Jet energy loss distributions and gradient tomography in heavy-ion collisions

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Based on:
1. Yayun He, Long-Gang Pang, Xin-Nian Wang, PRL 122, 252302 (2019)
2. Yayun He, Long-Gang Pang, Xin-Nian Wang, PRL 125, 122301 (2020)

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Motivation

QGP (quark-gluon plasma): a hot and dense medium predicted by QCD

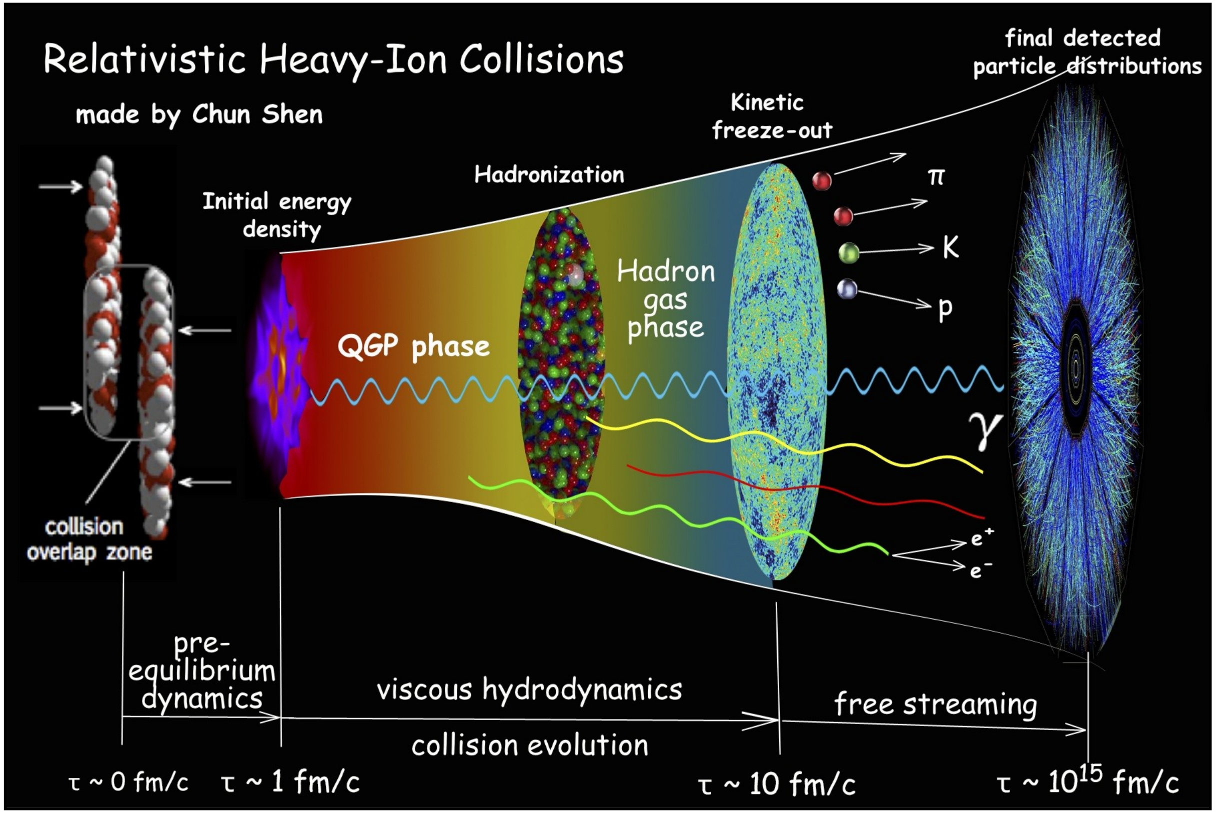


Fig: made by Chun Shen, https://u.osu.edu/vishnu/category/visualization/

Nucleus collision
+
Pre-equilibrium
+
Initial state
+
QGP evolution
+
Hadron rescattering
+
Detection

Motivation

What properties does the QGP have?

- The most perfect fluid $\eta/s \approx (1-2)/4\pi$ P. Romatschke and U. Romatschke, Phys. Rev. Lett. 99, 172301 (2007)
- The most vortical fluid $\omega/T \approx 0.001$ L. Adamczyk et al. [STAR Collaboration], Nature 548, 62 (2017)
- The most opaque medium $\hat{q}/T^3 \approx 4-8$ K. M. Burke et al. [JET Collaboration], Phys. Rev. C 90, no. 1, 014909 (2014).

How to probe the QGP?

Soft probes: hydrodynamics, …

Hard probes: large transverse momentum, such as jets, hadrons and heavy flavors

Jet quenching: jet energy loss and transverse momentum broadening due to jet-medium interaction

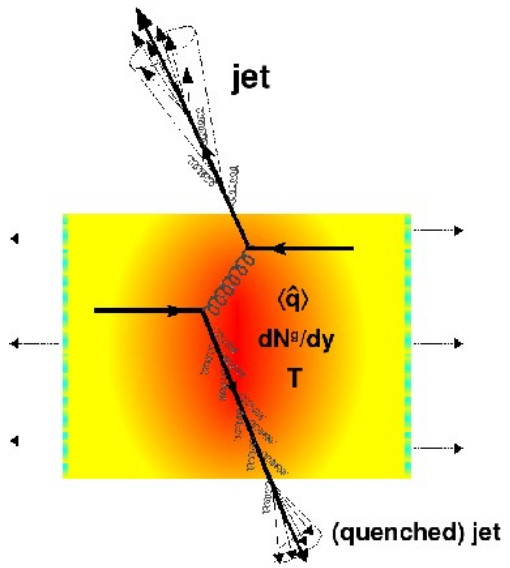


Fig: An illustration of jet quenching.
D. d'Enterria & B. Betz, (2009). 10.1007/978-3-642-02286-9_9.

Motivation

Jet quenching observables:

- Inclusive jet nuclear modification factors $R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d\sigma_{AA}^{jet}}{d\sigma_{pp}^{jet}}$

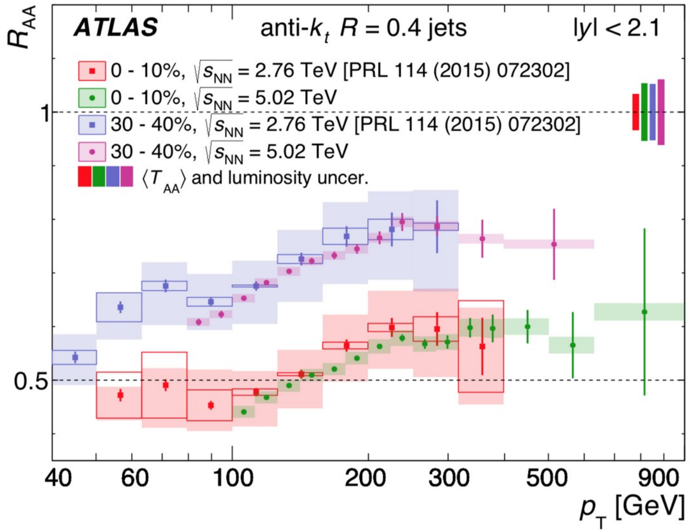
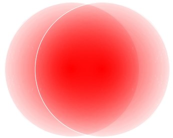


Fig: Inclusive jet nuclear modification factor.
ATLAS, Phys. Rev. Lett. 114 (2015),072302 arXiv:1411.2357,
ATLAS, Phys. Lett. B 790 (2019) 108, arXiv:1805.05635

0-10%



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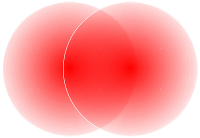

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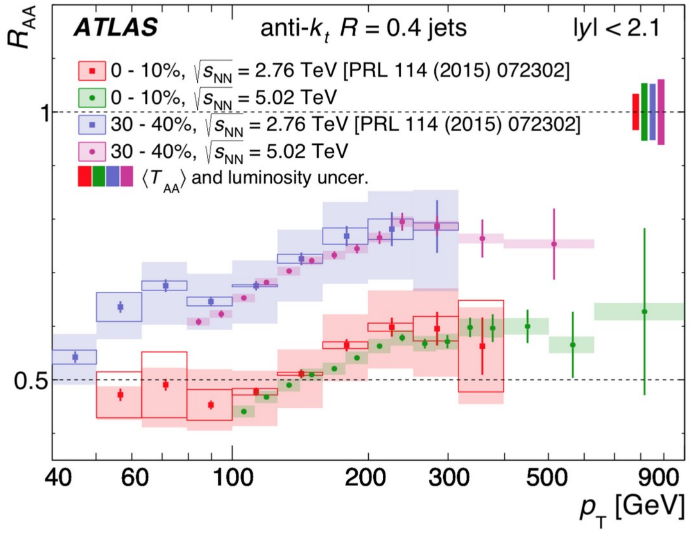

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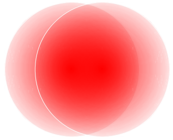

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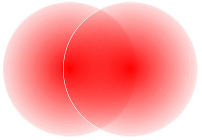


Jet quenching leads to a suppression!

Motivation

Jet quenching observables:

- Inclusive jet nuclear modification factors
- Gamma-triggered jet transverse momentum imbalance $x_{J\gamma} = p_T^{\text{jet}} / p_T^{\gamma}$
- Many more ...

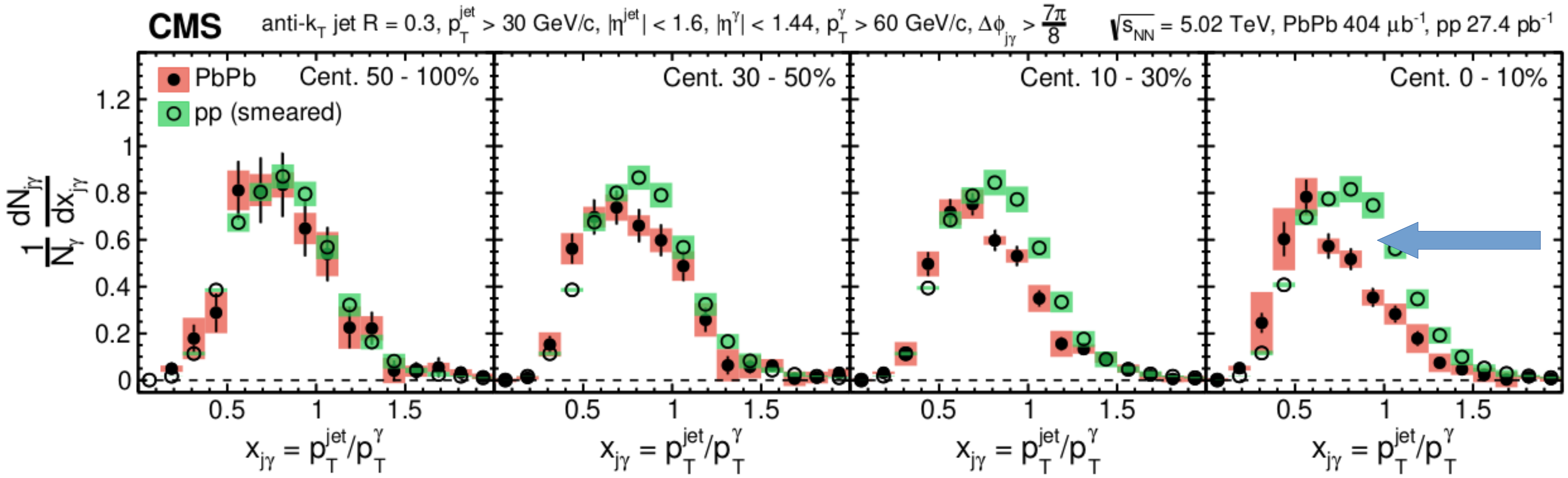


Fig: Gamma-triggered jet transverse momentum imlalance.
CMS, CMS-16-002

Jet quenching leads to a suppression!

How to extract jet quenching information from experimental data?

Bayesian extraction of jet energy loss distributions

$$\frac{d\sigma_{AA}^{\rm jet}}{dp_T dy}(p_T,R) \approx N_{\rm bin}(b)\int d\Delta p_T\,\frac{d\sigma_{pp}^{\rm jet}}{dp_T dy}(p_T+\Delta p_T,R)\,W_{AA}(\Delta p_T,p_T+\Delta p_T,R)$$

MC transport models: $\left.\begin{matrix}\sigma_{pp}^{\rm jet}(p_T)\\ W_{AA}(p_T,\Delta p_T)\end{matrix}\right\} \Longrightarrow \sigma_{AA}^{\rm jet}(p_T)$

Bayesian analysis: $\left.\begin{matrix}\sigma_{pp}^{\rm jet}(p_T)\\ \sigma_{AA}^{\rm jet}(p_T)\end{matrix}\right\} \Longrightarrow W_{AA}(p_T,\Delta p_T)$

Data-driven & model-independent

$$P(X|Y)=\frac{P(Y|X)P(X)}{P(Y)},Y: data, X: W_{AA}$$

Parameterize: $\langle\Delta p_T\rangle(p_T)=\beta p_T^{\gamma}\log(p_T)$

$$x=\frac{\Delta p_T}{\langle\Delta p_T\rangle} \qquad W_{AA}(x)=\frac{\alpha^{\alpha}x^{\alpha-1}e^{-\alpha x}}{\Gamma(\alpha)}$$

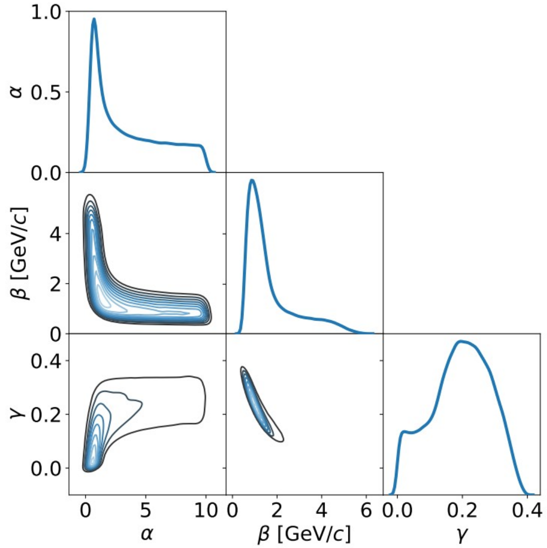
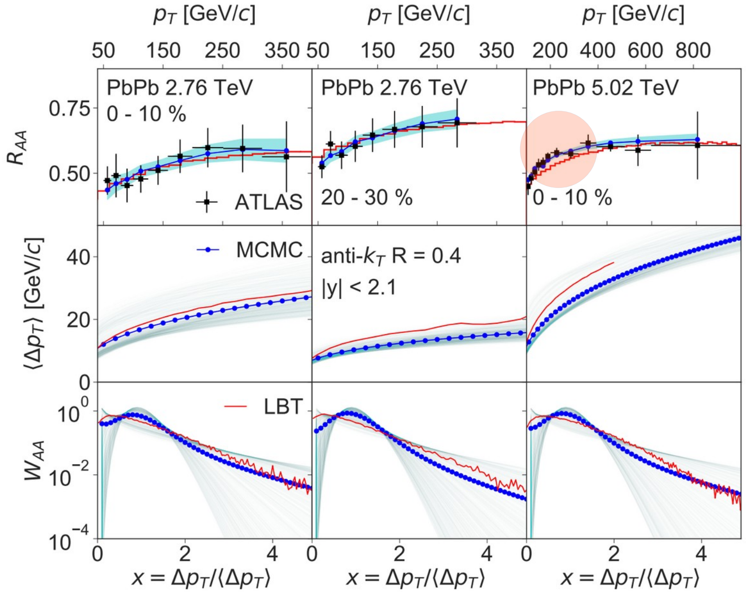


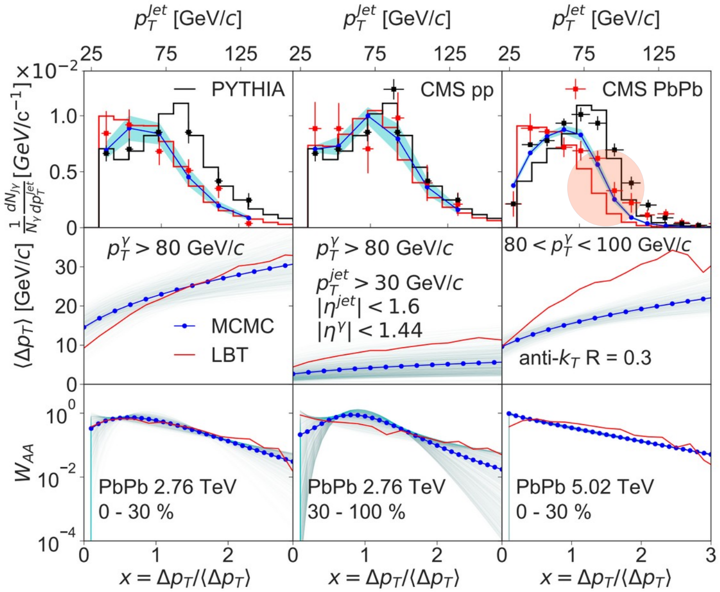
Fig: correlations of extracted parameters with 8 millions Monte Carlo Markov Chain (MCMC) samplings

Bayesian extraction of jet energy loss distributions

single inclusive jet in Pb+Pb			
	(0-10%)2.76 TeV	(20-30%)2.76 TeV	(0-10%)5.02 TeV
α	3.87 ± 2.93 (1.45 ± 0.01)	4.47 ± 2.83 (1.33 ± 0.02)	4.41 ± 2.86 (1.58 ± 0.02)
β	1.40 ± 1.12 (1.39 ± 0.06)	1.12 ± 0.47 (1.08 ± 0.07)	1.06 ± 0.97 (1.56 ± 0.06)
γ	0.21 ± 0.09 (0.21 ± 0.01)	0.15 ± 0.07 (0.20 ± 0.01)	0.26 ± 0.06 (0.23 ± 0.01)

γ-triggered jet in Pb+Pb			
	(0-30%)2.76 TeV	(30-100%)2.76 TeV	(0-30%)5.02 TeV
α	2.13 ± 1.28 (1.95 ± 0.12)	3.75 ± 2.81 (1.04 ± 0.06)	0.90 ± 0.09 (1.84 ± 0.13)
β	2.68 ± 1.40 (0.72 ± 0.06)	0.55 ± 0.44 (0.53 ± 0.04)	1.50 ± 0.85 (0.50 ± 0.04)
γ	0.16 ± 0.14 (0.44 ± 0.02)	0.13 ± 0.18 (0.30 ± 0.02)	0.21 ± 0.12 (0.56 ± 0.02)





What can we do with jet quenching?

Gradient tomography of jet quenching

The Boltzmann equation for elastic scattering:

$$k_a \cdot \partial f_a = \sum_{bcd} \prod_{i=b,c,d} \int \frac{d^3 k_i}{2\omega_i (2\pi)^3} (f_c f_d - f_a f_b) \times |\mathcal{M}_{ab\to cd}|^2 \frac{\gamma_b}{2} (2\pi)^4 \delta^4(k_a + k_b - k_c - k_d)$$

Small angle approximation without flow or drag:

Drift-diffusion equation:

$$\frac{k^\mu}{\omega} \partial_\mu f_a(\vec{k}, \vec{r}) = \frac{\hat{q}_a}{4} \vec{\nabla}^2_{k_\perp} f_a(\vec{k}, \vec{r})$$

$$\hat{q}_a = \sum_{bcd} \prod_{i=b,c,d} \int \frac{d^3 k_i}{2E_i (2\pi)^3} f_b(k_b) (\vec{k}_{a\perp} - \vec{k}_{c\perp})^2 |\mathcal{M}_{ab\to cd}|^2 \frac{\gamma_b}{2} (2\pi)^4 \delta^4(k_a + k_b - k_c - k_d)$$

For constant $\hat{q}$, one can obtain the analytic solution:

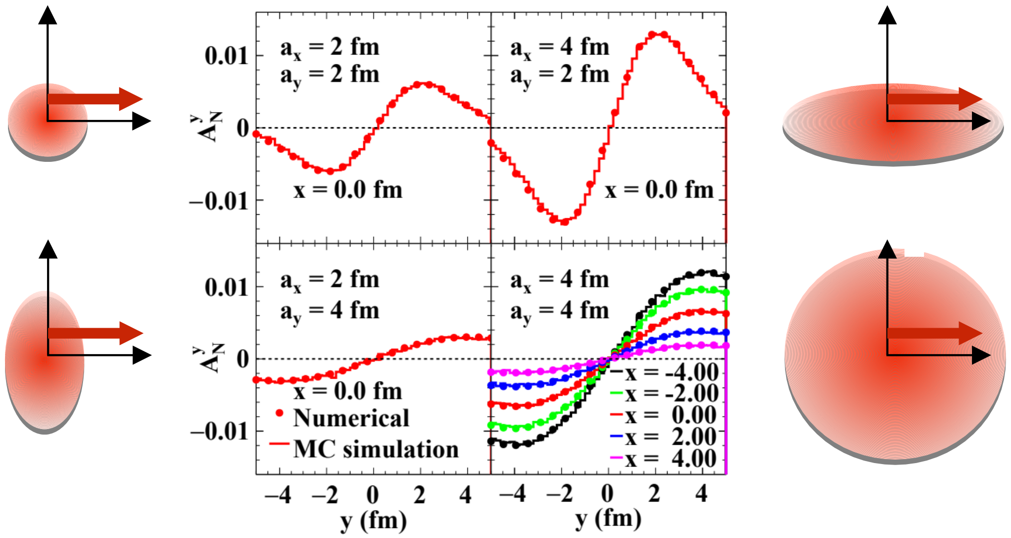
$$f_a(\vec{k}_\perp, \vec{r}_\perp, t) = 3 \left(\frac{4\omega}{\hat{q}_a t^2} \right)^2 e^{-(\vec{r}_\perp - \frac{\vec{k}_\perp}{2\omega} t)^2 \frac{12\omega^2}{\hat{q}_a t^3} - \frac{k_\perp^2}{\hat{q}_a t}}$$

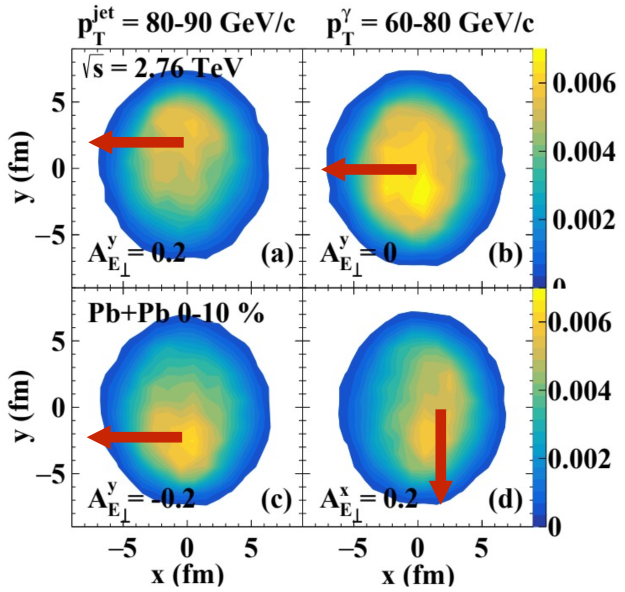
Diffusion width: $\sqrt{\langle k_\perp^2 \rangle} = \sqrt{\hat{q} t}$ $\qquad$ $\sqrt{\langle r_\perp^2 \rangle} = t \sqrt{(\hat{q} t/3)}/w$

Drift: $\vec{r}_\perp = (\vec{k}_\perp / 2w) t$

Gradient tomography of jet quenching

$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f(\vec{k},\vec{r}) \mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r d^3k f(\vec{k},\vec{r})}$$





A toy model: $\hat{q}(\vec{r}_\perp, t) = \frac{\hat{q}_0 t_0}{t_0 + t} e^{-x^2/a_x^2 - y^2/a_y^2}$

The LBT model, $p_T > 3\ \mathrm{GeV}/c$

Summary

- ✔ Jet energy loss distributions and averaged jet energy loss can be extracted from experimental data with the state-of-the-art Bayesian analysis.
- ✔ On average only a few number of out-of-cone jet-medium scatterings take place when a jet traverses the medium
- ✔ The gradient of qhat in the medium leads to jet transverse momentum asymmetry, which can be used to localize initial jet production positions

Outlook

- How to extract jet quenching information, such as the path length dependence of jet quenching, with multiple jet quenching observables from the experimental data?
- How to localize jet production points with machine learning technique?

Thanks for your attention!