Medium Excitation by Jets

[#jul23-jul26-jets]

Yasuki Tachibana for the JETSCAPE Collaboration

JETSCAPE

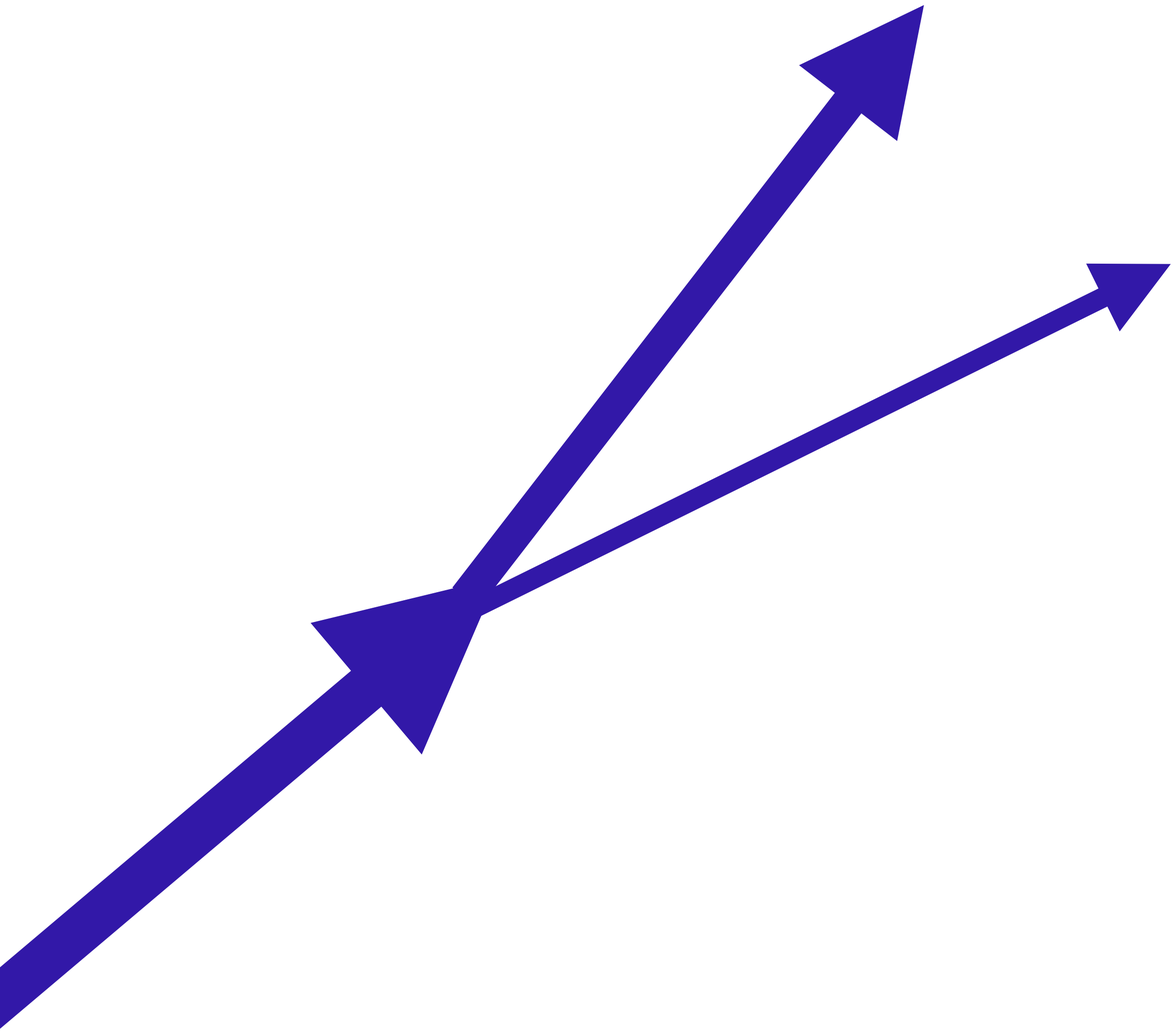
Online, July 23rd, 2021

#jul23-jul26-jets

JETSCAPE School 2021

Introduction

Modification of jet shower by a medium



- **Medium effect on hard partons**
  - Collisional energy loss
  - Medium modified/induced splittings

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- **Momentum transfer with medium**
  - The source for the modifications of

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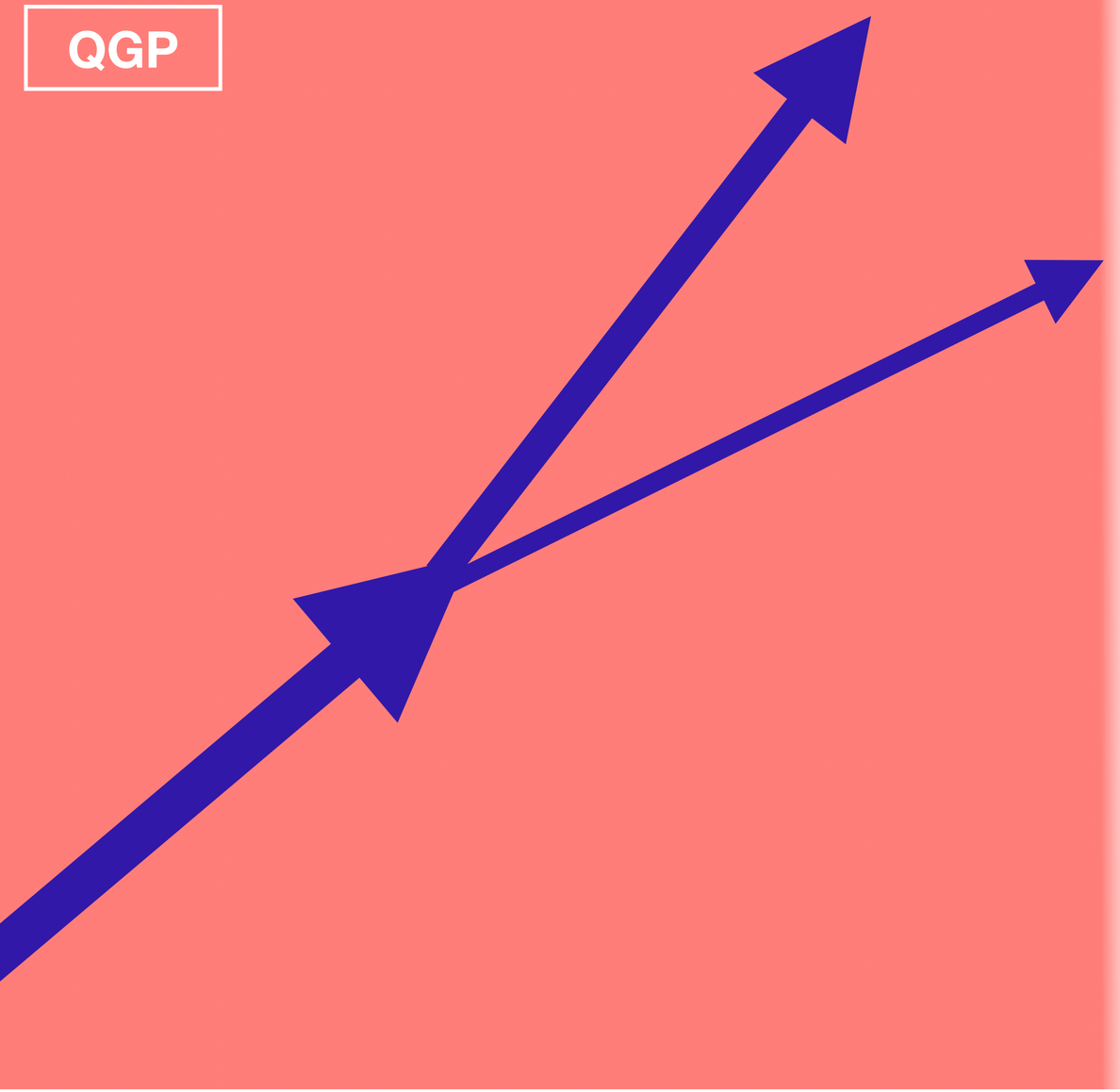

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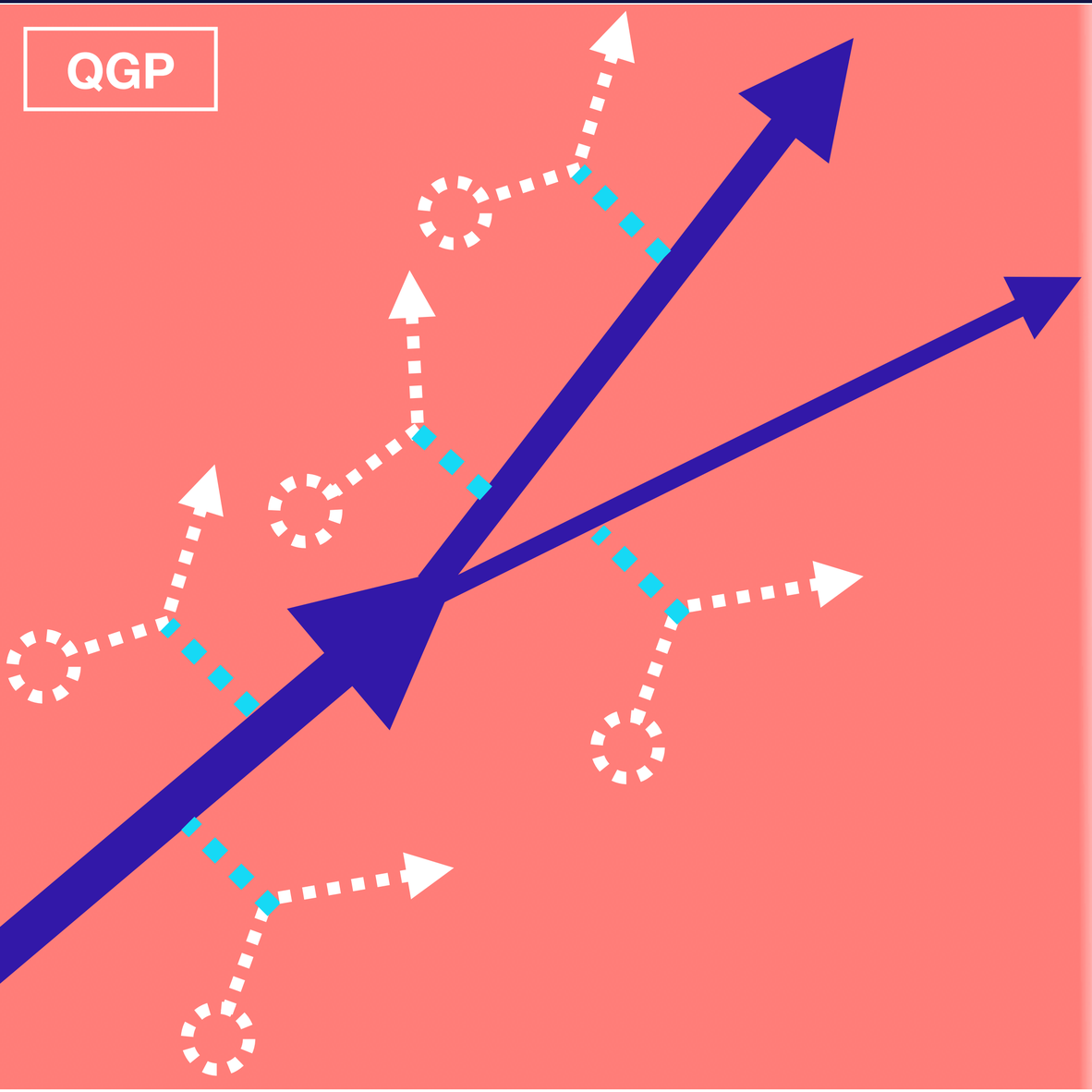

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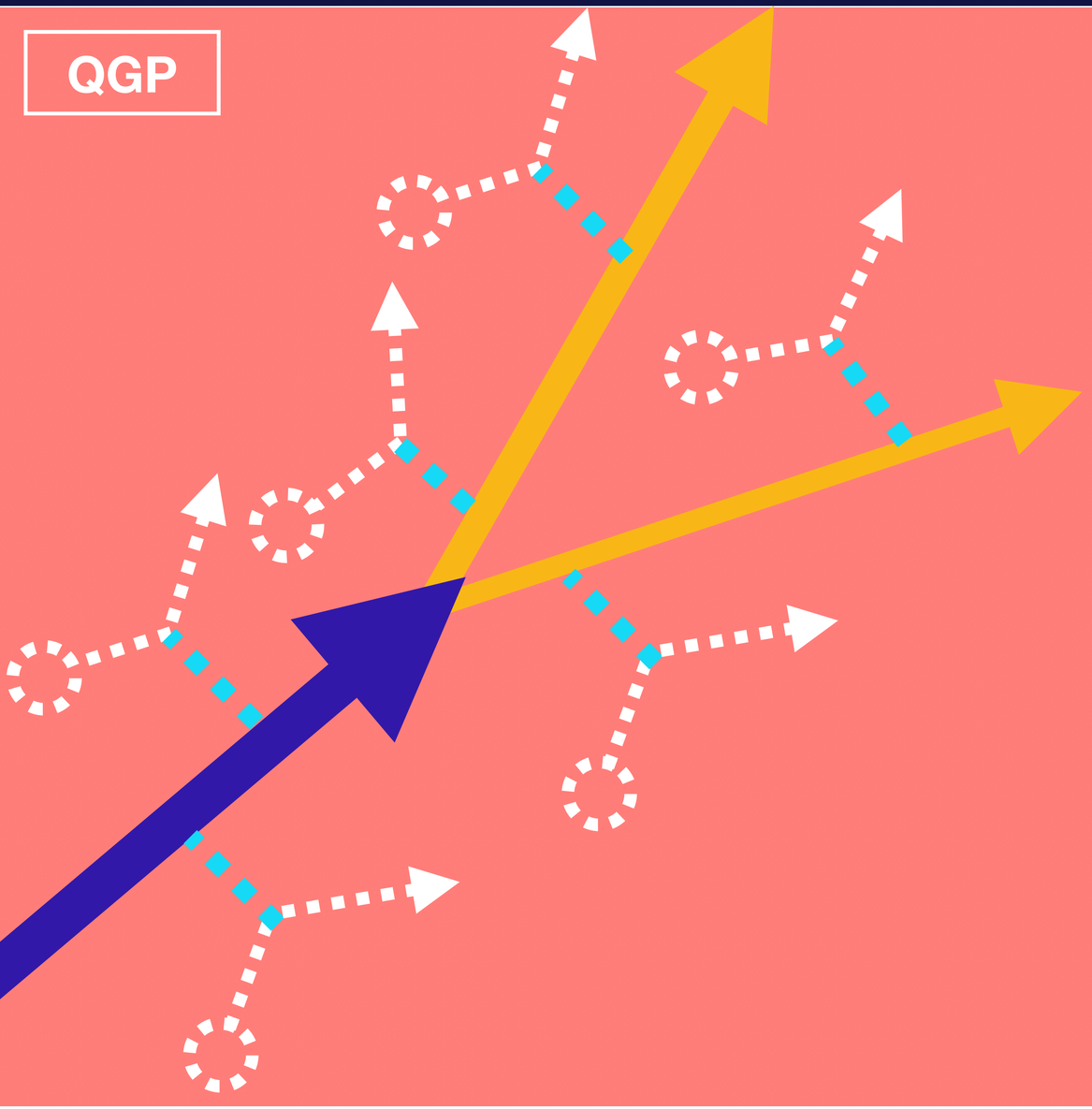

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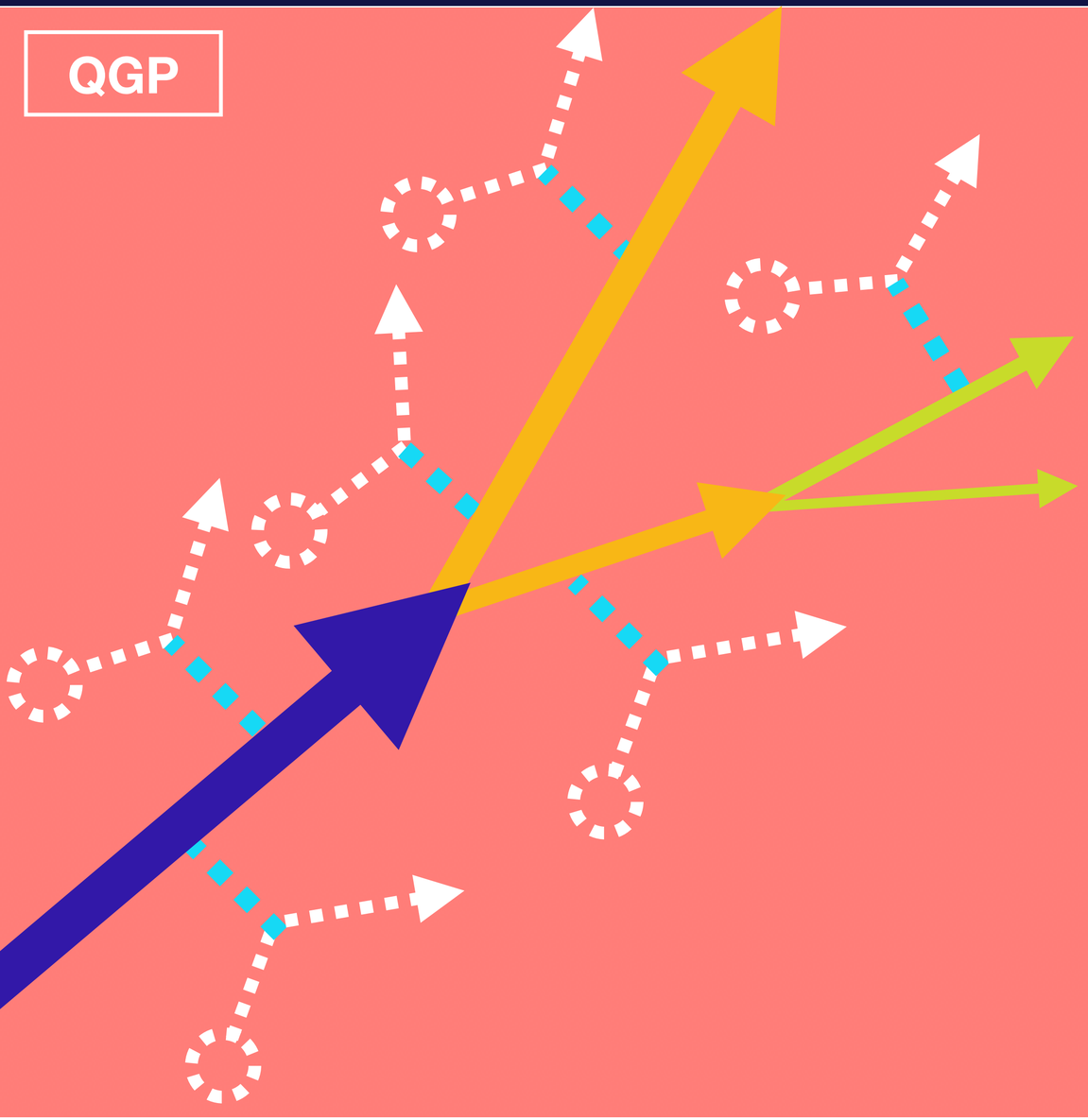

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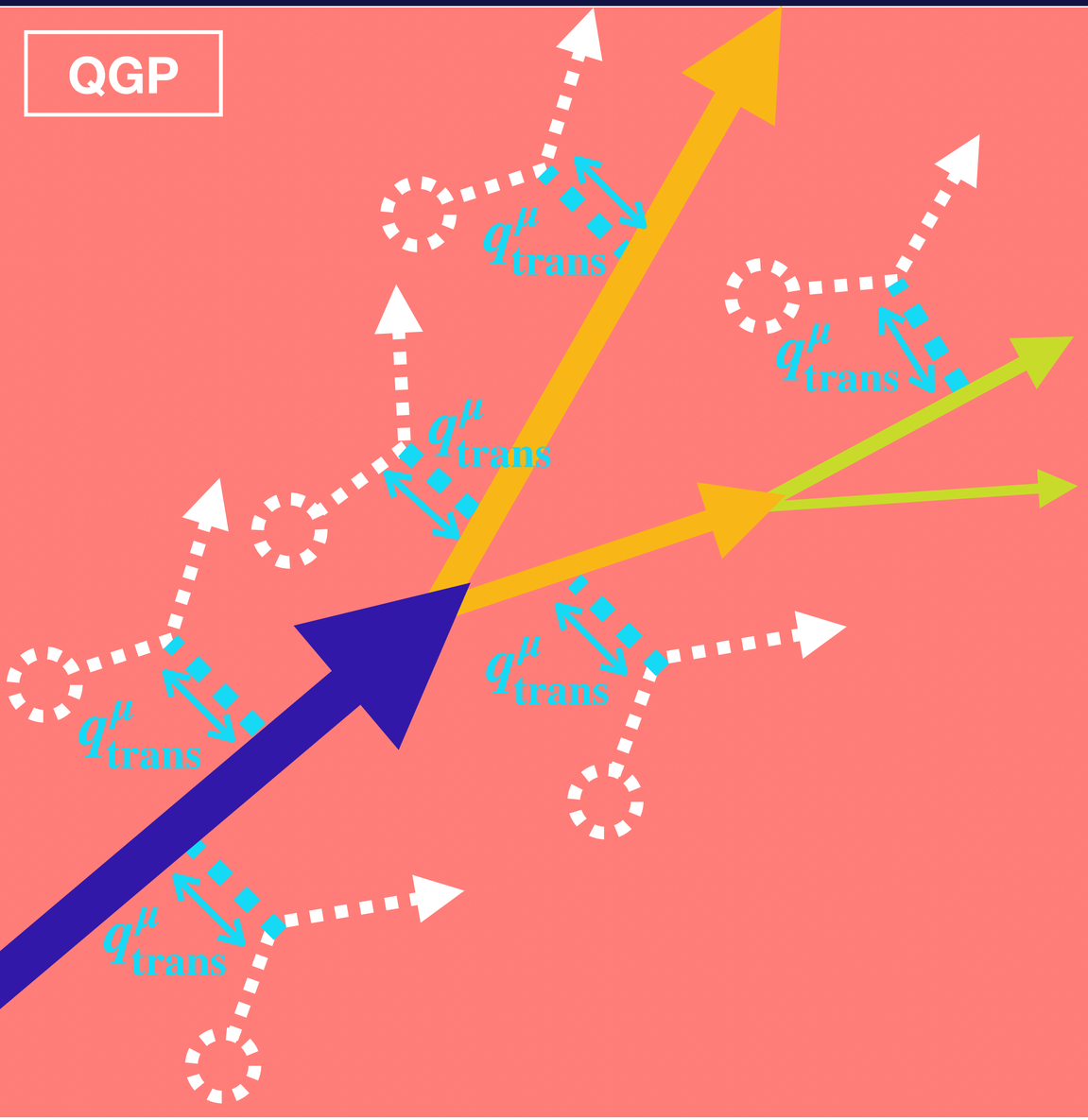

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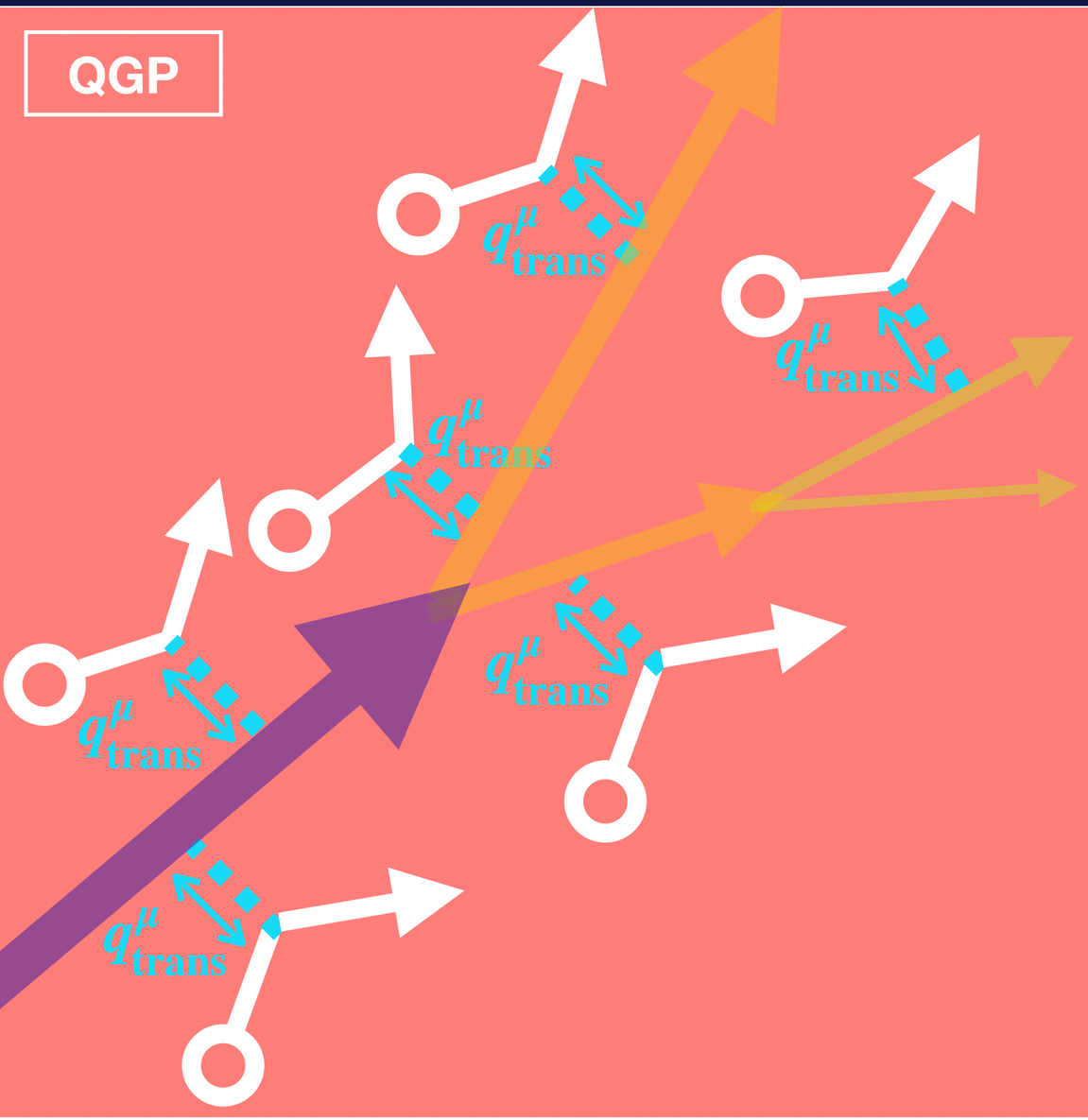

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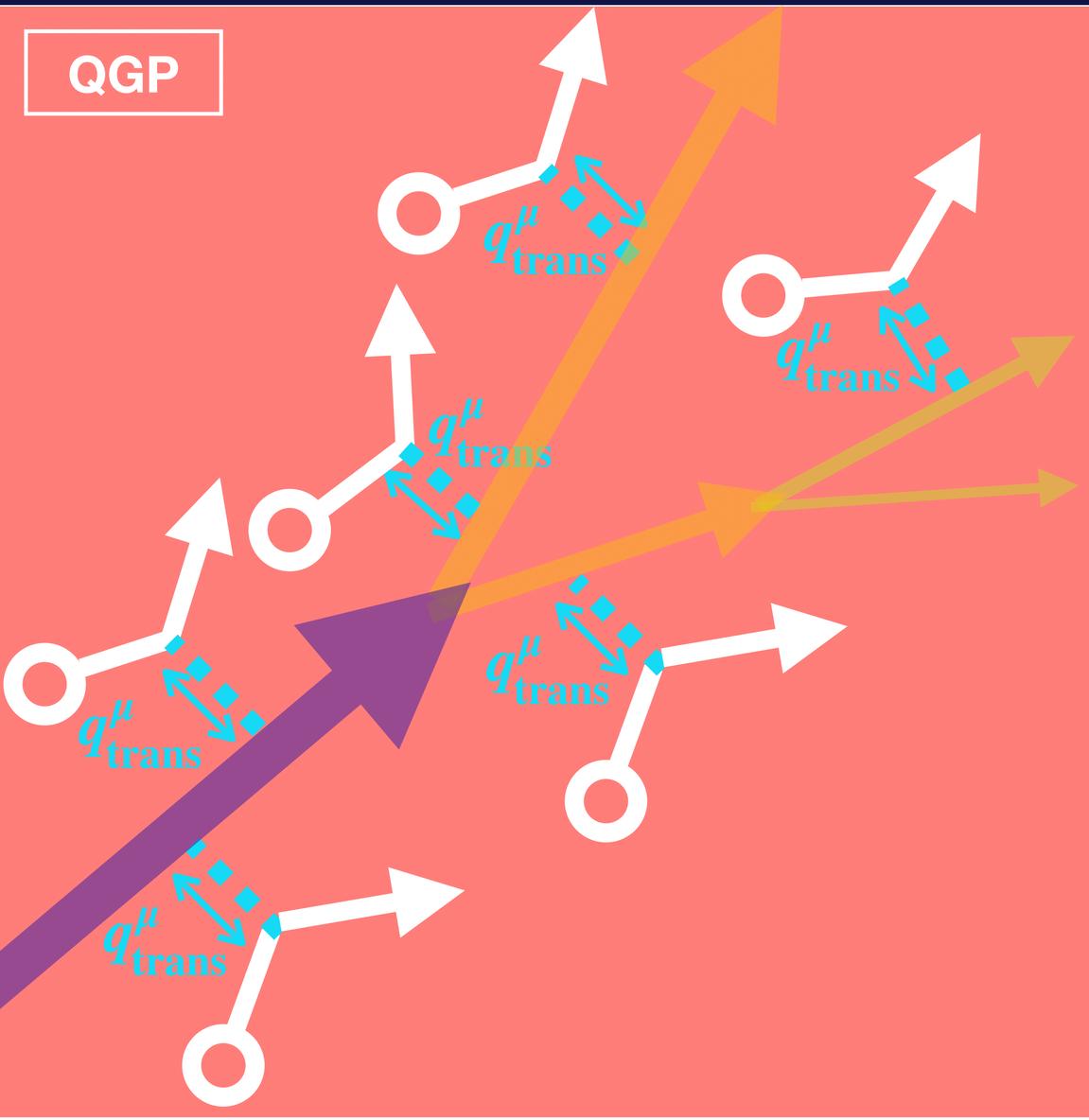

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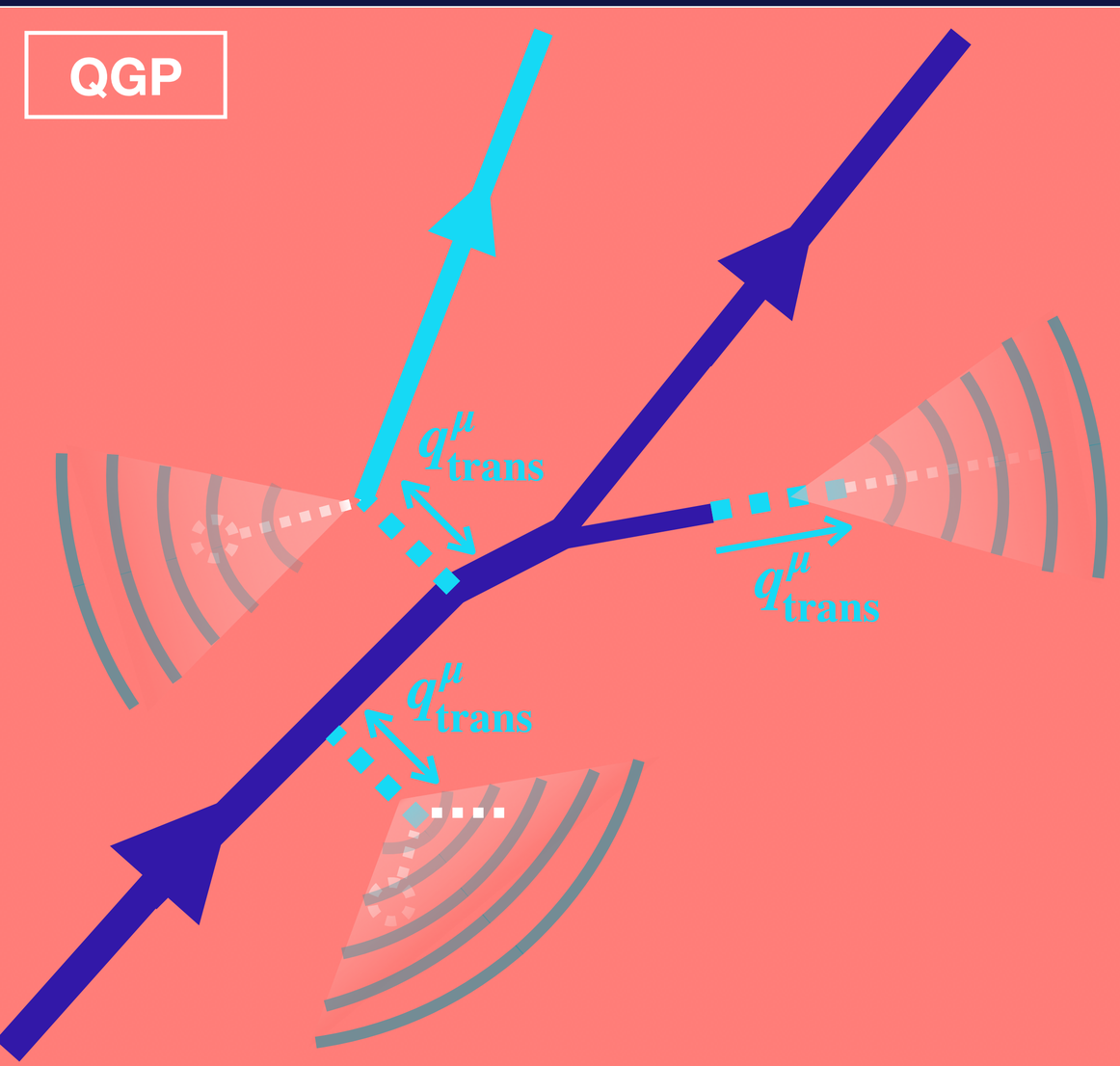
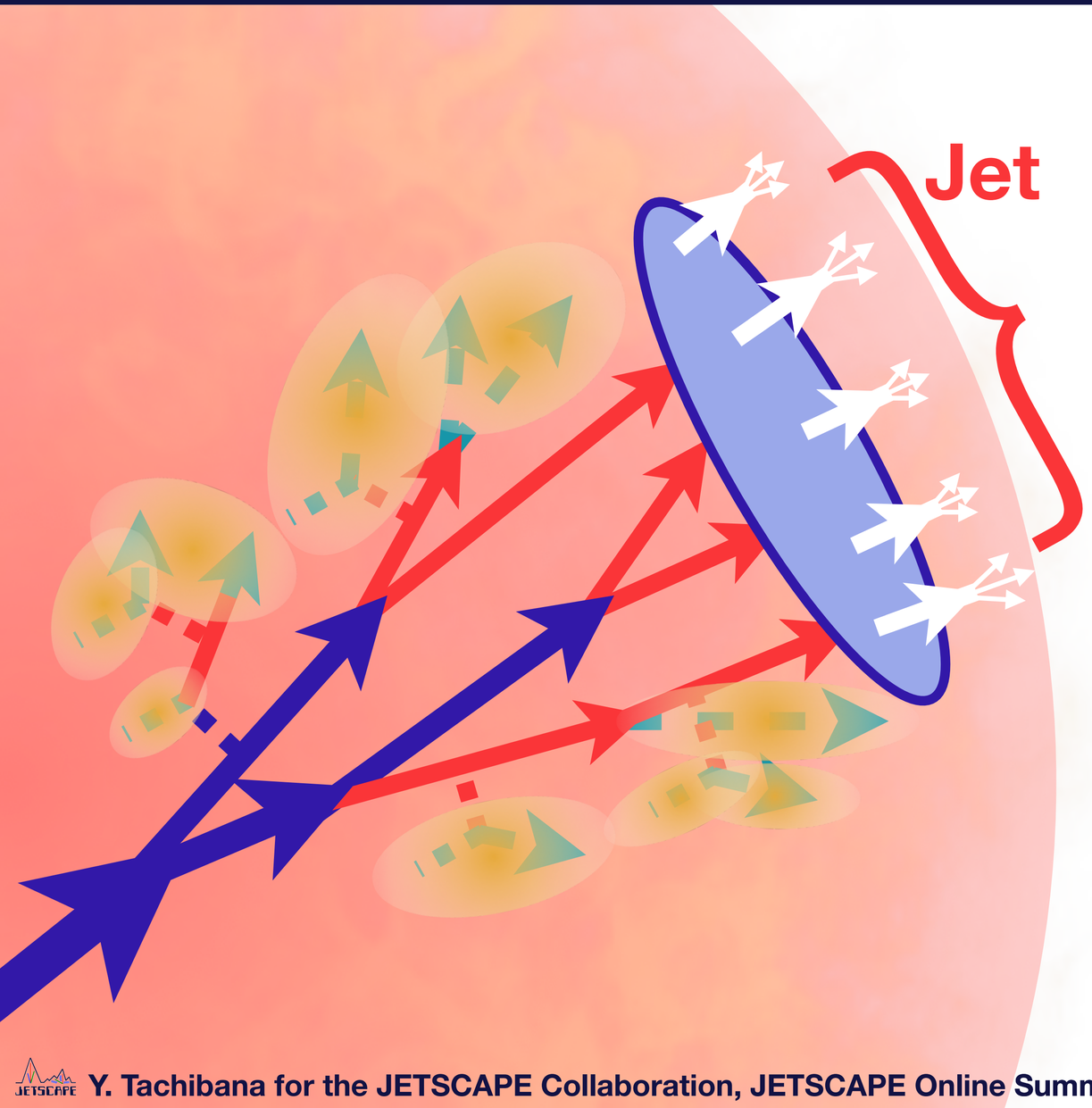
Medium response to jet partons



- **Momentum transfer from jet partons**
  - Medium constituents' reactions
  - Lead nonequilibrium processes involving medium constituents
- **In-medium thermalization**
  - Momentum transferred to the (locally) thermalized medium
  - Transition to hydrodynamic transport

Medium Response Effect in Heavy Ion Collisions



- **Jet-induced excitation of medium**
  - Transport momentum transferred from jet
  - Modify particle emission around jet

- **Particles from medium repsonse**
  - Soft, spread out from jet
  - Jet-correlated, cannot/should not be subtracted
  - Affect structures inside/around jet

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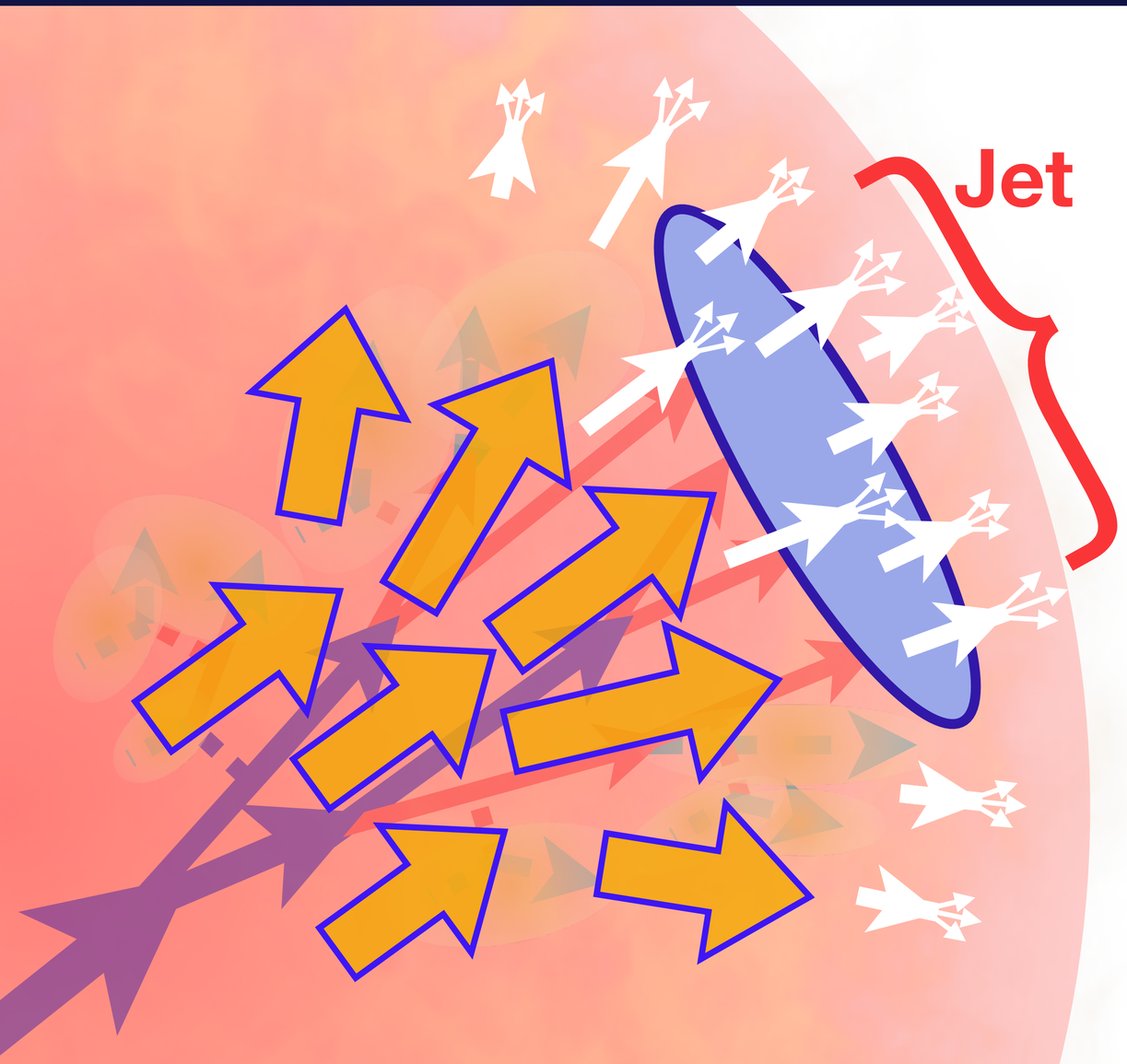

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- **Full picture of jet quenching in heavy-ion collisions**

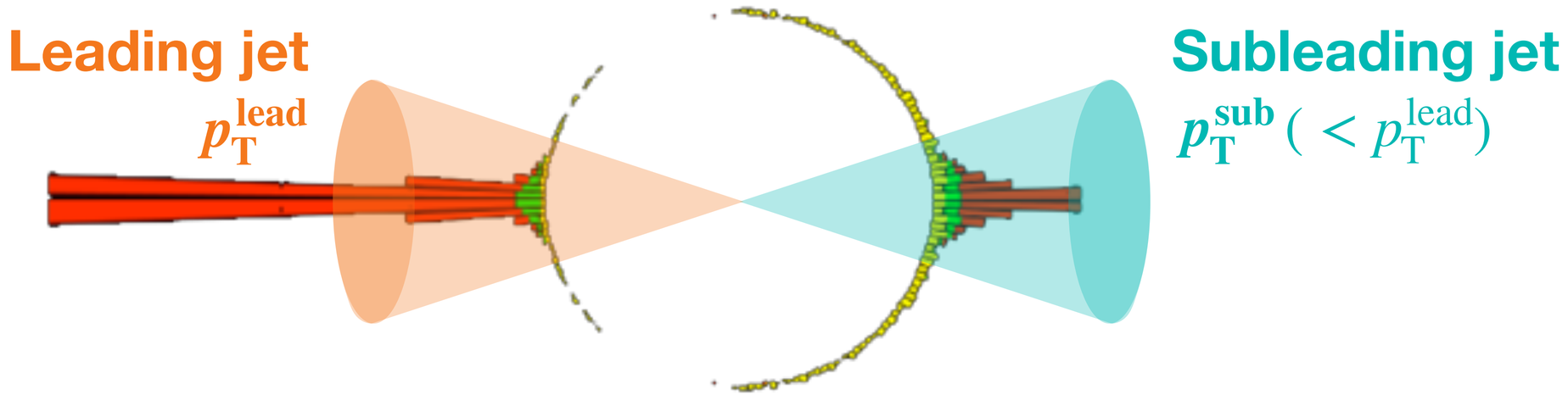
Re-distribution of the jet energy and momentum

CMS (’11)

>8 GeV

4-8 GeV

1-4 GeV



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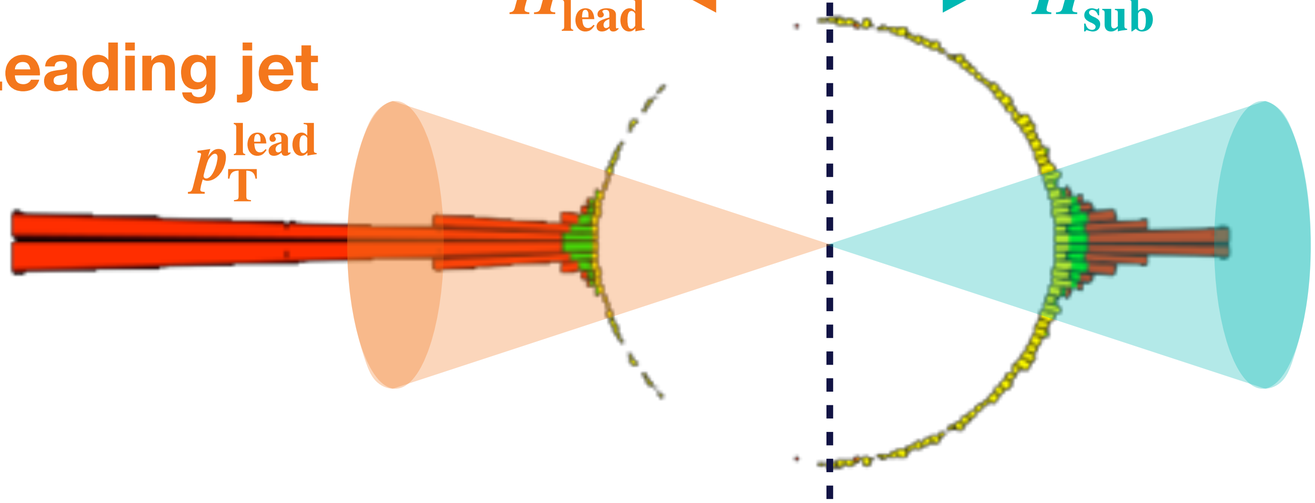
Balance

$$\sum_{i \in H_{\mathrm{lead}}} \vec{p}_i \simeq -\sum_{i \in H_{\mathrm{sub}}} \vec{p}_i$$

H_{lead} H_{sub}

Leading jet

$p_{\mathrm{T}}^{\mathrm{lead}}$



Subleading jet

$p_{\mathrm{T}}^{\mathrm{sub}} \; (< p_{\mathrm{T}}^{\mathrm{lead}})$

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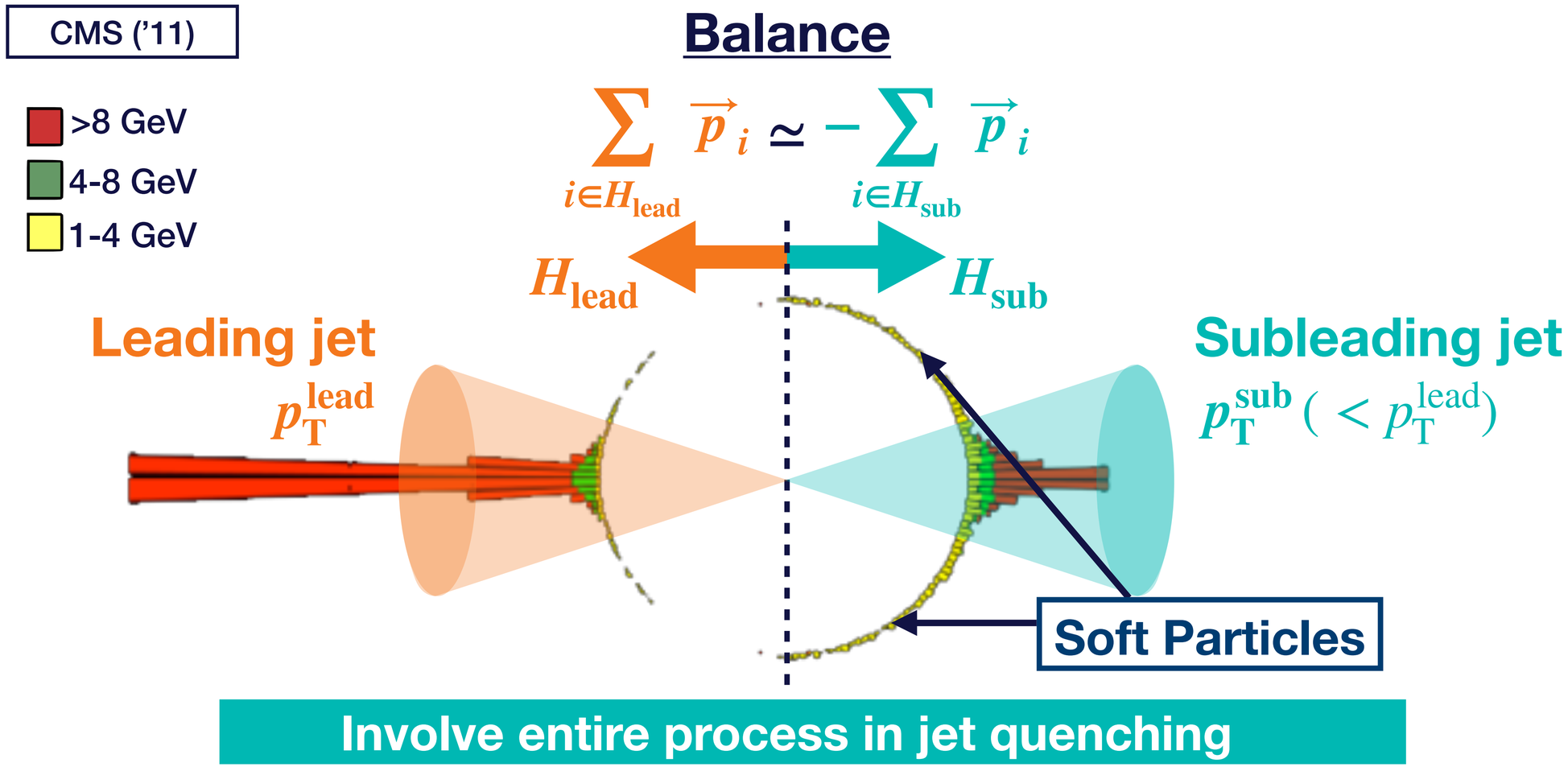
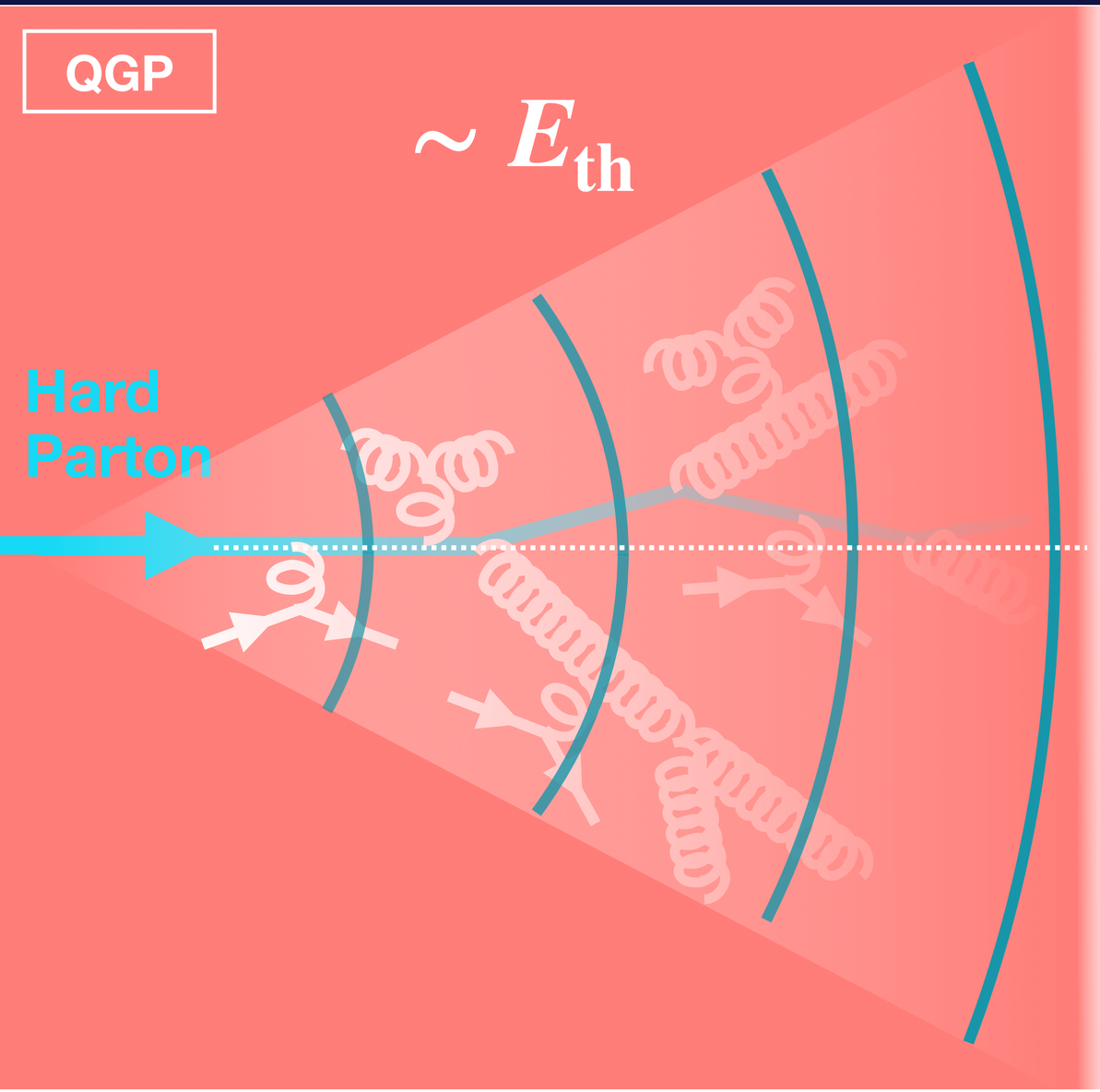


Involve entire process in jet quenching

Motivations



- **QGP properties involved with in-medium thermalization**

  E. Iancu, B. Wu ('15), YT, C. Shen, A. Majumder ('19), JETSCAPE ('19)…

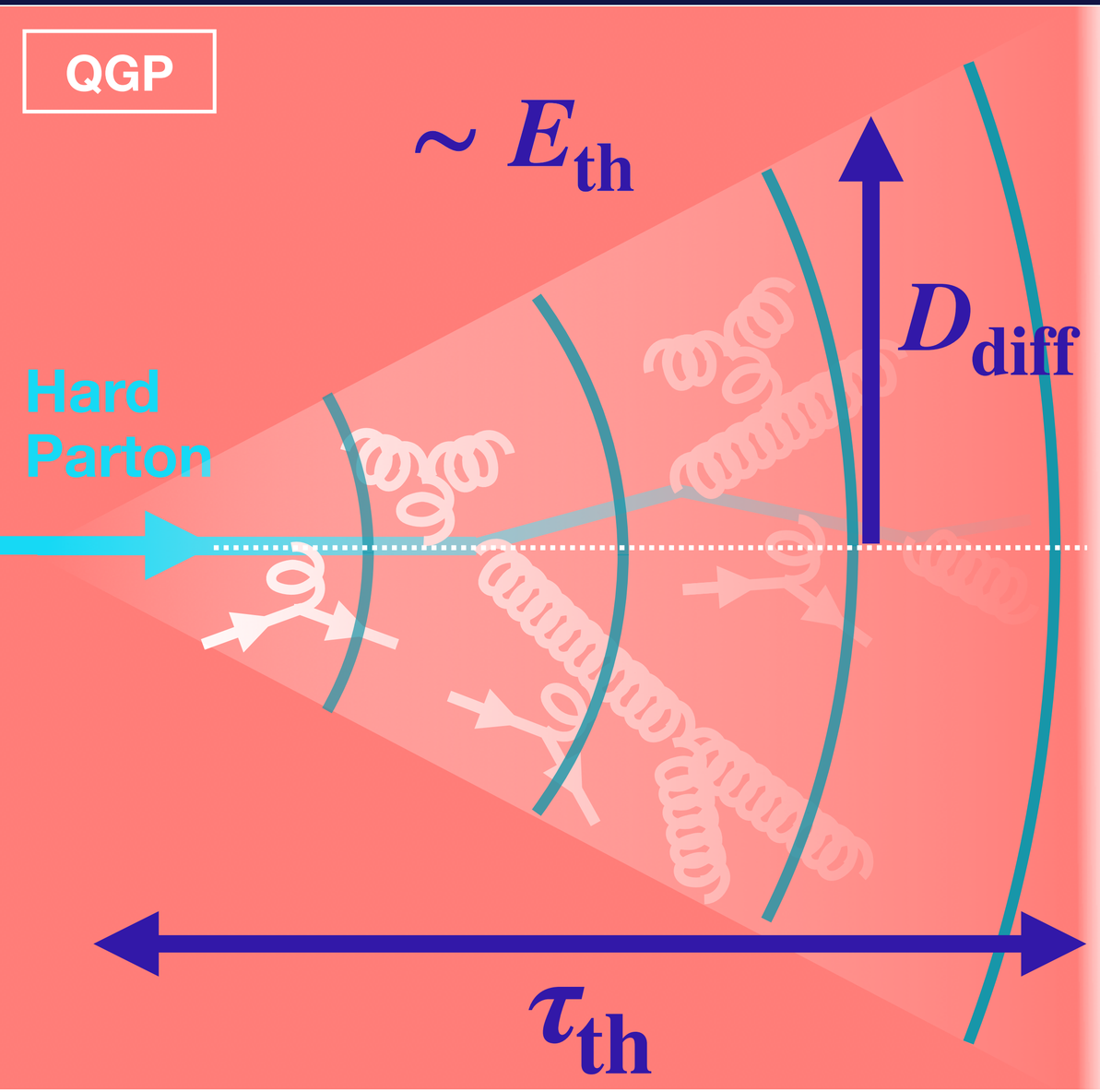
  - Partial thermalization of jet energy and momentum
  - Propagation as jet-induced hydrodynamic flow in medium

Thermalized part contribution in jet

Information of in-medium thermalization

Thermalization time τ_{th},
Diffusion coefficient D_{diff},
Typical energy scale E_{th}, etc.

Motivations



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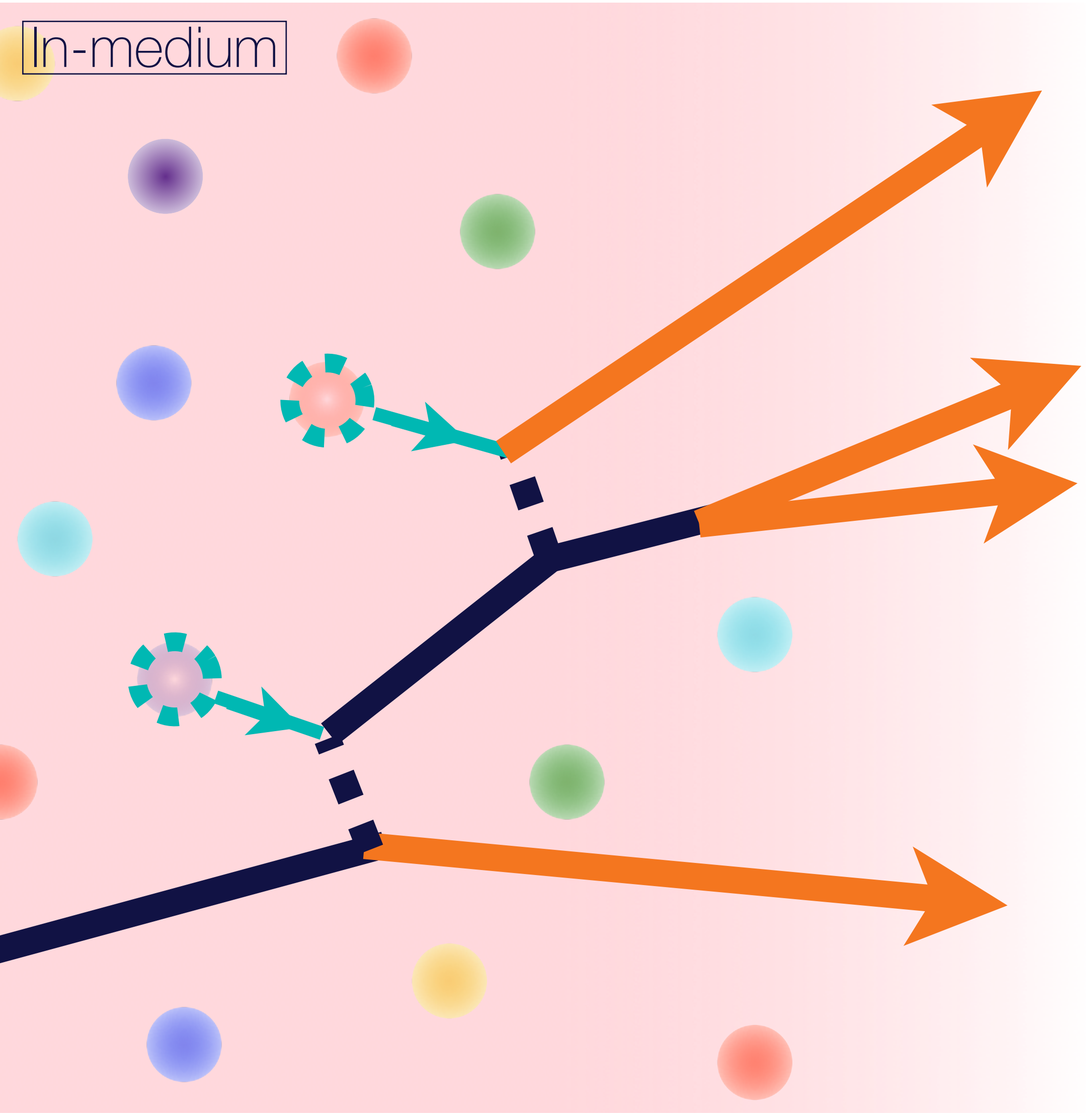
Description of medium response in JETSCAE

Weakly-coupled Description: Recoils

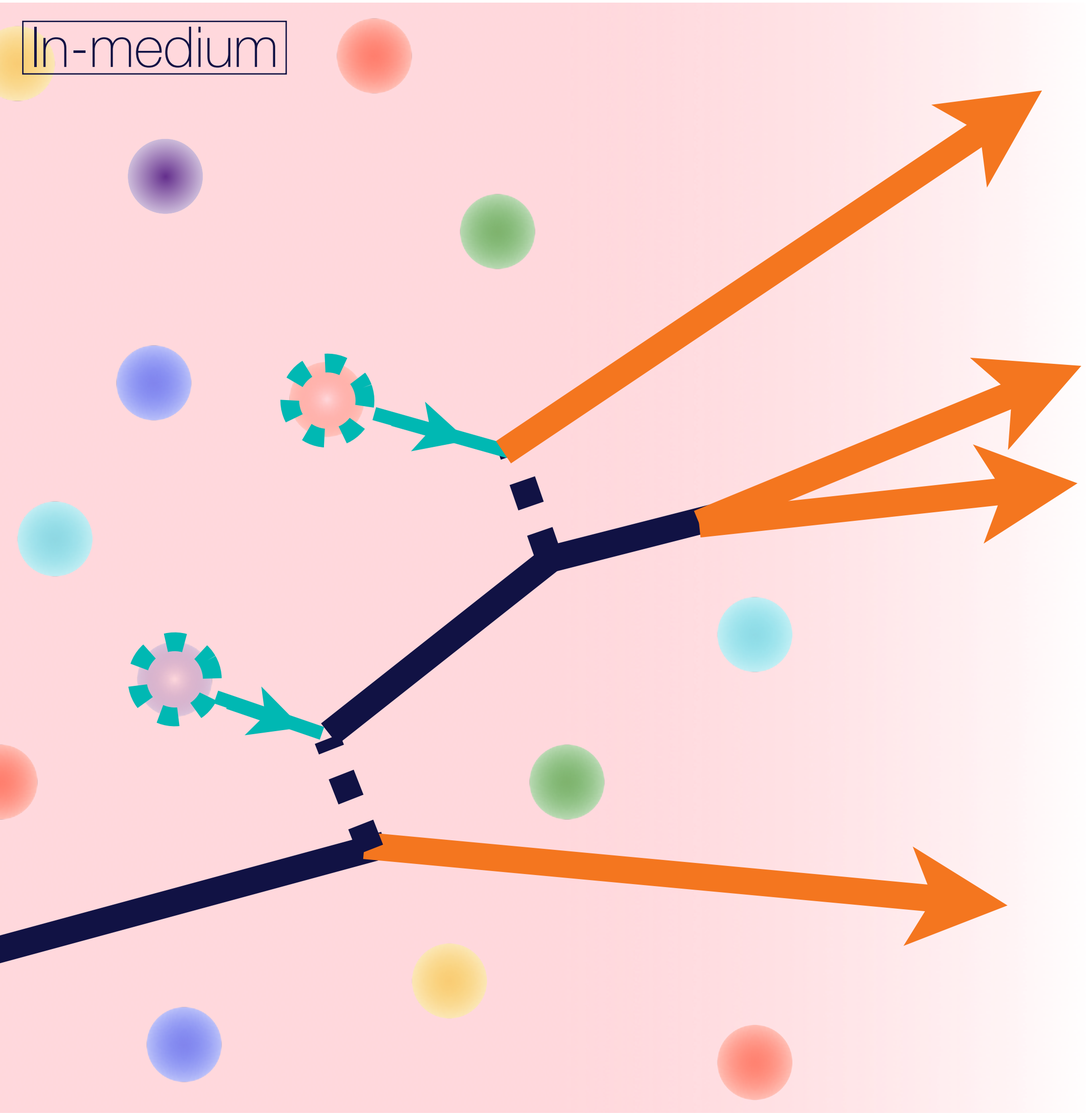
K. C. Zapp, F. Krauss, U. A. Wiedemann ('13), X.-N. Wang, Y. Zhu(13), T. Luo, et al.(15,18), C. Park, S. Jeon, C. Gale(18), S. Cao, A. Majumder (18)



Implemented in MATTER, LBT and MARTINI

- **Partons scattered off from medium**
  - Sample a parton from thermal QGP medium for each scattering
  - Add the recoiled partons to the jet shower
  - Reasonable for partons with $E > E_{\mathrm{med}}$
    (E_{med}: typical energy of medium constituents)

Weakly-coupled Description: Recoils



- **Picked up momentum from medium (a.k.a negative partons or holes)**
  - Original momenta of sampled thermal partons
  - Assumed to freestream
  - Subtracted from final signal

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{signal}} = \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{jet shower}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{picked-up}}$$

Strongly-coupled Description: Hydrodynamics

- **Conventional hydrodynamic equation**

$$\nabla_\mu T^{\mu\nu}_{\mathrm{med}}(x) = 0$$

$T^{\mu\nu}_{\mathrm{med}}$: energy-momentum tensor of medium fluid

- Energy momentum conservation in medium fluid

- **Hydrodynamic equation with source term**

e.g.) YT, N.-B. Chang, G.-Y. Qin (17,19), W. Chen, T. Luo, S. Cao, L. Pang, X.-N, Wang (18), YT, C. Shen, A. Majumder (20)

$$\nabla_\mu T^{\mu\nu}_{\mathrm{med}}(x) = J^\nu_{\mathrm{jet}}(x)$$

J^ν_{jet}: Incoming four-momentum density due to jet propagation (source term)

- Medium fluid evolution with energy-momentum deposition
- Bulk part particle with hydro response obtained via Cooper-Frye

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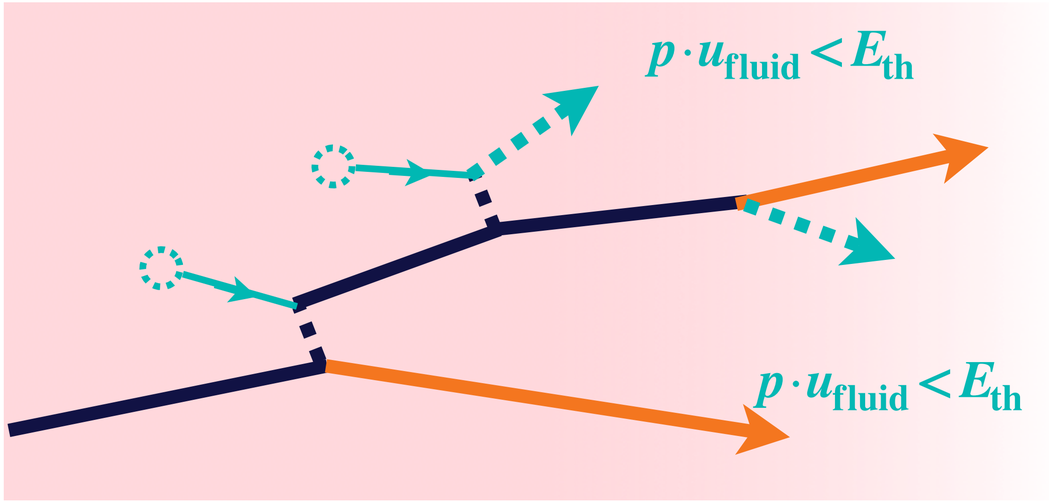
Modeled with Causal Diffusion (Liquefier) in JETSCAPE

Causal Diffusion and Source Profile

- **Energy-momentum deposition**
  - Soft parton absorption
  - Picked-up energy and momentum



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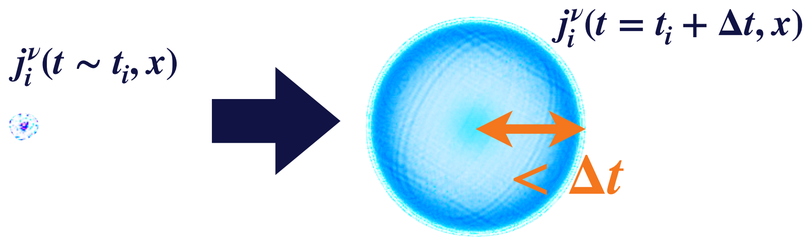
  - Relativistic diffusion equation

$$\left[\frac{\partial}{\partial t} + \tau_{\mathrm{diff}}\frac{\partial^2}{\partial t^2} - D_{\mathrm{diff}}\nabla^2\right] j^{\nu}(x) = 0$$

with initial condition

$$j^{\nu}(t = t_{\mathrm{dep}}, \vec{x}) = p^{\nu}_{\mathrm{dep.}}\delta^{(3)}(\vec{x} - \vec{x}_{\mathrm{dep}})$$



Parameters

E_{th}: Momentum scale for in-medium thermalization

Δt: Timescale for in-medium thermalization

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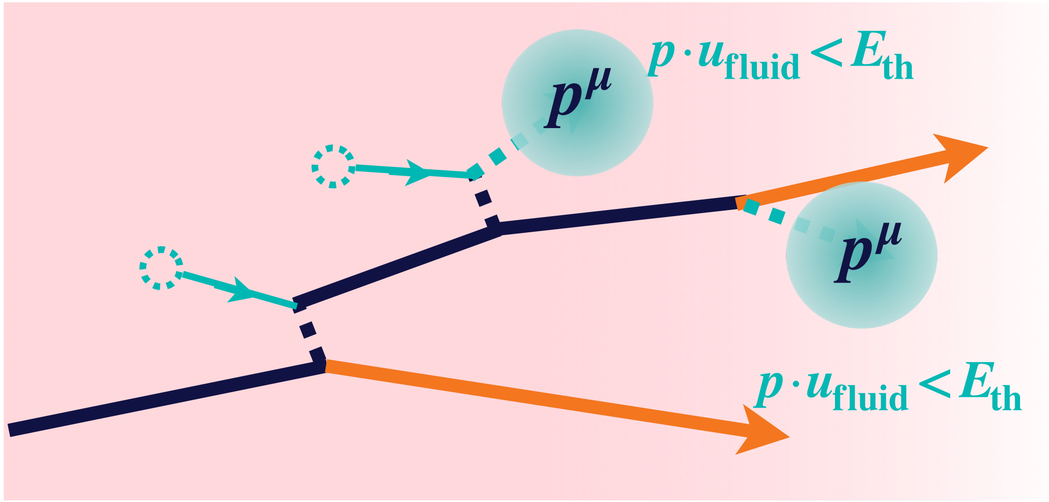

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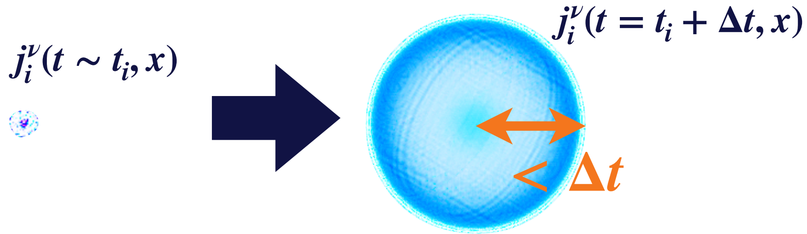

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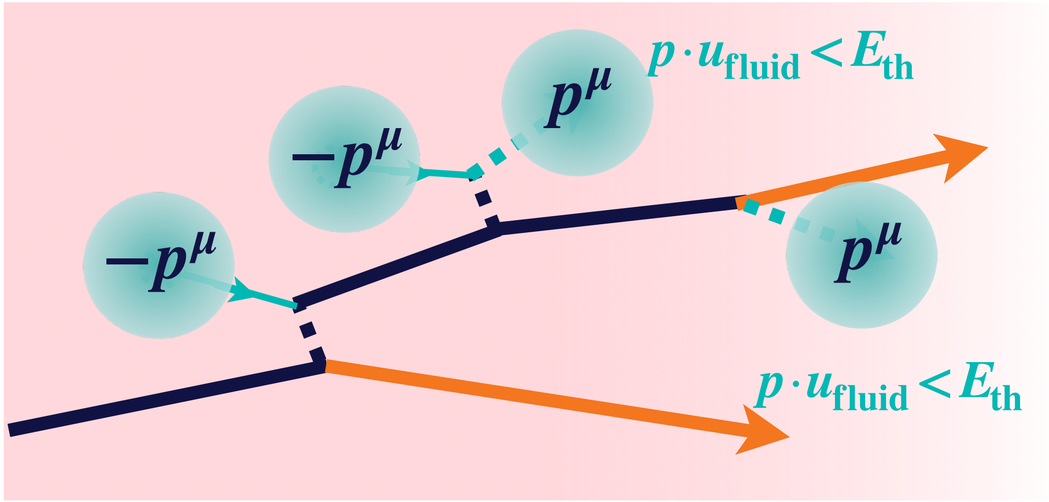

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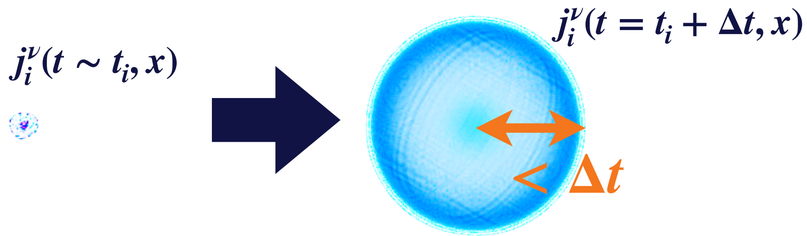

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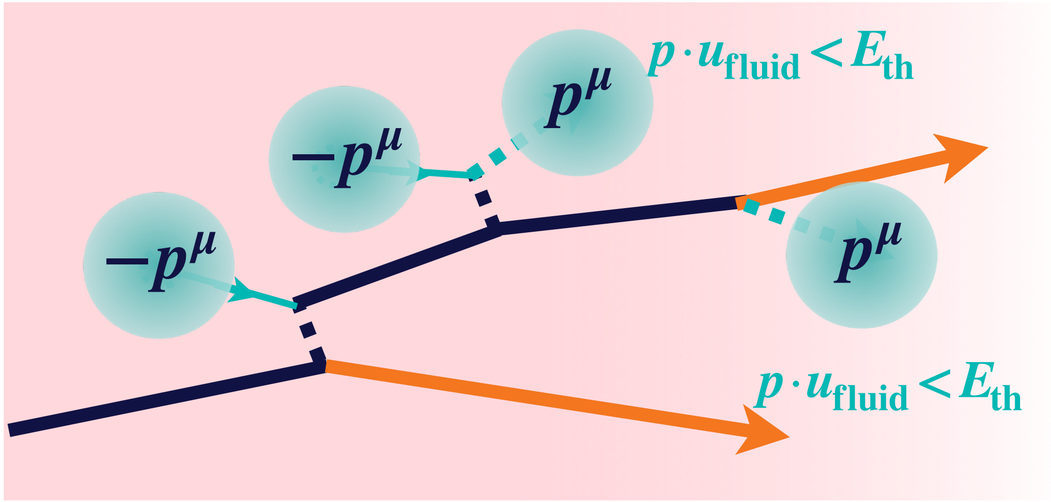

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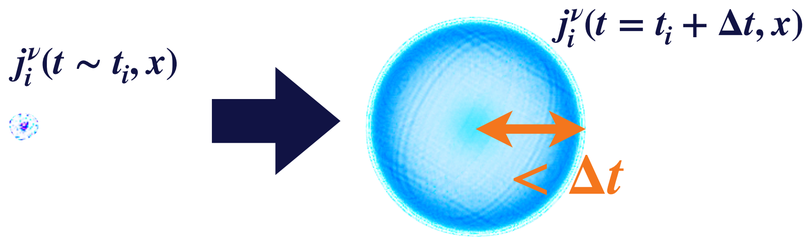

Para **Characterize dynamics during in-medium thermalization process**

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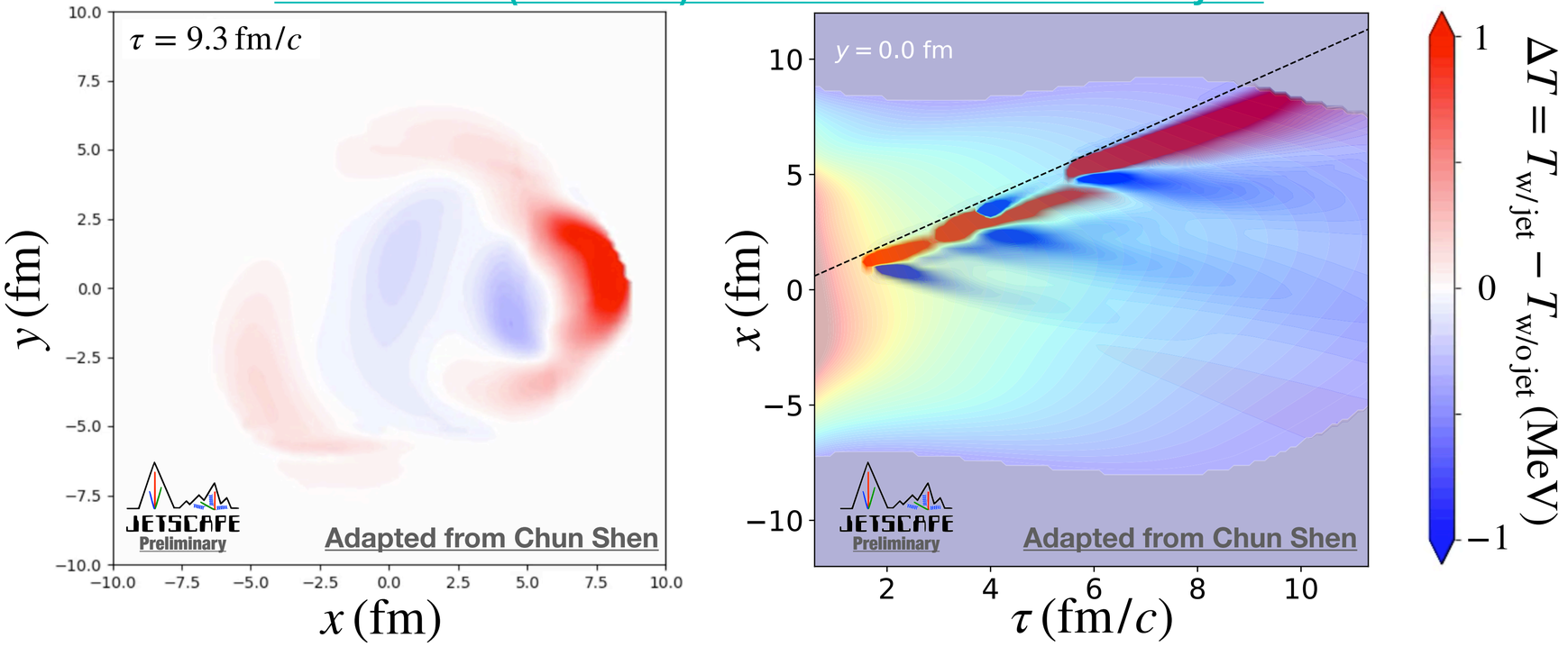
Evolution of Medium Response by Strongly Coupled Description

- **Hydrodynamic flow induced by jet momentum deposition**
  - Jet following flow by positive energy deposition
  - Diffusion wakes and flow by momentum picked-up from medium

Temperature field modification in medium by jet propagation

MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro



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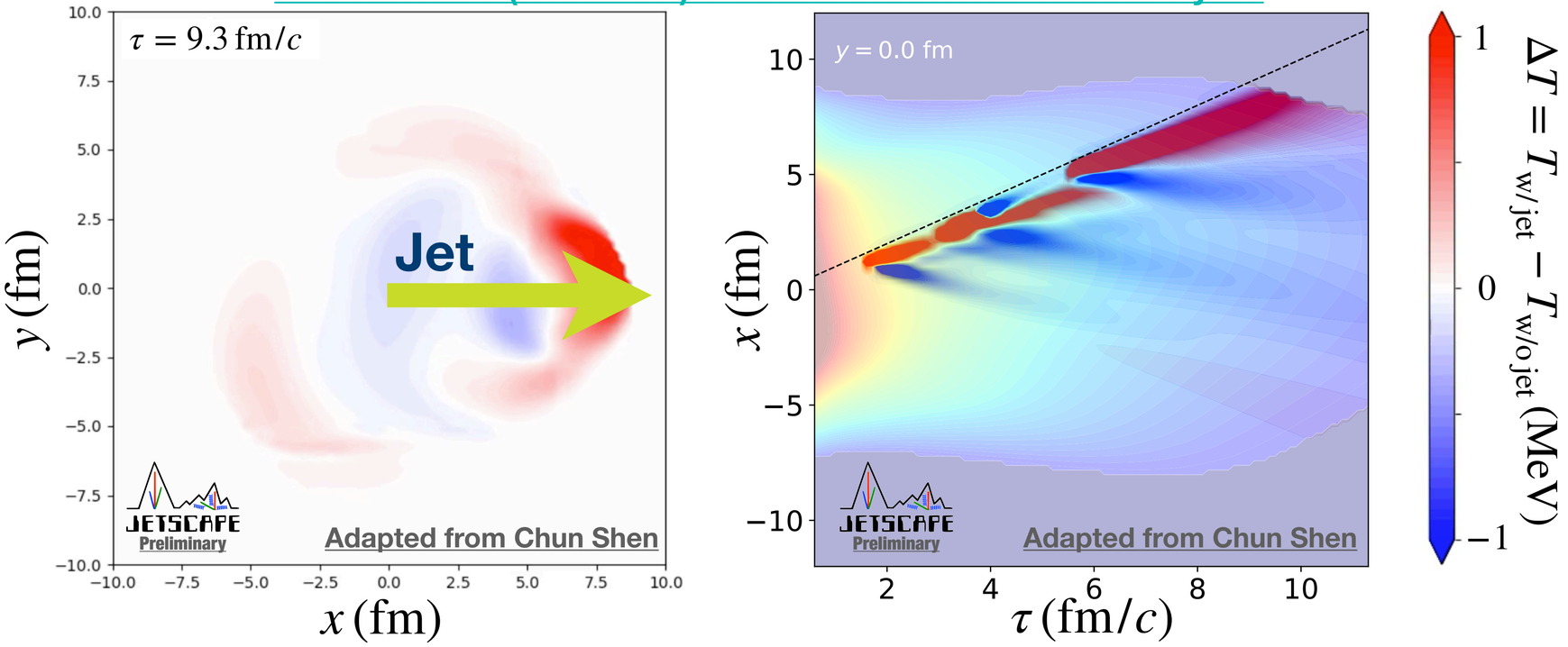

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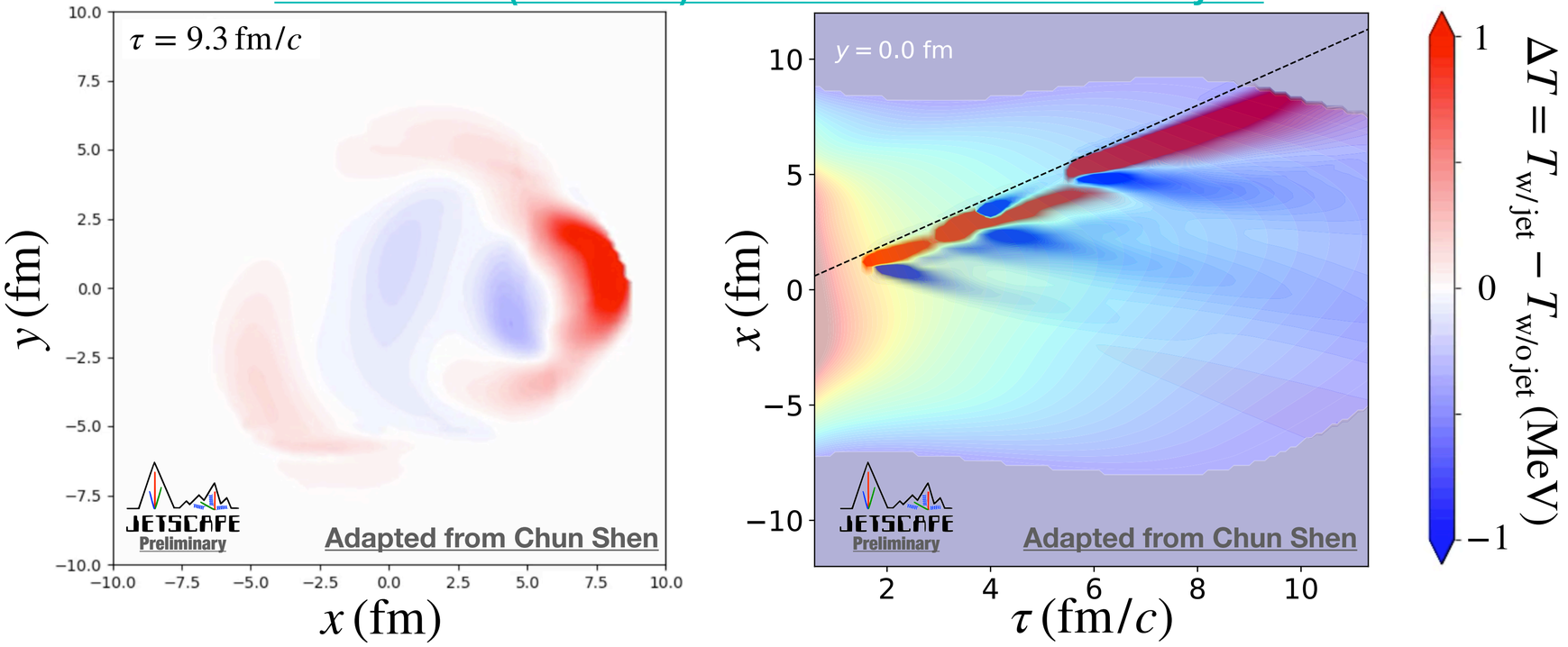

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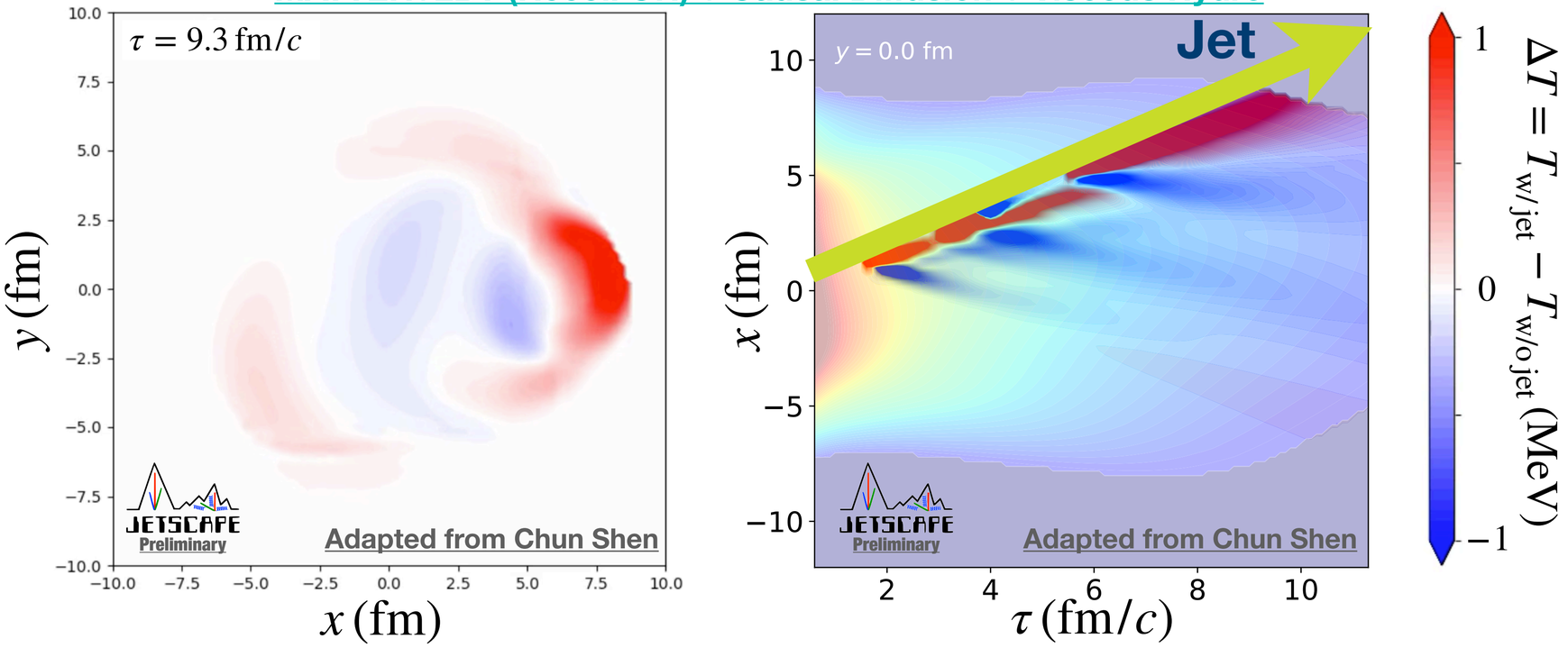

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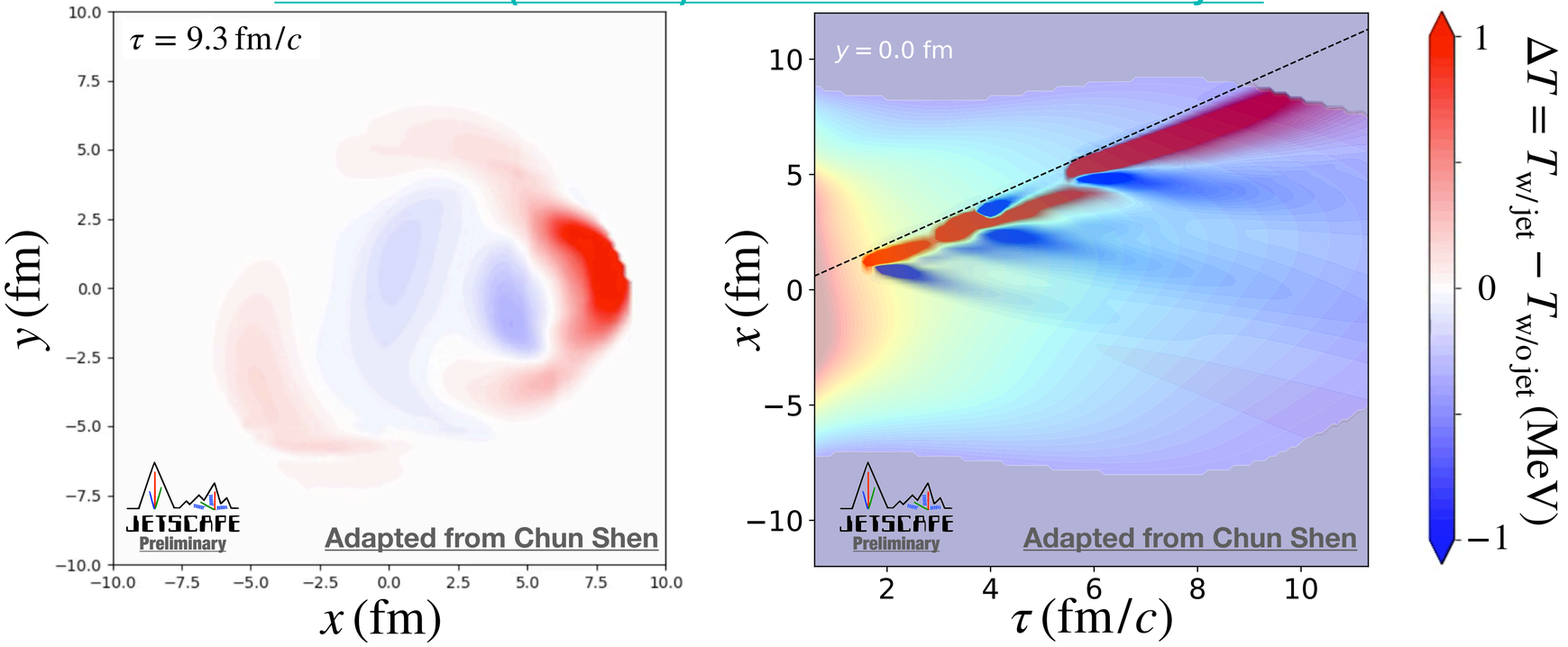

Signal from Strongly-coupled Description of Med. Res.

- Jet-modified spectrum of bulk medium (single event example)

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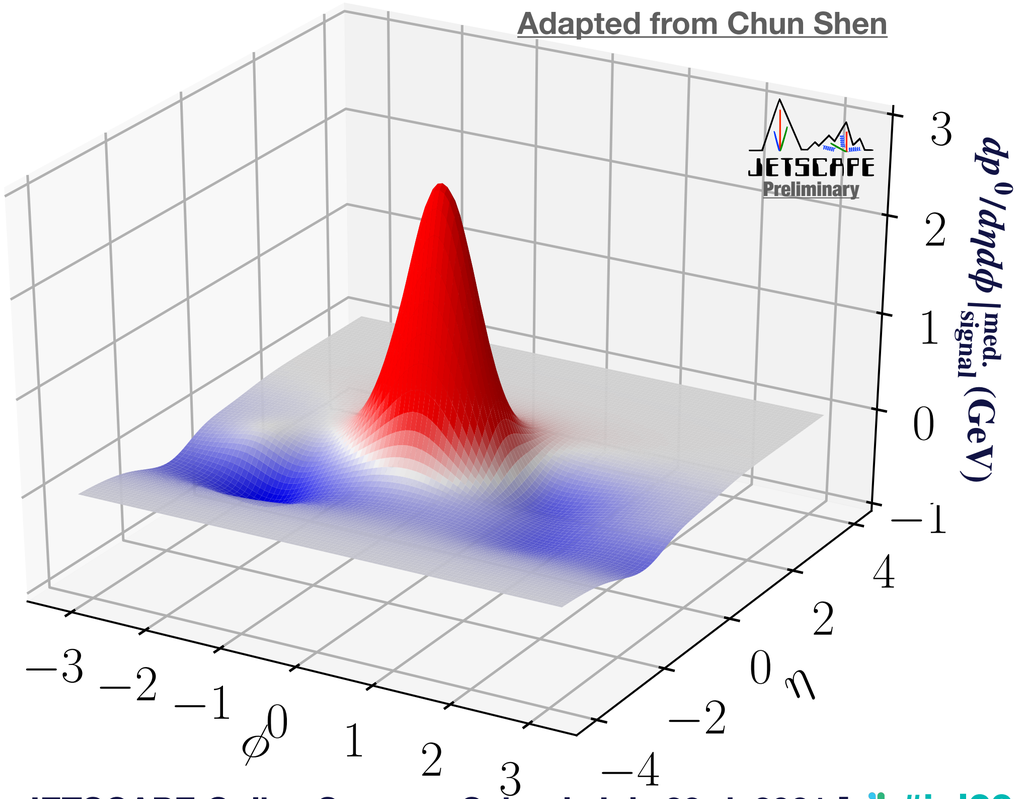

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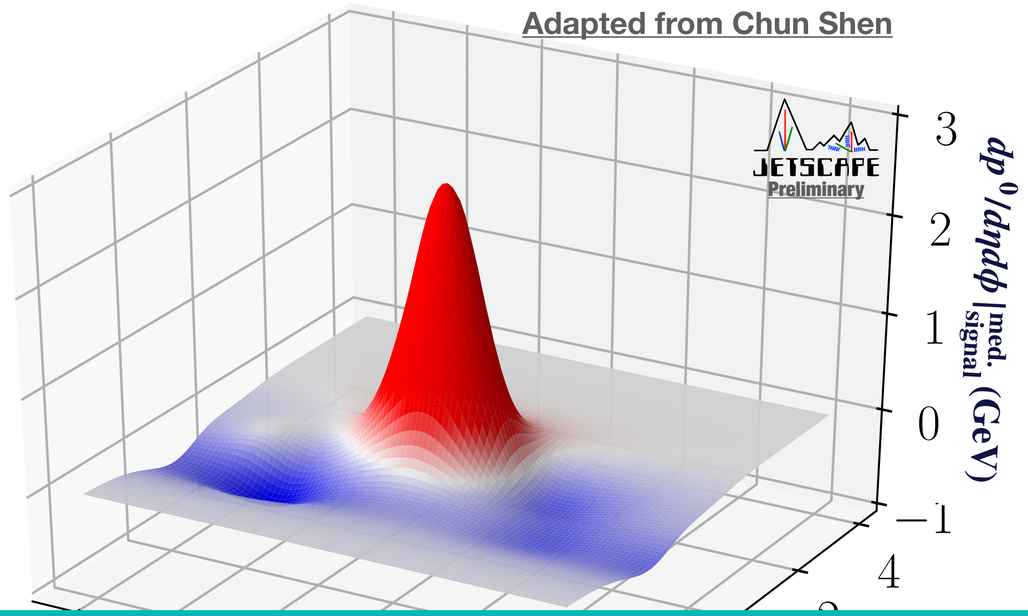
MATTER+LBT (Recoil ON) + Causal Diffusion + Viscous Hydro

Adapted from Chun Shen



- Jet-correlated structure in hadron emission from the bulk medium
- Negative contribution by medium response

#jul23-jul26-jets

JETSCAPE School 2021

Recent Results From JETSCAPE

(w/ Weakly-coupled Description by Recoils)

Y. Tachibana for the JETSCAPE Collaboration, JETSCAPE Online Summer School, July 23rd, 2021

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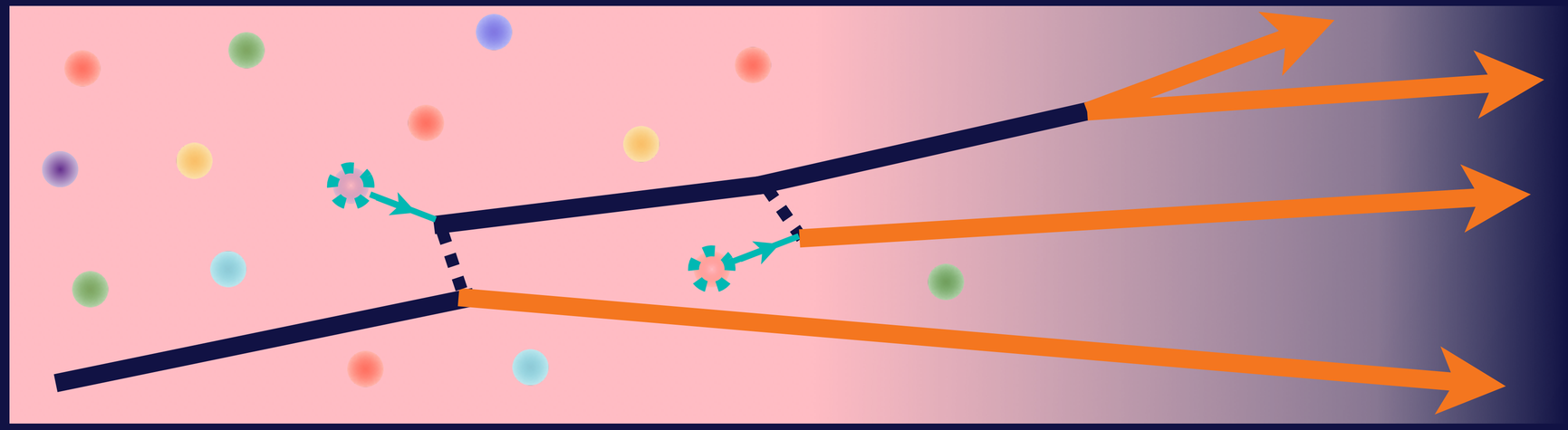

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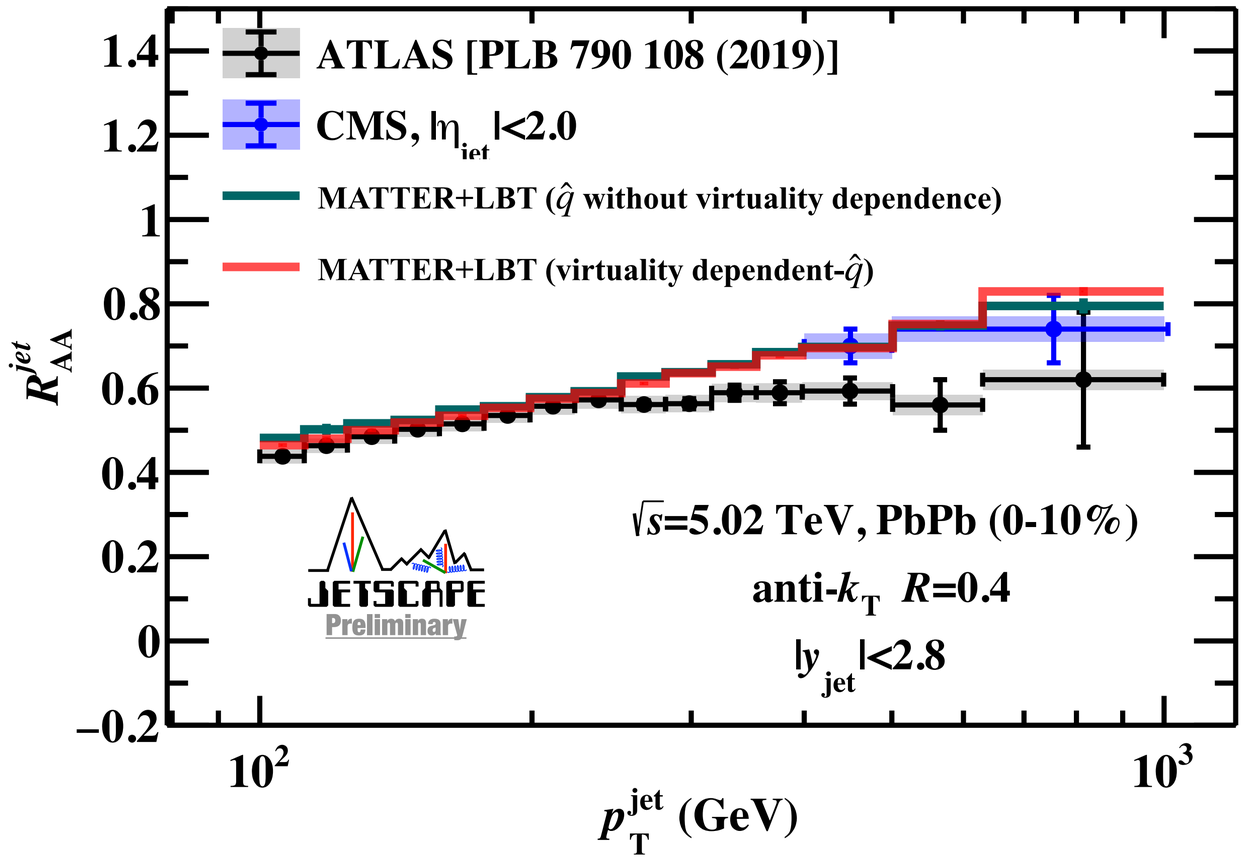
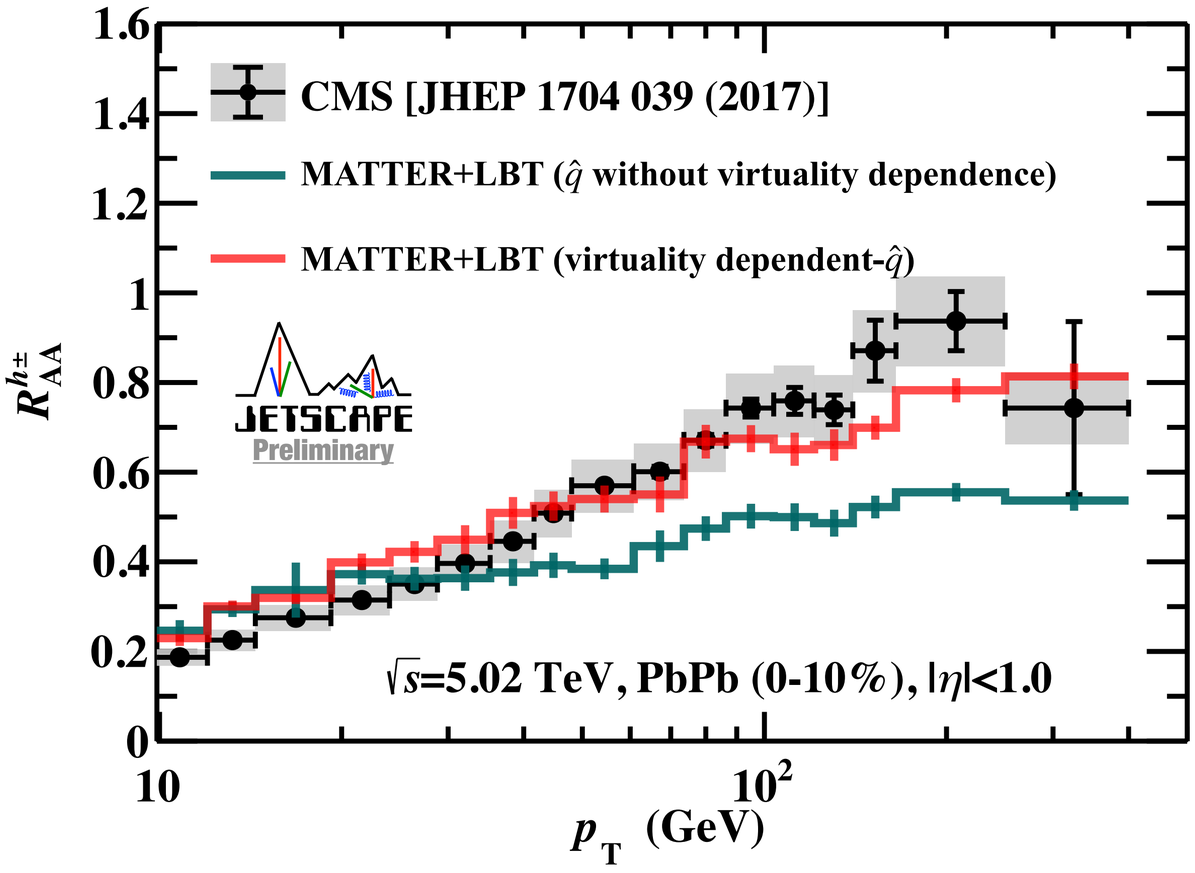
Results with Weakly-coupled Description of Med. Res.

- **Jet-R_{AA} and charged hadron-R_{AA}**
  - Tuned for PbPb (0-10%) collisions at 5.02 TeV and 2.76 TeV
  - Jet Shower by MATTER+LBT (with Recoil)





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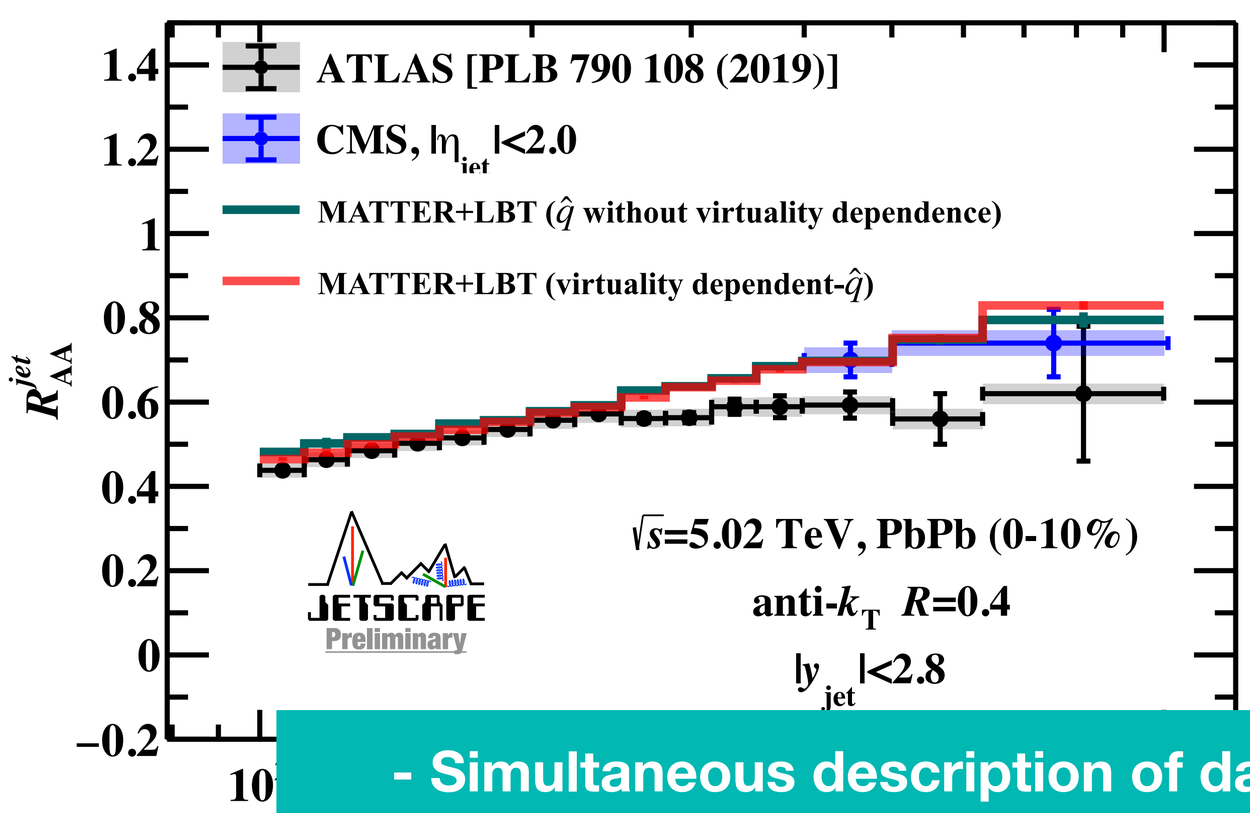
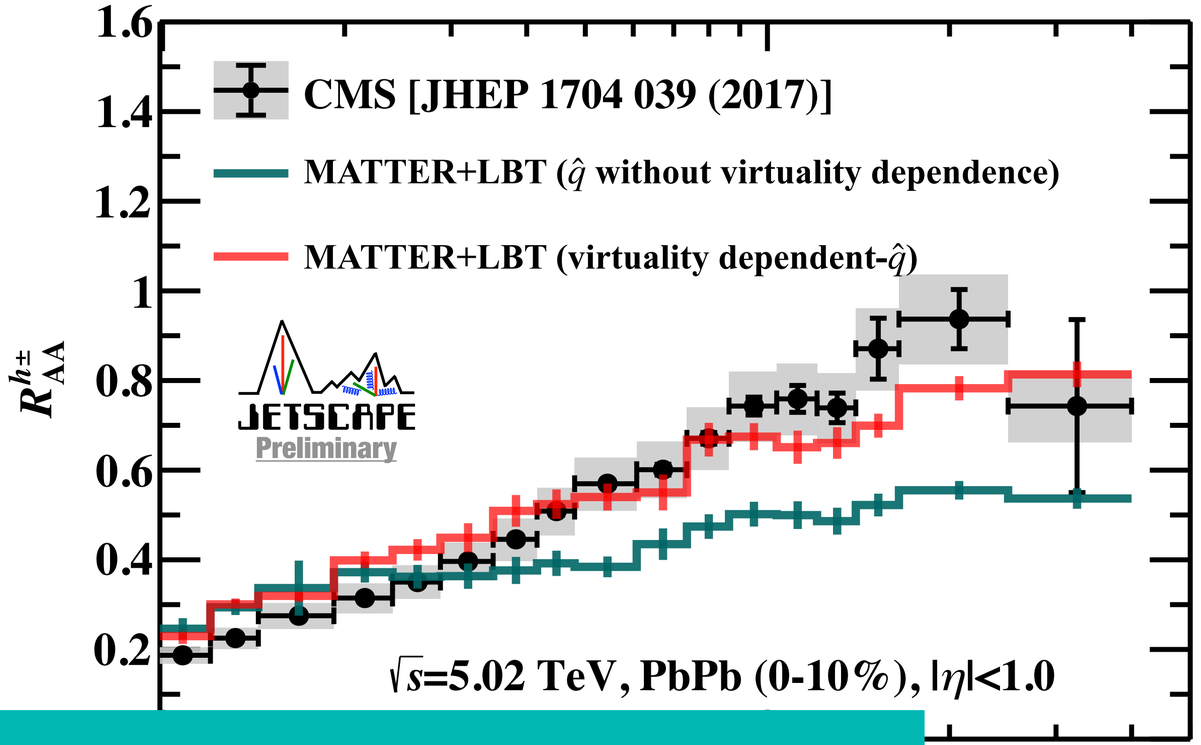


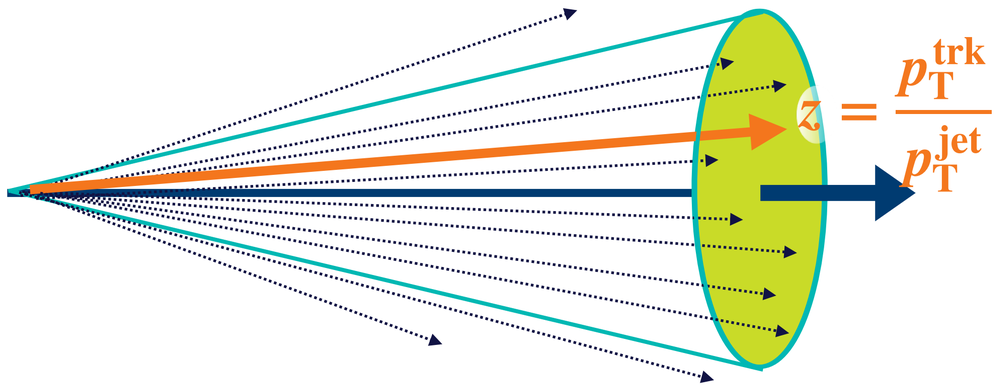


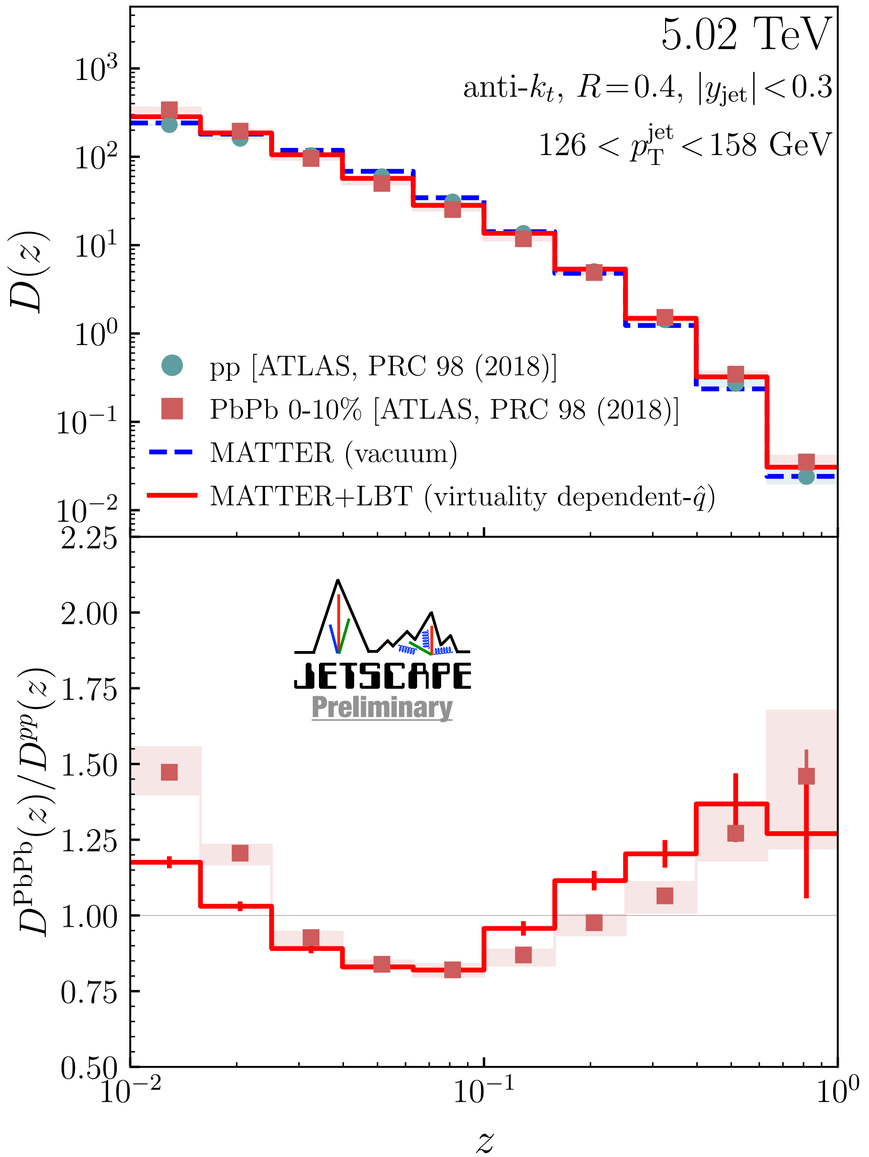
- Simultaneous description of data for jet and hadrons
- Significant effect of virtuality dependence of energy loss

Results with Weakly-coupled Description of Med. Res.

- **Jet fragmentation**
  - Momentum structure of jet

$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\bigg|_{\text{in jet}}$$





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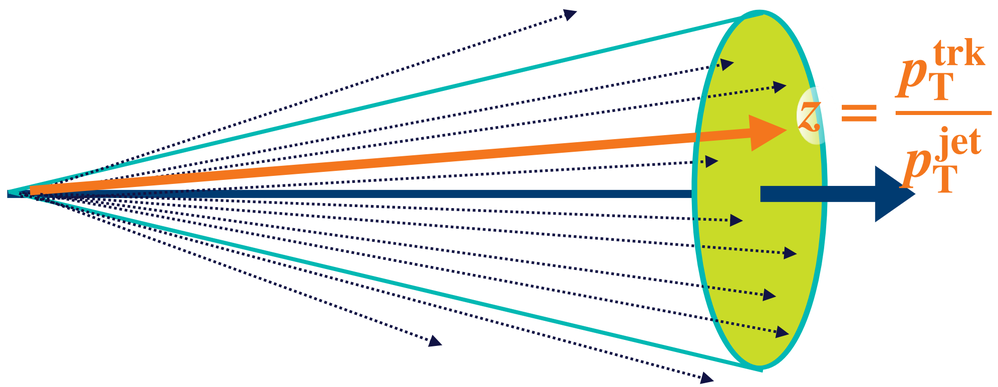
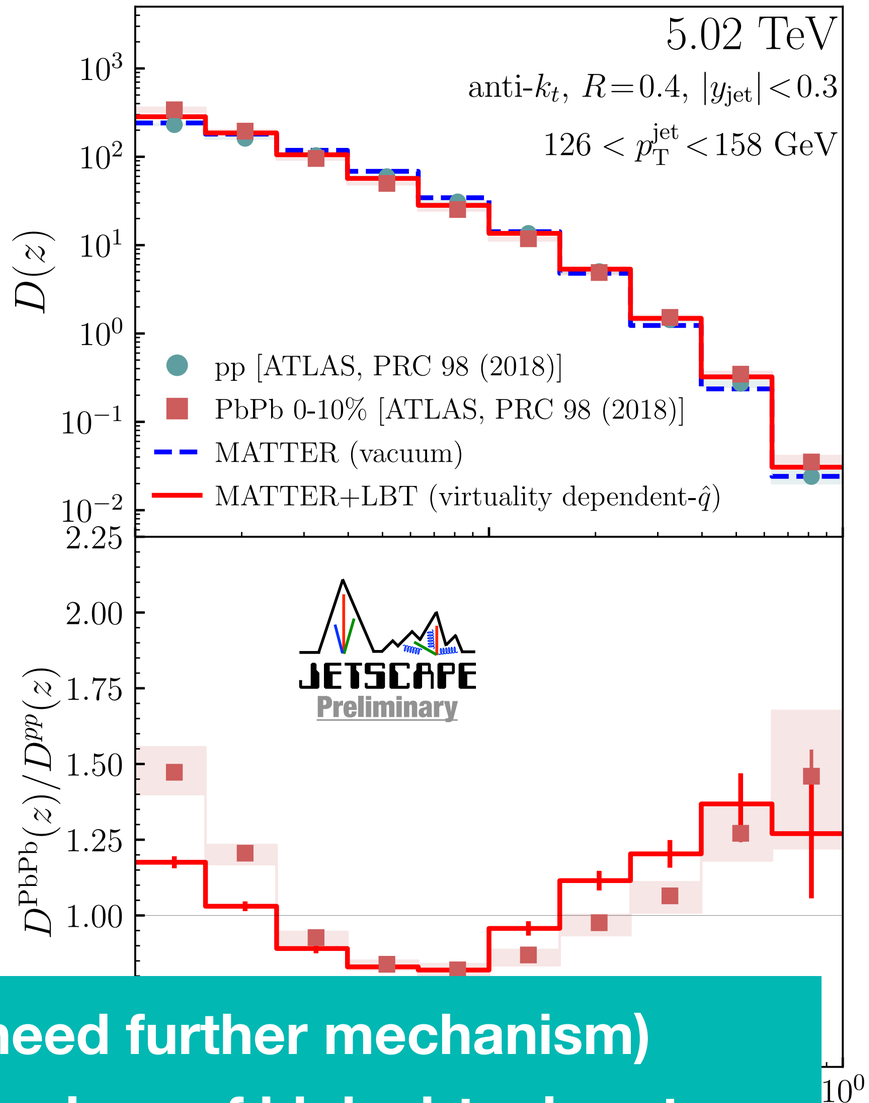


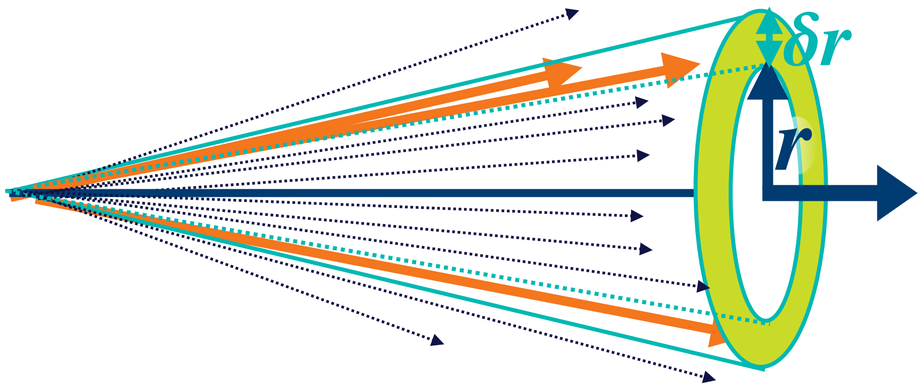


- Enhancement at small-z (but insufficient, need further mechanism)
- Enhancement at large-z due to small energy loss of high virtual partons

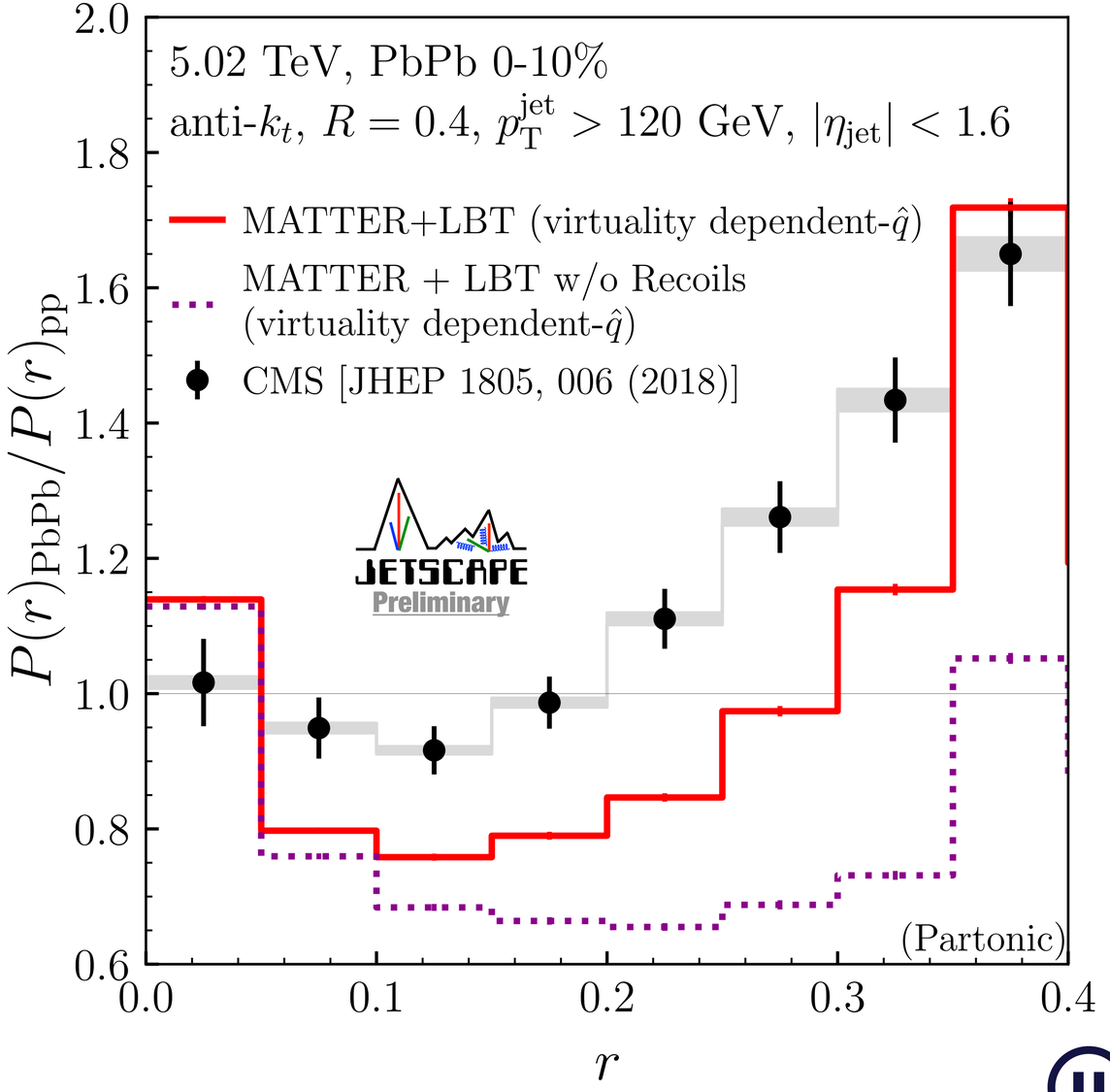
Results with Weakly-coupled Description of Med. Res.

- **Jet shape function**
  - Angular structure of jet

$$P(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk}\in(r\pm\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r}$$



$$r = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2}$$



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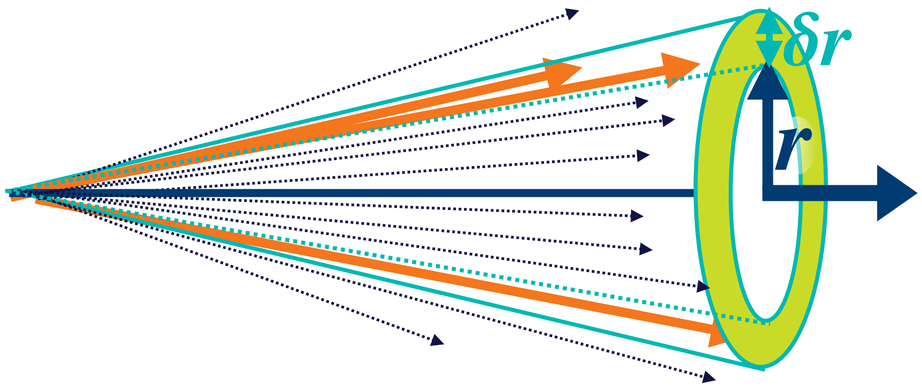
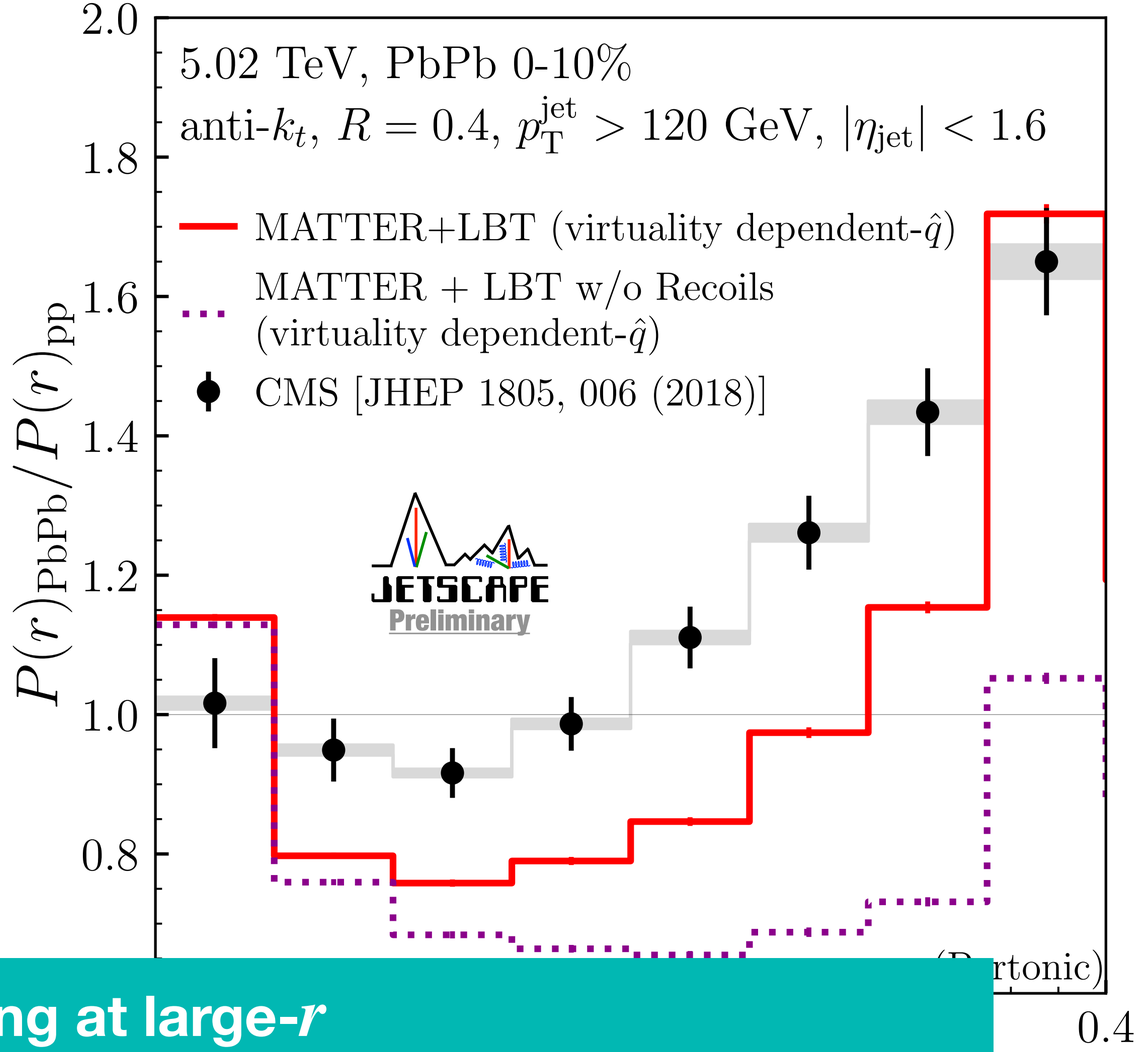




- Collimation at small-r and broadening at large-r
- Broadening at large-r by recoils' contribution

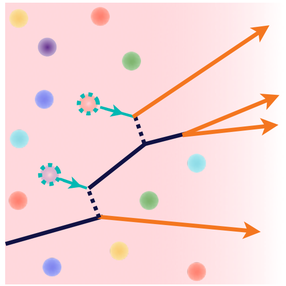
Summary

- **Medium response to jet quenching**
  - Medium constituents' reactions to interactions with jet
  - Contribute to jets observed in heavy ion collisions
  - Carry information of the in-medium thermalization process
  - Essential for comprehensive understanding of the jet quenching

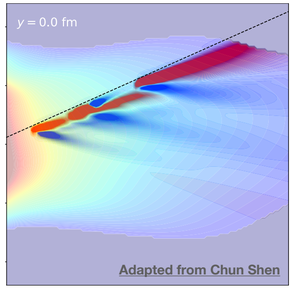
- **Implementation of medium response in JETSCAPE**
  - Weakly-coupled description → **Recoil (in MATTER, LBT and MARTINI)**
  - Strongly-coupled description → **Hydrodynamics (MUSIC, CLVisc)**
  - Intermediate stage. → **Causal Diffusion (Causal Liquefier)**

Summary

- **Weakly-coupled description of medium response**
  - Broadening and soft particle enhancement
  - Good description of jet observables



- **Strongly-coupled description of medium response**
  - No clear distinction of background → Need background subtraction
  - Jet-correlated structure in hadron emission from the bulk medium



- **Outlook**
  - Systematic studies to extract the detailed role of medium response
  - Further test of simulations and study of background subtraction
  - Full simulation with Strongly-coupled description of medium response

Backup

FAQ

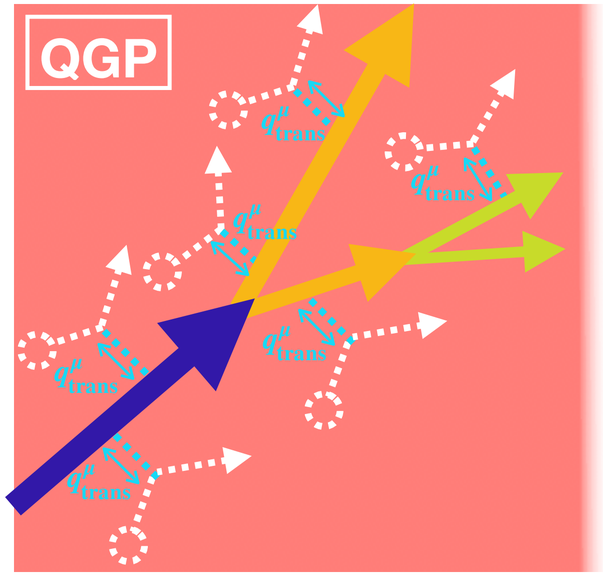
Q. Does medium response exist?

A. Medium response must always exist whenever jets interact with the medium. There are momentum transfers between jets and medium. Momentum is conserved for the whole system (jets+medium) in every single event.

Large modification of jet shower

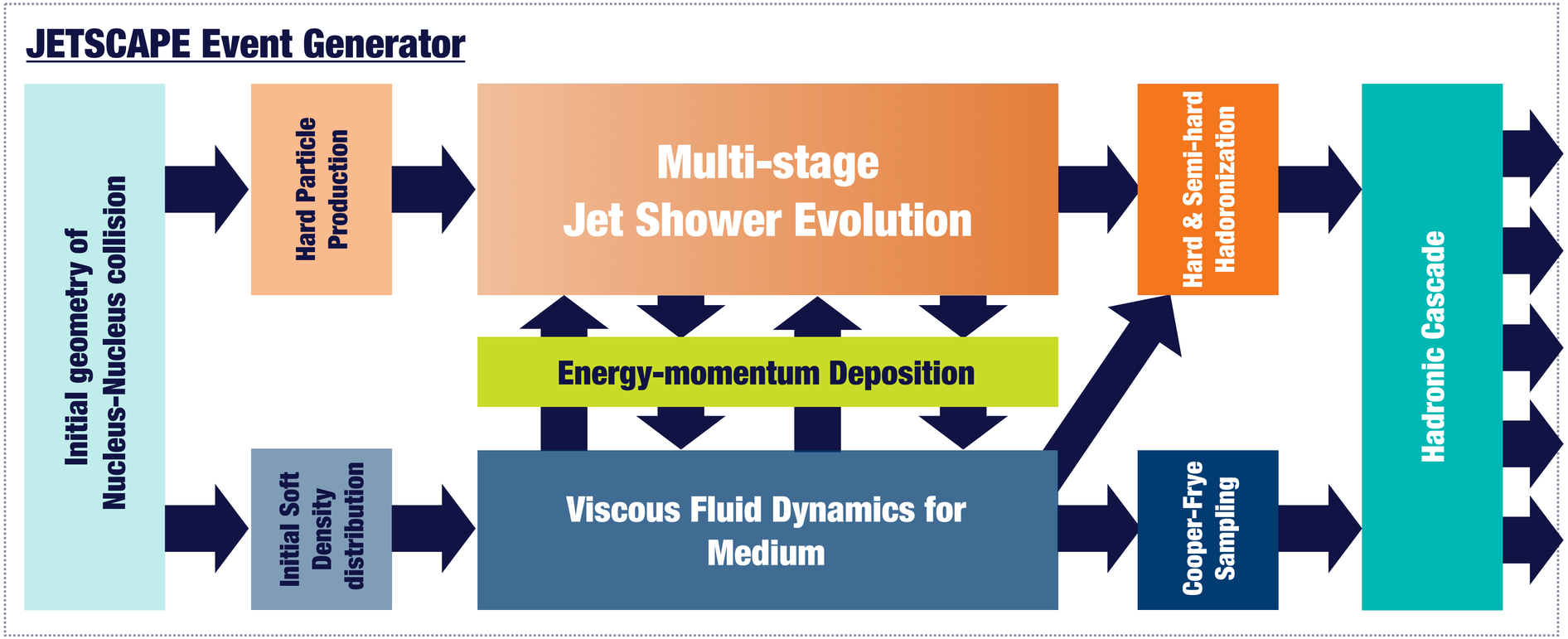
Large momentum transfer

Large effect of medium response



JETSCAPE

- **MC event generator package for heavy ion collisions**
  - JETSCAPE 2.0 available on GitH github.com/JETSCAPE
  - General, modular and highly extensible — Lecture by J. Mulligan



Soft Part → Lecture by C. Shen

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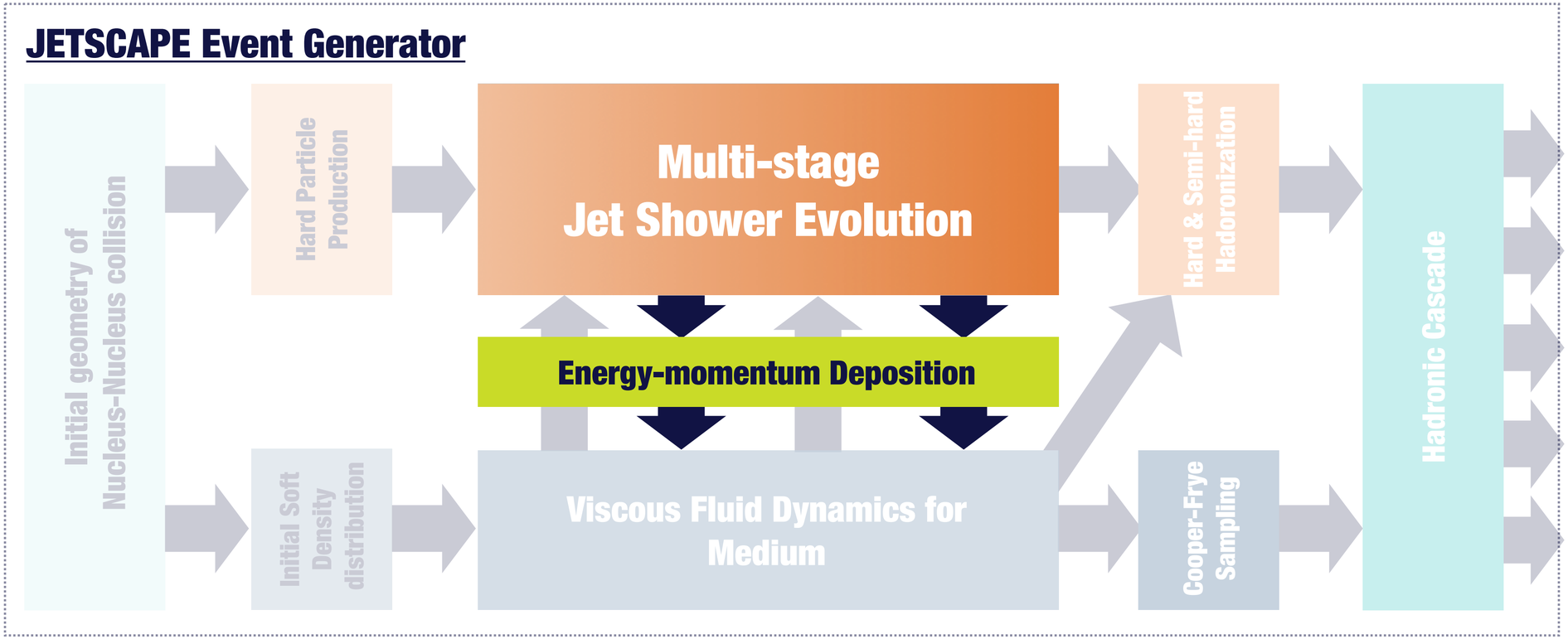

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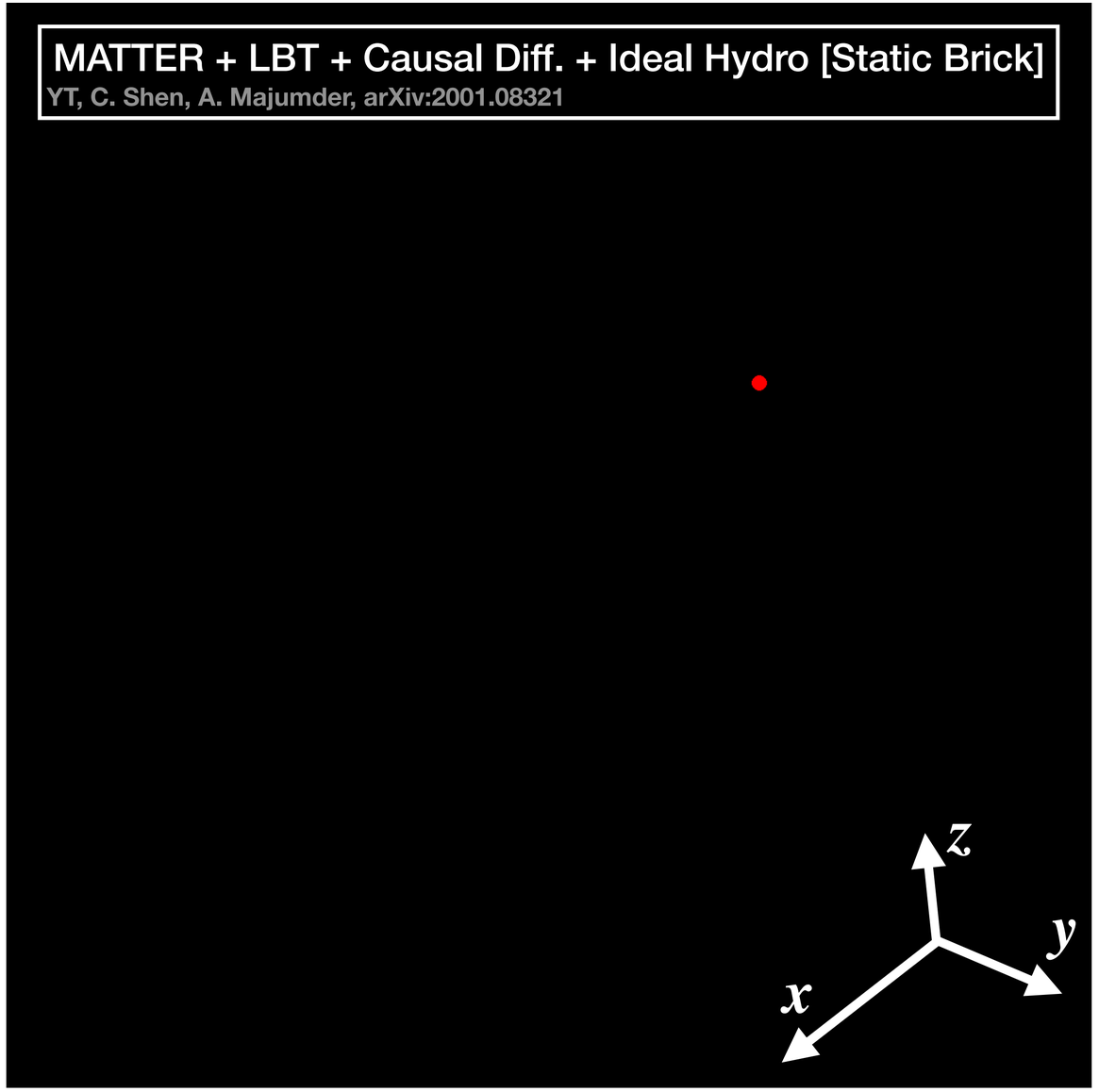
Hydrodynamic medium response to jet propagation



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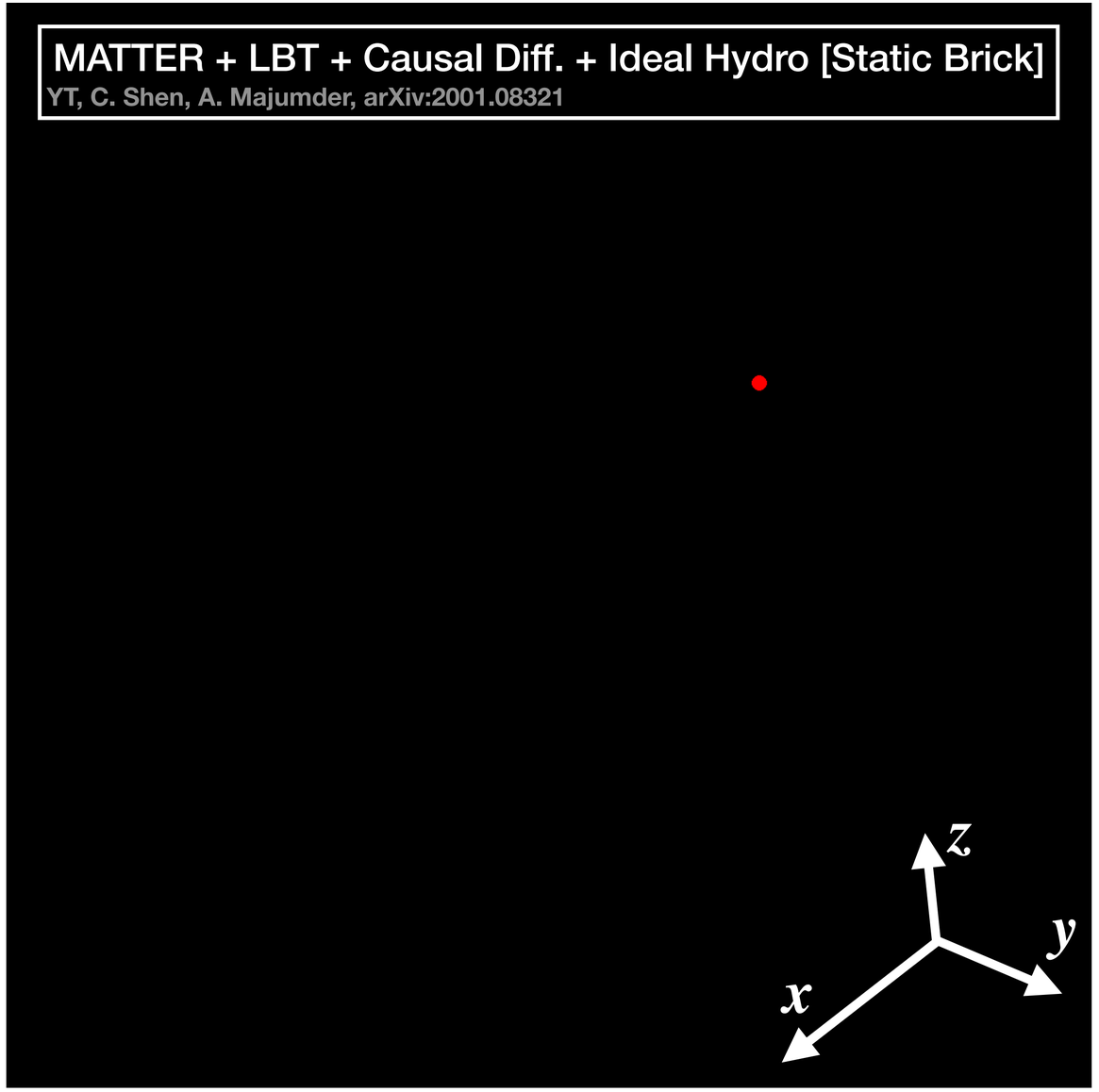
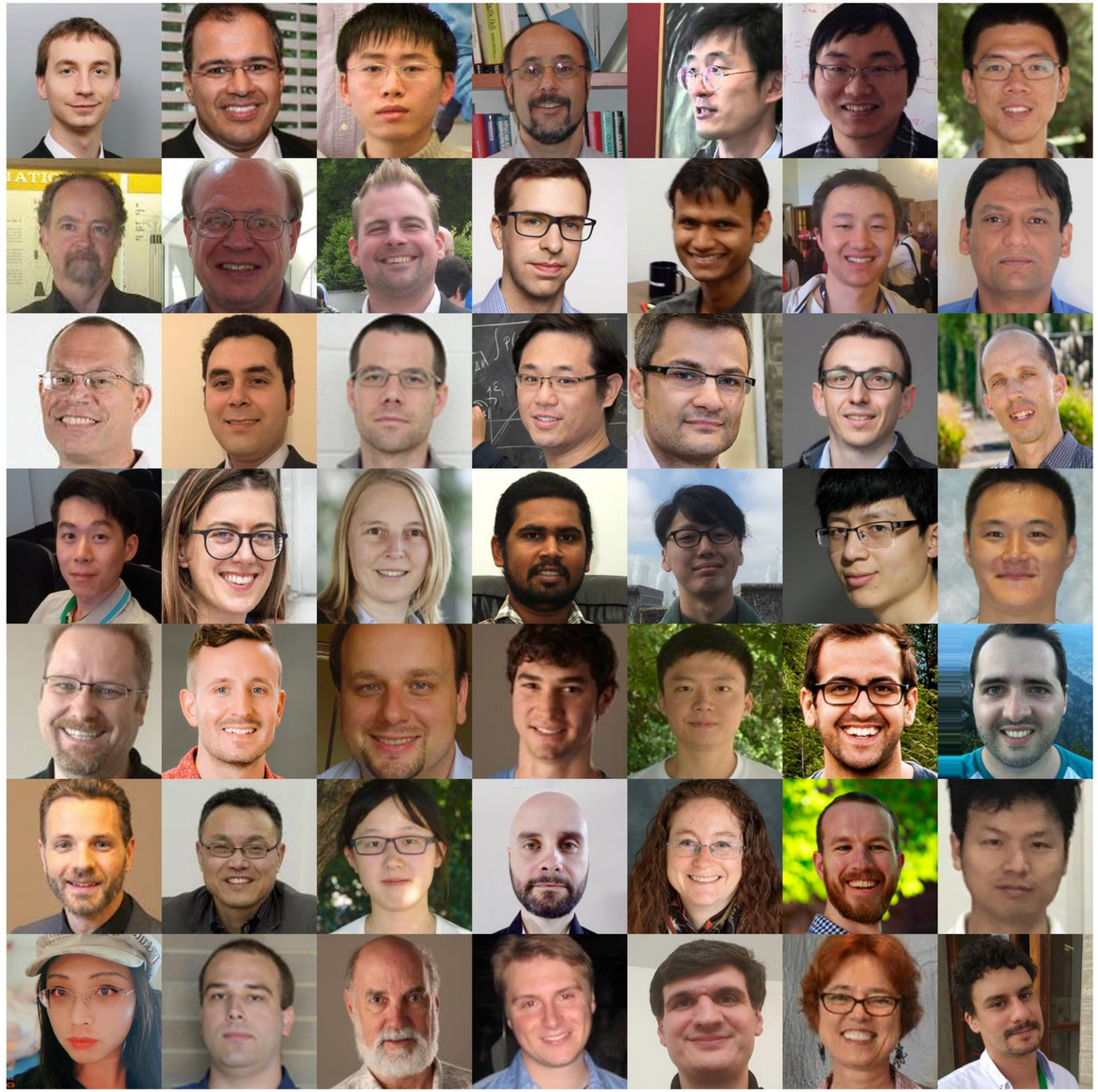


JETSCAPE Collaboration

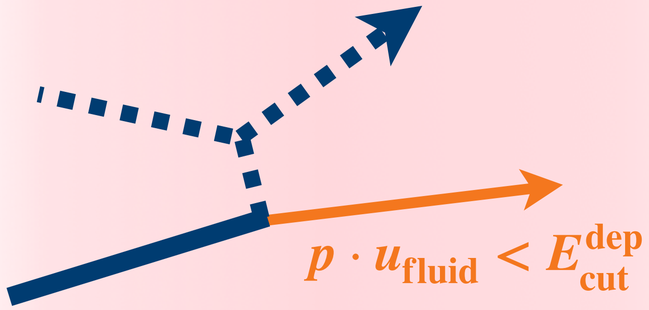


JETSCAPE

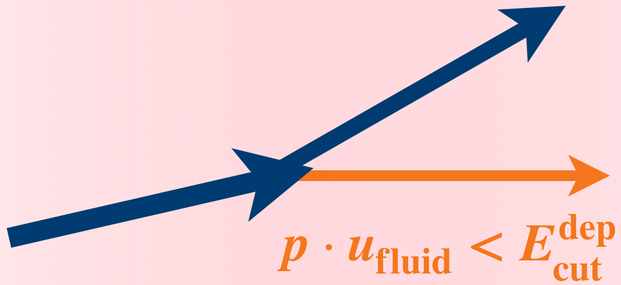
Strongly-coupled Description: Energy-momentum Depositions

- Positive deposition for partons with energy at medium's local rest frame $p \cdot u_{\rm fluid} < E^{\rm dep}_{\rm cut}$
- Negative deposition due to energy picked up from medium

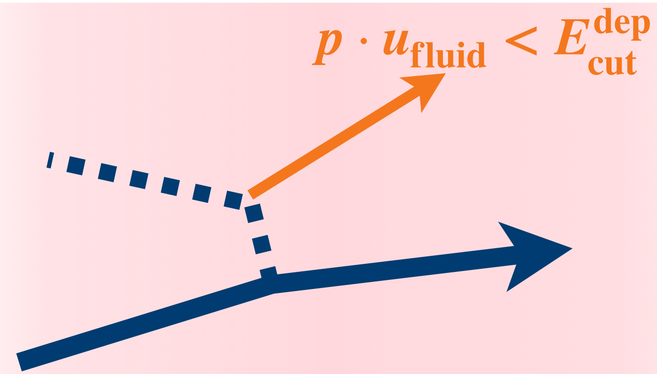
Shower parton soften by collision



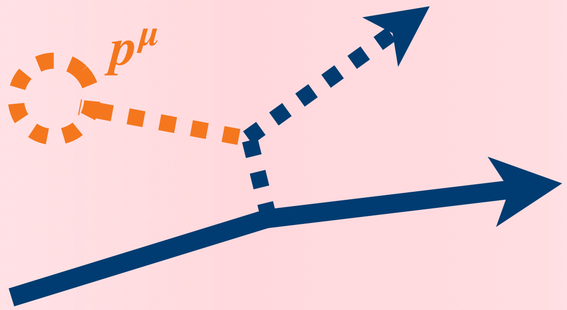
Soft radiated partons



Soft recoils in collisions



Medium parton kicked out by collision



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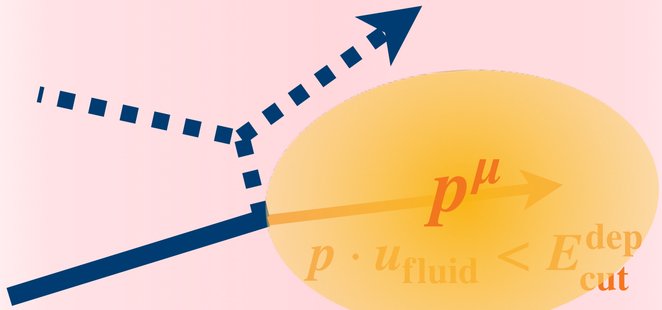

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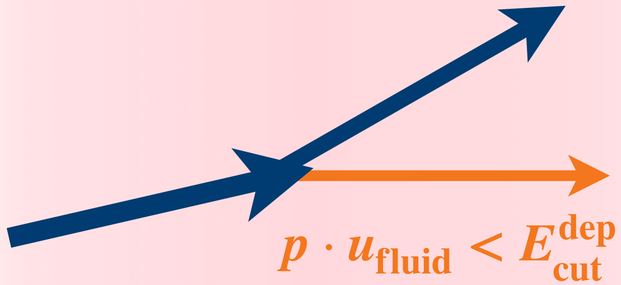

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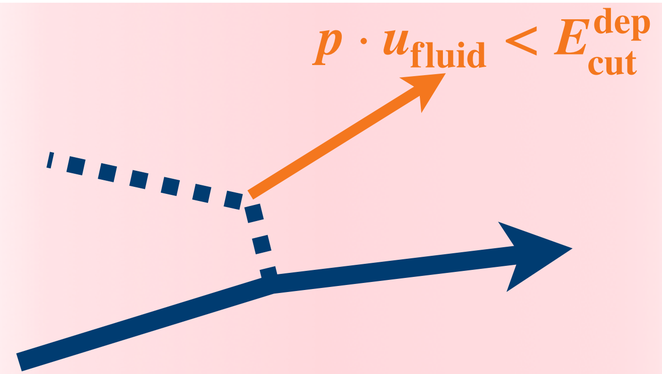

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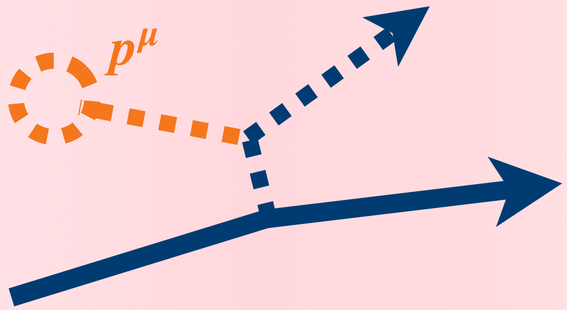

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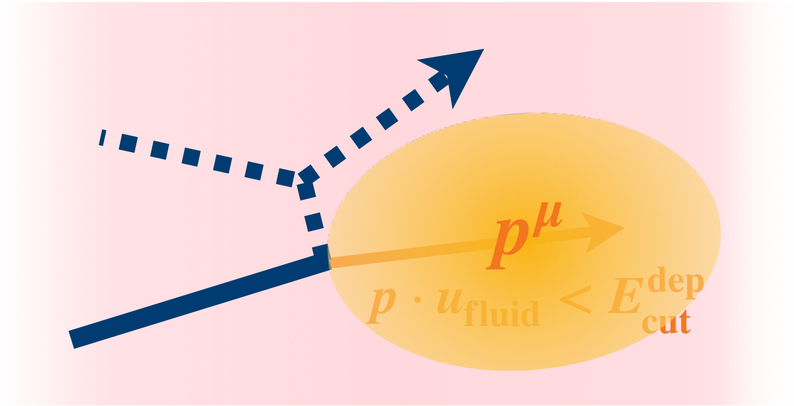

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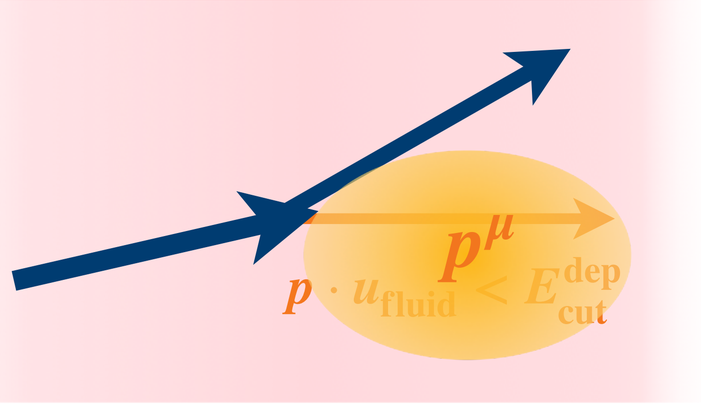

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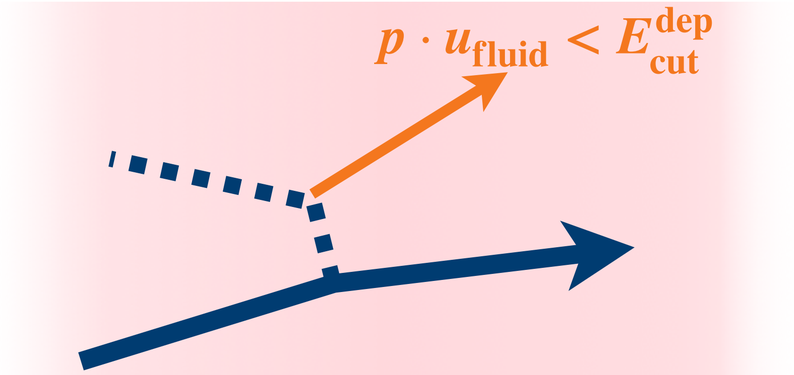

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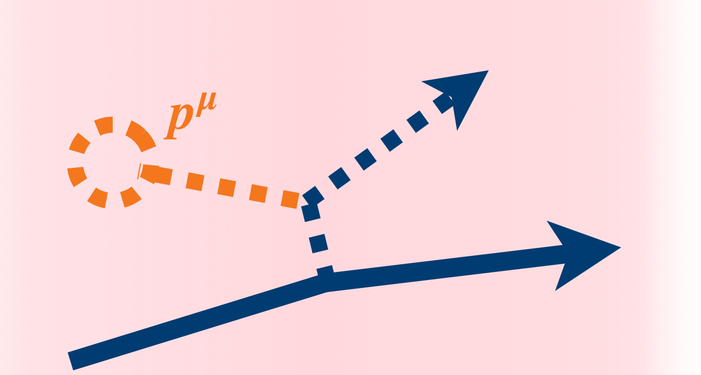

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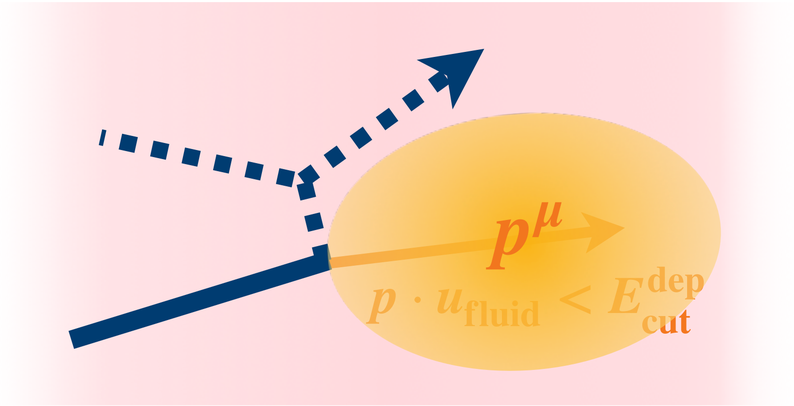

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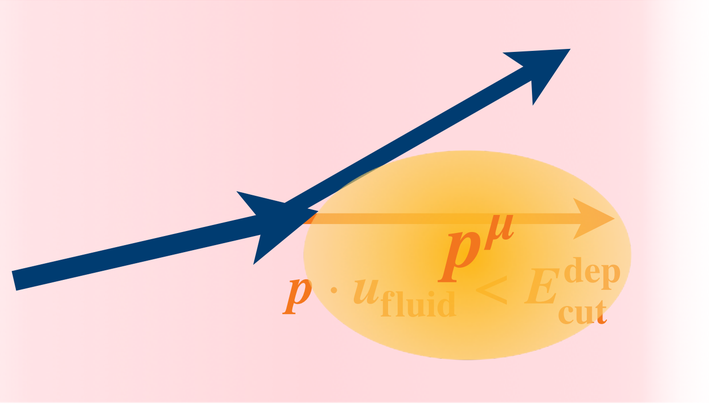

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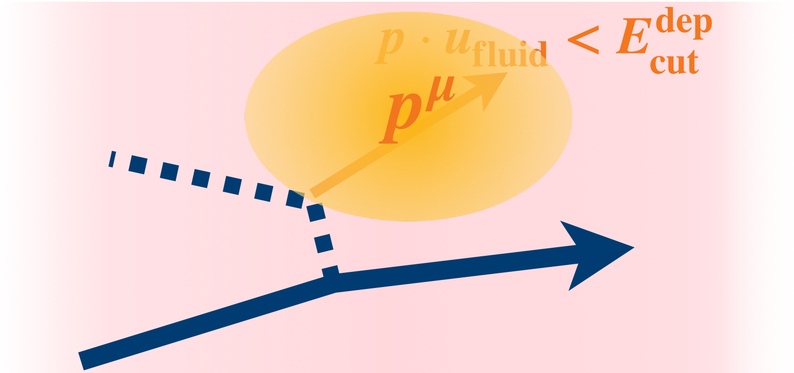

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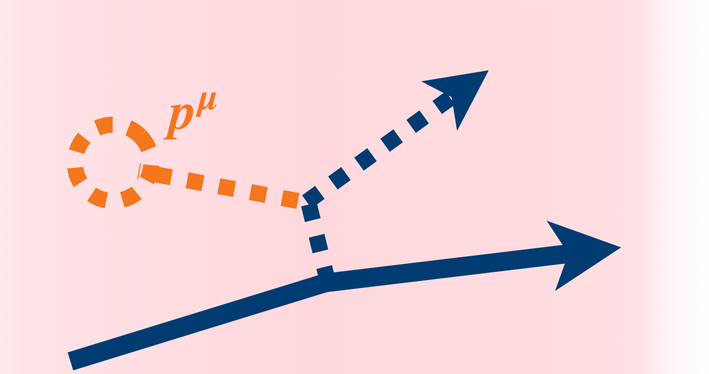

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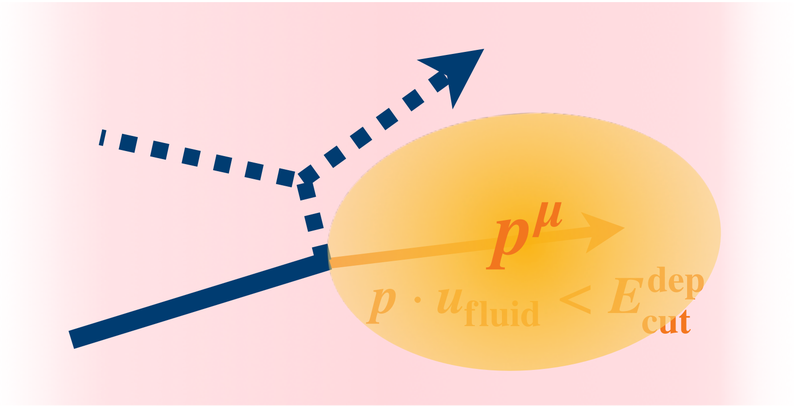

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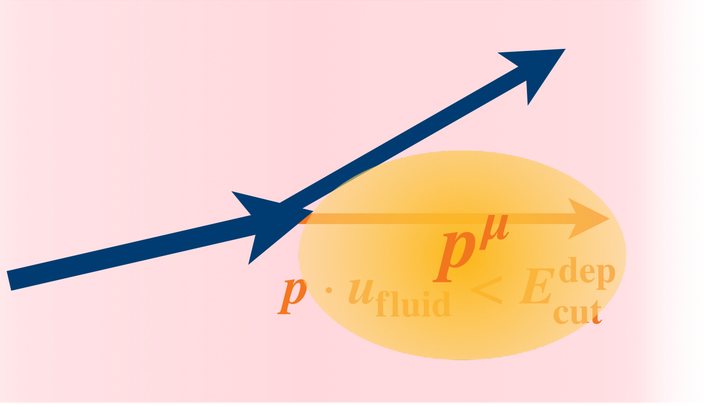

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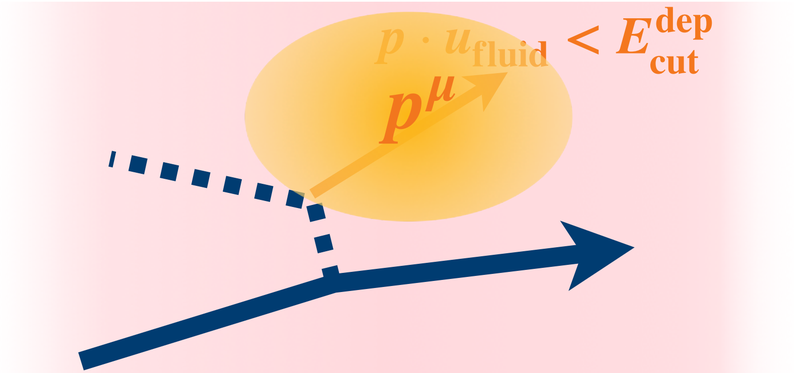

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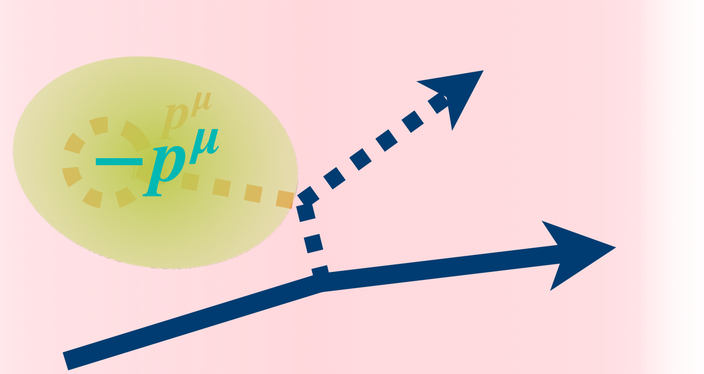


Strongly-coupled Description: Causal Formulation for Source Term

Source profile based on causal diffusion

YT, C. Shen, A. Majumder, in preparation

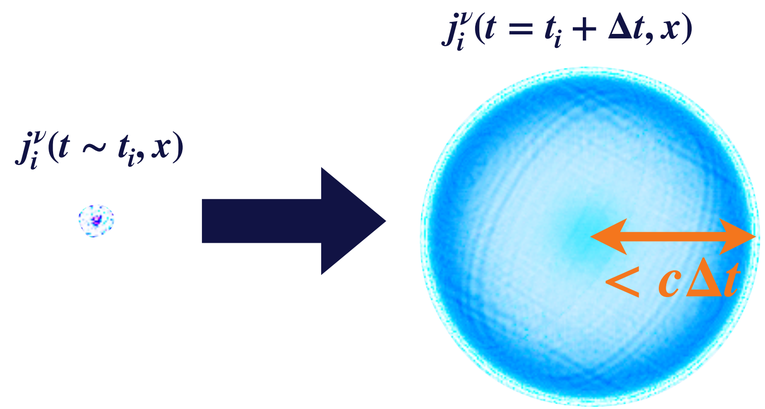
$$J^{\nu}_{\rm jet}(x) = \sum_i j^{\nu}_i(x)\,\delta\big(t - [t_i + \Delta t]\big)$$

- Underlying equation of motion: Relativistic diffusion equation

$$\left[\frac{\partial}{\partial t} + \tau_{\rm diff}\frac{\partial^2}{\partial t^2} - D_{\rm diff}\nabla^2\right] j^{\nu}_i(x) = 0$$

with initial condition $j^{\nu}_i(t = t_i, \vec{x}) = (\pm)_i p^{\nu}_i \delta^{(3)}(\vec{x} - \vec{x}_i)$ and $\dfrac{\partial j^{\nu}_i}{\partial t}(t = t_i, \vec{x}) = 0$

(i: deposited parton, $(\pm)_i$ for positive/negative deposition)



$D_{\rm diff}$: Diffusion coefficient

$\tau_{\rm diff}$: Relaxation time

Δt: Timescale for in-medium thermalization

Simulations with JETSCAPE 2.0

- **Settings for PbPb collisions at 5.02 TeV**

Jet Shower

- MATTER+LBT (Recoil ON, Virtuality separation $Q_0 = 2\,\mathrm{GeV}$)
- Initial condition from TRENTo+Pythia (MPI&ISR ON, $\hat{p}_\mathrm{T} = 100\text{-}150\,\mathrm{GeV}$)
  Moreland, Bernhard, Bass
- Lund hadronization

Source Term

- Causal profile generated via relativistic diffusion equation
- Absorption of partons with energy at LRF of medium $p \cdot u_\mathrm{fluid} < 2\,\mathrm{GeV}$

Medium Fluid

- TRENTo initial profile
- (3+1)-D viscous hydro calculation with source term by MUSIC
  Denicol, Gale, Jeon, Luzum, Paquet, Schenke, Shen
- Particle emission at freezeout via Cooper-Frye sampling

Energy-momentum Depositions from Jet Shower

- **Standard source profile and diffusion equation**
  - Gaussian smearing

$$J^{\nu}_{\rm jet}(x) = \sum_i \frac{(\pm)_i p_i^{\mu}}{(\sqrt{2\pi}\sigma)^3} \exp\left[-\frac{|\vec{x} - \vec{x}_i|^2}{2\sigma^2}\right] \delta\left(t - [t_i + \Delta t]\right)$$

i: deposited parton, $(\pm)_i$ for positive/negative deposition

Infinite tail → acausal

  - Underlying equation of motion: *Non-relativistic* diffusion equation

$$\left[\frac{\partial}{\partial t} - D_{\rm diff}\nabla^2\right] f(x) = 0$$

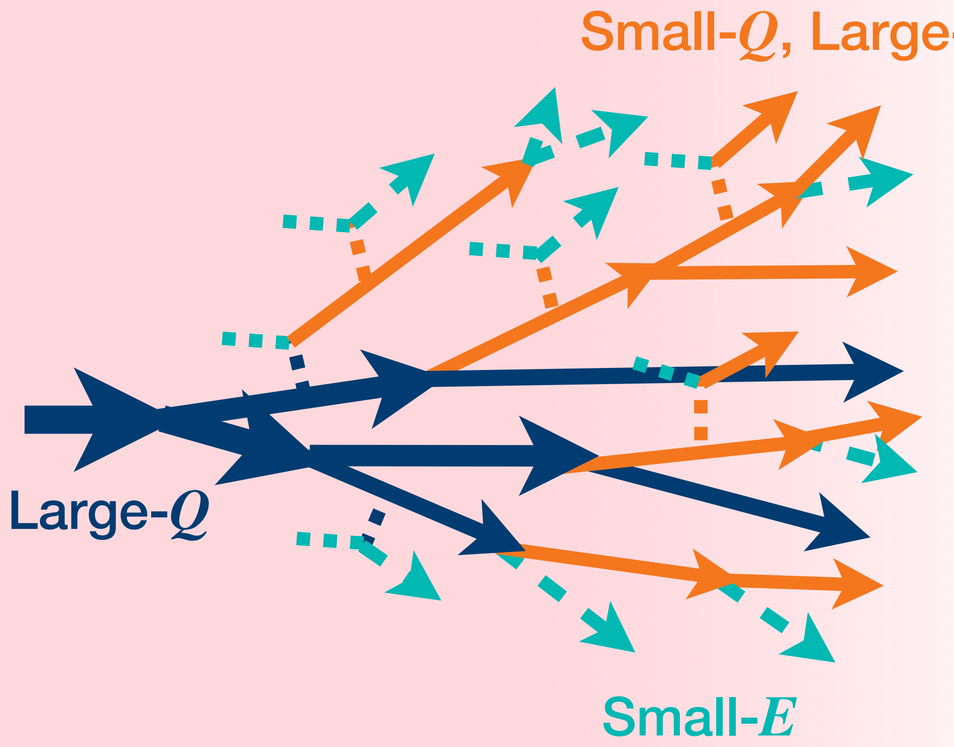
with initial condition $f(t = t_i, \vec{x}) = p_i^{\nu}\delta^{(3)}(\vec{x} - \vec{x}_i)$

and diffusion coefficient $D_{\rm diff} = \frac{\sigma^2}{2\Delta t}$

Weak

Majumder, Putschke (16), JETSCAPE (17)

In-medium



Q^2: virtuality (off-shellness)

Large-Q

Virtuality ordered splittings with small medium effect

Model: **MATTER**

Small-Q, Large-E

Splittings driven by in-medium scatterings

Models: **LBT, MARTINI**

Small-E

Energy-momentum diffusion into medium

Model: **AdS/CFT**

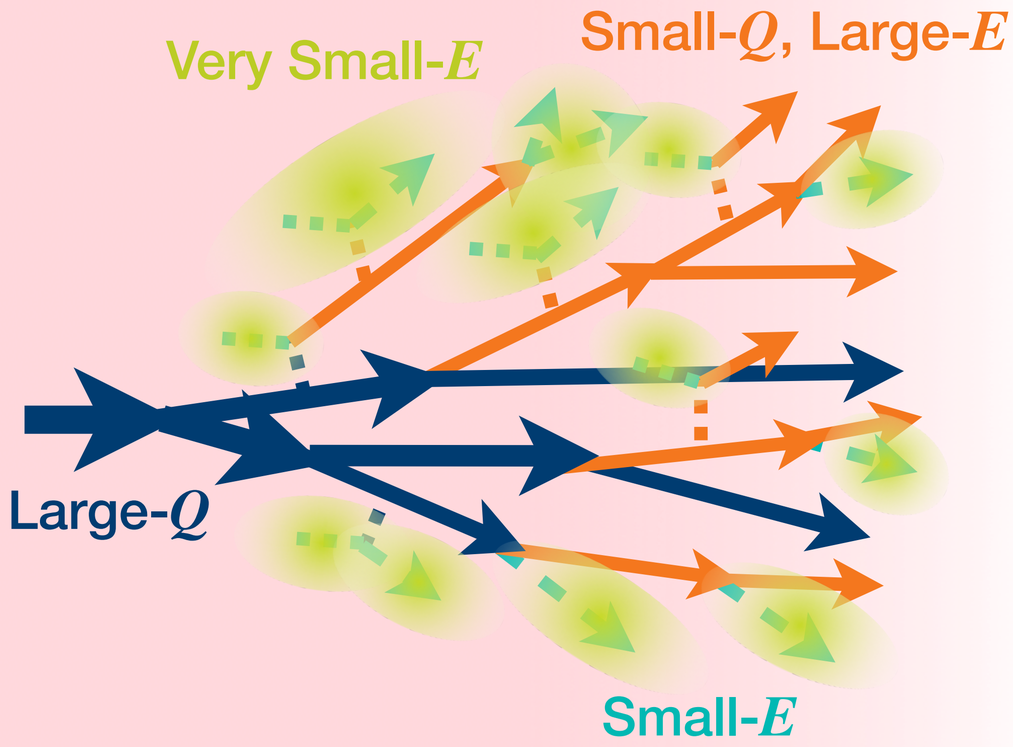
Event-by-event Jet Simulation → Talk by A. Kumar (Wed)

Heavy Quarks → Talk by G. Vujanovic (Tue)

Weak

Majumder, Putschke (16), JETSCAPE (17)

In-medium



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Model: **AdS/CFT**

Very Small-E

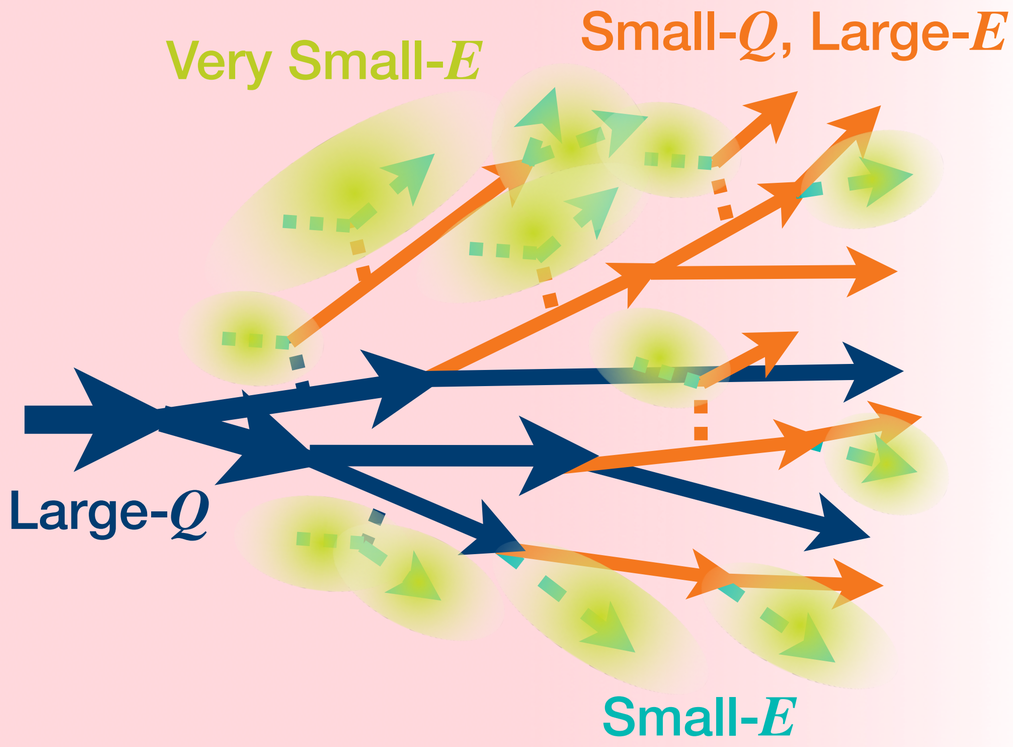
Hydrodynamical evolution with bulk medium

Model: **Hydrodynamics (e.g. MUSIC)**

Weak

Majumder, Putschke (16), JETSCAPE (17)

In-medium



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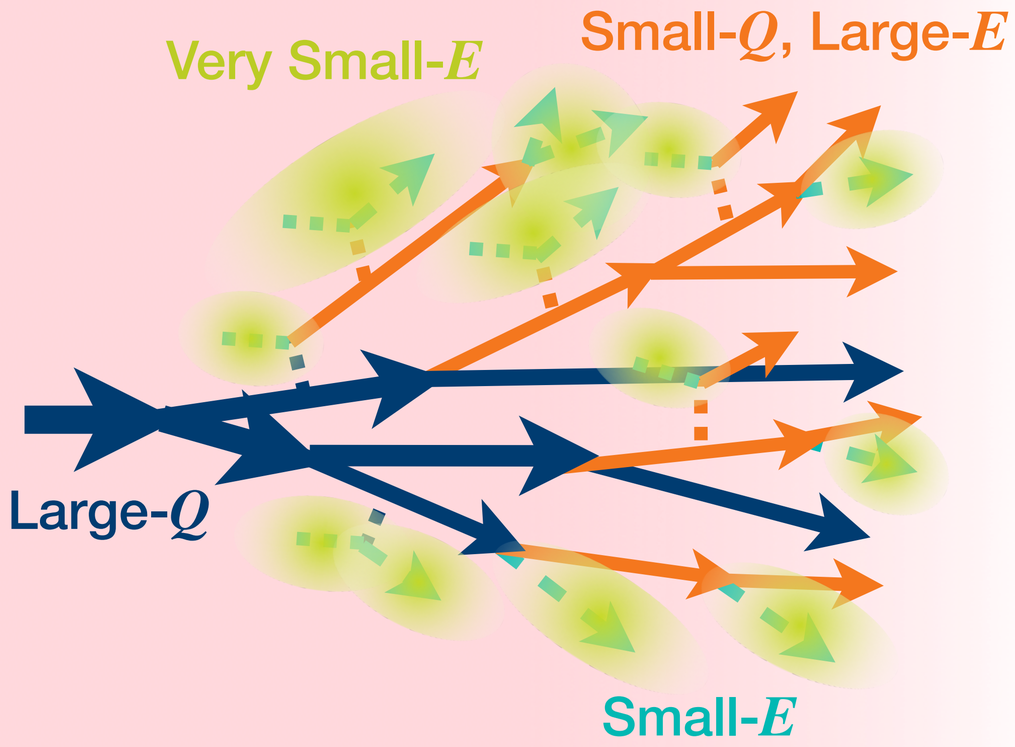

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Small-Q, Large-E

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Energy-momentum diffusion into medium

Model: **Causal Diffusion**

➡ **Source Profile for Fluid**

Very Small-E

Hydrodynamical evolution with bulk medium

Model: **Hydrodynamics (e.g. MUSIC)**

➡ **Hydrodynamic Response**