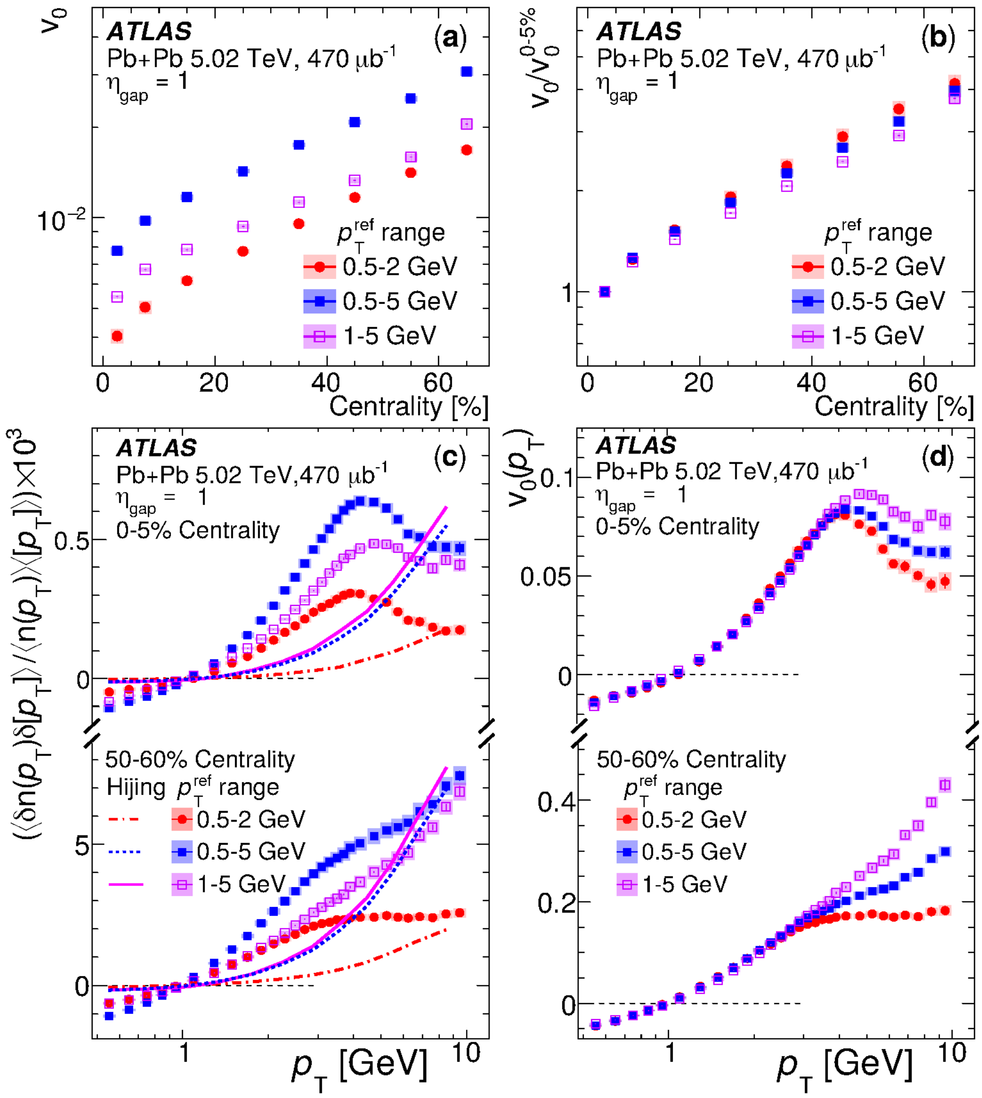

Figure 2: Centrality dependence of v_0 (**a**) and $v_0/v_0^{0-5\%}$ (**b**) for three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges, and normalized covariance from Eq. 1 (**c**) and $v_0(p_{\mathrm{T}})$ (**d**) obtained in 0–5% centrality (top) and 50–60% centrality (bottom) in three $p_{\mathrm{T}}^{\mathrm{ref}}$ ranges. The color lines indicate the predictions from Hijing model containing only non-flow correlations. Bars and shaded areas indicate statistical and total uncertainties, respectively.

which changes the shape of underlying spectrum and its EbE fluctuations. No such decrease is observed in peripheral collisions due to much smaller jet-quenching effects.

In Figure 2c, the covariance is compared to calculations from Hijing model containing only non-flow correlations. Hijing underpredicts the magnitude of the data at $p_{\mathrm{T}} < 6$ GeV, implying that the collective radial flow generates the most correlations in the data. Above $p_{\mathrm{T}} \approx 6$ GeV, Hijing predictions become comparable to the data, suggesting that the high p_{T} behavior of the covariance could be impacted by non-flow correlations, especially in peripheral collisions where jet quenching is reduced.

The impact of non-flow correlations on $v_0(p_{\mathrm{T}})$ is further investigated by varying η_{gap} between the subevents. A larger η_{gap} reduces the short-range non-flow contributions but also enhances the flow decorrelation

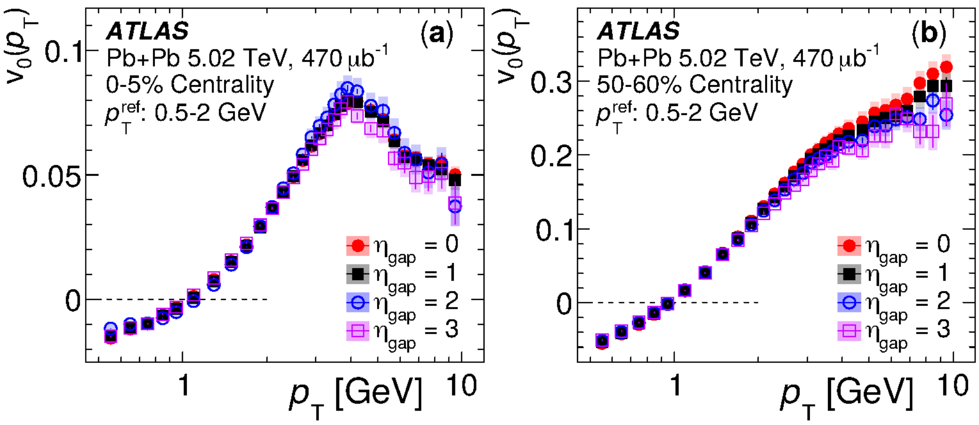

Figure 3: $v_0(p_T)$ for η_{gap}=0, 1, 2, and 3 in 0–5% (**a**) and 50–60% (**b**) centrality. Bars and shaded areas indicate statistical and total uncertainties, respectively.

effects [23, 42]. Figure 3 shows The $v_0(p_T)$ data in 0–5% and 50–60% centrality ranges for different η_{gap} selections. Little change is observed in central collisions when η_{gap} is varied from 0 to 3. In contrast, $v_0(p_T)$ in peripheral collisions at $p_T > 3$ GeV decreases slightly, which is consistent with residual non-flow contributions from away-side jet fragmentation. The weak dependence on η_{gap} supports the interpretation that radial flow is a long-range, global correlation similar to anisotropic flow. Based on these observations, $\eta_{gap} = 1$ is used as the default configuration.

Next, the shape of $v_0(p_T)$ across centralities is investigated using the normalized quantity $v_0(p_T)/v_0$, which has the advantage of being insensitive to the initial-state effects [26]. Figure 4 compares $v_0(p_T)$ and $v_0(p_T)/v_0$ for several centrality ranges. While $v_0(p_T)$ exhibits a pronounced centrality dependence, $v_0(p_T)/v_0$ is almost independent of centrality in the range $p_T \lesssim 2.5$ GeV. This observation indicates that the magnitude of $v_0(p_T)$ is primarily driven by the fluctuations in nuclear overlap area and density, which is larger in peripheral collisions [16, 18]. In contrast, the shape of $v_0(p_T)$ is governed by the hydrodynamic response $k_0(p_T) \approx v_0(p_T)/v_0$ [27], which is nearly independent of centrality. This scaling behavior is analogous to that observed for $v_n(p_T)/v_n$. However, $v_n(p_T)/v_n$ is sensitive to both shear and bulk viscosities, while $v_0(p_T)/v_0$ is mostly sensitive to bulk viscosity [3].

Above $p_T \approx 3$ GeV, where the non-flow contribution is more significant, this scaling is imperfect. Up to 40–50% centrality, $v_0(p_T)/v_0$ is observed to first rise and then fall, which could be due to the onset of jet quenching that reduces the momentum fluctuations. For more peripheral collisions, the data exhibit either a flat behavior or an increasing trend with p_T, consistent with a larger non-flow contribution at high p_T and in peripheral collisions.

Figure 5 compares the data from the 0–5% centrality range to hydrodynamic model predictions from Ref. [27], which are based on the Trento+MUSIC framework and incorporate either a constant shear viscosity or a temperature-dependent bulk viscosity. Because this calculation is not fully tuned to match the overall p_T spectra and its fluctuations, inspired by a conformal scaling argument [25], its authors recommend using the ratio $v_0(p_T)/v_0$ as a function of $p_T/\bar{p}_T$ to compare to the data, where $\bar{p}_T$ is the average transverse momentum in the range of 0.5–10 GeV in this analysis. The ratio $v_0(p_T)/v_0$ reduces the dependence on initial conditions, while the scaled quantity $p_T/\bar{p}_T$ further reduces dependencies on model descriptions.

As shown in Figure 5, the calculations with and without shear viscosity lead to similar predictions, whereas

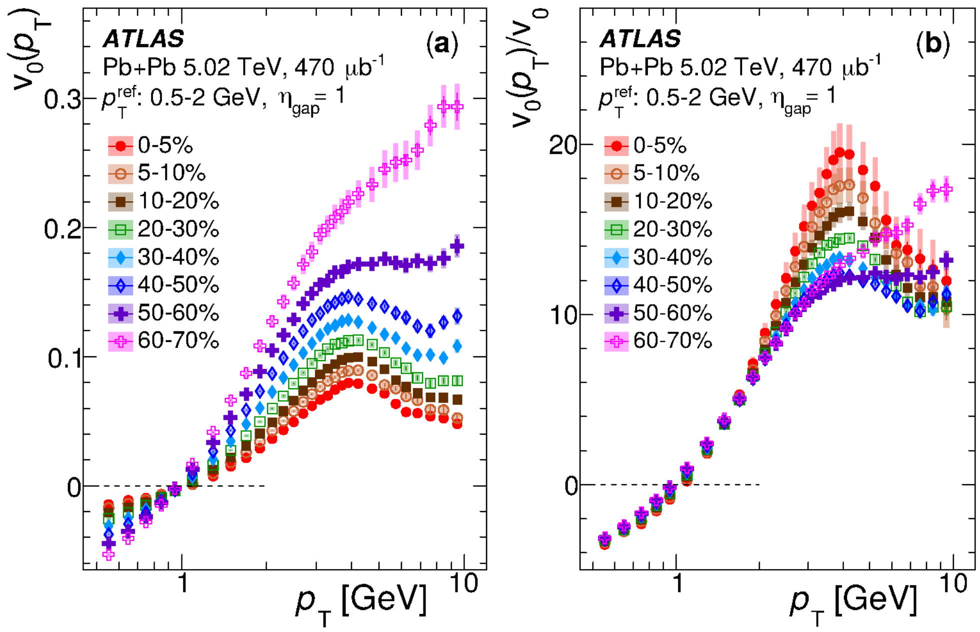

Figure 4: The $v_0(p_\mathrm{T})$ (**a**) and $v_0(p_\mathrm{T})/v_0$ (**b**) for different centrality ranges. Bars and shaded areas represent statistical and total uncertainties, respectively.

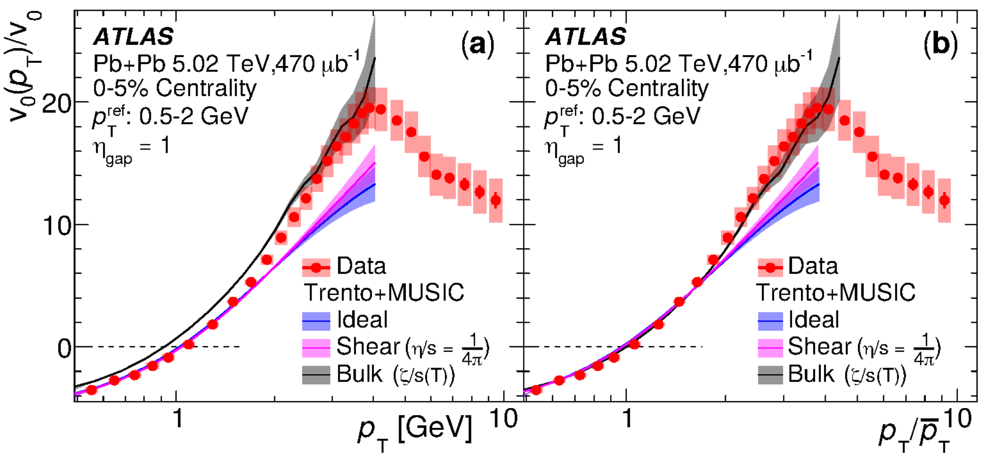

Figure 5: The $v_0(p_\mathrm{T})/v_0$ as a function of p_T (**a**) and $p_\mathrm{T}/\bar{p}_\mathrm{T}$ (**b**) in 0–5% centrality range, where $\bar{p}_\mathrm{T}$ is the mean p_T in 0.5–10 GeV. Bars and shaded areas represent statistical and total uncertainties, respectively. They are compared with hydrodynamic model predictions without viscosity (red), with constant shear viscosity (in terms of shear viscosity to entropy density ratio of $\eta/s = \frac{1}{4\pi}$, magenta), and with temperature-dependent bulk viscosity (grey). The shaded bands on the model curves represent the statistical uncertainties.

calculation with bulk viscosity alters both the zero-crossing in p_T and the high-p_T behavior. Without bulk viscosity, the model underestimates the data at high p_T, while adding bulk viscosity brings the predictions closer, albeit reducing the zero-crossing point. Rescaling the horizontal axis by $\bar{p}_\mathrm{T}$ further improves the agreement, highlighting the impact of bulk viscosity in the p_T-differential radial flow. Although the model predictions still require further tuning, this comparison shows clear sensitivity of the $v_0(p_\mathrm{T})$ data to the bulk viscosity of the QGP.

Summary. This Letter reports the first measurement of the p_{T}-differential radial flow fluctuations $v_0(p_{\mathrm{T}})$ using charged particle tracks over the range $0.5 < p_{\mathrm{T}} < 10$ GeV in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using the ATLAS detector at the LHC. This observable is extracted from the correlations between each event's p_{T}-differential spectrum and its average transverse momentum $[p_{\mathrm{T}}]$ in separate subevents. A characteristic rise of $v_0(p_{\mathrm{T}})$ up to 3–4 GeV, a decrease at higher p_{T}, and a sign change near 1 GeV are observed, which could be associated with an interplay between collective flow and jet quenching. The $v_0(p_{\mathrm{T}})$ is nearly independent of the pseudorapidity gap between subevents, supporting the long-range nature of the radial flow. A factorization test shows that $v_0(p_{\mathrm{T}})$ for $p_{\mathrm{T}} \lesssim 3$ GeV is nearly independent of the p_{T} range used to calculate $[p_{\mathrm{T}}]$, establishing the collective nature of the radial flow. Notably, the shape of $v_0(p_{\mathrm{T}})$ for $p_{\mathrm{T}} \lesssim 3$ GeV is nearly centrality-independent, implying a universal hydrodynamic response to radial expansion. Taken together, these results confirm three hallmarks of collectivity – long-range correlation, factorization, and centrality-independent shape – now demonstrated for radial flow. Comparisons with a hydrodynamic model reveal that $v_0(p_{\mathrm{T}})$ is sensitive to bulk viscosity, highlighting its potential for quantitative constraints on QGP transport properties.

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Carbone[71a,71b], R. Cardarelli[76a], J.C.J. Cardenas[8], M.P. Cardiff[27], G. Carducci[44b,44a], T. Carli[37], G. Carlino[72a], J.I. Carlotto[13], B.T. Carlson[132,s], E.M. Carlson[171], J. Carmignani[94], L. Carminati[71a,71b], A. Carnelli[4], M. Carnesale[37], S. Caron[116], E. Carquin[140g], I.B. Carr[107], S. Carrá[73a,73b], G. Carratta[24b,24a], A.M. Carroll[126], M.P. Casado[13,i], P. Casolaro[72a,72b], M. Caspar[48], F.L. Castillo[4], L. Castillo Garcia[13], V. Castillo Gimenez[169], N.F. Castro[133a,133e], A. Catinaccio[37], J.R. Catmore[128], T. Cavaliere[4], V. Cavaliere[30], L.J. Caviedes Betancourt[23b], E. Celebi[82], S. Cella[37], V. Cepaitis[56], K. Cerny[125], A.S. Cerqueira[83a], A. Cerri[74a,74b,al], L. Cerrito[76a,76b], F. Cerutti[18a], B. Cervato[71a,71b], A. Cervelli[24b], G. Cesarini[53], S.A. Cetin[82], P.M. Chabrillat[130], R. Chakkappai[66], S. Chakraborty[173], J. Chan[18a], W.Y. Chan[159], J.D. Chapman[33], E. Chapon[138], B. Chargeishvili[155b], D.G. Charlton[21], C. Chauhan[136], Y. Che[114a], S. Chekanov[6], S.V. Chekulaev[162a], G.A. Chelkov[39,a], B. Chen[157], B. Chen[171], H. Chen[114a], H. Chen[30], J. Chen[144a], J. Chen[148], M. Chen[129], S. Chen[89], S.J. Chen[114a], X. Chen[144a], X. Chen[15,ah], Z. Chen[62], C.L. Cheng[176], H.C. Cheng[64a], S. Cheong[149], A. Cheplakov[39], E. Cherepanova[117], R. Cherkaoui El Moursli[36e], E. Cheu[7], K. Cheung[65], L. Chevalier[138], V. Chiarella[53], G. Chiarelli[74a], G. Chiodini[70a], A.S. Chisholm[21], A. Chitan[28b], M. Chitishvili[169], M.V. Chizhov[39,t], K. Choi[11], Y. Chou[142], E.Y.S. Chow[116], K.L. Chu[175], M.C. Chu[64a], X. Chu[14,114c], Z. Chubinidze[53], J. Chudoba[134], J.J. Chwastowski [87], D. Cieri [112], K.M. Ciesla [86a], V. Cindro [95], A. Ciocio [18a], F. Cirotto [72a,72b], Z.H. Citron [175], M. Citterio [71a], D.A. Ciubotaru[28b], A. Clark [56], P.J. Clark [52], N. Clarke Hall [98], C. Clarry [161], S.E. Clawson [48], C. Clement [47a,47b], Y. Coadou [104], M. Cobal [69a,69c], A. Coccaro [57b], R.F. Coelho Barrue [133a], R. Coelho Lopes De Sa [105], S. Coelli [71a], L.S. Colangeli [161], B. Cole [42], P. Collado Soto [101], J. Collot [60], R. Coluccia[70a,70b], P. Conde Muiño [133a,133g], M.P. Connell [34c], S.H. Connell [34c], E.I. Conroy [129], F. Conventi [72a,aj], A.M. Cooper-Sarkar [129], L. Corazzina [75a,75b], F.A. Corchia [24b,24a], A. Cordeiro Oudot Choi [142], L.D. Corpe [41], M. Corradi [75a,75b], F. Corriveau [106,ac], A. Cortes-Gonzalez [159], M.J. Costa [169], F. Costanza [4], D. Costanzo [145], B.M. Cote [122], J. Couthures [4], G. Cowan [97], K. Cranmer [176], L. Cremer [49], D. Cremonini [24b,24a], S. Crépé-Renaudin [60], F. Crescioli [130], T. Cresta [73a,73b], M. Cristinziani [147], M. Cristoforetti [78a,78b], V. Croft [117], J.E. Crosby [124], G. Crosetti [44b,44a], A. Cueto [101], H. Cui [98], Z. Cui [7], W.R. Cunningham [59], F. Curcio [169], J.R. Curran [52], M.J. Da Cunha Sargedas De Sousa [57b,57a], J.V. Da Fonseca Pinto [83b], C. Da Via [103], W. Dabrowski [86a], T. Dado [37], S. Dahbi [154], T. Dai [108], D. Dal Santo [20], C. Dallapiccola [105], M. Dam [43], G. D'amen [30], V. D'Amico [111], J. Damp [102], J.R. Dandoy [35], D. Dannheim [37], G. D'anniballe [74a,74b], M. Danninger [148], V. Dao [151], G. Darbo [57b], S.J. Das [30], F. Dattola [48], S. D'Auria [71a,71b], A. D'Avanzo [72a,72b], T. Davidek [136], J. Davidson [173], I. Dawson [96], K. De [8], C. De Almeida Rossi [161], R. De Asmundis [72a], N. De Biase [48], S. De Castro [24b,24a], N. De Groot [116], P. de Jong [117], H. De la Torre [118], A. De Maria [114a], A. De Salvo [75a], U. De Sanctis [76a,76b], F. De Santis [70a,70b], A. De Santo [152], J.B. De Vivie De Regie [60], J. Debevc [95], D.V. Dedovich[39], J. Degens [94], A.M. Deiana [45], J. Del Peso [101], L. Delagrange [130], F. Deliot [138], C.M. Delitzsch [49], M. Della Pietra [72a,72b], D. Della Volpe [56], A. Dell'Acqua [37], L. Dell'Asta [71a,71b], M. Delmastro [4], C.C. Delogu [102], P.A. Delsart [60], S. Demers [178], M. Demichev [39], S.P. Denisov [38], H. Denizli [22a,m], L. D'Eramo [41], D. Derendarz [87], F. Derue [130], P. Dervan [94], A.M. Desai [1], K. Desch [25], F.A. Di Bello [57b,57a], A. Di Ciaccio [76a,76b], L. Di Ciaccio [4], A. Di Domenico [75a,75b], C. Di Donato [72a,72b], A. Di Girolamo [37], G. Di Gregorio [37], A. Di Luca [78a,78b], B. Di Micco [77a,77b], R. Di Nardo [77a,77b], K.F. Di Petrillo [40], M. Diamantopoulou [35], F.A. Dias [117], M.A. Diaz [140a,140b], A.R. Didenko [39], M. Didenko [169], S.D. Diefenbacher [18a], E.B. Diehl [108], S. Díez Cornell [48], C. Diez Pardos [147], C. Dimitriadi [150], A. Dimitrievska [21], A. Dimri [151], J. Dingfelder [25], T. Dingley [129], I-M. Dinu [28b], S.J. Dittmeier [63b], F. Dittus [37], M. Divisek [136], B. Dixit [94], F. Djama [104], T. Djobava [155b], C. Doglioni [103,100], A. Dohnalova [29a], Z. Dolezal [136], K. Domijan [86a], K.M. Dona [40], M. Donadelli [83d], B. Dong [109], J. Donini [41], A. D'Onofrio [72a,72b], M. D'Onofrio [94], J. Dopke [137], A. Doria [72a], N. Dos Santos Fernandes [133a], P. Dougan [103], M.T. Dova [92], A.T. Doyle [59], M.A. Draguet [129], M.P. Drescher [55], E. Dreyer [175], I. Drivas-koulouris [10], M. Drnevich [120], M. Drozdova [56], D. Du [62], T.A. du Pree [117], Z. Duan[114a], M. Dubau [4], F. Dubinin [39], M. Dubovsky [29a], E. Duchovni [175], G. Duckeck [111], P.K. Duckett[98], O.A. Ducu [28b], D. Duda [52], A. Dudarev [37], E.R. Duden [27], M. D'uffizi [103], L. Duflot [66], M. Dührssen [37], I. Duminica [28g], A.E. Dumitriu [28b], M. Dunford [63a], S. Dungs [49], K. Dunne [47a,47b], A. Duperrin [104], H. Duran Yildiz [3a], M. Düren [58], A. Durglishvili [155b], D. Duvnjak [35], G.I. Dyckes [18a], M. Dyndal [86a], B.S. Dziedzic [37], Z.O. Earnshaw [152], G.H. Eberwein [129], B. Eckerova [29a], S. Eggebrecht [55], E. Egidio Purcino De Souza [83e], G. Eigen [17], K. Einsweiler [18a], T. Ekelof [167], P.A. Ekman [100], S. El Farkh [36b], Y. El Ghazali [62], H. El Jarrari [37], A. El Moussaouy [36a], V. Ellajosyula [167], M. Ellert [167], F. Ellinghaus [177], T.A. Elliot [97], N. Ellis [37], J. Elmsheuser [30], M. Elsawy [119a], M. Elsing [37], D. Emeliyanov [137], Y. Enari [84], I. Ene [18a], S. Epari [110], D. Ernani Martins Neto [87], F. Ernst[37], M. Errenst [177], M. Escalier [66], C. Escobar [169], E. Etzion [157], G. Evans [133a,133b], H. Evans [68], L.S. Evans [97],

A. Ezhilov [38], S. Ezzarqtouni [36a], F. Fabbri [24b,24a], L. Fabbri [24b,24a], G. Facini [98], V. Fadeyev [139], R.M. Fakhrutdinov [38], D. Fakoudis [102], S. Falciano [75a], L.F. Falda Ulhoa Coelho [133a], F. Fallavollita [112], G. Falsetti [44b,44a], J. Faltova [136], C. Fan [168], K.Y. Fan [64b], Y. Fan [14], Y. Fang [14,114c], M. Fanti [71a,71b], M. Faraj [69a,69b], Z. Farazpay [99], A. Farbin [8], A. Farilla [77a], T. Farooque [109], J.N. Farr [178], S.M. Farrington [137,52], F. Fassi [36e], D. Fassouliotis [9], L. Fayard [66], P. Federic [136], P. Federicova [134], O.L. Fedin [38,a], M. Feickert [176], L. Feligioni [104], D.E. Fellers [18a], C. Feng [143a], Z. Feng [117], M.J. Fenton [165], L. Ferencz [48], B. Fernandez Barbadillo [93], P. Fernandez Martinez [67], M.J.V. Fernoux [104], J. Ferrando [93], A. Ferrari [167], P. Ferrari [117,116], R. Ferrari [73a], D. Ferrere [56], C. Ferretti [108], M.P. Fewell [1], D. Fiacco [75a,75b], F. Fiedler [102], P. Fiedler [135], S. Filimonov [39], M.S. Filip [28b,u], A. Filipčič [95], E.K. Filmer [162a], F. Filthaut [116], M.C.N. Fiolhais [133a,133c,c], L. Fiorini [169], W.C. Fisher [109], T. Fitschen [103], P.M. Fitzhugh [138], I. Fleck [147], P. Fleischmann [108], T. Flick [177], M. Flores [34d,ag], L.R. Flores Castillo [64a], L. Flores Sanz De Acedo [37], F.M. Follega [78a,78b], N. Fomin [33], J.H. Foo [161], A. Formica [138], A.C. Forti [103], E. Fortin [37], A.W. Fortman [18a], L. Foster [18a], L. Fountas [9,j], D. Fournier [66], H. Fox [93], P. Francavilla [74a,74b], S. Francescato [61], S. Franchellucci [56], M. Franchini [24b,24a], S. Franchino [63a], D. Francis [37], L. Franco [116], V. Franco Lima [37], L. Franconi [48], M. Franklin [61], G. Frattari [27], Y.Y. Frid [157], J. Friend [59], N. Fritzsche [37], A. Froch [56], D. Froidevaux [37], J.A. Frost [129], Y. Fu [109], S. Fuenzalida Garrido [140g], M. Fujimoto [104], K.Y. Fung [64a], E. Furtado De Simas Filho [83e], M. Furukawa [159], J. Fuster [169], A. Gaa [55], A. Gabrielli [24b,24a], A. Gabrielli [161], P. Gadow [37], G. Gagliardi [57b,57a], L.G. Gagnon [18a], S. Gaid [88b], S. Galantzan [157], J. Gallagher [1], E.J. Gallas [129], A.L. Gallen [167], B.J. Gallop [137], K.K. Gan [122], S. Ganguly [159], Y. Gao [52], A. Garabaglu [142], F.M. Garay Walls [140a,140b], C. García [169], A. Garcia Alonso [117], A.G. Garcia Caffaro [178], J.E. García Navarro [169], M. Garcia-Sciveres [18a], G.L. Gardner [131], R.W. Gardner [40], N. Garelli [164], R.B. Garg [149], J.M. Gargan [52], C.A. Garner [161], C.M. Garvey [34a], V.K. Gassmann [164], G. Gaudio [73a], V. Gautam [13], P. Gauzzi [75a,75b], J. Gavranovic [95], I.L. Gavrilenko [133a], A. Gavrilyuk [38], C. Gay [170], G. Gaycken [126], E.N. Gazis [10], A. Gekow [122], C. Gemme [57b], M.H. Genest [60], A.D. Gentry [115], S. George [97], T. Geralis [46], A.A. Gerwin [123], P. Gessinger-Befurt [37], M.E. Geyik [177], M. Ghani [173], K. Ghorbanian [96], A. Ghosal [147], A. Ghosh [165], A. Ghosh [7], B. Giacobbe [24b], S. Giagu [75a,75b], T. Giani [117], A. Giannini [62], S.M. Gibson [97], M. Gignac [139], D.T. Gil [86b], A.K. Gilbert [86a], B.J. Gilbert [42], D. Gillberg [35], G. Gilles [117], D.M. Gingrich [2,ai], M.P. Giordani [69a,69c], P.F. Giraud [138], G. Giugliarelli [69a,69c], D. Giugni [71a], F. Giuli [76a,76b], I. Gkialas [9,j], L.K. Gladilin [38], C. Glasman [101], M. Glazewska [20], R.M. Gleason [165], G. Glemža [48], M. Glisic [126], I. Gnesi [44b], Y. Go [30], M. Goblirsch-Kolb [37], B. Gocke [49], D. Godin [110], B. Gokturk [22a], S. Goldfarb [107], T. Golling [56], M.G.D. Gololo [34c], D. Golubkov [38], J.P. Gombas [109], A. Gomes [133a,133b], G. Gomes Da Silva [147], A.J. Gomez Delegido [169], R. Gonçalo [133a], L. Gonella [21], A. Gongadze [155c], F. Gonnella [21], J.L. Gonski [149], R.Y. González Andana [52], S. González de la Hoz [169], M.V. Gonzalez Rodrigues [48], R. Gonzalez Suarez [167], S. Gonzalez-Sevilla [56], L. Goossens [37], B. Gorini [37], E. Gorini [70a,70b], A. Gorišek [95], T.C. Gosart [131], A.T. Goshaw [51], M.I. Gostkin [39], S. Goswami [124], C.A. Gottardo [37], S.A. Gotz [111], M. Gouighri [36b], A.G. Goussiou [142], N. Govender [34c], R.P. Grabarczyk [129], I. Grabowska-Bold [86a], K. Graham [35], E. Gramstad [128], S. Grancagnolo [70a,70b], C.M. Grant [1], P.M. Gravila [28f], F.G. Gravili [70a,70b], H.M. Gray [18a], M. Greco [112], M.J. Green [1], C. Grefe [25], A.S. Grefsrud [17], I.M. Gregor [48], K.T. Greif [165], P. Grenier [149], S.G. Grewe [112], A.A. Grillo [139], K. Grimm [32], S. Grinstein [13,y], J.-F. Grivaz [66], E. Gross [175], J. Grosse-Knetter [55], L. Guan [108], G. Guerrieri [37], R. Guevara [128], R. Gugel [102], J.A.M. Guhit [108], A. Guida [19], E. Guilloton [173], S. Guindon [37], F. Guo [14,114c], J. Guo [144a],

L. Guo [48], L. Guo [114b,w], Y. Guo [108], A. Gupta [49], R. Gupta [132], S. Gupta[27], S. Gurbuz [25], S.S. Gurdasani [48], G. Gustavino [75a,75b], P. Gutierrez [123], L.F. Gutierrez Zagazeta [131], M. Gutsche [50], C. Gutschow [98], C. Gwenlan [129], C.B. Gwilliam [94], E.S. Haaland [128], A. Haas [120], M. Habedank [59], C. Haber [18a], H.K. Hadavand [8], A. Haddad [41], A. Hadef [50], A.I. Hagan [93], J.J. Hahn [147], E.H. Haines [98], M. Haleem [172], J. Haley [124], G.D. Hallewell [104], L. Halser [20], K. Hamano [171], H. Hamdaoui [167], M. Hamer [25], S.E.D. Hammoud [66], E.J. Hampshire [97], J. Han [143a], L. Han [114a], L. Han [62], S. Han [14], K. Hanagaki [84], M. Hance [139], D.A. Hangal [42], H. Hanif [148], M.D. Hank [131], J.B. Hansen [43], P.H. Hansen [43], D. Harada [56], T. Harenberg [177], S. Harkusha [179], M.L. Harris [105], Y.T. Harris [25], J. Harrison [13], N.M. Harrison [122], P.F. Harrison[173], M.L.E. Hart [98], N.M. Hartman [112], N.M. Hartmann [111], R.Z. Hasan [97,137], Y. Hasegawa [146], F. Haslbeck [129], S. Hassan [17], R. Hauser [109], M. Haviernik [136], C.M. Hawkes [21], R.J. Hawkings [37], Y. Hayashi [159], D. Hayden [109], C. Hayes [108], R.L. Hayes [117], C.P. Hays [129], J.M. Hays [96], H.S. Hayward [94], M. He [14,114c], Y. He [48], Y. He [98], N.B. Heatley [96], V. Hedberg [100], C. Heidegger [54], K.K. Heidegger [54], J. Heilman [35], S. Heim [48], T. Heim [18a], J.G. Heinlein [131], J.J. Heinrich [126], L. Heinrich [112], J. Hejbal [134], A. Held [176], S. Hellesund [17], C.M. Helling [170], S. Hellman [47a,47b], A.M. Henriques Correia[37], H. Herde [100], Y. Hernández Jiménez [151], L.M. Herrmann [25], T. Herrmann [50], G. Herten [54], R. Hertenberger [111], L. Hervas [37], M.E. Hesping [102], N.P. Hessey [162a], J. Hessler [112], M. Hidaoui [36b], N. Hidic [136], E. Hill [161], T.S. Hillersoy[17], S.J. Hillier [21], J.R. Hinds [109], F. Hinterkeuser [25], M. Hirose [127], S. Hirose [163], D. Hirschbuehl [177], T.G. Hitchings [103], B. Hiti [95], J. Hobbs [151], R. Hobincu [28e], N. Hod [175], A.M. Hodges [168], M.C. Hodgkinson [145], B.H. Hodkinson [129], A. Hoecker [37], D.D. Hofer [108], J. Hofer [169], M. Holzbock [37], L.B.A.H. Hommels [33], V. Homsak [129], B.P. Honan [103], J.J. Hong [68], T.M. Hong [132], B.H. Hooberman [168], W.H. Hopkins [6], M.C. Hoppesch [168], Y. Horii [113], M.E. Horstmann [112], S. Hou [154], M.R. Housenga [168], A.S. Howard [95], J. Howarth [59], J. Hoya [6], M. Hrabovsky [125], T. Hryn'ova [4], P.J. Hsu [65], S.-C. Hsu [142], T. Hsu [66], M. Hu [18a], Q. Hu [62], S. Huang [33], X. Huang [14,114c], Y. Huang [136], Y. Huang [114b], Y. Huang [102], Y. Huang [14], Z. Huang [66], Z. Hubacek [135], M. Huebner [25], F. Huegging [25], T.B. Huffman [129], M. Hufnagel Maranha De Faria [83a], C.A. Hugli [48], M. Huhtinen [37], S.K. Huiberts [17], R. Hulsken [106], C.E. Hultquist [18a], N. Huseynov [12,g], J. Huston [109], J. Huth [61], R. Hyneman [7], G. Iacobucci [56], G. Iakovidis [30], L. Iconomidou-Fayard [66], J.P. Iddon [37], P. Iengo [72a,72b], R. Iguchi [159], Y. Iiyama [159], T. Iizawa [159], Y. Ikegami [84], D. Iliadis [158], N. Ilic [161], H. Imam [36a], G. Inacio Goncalves [83d], S.A. Infante Cabanas [140c], T. Ingebretsen Carlson [47a,47b], J.M. Inglis [96], G. Introzzi [73a,73b], M. Iodice [77a], V. Ippolito [75a,75b], R.K. Irwin [94], M. Ishino [159], W. Islam [176], C. Issever [19], S. Istin [22a,an], K. Itabashi [84], H. Ito [174], R. Iuppa [78a,78b], A. Ivina [175], V. Izzo [72a], P. Jacka [135], P. Jackson [1], P. Jain [48], K. Jakobs [54], T. Jakoubek [175], J. Jamieson [59], W. Jang [159], S. Jankovych [136], M. Javurkova [105], P. Jawahar [103], L. Jeanty [126], J. Jejelava [155a,af], P. Jenni [54,f], C.E. Jessiman [35], C. Jia [143a], H. Jia [170], J. Jia [151], X. Jia [14,114c], Z. Jia [114a], C. Jiang [52], Q. Jiang [64b], S. Jiggins [48], M. Jimenez Ortega [169], J. Jimenez Pena [13], S. Jin [114a], A. Jinaru [28b], O. Jinnouchi [141], P. Johansson [145], K.A. Johns [7], J.W. Johnson [139], F.A. Jolly [48], D.M. Jones [152], E. Jones [48], K.S. Jones[8], P. Jones [33], R.W.L. Jones [93], T.J. Jones [94], H.L. Joos [55,37], R. Joshi [122], J. Jovicevic [16], X. Ju [18a], J.J. Junggeburth [37], T. Junkermann [63a], A. Juste Rozas [13,y], M.K. Juzek [87], S. Kabana [140f], A. Kaczmarska [87], M. Kado [112], H. Kagan [122], M. Kagan [149], A. Kahn [131], C. Kahra [102], T. Kaji [159], E. Kajomovitz [156], N. Kakati [175], N. Kakoty [13], I. Kalaitzidou [54], S. Kandel [8], N.J. Kang [139], D. Kar [34g], K. Karava [129], E. Karentzos [25], O. Karkout [117], S.N. Karpov [39], Z.M. Karpova [39], V. Kartvelishvili [93], A.N. Karyukhin [38],

E. Kasimi [158], J. Katzy [48], S. Kaur [35], K. Kawade [146], M.P. Kawale [123], C. Kawamoto [89], T. Kawamoto [62], E.F. Kay [37], F.I. Kaya [164], S. Kazakos [109], V.F. Kazanin [38], J.M. Keaveney [34a], R. Keeler [171], G.V. Kehris [61], J.S. Keller [35], J.J. Kempster [152], O. Kepka [134], J. Kerr [162b], B.P. Kerridge [137], B.P. Kerševan [95], L. Keszeghova [29a], R.A. Khan [132], A. Khanov [124], A.G. Kharlamov [38], T. Kharlamova [38], E.E. Khoda [142], M. Kholodenko [133a], T.J. Khoo [19], G. Khoriauli [172], Y. Khoulaki [36a], J. Khubua [155b,*], Y.A.R. Khwaira [130], B. Kibirige[34g], D. Kim [6], D.W. Kim [47a,47b], Y.K. Kim [40], N. Kimura [98], M.K. Kingston [55], A. Kirchhoff [55], C. Kirfel [25], F. Kirfel [25], J. Kirk [137], A.E. Kiryunin [112], S. Kita [163], O. Kivernyk [25], M. Klassen [164], C. Klein [35], L. Klein [172], M.H. Klein [45], S.B. Klein [56], U. Klein [94], A. Klimentov [30], T. Klioutchnikova [37], P. Kluit [117], S. Kluth [112], E. Kneringer [79], T.M. Knight [161], A. Knue [49], M. Kobel [50], D. Kobylianskii [175], S.F. Koch [129], M. Kocian [149], P. Kodyš [136], D.M. Koeck [126], T. Koffas [35], O. Kolay [50], I. Koletsou [4], T. Komarek [87], K. Köneke [55], A.X.Y. Kong [1], T. Kono [121], N. Konstantinidis [98], P. Kontaxakis [56], B. Konya [100], R. Kopeliansky [42], S. Koperny [86a], K. Korcyl [87], K. Kordas [158,d], A. Korn [98], S. Korn [55], I. Korolkov [13], N. Korotkova [38], B. Kortman [117], O. Kortner [112], S. Kortner [112], W.H. Kostecka [118], M. Kostov [29a], V.V. Kostyukhin [147], A. Kotsokechagia [37], A. Kotwal [51], A. Koulouris [37], A. Kourkoumeli-Charalampidi [73a,73b], C. Kourkoumelis [9], E. Kourlitis [112], O. Kovanda [126], R. Kowalewski [171], W. Kozanecki [126], A.S. Kozhin [38], V.A. Kramarenko [38], G. Kramberger [95], P. Kramer [25], M.W. Krasny [130], A. Krasznahorkay [105], A.C. Kraus [118], J.W. Kraus [177], J.A. Kremer [48], N.B. Krengel [147], T. Kresse [50], L. Kretschmann [177], J. Kretzschmar [94], P. Krieger [161], K. Krizka [21], K. Kroeninger [49], H. Kroha [112], J. Kroll [134], J. Kroll [131], K.S. Krowpman [109], U. Kruchonak [39], H. Krüger [25], N. Krumnack[81], M.C. Kruse [51], O. Kuchinskaia [39], S. Kuday [3a], S. Kuehn [37], R. Kuesters [54], T. Kuhl [48], V. Kukhtin [39], Y. Kulchitsky [39], S. Kuleshov [140d,140b], J. Kull [1], E.V. Kumar [111], M. Kumar [34g], N. Kumari [48], P. Kumari [162b], A. Kupco [134], T. Kupfer[49], A. Kupich [38], O. Kuprash [54], H. Kurashige [85], L.L. Kurchaninov [162a], O. Kurdysh [4], Y.A. Kurochkin [38], A. Kurova [38], M. Kuze [141], A.K. Kvam [105], J. Kvita [125], N.G. Kyriacou [108], C. Lacasta [169], F. Lacava [75a,75b], H. Lacker [19], D. Lacour [130], N.N. Lad [98], E. Ladygin [39], A. Lafarge [41], B. Laforge [130], T. Lagouri [178], F.Z. Lahbabi [36a], S. Lai [55], J.E. Lambert [171], S. Lammers [68], W. Lampl [7], C. Lampoudis [158,d], G. Lamprinoudis [102], A.N. Lancaster [118], E. Lançon [30], U. Landgraf [54], M.P.J. Landon [96], V.S. Lang [54], O.K.B. Langrekken [128], A.J. Lankford [165], F. Lanni [37], K. Lantzsch [25], A. Lanza [73a], M. Lanzac Berrocal [169], J.F. Laporte [138], T. Lari [71a], D. Larsen [17], L. Larson [11], F. Lasagni Manghi [24b], M. Lassnig [37], S.D. Lawlor [145], R. Lazaridou[173], M. Lazzaroni [71a,71b], H.D.M. Le [109], E.M. Le Boulicaut [178], L.T. Le Pottier [18a], B. Leban [24b,24a], F. Ledroit-Guillon [60], T.F. Lee [162b], L.L. Leeuw [34c], M. Lefebvre [171], C. Leggett [18a], G. Lehmann Miotto [37], M. Leigh [56], W.A. Leight [105], W. Leinonen [116], A. Leisos [158,v], M.A.L. Leite [83c], C.E. Leitgeb [19], R. Leitner [136], K.J.C. Leney [45], T. Lenz [25], S. Leone [74a], C. Leonidopoulos [52], A. Leopold [150], J.H. Lepage Bourbonnais [35], R. Les [109], C.G. Lester [33], M. Levchenko [38], J. Levêque [4], L.J. Levinson [175], G. Levrini [24b,24a], M.P. Lewicki [87], C. Lewis [142], D.J. Lewis [4], L. Lewitt [145], A. Li [30], B. Li [143a], C. Li[108], C-Q. Li [112], H. Li [143a], H. Li [103], H. Li [15], H. Li[62], H. Li [143a], J. Li [144a], K. Li [14], L. Li [144a], R. Li [178], S. Li [14,114c], S. Li [144b,144a], T. Li [5], X. Li [106], Z. Li [159], Z. Li [14,114c], Z. Li [62], S. Liang [14,114c], Z. Liang [14], M. Liberatore [138], B. Liberti [76a], K. Lie [64c], J. Lieber Marin [83e], H. Lien [68], H. Lin [108], S.F. Lin [151], L. Linden [111], R.E. Lindley [7], J.H. Lindon [37], J. Ling [61], E. Lipeles [131], A. Lipniacka [17], A. Lister [170], J.D. Little [68], B. Liu [14], B.X. Liu [114b], D. Liu [144b,144a], D. Liu [139], E.H.L. Liu [21], J.K.K. Liu [120], K. Liu [144b], K. Liu [144b,144a], M. Liu [62], M.Y. Liu [62], P. Liu [14], Q. Liu [144b,142,144a], X. Liu [62], X. Liu [143a], Y. Liu [114b,114c], Y.L. Liu [143a], Y.W. Liu [62],

Z. Liu [66,l], S.L. Lloyd [96], E.M. Lobodzinska [48], P. Loch [7], E. Lodhi [161], T. Lohse [19], K. Lohwasser [145], E. Loiacono [48], J.D. Lomas [21], J.D. Long [42], I. Longarini [165], R. Longo [168], A. Lopez Solis [13], N.A. Lopez-canelas [7], N. Lorenzo Martinez [4], A.M. Lory [111], M. Losada [119a], G. Löschcke Centeno [152], X. Lou [47a,47b], X. Lou [14,114c], A. Lounis [66], P.A. Love [93], M. Lu [66], S. Lu [131], Y.J. Lu [154], H.J. Lubatti [142], C. Luci [75a,75b], F.L. Lucio Alves [114a], F. Luehring [68], B.S. Lunday [131], O. Lundberg [150], J. Lunde [37], N.A. Luongo [6], M.S. Lutz [37], A.B. Lux [26], D. Lynn [30], R. Lysak [134], V. Lysenko [135], E. Lytken [100], V. Lyubushkin [39], T. Lyubushkina [39], M.M. Lyukova [151], M.Firdaus M. Soberi [52], H. Ma [30], K. Ma [62], L.L. Ma [143a], W. Ma [62], Y. Ma [124], J.C. MacDonald [102], P.C. Machado De Abreu Farias [83e], R. Madar [41], T. Madula [98], J. Maeda [85], T. Maeno [30], P.T. Mafa [34c,k], H. Maguire [145], M. Maheshwari[33], V. Maiboroda [66], A. Maio [133a,133b,133d], K. Maj [86a], O. Majersky [48], S. Majewski [126], R. Makhmanazarov [38], N. Makovec [66], V. Maksimovic [16], B. Malaescu [130], J. Malamant[128], Pa. Malecki [87], V.P. Maleev [38], F. Malek [60,p], M. Mali [95], D. Malito [97], U. Mallik [80,*], A. Maloizel [5], S. Maltezos[10], A. Malvezzi Lopes [83d], S. Malyukov[39], J. Mamuzic [13], G. Mancini [53], M.N. Mancini [27], G. Manco [73a,73b], J.P. Mandalia [96], S.S. Mandarry [152], I. Mandić [95], L. Manhaes de Andrade Filho [83a], I.M. Maniatis [175], J. Manjarres Ramos [91], D.C. Mankad [175], A. Mann [111], T. Manoussos [37], M.N. Mantinan [40], S. Manzoni [37], L. Mao [144a], X. Mapekula [34c], A. Marantis [158], R.R. Marcelo Gregorio [96], G. Marchiori [5], M. Marcisovsky [134], C. Marcon [71a], E. Maricic [16], M. Marinescu [48], S. Marium [48], M. Marjanovic [123], A. Markhoos [54], M. Markovitch [66], M.K. Maroun [105], G.T. Marsden[103], E.J. Marshall [93], Z. Marshall [18a], S. Marti-Garcia [169], J. Martin [98], T.A. Martin [137], V.J. Martin [52], B. Martin dit Latour [17], L. Martinelli [75a,75b], M. Martinez [13,y], P. Martinez Agullo [169], V.I. Martinez Outschoorn [105], P. Martinez Suarez [13], S. Martin-Haugh [137], G. Martinovicova [136], V.S. Martoiu [28b], A.C. Martyniuk [98], A. Marzin [37], D. Mascione [78a,78b], L. Masetti [102], J. Masik [103], A.L. Maslennikov [39], S.L. Mason [42], P. Massarotti [72a,72b], P. Mastrandrea [74a,74b], A. Mastroberardino [44b,44a], T. Masubuchi [127], T.T. Mathew [126], J. Matousek [136], D.M. Mattern [49], J. Maurer [28b], T. Maurin [59], A.J. Maury [66], B. Maček [95], C. Mavungu Tsava [104], D.A. Maximov [38], A.E. May [103], E. Mayer [41], R. Mazini [34g], I. Maznas [118], S.M. Mazza [139], E. Mazzeo [37], J.P. Mc Gowan [171], S.P. Mc Kee [108], C.A. Mc Lean [6], C.C. McCracken [170], E.F. McDonald [107], A.E. McDougall [117], L.F. Mcelhinney [93], J.A. Mcfayden [152], R.P. McGovern [131], R.P. Mckenzie [34g], T.C. Mclachlan [48], D.J. Mclaughlin [98], S.J. McMahon [137], C.M. Mcpartland [94], R.A. McPherson [171,ac], S. Mehlhase [111], A. Mehta [94], D. Melini [169], B.R. Mellado Garcia [34g], A.H. Melo [55], F. Meloni [48], A.M. Mendes Jacques Da Costa [103], L. Meng [93], S. Menke [112], M. Mentink [37], E. Meoni [44b,44a], G. Mercado [118], S. Merianos [158], C. Merlassino [69a,69c], C. Meroni [71a,71b], J. Metcalfe [6], A.S. Mete [6], E. Meuser [102], C. Meyer [68], J-P. Meyer [138], Y. Miao[114a], R.P. Middleton [137], M. Mihovilovic [66], L. Mijović [52], G. Mikenberg [175], M. Mikestikova [134], M. Mikuž [95], H. Mildner [102], A. Milic [37], D.W. Miller [40], E.H. Miller [149], L.S. Miller [35], A. Milov [175], D.A. Milstead[47a,47b], T. Min[114a], A.A. Minaenko [38], I.A. Minashvili [155b], A.I. Mincer [120], B. Mindur [86a], M. Mineev [39], Y. Mino [89], L.M. Mir [13], M. Miralles Lopez [59], M. Mironova [18a], M.C. Missio [116], A. Mitra [173], V.A. Mitsou [169], Y. Mitsumori [113], O. Miu [161], P.S. Miyagawa [96], T. Mkrtchyan [63a], M. Mlinarevic [98], T. Mlinarevic [98], M. Mlynarikova [37], S. Mobius [20], M.H. Mohamed Farook [115], S. Mohapatra [42], S. Mohiuddin [124], G. Mokgatitswane [34g], L. Moleri [175], U. Molinatti [129], L.G. Mollier [20], B. Mondal [147], S. Mondal [135], K. Mönig [48], E. Monnier [104], L. Monsonis Romero[169], J. Montejo Berlingen [13], A. Montella [47a,47b], M. Montella [122], F. Montereali [77a,77b], F. Monticelli [92], S. Monzani [69a,69c], A. Morancho Tarda [43], N. Morange [66], A.L. Moreira De Carvalho [48], M. Moreno Llácer [169], C. Moreno Martinez [56], J.M. Moreno Perez[23b],

P. Morettini [57b], S. Morgenstern [37], M. Morii [61], M. Morinaga [159], M. Moritsu [90],
F. Morodei [75a,75b], P. Moschovakos [37], B. Moser [54], M. Mosidze [155b], T. Moskalets [45],
P. Moskvitina [116], J. Moss [32], P. Moszkowicz [86a], A. Moussa [36d], Y. Moyal [175],
H. Moyano Gomez [13], E.J.W. Moyse [105], O. Mtintsilana [34g], S. Muanza [104], M. Mucha[25],
J. Mueller [132], R. Müller [37], G.A. Mullier [167], A.J. Mullin[33], J.J. Mullin[51], A.C. Mullins[45],
A.E. Mulski [61], D.P. Mungo [161], D. Munoz Perez [169], F.J. Munoz Sanchez [103],
W.J. Murray [173,137], M. Muškinja [95], C. Mwewa [48], A.G. Myagkov [38,a], A.J. Myers [8],
G. Myers [108], M. Myska [135], B.P. Nachman [18a], K. Nagai [129], K. Nagano [84], R. Nagasaka[159],
J.L. Nagle [30,ak], E. Nagy [104], A.M. Nairz [37], Y. Nakahama [84], K. Nakamura [84], K. Nakkalil [5],
A. Nandi [63b], H. Nanjo [127], E.A. Narayanan [45], Y. Narukawa [159], I. Naryshkin [38],
L. Nasella [71a,71b], S. Nasri [119b], C. Nass [25], G. Navarro [23a], J. Navarro-Gonzalez [169],
A. Nayaz [19], P.Y. Nechaeva [38], S. Nechaeva [24b,24a], F. Nechansky [134], L. Nedic [129], T.J. Neep [21],
A. Negri [73a,73b], M. Negrini [24b], C. Nellist [117], C. Nelson [106], K. Nelson [108], S. Nemecek [134],
M. Nessi [37,h], M.S. Neubauer [168], J. Newell [94], P.R. Newman [21], Y.W.Y. Ng [168], B. Ngair [119a],
H.D.N. Nguyen [110], J.D. Nichols [123], R.B. Nickerson [129], R. Nicolaidou [138], J. Nielsen [139],
M. Niemeyer [55], J. Niermann [37], N. Nikiforou [37], V. Nikolaenko [38,a], I. Nikolic-Audit [130],
P. Nilsson [30], I. Ninca [48], G. Ninio [157], A. Nisati [75a], R. Nisius [112], N. Nitika [69a,69c],
J-E. Nitschke [50], E.K. Nkadimeng [34b], T. Nobe [159], T. Nommensen [153], M.B. Norfolk [145],
B.J. Norman [35], M. Noury [36a], J. Novak [95], T. Novak [95], R. Novotny [135], L. Nozka [125],
K. Ntekas [165], N.M.J. Nunes De Moura Junior [83b], J. Ocariz [130], A. Ochi [85], I. Ochoa [133a],
S. Oerdek [48,z], J.T. Offermann [40], A. Ogrodnik [136], A. Oh [103], C.C. Ohm [150], H. Oide [84],
M.L. Ojeda [37], Y. Okumura [159], L.F. Oleiro Seabra [133a], I. Oleksiyuk [56], G. Oliveira Correa [13],
D. Oliveira Damazio [30], J.L. Oliver [165], R. Omar [68], Ö.O. Öncel [54], A.P. O'Neill [20],
A. Onofre [133a,133e,e], P.U.E. Onyisi [11], M.J. Oreglia [40], D. Orestano [77a,77b], R. Orlandini [77a,77b],
R.S. Orr [161], L.M. Osojnak [131], Y. Osumi [113], G. Otero y Garzon [31], H. Otono [90],
M. Ouchrif [36d], F. Ould-Saada [128], T. Ovsiannikova [142], M. Owen [59], R.E. Owen [137],
V.E. Ozcan [22a], F. Ozturk [87], N. Ozturk [8], S. Ozturk [82], H.A. Pacey [129], K. Pachal [162a],
A. Pacheco Pages [13], C. Padilla Aranda [13], G. Padovano [75a,75b], S. Pagan Griso [18a],
G. Palacino [68], A. Palazzo [70a,70b], J. Pampel [25], J. Pan [178], T. Pan [64a], D.K. Panchal [11],
C.E. Pandini [60], J.G. Panduro Vazquez [137], H.D. Pandya [1], H. Pang [138], P. Pani [48],
G. Panizzo [69a,69c], L. Panwar [130], L. Paolozzi [56], S. Parajuli [168], A. Paramonov [6],
C. Paraskevopoulos [53], D. Paredes Hernandez [64b], A. Pareti [73a,73b], K.R. Park [42], T.H. Park [112],
F. Parodi [57b,57a], J.A. Parsons [42], U. Parzefall [54], B. Pascual Dias [41], L. Pascual Dominguez [101],
E. Pasqualucci [75a], S. Passaggio [57b], F. Pastore [97], P. Patel [87], U.M. Patel [51], J.R. Pater [103],
T. Pauly [37], F. Pauwels [136], C.I. Pazos [164], M. Pedersen [128], R. Pedro [133a], S.V. Peleganchuk [38],
O. Penc [134], E.A. Pender [52], S. Peng [15], G.D. Penn [178], K.E. Penski [111], M. Penzin [38],
B.S. Peralva [83d], A.P. Pereira Peixoto [142], L. Pereira Sanchez [149], D.V. Perepelitsa [30,ak],
G. Perera [105], E. Perez Codina [37], M. Perganti [10], H. Pernegger [37], S. Perrella [75a,75b],
O. Perrin [41], K. Peters [48], R.F.Y. Peters [103], B.A. Petersen [37], T.C. Petersen [43], E. Petit [104],
V. Petousis [135], A.R. Petri [71a,71b], C. Petridou [158,d], T. Petru [136], A. Petrukhin [147], M. Pettee [18a],
A. Petukhov [82], K. Petukhova [37], R. Pezoa [140g], L. Pezzotti [24b,24a], G. Pezzullo [178],
L. Pfaffenbichler [37], A.J. Pfleger [37], T.M. Pham [176], T. Pham [107], P.W. Phillips [137],
G. Piacquadio [151], E. Pianori [18a], F. Piazza [126], R. Piegaia [31], D. Pietreanu [28b],
A.D. Pilkington [103], M. Pinamonti [69a,69c], J.L. Pinfold [2], B.C. Pinheiro Pereira [133a],
J. Pinol Bel [13], A.E. Pinto Pinoargote [130], L. Pintucci [69a,69c], K.M. Piper [152], A. Pirttikoski [56],
D.A. Pizzi [35], L. Pizzimento [64b], A. Plebani [33], M.-A. Pleier [30], V. Pleskot [136], E. Plotnikova[39],
G. Poddar [96], R. Poettgen [100], L. Poggioli [130], S. Polacek [136], G. Polesello [73a], A. Poley [148],

A. Polini [24b], C.S. Pollard [173], Z.B. Pollock [122], E. Pompa Pacchi [123], N.I. Pond [98], D. Ponomarenko [68], L. Pontecorvo [37], S. Popa [28a], G.A. Popeneciu [28d], A. Poreba [37], D.M. Portillo Quintero [162a], S. Pospisil [135], M.A. Postill [145], P. Postolache [28c], K. Potamianos [173], P.A. Potepa [86a], I.N. Potrap [39], C.J. Potter [33], H. Potti [153], J. Poveda [169], M.E. Pozo Astigarraga [37], R. Pozzi [37], A. Prades Ibanez [76a,76b], J. Pretel [171], D. Price [103], M. Primavera [70a], L. Primomo [69a,69c], M.A. Principe Martin [101], R. Privara [125], T. Procter [86b], M.L. Proffitt [142], N. Proklova [131], K. Prokofiev [64c], G. Proto [112], J. Proudfoot [6], M. Przybycien [86a], W.W. Przygoda [86b], A. Psallidas [46], J.E. Puddefoot [145], D. Pudzha [53], D. Pyatiizbyantseva [116], J. Qian [108], R. Qian [109], D. Qichen [103], Y. Qin [13], T. Qiu [52], A. Quadt [55], M. Queitsch-Maitland [103], G. Quetant [56], R.P. Quinn [170], G. Rabanal Bolanos [61], D. Rafanoharana [112], F. Raffaeli [76a,76b], F. Ragusa [71a,71b], J.L. Rainbolt [40], J.A. Raine [56], S. Rajagopalan [30], E. Ramakoti [39], L. Rambelli [57b,57a], I.A. Ramirez-Berend [35], K. Ran [48,114c], D.S. Rankin [131], N.P. Rapheeha [34g], H. Rasheed [28b], D.F. Rassloff [63a], A. Rastogi [18a], S. Rave [102], S. Ravera [57b,57a], B. Ravina [37], I. Ravinovich [175], M. Raymond [37], A.L. Read [128], N.P. Readioff [145], D.M. Rebuzzi [73a,73b], A.S. Reed [112], K. Reeves [27], J.A. Reidelsturz [177], D. Reikher [126], A. Rej [49], C. Rembser [37], H. Ren [62], M. Renda [28b], F. Renner [48], A.G. Rennie [59], A.L. Rescia [48], S. Resconi [71a], M. Ressegotti [57b,57a], S. Rettie [37], W.F. Rettie [35], M.M. Revering [33], E. Reynolds [18a], O.L. Rezanova [39], P. Reznicek [136], H. Riani [36d], N. Ribaric [51], E. Ricci [78a,78b], R. Richter [112], S. Richter [47a,47b], E. Richter-Was [86b], M. Ridel [130], S. Ridouani [36d], P. Rieck [120], P. Riedler [37], E.M. Riefel [47a,47b], J.O. Rieger [117], M. Rijssenbeek [151], M. Rimoldi [37], L. Rinaldi [24b,24a], P. Rincke [167,55], G. Ripellino [167], I. Riu [13], J.C. Rivera Vergara [171], F. Rizatdinova [124], E. Rizvi [96], B.R. Roberts [18a], S.S. Roberts [139], D. Robinson [33], M. Robles Manzano [102], A. Robson [59], A. Rocchi [76a,76b], C. Roda [74a,74b], S. Rodriguez Bosca [37], Y. Rodriguez Garcia [23a], A.M. Rodríguez Vera [118], S. Roe[37], J.T. Roemer [37], O. Røhne [128], R.A. Rojas [37], C.P.A. Roland [130], A. Romaniouk [79], E. Romano [73a,73b], M. Romano [24b], A.C. Romero Hernandez [168], N. Rompotis [94], L. Roos [130], S. Rosati [75a], B.J. Rosser [40], E. Rossi [129], E. Rossi [72a,72b], L.P. Rossi [61], L. Rossini [54], R. Rosten [122], M. Rotaru [28b], B. Rottler [54], D. Rousseau [66], D. Rousso [48], S. Roy-Garand [161], A. Rozanov [104], Z.M.A. Rozario [59], Y. Rozen [156], A. Rubio Jimenez [169], V.H. Ruelas Rivera [19], T.A. Ruggeri [1], A. Ruggiero [129], A. Ruiz-Martinez [169], A. Rummler [37], Z. Rurikova [54], N.A. Rusakovich [39], H.L. Russell [171], G. Russo [75a,75b], J.P. Rutherfoord [7], S. Rutherford Colmenares [33], M. Rybar [136], P. Rybczynski [86a], A. Ryzhov [45], J.A. Sabater Iglesias [56], H.F-W. Sadrozinski [139], F. Safai Tehrani [75a], S. Saha [1], M. Sahinsoy [82], B. Sahoo [175], A. Saibel [169], B.T. Saifuddin [123], M. Saimpert [138], G.T. Saito [83c], M. Saito [159], T. Saito [159], A. Sala [71a,71b], A. Salnikov [149], J. Salt [169], A. Salvador Salas [157], F. Salvatore [152], A. Salzburger [37], D. Sammel [54], E. Sampson [93], D. Sampsonidis [158,d], D. Sampsonidou [126], J. Sánchez [169], V. Sanchez Sebastian [169], H. Sandaker [128], C.O. Sander [48], J.A. Sandesara [176], M. Sandhoff [177], C. Sandoval [23b], L. Sanfilippo [63a], D.P.C. Sankey [137], T. Sano [89], A. Sansoni [53], M. Santana Queiroz[18b], L. Santi [37], C. Santoni [41], H. Santos [133a,133b], A. Santra [175], E. Sanzani [24b,24a], K.A. Saoucha [88b], J.G. Saraiva [133a,133d], J. Sardain [7], O. Sasaki [84], K. Sato [163], C. Sauer[37], E. Sauvan [4], P. Savard [161,ai], R. Sawada [159], C. Sawyer [137], L. Sawyer [99], C. Sbarra [24b], A. Sbrizzi [24b,24a], T. Scanlon [98], J. Schaarschmidt [142], U. Schäfer [102], A.C. Schaffer [66,45], D. Schaile [111], R.D. Schamberger [151], C. Scharf [19], M.M. Schefer [20], V.A. Schegelsky [38], D. Scheirich [136], M. Schernau [140f], C. Scheulen [56], C. Schiavi [57b,57a], M. Schioppa [44b,44a], B. Schlag [149], S. Schlenker [37], J. Schmeing [177], E. Schmidt [112], M.A. Schmidt [177], K. Schmieden [102], C. Schmitt [102], N. Schmitt [102], S. Schmitt [48], N.A. Schneider [111], L. Schoeffel [138], A. Schoening [63b], P.G. Scholer [35],

E. Schopf[147], M. Schott[25], S. Schramm[56], T. Schroer[56], H-C. Schultz-Coulon[63a], M. Schumacher[54], B.A. Schumm[139], Ph. Schune[138], H.R. Schwartz[139], A. Schwartzman[149], T.A. Schwarz[108], Ph. Schwemling[138], R. Schwienhorst[109], F.G. Sciacca[20], A. Sciandra[30], G. Sciolla[27], F. Scuri[74a], C.D. Sebastiani[37], K. Sedlaczek[118], S.C. Seidel[115], A. Seiden[139], B.D. Seidlitz[42], C. Seitz[48], J.M. Seixas[83b], G. Sekhniaidze[72a], L. Selem[60], N. Semprini-Cesari[24b,24a], A. Semushin[179], D. Sengupta[56], V. Senthilkumar[169], L. Serin[66], M. Sessa[72a,72b], H. Severini[123], F. Sforza[57b,57a], A. Sfyrla[56], Q. Sha[14], E. Shabalina[55], H. Shaddix[118], A.H. Shah[33], R. Shaheen[150], J.D. Shahinian[131], M. Shamim[37], L.Y. Shan[14], M. Shapiro[18a], A. Sharma[37], A.S. Sharma[170], P. Sharma[30], P.B. Shatalov[38], K. Shaw[152], S.M. Shaw[103], Q. Shen[144a], D.J. Sheppard[148], P. Sherwood[98], L. Shi[98], X. Shi[14], S. Shimizu[84], C.O. Shimmin[178], I.P.J. Shipsey[129,*], S. Shirabe[90], M. Shiyakova[39,aa], M.J. Shochet[40], D.R. Shope[128], B. Shrestha[123], S. Shrestha[122,am], I. Shreyber[39], M.J. Shroff[171], P. Sicho[134], A.M. Sickles[168], E. Sideras Haddad[34g,166], A.C. Sidley[117], A. Sidoti[24b], F. Siegert[50], Dj. Sijacki[16], F. Sili[92], J.M. Silva[52], I. Silva Ferreira[83b], M.V. Silva Oliveira[30], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[37], E.L. Simpson[103], H. Simpson[152], L.R. Simpson[6], S. Simsek[82], S. Sindhu[55], P. Sinervo[161], S.N. Singh[27], S. Singh[30], S. Sinha[48], S. Sinha[103], M. Sioli[24b,24a], K. Sioulas[9], I. Siral[37], E. Sitnikova[48], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[21], P. Skubic[123], M. Slawinska[87], I. Slazyk[17], I. Sliusar[128], V. Smakhtin[175], B.H. Smart[137], S.Yu. Smirnov[140b], Y. Smirnov[82], L.N. Smirnova[38,a], O. Smirnova[100], A.C. Smith[42], D.R. Smith[165], J.L. Smith[103], M.B. Smith[35], R. Smith[149], H. Smitmanns[102], M. Smizanska[93], K. Smolek[135], P. Smolyanskiy[135], A.A. Snesarev[39], H.L. Snoek[117], S. Snyder[30], R. Sobie[171,ac], A. Soffer[157], C.A. Solans Sanchez[37], E.Yu. Soldatov[39], U. Soldevila[169], A.A. Solodkov[34g], S. Solomon[27], A. Soloshenko[39], K. Solovieva[54], O.V. Solovyanov[41], P. Sommer[50], A. Sonay[13], A. Sopczak[135], A.L. Sopio[52], F. Sopkova[29b], J.D. Sorenson[115], I.R. Sotarriva Alvarez[141], V. Sothilingam[63a], O.J. Soto Sandoval[140c,140b], S. Sottocornola[68], R. Soualah[88a], Z. Soumaimi[36e], D. South[48], N. Soybelman[175], S. Spagnolo[70a,70b], M. Spalla[112], D. Sperlich[54], B. Spisso[72a,72b], D.P. Spiteri[59], L. Splendori[104], M. Spousta[136], E.J. Staats[35], R. Stamen[63a], E. Stanecka[87], W. Stanek-Maslouska[48], M.V. Stange[50], B. Stanislaus[18a], M.M. Stanitzki[48], B. Stapf[48], E.A. Starchenko[38], G.H. Stark[139], J. Stark[91], P. Staroba[134], P. Starovoitov[88b], R. Staszewski[87], G. Stavropoulos[46], A. Stefl[37], P. Steinberg[30], B. Stelzer[148,162a], H.J. Stelzer[132], O. Stelzer-Chilton[162a], H. Stenzel[58], T.J. Stevenson[152], G.A. Stewart[37], J.R. Stewart[124], M.C. Stockton[37], G. Stoicea[28b], M. Stolarski[133a], S. Stonjek[112], A. Straessner[50], J. Strandberg[150], S. Strandberg[47a,47b], M. Stratmann[177], M. Strauss[123], T. Strebler[104], P. Strizenec[29b], R. Ströhmer[172], D.M. Strom[126], R. Stroynowski[45], A. Strubig[47a,47b], S.A. Stucci[30], B. Stugu[17], J. Stupak[123], N.A. Styles[48], D. Su[149], S. Su[62], X. Su[62], D. Suchy[29a], K. Sugizaki[131], V.V. Sulin[38], M.J. Sullivan[94], D.M.S. Sultan[129], L. Sultanaliyeva[38], S. Sultansoy[3b], S. Sun[176], W. Sun[14], O. Sunneborn Gudnadottir[167], N. Sur[100], M.R. Sutton[152], H. Suzuki[163], M. Svatos[134], P.N. Swallow[33], M. Swiatlowski[162a], T. Swirski[172], A. Swoboda[37], I. Sykora[29a], M. Sykora[136], T. Sykora[136], D. Ta[102], K. Tackmann[48,z], A. Taffard[165], R. Tafirout[162a], Y. Takubo[84], M. Talby[104], A.A. Talyshev[38], K.C. Tam[64b], N.M. Tamir[157], A. Tanaka[159], J. Tanaka[159], R. Tanaka[66], M. Tanasini[151], Z. Tao[170], S. Tapia Araya[140g], S. Tapprogge[102], A. Tarek Abouelfadl Mohamed[109], S. Tarem[156], K. Tariq[14], G. Tarna[37], G.F. Tartarelli[71a], M.J. Tartarin[91], P. Tas[136], M. Tasevsky[134], E. Tassi[44b,44a], A.C. Tate[168], G. Tateno[159], Y. Tayalati[36e,ab], G.N. Taylor[107], W. Taylor[162b], A.S. Tegetmeier[91], P. Teixeira-Dias[97], J.J. Teoh[161], K. Terashi[159], J. Terron[101], S. Terzo[13], M. Testa[53], R.J. Teuscher[161,ac],

A. Thaler [79], O. Theiner [56], T. Theveneaux-Pelzer [104], D.W. Thomas[97], J.P. Thomas [21], E.A. Thompson [18a], P.D. Thompson [21], E. Thomson [131], R.E. Thornberry [45], C. Tian [62], Y. Tian [56], V. Tikhomirov [82], Yu.A. Tikhonov [39], S. Timoshenko[38], D. Timoshyn [136], E.X.L. Ting [1], P. Tipton [178], A. Tishelman-Charny [30], K. Todome [141], S. Todorova-Nova [136], L. Toffolin [69a,69c], M. Togawa [84], J. Tojo [90], S. Tokár [29a], O. Toldaiev [68], G. Tolkachev [104], M. Tomoto [84,113], L. Tompkins [149,o], E. Torrence [126], H. Torres [91], E. Torró Pastor [169], M. Toscani [31], C. Tosciri [40], M. Tost [11], D.R. Tovey [145], T. Trefzger [172], P.M. Tricarico [13], A. Tricoli [30], I.M. Trigger [162a], S. Trincaz-Duvoid [130], D.A. Trischuk [27], A. Tropina[39], L. Truong [34c], M. Trzebinski [87], A. Trzupek [87], F. Tsai [151], M. Tsai [108], A. Tsiamis [158], P.V. Tsiareshka[39], S. Tsigaridas [162a], A. Tsirigotis [158,v], V. Tsiskaridze [155a], E.G. Tskhadadze [155a], M. Tsopoulou [158], Y. Tsujikawa [89], I.I. Tsukerman [38], V. Tsulaia [18a], S. Tsuno [84], K. Tsuri [121], D. Tsybychev [151], Y. Tu [64b], A. Tudorache [28b], V. Tudorache [28b], S.B. Tuncay [129], S. Turchikhin [57b,57a], I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [39,ad], P.M. Tuts [42], S. Tzamarias [158,d], E. Tzovara [102], Y. Uematsu [84], F. Ukegawa [163], P.A. Ulloa Poblete [140c,140b], E.N. Umaka [30], G. Unal [37], A. Undrus [30], G. Unel [165], J. Urban [29b], P. Urrejola [140a], G. Usai [8], R. Ushioda [160], M. Usman [110], F. Ustuner [52], Z. Uysal [82], V. Vacek [135], B. Vachon [106], T. Vafeiadis [37], A. Vaitkus [98], C. Valderanis [111], E. Valdes Santurio [47a,47b], M. Valente [37], S. Valentinetti [24b,24a], A. Valero [169], E. Valiente Moreno [169], A. Vallier [91], J.A. Valls Ferrer [169], D.R. Van Arneman [117], T.R. Van Daalen [142], A. Van Der Graaf [49], H.Z. Van Der Schyf [34g], P. Van Gemmeren [6], M. Van Rijnbach [37], S. Van Stroud [98], I. Van Vulpen [117], P. Vana [136], M. Vanadia [76a,76b], U.M. Vande Voorde [150], W. Vandelli [37], E.R. Vandewall [124], D. Vannicola [157], L. Vannoli [53], R. Vari [75a], M. Varma [178], E.W. Varnes [7], C. Varni [118], D. Varouchas [66], L. Varriale [169], K.E. Varvell [153], M.E. Vasile [28b], L. Vaslin[84], M.D. Vassilev [149], A. Vasyukov [39], L.M. Vaughan [124], R. Vavricka[136], T. Vazquez Schroeder [13], J. Veatch [32], V. Vecchio [103], M.J. Veen [105], I. Veliscek [30], I. Velkovska [95], L.M. Veloce [161], F. Veloso [133a,133c], S. Veneziano [75a], A. Ventura [70a,70b], A. Verbytskyi [112], M. Verducci [74a,74b], C. Vergis [96], M. Verissimo De Araujo [83b], W. Verkerke [117], J.C. Vermeulen [117], C. Vernieri [149], M. Vessella [165], M.C. Vetterli [148,ai], A. Vgenopoulos [102], N. Viaux Maira [140g], T. Vickey [145], O.E. Vickey Boeriu [145], G.H.A. Viehhauser [129], L. Vigani [63b], M. Vigl [112], M. Villa [24b,24a], M. Villaplana Perez [169], E.M. Villhauer[40], E. Vilucchi [53], M. Vincent [169], M.G. Vincter [35], A. Visibile[117], C. Vittori [37], I. Vivarelli [24b,24a], E. Voevodina [112], F. Vogel [111], J.C. Voigt [50], P. Vokac [135], Yu. Volkotrub [86b], E. Von Toerne [25], B. Vormwald [37], K. Vorobev [51], M. Vos [169], K. Voss [147], M. Vozak [37], L. Vozdecky [123], N. Vranjes [16], M. Vranjes Milosavljevic [16], M. Vreeswijk [117], N.K. Vu [144b,144a], R. Vuillermet [37], O. Vujinovic [102], I. Vukotic [40], I.K. Vyas [35], J.F. Wack [33], S. Wada [163], C. Wagner[149], J.M. Wagner [18a], W. Wagner [177], S. Wahdan [177], H. Wahlberg [92], C.H. Waits [123], J. Walder [137], R. Walker [111], K. Walkingshaw Pass[59], W. Walkowiak [147], A. Wall [131], E.J. Wallin [100], T. Wamorkar [18a], A. Wang [62], A.Z. Wang [139], C. Wang [102], C. Wang [11], H. Wang [18a], J. Wang [64c], P. Wang [103], P. Wang [98], R. Wang [61], R. Wang [6], S.M. Wang [154], S. Wang [14], T. Wang [62], T. Wang [62], W.T. Wang [80], W. Wang [14], X. Wang [168], X. Wang [144a], X. Wang [48], Y. Wang [114a], Y. Wang [62], Z. Wang [108], Z. Wang [144b], Z. Wang [108], C. Wanotayaroj [84], A. Warburton [106], A.L. Warnerbring [147], N. Warrack [59], S. Waterhouse [97], A.T. Watson [21], H. Watson [52], M.F. Watson [21], E. Watton [59], G. Watts [142], B.M. Waugh [98], J.M. Webb [54], C. Weber [30], H.A. Weber [19], M.S. Weber [20], S.M. Weber [63a], C. Wei [62], Y. Wei [54], A.R. Weidberg [129], E.J. Weik [120], J. Weingarten [49], C. Weiser [54], C.J. Wells [48], T. Wenaus [30], B. Wendland [49], T. Wengler [37], N.S. Wenke[112], N. Wermes [25], M. Wessels [63a], A.M. Wharton [93], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [165], L. Wickremasinghe [127], W. Wiedenmann [176],

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