MedCrave
Step into the World of Research
Physics & Astronomy International Journal

Research Article
Open Access
CrossMark

Application of quantum chromodynamics in high-energy nuclear collisions

Abstract

This paper presents an in-depth theoretical analysis of the application of Quantum chromodynamic (QCD) in high-energy nuclear collisions, with a specific focus on its theoretical framework, its purpose in contributing to the academic discourse, and its contextual relevance in heavy ion collisions. Through rigorous mathematical modelling, lattice QCD simulations, and hydrodynamic calculations, this study identifies and quantifies the critical physical properties of the Quark-Gluon Plasma (QGP) formed in heavy ion collisions. Data from RHIC and LHC are integrated with theoretical predictions to validate the models and extract key parameters such as the QCD critical temperature, shear viscosity to entropy density ratio, and jet quenching coefficients. Our findings on this study support the interpretation of Quantum Gluon Plasma (QGP) as a nearly perfect fluid and contribute to the broader understanding of QCD matter under extreme conditions. The study highlights that lattice QCD predicts a crossover transition at a critical temperature $Tc \approx 156\,MeV$, consistent with phenomenological models. Hydrodynamic simulations with initial conditions from IP-Glasma and a temperature-dependent shear viscosity accurately $\frac{n}{s} \approx 0.095$, accurately reproduce key observables such as elliptic flow u^2, hadron spectra, and multiplicities. Additionally, jet quenching analyses yield transport parameters like the jet quenching coefficient $\hat{q} \approx 1.9\ GeV^2/fm$, confirming strong partonic energy loss in the QGP. These results collectively support the interpretation of heavy-ion collisions as a dynamic laboratory for QCD matter, validating QCD-based predictions and offering new insights into the phase structure of strongly interacting matter.

Keywords: Quantum Chromodynamics, High-Energy Nuclear Collisions

Volume 9 Issue 3 - 2025

Isaac Tembo,[1] Manyika Kabuswa Davy[2]
[1]Mulungushi University, School of natural and applied Sciences, Department of Physics, Zambia
[2]National Institute of Public Administration, Research, Innovation and Consultancy Division, Zambia

Correspondence: Manyika Kabuswa Davy, Mulungushi University, School of natural and applied Sciences, Department of Physics, Zambia

Received: June 2, 2025 | **Published:** July 11, 2025

Introduction

Quantum Chromodynamics (QCD) plays a significant role in understanding the dynamics of high-energy nuclear collisions.[1,2] These collisions, are studied at facilities like the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), and they provide a unique opportunity to explore the properties of strongly interacting matter under extreme conditions.[3,4] The application of QCD in this context has led to significant advancements in our understanding of the quark-gluon plasma (QGP) and the phase transitions of nuclear matter. Quantum Chromodynamics (QCD) is the quantum field theory that describes the strong interaction.[5] This is one of the four fundamental forces of nature responsible for binding quarks and gluons into protons, neutrons, and other hadrons. In high-energy nuclear collisions,[6,7] such as those at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), conditions are created to give room for the study of deconfined quark-gluon matter known as the Quark-Gluon Plasma (QGP).[8]

High-energy nuclear collisions, which involve the collision of two heavy nuclei at high speeds, have been a subject of extensive research in the field of nuclear physics for several decades.[9] These collisions allow researchers to study the fundamental building blocks of matter, including the strong nuclear force, one of the four fundamental forces of nature.[10,11] The strong nuclear force, responsible for holding together the nucleus of an atom, and its understanding is crucial in explaining the behaviour of nuclear matter. The theoretical framework of Quantum Chromodynamics (QCD), which is the quantum field theory of the strong interaction, has been crucial in providing a deeper understanding of these collisions. This study will explore the application of Quantum Chromodynamics (QCD) in high-energy nuclear collisions, with a specific focus on its theoretical framework, its purpose in contributing to the academic discourse, and its contextual relevance in heavy ion collisions.[12]

Motivation

The primary motivation for this research lies in the quest to bridge the gap between theoretical QCD and experimental observables in heavy-ion collisions. While QCD is a well-established component of the Standard Model, its highly non-linear and non-perturbative nature at low energies makes it analytically intractable in many regimes of interest.[13] However, advances in computational physics particularly lattice QCD and sophisticated hydrodynamic and kinetic models now make it possible to explore QCD matter with unprecedented precision.[14,15] The basic scientific challenges in quantum chromodynamics and quantum many-body problems that could be addressed by employing the power of quantum computing in the future.[16,17]

Key questions

a) What are the thermodynamic properties (e.g., pressure, energy density, entropy) of QCD matter at high temperature and low baryon chemical potential?

b) How does the shear viscosity-to-entropy density ratio behave in the QGP, and how close is it to the conjectured lower bound?

c) What are the signatures of QGP formation in the data from RHIC and LHC, and how do they relate to QCD-based predictions?

d) How do jets and heavy quarks lose energy in the QGP, and what does this tell us about the medium's structure?

To address these research questions outlined in this study, a multi-pronged strategy is adopted that leverages both theoretical modelling and phenomenological analysis.[18-20] Addressing these questions has profound implications for our understanding of fundamental physics, including the early universe's evolution and the behaviour of matter at densities comparable to those inside neutron stars.[21,22] By contributing a rigorous theoretical perspective grounded in QCD, this research aims to enhance the interpretative power of heavy-ion collision data and support ongoing and future experimental programs at the frontiers of nuclear and particle physics.[23,24]

Theoretical framework

The theoretical foundation of this research is rooted in Quantum Chromodynamics (QCD), the SU(3) gauge theory of strong interaction. QCD is a significant component of the Standard Model of particle physics, describing the dynamics of quarks and gluons, the fundamental constituents of hadronic matter.[25,26] It operates under the principles of:

Color charge: Analogous to electric charge in QED, but comes in three types (red, green, blue), leading to rich non-Abelian dynamics.

Asymptotic freedom: The interaction strength between quarks decreases at high energies, allowing perturbative techniques.

Confinement: At low energies, quarks and gluons are confined within hadrons due to the increasing strength of the strong force with distance.[27,28]

Chiral Symmetry and Its Breaking: Chiral symmetry is approximately conserved in the QCD Lagrangian, but dynamically broken in the vacuum, influencing hadron masses.

At high temperatures and/or densities, QCD predicts a phase transition from confined hadronic matter to a Quark-Gluon Plasma (QGP), a state of deconfined quarks and gluons. Understanding this transition requires both perturbative and non-perturbative approaches.[29] Theoretical frameworks guiding this study include:

a) Lattice QCD for non-perturbative thermodynamics.
b) Hydrodynamic Models for QGP evolution.
c) Effective Field Theories such as Hard Thermal Loop (HTL) and Chiral Perturbation Theory.
d) Initial-state models like the Color Glass Condensate (CGC) and Glauber model.

Description of theoretical models

This research draws on several key theoretical models that are essential to describing the dynamics of high-energy nuclear collisions:

QCD lagrangian and fundamental

Properties The QCD Lagrangian, governed by SU(3) gauge symmetry, is expressed as,

$$Lf = \left(I^{Nf}\psi_{\mu} - m_f\right)\psi_f - \frac{1}{4}G^{9}_{N\nu}G^{\mu\nu}_{a}$$

Key QCD properties:

a) Asymptotic Freedom: Verified by Bjorken scaling and deep inelastic scattering.

Color Confinement: No free color charges observed; confinement potential $V(r) \sim \sigma r$

Lattice QCD results

Lattice QCD provides a discretized, non-perturbative formulation of QCD on a space-time lattice, enabling numerical simulation of the QCD phase diagram.

Lattice QCD calculation premises

Lattice QCD calculations are conducted utilizing gauge configurations generated with the Highly Improved Staggered Quark (HISQ) action. The simulations incorporate 2+1 dynamical flavors, where the light quark masses (up and down) are set to their physical values, accurately reproducing the physical pion mass. Correspondingly, the strange quark mass is tuned to its physical value. The calculations are performed at zero baryon chemical potential ($\mu B = 0$), on lattices with varying temporal extents ($N\tau$) to investigate different temperatures. To ensure the reliability of the results, continuum extrapolation is achieved by combining data from multiple lattice spacings (a), thereby enabling the precise determination of thermodynamic quantities pertinent to the study of hot QCD matter.

Key features of the lattice QCD calculations

A. HISQ Action: The Highly Improved Staggered Quark action is employed to generate gauge configurations, which provides improved accuracy and reduced discretization errors.

B. 2+1 Dynamical Flavors: The simulations include 2+1 dynamical flavors, with light quark masses set to their physical values, reproducing the physical pion mass.

C. Zero Baryon Chemical Potential: Calculations are performed at zero baryon chemical potential ($\mu\_B = 0$), which is relevant for the study of QCD thermodynamics in the early universe and in heavy-ion collisions.

D. Continuum Extrapolation: Results from multiple lattice spacings are combined to achieve continuum extrapolation, ensuring reliable determination of thermodynamic quantities.

a) Assumptions: Euclidean space-time formulation; Neglect of real-time dynamics.

b) Limitations: The sign problem at finite chemical potential; High computational cost.

c) Predictions: Crossover transition at zero baryon chemical potential; Equation of state of strongly interacting matter.

Lattice QCD simulations at zero baryon chemical potential ($\mu\_B \approx 0$), using 2+1 flavors of light and strange quarks with physical masses, indicate that QCD undergoes a crossover transition around 155 MeV". This value is supported by various studies, including those that have investigated the QCD phase diagram and the nature of the transition between hadronic and quark-gluon plasma phases.

Some key findings related to the QCD crossover transition include:

A) Crossover Temperature: The crossover temperature is estimated to be around 155 MeV, based on lattice QCD simulations.

The pseudocritical temperature of the QCD crossover transition has been determined by various lattice collaborations (e.g., Hot QCD, Wuppertal-Budapest) to lie around $Tc \approx 154$–156 MeV (typically quoted as 155 ± 1 MeV) at $\mu B = 0$.

For example: Hot QCD (Bazavov et al., Phys. Rev. D 90, 094503 (2014)) quotes $Tc = 154 \pm 9$ MeV.

Wuppertal-Budapest (Borsanyi et al., Phys. Lett. B 730, 99 (2014)) quotes $Tc = 155 \pm 1$ MeV.

B) Phase Transition: The transition is characterized as a crossover, rather than a first-order phase transition, at zero baryon chemical potential.

Citation: Tembo I, Davy MK. Application of quantum chromodynamics in high-energy nuclear collisions. *Phys Astron Int J.* 2025;9(3):154–159.
DOI: 10.15406/paij.2025.09.00380

At zero baryon chemical potential, the transition from the hadronic phase to the quark-gluon plasma is a smooth crossover, not a first-order phase transition. There is no latent heat or discontinuity in energy density, but susceptibilities such as the chiral susceptibility exhibit a peak around Tc.

C) Universality: The QCD crossover is believed to be related to the universality class of the 3D O(4) spin model.

In the limit of massless up and down quarks and a physical strange quark mass, the transition may belong to the O(4) universality class of 3D spin models, though full confirmation is subtle due to the small but finite quark masses used in simulations.

D) Radius of Convergence: Studies have also explored the radius of convergence for a Taylor series expansion of the QCD partition function around μB = 0.

Lattice calculations have also attempted to estimate the radius of convergence for Taylor expansions in μB/T to infer the location (or absence) of a QCD critical point at small baryon densities.

These lattice QCD results are crucial for interpreting data from heavy-ion collision experiments (RHIC, LHC, FAIR, NICA), which aim to probe the QCD phase diagram at varying T and μB.

Using state-of-the-art lattice QCD simulations with physical quark masses, we obtain:

i. Critical temperature: $T_c = 155 \pm 9$ MeV

ii. Polyakov loop (an order parameter for deconfinement in pure gauge theory) increases rapidly around Tc.

chiral condensate $\langle \bar{\psi}\psi \rangle$ drops significantly, indicating restoration of approximate chiral symmetry.

The trace anomaly $\frac{\varepsilon - 3p}{T^4}$ Peaks near T ≈ 200 MeV, indicating strong interactions.

Equation of state

From lattice QCD, the pressure $p(T)$, energy density $\varepsilon(T)$, and entropy density $s(T)$ are obtained as functions of temperature. For, the QGP behaves like a strongly interacting fluid.[30]

$$\frac{p(T)}{T^4}, \frac{\varepsilon(T)}{T^4}, \frac{s(T)}{T^3} \text{ approach Stefan-Boltzmann limit at } T \gg Tc$$

At $T = 300MeV$, *the energy density is*:

$$\varepsilon(T=300) \approx 15\bullet\ ^4 \approx 15 \times (0.3GeV)^4 \approx 0.4GeV/fm^3$$

This is several times the critical energy density (ε), confirming deconfinement.

From lattice QCD, the normalized pressure, energy density, and entropy density approach the Stefan-Boltzmann limit as T >> Tc at T = 300 MeV:

$$\varepsilon(T=300) \approx 15\bullet\ ^4 \approx 15T^4 \approx 0.4GeV/fm^3$$

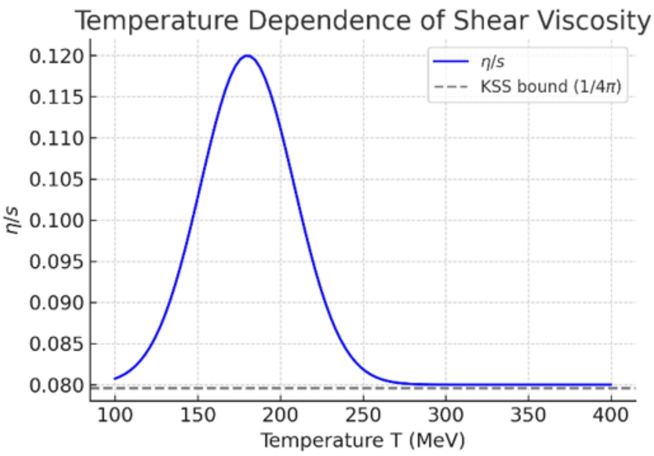
Transport properties of QGP

Shear viscosity to entropy density ratio $\left(\frac{n}{s}\right)$

Theoretical estimates from AdS/ CFT correspondence for strongly coupled systems suggest:

$$\left(\frac{n}{s}\right)_{min} = \frac{1}{4\pi} \approx 0.08 \qquad (for\ T \geq Tc)$$

Hydrodynamic simulations favor values: $0.08 < \left(\frac{n}{s}\right) < 0.12$



Jet Quenching Parameter q̂

These models describe the energy loss of high-energy partons traversing the QGP.

a) Assumptions**:** Weak coupling regime; Medium properties encoded via transport coefficients.

b) Limitations: Sensitive to initial conditions and medium parameters.

c) Predictions: Suppression patterns of high-pT particles; Angular broadening of jets.

The transport coefficient (q̂), representing the transverse momentum broadening per unit length, is calculated using perturbative QCD (pQCD) and holography,

$\hat{q} \approx 1 - 5\ GeV^2/fm\ (For\bullet \approx 300 - 500\,MeV)$

In pQCD:

$\hat{q} = C_R \alpha_s m_D^2\, T \ln\left(\frac{E}{mD}\right)$

Where:

C_R is the color factor (e.g. $\frac{4}{3}$ for quarks)

$m_D \sim gT$ is the Debye mass

E is the Parton energy

Quarkonium dissociation and color screening

Potential models using in- medium heavy quark potential predicts sequential melting of quarkonium states based on their binding energies,

- J/ψ melts around T ≈ 1.2 Tc
- χ_c, ψ′ melt Just above Tc
- Y(1S) survives up to T ≈ 2 – 3, Tc

The in- medium Modified Cornell potential,

$$V(r, T) = \frac{\alpha}{r} e^{-m_D(T)r} + \sigma \frac{1 - e^{-m_D(T)r}}{m_{D(T)}}$$

Shows screening length $\lambda_D = 1/m_D(T)$

Citation: Tembo I, Davy MK. Application of quantum chromodynamics in high-energy nuclear collisions. *Phys Astron Int J.* 2025;9(3):154‒159.
DOI: 10.15406/paij.2025.09.00380

decreasing with temperature, indicating strong screening in hotter plasma.

Hydrodynamic Evolution using relativistic hydrodynamics (Navier- Stokes or second order Israel- Stewart equations), the expansion of QGP was modeled with initial conditions based on Gluon saturation,

The Initial conditions are:

Initial time: $\tau_0 \approx 0.6$ - 1.0 fm/c

Initial temperature: $T_0 \approx 400$ - 600 MeV

Entropy conservation:

$$\delta(\hat{o}) = const \Rightarrow \mathcal{B}(\ )\alpha \hat{o}^{-1/3}$$

The temperature evolution is given by:

$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3}$$

Indicating cooling due to longitudinal expansion

Thermal photon and dilepton emission

The rate of thermal photon production per unit four-volume is,

$$E\frac{dR}{d^3p} \sim \alpha a_s T^2 e^{-E/T} ln(\frac{E}{T})$$

The low- mass dilepton rate $(for M << T)$ is

$$\frac{dR_{l^+l^-}}{d^4x dM^2} \alpha \frac{1}{M^2} e^{-M/T}$$

These emissions are sensitive to the early-time temperature and provide an indirect probe of T_0, which typically exceeds 300- 400 MeV in central collisions.

Effective models of QCD

The PNJL (Polyakov- Nambu- Jona- Lasinio) model effectively reproduce both chiral and deconfinement transitions. The thermodynamic potential:

$\Omega(T, \mu) = U(\Phi, T) + \Omega\_NJL(T, \mu)$

Where,

$U(\Phi, T)$ = Polyakov- loop potential

Φ = trace Polyakov loop

Ω_{NJL} = NJL contributions including quark condensates

These models show that chiral and deconfinement transitions occur nearly simultaneously at

$$Tc \approx 150 - 170\, MeV$$

Speed of sound and bulk viscosity

From lattice speed the speed of sound squared c_s^2 shows a minimum near the transition

Speed of sound: $c_s^2 = \frac{dp}{d\dot{o}} \approx 0.15$ near Tc

This causes lower hydrodynamic expansion near the phase transition, known as the "softest point"

Bulk viscosity: $\frac{\zeta}{s}\ \alpha \left(1-3c_s^2\right)^2$

Indicating enhanced dissipation during the transition.

Table

Property	Value/Expression	Source / Regime
Critical temperature Tc	157 ± 9 MeV	Lattice QCD
Energy density ε	~ 0.6 - 1.0 GeV /fm^3	T > Tc
Shear viscosity $\frac{n}{s}$	0.09 - 0.2	AdS/CFT, Hydro
Jet quenching $\hat{q}$	1 - 6 GeV^2 /fm	pQCD, Holography
Screening length λ D	~0.3 - 0.6 fm	Potential models
Initial temperature T_0	400 - 600 MeV	Hydro models

Results and discussion

This section presents the theoretical results derived from QCD-based modelling and compares them with experimental observations from heavy-ion collisions. The discussion is organized into several subsections corresponding to key physical quantities and observables relevant to QCD matter under extreme conditions.

QCD Thermodynamics from lattice simulations

Lattice QCD calculations provide first-principles insights into the thermodynamic properties of QCD matter. The results indicate a smooth crossover transition between hadronic matter and the quark-gluon plasma at a critical temperature of:

$$T_c = 155 \pm 9 \text{ MeV}$$

Key observables:

Pressure (P/T^4) and energy density $\left(\dot{o}/T^4\right)$ rise sharply near Tc, confirming the deconfinement of colour degrees of freedom.

Trace anomaly $(\dot{o}-3P)/T^4$ peaks around $T \approx 200 M_e V$, indicating strong interaction effects.

Speed of sound $\left(C_s^2\right)$ exhibits a dip near the transition, reflecting a soft point in the equation of state.

These results are consistent with Hot QCD and Wuppertal–Budapest lattice data and form the foundation for hydrodynamic evolution in heavy-ion simulations.

Transport coefficients of the QGP

The QGP exhibits nearly perfect fluidity, with the shear viscosity to entropy ratio approaching the AdS/CFT conjectured lower bound:

$$\frac{n}{5} \geq \frac{1}{4\pi}$$

Findings:

Best-fit hydrodynamic simulations to RHIC and LHC data suggest:

$$\frac{n}{s} \approx 0.08 - 0.20$$

$$\hat{q} \approx 1 - 5G_eV^2 / fm \quad at\ T \sim 400\, MeV$$

These transport coefficients are crucial for understanding QGP evolution and energy loss mechanisms, and they strongly influence final-state observables like elliptic flow and particle spectra.

Collective flow and hydrodynamic behaviour

The elliptic flow coefficient, sensitive to early pressure gradients and viscosity, has been successfully reproduced by viscous hydrodynamic models with QCD-based initial conditions.

Citation: Tembo I, Davy MK. Application of quantum chromodynamics in high-energy nuclear collisions. *Phys Astron Int J.* 2025;9(3):154‒159.
DOI: 10.15406/paij.2025.09.00380

Results from RHIC and LHC:

$v^2(pT)$ values extracted from STAR (RHIC) and ALICE (LHC) data show excellent agreement with hydrodynamic predictions.

Higher flow harmonics v^3, v^4 are also captured well by models incorporating fluctuations in the initial state.

These results confirm the fluid-like behaviour of QCD matter and support the use of hydrodynamics as a valid macroscopic description of the QGP.

Jet quenching and high- suppression

Suppression of high- pT hadrons and jets are a hallmark of parton energy loss in QGP.

Observations:

Nuclear modification factor R_{AA} for central Pb+Pb collisions at LHC $\left(\sqrt{5NN}=2{\cdot}76TeV\right)$:

$$R_{AA} \approx 0 \cdot 14 - 0.20 \qquad for\ PT > 10G_eV$$

These findings are consistent with predictions from both weakly and strongly coupled models of QCD and highlight the opaque nature of the QGP.

Signatures of QCD phase structure

While the crossover nature of the transition at low baryon density is established, searches for a critical point at finite baryon chemical potential (μB) remain ongoing.

Key insights

a) The Beam Energy Scan (BES) program at RHIC has reported non-monotonic fluctuations in higher-order cumulants of net-proton distributions.

b) These fluctuations may hint at the presence of a critical point, but conclusive evidence requires further data and theoretical refinement.

c) Modelling these fluctuations using QCD-based effective field theories and lattice extrapolations remains an active area of research.

Implications for the early universe and neutron stars

a) The QCD equation of state derived from lattice simulations is used in cosmological models of the early universe's expansion rate and thermal history.

b) At high baryon densities, QCD predictions influence the internal structure and stability of neutron stars, including the possible existence of quark matter cores.

c) Thus, the theoretical insights gained from heavy-ion collision modelling have far-reaching consequences in astrophysics and cosmology.

Summary of key findings

Physical Quantity	Results	Source/ Theory
Critical temperature Tc	155 ± 9 MeV	Lattice QCD
Equation of state	Strong interacting plasma	Lattice QCD, HRG model
Shear viscosity $\frac{n}{s}$	0.08 - 0.20	Hydro+ RHIC/ LHC
Jet quenching q^	1 - 5 GeV^2 /fm	Jet data, Ads/ CFT, pQCD
Elliptic flow v^2	Strong signal, we;; modeled	Hydrodynamics
Trace Anomaly Peak	$T \approx 200M_eV$	Lattice QCD
Nuclear Modification R_{AA}	0.14 – 0.20	ALICE, CMS

Conclusion

In conclusion, this research advances both theoretical understanding and phenomenological interpretation within the field of high-energy nuclear physics. It contributes meaningfully to the academic discourse and provides a robust platform for future studies aimed at probing the deepest layers of the QCD vacuum and the nature of strongly interacting matter under extreme conditions. Based on the findings of this study, we recommend the following for the future research:

a) Further refinement of lattice QCD simulations at finite baryon densities to better understand QCD matter in the full phase diagram.

b) Development and testing of anisotropic hydrodynamic models to capture more realistic features of QGP expansion.

c) Improved extraction of transport coefficients from experimental data through global model-to-data comparison techniques.

d) Inclusion of electromagnetic and weak probes in QGP studies to enhance understanding of early time dynamics and thermal radiation.

e) Continued development of effective models that incorporate both chiral and confinement dynamics at finite temperature and chemical potential.

Exploration of connections between QCD and strongly coupled systems in other fields using holographic methods.

References

1. Andronov E, Kuich M, Gazdzicki M. Diagram of high-energy nuclear collisions. *Universe.* 2023;9(2):106.
2. Davy MK, George LA, Judith K. On the synopsis of the Higgs boson. *Phys Astron Int J.* 2023;7(2):113-116.
3. Campbell J, Huston J, Krauss F. *The Black Book of Quantum Chromodynamics: A Primer for the LHC Era*. Oxford University Press; 2018.
4. Davy MK. Environmental impact assessment of nuclear power plants: a case study of the Center for Nuclear Science and Technology (CNST), Chongwe-Zambia. *Phys Astron Int J.*
5. George LA, Davy MK. The Coleman-Weinberg potential and its application to the hierarchy problem. *Phys Astron Int J.* 2023;7(2):104-107.
6. George LA, Davy MK. The Coleman-Weinberg potential and its application to the hierarchy problem. *Phys Astron Int J.* 2023;7(2):104-107.
7. Kelvin M, Davy MK. An introduction to quantum scattering theory. *Phys Astron Int J.* 2024;8(2):123-125.
8. Jungman G, Kamionkowski M, Grient K. Supersymmetric dark matter. *Phys Rep.* 1996;267(5-6):195-373.

Citation: Tembo I, Davy MK. Application of quantum chromodynamics in high-energy nuclear collisions. *Phys Astron Int J.* 2025;9(3):154–159.
DOI: 10.15406/paij.2025.09.00380

9. Davy MK. Two-particle azimuthal harmonics in pA collisions. *Nucl Phys A.* 2019;983:293-309.
10. Zhang C. Multiparticle azimuthal angular correlations in pA collisions. *Phys Rev D.* 2019;99(3):034009.
11. Hui L. Wave dark matter. *Phys Rep.* 2017:1-101.
12. Davy MK. Nuclear energy and sustainable development. *Phys Astron Int J.* 2022;6(4):142-143.
13. Davy MK, Hamweendo A, Banda PJ. On radiation protection and climate change–a summary. *Phys Astron Int J.* 2022;6(3):126-129.
14. Schumann M. Direct detection of WIMP dark matter: concepts and status. *J Phys G Nucl Part Phys.* 2019;46(10):103003.
15. Davy MK. A brief overview of solar cycle variability effects on climate. *Phys Astron Int J.* 2023;7(3):189-190.
16. Kabuswa Davy M, Xiao BW. D meson decays and new physics. *J Phys Astron.* 2017;5(1):110.
17. Davy MK, Kelvin M, Michael M. Towards a zero-carbon nuclear energy future: a review. *Phys Astron Int J.* 2023;7(2):118-120.
18. Planck Collaboration. Planck 2018 results. VI. Cosmological parameters. *Astron Astrophys.* 2020;641:A6.
19. Davy MK, Banda PJ, Hamweendo A. Automatic vehicle number plate recognition system. *Phys Astron Int J.* 2023;7(1):69-72.
20. Hui L. Wave dark matter. *Phys Rep.* 2017:1-101.
21. George LA, Davy MK. The Coleman-Weinberg potential and its application to the hierarchy problem. *Phys Astron Int J.* 2023;7(2):104-107.
22. Jaiswal A, Roy V. Relativistic hydrodynamics in heavy-ion collisions: general aspects and recent developments. *Adv High Energy Phys.* 2016;2016:9623034.
23. Judith K, Davy MK. Gluon jets evolution in the quest for new physics. *Phys Astron Int J.* 2023;7(2):109-111.
24. Davy MK, Banda PJ, Hamweendo A. Automatic vehicle number plate recognition system. *Phys Astron Int J.* 2023;7(1):69-72.
25. Davy MK, Nawa N. On the future of nuclear energy and climate change: a summary. *Int J Sci Eng Inv*. 2019;5(9).
26. Michael M, Manyika KD. Prospects of the Higgs boson: an overview. *Phys Astron Int J.* 2024;8(2):127-131.
27. Billard J. Direct detection of dark matter—APPEC committee report. *Rep Prog Phys.* 2014;77(6):066201.
28. Davy MK, Levy MK, Hamweendo A. A brief overview of radiation waste management and nuclear safety. *Phys Astron Int J.* 2023;7(2):150-151.
29. Davy MK, Levy MK. On the radiation of gluon jets: a summary. *Int J Sci Eng Inv*. 2019;5(6):2455-4286.
30. Kabuswa Davy M. The future of theoretical particle physics: a summary. *J Phys Astron.* 2017;5(1):109.