Hybrid approach to relativistic heavy-ion collisions at the RHIC BES energies

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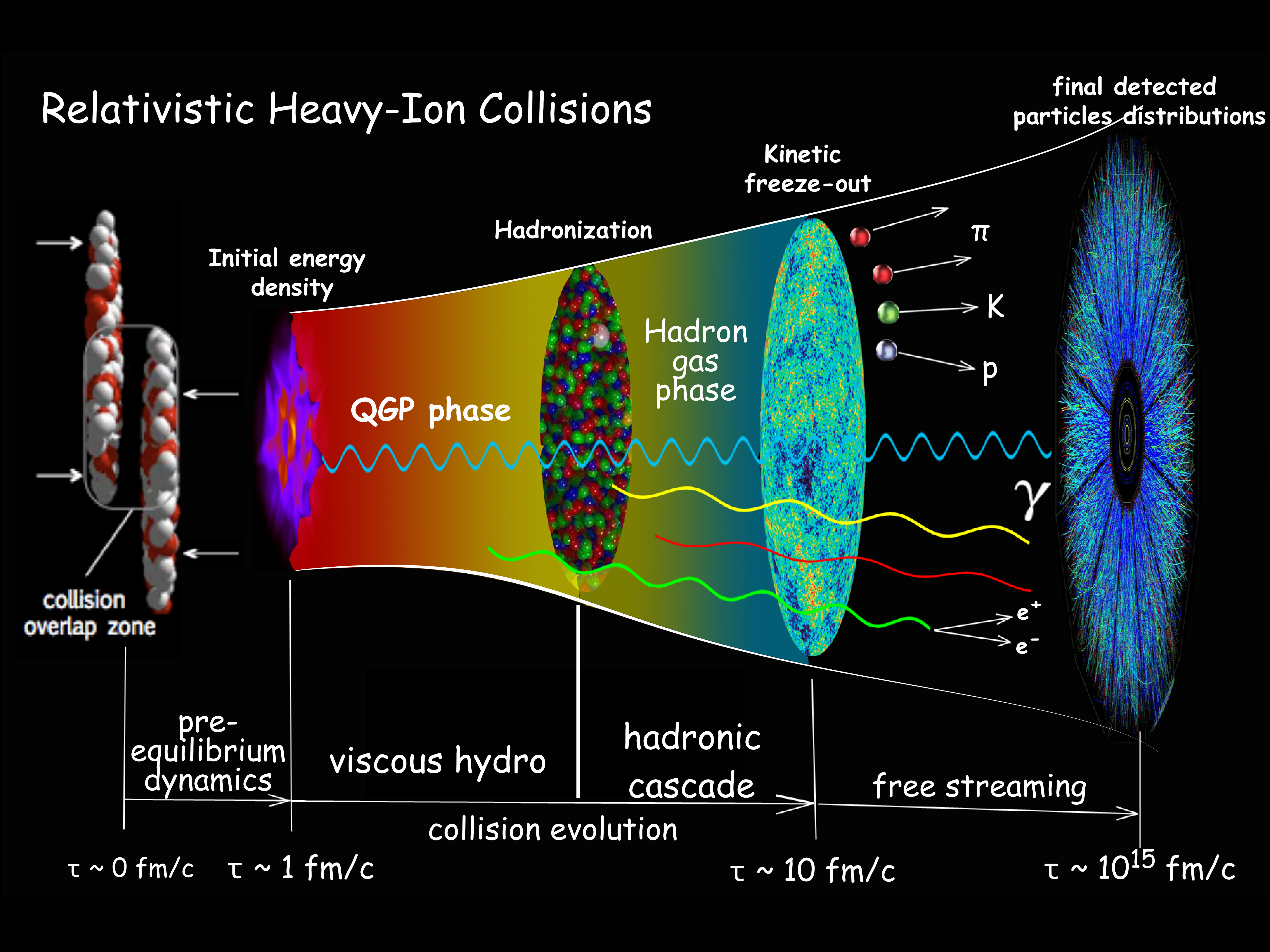
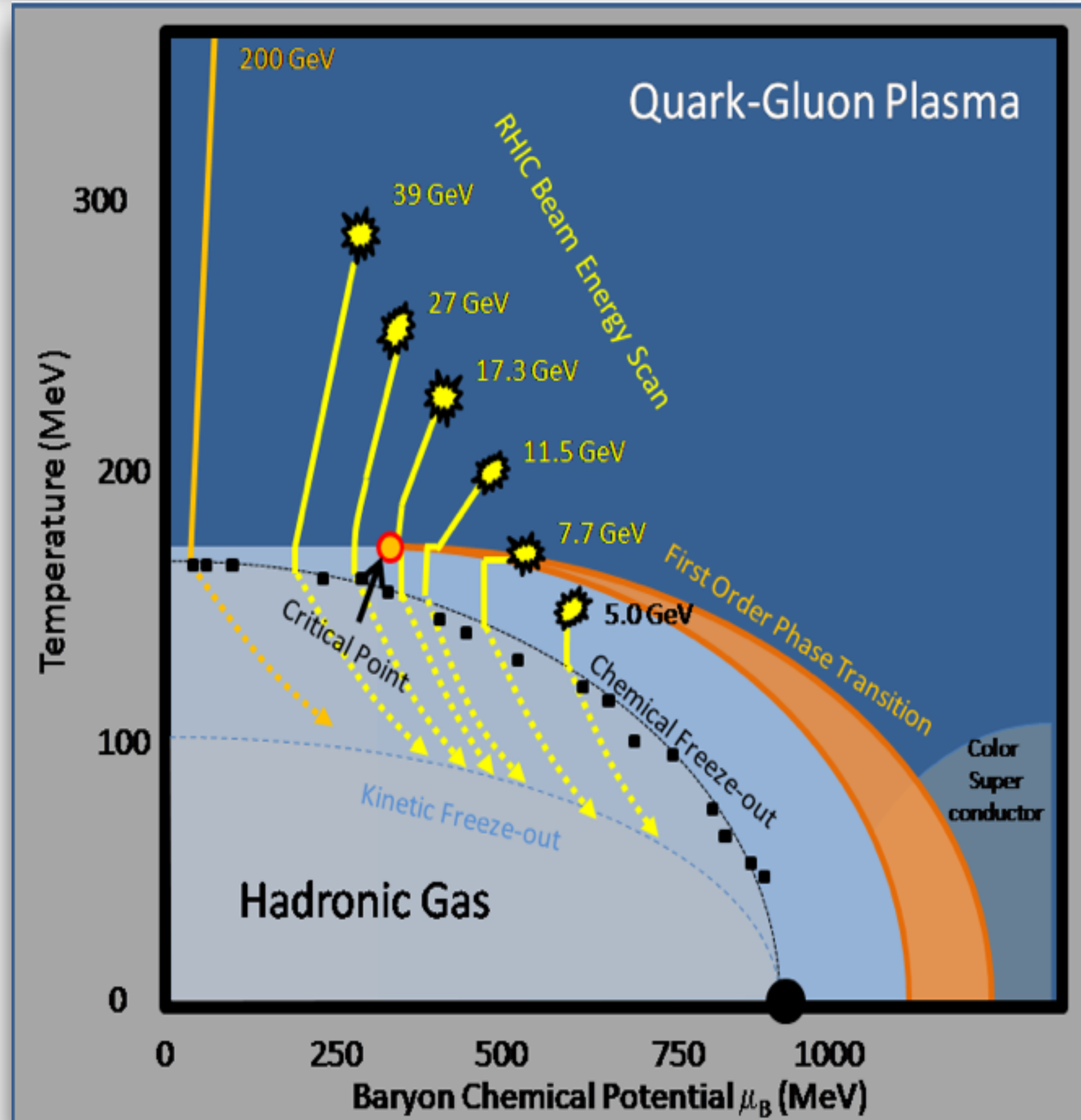
In collaboration with Gabriel Denicol, Akihiko Monnai, Bjoern Schenke, Sangyong Jeon, and Charles Gale

May 10, 2016 Indiana University Bloomington



Relativistic Heavy-Ion Collisions
final detected particles distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e^+
e^-
collision overlap zone
pre-equilibrium dynamics
viscous hydro
hadronic cascade
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^{15} fm/c

Exploring the phases of QCD



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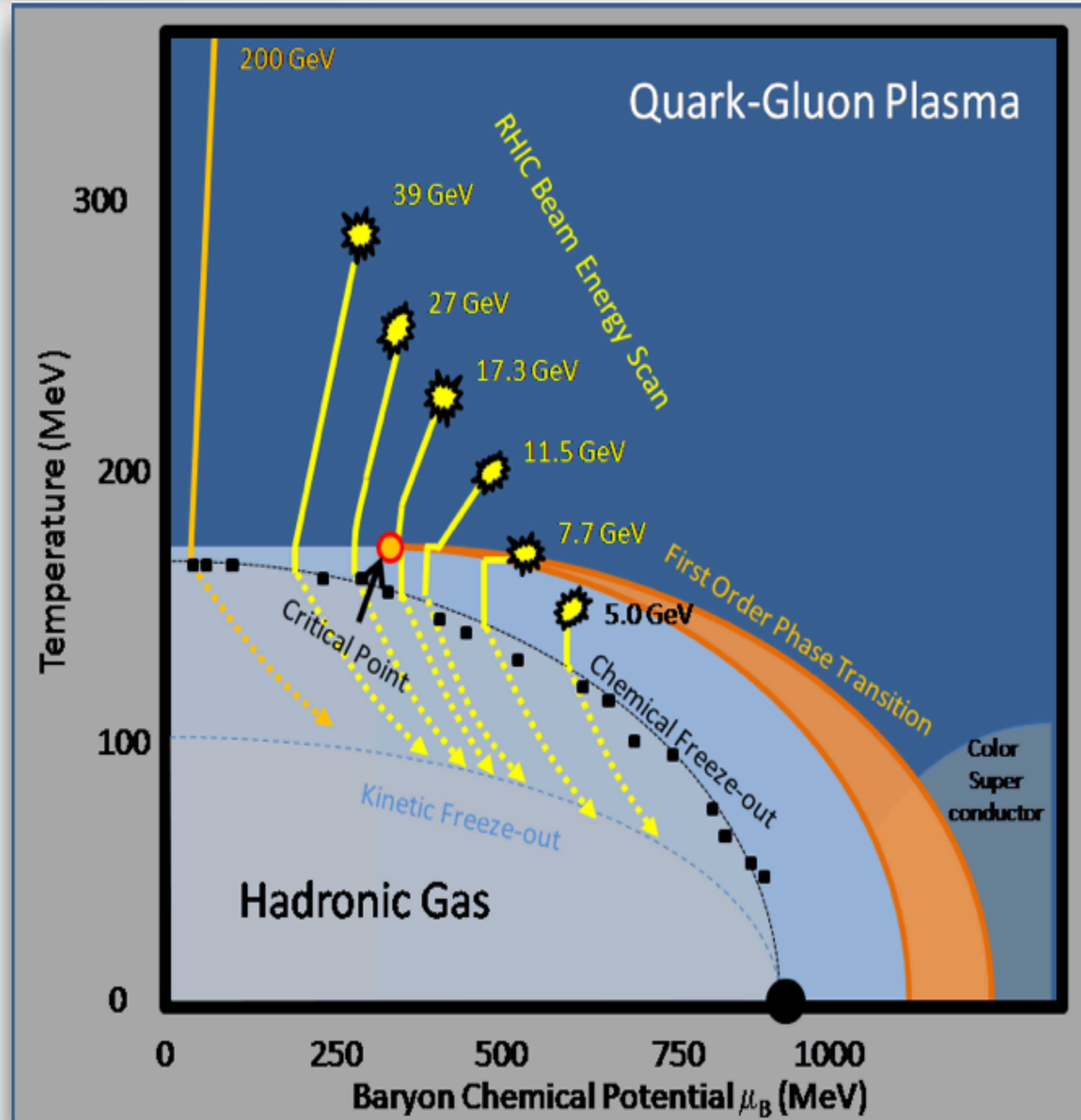
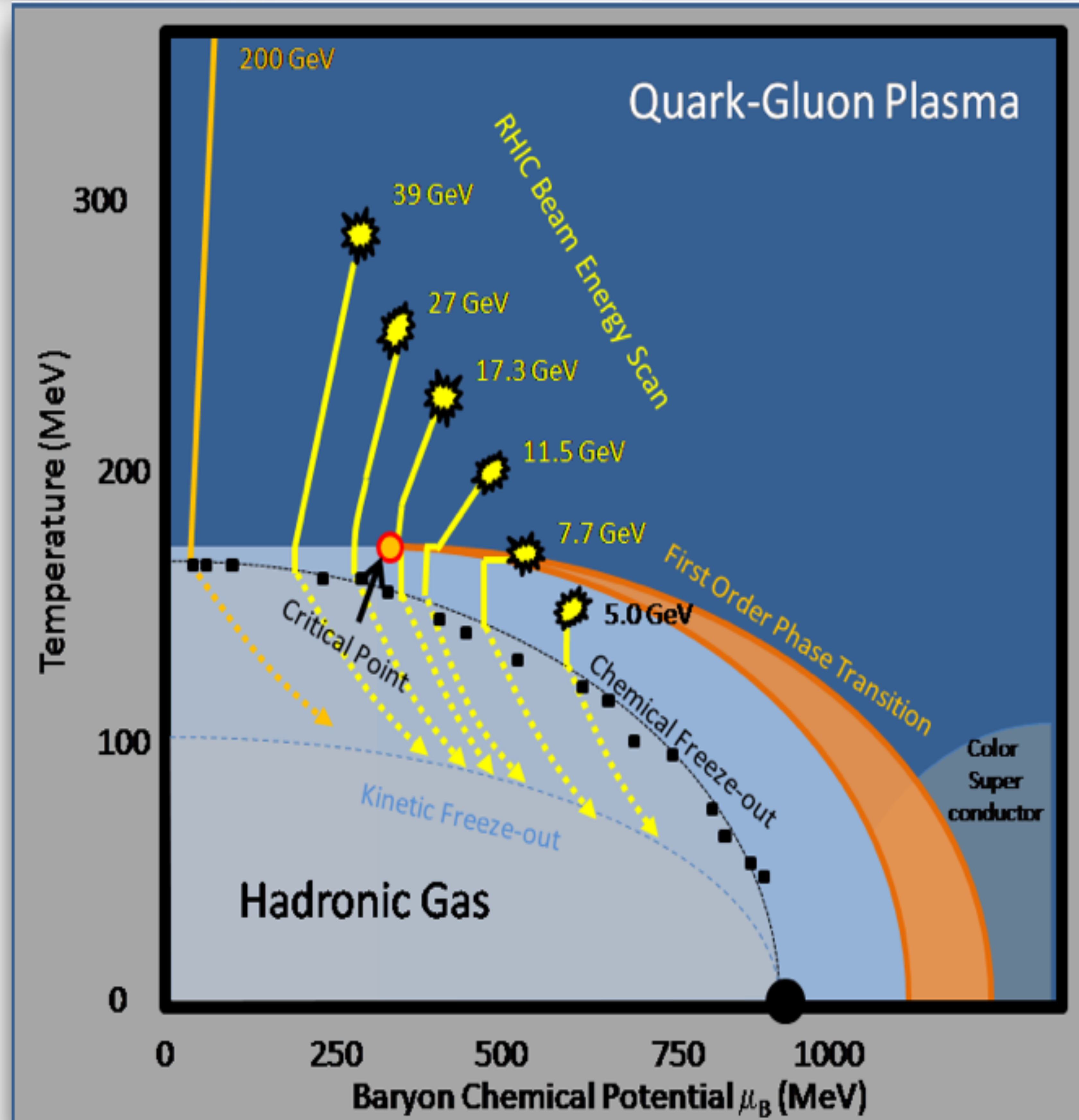


- Event-by-event fluctuating initial conditions
- (3+1)-d dissipative hydrodynamic modelling of the QGP
- Microscopic description for hadronic phase

Exploring the phases of QCD



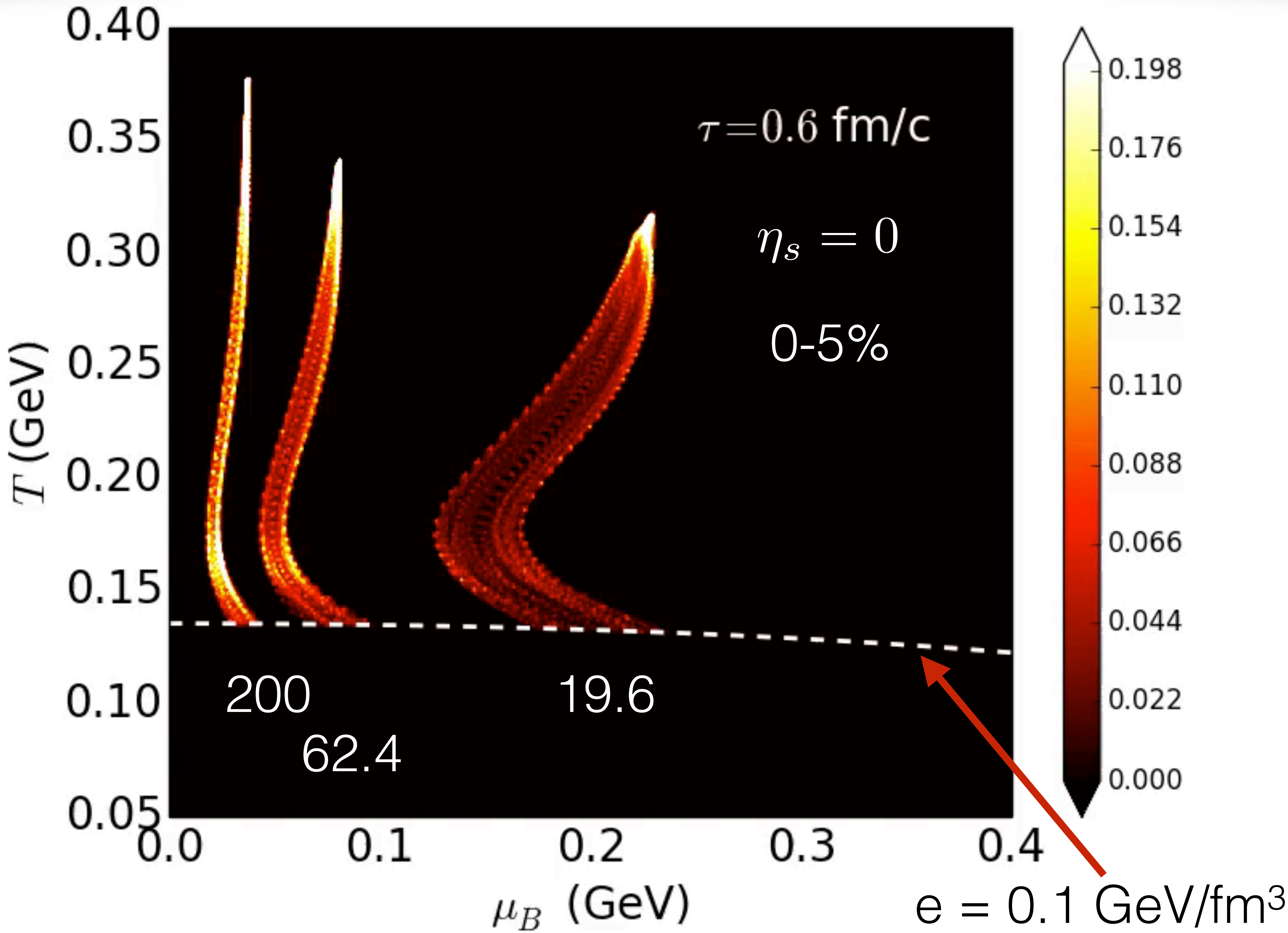
- Event-by-event fluctuating initial conditions

  (AMPT, UrQMD, MCGlb*, ...)
- (3+1)-d dissipative hydrodynamic modelling of the QGP

  MUSIC
- Microscopic description for hadronic phase

  UrQMD/JAM

Compass for the QCD phase diagram



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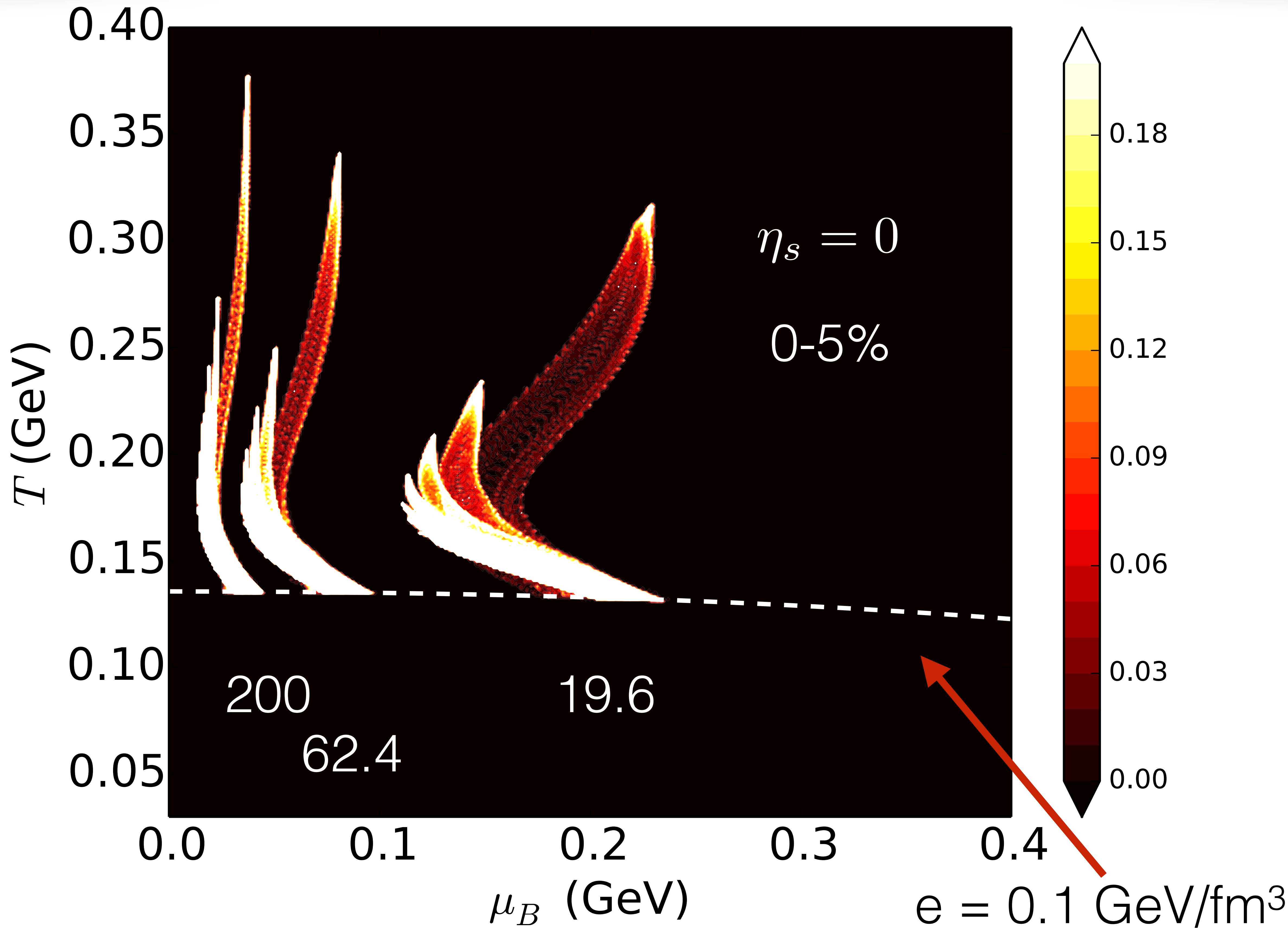


Initialize MUSIC with net baryon density

In every event, the net baryon number is

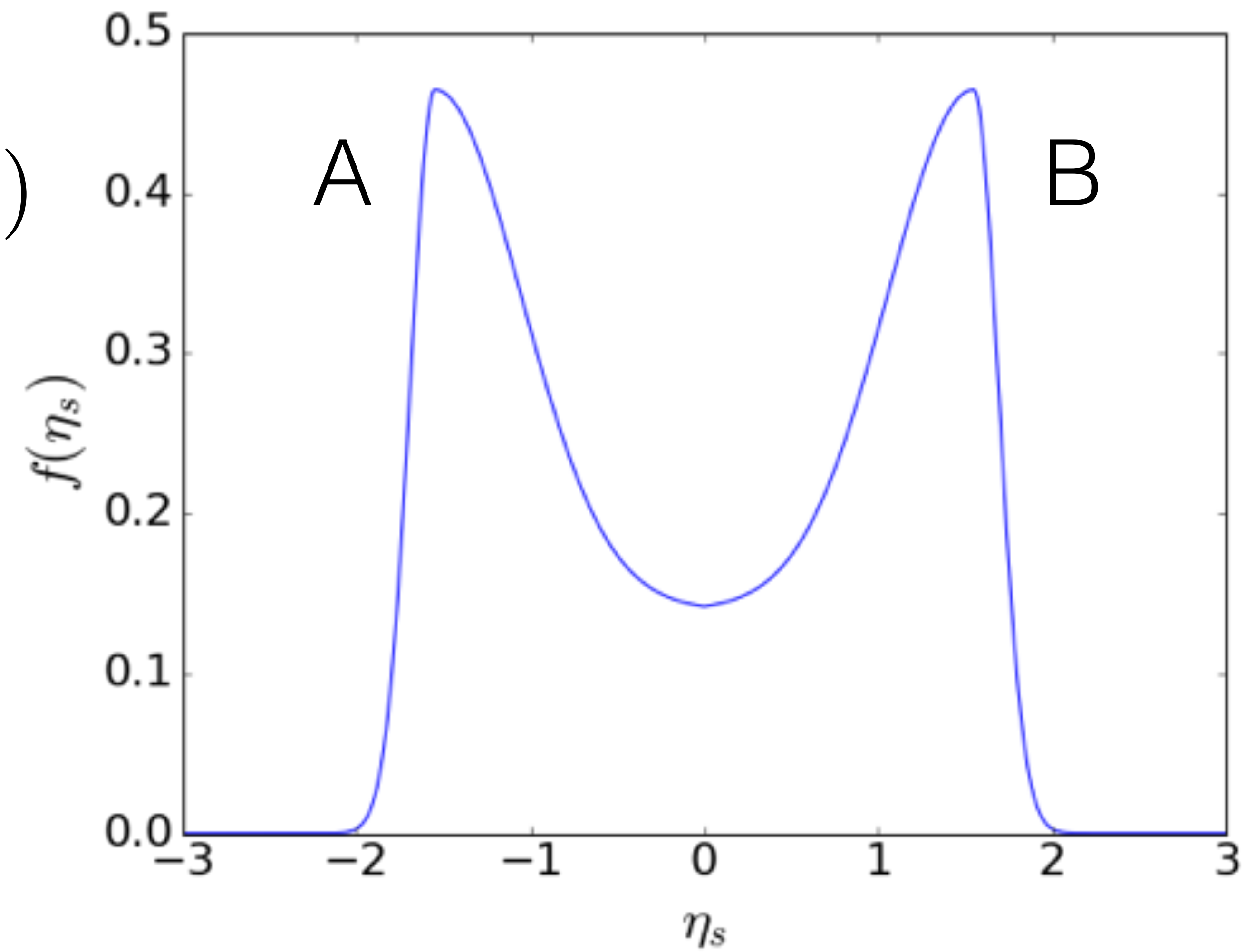
$$\int \tau_0 d\eta_s \int d^2\mathbf{x}_\perp \rho_B(\mathbf{x}_\perp, \eta_s) = N_{\rm part}.$$

For Glauber initial conditions, we assume

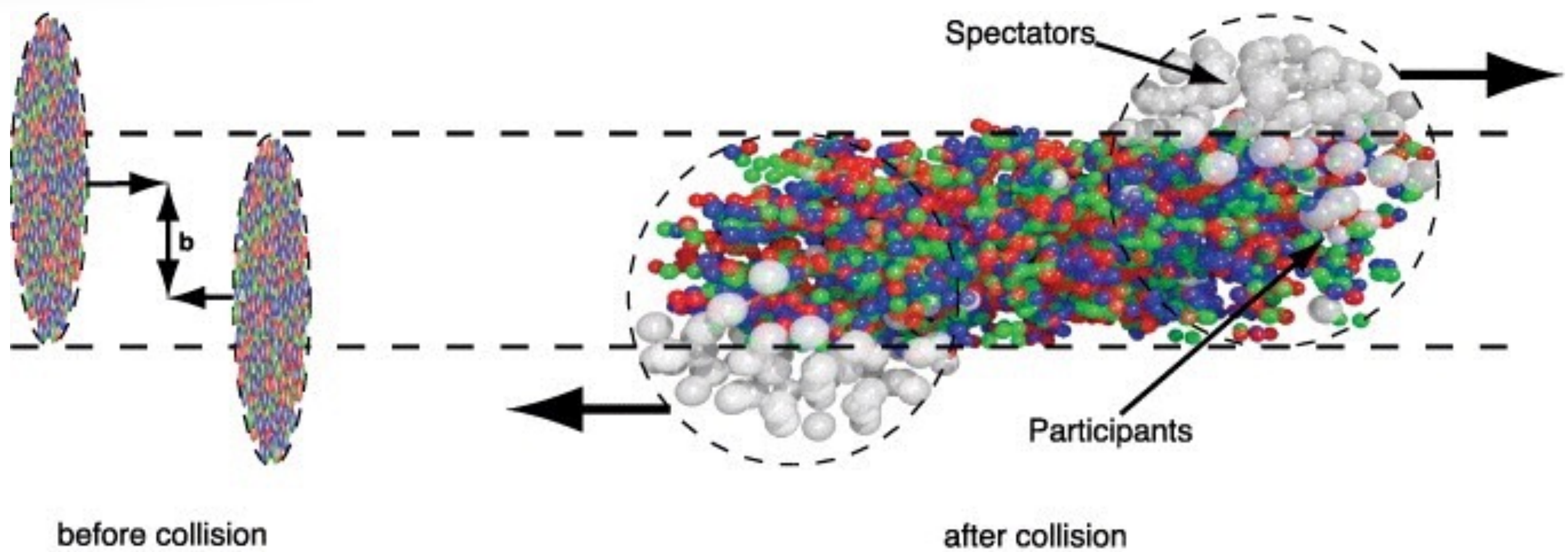
$$\rho_B(\mathbf{x}_\perp, \eta_s) = f_L(\eta_s) T_A(\mathbf{x}_\perp) + f_R(\eta_s) T_B(\mathbf{x}_\perp)$$

$$f_{L,R}(\eta_s) = \left(1 \mp \frac{\eta_s}{y_{\rm beam}}\right) f(\eta_s)$$

$$\int \tau_0 d\eta_s f_{L,R}(\eta_s) = 1$$

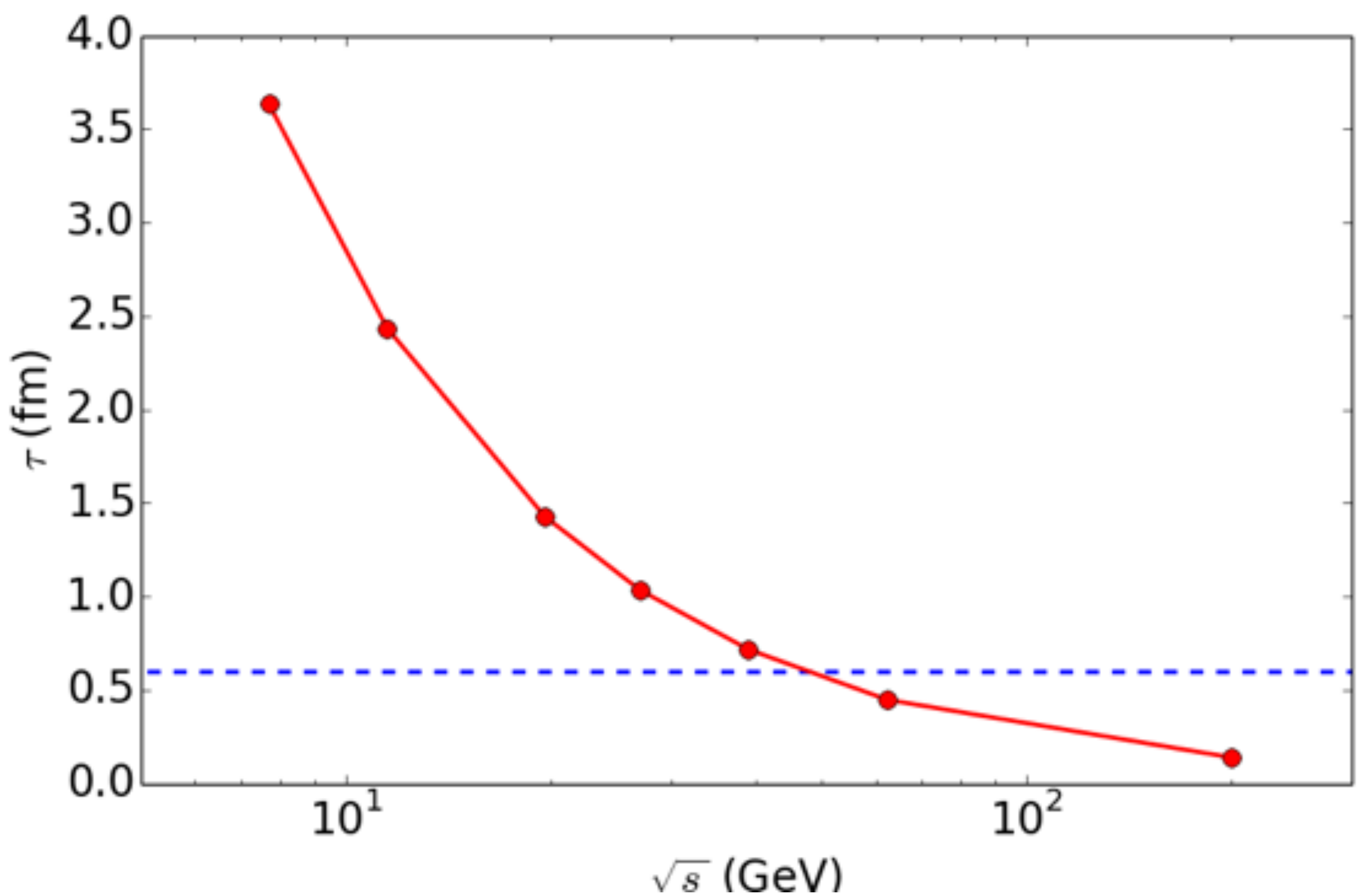


When to start hydrodynamics?



Two nuclei overlapping time

$$\tau \sim \frac{2R}{\gamma v_z}$$



- Nuclei overlapping time is large at low collision energy
- Pre-equilibrium dynamics can play an important role

$$\tau_0 = \max\left\{\frac{2R}{\gamma v_z}, 0.6\right\}\ \mathrm{fm}$$

Dissipative hydrodynamics

Energy momentum tensor

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

$$\partial_\mu T^{\mu\nu} = T^{\mu\nu};_\mu = 0$$

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

Conserved currents

$$J^\mu = nu^\mu + q^\mu$$

$$\partial_\mu J^\mu = 0$$

$$D = u^\mu \partial_\mu$$

$$\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$$

$$\theta = \partial_\mu u^\mu$$

Dissipative part:

G. S. Denicol *et al.*, Phys. Rev. D **89**, 074005 (2014)

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} + \frac{l_{\pi q}}{\tau_\pi}\nabla^{\langle\mu}q^{\nu\rangle} + \frac{\lambda_{\pi q}}{\tau_\pi}q^{\langle\mu}\nabla^{\nu\rangle}\frac{\mu_B}{T}$$

$$\Delta^{\mu\nu} Dq_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa\nabla^\mu\frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q}q^\mu\theta - \frac{\lambda_{qq}}{\tau_q}q_\nu\sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda\pi^\lambda_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla_\nu\frac{\mu_B}{T}$$

Transport coefficients

Dissipative part:

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With non-zero μ, we choose $\frac{\eta T}{e+\mathcal{P}} = 0.08$ $\tau_\pi = \frac{5\eta}{e+\mathcal{P}} = \frac{0.4}{T}$

In the relaxation time approximation, the net baryon diffusion constant can be related to shear viscosity as,

(in the massless and small μ/T limits)

$$\kappa = \frac{5}{3}\frac{\eta T}{e+\mathcal{P}}\frac{n_B}{\mu_B} = C\frac{n_B}{\mu_B} \qquad \tau_q = \frac{C}{T}$$

To study the effects of diffusion, we choose the constant C independent of η

$$\delta_{qq} = \tau_q \quad \lambda_{qq} = \frac{3}{5}\tau_q$$

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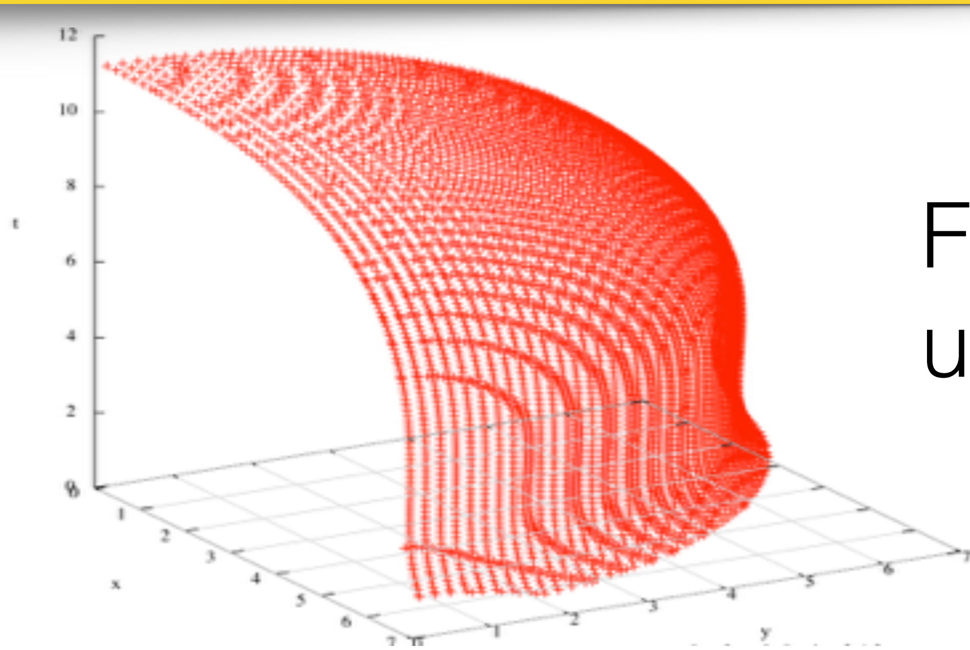
G. S. Denicol *et al.*, Phys. Rev. D **89**, 074005 (2014)

Convert to particles



Freeze-out hyper surface is determined using **Cornelius** freeze-out algorithm

P. Huovinen and H. Petersen, Eur. Phys. J. A **48**, 171 (2012)

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int p^\mu d^3\sigma_\mu(x)\left(f_0(x,p) + \delta f(x,p)\right)$$

$$f_0^i(x,p) = \frac{1}{e^{(E - b_i\mu_B(x))/T(x)} \pm 1}$$

From the relaxation time approximation,

$$\delta f_0^i(x,p) = f_0^i(x,p)(1 \pm f_0^i(x,p))\left(\frac{n_B}{e+\mathcal{P}} - \frac{b_i}{E}\right)\frac{p\cdot q}{\hat{\kappa}}$$

$$\hat{\kappa} = \kappa/\tau_q$$

$\hat{\kappa}(T,\mu_B)$ is calculated using hadron resonance gas model

Diffusion δf is essential

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int p^\mu d^3\sigma_\mu(x)\left(f_0(x,p) + \delta f(x,p)\right)$$

$$f_0^i(x,p) = \frac{1}{e^{(E-b_i\mu_B(x))/T(x)} \pm 1}$$

$$\delta f_0^i(x,p) = f_0^i(x,p)(1 \pm f_0^i(x,p))\left(\frac{n_B}{e+\mathcal{P}} - \frac{b_i}{E}\right)\frac{p\cdot q}{\hat{\kappa}}$$

$$N^B - N^{\bar{B}} = \int d^3\sigma_\mu \sum \frac{g_i}{(2\pi)^3}\int_p p^\mu \left[(f_0^B(x,p) - f_0^{\bar{B}}(x,p)) + (\delta f^B(x,p) - \delta f^{\bar{B}}(x,p))\right]$$

$$= \int d^3\sigma_\mu(n_B u^\mu + q^\mu)$$

$$\partial_\mu(n_B u^\mu + q^\mu) = 0$$

$N^B - N^{\bar{B}}$ is conserved

- With diffusion, δf is essential to ensure net baryon number conservation

Diffusion δf is essential

$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int p^\mu d^3\sigma_\mu(x)(f_0(x,p) + \delta f(x,p))$$

$$f_0^i(x,p) = \frac{1}{e^{(E - b_i\mu_B(x))/T(x)} \pm 1}$$

$$\delta f_0^i(x,p) = f_0^i(x,p)(1 \pm f_0^i(x,p))\left(\frac{n_B}{e+\mathcal{P}} - \frac{b_i}{E}\right)\frac{p\cdot q}{\hat{\kappa}}$$

$$N^B - N^{\bar{B}} = \int d^3\sigma_\mu \sum \frac{g_i}{(2\pi)^3}\int_p p^\mu \left[(f_0^B(x,p \ldots x,p))\right]$$

$$= \int d^3\sigma_\mu(n_B u^\mu + q^\mu)$$

$$\partial_\mu(n_B u^\mu + q^\mu) = 0$$

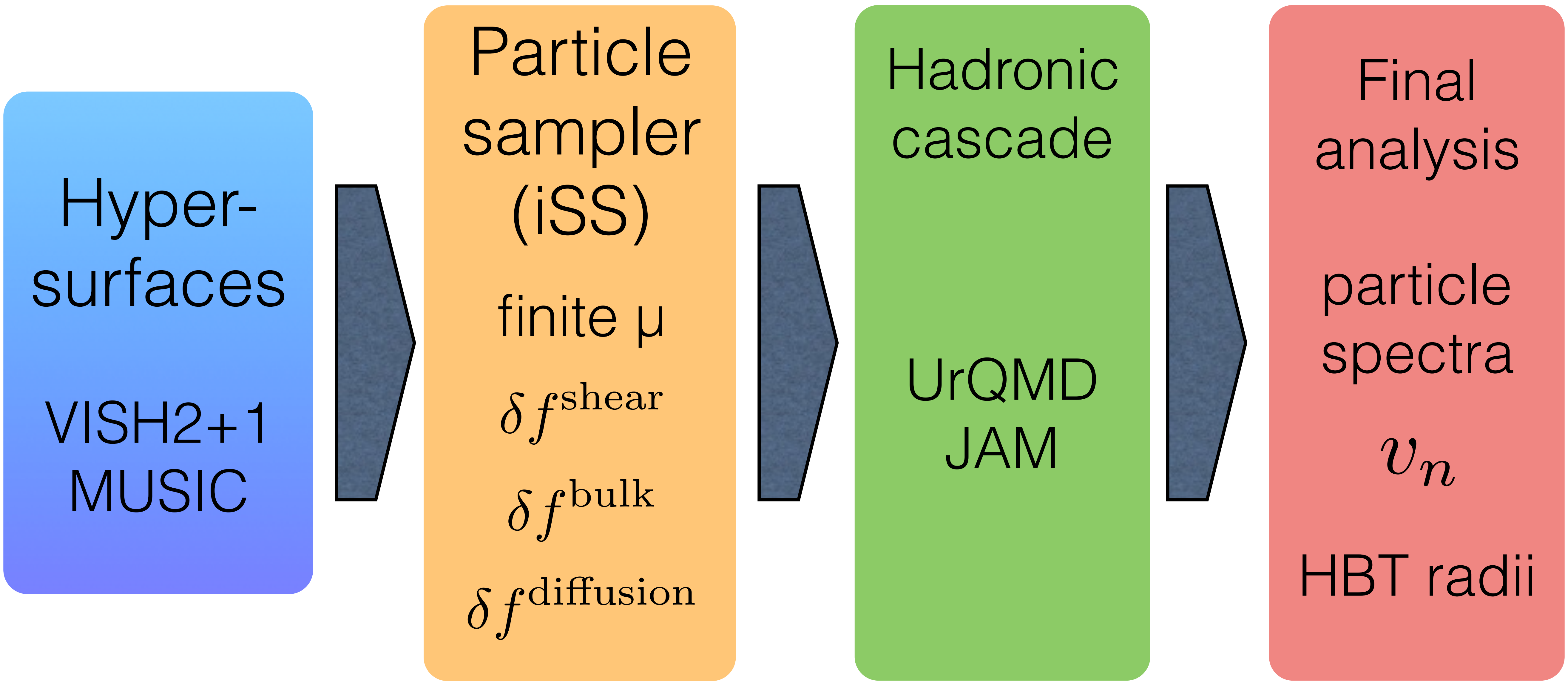
Conservation laws (net baryon number and total energy) are checked at every time step; the relative violation is below 1×10^{-5}

- With diffusion, δf is essential to e… conservation

Switching to hadronic cascade

Fork me on GitHub

Afterburner toolkit:

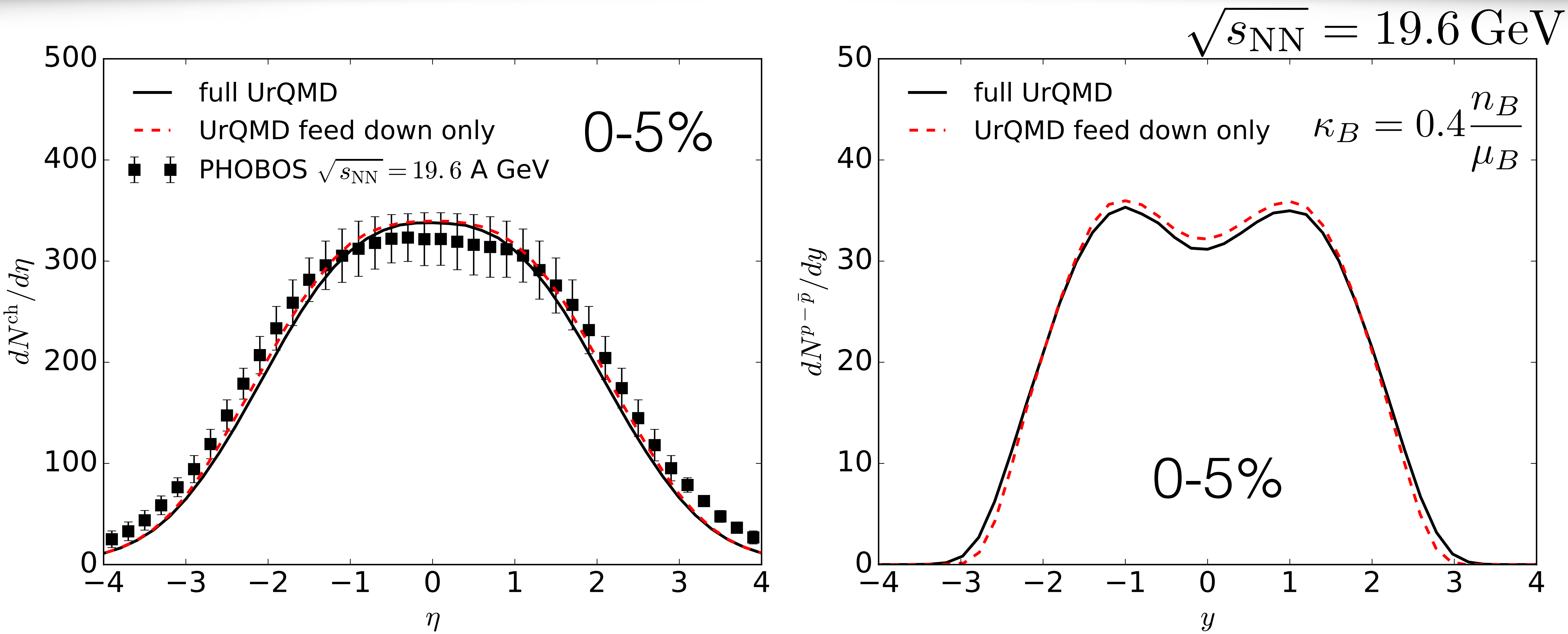


- **Efficient, well-tested, and open source**

https://github.com/chunshen1987/HBTcorrelation_MCafterburner

Results

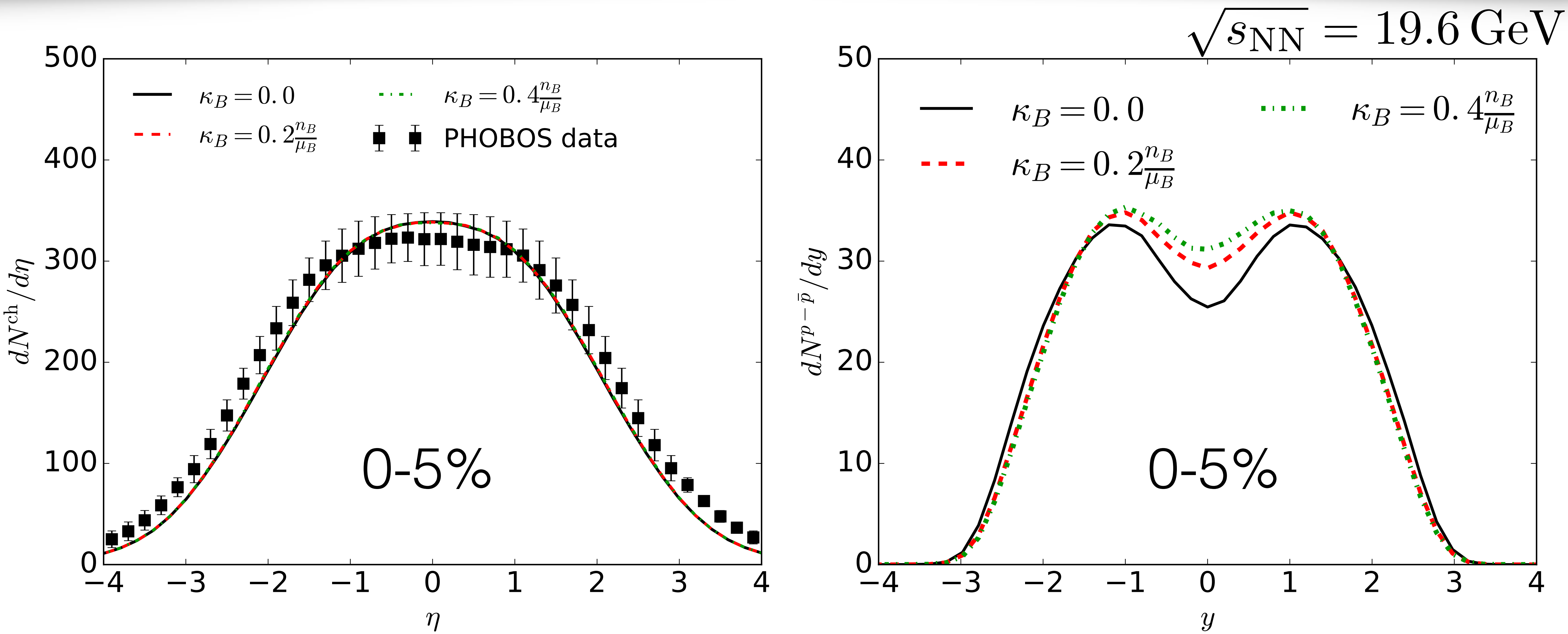
Effects of hadronic afterburner on particle yields



- Hadronic afterburner has little effects on charged hadron pseudo-rapidity distribution
- Net proton rapidity profile is slightly flatter after hadronic scatterings

more sensitive to early stage dynamics

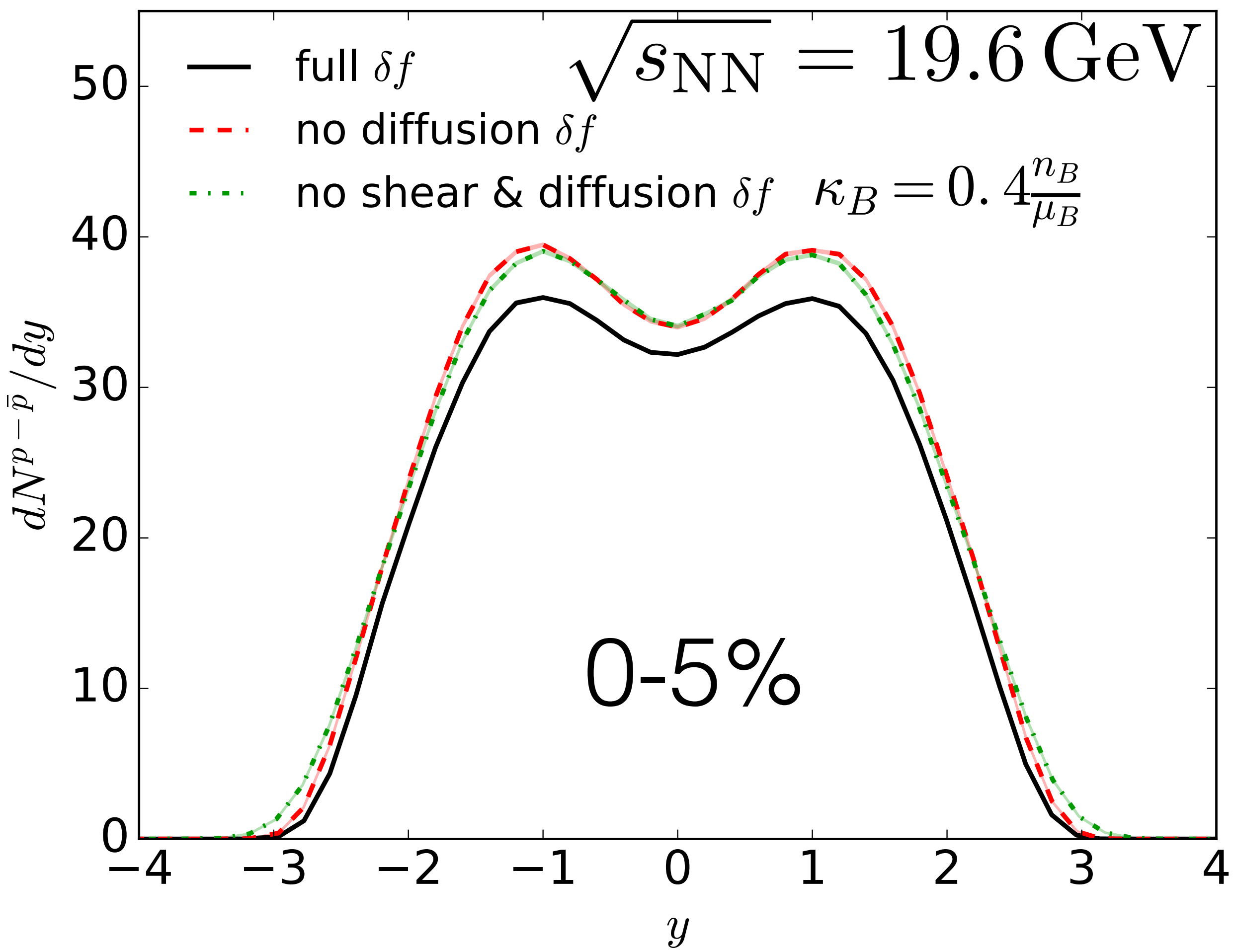
Effects of net baryon diffusion on particle yields



- Net baryon diffusion has little effects on charged hadron pseudo-rapidity distribution
- More net baryon numbers are transported to mid-rapidity with a larger diffusion constant

Constraints on net baryon diffusion?

Effects of net baryon diffusion on particle yields



On the switching hyper-surface,

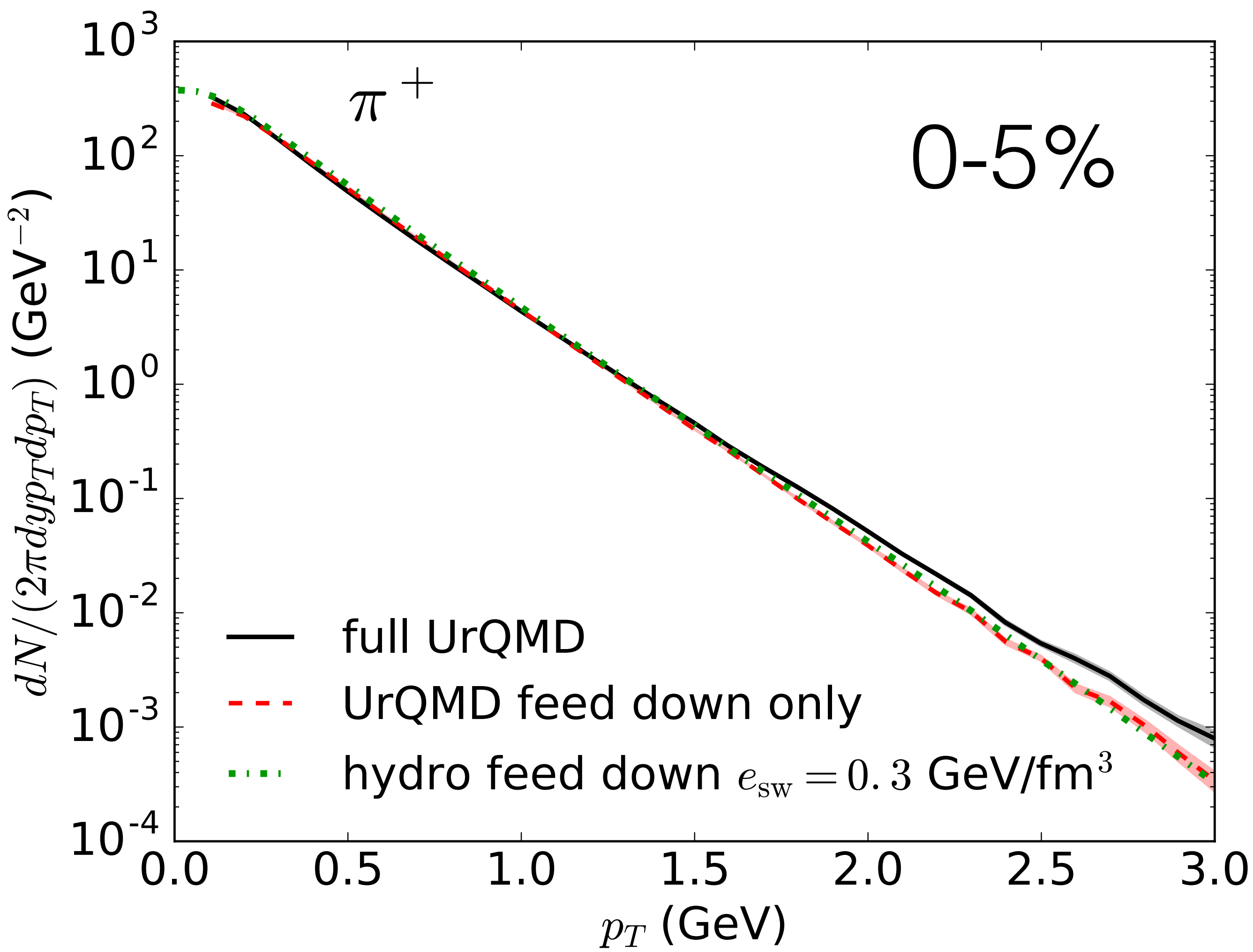
	$\kappa_B = 0.0$	$\kappa_B = 0.2\frac{n_B}{\mu_B}$	$\kappa_B = 0.4\frac{n_B}{\mu_B}$
$\langle\mu_B\rangle$ (GeV)	0.23	0.25	0.26
σ_{μ_B} (GeV)	0.076	0.062	0.06

- The diffusion δf **changes** net proton number
- Larger diffusion constant results a ~20 MeV larger averaged chemical potential on the switching hyper-surface; It reduces the standard deviation of μ_B by ~15%

mapping the QCD phase diagram in precision

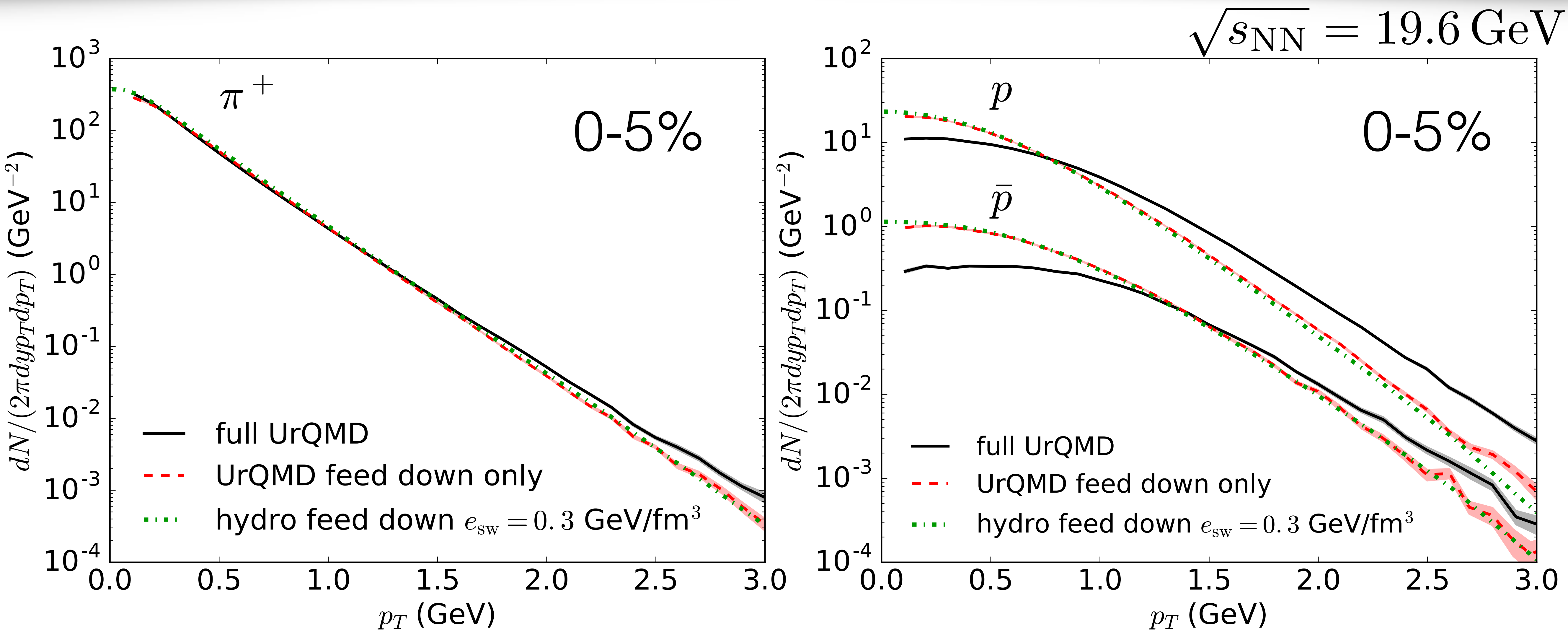
Effects of hadronic afterburner on pid spectra

$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$



- Hadronic afterburner harden pion spectra at high p_T

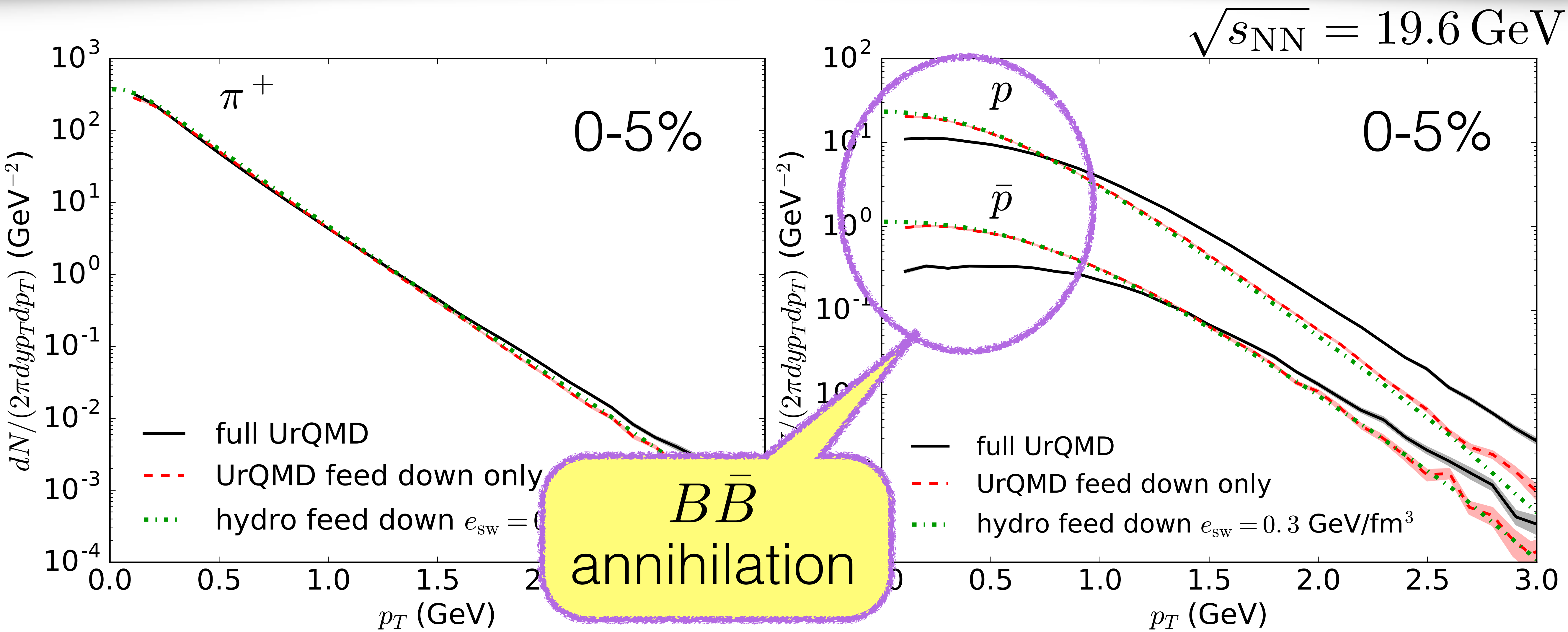
Effects of hadronic afterburner on pid spectra



- Hadronic afterburner harden pion spectra at high p_T
- Heavy baryon spectra are largely affected

hadronic afterburner is essential for baryon spectra

Effects of hadronic afterburner on pid spectra



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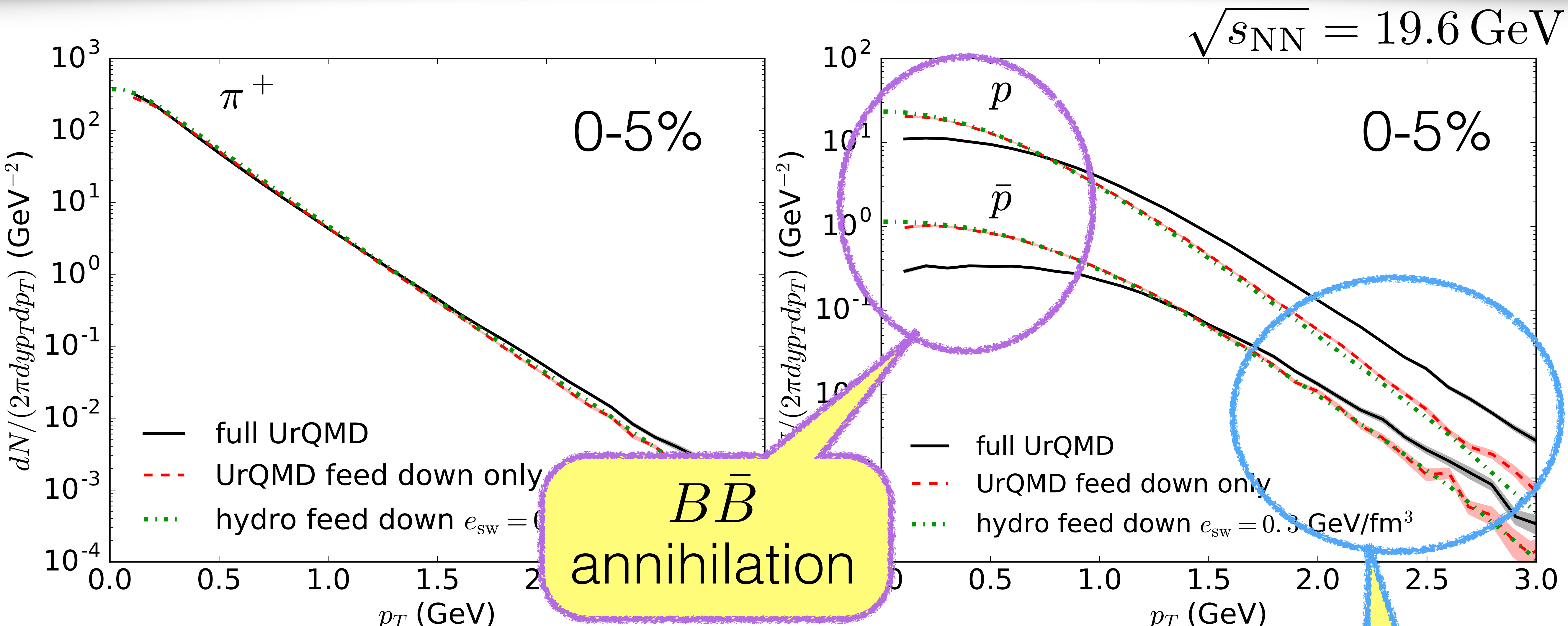

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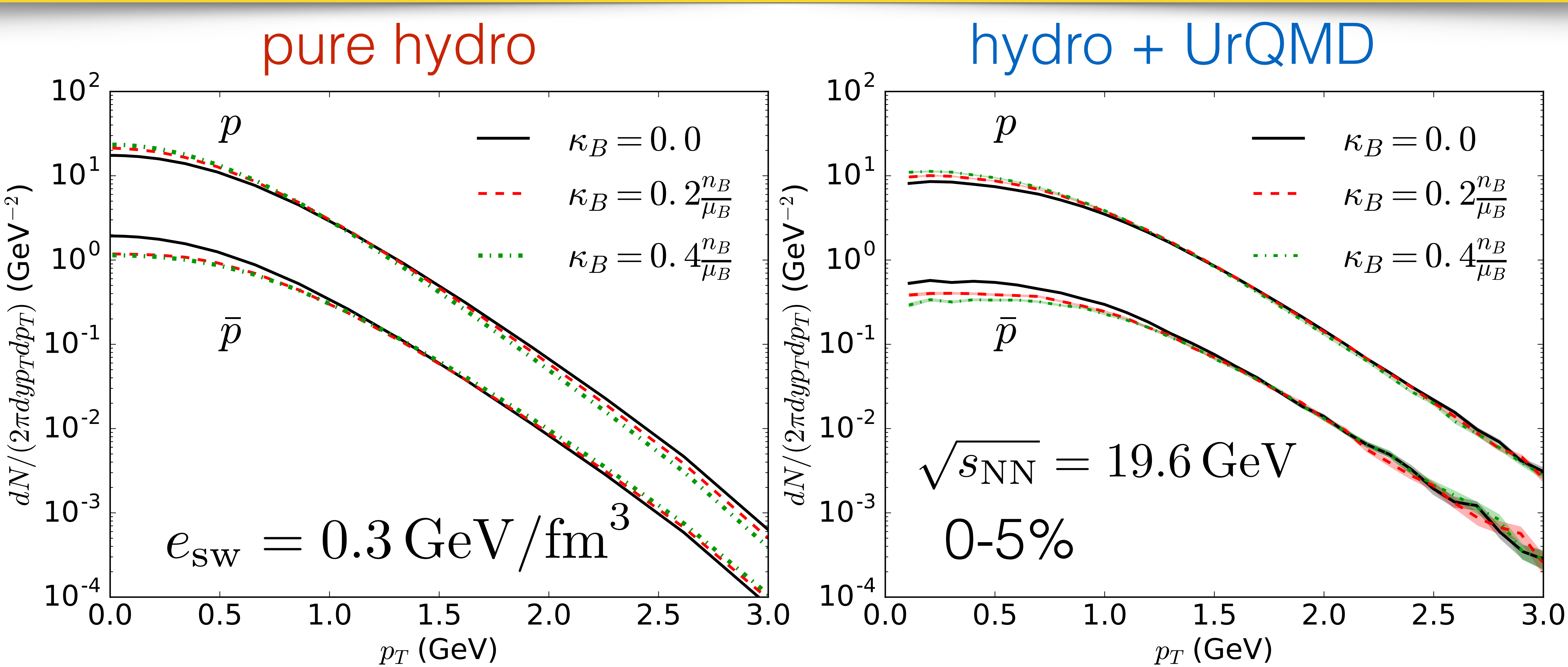
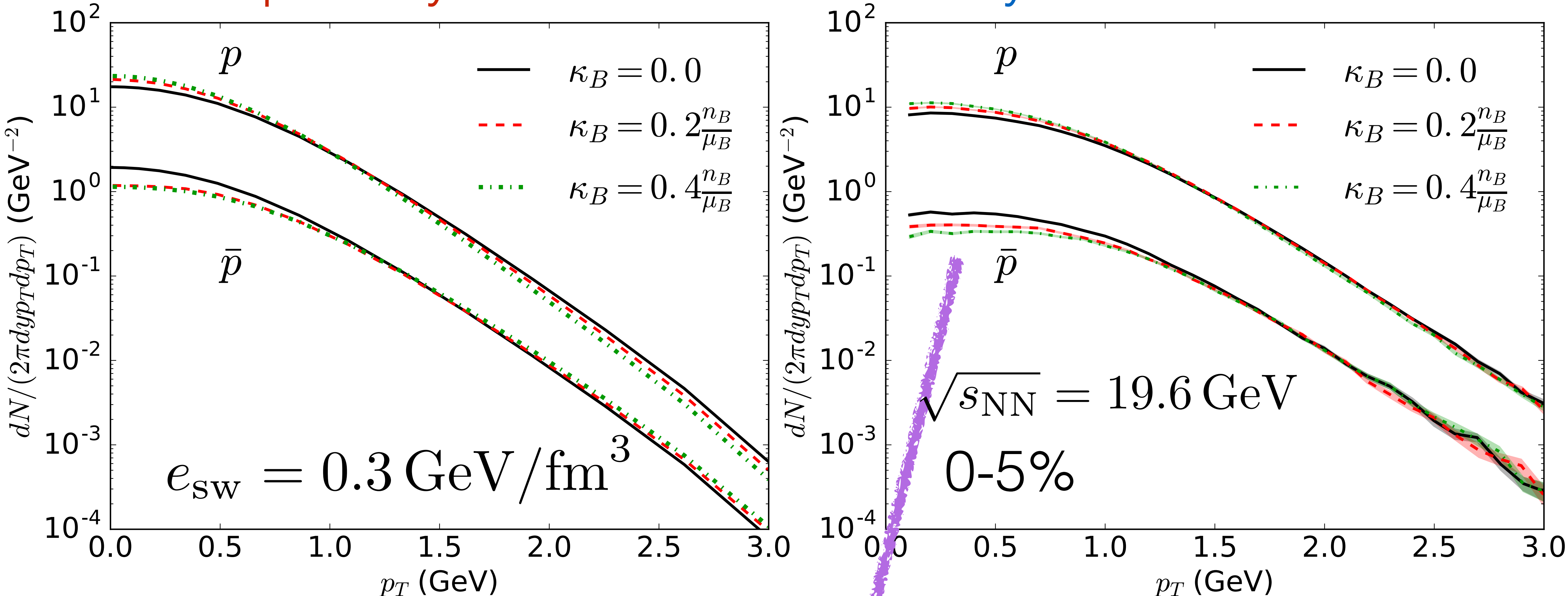
Effects of net baryon diffusion on pid spectra



- Hadronic scatterings erase the diffusion effects at high p_T

Effects of net baryon diffusion on pid spectra

pure hydro　　　　　　　　　　　hydro + UrQMD

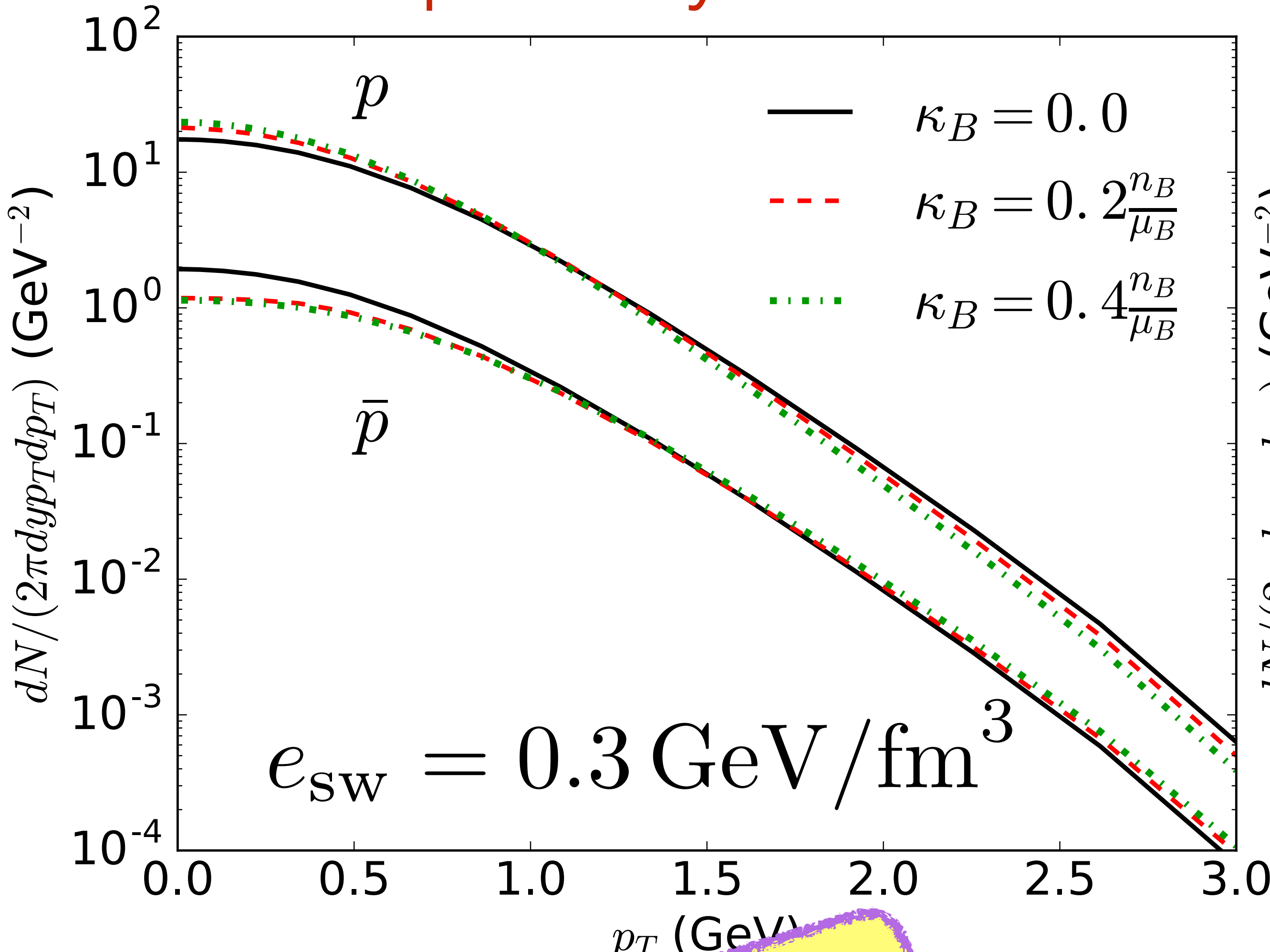


- Hadronic scatterings erase the diffusion effects at high p_T

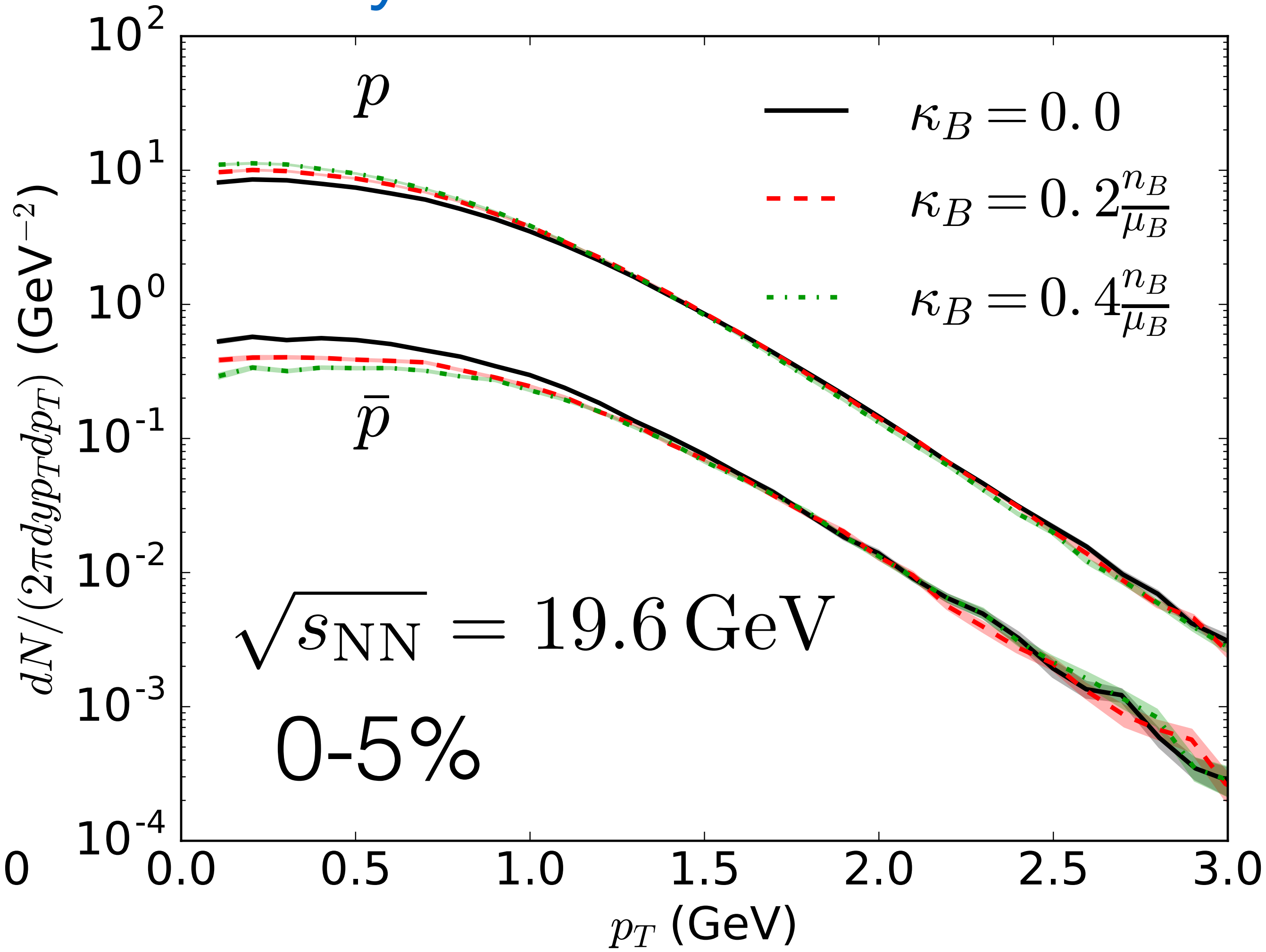
	$\kappa_B = 0.0$	$\kappa_B = 0.2\frac{n_B}{\mu_B}$	$\kappa_B = 0.4\frac{n_B}{\mu_B}$
$\langle p_\perp \rangle^{\bar{p}} - \langle p_\perp \rangle^{p}$ (GeV)	0.042	0.108	0.162

Effects of net baryon diffusion on pid spectra

pure hydro



hydro + UrQMD

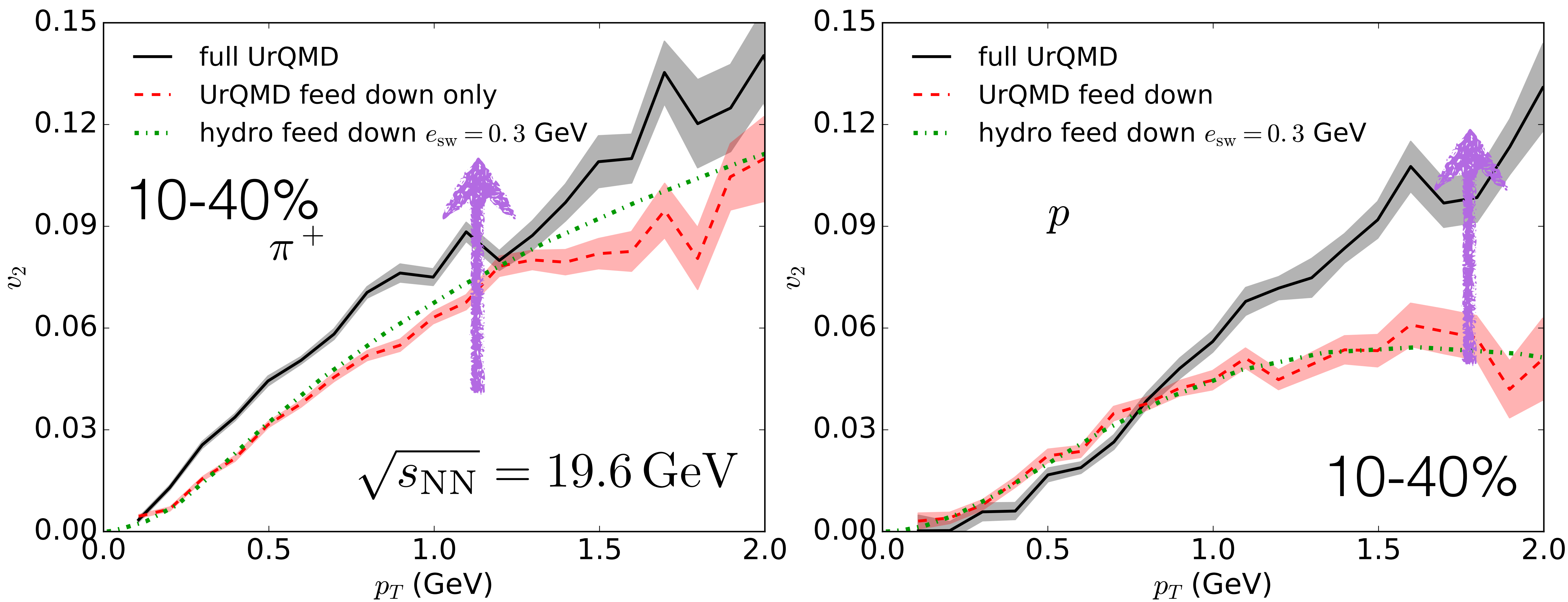


- Hadr… gs erase the diffusion effects at high p_T

set constraints on net baryon diffusion

	$\kappa_B = 0.0$	$\kappa_B = 0.2\frac{n_B}{\mu_B}$	$\kappa_B = 0.4\frac{n_B}{\mu_B}$
$\langle p_\perp \rangle^{\bar{p}} - \langle p_\perp \rangle^{p}$ (GeV)	0.042	0.108	0.162

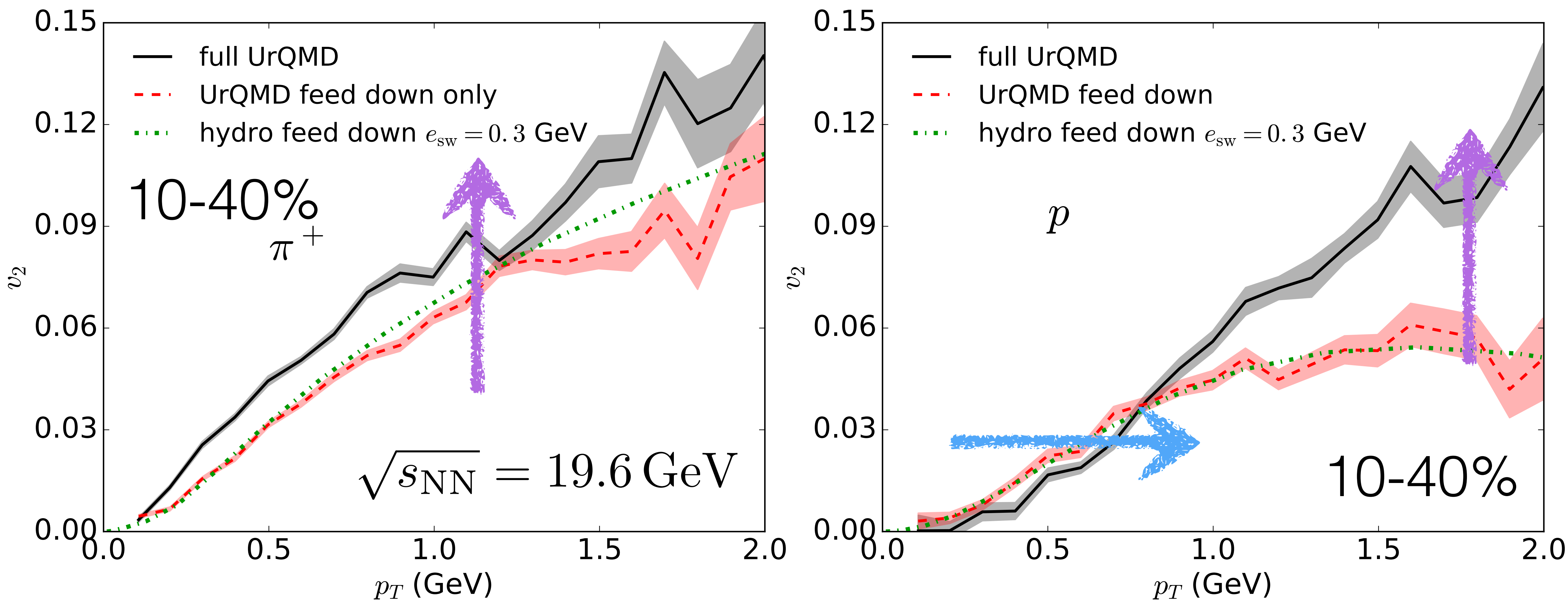
Effects of hadronic afterburner on pid v_2



- Momentum anisotropy keeps developing in the UrQMD phase

hadronic afterburner is essential

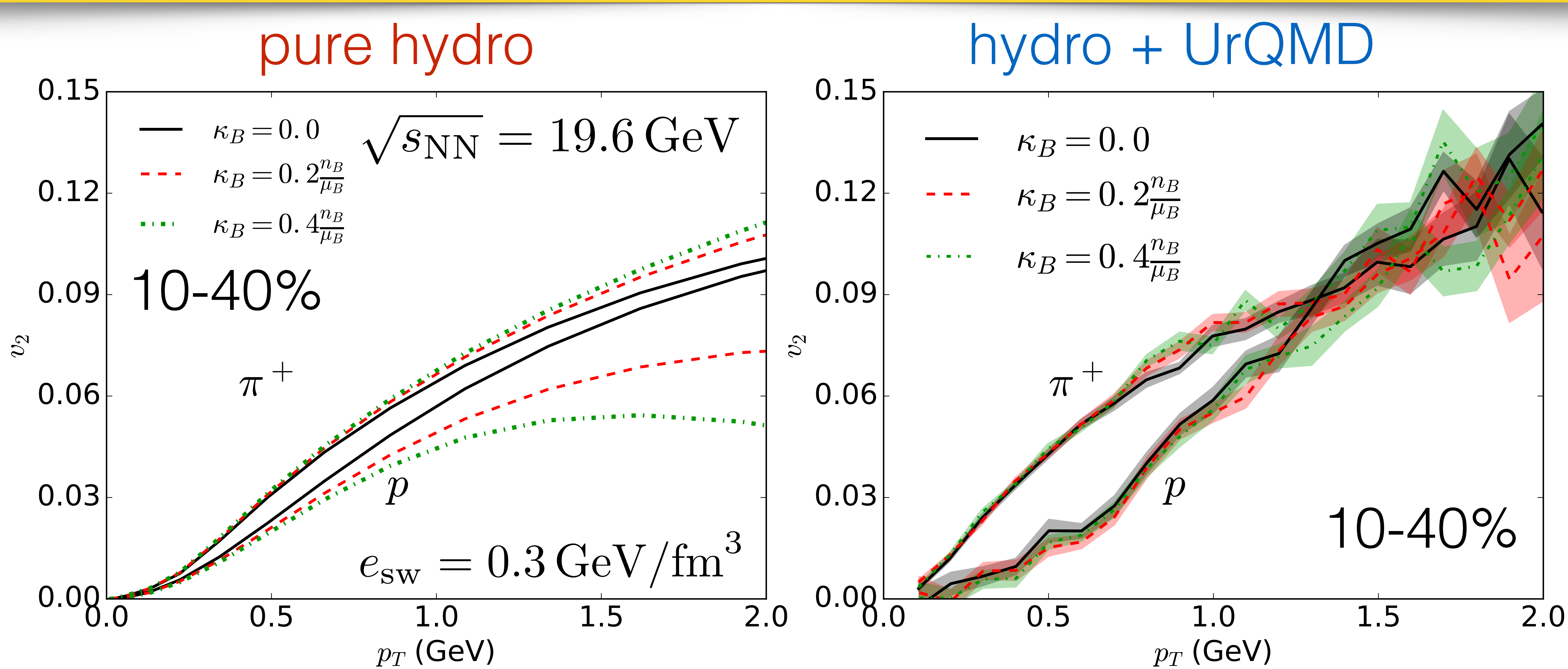
Effects of hadronic afterburner on pid v_2



- Momentum anisotropy keeps developing in the UrQMD phase
- Low p_T proton v_2 is blue shifted because of the pion "wind"

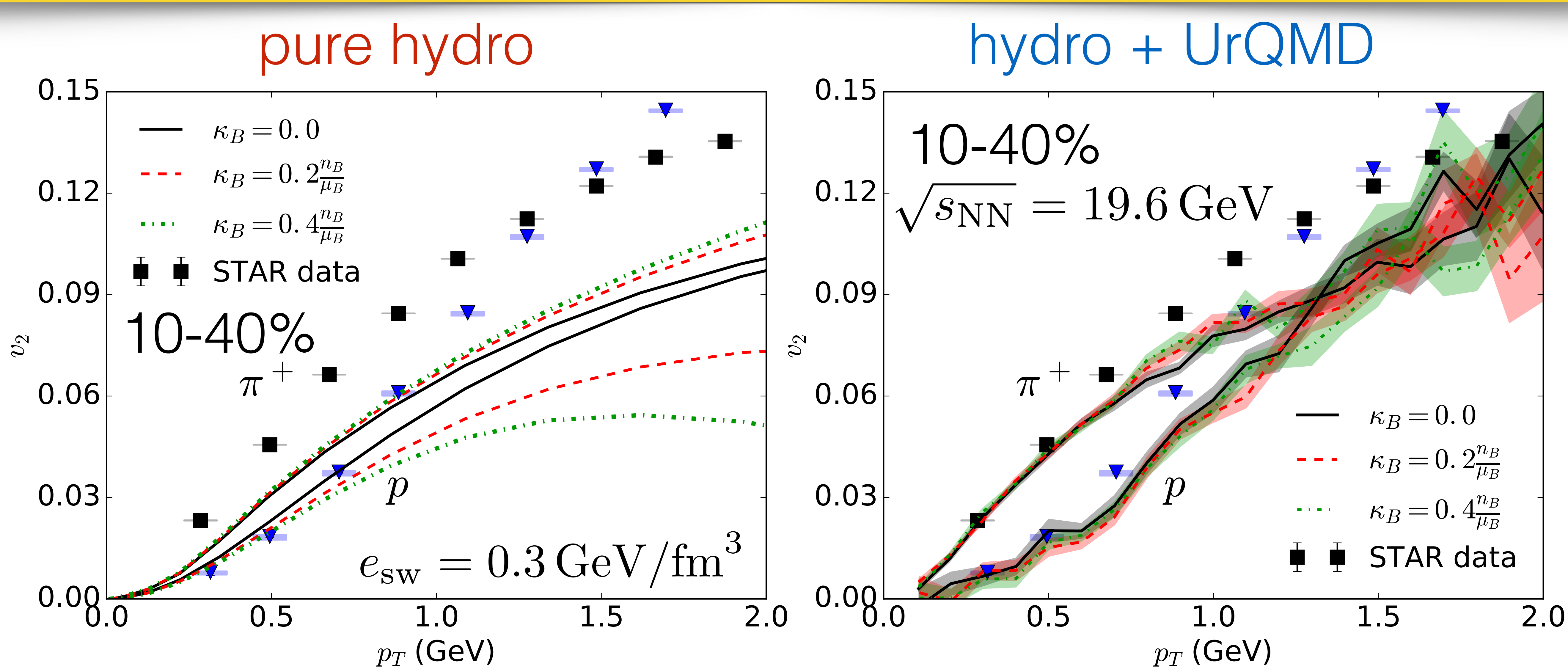
hadronic afterburner is essential

Effects of net baryon diffusion on pid v_2



- Hadronic scatterings wash out most of the diffusion effects on pid v_2

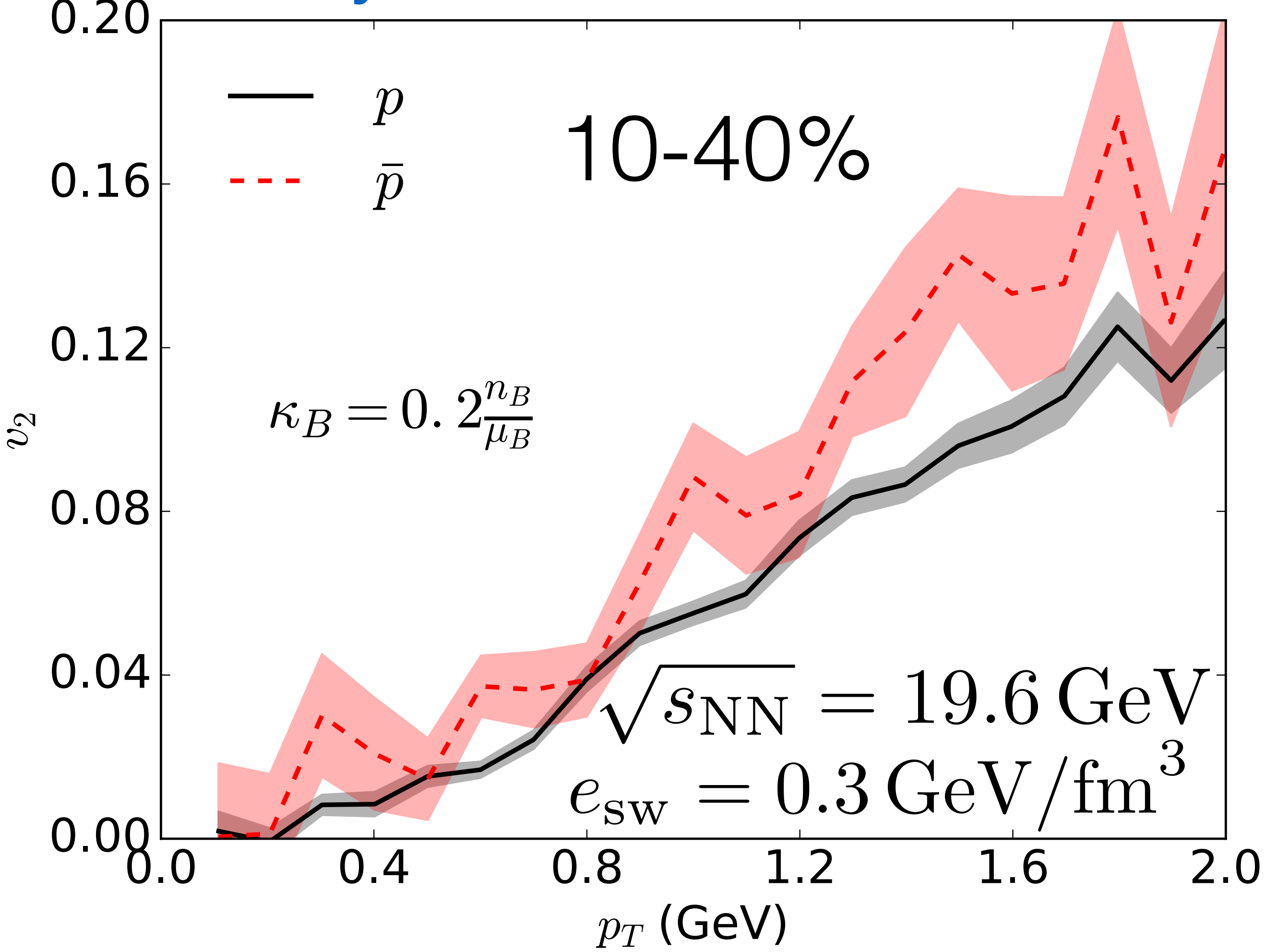
Effects of net baryon diffusion on pid v_2



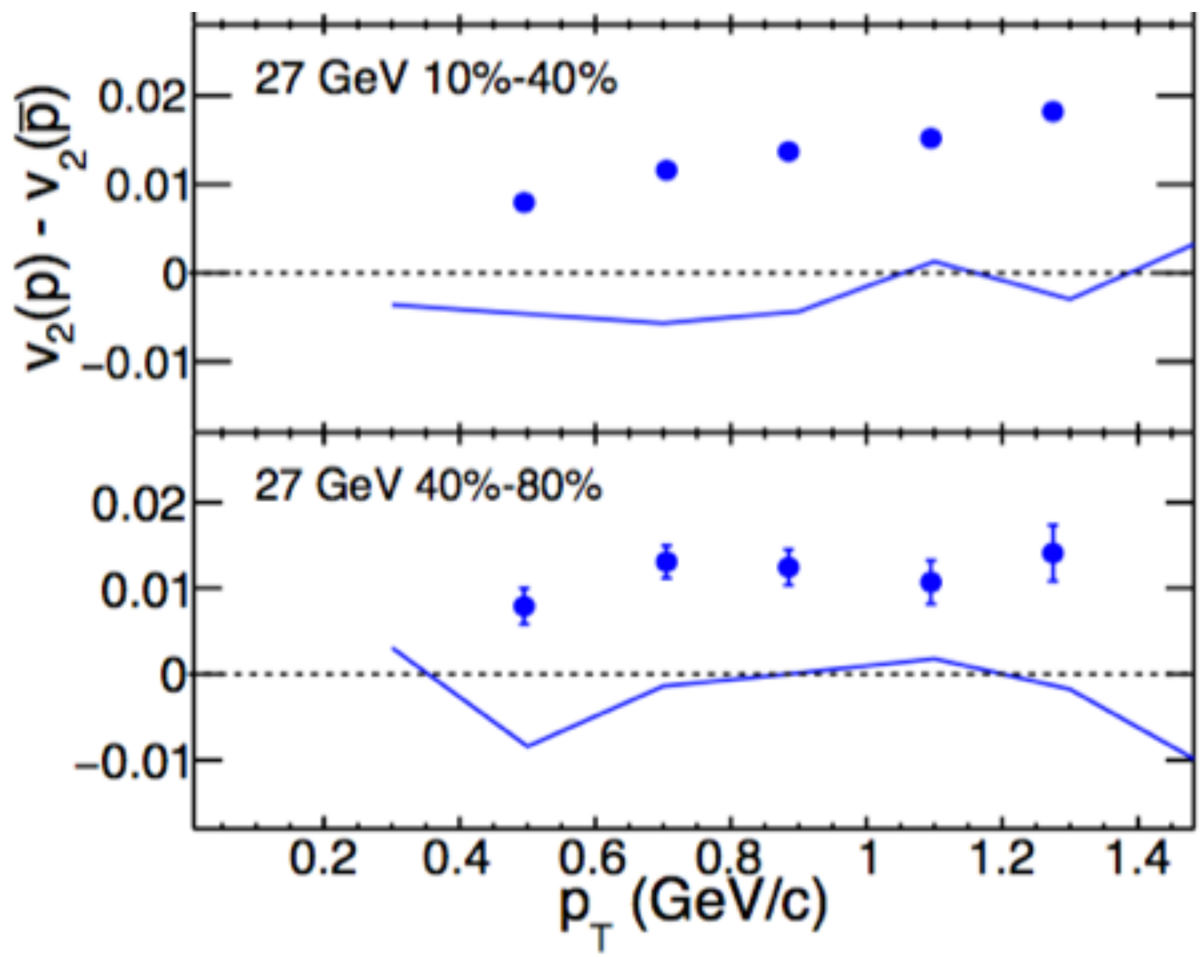
- Hadronic scatterings wash out most of the diffusion effects on pid v_2
- Splitting between π and p v_2 in the STAR measurement is better reproduced with hybrid simulations

$v_2(p)$ vs $v_2(\bar{p})$

hydro + UrQMD



AMPT arXiv:1509.08397

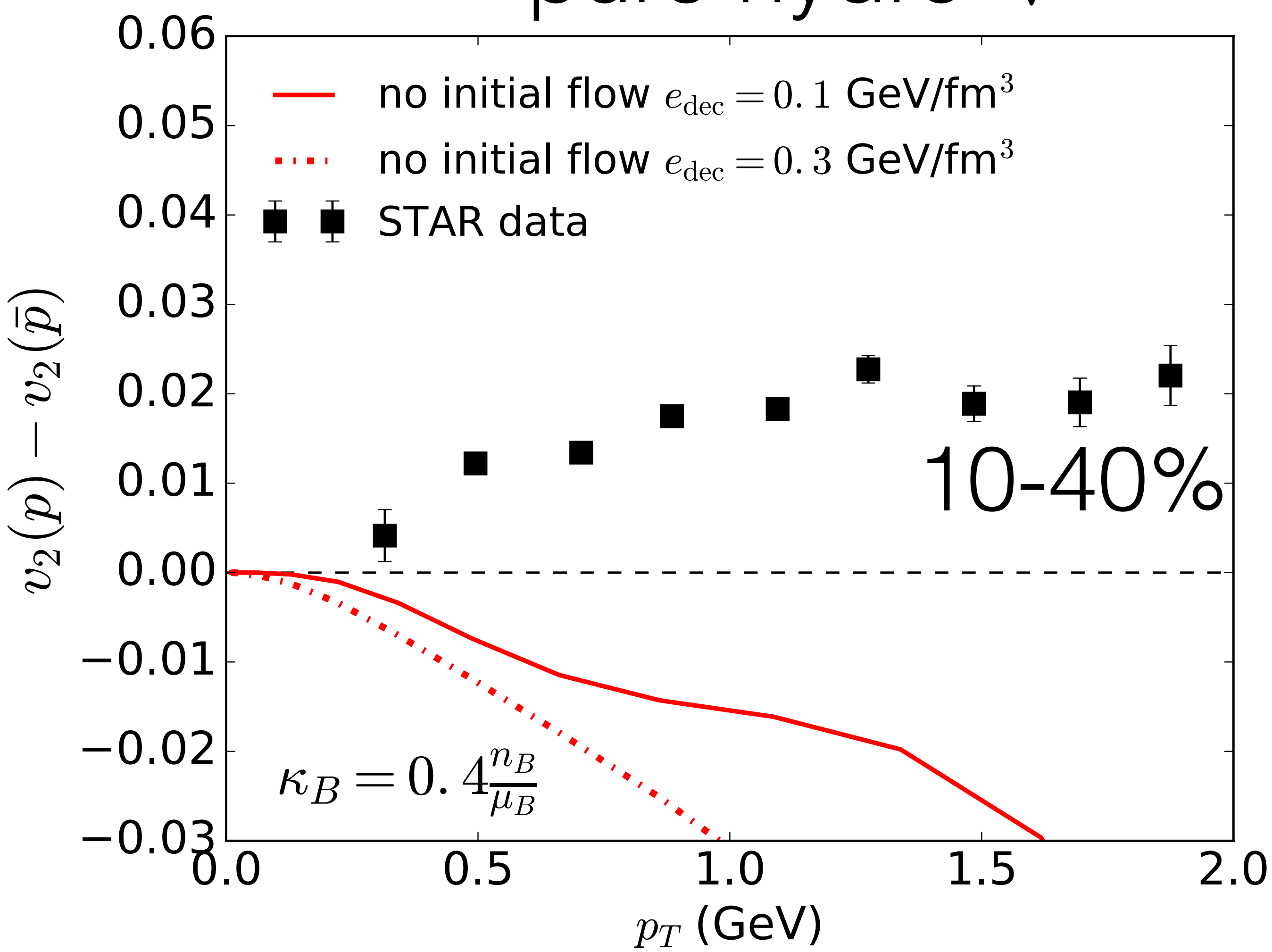


- Theory simulations give $v_2(\bar{p}) > v_2(p)$, which is opposite compared to the STAR data

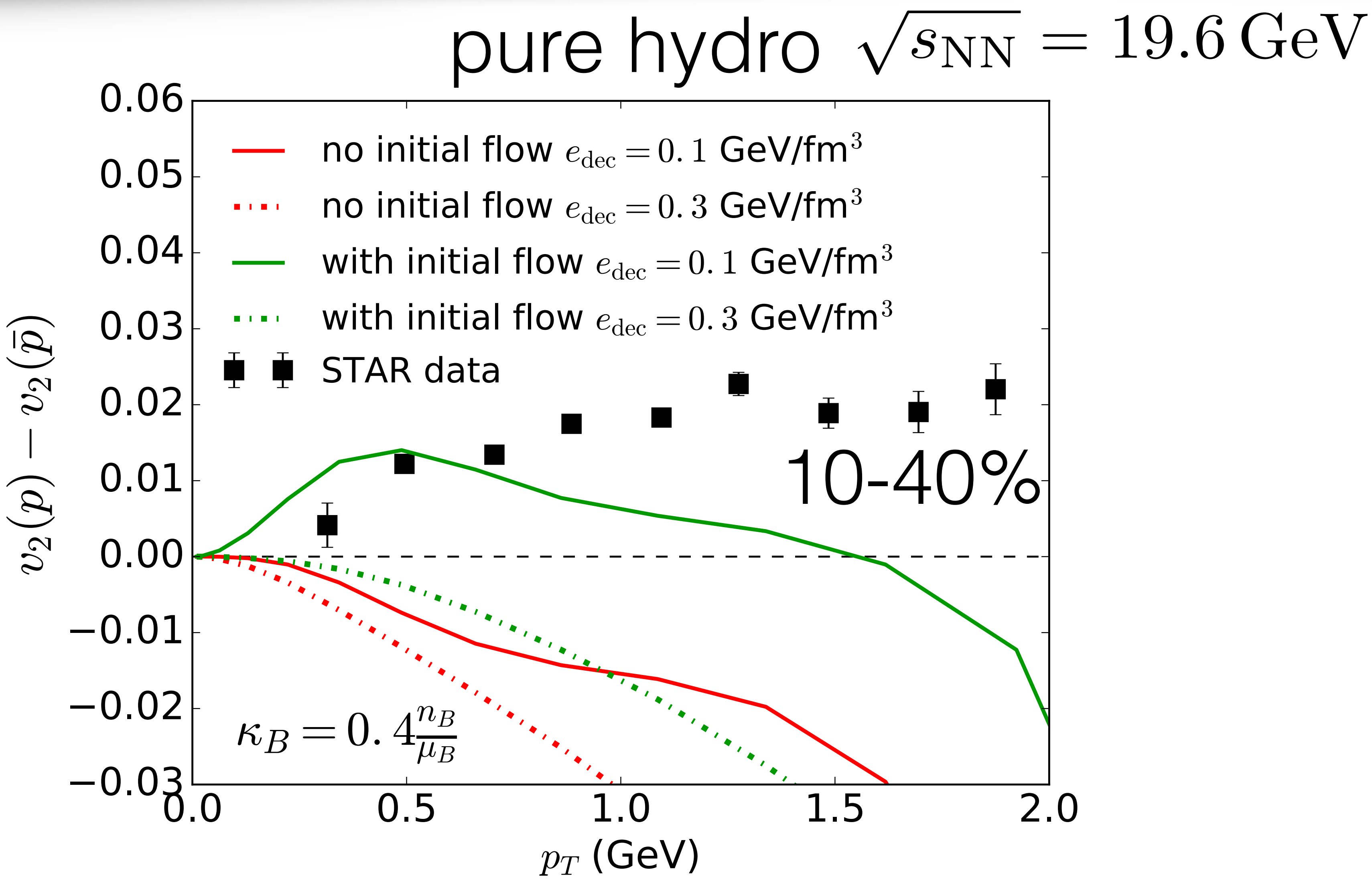
mean field effects in the hadronic phase?

$v_2(p)$ vs $v_2(\bar{p})$

pure hydro $\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$



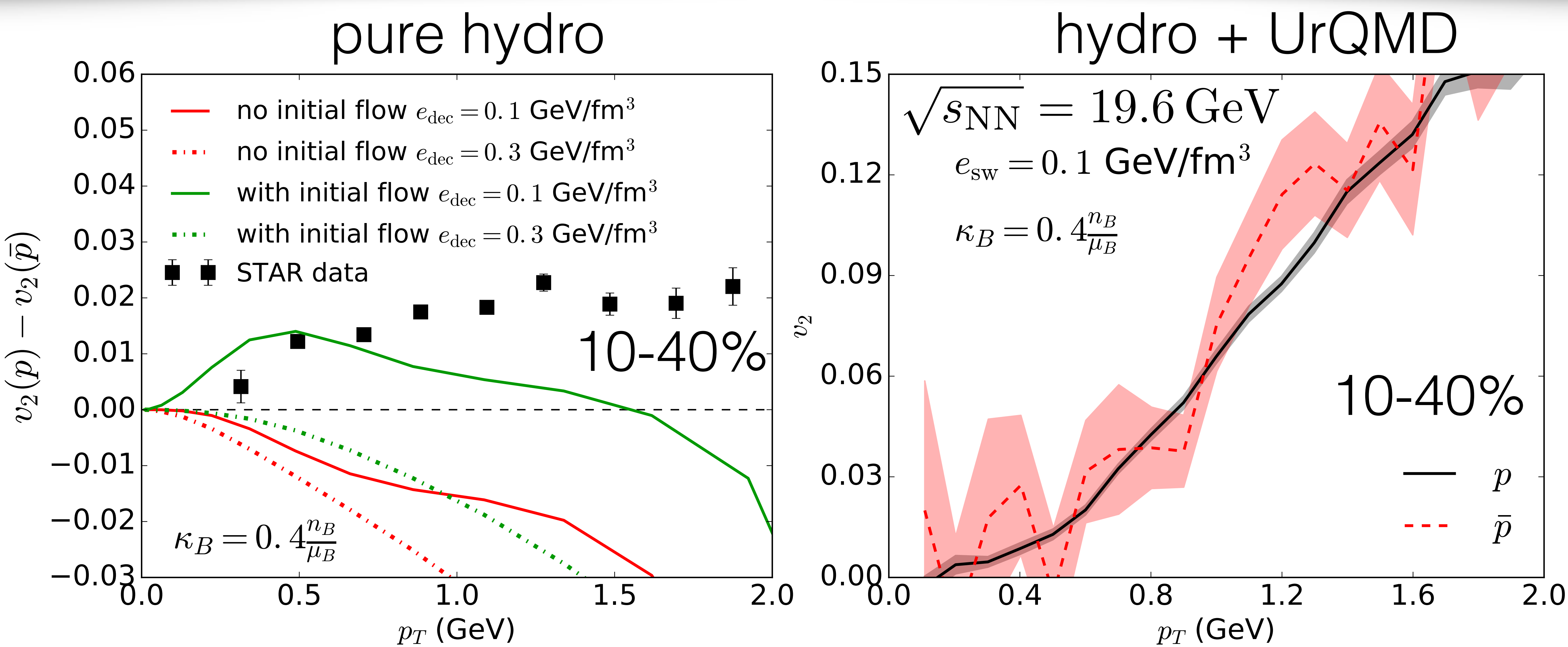
$v_2(p)$ vs $v_2(\bar{p})$



- Hydrodynamic simulations with initial flow and a lower decoupling energy density can give positive $v_2(p) - v_2(\bar{p})$

sensitive to pre-equilibrium flow and late stage dynamics

$v_2(p)$ vs $v_2(\bar{p})$



- Hydrodynamic simulations with initial flow and a lower decoupling energy density can give positive $v_2(p) - v_2(\bar{p})$
- Current statistics is still not enough for anti-proton in the hybrid approach

sensitive to pre-equilibrium flow and late stage dynamics

Explore the pre-equilibrium dynamics

A transport approach:

MC-Glauber

$e(x, y, \eta_s)$

$n_B(x, y, \eta_s)$

EoS: T, μ_B

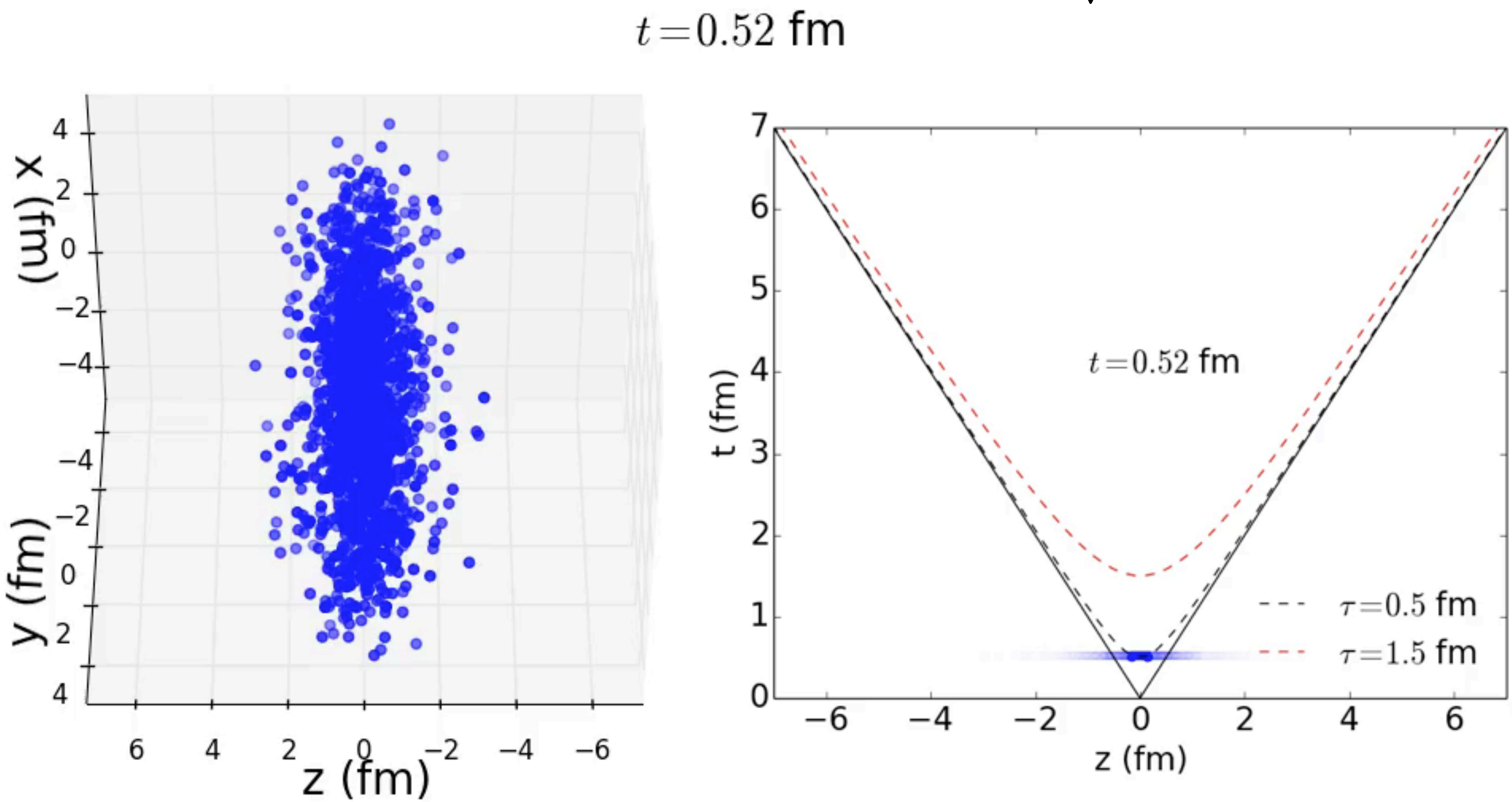
Sample partons until the total energy of system is reached

Feed into a transport simulation

Freeze out particles at a constant tau surface and build $T^{\mu\nu}$

Explore the pre-equilibrium dynamics

$\sqrt{s_{\mathrm{NN}}} = 19.6\,\mathrm{GeV}$



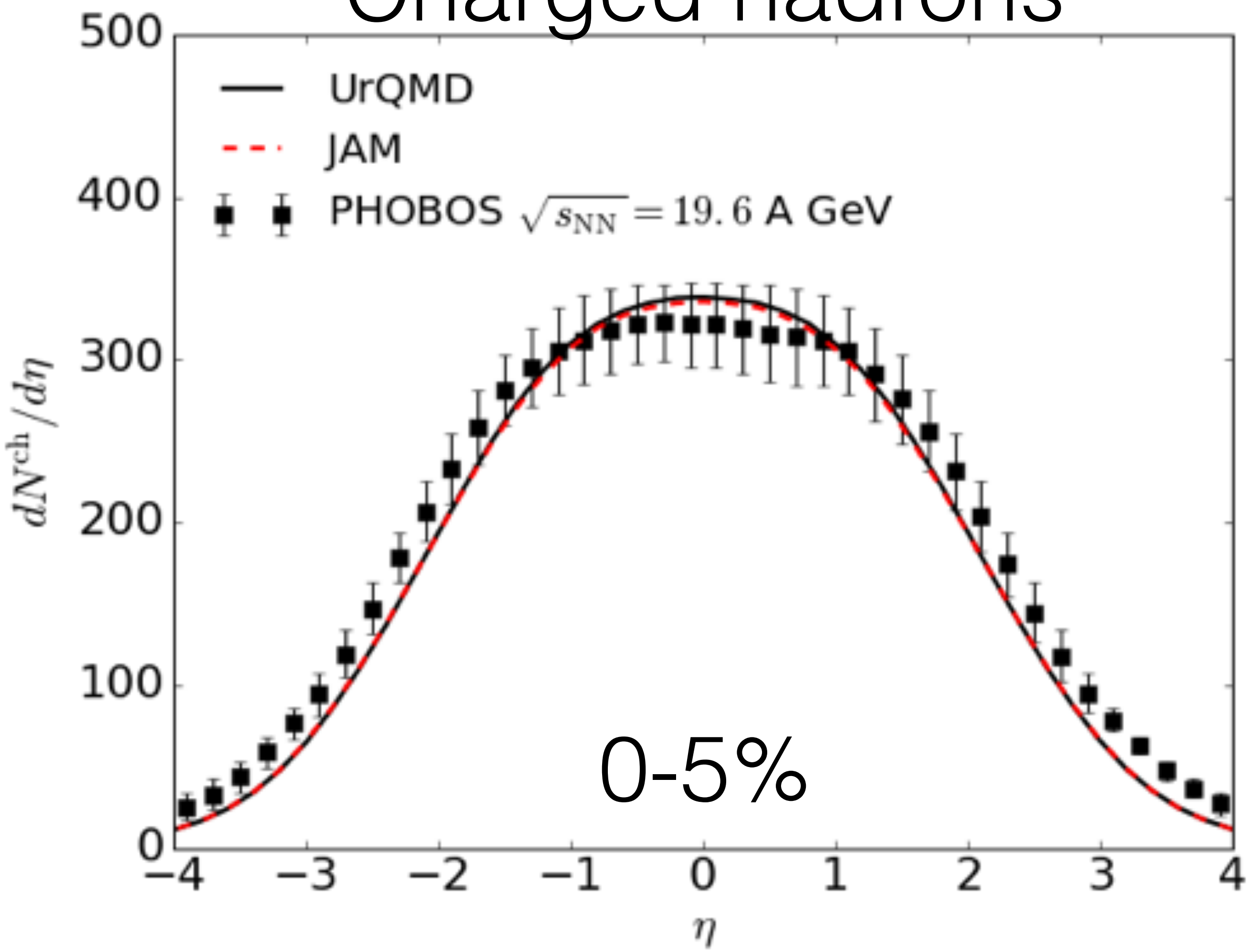
Elastic scatterings with a constant cross section

Is hadronic cascade under control?

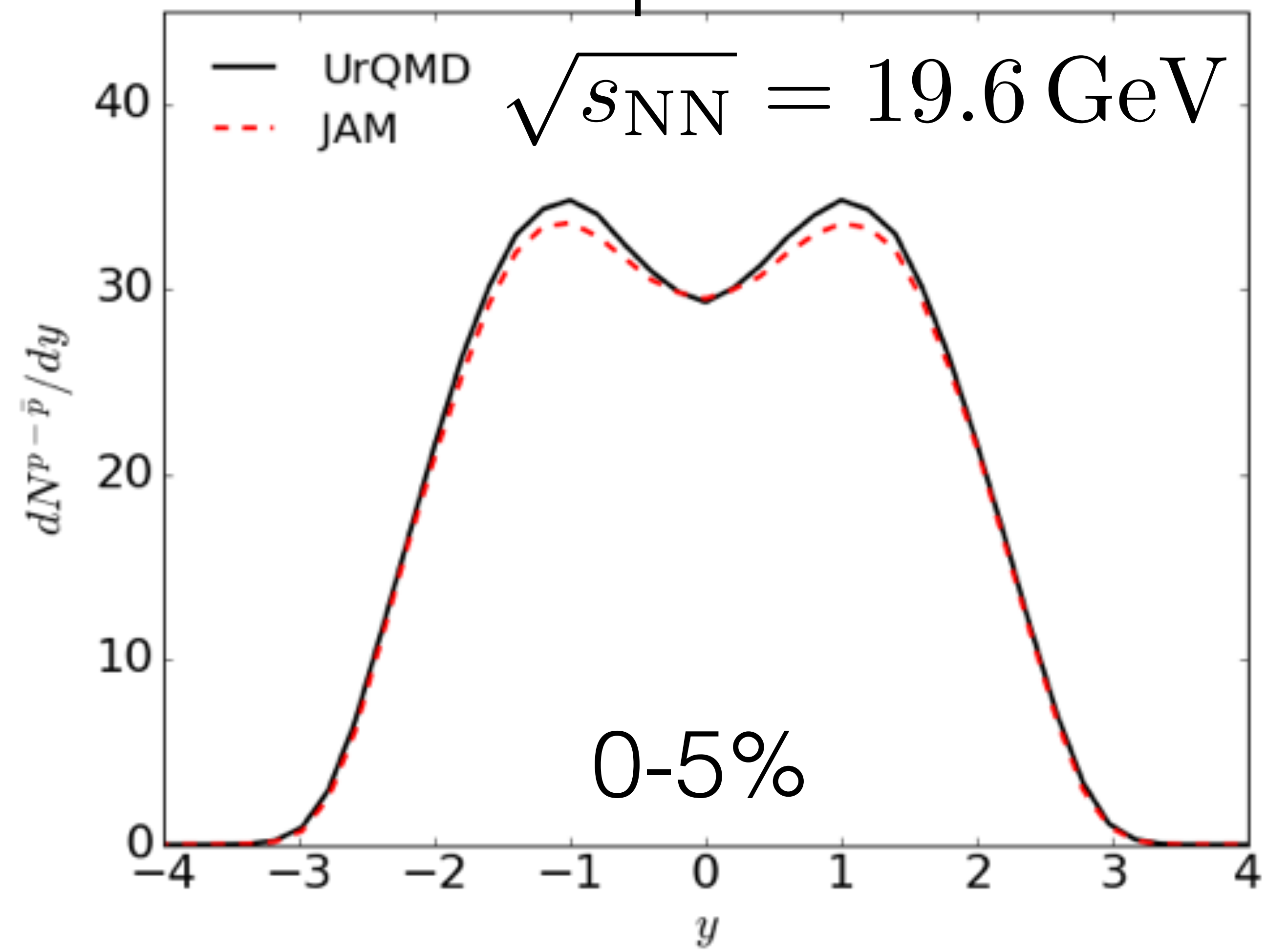
JAM **UrQMD**

Quantify uncertainties in hadronic cascade

Charged hadrons



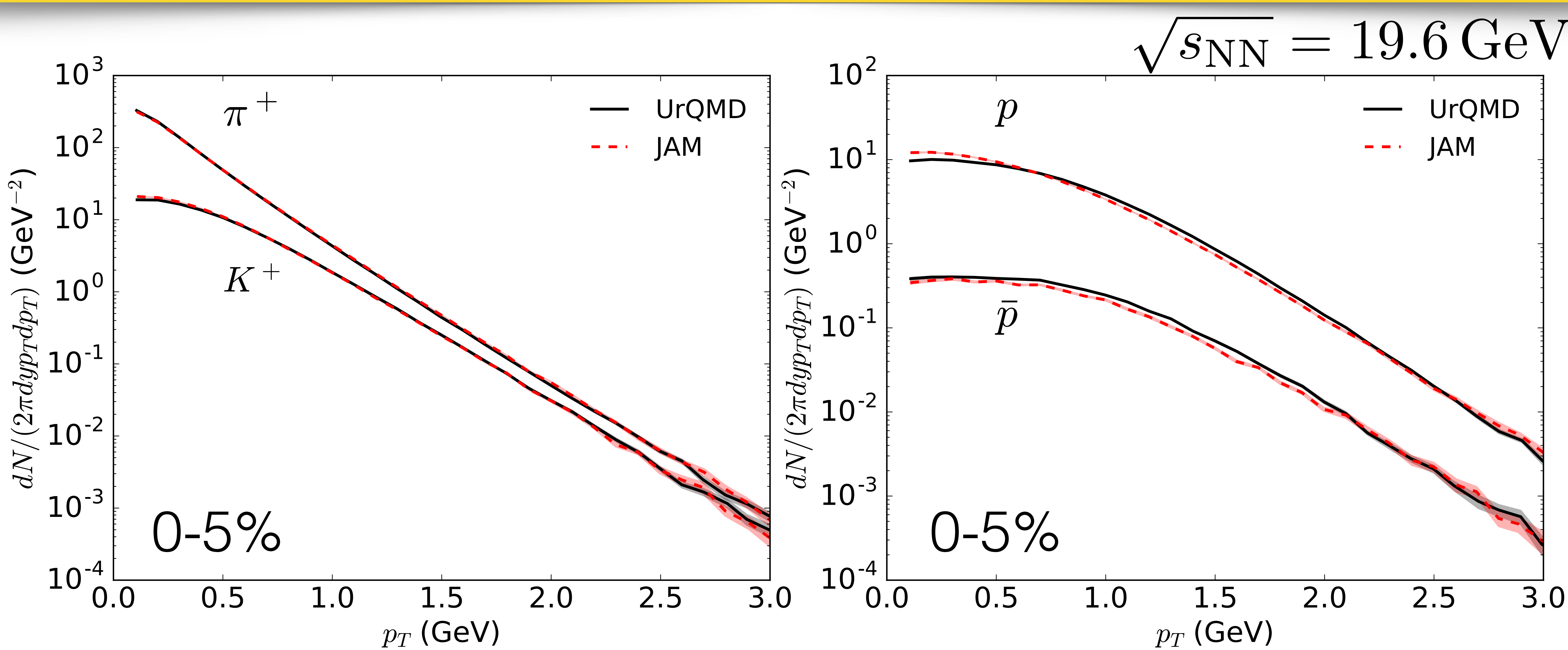
Net protons



- UrQMD and JAM produce very close results for particle rapidity distributions
- Only some small noticeable differences in net proton rapidity distribution

differences in cross sections/resonances?

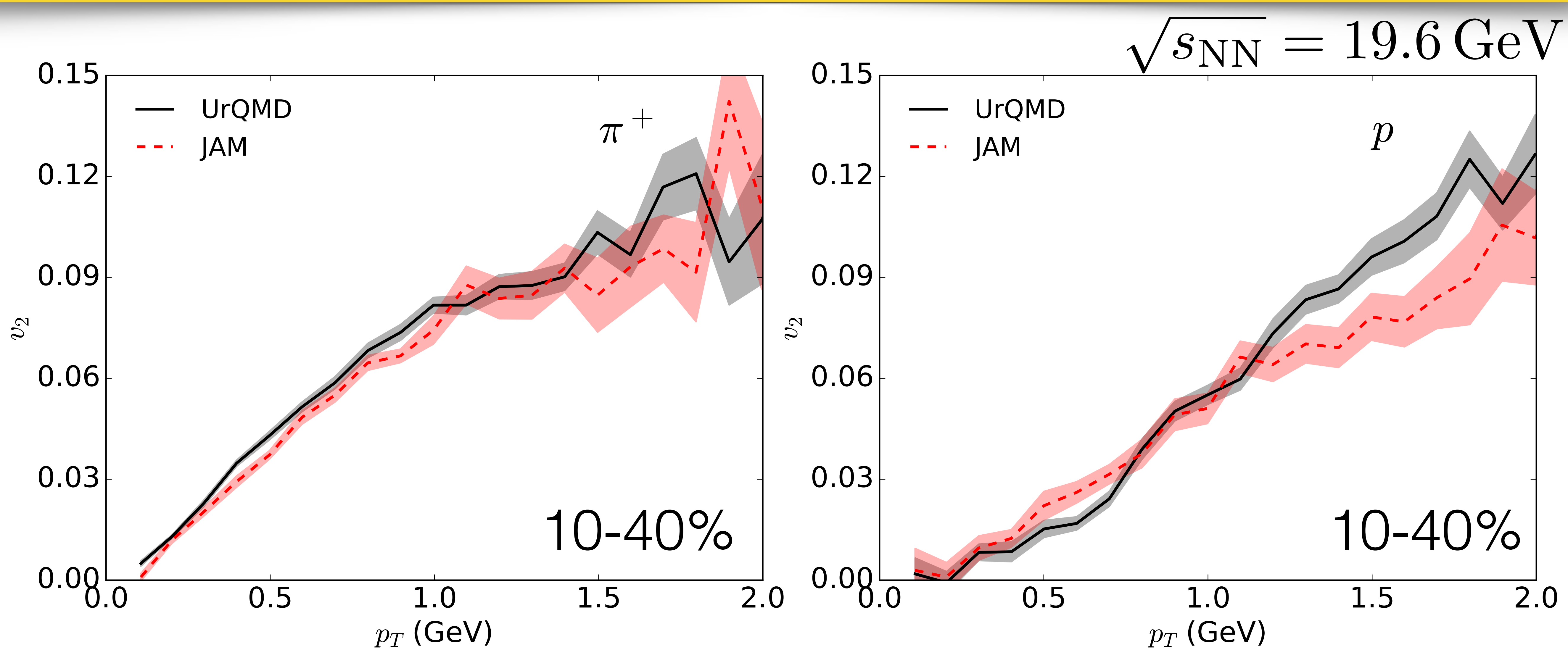
Quantify uncertainties in hadronic cascade



- Light meson spectra are very close from the two cascade simulations
- Baryon spectra have some small noticeable differences

differences in cross sections/resonances?

Quantify uncertainties in hadronic cascade

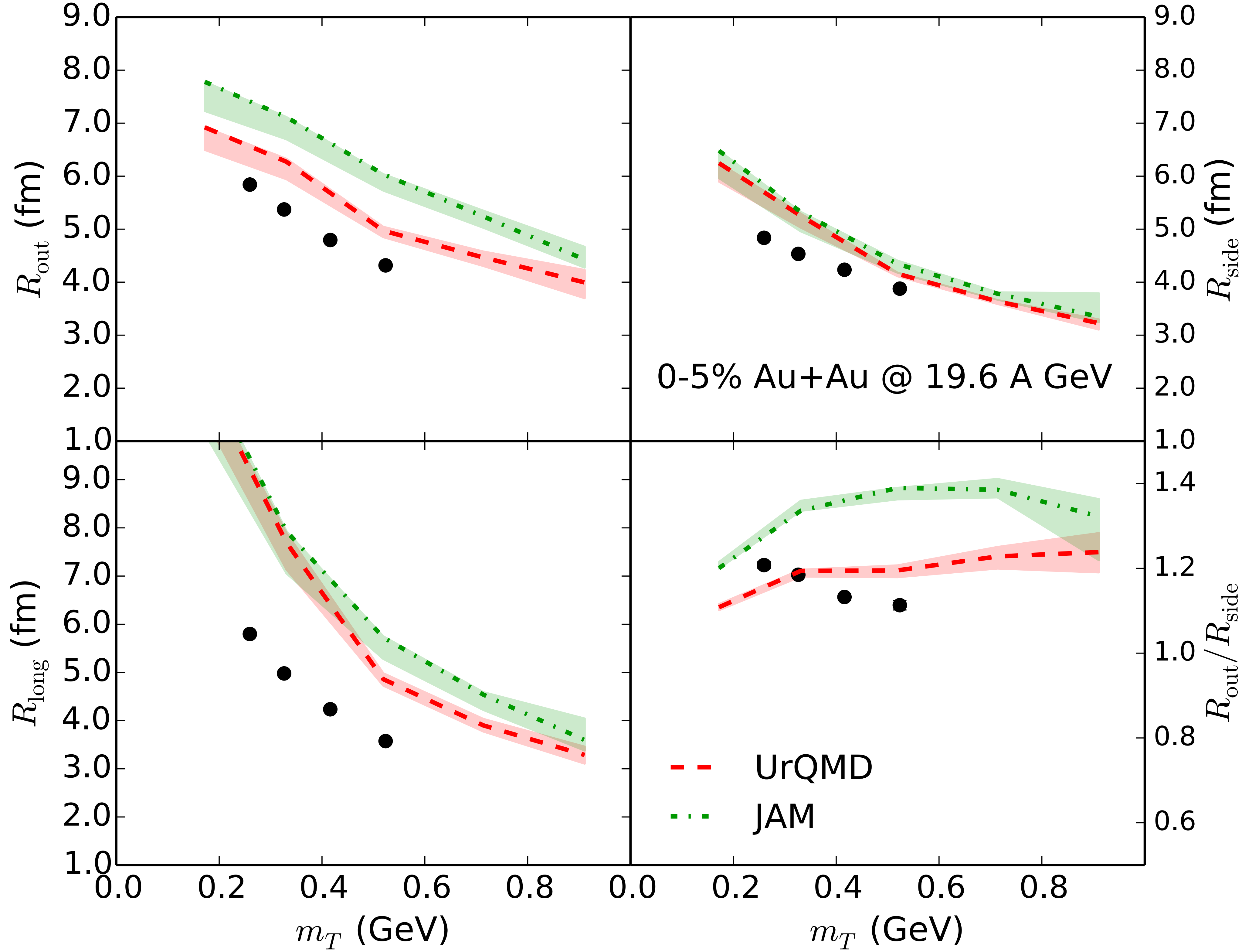


- Pid v_2 from the two hadronic cascade simulations are close to each other

differences in cross sections/resonances?

Quantify uncertainties in hadronic cascade

Identical pion HBT radii:



differences in cross sections/resonances?

Conclusions

- We present preliminary study of the *collectivity* in RHIC BES program using hybrid hydrodynamics + hadronic cascade simulations

  full **(3+1)-d** simulations with net baryon diffusion

- Including a hadronic cascade phase is indispensable for the BES energy collisions; UrQMD vs JAM provides some ideas about the current theoretical uncertainties
- Identify a few experiment observables that could constrain the net baryon diffusion

$$dN^{p-\bar{p}}/dy \qquad\qquad \langle p_\perp \rangle^{\bar{p}} - \langle p_\perp \rangle^{p}$$

- The ordering between $v_2(p)$ and $v_2(\bar{p})$ are sensitive to pre-equilibrium flow as well as late stage dynamics

Coming soon

- Implement more conserved currents

  net strangeness and net electric charge

  need Equation of State

- Study the second order non-linear couplings between shear, bulk, and diffusions

  need transport coefficients

  go beyond the relaxation time approximation?

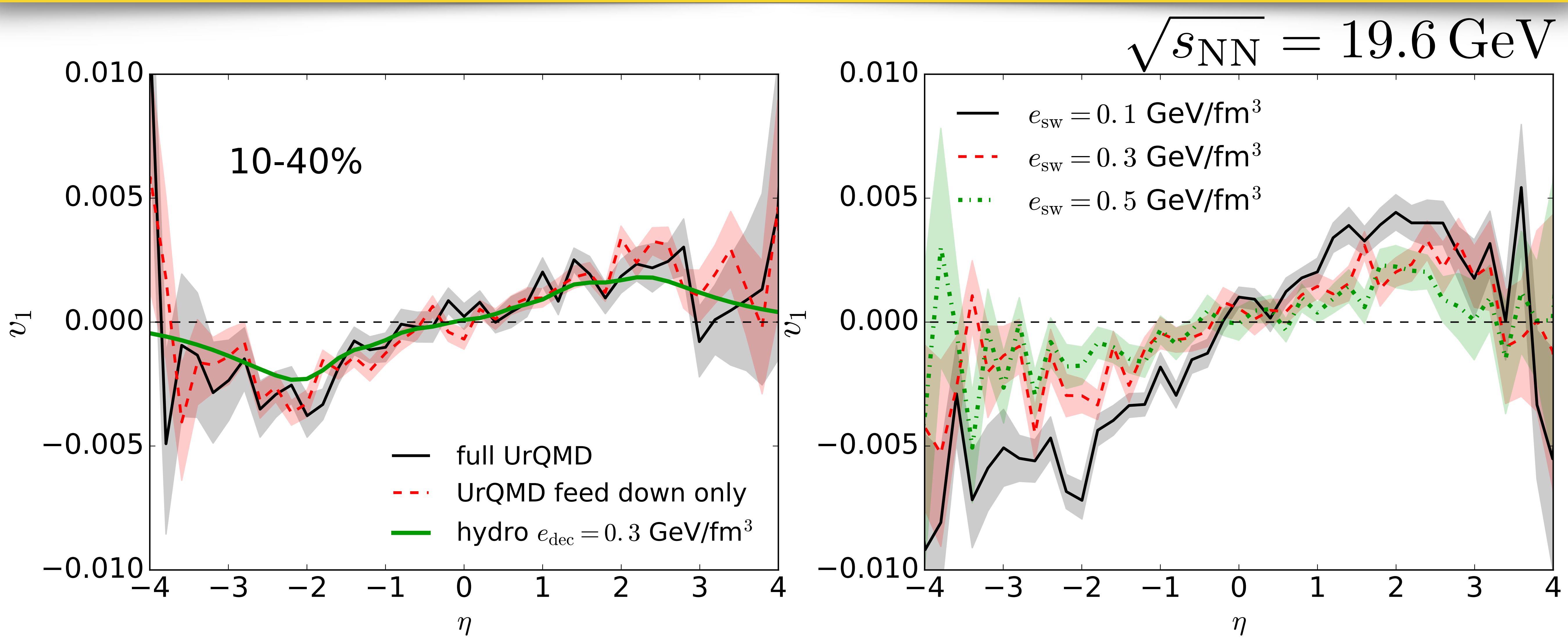
- Explore initial state fluctuations and the effects from a pre-equilibrium stage

  baryon doped Glasma, thermalization, $\frac{dv_1^{p-\bar{p}}}{dy}$?

- Evolve critical and non-critical fluctuations
- Couple to EM fields for studying the Chiral Magnetic Effects

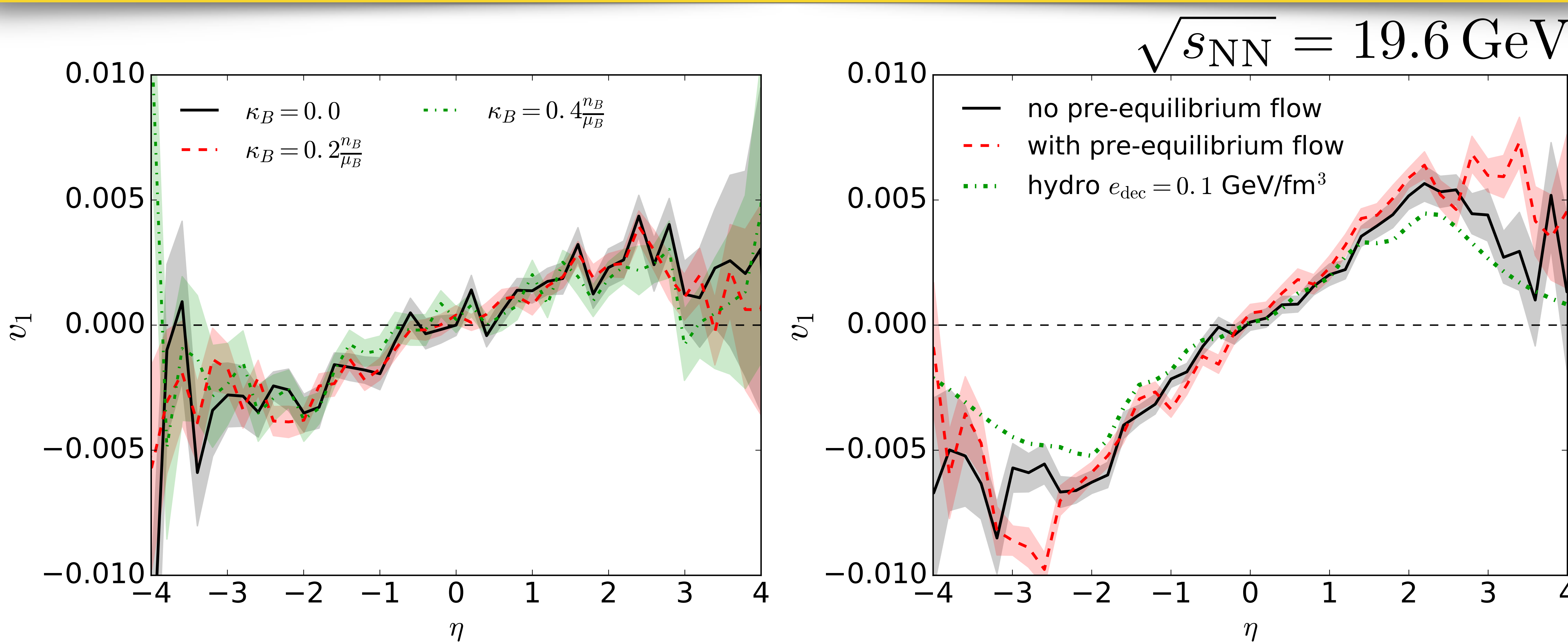
back ups

Preliminary results for v_1



- Hadronic afterburner does not affect charged hadron $v_1(y)$ much
- A lower switching energy density results a larger v_1 signal

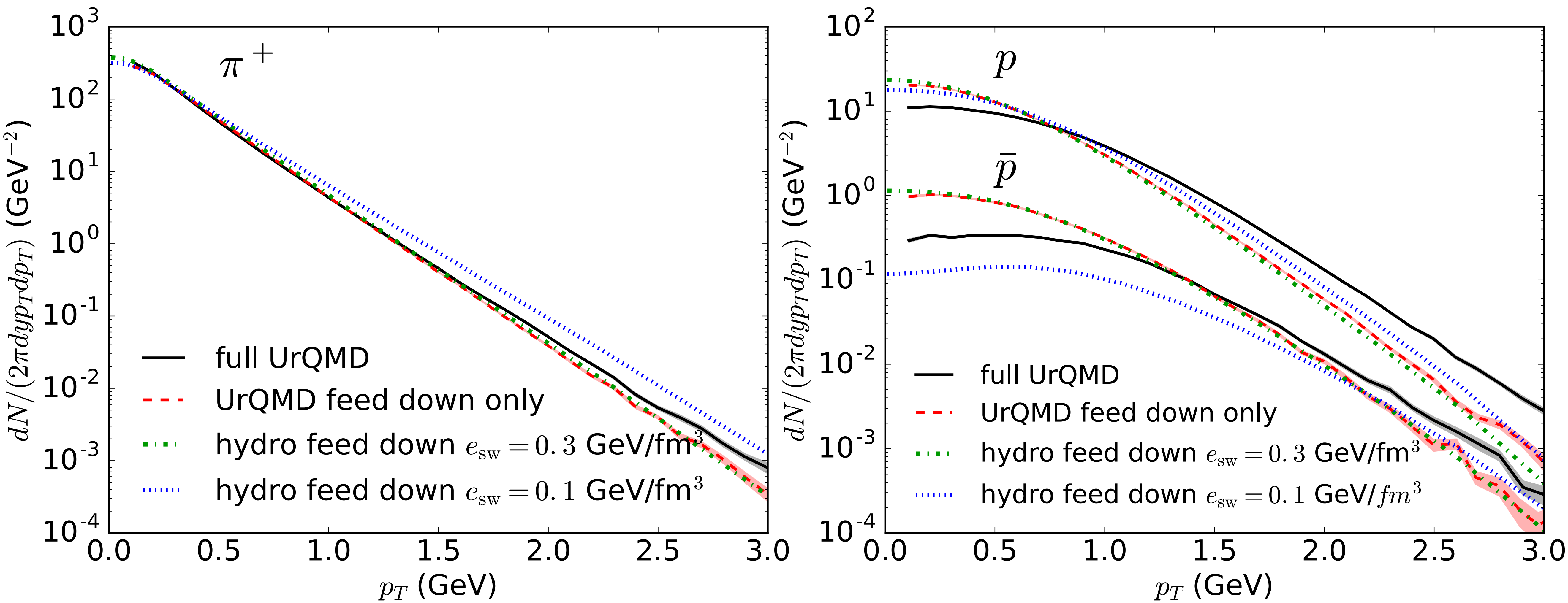
Preliminary results for v_1



- Baryon diffusion does not affect the charge hadron v_1
- Charged hadron v_1 shows little sensitivity to pre-equilibrium flow

Will a lower decoupling temperature fix this?

By evolving the fireball with hydrodynamics to a lower energy density,

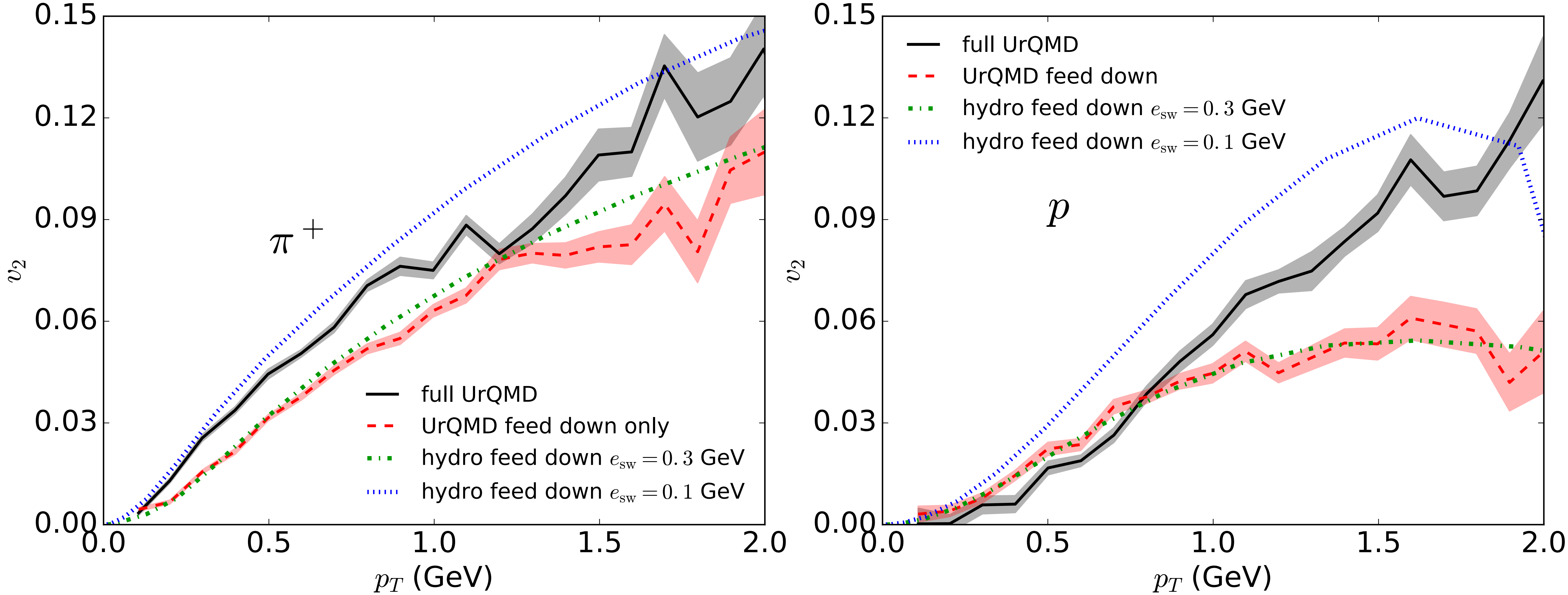


- pion spectrum is too flat
- hadronic chemistry changes a lot — need PCE EoS

hadronic afterburner is essential

Will a lower decoupling temperature fix this?

By evolving the fireball with hydrodynamics to a lower energy density,

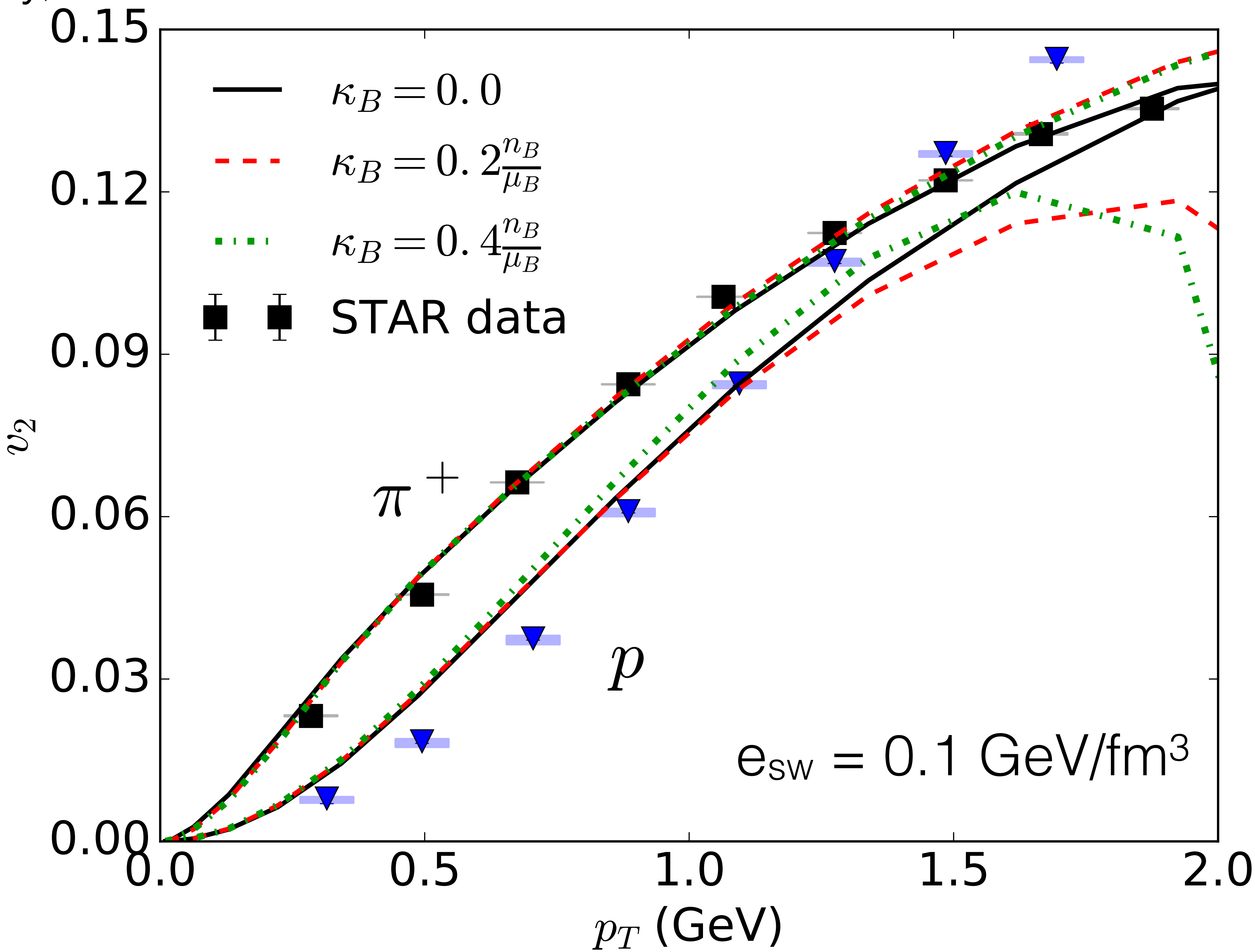


- The blue shift in proton v_2 can not be reproduced with hydro

hadronic afterburner is essential

Will a lower decoupling temperature fix this?

By evolving the fireball with hydrodynamics to a lower energy density,



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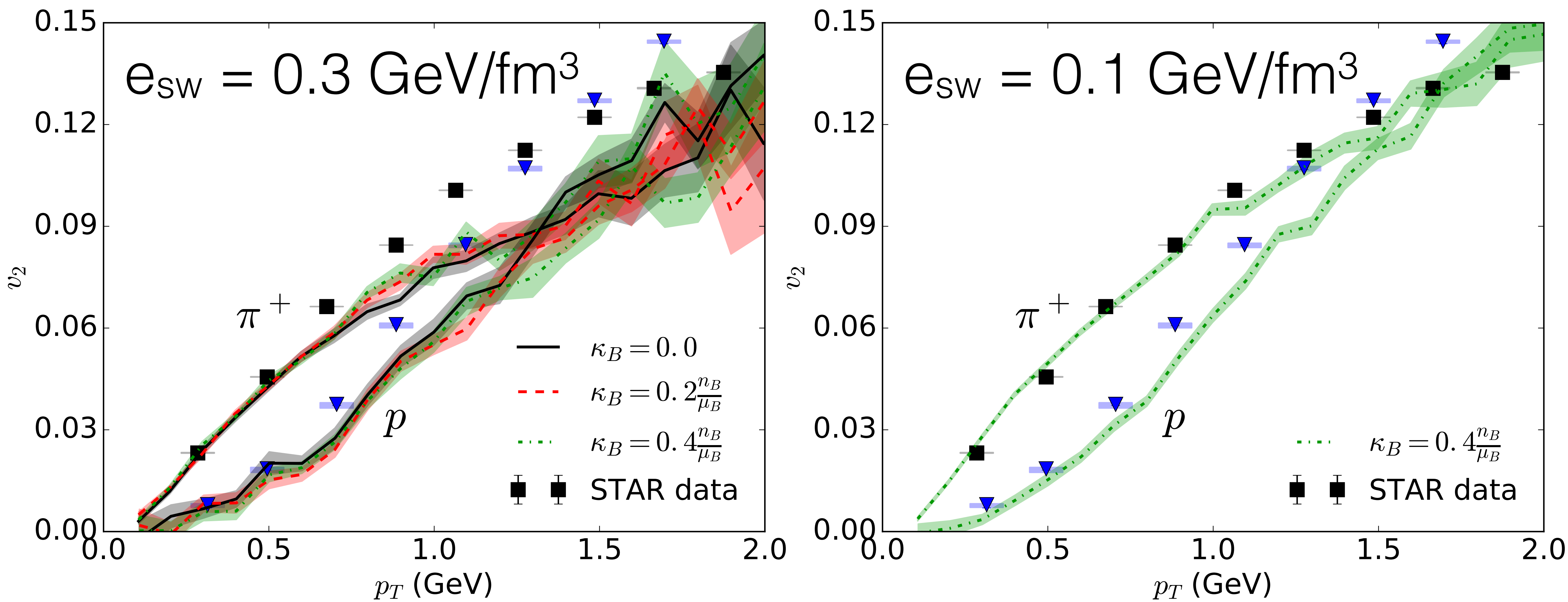
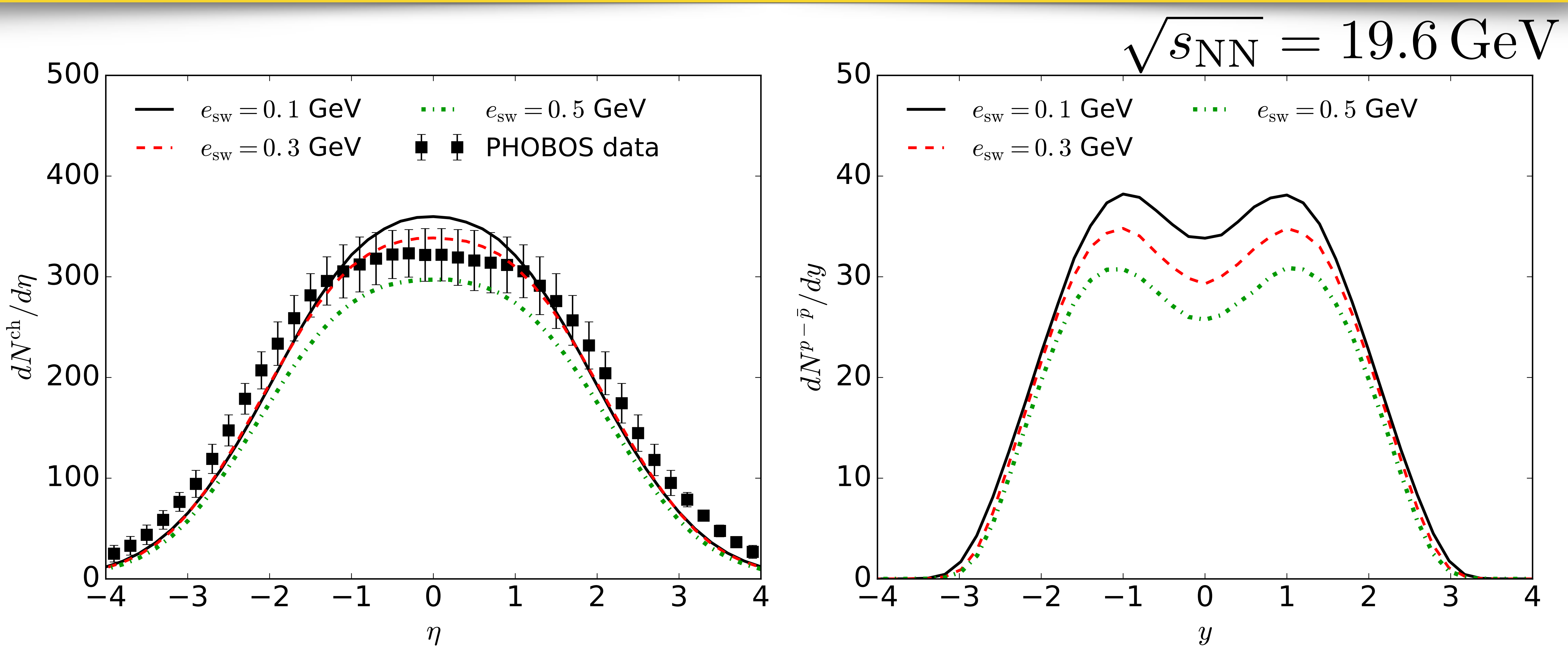


- A more viscous phase from UrQMD compared to hydro

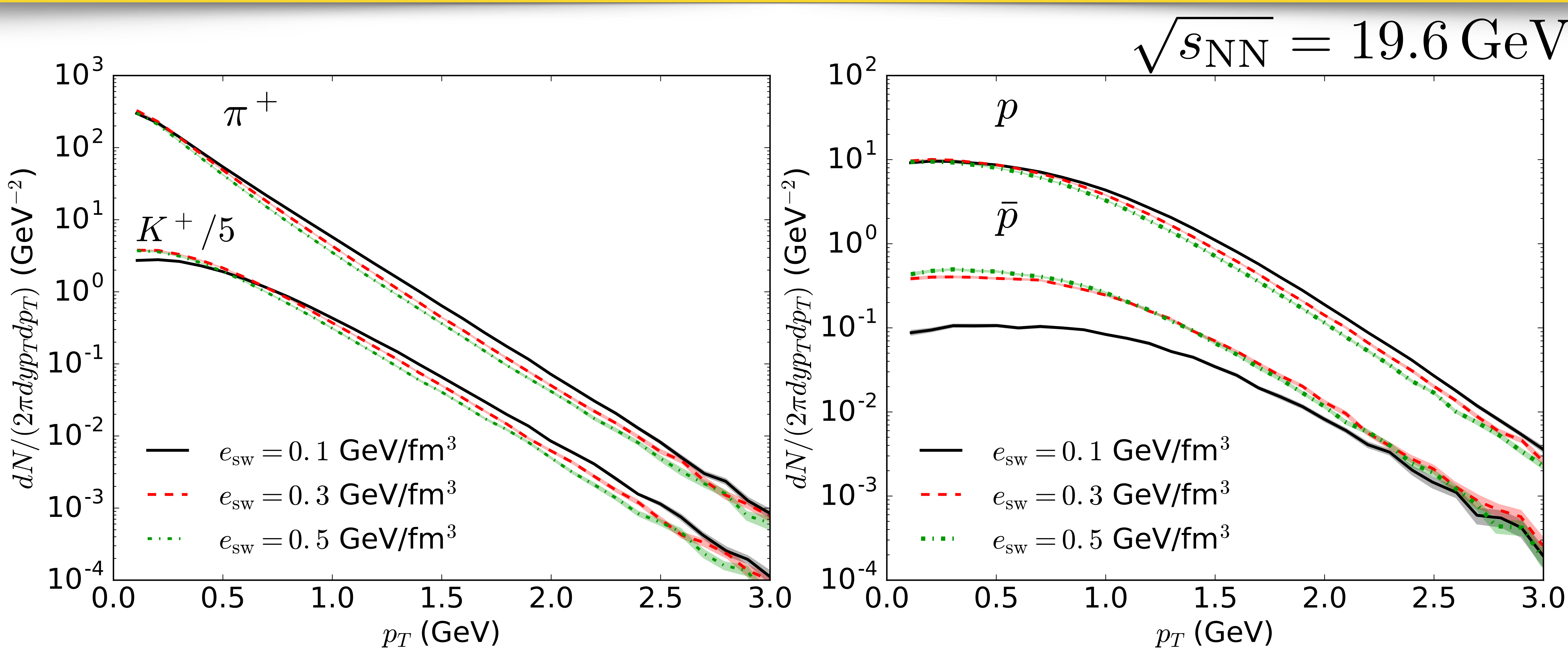
When to switch from hydro to cascade?



- Different switching energy density can result different chemical contents in hadronic phase

Hadronic chemistry determines the e_{sw}

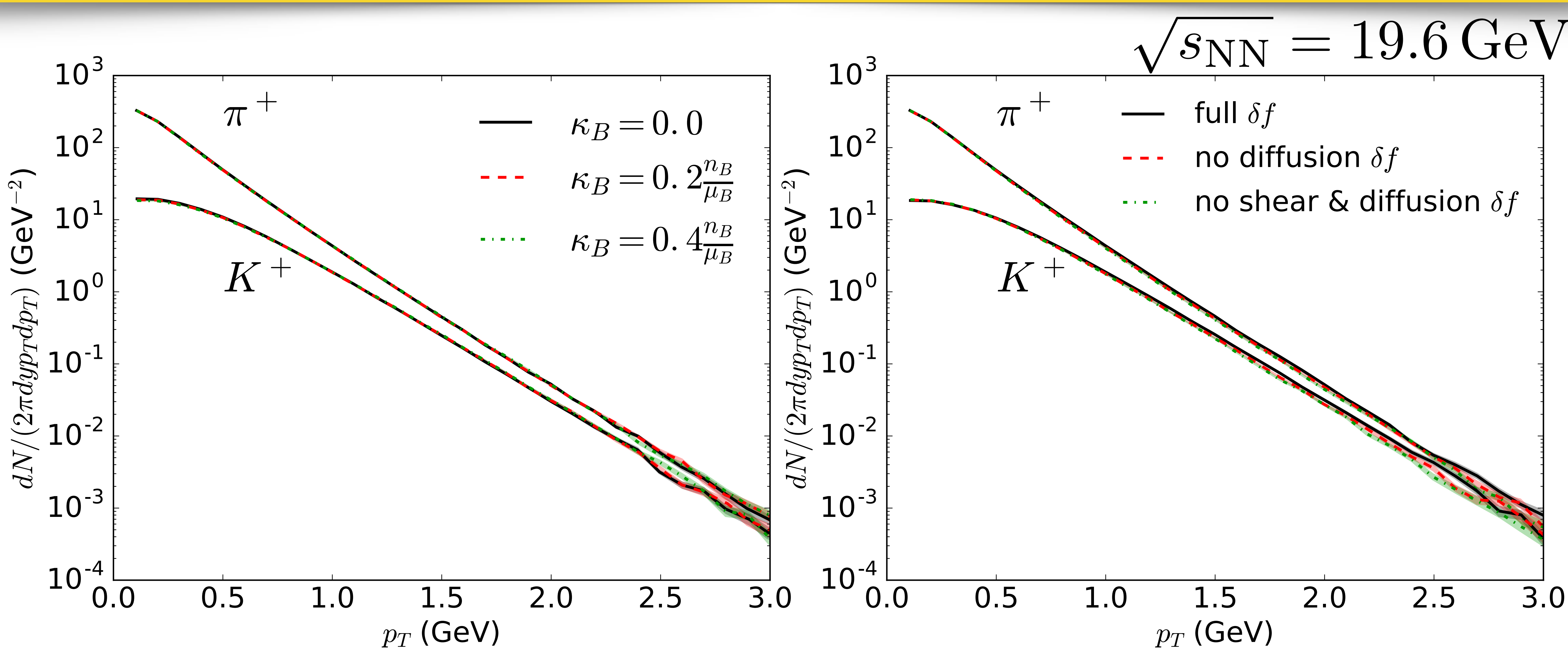
When to switch from hydro to cascade?



- Different switching energy density can result different chemical contents in hadronic phase
- Hydrodynamics generates more radial flow than hadronic cascade

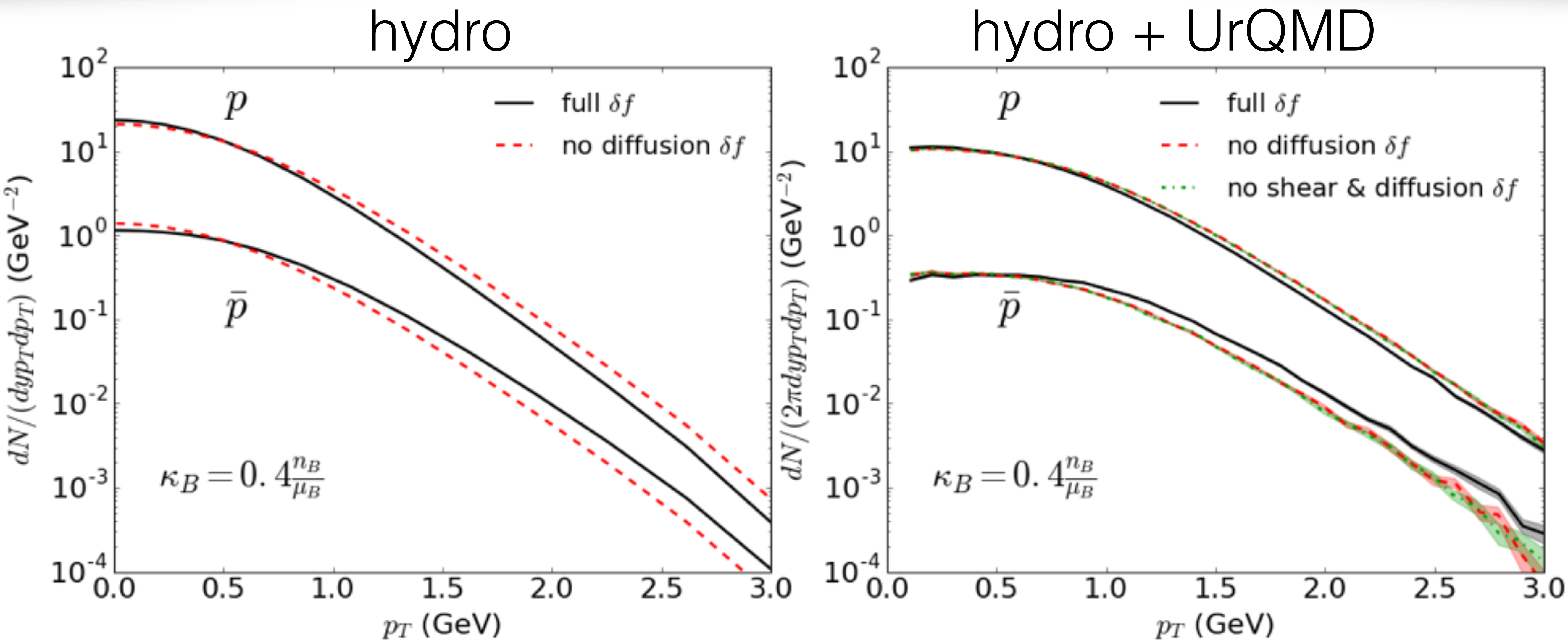
Hadronic chemistry determines the e_{sw}

Effects of net baryon diffusion on pid spectra



- Net baryon diffusion has negligible effects on light meson spectra

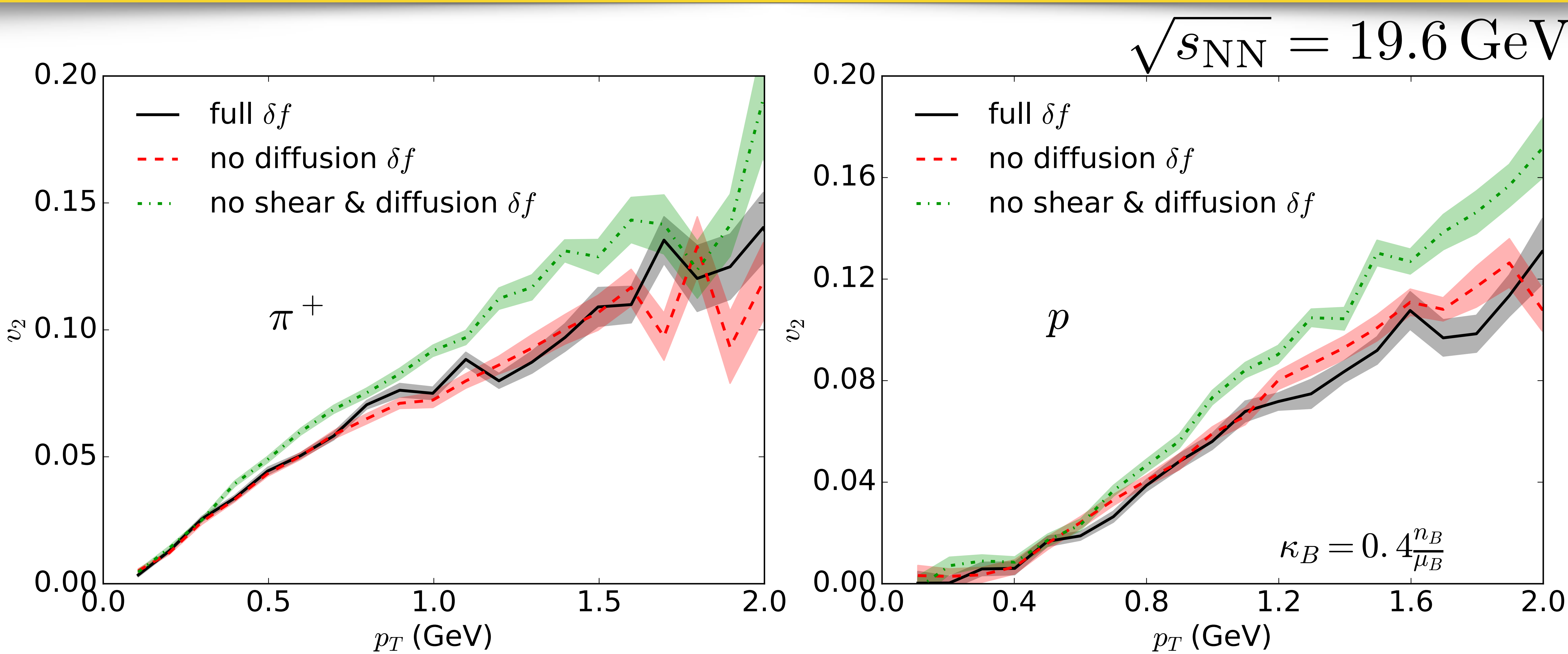
Effects of net baryon diffusion on pid spectra



$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

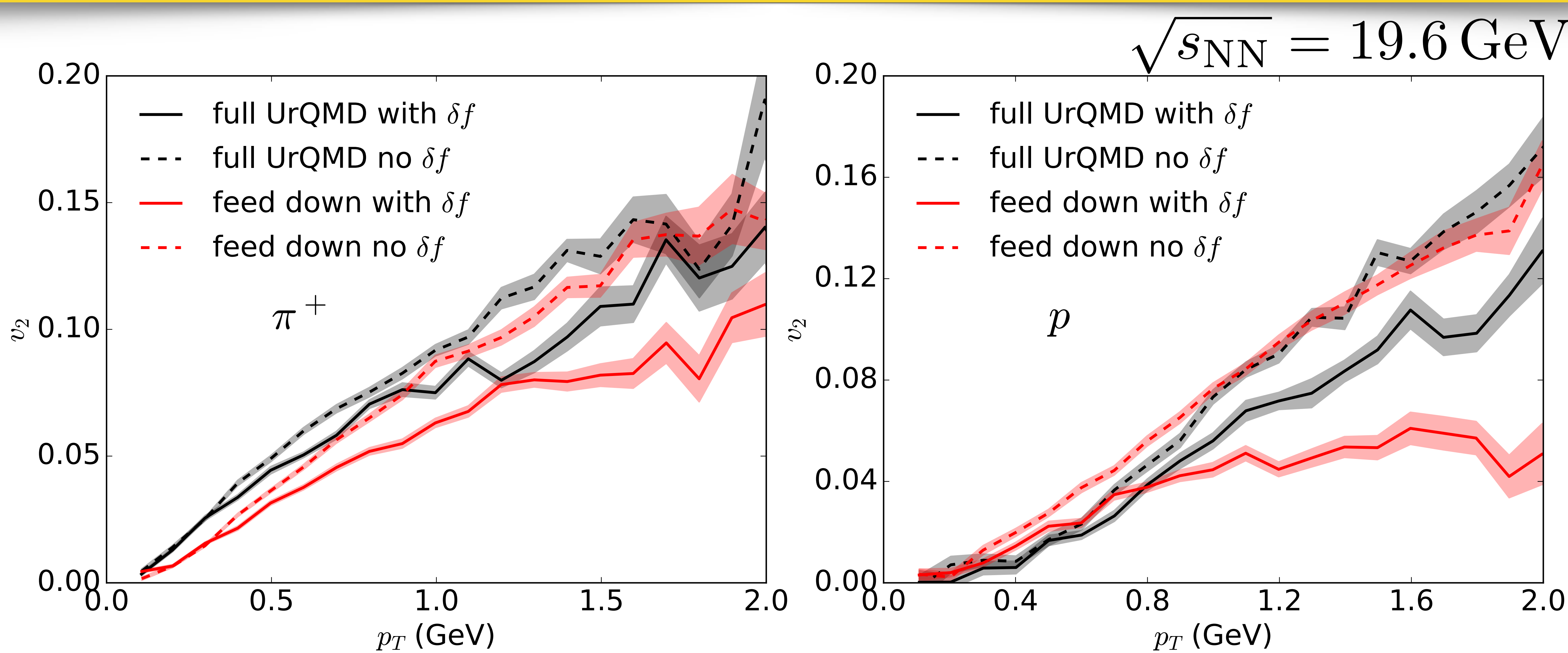
- Diffusion δf shows larger effects on proton and anti-proton spectra than shear δf

δf effects on pid v_2



- Net baryon diffusion δf has negligible effects on pid v_2

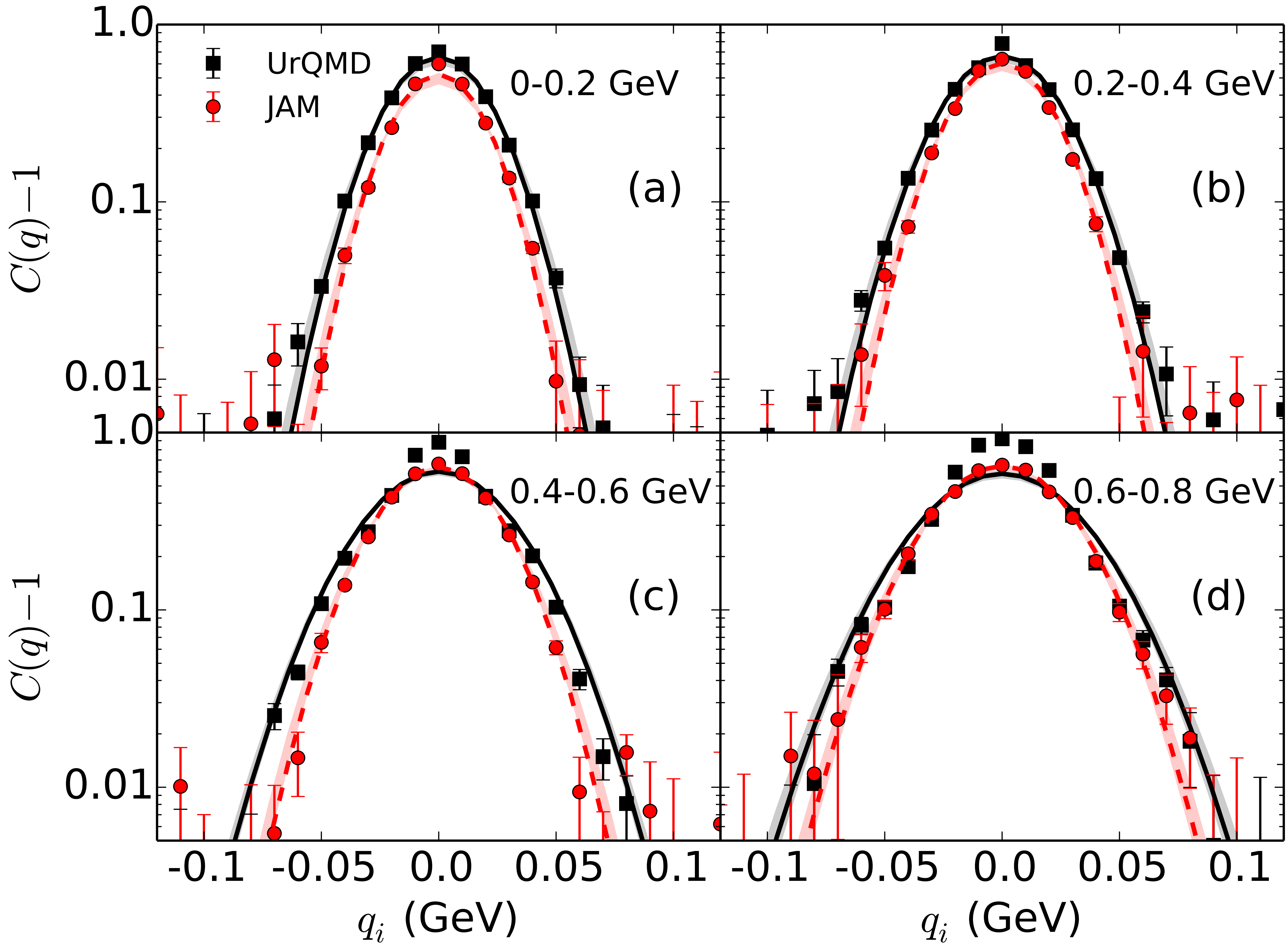
δf effects on pid v_2



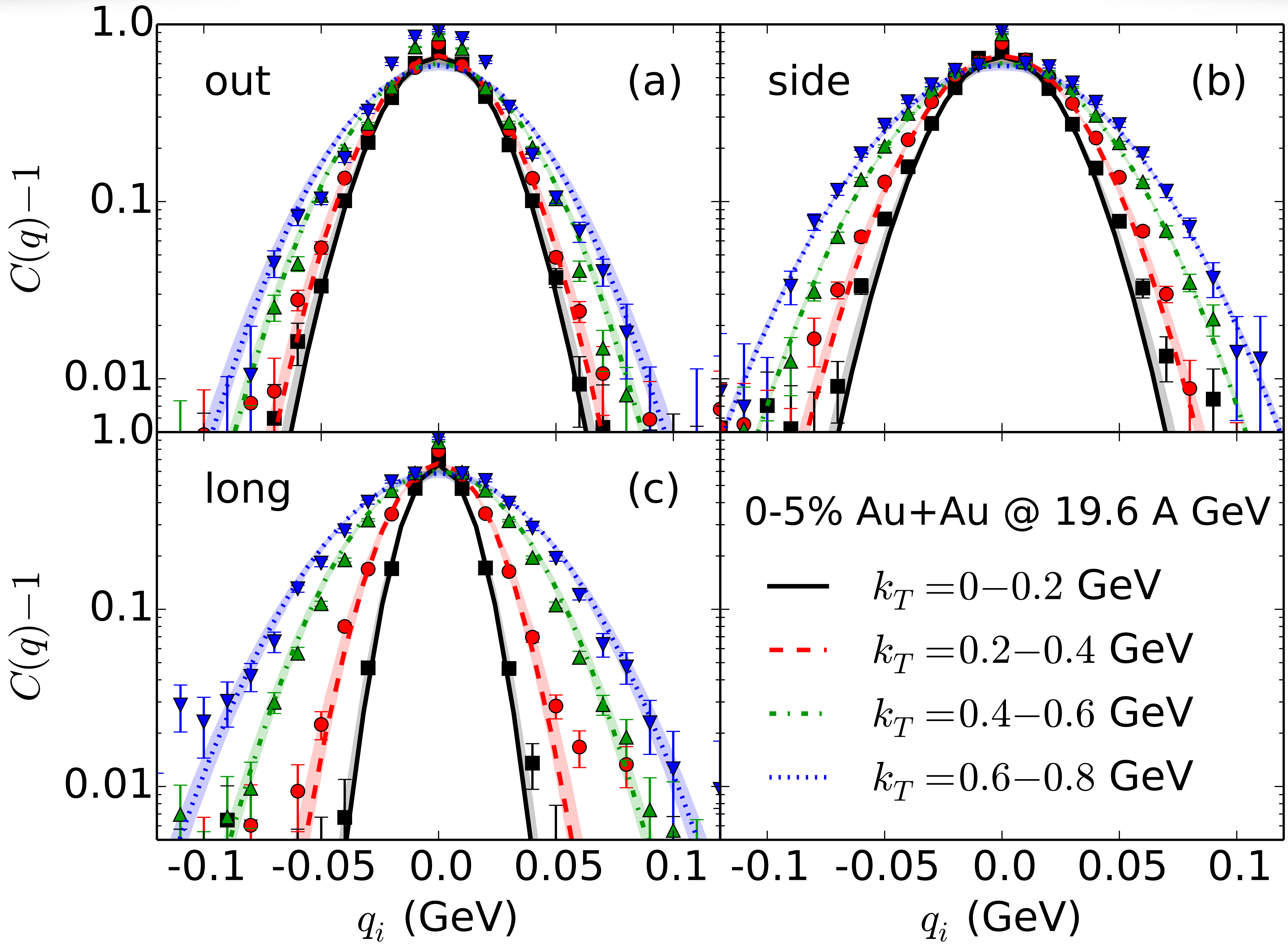
- The shear δf corrections to pid v_2 are smaller once hadronic scatterings are included

Quantify uncertainties in hadronic cascade

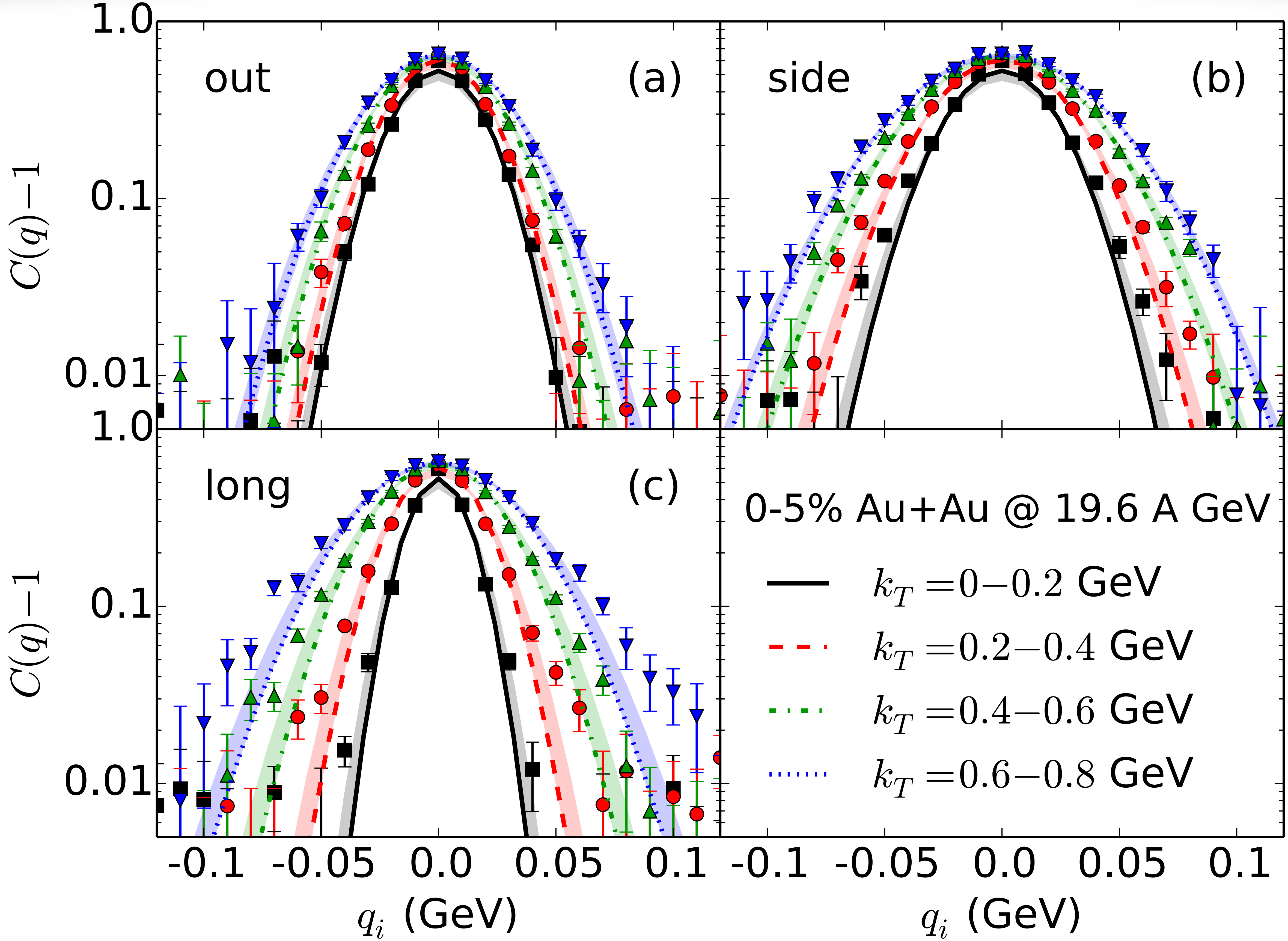
Identical pion HBT radii: out direction



HBT correlation functions (UrQMD)

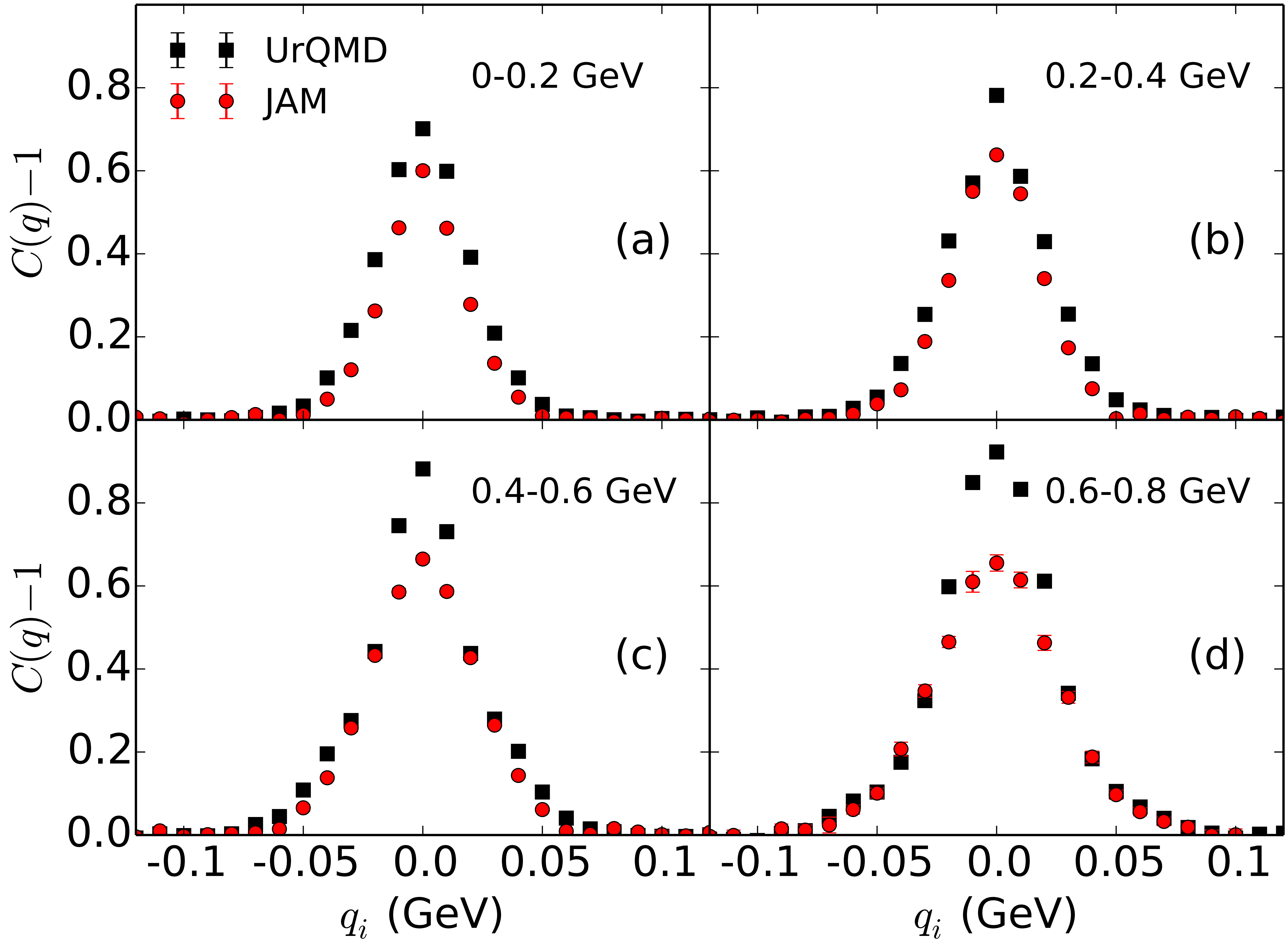


HBT correlation functions (JAM)



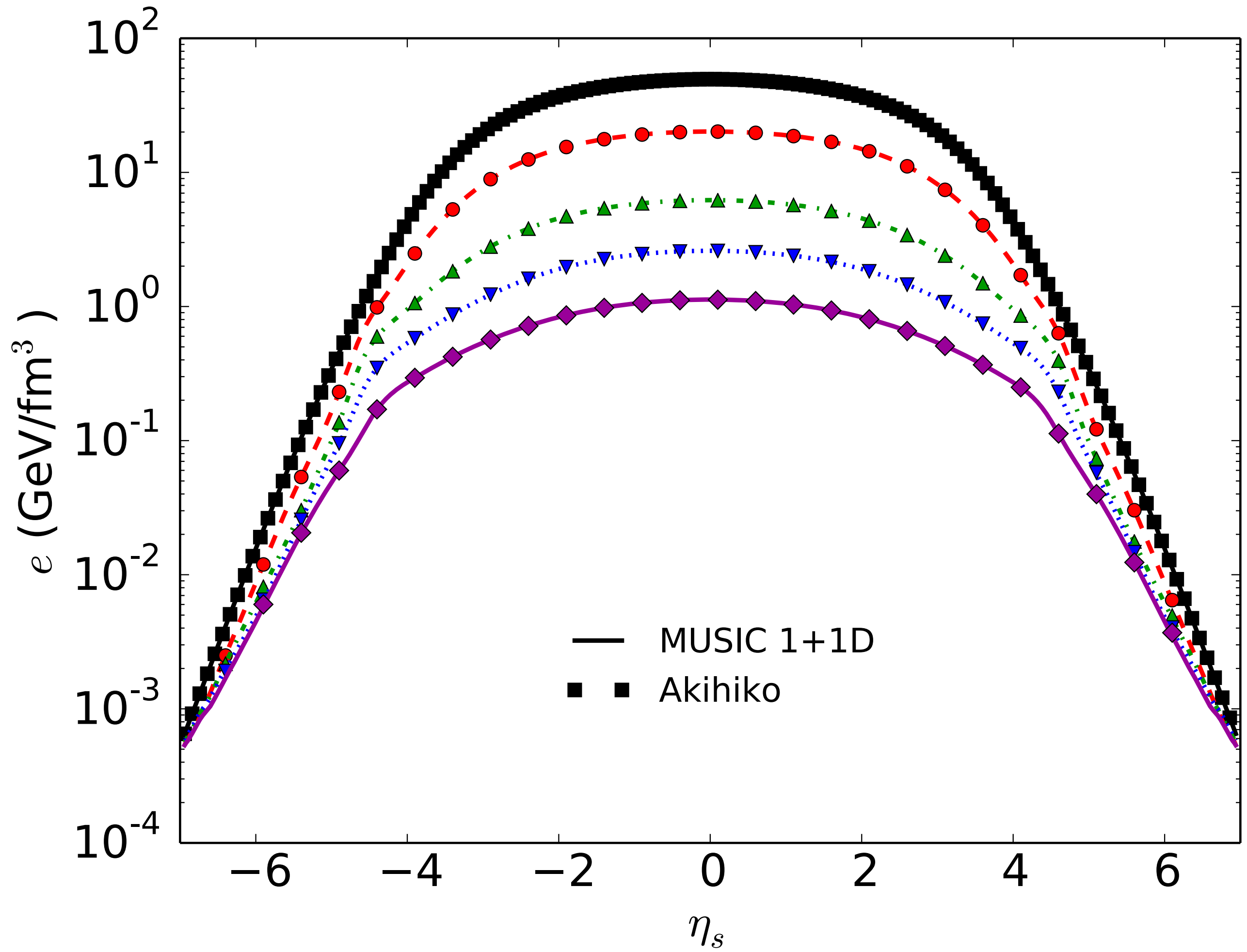
HBT correlation functions (UrQMD vs JAM)

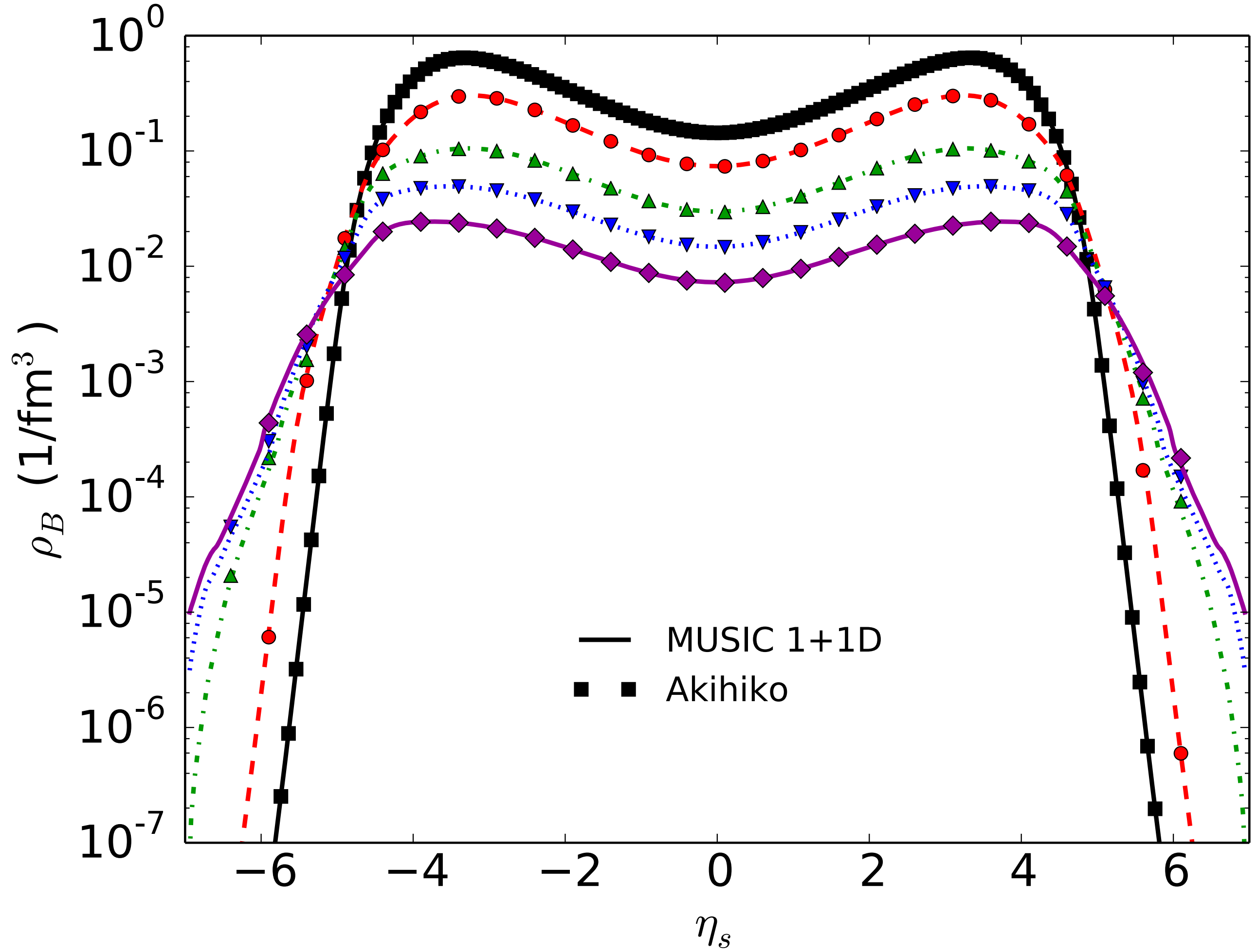
Out direction:



Code Check

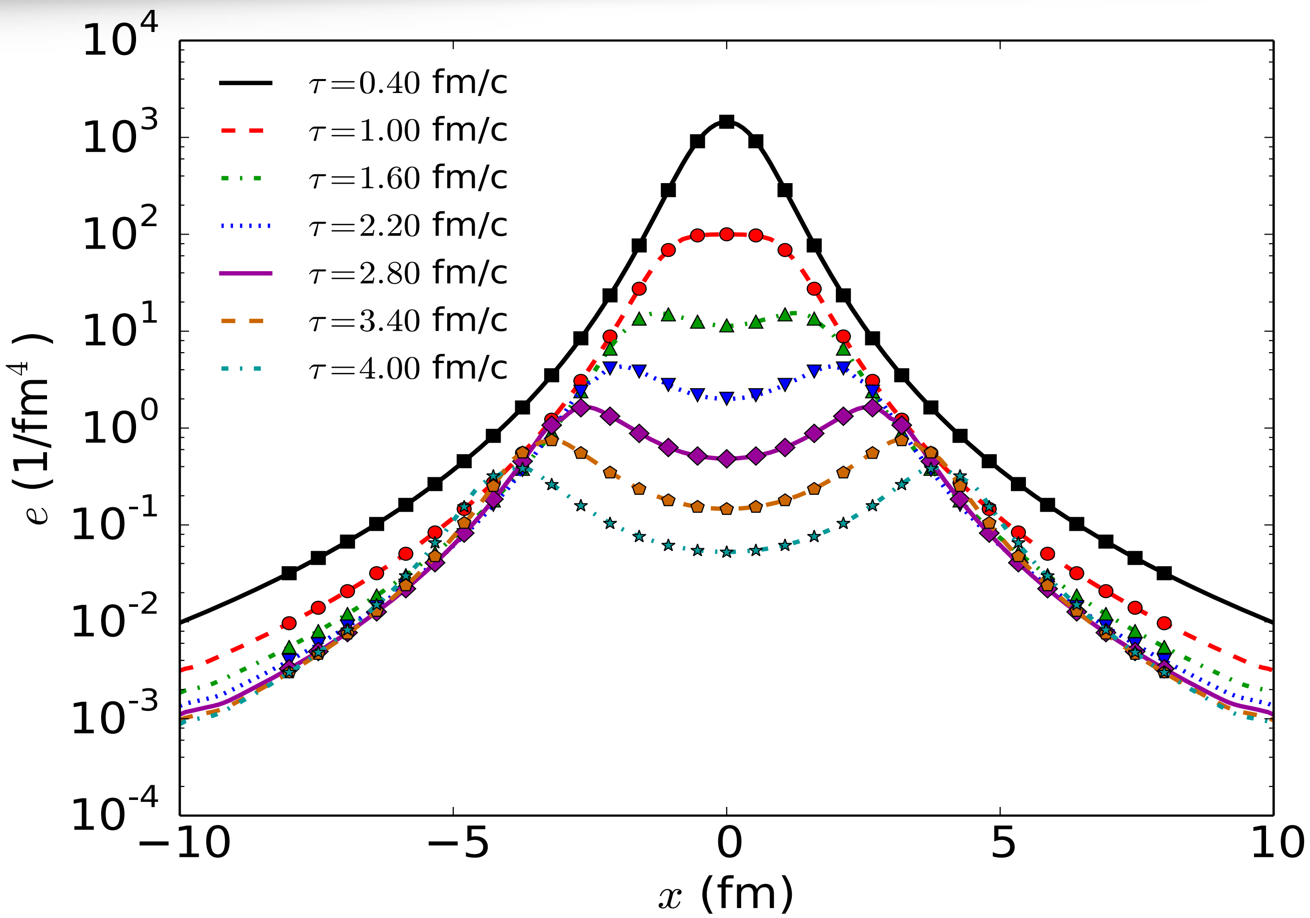
1+1D cross check:

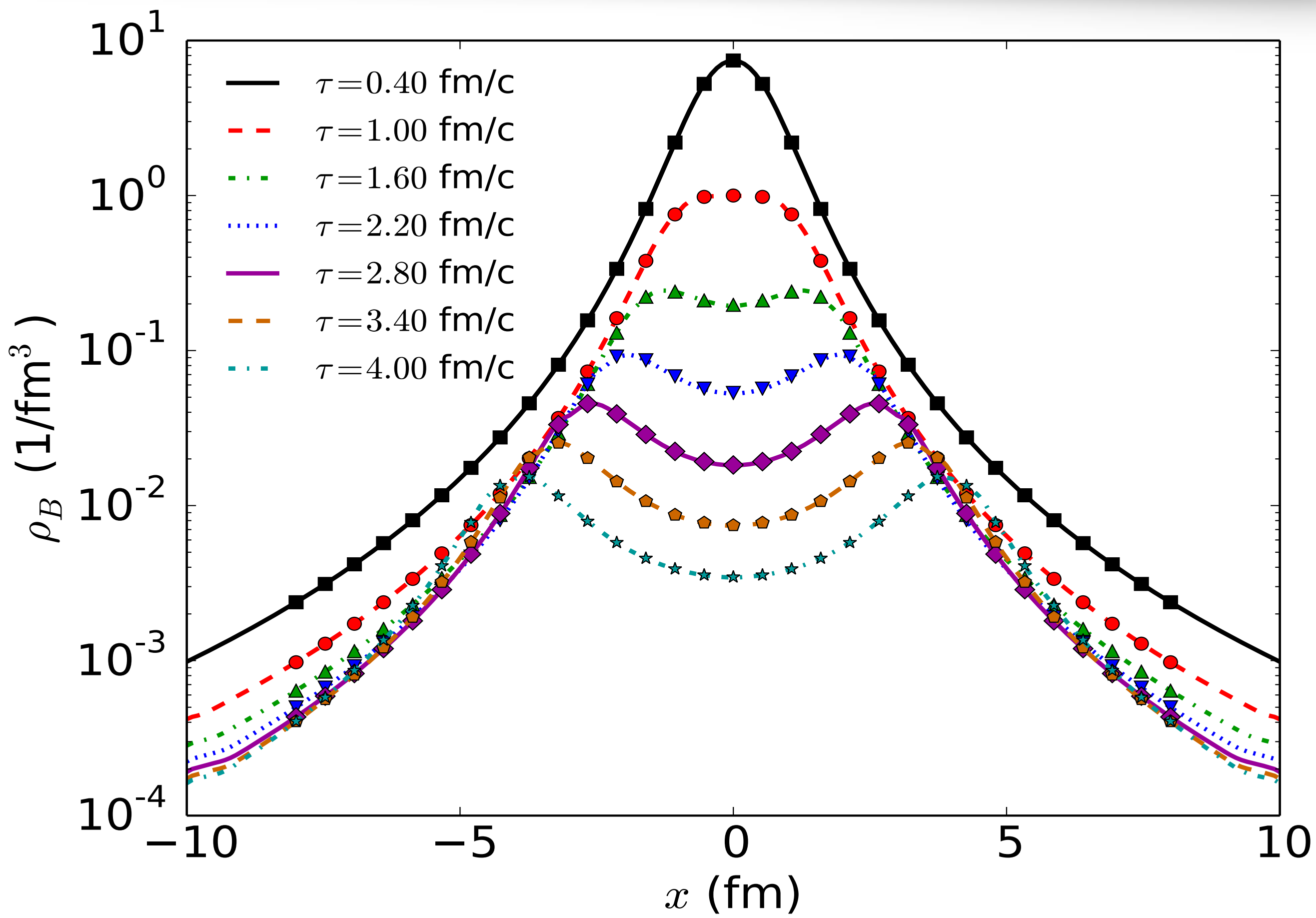


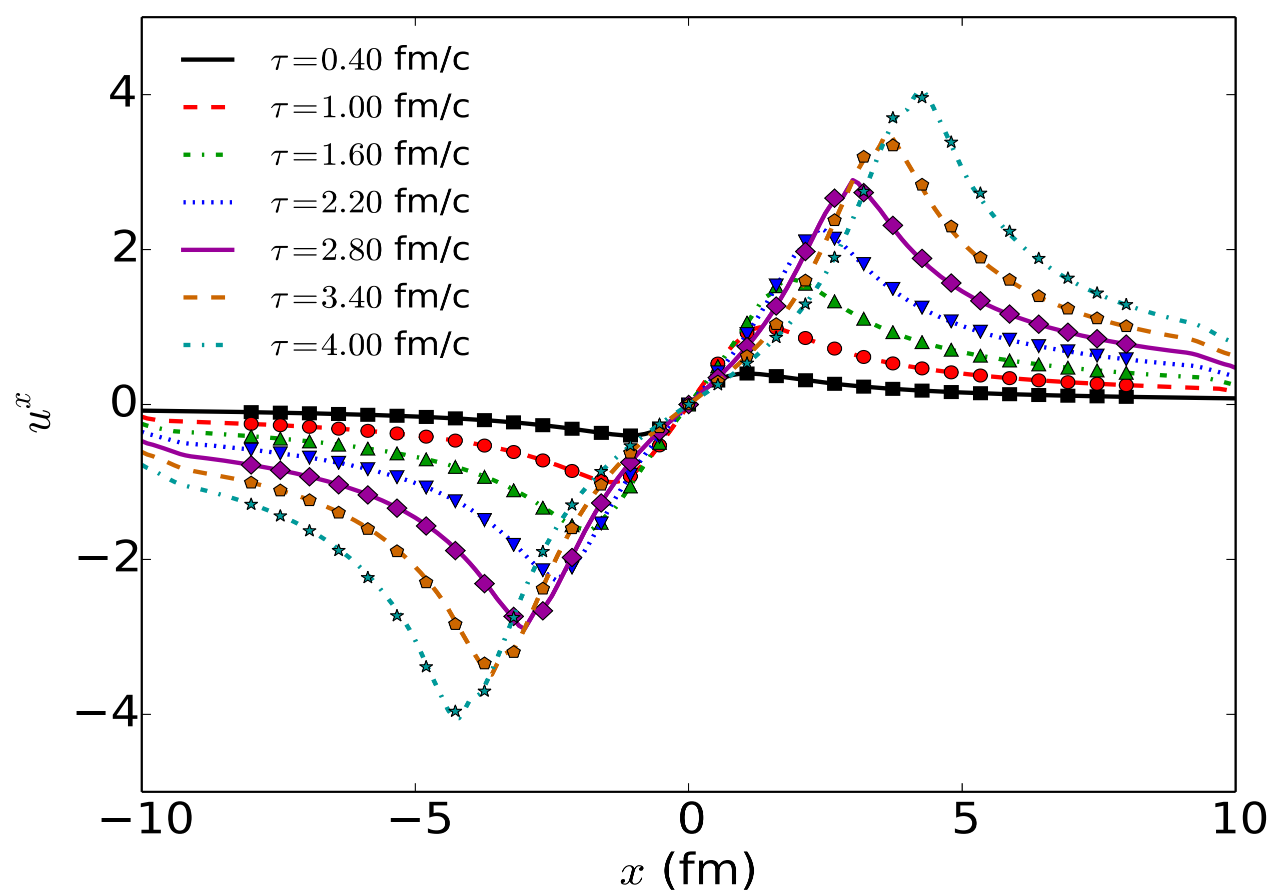


MUSIC results agree very well with Akihiko's results

Code Check

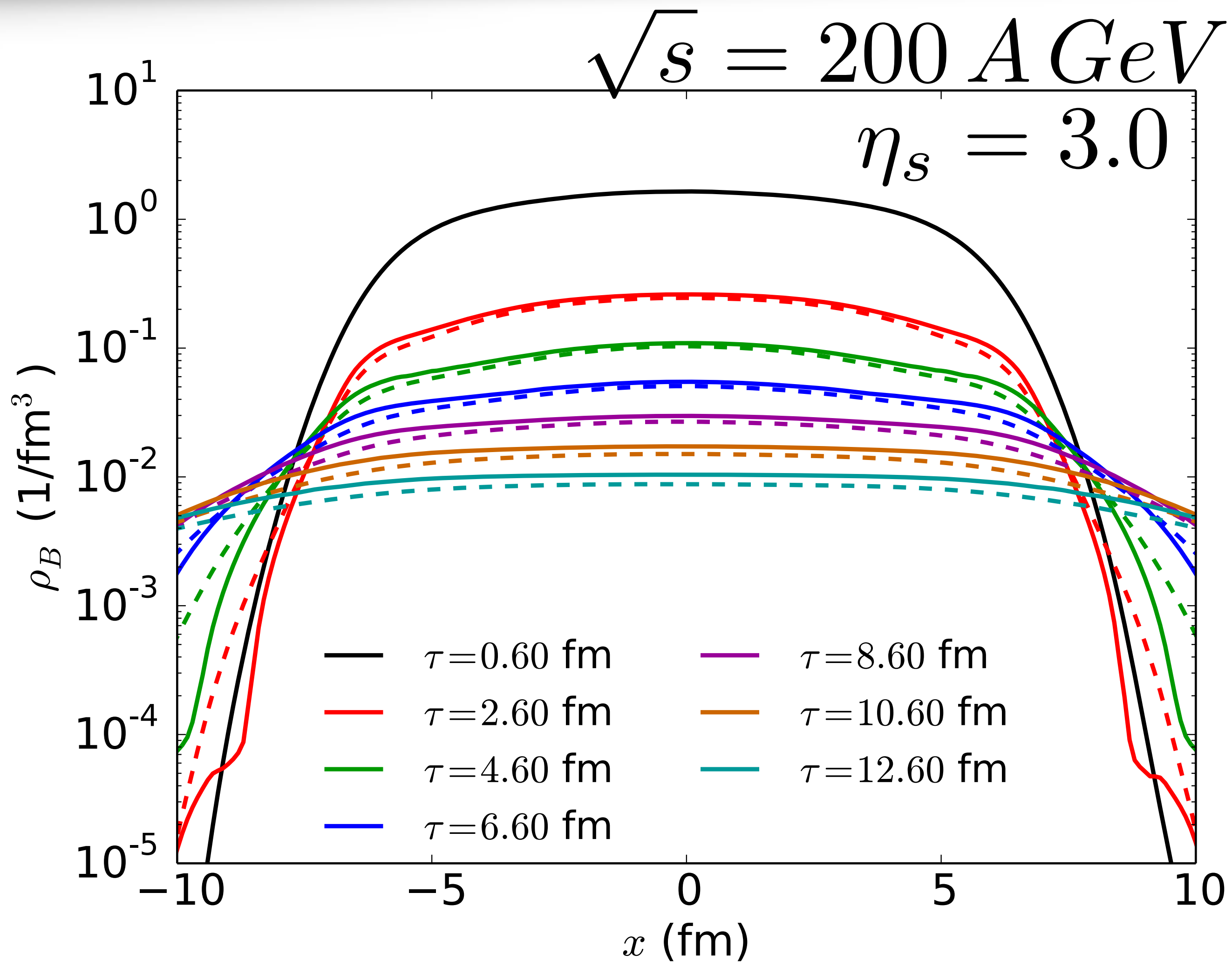






- MUSIC with baryon propagation passed ideal Gubser flow test for the transverse dynamics

Dynamic evolution of net baryon current with diffusion



solid: with diffusion dashed: no diffusion

- With diffusion, ρ_B is larger in the center of the transverse plane

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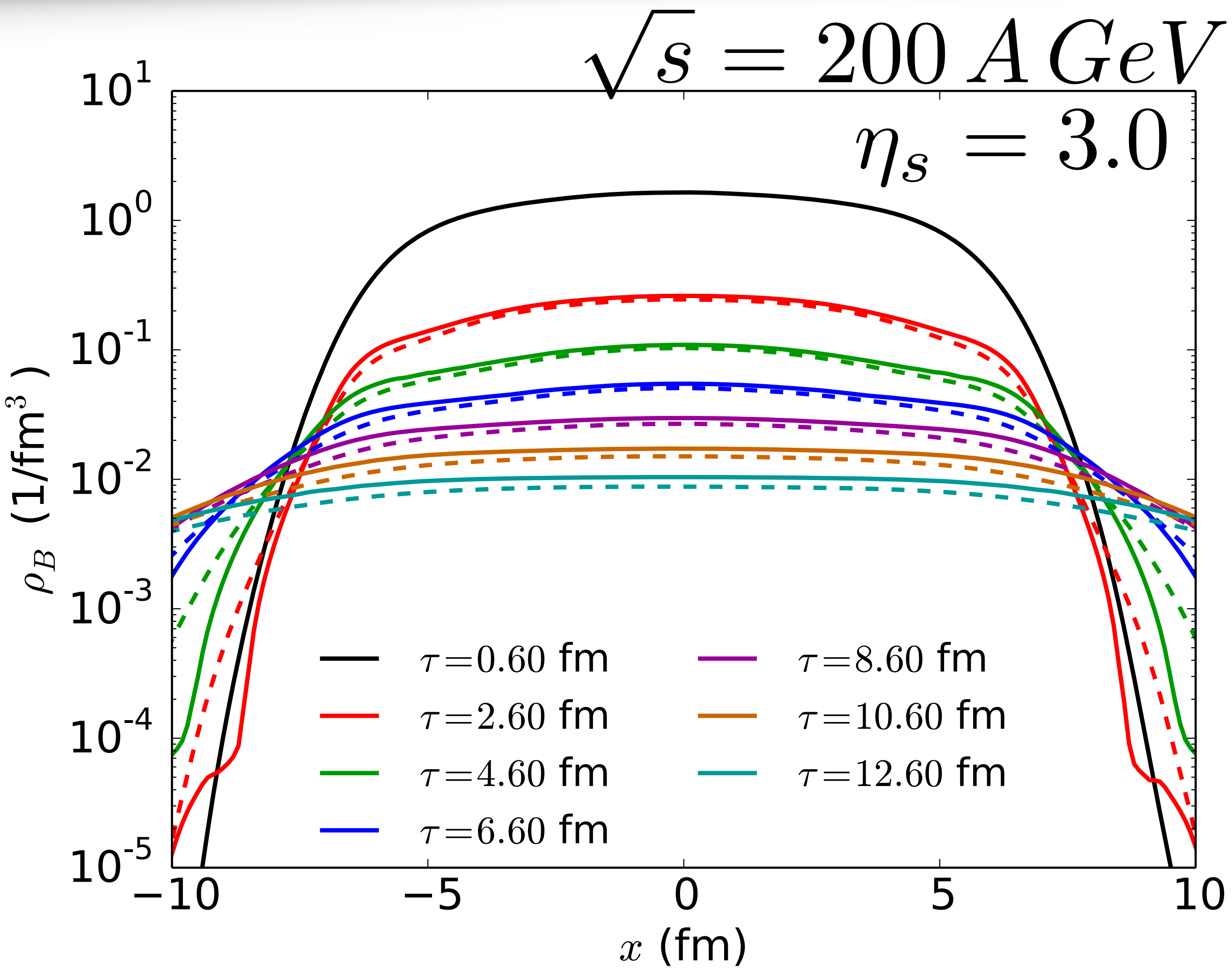

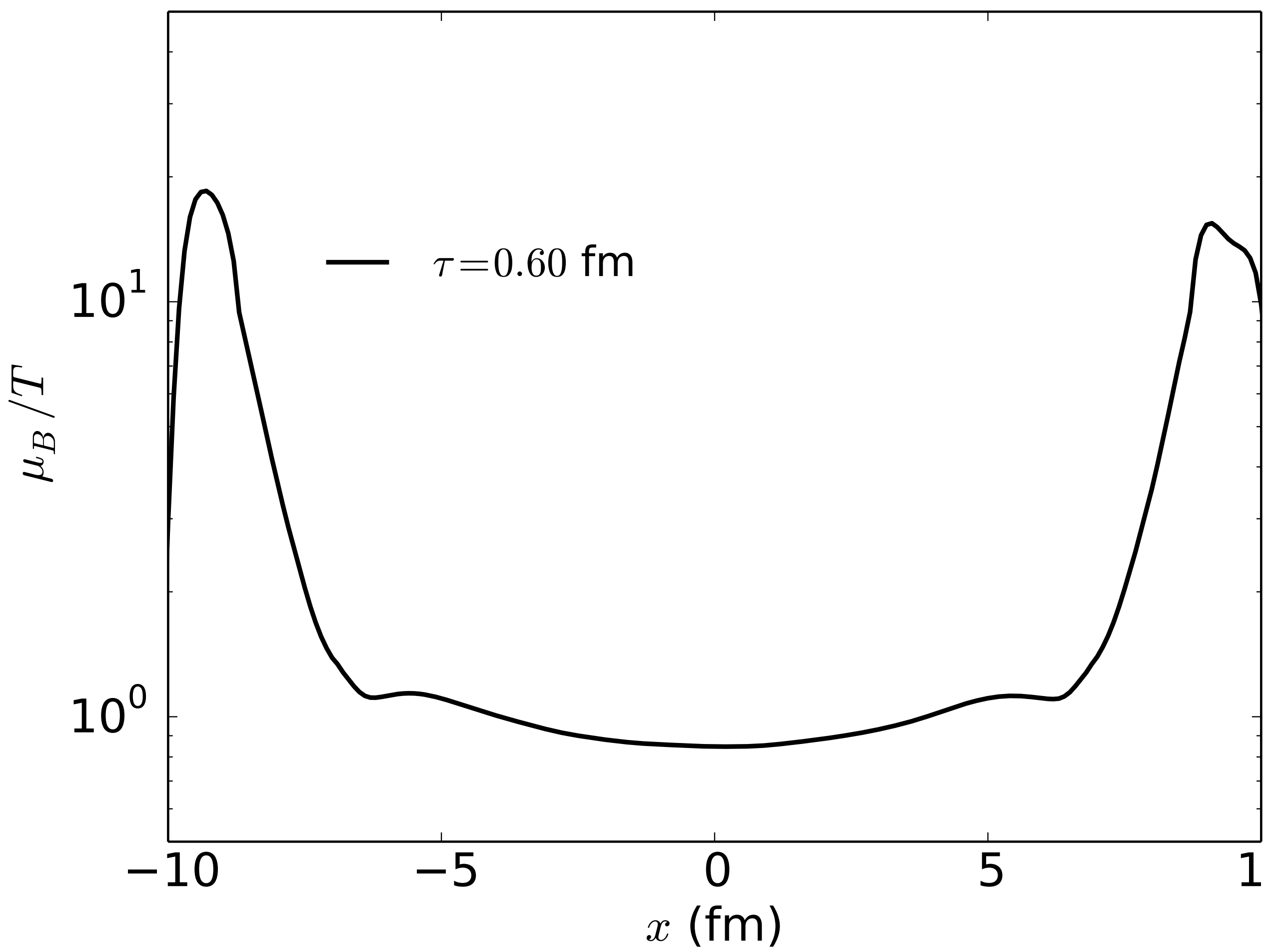

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- With diffusion, ρ_B is larger in the center of the transverse plane
- The dynamics of ρ_B is driven by the evolution of u^μ and $\nabla^\mu \frac{\mu_B}{T}$

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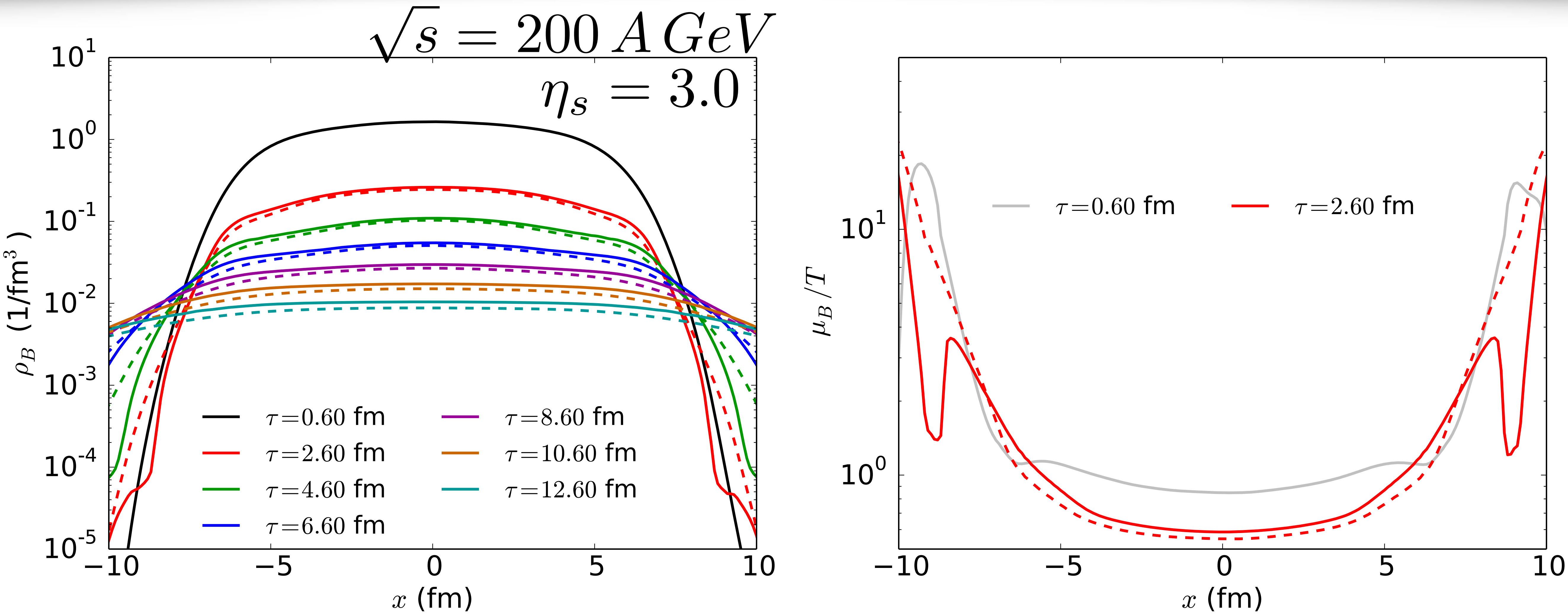

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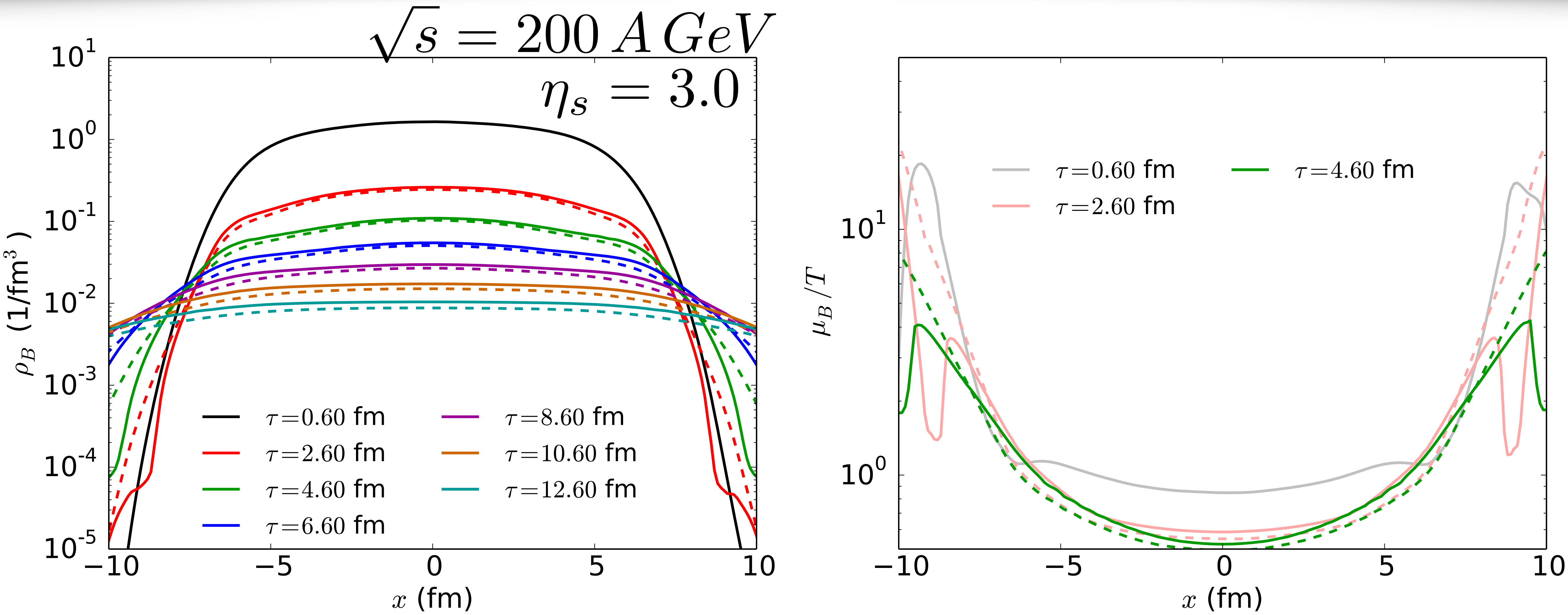

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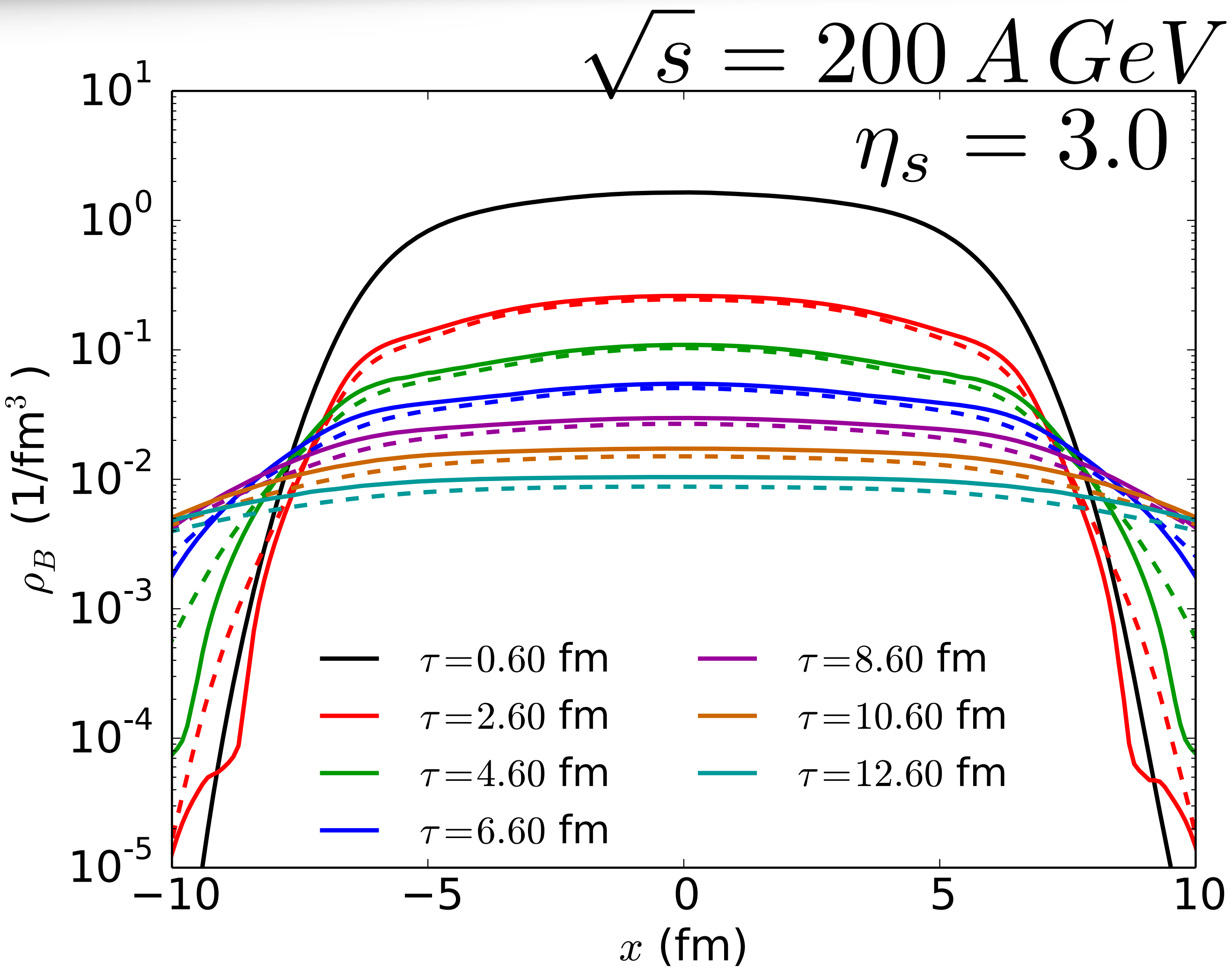

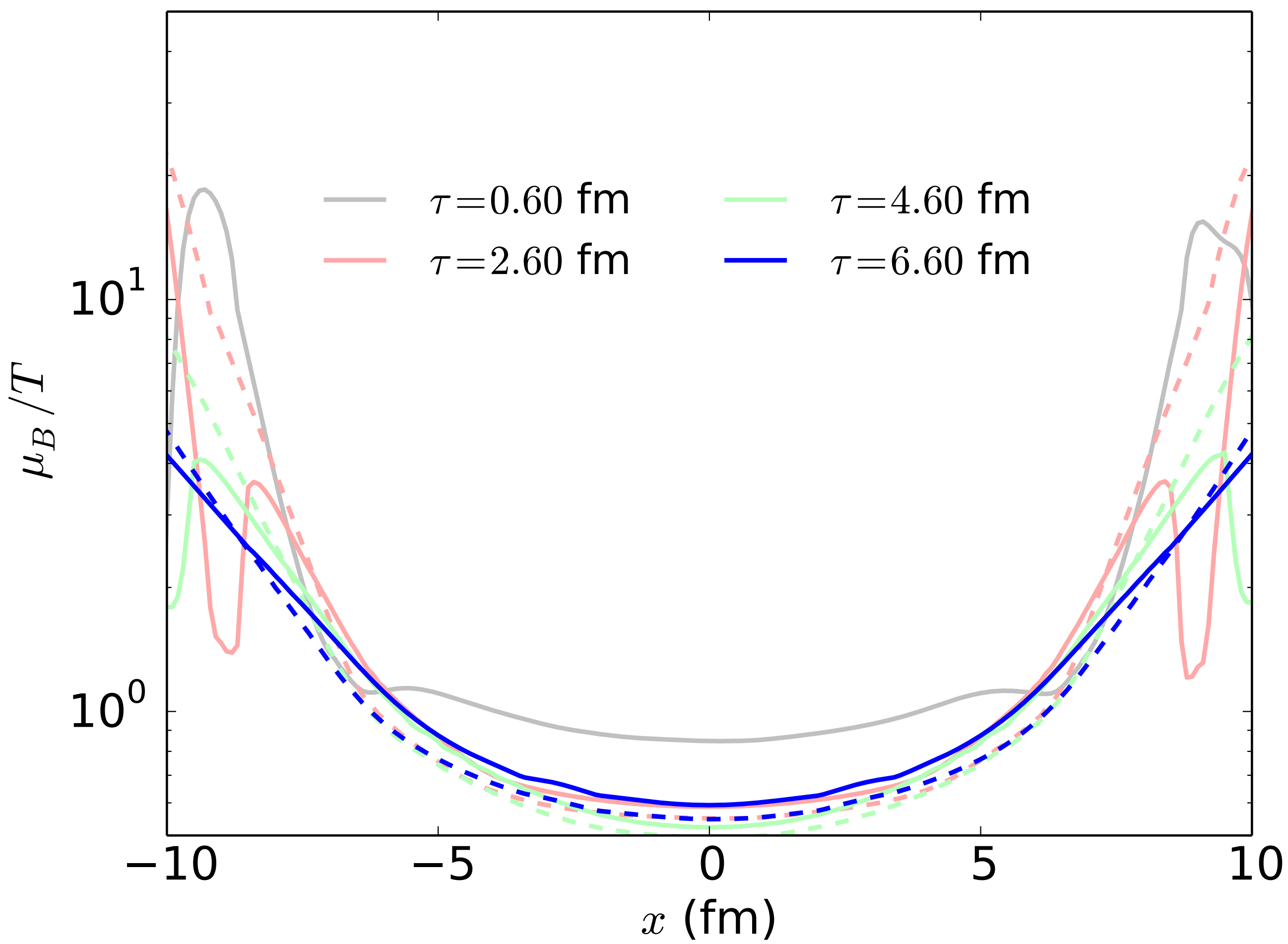

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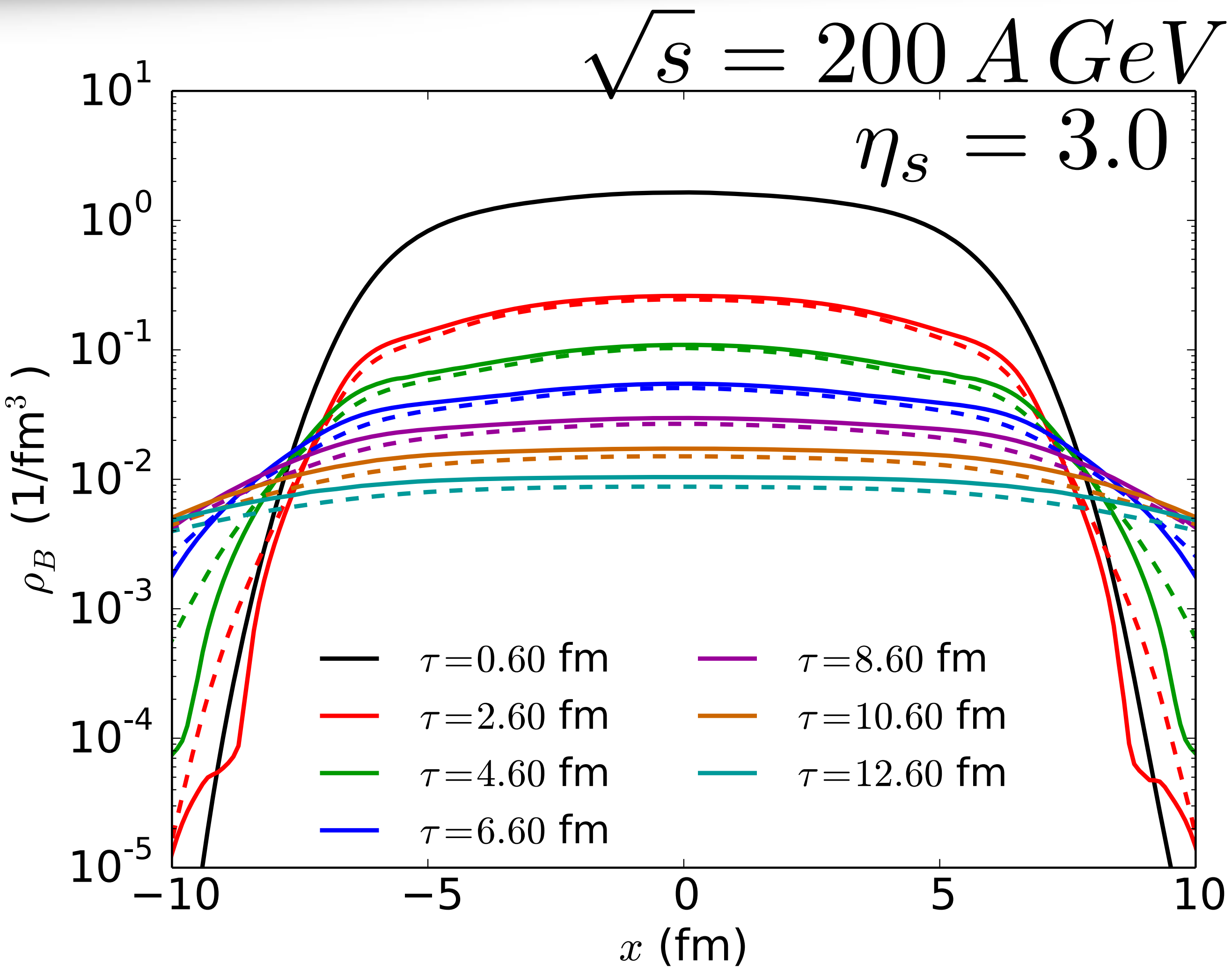

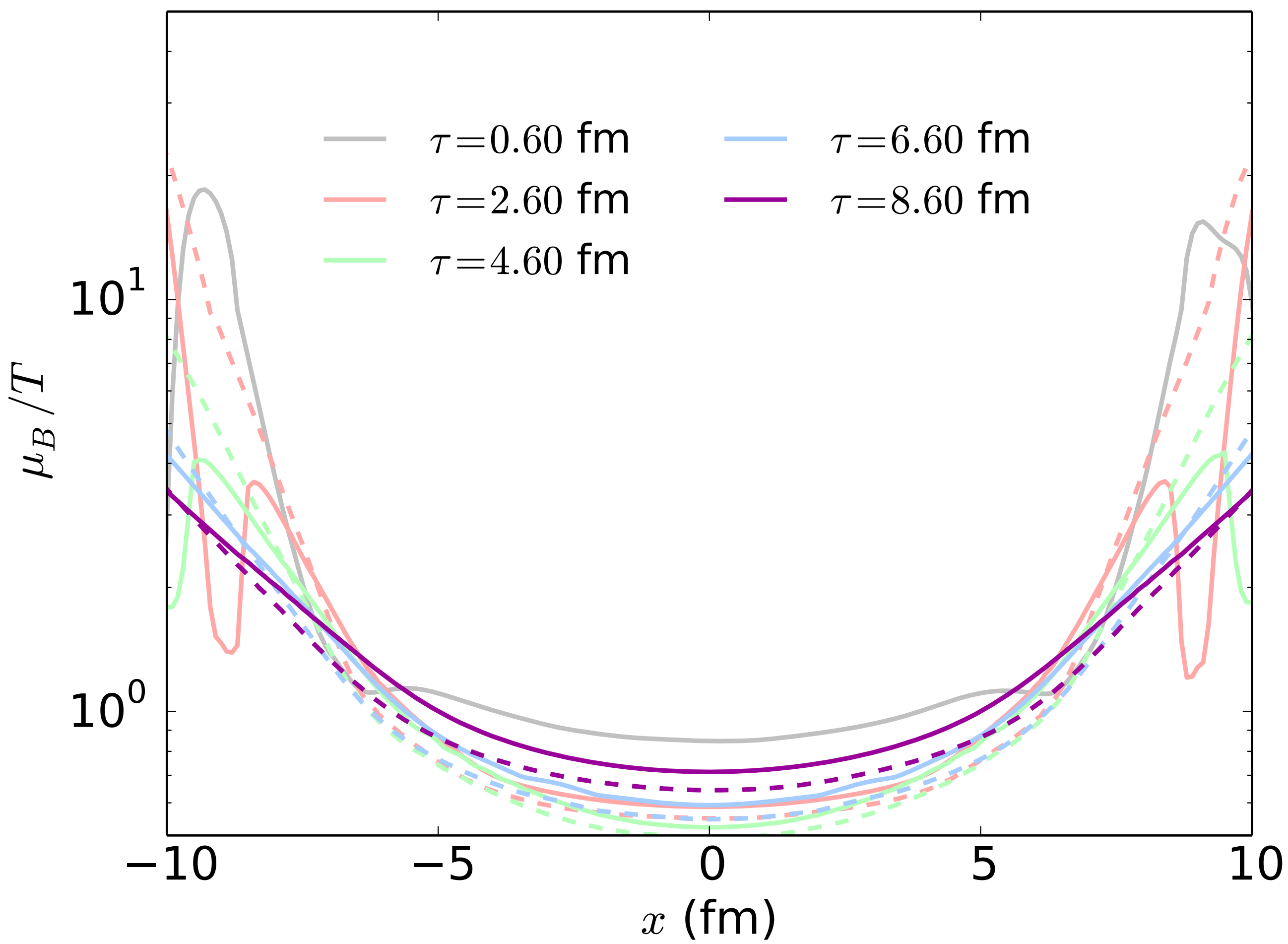

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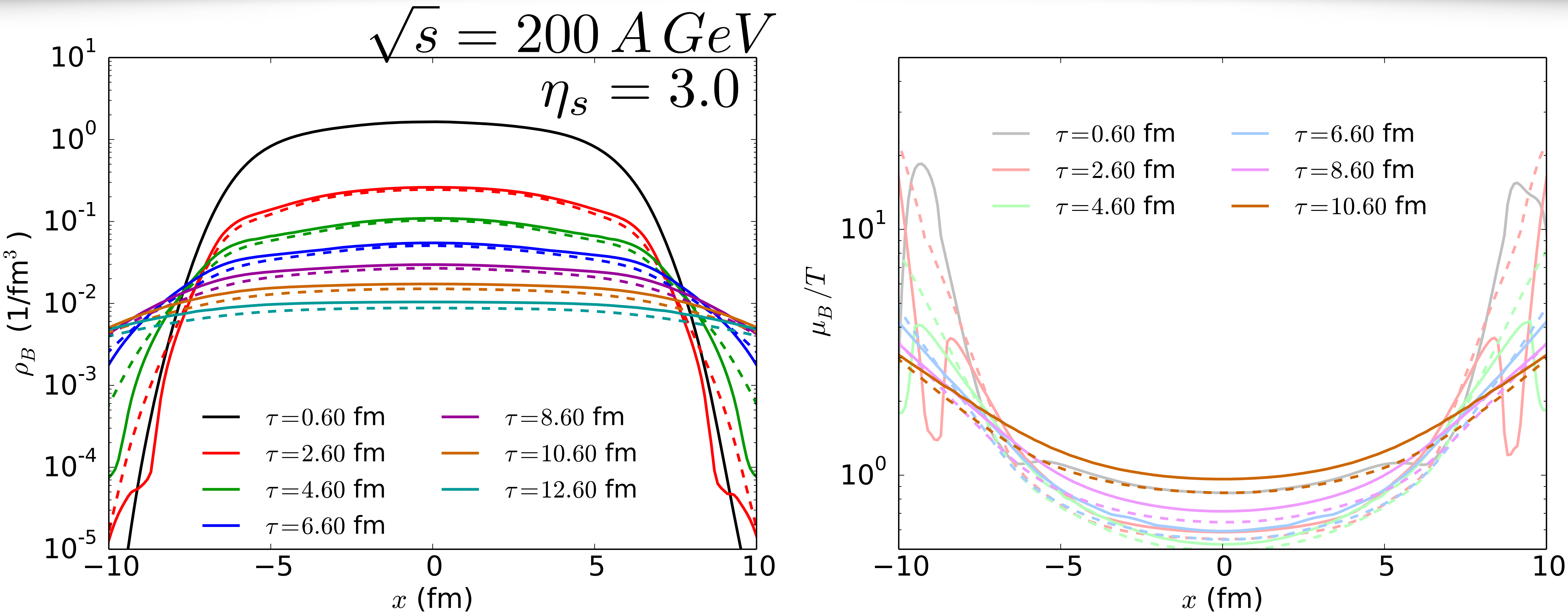

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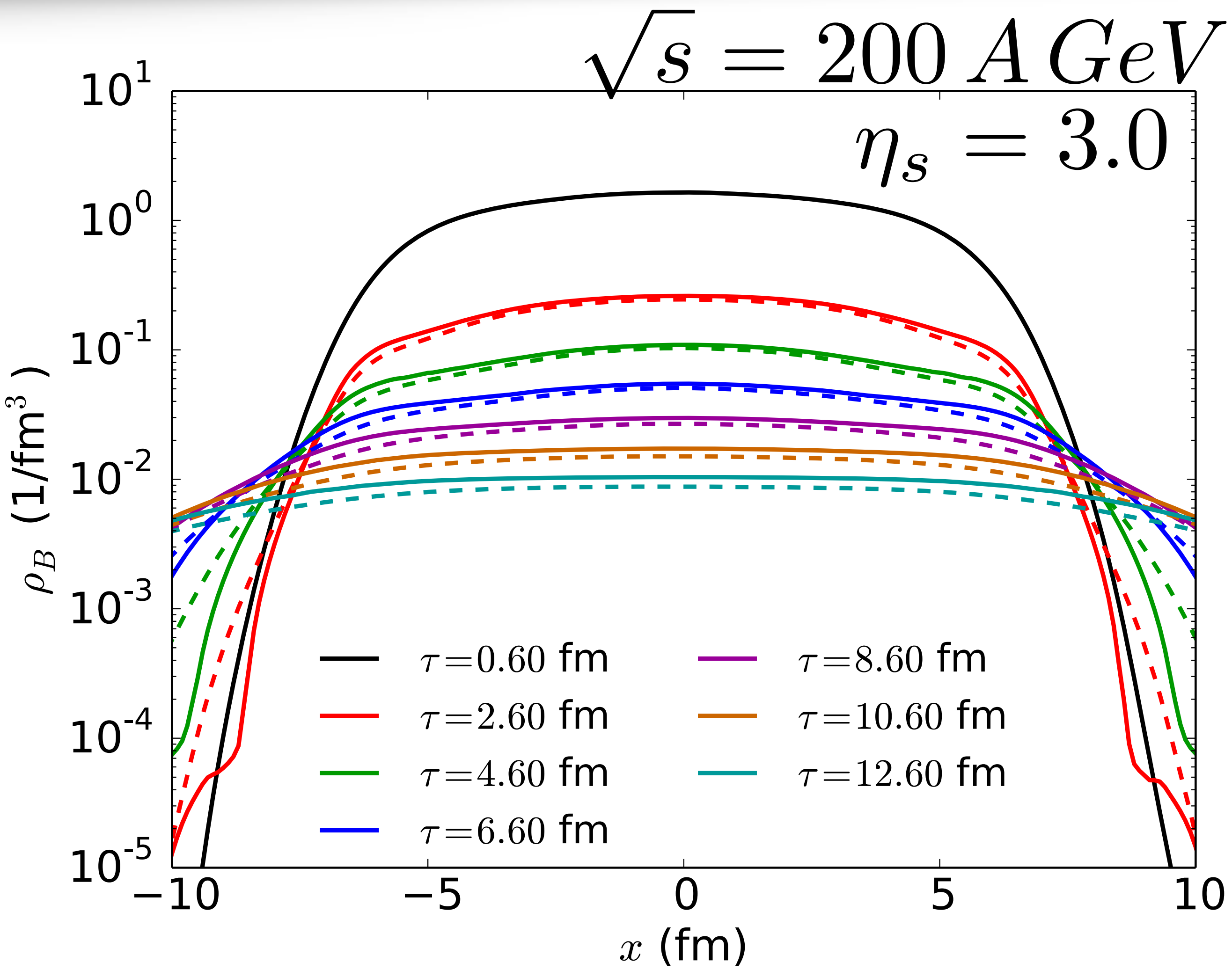

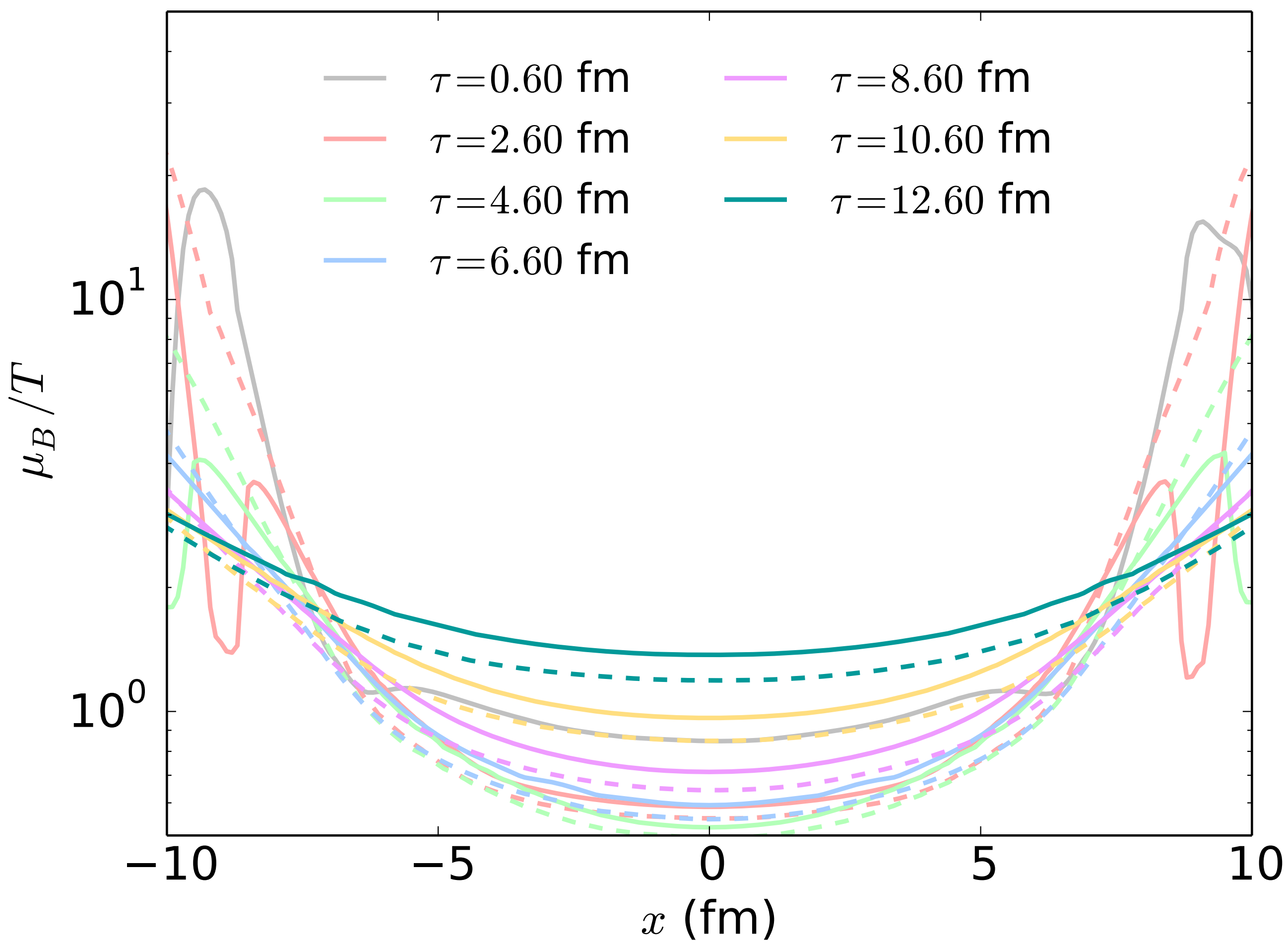

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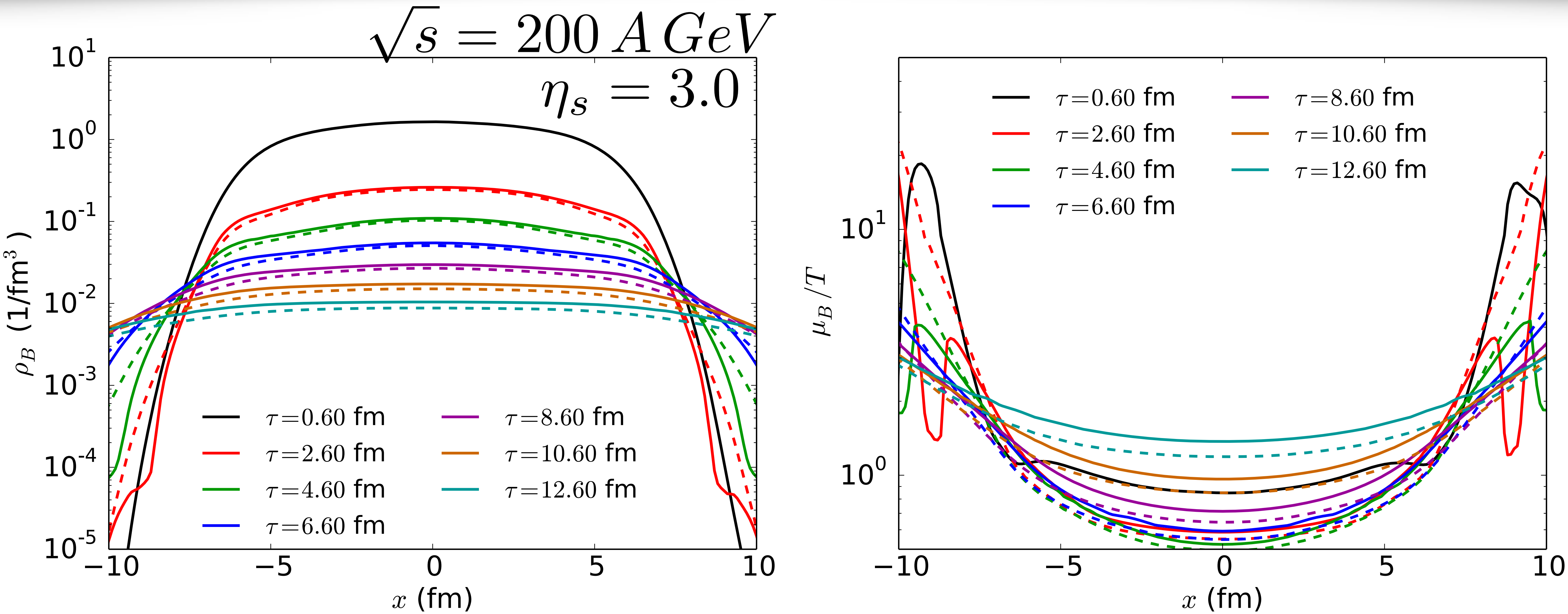

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Stabilizing MUSIC with diffusion

We implement quest_revert for q^μ to stabilize the hydro evolution with diffusion,

$$u^\mu q_\mu = 0 \quad \longrightarrow \quad q^0 = \frac{u^i q^i}{u^0}$$

The size of q^μ

$$\xi_q \equiv \frac{\sqrt{-q^\mu q_\mu}}{|\rho_B|} \frac{1}{\mathrm{prefactor} \times \tanh(e/e_{\mathrm{dec}})}$$

$$\mathrm{prefactor} = 300$$

If $\xi_q > \xi_q^{\max}$

$$\xi_q^{\max} = 0.1$$

$$\tilde{q}^\mu = \frac{\xi_q^{\max}}{\xi_q} q^\mu$$

Stabilizing MUSIC with diffusion

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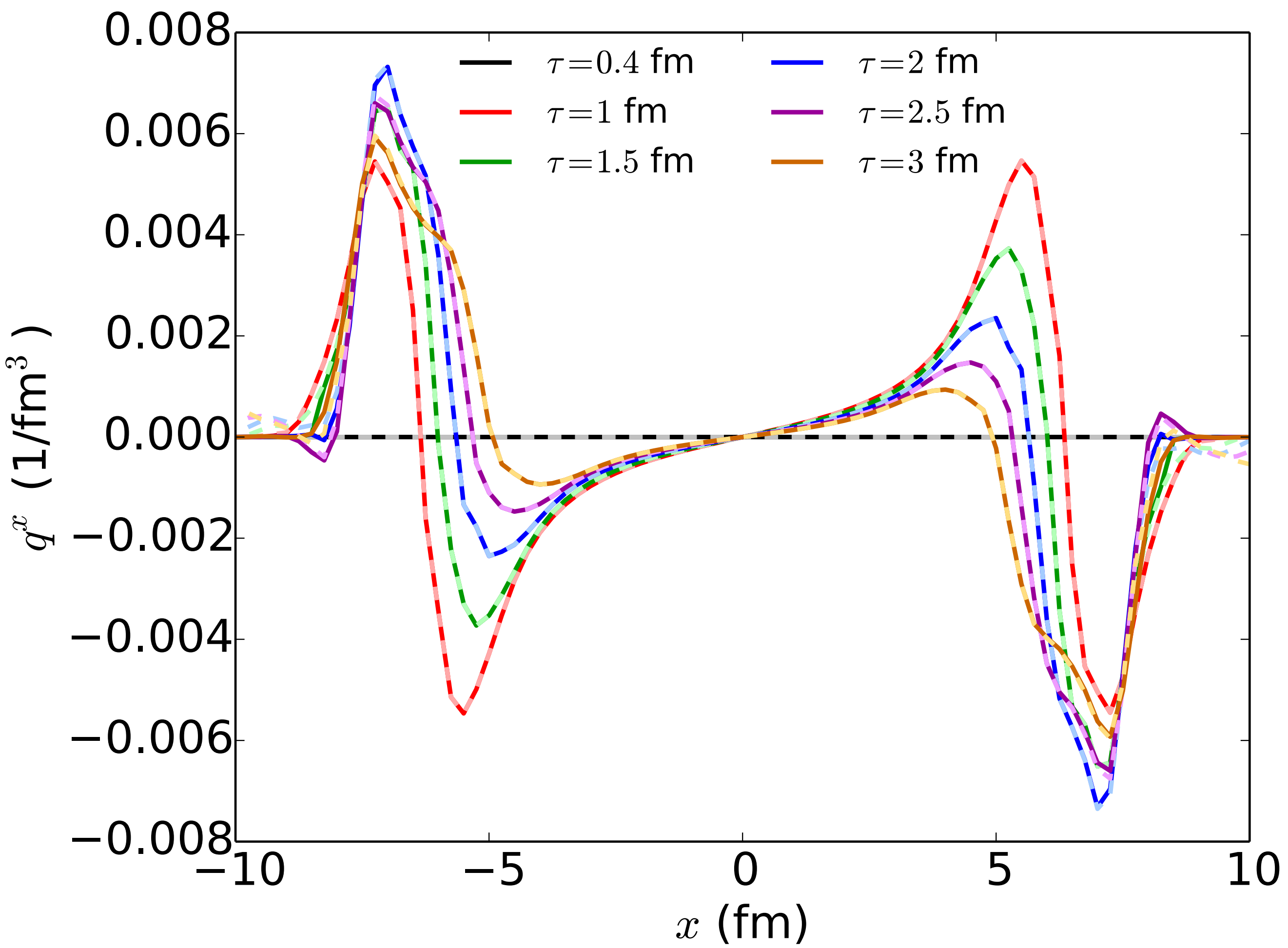

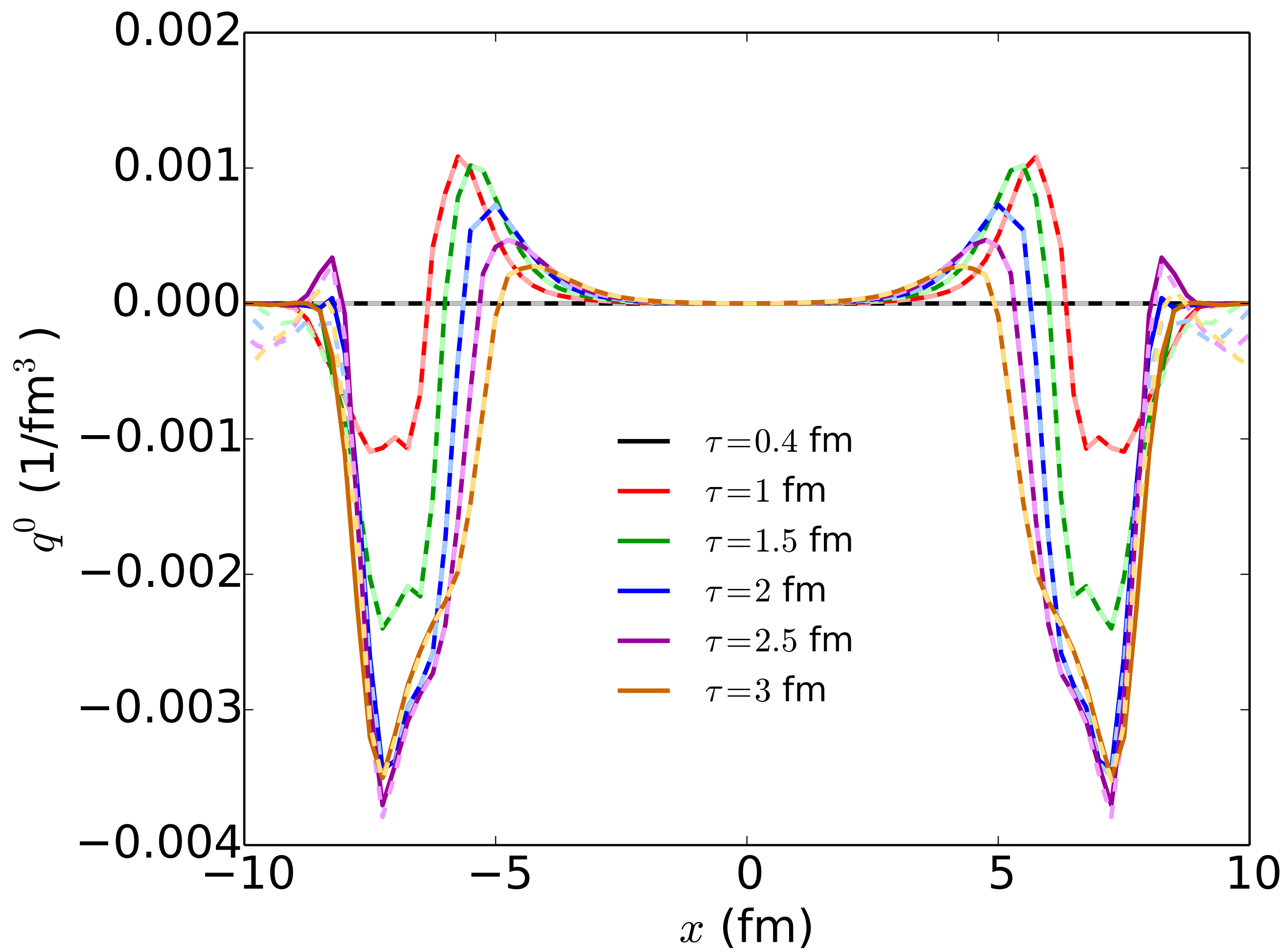

most of the modifications are at the edges of the fireball