

UCLA

UCLA Previously Published Works

Title

Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC

Permalink

<https://escholarship.org/uc/item/9hd5v9sb>

Journal

Physical Review Letters, 135(7)

ISSN

0031-9007

Authors

Aboona, BE

Adam, J

Adamczyk, L

et al.

Publication Date

2025-08-15

DOI

10.1103/2qhx-cp79

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC

B. E. Aboona,⁵⁷ J. Adam,¹⁷ L. Adamczyk,³ I. Aggarwal,⁴⁴ M. M. Aggarwal,⁴⁴ Z. Ahammed,⁶⁵ A. K. Alshammri,³³
 E. C. Aschenauer,⁷ S. Aslam,²² J. Atchison,² V. Bairathi,⁵⁵ X. Bao,⁵¹ K. Barish,¹² S. Behera,²⁸ R. Bellwied,²⁵
 P. Bhagat,³² A. Bhasin,³² S. Bhatta,⁵⁴ S. R. Bhosale,³ J. Bielcik,¹⁷ J. Bielcikova,⁴² J. D. Brandenburg,⁴³
 C. Broodo,²⁵ X. Z. Cai,⁵² H. Caines,⁶⁹ M. Calderón de la Barca Sánchez,¹⁰ D. Cebra,¹⁰ J. Ceska,¹⁷ I. Chakaberia,³⁶
 P. Chaloupka,¹⁷ B. K. Chan,¹¹ Z. Chang,³⁰ A. Chatterjee,¹⁹ D. Chen,¹² J. Chen,⁵¹ J. H. Chen,²² Q. Chen,²³
 Z. Chen,⁵¹ J. Cheng,⁶⁰ Y. Cheng,¹¹ W. Christie,⁷ X. Chu,⁷ S. Corey,⁴³ H. J. Crawford,⁹ M. Csanád,²⁰
 G. Dale-Gau,¹⁴ A. Das,¹⁷ I. M. Deppner,²⁴ A. Deshpande,⁵⁴ A. Dhamija,⁴⁴ A. Dimri,⁵⁴ P. Dixit,²⁷ X. Dong,³⁶
 J. L. Drachenberg,² E. Duckworth,³³ J. C. Dunlop,⁷ J. Engelage,⁹ G. Eppley,⁴⁶ S. Esumi,⁶¹ O. Evdokimov,¹⁴
 O. Eyser,⁷ R. Fatemi,³⁴ S. Fazio,⁸ Y. Feng,⁴⁵ E. Finch,⁵³ Y. Fisyak,⁷ F. A. Flor,⁶⁹ C. Fu,³¹ T. Fu,⁵¹
 C. A. Gagliardi,⁵⁷ T. Galatyuk,¹⁸ T. Gao,⁵¹ F. Geurts,⁴⁶ N. Ghimire,⁵⁶ A. Gibson,⁶⁴ K. Gopal,²⁸ X. Gou,⁵¹
 D. Grosnick,⁶⁴ A. Gu,²⁶ A. Gupta,³² A. Hamed,⁵ R. J. Hamilton,⁶⁹ X. Han,⁴³ S. Harabasz,¹⁸ M. D. Harasty,¹⁰
 J. W. Harris,⁶⁹ H. Harrison-Smith,³⁴ L. B. Havener,⁶⁹ X. H. He,³¹ Y. He,⁵¹ N. Herrmann,²⁴ L. Holub,¹⁷
 C. Hu,⁶² Q. Hu,³¹ Y. Hu,³⁶ H. Huang,^{41,1} H. Z. Huang,¹¹ S. L. Huang,⁵⁴ T. Huang,¹⁴ Y. Huang,²⁰ Y. Huang,¹³
 T. J. Humanic,⁴³ M. Isshiki,⁶¹ W. W. Jacobs,³⁰ A. Jalotra,³² C. Jena,²⁸ A. Jentsch,⁷ Y. Ji,³⁶ J. Jia,^{54,7} C. Jin,⁴⁶
 N. Jindal,⁴³ X. Ju,⁴⁸ E. G. Judd,⁹ S. Kabana,⁵⁵ D. Kalinkin,³⁴ K. Kang,⁶⁰ D. Kapukchyan,¹² K. Kauder,⁷
 D. Keane,³³ M. Kesler,³³ A. Khanal,⁶⁷ Y. V. Khyzhniak,⁴³ D. P. Kikoła,⁶⁶ J. Kim,⁷ D. Kincses,²⁰ I. Kisel,²¹
 A. Kiselev,⁷ A. G. Knospe,³⁷ J. Kołaś,⁶⁶ B. Korodi,⁴³ L. K. Kosarzewski,⁴³ L. Kumar,⁴⁴ M. C. Labonte,¹⁰
 R. Lacey,⁵⁴ J. M. Landgraf,⁷ C. Larson,³⁴ J. Lauret,⁷ A. Lebedev,⁷ J. H. Lee,⁷ Y. H. Leung,²⁴ C. Li,¹³
 D. Li,⁴⁸ H-S. Li,⁴⁵ H. Li,⁶⁸ H. Li,²³ W. Li,⁴⁶ X. Li,⁴⁸ X. Li,⁴⁸ Y. Li,⁶⁰ Z. Li,⁴⁹ Z. Li,⁴⁸ X. Liang,¹² Y. Liang,³³
 R. Licenik,^{42,17} T. Lin,⁵¹ Y. Lin,²³ M. A. Lisa,⁴³ C. Liu,³¹ G. Liu,⁴⁹ H. Liu,²⁶ L. Liu,¹³ Z. Liu,¹³ T. Ljubicic,⁴⁶
 O. Lomicky,¹⁷ R. S. Longacre,⁷ E. M. Loyd,¹² T. Lu,³¹ J. Luo,⁴⁸ X. F. Luo,¹³ L. Ma,²² R. Ma,⁷ Y. G. Ma,²²
 N. Magdy,⁵⁸ D. Mallick,¹³ R. Manikandhan,²⁵ S. Margetis,³³ C. Markert,⁵⁹ O. Matonoha,¹⁷ O. Mezhangskaya,¹⁷
 K. Mi,¹³ S. Mioduszewski,⁵⁷ B. Mohanty,⁴⁰ B. Mondal,⁴⁰ M. M. Mondal,⁴⁰ I. Mooney,⁶⁹ J. Mrázková,^{42,17}
 M. I. Nagy,²⁰ C. J. Naim,⁵⁴ A. S. Nain,⁴⁴ J. D. Nam,⁵⁶ M. Nasim,²⁷ H. Nasrulloh,⁴⁸ D. Neff,¹¹ J. M. Nelson,⁹
 M. Nie,⁵¹ G. Nigmatkulov,¹⁴ T. Niida,⁶¹ T. Nonaka,⁶¹ G. Odyniec,³⁶ A. Ogawa,⁷ S. Oh,⁵⁰ K. Okubo,⁶¹
 B. S. Page,⁷ S. Pal,¹⁷ A. Pandav,³⁶ A. Panday,²⁷ A. K. Pandey,³¹ T. Pani,⁴⁷ A. Paul,¹² S. Paul,⁵⁴ D. Pawłowska,⁶⁶
 C. Perkins,⁹ J. Pluta,⁶⁶ B. R. Pokhrel,⁵⁶ I. D. Ponce Pinto,⁶⁹ M. Posik,⁵⁶ E. Pottebaum,⁶⁹ S. Prodhon,²⁸
 T. L. Protzman,³⁷ A. Prozorov,¹⁷ V. Prozorova,¹⁷ N. K. Pruthi,⁴⁴ M. Przybycien,³ J. Putschke,⁶⁷ Z. Qin,⁶⁰
 H. Qiu,³¹ C. Racz,¹² S. K. Radhakrishnan,³³ A. Rana,⁴⁴ R. L. Ray,⁵⁹ R. Reed,³⁷ C. W. Robertson,⁴⁵
 M. Robotkova,^{42,17} M. A. Rosales Aguilar,³⁴ D. Roy,⁴⁷ P. Roy Chowdhury,⁶⁶ L. Ruan,⁷ A. K. Sahoo,²⁷
 N. R. Sahoo,²⁸ H. Sako,⁶¹ S. Salur,⁴⁷ S. S. Sambyal,³² J. K. Sandhu,³⁷ S. Sato,⁶¹ B. C. Schaefer,³⁷ N. Schmitz,³⁸
 F-J. Seck,¹⁸ J. Seger,¹⁶ R. Seto,¹² P. Seyboth,³⁸ N. Shah,²⁹ P. V. Shanmuganathan,⁷ T. Shao,²² M. Sharma,³²
 N. Sharma,²⁷ R. Sharma,²⁸ S. R. Sharma,²⁸ A. I. Sheikh,³³ D. Shen,⁵¹ D. Y. Shen,³¹ K. Shen,⁴⁸ S. Shi,¹³
 Y. Shi,⁵¹ F. Si,⁴⁸ J. Singh,⁵⁵ S. Singha,³¹ P. Sinha,²⁸ M. J. Skoby,^{6,45} N. Smirnov,⁶⁹ Y. Söhngen,²⁴ Y. Song,⁶⁹
 T. D. S. Stanislaus,⁶⁴ M. Stefaniak,⁴³ Y. Su,⁴⁸ M. Sumner,⁴² X. Sun,³¹ Y. Sun,⁴⁸ B. Surrow,⁵⁶ M. Svoboda,^{42,17}
 Z. W. Sweger,¹⁰ A. C. Tamis,⁶⁹ A. H. Tang,⁷ Z. Tang,⁴⁸ T. Tarnowsky,³⁹ J. H. Thomas,³⁶ A. R. Timmins,²⁵
 D. Tlusty,¹⁶ T. Todoroki,⁶¹ D. Torres Valladares,⁴⁶ S. Trentalange,¹¹ P. Tribedy,⁷ S. K. Tripathy,⁶⁶ T. Truhlar,¹⁷
 B. A. Trzeciak,¹⁷ O. D. Tsai,^{11,7} C. Y. Tsang,^{33,7} Z. Tu,⁷ J. Tyler,⁵⁷ T. Ullrich,⁷ D. G. Underwood,^{4,64}
 G. Van Buren,⁷ J. Vanek,⁷ I. Vassiliev,²¹ F. Videbæk,⁷ S. A. Voloshin,⁶⁷ F. Wang,⁴⁵ G. Wang,¹¹ G. Wang,¹³
 J. S. Wang,²⁶ J. Wang,⁵¹ K. Wang,⁴⁸ X. Wang,⁵¹ Y. Wang,⁴⁸ Y. Wang,¹³ Y. Wang,⁶⁰ Z. Wang,⁵¹ A. J. Watroba,³
 J. C. Webb,⁷ P. C. Weidenkaff,²⁴ G. D. Westfall,³⁹ D. Wielanek,⁶⁶ H. Wieman,³⁶ G. Wilks,¹⁴ S. W. Wissink,³⁰
 R. Witt,⁶³ C. P. Wong,⁷ J. Wu,¹³ J. Wu,⁶² X. Wu,¹¹ X. Wu,⁴⁸ X. Wu,¹³ B. Xi,²² Z. G. Xiao,⁶⁰ G. Xie,⁶² W. Xie,⁴⁵
 H. Xu,²⁶ N. Xu,¹³ Q. H. Xu,⁵¹ Y. Xu,⁵¹ Y. Xu,¹³ Z. Xu,³³ Z. Xu,⁴ G. Yan,⁵¹ Z. Yan,⁵⁴ C. Yang,⁵¹ Q. Yang,⁵¹
 S. Yang,⁴⁹ Y. Yang,^{1,41} Z. Ye,⁴⁹ Z. Ye,³⁶ L. Yi,⁵¹ Y. Yu,⁵¹ H. Zbroszczyk,⁶⁶ W. Zha,⁴⁸ C. Zhang,²² D. Zhang,⁴⁹
 J. Zhang,⁵¹ S. Zhang,¹⁵ W. Zhang,⁴⁹ X. Zhang,³¹ Y. Zhang,³¹ Y. Zhang,⁴⁸ Y. Zhang,⁵¹ Y. Zhang,²³ Z. Zhang,⁷
 Z. Zhang,¹⁴ F. Zhao,³⁵ J. Zhao,²² M. Zhao,⁷ S. Zhou,¹³ Y. Zhou,¹³ X. Zhu,⁶⁰ M. Zurek,^{4,7} and M. Zyzak²¹

(STAR Collaboration)

¹Academia Sinica, Taipei 115201

²Abilene Christian University, Abilene, Texas 79699

³AGH University of Krakow, FPACS, Cracow 30-059, Poland

- ⁴Argonne National Laboratory, Argonne, Illinois 60439
- ⁵American University in Cairo, New Cairo 11835, Egypt
- ⁶Ball State University, Muncie, Indiana 47306
- ⁷Brookhaven National Laboratory, Upton, New York 11973
- ⁸University of Calabria & INFN-Cosenza, Rende 87036, Italy
- ⁹University of California, Berkeley, California 94720
- ¹⁰University of California, Davis, California 95616
- ¹¹University of California, Los Angeles, California 90095
- ¹²University of California, Riverside, California 92521
- ¹³Central China Normal University, Wuhan, Hubei 430079
- ¹⁴University of Illinois at Chicago, Chicago, Illinois 60607
- ¹⁵Chongqing University, Chongqing, 401331
- ¹⁶Creighton University, Omaha, Nebraska 68178
- ¹⁷Czech Technical University in Prague, FNSPE, Prague 115 19, Czech Republic
- ¹⁸Technische Universität Darmstadt, Darmstadt 64289, Germany
- ¹⁹National Institute of Technology Durgapur, Durgapur - 713209, India
- ²⁰ELTE Eötvös Loránd University, Budapest H-1117, Hungary
- ²¹Frankfurt Institute for Advanced Studies FIAS, Frankfurt 60438, Germany
- ²²Fudan University, Shanghai, 200433
- ²³Guangxi Normal University, Guilin, 541004
- ²⁴University of Heidelberg, Heidelberg 69120, Germany
- ²⁵University of Houston, Houston, Texas 77204
- ²⁶Huzhou University, Huzhou, Zhejiang 313000
- ²⁷Indian Institute of Science Education and Research (IISER), Berhampur 760010, India
- ²⁸Indian Institute of Science Education and Research (IISER) Tirupati, Tirupati 517507, India
- ²⁹Indian Institute Technology, Patna, Bihar 801106, India
- ³⁰Indiana University, Bloomington, Indiana 47408
- ³¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, Gansu 730000
- ³²University of Jammu, Jammu 180001, India
- ³³Kent State University, Kent, Ohio 44242
- ³⁴University of Kentucky, Lexington, Kentucky 40506-0055
- ³⁵Lanzhou University, Lanzhou 730000
- ³⁶Lawrence Berkeley National Laboratory, Berkeley, California 94720
- ³⁷Lehigh University, Bethlehem, Pennsylvania 18015
- ³⁸Max-Planck-Institut für Physik, Munich 80805, Germany
- ³⁹Michigan State University, East Lansing, Michigan 48824
- ⁴⁰National Institute of Science Education and Research, HBNI, Jatni 752050, India
- ⁴¹National Cheng Kung University, Tainan 70101
- ⁴²Nuclear Physics Institute of the CAS, Rez 250 68, Czech Republic
- ⁴³The Ohio State University, Columbus, Ohio 43210
- ⁴⁴Panjab University, Chandigarh 160014, India
- ⁴⁵Purdue University, West Lafayette, Indiana 47907
- ⁴⁶Rice University, Houston, Texas 77251
- ⁴⁷Rutgers University, Piscataway, New Jersey 08854
- ⁴⁸University of Science and Technology of China, Hefei, Anhui 230026
- ⁴⁹South China Normal University, Guangzhou, Guangdong 510631
- ⁵⁰Sejong University, Seoul, 05006, South Korea
- ⁵¹Shandong University, Qingdao, Shandong 266237
- ⁵²Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800
- ⁵³Southern Connecticut State University, New Haven, Connecticut 06515
- ⁵⁴State University of New York, Stony Brook, New York 11794
- ⁵⁵Instituto de Alta Investigación, Universidad de Tarapacá, Arica 1000000, Chile
- ⁵⁶Temple University, Philadelphia, Pennsylvania 19122
- ⁵⁷Texas A&M University, College Station, Texas 77843
- ⁵⁸Texas Southern University, Houston, Texas 77004
- ⁵⁹University of Texas, Austin, Texas 78712
- ⁶⁰Tsinghua University, Beijing 100084
- ⁶¹University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan
- ⁶²University of Chinese Academy of Sciences, Beijing, 101408
- ⁶³United States Naval Academy, Annapolis, Maryland 21402
- ⁶⁴Valparaiso University, Valparaiso, Indiana 46383
- ⁶⁵Variable Energy Cyclotron Centre, Kolkata 700064, India
- ⁶⁶Warsaw University of Technology, Warsaw 00-661, Poland
- ⁶⁷Wayne State University, Detroit, Michigan 48201

⁶⁸Wuhan University of Science and Technology, Wuhan, Hubei 430065
⁶⁹Yale University, New Haven, Connecticut 06520
(Dated: August 13, 2025)

Partonic collectivity is one of the necessary signatures for the formation of quark-gluon plasma in high-energy nuclear collisions. Number of constituent quarks (NCQ) scaling has been observed for hadron elliptic flow v_2 in top energy nuclear collisions at the Relativistic Heavy Ion Collider and the LHC, and this has been theoretically suggested as strong evidence for partonic collectivity. In this Letter, a systematic analysis of v_2 of $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9$, and 4.5 GeV, with the STAR experiment at the Relativistic Heavy Ion Collider, is presented. NCQ scaling is markedly violated at 3.2 GeV, consistent with a hadronic-interaction dominated equation of state. However, as the collision energy increases, a gradual evolution to NCQ scaling is observed. This beam-energy dependence of v_2 for all hadrons studied provides evidence for the onset of dominant partonic interactions by $\sqrt{s_{NN}} = 4.5$ GeV.

Elliptic flow (v_2), the second-order harmonic coefficient in the Fourier expansion of the final state particle azimuthal distribution with respect to the reaction plane, is sensitive to constituent interactions and the degrees of freedom of the matter created in heavy-ion collisions [1]. The significant v_2 signal and the number of constituent quarks (NCQ) scaling of this elliptic flow are considered as evidence of quark-gluon plasma (QGP) formation in high-energy relativistic heavy-ion collisions [2–6].

NCQ scaling is understood within the coalescence picture, where hadrons are formed through quark recombination [7]. In this framework, light quarks (u, d, s) are assumed to exhibit collective behavior consistent with hydrodynamic flow, leading to a universal pattern of hadron v_2 when scaled by the number of constituent quarks, indicating the presence of quark degrees of freedom in the medium. As the collision energy gradually decreases below a certain threshold, the high temperature and energy density conditions necessary for the formation of QGP will no longer be satisfied. Consequently, the NCQ scaling of elliptic flow is expected to disappear. The Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory (RHIC) aims to explore the quantum chromodynamics (QCD) phase structure by lowering the collision energy, spanning an energy range from $\sqrt{s_{NN}} = 3$ to 62.4 GeV, in search of possible signals for a QCD first-order phase boundary and a critical point through heavy-ion collision experiments [8–11].

In the elliptic flow measurements of the first phase of the RHIC BES, we observed a relatively good agreement of NCQ scaling in collisions with $\sqrt{s_{NN}} \geq 7.7$ GeV [12–15], although observations of a possible deviation from NCQ scaling, around 2σ , were noted for the ϕ meson v_2 in collisions at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV [12–15]. Further investigation with larger data samples is warranted. The latest published elliptic flow results from the STAR experiment at $\sqrt{s_{NN}} = 3$ GeV show that NCQ scaling breaks among $\pi^\pm$, $K^\pm$, and p at this energy [16].

The second phase of the RHIC BES (BES-II) focuses on energies ranging from $\sqrt{s_{NN}} = 3$ to 19.6 GeV, corresponding to a baryon chemical potential range of 750 to

205 MeV [17–19]. To do so, STAR has conducted a series of detector upgrades for BES-II, including an inner time projection chamber (iTTPC) to improve the track quality [20]; an event plane detector (EPD) to measure the collision centrality and the event plane of the collision event [21]; an endcap time of flight (eTOF) to enhance the particle identification capability in the midrapidity region for the fixed-target (FXT) program [22].

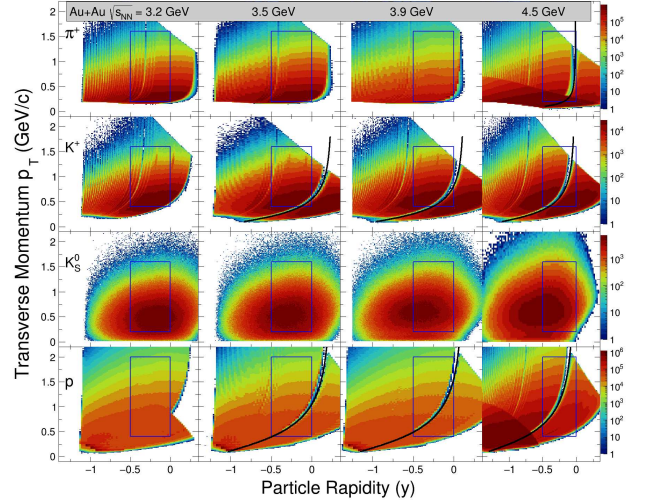


FIG. 1. The transverse momentum (p_T) and identified particle rapidity (y , in the center-of-mass frame) distributions for π^+ , K^+ , K_S^0 , and p from Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9$, and 4.5 GeV. To the right of the black curve is the acceptance provided by eTOF. The blue boxes represent the acceptance ($-0.5 < y < 0$) used for elliptic flow measurements.

In this Letter, we report v_2 measurements for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9$, and 4.5 GeV. The data were collected during the 2019 and 2020 runs of the STAR FXT program at RHIC, with $220, 100, 100$, and 120×10^6 minimum-bias events at $3.2, 3.5, 3.9$, and 4.5 GeV, respectively. Datasets for collision energies above 4.5 GeV in FXT mode are not included due to limited midrapidity coverage. The primary vertex position of each event along the beam di-

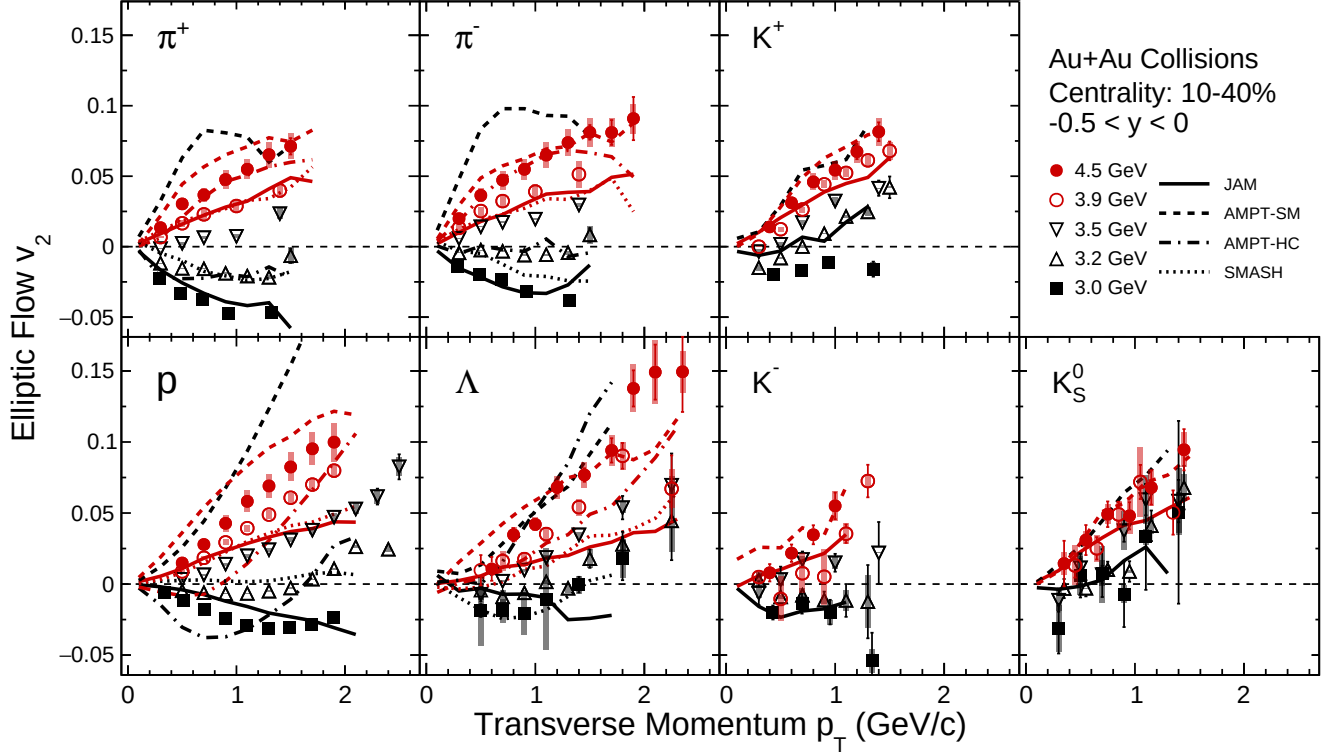


FIG. 2. Transverse momentum (p_T) dependence of v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$, and 4.5 GeV. Statistical and systematic uncertainties are shown as bars and bands, respectively. Different curves represent the results from JAM (solid), AMPT-SM (dashed), AMPT-HC (dash-dotted), and SMASH (dotted) calculations: red for 4.5 GeV, and black for 3.0 GeV. For clarity, the uncertainties of the model calculations (relative error $\leq 10\%$) are not shown. Calculations of SMASH and AMPT-HC for $K^\pm$, K_S^0 are omitted, as the results are too similar to JAM to be clearly distinguished. Additionally, the K^- results at 3.0 GeV are not presented due to the low production yield in the model.

region is selected to be within 2 cm from the target, which was located 200 cm from the center of the time projection chamber (TPC). Additionally, the vertex location along the radial direction is chosen to be smaller than 2 cm to eliminate possible beam interactions with the vacuum pipe. Runs where the mean value of physics variables, such as azimuthal angle and pseudorapidity, deviates from the overall mean by more than 5 standard deviations are labeled as bad runs and excluded from the analysis [23]. Pileup events, resulting from the long drift time of TPC electrons relative to the time interval between beam bunches, leading to the misidentification of multiple events as a single event, are removed by correlating the TPC multiplicity with the time of flight (TOF) matched multiplicity. Collision centralities are determined by fitting the TPC-measured charged particle multiplicity with a Monte Carlo Glauber model [24], where 0% indicates full nuclear overlap (most central collisions). To select high-quality tracks, we require a distance of closest approach from the vertex ≤ 3 cm and a minimum of 15 space points within the acceptance of the TPC. For particle identification of $\pi^\pm$, $K^\pm$, and p , a combination of the TPC and the TOF detector is used, which

relies on the ionization energy loss information and time-of-flight information, respectively. A minimum identification purity of $> 90\%$ is required for elliptic flow measurements, with the particle identification contamination effect estimated as a systematic uncertainty source. The strange hadrons K_S^0 and Λ are reconstructed by pairing their daughter tracks via the Kalman filter particle package [25, 26].

The transverse momentum (p_T) and rapidity (y , in the center-of-mass frame) distributions of identified particles $\pi^\pm$, $K^\pm$, K_S^0 , and p from Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9$, and 4.5 GeV are shown in Fig. 1. The additional acceptance provided by the eTOF (right side of the black curve) is particularly evident at forward rapidities. The blue boxes show the region ($-0.5 < y < 0$) used to determine the elliptic flow measurements reported in this Letter. Because of the asymmetry of the phase space acceptance in fixed-target collisions, the three-sub event method is applied to reconstruct the event plane and es-

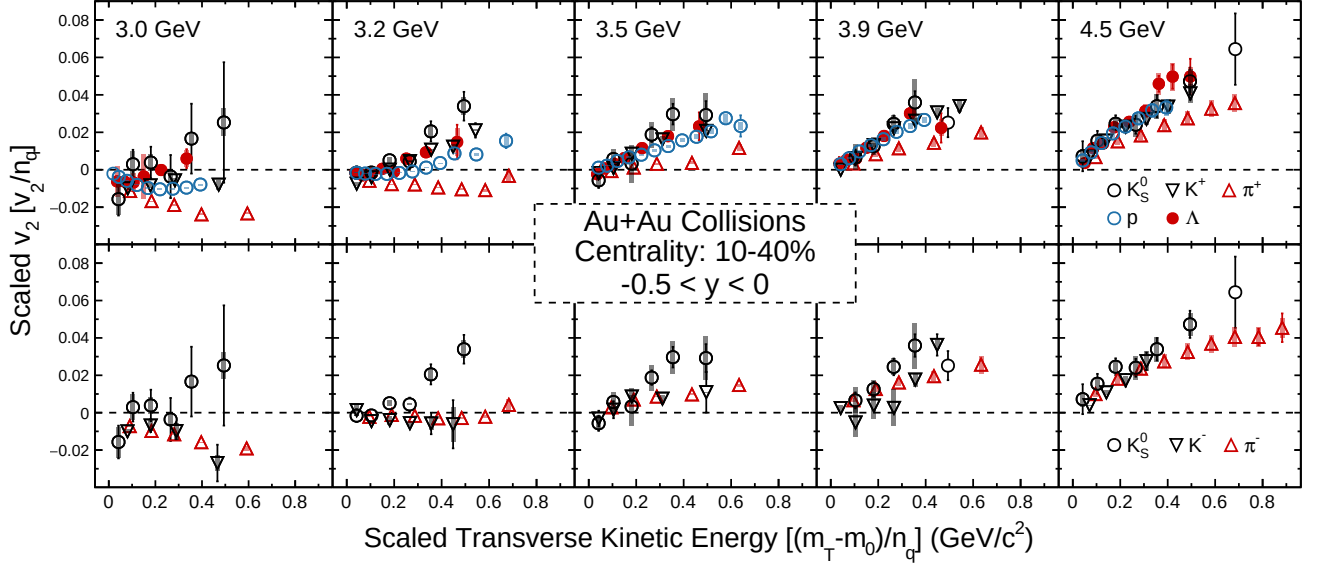


FIG. 3. The number of constituent quarks n_q scaled v_2 as a function of n_q scaled transverse kinetic energy for particles (upper panel) and antiparticles (lower panel) in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$, and 4.5 GeV. Statistical and systematic uncertainties are shown as bars and bands, respectively.

timate the event plane resolution [29]:

$$R(a) = \sqrt{\frac{\langle \cos[n(\Psi_m^a - \Psi_m^b)] \rangle \langle \cos[n(\Psi_m^a - \Psi_m^c)] \rangle}{\langle \cos[n(\Psi_m^b - \Psi_m^c)] \rangle}}, \quad (1)$$

where n denotes the corresponding Fourier coefficient v_n , and m indicates the m th order harmonic event plane. Ψ_m^a , Ψ_m^b , and Ψ_m^c represent the three-sub event planes, determined with pseudorapidity (η_{Lab}) ranges of [3.2, 6.1], [2.8, 3.1], and [0, 1.0], respectively, in the laboratory frame. The first-order coefficient (v_1) is more significant than v_2 within this energy region [19, 30], and ψ_1 and ψ_2 are strongly correlated. Therefore, v_2 is measured with respect to the first-order event plane, with event plane resolution about 20%–40% in mid-central 10%–40% collisions. Possible contributions from rapidity-even v_1 due to dipolar fluctuations are expected to be subdominant at these collision energies.

The p_T dependence of v_2 measurements considers the detector efficiency as a function of transverse momentum p_T and rapidity y . This efficiency encompasses the track reconstruction efficiency of the TPC and the TOF matching efficiency for $\pi^\pm$, $K^\pm$, and p , as well as the additional reconstruction efficiency for K_S^0 and Λ . These efficiencies are estimated using the embedding method within the STAR analysis framework [19, 31–33].

The systematic uncertainties in the measurements are determined by varying the analysis cuts mentioned above, which include track quality cuts, particle identification cuts, and event plane resolution. For each cut variable, we assign the maximum deviation from the default value as the systematic error originating from that

source. Assuming these sources are uncorrelated, the total systematic uncertainty is calculated by summing them together quadratically. A Barlow check [34] was implemented to eliminate the uncertainties introduced by statistical fluctuations during this process. The largest systematic uncertainty in proton v_2 at 4.5 GeV, arising from event plane resolution, is less than 13.3%. The systematic uncertainty from particle identification cuts is less than 1.5%, and less than 1.7% for track quality cuts.

Figure 2 presents the p_T dependence of v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$, and 4.5 GeV. The data at 3.2, 3.5, 3.9, and 4.5 GeV represent new measurements, while the 3.0 GeV data are taken from a previous publication [16]. Because of the rarity of $\bar{p}$ and $\bar{\Lambda}$ in this collision energy range, measurements of the elliptic flow for these two particles are not available. At lower collision energies, the passing time of projectile and target spectators is comparable to the mean freeze-out time of produced particles [35–37]. As a result, in-plane expansion is hindered by the spectators, leading to negative v_2 values [30, 38]. This effect, known as spectator shadowing, is particularly evident at 3.0 GeV, where hadrons dominate the medium’s degrees of freedom, characterized by large cross sections and short mean-free paths. However, as the collision energy increases, the suppression effect weakens, and v_2 transitions from negative to positive between 3.0 and 4.5 GeV, as shown in Fig. 2. This trend suggests the gradual emergence of partonic degrees of freedom, where interactions are governed by smaller partonic cross sections and longer mean-free paths.

Comparisons with transport models further support

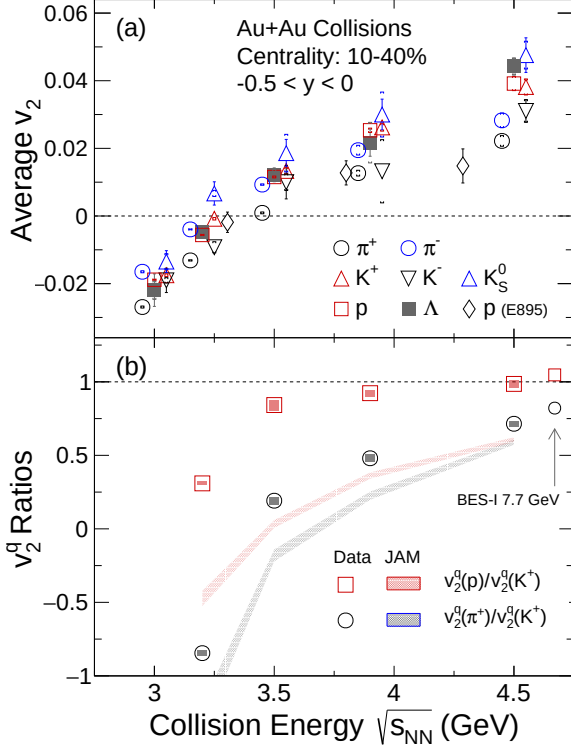


FIG. 4. (a) Energy dependence of p_T integrated v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality from Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$, and 4.5 GeV. For clarity, the x axis values of pions and kaons are shifted by ± 0.05 respectively. Proton data of E895 collaboration are from Refs. [27, 28]. (b) Energy dependence of n_q scaled v_2 ratios of $v_2^q(\pi^+)/v_2^q(K^+)$ and $v_2^q(p)/v_2^q(K^+)$ at $(m_T - m_0)/n_q = 0.4$ GeV/ c^2 in the same centrality. The ratios at 7.7 GeV are calculated based on the data in Ref. [13]. Statistical and systematic uncertainties are shown as bars and bands, respectively. The JAM calculations with baryonic mean field are shown as dashed bands.

this interpretation. The calculations from the Jet AA Microscopic Transport Model (JAM) [39, 40], Multi-Phase Transport Model: Hadron Cascade (AMPT-HC) and String Melting (AMPT-SM) mode [41, 42], and Simulating Many Accelerated Strongly interacting Hadrons (SMASH) [43] are represented by the curves. For the lowest collision energy 3.0 GeV, the hadronic transport models JAM, AMPT-HC, and SMASH qualitatively describe the v_2 data. The multiphase transport model AMPT-SM (black dashed curve) predicts the opposite sign of v_2 because it does not account for the finite thickness of the incoming nuclei, thus missing the potential shadowing effect from spectator nucleons. For 4.5 GeV, the hadronic transport models generally underestimate the v_2 data (except $\pi^\pm$ from AMPT-HC); in contrast, AMPT-SM, which incorporates partonic interactions, better describes the v_2 data. This suggests that parton interactions and

the coalescence play an important role in generating such a significant v_2 signal. Detailed comparison of the model calculations can be found in Supplemental Material [44].

NCQ scaling is expected to reflect the effective degrees of freedom of the medium. The elliptic flow scaled by the number of constituent quarks, v_2/n_q , as a function of the scaled transverse kinetic energy $(m_T - m_0)/n_q$ for particles (upper panel) and antiparticles (lower panel) separately in 10%–40% centrality for Au+Au collisions is shown in Fig. 3, where $m_T = \sqrt{(p_T^2 + m_0^2)}$, m_0 is the rest mass of the particle. In collisions at 3.0 and 3.2 GeV, it can be clearly observed that the NCQ scaling is broken, with each particle exhibiting a different trend. As the collision energy increases from 3.0 to 4.5 GeV, the NCQ scaling becomes evident. These observations suggest that hadronic interactions dominate the equation of state of the created matter at 3.0 and 3.2 GeV, while partonic interactions become more important at collision energies greater than 3.2 GeV. On the model side, JAM better describes the NCQ breaking at 3.0 GeV but fails to capture the scaling behavior at 4.5 GeV; AMPT-SM shows better scaling behavior than hadronic transport models at 4.5 GeV. Notably, the v_2 of $\pi^\pm$ is smaller than the scaling of other particles at 4.5 GeV. The p_T/n_q scaling exhibits better performance than $(m_T - m_0)/n_q$ for $\pi^\pm$, suggesting that the deviation at this energy is primarily attributed to the significantly smaller mass of pions compared to other hadrons. It is noteworthy that the original NCQ scaling was proposed based on p_T [7, 45]. Detailed model comparisons and scaling results are given in Supplemental Material [44].

We further investigate the p_T integrated v_2 as a function of collision energy. Figure 4 (a) shows the energy dependence of p_T integrated v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality from Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$, and 4.5 GeV. The integrated v_2 is calculated within $0.2 < p_T(\text{GeV}/c) < 1.6$ for $\pi^\pm$, $0.4 < p_T(\text{GeV}/c) < 1.6$ for $K^\pm, K_S^0$, $0.4 < p_T(\text{GeV}/c) < 2.0$ for p, Λ . p_T integrated v_2 changes from negative to positive as the energy increases from 3.0 to 4.5 GeV, crossing zero at about 3.2 GeV. Compared to previously published results from the E895 Collaboration [27, 28], our data show good agreement near the zero-crossing point. At higher energies, however, our measurements yield larger v_2 values, which may be attributed to the use of mid-central (10%–40%) collisions, whereas the E895 results correspond to collisions with an impact parameter of 5–7 fm (approximately 10–15% centrality). Clear differences between π^- and π^+ are observed at each energy, and the differences become smaller as the energy increases. This is consistent with the picture of the baryon number transport—quarks transported from beam rapidity to midrapidity experience more violent scatterings than quarks produced at midrapidity [46]. Additionally, the initial nuclear matter is a neutron-rich environment, causing a larger transported effect for π^- ($\bar{u}d$) com-

pared to $\pi^+(u\bar{d})$. Although the uncertainties are large for $K^\pm, K_S^0$, these three kaons exhibit ordering behavior, i.e., $K_S^0(d\bar{s}) > K^+(u\bar{s}) > K^-(\bar{u}s)$, which is also consistent with the transported effect. These observations indicate the effect of the transported quarks is also present even at this energy region where the baryon density is high. On the other side, the v_2 of p and Λ are consistent within statistical uncertainties.

In order to quantify the trend of NCQ scaling with collision energy, Fig. 4 (b) shows the n_q scaled v_2 ratios of $v_2^q(\pi^+)/v_2^q(K^+)$ and $v_2^q(p)/v_2^q(K^+)$ at $(m_T - m_0)/n_q = 0.4$ GeV/ c^2 as a function of collision energy, where the v_2^q represents the n_q scaled v_2 (v_2/n_q). The ratio of $v_2^q(p)/v_2^q(K^+)$ is close to unity at 3.9 and 4.5 GeV, while it deviates significantly at 3.2 GeV. Although hadronic model JAM calculations fit the $v_2(p_T)$ data better at lower collision energies, they underestimate the ratios throughout the energy range studied.

In summary, we present the elliptic flow of identified hadrons $\pi^\pm, K^\pm, K_S^0, p$, and Λ in Au+Au collisions at $\sqrt{s_{NN}} = 3.2, 3.5, 3.9$, and 4.5 GeV. The v_2 of these particles changes from negative to positive around 3.2 GeV. At the lower colliding energy, $\sqrt{s_{NN}} \leq 3.2$ GeV, NCQ scaling breaks down and the calculations from the hadronic transport model JAM reproduce the transverse momentum dependence of the measured $v_2(p_T)$, implying hadronic interaction dominance. As collision energy increases, a gradual onset of NCQ scaling is observed and the hadronic transport model underpredicts, while the multiphase transport model more accurately captures the collectivity observed in the 4.5 GeV data. The observed breakdown and subsequent onset of NCQ scaling suggest a dominance of partonic interactions in collisions at $\sqrt{s_{NN}} \geq 4.5$ GeV, signaling the emergence of partonic collectivity and the possible formation of QGP. These results shed light on the energy-dependent onset of QGP and contribute to the broader effort to map the QCD phase diagram.

Acknowledgments—We thank the RHIC Operations Group and SDCC at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Office of Nuclear Physics within the U.S. DOE Office of Science, the U.S. National Science Foundation, the Ministry of Science and Technology of China and the Chinese Ministry of Education, National Natural Science Foundation of China, Chinese Academy of Science, NSTC Taipei, the National Research Foundation of Korea, Czech Science Foundation and Ministry of Education, Youth and Sports of the Czech Republic, Hungarian National Research, Development and Innovation Office, New National Excellency Programme of the Hungarian Ministry of Human Capacities, Department of Atomic Energy and Department of Science and Technology of the Government of India, the National Science Centre and WUT ID-UB of Poland, the Ministry of Sci-

ence, Education and Sports of the Republic of Croatia, German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), Helmholtz Association, Ministry of Education, Culture, Sports, Science, and Technology (MEXT), and Japan Society for the Promotion of Science (JSPS).

Data Availability—The data that support the findings of this article are openly available [47].

-
- [1] S. A. Voloshin, A. M. Poskanzer, and R. Snellings, *Landolt-Bornstein* **23**, 293 (2010).
 - [2] J. Adams *et al.* (STAR), *Nucl. Phys. A* **757**, 102 (2005).
 - [3] K. Adcox *et al.* (PHENIX), *Nucl. Phys. A* **757**, 184 (2005).
 - [4] L. Adamczyk *et al.* (STAR), *Phys. Rev. Lett.* **116**, 062301 (2016).
 - [5] L. Adamczyk *et al.* (STAR), *Phys. Rev. Lett.* **118**, 212301 (2017).
 - [6] P. Braun-Munzinger and J. Stachel, *Nature* **448**, 302 (2007).
 - [7] D. Molnar and S. A. Voloshin, *Phys. Rev. Lett.* **91**, 092301 (2003).
 - [8] K. Fukushima and T. Hatsuda, *Rept. Prog. Phys.* **74**, 014001 (2011).
 - [9] A. Bzdak *et al.*, *Phys. Rept.* **853**, 1 (2020).
 - [10] X. Luo, S. Shi, N. Xu, and Y. Zhang, *Particles* **3**, 278 (2020).
 - [11] J.-H. Chen *et al.*, *Nuclear Science and Techniques* **35**, 214 (2024).
 - [12] L. Adamczyk *et al.* (STAR), *Phys. Rev. Lett.* **110**, 142301 (2013).
 - [13] L. Adamczyk *et al.* (STAR), *Phys. Rev. C* **88**, 014902 (2013).
 - [14] L. Adamczyk *et al.* (STAR), *Phys. Rev. C* **93**, 014907 (2016).
 - [15] L. Adamczyk *et al.* (STAR), *Phys. Rev. C* **86**, 054908 (2012).
 - [16] M. S. Abdallah *et al.* (STAR), *Phys. Lett. B* **827**, 137003 (2022).
 - [17] J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton, *Phys. Rev. C* **73**, 034905 (2006).
 - [18] A. Andronic, P. Braun-Munzinger, and J. Stachel, *Nucl. Phys. A* **772**, 167 (2006).
 - [19] L. Adamczyk *et al.* (STAR), *Phys. Rev. C* **96**, 044904 (2017).
 - [20] C. Yang (STAR), *Nucl. Phys. A* **967**, 800 (2017).
 - [21] J. Adams *et al.*, *Nucl. Instrum. Meth. A* **968**, 163970 (2020).
 - [22] K. Wang *et al.*, *Nucl. Instrum. Meth. A* **1057**, 168778 (2023).
 - [23] M. Abdallah *et al.* (STAR), *Phys. Rev. C* **105**, 014901 (2022).
 - [24] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, *Ann. Rev. Nucl. Part. Sci.* **57**, 205 (2007).
 - [25] I. Kisel (CBM), *J. Phys. Conf. Ser.* **1070**, 012015 (2018).
 - [26] A. Banerjee, I. Kisel, and M. Zyzak, *Int. J. Mod. Phys. A* **35**, 2043003 (2020).
 - [27] C. Pinkenburg *et al.* (E895), *Phys. Rev. Lett.* **83**, 1295 (1999).

- [28] N. Herrmann, J. P. Wessels, and T. Wienold, *Ann. Rev. Nucl. Part. Sci.* **49**, 581 (1999).
- [29] A. M. Poskanzer and S. A. Voloshin, *Phys. Rev. C* **58**, 1671 (1998).
- [30] J. Adamczewski-Musch *et al.* (HADES), *Phys. Rev. Lett.* **125**, 262301 (2020).
- [31] B. I. Abelev *et al.* (STAR), *Phys. Rev. C* **79**, 034909 (2009).
- [32] M. M. Aggarwal *et al.* (STAR), *Phys. Rev. C* **83**, 024901 (2011), [Erratum: *Phys.Rev.C* 107, 049903 (2023)].
- [33] M. Abdallah *et al.* (STAR), *Phys. Rev. C* **104**, 024902 (2021), [Erratum: *Phys.Rev.C* 111, 029902 (2025)].
- [34] R. Barlow, Systematic errors: Facts and fictions (2002), arXiv:hep-ex/0207026.
- [35] H. Liu, S. Panitkin, and N. Xu, *Phys. Rev. C* **59**, 348 (1999).
- [36] A. Le Fèvre, Y. Leifels, C. Hartnack, and J. Aichelin, *Phys. Rev. C* **98**, 034901 (2018).
- [37] Z.-W. Liu and S. Shi, *Phys. Rev. C* **110**, 034903 (2024).
- [38] J. Adamczewski-Musch *et al.* (HADES), *Eur. Phys. J. A* **59**, 80 (2023).
- [39] Y. Nara and A. Ohnishi, *Phys. Rev. C* **105**, 014911 (2022).
- [40] Y. Nara, A. Jinno, K. Murase, and A. Ohnishi, *Phys. Rev. C* **106**, 044902 (2022).
- [41] Z.-W. Lin *et al.*, *Phys. Rev. C* **72**, 064901 (2005).
- [42] G.-C. Yong, *Phys. Lett. B* **848**, 138327 (2024).
- [43] J. Weil *et al.* (SMASH), *Phys. Rev. C* **94**, 054905 (2016).
- [44] See Supplemental Material at <https://doi.org/10.1103/2qhx-cp79> for details.
- [45] S. A. Voloshin, *J. Phys. Conf. Ser.* **9**, 276 (2005).
- [46] J. C. Dunlop, M. A. Lisa, and P. Sorensen, *Phys. Rev. C* **84**, 044914 (2011).
- [47] STAR Collaboration, “Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC,” *HEPData* (2025).

Supplemental Material: Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC

B. E. Aboona,⁵⁷ J. Adam,¹⁷ L. Adamczyk,³ I. Aggarwal,⁴⁴ M. M. Aggarwal,⁴⁴ Z. Ahammed,⁶⁵ A. K. Alshammri,³³ E. C. Aschenauer,⁷ S. Aslam,²² J. Atchison,² V. Bairathi,⁵⁵ X. Bao,⁵¹ K. Barish,¹² S. Behera,²⁸ R. Bellwied,²⁵ P. Bhagat,³² A. Bhasin,³² S. Bhatta,⁵⁴ S. R. Bhosale,³ J. Bielcik,¹⁷ J. Bielcikova,⁴² J. D. Brandenburg,⁴³ C. Broodo,²⁵ X. Z. Cai,⁵² H. Caines,⁶⁹ M. Calderón de la Barca Sánchez,¹⁰ D. Cebra,¹⁰ J. Ceska,¹⁷ I. Chakaberia,³⁶ P. Chaloupka,¹⁷ B. K. Chan,¹¹ Z. Chang,³⁰ A. Chatterjee,¹⁹ D. Chen,¹² J. Chen,⁵¹ J. H. Chen,²² Q. Chen,²³ Z. Chen,⁵¹ J. Cheng,⁶⁰ Y. Cheng,¹¹ W. Christie,⁷ X. Chu,⁷ S. Corey,⁴³ H. J. Crawford,⁹ M. Csanád,²⁰ G. Dale-Gau,¹⁴ A. Das,¹⁷ I. M. Deppner,²⁴ A. Deshpande,⁵⁴ A. Dhamija,⁴⁴ A. Dimri,⁵⁴ P. Dixit,²⁷ X. Dong,³⁶ J. L. Drachenberg,² E. Duckworth,³³ J. C. Dunlop,⁷ J. Engelage,⁹ G. Eppley,⁴⁶ S. Esumi,⁶¹ O. Evdokimov,¹⁴ O. Eyser,⁷ R. Fatemi,³⁴ S. Fazio,⁸ Y. Feng,⁴⁵ E. Finch,⁵³ Y. Fisyrak,⁷ F. A. Flor,⁶⁹ C. Fu,³¹ T. Fu,⁵¹ C. A. Gagliardi,⁵⁷ T. Galatyuk,¹⁸ T. Gao,⁵¹ F. Geurts,⁴⁶ N. Ghimire,⁵⁶ A. Gibson,⁶⁴ K. Gopal,²⁸ X. Gou,⁵¹ D. Grosnick,⁶⁴ A. Gu,²⁶ A. Gupta,³² A. Hamed,⁵ R. J. Hamilton,⁶⁹ X. Han,⁴³ S. Harabasz,¹⁸ M. D. Harasty,¹⁰ J. W. Harris,⁶⁹ H. Harrison-Smith,³⁴ L. B. Havener,⁶⁹ X. H. He,³¹ Y. He,⁵¹ N. Herrmann,²⁴ L. Holub,¹⁷ C. Hu,⁶² Q. Hu,³¹ Y. Hu,³⁶ H. Huang,^{41,1} H. Z. Huang,¹¹ S. L. Huang,⁵⁴ T. Huang,¹⁴ Y. Huang,²⁰ Y. Huang,¹³ T. J. Humanic,⁴³ M. Isshiki,⁶¹ W. W. Jacobs,³⁰ A. Jalotra,³² C. Jena,²⁸ A. Jentsch,⁷ Y. Ji,³⁶ J. Jia,^{54,7} C. Jin,⁴⁶ N. Jindal,⁴³ X. Ju,⁴⁸ E. G. Judd,⁹ S. Kabana,⁵⁵ D. Kalinkin,³⁴ K. Kang,⁶⁰ D. Kapukchyan,¹² K. Kauder,⁷ D. Keane,³³ M. Kesler,³³ A. Khanal,⁶⁷ Y. V. Khyzhniak,⁴³ D. P. Kikoła,⁶⁶ J. Kim,⁷ D. Kincses,²⁰ I. Kisel,²¹ A. Kiselev,⁷ A. G. Knospe,³⁷ J. Kolaś,⁶⁶ B. Korodi,⁴³ L. K. Kosarzewski,⁴³ L. Kumar,⁴⁴ M. C. Labonte,¹⁰ R. Lacey,⁵⁴ J. M. Landgraf,⁷ C. Larson,³⁴ J. Lauret,⁷ A. Lebedev,⁷ J. H. Lee,⁷ Y. H. Leung,²⁴ C. Li,¹³ D. Li,⁴⁸ H-S. Li,⁴⁵ H. Li,⁶⁸ H. Li,²³ W. Li,⁴⁶ X. Li,⁴⁸ X. Li,⁴⁸ Y. Li,⁶⁰ Z. Li,⁴⁹ Z. Li,⁴⁸ X. Liang,¹² Y. Liang,³³ R. Licenik,^{42,17} T. Lin,⁵¹ Y. Lin,²³ M. A. Lisa,⁴³ C. Liu,³¹ G. Liu,⁴⁹ H. Liu,²⁶ L. Liu,¹³ Z. Liu,¹³ T. Ljubicic,⁴⁶ O. Lomicky,¹⁷ R. S. Longacre,⁷ E. M. Loyd,¹² T. Lu,³¹ J. Luo,⁴⁸ X. F. Luo,¹³ L. Ma,²² R. Ma,⁷ Y. G. Ma,²² N. Magdy,⁵⁸ D. Mallick,¹³ R. Manikandhan,²⁵ S. Margetis,³³ C. Markert,⁵⁹ O. Matonoha,¹⁷ O. Mezhanaka,¹⁷ K. Mi,¹³ S. Mioduszewski,⁵⁷ B. Mohanty,⁴⁰ B. Mondal,⁴⁰ M. M. Mondal,⁴⁰ I. Mooney,⁶⁹ J. Mrazkova,^{42,17} M. I. Nagy,²⁰ C. J. Naim,⁵⁴ A. S. Nain,⁴⁴ J. D. Nam,⁵⁶ M. Nasim,²⁷ H. Nasrulloh,⁴⁸ D. Neff,¹¹ J. M. Nelson,⁹ M. Nie,⁵¹ G. Nigmatkulov,¹⁴ T. Niida,⁶¹ T. Nonaka,⁶¹ G. Odyniec,³⁶ A. Ogawa,⁷ S. Oh,⁵⁰ K. Okubo,⁶¹ B. S. Page,⁷ S. Pal,¹⁷ A. Pandav,³⁶ A. Panday,²⁷ A. K. Pandey,³¹ T. Pani,⁴⁷ A. Paul,¹² S. Paul,⁵⁴ D. Pawlowska,⁶⁶ C. Perkins,⁹ J. Pluta,⁶⁶ B. R. Pokhrel,⁵⁶ I. D. Ponce Pinto,⁶⁹ M. Posik,⁵⁶ E. Pottebaum,⁶⁹ S. Prodhon,²⁸ T. L. Protzman,³⁷ A. Prozorov,¹⁷ V. Prozorova,¹⁷ N. K. Pruthi,⁴⁴ M. Przybycien,³ J. Putschke,⁶⁷ Z. Qin,⁶⁰ H. Qiu,³¹ C. Racz,¹² S. K. Radhakrishnan,³³ A. Rana,⁴⁴ R. L. Ray,⁵⁹ R. Reed,³⁷ C. W. Robertson,⁴⁵ M. Robotkova,^{42,17} M. A. Rosales Aguilar,³⁴ D. Roy,⁴⁷ P. Roy Chowdhury,⁶⁶ L. Ruan,⁷ A. K. Sahoo,²⁷ N. R. Sahoo,²⁸ H. Sako,⁶¹ S. Salur,⁴⁷ S. S. Sambyal,³² J. K. Sandhu,³⁷ S. Sato,⁶¹ B. C. Schaefer,³⁷ N. Schmitz,³⁸ F-J. Seck,¹⁸ J. Seger,¹⁶ R. Seto,¹² P. Seyboth,³⁸ N. Shah,²⁹ P. V. Shanmuganathan,⁷ T. Shao,²² M. Sharma,³² N. Sharma,²⁷ R. Sharma,²⁸ S. R. Sharma,²⁸ A. I. Sheikh,³³ D. Shen,⁵¹ D. Y. Shen,³¹ K. Shen,⁴⁸ S. Shi,¹³ Y. Shi,⁵¹ F. Si,⁴⁸ J. Singh,⁵⁵ S. Singha,³¹ P. Sinha,²⁸ M. J. Skoby,^{6,45} N. Smirnov,⁶⁹ Y. Söhngen,²⁴ Y. Song,⁶⁹ T. D. S. Stanislaus,⁶⁴ M. Stefaniak,⁴³ Y. Su,⁴⁸ M. Sumner,⁴² X. Sun,³¹ Y. Sun,⁴⁸ B. Surrow,⁵⁶ M. Svoboda,^{42,17} Z. W. Sweger,¹⁰ A. C. Tamis,⁶⁹ A. H. Tang,⁷ Z. Tang,⁴⁸ T. Tarnowsky,³⁹ J. H. Thomas,³⁶ A. R. Timmins,²⁵ D. Thusty,¹⁶ T. Todoroki,⁶¹ D. Torres Valladares,⁴⁶ S. Trentalange,¹¹ P. Tribedy,⁷ S. K. Tripathy,⁶⁶ T. Truhlar,¹⁷ B. A. Trzeciak,¹⁷ O. D. Tsai,^{11,7} C. Y. Tsang,^{33,7} Z. Tu,⁷ J. Tyler,⁵⁷ T. Ullrich,⁷ D. G. Underwood,^{4,64} G. Van Buren,⁷ J. Vanek,⁷ I. Vassiliev,²¹ F. Videbæk,⁷ S. A. Voloshin,⁶⁷ F. Wang,⁴⁵ G. Wang,¹¹ G. Wang,¹³ J. S. Wang,²⁶ J. Wang,⁵¹ K. Wang,⁴⁸ X. Wang,⁵¹ Y. Wang,⁴⁸ Y. Wang,¹³ Y. Wang,⁶⁰ Z. Wang,⁵¹ A. J. Watroba,³ J. C. Webb,⁷ P. C. Weidenkaff,²⁴ G. D. Westfall,³⁹ D. Wielanek,⁶⁶ H. Wieman,³⁶ G. Wilks,¹⁴ S. W. Wissink,³⁰ R. Witt,⁶³ C. P. Wong,⁷ J. Wu,¹³ J. Wu,⁶² X. Wu,¹¹ X. Wu,⁴⁸ X. Wu,¹³ B. Xi,²² Z. G. Xiao,⁶⁰ G. Xie,⁶² W. Xie,⁴⁵ H. Xu,²⁶ N. Xu,¹³ Q. H. Xu,⁵¹ Y. Xu,⁵¹ Y. Xu,¹³ Z. Xu,³³ Z. Xu,⁴ G. Yan,⁵¹ Z. Yan,⁵⁴ C. Yang,⁵¹ Q. Yang,⁵¹ S. Yang,⁴⁹ Y. Yang,^{1,41} Z. Ye,⁴⁹ Z. Ye,³⁶ L. Yi,⁵¹ Y. Yu,⁵¹ H. Zbroszczyk,⁶⁶ W. Zha,⁴⁸ C. Zhang,²² D. Zhang,⁴⁹ J. Zhang,⁵¹ S. Zhang,¹⁵ W. Zhang,⁴⁹ X. Zhang,³¹ Y. Zhang,³¹ Y. Zhang,⁴⁸ Y. Zhang,⁵¹ Y. Zhang,²³ Z. Zhang,⁷ Z. Zhang,¹⁴ F. Zhao,³⁵ J. Zhao,²² M. Zhao,⁷ S. Zhou,¹³ Y. Zhou,¹³ X. Zhu,⁶⁰ M. Zurek,^{4,7} and M. Zyzak²¹

(STAR Collaboration)

- ² Abilene Christian University, Abilene, Texas 79699
- ³ AGH University of Krakow, FPACS, Cracow 30-059, Poland
- ⁴ Argonne National Laboratory, Argonne, Illinois 60439
- ⁵ American University in Cairo, New Cairo 11835, Egypt
- ⁶ Ball State University, Muncie, Indiana 47306
- ⁷ Brookhaven National Laboratory, Upton, New York 11973
- ⁸ University of Calabria & INFN-Cosenza, Rende 87036, Italy
- ⁹ University of California, Berkeley, California 94720
- ¹⁰ University of California, Davis, California 95616
- ¹¹ University of California, Los Angeles, California 90095
- ¹² University of California, Riverside, California 92521
- ¹³ Central China Normal University, Wuhan, Hubei 430079
- ¹⁴ University of Illinois at Chicago, Chicago, Illinois 60607
- ¹⁵ Chongqing University, Chongqing, 401331
- ¹⁶ Creighton University, Omaha, Nebraska 68178
- ¹⁷ Czech Technical University in Prague, FNSPE, Prague 115 19, Czech Republic
- ¹⁸ Technische Universität Darmstadt, Darmstadt 64289, Germany
- ¹⁹ National Institute of Technology Durgapur, Durgapur - 713209, India
- ²⁰ ELTE Eötvös Loránd University, Budapest H-1117, Hungary
- ²¹ Frankfurt Institute for Advanced Studies FIAS, Frankfurt 60438, Germany
- ²² Fudan University, Shanghai, 200433
- ²³ Guangxi Normal University, Guilin, 541004
- ²⁴ University of Heidelberg, Heidelberg 69120, Germany
- ²⁵ University of Houston, Houston, Texas 77204
- ²⁶ Huzhou University, Huzhou, Zhejiang 313000
- ²⁷ Indian Institute of Science Education and Research (IISER), Berhampur 760010, India
- ²⁸ Indian Institute of Science Education and Research (IISER) Tirupati, Tirupati 517507, India
- ²⁹ Indian Institute Technology, Patna, Bihar 801106, India
- ³⁰ Indiana University, Bloomington, Indiana 47408
- ³¹ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, Gansu 730000
- ³² University of Jammu, Jammu 180001, India
- ³³ Kent State University, Kent, Ohio 44242
- ³⁴ University of Kentucky, Lexington, Kentucky 40506-0055
- ³⁵ Lanzhou University, Lanzhou 730000
- ³⁶ Lawrence Berkeley National Laboratory, Berkeley, California 94720
- ³⁷ Lehigh University, Bethlehem, Pennsylvania 18015
- ³⁸ Max-Planck-Institut für Physik, Munich 80805, Germany
- ³⁹ Michigan State University, East Lansing, Michigan 48824
- ⁴⁰ National Institute of Science Education and Research, HBNI, Jatni 752050, India
- ⁴¹ National Cheng Kung University, Tainan 70101
- ⁴² Nuclear Physics Institute of the CAS, Rez 250 68, Czech Republic
- ⁴³ The Ohio State University, Columbus, Ohio 43210
- ⁴⁴ Panjab University, Chandigarh 160014, India
- ⁴⁵ Purdue University, West Lafayette, Indiana 47907
- ⁴⁶ Rice University, Houston, Texas 77251
- ⁴⁷ Rutgers University, Piscataway, New Jersey 08854
- ⁴⁸ University of Science and Technology of China, Hefei, Anhui 230026
- ⁴⁹ South China Normal University, Guangzhou, Guangdong 510631
- ⁵⁰ Sejong University, Seoul, 05006, South Korea
- ⁵¹ Shandong University, Qingdao, Shandong 266237
- ⁵² Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800
- ⁵³ Southern Connecticut State University, New Haven, Connecticut 06515
- ⁵⁴ State University of New York, Stony Brook, New York 11794
- ⁵⁵ Instituto de Alta Investigación, Universidad de Tarapacá, Arica 1000000, Chile
- ⁵⁶ Temple University, Philadelphia, Pennsylvania 19122
- ⁵⁷ Texas A&M University, College Station, Texas 77843
- ⁵⁸ Texas Southern University, Houston, Texas 77004
- ⁵⁹ University of Texas, Austin, Texas 78712
- ⁶⁰ Tsinghua University, Beijing 100084
- ⁶¹ University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan
- ⁶² University of Chinese Academy of Sciences, Beijing, 101408
- ⁶³ United States Naval Academy, Annapolis, Maryland 21402
- ⁶⁴ Valparaiso University, Valparaiso, Indiana 46383
- ⁶⁵ Variable Energy Cyclotron Centre, Kolkata 700064, India

⁶⁶Warsaw University of Technology, Warsaw 00-661, Poland
⁶⁷Wayne State University, Detroit, Michigan 48201
⁶⁸Wuhan University of Science and Technology, Wuhan, Hubei 430065
⁶⁹Yale University, New Haven, Connecticut 06520
(Dated: August 13, 2025)

DATA-MODEL COMPARISON: p_T DEPENDENCE OF v_2

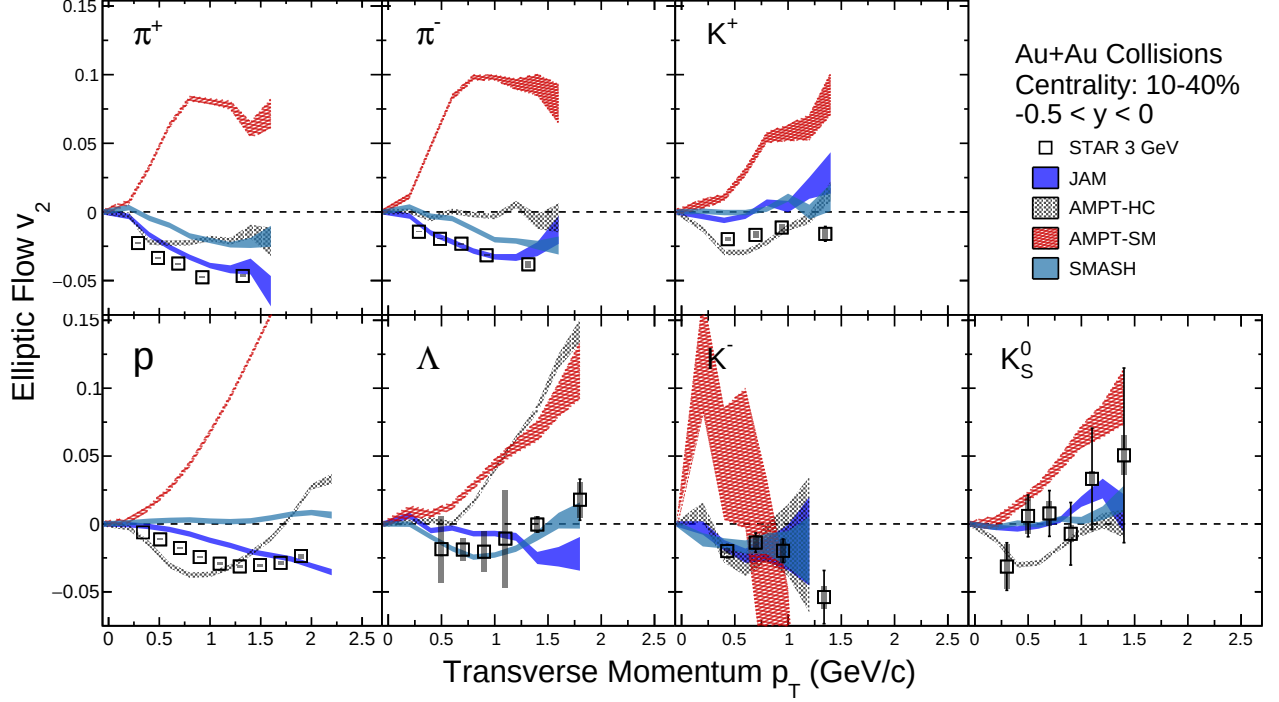


FIG. 1. Transverse momentum (p_T) dependence of v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 3.0$ GeV. Statistical and systematic uncertainties are shown as bars and bands, respectively. Different bands represent the results from JAM (blue), AMPT-HC (black), AMPT-SM (red), and SMASH (cyan) calculations.

Figure 1 presents the p_T dependence of $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 3.0$ GeV. Calculations from different models are represented by the bands, where the “JAM” means Jet AA Microscopic Transport Model [1, 2] with soft Equation Of State (EOS); “AMPT-HC” and “AMPT-SM” refer to Hadron Cascade and String Melting mode of the Multi-Phase Transport Model [3, 4]; “SMASH” means Simulating Many Accelerated Strongly interacting Hadrons [5] with soft EOS. The hadronic transport models JAM, AMPT-HC, and SMASH qualitatively describe the v_2 data, while the multi-phase transport model AMPT-SM (red band) predicts the opposite sign of v_2 , because it does not account for the finite thickness of the incoming nuclei, thus missing the potential shadowing effect from spectator nucleons.

Figure 2 shows the p_T dependence of $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 4.5$ GeV. The hadronic transport models generally underestimate the v_2 data (except $\pi^\pm$ from AMPT-HC); in contrast, AMPT string melting mode better describes the v_2 data.

NUMBER OF CONSTITUENT QUARKS SCALING: v_2/n_q VS. p_T/n_q

Figure 3 represents the number of constituent quarks n_q scaled v_2 as a function of n_q scaled p_T for particles and anti-particles separately in 10%–40% centrality for Au+Au collisions. The p_T/n_q scaling exhibits better performance

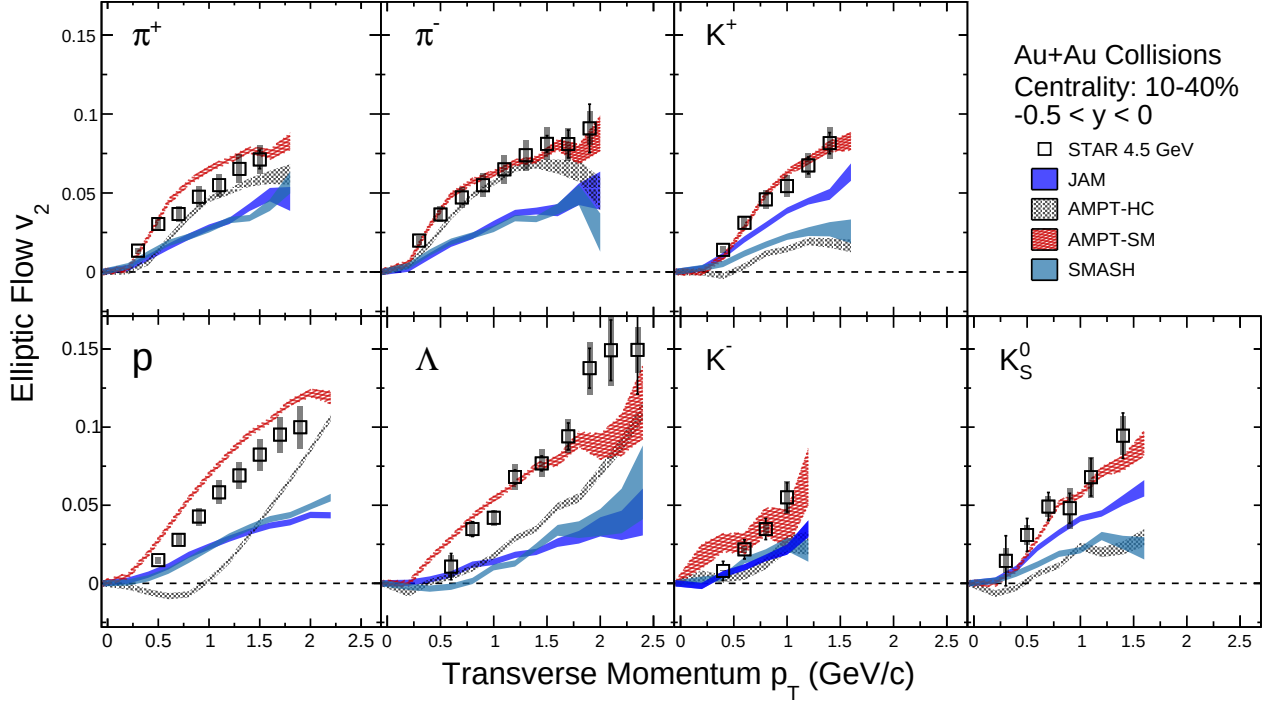


FIG. 2. Transverse momentum (p_T) dependence of v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 4.5$ GeV. Statistical and systematic uncertainties are shown as bars and bands, respectively. Different bands represent the results from JAM (blue), AMPT-HC (black), AMPT-SM (red), and SMASH (cyan) calculations.

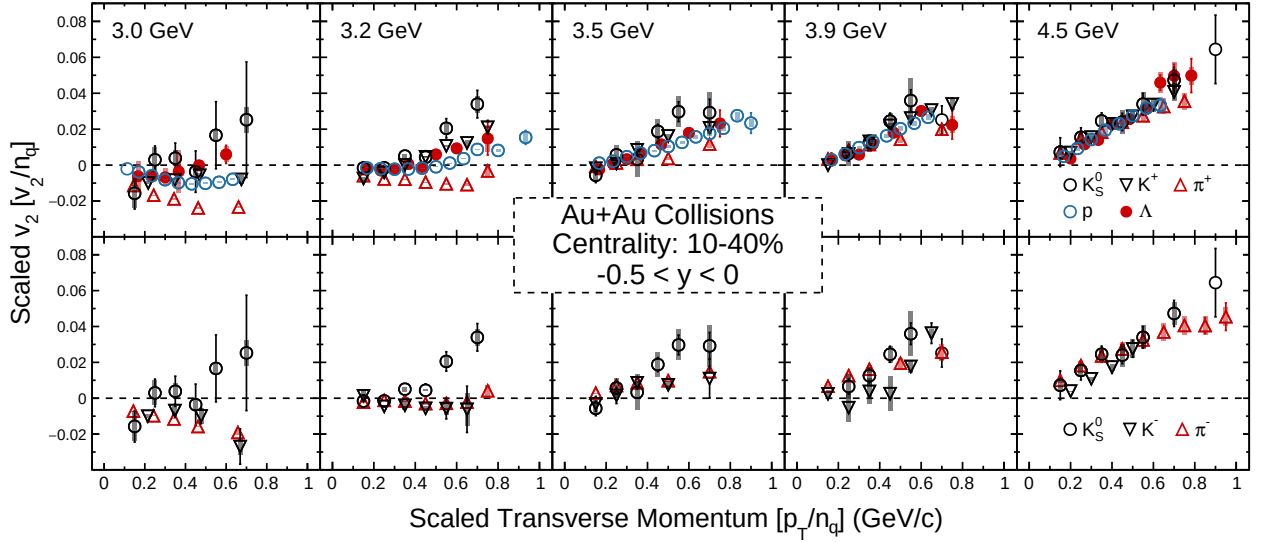


FIG. 3. The number of constituent quarks n_q scaled v_2 as a function of n_q scaled transverse momentum for particles (upper panel) and anti-particles (lower panel) in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9,$ and 4.5 GeV.

than $(m_T - m_0)/n_q$ scaling for $\pi^\pm$, suggesting that the $\pi^\pm$ deviation on $(m_T - m_0)/n_q$ scaling at 4.5 GeV, may primarily be attributed to the significantly smaller mass of pions compared to other hadrons. Notably, the original NCQ scaling was proposed based on p_T [6, 7].

Figure 4 shows the number of constituent quarks n_q scaled v_2 for $\pi^\pm$, $K^\pm$, K_S^0 , p , and Λ in 10%–40% centrality at Au+Au collisions $\sqrt{s_{NN}} = 3.0$ and 4.5 GeV from model calculations using JAM, SMASH, AMPT-HC, and AMPT-SM.

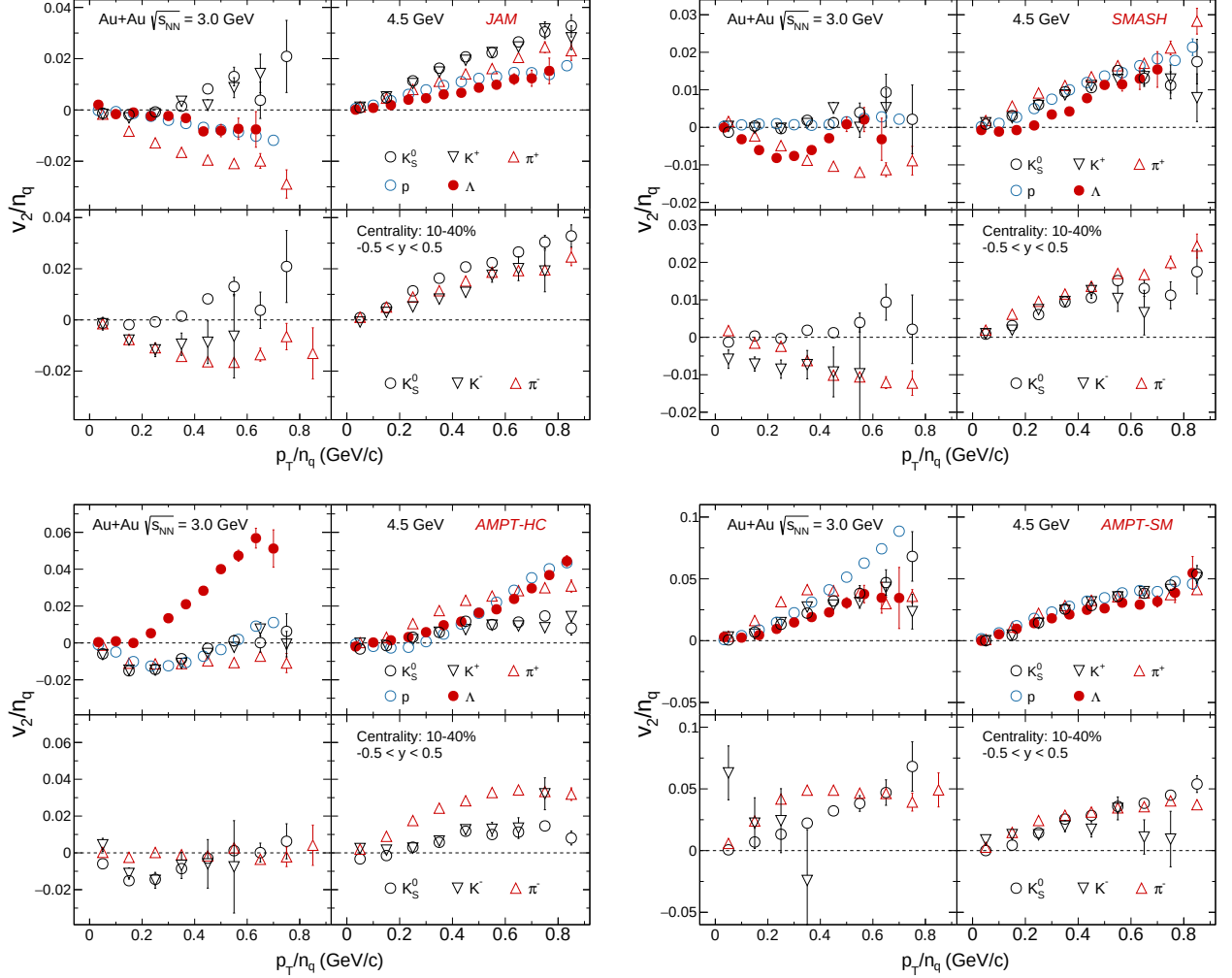


FIG. 4. The number of constituent quarks n_q scaled v_2 as a function of n_q scaled transverse momentum in 10%–40% centrality for Au+Au collisions at $\sqrt{s_{\text{NN}}} = 3.0$ and 4.5 GeV from model calculations using JAM, SMASH, AMPT-HC, and AMPT-SM.

JAM model well captures the NCQ scaling broken at 3.0 GeV, but no scaling is observed at 4.5 GeV. This may be attributed to JAM being a purely hadronic transport model, where only hadronic interactions are included during the medium evolution. SMASH and AMPT-HC partially describe the v_2 data at 3 GeV. However, SMASH greatly underestimates v_2 at 4.5 GeV as shown in Fig. 2, and AMPT-HC shows a larger deviation from NCQ scaling at the same energy. In the multi-phase transport model, the HC mode better reproduces the data at 3.0 GeV. However, at 4.5 GeV, the SM mode exhibits better NCQ scaling, suggesting that the inclusion of partonic interactions significantly play a key role in enhancing the scaling behavior.

-
- [1] Y. Nara and A. Ohnishi, Phys. Rev. C **105**, 014911 (2022).
 - [2] Y. Nara, A. Jinno, K. Murase, and A. Ohnishi, Phys. Rev. C **106**, 044902 (2022).
 - [3] Z.-W. Lin et al., Phys. Rev. C **72**, 064901 (2005).
 - [4] G.-C. Yong, Phys. Lett. B **848**, 138327 (2024).
 - [5] J. Weil et al. (SMASH), Phys. Rev. C **94**, 054905 (2016).
 - [6] D. Molnar and S. A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003).
 - [7] S. A. Voloshin, J. Phys. Conf. Ser. **9**, 276 (2005).