Hard Probes 2020

online

Medium response from mini-jets and in-medium hadronization

Sangwook Ryu

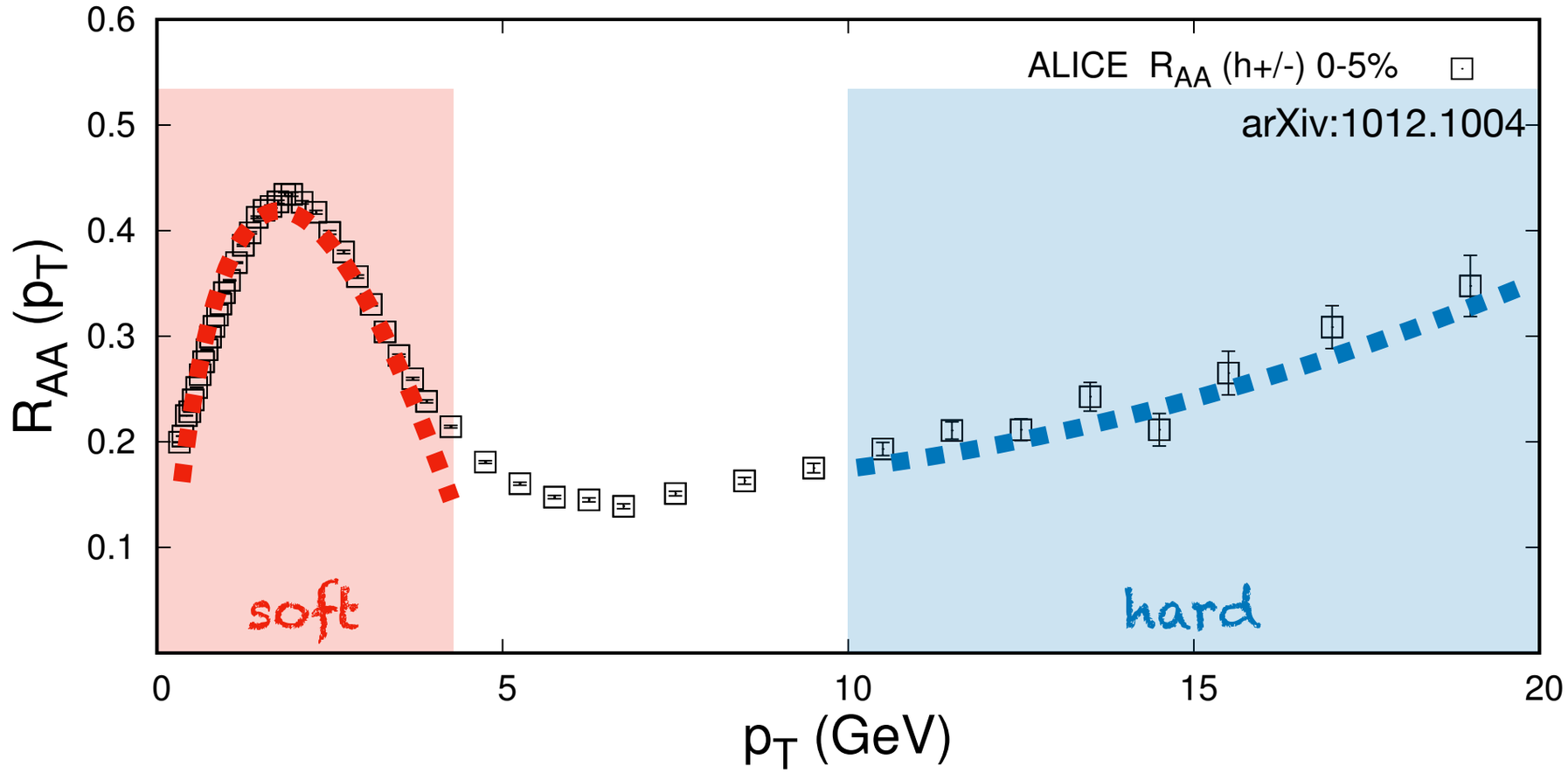
In collaboration with
Scott McDonald, **Chun Shen**, **Sangyong Jeon** and **Charles Gale**

compute canada | calcul canada

WAYNE STATE UNIVERSITY

DAAD

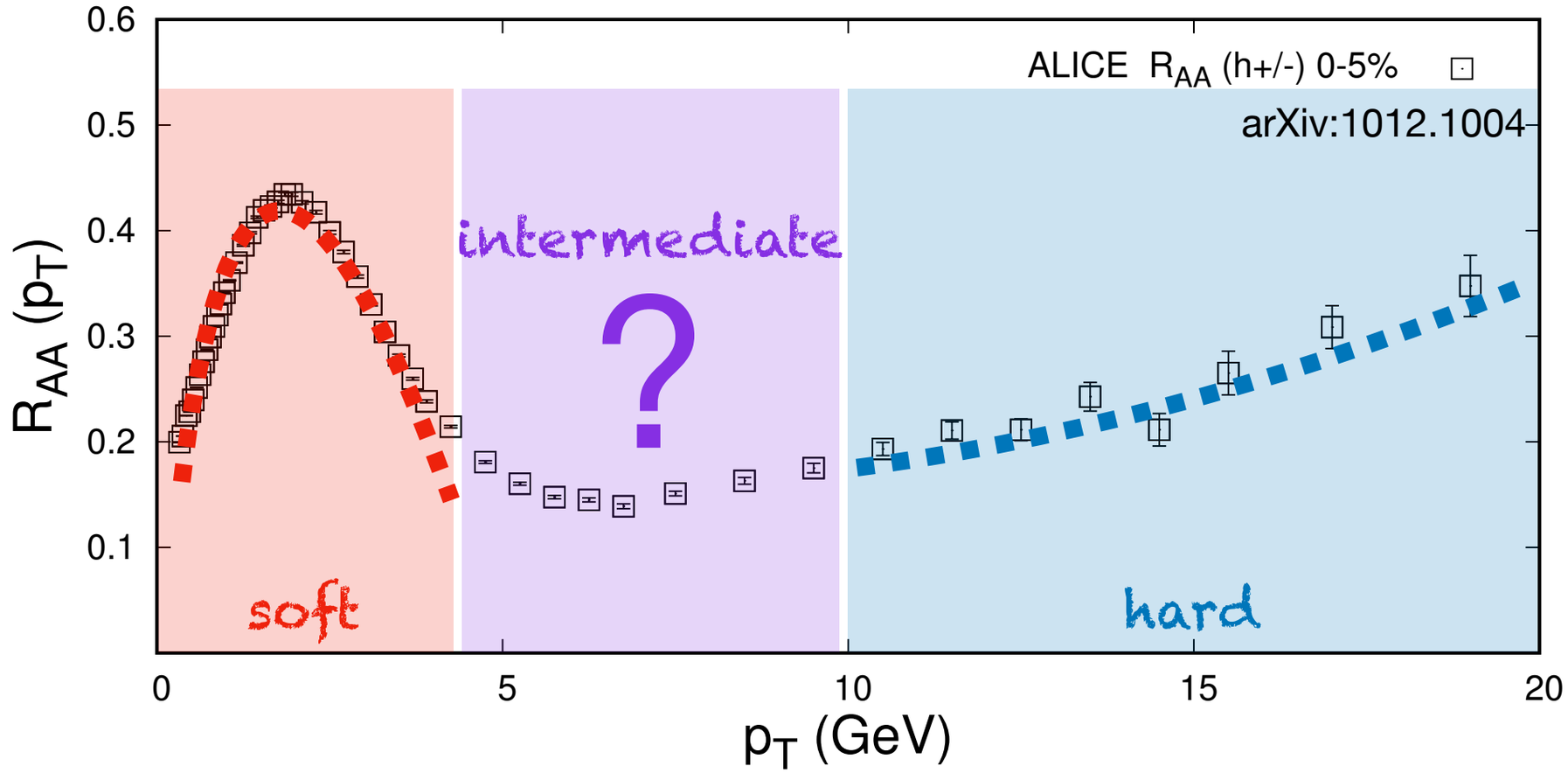
Introduction



- Ultra-relativistic heavy ion phenomenology has been focusing on understanding properties of QGP including (but not limited to)
  - transport coefficients (e.g., shear and bulk viscosities) and
  - jet-medium interaction between QGP and energetic jets.

- Many extensive studies have been looking at low-$p_T\,(< 2.5\,\mathrm{GeV})$ or high-$p_T\,(> 10\,\mathrm{GeV})$ regimes.

Introduction



- What happens in the intermediate-p_T regime, where thermal $\simeq$ mini-jet contributions?
  - mini-jet contribution can affect the intermediate and low-p_T observables.
  - necessary for better understanding of QGP

- Prerequisite : An extended hybrid approach, which can handle mini-jet production and energy loss.

Framework
Overview

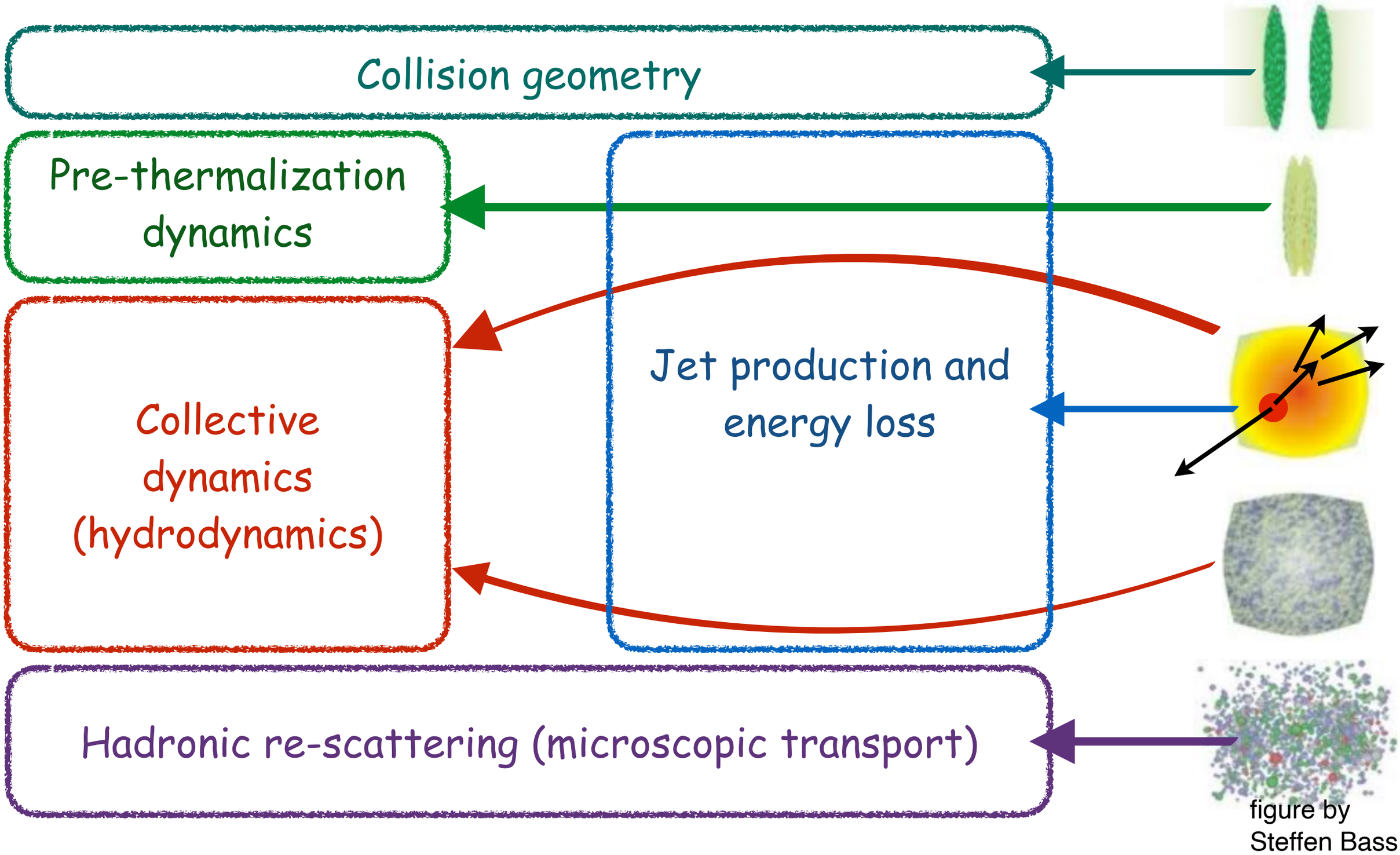


figure by Steffen Bass

Framework

Overview - bulk dynamics of fireball

Collision geometry

Pre-thermalization dynamics

Distribution of participants and binary collisions

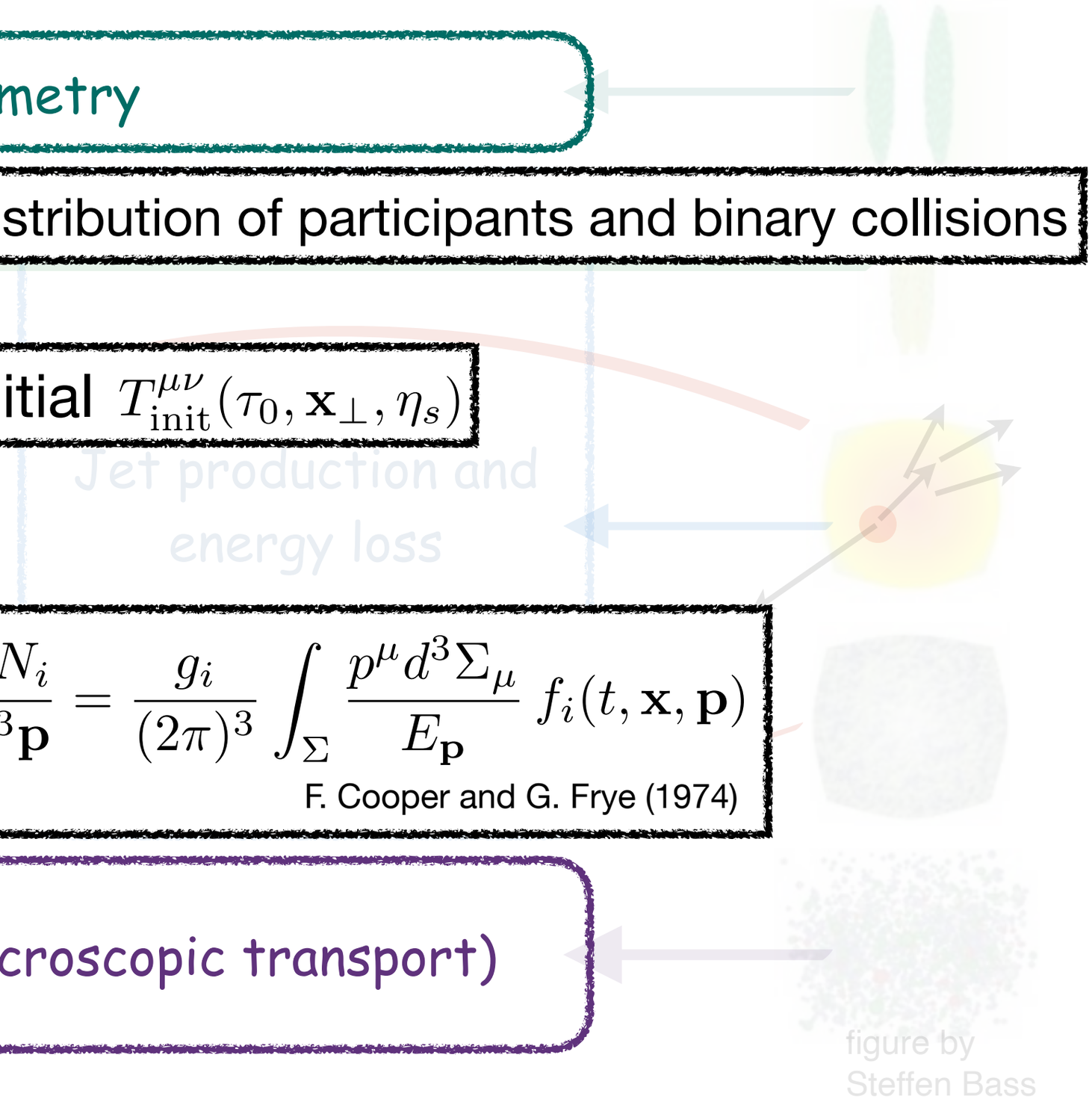
Initial $T^{\mu\nu}_{\rm init}(\tau_0, \mathbf{x}_\perp, \eta_s)$

Collective dynamics (hydrodynamics)

$$\frac{dN_i}{d^3\mathbf{p}} = \frac{g_i}{(2\pi)^3} \int_\Sigma \frac{p^\mu d^3\Sigma_\mu}{E_\mathbf{p}} f_i(t, \mathbf{x}, \mathbf{p})$$

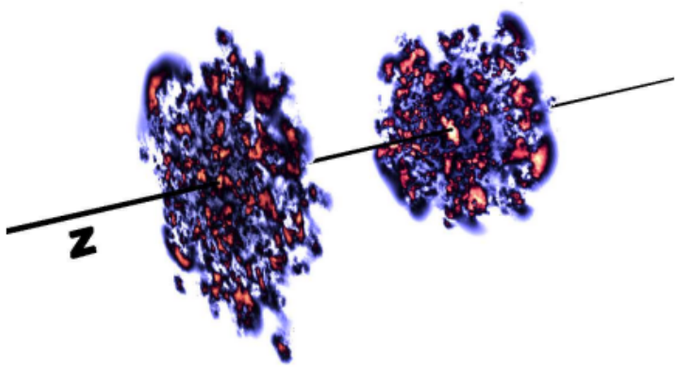
F. Cooper and G. Frye (1974)

Hadronic re-scattering (microscopic transport)



Framework

Bulk dynamics of fireball



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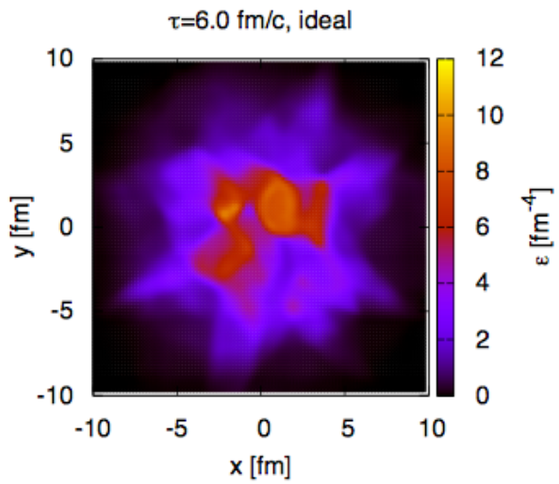

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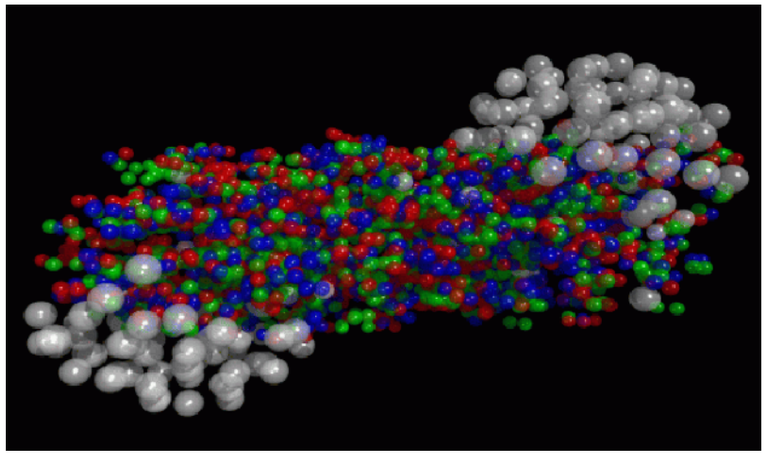


IP-Glasma
pre-thermalization

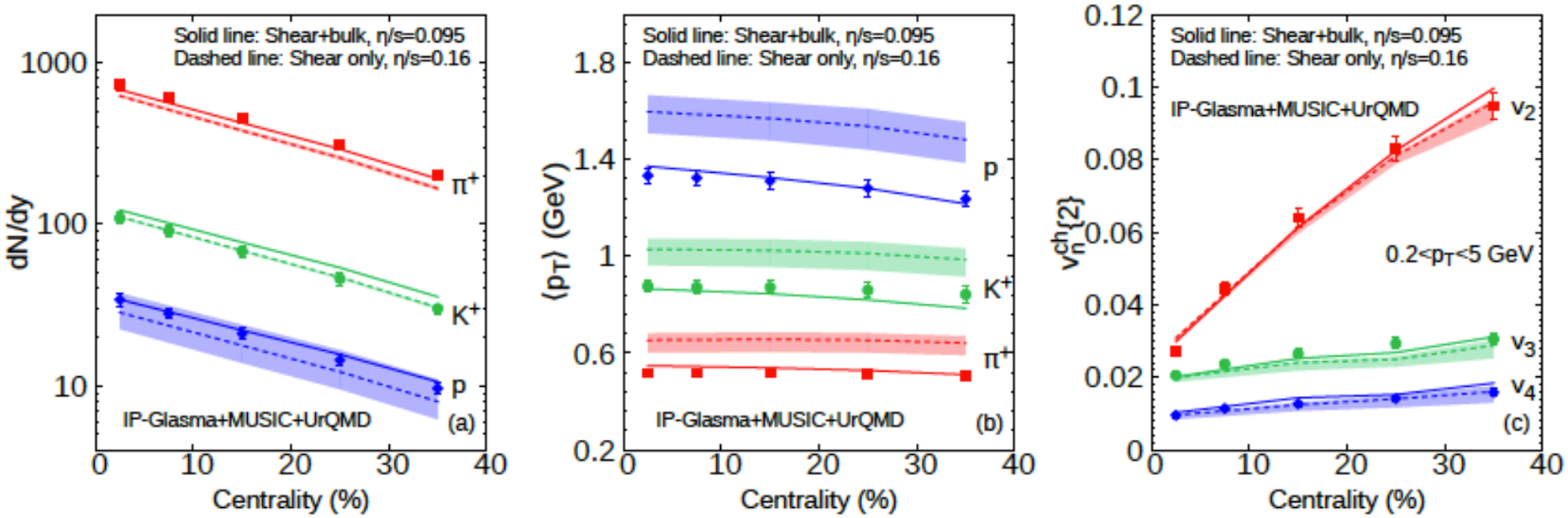
B. Schenke, P. Tribedy and R. Venugopalan (2012)

MUSIC
viscous hydrodynamics

B. Schenke, S. Jeon and C. Gale (2010, 2011)

UrQMD
hadronic rescatterings

S. Bass, *et al*. (1998)
M. Bleicher, *et al*. (1999)



S. Ryu, J-F. Paquet, G. Denicol, C. Shen, B. Schenke, S. Jeon and C. Gale (2015)

Framework

Overview - (mini-)jet energy loss and medium response

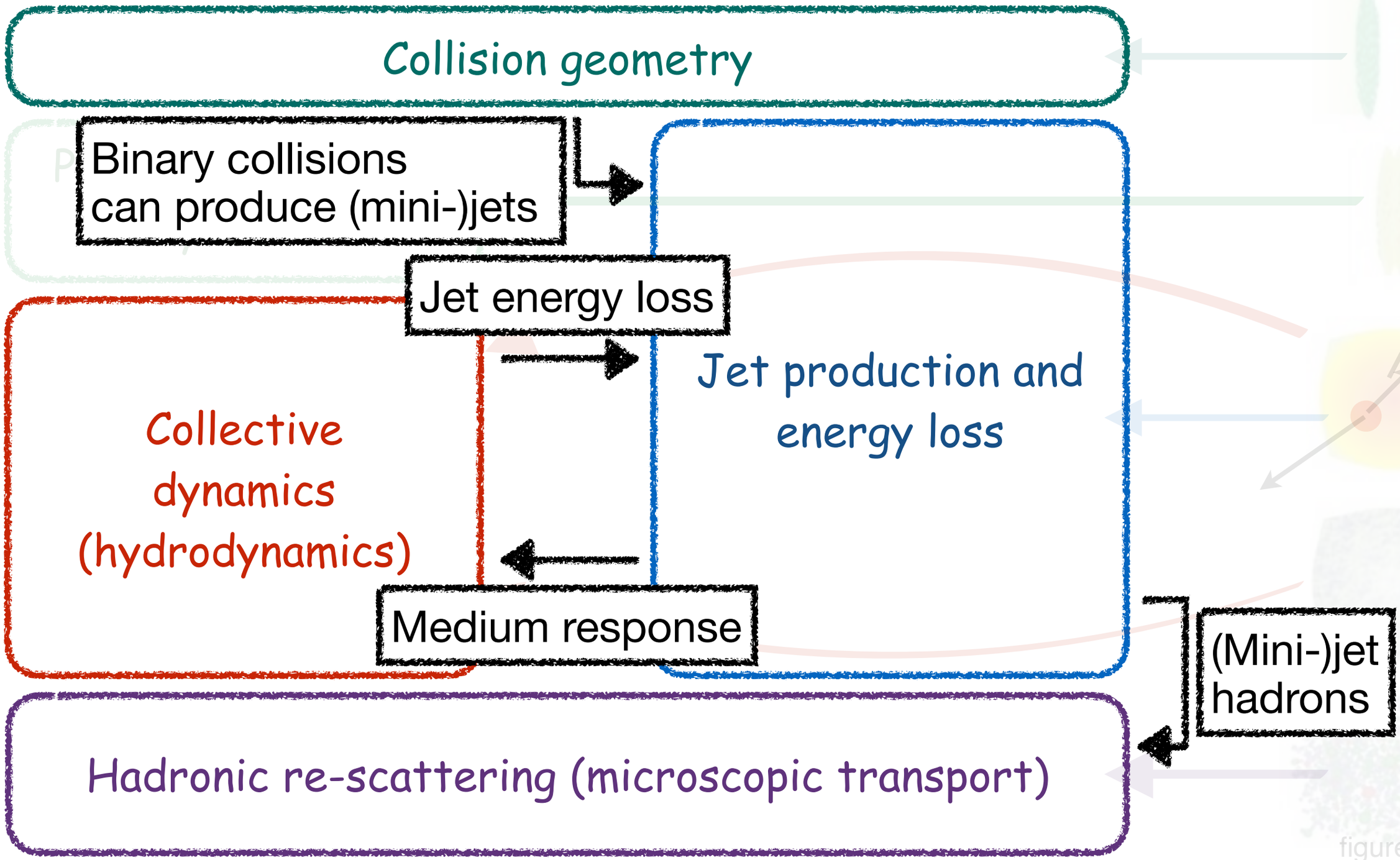


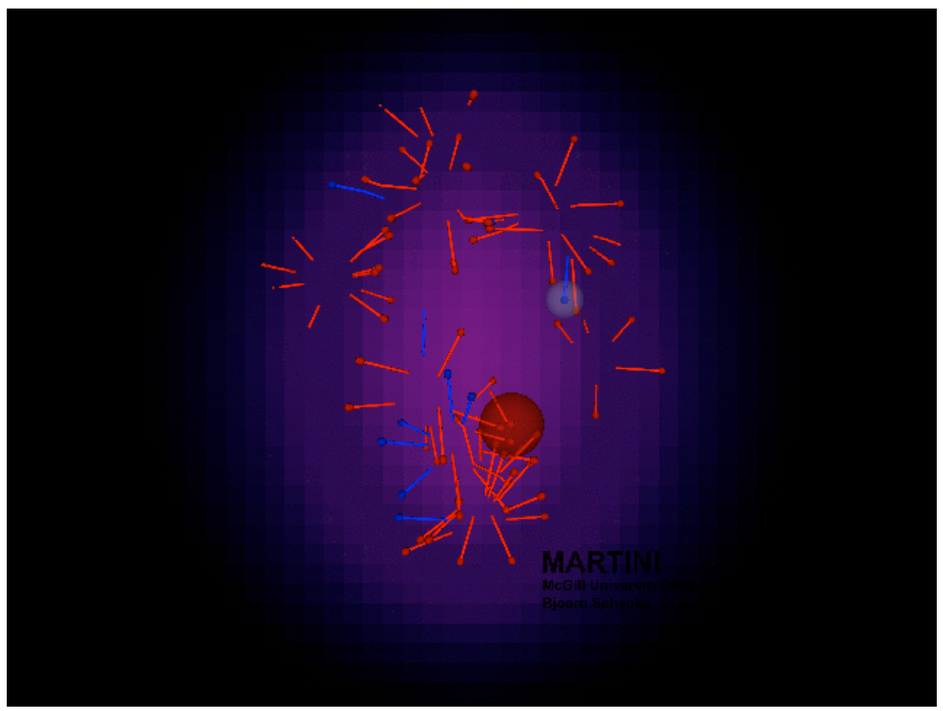
figure by Steffen Bass

Framework

(Mini-)jet energy loss and medium response

MARTINI : Modular Algorithm for Relativistic Treatment of heavy IoN Interaction

B. Schenke, C. Gale and S. Jeon (2010)



Hard process at the position of binary collision (PYTHIA)

↓

Energy loss

- Radiation (AMY)
  P. Arnold, G. Moore and L. Yaffe (2002)
- Collision (with thermal partons)
  B. Schenke, C. Gale and G-Y. Qin (2009)
  G-Y. Qin *et al*. (2008)

↓

Fragmentation into hadrons
(PYTHIA / LUND string model)

Framework

(Mini-)jet energy loss and medium response

MARTINI : Modular Algorithm for Relativistic Treatment of heavy IoN Interaction

B. Schenke, C. Gale and S. Jeon (2010)

Hard process at the position of binary collision (PYTHIA)

T. Sjostrand (1994)

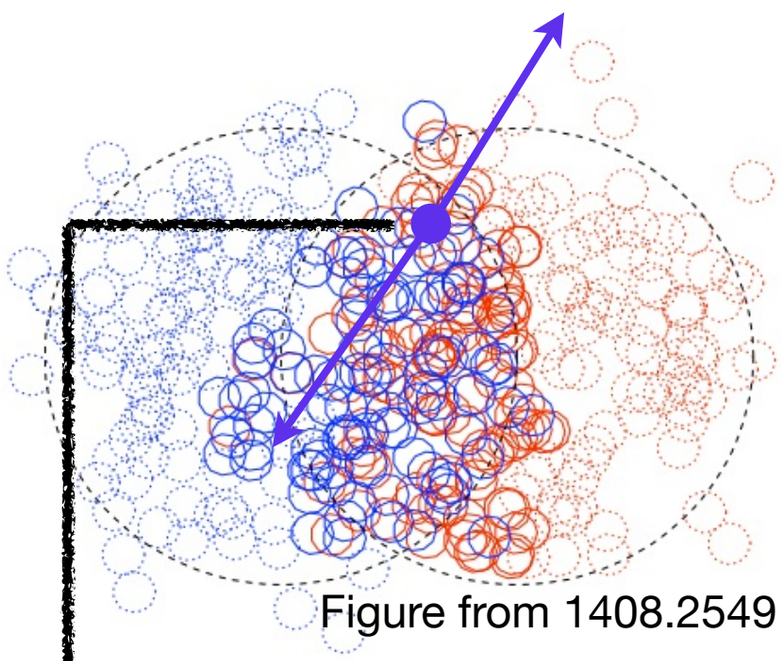


Figure from 1408.2549

Energy loss

- Radiation (AMY)

  P. Arnold, G. Moore and L. Yaffe (2002)

- Collision (with thermal partons)

  B. Schenke, C. Gale and G-Y. Qin (2009)

  G-Y. Qin *et al*. (2008)

Probability to have a hard collision producing (mini-)jets

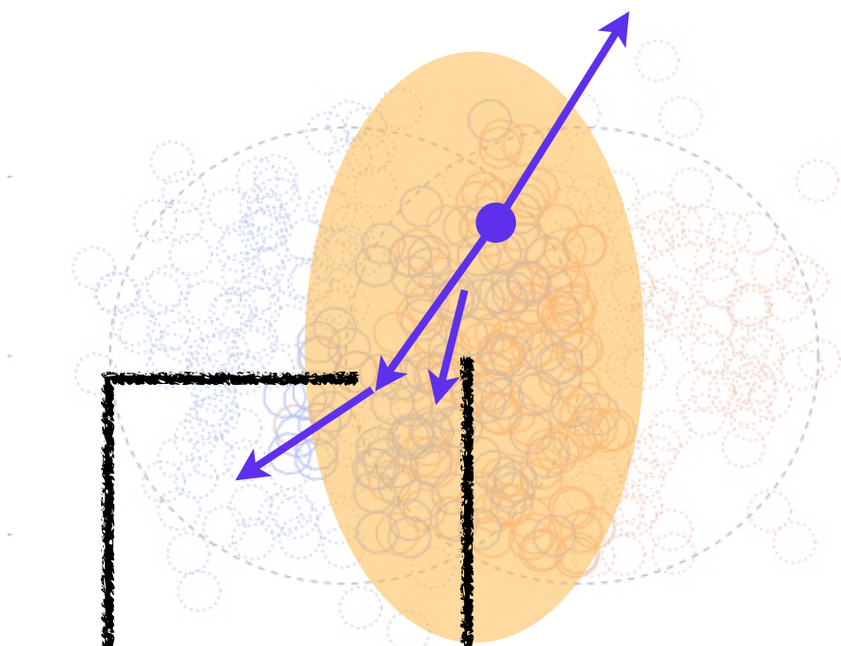
$$P_{\text{hard}} = \frac{1}{\sigma_{\text{inel}}} \sum_{i,j} \int dx_1 f_i(x_1) \int dx_2 f_j(x_2)\, \hat{\sigma}_{i,j}(x_1, x_2; \hat{p}_{T,\text{min}})$$

Framework

(Mini-)jet energy loss and medium response

MARTINI : Modular Algorithm for Relativistic Treatment of heavy IoN Interaction

B. Schenke, C. Gale and S. Jeon (2010)



Hard process at the position of binary collision (PYTHIA)

Energy loss
- Radiation (AMY)
  P. Arnold, G. Moore and L. Yaffe (2002)
- Collision (with thermal partons)
  B. Schenke, C. Gale and G-Y. Qin (2009)
  G-Y. Qin *et al*. (2008)

Two limiting cases for low-energy partons ($p < 4T$)
- free-streaming (weak coupling limit)
- diffusion of energy/momentum (strong coupling limit)

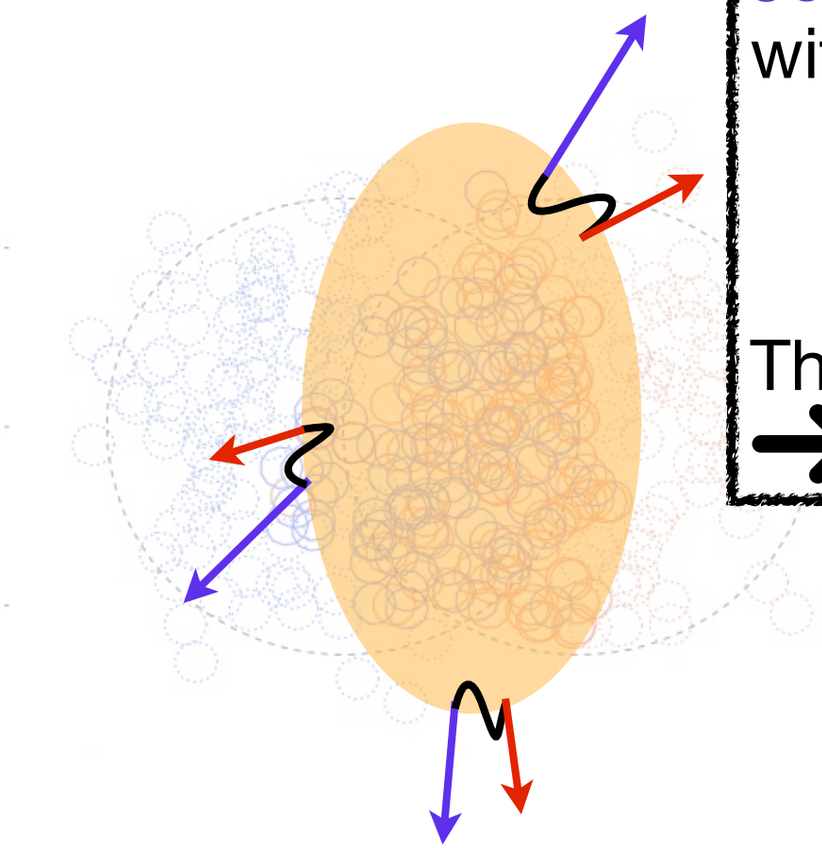
Other feedbacks (from e.g., elastic coll.) go into diffusive sources.

Framework

(Mini-)jet energy loss and medium response

MARTINI : Modular Algorithm for Relativistic Treatment of heavy IoN Interaction

B. Schenke, C. Gale and S. Jeon (2010)



Jet parton + Thermal parton
with probability distribution of string mass

$$\frac{dP}{dm} \propto m \, \exp\left(-\frac{m}{T_{\text{final}}}\right)$$

Thermal parton kicked out of medium
→ negative contribution to the response

- Collision (with thermal partons)

B. Schenke, C. Gale and G-Y. Qin (2009)
G-Y. Qin *et al*. (2008)

Fragmentation into hadrons
(PYTHIA / LUND string model)

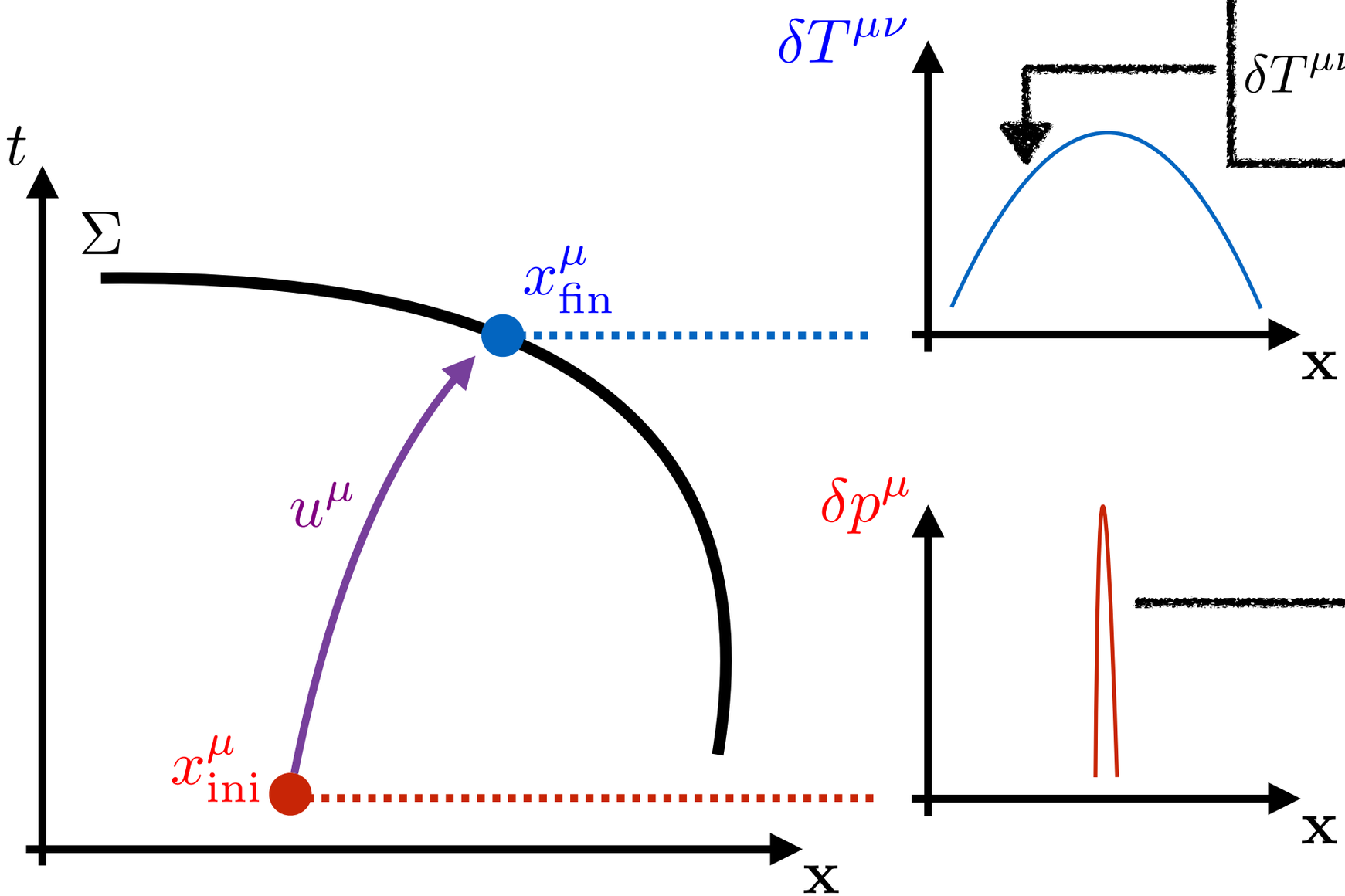
B. Andersson, G. Gustafson,
G. Ingelman and T. Sjostrand (1983)

Framework

(Mini-)jet energy loss and medium response

Medium response : diffusive perturbation to the energy-stress tensor

$$\delta T^{\mu\nu} = \frac{\delta p^\mu \delta p^\nu}{\delta p^0}\, \rho_x(t, \mathbf{x})$$

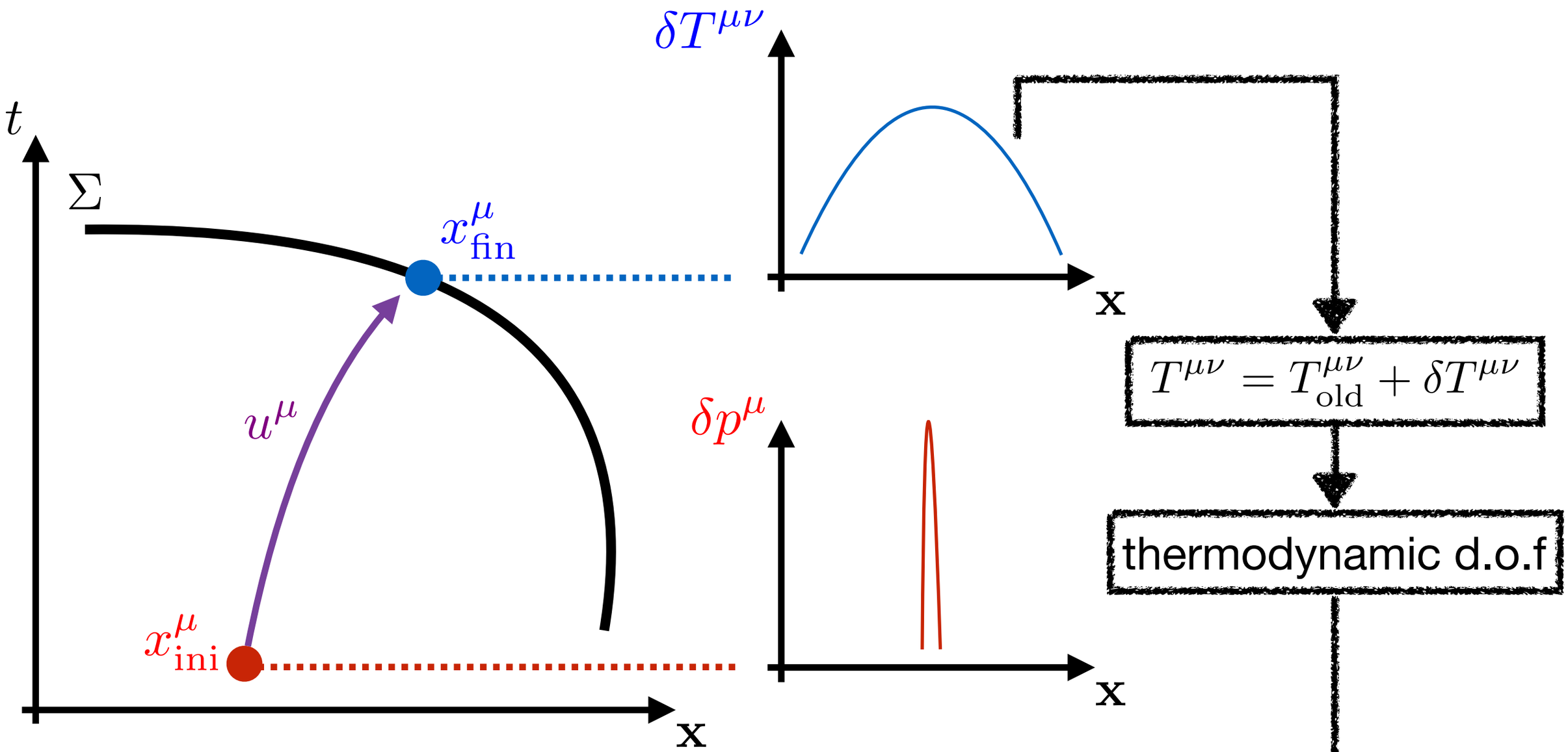


Causal diffusion equation : $\left(\frac{\partial}{\partial t} - D\nabla_x^2 + \tau_D \frac{\partial^2}{\partial t^2}\right) \rho_x(t, \mathbf{x}) = 0$

Framework

(Mini-)jet energy loss and medium response

Medium response : diffusive perturbation to the energy-stress tensor

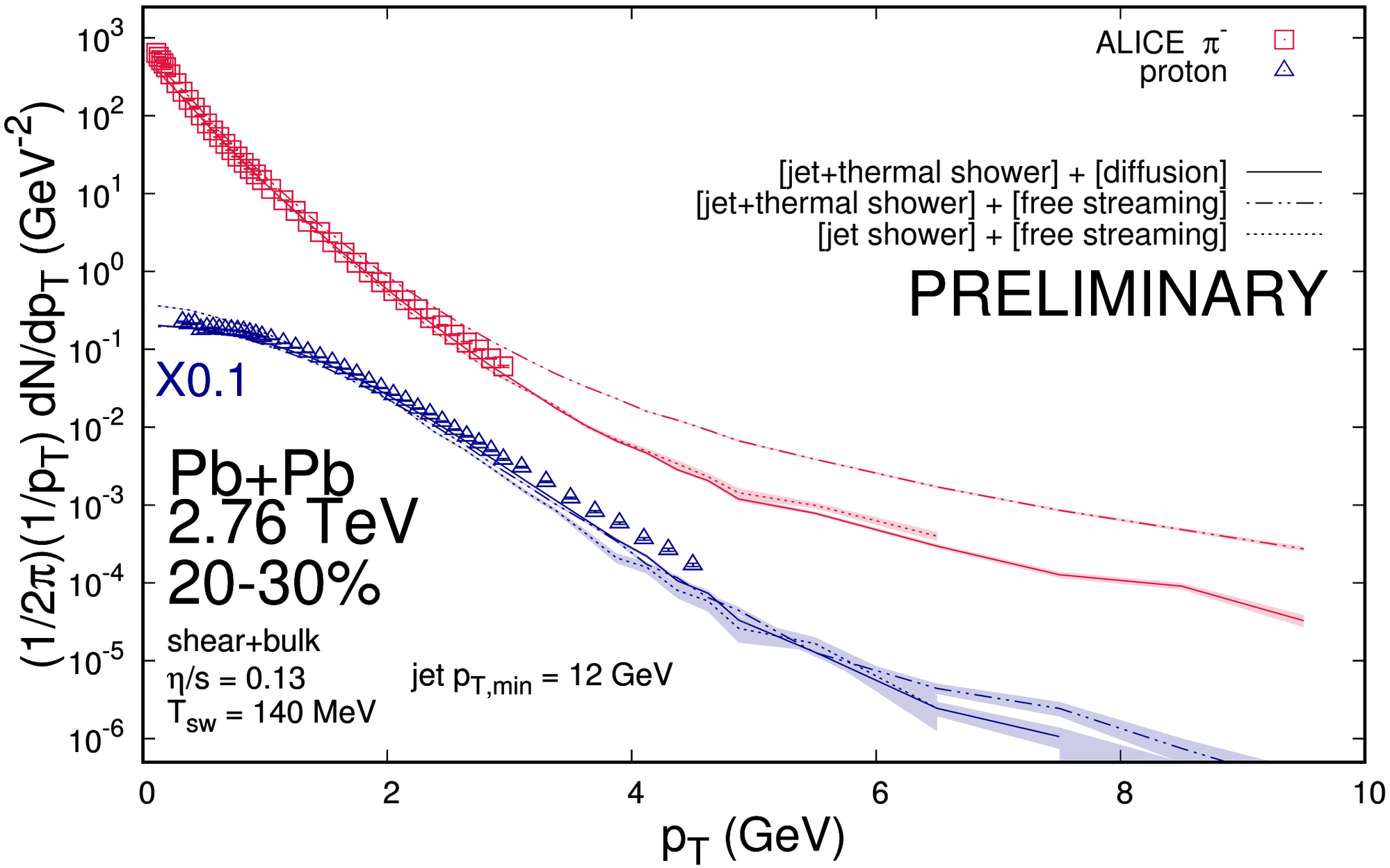


$$E_{\mathbf{p}} \frac{dN}{d^3\mathbf{p}} = \int_\Sigma p^\mu d^3\Sigma_\mu \, f(t, \mathbf{x}, \mathbf{p}\,; T, u^\mu, \pi^{\mu\nu}, \Pi)$$

Results

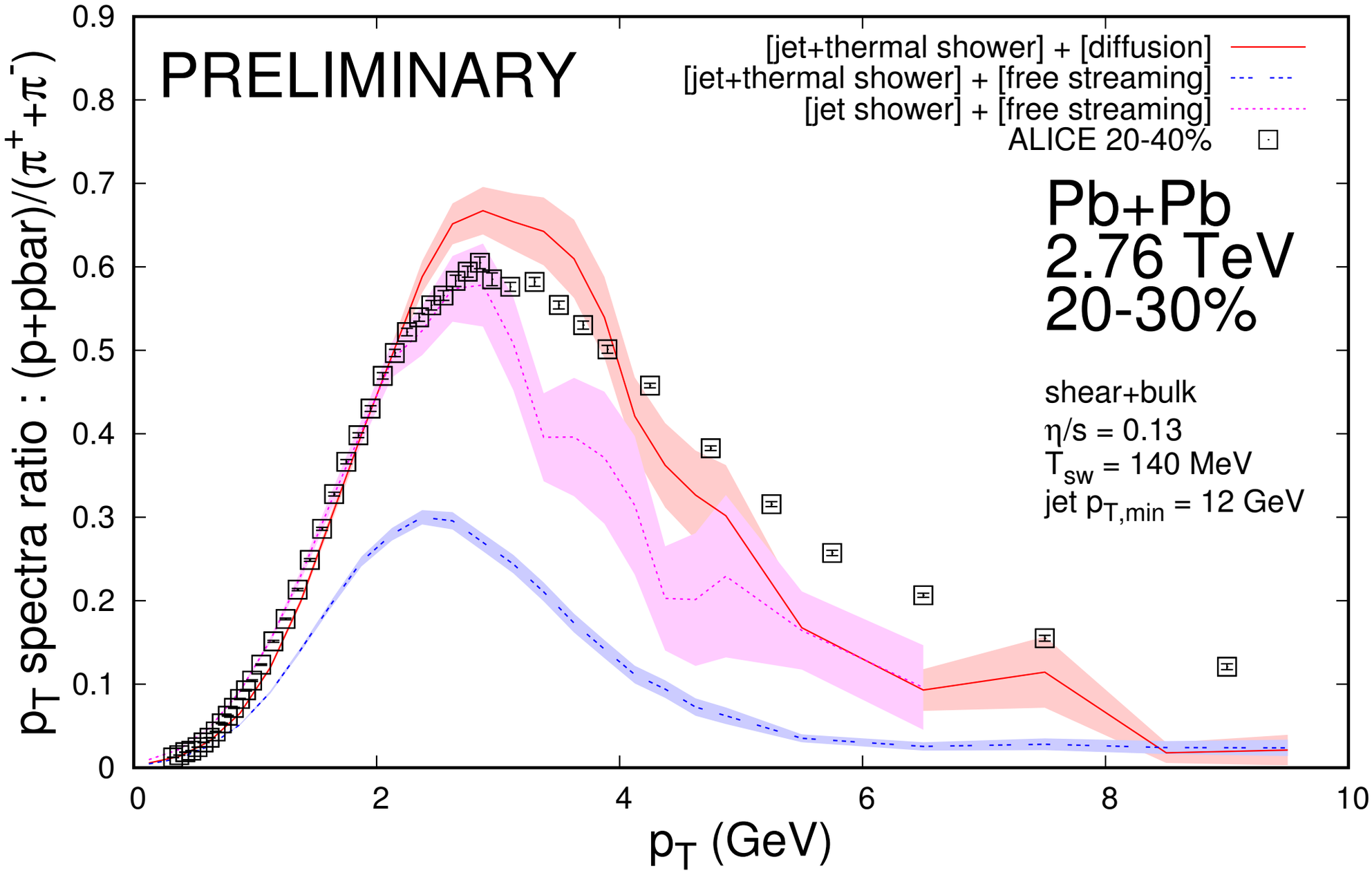
- Radial expansion
- Flow anisotropies

Results
Radial expansion



Kinematics and chemistry of hadrons vary
depending on hadronization and treatment of low-energy partons

Results
Radial expansion



Results
Radial expansion

Jet-thermal shower + diffusion response + hydrodynamics

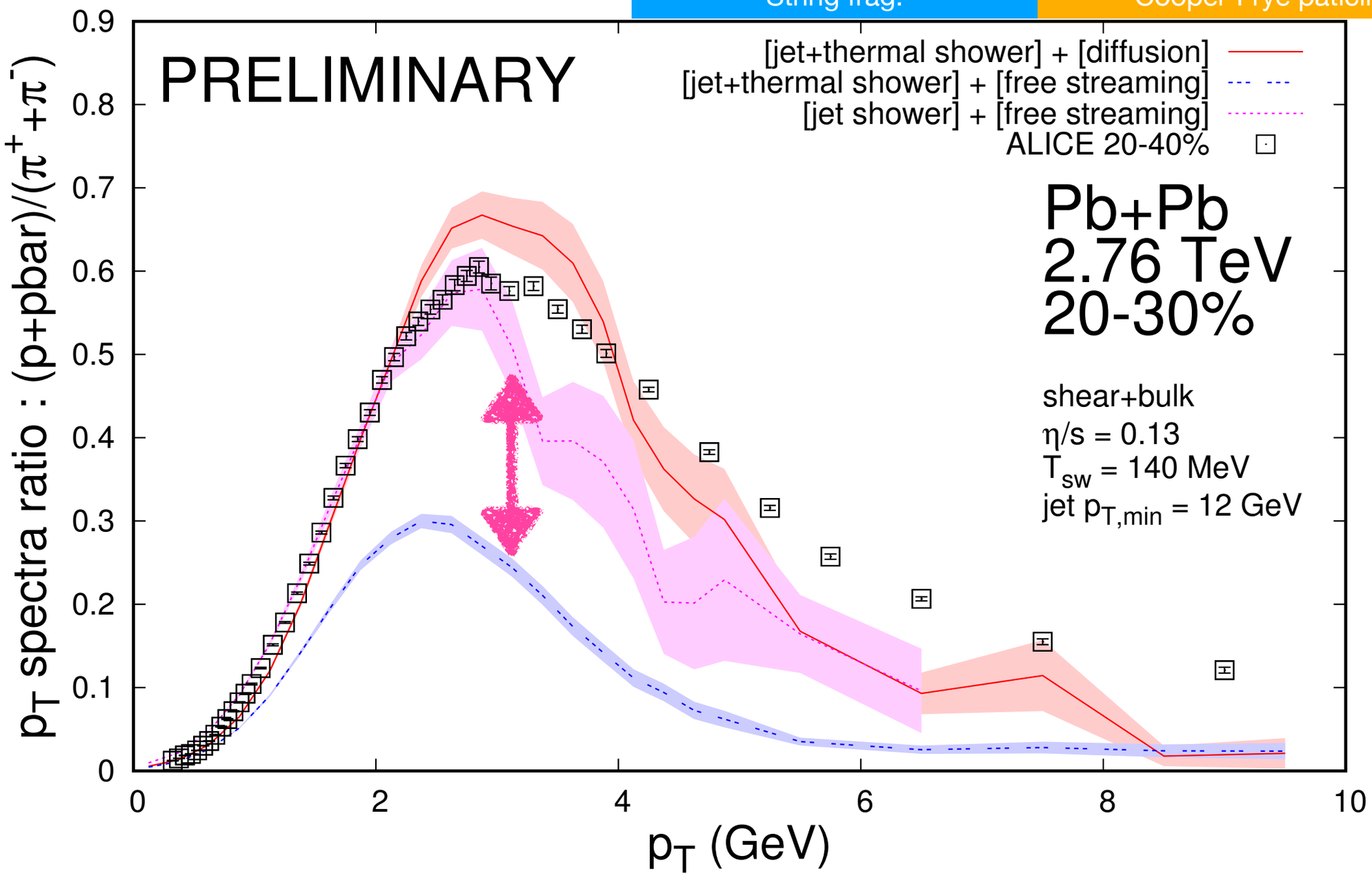
String frag.	Cooper-Frye paticlization

Jet-thermal shower + free-streaming response + hydrodynamics

String frag.	Cooper-Frye paticlization

Jet shower + hydrodynamics

String frag.	Cooper-Frye paticlization



Jet-thermal parton shower at hadronization consumes energy of medium.
- more particle productions from PYTHIA string fragmentation relative to thermal emissions

Results
Radial expansion

Jet-thermal shower + diffusion response + hydrodynamics

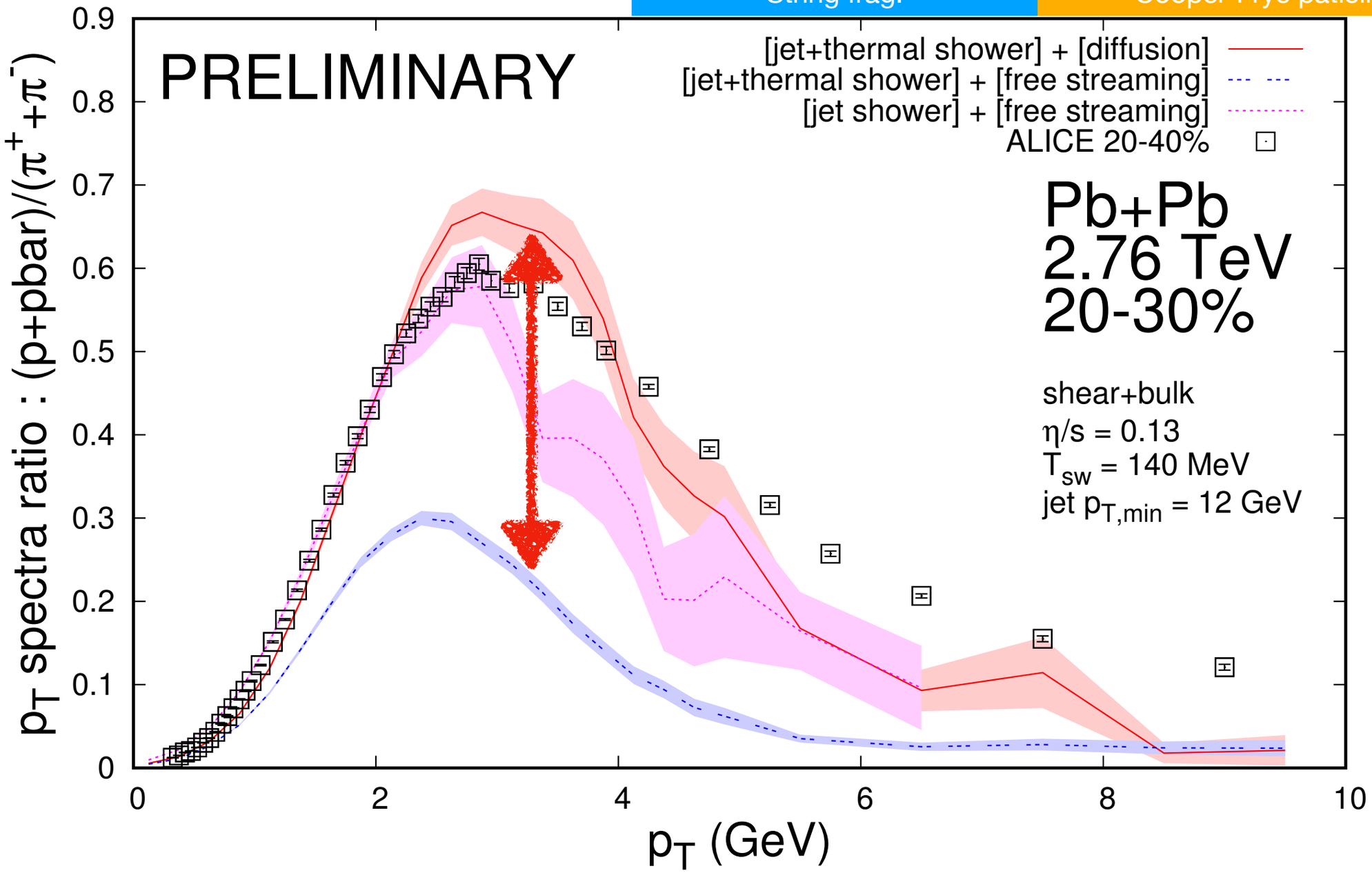
String frag.	Cooper-Frye paticlization

Jet-thermal shower + free-streaming response + hydrodynamics

String frag.	Cooper-Frye paticlization

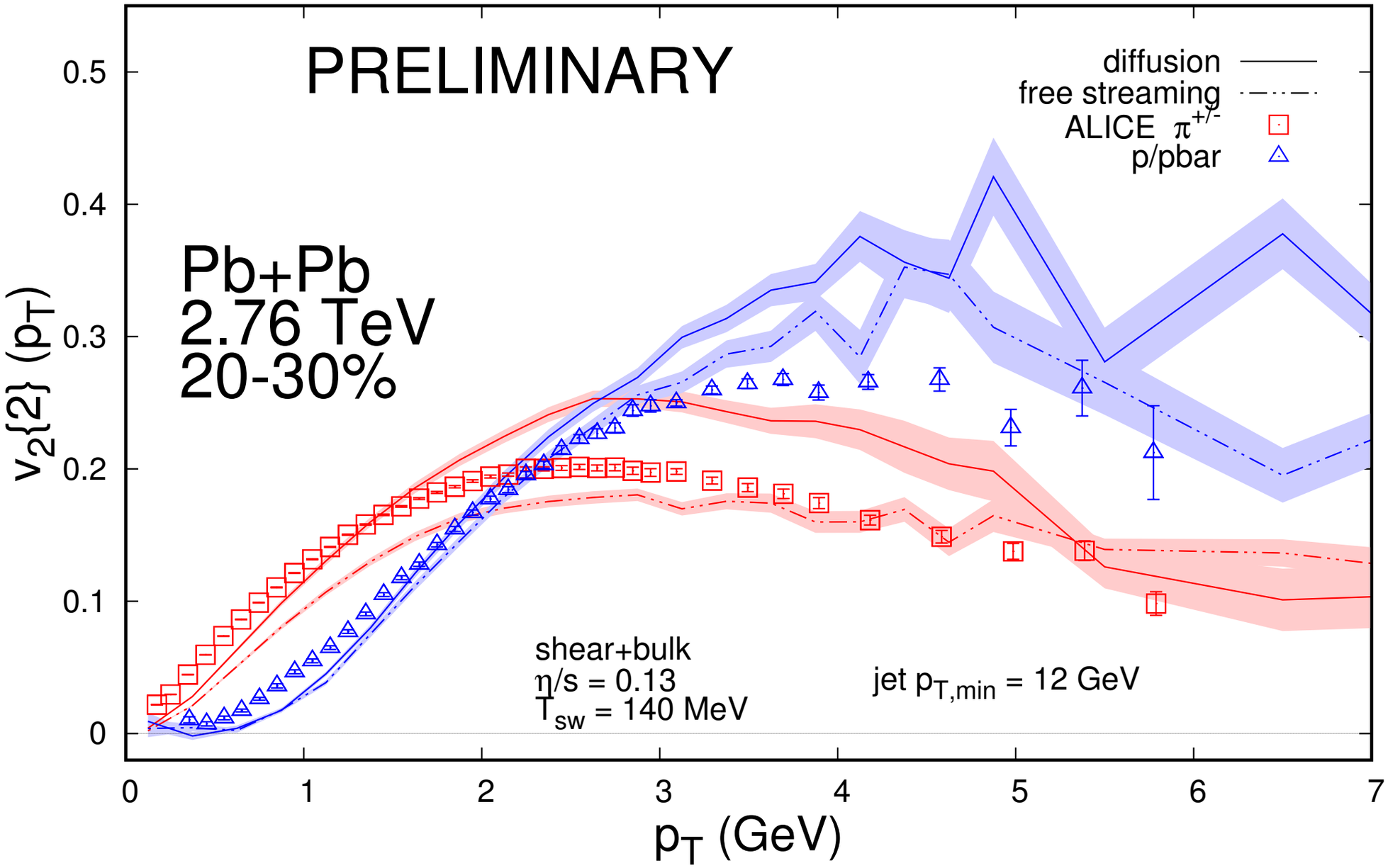
Jet shower + hydrodynamics

String frag.	Cooper-Frye paticlization

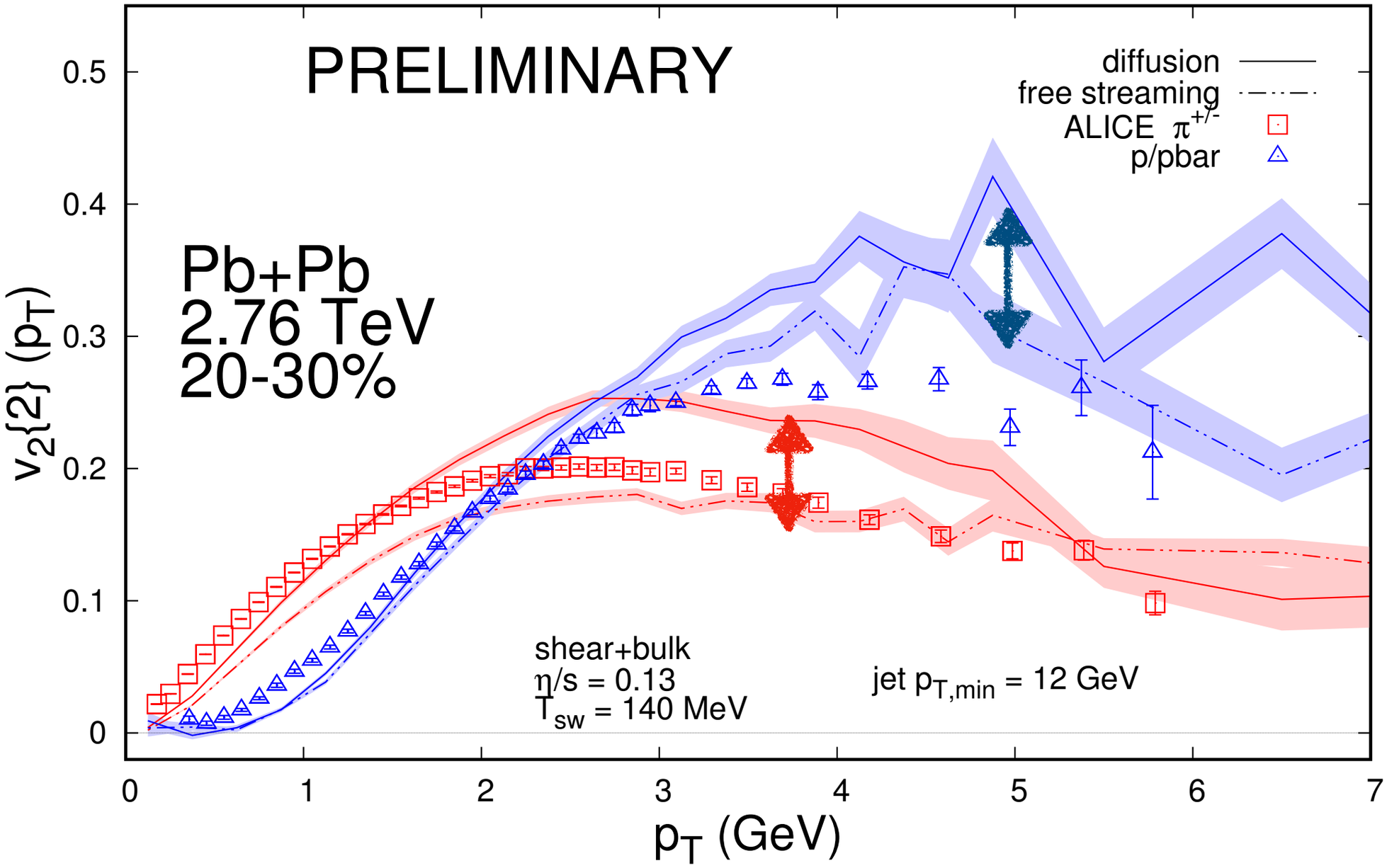


The strongly-coupled diffusion description of low-energy jet partons with Cooper-Frye particliazation improves the p/π ratio compared to those from the string fragmentation.

Results
Flow anisotropies

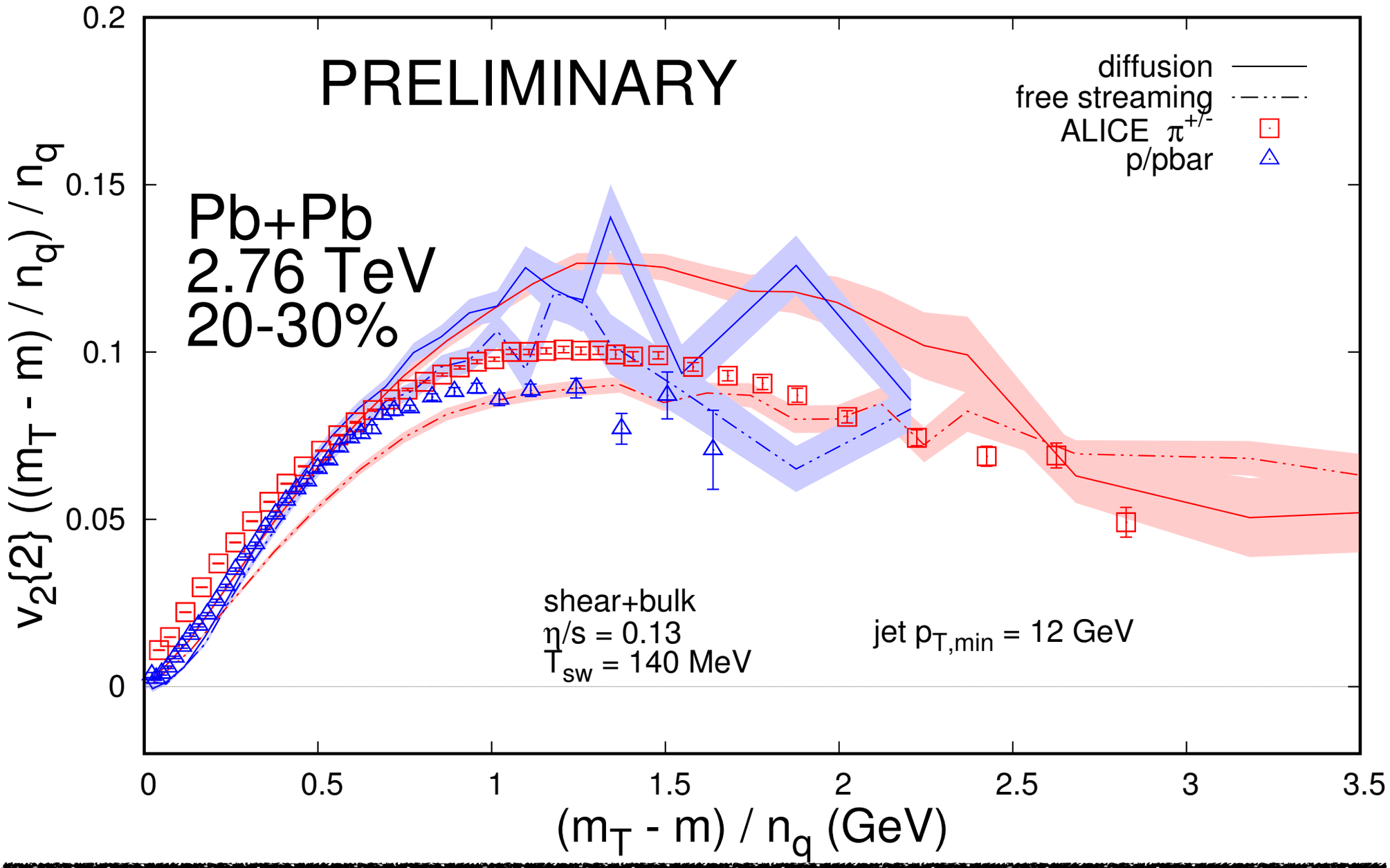


Results
Flow anisotropies



Free-streaming (mini-)jets are more isotropic.
- more (mini-)jet contributions decreases flow anisotropy.

Results
Flow anisotropies



Quark number scaling is broken in different way.
- Thermal parton shower in hadronization changes kinematics.

Conclusions and Outlook

- We present a comprehensive hybrid approach to study the interplay between QCD mini-jets and bulk medium
  - Mini-jet production, energy-loss, and medium response
  - Event-by-event hydrodynamics + hadronic transport approach
  - Study measurements for $0 < p_T < 10\,\mathrm{GeV}$ in a unified framework

- Hadron chemistry and anisotropic flow at the intermediate p_T region can unravel
  - In medium hadronization
  - Hydrodynamic response from low-energy jet partons

- Future systematic studies will help to elucidate the microscopic to macroscopic properties of the QGP.
  - Hydrodynamization of energy-momentum currents from mini-jets
  - Independent constraints on the QGP viscosity and charge diffusion

Backup Slides

Framework

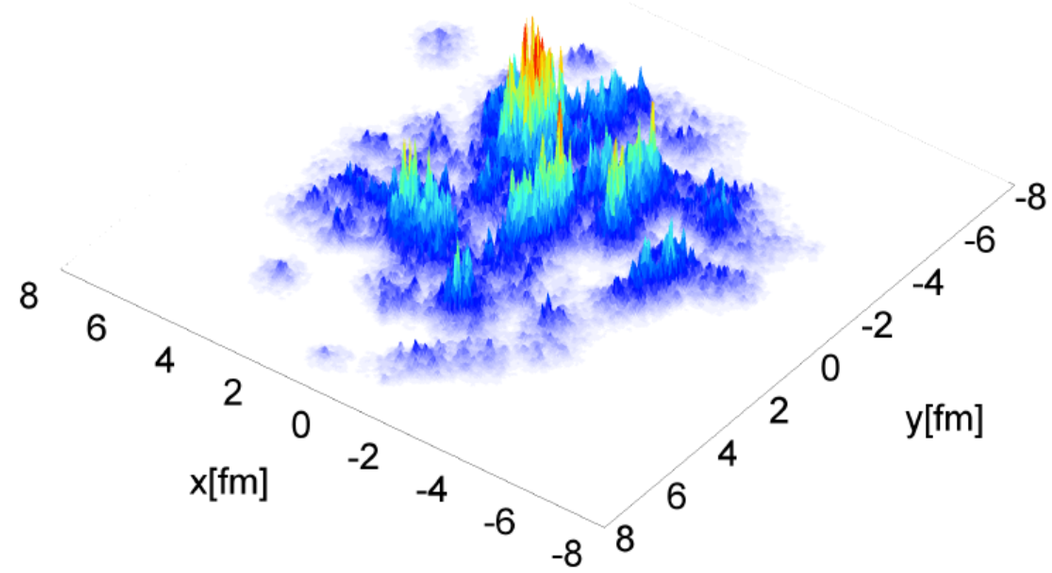
IP-Glasma pre-thermalization dynamics

B. Schenke, P. Tribedy and R. Venugopalan (2012)

Classical YM dynamics with color sources in nuclei

color charge distribution

$$\langle \rho^a(\mathbf{x}'_T)\, \rho^a(\mathbf{x}''_T)\rangle$$
$$= g^2 \mu_A^2 \delta^{ab} \delta^2(\mathbf{x}'_T - \mathbf{x}''_T)$$



▼ gluon field from each nucleus

$$A^i_{(1,2)}(\mathbf{x}_T)$$
$$= \frac{i}{g} U_{(1,2)}(\mathbf{x}_T)\, \partial_i U^\dagger_{(1,2)}(\mathbf{x}_T)$$
$$U_{(1,2)}(\mathbf{x}_T) = \mathcal{P} \exp\left[-ig \int dx^\pm \frac{\rho_{(1,2)}(\mathbf{x}_T, x^\pm)}{\nabla_T^2 - m^2} \right]$$

▼ initial gluon field after collision

$$A^i(\tau = +0) = A^i_{(1)} + A^i_{(2)}$$
$$A^\eta(\tau = +0) = \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}]$$

▶ energy density profile at $\tau = \tau_0$

$$\partial_\mu F^{\mu\nu} - ig[A_\mu, F^{\mu\nu}] = 0$$
$$T^\mu{}_\nu(\tau = \tau_0) u^\nu = \epsilon\, u^\mu$$

Framework

MUSIC viscous hydrodynamics B. Schenke, S. Jeon, and C. Gale (2010)

hydrodynamic equations of motion

Conservation equation $\partial_\mu T^{\mu\nu} = 0$

Decomposition $$T^{\mu\nu} = \epsilon_0 u^\mu u^\nu - \left(P_0(\epsilon_0) + \Pi\right)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

bulk

shear

EoS

hotQCD lattice + HRG

Framework

MUSIC viscous hydrodynamics B. Schenke, S. Jeon, and C. Gale (2010)

equation of motion for viscous corrections
(response of the system to spatial gradient)

shear viscosity relaxation equation

$$\dot{\pi}^{\langle\mu\nu\rangle} = -\frac{\pi^{\mu\nu}}{\tau_\pi} + \frac{1}{\tau_\pi}\Big(2\eta\,\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\,\sigma^{\mu\nu}\Big)$$

bulk viscosity relaxation equation

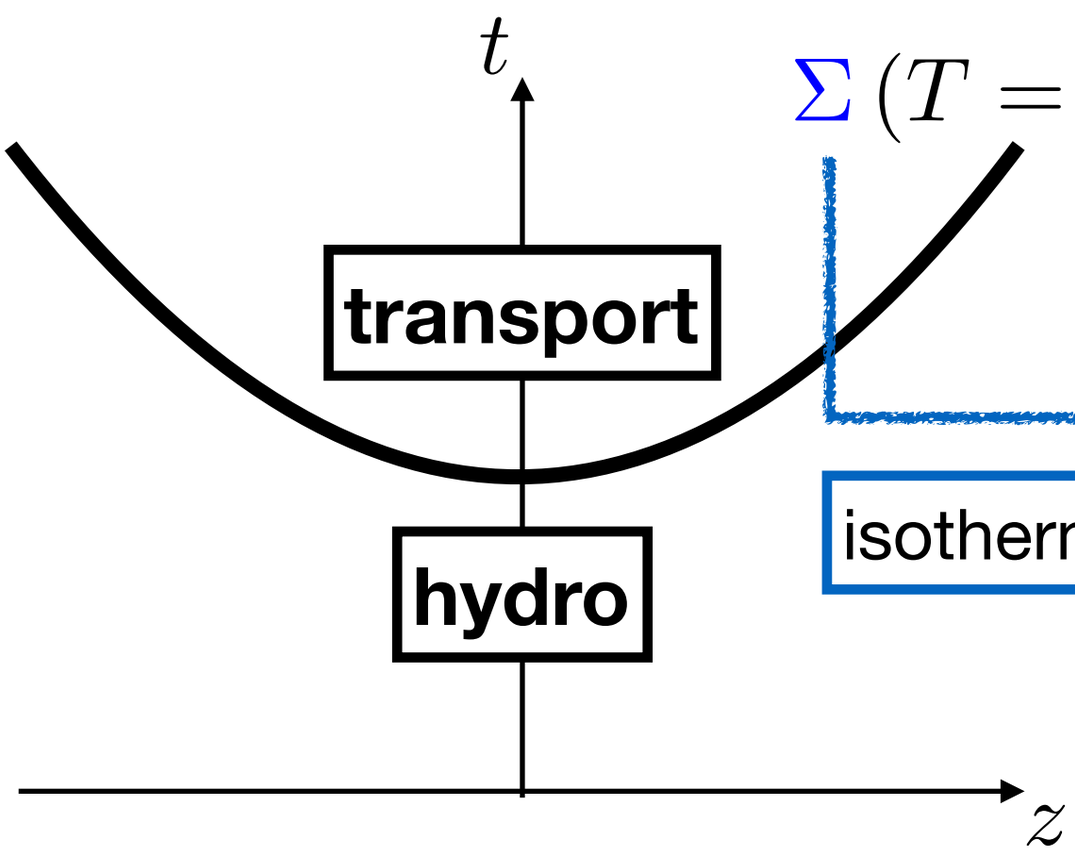
$$\dot{\Pi} = -\frac{\Pi}{\tau_\Pi} + \frac{1}{\tau_\Pi}\left(-\zeta\,\theta - \delta_{\Pi\Pi}\Pi\,\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}\right)$$

G. Denicol, S. Jeon, and C. Gale (2014)

Framework

Cooper-Frye particlization F. Cooper and G. Frye (1974)

sampling particles according to the Cooper-Frye formula
(transform hydrodynamic information into particles)



$\Sigma\,(T = T_{\rm sw})$

$$\frac{dN}{d^3\mathbf{p}} = \int_{\Sigma} \frac{p^\mu d^3\Sigma_\mu}{E_{\mathbf{p}}} f(x, \mathbf{p})$$

isothermal hypersurface

hydrodynamic information
(temperature, flow velocity, …)

Framework

Cooper-Frye particlization F. Cooper and G. Frye (1974)

sampling particles according to the Cooper-Frye formula
(transform hydrodynamic information into particles)

$$\left.\frac{dN}{d^3\mathbf{p}}\right|_{\text{1-cell}} = \left[f_0(x,\mathbf{p}) + \delta f_{\text{shear}}(x,\mathbf{p}) + \delta f_{\text{bulk}}(x,\mathbf{p})\right] \frac{p^\mu \Delta^3 \Sigma_\mu}{E_{\mathbf{p}}}$$

$$f_0(x,\mathbf{p}) = \frac{1}{\exp\left[(p\cdot u)/T\right] \mp 1}$$

$$\delta f_{\text{shear}}(x,\mathbf{p}) = f_0(1 \pm f_0)\frac{p^\mu p^\nu \pi^{\mu\nu}}{2T^2(\epsilon_0 + P_0)}$$

P. Bozek (2010)

$$\delta f_{\text{bulk}}(x,\mathbf{p}) = -f_0(1 \pm f_0)\frac{C_{\text{bulk}}\Pi}{T}\left[c_s^2(p\cdot u) - \frac{(-p^\mu p^\nu \Delta_{\mu\nu})}{3(p\cdot u)}\right]$$

$$\frac{1}{C_{\text{bulk}}} = \frac{1}{3T}\sum_n m_n^2 \int \frac{d^3\mathbf{k}}{(2\pi)^3 E_{\mathbf{k}}} f_{n,0}(1 \pm f_{n,0})\left(c_s^2 E_{\mathbf{k}} - \frac{|\mathbf{k}|^2}{3E_{\mathbf{k}}}\right)$$

Framework

Cooper-Frye particlization F. Cooper and G. Frye (1974)

sampling particles according to the Cooper-Frye formula
(transform hydrodynamic information into particles)

1. sample number of particles based on Poisson distribution

$$\bar{N}|_{\text{1-cell}} = \begin{cases} [n_0(x) + \delta n_{\text{bulk}}(x)]\, u^\mu \Delta\Sigma_\mu & \text{if} \quad u^\mu \Delta\Sigma_\mu \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

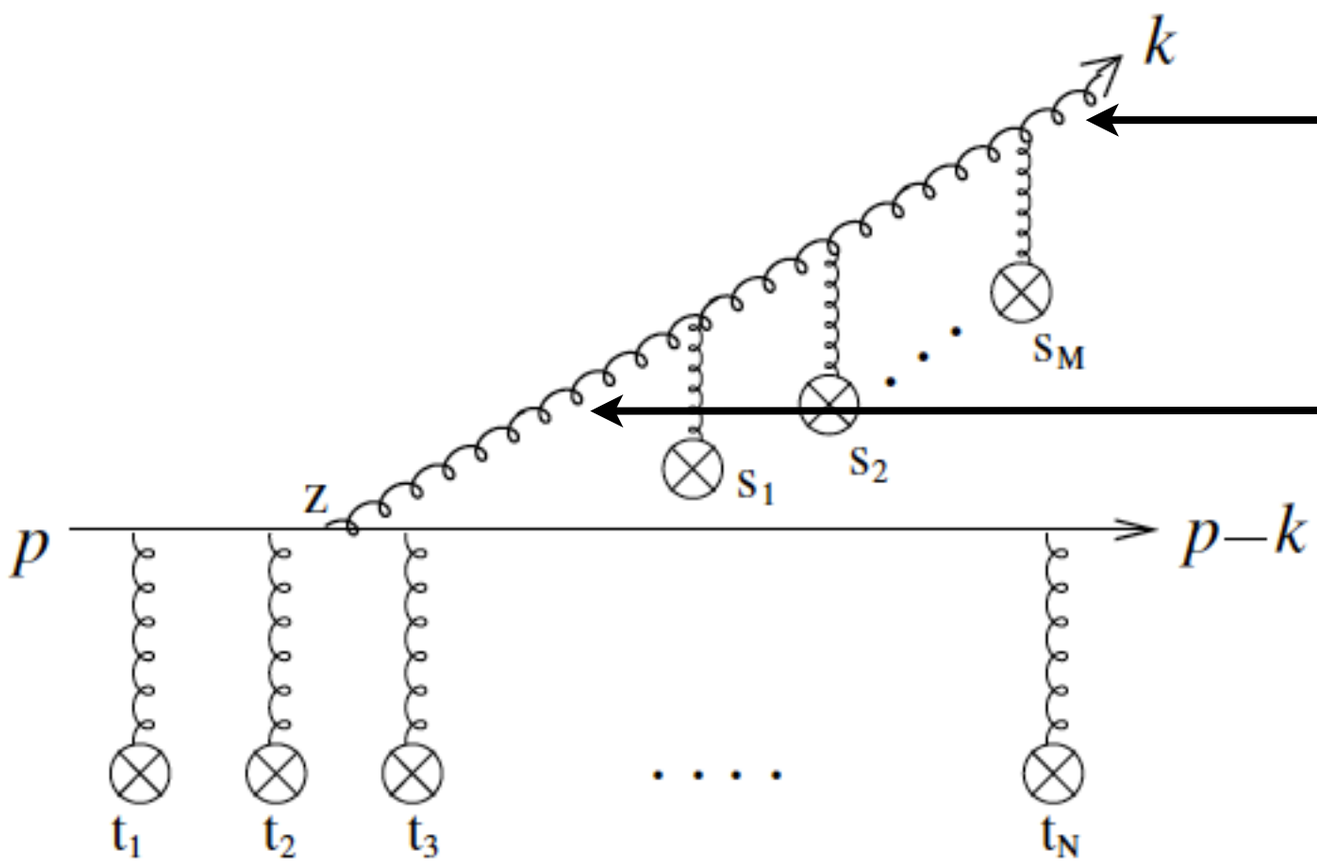
$$n_0(x) = d \int \frac{d^3\mathbf{k}}{(2\pi)^3} f_0(\mathbf{k})$$

$$\delta n_{\text{bulk}}(x) = d \int \frac{d^3\mathbf{k}}{(2\pi)^3} \delta f_{\text{bulk}}(\mathbf{k})$$

2. sample momentum of each particles
according to the Cooper-Frye formula shown in the main slide

Framework

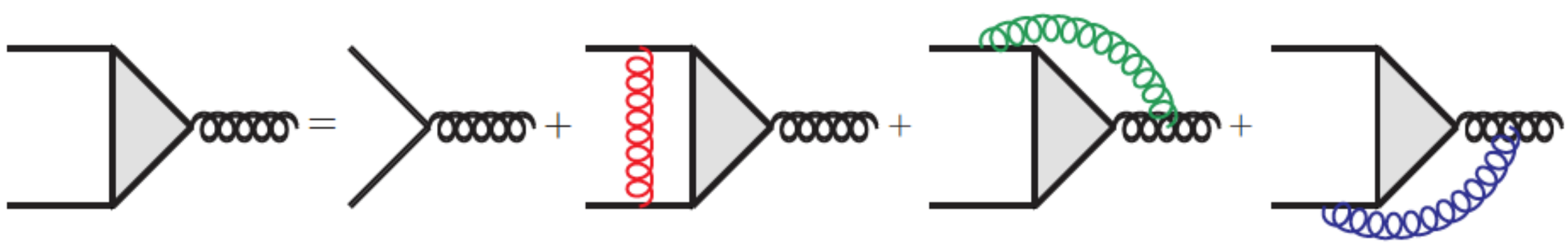
Radiative energy loss (AMY) P. Arnold, G. Moore and L. Yaffe (2002)



Collinear emission

Nearly on-shell intermediate propagator

Infinite number of diagrams
➤ Integral equations

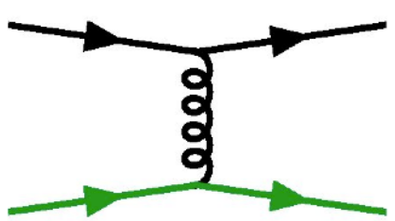


figures by G-Y. Qin

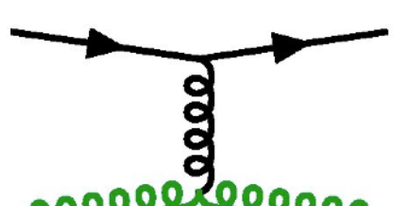
Framework

Collisional energy loss

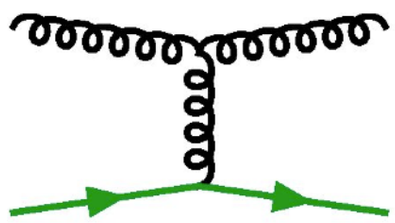
B. Schenke, C. Gale and G-Y. Qin (2009) ; G-Y. Qin *et al*. (2008)



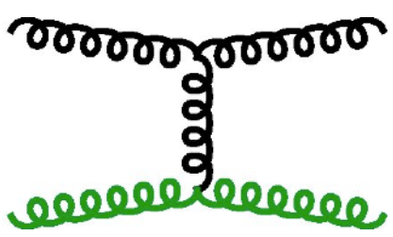
$$\left.\frac{dE}{dt}\right|_{qq} = \frac{2}{9} n_f \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_f \frac{23}{12} + c_s\right]$$



$$\left.\frac{dE}{dt}\right|_{qg} = \frac{4}{3} \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_b \frac{13}{6} + c_s\right]$$



$$\left.\frac{dE}{dt}\right|_{gq} = \frac{1}{2} n_f \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_f \frac{13}{6} + c_s\right]$$

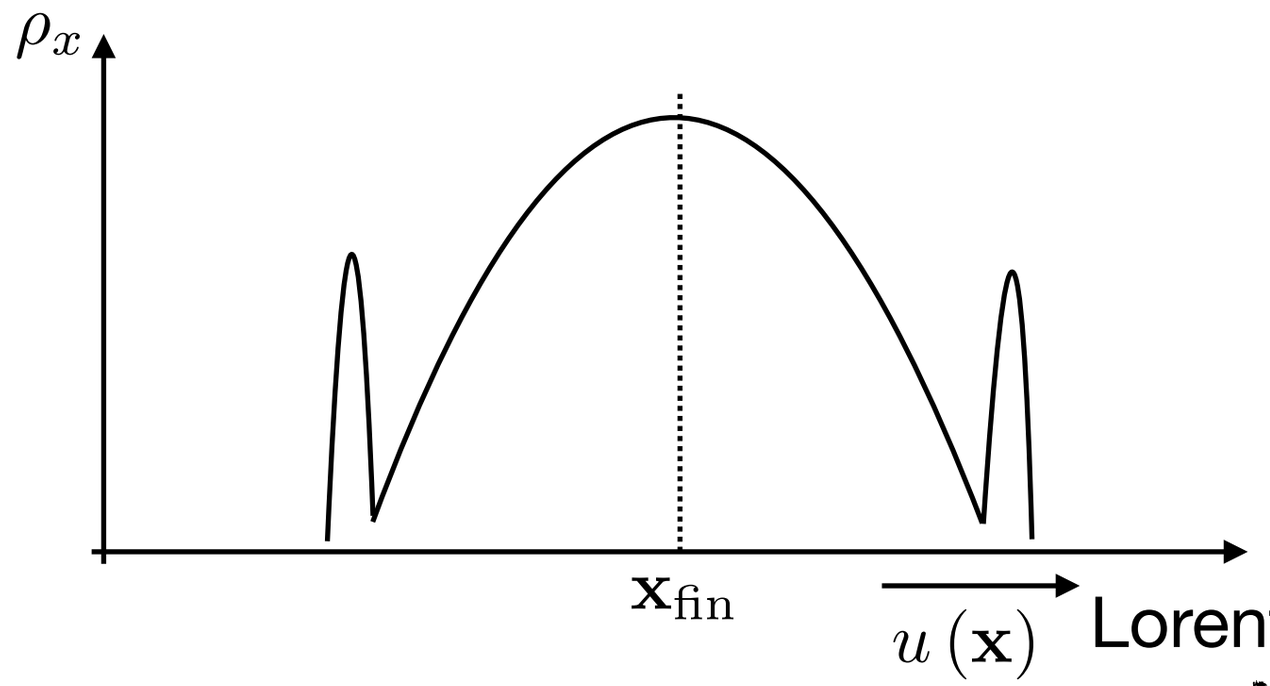


$$\left.\frac{dE}{dt}\right|_{gg} = 3 \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_b \frac{131}{48} + c_s\right]$$

Framework

(Mini-)jet energy loss and medium response

Medium response : diffusive perturbation to the energy-stress tensor



Lorentz contraction

$$\delta T^{\mu\nu}_{i,\hat{j}} = \rho_x(s_{{\rm fin},\hat{j}} + \delta x^{\alpha}_{i\hat{j}}\, u_\alpha(x_{{\rm fin},\hat{j}}), \delta\mathbf{x}_{i\hat{j}})\, u^\beta(x_i)\, u_\beta(x_{{\rm fin},\hat{j}}) \times \left[\frac{q^\mu_{\hat{j}} q^\nu_{\hat{j}}}{q^0_{\hat{j}}} + Q_{\hat{j}}\left(u^\mu u^\nu(x_i) - \frac{P_{\rm sw}}{\epsilon_{\rm sw}}\Delta^{\mu\nu}(x_i)\right)\right]$$

energy conservation $q^0_{\hat{j}} = \int_\Sigma d^3\Sigma_\nu \delta T^{0\nu}_{\hat{j}} \quad \rightarrow \quad \sum_i (\Delta^3\Sigma_i)_\nu \delta T^{0\nu}_{i,\hat{j}}$

Framework

(Mini-)jet energy loss and medium response

Medium response : diffusive perturbation to the energy-stress tensor

$$
\begin{aligned}
T^{\mu\nu} &= \epsilon_{\rm old} u^\mu_{\rm old} u^\nu_{\rm old} - (P_{\rm old} + \Pi_{\rm old})(g^{\mu\nu} - u^\mu_{\rm old} u^\nu_{\rm old}) + \pi^{\mu\nu}_{\rm old} + \delta T^{\mu\nu} \\
&= \epsilon\, u^\mu u^\nu - (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu} + (1-a)\,\delta T^{\mu\nu}
\end{aligned}
$$

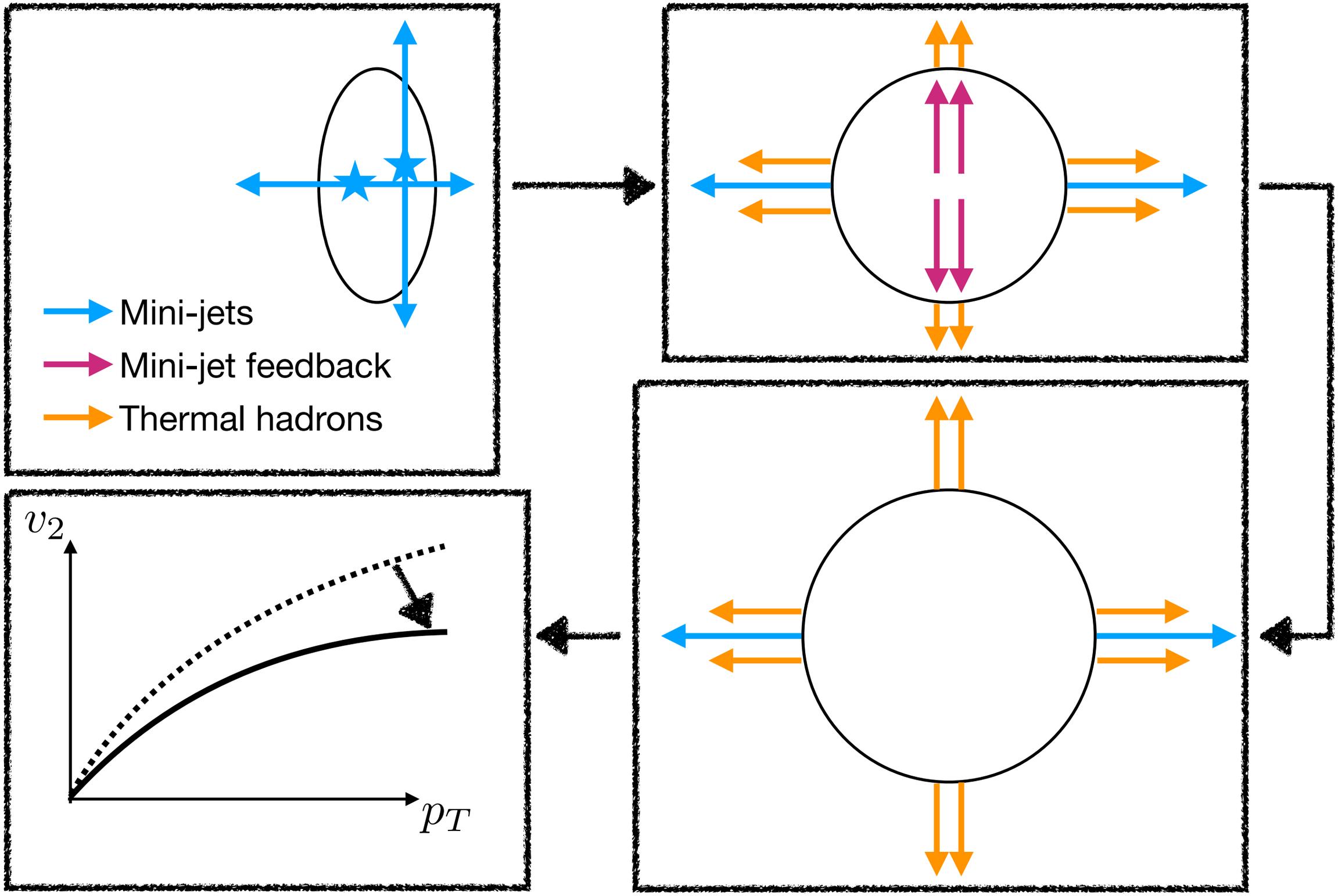
Cooper-Frye particlization sampling
with new hydrodynamic d.o.f $(\epsilon,\, P,\, u^\mu,\, \pi^{\mu\nu},\, \Pi)$

momentum of a thermal hadron : $p^i + b\,(1-a)\,\delta T^{i\nu} \Delta^3 \Sigma_\nu$

determined by requiring energy conservation

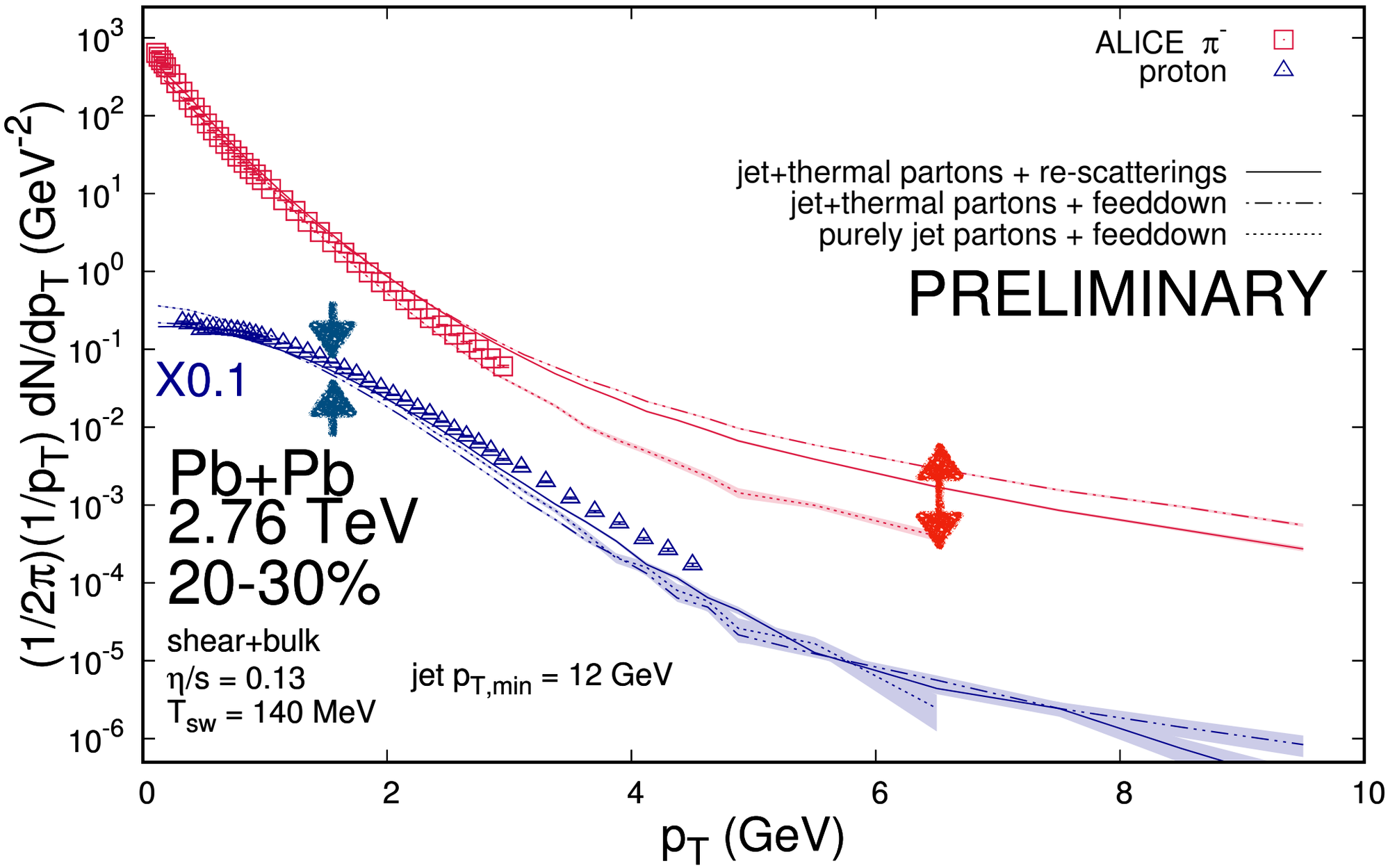
Results

What if we have medium response to (mini-)jet feedback?



Results

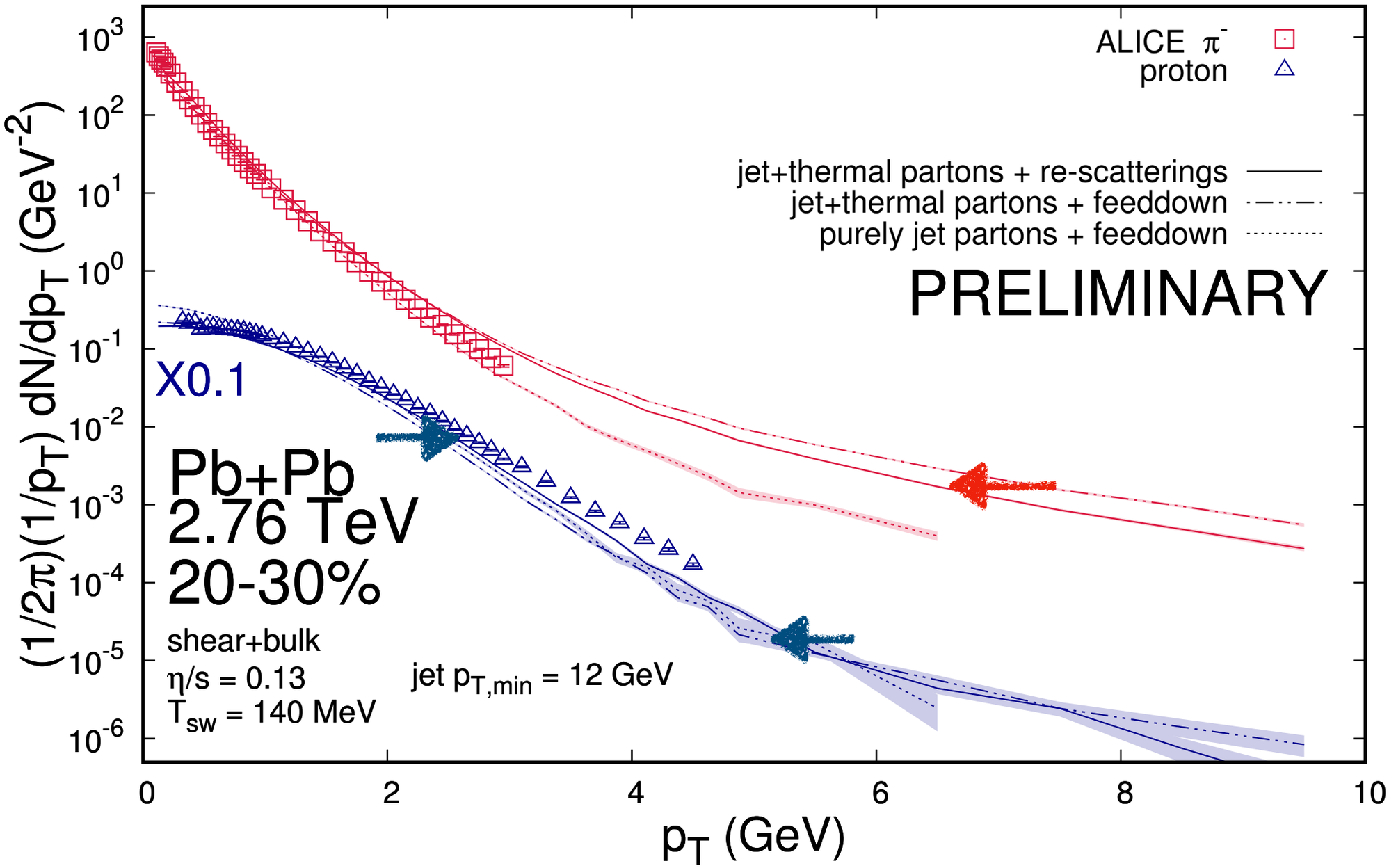
Radial expansion : hadronization and onward re-scatterings



Contributions from thermal partons increase mini-jet production but decreases thermal contribution.

Results

Radial expansion : hadronization and onward re-scatterings

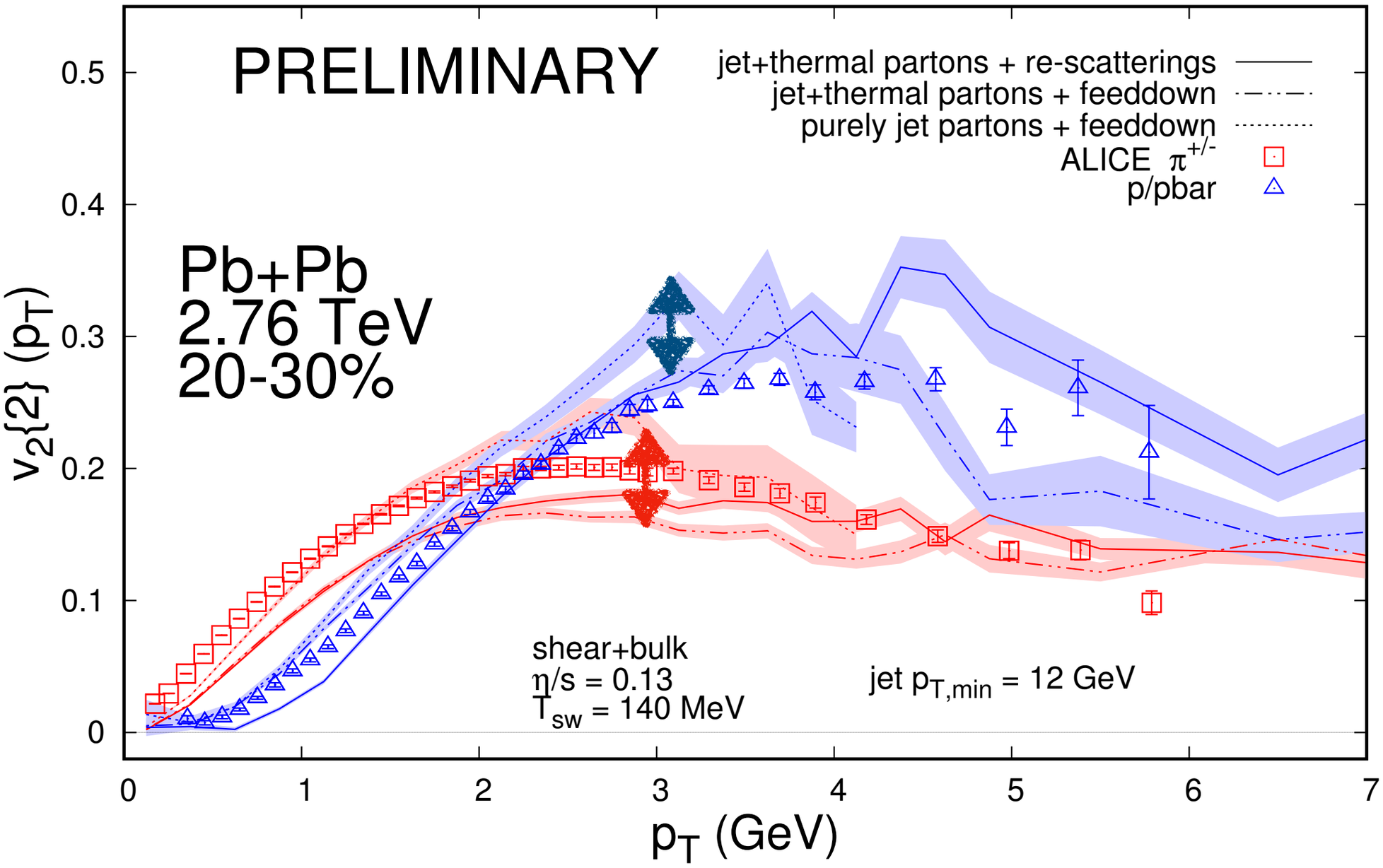


deceleration of pions

deceleration of high-p_T protons
and acceleration of low-p_T protons

Results

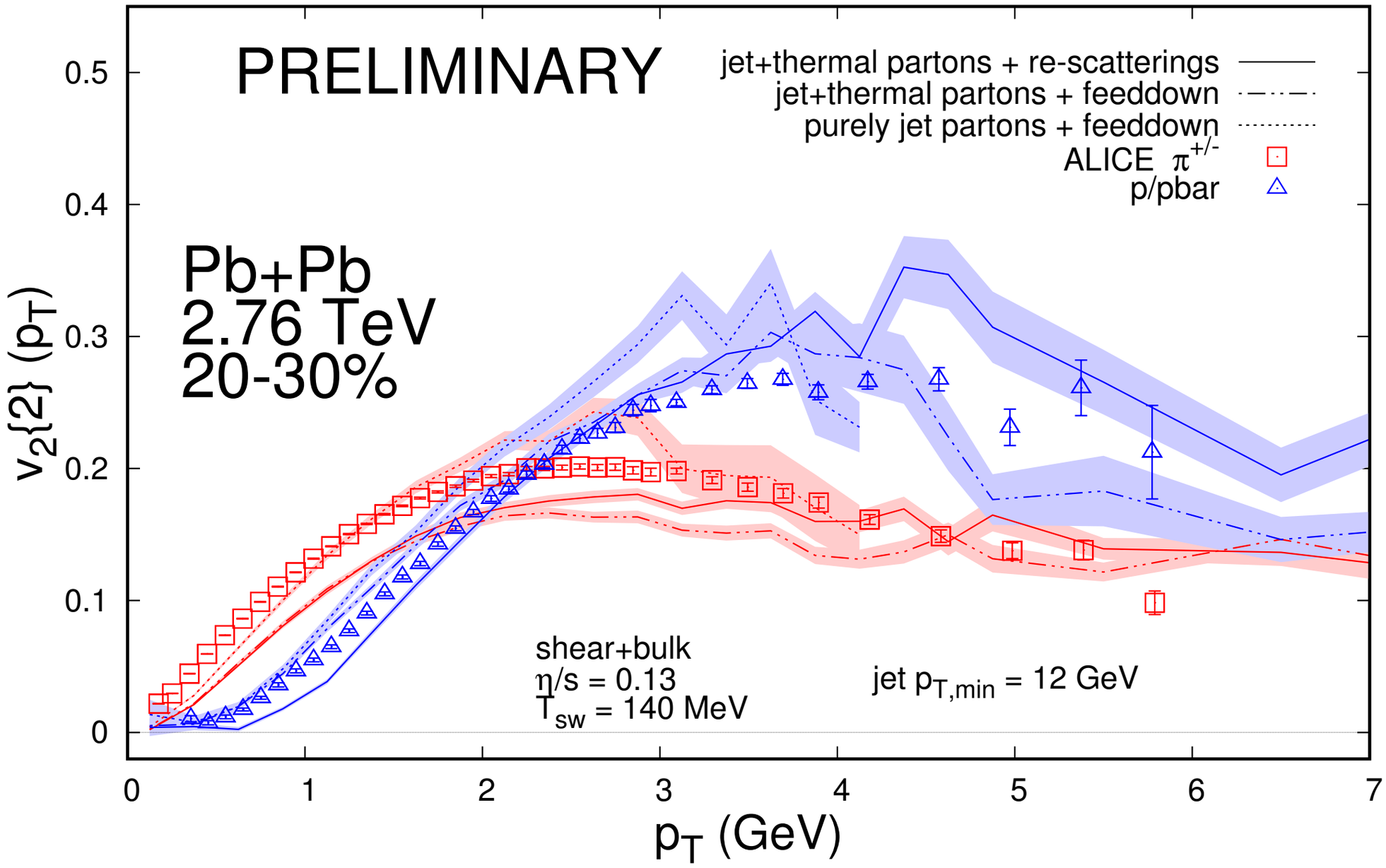
Flow anisotropies : hadronization and onward re-scatterings



Response to thermal partons kicked out drops down flow anisotropy.

Results

Flow anisotropies : hadronization and onward re-scatterings



change p_T dependence of the flow anisotropy