Transport meeting (Nov 30, 2016)

Jet quenching in the hadronic phase
within a hybrid approach

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Introduction

- By colliding heavy nuclei (at RHIC and the LHC), we can
  ➤ create quark-gluon plasma (QGP) and
  ➤ study its properties (e.g. transport coefficients).

- This can be done by creating a realistic dynamical model of heavy ion collisions

- Different aspects of QGP and hadronic matter influence each other. e.g.,
  ➤ non-zero ζ/s alters the estimate of η/s
  ➤ jet quenching in hadronic phase changes determination of the jet-medium interaction in QGP

- Goal : hybrid model covering all these different aspects.

PART 1

Hybrid approach and
description of soft (low-p_T) physics

PART 2

Jet production and energy loss
for hard (high-p_T) physics

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Hybrid approach and description of soft (low-p_T) physics

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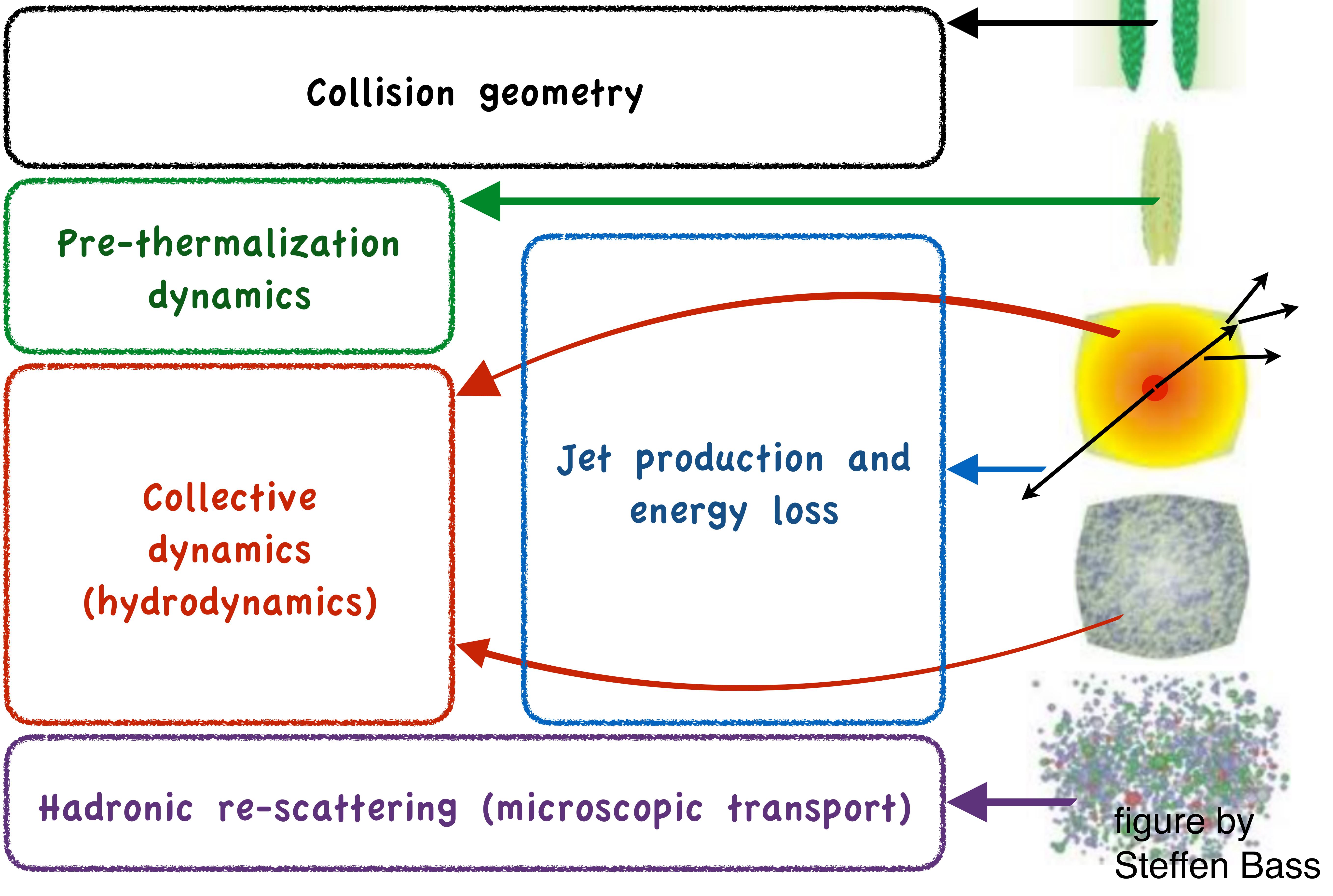
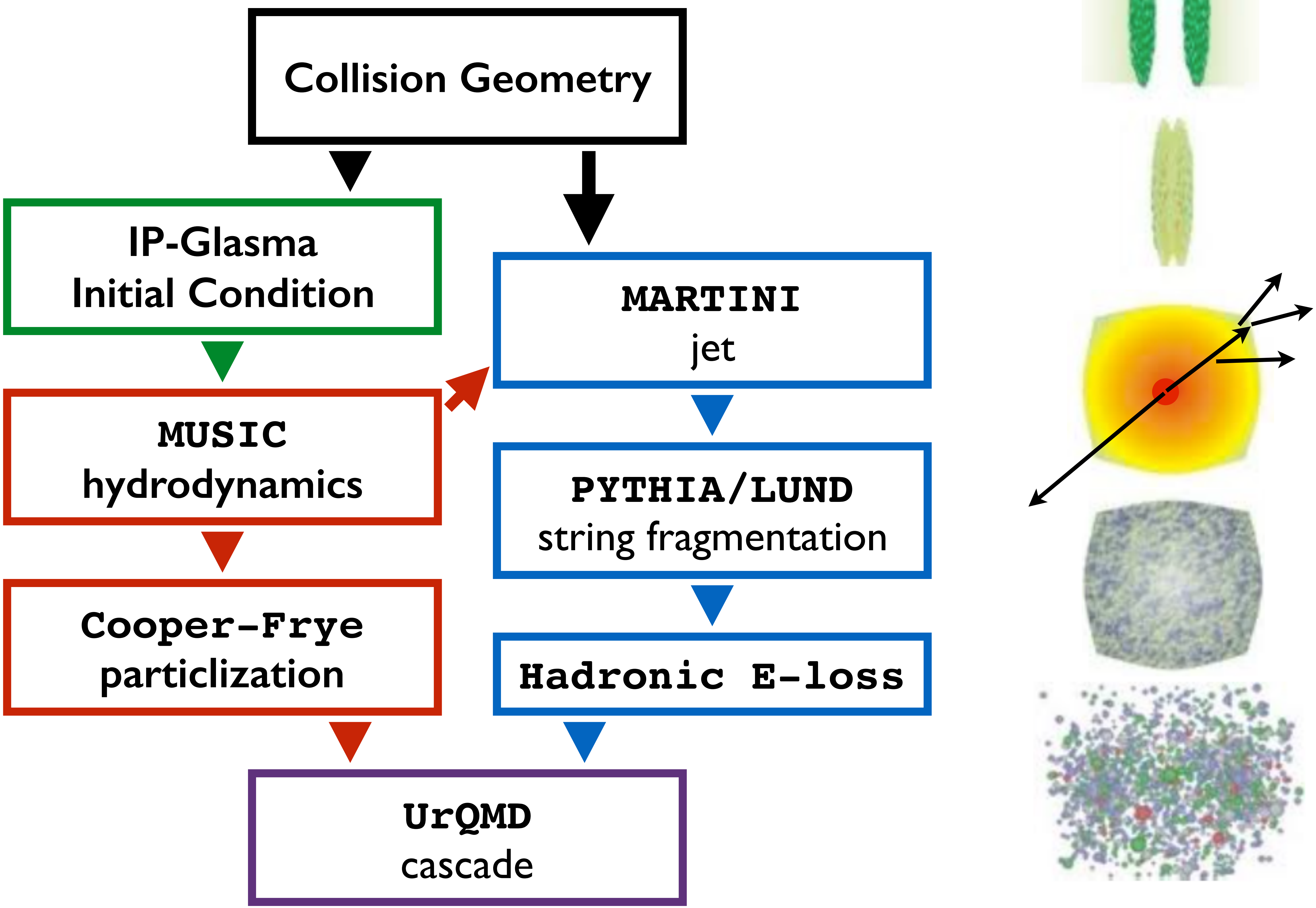
Hybrid approach



Model Structure



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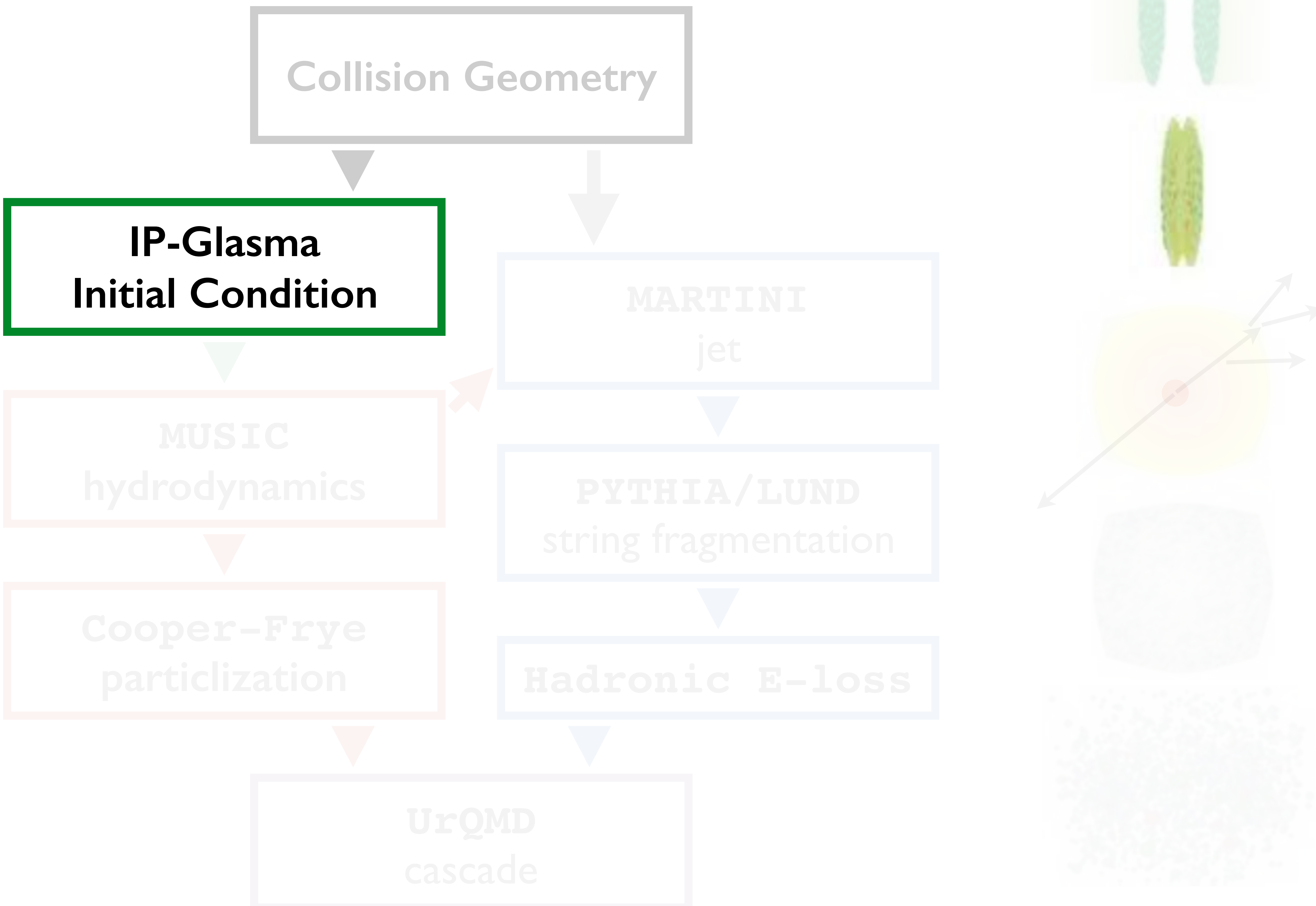


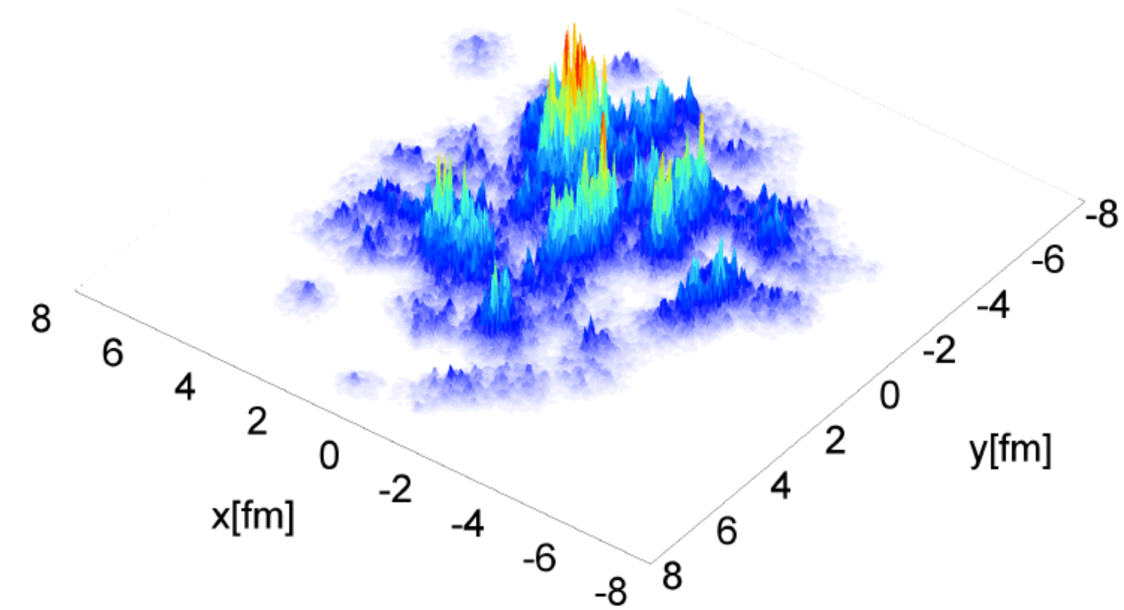
Model : IP-Glasma I.C.

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 $\tau = \tau_0$

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

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

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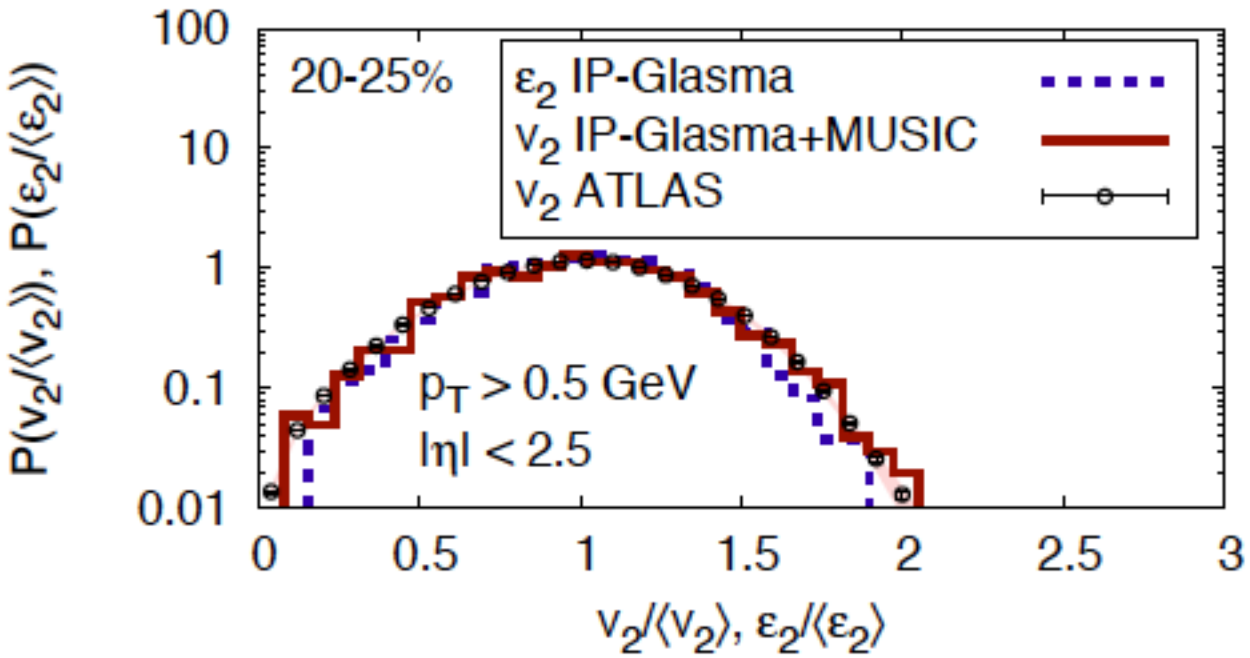
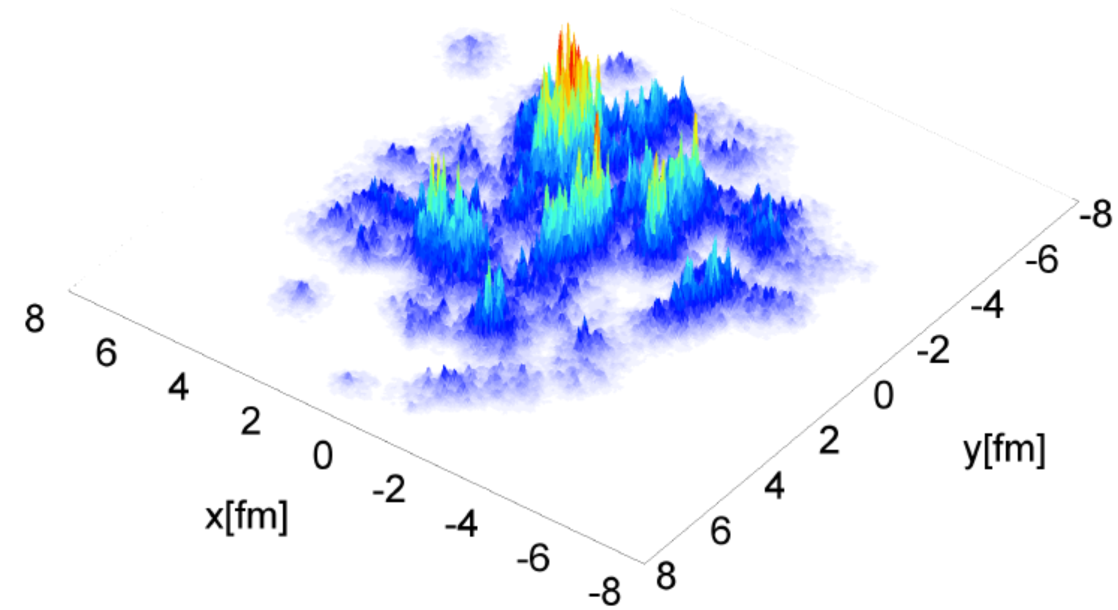
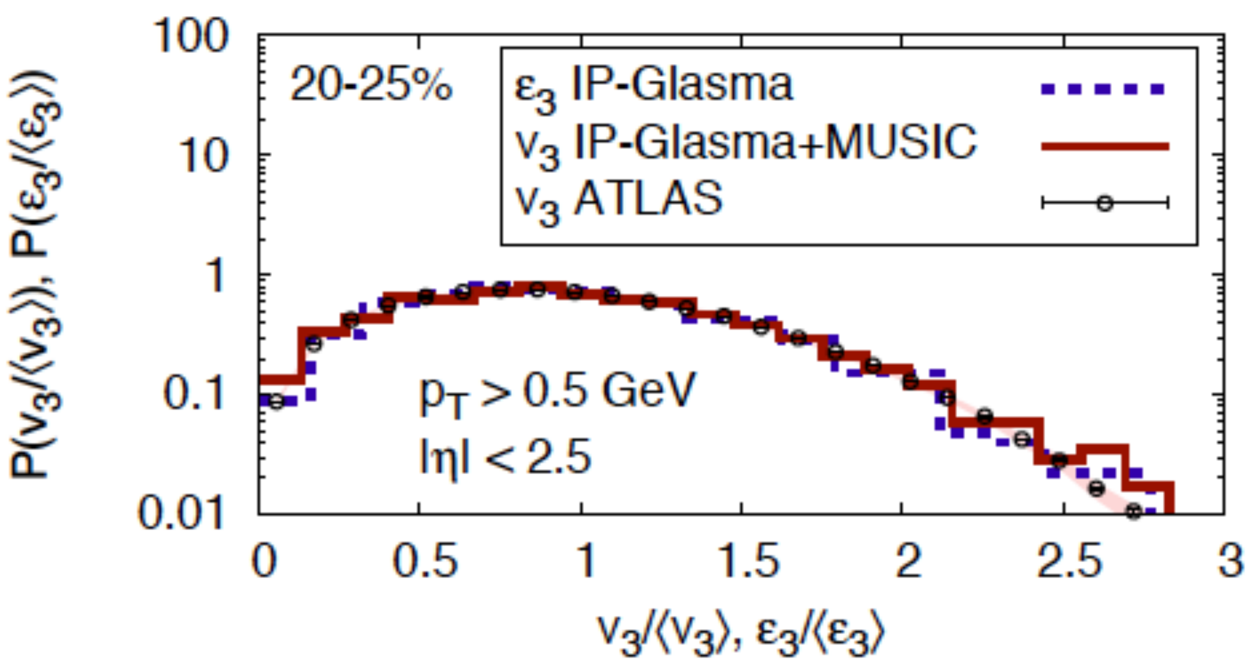


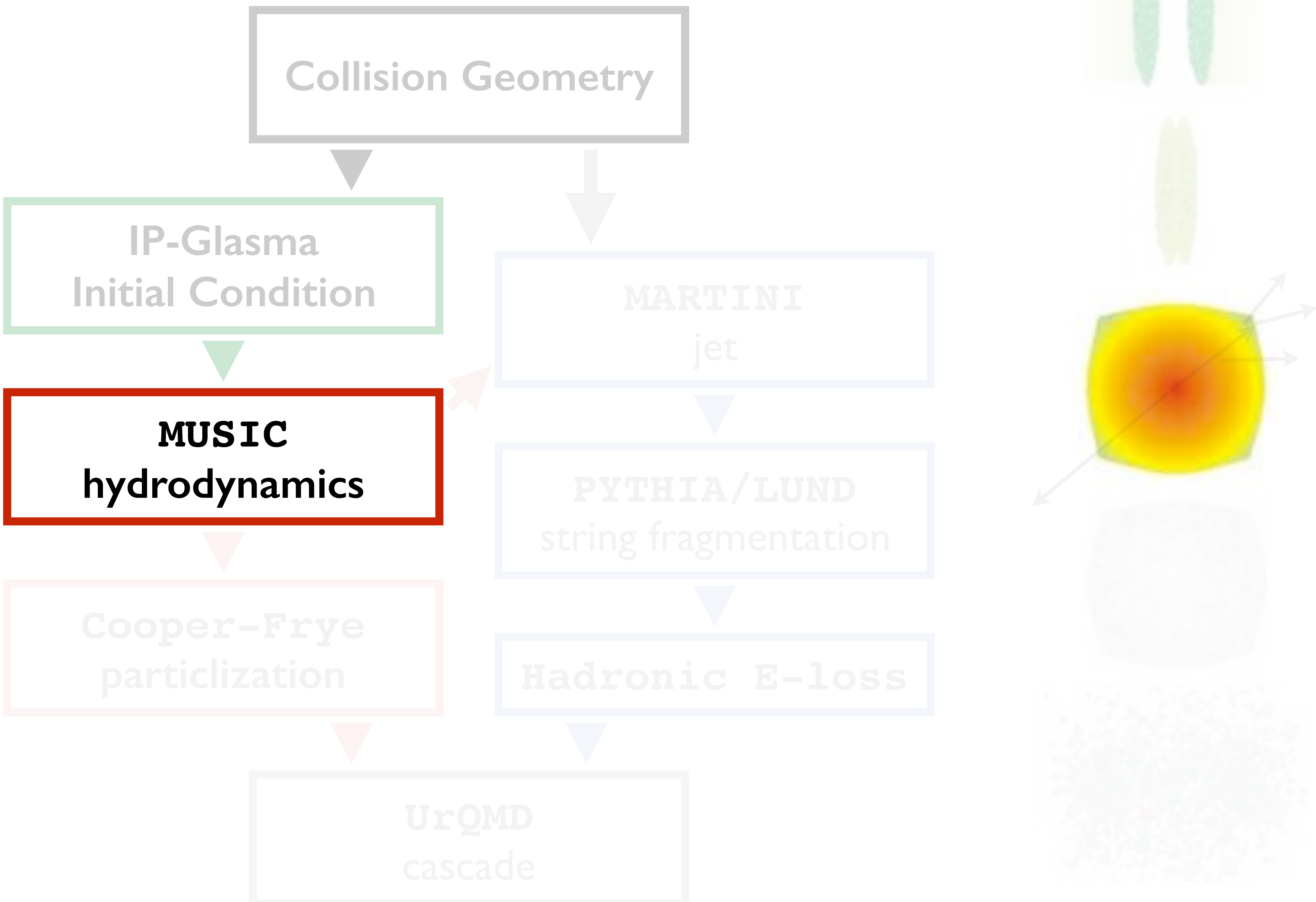




well describes v_n distribution

C. Gale, S. Jeon, B. Schenke, P. Tribedy and R. Venugopalan (2012)

Model Structure



Model : MUSIC hydro

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

hydrodynamic equations of motion

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

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

EoS bulk shear

Local 3-metric $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

Local 3-gradient $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$

Model : MUSIC hydro

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

equation of motion for viscous corrections

shear viscosity relaxation equation

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

expansion rate

$$\theta = \nabla_\mu u^\mu$$

shear tensor

$$\sigma^{\mu\nu} = \frac{1}{2}\left[\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{3}{2}\Delta^{\mu\nu}\left(\nabla_\alpha u^\alpha\right)\right] \equiv \nabla^{\langle\mu}u^{\nu\rangle}$$

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$$-\tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\,\sigma^{\mu\nu}\Big)$$

shear

$$\frac{\eta}{s} = \mathrm{const}$$

Model : MUSIC hydro

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

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shear viscosity relaxation equation

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

14-moment approximation in the small mass limit

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

$$\frac{\eta}{\tau_\pi} = \frac{1}{5}(\epsilon_0 + P_0) \qquad \frac{\delta_{\pi\pi}}{\tau_\pi} = \frac{4}{3} \qquad \frac{\lambda_{\pi\Pi}}{\tau_\pi} = \frac{6}{5} \qquad \frac{\tau_{\pi\pi}}{\tau_\pi} = \frac{10}{7}$$

second-order transport coefficients

Model : MUSIC hydro

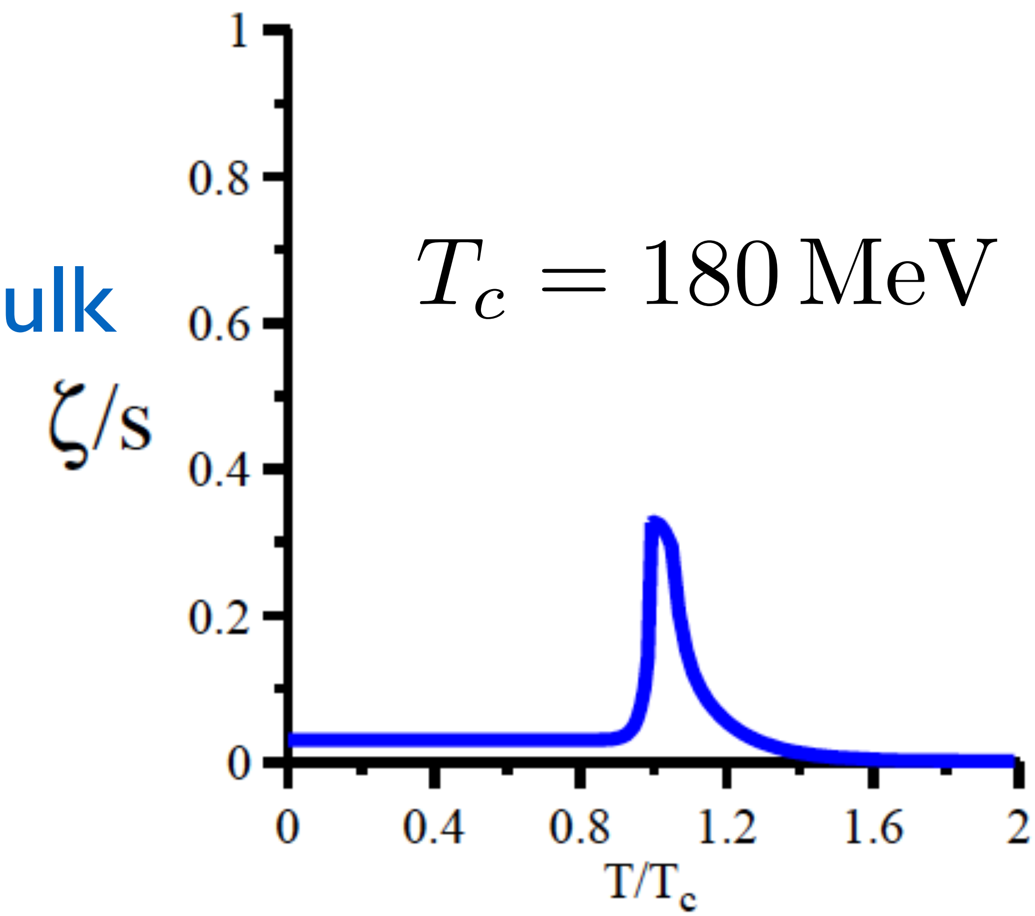
B. Schenke, S. Jeon, and C. Gale (2010)

equation of motion for viscous corrections

bulk viscosity relaxation equation

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

bulk



F. Karsch, D. Kharzeev and K. Tuchin (2008)

J. Noronha-Hostler, J. Noronha and C. Greiner (2009)

Model : MUSIC hydro

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

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14-moment approximation in the small mass limit

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

$$\frac{\zeta}{\tau_\Pi} = 15\left(\frac{1}{3} - c_s^2\right)^2 (\epsilon_0 + P_0)$$

$$\frac{\delta_{\Pi\Pi}}{\tau_\Pi} = \frac{2}{3} \qquad \frac{\lambda_{\Pi\pi}}{\tau_\Pi} = \frac{8}{5}\left(\frac{1}{3} - c_s^2\right)$$

second-order
transport coefficients

Model : Equation of state

P. Huovinen, and P. Petreczky (2010)

Equation of state : hadron gas + lattice data

Only those included in UrQMD

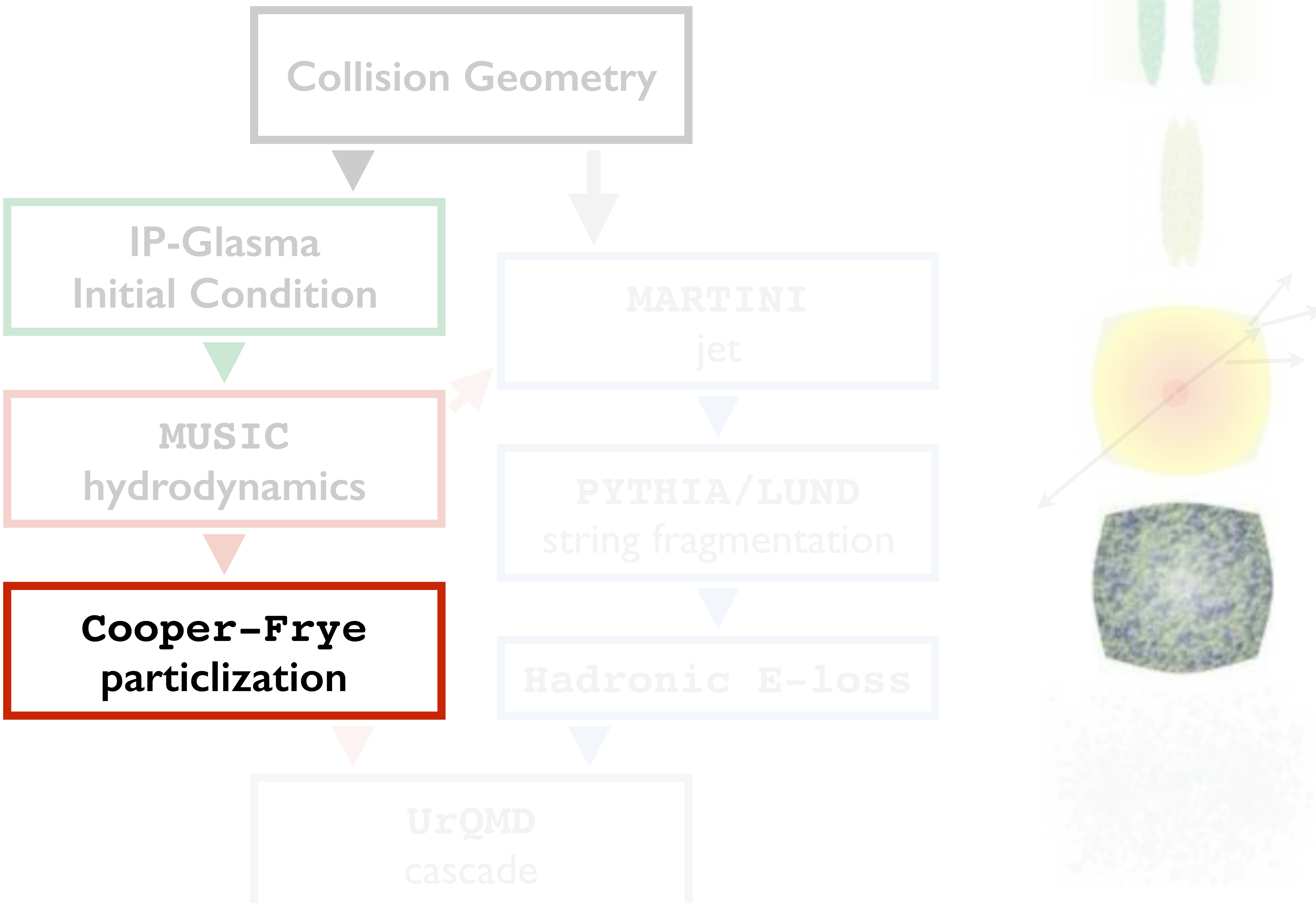
Cross over phase transition around T = 180 MeV

Initial condition + Hydro equation + EoS

Hydrodynamic evolution

Up to the isothermal hypersurface at $T_{\mathrm{sw}} = 145\,\mathrm{MeV}$
to switch from hydrodynamics to transport

Model Structure



Model : Cooper-Frye sampling

F. Cooper and G. Frye (1974)

sampling particles according to the Cooper-Frye formula

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

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

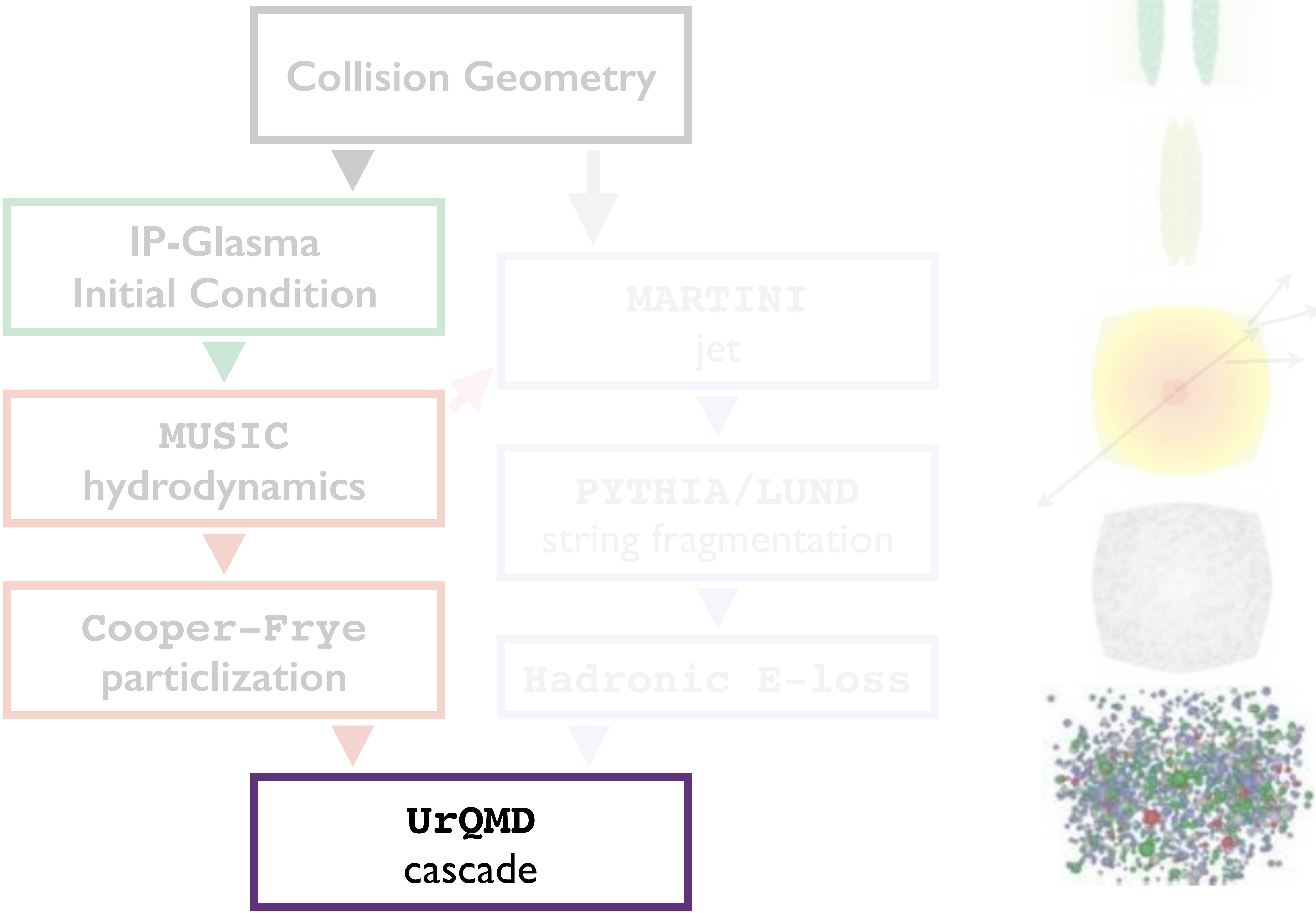
$$\delta f_{\text{shear}}(x,\mathbf{p}) = f_0(1\pm f_0)\frac{p^\mu p^\nu \pi^{\mu\nu}}{2T^2(\epsilon_0 + P_0)}$$

P. Bozek (2010)

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

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

Model Structure



Model : UrQMD cascade

Ultra-relativistic Quantum Molecular Dynamics

S. A. Bass *et al*. (1998)

Monte-Carlo implementation of transport theory

$$p^\mu \frac{\partial}{\partial x^\mu} f_i(x,p) = \mathcal{C}_i[f]$$

Which species? : 55 baryons + 32 mesons with masses up to 2.25 GeV

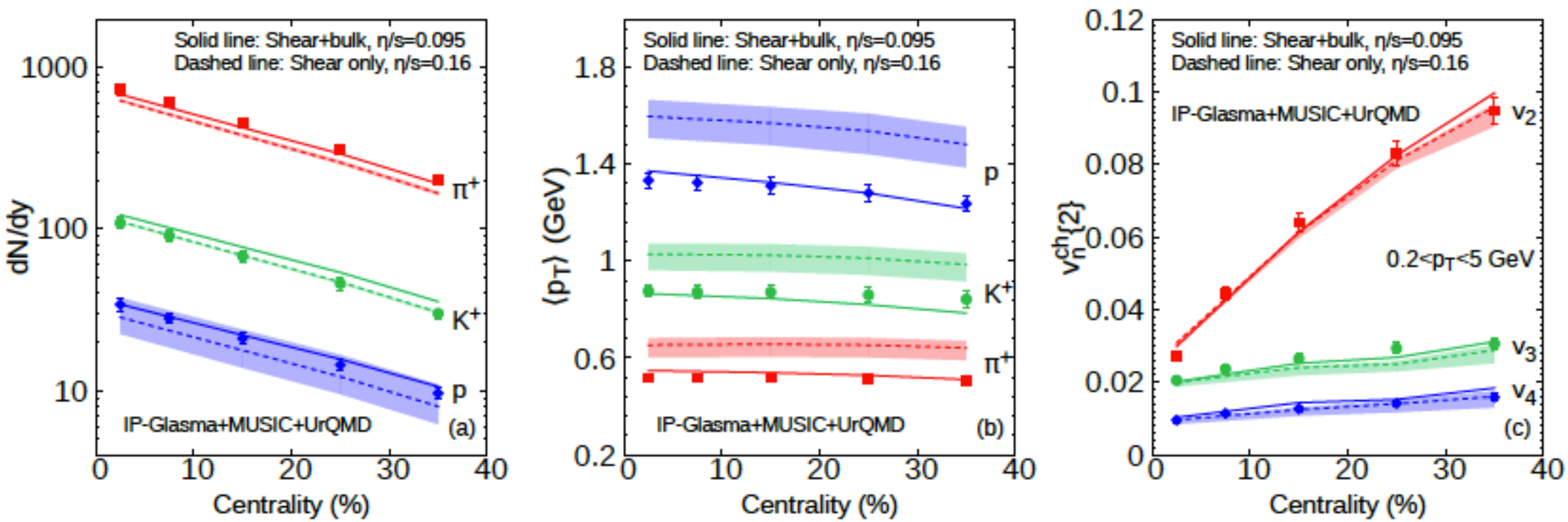
Cross sections : based on experimental data
Jet-hadron interaction by PYTHIA

Keeps track of particle trajectories

Description of soft physics

PRL 2015 (arXiv:1502.01675)

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

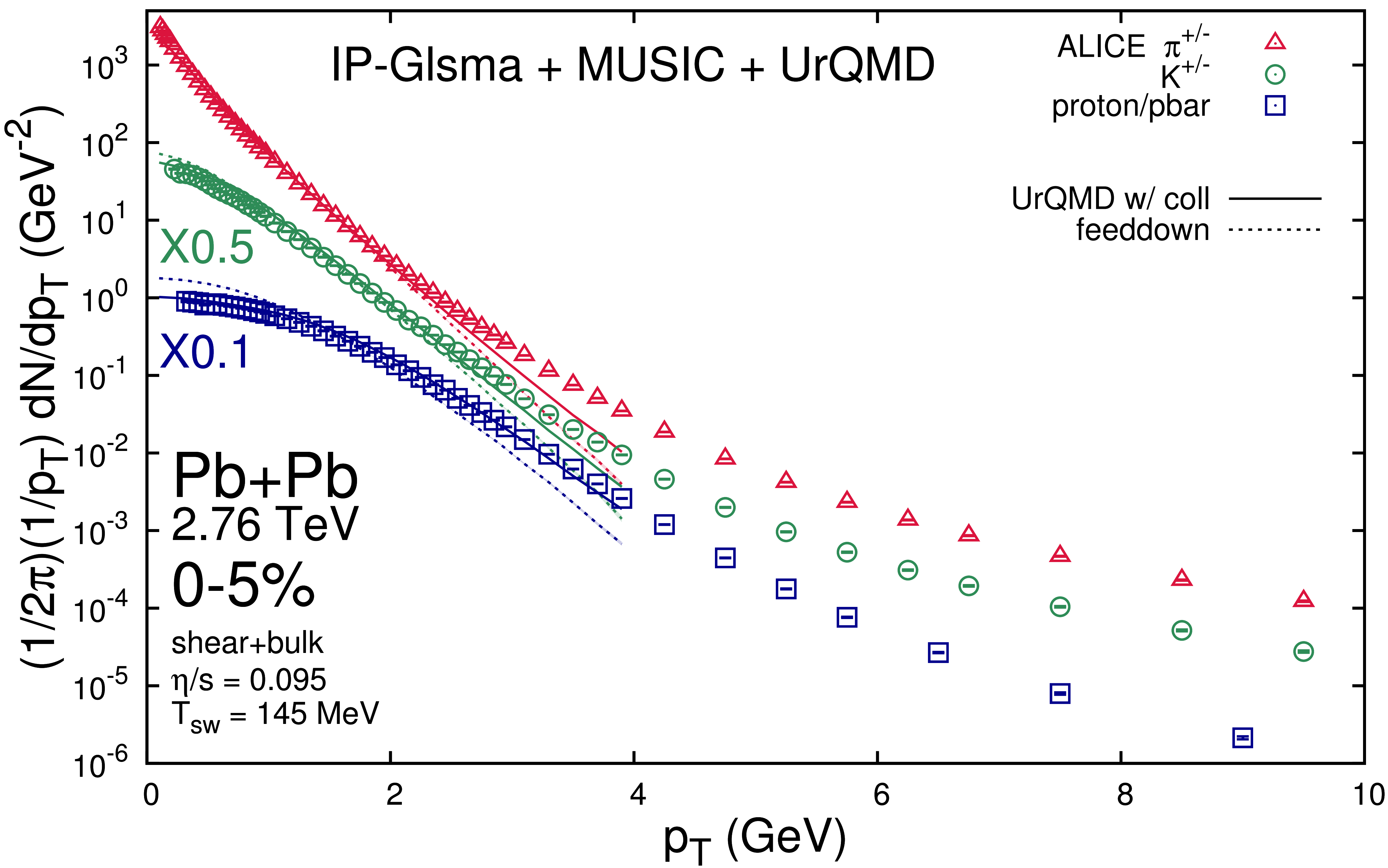


Parameters are tuned to fit **multiplicity, mean** p_T and **integrated flow coefficients** v_n.

The **bulk viscosity is crucial** to describe those observables.

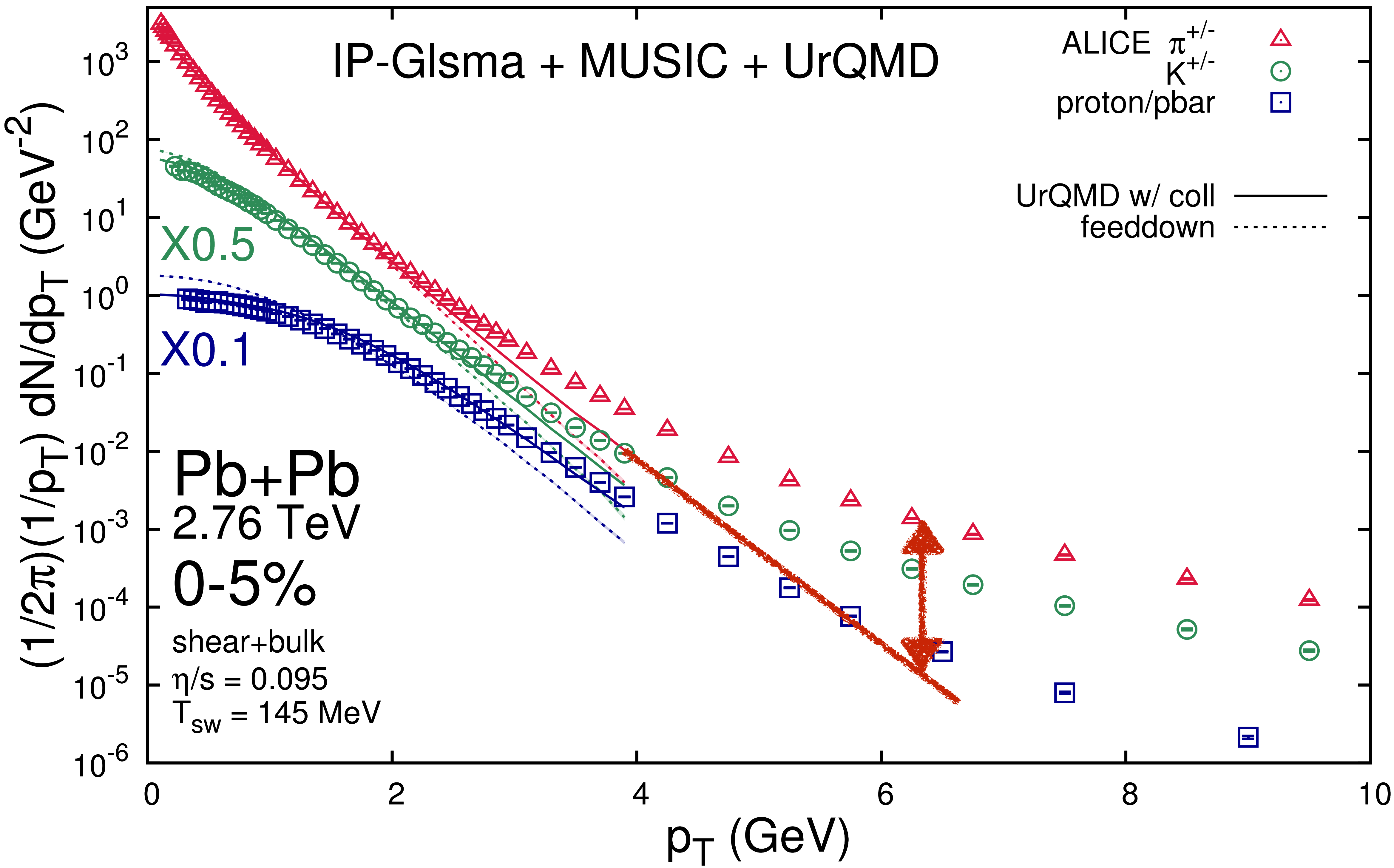
The **shear viscosity** $\frac{\eta}{s} = 0.095$ is favored.

Spectra at the LHC



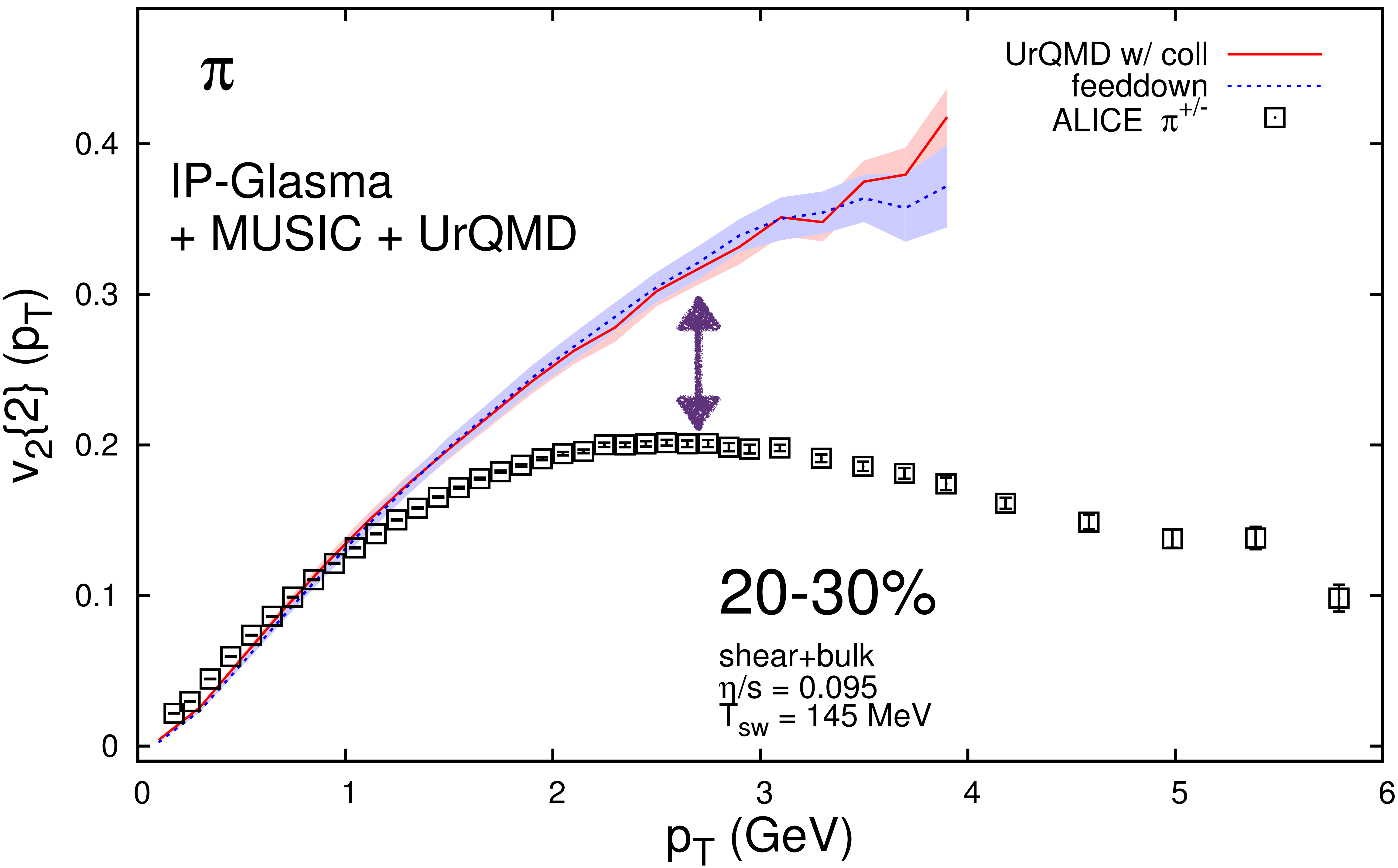
The low-p_T spectra are well described.

Spectra at the LHC



Jet production and energy-loss are necessary.

Spectra at the LHC



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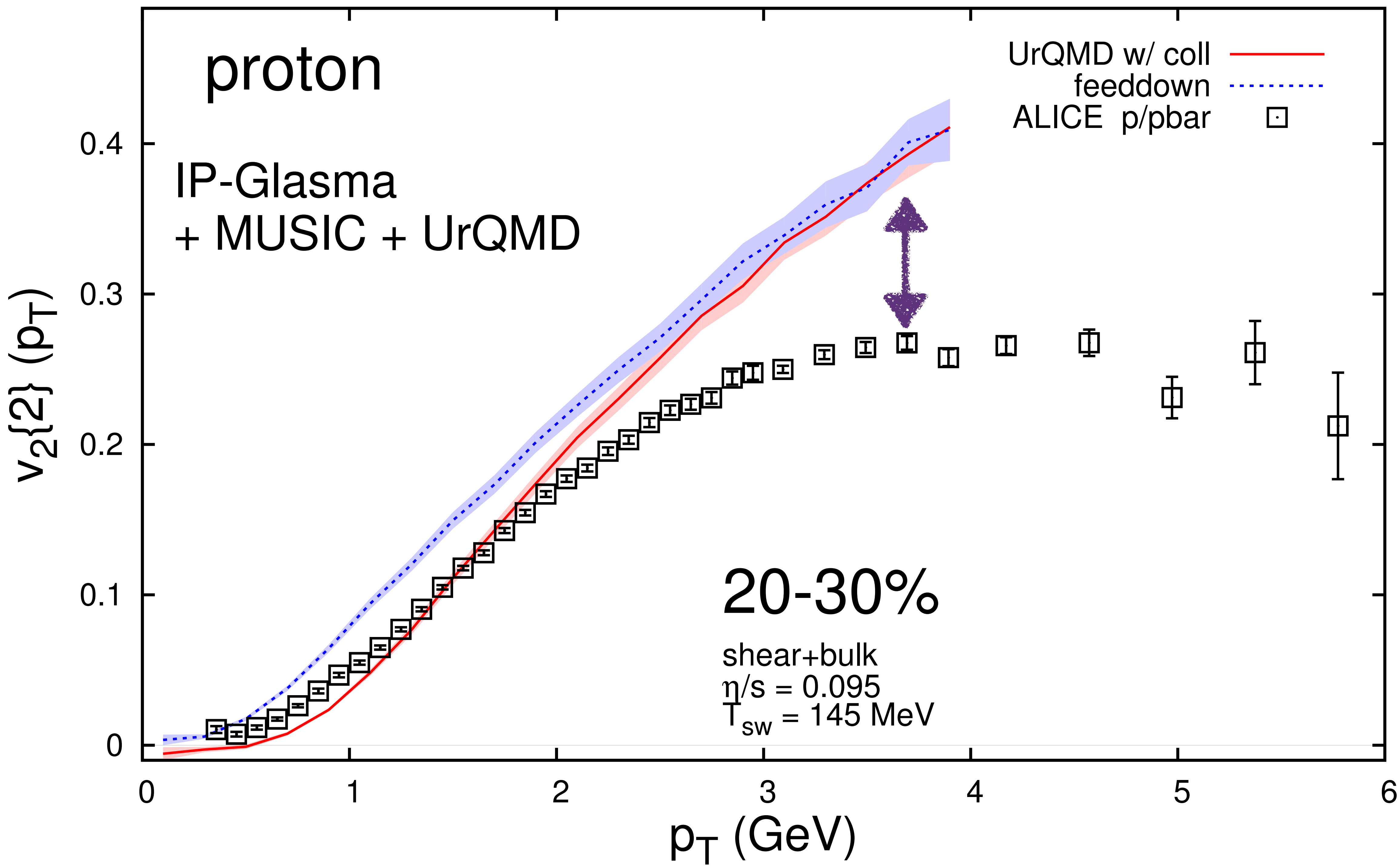

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Hybrid approach and
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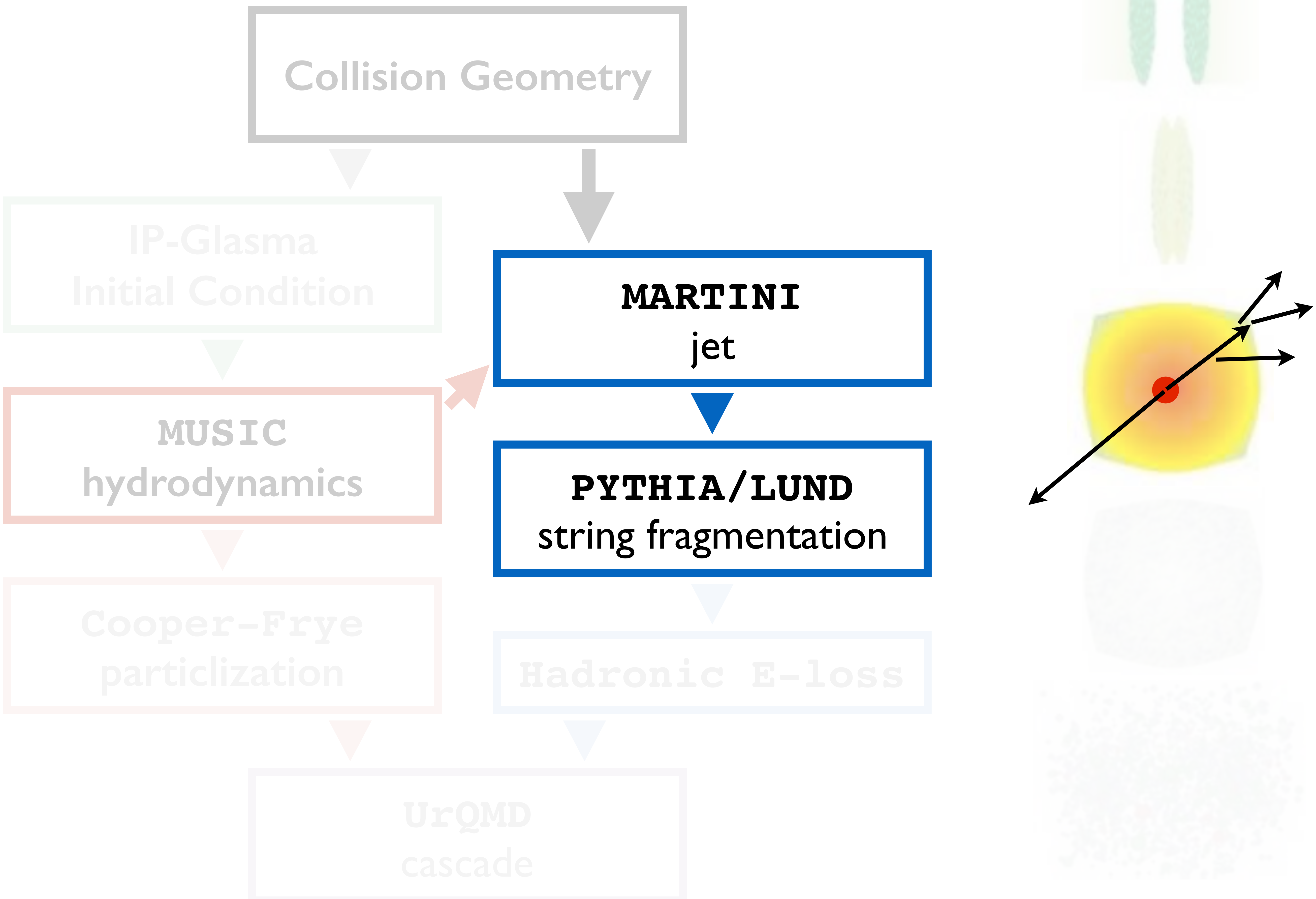
Jet production and energy loss
for hard (high-p_T) physics

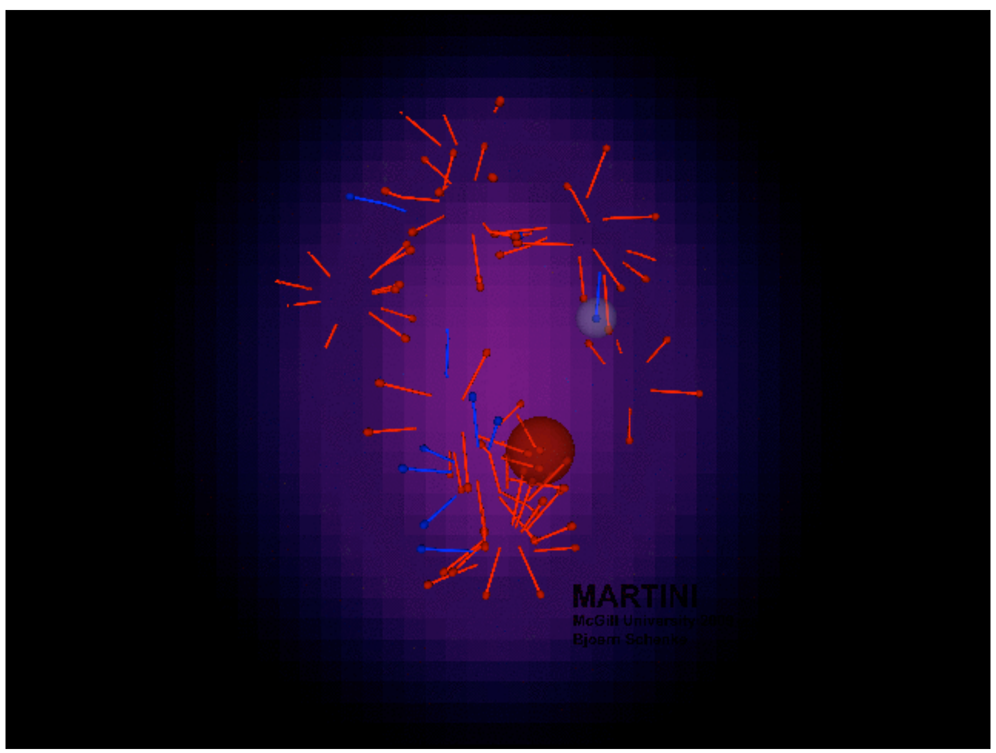
Model Structure



Model : MARTINI jets

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)
- Collision (with thermal partons)

Fragmentation into hadrons (PYTHIA / LUND string model)

Model : MARTINI jets

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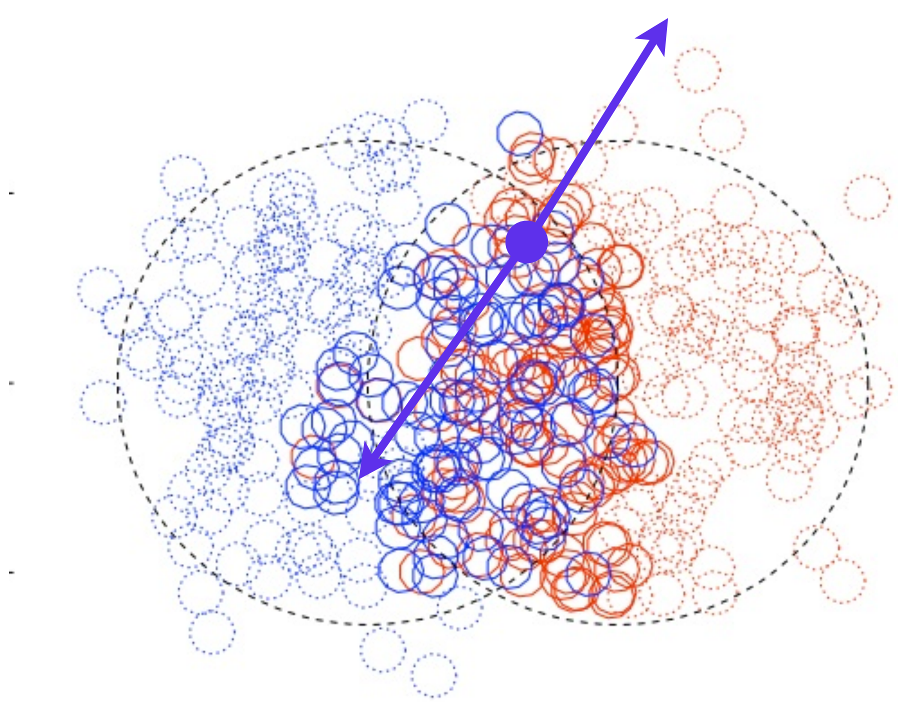

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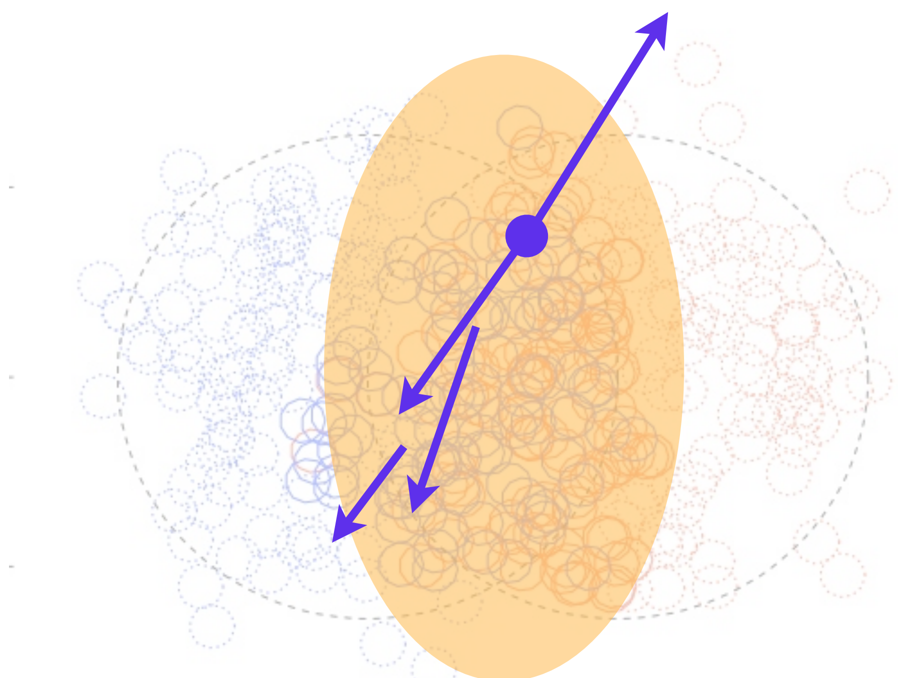

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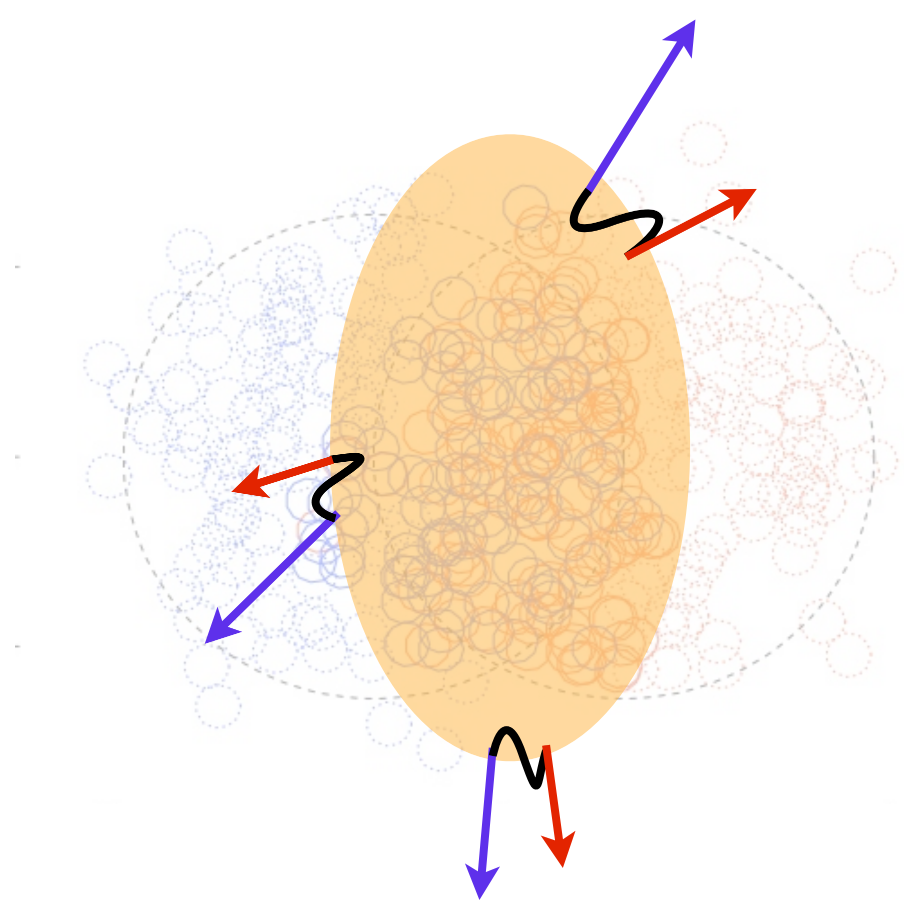

Hard process at the position of binary collision (PYTHIA)

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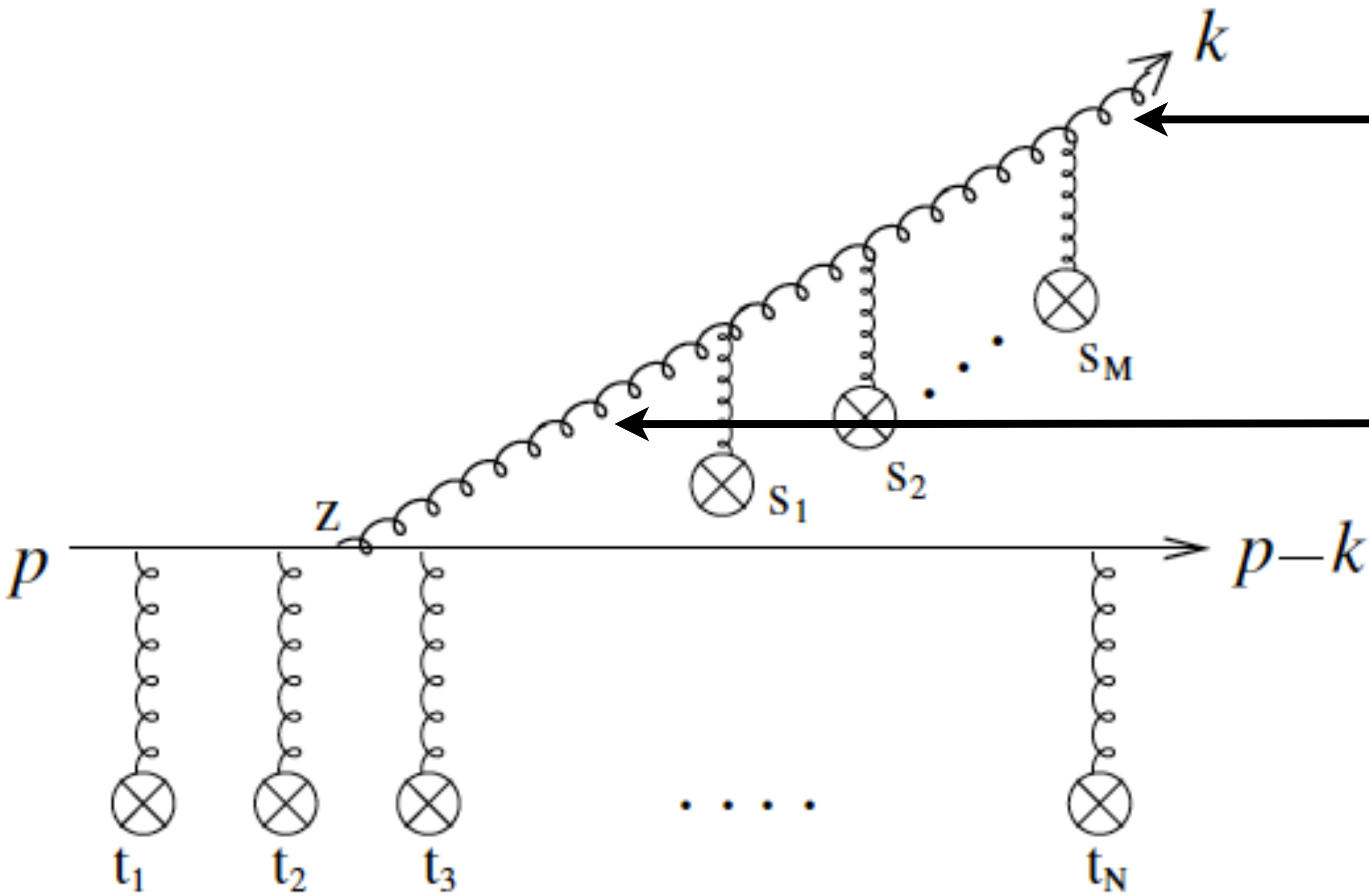
Model : jet energy loss

Radiative energy loss (AMY)

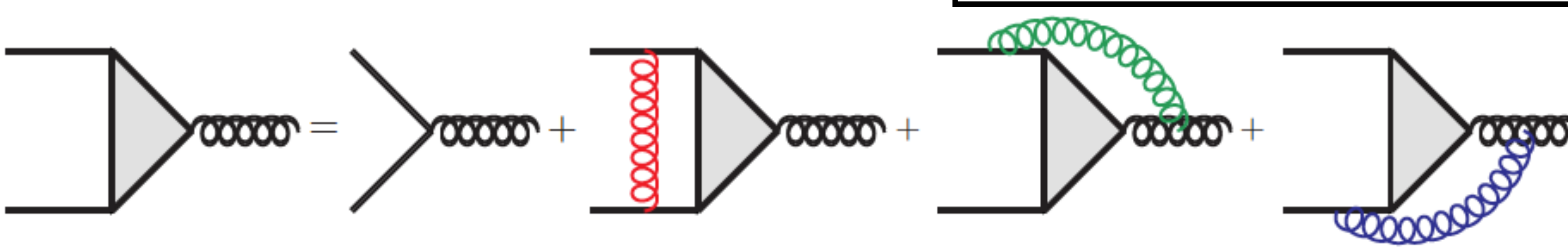
P. Arnold, G. Moore and L. Yaffe (2002)



Collinear emission

Nearly on-shell intermediate propagator

Infinite number of diagrams
> Integral equations



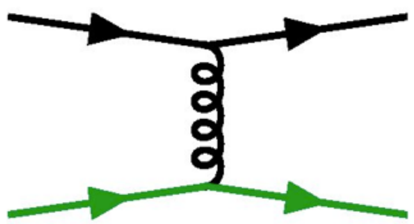
figures by G-Y. Qin

Model : jet energy loss

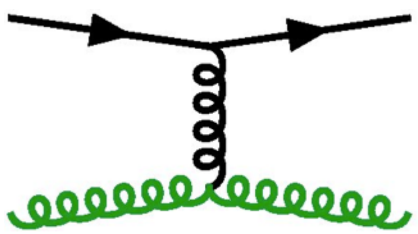
Collisional energy loss (soft approximation)

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

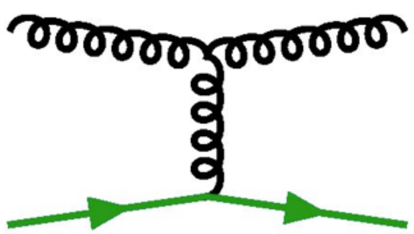
G-Y. Qin et al. (2008)



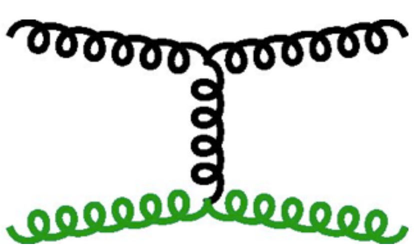
$$\left.\frac{dE}{dt}\right|_{qq} = \frac{2}{9} n_f \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_f \frac{23}{12} + c_s \right]$$



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

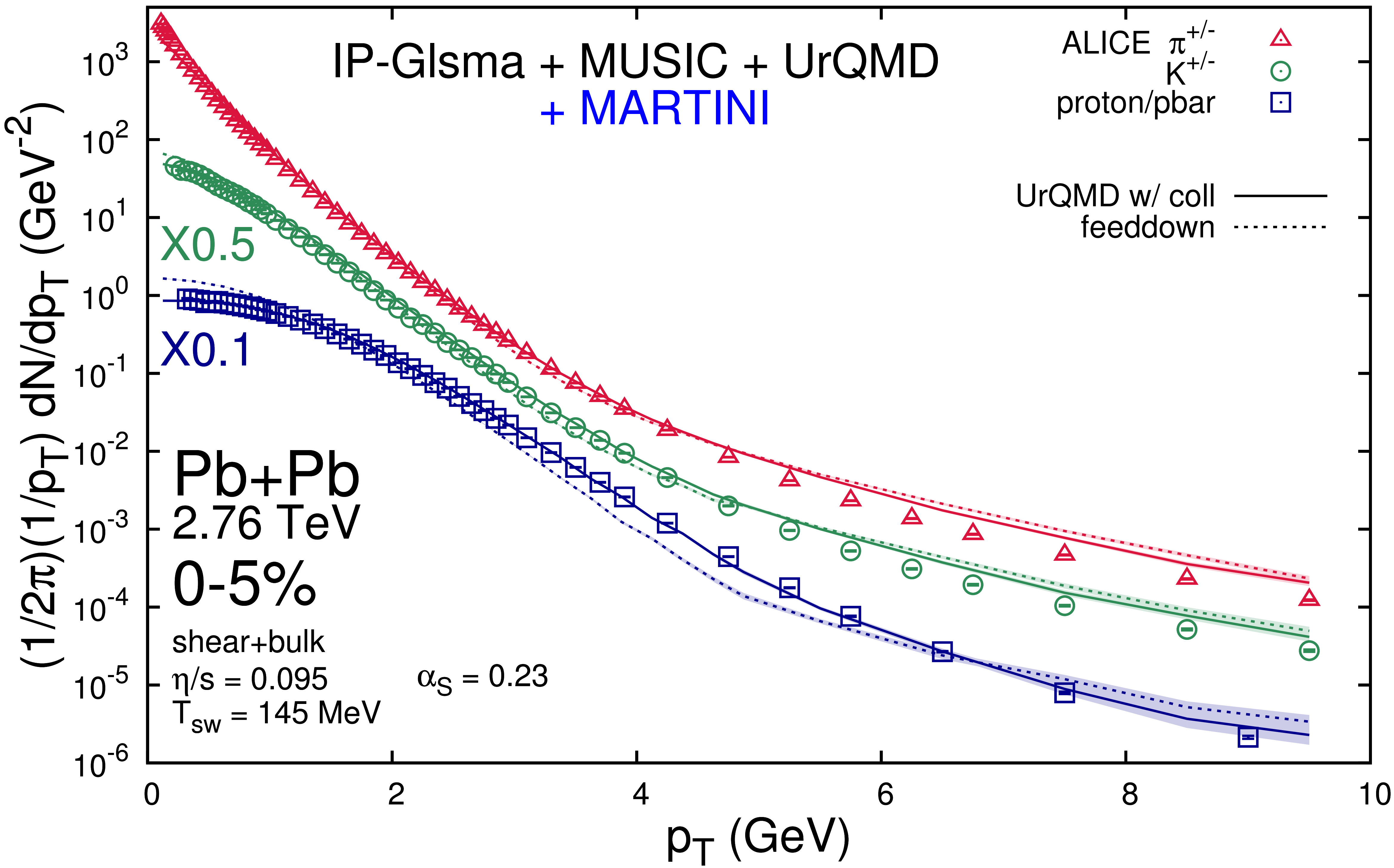


$$\left.\frac{dE}{dt}\right|_{gq} = \frac{1}{2} n_f \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_f \frac{13}{6} + c_s \right]$$



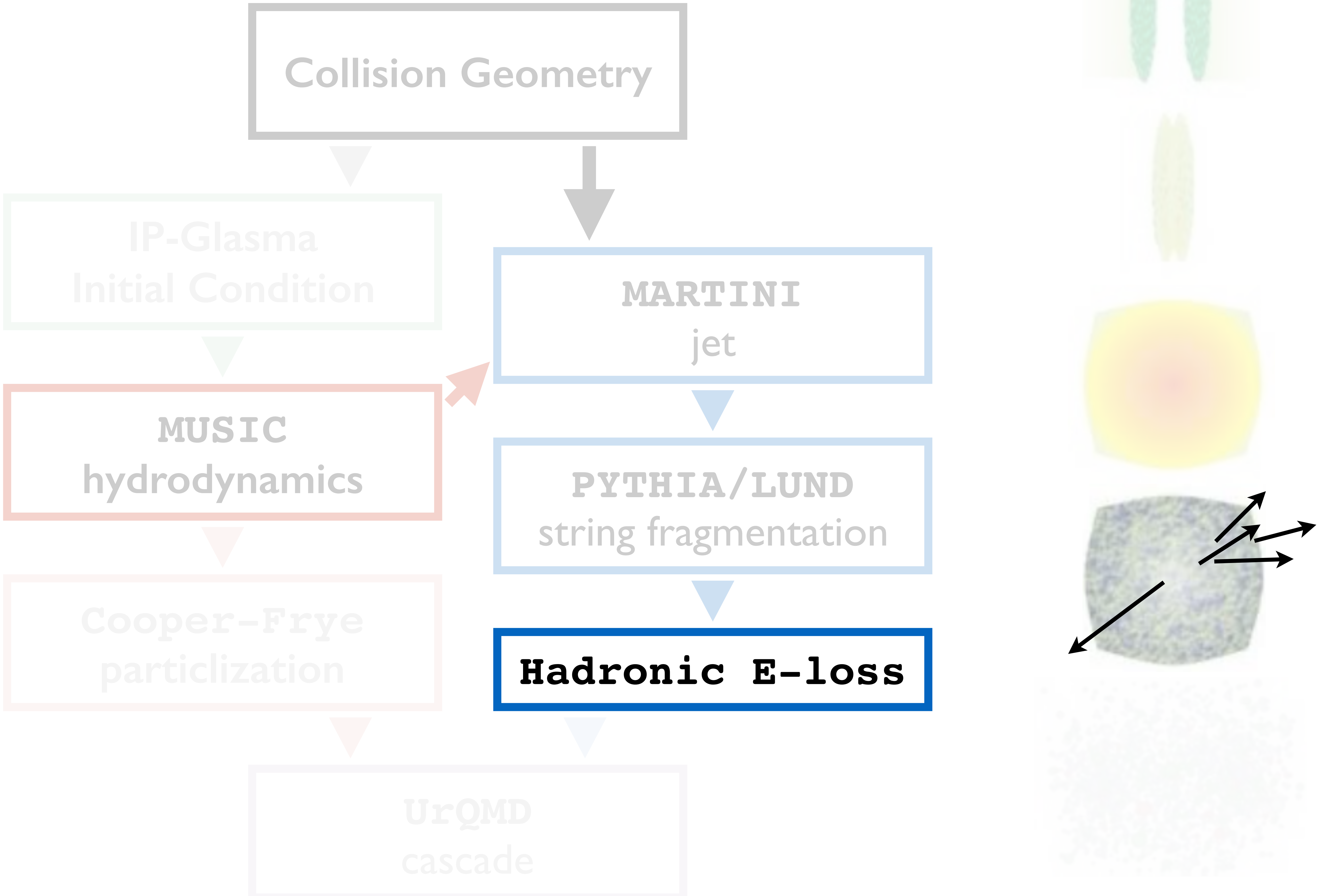
$$\left.\frac{dE}{dt}\right|_{gg} = 3 \pi \alpha_s^2 T^2 \left[\ln \frac{ET}{m_g^2} + c_b \frac{131}{48} + c_s \right]$$

Spectra with MARTINI

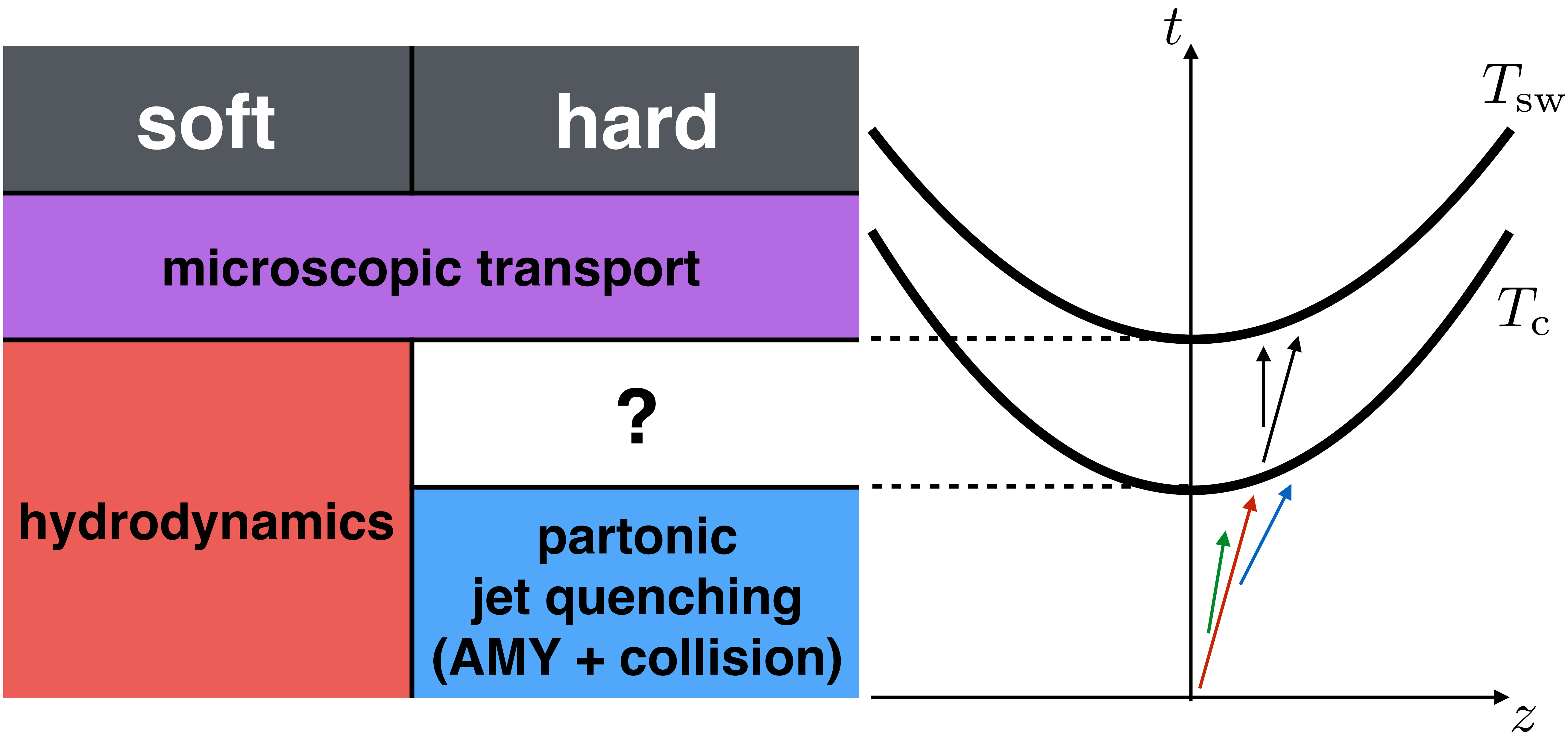


It can be extended toward the higher p_T range.

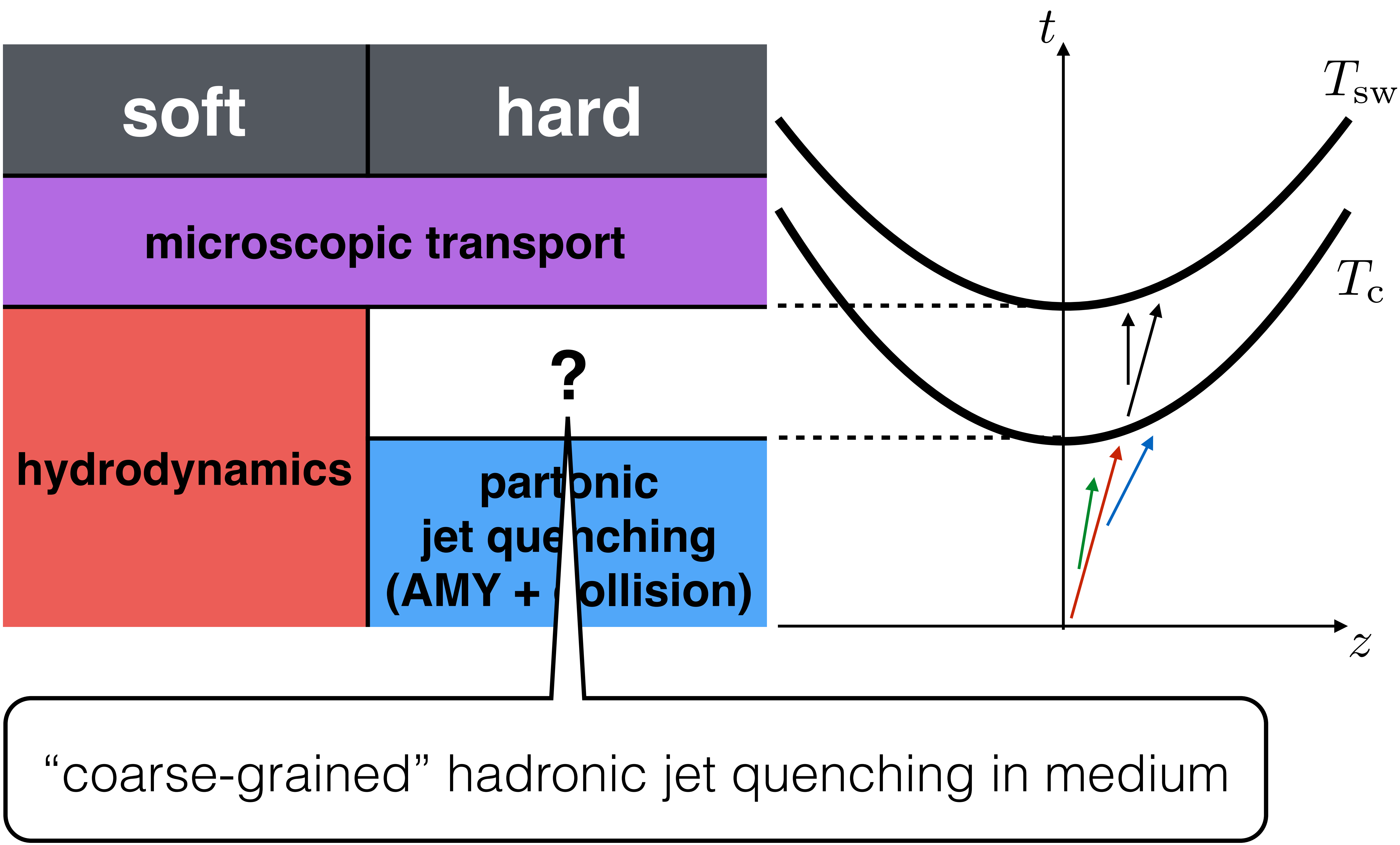
Model Structure



Model : Jet quenching

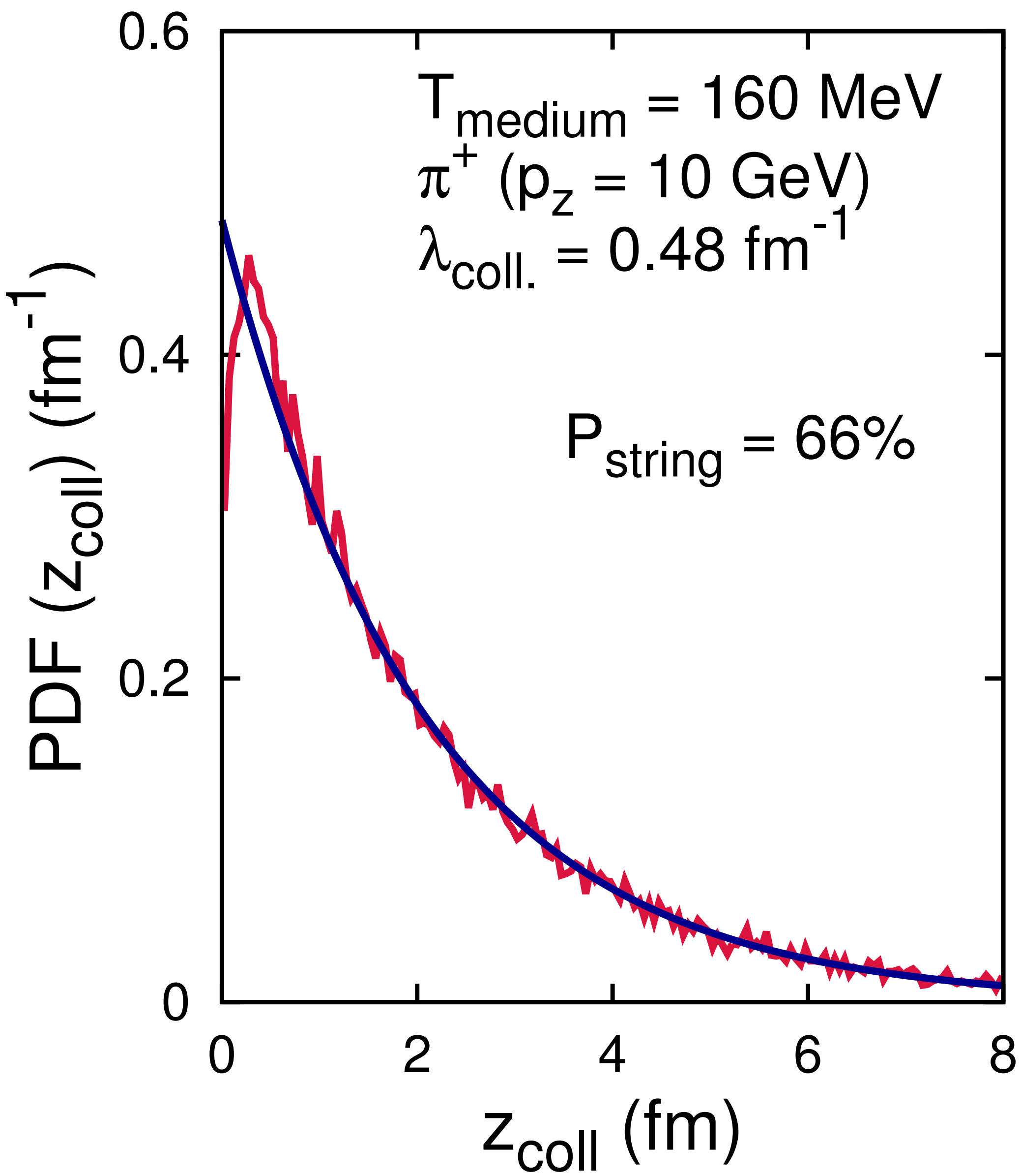


Model : Jet quenching



Model : Jet quenching

Does the jet experience collisions?



$$\mathrm{PDF}\left(z_{\mathrm{coll}}\right) = \lambda \exp\left(-\lambda z_{\mathrm{coll}}\right)$$

Probability that the jet has collision after travelling Δx is $\lambda \Delta x$.

Scale the probability to take
1. formation time (out of string)
2. different quark contents (AQM)

into account

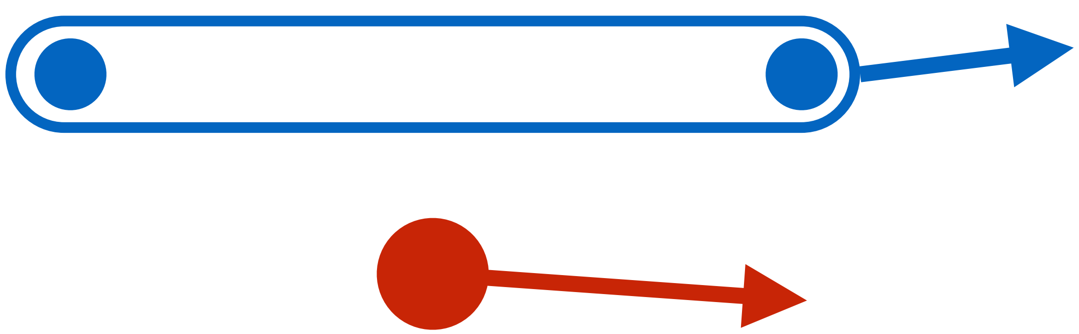
Determine the process (mostly elastic or string excitation)

Model : Jet quenching

String excitation and fragmentation

$$p^{\mu}_{\mathrm{jet}} = \left(\sqrt{m^2_{\mathrm{jet}} + P^2_{\mathrm{jet}}}, \mathbf{0}, P_{\mathrm{jet}}\right)$$

$$p^{\mu}_{\mathrm{th,i}} = (m_{\mathrm{th}}, \mathbf{0}, 0)$$



$$p^{\mu}_{\mathrm{string}} = (E_{\mathrm{string}}, -\mathbf{p}_{\perp}, P_{\mathrm{jet}} - p_{\parallel})$$

$$p^{\mu}_{\mathrm{th,f}} = \left(\sqrt{m^2_{\mathrm{th}} + p^2_{\perp} + p^2_{\parallel}}, \mathbf{p}_{\perp}, p_{\parallel}\right)$$

Model : Jet quenching

String excitation and fragmentation

1. determine transverse momentum transfer

$$\mathrm{PDF}\left(\mathbf{p}_{\perp}\right) = \frac{1}{\pi\sigma^2}\exp\left(-\frac{p_{\perp}^2}{\sigma^2}\right)$$

2. determine string mass

$$\mathrm{PDF}\left(M_{\mathrm{string}}\right) \sim M_{\mathrm{string}} \sim \text{density of state}$$

$$\begin{aligned} M_{\mathrm{min}} &= m_{\mathrm{jet}} \\ M_{\mathrm{max}} &= \left[(\sqrt{s} - m_{\perp,\mathrm{th}})^2 - p_{\perp}^2\right]^{1/2} \end{aligned}$$

$$\text{where} \quad m_{\perp,\mathrm{th}} = \left(m_{\mathrm{th}}^2 + p_{\perp}^2\right)^{1/2}$$

Model : Jet quenching

String excitation and fragmentation

3. determine momenta of the string and (thermal) hadron

$$y_{\mathrm{th}} = \mathrm{asinh}\left(\frac{P_{\mathrm{jet}}}{\sqrt{s}}\right) - \mathrm{acosh}\left(\frac{s + m_{\mathrm{th}}^2 - M_{\mathrm{string}}^2}{2\, m_{\perp,\mathrm{th}}\sqrt{s}}\right)$$

$$p_{\parallel} = m_{\perp,\mathrm{th}} \sinh y_{\mathrm{th}}$$

$$E_{\mathrm{string}} = \left[M_{\mathrm{string}}^2 + p_{\perp}^2 + \left(P_{\mathrm{jet}} - p_{\parallel}\right)^2\right]^{1/2}$$

$$p_{\mathrm{string}}^{\pm} = \frac{1}{\sqrt{2}}\left[E_{\mathrm{string}} \pm \left(P_{\mathrm{jet}} - p_{\parallel}\right)\right]$$

4. fragment string based on LUND/PYTHIA model **: TBD**

Conclusion

- A hybrid model, involving both the soft and hard physics of heavy ion collisions, is presented.
- The low-p_T distribution is well reproduced, while we need jet production and energy-loss to extend toward the higher p_T regime.
- Jet quenching in hadronic phase is currently under investigation to improve this hybrid approach.

Backup Slides

Model : Cooper-Frye sampling

F. Cooper and G. Frye (1974)

sampling particles according to the Cooper-Frye formula

1. sample number of particles based on Poisson distribution

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

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

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

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

Model : jet energy loss

Radiative energy loss (AMY)

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

$$\frac{d\Gamma}{dk}(p,k) = \frac{C_s g^2}{16\pi p^7}\frac{e^{k/T}}{e^{k/T}\mp 1}\frac{e^{(p-k)/T}}{e^{(p-k)/T}\mp 1}\left\{\begin{array}{cc} \frac{1+(1-x)^2}{x^3(1-x)^2} & q\to qg \\ N_f\frac{x^2+(1-x)^2}{x^2(1-x)^2} & g\to q\bar{q} \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g\to gg \end{array}\right\}$$

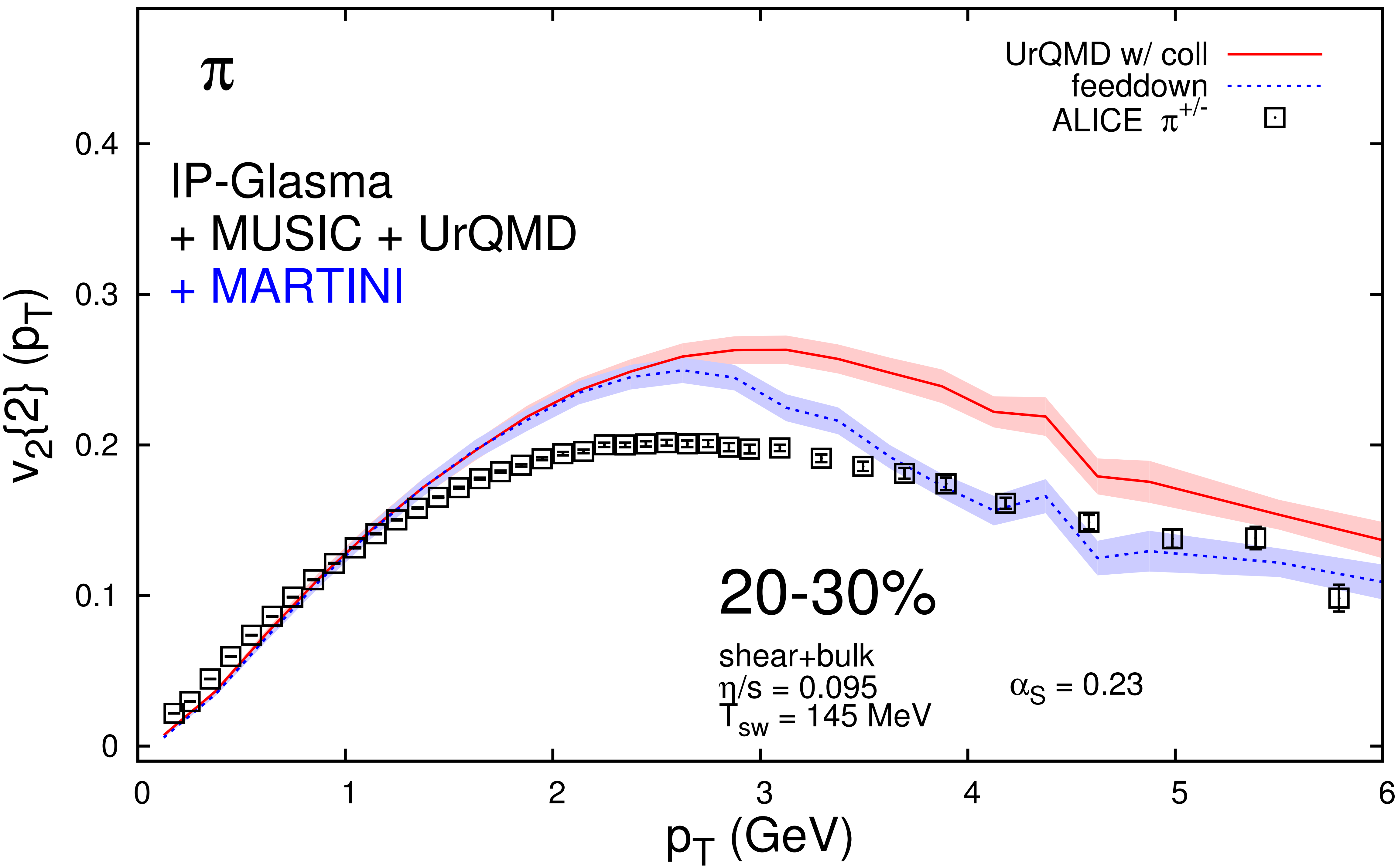
$$\times\int\frac{d^2\mathbf{h}}{(2\pi)^2}2\mathbf{h}\cdot\mathrm{Re}\,\mathbf{F}(\mathbf{h},p,k)$$

$$2\mathbf{h} = i\,\delta E(\mathbf{h},p,k)\mathbf{F}(\mathbf{h},p,k) + g_s^2\int\frac{d^2\mathbf{q}_\perp}{(2\pi)^2}\frac{m_D^2}{\mathbf{q}_\perp^2(\mathbf{q}_\perp^2+m_D^2)}$$
$$\times\Big\{(C_s - C_A/2)[\mathbf{F}(\mathbf{h})-\mathbf{F}(\mathbf{h}-k\,\mathbf{q}_\perp)] + (C_A/2)[\mathbf{F}(\mathbf{h})-\mathbf{F}(\mathbf{h}+p\,\mathbf{q}_\perp)]$$
$$+(C_A/2)[\mathbf{F}(\mathbf{h})-\mathbf{F}(\mathbf{h}-(p-k)\,\mathbf{q}_\perp)]\Big\}$$

$$\delta E(\mathbf{h},p,k) = \frac{\mathbf{h}^2}{2pk(p-k)} + \frac{m_k^2}{2k} + \frac{m_{(p-k)}^2}{2(p-k)} - \frac{m_p^2}{2p}$$

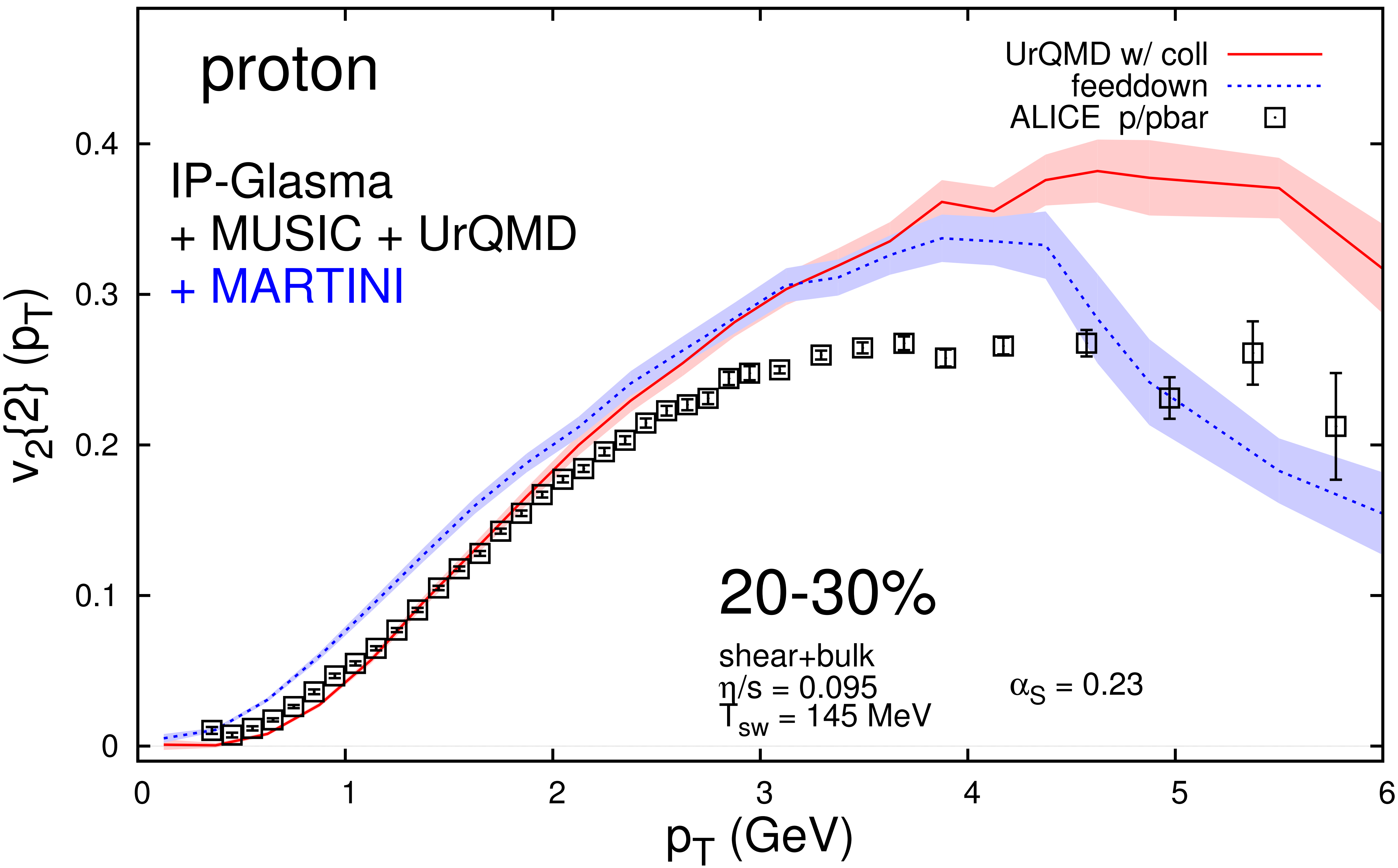
$$\mathbf{h}\equiv(\mathbf{k}\times\mathbf{p})\times\mathbf{e}_{||}$$

Spectra with MARTINI



It can be extended toward the higher p_T range.

Spectra with MARTINI



It can be extended toward the higher p_T range.