Measurement of $\phi$-meson production at forward rapidity in $p+p$ collisions at $\sqrt{s}=510$ GeV and its energy dependence from $\sqrt{s}=200$ GeV to 7 TeV

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I. INTRODUCTION

The $\phi(1020)$-vector-meson production in $p+p$ collisions was intensively studied by various experiments at different colliding energies and in different rapidity ranges [1–18]. It is the lightest bound state of $s$ and $\bar{s}$ quarks and is considered a good probe to study strangeness production in $p+p$ collisions. Production of $\phi$ mesons from an initial nonstrange colliding system, such as $p+p$ collisions, is substantially suppressed in comparison to $\omega$ and $\rho$ vector mesons due to the Okubo-Zweig-Iizuka (OZI) rule [19–21]. The $\phi$-meson production at low transverse momentum is dominated by soft processes and is sensitive to the hadronization mechanism, while hard processes become dominant at higher transverse momentum. In $p+p$ collisions, the production of strangeness is in general not well described by generators such as PYTHIA, which tend to underestimate the production of strange particles [10, 22–24]. The study of $\phi$-meson production in $p+p$ collisions is an important tool to study quantum chromodynamics (QCD), providing data to tune phenomenological QCD models in which an interplay is mandatory between perturbative QCD calculations, used in particular for hard parton production dominant at higher $p_T$, and phenomenological QCD models, needed to describe the nonperturbative hadronization into strange hadrons like the $\phi$ meson.

In addition, recently, a long-range near-side angular correlation was observed in $p+p$ collisions at Large-Hadron-Collider (LHC) energies [25–27], which led to the observation of collectivity in $p+p$ collisions [28]. This observation generated various explanations [29], including those based on the color-glass-condensate (CGC) model [30], and collective hydrodynamic flow [31] or color reconnection [32, 33]. Being the heaviest easily accessible meson made of light quarks, $\phi$-meson production provides the largest lever arm accessible to study effects that scale with mass, as should be the case for collective effects [34].

The study of $\phi$-meson production in $p+p$ collisions can be an important tool to gain insight into new phenomena, such as long-range angular correlations, that would have a direct impact in the field of relativistic heavy-ion collisions. The $\phi$-meson production is an excellent observable to probe the strangeness enhancement in the quark-gluon plasma created in heavy-ion collisions [35–37].

We report the $\phi$-meson-production cross section measured in $p+p$ collisions at $\sqrt{s} = 510$ GeV. The analysis uses a data sample of 144.6 pb$^{-1}$ of integrated luminosity obtained by the PHENIX experiment in 2013. The cross section is averaged over the rapidity ($y$) interval $1.2 < |y| < 2.2$ and reported in several bins of transverse momentum ($p_T$) in the range $2 < p_T < 7$ GeV/$c$. The results are compared to several model predictions [24, 34, 38–41] and to the measurements previously reported by the PHENIX experiment at $\sqrt{s} = 200$ GeV [15] and by the LHC experiments measuring the $\phi$-meson-production cross section at forward rapidity at $\sqrt{s} = 2.76$ and 7 TeV [10–13, 17]. Measurements from experiments at the Relativistic Heavy Ion Collider (RHIC) and the LHC allow extracting the energy dependence of the $\phi$-meson-production cross section in the rapidity range $1.2 < y < 2.2$, which provide information to further constrain model predictions.

II. EXPERIMENTAL SETUP

A complete description of the PHENIX detector can be found in Ref. [42]. The results presented here are obtained by measuring the $\phi$ meson via its $\mu^+\mu^-$ decay channel using both PHENIX muon spectrometers covering forward and backward pseudorapidities, $1.2 < |\eta| < 2.2$, and the full azimuth.

Each muon arm spectrometer comprises hadron absorbers, a muon tracker (MuTr), which resides in a radial field magnet, and a muon identifier (MuID). The absorbers are situated in front of the MuTr to provide hadron (mostly pion and kaon) rejection and are built of 19 cm of copper, 60 cm of iron, and 36.2 cm of stainless steel. The MuTr comprises three sets of cathode strip chambers in a radial magnetic field with an inte-
grated bending power of 0.8 T.m. The final component is the MuID, which has five alternating steel absorbers and Iarocci tubes to further reduce the number of punch-through hadrons misidentified as muons. Muon candidates are identified by reconstructed tracks in the MuTr matched to MuID tracks that penetrate through to the last MuID plane.

Another detector system relevant to this analysis is the beam-beam counter (BBC), comprising two arrays of 64 Čerenkov counters, located on both sides of the interaction point and covering the pseudorapidity $3.1 < |\eta| < 3.9$. The BBC system is used to measure the $p+p$ collision vertex position along the beam axis ($z_{vtx}$) with 2 cm resolution and to provide the minimum bias (MB) trigger.

### III. DATA ANALYSIS

The results presented here are based on the data sample collected by PHENIX during the 2013 $p+p$ run at $\sqrt{s} = 510$ GeV. The BBC counters provide the MB trigger, which requires at least one hit in each of the BBCs. Events, in coincidence with the MB trigger, containing a muon pair within the acceptance of the spectrometer are selected by the level-1 dimuon trigger requiring that at least two tracks penetrate through the MuID to its last layer. A total of $5.3 \times 10^8$ dimuon triggered events are recorded, which corresponds to a sampled integrated luminosity of 144.6 pb$^{-1}$.

#### A. Raw yield extraction

A set of quality assurance cuts is applied to the data to select $p+p$ events and muon candidates as well as to improve the signal-to-background ratio. Good $p+p$ events are selected by requiring that the collision occurs in the fiducial interaction region $|z_{vtx}| < 30$ cm as measured by the BBC. No selection is made on the event’s charged particle multiplicity. The MuTr tracks are matched to the MuID tracks at the first MuID layer in both position and angle. In addition, the track is required to have more than a minimum number of possible hits in the MuTr (12 out of the maximum 16) and MuID (6 out of the maximum 10), and cuts on the individual track $\chi^2$ values are applied. Furthermore, there is a minimum allowed single muon momentum along the beam axis, $p_z$, which is reconstructed and energy-loss corrected at the collision vertex, of 2.4 GeV/$c$ corresponding to the momentum cut effectively imposed by the absorbers. Finally, a cut on the $\chi^2$ of the fit to the common vertex of the two candidate tracks near the interaction point is made.

The invariant mass distribution is formed by combining muon candidate tracks of opposite charges. This unlike-sign dimuon spectrum is composed of correlated and uncorrelated pairs. In the low-mass region (below $\approx 1.5$ GeV/$c^2$) the correlated pairs arise from the two-body and Dalitz decays of the light neutral mesons $\eta$, $\rho$, $\omega$, $\eta'$, and $\phi$ as well as semi-muonic decays of correlated charmed hadrons (and beauty in a negligible contribution). The uncorrelated pairs are mainly coming from semi-muonic decays of pions and kaons and punch-through hadrons, and form the so-called combinatorial background. The ratio of $\phi$-meson signal over combinatorial background is of the order of 0.7. This combinatorial background is estimated using two methods: the first one derives the combinatorial background from the distribution formed within the same event by the muon candidates of the same sign (like-sign pairs); and the second one derives the combinatorial background from the pairs formed by muon candidates of opposite charges (unlike-sign pairs) coming from different events (mixed-event). The normalization of the mass distribution of the combinatorial background using the same-event like-sign dimuon distributions ($N_{\pi\pi}$ and $N_{\pi\pi}$) is calculated as: $N_{CB} = 2\sqrt{N_{++}N_{--}}$.

The mixed-event like-sign dimuon mass distribution is normalized to the same-event like-sign combinatorial background distribution in the invariant mass range $0.2 - 2.5$ GeV/$c^2$. This factor is then used to normalize the mixed-event unlike-sign dimuon mass distribution. Figure 1 shows the unlike-sign dimuon spectrum together with the combinatorial background estimated by both methods that agree within 15% in the invariant mass range of interest ($0.8 < M_{\mu\mu} < 1.3$ GeV/$c^2$).

The signal invariant mass spectrum is extracted by first subtracting the uncorrelated combinatorial background spectra from the unlike-sign spectra. The signal spectra are then fitted to extract the $\phi$ contribution. The mass resolution of both muon spectrometers is estimated using Monte Carlo simulation to be 93 (94) MeV/$c^2$ for the lowest $p_T$ bin ($2 < p_T < 2.5$ GeV/$c$) and up to 114 (111) MeV/$c^2$ for the highest $p_T$ bin ($5 < p_T < 7$ GeV/$c$) for the negative (positive) pseudorapidity muon spectrometer. Those resolutions being greater than the natural widths of the $\phi$ and $\omega$, the two-body decay of $\phi
and ω contributions are described by Gaussians while the two-body decay of the ρ-meson contribution is described by a Breit-Wigner distribution convoluted with a Gaussian. The contribution from ρ dimuon decay is fixed by the assumption that the production cross section of ρ and ω are related such as σ_ρ = 1.15 × σ_ω, as measured in Ref. [12] and used in previous PHENIX analysis related to φ-meson production in the dimuon decay channel [15, 43, 44]. To evaluate the shape of the correlated background, a PYTHIA [45] MB simulation followed by GEANT3 [46] transport and detector response simulation of the PHENIX detector is performed. The correlated background distribution is found to be well described by an exponential plus a polynomial of first order (χ²/ndf ≤ 1). To summarize, eight free parameters are needed to describe the signal spectrum: two parameters for the ϕ and (ω + ρ) signal normalizations, two parameters to describe relative changes of Gaussian widths and central masses with respect to simulation estimates and four parameters to describe the correlated background distribution and its normalization. The starting values of the free parameters describing the shapes of the different distributions are taken to be the ones from the Monte Carlo simulation.

Figure 2 shows the fit results for the entire p_T range at backward rapidity. Extracted peak positions and widths are found to be in good agreement with Monte Carlo simulations.

B. Detector acceptance and reconstruction efficiency

The product of detector acceptance and reconstruction efficiency, η_{rec}, of dimuon decays of φ mesons is determined by the full event reconstruction of the φ-meson signal run through a full GEANT3 simulation of the 2013 PHENIX detector setup, and embedded in MB real-data. The p_T distribution of the simulated φ-meson signal is iteratively re-weighted to match the data p_T distribution, the initial p_T distribution being obtained from PYTHIA6 [45] using tune ATLAS_CSC [38]. The embedded simulated events are then reconstructed in the same manner as data with the same cuts applied as in the real data analysis. The η_{rec} factor is extracted from the simulation as the ratio of reconstructed φ distribution over the generated one in the same kinematic range. Figure 3 shows the η_{rec} as a function of φ-meson p_T and rapidity. The main sources of the relative difference between both spectrometers η_{rec} are different detection efficiencies of the MuTr and MuID systems and different amount of absorber material.
The inelastic cross sections given by pythia8 the uncertainties of all the trials. Table I summarizes the certainty on the central value is the quadratic mean of from the trials is used as the central value, and the uncertainty is added. The quadratic mean of the raw yields extracted by an exponential plus second-order polynomial. The exponential plus first-order polynomial and correlated background and (2) the correlated background are fit by an exponential plus first-order polynomial and correlated background distributions used. To estimate this uncertainty, different rapidity fluctuation and efficiency uncertainties and a 6.6% uncertainty from the measured MuID tube efficiency are assigned [15]. Simulation parameters are adjusted in order to reproduce the tracking efficiency observed in the data. While the relative tracking efficiency is validated using $J/\psi \rightarrow \mu \mu$ data, data-driven evaluation of the absolute tracking efficiency are not available. Therefore, we assign 10% uncertainty for the absolute tracking efficiency as a conservative value [51].

Finally, Type-C is an overall normalization uncertainty, which allows the data points to move together by a common multiplicative factor. Type-C is composed of 10% uncertainty assigned for the BBC cross section and efficiency uncertainties and a 6.6% uncertainty from the measurement of $B_{R_{\phi \rightarrow \mu^{-}\mu^{+}}}$. Type-A is a point-to-point uncorrelated uncertainty which allows the data points to move independently with respect to one another and are added in quadrature with statistical uncertainties. A systematic uncertainty equal to the difference between the central and the extreme values of the extracted yields accounts for the systematic uncertainty related to the background description as a whole. The systematic uncertainty associated with the signal extraction method ranges from 3 to 23%, depending on the $p_T$ bin and the muon spectrometer considered (negative/positive rapidity).

Type-B is a point-to-point correlated uncertainty which allows the data points to move coherently. To evaluate the $A_{\text{rec}}$ systematic uncertainty, different $p_T$ and rapidity input distributions of the simulated $\phi$ mesons are used. The $p_T$ distribution is allowed to vary over the range of the data statistical uncertainty (statistical plus Type-A systematics uncertainties added in quadrature, see above), yielding an up to 8% uncertainty. The rapidity distribution shapes given by five generator models (PYTHIA6, PYTHIA8, PHOJET, EPOS3 and EPOS-LHC) are used as input rapidity distributions of the simulated $\phi$ mesons, resulting in up to 5% uncertainty. The relative systematic uncertainty of acceptance caused by the fluctuation of vertex width is estimated to be 3.5% [51]. A 4% uncertainty from the measured MuID tube efficiency and a 2% uncertainty from MuTr chamber efficiency are assigned [15]. Simulation parameters are adjusted in order to reproduce the tracking efficiency observed in the data. While the relative tracking efficiency is validated using $J/\psi \rightarrow \mu \mu$ data, data-driven evaluation of the absolute tracking efficiency are not available. Therefore, we assign 10% uncertainty for the absolute tracking efficiency as a conservative value [51].

Finally, Type-C is an overall normalization uncertainty, which allows the data points to move together by a common multiplicative factor. Type-C is composed of 10% uncertainty assigned for the BBC cross section and efficiency uncertainties and a 6.6% uncertainty from the measurement of $B_{R_{\phi \rightarrow \mu^{-}\mu^{+}}}$.

### IV. RESULTS

The $p_T$-dependent differential cross section is calculated independently for each muon arm, then the results are combined using the best-linear-unbiased-estimate method [52]. The $p_T$ integrated $(2 < p_T < 7 \text{ GeV/c})$ cross section $d\sigma_\phi/dy$ is given in Table II. Results obtained using the two muon spectrometers are consistent within uncertainties. Combining both arm results, the integrated cross section in the kinematic range $2 < p_T < 7 \text{ GeV/c}$ and $1.2 < |y| < 2.2$ is $\sigma_\phi = 2.28 \pm 0.09 \text{(stat)} \pm 0.14 \text{(syst)} \times 10^{-2} \text{ mb}$, to which a 12% normalization uncertainty applies.

The $\phi$-meson-differential cross section as a function of $p_T$ measured in $p+p$ collisions at $\sqrt{s} = 510 \text{ GeV}$ is shown in Fig. 4 and listed in Table III. The data points are bin shifted in $p_T$ using the Lafferty and Wyatt method [53].

### TABLE I. Systematic uncertainties associated with the differential cross section calculation.

| Type | Origin | Value |
|------|--------|-------|
| A    | Signal extraction | 3-23% |
| B    | $A_{\text{rec}}$: $p_T$ input distribution | 2-8% |
| B    | $A_{\text{rec}}$: Rapidity input distribution | 3-5% |
| B    | $A_{\text{rec}}$: Vertex width fluctuation | 3.5% |
| B    | $A_{\text{rec}}$: MuID hit efficiency | 4% |
| B    | $A_{\text{rec}}$: MuTr hit efficiency | 2% |
| B    | $A_{\text{rec}}$: MuTr tracking efficiency | 10% |
| C    | MB trigger efficiency | 10% |
| C    | $B_{R_{\phi \rightarrow \mu^{-}\mu^{+}}}$ | 6.6% |

### C. Differential cross section extraction

The $p_T$-dependent differential cross section is calculated according to:

$$\frac{d^2\sigma_\phi}{dp_T \ dy} = \frac{N_{\text{raw}}}{A_{\text{rec}} \Delta p_T \Delta y} \frac{\epsilon_{\text{BBC}}}{\sigma_{\text{pp}}^{\text{BBC}} \sigma_{\text{MB}}^{\text{BBC}}},$$

where $BR_{\phi \rightarrow \mu^{-}\mu^{+}} = (2.87 \pm 0.19) \times 10^{-4}$ is the branching ratio of $\phi$ decay to dimuon [47]. $N_{\text{raw}}$ is the extracted $\phi$ raw yield for each $p_T$ bin, $\sigma_{\text{pp}}^{\text{BBC}} = 4.16 \times 10^{12}$ is the number of sampled MB events. The BBC trigger samples a cross section of $\sigma_{\text{pp}}^{\text{BBC}} = 32.5 \pm 3.2$ mb in $p+p$ collisions, according to Vernier scans, however, it samples a larger fraction of the cross section when the collision includes a hard scattering process [48]. Studies with high $p_T \pi^0$ yields show an increase of the luminosity scanned by the BBC by a factor of $1/\epsilon_{\text{BBC}}$, $\epsilon_{\text{BBC}} = 0.91 \pm 0.04$ [49]. The inelastic cross sections given by PYTHIA8 [50] for $\sqrt{s} = 500$ and 510 GeV $p+p$ collisions differ by 0.3%, therefore no correction or additional systematic uncertainty is added.

### D. Systematic uncertainties

The main source of systematic uncertainties in the signal extraction comes from the uncorrelated and correlated background distributions used. To estimate this uncertainty, the extracted $\phi$ raw yields are compared using the following two methods: (1) the mixing and like-sign pair methods are separately used for subtraction of uncorrelated background and (2) the correlated background is fit by an exponential plus first-order polynomial and by an exponential plus second-order polynomial. The extracted $\phi$ raw yields are consistent among all different fit trials. The quadratic mean of the raw yields extracted from the trials is used as the central value, and the uncertainty on the central value is the quadratic mean of the uncertainties of all the trials. Table I summarizes the systematic uncertainties.
TABLE II. The $\phi$-meson-production cross section $d\sigma_\phi/dy$ in $p+p$ collisions at $\sqrt{s} = 510$ GeV integrated in the transverse momentum range $2 < p_T < 7$ GeV/c. The first uncertainty represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B and the third one is the additional $\pm 12\%$ Type-C normalization systematic uncertainty.

| $y$ range | $d\sigma_\phi/dy$ (mb) |
|-----------|-----------------------|
| $1.2 < y < 2.2$ | $(2.13 \pm 0.14 \pm 0.16 \pm 0.26) \times 10^{-2}$ |
| $-2.2 < y < -1.2$ | $(2.46 \pm 0.12 \pm 0.18 \pm 0.30) \times 10^{-2}$ |
| $1.2 < |y| < 2.2$ | $(2.28 \pm 0.09 \pm 0.14 \pm 0.27) \times 10^{-2}$ |

TABLE III. The $\phi$-meson-differential-production cross section $d^2\sigma_\phi/dp_Tdy$ for $1.2 < |y| < 2.2$ in $p+p$ collisions at $\sqrt{s} = 510$ GeV. $p_T$ is the $p_T$ at which the data point is plotted (see text for details). The first uncertainty represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B and the third one is the additional $\pm 12\%$ Type-C normalization systematic uncertainty.

| $p_T$ range | $p_T$ | $d^2\sigma_\phi/dp_Tdy$ (mb/(GeV/c)) |
|-------------|-------|-----------------------------------|
| $2.0-2.5$   | 2.24  | $(2.16 \pm 0.17 \pm 0.23 \pm 0.26) \times 10^{-2}$ |
| $2.5-3.0$   | 2.74  | $(1.20 \pm 0.05 \pm 0.12 \pm 0.14) \times 10^{-2}$ |
| $3.0-3.5$   | 3.24  | $(6.26 \pm 0.36 \pm 0.61 \pm 0.75) \times 10^{-3}$ |
| $3.5-4.0$   | 3.74  | $(2.70 \pm 0.20 \pm 0.30 \pm 0.32) \times 10^{-3}$ |
| $4.0-5.0$   | 4.44  | $(1.06 \pm 0.07 \pm 0.11 \pm 0.13) \times 10^{-3}$ |
| $5.0-7.0$   | 5.79  | $(1.97 \pm 0.19 \pm 0.20 \pm 0.24) \times 10^{-4}$ |

![FIG. 4. (a) $d^2\sigma_\phi/dp_Tdy$ measurements in $p+p$ collisions at $\sqrt{s} = 510$ GeV fitted by a Tsallis function. Error bars represent the statistical uncertainty and the boxes the Type-B and Type-C systematic uncertainties added in quadrature. (b) and (c) Comparison between the data and predictions of six models (PYTHIA6 using tune ATLAS_CSC, PYTHIA8 using tune Monash2013, PHOJET 1.12, EPOS-LHC, AMPT v1.26, and EPOS3.117) shown as the ratio of the model to the data fitted by a Tsallis function. (c) The data are compared to EPOS3 predictions using three different options of the model (see text for details).](image-url)

The $\phi$ mesons are also produced and absorbed from hadronic matter via various hadronic reactions (baryon-baryon, meson-baryon and meson-meson scatterings) [41].

The EPOS3 model includes, in addition to the description of the initial scattering based on a Gribov-Regge approach [61], a viscous hydrodynamic expansion of the created system followed by a hadronization phase and a final state hadronic cascade using the URQMD model [62, 63]. In EPOS3, the hydrodynamic evolution and the hadronic cascade can be turned on or off, separately. The so-called “Full” version of EPOS3 includes hydrodynamic expansion of the created system followed by a final state hadronic cascade. The EPOS3 “No-Casc” version does not include the final state hadronic cascade and “No-Hydro/No-Casc” has both hydrodynamic and the final state hadronic cascade turned off. The EPOS-LHC calcu-
FIG. 5. Same as Fig. 4 for PHENIX measurement at $\sqrt{s} = 200$ GeV [15].

FIG. 6. Same as Fig. 4 for ALICE measurement at $\sqrt{s} = 2.76$ TeV [17].

FIG. 7. Same as Fig. 4 for ALICE measurement at $\sqrt{s} = 7$ TeV [12].

FIG. 8. Same as Fig. 4 for LHCb measurement at $\sqrt{s} = 7$ TeV [10].
loration presented in Fig. 4 is performed including a parameterized viscous hydrodynamic expansion of the created partonic system.

As shown in panels (b) and (c) of Fig. 4, the experimental data are better reproduced by the AMPT model and by EPOS3 without the hadronic cascade. The EPOS3 “Full” and EPOS-LHC overestimate the φ-meson production, and PHOJET and PYTHIA models tend to underestimate it by a factor of two. A previous study of Monash2013 tune of PYTHIA8 showed that the calculated transverse-momentum spectra of φ mesons is overestimating the experimental data at very soft momenta (below \( \sim 500 \) MeV/c) and underestimates it at higher momenta, the overall yield of φ mesons being correctly reproduced [24].

Additional calculations using the AMPT model with string melting (version 2.26) were performed. The φ-meson-production yield was found to be a factor of two higher than the one extracted using the default AMPT model with approximately the same parameter settings as used for the RHIC data. The difference between the mean and the extreme value of the production cross section is \( \sim 500 \) MeV/c.

V. ENERGY DEPENDENCE OF φ-MESON PRODUCTION

The PHENIX experiment previously measured the φ-meson cross section at forward rapidity and for \( 1 < p_T < 7 \) GeV/c in p+p collisions at \( \sqrt{s} = 200 \) GeV [15]. At the LHC, the ALICE experiment measured the φ-meson-production cross section via its dimuon decay channel in p+p collisions at forward rapidity \( 2.5 < y < 4.0 \) and for \( 1 < p_T < 5 \) GeV/c at \( \sqrt{s} = 2.76 \) TeV [16] and 7 TeV [12]. Measurement of the φ-meson production was also performed via the \( K^+K^- \) decay channel at midrapidity \( |y| < 0.5 \) and for \( 0.4 < p_T < 6 \) GeV/c at \( \sqrt{s} = 7 \) TeV [13]. The LHCb experiment measured the inclusive φ-meson-production cross section in the \( K^+K^- \) decay channel in the kinematic range \( 2.44 < y < 4.06 \) and \( 0.6 < p_T < 5 \) GeV/c in p+p collisions at \( \sqrt{s} = 7 \) TeV [10].

Figures 5–8 show comparisons between the \( d^2\sigma/df_Tdy \) measurements at forward rapidities done by PHENIX at \( \sqrt{s} = 200 \) GeV [15], by ALICE at \( \sqrt{s} = 2.76 \) TeV [16] and 7 TeV [12] and by LHCb at \( \sqrt{s} = 7 \) TeV [10], respectively, along with model predictions. The AMPT model is in good agreement with the measured cross sections at both RHIC energies, but overestimates the production cross section at LHC energies, especially at 7 TeV. The PYTHIA6 and PHOJET calculations at LHC energies are in better agreement with the data than at RHIC energies, where the models underestimate the measured production cross section. The PYTHIA8 prediction underestimates the cross section for all four energies.

Panel (c) of Figs. 4–8 show the comparison between the measurements fitted by a Tsallis function and EPOS3 using three different model settings (see above for details). The comparison of those results reveals the effect of the hydrodynamic expansion of the partonic system created in p+p collisions and of the final state hadronic cascade on the φ-meson production. The hydrodynamic evolution does not impact the φ-meson production at RHIC energies (“No-Casc” and “No-Hydro/No-Casc” curves are almost identical on panel (c) of Figs 4–8. A significant effect appears at \( \sqrt{s} = 2.76 \) TeV and becomes stronger at 7 TeV where the φ-meson-production cross section increases by a factor of two for the \( p_T \) range 1–3 GeV/c when turning on the hydrodynamic evolution. The same behavior was already observed for the production of \( \Lambda^0, K_s, \) and \( \Xi \) in p+p collisions at 7 TeV [34], showing that the flow effects increase with the mass of the particle. The final state hadronic cascade using the URQMD model enhances the φ-meson-production cross section in the entire \( p_T \) range and for all collision energies. The EPOS3 “No-Casc” is the best configuration to reproduce the experimental data over the full collision energy range, while the addition of the URQMD hadronic cascade overestimates the φ-meson production compared to the experimental data.

In the following, the φ-meson cross sections in the forward rapidity range \( 1.2 < y < 2.2 \) at the different measured energies (0.2, 0.51, 2.76 and 7 TeV) are presented. The \( p_T \) range is fixed to \( 2 < p_T < 5 \) GeV/c which is the common range of all experimental measurements.

The cross sections measured by PHENIX in the kinematic range \( 1.2 < y < 2.2 \) and \( 2 < p_T < 5 \) GeV/c are:

\[
\begin{align*}
\sigma_\phi(200 \text{ GeV}) &= (1.10 \pm 0.17) \times 10^{-2} \text{ mb}, \\
\sigma_\phi(510 \text{ GeV}) &= (2.24 \pm 0.32) \times 10^{-2} \text{ mb},
\end{align*}
\]

where the uncertainties correspond to the quadratic sums of the statistical and systematic uncertainties.

The rapidity domains of the LHC measurements are different from those of PHENIX. Accordingly, to compare with PHENIX measurements the LHC measurements are extrapolated to the same rapidity coverage (i.e., \( 1.2 < y < 2.2 \)). The procedure followed here is to fit the LHC data points using the \( d\sigma/df_T \) shapes obtained using the different models mentioned above, the only free parameter being the normalization of the simulated \( d\sigma/df_T \) distributions. Figure 9 shows the LHC \( p_T \) integrated data points overlaid on the \( d\sigma/df_T \) distributions obtained using PYTHIA6, PYTHIA8, PHOJET, EPOS3, EPOS-LHC and AMPT models at \( \sqrt{s} = 7 \) TeV (a) before and (b) after the minimization procedure.

The LHC \( d\sigma/df_T \) at \( 1.2 < y < 2.2 \) is calculated as the quadratic mean of the \( d\sigma/df_T \) from each of the model fits. The difference between the mean and the extreme value is taken as a systematic uncertainty, due to the rapidity shifting procedure, and added in quadrature to the experimental uncertainties. This uncertainty is 22.1% for the 2.76 TeV measurement and 15.5% at 7 TeV. The obtained cross sections in \( 1.2 < y < 2.2 \) and \( 2 < p_T < 5 \) GeV/c at LHC energies are:

\[
\begin{align*}
\sigma_\phi(2.76 \text{ TeV}) &= (1.15 \pm 0.28) \times 10^{-1} \text{ mb}, \\
\sigma_\phi(7 \text{ TeV}) &= (2.23 \pm 0.35) \times 10^{-1} \text{ mb}.
\end{align*}
\]
Figure 10 shows the energy dependence of the partial-\(\phi\)-meson-production cross section integrated in 1.2 < \(y\) < 2.2 and 2 < \(p_T\) < 5 GeV/c in \(p+p\) collisions compared to PHENIX, PHOJET, EPOS3, and EPOS-LHC model predictions. The LHC data points are interpolated at the PHENIX forward rapidity, see text for details.

In EPOS3, when the hydrodynamic evolution is turned off the hadrons are produced via string decays. On the other hand, when hydrodynamic calculation is included, the various string segments originating from the initial Pomerons are separated into two collections named “core” and “corona”. The “core” part will experience the hydrodynamic evolution while the segments in the “corona” will leave the bulk matter and decay to hadrons. String segments are placed in the “core” or “corona” depending on their transverse momenta and on the local string density [34]. After its hydrodynamical evolution, the “core” hadronizes following the Cooper-Frye freeze-out procedure. Figure 12 shows the “core” and the “corona” contributions to the production of \(\phi\) mesons in \(p+p\) collisions for the four energies studied.
in this work. The contribution of the “core” part increases with the colliding energy, being negligible compared to the “corona” contribution at RHIC energies and of the same order of magnitude at LHC energies for $1 < p_T < 3$ GeV/$c$. The difference in the shape of the $p_T$ distributions between the “core” and the “corona” part (shift from low to intermediate $p_T$) is due to the fact that in the “core” the φ mesons are produced from “fluid cells characterized by a radial flow velocities” [34]. The heavier the particle is the more transverse momentum it receives from this mechanism.

The EPOS3 model shows that the hydrodynamic flow induces a shift from low to intermediate $p_T$ of the produced φ mesons. A similar effect is obtained from tuning the color reconnection mechanism in PYTHIA8 [32, 33]. The study of the $(p_T)$ as a function of the charged particle multiplicity produced in $p+p$ collisions and its evolution versus the colliding energy would be a relevant observable of such effect, and would allow to discriminate between alternative models. In addition to the already published data at $\sqrt{s} = 2.76$ and 7 TeV regarding the production of φ mesons at forward rapidity, the LHC experiments took data in $p+p$ collisions at 5, 8, and recently 13 TeV where the effect should be even larger.

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**VI. SUMMARY AND CONCLUSIONS**

In summary, the φ-meson-production differential cross section is measured in $p+p$ collisions at $\sqrt{s} =$510 GeV in the kinematic range $1.2 < |y| < 2.2$ and $2 < p_T < 7$ GeV/$c$. The cross section integrated in $p_T$ and averaged over positive and negative rapidities is $\sigma_\phi = (2.28 \pm 0.09 \text{ (stat)}) \pm 0.14 \text{ (syst)} \pm 0.27 \text{ (norm)} \times 10^{-2}$ mb. The measured $p_T$-differential cross section is compared to various model predictions based on PYTHIA6, PYTHIA8, PHOJET, AMPT, EPOS3 and EPOS-LHC generators. The default AMPT model and the EPOS3 model without hadronic cascade provide the best description of the data.

The energy dependence of the φ-meson-production cross section is studied in the kinematic range $1.2 < y < 2.2$ and $2 < p_T < 5$ GeV/$c$, shifting LHC measurements to the same rapidity range as PHENIX measurements. The EPOS3 model shows that the addition of the hydrodynamic evolution of the system induces an enhancement of the φ-meson production at the LHC energies for $1 < p_T < 3$ GeV/$c$ whereas no effect is seen for RHIC energies. The LHC measurements tend to favor the scenario with hydrodynamic evolution of the system included in EPOS3 showing a possible hint of collective effects in $p+p$ collisions at high energy.

![Graph showing core (dashed curves) and corona (solid curves) contributions to the production of φ mesons in $p+p$ collisions at 0.2 [blue], 0.51 [black], 2.76 [red] and 7 TeV [green].](image-url)
[1] D. Drijard et al. (Annecy(LAPP)-CERN-College de France-Dortmund-Heidelberg-Warsaw Collaboration), “Production of Vector and Tensor Mesons in Proton Proton Collisions at $\sqrt{s} = 52.5$ GeV,” Z. Phys. C 9, 293 (1981).

[2] C. Daum et al. (ACCMOR Collaboration), “Inclusive $\phi$ Meson Production in 93-GeV and 63-GeV Hadron Interaction,” Nucl. Phys. B 186, 205 (1981).

[3] T. Alesseon et al. (Axial Field Spectrometer Collaboration), “Inclusive Vector-Meson Production in the Central Region of $pp$ Collisions at $\sqrt{s} = 63$ GeV,” Nucl. Phys. B 203, 27 (1982), [Erratum: Nucl. Phys. B 229, 541 (1983)].

[4] G. J. Bobbink et al., “The Production of High Momentum Particles and Resonances in $pp$ Collisions at the CERN Intersecting Storage Rings,” Nucl. Phys. B 217, 11 (1983).

[5] M. Aguilar-Benitez et al. (“Inclusive particle production in 400 GeV/c $pp$ interactions,” Z. Phys. C 50, 405 (1991).

[6] T. Ale Coxopoulos et al. (E735 Collaboration), “Phi meson production from $p$ anti-$p$ collisions at $\sqrt{s} = 1.8$ TeV,” Z. Phys. C 67, 411 (1995).

[7] S. V. Afanasiev et al. (NA49 Collaboration), “Production of phi mesons in $p+p$, $p+Pb$ and central $Pb+Pb$ collisions at $E$ (beam) = 158A GeV,” Phys. Lett. B 491, 59 (2000).

[8] B. I. Abelev et al. (STAR Collaboration), “Measurements of phi meson production in relativistic heavy-ion collisions at RHIC,” Phys. Rev. C 79, 064903 (2009).

[9] A. Adare et al. (PHENIX Collaboration), “Measurement of neutral mesons in $p$+p collisions at $\sqrt{s} = 200$ GeV and scaling properties of hadron production,” Phys. Rev. D 83, 052004 (2011).

[10] R. Aaij et al. (LHCb Collaboration), “Measurement of the inclusive $\phi$ cross-section in $pp$ collisions at $\sqrt{s} = 7$ TeV,” Phys. Lett. B 703, 267 (2011).

[11] K. Aamodt et al. (ALICE Collaboration), “Strange particle production in proton-proton collisions at $\sqrt{s} = 0.9$ TeV with ALICE at the LHC,” Eur. Phys. J. C 71, 1594 (2011).

[12] B. Abelev et al. (ALICE Collaboration), “Light vector meson production in $pp$ collisions at $\sqrt{s} = 7$ TeV,” Phys. Lett. B 710, 557 (2012).

[13] B. Abelev et al. (ALICE Collaboration), “Production of $K^*$ (892)$^0$ and $\phi$(1020) in $pp$ collisions at $\sqrt{s} = 7$ TeV,” Eur. Phys. J. C 72, 2183 (2012).

[14] T. Aaltonen et al. (CDF Collaboration), “Production of $K_0^*$, $K^{*\pm}$(892) and $\phi^o$(1020) in minimum bias events and $K_0^*$ and $\Lambda^0_\Lambda$ in jets in $pp$ collisions at $\sqrt{s} = 1.96$ TeV,” Phys. Rev. D 88, 092005 (2013).

[15] A. Adare et al. (PHENIX Collaboration), “Low-mass vector-meson production at forward rapidity in $p+\bar{p}$ collisions at $\sqrt{s} = 200$ GeV,” Phys. Rev. D 90, 052002 (2014).}

[16] G. Aad et al. (ATLAS Collaboration), “The differential production cross section of the $\phi$ (1020) meson in $p+\bar{p}$ collisions measured with the ATLAS detector,” Eur. Phys. J. C 74, 2895 (2014).

[17] J. Adam et al. (ALICE Collaboration), “$\phi$-meson production at forward rapidity in $p$-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in $pp$ collisions at $\sqrt{s} = 2.76$ TeV,” Phys. Lett. B 768, 203 (2017).

[18] J. Adam et al. (ALICE Collaboration), “$K^*$ (892)$^0$ and $\phi$(1020) meson production at high transverse momentum in $pp$ and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,” Phys. Rev. C 95, 064906 (2017).

[19] S. Okubo, “Phi meson and unitary symmetry model,” Phys. Lett. 5, 165 (1963).

[20] G. Zweig, “An SU(3) model for strong interaction symmetry and its breaking. Version 1,” CERN-TH-401 (1964).

[21] J. Iizuka, “Systematics and phenomenology of meson family,” Prog. Theor. Phys. Suppl. 37, 21 (1966).

[22] B. Abelev et al. (ALICE Collaboration), “Multi-strange baryon production in $pp$ collisions at $\sqrt{s} = 7$ TeV with ALICE,” Phys. Lett. B 712, 309 (2012).

[23] V. Khachatryan et al. (CMS collaboration), “Strange Particle Production in $pp$ Collisions at $\sqrt{s} = 0.9$ and 7 TeV,” ( ), J. High Energy Phys. 05 (2011) 064.

[24] P. Skands, S. Carranza, and J. Rojo, “Tuning PYTHIA8.1: the Monash 2013 Tune,” Eur. Phys. J. C 74, 3024 (2014).

[25] V. Khachatryan et al. (CMS Collaboration), “Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC,” ( ), J. High Energy Phys. 09 (2010) 091.

[26] V. Khachatryan et al. (CMS Collaboration), “Measurement of long-range near-side two-particle angular correlations in $pp$ collisions at $\sqrt{s} = 13$ TeV,” Phys. Rev. Lett. 116, 172302 (2016).

[27] G. Aad et al. (ATLAS Collaboration), “Observation of Long-Range Elliptic Azimuthal Anisotropies in $pp$ Collisions at the ATLAS Detector,” Phys. Rev. Lett. 116, 172301 (2016).

[28] V. Khachatryan et al. (CMS Collaboration), “Evidence for collectivity in $pp$ collisions at the LHC,” Phys. Lett. B 765, 193 (2017).

[29] W. Li, “Observation of a ‘Ridge’ correlation structure in high multiplicity proton-proton collisions: A brief review,” Mod. Phys. Lett. A 27, 1230018 (2012).

[30] A. Dumitru, K. Dusling, F. Gelis, J. Jalilian-Marian, T. Lappi, and R. Venugopalan, “The Ridge in proton-proton collisions at the LHC,” Phys. Lett. B 697, 21 (2011).

[31] P. Bozek, “Elliptic flow in proton-proton collisions at $\sqrt{s} = 7$ TeV,” Eur. Phys. J. C 71, 1530 (2011).

[32] C. Bierlich and J. R. Christiansen, “Effects of color reconnection on hadron flavor observables,” Phys. Rev. D 92, 094010 (2015).

[33] T. Martin, P. Skands, and S. Farrington, “Probing Collective Effects in Hadronisation with the Extremes of the Underlying Event,” Eur. Phys. J. C 76, 299 (2016).

[34] K. Werner, B. Guiot, I. Karpenko, and T. Pierog, “Analysing radial flow features in $p$-Pb and $p$–$p$ collisions at several TeV by studying identified particle production in EPOS3,” Phys. Rev. C 89, 064903 (2014).

[35] J. Rafelski and B. Müller, “Strangeness production in the quark-gluon plasma,” Phys. Rev. Lett. 48, 1066 (1982).

[36] A. Shor, “$\varphi$-meson production as a probe of the quark-gluon plasma,” Phys. Rev. Lett. 54, 1122 (1985).

[37] P. Koch, B. Müller, and J. Rafelski, “Strangeness in relativistic heavy ion collisions,” Phys. Reports 142, 167 (1986).
[38] T. Sjöstrand and P. Z. Skands, “Transverse-momentum-ordered showers and interleaved multiple interactions,” Eur. Phys. J. C 39, 129 (2005).
[39] F. W. Bopp, R. Engel, and J. Ranft, “Rapidity gaps and the PHOJET Monte Carlo,” in High energy physics. Proceedings, LAFFEX International School, Session C, Workshop on Diffractive Physics, LISHEP’98, Rio de Janeiro, Brazil, February 16-20 (1998) p. 729, hep-ph/9803437.
[40] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner, “EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider,” Phys. Rev. C 92, 034906 (2015).
[41] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, “A Multi-phase transport model for relativistic heavy ion collisions,” Phys. Rev. C 72, 064901 (2005).
[42] K. Adcox et al. (PHENIX Collaboration), “PHENIX detector overview,” Nucl. Instrum. Methods Phys. Res., Sec. A 499, 469 (2003).
[43] A. Adare et al. (PHENIX Collaboration), “φ meson production in d+Au collisions at √sNN = 200 GeV,” Phys. Rev. C 92, 044909 (2015).
[44] A. Adare et al. (PHENIX Collaboration), “φ meson production in the forward/backward rapidity region in Cu+Au collisions at √sNN = 200 GeV,” Phys. Rev. C 93, 024904 (2016).
[45] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA6.4 Physics and Manual,” J. High Energy Phys. 05 (2006) 026.
[46] R. Brun, F. Carminati, and S. Giani, “GEANT Detector Description and Simulation Tool,” CERN-W-5013 (1994).
[47] K. A. Olive et al. (Particle Data Group), “Review of Particle Physics,” Chin. Phys. C 38, 090001 (2014).
[48] A. Adare et al. (PHENIX Collaboration), “Cross Section and Parity Violating Spin Asymmetries of W± Boson Production in Polarized p + p Collisions at √s = 500 GeV,” Phys. Rev. Lett. 106, 062001 (2011).
[49] A. Adare et al. (PHENIX Collaboration), “Inclusive cross section and double-helicity asymmetry for π0 production at midrapidity in p+p collisions at √s = 510 GeV,” Phys. Rev. D 93, 011501 (2016).
[50] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, “An Introduction to PYTHIA8.2,” Comput. Phys. Commun. 191, 159 (2015).
[51] H. Oide, Measurement of longitudinal spin asymmetry in production of muons from W/Z boson decays in polarized p + p collisions at √s = 500 GeV with the PHENIX detector at RHIC, Ph.D. thesis, Tokyo U. (2012).
[52] R. Nisius, “On the combination of correlated estimates of a physics observable,” Eur. Phys. J. C 74, 3004 (2014).
[53] G. D. Lafferty and T. R. Wyatt, “Where to stick your data points: The treatment of measurements within wide bins,” Nucl. Instrum. Methods Phys. Res., Sec. A 355, 541 (1995).
[54] J. Cleymans and D. Worku, “Relativistic Thermodynamics: Transverse Momentum Distributions in High-Energy Physics,” Eur. Phys. J. A 48, 160 (2012).
[55] X.-N. Wang and M. Gyulassy, “HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions,” Phys. Rev. D 44, 3501 (1991).
[56] B. Zhang, “ZPC 1.0.1: A Parton cascade for ultrarelativistic heavy ion collisions,” Comput. Phys. Commun. 109, 193 (1998).
[57] B. Andersson, G. Gustafson, and B. Soderberg, “A General Model for Jet Fragmentation,” Z. Phys. C 20, 317 (1983).
[58] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, “Parton Fragmentation and String Dynamics,” Phys. Reports 97, 31 (1983).
[59] B.-A. Li and C. M. Ko, “Formation of superdense hadronic matter in high-energy heavy ion collisions,” Phys. Rev. C 52, 2037 (1995).
[60] Jun Xu and C. M. Ko, “Triangular flow in heavy ion collisions in a multiphase transport model,” Phys. Rev. C 84, 014903 (2011).
[61] H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, “Parton-based Gribov-Regge theory,” Phys. Rept. 350, 93 (2001).
[62] S. A. Bass et al., “Microscopic models for ultrarelativistic heavy ion collisions,” Prog. Part. Nucl. Phys. 41, 255 (1998).
[63] M. Bleicher et al., “Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model,” J. Phys. G 25, 1859 (1999).