A deep neural network based estimator for elliptic flow in heavy-ion collisions

Based on: N. Mallick, S. Prasad, A. N. Mishra, R. Sahoo, and G. G. Barnaföldi,
Phys. Rev. D. 105, 114022 (2022)

Workshop on Applications of Artificial Intelligence and Machine Learning

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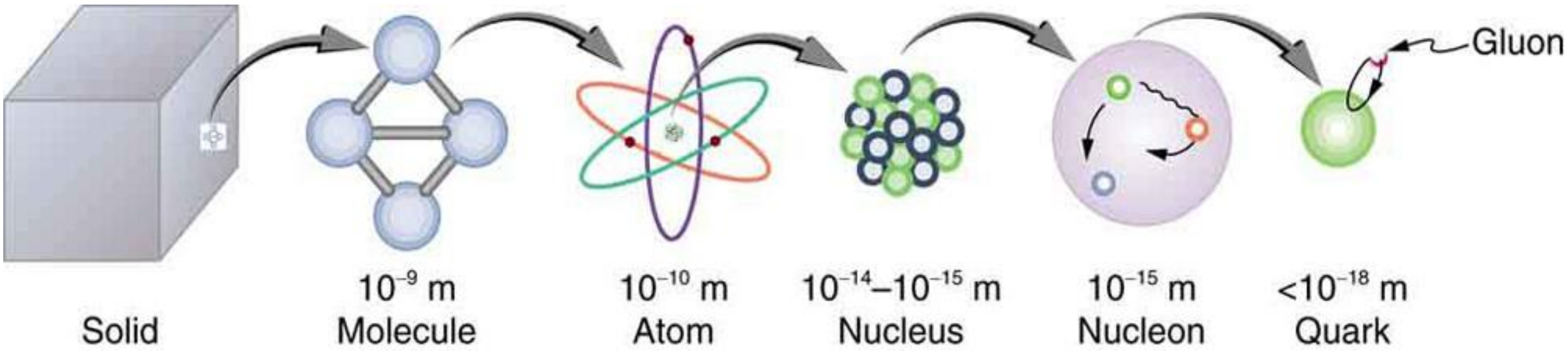
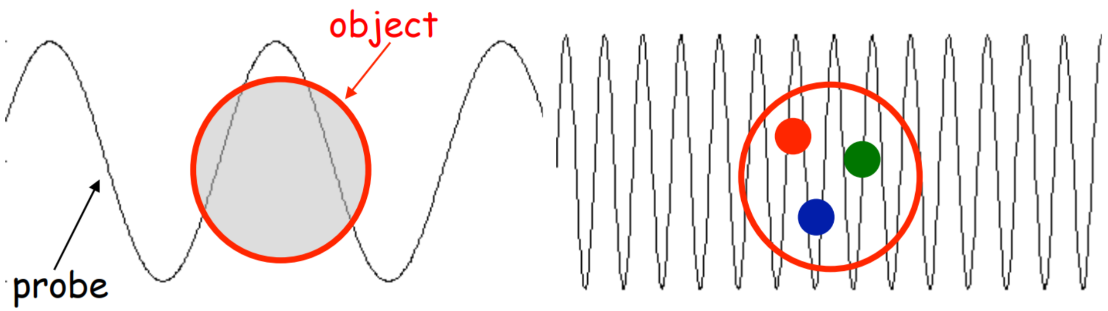
Outline

- Heavy-ion collisions and Quark gluon plasma
- Elliptic flow
- Deep Neural Network
- Input to the Model
- DNN Architecture
- Quality Assurance
- Results
- Summary and Outlook

Constituents of matter



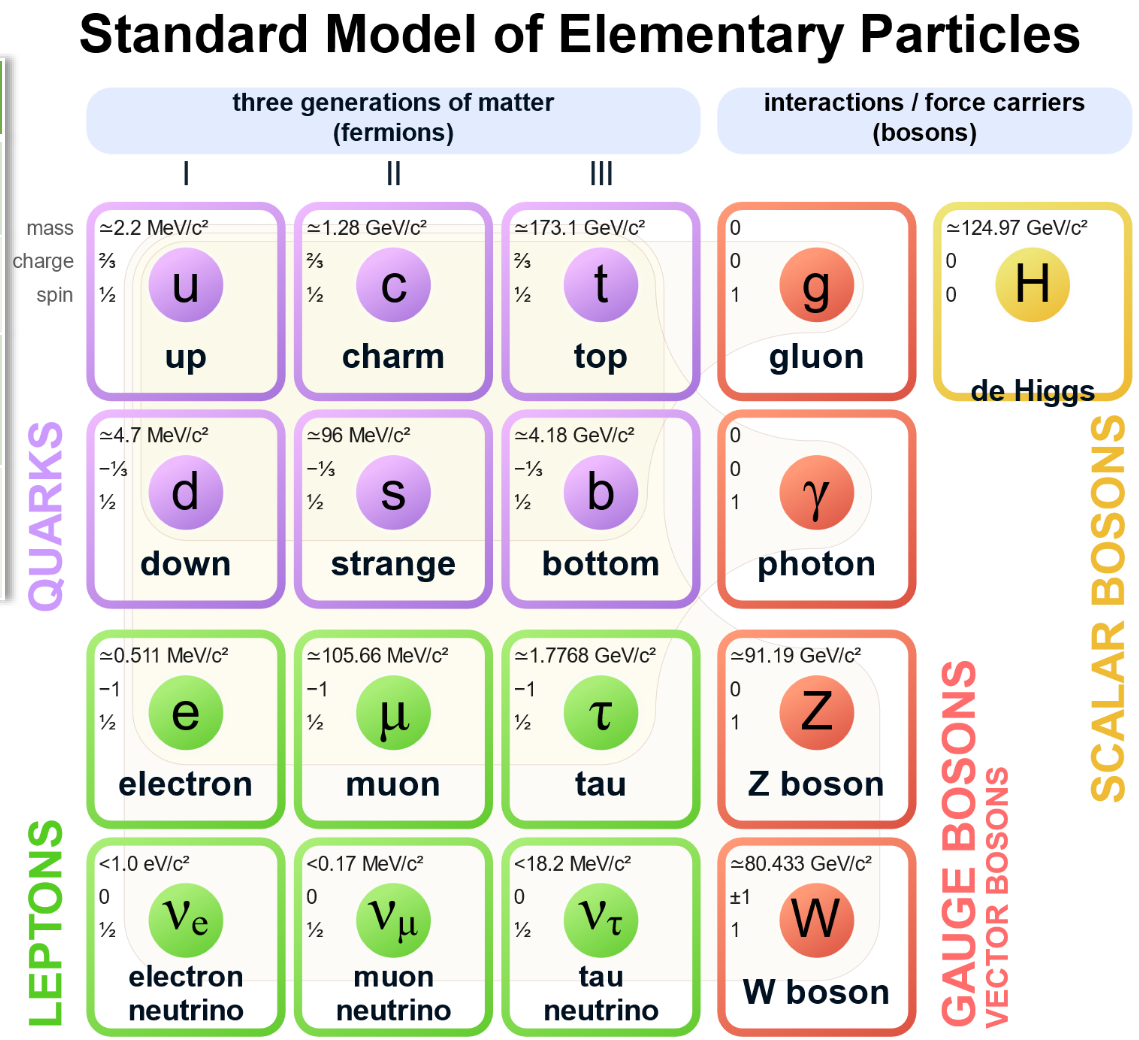
- Energy is related to wavelength by de Broglie's formula: $p = h/\lambda$
- To probe inside smaller objects we need higher energy



[1] R. Sahoo, "Relativistic Kinematics", [arXiv:1604.02651 [nucl-ex]]

Fundamental interactions

	Gravitational	Weak	Electromagnetic	Strong
Acts on	Mass-Energy	Flavour	Electric Charge	Color Charge
Strength	$\approx 10^{-36}$	$\approx 10^{-7}$	1	≈ 100
Particles mediating	graviton	$W^{\pm}, Z^{0}$	γ	Gluons
Particle experiencing	All	Leptons, quarks	Electrically charged	Quarks, gluons



Hadrons

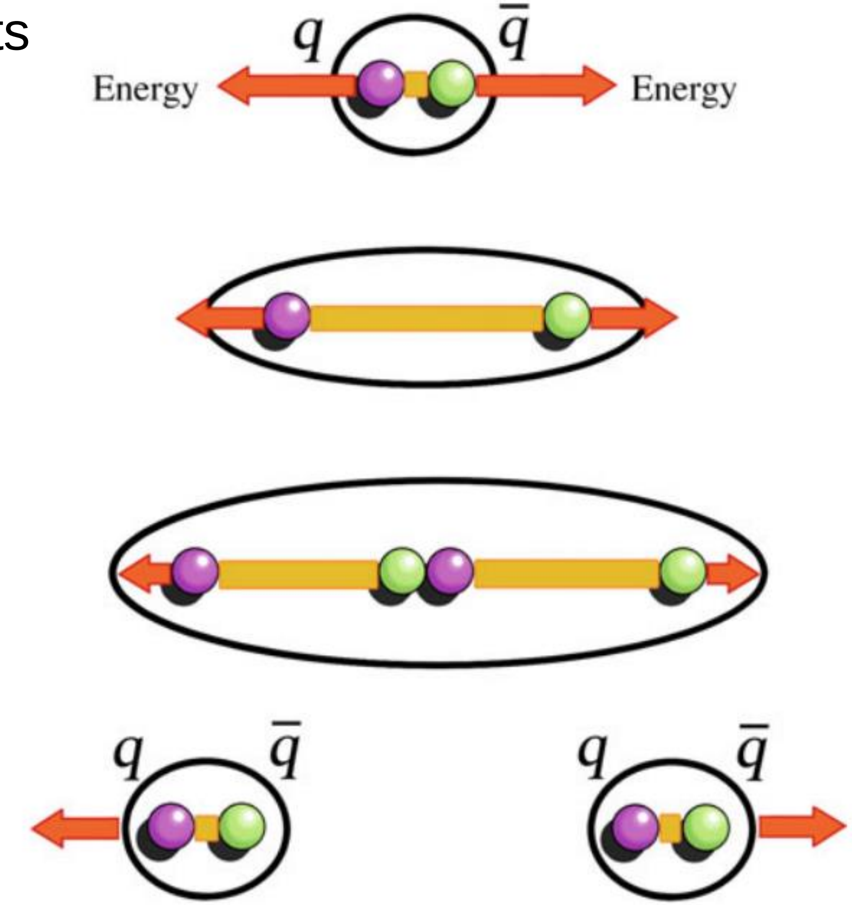
- Baryons (qqq)
- Mesons $(\bar{q}q)$

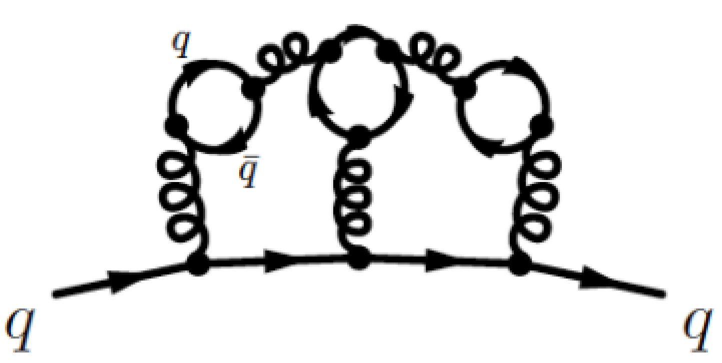
- QED: Quantum Electrodynamics: Theory of electromagnetic interaction
- QCD: Quantum Chromodynamics: Theory of Strong interaction

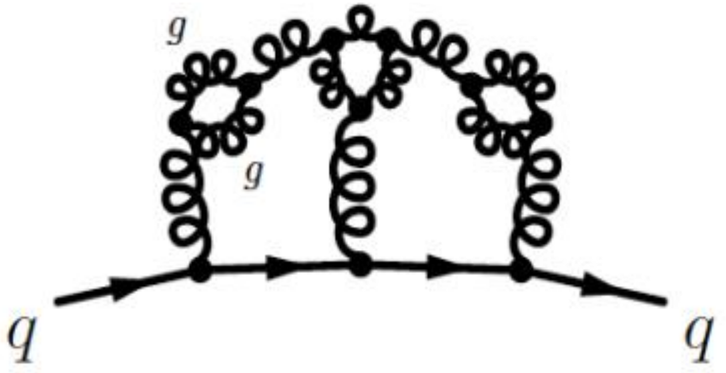
Perkins, D. (2000). *Introduction to High Energy Physics* (4th ed.). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511809040

Strong Interaction

- Unlike QED, in QCD gluons have color charge which permits gluon-gluon interaction
- Color charges can't freely exist : Color confinement
- At high energies, α_s becomes smaller : Asymptotic freedom



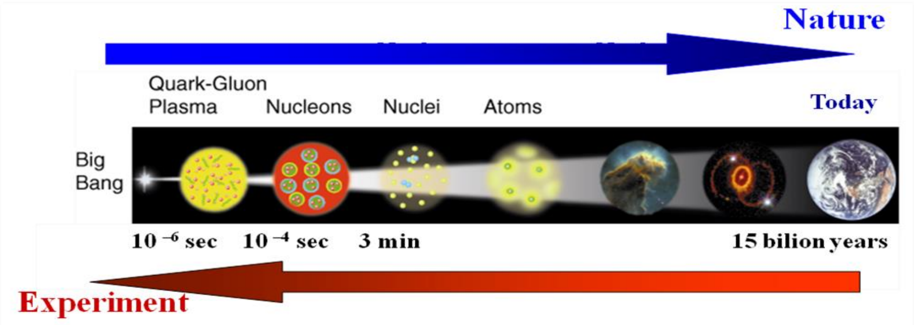


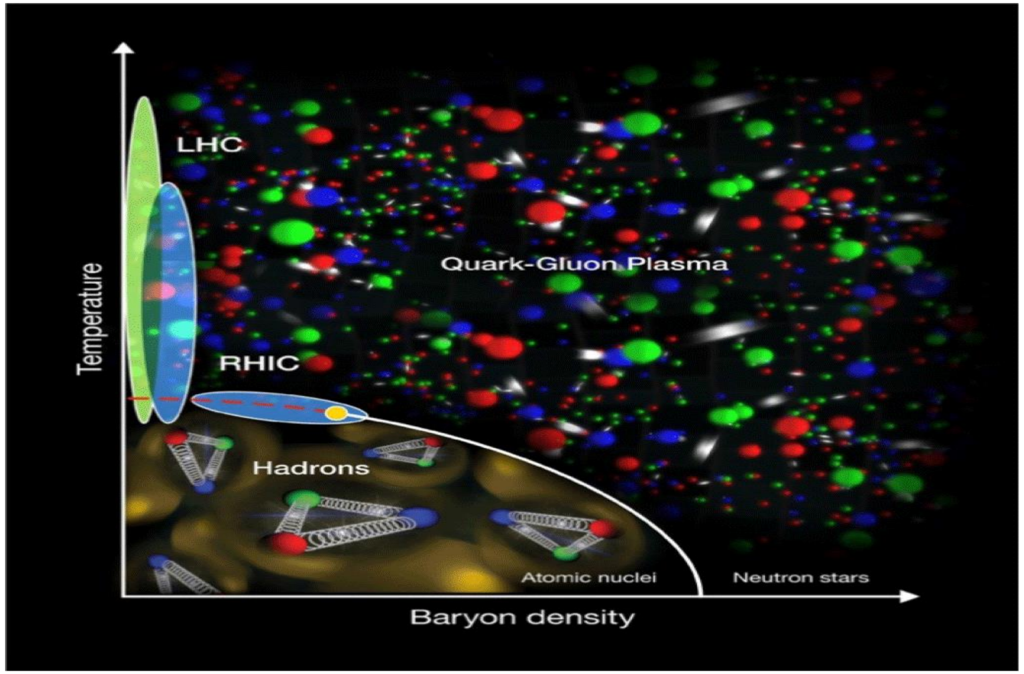


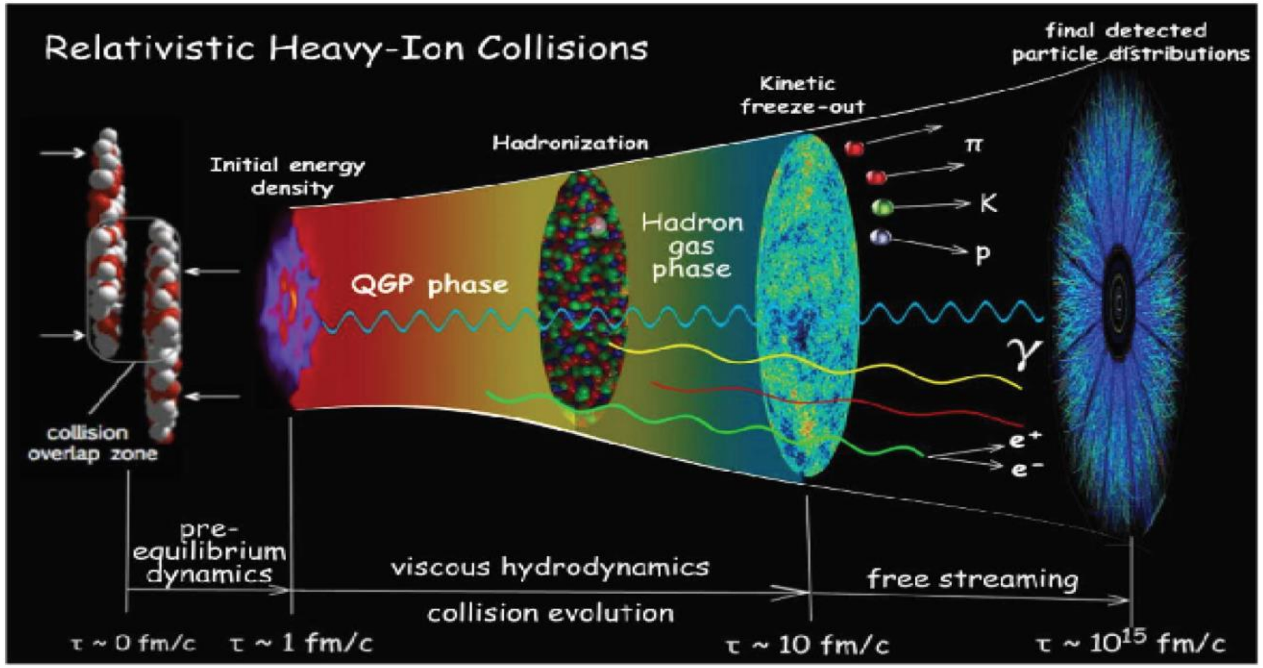
Obertelli, A., Sagawa, H. (2021). Nuclear Physics and Standard Model of Elementary Particles. In: Modern Nuclear Physics. UNITEXT for Physics. Springer, Singapore

Heavy-ion collisions (HIC) and Quark gluon plasma (QGP)

- Quark gluon plasma (QGP) is a hot and dense state of deconfined quarks and gluons in thermal equilibrium
- The value of the strong coupling constant decreases as the energy density increases: Asymptotic Freedom

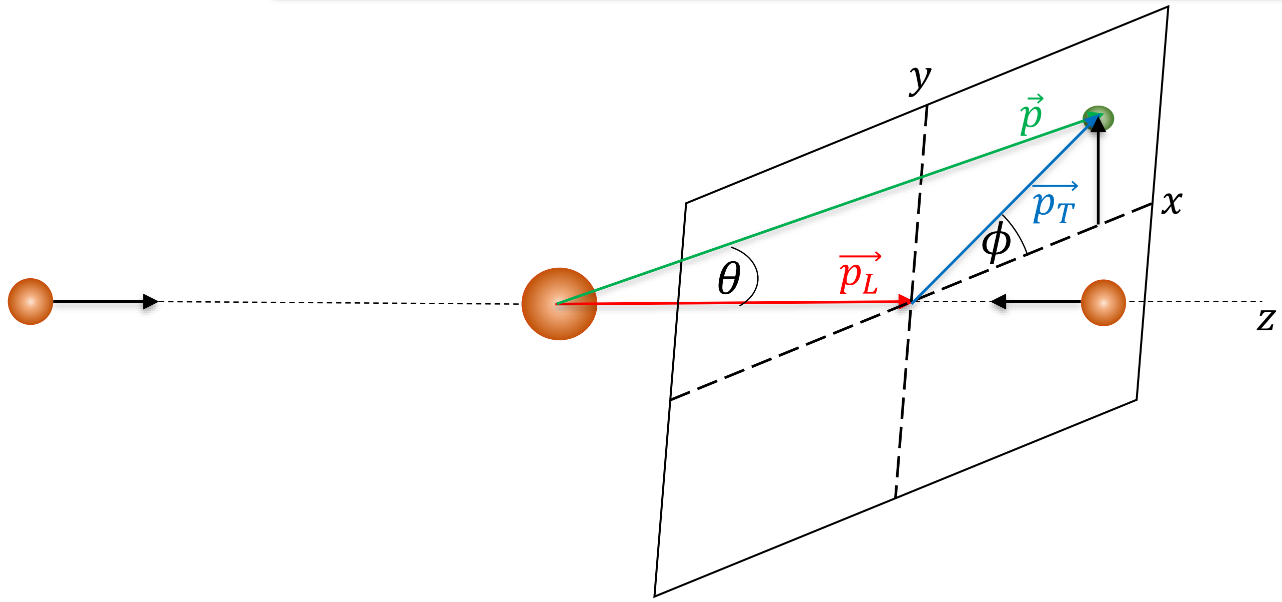


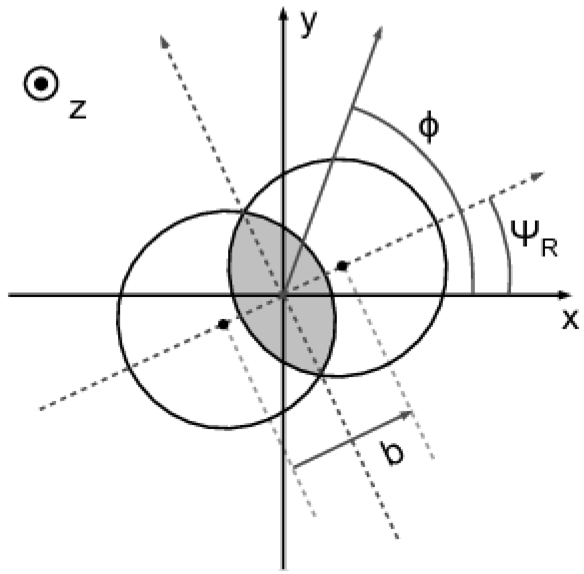




[1] R. Sahoo, AAPPS Bull. 29, 16 (2019).
[2] U. Heinz, Int. J. Mod. Phys. A 30, 1530011 (2015).
[3] R. Sahoo, and T. K. Nayak, Curr. Sci. 121, 1403 (2021).

Kinematic Observable in HIC

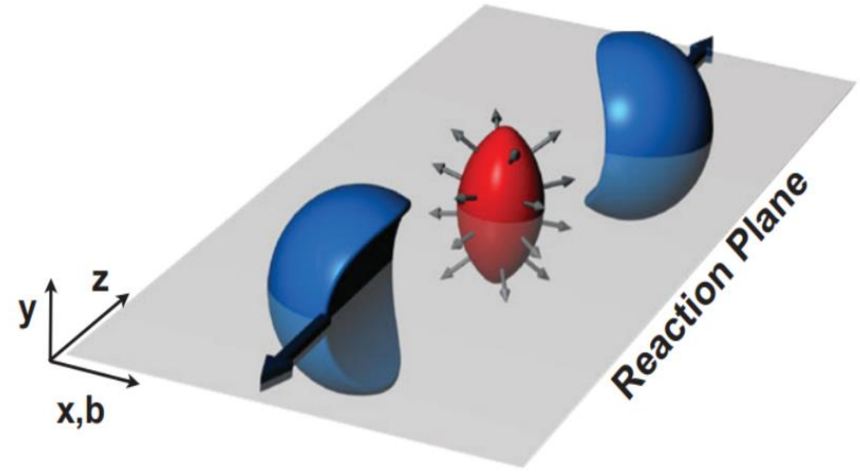


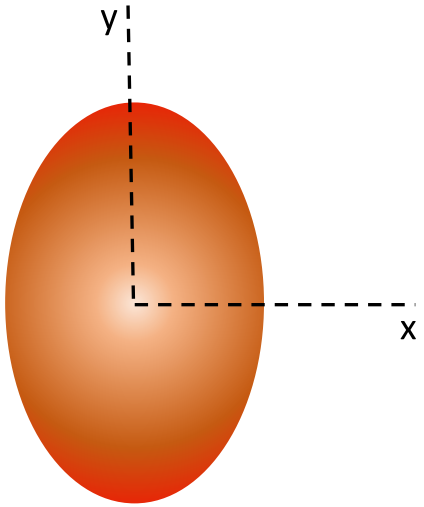


- Transverse Momentum, $p_T = \sqrt{p_x^2 + p_y^2}$
- Azimuthal Angle, $\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$
- Polar angle, $\theta = \tan^{-1}\left(\frac{p_T}{p_z}\right)$
- Rapidity, $y = \frac{1}{2}\ln\left(\frac{E+p_Z}{E-p_Z}\right)$
- Pseudo-rapidity, $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$
- Reaction plane angle, ψ_R: Angle made by impact parameter (b) with x-axis

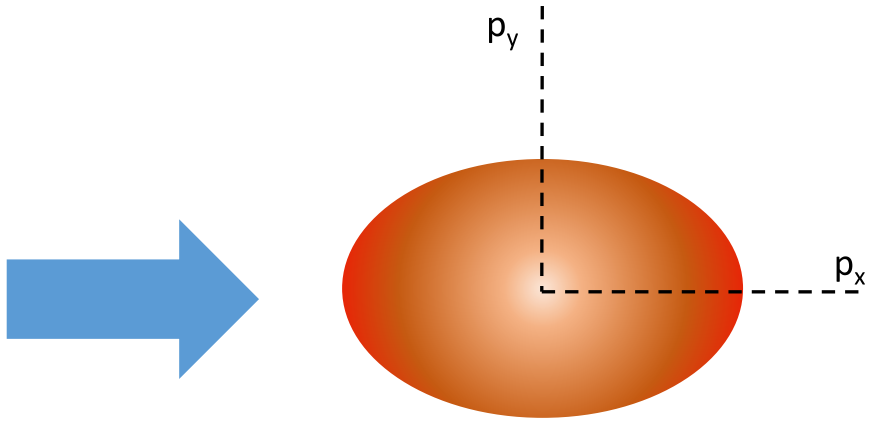
[1] R. Sahoo, "Relativistic Kinematics", [arXiv:1604.02651 [nucl-ex]]

Elliptic Flow (v_2)





Initial Spatial Anisotropy



Final Azimuthal Momentum Space Anisotropy

- Anisotropic flow: hydrodynamic response to spatial deformation of the initial density profile.

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right) = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + \underbrace{2v_1\cos(\phi - \psi_1)}_{\text{Directed flow}} + \underbrace{2v_2\cos[2(\phi - \psi_2)]}_{\text{Elliptic flow}} + \underbrace{2v_3\cos[3(\phi - \psi_3)}_{\text{Triangular flow}} + ...]\right)$$

$$\boxed{v_2 = \langle \cos[2(\phi - \psi_2)] \rangle}$$

N. Mallick, R. Sahoo and S. Tripathy, and A. Ortiz, J. Phys. G 48, 045104 (2021)
B. B. Abelev et al. [ALICE Collaboration], JHEP 1506, 190 (2015)

Deep Neural Network (DNN)

- It is an ML algorithm inspired by the structure of the neurons in the animal brain

- Three key layers

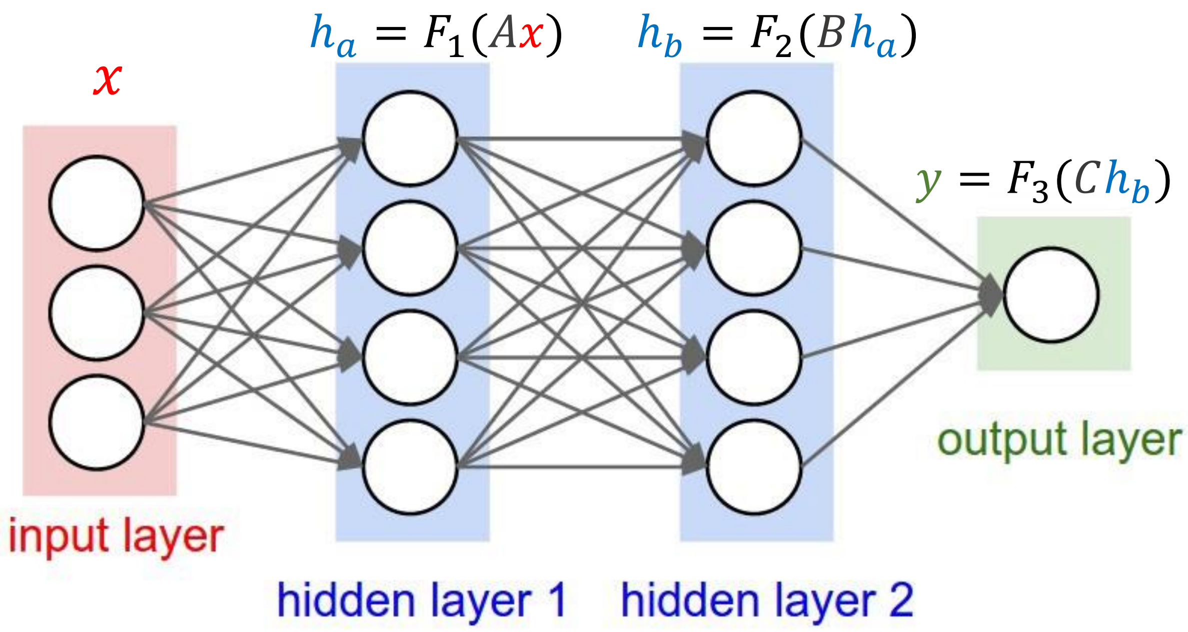
  Input layer: Takes different features as input
  Hidden layer: Connects to different neurons to weights
  Output layer: gives the result as a number or class

- Weights: represents the importance of a neuron

- Activation function: Guides the outcome of each node

- Cost function: Evaluates the accuracy of the prediction

- Optimizer: Methods/Algorithms used to minimize the cost function by updating the weights



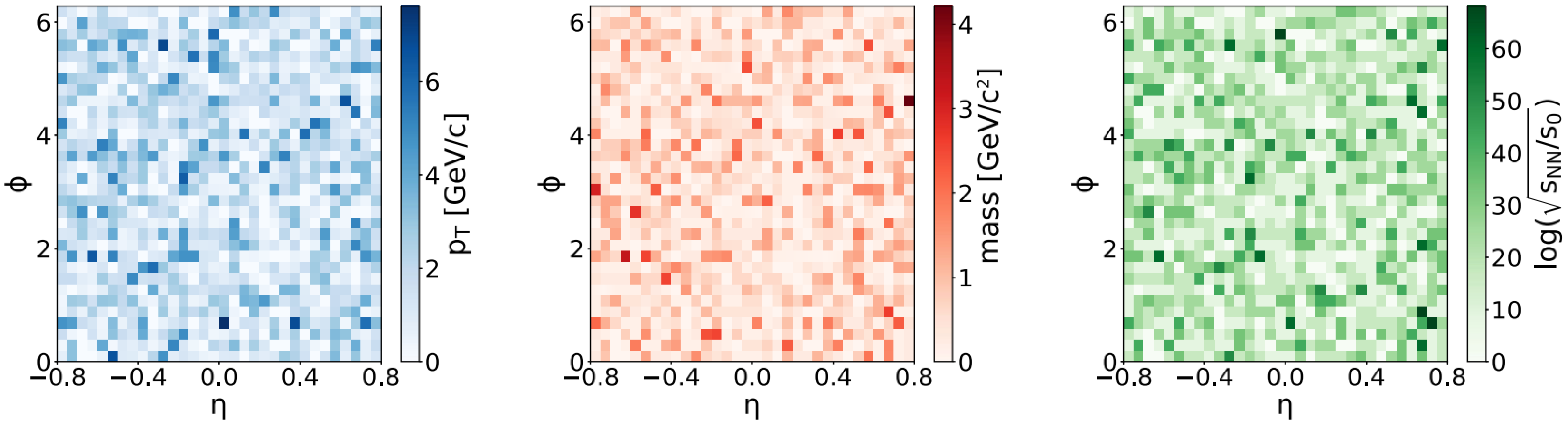
- For an input layer x, two hidden layers, the output y can be represented as:

$$y = F_3\left(CF_2\left(BF_1(Ax)\right)\right)$$

A, B, C represent the weight matrices
F_1, F_2, F_3 represent the activation functions

Input to the Model

- Elliptic flow (v_2) is an event property, depends upon: η, mass, p_T, centrality, etc.
- v_2 is calculated using the event plane method and ψ_R is set to zero in AMPT. ($\Rightarrow\ v_2 = \langle\cos(2\phi)\rangle$)
- $(\eta - \phi)$ space is considered as primary input space, divided into (32x32) bin space
- Weighted p_T, mass and $\log(\sqrt{(s_{NN}/s_0)})$ are taken as input to the DNN architecture.
- $32 \times 32 \times 3$ $(= 3072)$ features per event
- Trained with 150K minimum bias events of Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV simulated with AMPT.



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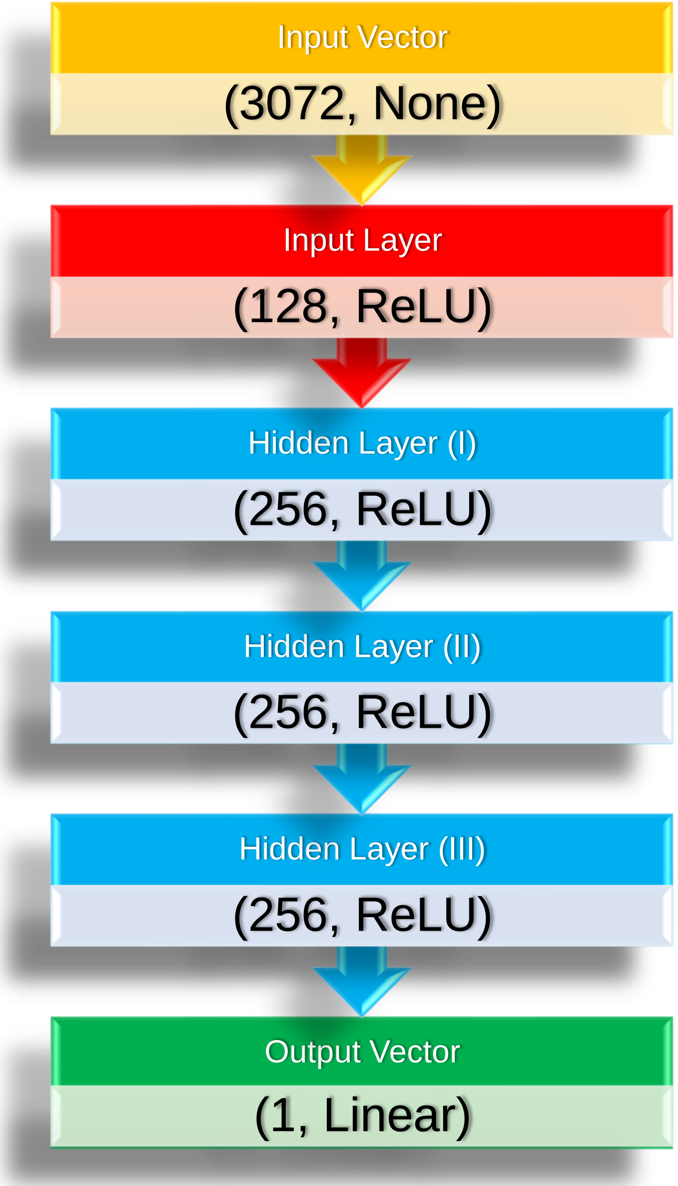
DNN Architecture

- Each event has 3072 input features mapped into the first dense layer with 128 nodes and ReLU activation function
- 3 hidden layers with 256 nodes and ReLU activation function
- The final layer has single node as v_2 and linear activation function is used
- ReLU (x) = max$(0, x)$
- Cost Function: mean squared error
- Optimiser: adam
- Early stopping mechanism is used to stop the training
- Early stopping patience level of maximum 10 epochs
- Max Epoch=60, batch size = 32



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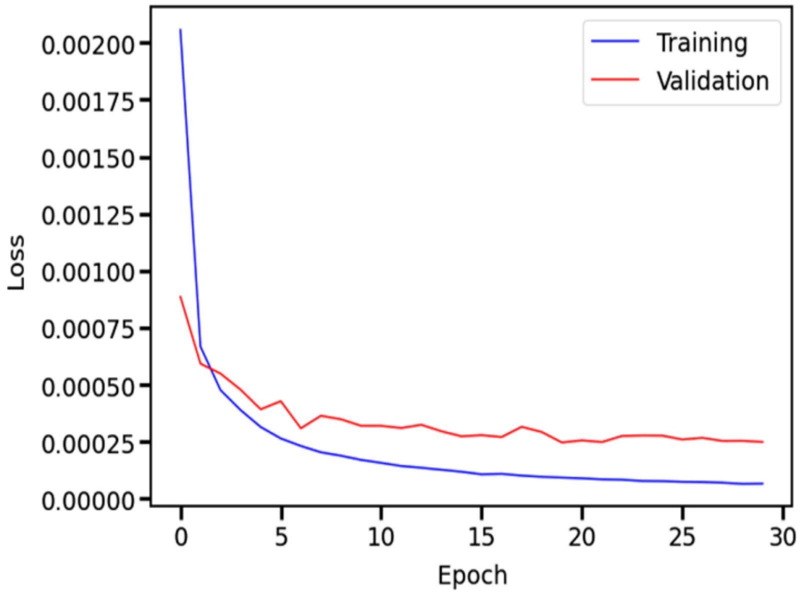
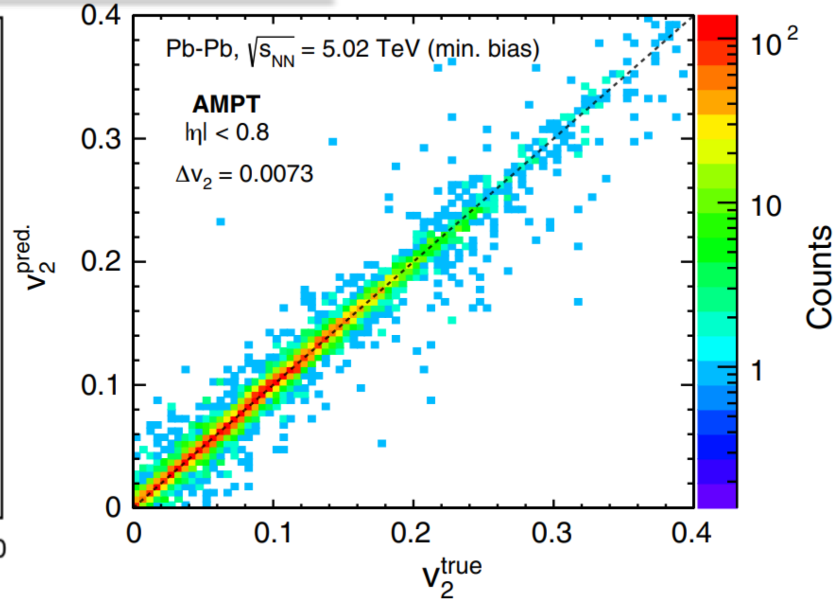
Quality Assurance

- Loss is the mean squared error of predicted v_2 w.r.t true v_2
- Loss is in the order of 10^{-4} : Good training
- Less to no overfitting/underfitting.





- Mean absolute error (MAE) of v_2 is defined as:

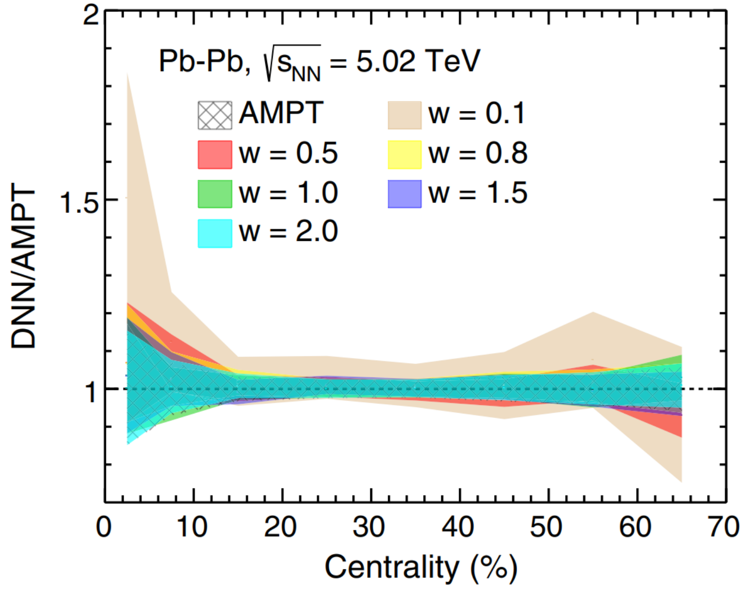
$$\Delta v_2 = \frac{1}{N_{\text{events}}} \sum_{n=1}^{N_{\text{events}}} |v_{2_n}^{\text{true}} - v_{2_n}^{\text{pred}}|$$

- $v_2^{true} = v_2^{pred}$ straight line is well populated
- 32x32 bin size is faster and has optimum performance compared to other bin size
- Model is quite sturdy and less sensitive to noise of different weights

- Modified j^{th} feature of i^{th} event:

$$F'_{ij} = F_{ij} + X_{ij}/w$$

w: weight
$X_{ij} \in (-\sigma_j, \sigma_j)$ is a random number



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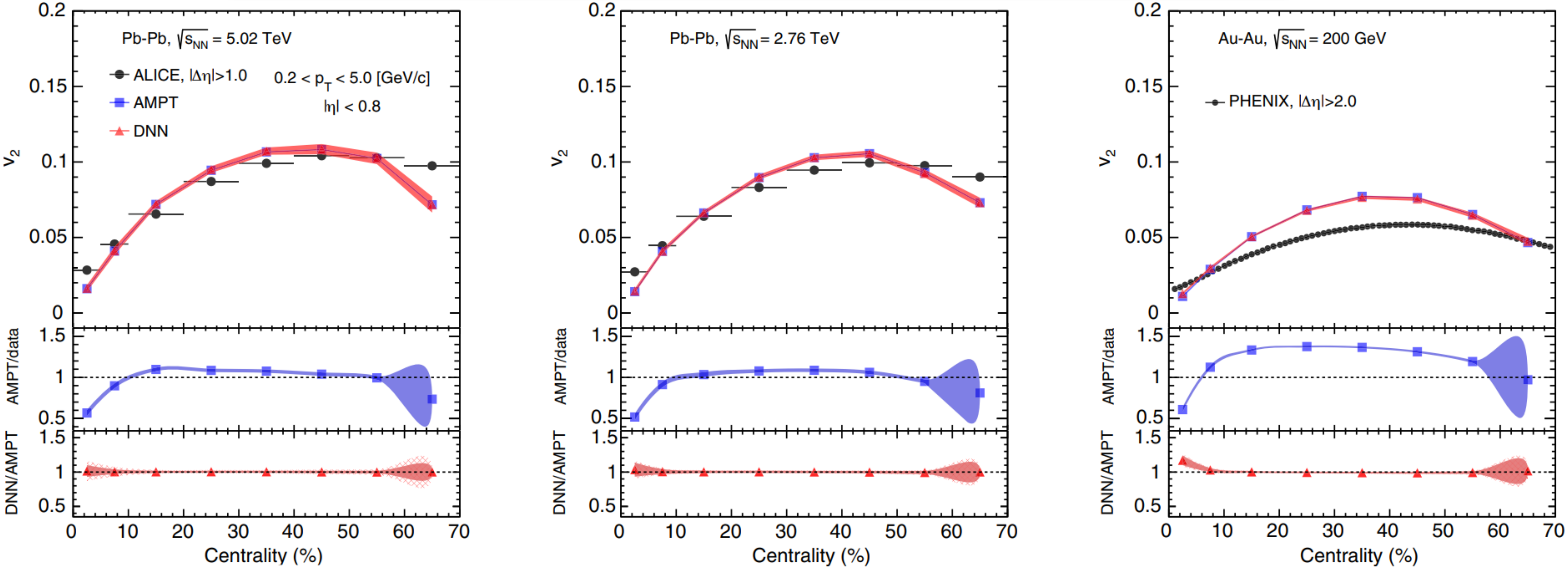
Results and Discussions



- AMPT results do not match with experimental data, which can be optimised with different settings available in AMPT

- DNN predictions almost match with the v_2 value from the AMPT, not only at LHC but also at RHIC energies, which is new to DNN

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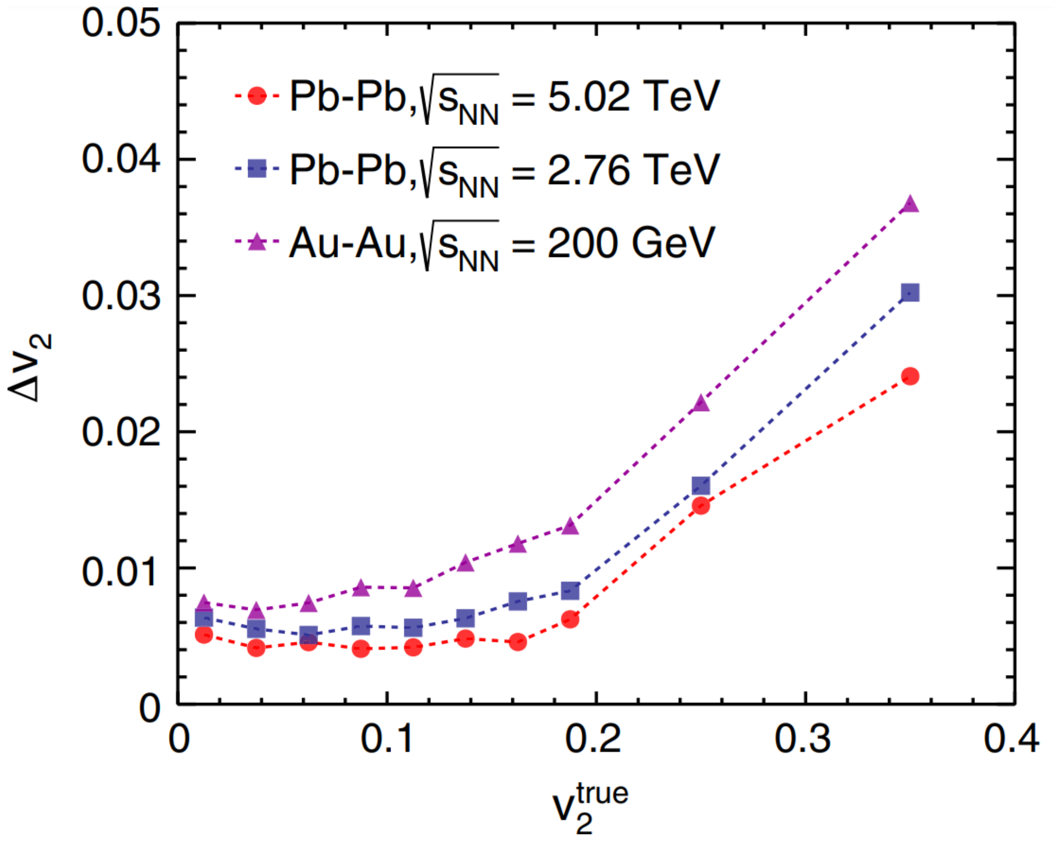
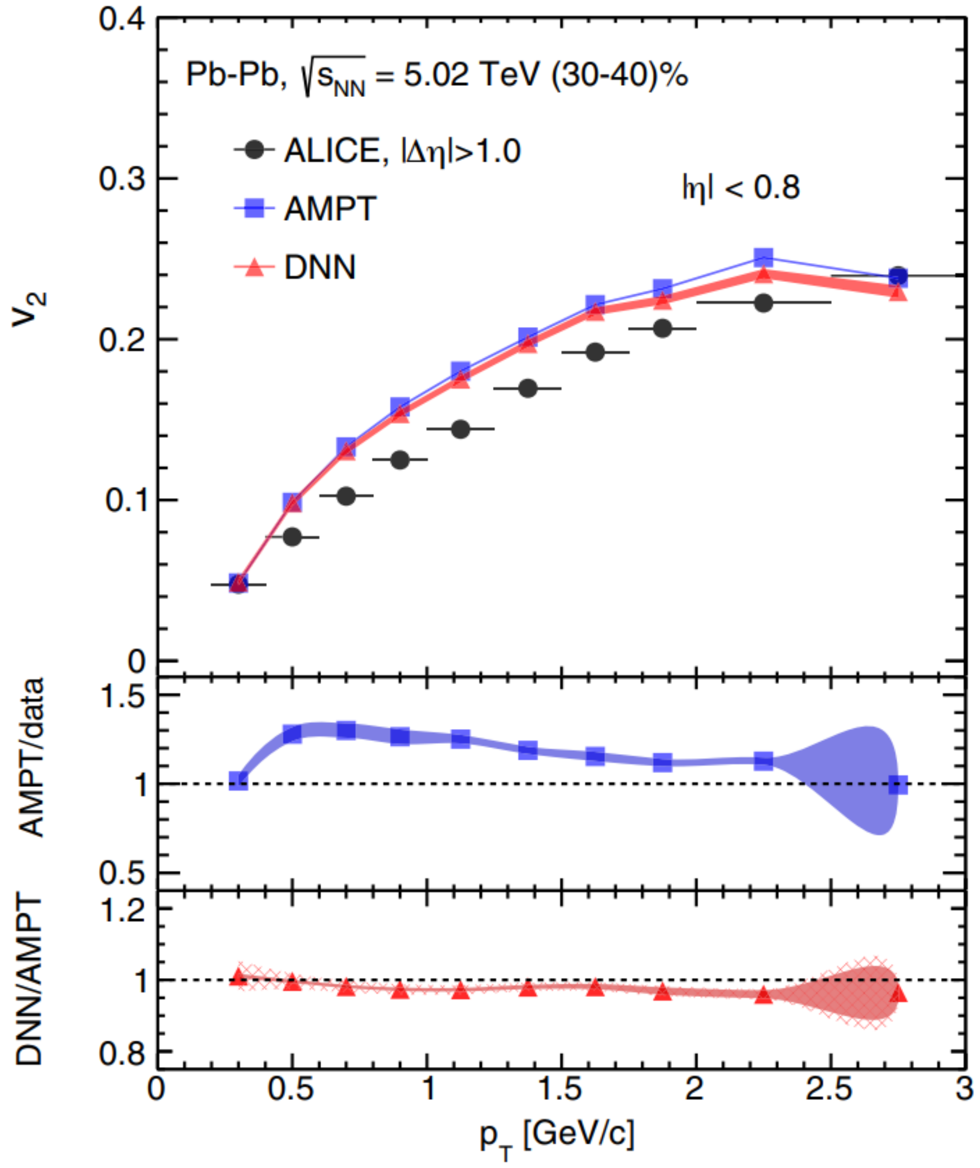
Results and Discussions





- Δv_2, is less than 10% of the true v_2
- Δv_2 is least for the case where it's trained
- DNN retains the p_T dependence, and matches with v_2 from AMPT in low p_T region.

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Summary

- Elliptic flow is one of the important observables to understand the physics of QGP, and it can be successfully predicted with machine learning based DNN algorithm
- The DNN model retains the centrality, energy and p_T dependence and predicts with accuracy
- The DNN model is quite robust and it's less sensitive to input data with uncorrelated noise

Outlook

- The DNN model is yet to be tested for particle dependence (mass dependence)
- If the model retains the particle mass dependence, it could be further tested for different scalings available for elliptic flow
- In AMPT, we have set $\psi_R = 0$, we are working on the model to learn random orientation of ψ and its dependence

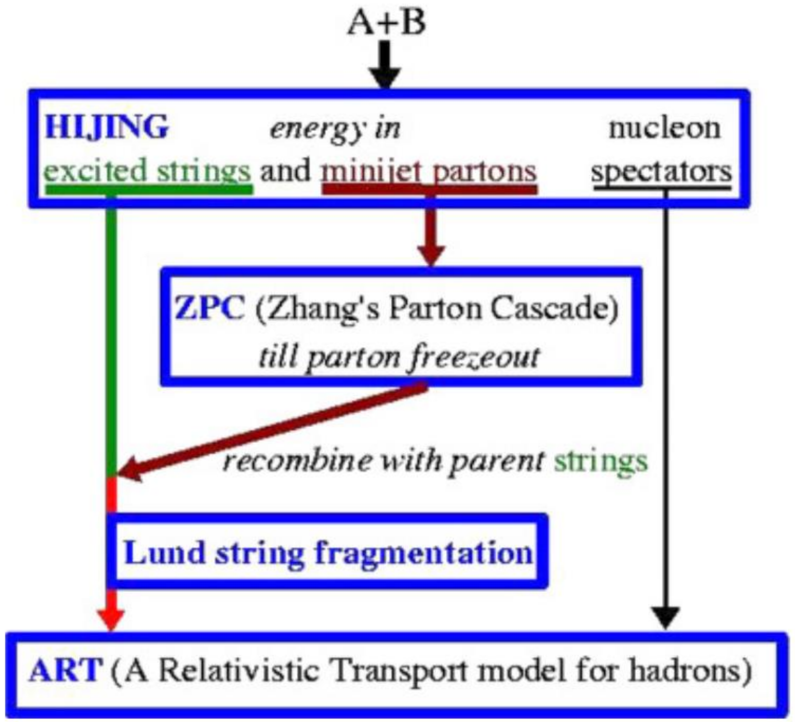
Thank You

For the attention

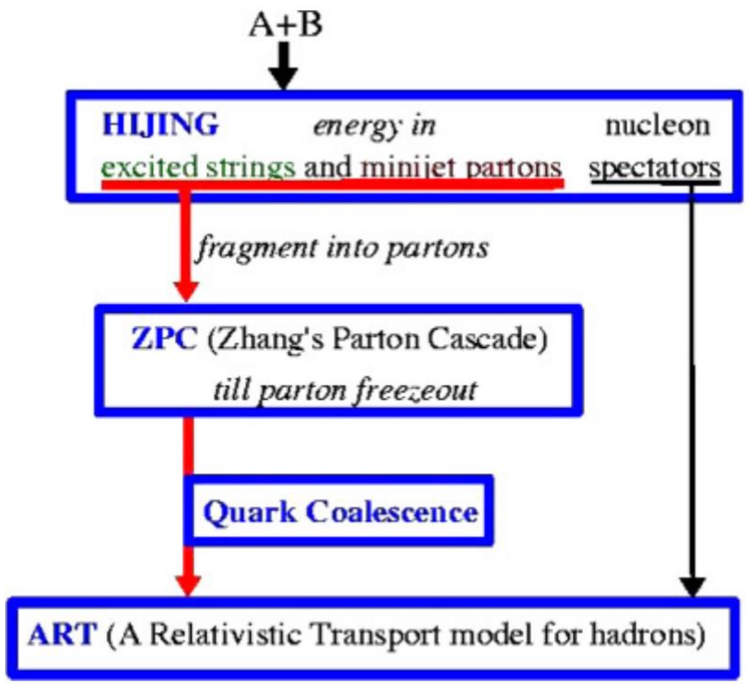
Backup Slides

A Multi-phase Transport Model (AMPT)

- Initialisation of collisions (HIJING)
- Parton Transport (ZPC)
- Hadronisation (Lund string fragmentation / Quark coalescence)
- Hadron Transport (ART)



Default Version



SM Version

Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, and Subrata Pal, Phys. Rev. C 72, 064901 (2005)