Information field based global Bayesian inference of the jet transport coefficient

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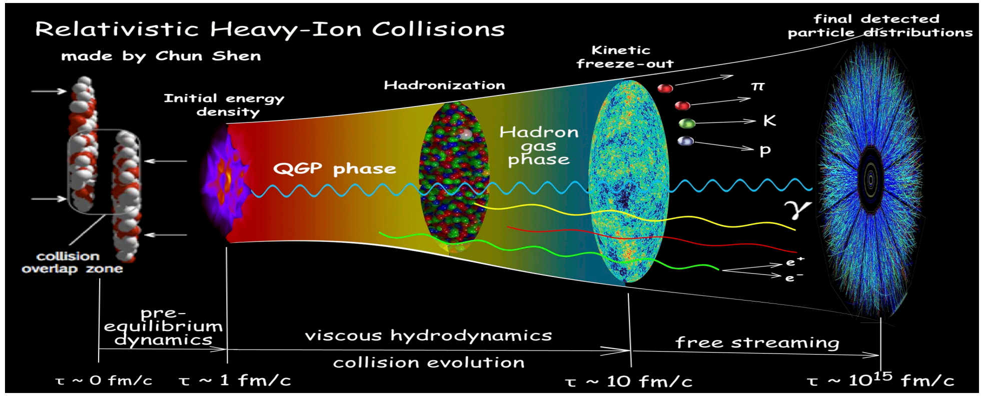
[PRC 108, L011901 (2023); arXiv: 2208.14419]

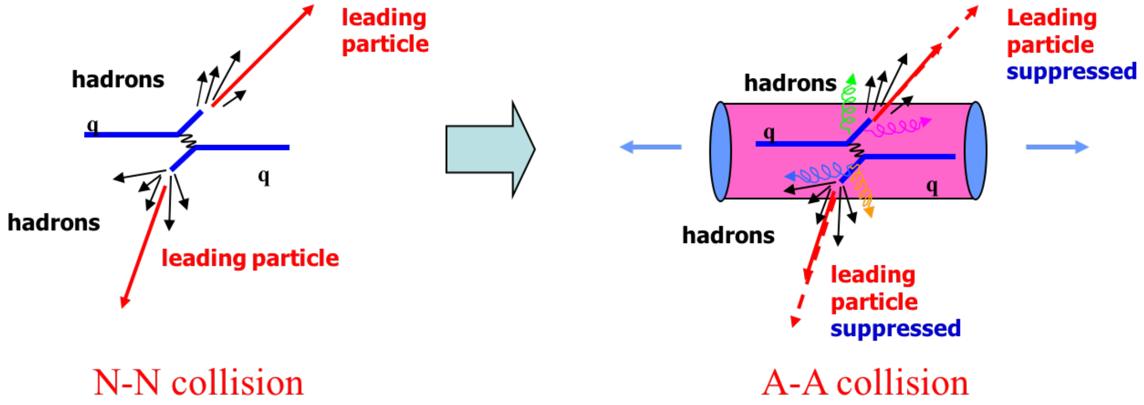
2024/5/17

Outline

- Motivation
- NLO parton model with energy loss
- Bayesian inference of $\hat{q}(T)$ with information field (IF)
  - IF-assisted sensitivity analysis
  - Global Bayesian inference of $\hat{q}(T)$
  - Validation and prediction
- Summary

Motivation





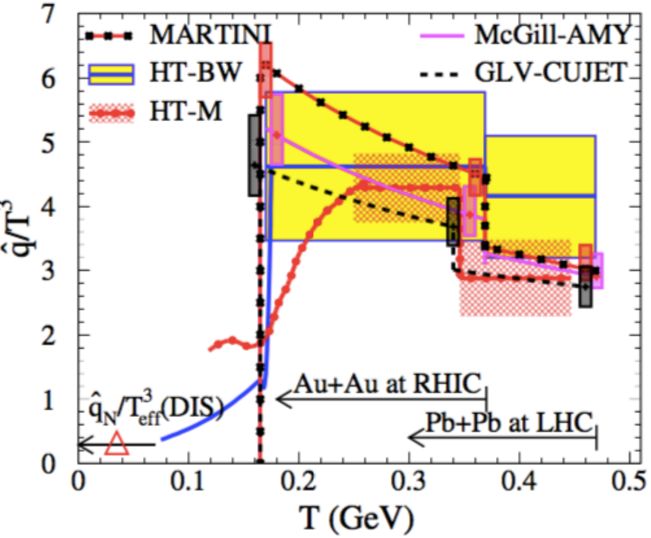
- Quark-gluon plasma (QGP) has been created in high-energy HIC.

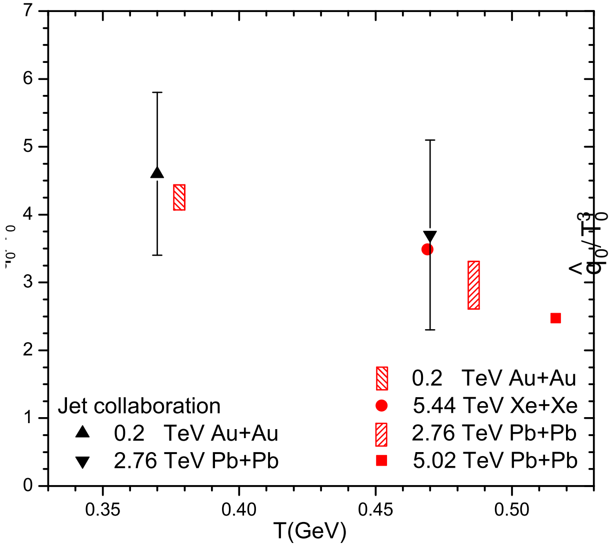
- Jet quenching is an extremely useful tool to explore the properties of QGP.
[X.-N. Wang and M. Gyulassy, PRL 68, 1480 (1992)]

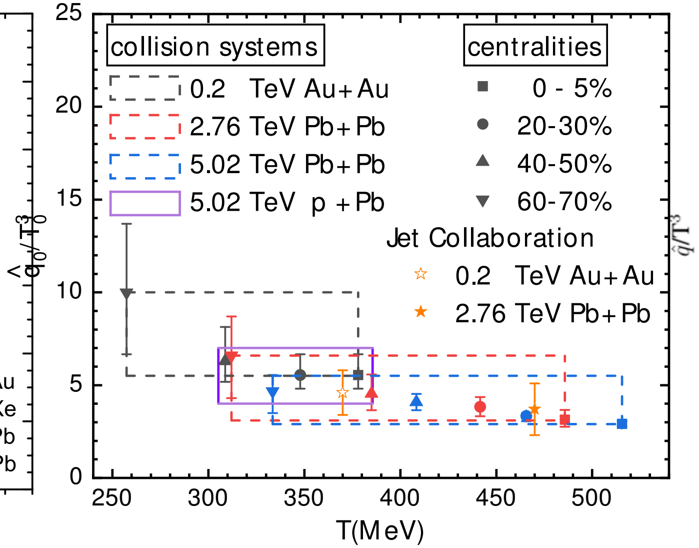
- The energetic jet losses a large amount of its energy via radiating gluon induced by multiple scatterings, leading to the suppression of the yield of high-p_{T} jets and hadrons.
- Jet energy loss in QGP medium: $\dfrac{dE}{dL} = \dfrac{\alpha_s N_c}{4}\hat{q}L.$
- Jet transport parameter: hard parton's transverse momentum broadening squared per unit length.

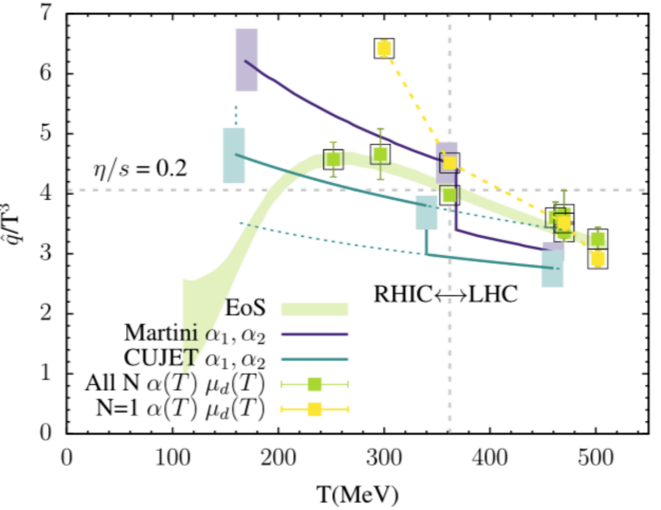
$$\hat{q} = \rho \int dq_{\mathrm{T}}^2 \frac{d\sigma}{dq_{\mathrm{T}}^2} q_{\mathrm{T}}^2.$$ [BDMPS, NPB 483 (1997) 291]

Motivation: past efforts in the extraction of $\hat{q}/T^3$

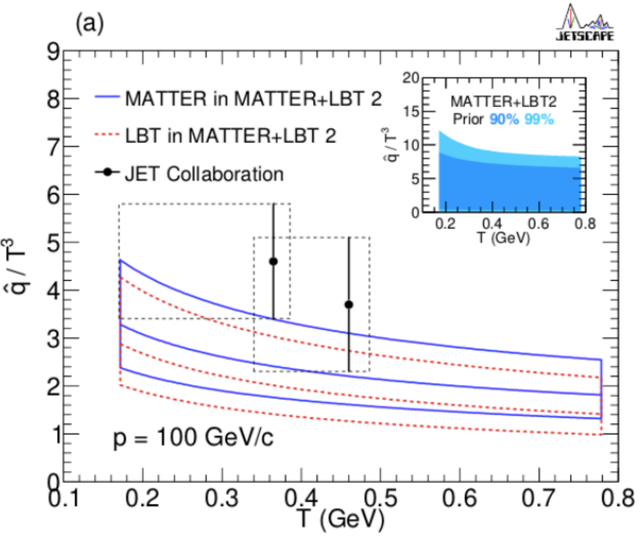


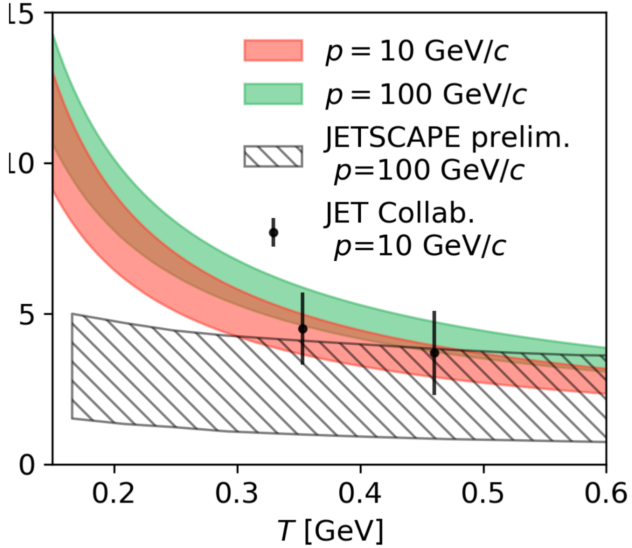






[The JET colla., PRC 90. 014909] [***M. Xie***, H.Z. Zhang, et al., EPJC (2019)] [***M. Xie***, X.N. Wang, H.Z. Zhang, PRC (2021)] [X. Feal, et al., PLB (2021)]





- Form: $\hat{q}/T^3 \propto C \longrightarrow \hat{q}/T^3(T)$
- Observable: single $\longrightarrow$ multiple
- Method: $\chi^2 \longrightarrow$ Bayesian inference
- Explicit parametrizations introduce unwarranted long-range correlations between different T regions.
- Uncertainty is large.

[S. Cao et al. (JETSCAPE), PRC (2021) [WY Ke, X.N. Wang, JHEP (2021)]

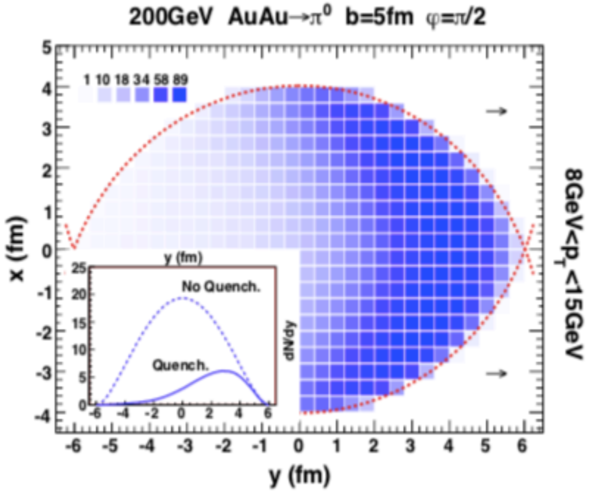
- Aim: the T dependence of $\hat{q}/T^3$.

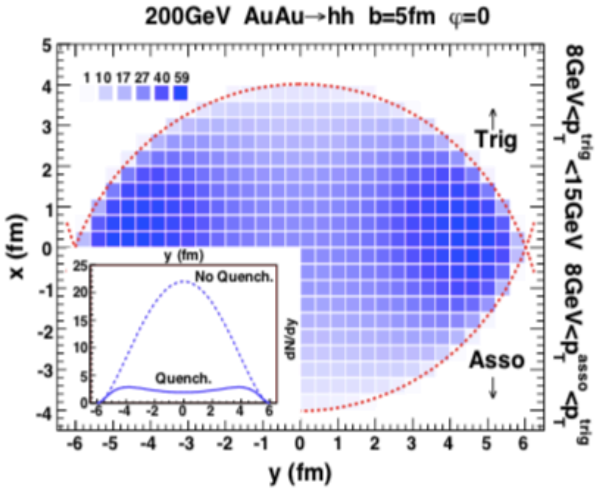
- Data: all existing experimental data on $R^h_{AA}, I^{hh}_{AA}, I^{\gamma h}_{AA}$ at RHIC and LHC with a wide range of centralities.

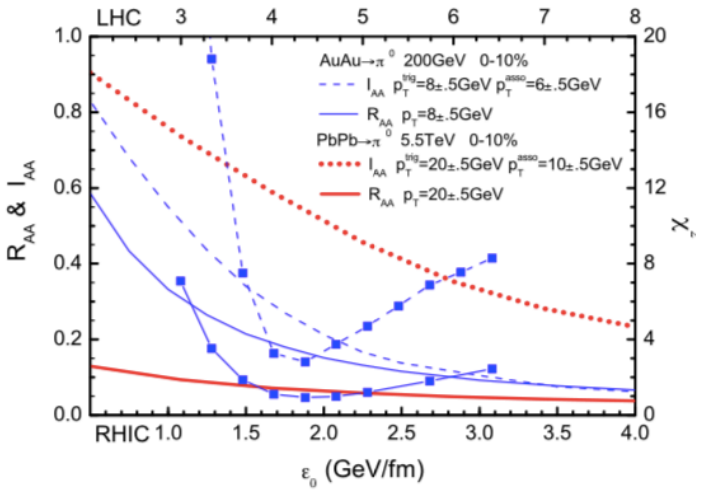
Single hadron, γ-hadron, di-hadron suppressions are direct consequences of JQ.

Dihadron and γ-hadron correlations are known to be more sensitive to the parton energy loss.

[H. Z. Zhang J.F. Owens, E. K. Wang and X.-N. Wang, PRL 98 (2007) 212301, PRL 103 (2009) 032302]





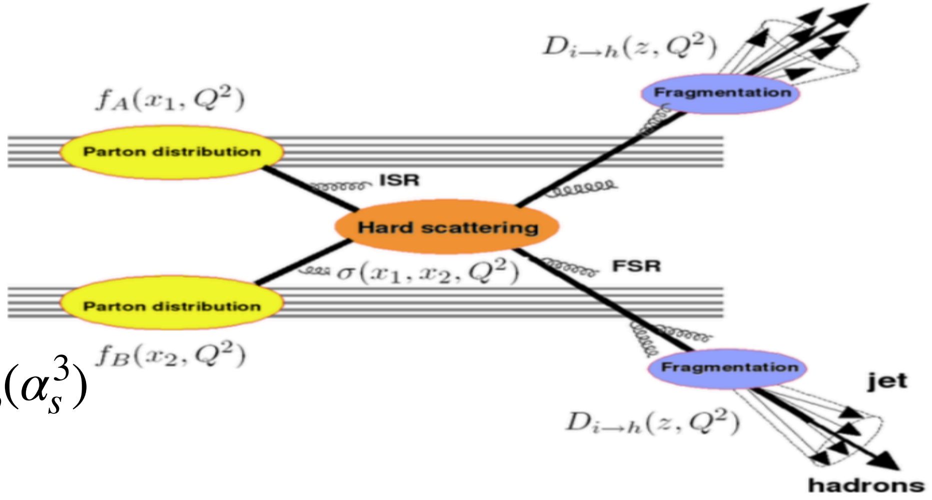


- Analysis method: Information field theory assisted Bayesian inference

IF approach models the prior distribution of the unknown function that is free of long-range correlations

[Torsten A. Enßlin, Annalen Phys. 531 (2019) 3, 1800127], [J. C. Lemm, arXiv: physics/9912005]

pQCD parton model   In p+p collisions：



Single hadron: [J.F.Owens, Rev. Mod. Phys 59,465(1987)]

$$\frac{d\sigma^h_{pp}}{dyd^2p_{\mathrm{T}}} = \sum_{abcd}\int dx_a dx_b f_{a/p}(x_a,\mu^2) f_{b/p}(x_b,\mu^2)\frac{1}{\pi}\frac{d\sigma_{ab\to cd}}{d\hat{t}}\frac{D_{h/c}(z_c,\mu^2)}{z_c} + \Delta\sigma^h_{pp}(\alpha_s^3)$$

Di-hadron:

$$\frac{d\sigma^{hh}_{pp}}{dy^c_h d^2p^{h_c}_{\mathrm{T}} dy^d_h d^2p^{h_d}_{\mathrm{T}}} = \sum_{abcd}\int dz_c dz_d f_{a/p}\left(x_a,\mu^2\right) f_{b/p}\left(x_b,\mu^2\right)\frac{x_a x_b}{\pi z_c^2 z_d^2}\frac{d\sigma_{ab\to cd}}{d\hat{t}} D_{h/c}\left(z_c,\mu^2\right) D_{h/d}\left(z_d,\mu^2\right)\delta^2\left(\vec{p}^{\,c}_{\mathrm{T}} + \vec{p}^{\,d}_{\mathrm{T}}\right) + \Delta\sigma^{hh}_{pp}(\alpha_s^3)$$

γ-hadron: only consider direct photon [***M. Xie***, X.N. Wang, H.Z. Zhang, PRC 103, 034911 (2021)]

$$\frac{d\sigma^{\gamma h}_{pp}}{dy_\gamma d^2p^\gamma_{\mathrm{T}} dy_h d^2p^h_{\mathrm{T}}} = \sum_{abd}\int dz_d f_{a/p}\left(x_a,\mu^2\right) f_{b/p}\left(x_b,\mu^2\right)\frac{x_a x_b}{\pi z_d^2}\frac{d\sigma_{ab\to\gamma d}}{d\hat{t}} D_{h/d}\left(z_d,\mu^2\right)\delta^2\left(\vec{p}^{\,\gamma}_{\mathrm{T}} + \frac{\vec{p}^{\,h}_{\mathrm{T}}}{z_d}\right) + \Delta\sigma^{\gamma h}_{pp}\left(\alpha_e\alpha_s^2\right)$$

Triggered fragmentation functions:

$$D^{\mathrm{trig}}_{pp}\left(z_{\mathrm{T}}\right) = p^{\mathrm{trig}}_{\mathrm{T}}\frac{d\sigma_{pp}/dy^{\mathrm{trig}}dp^{\mathrm{trig}}_{\mathrm{T}}dy^{\mathrm{assoc}}dp^{\mathrm{assoc}}_{\mathrm{T}}}{d\sigma_{pp}/dy^{\mathrm{trig}}dp^{\mathrm{trig}}_{\mathrm{T}}}, z_{\mathrm{T}} = p^{\mathrm{assoc}}_{\mathrm{T}}/p^{\mathrm{trig}}_{\mathrm{T}}.$$

$f_{a/p}(x_a,\mu^2)$: CT14 PDF

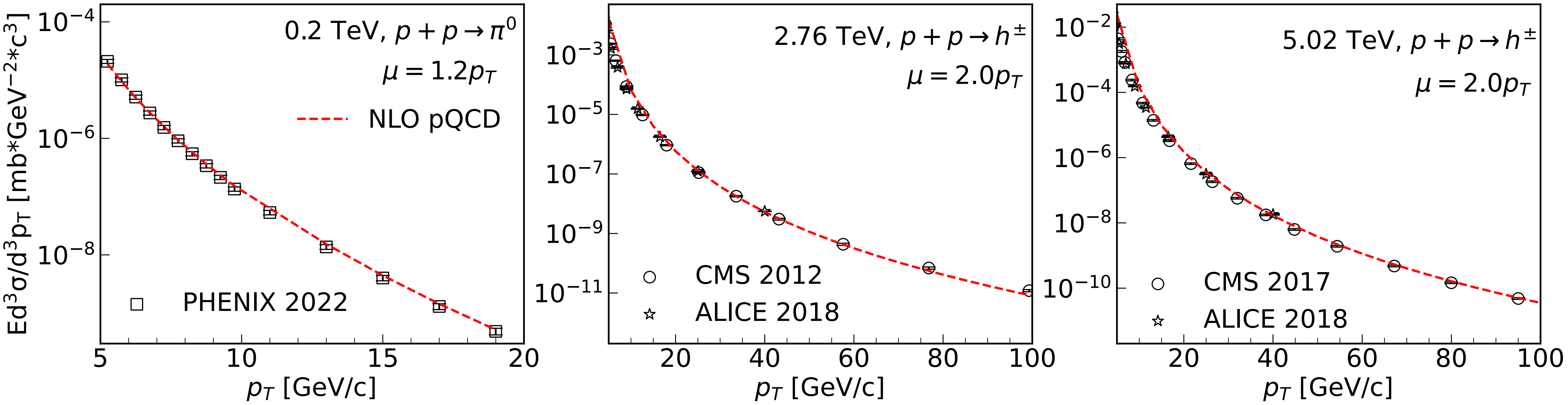
[CT14, Phys. Rev. D 95, 034003 (2017)]

$D_{h/d}(z_d,\mu^2)$: KKP FFs

[KKP, Nucl. Phys. B 582,514(2000)]

pp baselines

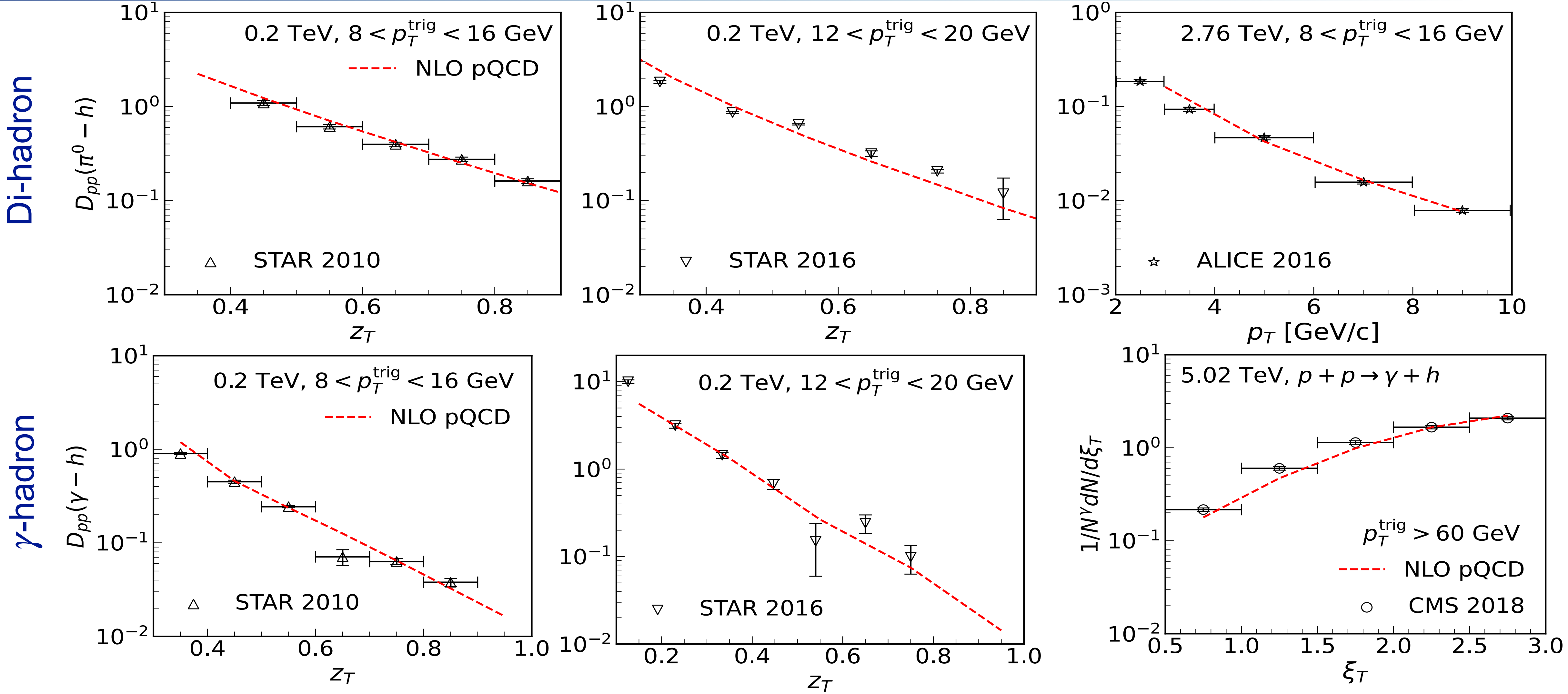
Single hadron:



NLO pQCD describes data very well in p+p collisions.

Data from [PHENIX, Phys. Rev. Lett. 101, 232301 (2008), Phys. Rev. C 105, 064902 (2022)]
[CMS, Eur. Phys. J. C 72, 1945 (2012), JHEP 04, 039 (2017)], [ALICE, JHEP 11, 013 (2018)]

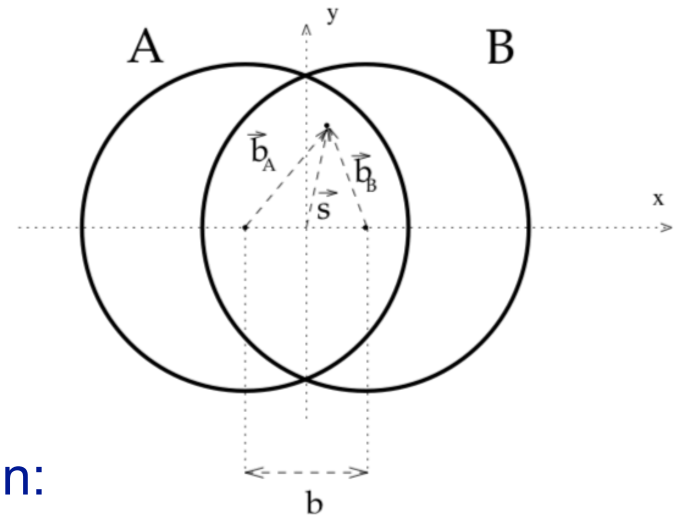
pp baselines

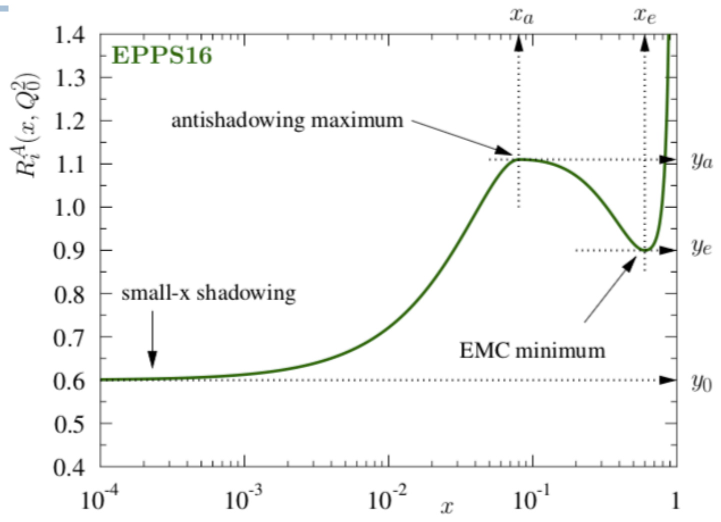


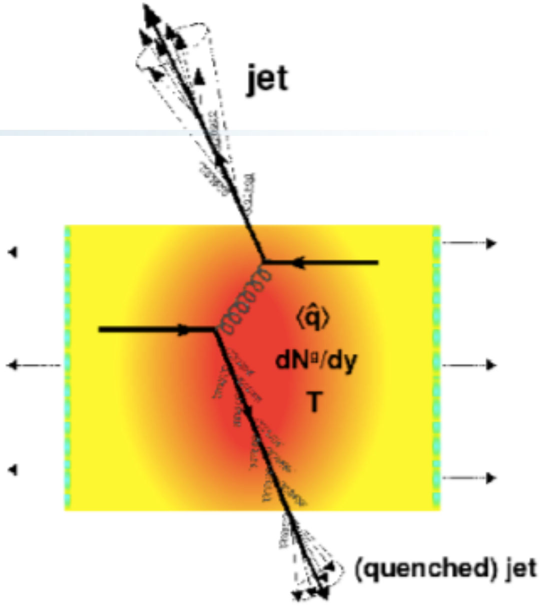
NLO pQCD parton model can give a good description of all the experimental data on single hadron, γ-hadron, and di-hadron production spectra at large p_T in p+p collisions.

pQCD parton model

In A+A collisions：







Di-hadron:

$$\frac{dN_{AB}^{hh}}{dy_h^c d^2p_T^{h_c} dy_h^d d^2p_T^{h_d}} = \sum_{abcd} \int d^2r dz_c dz_d t_A(\vec{r}) t_B(\vec{r}+\vec{b}) f_{a/A}(x_a, \mu^2, \vec{r}) f_{b/B}\left(x_b, \mu^2, \vec{r}+\vec{b}\right) \frac{x_a x_b}{\pi z_c^2 z_d^2} \frac{d\sigma_{ab\to cd}}{d\hat{t}}$$

$$\times \tilde{D}_{h/c}\left(z_c, \mu^2, \Delta E_c\right) \tilde{D}_{h/d}\left(z_d, \mu^2, \Delta E_d\right) \delta^2\left(\vec{p}_T^{\,c} + \vec{p}_T^{\,d}\right) + \mathcal{O}\left(\alpha_s^3\right)$$

$t_A(\vec{r})$: nuclear thickness functions, integrating the Woods – Saxon nuclear density distribution;

$f_{a/A}(x_a, \mu^2, \vec{r})$: EPPS16 nPDF [EPPS16, Eur. Phys. J. C 77, 163 (2017)]

$\tilde{D}_{h/d}(z_d, \mu^2, \Delta E_d)$: medium – modifed FFs

Medium-modified FFs

$$\tilde{D}_{h/d}(z_d,\mu^2,\Delta E_d) = (1-e^{-\langle N_g\rangle})\left[\frac{z_d'}{z_d}D_{h/d}(z_d',\mu^2)+\langle N_g\rangle\frac{z_g{}'}{z_d}D_{h/g}(z_g{}',\mu^2)\right]+e^{-\langle N_g\rangle}D_{h/d}(z_d,\mu^2)$$

[X.-N. Wang, PRC70 (2004) 031901], [H. Z. Zhang, J.F. Owens, Enke Wang, X.-N. Wang, PRL 98.212301 (2007);103, 032302 (2009)]

High-Twist approach:

$$\frac{\Delta E_d}{E} = \frac{2C_A\alpha_s}{\pi}\int d\tau\int\frac{dl_T^2}{l_T^4}\int dz\,[1+(1-z)^2]\,\hat{q}_d\left(\tau,\vec{r}+(\tau-\tau_0)\,\vec{n}\right)\sin^2\!\left(\frac{l_T^2(\tau-\tau_0)}{4z(1-z)E}\right)$$

[W.T. Deng and X.-N. Wang, PRC 81,024902(2010], [E. Wang and X.-N. Wang, PRL 87, 142301 (2001); 89, 162301 (2002)]

$$\left\langle N_g^d\right\rangle = \frac{2C_A\alpha_s}{\pi}\int_{\tau_0}^{\infty}d\tau\int\frac{dl_T^2}{l_T^4}\int\frac{dz}{z}\,[1+(1-z)^2]\,\hat{q}_d\left(\tau,\vec{r}+(\tau-\tau_0)\,\vec{n}\right)\sin^2\left[\frac{l_T^2\,(\tau-\tau_0)}{4z(1-z)E}\right]$$

[N.B. Chang, W.T. Deng and X.-N. Wang, Phys. Rev. C 89, 03491 (2014)1

Observables：nuclear modification factor

$$R_{AB} = \frac{dN_{AB}/dyd^2p_T}{T_{AB}(\vec{b})d\sigma_{pp}/dyd^2p_T};\;\; I_{AB}\left(z_T\right) = \frac{D_{AB}\left(z_T\right)}{D_{pp}\left(z_T\right)}.$$

IF-assisted Bayesian inference of $\hat{q}(T)$

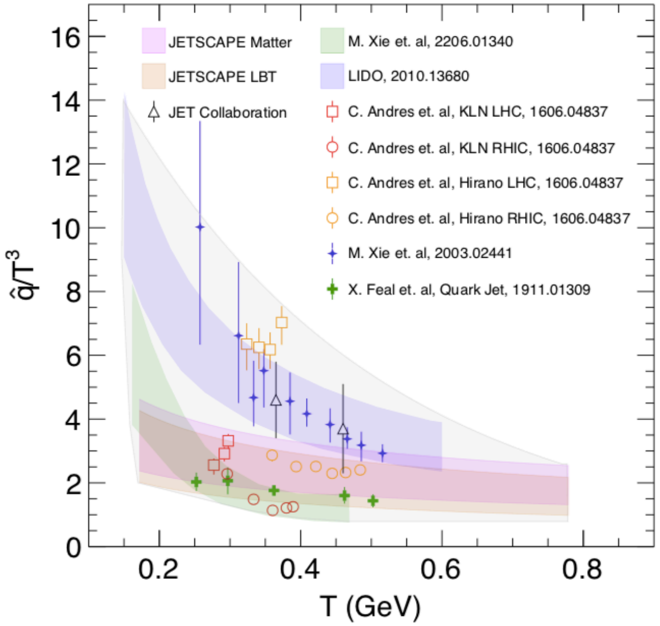
Construction of the functional prior $\hat{q}(T)$:

Gaussian random field (F): $\langle F(x) \rangle = \mu(x)$; $\langle [F(x) - \mu(x)] \, [F(x') - \mu(x')] \rangle = C(x, x')$

[W. Bialek, C.G. Callan, et al, PRL 77, 4693 (1996)] [T. Ensslin, AIP Conf. Proc. 1553, 184 (2013)] [Y.Y. He, X.-N. Wang, et al, PRC 91,054908(2015)]

$F(x) = \ln(\hat{q}/T^3)$; $x = \ln(T/\mathrm{GeV})$; $\qquad \mu(x) \equiv \mathrm{C}$; $C(x, x') = \sigma^2 \exp\left[-(x - x')^2/2l^2\right]$

The l indicates that the high-T prior is unaffected by data that are only sensitive to $\hat{q}(T)$ at low T.



[L. Apolinário, Y.J. Lee, M. Winn, Prog. Part. Nucl. Phys. 127 (2022) 103990]

$\mu = \langle \ln(\hat{q}/T^3) \rangle = 1.36$, $\sigma = 0.7$;

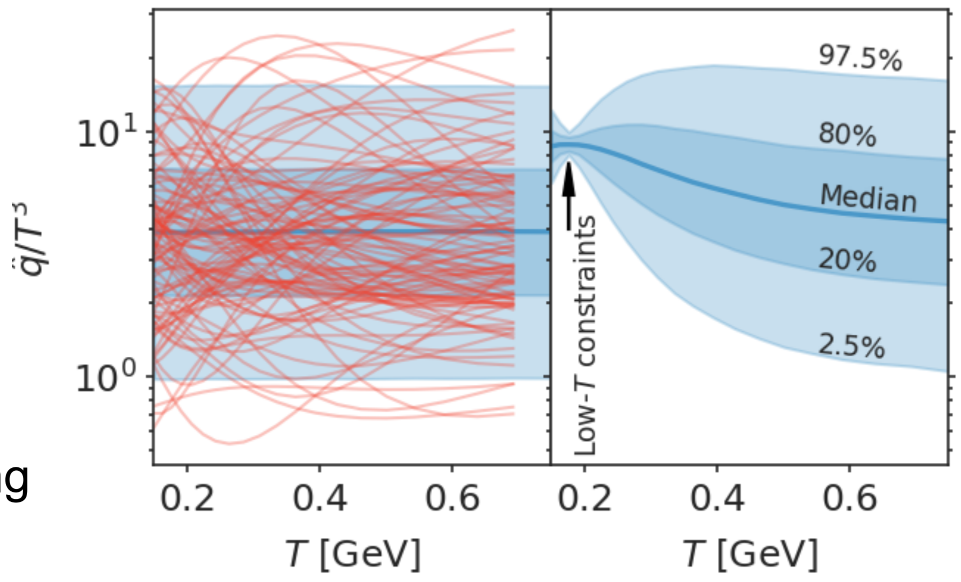
$T_c < T < 4T_c : 0.8 < \hat{q}/T^3 < 15$,

$T_c = 0.165$ GeV.

$l = \ln(\frac{T_{\max}}{T_{\min}}) \approx \ln 2$;

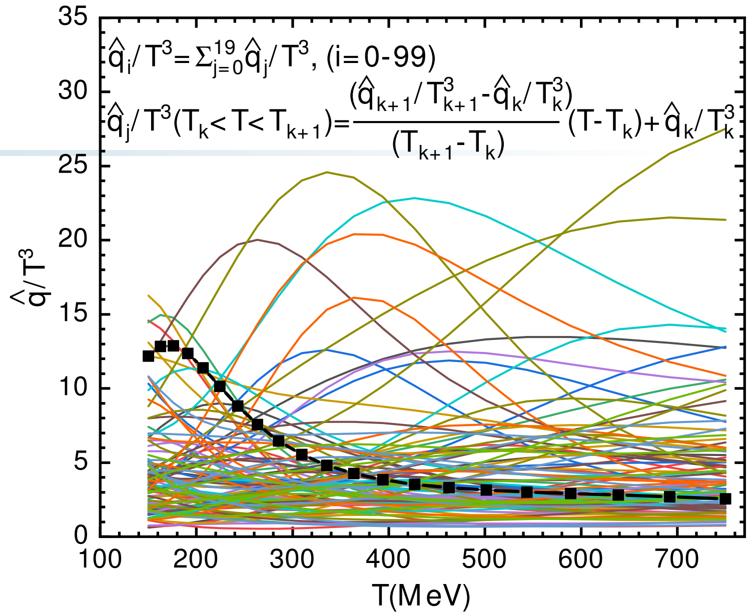
The smallest $\ln(T_{\max}/T_{\min})$ in the hydrodynamic simulations of all colliding systems and centralities.

Random realizations of prior $\hat{q}/T^3$



$\hat{q}$ individual variation in different T region.

NLO pQCD model with 100 prior $\hat{q}(T)$



Input parameter matrix

$$\left[\frac{\hat{q}}{T^3}\right]_i = \sum_{j=1}^{20} \theta\left(T-T_j\right)\theta\left(T_{j+1}-T\right)\left(\left[\frac{\hat{q}}{T^3}\right]_{i,j+1}\Delta_j + \left[\frac{\hat{q}}{T^3}\right]_{i,j}\left(1-\Delta_j\right)\right)$$

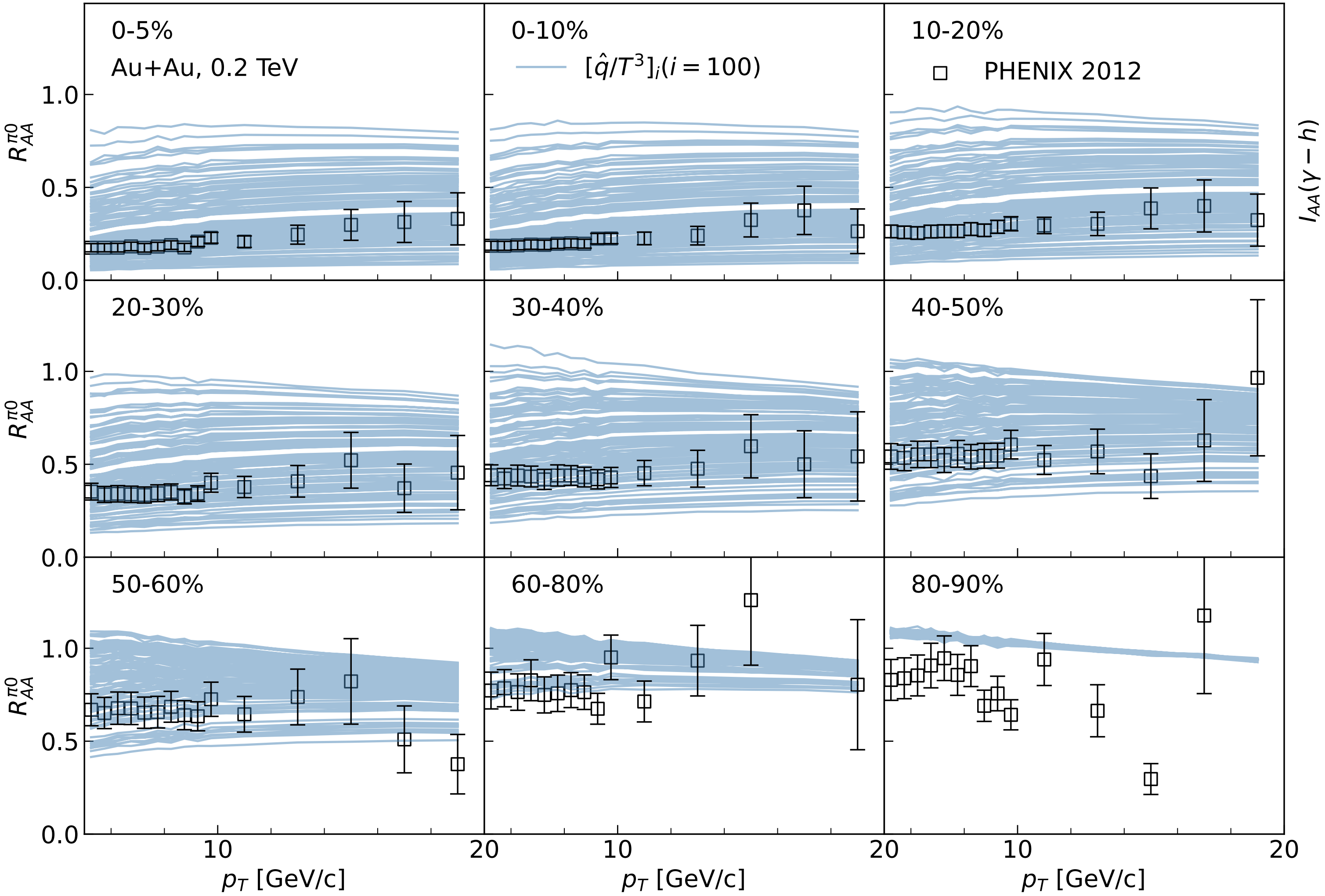
$$\Delta_j = \frac{T-T_j}{T_{j+1}-T_j},\ i=1-100,\ j=1,\ 20.$$

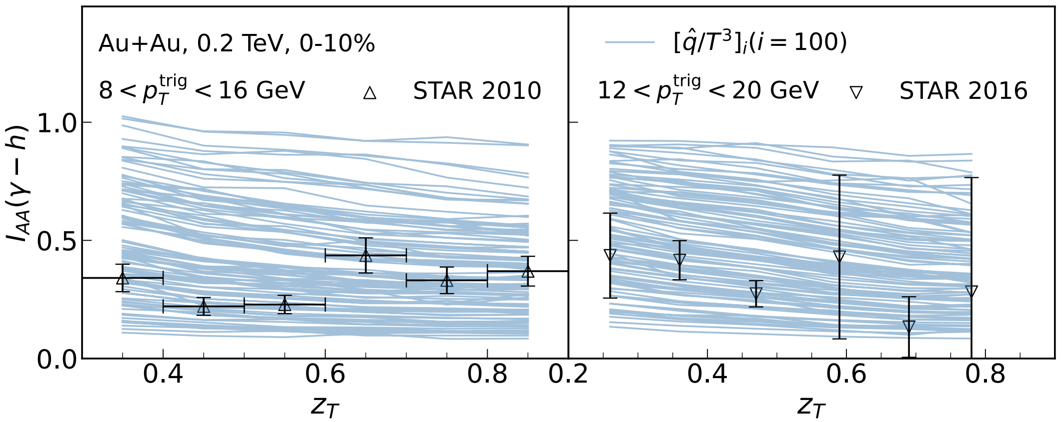
The hydrodynamic evolution of the QGP medium provided by the CLVisc (3+1) D hydrodynamic model.

[L. G. Pang, Q. Wang, X.-N. Wang, Phys.Rev.C 86 (2012) 024911], [L. G. Pang, H. Petersen, X.-N. Wang,Phys.Rev.C 97 (2018) 6, 064918]

- $R_{AA}^{\pi^0}$ in 0-5%, 0-10%, 10-20%, 20-30%, 30-40%, 40-50% Au-Au collisions at 0.2 TeV;
- $R_{AA}^{h^\pm}$ in 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50% Pb-Pb collisions at 2.76 TeV;
- $R_{AA}^{h^\pm}$ in 0-5%, 5-10%, 10-20%, 10-30%, 20-30%, 30-50% Pb-Pb collisions at 5.02 TeV;
- $I_{AA}^{\gamma h^\pm}$ in 0-10% Au-Au collisions at 0.2 TeV, (3 trigger ranges);
- $I_{AA}^{\pi^0 h^\pm}$ in 0-10% Au-Au collisions at 0.2 TeV, (3 trigger ranges);
- $I_{AA}^{h^\pm h^\pm}$ in 0-5%, 0-10% Pb-Pb collisions at 2.76 TeV, (6 trigger ranges).

Model calculations with 100 prior $\hat{q}(T)$

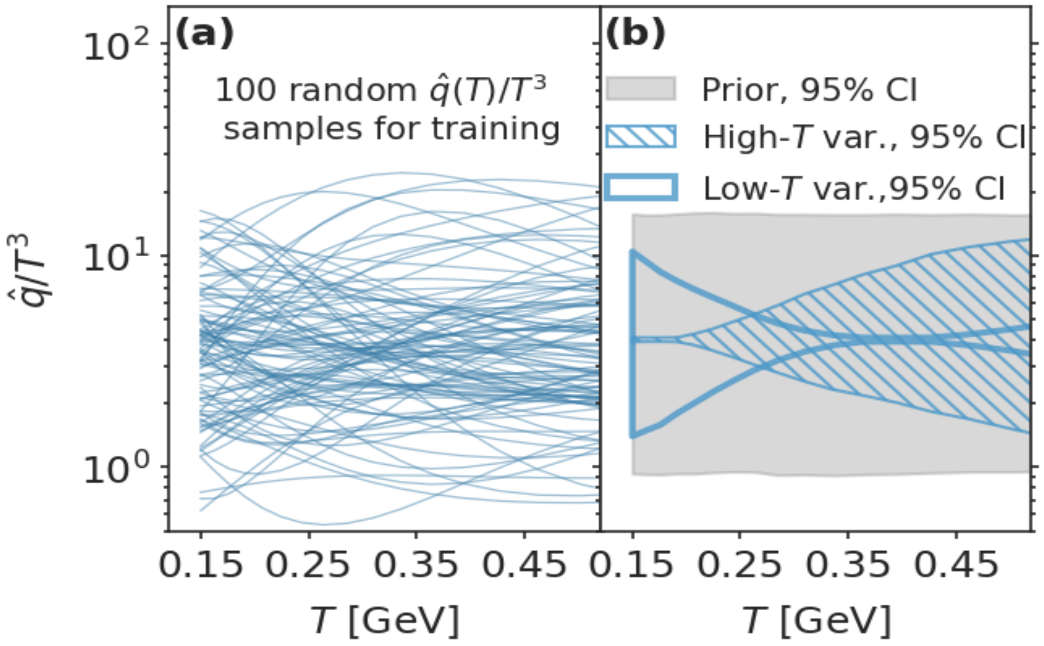




- 2500 curves of R_{AA}
- 500 curves of $I_{AA}^{\gamma h}$;
- 1000 curves of I_{AA}^{hh}

Data sets $(\hat{q}_{ij}, \mathbf{y}_{ik})$ of the NLO pQCD calculations to train Gaussian Process emulators.

IF-assisted sensitivity analysis

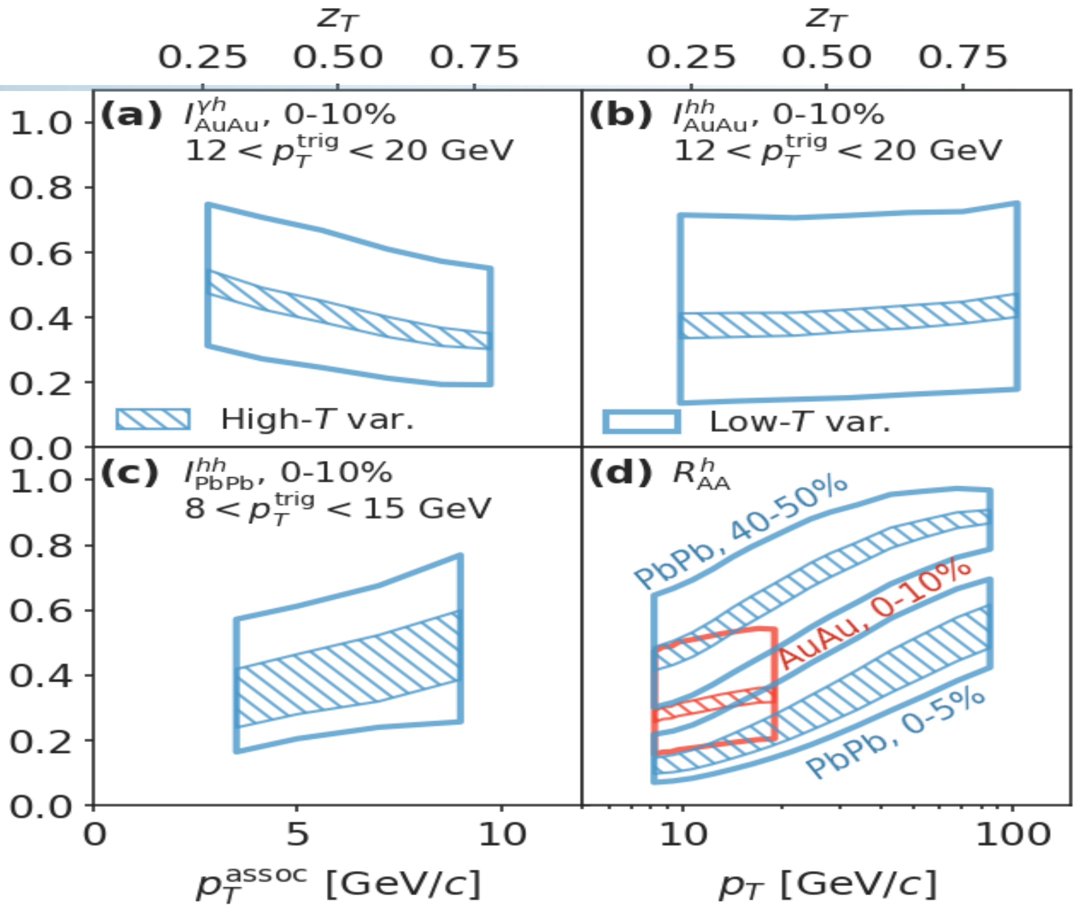


High-T var:

$$0.15 < T < 0.2 \text{ GeV}, \; \hat{q}/T^3 = 4 \pm 0.1$$

Low-T var:

$$0.3 < T < 0.4 \text{ GeV}, \; \hat{q}/T^3 = 4 \pm 0.1$$



- The sensitivities of R_{AA} and I_{AA} to high-T $\hat{q}$ increase from RHIC to LHC energies and from peripheral to central collisions.
- The prior $\hat{q}/T^3$ at high T and low T are uncorrelated.
- I_{AA} are slightly more sensitive to high-T $\hat{q}$ than R_{AA}.

Global Bayesian inference of $\hat{q}(T)$

- Prior distribution of the random function:

[Jorsten A. Enßlin Annalen Phys. 531 (2019) 3, 1800127]

$$P_0[F] = \exp\left[-\frac{1}{2}\int dx dx' \delta F(x) C^{-1}(x,x') \delta F(x')\right]$$

- Posterior distribution :

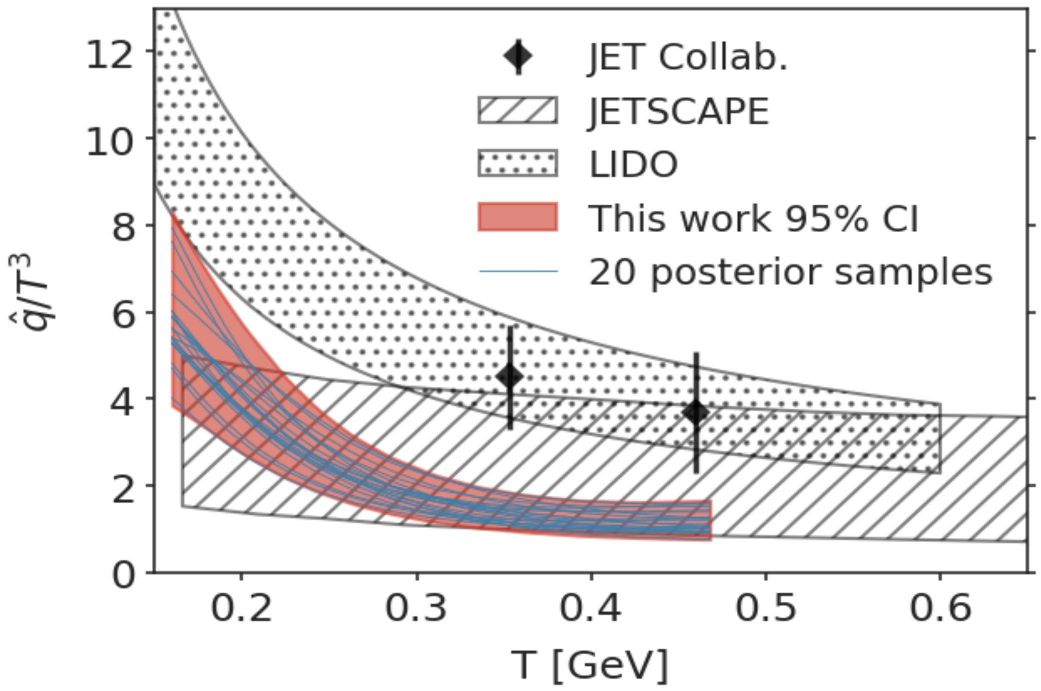
[python library emcee: multi-dimensional Gaussian]

$$P[F(x)] \propto P_0[F(x)] \times \text{Likelihood}$$
$$= \frac{\mathcal{N}}{\sqrt{\det(C)}} \exp\{-\frac{1}{2}\int dx dx' \delta F(x) C^{-1}(x,x')\, \delta F(x')$$
$$-\frac{1}{2}\left(M'[F] - y_{\exp}\right)^T \Sigma_{\text{error}}^{-1} \left(M'[F] - y_{\exp}\right)\}$$

$M'[F]$: NLO pQCD calculations; $y_{\exp}$: experimental data .

- To marginalize the values of F^* at a fixed input x^*

$$p(F^*) = \int [\mathscr{D}F]\delta(F(x^*) - F^*) P[F(x)]$$



[JET Collaboration: PRC 90, 014909 (2014)]

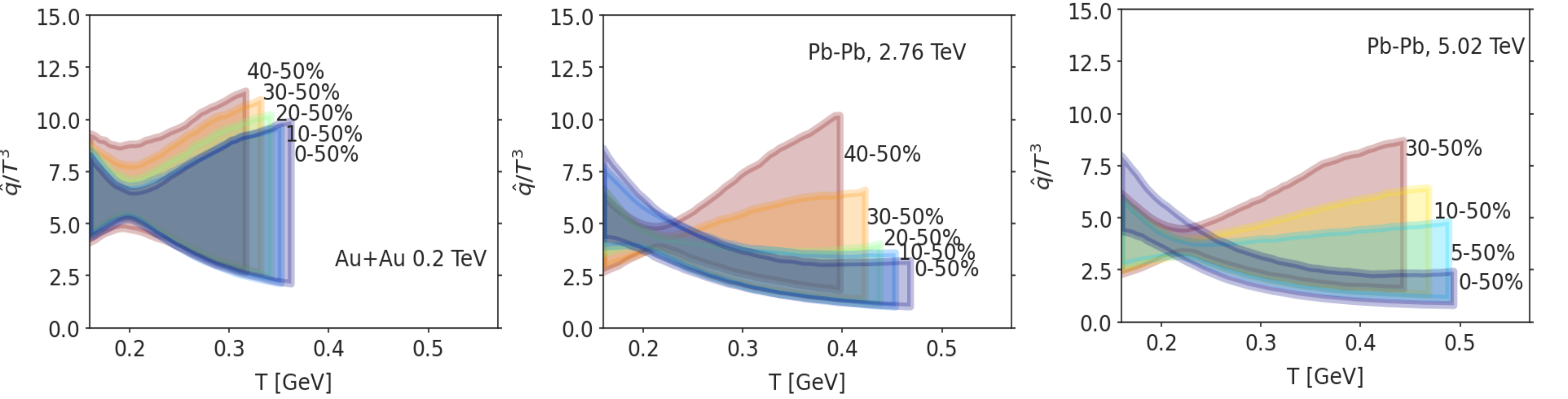
[JETSCAPE: PRC 104, 024905 (2021)]

[LIDO, W.Y. Ke, X.-N. Wang, JHEP 05041]

- The extracted $\hat{q}/T^3$ is consistent with previous studies but exhibits a stronger temperature dependence.

Progressive constraining power

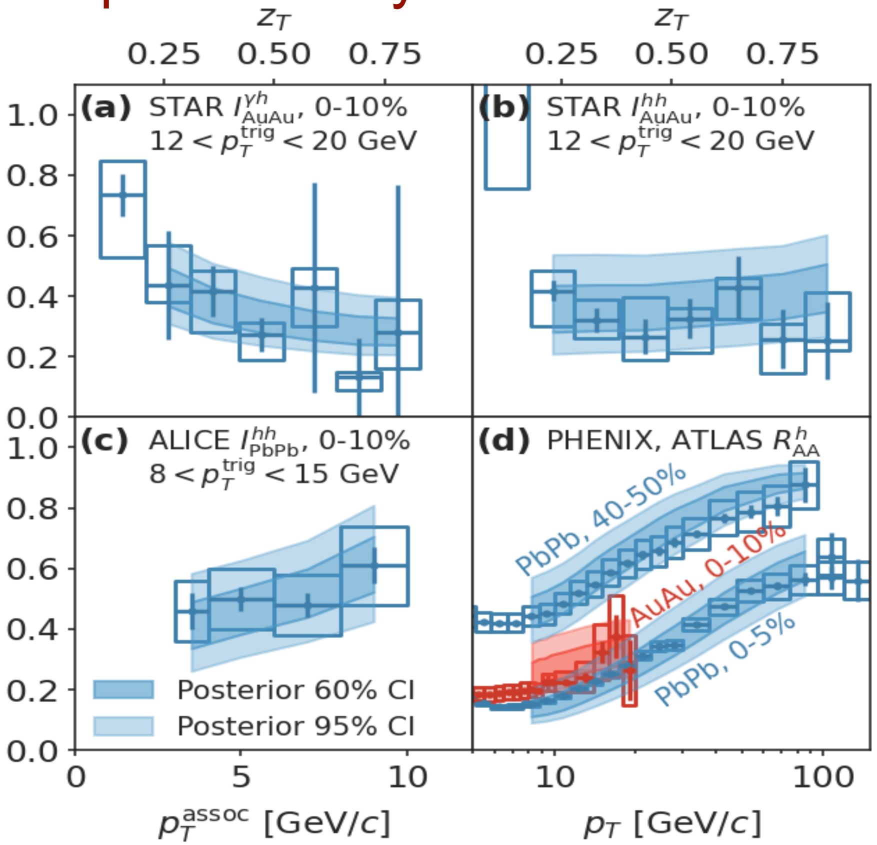
From low-T ⟶ high-T region; peripheral ⟶ central collisions; RHIC ⟶ LHC energies.



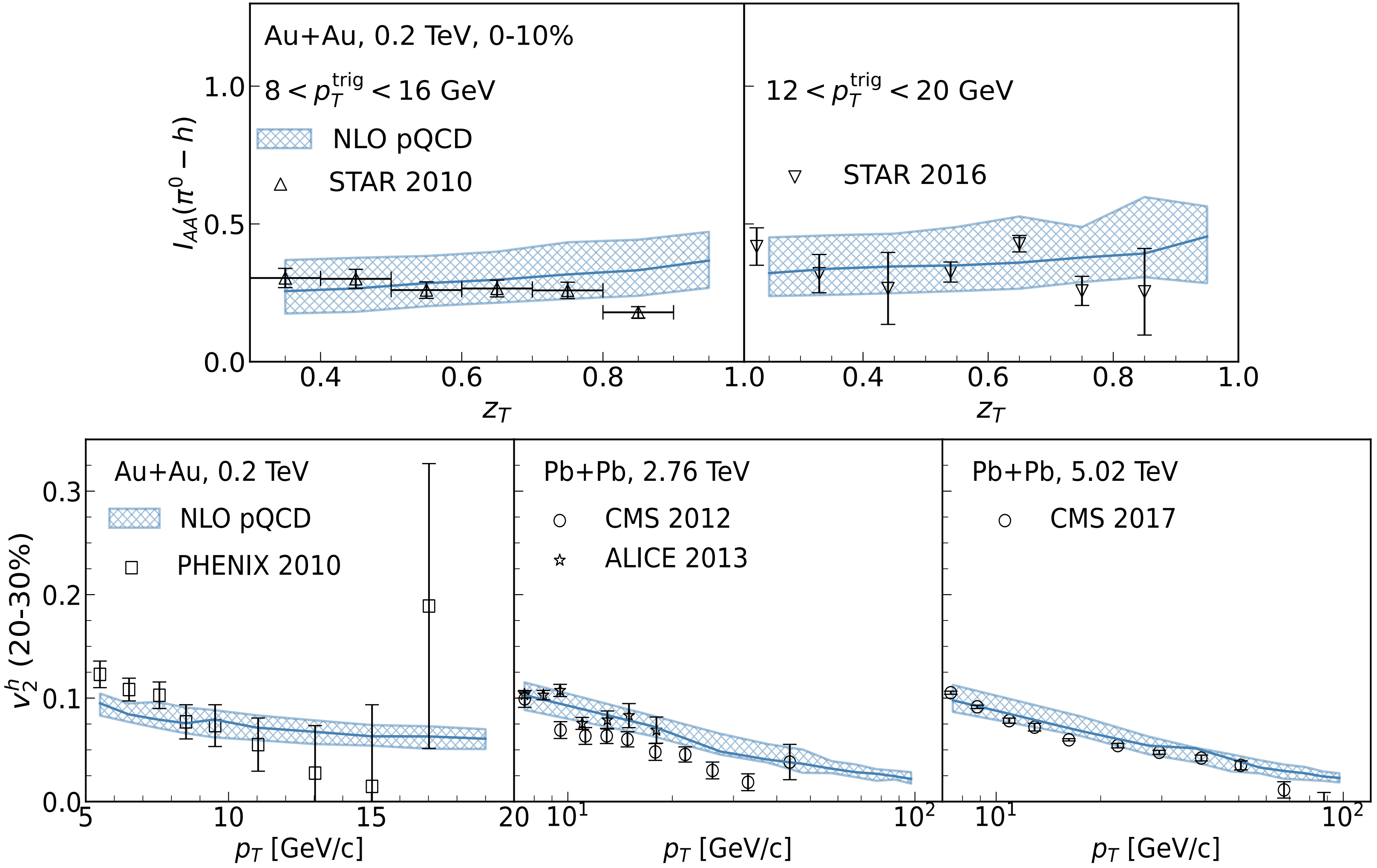
- $\hat{q}/T^3$ is progressively more constrained at higher T as one includes data from more central collisions and from higher colliding energies.
- The IF approach strongly suppresses correlations between high and low T prior values of $\hat{q}/T^3$.

The posterior distribution of the observables

predicted by the emulator



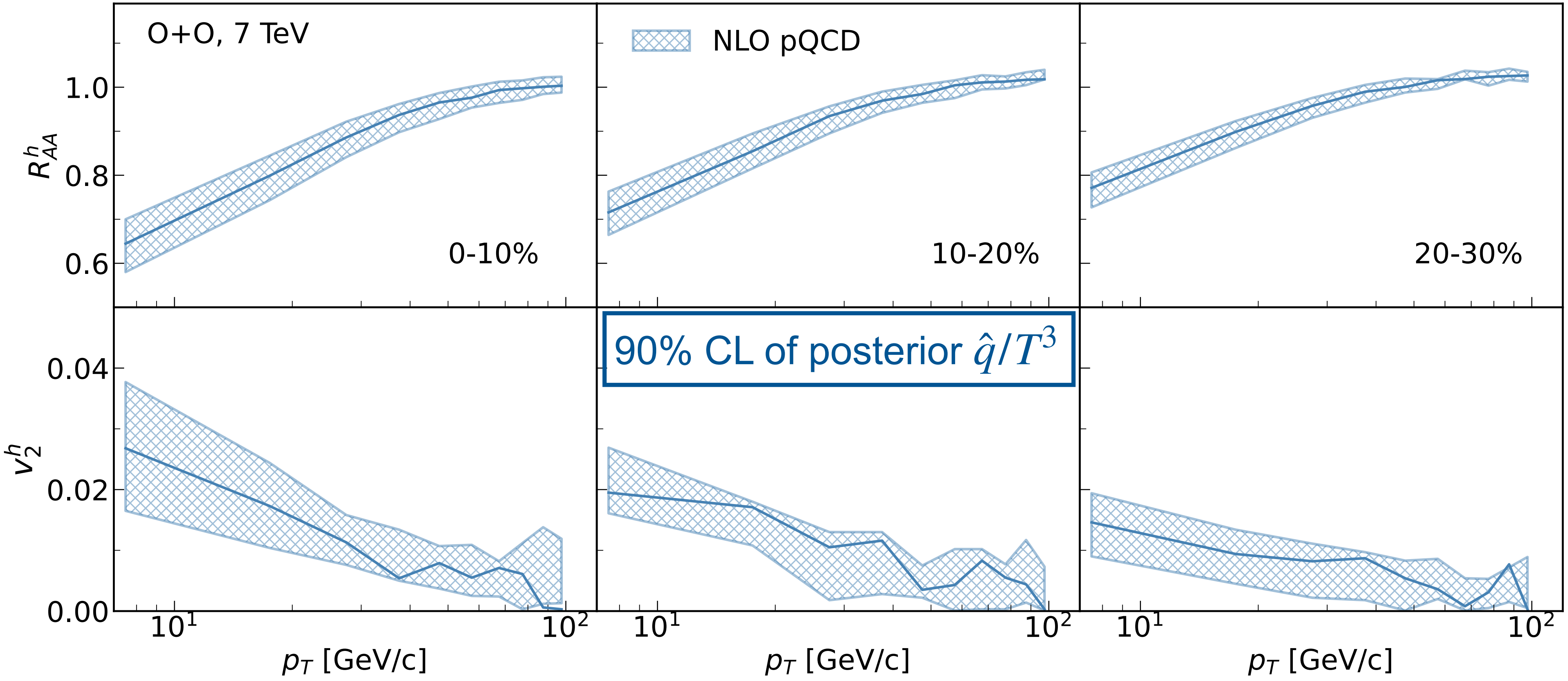
calculated by NLO pQCD model



- The experimental data over a large range of $p_{\rm T}$, centralities and colliding energies are well reproduced.

Prediction O-O collisions at 7 TeV Assume the QGP matter is formed.

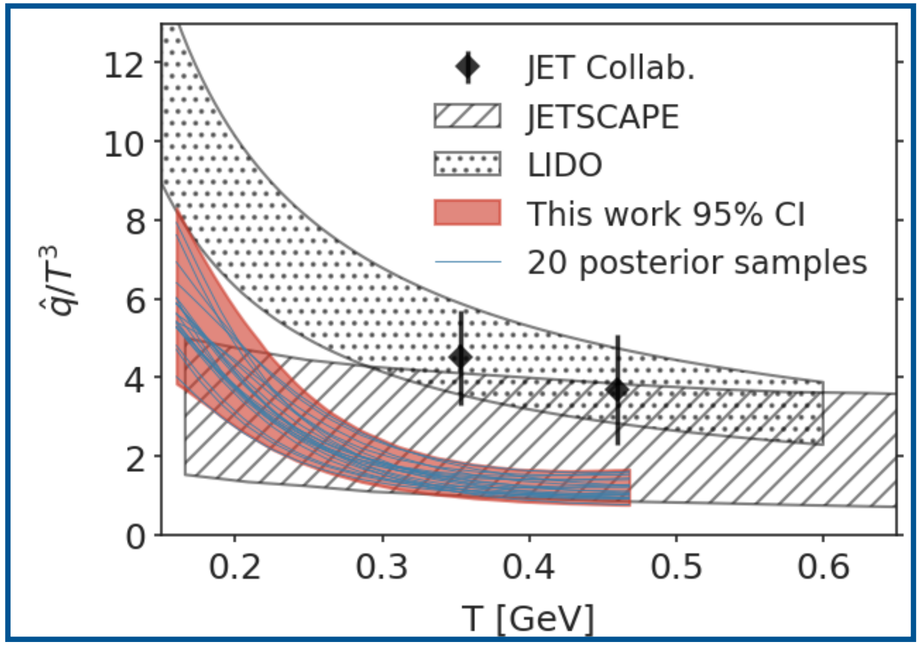
O-O collisions are proposed as an intermediate colliding system between heavy-ion and p-A collisions to investigate the properties of dense matter in small systems.



- In most central collisions, the suppression of single hadron is about 30~40% at p_{T} = 7.5 ~ 10 GeV/c.
- The v_2 is only 0.03 at p_{T}~7.5 GeV/c in 0-10% collisons.

Summary

- We applied the IF approach to the first global Bayesian inference of the $\hat{q}/T^3$ from combined experimental data on R^h_{AA}, I^{hh}_{AA}, and $I^{\gamma h}_{AA}$ in HIC at both RHIC and LHC energies.
- The IF approach can provide progressive constraints on $\hat{q}$ from low to high T when experimental data in more central collisions and at higher colliding energies are included.
- The extracted $\hat{q}/T^3$ is consistent with previous studies but exhibits a stronger T dependence.



Thank you for your attention!