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Hot **QCD** Matter 2025
(Series 3)



Energy-Dependent Pseudorapidity Distributions in Heavy-Ion Collisions: Connection to Baryon Stopping and System Size

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Overview



**01 Introduction to Pseudorapidity
Distributions**

02 Landau Hydrodynamic Model

03 Double Gaussian Fitting Approach

04 Novel erf-Modified Gaussian Fitting

05 Results from New Fitting Function

06 Physical Interpretations

07 Parameter Extrapolation

08 Conclusion

Definition & Physical Meaning

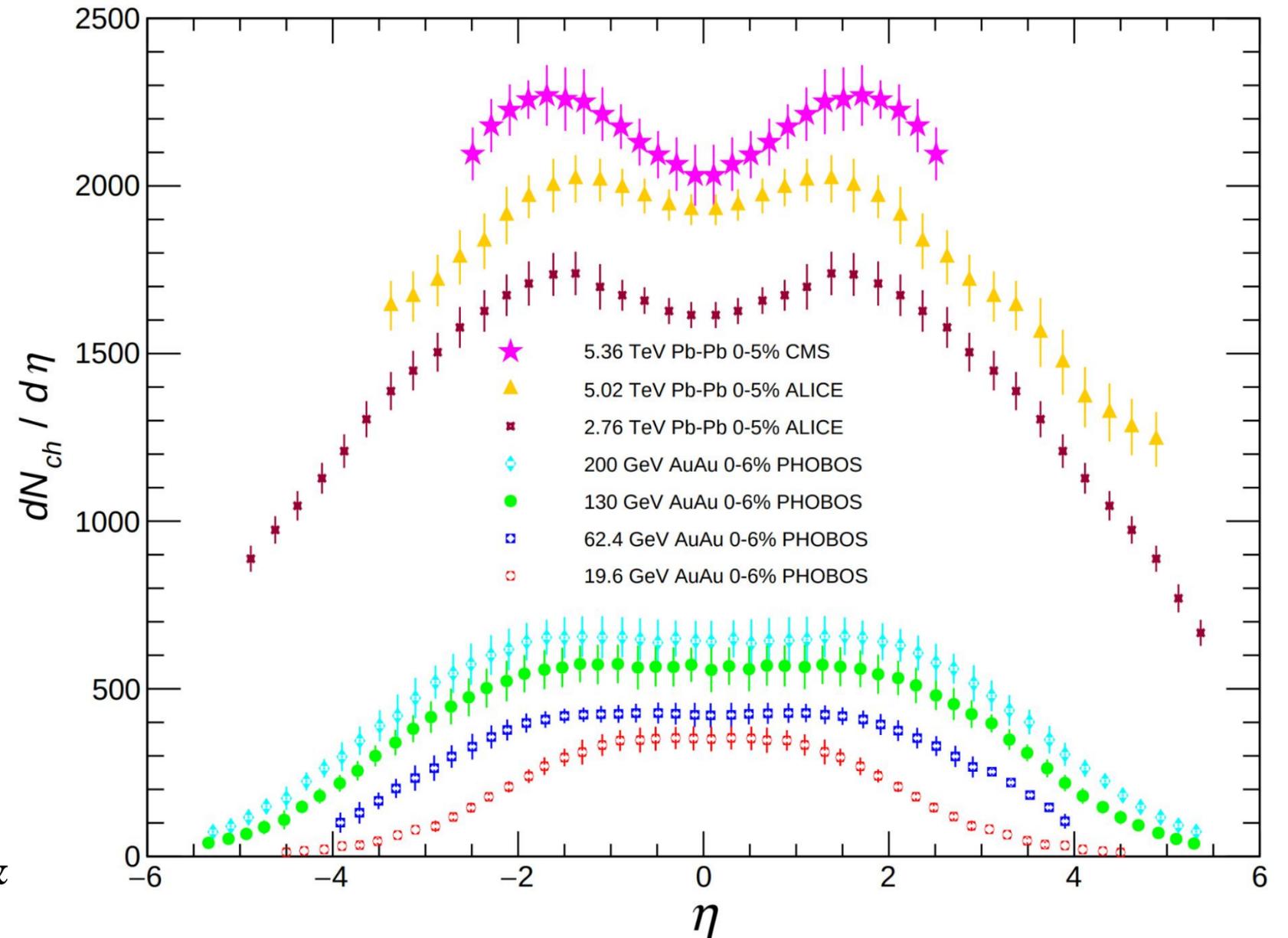
↻ Pseudorapidity: $\eta \equiv -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]$

- approximately rapidity(y) at high energies

↻ $\frac{dN_{ch}}{d\eta}$: charged particle multiplicity per per unit η interval

↻ Measures particle density as function of angle/longitudinal position

↻ Direct probe of initial energy deposition & subsequent particle production



[RHIC: Phys. Rev. C 110, 014904 \(2024\), L. Du](#)

[LHC: HEPData repository](#)

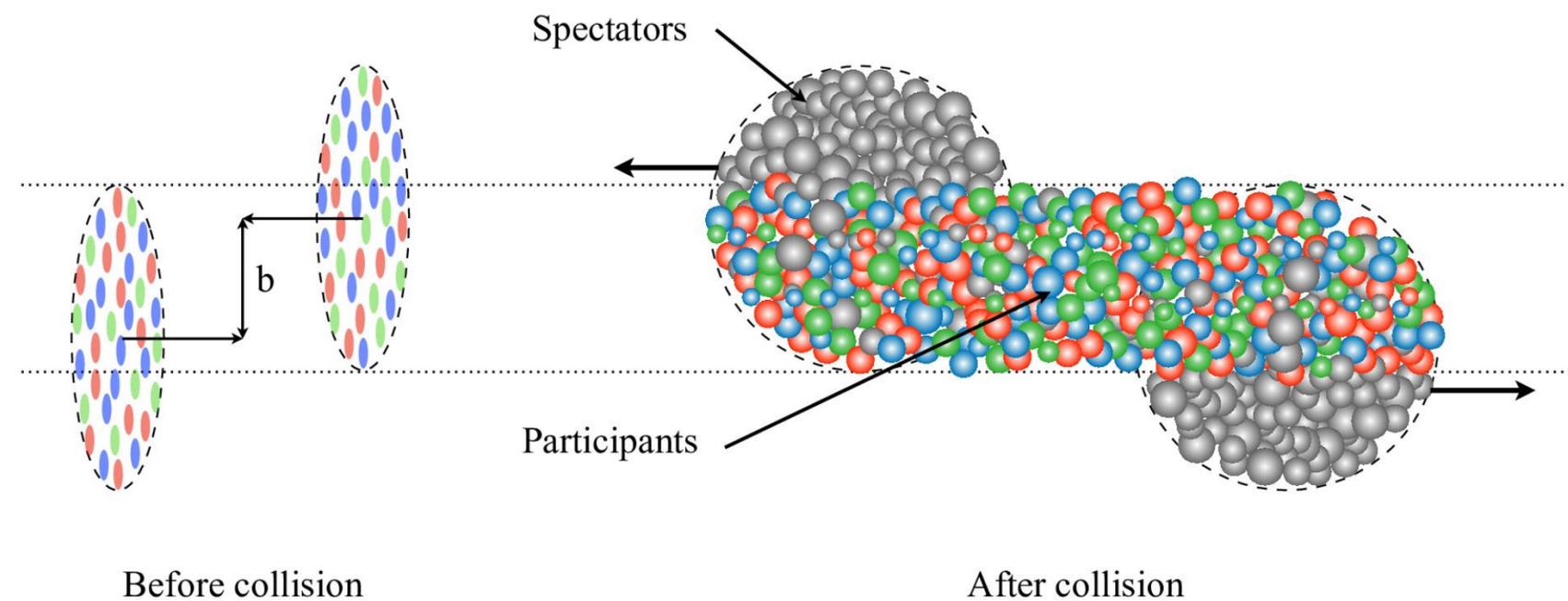
Why Pseudorapidity Distributions Matter?

↻ Shape evolution from narrow (low energy) to broad (high energy)

↻ Sensitive to equation of state(EOS) & phase transitions

↻ Baseline for understanding more complex observables

↻ Transition from baryon stopping to transparency regime



[Reproduced from LHCb Collaboration, JINST 17 \(2022\) P05009](#)

Original Landau Distribution:



Original Landau form:

$$\frac{dN}{d\lambda} (\text{Landau}) \propto \exp\left\{\sqrt{L^2 - \lambda^2}\right\}, \text{ where } L = \ln \gamma = \ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

& λ originally represented **polar angle** ($e^{-\lambda} = \theta$) in Landau's work.

Question: Should λ be rapidity y or pseudorapidity η ?



Predicts **single Gaussian-like distribution** with width proportional to L .



Good agreement with data from **AGS** to **RHIC** energies (**within 5-10%**).

$$\frac{dN_{ch}}{d\eta} = \frac{N}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\eta - \eta_0)^2}{2\sigma^2}\right]$$



Model assumes **complete stopping** (**Landau limiting case**) & shows **limiting fragmentation** at forward rapidities.

valid only for : $|\eta| \ll L$

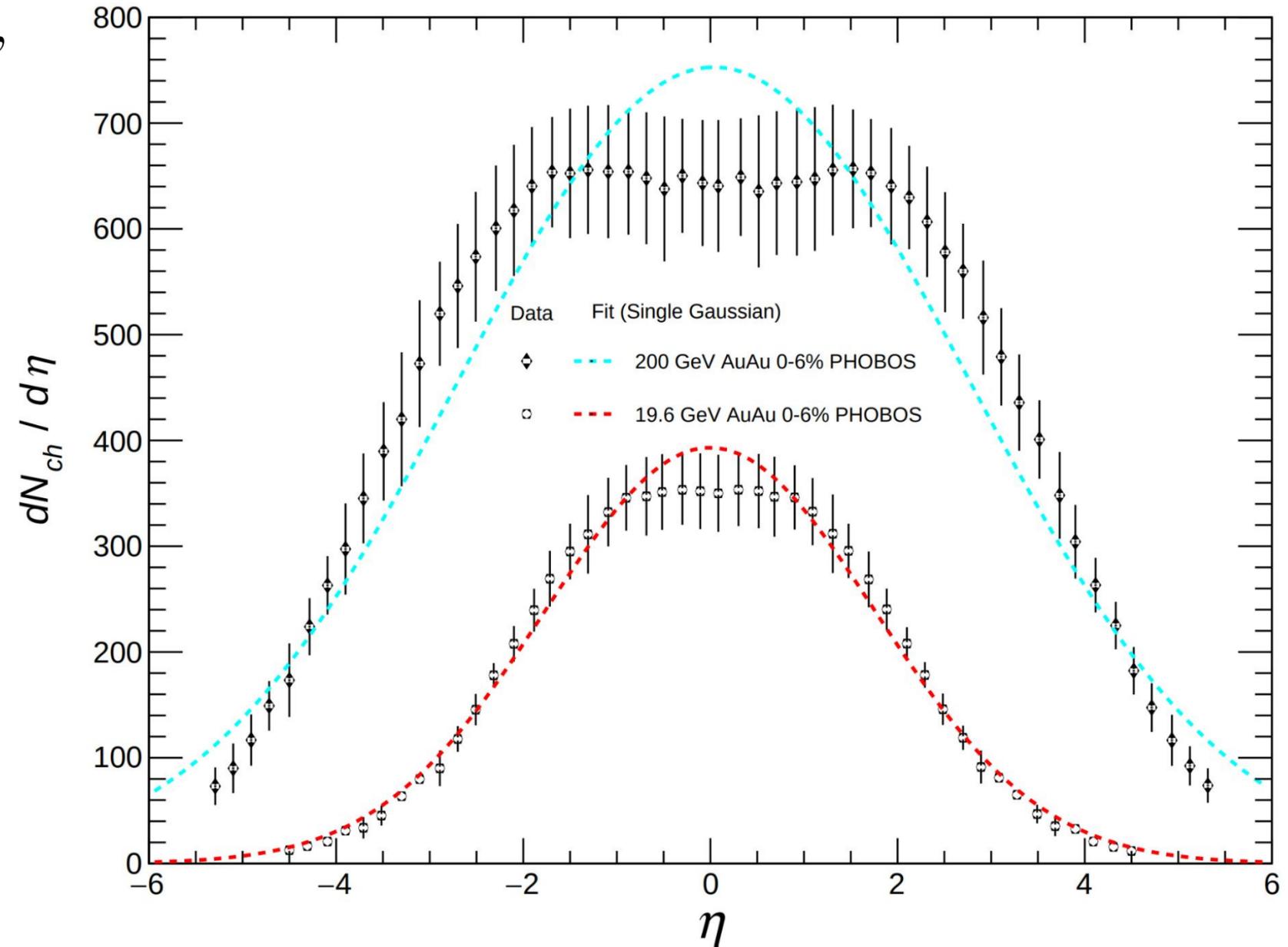
Why Single Distribution Fails at RHIC & LHC?

At **RHIC & LHC energies**: L becomes very large, violating $|\eta| \ll L$ assumption

Shape evolution from **narrow** (low energy) to **broad** (high energy), results in **double-humped/asymmetric** distributions

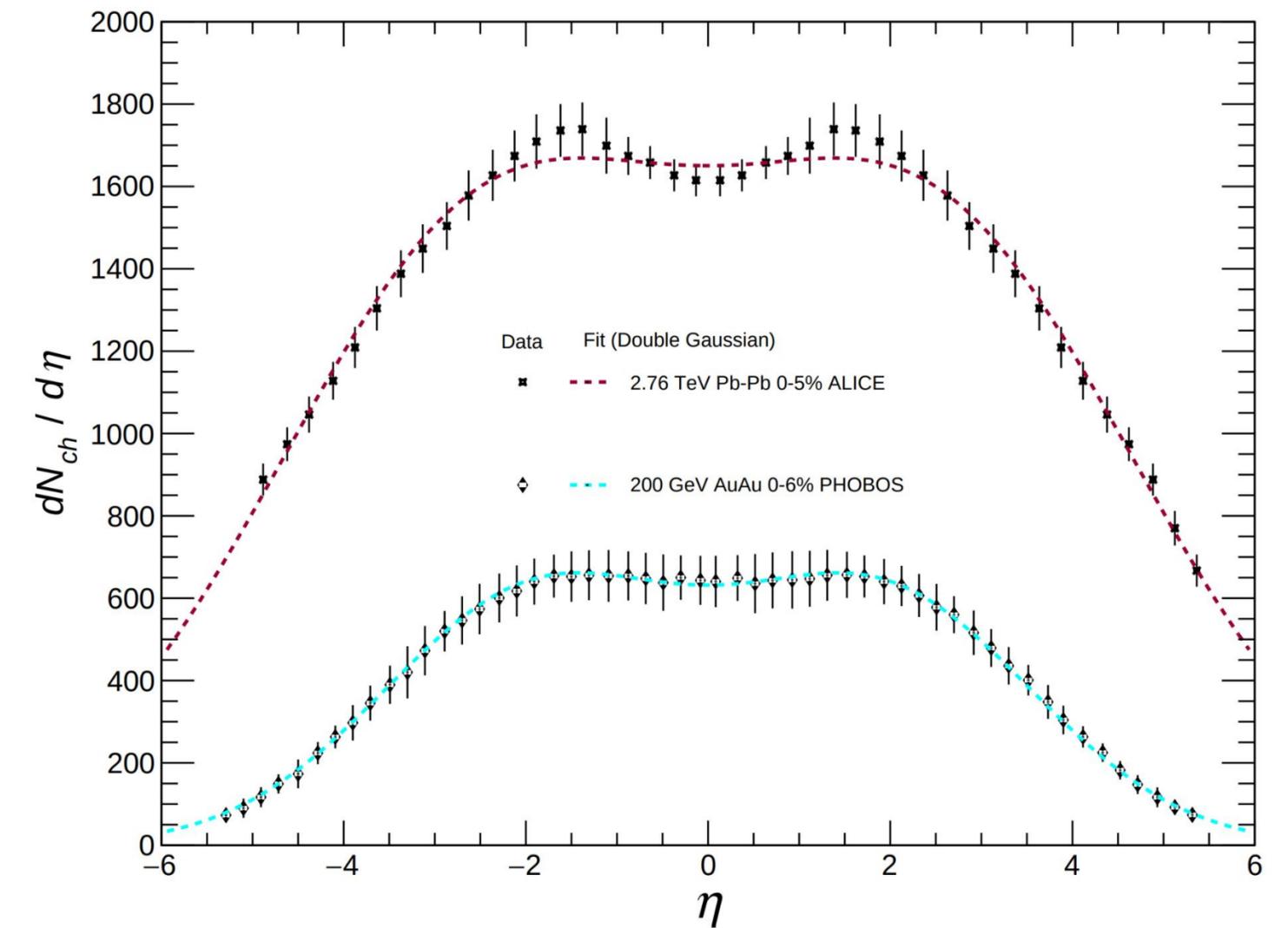
Transition to transparency regime - **incomplete** energy deposition

Need for **multi-component description** beyond single **Landau form**(which assumes **complete** stopping)



Limitations of the Double-Gaussian(DG) Approach at LHC Energies

- **Traditional method:** Sum of two symmetric Gaussians to capture non-Gaussian features
- **Successful at RHIC energies:** Good description of Au+Au collisions from $\sqrt{s_{NN}} = 19.6-200$ GeV with smooth parameter evolution
- **Breakdown at LHC energies:** Fails to capture asymmetries and shape evolution as dynamics shift from stopping to transparency.
- Cannot reproduce **central dip** at LHC from **incomplete overlap** of FRs and **leading particle effects** in the transparency regime.



$$f(\eta) = A_1 \cdot e^{-\frac{(\eta-\mu_1)^2}{2\sigma_1^2}} + A_2 \cdot e^{-\frac{(\eta-\mu_2)^2}{2\sigma_2^2}}$$

Modified Gaussian: Overcoming the Limits of DG Fits



Extended functional form : $A \cdot e^{-\frac{(\eta-\mu)^2}{2\sigma^2}} \cdot (1 + \text{erf}(\lambda\eta))$

Gaussian modulated by error function



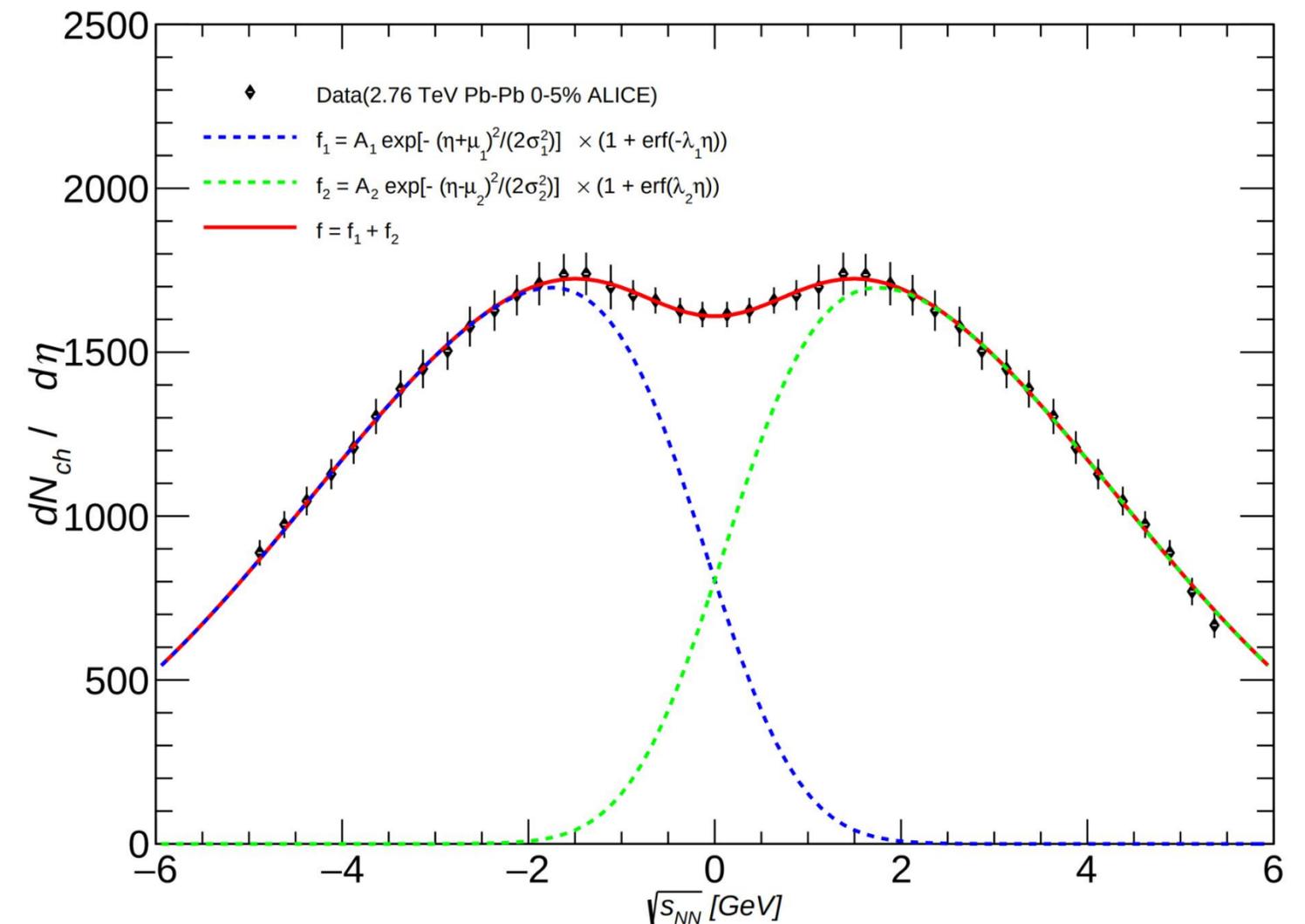
Erf term \Rightarrow **controlled asymmetric distortions** accounting for **incomplete source overlap** & **central dip formation** at higher energies.



Energy-dependent λ parameter systematically evolves with **collision energy** - **description of shape changes** as nuclear matter **transparency** increases.



Complex distribution features: Captures **central concavity** & **forward-backward asymmetries** beyond RHIC, where **DG** fails.



$$f(\eta) = A_1 \cdot e^{-\frac{(\eta-\mu_1)^2}{2\sigma_1^2}} \cdot (1 + \text{erf}(-\lambda_1\eta)) + A_2 \cdot e^{-\frac{(\eta-\mu_2)^2}{2\sigma_2^2}} \cdot (1 + \text{erf}(\lambda_2\eta))$$

Results From New Fitting Function



Superior fitting quality: *erf*-modified Gaussian provides excellent χ^2/ndf compared to **DG** across **RHIC-LHC**

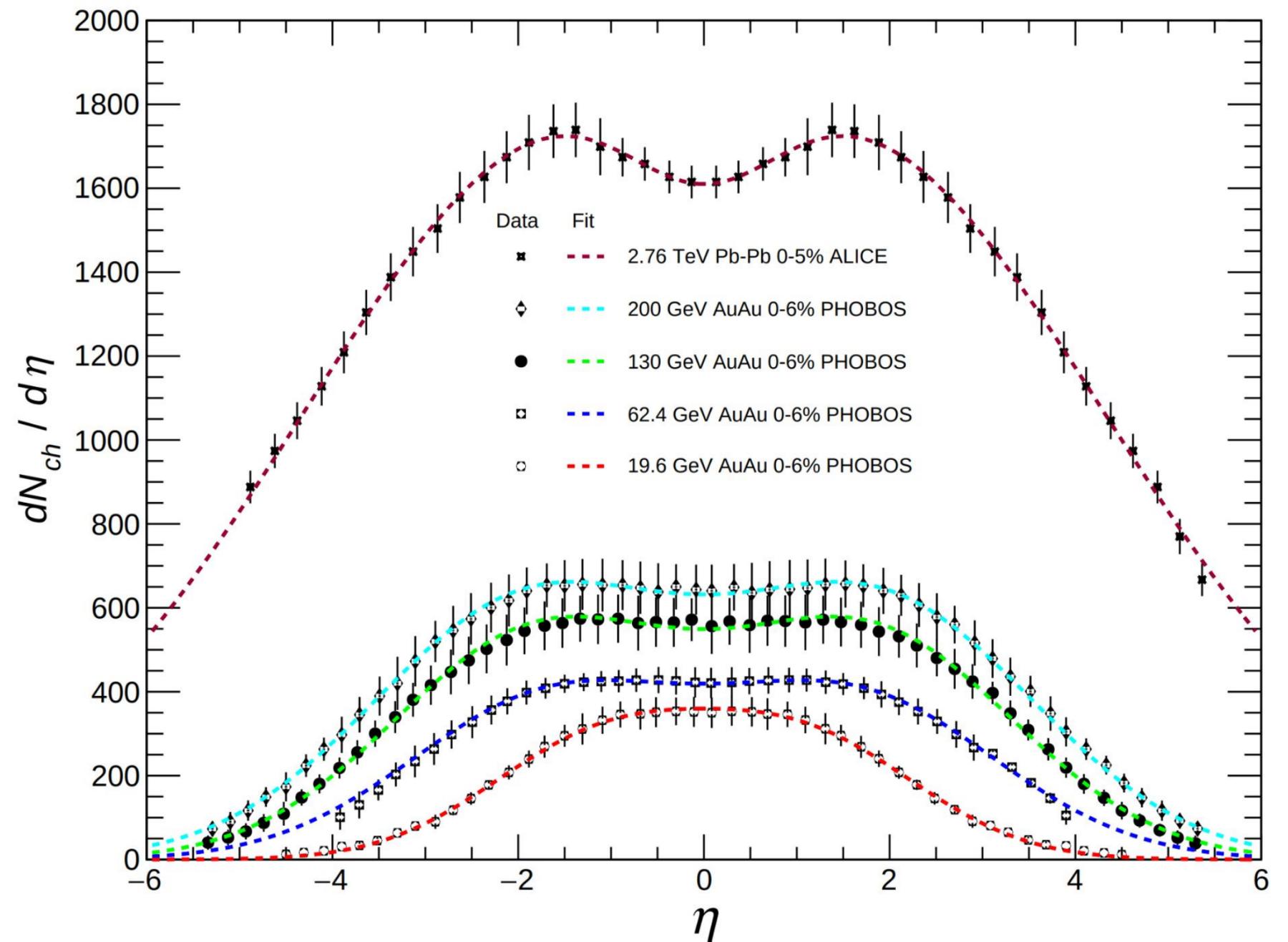
$\chi^2/ndf(2.76\text{TeV})$:

Double Gaussian Fit:
0.373

EF Modified Gaussian Fit:
0.085



Captures fine structure: **Central dip**, **asymmetric tails** & **energy-dependent shape evolution** that traditional methods miss.



Systematic Parameter Extraction



Clean energy dependence
observed for amplitudes
(A_1 , A_2), widths (σ_1 , σ_2)



Systematic scaling:

A 's and σ 's follow
power-law form:

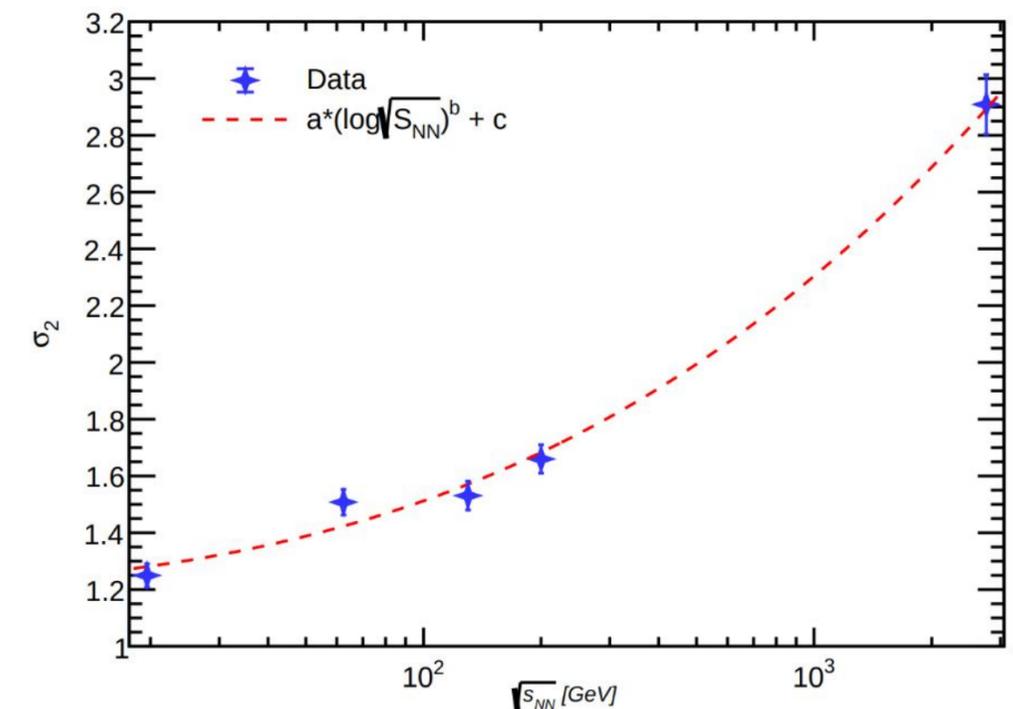
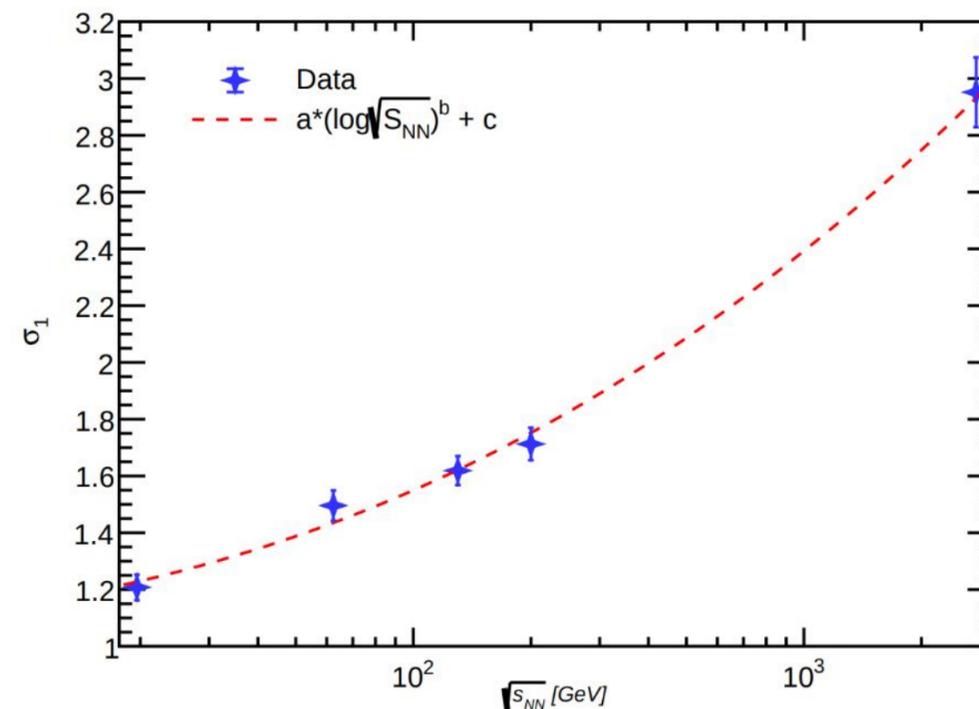
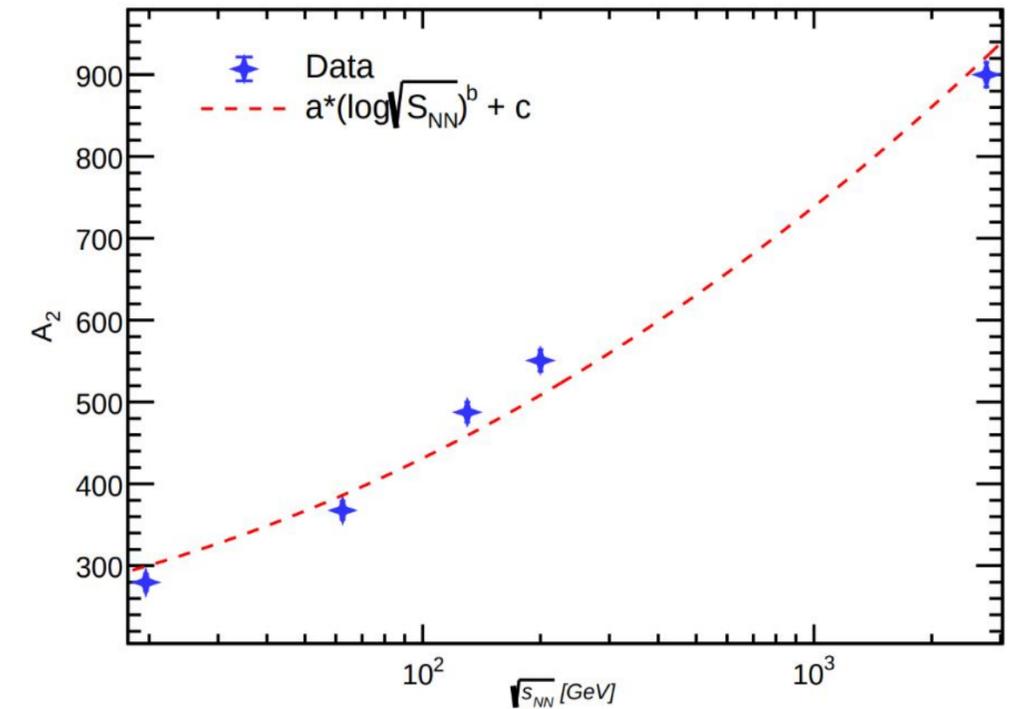
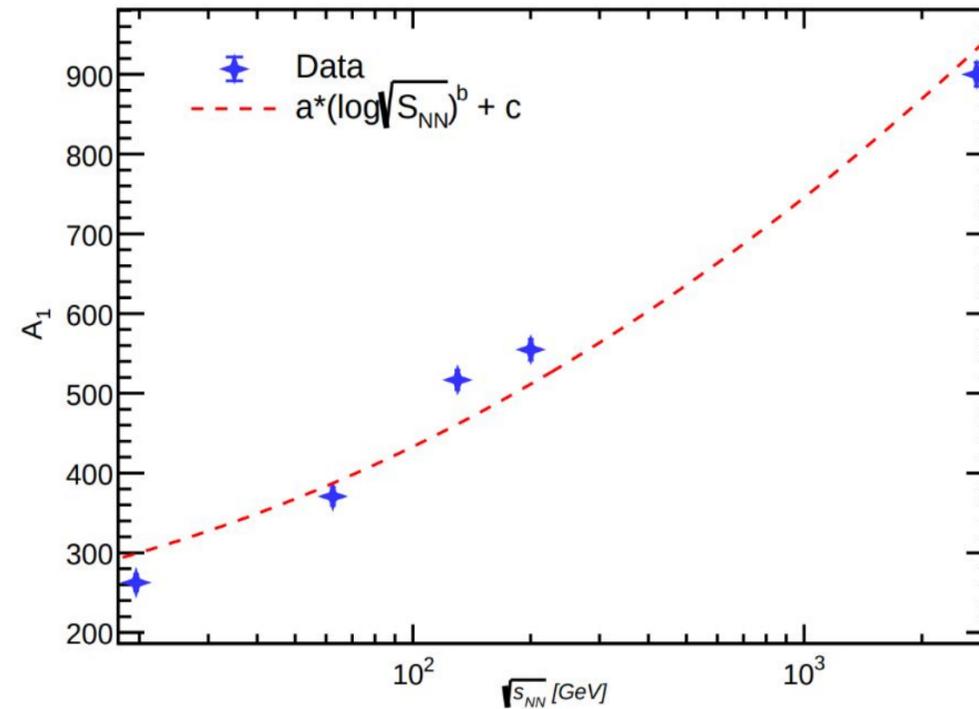
$$a \cdot [\ln(\sqrt{s_{NN}})]^b + c$$

with excellent fit quality.



Physical interpretation:

Reflects underlying collision
dynamics and thermodynamic
scaling in **HI** systems.

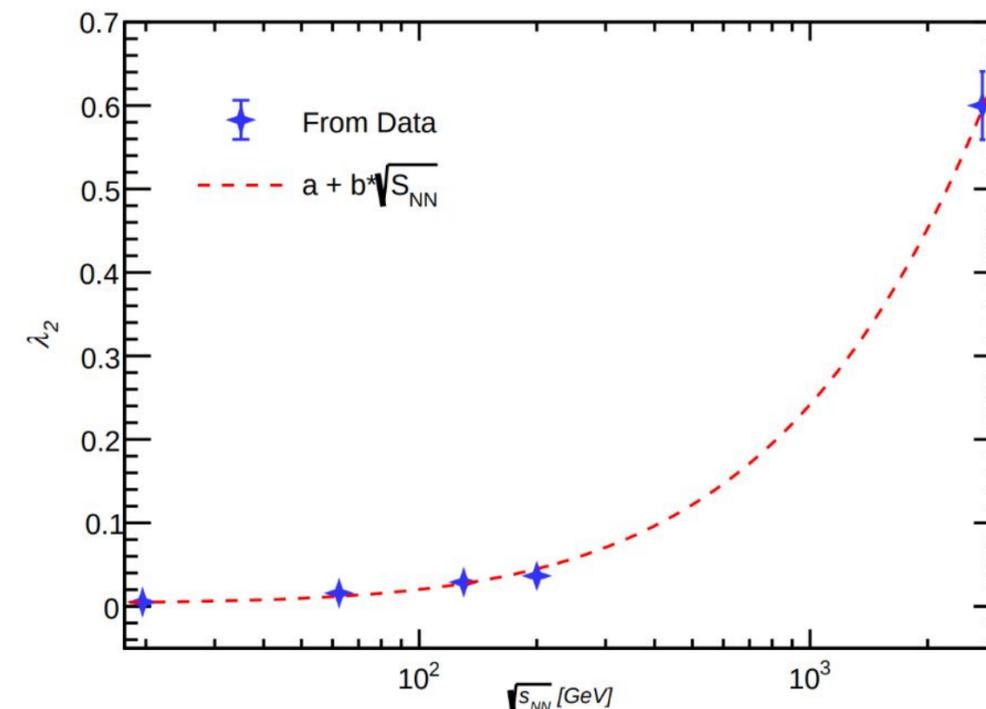
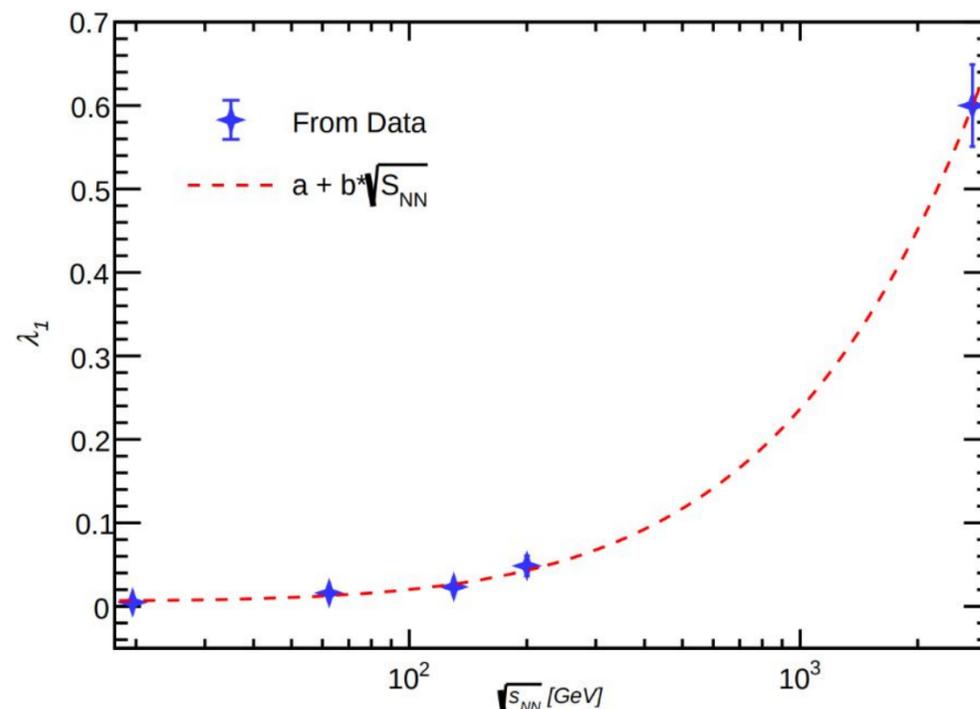


λ & Peak-to-Peak Distance Evolution:



λ parameters control **central dip** formation - smooth energy dependence with **linear scaling**:

$$\lambda_1, \lambda_2 = a + b \cdot \sqrt{s_{NN}}$$

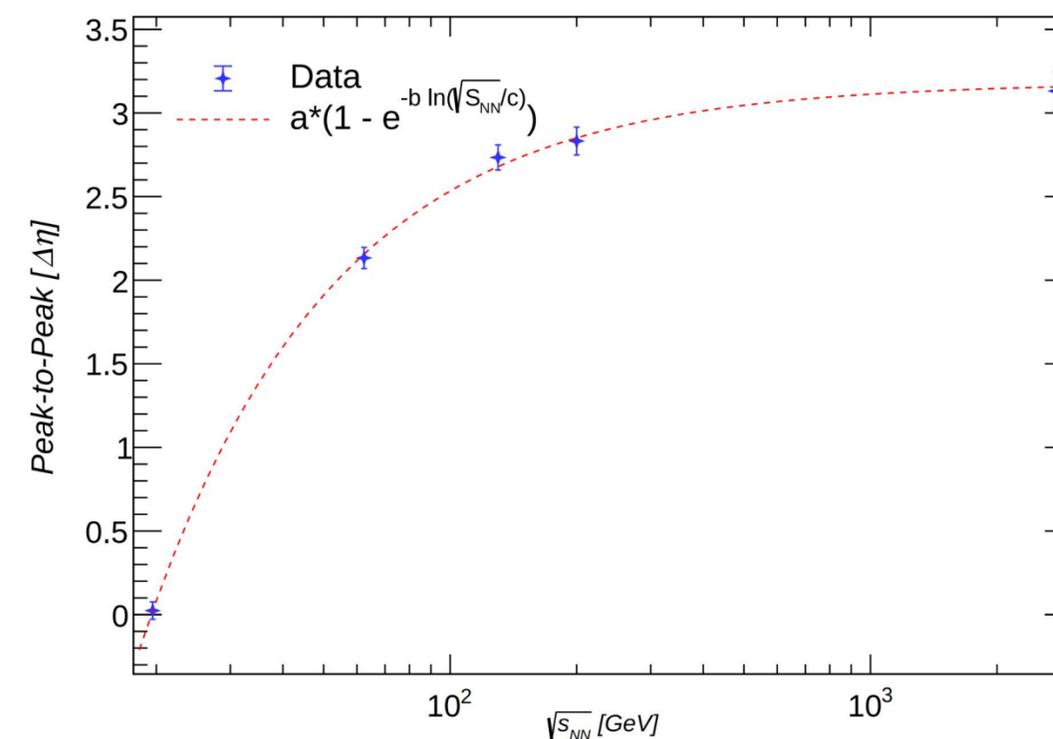


λ magnitude **increases** with **energy** reflecting **deeper central concavity** as system transitions from **stopping** to **transparency** regime



P2P distance evolution from **FR** separation at **RHIC** to **broader** distributions at **LHC** follows **exp. saturation**:

$$d_{p2p} = a \cdot \{1 - \exp[-b \cdot \ln(\sqrt{s_{NN}}/s_0)]\}$$



λ - μ_B Connection: $\lambda = \text{avg.}(\lambda_1, \lambda_2)$ shows scaling

$$\lambda \propto 1/\mu_B,$$

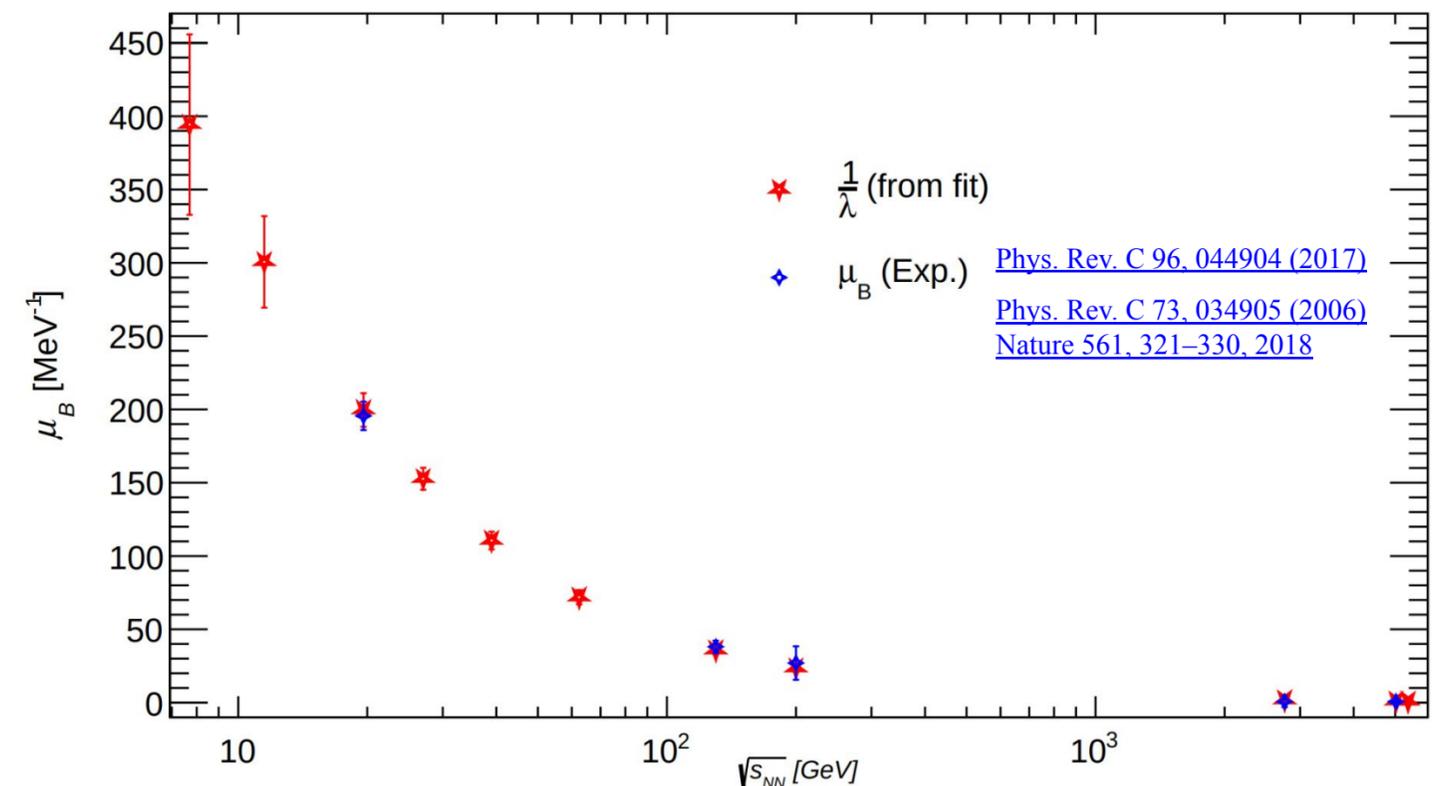
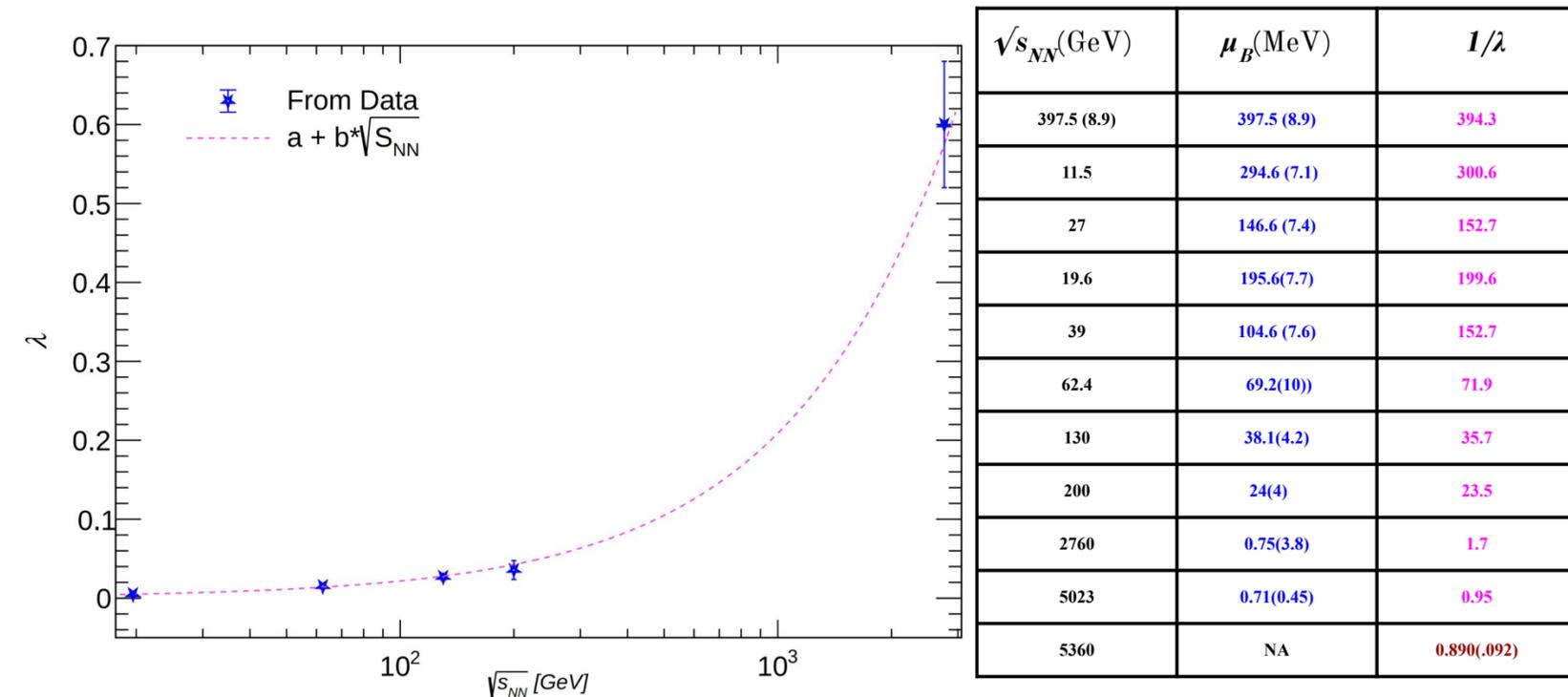
where λ controls **central dip** formation & μ_B - baryon chemical potential.

Energy Dependence Correlation:

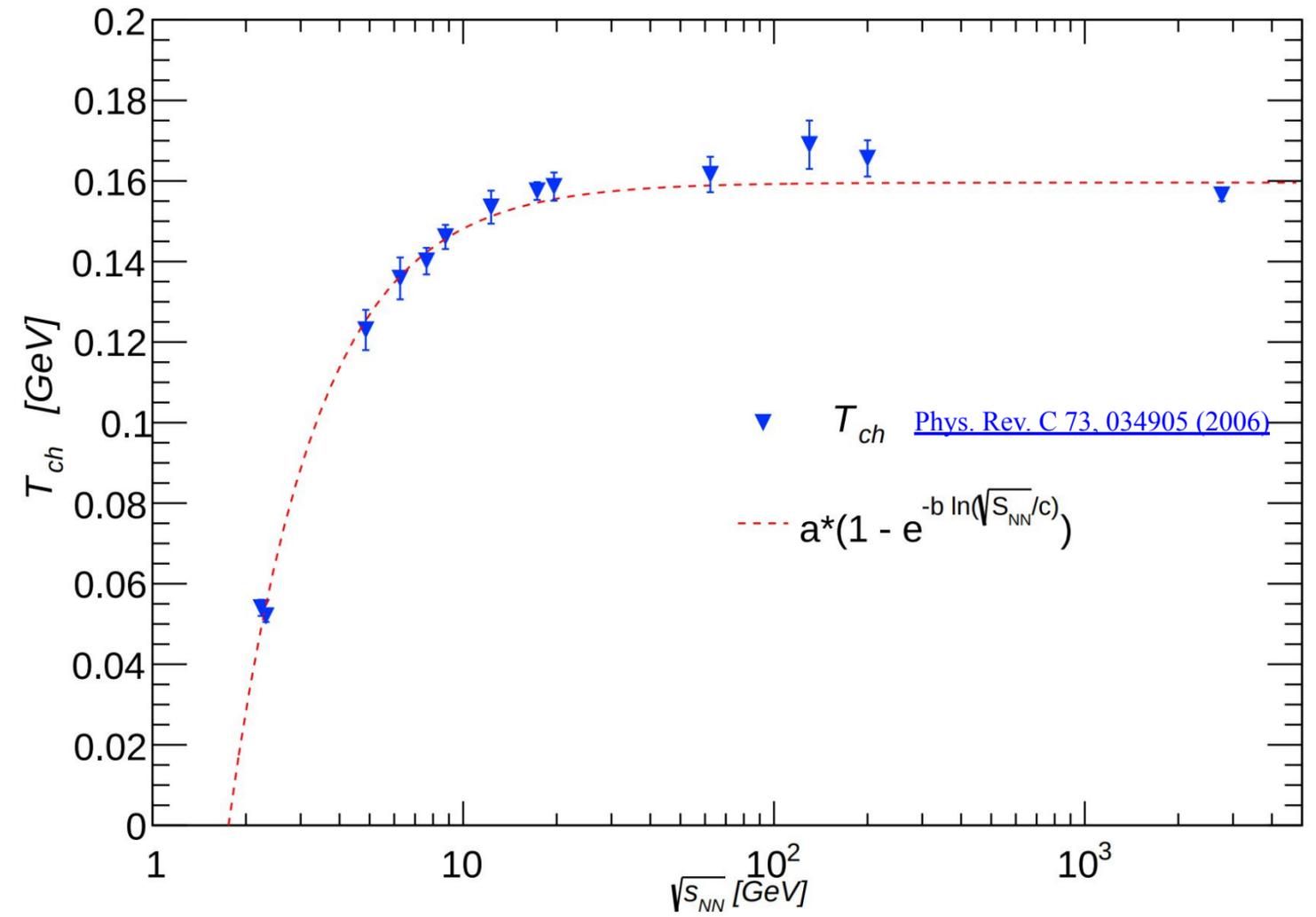
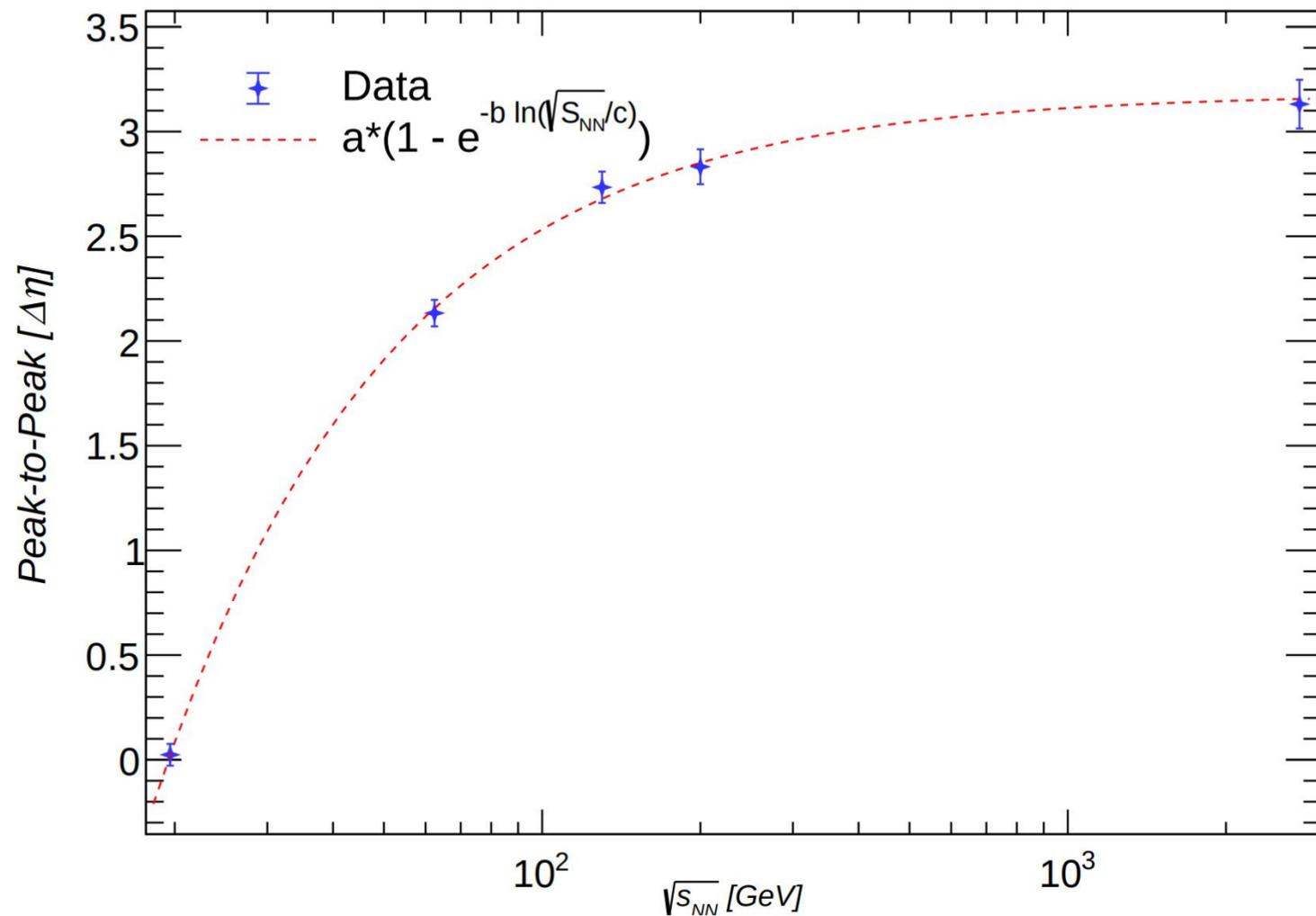
Similar energy scaling from **RHIC** to **LHC** \Rightarrow

λ reflects **baryon stopping mechanisms**.

Physical Significance: λ acts as an **effective inward force** from the **collision core**, opposing **source spreading** and generating the **central dip**.



Peak-2-Peak Separation & Chemical Freeze Out Temperature

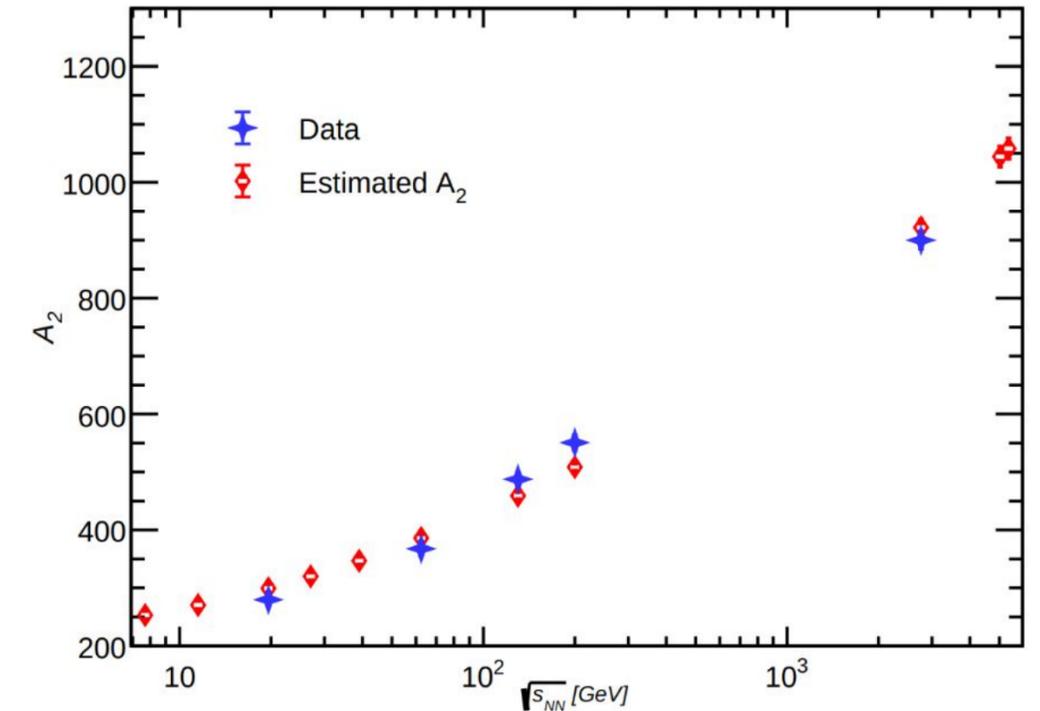
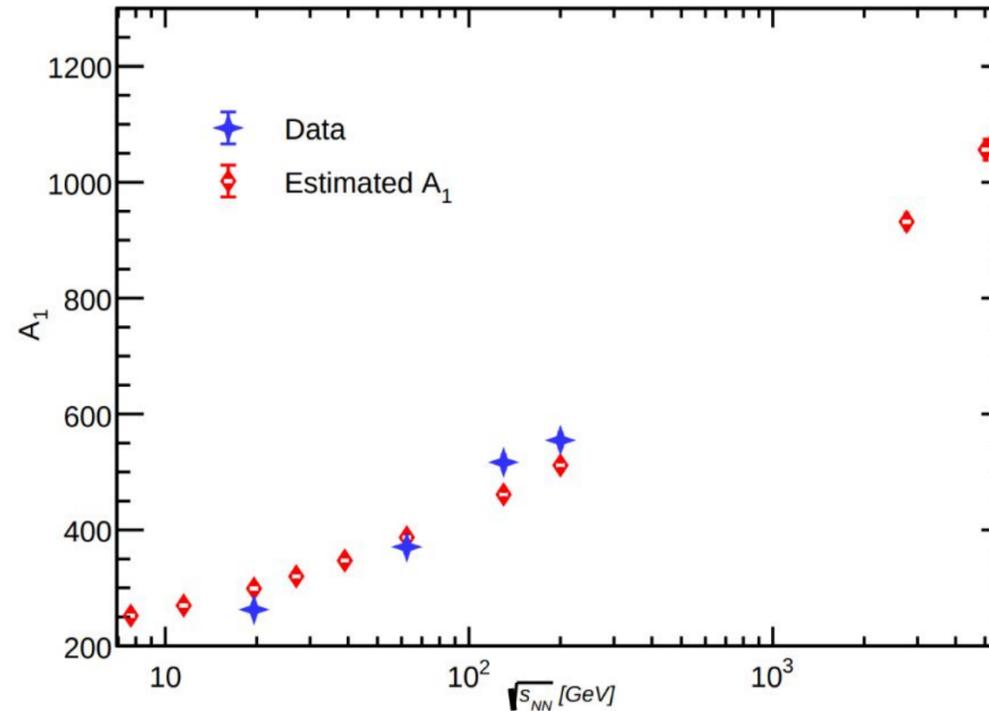


Physical Interpretation: $d_{p2p} \Rightarrow$ eff. system size, $T_{ch} \Rightarrow$ inelastic collisions cease. Both follow identical **exp. sat. scaling** \Rightarrow **geometric expansion** \Leftrightarrow **thermal evolution**. System size & chemical freeze-out follow the same energy dependence, approaching the transparency limit.

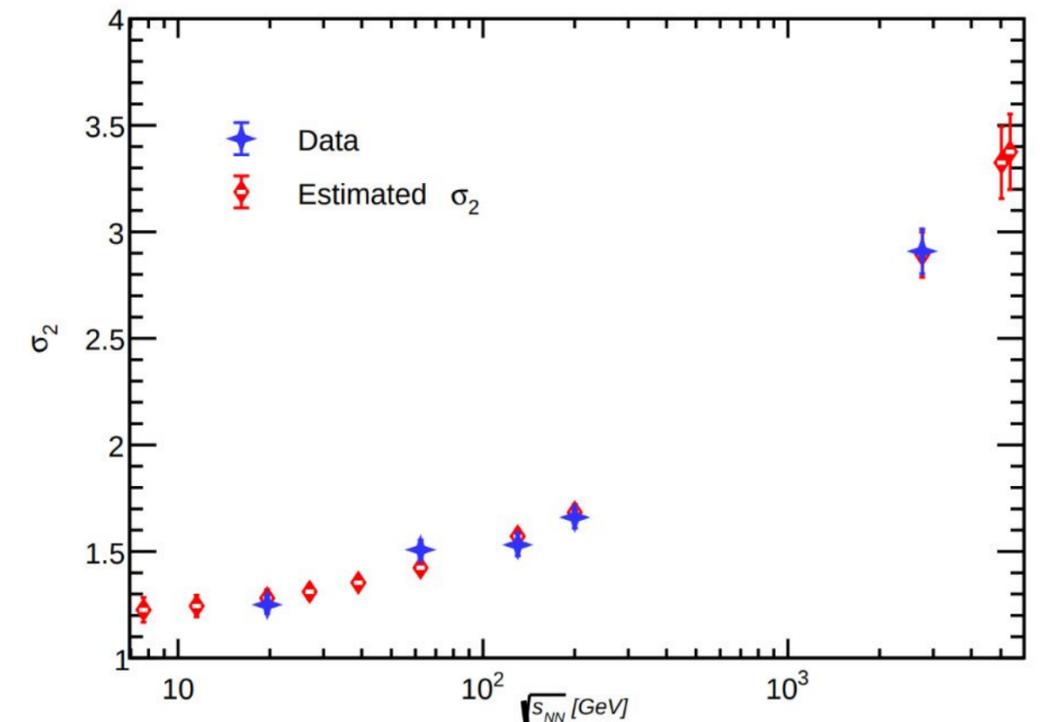
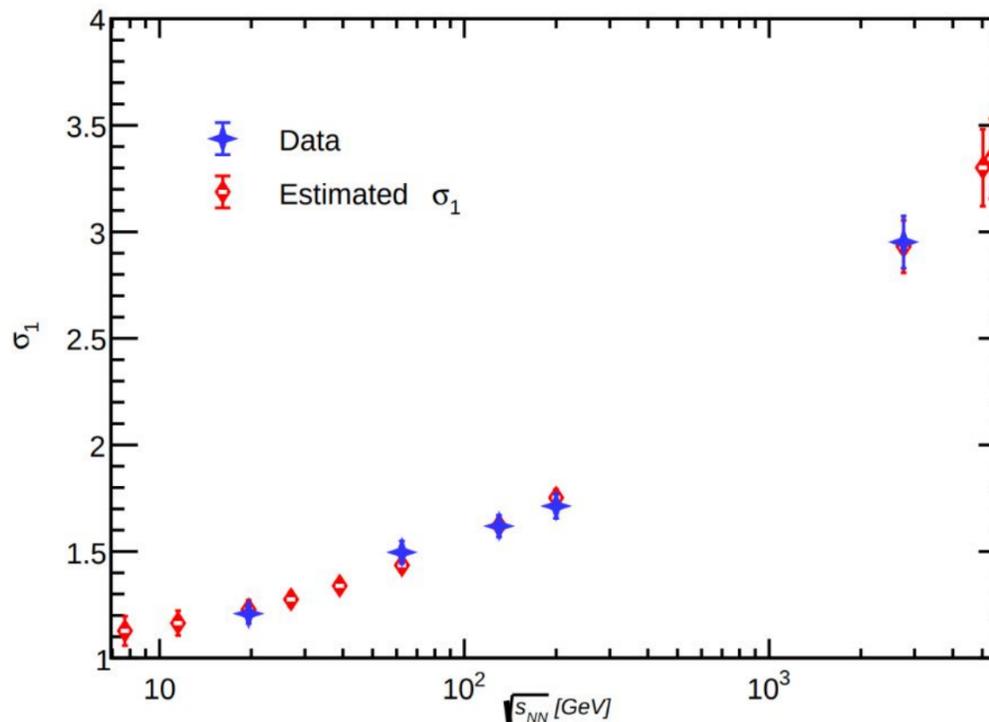
Predictive Capability



Fitted scaling laws enable predictions for A_1 , A_2 & σ_1 , σ_2 at energies with incomplete η coverage (5.02, 5.36 TeV).

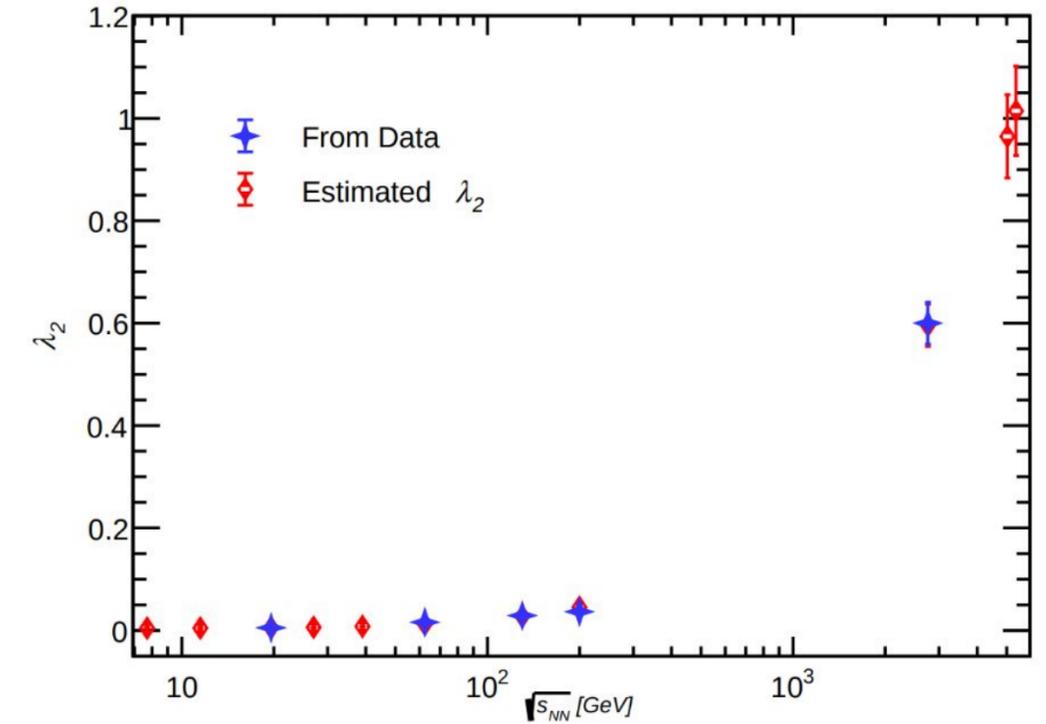
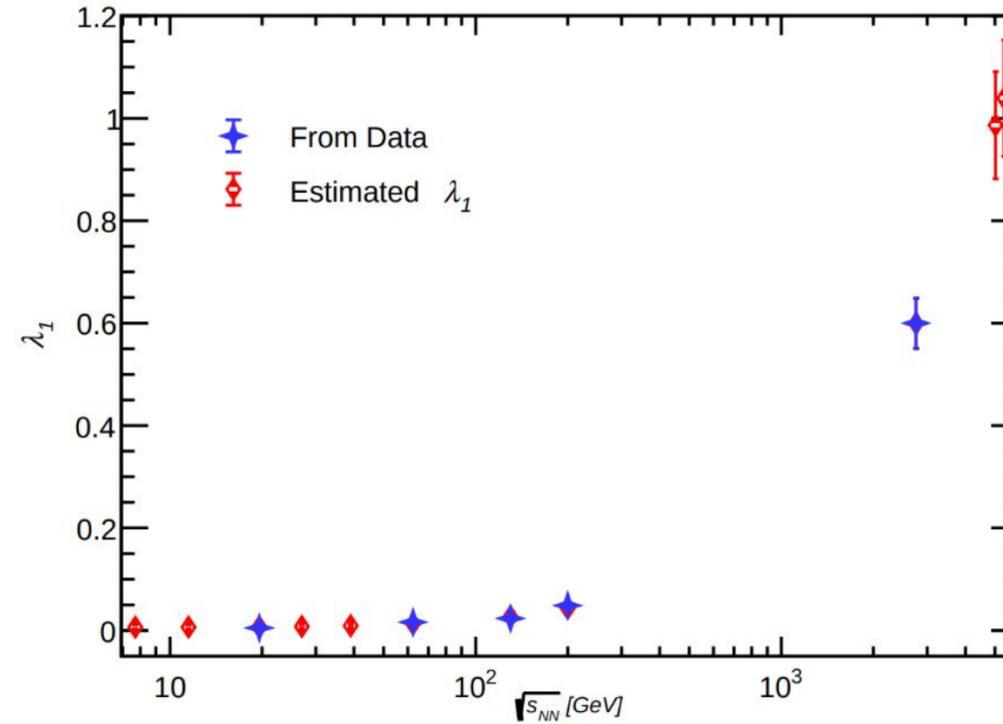


Scaling functions estimates for N/A RHIC energies (7.7, 11.5, 27, 39 GeV) where A 's & σ 's can be reliably predicted.





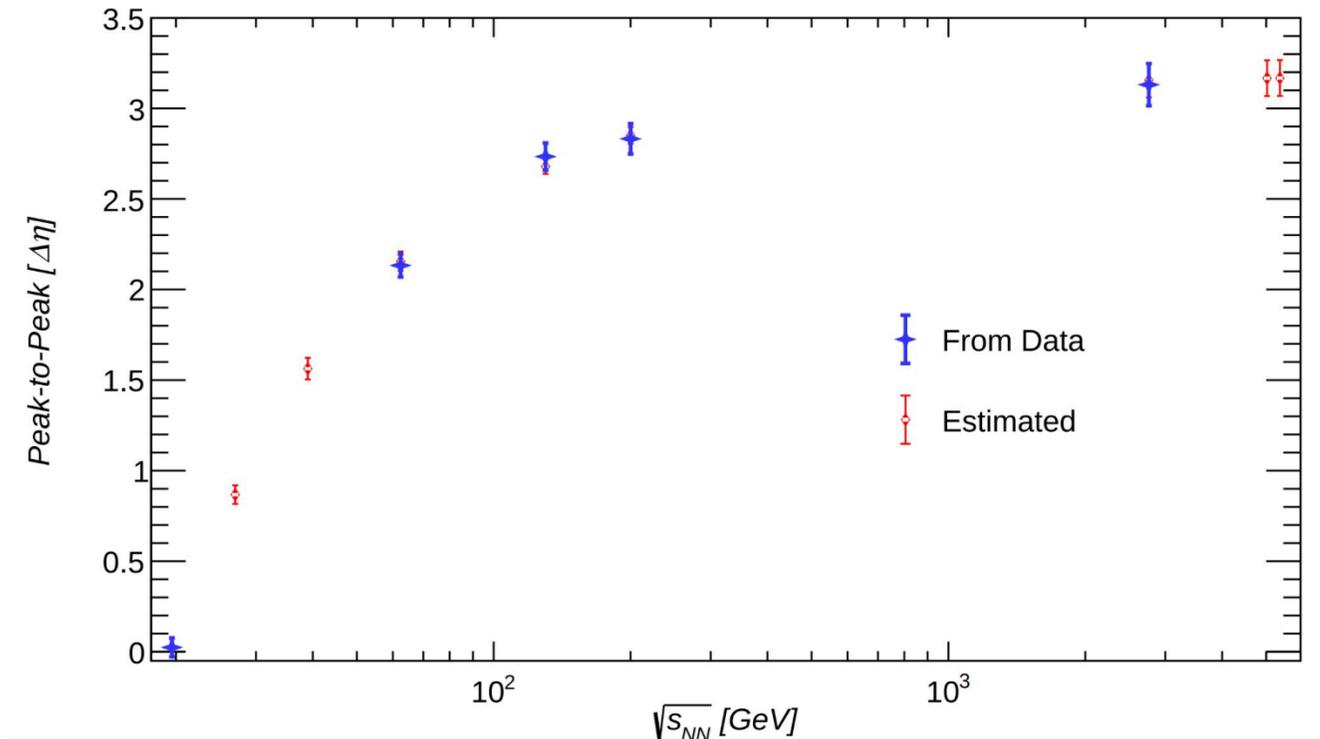
Predictions for λ_1 , λ_2 & *peak-to-peak distances* energies with incomplete η coverage, e.g., (5.02, 5.36 TeV).



Systematic framework:
Power-law & exponential fits unify data across **RHIC** to **LHC** energies.



Systematic Validation tool:
Testable against future data to verify physical scaling laws.



Validation of Predictions at Higher Energies



Successful validation: Predictions at **5.02** & **5.36 TeV** agree with limited- η data.

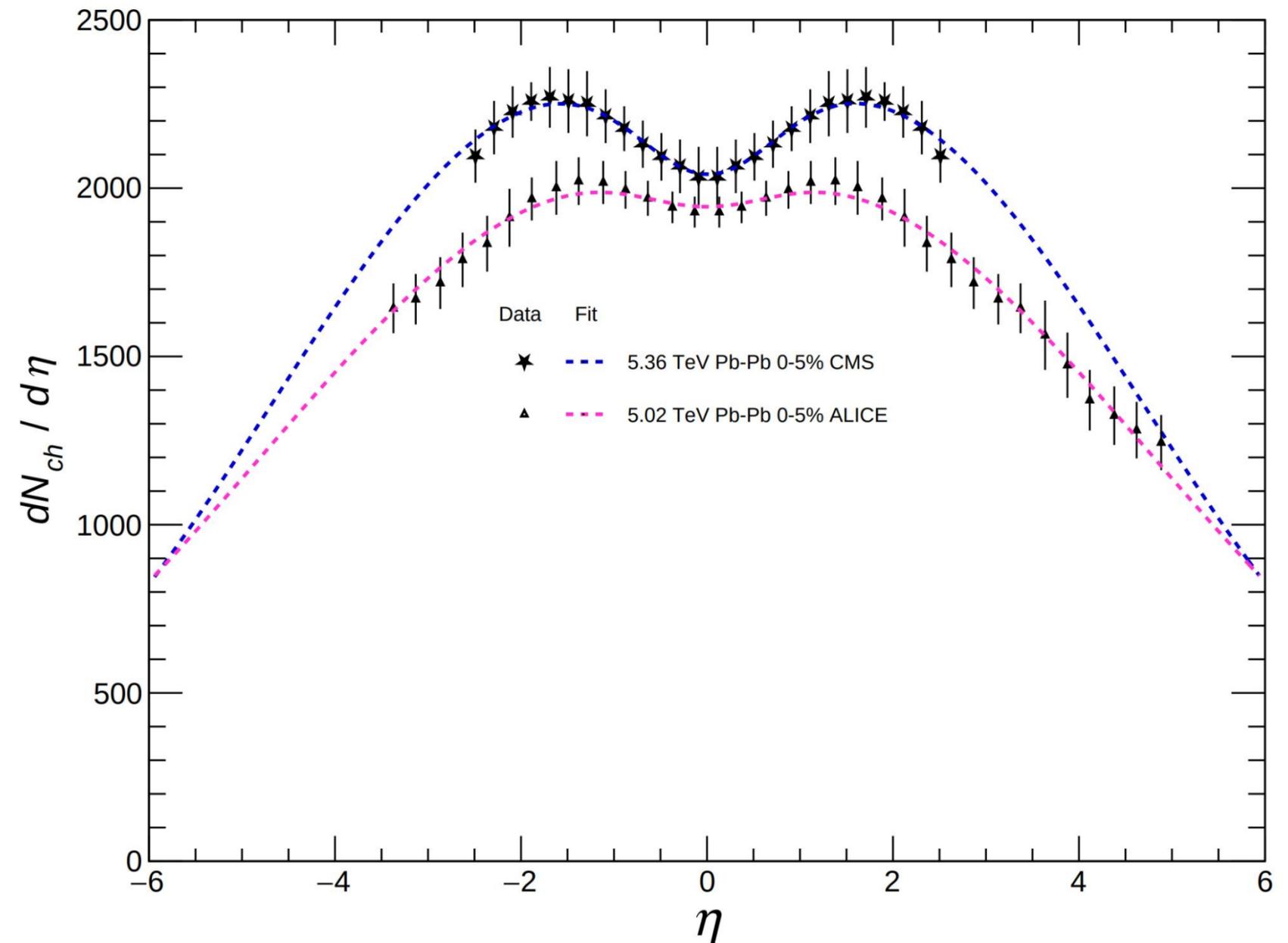


Good fitting quality: *erf*-modified Gaussian fits give low χ^2/ndf at high energies

χ^2/ndf : **0.189** (for **5.02 TeV**)
0.070 (for **5.36 TeV**)



Parameter consistency: Extracted parameters match scaling-law predictions.



- 01 **Novel fitting approach:** *erf*-modified Gaussian successfully describes $dN_{ch}/d\eta$ from **RHIC** to **LHC**, capturing **central dip** and **asymmetries** missed by double-Gaussian fits.
- 02 **Systematic energy scaling:** All fitting parameters follow well-defined **scaling laws** with collision energy.
- 03 **Physical insights:** λ correlates with $1/\mu_B$, reflects source interaction strength; while d_{p2p} mirrors T_{ch} evolution.
- 04 **Predictive framework:** Est. scaling laws enable reliable **extrapolation** to higher energies and **interpolation** of data gaps.
- 05 **Future applications:** Useful for **asymmetric systems** (**p+Pb**) with forward–backward asymmetries & for **low-x** studies where **saturation** modifies distributions.

Conclusion





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Thank You
Questions?

