Event-by-event jet-induced hydro response from Generative model

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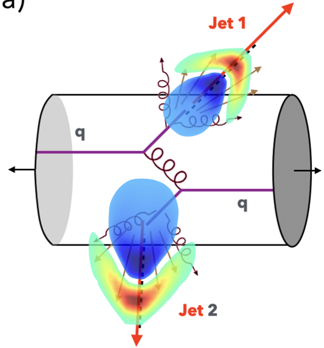
outline

- Introduction
- Initial training datasets
- Generative model: Flow matching model
- 3D $\frac{dN}{dp_T d\eta d\phi}$ results

Introduction

Initial hard process

(a)



zhong y arXiv:2501.03419v3

Jet ⟷ QGP (interaction)

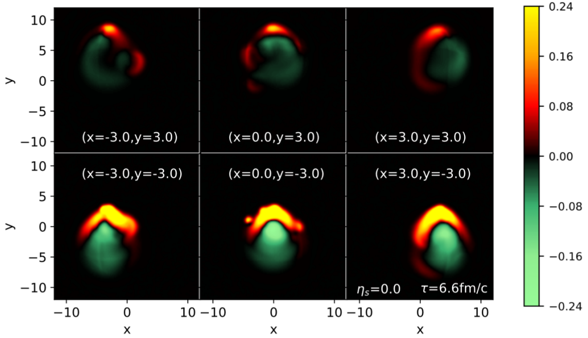
↓

Jet energy loss
Transverse momentum broadening

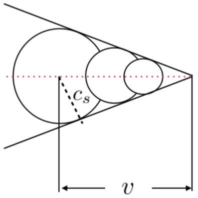
↓

Jet-induced medium response

Jet-induced medium response



zhong Y, et al. arXiv:2206.06393



马赫锥形成示意图

$$\sin\theta = \frac{c_s}{v}$$

$$c_s = \sqrt{\frac{dp}{d\epsilon}}$$

Motivation of using machine learning method

- **Large grid number**: $200 \times 200 \times 100$ cells per timestep per event
- **High computational cost**: 7-10 minutes per event on A100 GPU (80GB VRAM)
- **Research goal**: Establish relationship between initial conditions and final particle spectra
  - Using generative models to bypass expensive hydrodynamic calculations

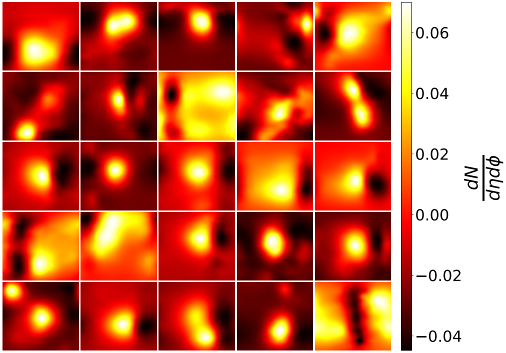
Initial datasets

CoLBT γ-jet training datasets

- **Source**: CoLBT-hydro model, $0-10\%$Pb+Pb, $\sqrt{s_{\rm NN}}=5.02$ TeV The γ p_T cut is 100GeV, and the jet p_T cut is 10GeV.
- **16,000 events** containing:
  - Initial parton showers and γ information
  - Final particle spectra $\frac{dN}{p_T dp_T d\eta d\phi}$ ($p_T \in [0,4]$ GeV/c, $\eta \in [-2.7, 2.7]$, $\phi \in [0, 2\pi]$)
  - 50 PCA features extracted from each 3D spectrum
- **Processing**:
  - Jet reconstruction with anti-k_T algorithm (FASTJET)
  - Data rotation: γ at $\phi = 0$, jet at $\phi = \pi$

Datasets sampling

25 2D distributions sampled from CoLBT training datasets



- **Axes**: $\phi \in [0, 2\pi]$ (x), $\eta \in [-2.7, 2.7]$ (y)
- **Bright positive region**: Mach cone front wake
- **Dark negative region**: Diffusion wake behind jet partons
- **Background subtracted**: Hydro without jet contribution removed

Flow matching

Generative model

Sora:

Prompt: Full body, anime art, Young woman practicing martial arts with steel gloves, Chinese dragon in the background, sky garden sanctuary, 4k

Flow matching advantage

- Constructing a "continuous flow" from a simple distribution (such as Gaussian noise) to a complex data distribution
- Without relying on complex intermediate processes (like iterative denoising), enables fast training and sampling, as well as stable training.

Differential Equation Foundation

$$\frac{dx}{dt} = u(x,t)$$

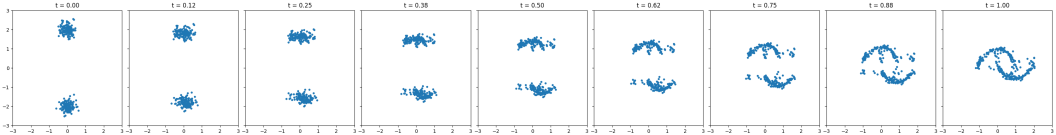
Known initial condition $x(t_0)$ and $u(x,t)$ enables solution $x(t)$

Flow Matching Approach

- Neural network representation: $u_\theta(x,t)$
- Known initial distribution: $x \sim P_0$ at $t = 0$
- Discrete evolution:

$$\frac{x_{i+1} - x_i}{\Delta t} = u_\theta(t_i, x_i) \Rightarrow x_{i+1} = x_i + \Delta t \cdot u_\theta(t_i, x_i)$$

An example of Flow matching



- Start: Sample (x_1, x_2) from bimodal Gaussian at $t = 0$
- Apply iterative transformations using velocity field $u_\theta(x, t)$
- Follow: $x_{i+1} = x_i + \Delta t \cdot u_\theta(t_i, x_i)$
- End: Obtain sample from crescent distribution at $t = 1.0$

Loss function

- **Probability path**: Linear interpolation between distributions

$$x(t) = tx_1 + (1-t)x_0$$

- **Time derivative**:

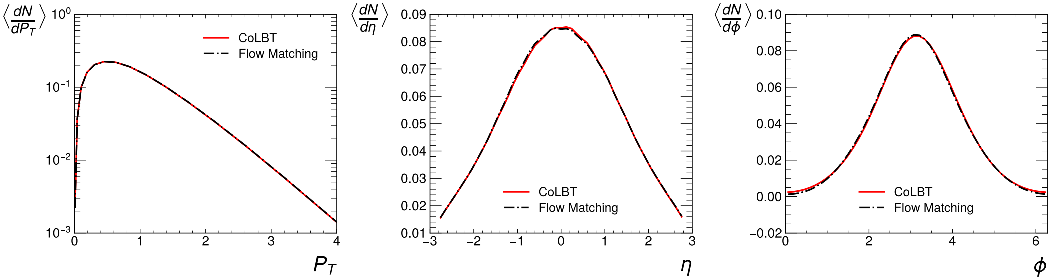
$$\frac{dx}{dt} = x_1 - x_0$$

- **Loss function**: Difference between actual and predicted evolution

$$\mathcal{L}(\theta) = ||u_\theta(x,t) - (x_1 - x_0)||$$

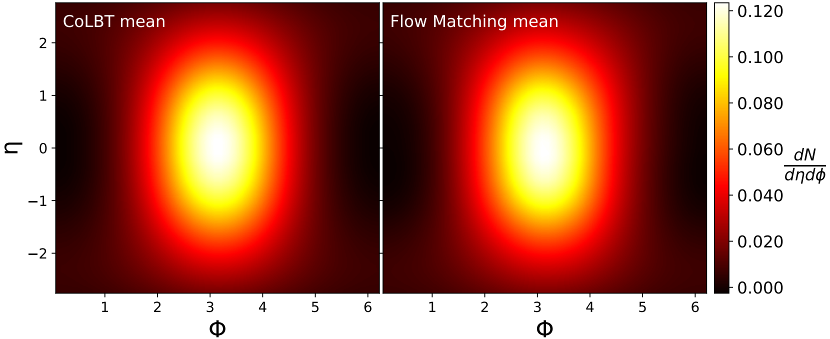
3D Spectra Results

Distribution Comparisons



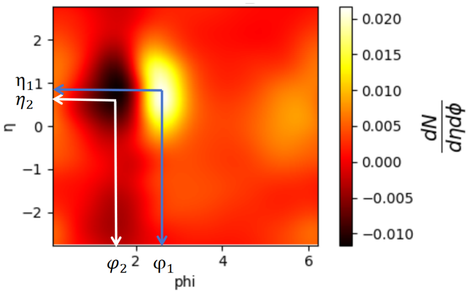
- **Left**: p_T distribution (integrated over η and ϕ)
- **Middle**: η distribution (integrated over p_T and ϕ)
- **Right**: ϕ distribution (integrated over p_T and η)

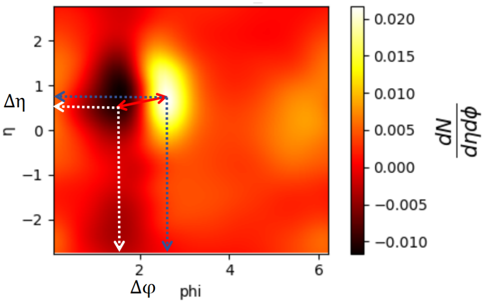
Average 2D Particle Spectrum Comparison



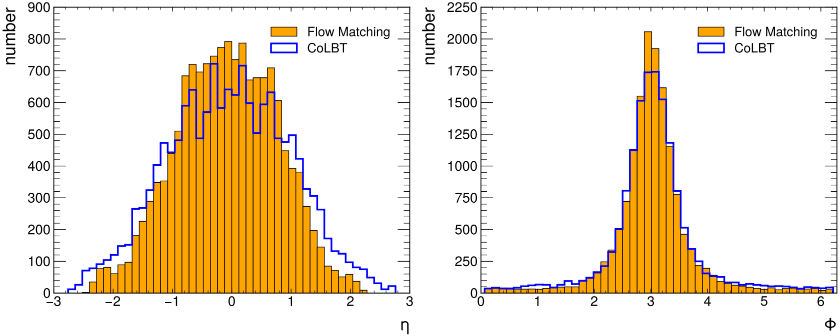
- **Left**: Average of all real events for $\frac{dN}{d\eta d\phi}$
- **Right**: Average of all corresponding generated events

Extreme Points Distance Analysis



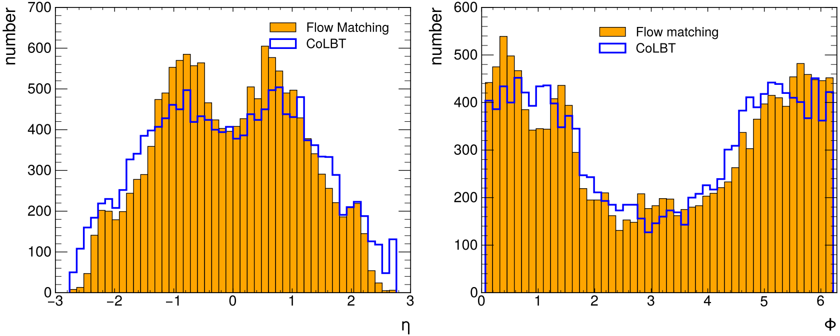


Front wake location



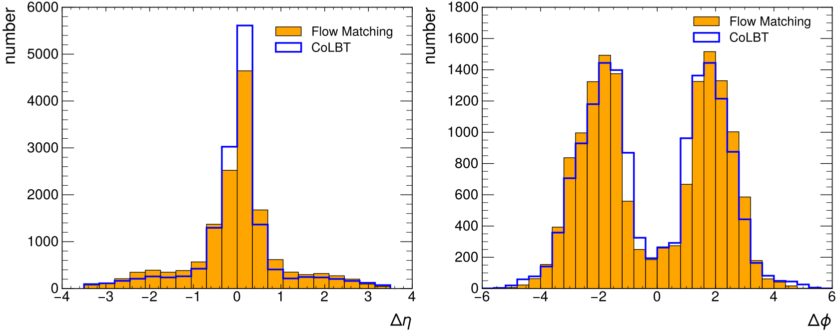
- **Left**: Statistical η values distribution at brightest points (Front wake)
- **Right**: Statistical ϕ values distribution at brightest points

Diffusion wake location



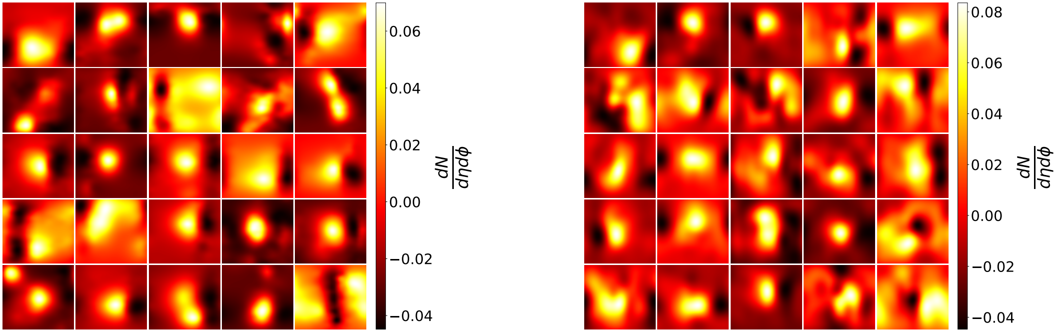
- **Left**: Statistical η values distribution at darkest points (Diffusion wake)
- **Right**: Statistical ϕ values distribution at darkest points

Extreme Points Distance Analysis



- **Left**: η-direction difference between brightest (Front wake) and darkest (Diffusion wake) points
- **Right**: ϕ-direction difference between these points

Random sampling



- **Left**: 25 randomly sampled real events
- **Right**: Corresponding generated events
- 2D $\frac{dN}{d\eta d\phi}$ distributions from $p_T \in [0, 4]$ GeV-integrated 3D spectra

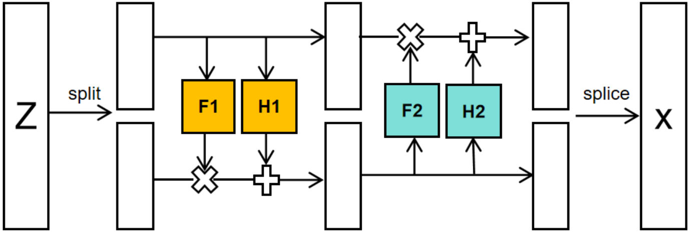
Model Performance Summary

- **Average Spectra**: Perfectly reproduces averaged particle spectra
- **Feature Distribution**: Accurately captures event-by-event location distributions of Front wake and diffusion wake
- **Fluctuation Stability**: Maintains particle spectrum within same order of magnitude under large fluctuations
- **Computational Efficiency**: 1 million events generated per second on NVIDIA RTX 4090 GPU vs. conventional CoLBT model on A100

Thank you

Back up

A little trick between two adjacent blocks of RealNVP:



CoLBT model

LBT model

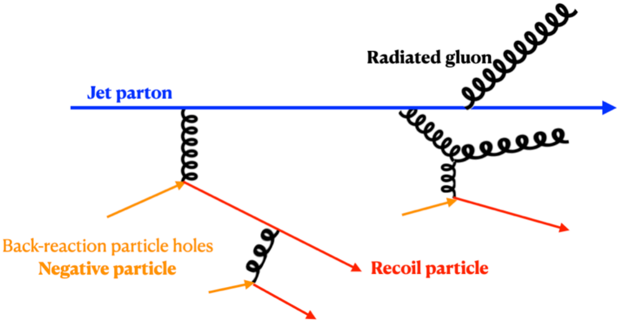
The jet transport through the QGP medium:

$$p_a \partial f_a = \int \prod_{i=b,c,d} \frac{d^3 p_i}{2E_i(2\pi)^3} \frac{\gamma_b}{2} (f_c f_d - f_a f_b) |M_{ab\to cd}|^2$$
$$\times S_2(\hat{s}, \hat{t}, \hat{u})(2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) + inelastic, \quad (1)$$

- phase space distribution: $f_i = (2\pi)^3 \delta^3(\vec{P} - \vec{P_i})\delta(\vec{x} - \vec{x_i} - \vec{v_i}t)\ (i = a, c)$.
- thermal parton distribution: $f_i = 1/(e^{p\cdot u/T} \pm 1)(i = b, d)$
- **Medium-induced gluons(High-twist)**[Wang, Guo 2001]

$$\frac{dN_g^a}{dz dk_\perp^2 dt} = \frac{2\alpha_s C_A \hat{q}_a(x) P_a(z) k_\perp^4}{\pi\left(k_\perp^2 + z^2 m^2\right)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right) \quad (2)$$

LBT model



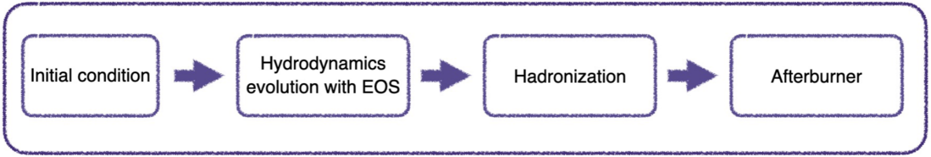
LBT Tracked partons

- Jet shower partons
- Thermal recoil partons
- Radiated gluons
- Negative partons

medium response = particle holes + soft partons

CLVisc model

CCNU-LBNL viscous hydrodynamic model: 3+1D viscous hydro evolution model



High-Energy Collision Characteristics (LHC Energy Region)

- Net baryon number is approximately zero, baryon number conservation can be neglected
- $\nabla_\mu N^\mu = 0$

CLVisc model

Energy-momentum conservation:

$$\nabla_{\mu} T^{\mu\nu} = 0$$

Energy-momentum tensor composition:

$$T^{\mu\nu} = e u^{\mu} u^{\nu} - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

e: energy density

u^{μ}: fluid four-velocity

P: thermodynamic pressure

Π: bulk viscous pressure

$\pi^{\mu\nu}$: shear viscous tensor

CLVisc model

- Solves relativistic hydrodynamics with source terms:

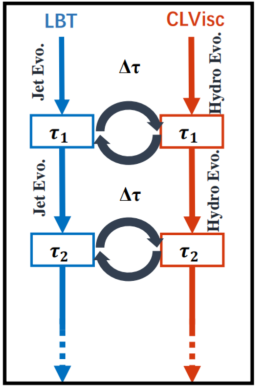
$$\nabla_\mu T^{\mu\nu} = j^\nu$$

- Source term implementation:

$$J^\nu = \sum_i \frac{\theta(p^0_{\text{cut}} - p_i \cdot u) p_i^\nu / \Delta\tau}{\tau (2\pi)^{3/2} \sigma_r^2 \sigma_{\eta_s}} \exp\left[-\frac{(\vec{x}_\perp - \vec{x}_{\perp,i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2} \right]$$

- Gaussian deposition in transverse plane (σ_r) and spacetime rapidity (σ_{η_s})
- Cutoff condition: $\theta(p^0_{\text{cut}} - p_i \cdot u)$

CoLBT model



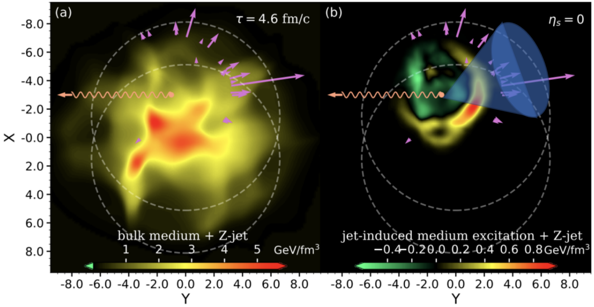
wei chen

- **Couples two complementary models:**
  - **LBT**: Energetic partons (jet showers and recoil)($E_{cut} > 2GeV$)
  - **CLVisc**: Bulk/soft partons via hydrodynamics
- **Medium evolution with source terms:**

$$\nabla_\mu T^{\mu\nu} = j^\nu$$

  - Energy-momentum deposition from partons
  - Self-consistent QGP medium evolution

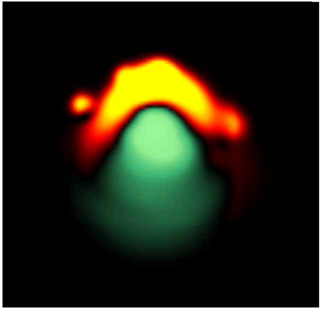
CoLBT: Jet-induced hydro response



Chen, Yang, He, Ke, Pang and Wang, PRL 127 (2021) 8, 082301

- The CoLBT was runned twice with and without jet to subtract hydro bachground.
- The Mach-cone-like jet-induced medium response is clear in right panel.

Medium response and soft gluon radiation



Zhong Y, et al.
arXiv:2206.02393

- **Soft hadron enhancement** along jet direction due to medium response
- **Similar effect** from medium-induced gluon radiation
- **Diffusion wake**: Distinct component of jet-induced response
  - Causes depletion of soft hadrons opposite to jet direction