

A Coupled Source Description of Pseudorapidity Distributions from RHIC to LHC: Emergent $1/\mu_B$ Scaling and Limiting Fragmentation

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ABSTRACT: One of the most remarkable observations in heavy-ion collisions is the systematic regularity exhibited by pseudorapidity distributions of charged particles across collision energies. While single-source models fail at higher energies and independent multi-source approaches do not reproduce the central dip observed at LHC energies, a unified description across the full RHIC-LHC energy range remains elusive. These distributions from Au+Au collisions at RHIC ($\sqrt{s_{NN}} = 19.6\text{--}200$ GeV) and Pb+Pb collisions at LHC ($\sqrt{s_{NN}} = 2.76\text{--}5.36$ TeV) are analyzed using a novel parametrization based on coupled Gaussian sources where the interaction strength is quantified by parameter λ . This coupled two-source model captures the interaction between forward and backward sources through the medium formed in the collision. Remarkably, λ exhibits empirical scaling behavior resembling $1/\mu_B$, suggesting sensitivity to baryon stopping and the strongly-interacting medium. All fitting parameters follow systematic energy trends, with the peak-to-peak distance and chemical freeze-out temperature exhibiting identical exponential saturation patterns, indicating that geometric expansion and thermal evolution share a common underlying dynamics governed by QCD phase structure. Furthermore, the approach naturally preserves limiting fragmentation behavior across all energies, in contrast to independent source models that suggest its violation at LHC energies. Although the theoretical basis requires further investigation, these empirical correlations successfully unify charged particle production across nearly two orders of magnitude in collision energy, revealing fundamental connections to underlying collision dynamics.

KEYWORDS: Heavy-Ion Collisions, Pseudorapidity Distribution, Baryon Stopping, Scaling Behavior, RHIC, LHC, Coupled two-source model.

Contents

1	Introduction	1
2	Parametrization of Pseudorapidity Distributions	4
3	Physical Interpretation and Predictive Capability	8
3.1	Energy Scaling of the Modulation Parameter	8
3.2	Peak-to-Peak Distance and System Size	10
3.3	Predictive Capability: Extension to Incomplete Pseudorapidity Coverage	11
3.4	Limiting Fragmentation Behavior	11
4	Summary and Conclusions	14

1 Introduction

Heavy-ion collisions have become the standard tool for studying the deconfined state of partons (QGP) [1–5]. The exact mechanism of particle production and the size of the QGP medium remain a mystery in heavy-ion experiments. The complexity of heavy-ion collisions makes it impossible to directly measure every relevant quantity [6]. Although experiments provide direct access to certain observables, extracting other characteristics of the system requires theoretical modeling and interpretation of the measured distributions [6, 7]. Pseudorapidity density distribution of charged hadrons is one of the most fundamental observables that can be studied to extract information about the collision dynamics. Using these distributions at energies from RHIC and the highest LHC energies, this study attempts to uncover systematic patterns in particle production and to extract information about source characteristics and their evolution with collision energy. The shape and width of pseudorapidity distributions encode crucial information about the longitudinal dynamics, source separation, and the degree of baryon stopping.

In the literature, single-source and multi-source descriptions have been used to model the rapidity and pseudorapidity distributions of charged particles [8–12]. One of the simplest and earliest approaches is the Landau hydrodynamic model [13, 14], which describes these distributions using a single Gaussian-like form and assumes full stopping for nucleus-nucleus collisions [15, 16]. The original Landau distribution is given by $dN/d\lambda \propto \exp\{\sqrt{L^2 - \lambda^2}\}$, where $L = \ln(\sqrt{s_{NN}}/2m_p)$ represents the logarithm of the Lorentz contraction factor [8, 13, 14]. However, a fundamental ambiguity persists regarding whether the variable in Landau’s formulation represents rapidity (y) or pseudorapidity (η). In Landau’s original work, the variable was used to represent the polar angle through the relation $e^{-\lambda} = \theta$, leading to ongoing debate about the appropriate kinematic variable (

y [8, 17] or η [18, 19]). Wong reexamined this formulation and proposed a modified distribution $dN/dy \propto \exp\{\sqrt{y_b^2 - y^2}\}$, where $y_b = \ln(\sqrt{s_{NN}}/m_p)$ is the rapidity of the beam nucleon, which can be well approximated by a Gaussian form $dN/dy \propto \exp\{-y^2/2L\}$ [20]. This Gaussian representation has shown good agreement with experimental data from AGS to RHIC energies, typically within 5-10% (see, e.g., BRAHMS results [21–23] and Refs. [17, 24]). The model also accurately captures the energy dependence of total charged multiplicity and exhibits limiting fragmentation at forward rapidities [17, 24].

Despite these successes at lower energies, the single Gaussian Landau description encounters significant limitations at higher collision energies [25, 26]. As shown in Figure 1 (left), while the Landau form adequately describes pseudorapidity distributions at $\sqrt{s_{NN}} = 19.6$ GeV, it fails to capture the shape evolution observed at RHIC and LHC energies. The distributions exhibit a transition from narrow (low energy) to broad (high energy) shapes, developing double-humped or asymmetric features that cannot be explained by a single Gaussian.

This evolution reflects the transition from the stopping regime to the transparency regime. It is now understood that nucleus-nucleus collisions at RHIC energies are neither fully stopped nor fully transparent [15, 16, 27]. Incident nuclei penetrate the target, incomplete energy deposition leads to reduced baryon stopping, and the collision energy becomes distributed across different rapidity regions [28]. A significant portion is deposited in the collision region to form a central fireball, while the penetrating matter contributes to particle production in the forward and backward rapidity regions. The observed charged hadron pseudorapidity distribution thus represents the combined contributions from these multiple sources. Consequently, multi-component descriptions beyond the single Landau form become necessary to capture the rich structure of pseudorapidity distributions at modern collider energies.

To connect theoretical models with experimental measurements, conversions between rapidity and pseudorapidity distributions are frequently employed using Jacobian transformations [29, 30]. However, at LHC energies, the standard Jacobian transformation does not fully describe the pseudorapidity distribution near midrapidity [31, 32]. Furthermore, Liu et al. [30] demonstrated that the commonly used Jacobian conversion formulas are incomplete, as they erroneously treat the transverse momentum as a given quantity rather than an integrated variable, leading to systematic biases. This limitation motivates the direct modeling of pseudorapidity distributions without relying on rapidity-to-pseudorapidity conversions.

An alternative approach adopted in the literature is the double Gaussian method, which models the distribution as a sum of two independent Gaussian sources [33, 34]:

$$\frac{dN}{d\eta} = A_1 \exp\left\{-\frac{(\eta - \eta_1)^2}{2\sigma_1^2}\right\} + A_2 \exp\left\{-\frac{(\eta - \eta_2)^2}{2\sigma_2^2}\right\}. \quad (1.1)$$

The functional form of this distribution reflects both the contributions from the colliding nuclei and the extent of nuclear stopping occurring during the interaction. This formulation has proven successful at RHIC energies, providing a good description of Au+Au collisions from $\sqrt{s_{NN}} = 19.6$ to 200 GeV with a smooth evolution of fit parameters [33].

However, the double Gaussian approach encounters significant challenges at LHC energies, particularly at $\sqrt{s_{NN}} = 2.76$ TeV and above. This discrepancy is already evident at $\sqrt{s_{NN}} = 2.76$ TeV, as shown in Figure 1 (right). Most critically, the double Gaussian model cannot reproduce the central dip observed near $\eta \approx 0$ at LHC energies, which arises from the incomplete overlap of forward-backward sources and leading particle effects as the collision dynamics shifts from the stopping-dominated regime to the transparency regime [26]. The assumption of independent sources becomes physically untenable when the sources are expected to interact through the strongly-coupled medium formed in the collision.

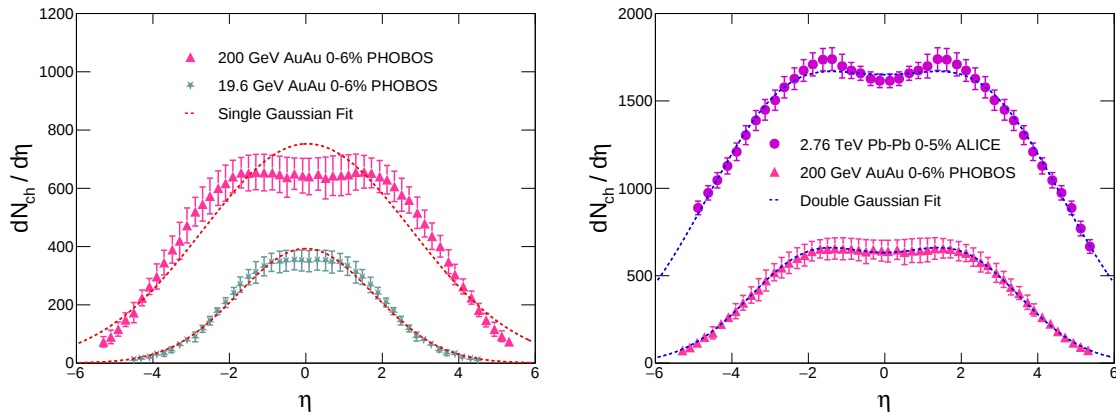


Figure 1: (color online) Limitations of traditional parametrizations. Left: Single-Gaussian fits to PHOBOS data at $\sqrt{s_{NN}} = 19.6$ and 200 GeV, illustrating the inability of a single source component to describe the broad midrapidity plateau at higher energies. Right: Double-Gaussian fits to PHOBOS (200 GeV) and ALICE (2.76 TeV) data, showing that even two independent sources fail to reproduce the characteristic central dip observed at LHC energies.

To overcome these limitations, this study introduces a novel fitting approach based on coupled Gaussian sources modulated by an error function. Unlike independent multi-source models, the present framework incorporates the interaction between sources through a modulation factor of the form $[1 + \text{erf}(\lambda\eta)]$, where the parameter λ quantifies the strength of coupling between the forward and backward sources. This approach successfully unifies the description of charged particle production from RHIC to the highest LHC energies, revealing systematic energy trends in the fitting parameters that connect geometric expansion with thermal evolution of the system.

The remainder of this paper is organized as follows. In Section 2, the coupled two-source parametrization with error-function modulation is introduced, along with the physical motivation for this formulation, and the systematic energy dependence of the extracted fitting parameters from RHIC and LHC data is presented. Section 3 provides a physical interpretation of key parameters, examining the empirical connection between the coupling parameter λ and the baryon chemical potential μ_B , as well as the relationship between

peak-to-peak distance and system thermodynamics. This section also validates predictive capability of the framework through fits to incomplete pseudorapidity coverage at $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV, and tests consistency with limiting fragmentation behavior. Finally, Section 4 summarizes findings and discusses implications for understanding the evolution of collision dynamics from RHIC to LHC energies.

2 Parametrization of Pseudorapidity Distributions

To capture the coupled nature of particle production sources in heavy-ion collisions, we propose a modified two-source Gaussian parametrization with error function modulation:

$$\frac{dN_{\text{ch}}}{d\eta} = A_1 \exp\left\{-\frac{(\eta - \mu_1)^2}{2\sigma_1^2}\right\} [1 + \text{erf}(-\lambda_1\eta)] + A_2 \exp\left\{-\frac{(\eta - \mu_2)^2}{2\sigma_2^2}\right\} [1 + \text{erf}(\lambda_2\eta)], \quad (2.1)$$

where A_1 and A_2 are the amplitude parameters characterizing the strength of the backward and forward sources, respectively; μ_1 and μ_2 are the mean positions of the Gaussian components in pseudorapidity space (with $|\mu_1| \approx |\mu_2|$ expected from symmetry); σ_1 and σ_2 are the width parameters describing the longitudinal extent of each source; and λ_1 and λ_2 are the error function modulation parameters that control the coupling between sources.

The key innovation in Eq. (2.1) is the error function modulation factor $[1 + \text{erf}(\lambda\eta)]$. This term introduces asymmetry and coupling between the forward and backward sources, allowing the parametrization to capture the central dip observed at higher collision energies. Importantly, the error function modulation primarily affects the region near midrapidity ($\eta \approx 0$), while the distributions retain their Gaussian character away from the central region, near the peak positions $\mu_{1,2}$. This localized modification is physically motivated by the fact that midrapidity represents the region of maximum overlap between the colliding nuclei, where medium effects are strongest.

The physical picture underlying this parametrization can be understood from the energy evolution of particle production mechanisms [26, 31]. At lower RHIC energies ($\sqrt{s_{NN}} \lesssim 20$ GeV), fragmentation sources dominate, leading to relatively symmetric distributions well-described by independent Gaussians. However, at higher energies, particle production at midrapidity becomes increasingly influenced by gluon-gluon interactions in the strongly-coupled medium [26]. Rather than explicitly modeling separate gluonic and fragmentation sources, the present approach phenomenologically captures their combined effect through the error function modulation: small λ values (weak modulation) correspond to the near-independent source regime at lower energies, while larger λ values (strong modulation) reflect the enhanced medium effects and modified particle production at midrapidity characteristic of higher energies. The observed central dip emerges naturally from this coupling, consistent with the growing importance of midrapidity gluonic contributions.

Figure 2 illustrates both the schematic representation of the two-source picture and the application to experimental data. The left panel shows a schematic decomposition at $\sqrt{s_{NN}} = 2.76$ TeV, where the blue and green hatched areas represent the contributions from forward and backward sources originating from the projectile and target nuclei, respectively. The overlap region (pink hatched area) visualizes the degree of source interaction and

nuclear stopping achieved in the collision. The extent of this overlap is directly related to the central structure of the distribution. Reduced overlap results in a pronounced dip at $\eta \approx 0$, while increased overlap leads to a flatter distribution. The error function modulation $[1 + \text{erf}(\lambda\eta)]$ modifies the tails of each Gaussian source toward the central region, causing them to fall off more rapidly than a pure Gaussian. This modification phenomenologically captures the coupling and interaction between the two sources through the medium formed in the overlap region. The parameter λ thus quantifies the strength of this interaction, increasing with collision energy as the medium effects become more pronounced.

The parametrization has been applied to experimental data from Au+Au collisions at RHIC energies ($\sqrt{s_{NN}} = 19.6, 62.4, 130$, and 200 GeV) [27, 35, 36] and Pb+Pb collisions at LHC energies ($\sqrt{s_{NN}} = 2.76, 5.02$, and 5.36 TeV) [25, 37, 38]. The fits are performed using binned χ^2 minimization implemented in the ROOT framework’s Minuit2 package [39]. All fits are performed for the 0-5% most central collisions to minimize geometric fluctuations.

The right panel of Figure 2 demonstrates the fitting results across all collision energies from RHIC to LHC. The parametrization provides excellent agreement with experimental data, capturing both the broadening of distributions with energy and the emergence of the central dip at LHC energies. Notably, at $\sqrt{s_{NN}} = 2.76$ TeV, this approach yields $\chi^2/\text{ndf} = 0.373$, significantly improved compared to the double Gaussian fit, which fails to reproduce the concave structure near midrapidity.

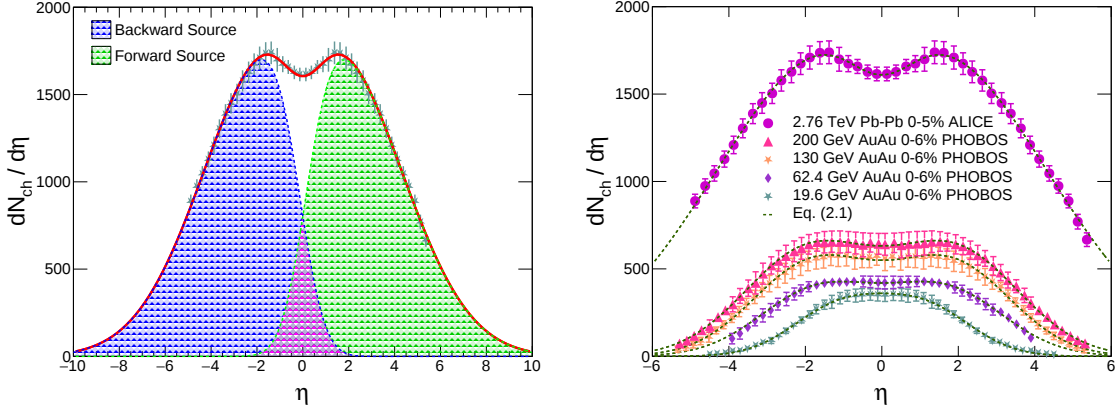


Figure 2: (color online)(Left) Schematic illustration of the two-source picture with error function modulation for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The blue and green hatched areas represent contributions from forward and backward sources; the pink overlap region visualizes source interaction near midrapidity. (Right) Pseudorapidity distributions of charged particles in central (0-5%) Au+Au collisions at RHIC and Pb+Pb collisions at LHC. Points represent experimental data, dashed curves show fits using Eq. (2.1).

The extracted fit parameters are presented in Figures 3–6 as a function of collision energy. All the errors shown in these figures correspond to the uncertainties from the fitting procedure. The fit parameters follow systematic trends with collision energy:

- (i) The amplitude parameters A_1 and A_2 , shown in Figure 3, increase with collision

energy as expected from the increasing particle multiplicity at higher energies.

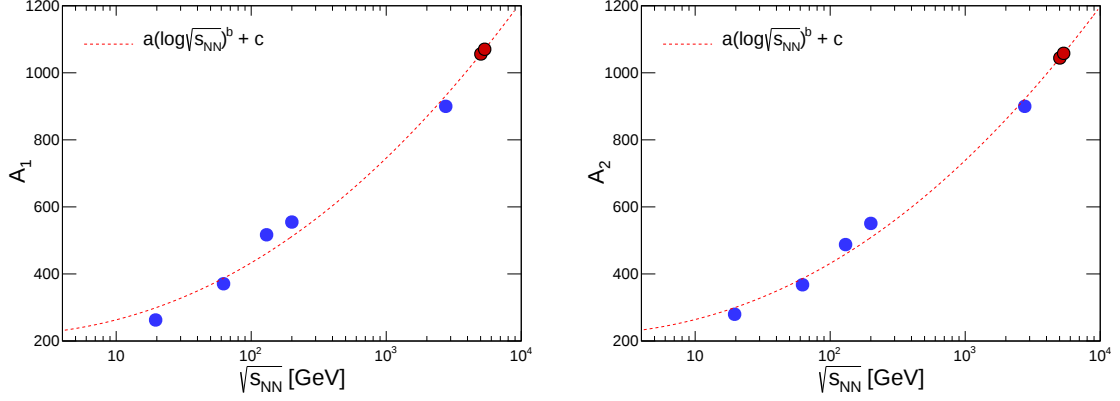


Figure 3: (color online) Energy dependence of the fitted amplitude parameters A_1 (left) and A_2 (right). The dashed red curves correspond to fits using the functional form $a(\log \sqrt{s_{NN}})^b + c$, demonstrating a systematic increase of both amplitudes with collision energy. The dark red circles indicate the extrapolated values at $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV.

(ii) The width parameters σ_1 and σ_2 , shown in Figure 4, increase systematically with collision energy, reflecting the longitudinal expansion of the system. The systematic increase in widths from RHIC to LHC energies quantifies the transition toward greater transparency and reduced baryon stopping.

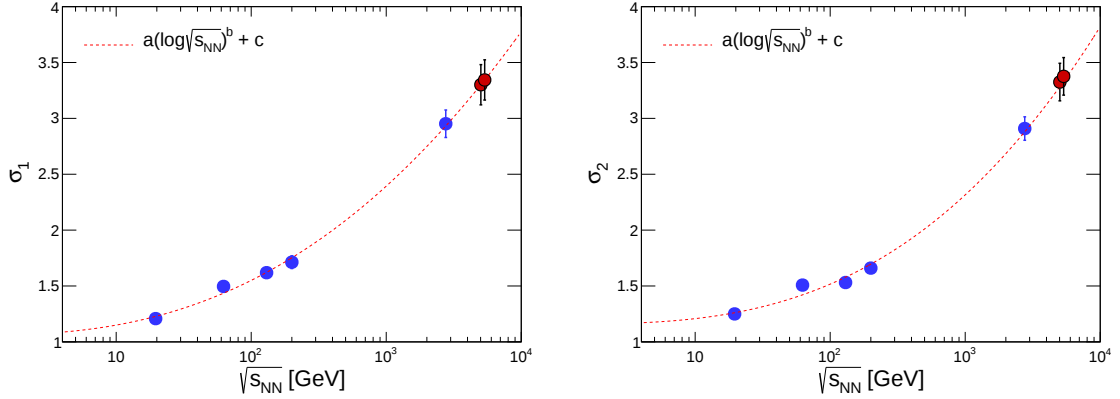


Figure 4: (color online) Energy dependence of the fitted width parameters σ_1 (left) and σ_2 (right). The dashed red curves correspond to fits using the functional form $a(\log \sqrt{s_{NN}})^b + c$, indicating a systematic broadening of both source components with increasing collision energy. The dark red circles show the extrapolated values at $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV.

(iii) The error function modulation parameters λ_1 and λ_2 , shown in Figure 5, exhibit smooth linear scaling with collision energy. The magnitude of λ increases with energy, directly reflecting the deepening of the central concavity as the system transitions from

the stopping-dominated regime at RHIC to the transparency regime at LHC. Since the error function modulation is concentrated near midrapidity, the increasing λ with energy quantifies the enhanced modification in the overlap region at higher collision energies. The preservation of Gaussian shapes away from midrapidity indicates that fragmentation characteristics persist at forward/backward rapidities, while the coupling strength λ captures the evolution of central region dynamics.

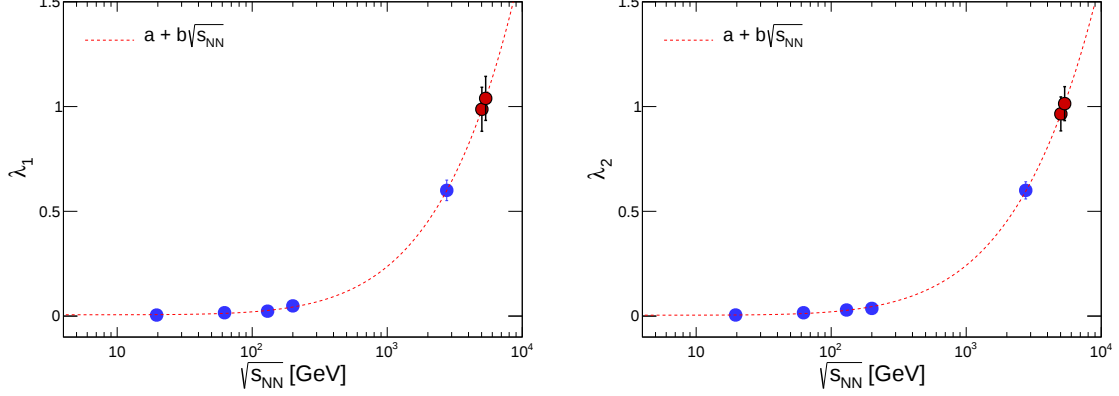


Figure 5: (color online) Energy dependence of the fitted modulation parameters λ_1 (left) and λ_2 (right). The dashed red curves correspond to fits of the form $a + b\sqrt{s_{NN}}$, showing the rapid rise of both parameters at high collision energies. The dark red circles denote the extrapolated values at $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV.

(iv) The peak positions μ_1 and μ_2 show opposite trends with increasing beam energy, meaning that the peak positions in η spread out more at higher energies. The separation between the two Gaussian peaks, $d_{p2p} = |\mu_1 - \mu_2|$, characterizes the geometric separation of sources in pseudorapidity space. Figure 6 shows that d_{p2p} evolves from the fragmentation region separation at RHIC energies to broader distributions at LHC energies, following an exponential saturation form:

$$d_{p2p} = a \left[1 - \exp \left\{ -b \ln \left(\frac{\sqrt{s_{NN}}}{c} \right) \right\} \right], \quad (2.2)$$

where the saturation behavior reflects the approach toward the transparency limit at the highest LHC energies.

The systematic energy trends observed in all fitting parameters demonstrate that the parametrization captures the essential features of collision dynamics across nearly two orders of magnitude in collision energy. The smooth evolution of parameters, particularly the linear scaling of λ with $\sqrt{s_{NN}}$ and the saturation behavior of d_{p2p} , provides quantitative insights into the progression from the stopping to the transparency regime.

The parametrization introduces additional parameters (λ_1 , λ_2) compared to the independent double Gaussian model. However, as will be demonstrated in Section 3, the modulation parameters exhibit systematic energy scaling and empirical correlations with

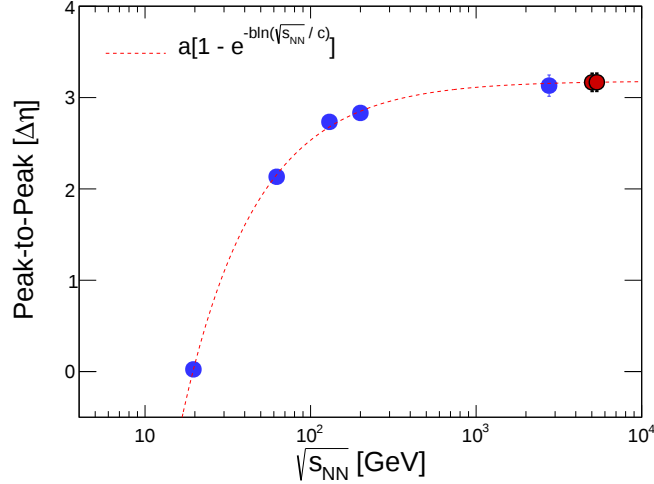


Figure 6: (color online) Energy dependence of the peak-to-peak distance d_{p2p} extracted from the two-source parametrization. The dashed red curve shows the exponential saturation fit given by Eq. (2.2), illustrating the rapid rise and subsequent saturation of d_{p2p} with increasing $\sqrt{s_{NN}}$. The dark red circle denotes the extrapolated values at $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV.

the baryon chemical potential μ_B , a fundamental thermodynamic quantity that characterizes the system. This connection indicates that λ is not merely an additional fitting degree of freedom but rather a phenomenological parameter that encodes physical information about the collision dynamics. The superior fit quality at LHC energies, combined with the preservation of limiting fragmentation behavior (Section 3), further validates that the error function modulation captures essential physics beyond simple empirical fitting.

3 Physical Interpretation and Predictive Capability

3.1 Energy Scaling of the Modulation Parameter

The systematic energy dependence of the error function modulation parameters λ_1 and λ_2 motivates examination of their average value $\lambda = (\lambda_1 + \lambda_2)/2$. As discussed in Section 2, the parameter λ quantifies the strength of coupling between forward and backward sources, with larger values corresponding to enhanced modification of the source tails near midrapidity and more pronounced central dip structure. Figure 7(a) shows that λ exhibits smooth scaling with collision energy, following the linear form:

$$\lambda = a + b\sqrt{s_{NN}} \quad (3.1)$$

This systematic linear scaling across RHIC and LHC energies indicates that the strength of source interaction increases monotonically with collision energy.

To investigate whether λ connects to known thermodynamic properties of the collision system, its relationship with the baryon chemical potential μ_B is examined. The baryon

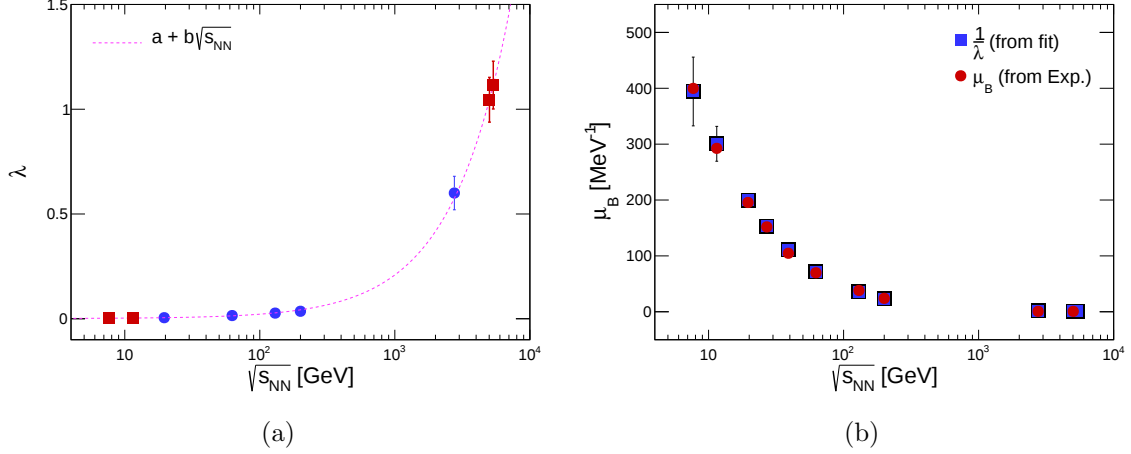


Figure 7: (color online) Energy dependence of the average modulation parameter $\lambda = (\lambda_1 + \lambda_2)/2$ (a). The dashed line represents a linear fit according to Eq. (3.1). Correlation between $1/\lambda$ and baryon chemical potential μ_B (b). The observed linear trend suggests an empirical connection between the modulation parameter and baryon stopping dynamics.

chemical potential characterizes the net baryon density at chemical freeze-out and decreases with collision energy following the parametrization [40]:

$$\mu_B(\sqrt{s_{NN}}) = \frac{d}{1 + e\sqrt{s_{NN}}}, \quad (3.2)$$

where $d = 1.308$ GeV and $e = 0.273$ GeV⁻¹ are determined from statistical thermal model analyses of particle yields across different collision energies.

Figure 7(b) shows the correlation between $1/\lambda$ and μ_B for the energies studied. The data points follow a linear trend, indicating empirical scaling:

$$\frac{1}{\lambda} \propto \mu_B.$$

This observed correlation reveals that $1/\lambda$ exhibits similar energy dependence as the baryon chemical potential. Since μ_B reflects the degree of baryon stopping and net baryon density in the system, this empirical relationship suggests that the modulation parameter λ , which controls the source coupling strength, is sensitive to baryon transport mechanisms. At lower energies where baryon stopping is significant, larger μ_B values correspond to smaller λ (weaker source coupling), consistent with more independent source behavior. Conversely, at higher LHC energies where baryon stopping is minimal ($\mu_B \rightarrow 0$), larger λ values reflect stronger source interaction through the expanding medium.

It is important to emphasize that Eq. (3.1) represents an empirical observation rather than a theoretical derivation. The parametrization in Eq. (2.1) is phenomenological, introduced to describe the shapes of pseudorapidity distributions through modulation by an error function. The observed scaling between $1/\lambda$ and μ_B emerges from the data and suggests an underlying connection between the geometric structure of particle production (source coupling) and thermodynamic properties (baryon density), but establishing the

microscopic origin of this relationship requires further theoretical investigation. Nevertheless, the systematic nature of this correlation provides evidence that λ captures physically meaningful information about collision dynamics beyond simple empirical fitting.

3.2 Peak-to-Peak Distance and System Size

The peak-to-peak distance $d_{p2p} = |\mu_1 - \mu_2|$ provides a direct measure of the effective longitudinal separation between production sources in pseudorapidity space. As shown in Figure 6, d_{p2p} exhibits systematic evolution with collision energy, following exponential saturation behavior described by Eq. (2.2). At lower RHIC energies, the sources remain relatively close, reflecting significant baryon stopping. As energy increases toward the LHC regime, d_{p2p} grows substantially, approaching an asymptotic limiting value that characterizes the transparency limit where baryon stopping is minimized. This saturation represents the maximum effective longitudinal system size that can be achieved for these collision systems.

To investigate potential connections between geometric and thermodynamic properties, the energy scaling of d_{p2p} is compared with the chemical freeze-out temperature T_{ch} . The chemical freeze-out temperature, extracted from statistical thermal model analyses [40, 41], characterizes the temperature at which inelastic collisions cease and particle yields become fixed.

Figure 8 shows the energy dependence of T_{ch} values for central heavy-ion collisions from SIS to LHC energies [40]. Remarkably, T_{ch} exhibits similar exponential saturation behavior:

$$T_{\text{ch}} = T_0 \left[1 - \exp \left\{ -\alpha \ln \left(\frac{\sqrt{s_{NN}}}{s_0} \right) \right\} \right], \quad (3.3)$$

where $T_0 = 159.6 \pm 1.2$ MeV represents the saturation temperature. At LHC energies, $T_{\text{ch}} \approx 156\text{--}157$ MeV [41], essentially reaching the QCD crossover temperature predicted by lattice QCD.

The functional similarity between Eqs. (2.2) and (3.3) reveals a profound connection: the effective system size (d_{p2p}) and the thermal state at chemical freeze-out (T_{ch}) follow identical energy scaling patterns, with saturation occurring in the same energy regime. This parallel behavior indicates that geometric expansion and thermal evolution share common underlying dynamics governed by the QCD phase structure. As collision energy increases, reduced baryon stopping drives larger d_{p2p} values while higher initial energy densities produce higher temperatures. However, both quantities saturate because chemical freeze-out is fundamentally constrained by QCD thermodynamics at the phase boundary. Once the system reaches the QCD crossover temperature, further increases in energy primarily affect the QGP lifetime and volume, rather than the freeze-out conditions themselves. The fact that the phenomenological parametrization naturally captures this connection, even without explicit implementation of QCD thermodynamics, provides further validation that the source interaction mechanism encodes essential aspects of the underlying collision dynamics and their relation to the QCD phase boundary.

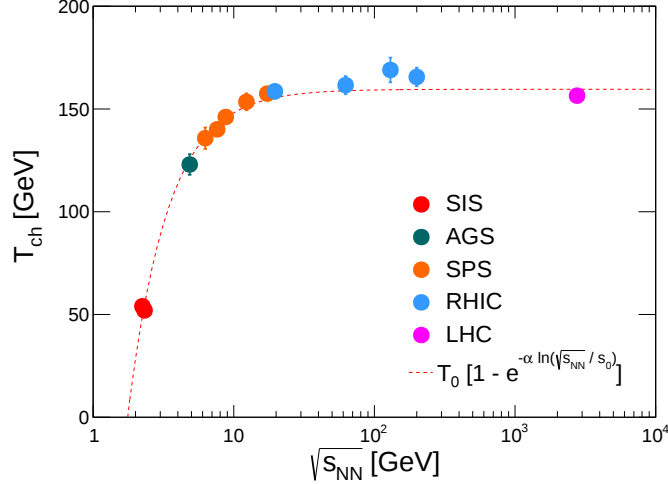


Figure 8: (color online) Energy dependence of the chemical freeze-out temperature T_{ch} compiled from SIS, AGS, SPS, RHIC, and LHC measurements. The dashed red curve shows the exponential saturation fit given by Eq. (3.3), illustrating the rapid increase and subsequent saturation of T_{ch} with collision energy. This behavior mirrors the functional form observed in the peak-to-peak distance d_{p2p} , highlighting a common underlying energy scaling.

3.3 Predictive Capability: Extension to Incomplete Pseudorapidity Coverage

To test the predictive capability of this parametrization framework, it is applied to Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (ALICE) [37] and 5.36 TeV (CMS) [38], where experimental data are available only over limited pseudorapidity ranges. For these energies, the systematic energy trends established from the complete datasets at 19.6, 62.4, 130, 200 GeV, and 2.76 TeV constrain the fitting parameters.

Figure 9 shows the parametrization results for these partial datasets. Despite the limited η coverage, the framework successfully describes the available data points, demonstrating consistency with the established energy scaling patterns. The fitted parameters at 5.02 and 5.36 TeV follow smoothly from the trends observed at lower and higher energies, supporting the robustness of this approach across the full RHIC-LHC energy range.

The successful description of these partial datasets validates the systematic energy dependence of the fitting parameters and demonstrates that the framework can be reliably extended to energies where complete pseudorapidity distributions are not yet available. This predictive capability suggests that the parametrization captures essential features of the collision dynamics beyond simple empirical fitting.

3.4 Limiting Fragmentation Behavior

To further validate this parametrization framework, its behavior is examined in the context of limiting fragmentation. In high-energy hadronic collisions, the limiting fragmentation hypothesis [42–44] predicts that pseudorapidity densities, when scaled by the number of participating nucleon pairs and plotted as a function of $\eta - y_{beam}$ (where $y_{beam} =$

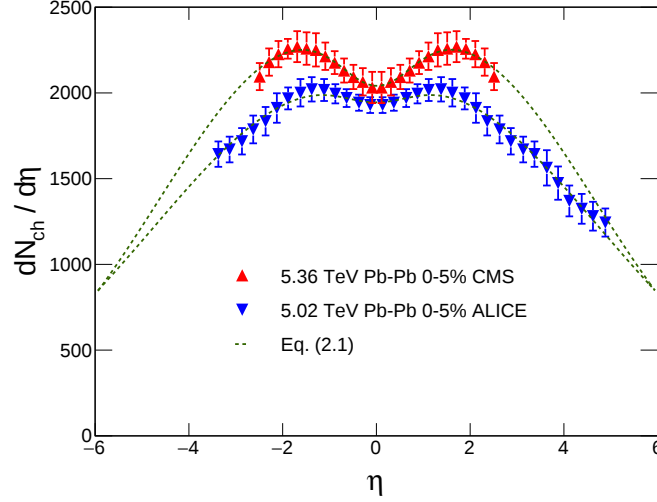


Figure 9: (color online) Parametrization results for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (ALICE) and 5.36 TeV (CMS), where only partial pseudorapidity coverage is available. The points denote the measured charged-particle pseudorapidity densities, while the dashed green curves show the predictions of Eq. (2.1) using parameter values constrained by their systematic energy dependence.

$\ln(\sqrt{s_{NN}}/2m_p)$), should converge to a universal curve near the beam rapidity. This behavior indicates that particle production observed in the rest frame of a colliding hadron becomes largely insensitive to the collision energy at sufficiently high $\sqrt{s_{NN}}$.

Recent studies using double Gaussian parametrizations have suggested that limiting fragmentation appears to be violated at the highest LHC energies, particularly at $\sqrt{s_{NN}} = 5.02$ TeV [45]. However, these conclusions relied on extrapolations using independent double Gaussian fits, which may not adequately capture the coupling between sources at high energies.

Figure 10 shows $(dN_{ch}/d\eta)/(\langle N_{part} \rangle/2)$ as a function of $\eta - y_{beam}$ for central Au+Au collisions at RHIC and Pb+Pb collisions at LHC. The values of $\langle N_{part} \rangle$ for different collision systems and energies are listed in Table 1 and are obtained from Monte Carlo Glauber model calculations [35, 46–50]. Due to the lack of experimental data in the fragmentation region at LHC energies, the parametrization [Eq. (2.1)] is used to extrapolate into this region.

In contrast to previous findings with double Gaussian fits [45], the coupled two-source parametrization with error function modulation exhibits limiting fragmentation behavior even at the highest LHC energy of 5.36 TeV. The scaled distributions converge to a universal curve in the beam rapidity region, indicating that limiting fragmentation remains approximately valid when the coupling between forward and backward sources is properly accounted for. This observation highlights a key advantage of this approach: the error function modulation concentrates modifications near midrapidity while preserving fragmentation characteristics at forward/backward rapidities, thereby naturally maintaining the limiting fragmentation scaling. The systematic energy dependence of λ enables

System	Centrality	$\langle N_{\text{part}} \rangle$
Au+Au 19.6 GeV	0–6%	337 ± 12
Au+Au 62.4 GeV	0–6%	335 ± 11
Au+Au 130 GeV	0–6%	340 ± 11
Au+Au 200 GeV	0–6%	344 ± 11
Pb+Pb 2.76 TeV	0–5%	382.8 ± 3.1
Pb+Pb 5.02 TeV	0–5%	383.4 ± 17.8
Pb+Pb 5.36 TeV	0–5%	383.6 ± 0.8

Table 1: Average number of participants $\langle N_{\text{part}} \rangle$ for central Au+Au collisions at RHIC and Pb+Pb collisions at LHC, obtained from Monte Carlo Glauber model calculations [35, 46–50].

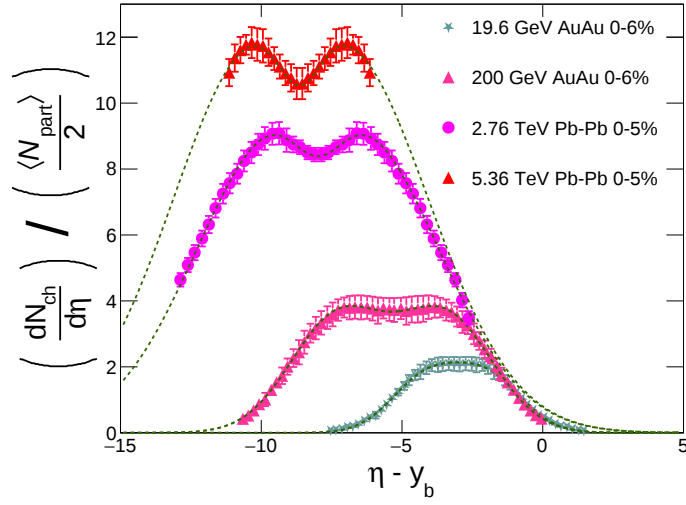


Figure 10: (color online) Number of participant pair normalized pseudorapidity distribution $(dN_{\text{ch}}/d\eta)/(\langle N_{\text{part}} \rangle/2)$ as a function of $\eta - y_{\text{beam}}$ for central Au+Au collisions at RHIC and Pb+Pb collisions at LHC. Points represent experimental data, dashed curves show extrapolations using Eq. (2.1). The convergence near $\eta - y_{\text{beam}} \approx 0$ demonstrates limiting fragmentation behavior.

a smooth transition from RHIC to LHC energies while respecting this fundamental constraint, a feature absent in independent source models.

While extrapolation to the fragmentation region remains assumption-based, pending complete experimental coverage, the fact that the parametrization naturally produces limiting fragmentation without explicit constraints and simultaneously provides superior mid-rapidity fits suggests that it captures essential collision dynamics more comprehensively than independent source models.

These combined results, the successful description of central rapidity structure, accurate predictions for incomplete datasets, and preservation of limiting fragmentation, demonstrate that the coupled two-source framework with error function modulation pro-

vides a robust and physically consistent description of charged particle production across the full RHIC-LHC energy range.

4 Summary and Conclusions

A phenomenological parametrization has been developed that achieves a unified description of charged particle pseudorapidity distributions across the full RHIC-LHC energy range, spanning nearly two orders of magnitude in collision energy. By extending the traditional two-source Gaussian model through error function modulation, the approach successfully captures the complex evolution from stopping-dominated dynamics at RHIC to transparency-dominated regime at LHC, including the characteristic central dip structure at higher energies that independent source models have failed to reproduce. The parametrization provides excellent agreement with experimental data across $\sqrt{s_{NN}} = 19.6$ GeV to 5.36 TeV, significantly outperforming traditional approaches with $\chi^2/\text{ndf} = 0.373$ at 2.76 TeV, where double Gaussian fits fail to reproduce the central dip structure. Most remarkably, the analysis reveals three fundamental connections that transcend simple empirical fitting: (i) the coupling parameter λ exhibits striking empirical correlation with the inverse baryon chemical potential, $1/\lambda \propto \mu_B$, establishing an unexpected link between geometric source structure and thermodynamic properties; (ii) the peak-to-peak distance d_{p2p} and chemical freeze-out temperature T_{ch} follow identical exponential saturation patterns, demonstrating that geometric expansion and thermal evolution share a common underlying dynamics governed by QCD phase structure; and (iii) unlike independent source models that suggest violation at LHC energies, the coupled-source framework naturally preserves limiting fragmentation across all collision energies, revealing the critical role of source interaction in maintaining this fundamental scaling property.

The systematic energy dependence of all extracted parameters, including amplitudes, widths, coupling strengths, and source separations, provides quantitative insights into the progression from baryon-stopping to transparency regimes. The predictive capability of the framework is validated through the successful description of incomplete data at 5.02 and 5.36 TeV. The localized nature of the error function modulation, concentrating modifications near midrapidity while preserving fragmentation characteristics at forward/backward rapidities, proves essential for simultaneously capturing both the central dip structure at LHC energies and the limiting fragmentation behavior across the full energy range, which are features that cannot be reconciled within independent source models. While the phenomenological construction requires further theoretical investigation to establish the microscopic origin of these correlations, the systematic connections observed between λ and μ_B , and between d_{p2p} and T_{ch} , strongly suggest that the proposed modification encodes fundamental aspects of collision dynamics and their relationship to QCD thermodynamics. The success of this coupled-source framework in symmetric systems naturally raises questions about its applicability to asymmetric collision systems such as p+Pb, where the interplay between different source sizes and the influence of saturation effects at low Bjorken- x could be explored through appropriate modifications of the coupling mechanism. This work thus provides not only a practical and powerful tool for analyzing particle production pat-

terns in heavy-ion collisions but also reveals unexpected empirical regularities that point toward deeper connections between geometric structure and thermodynamic evolution in the transition from hadronic matter to the quark-gluon plasma, potentially offering new perspectives on particle production mechanisms across diverse collision systems.

Acknowledgments

The authors gratefully acknowledge Poojan Angiras, Manisha Rana, and Sachin Rana for valuable discussions and feedback. Part of this study has been presented at the HOT QCD 3.0 conference.

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