JETSCAPE

The Next Generation of Jet Monte-Carlo

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Why JETSCAPE?

- Almost two decades from the start of RHIC: the qualitative picture of nuclear modification of jet is generally accepted
- Precise measurement of jet in the near future (e.g. sPHENIX) motivates precise quantitative understanding of jet theory
- Requires sophisticated Monte-Carlo event generator of jet in heavy-ion collisions that includes both advanced jet energy loss theory and modern statistical and computational techniques

What is JETSCAPE Collaboration? (http://jetscape.wayne.edu)

- The ***J***et ***E***nergy-loss ***T***omography with a ***S***tatistically and ***C***omputationally ***A***dvanced ***P***rogram ***E***nvelope ***Collaboration***

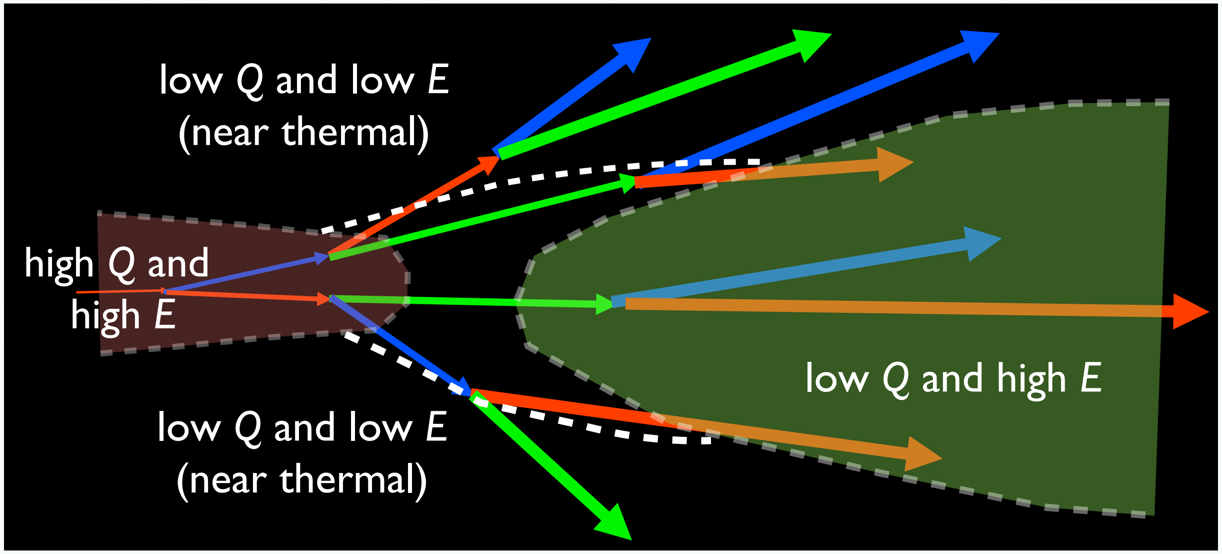
What does JETSCAPE promise?

- Develop state of the art theoretical model of jet energy loss
- Develop statistic tool for extracting crucial physical parameters from model to data comparison
- Develop a user-friendly Monte-Carlo package of the above two

Part I: Modeling Multistage Jet Evolution

The **JETSCAPE** Collaboration work **arxiv:1705.00050**

Full evolution of jets in heavy-ion collisions

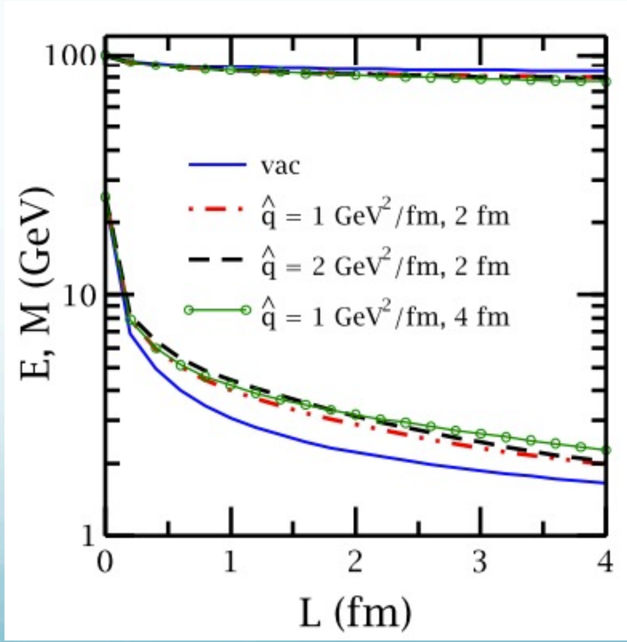


Jet partons are produced with high *Q* and high *E* (**DGLAP, higher-twist**)

-> lose *Q* faster than *E* [Majumder and Putschke, PRC 93 (2016) 054909]

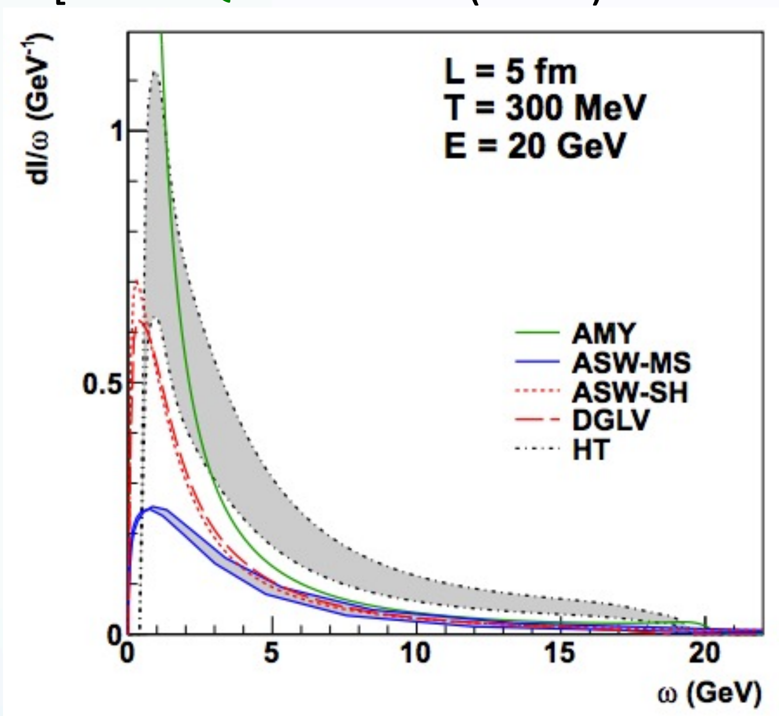
-> low *Q* and high *E* (**Transport, higher-twist, AMY**)

-> low *Q* and low *E* (near thermal) (**strongly coupled approach**)

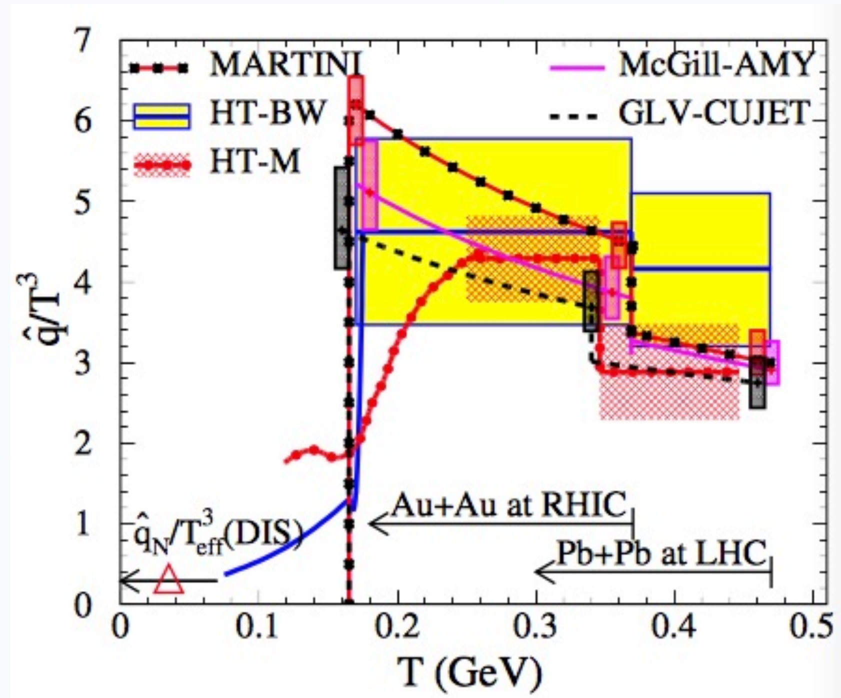


Milestones of collaboration work

[**TECHQM**: PRC 86 (2012) 064904]



[**JET**: PRC 90 (2014) 014909]



TECHQM: comparison of medium-induced gluon spectra in a brick

JET: constraint of $\hat{q}$ in realistic hydro medium using different theories

JETSCAPE: to ***combine*** different theories into a unified approach and provide a ***Monte-Carlo generator***: DGLAP (high Q) + transport (low Q) + strongly coupled (thermal)

JETSCAPE

Stage 1: high *Q* and high *E*

DGLAP evolution for parton fragmentation function at high *Q*:

$$\frac{\partial}{\partial Q^2} D(z, Q^2) = \frac{\alpha_s}{2\pi} \frac{1}{Q^2} \int_z^1 \frac{dy}{y} P(y) D\left(\frac{z}{y}, Q^2\right)$$

Sudakov form factor (probability of NO detectable splitting between *Q* and Q_{max}):

$$\Delta(Q_{\max}, Q) = \exp\left[-\frac{\alpha_s}{2\pi} \int_{Q^2}^{Q^2_{\max}} \frac{dQ^2}{Q^2} \int_{z_c}^{1-z_c} \frac{dy}{y} P(y)\right]$$

Splitting function:

$$P_i(y) = P_i^{\text{vac}}(y) + P_i^{\text{med}}(y)$$

$$P_i^{\text{med}}(y, k_\perp^2) = \frac{2C_A \alpha_s}{\pi k_\perp^4} P_i^{\text{vac}}(y) \int_{t_i}^{t_{\max}} dt \hat{q}_i(t) \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

[*higher-twist* energy loss formalism: Guo and Wang (2000), Majumder (2012)]

i: *q->qg, g->gg, or g->q$\bar{q}$*

$\hat{q}$: $dp_\perp^2/dt$ of quark/gluon due to 2->2 scatterings

Stage 1: high *Q* and high *E*

MATTER (The **M**odular **A**ll **T**wist **T**ransverse-scattering **E**lastic-drag and **R**adiation) [Wayne: PRC 88, 014909, arXiv:1702.05862)]

Monte-Carlo Implementation: $0 < r < 1$

$r \geq \Delta(Q_{\rm max}, Q_0)$ splitting happens above Q_0 (min. allowed virtuality)

$$r \leq \Delta(Q_{\rm max}, Q) = \frac{\Delta(Q_{\rm max}, Q_0)}{\Delta(Q, Q_0)}$$ no splitting above *Q*

→ splitting happens at (or below) scale *Q*

For a given splitting, the p^+ fraction of the two daughter partons are determined by *P*(*z*), and p_T w.r.t. the parent parton is determined by the difference in invariant mass between the parent and daughters.

This *Q* also gives the new $Q_{\rm max}$ for the next splitting (iteration)

→ a vituality-ordered parton showers from initial $Q_{\rm max}$ to Q_0

Stage 2: low *Q* and high *E*

Switch to time-ordered transport model that simulates parton showers at (or below) Q_0 (with on-shell approximation)

LBT (**L**inear **B**oltzmann **T**ransport)

[LBL-CCNU: PRL 111 (2013) 062301, PRC 94 (2016) 014909, arXiv:1704.03648]

Evolution of jet parton "1": $p_1 \cdot \partial f_1(x_1, p_1) = E_1(\mathcal{C}_{\rm el} + \mathcal{C}_{\rm inel})$

Elastic Scattering rate:

$$\Gamma^{\rm el}_{12\to34}(\vec{p}_1) = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4} \times f_2(\vec{p}_2)S_2(s,t,u)(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)|\mathcal{M}_{12\to34}|^2$$

Inelastic scattering rate (average gluon number per *Δt*):

$$\Gamma^{\rm inel} = \langle N_g\rangle(E,T,t,\Delta t)/\Delta t = \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

- Medium-induced gluon spectrum is taken from HT (same as MATTER)
- Multiple gluon emission in *Δt* is allowed – assuming Possion distribution

Separation scale between MATTER and LBT

MATTER (*virtuality-ordered*) evolves partons down to Q_0 and LBT (*time-ordered*) continues parton evolution below Q_0

- **Fixed Q_0** (both in vacuum and medium): 1, 2 or 3 GeV will be used and compared.
- **Dynamical Q_0** (virtuality gain from scattering with the medium):

$$Q_0^2 = \hat{q}\tau_f \qquad \tau_f = 2E/Q_0^2$$

$$\Longrightarrow \quad Q_0^2 = \sqrt{2E\hat{q}}$$

$$\hat{q} = C_R \alpha_s \mu_D^2 T \log\left(\frac{6ET}{\mu_D^2}\right) \qquad \mu_D^2 = 6\pi\alpha_s T^2$$

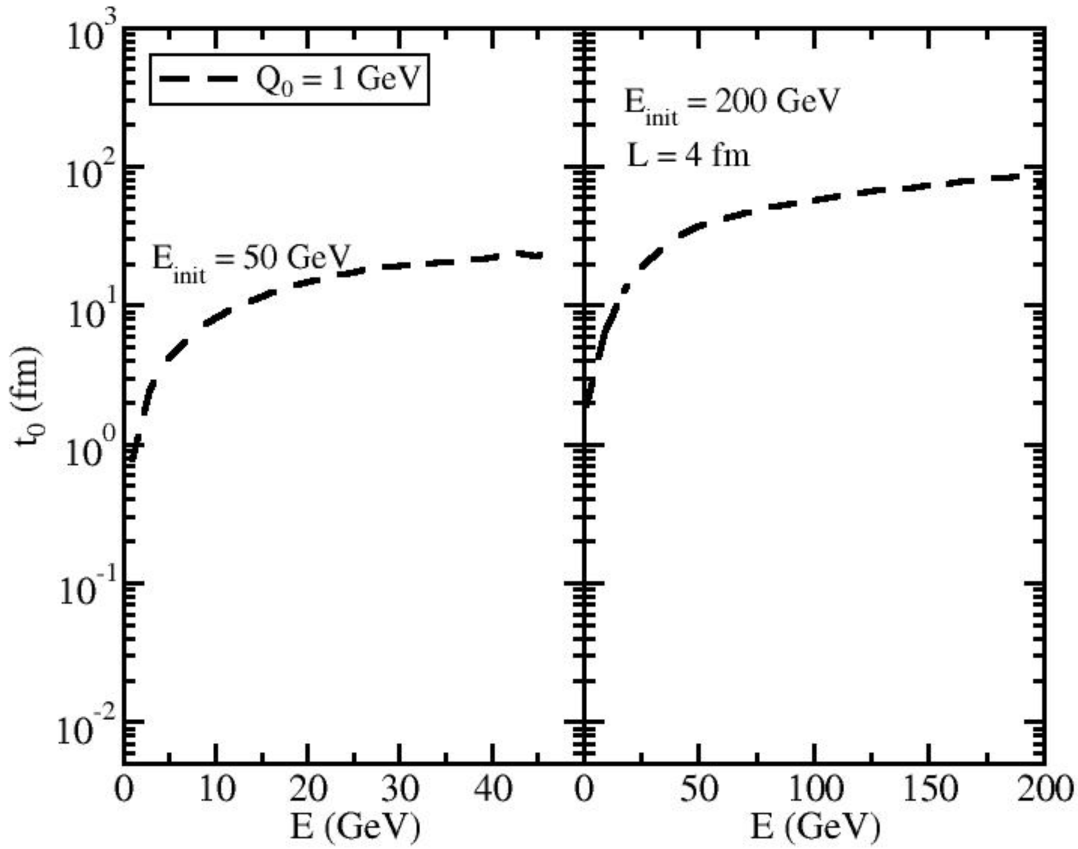
* Dynamical Q_0 is only meaningful in a thermal medium, in vacuum, Q_0 = 1 GeV vacuum

In this work, static medium with T = 250 MeV is used. Effects of medium length L and initial parton (quark) energy E will be investigated.

Switching t_0 between MATTER and LBT

$t_0 = \sum_i 2E_i/Q_i^2$ when a given parton hit Q_0 after multiple splittings

The time MATTER takes to evolve jet parton down to Q_0 is NOT small (vs. τ_0).



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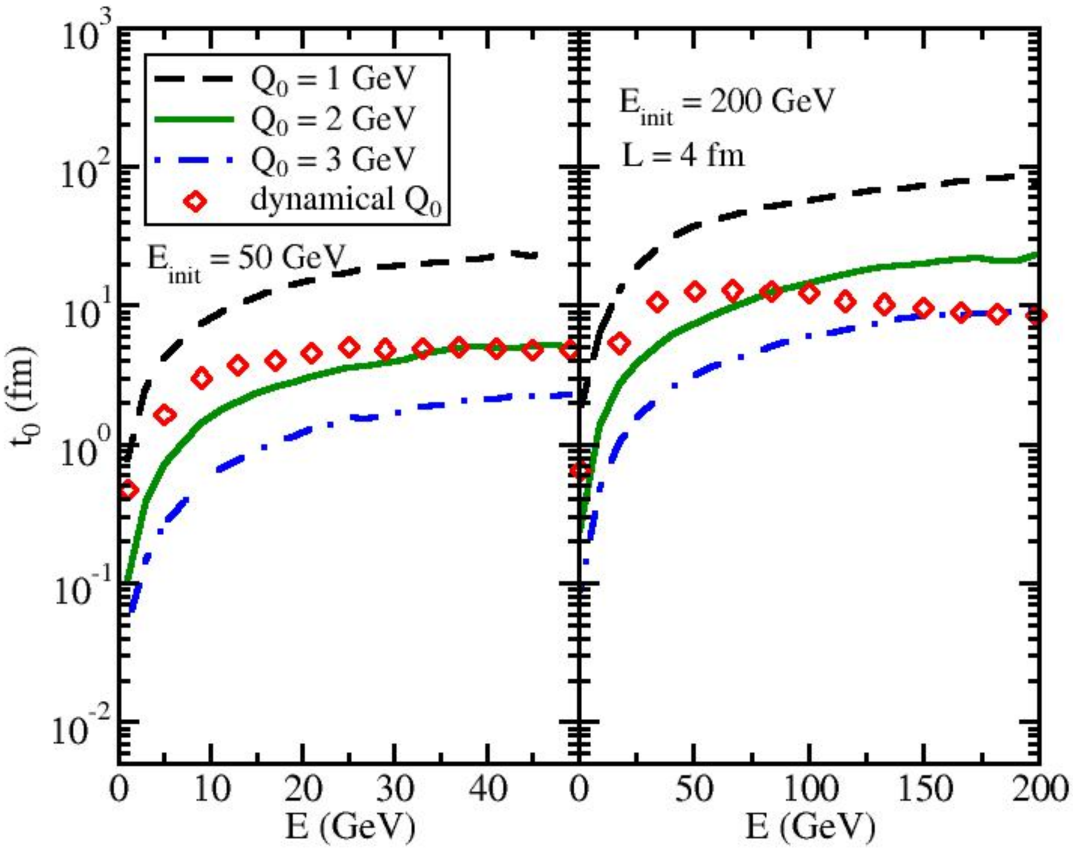

The time MATTER takes to evolve jet parton down to Q_0 is NOT small (vs. τ_0).

Separation time (t_0) decrease if E_{init} decreases or Q_0 increases.

For E_{init} = 50 GeV, L = 4 fm, dynamical Q_0 is consistent with 2 GeV at the high E end, but approaches 1 GeV at low energy. For E_{init} = 200 GeV, dynamical Q_0 starts at 3 GeV at the high E end.

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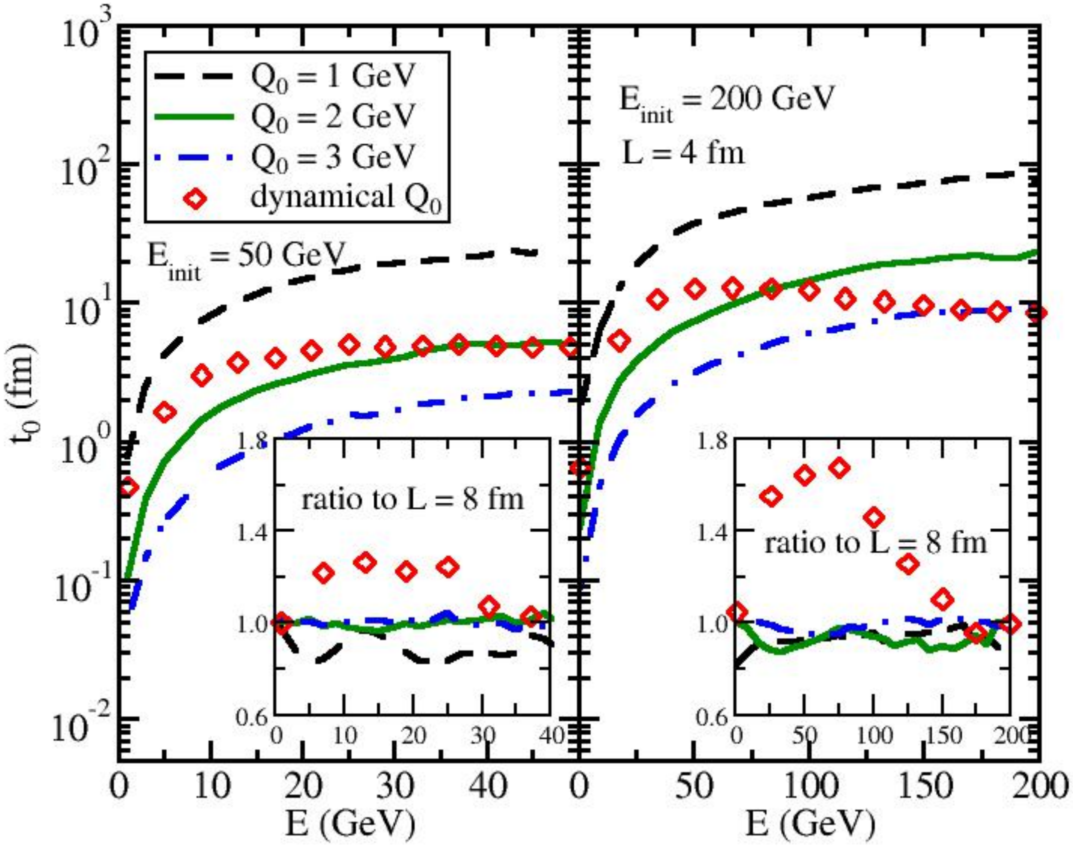

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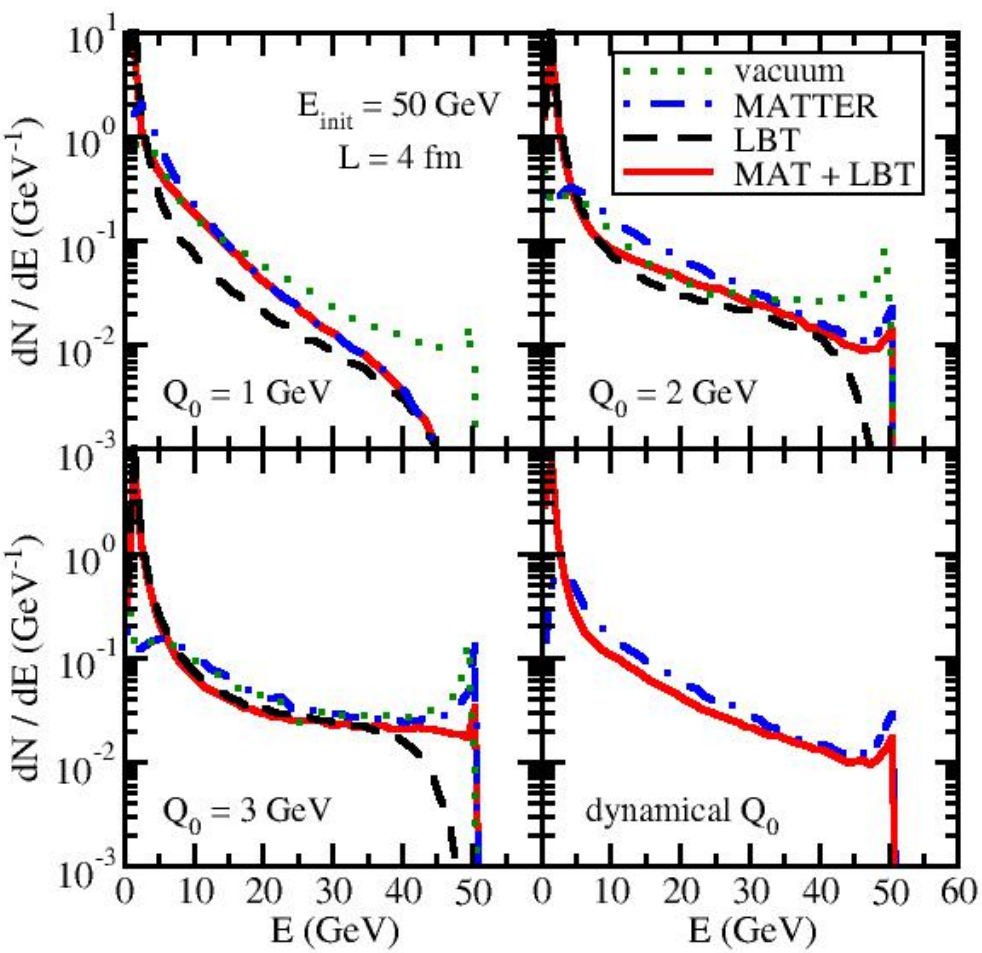
For fixed Q_0, changing from L = 4 to 8 fm increases scattering process (virtuality gain) and thus may delay t_0; for dynamical Q_0, extending L increases the range where larger Q_0 is applied and shortens t_0.

dN/dE for E_i = 50 GeV and L = 4 fm

Energy distribution of final shower partons from a single quark at E = 50 GeV through a brick with T = 250 MeV and L = 4 fm



Vacuum: Sudakov type of shower with vacuum splitting function

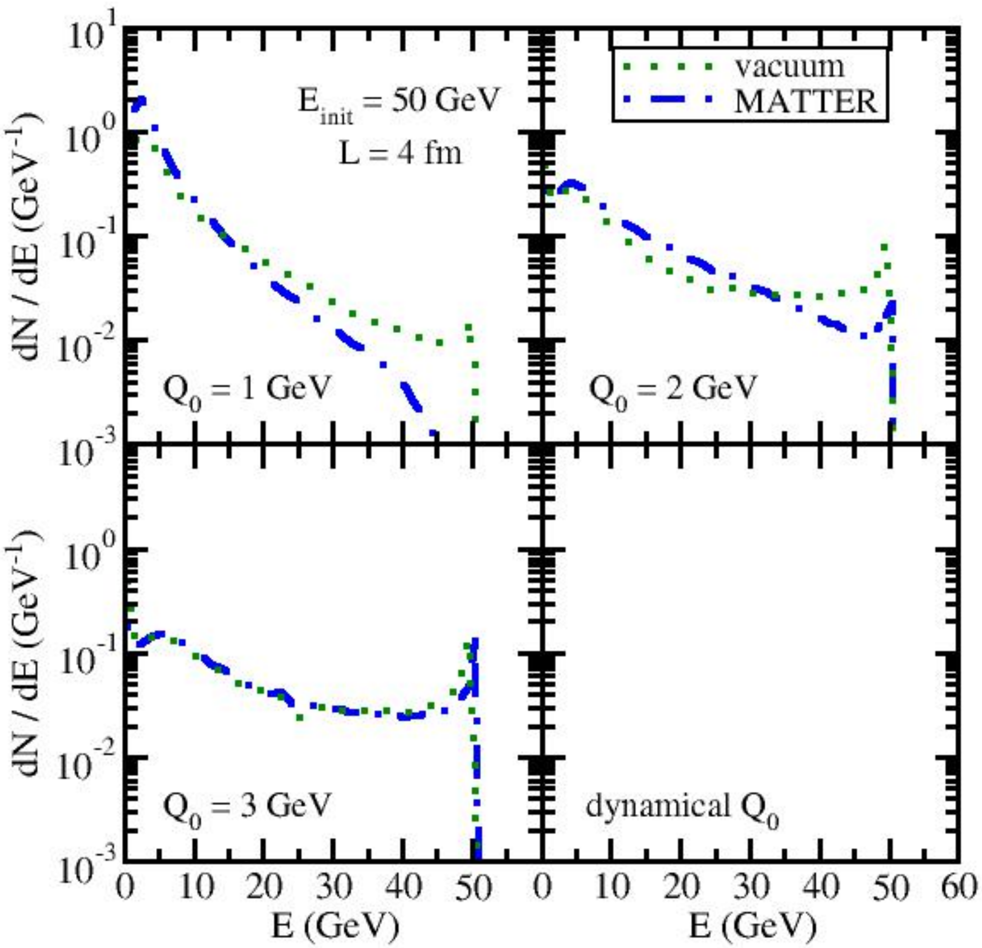
MATTER: Sudakov type of shower with vacuum + medium modified splitting function

LBT: Partons from vacuum shower evolve the entire 4 fm in LBT

MATTER + LBT: Combined scheme – partons evolve in MATTER up to t_0 and then in LBT up to 4 fm

dN/dE for E_i = 50 GeV and *L* = 4 fm

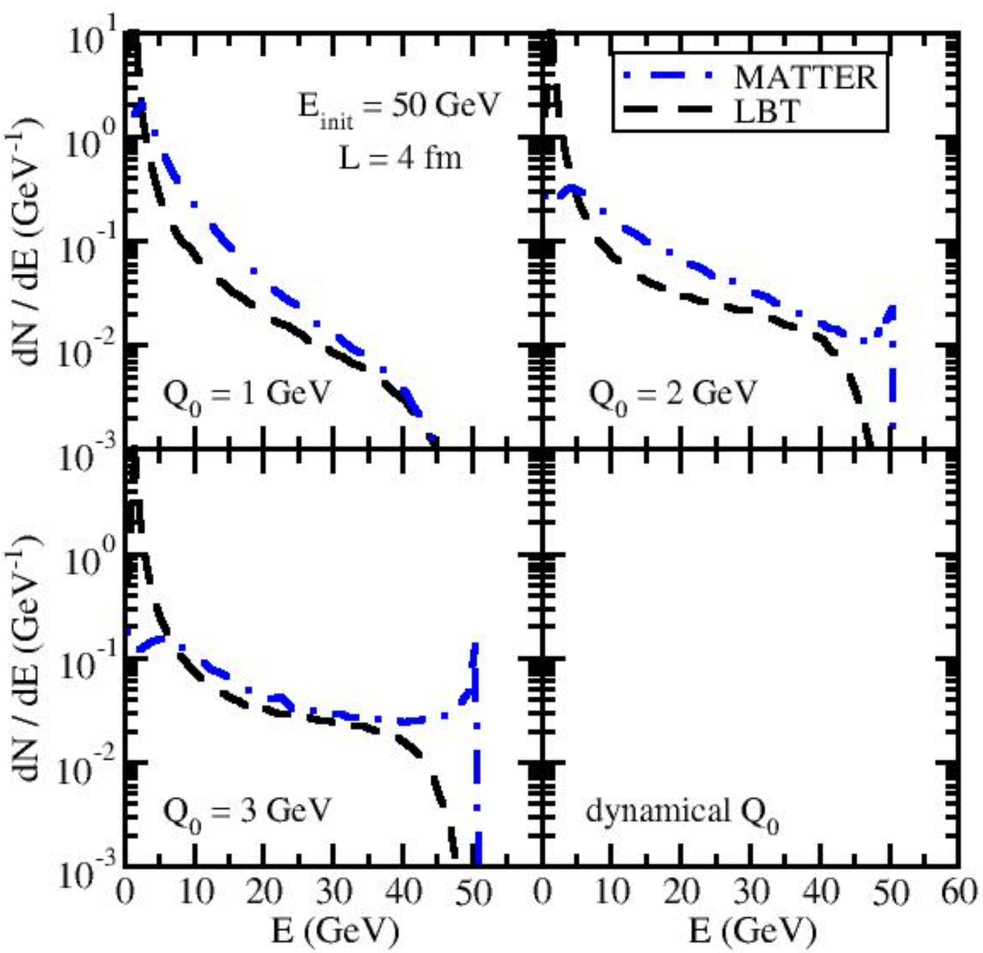
Energy distribution of final shower partons from a single quark at *E* = 50 GeV through a brick with *T* = 250 MeV and *L* = 4 fm



For E_{init} = 50 GeV, MATTER evolution (w.r.t vacuum shower) is weak if Q_0 > 2 GeV (scale of the medium $\hat{q}\tau_f$).

dN/dE for E_i = 50 GeV and *L* = 4 fm

Energy distribution of final shower partons from a single quark at *E* = 50 GeV through a brick with *T* = 250 MeV and *L* = 4 fm



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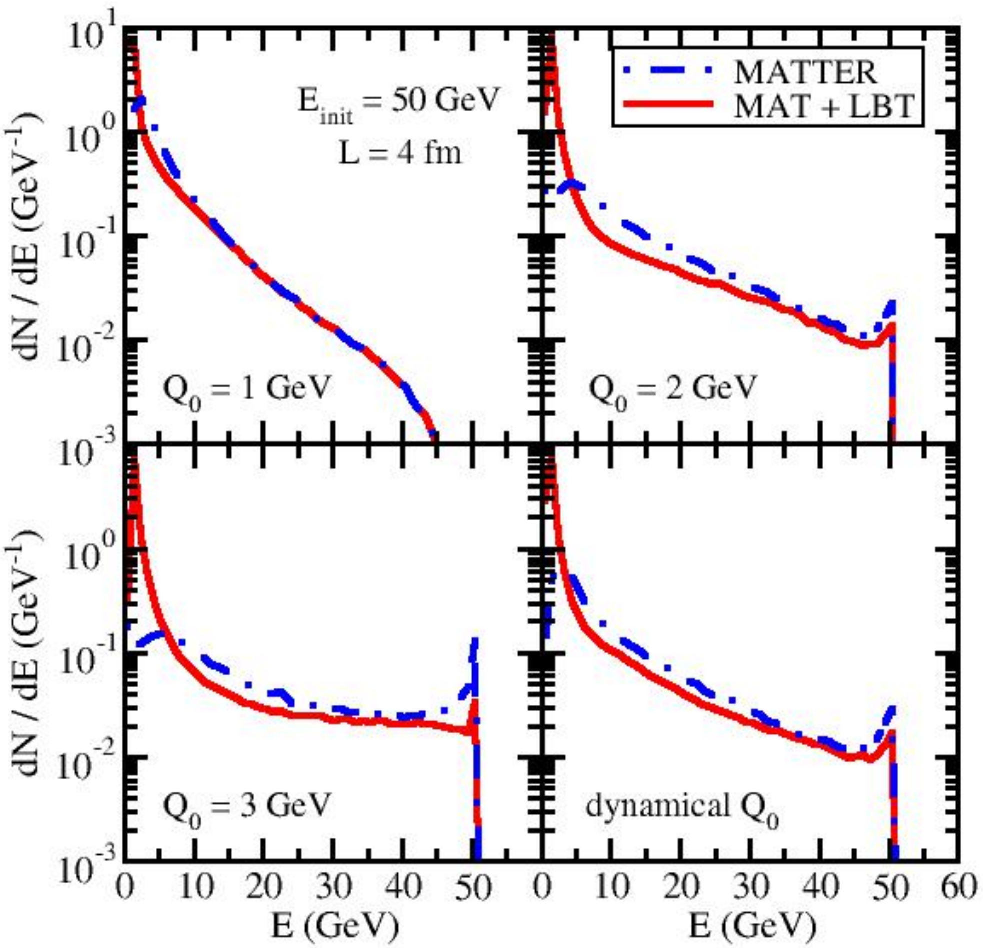
Pure LBT evolution is stronger than pure MATTER since there is no constraint from scale dependence in time-ordered transport model.

dN/*dE* for E_i = 50 GeV and *L* = 4 fm

Energy distribution of final shower partons from a single quark at *E* = 50 GeV through a brick with *T* = 250 MeV and *L* = 4 fm



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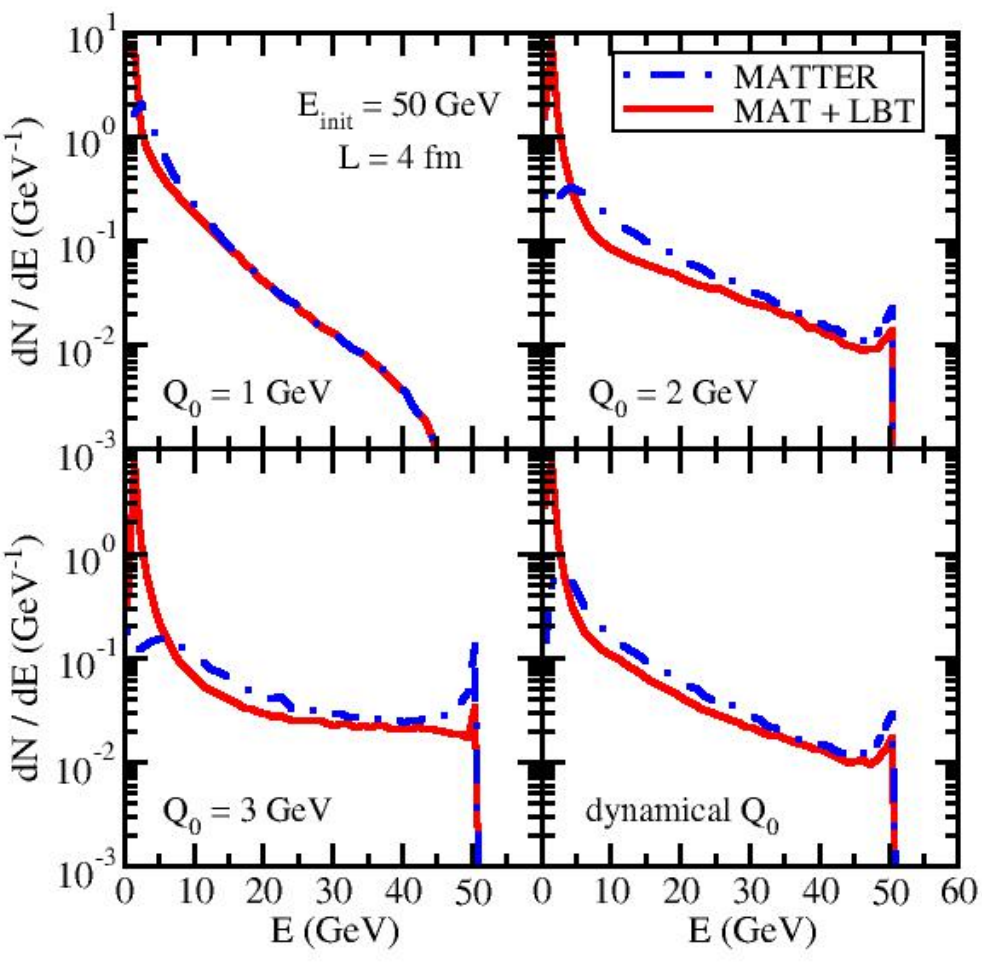
Effect of LBT in MATTER + LBT is strong for low energy partons, but is weaker for high energy ones since it took longer time for them to hit Q_0 in MATTER.

dN/dE for E_i = 50 GeV and L = 4 fm

Energy distribution of final shower partons from a single quark at E = 50 GeV through a brick with T = 250 MeV and L = 4 fm



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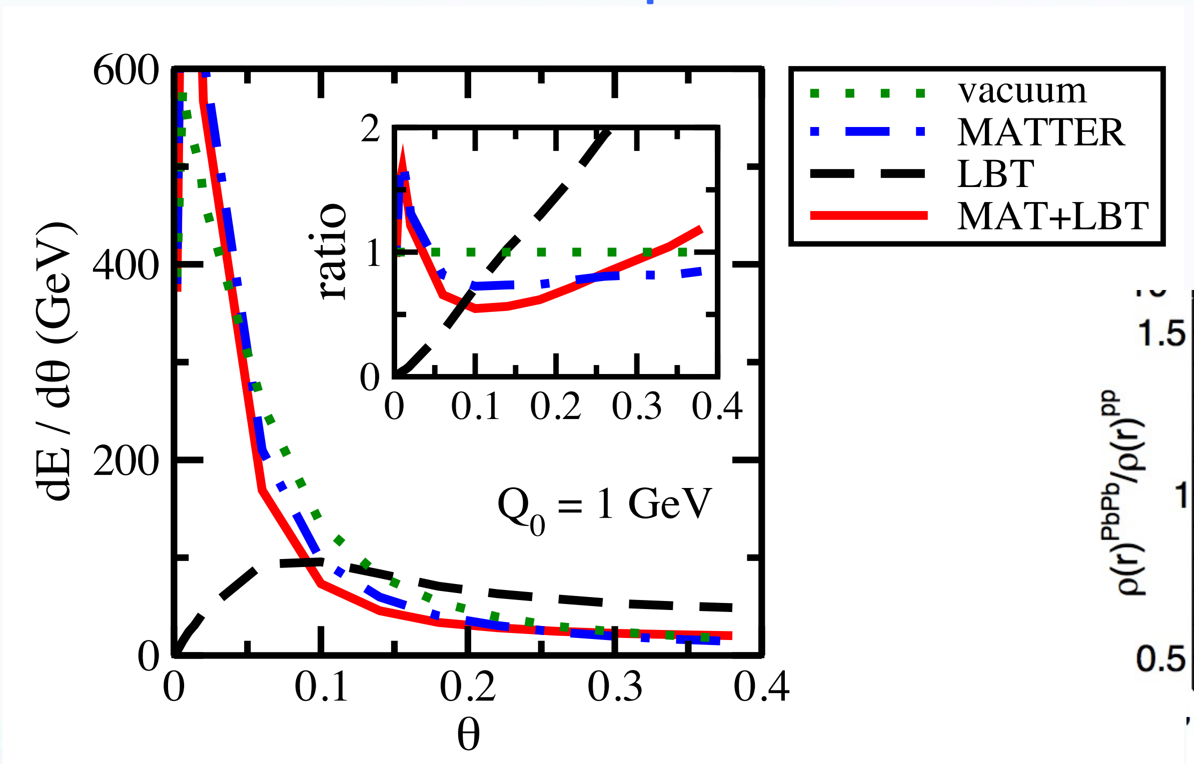
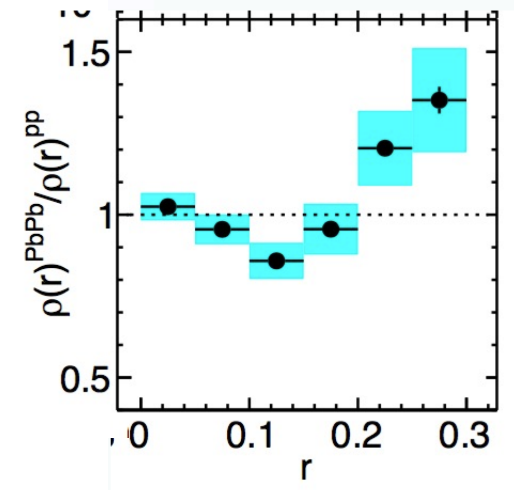
Dynamical Q_0 is close to the fixed Q_0 = 2 GeV case when E_{init} = 50 GeV.

$dE/d\vartheta$ for E_i = 50 GeV and L = 4 fm





- In medium evolution changes the jet shape – depletes energy in small cone and enhance energy in large cone.
- LBT is more effective than MATTER in shifting energy distribution into larger angle since elastic scattering is included in LBT.
- Interesting non-monotonic behavior at Q_0 = 1 GeV -- enhanced Sudakov type splitting at very small *r* and LBT scattering at large *r*.

Future development of physics model

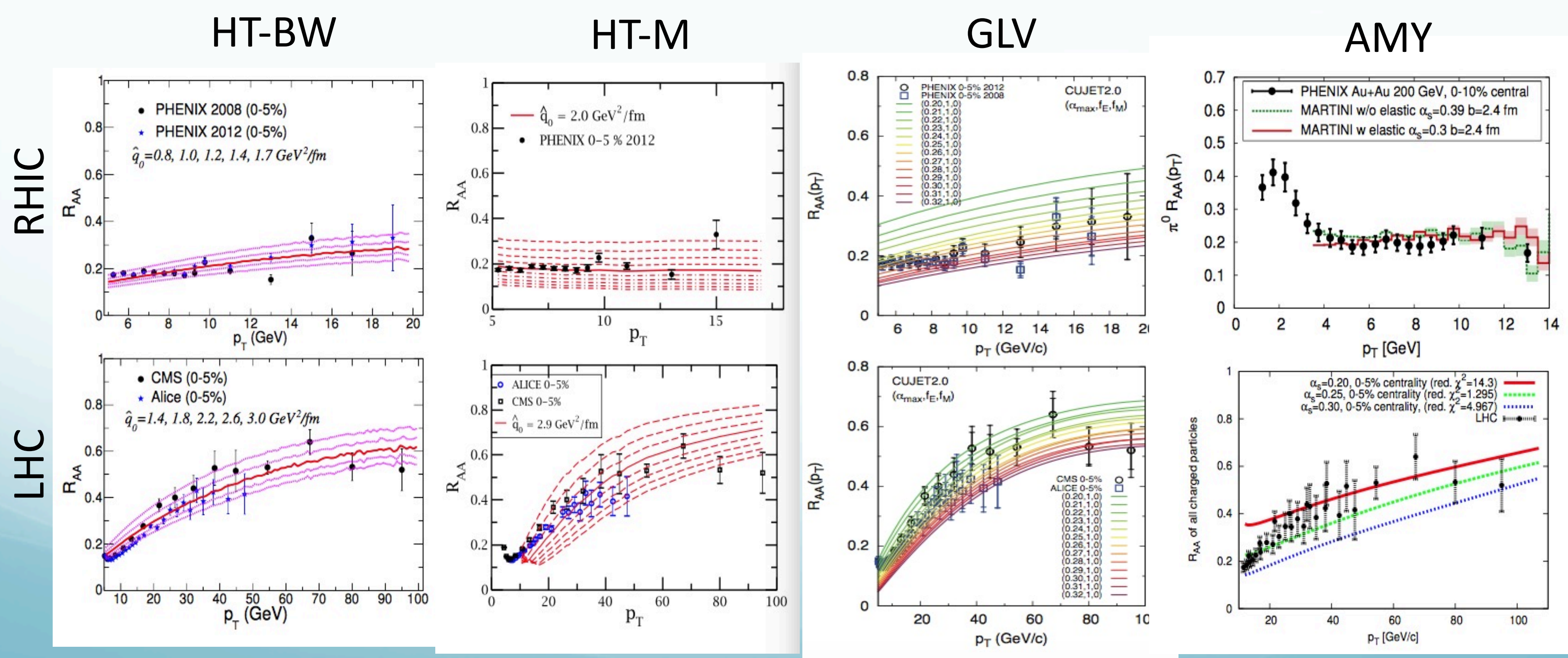
- Will implement the combined energy loss approach in realistic hydrodynamic medium, and study observables at hadron level with fragmentation + coalescence model
- Will include more approaches into the same framework, such as the strongly coupled approach for the near thermal partons

Part II: Statistic Analysis for Jet

Physics motivation of statistics analysis

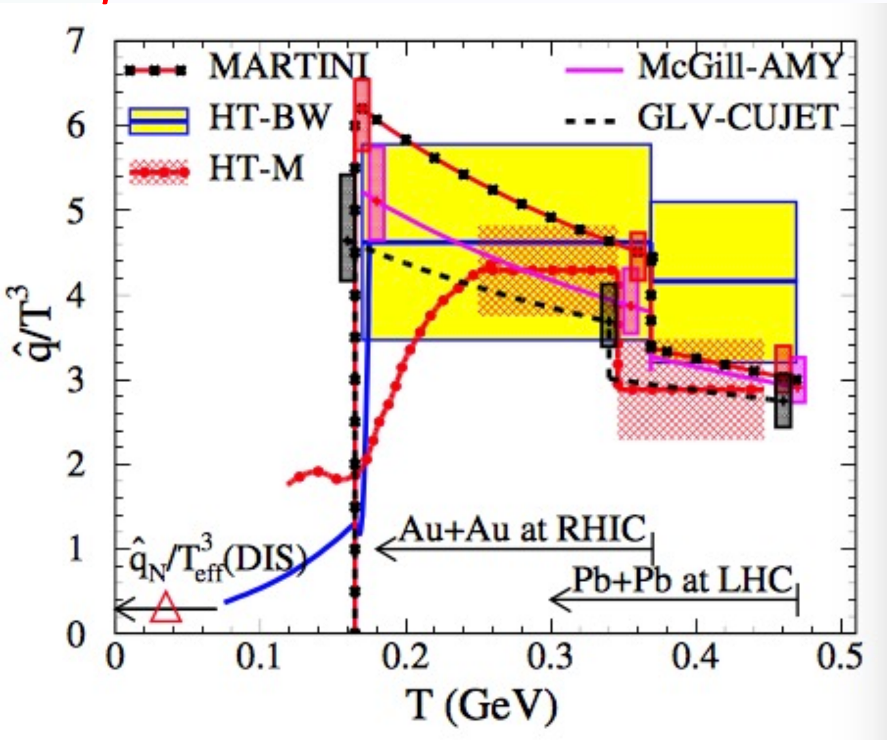
Compare physics model to experimental data and extract crucial parameters that quantify the properties of the quark-gluon plasma created in relativistic heavy-ion collisions.

Example: JET Collaboration work [PRC 90 (2014) 014909]



Physics motivation of statistics analysis

Constraint $\hat{q}$ from the JET Collaboration



$\hat{q}$: transverse momentum broadening of jet per unit time inside a medium due to elastic scattering with the medium

- Single parameter is used $\hat{q}$ or α_s for each model
- Each model is compared to only one set of experimental data from RHIC and one from LHC separately
- A jump of $\hat{q}$ as function of temperature (*T*)
- Smooth function of *T* needs multi-dimensional parameter space and simultaneous comparison to multiple data sets – ***computational expensive***

Model to data comparison setup: physics

Model: LBT (Linear Boltzmann Transport model)

Data: Simultaneous description of single hadron R_{AA} from RHIC to LHC (AuAu@200GeV, PbPb@2760GeV and PbPb@5020GeV, 2 centrality bins for each system, 6 data sets in total)

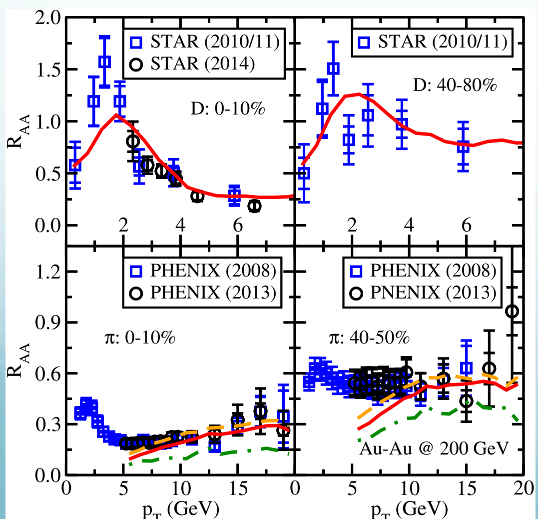
Parameters: 2-dimensinal parameter space (α_s^{med} and Λ^{jet}):

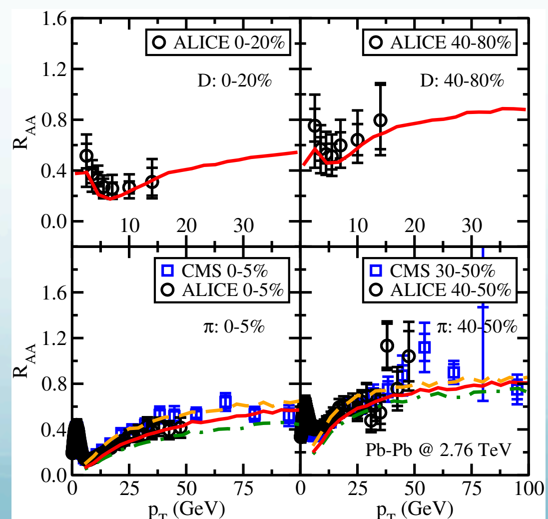
(1) fixed strong coupling α_s^{med} for thermal medium (low energy scale)

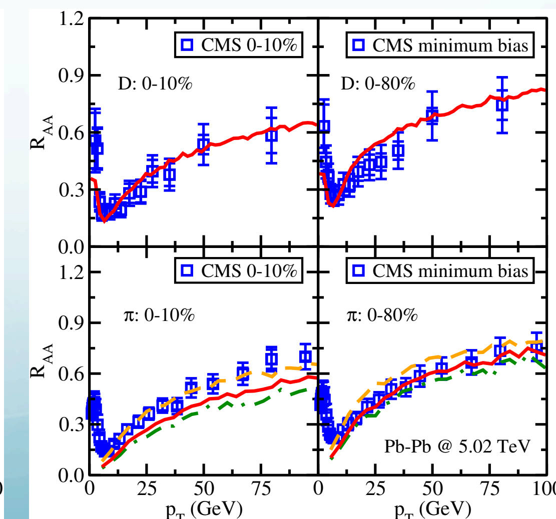
(2) Running coupling constant for jet-medium interaction

$$\alpha_s^{\mathrm{jet}} = \frac{4\pi}{9}\left[\ln\left(\frac{ET}{\Lambda_{\mathrm{jet}}^2}\right)\right]^{-1}$$

including energy and temperature dependence



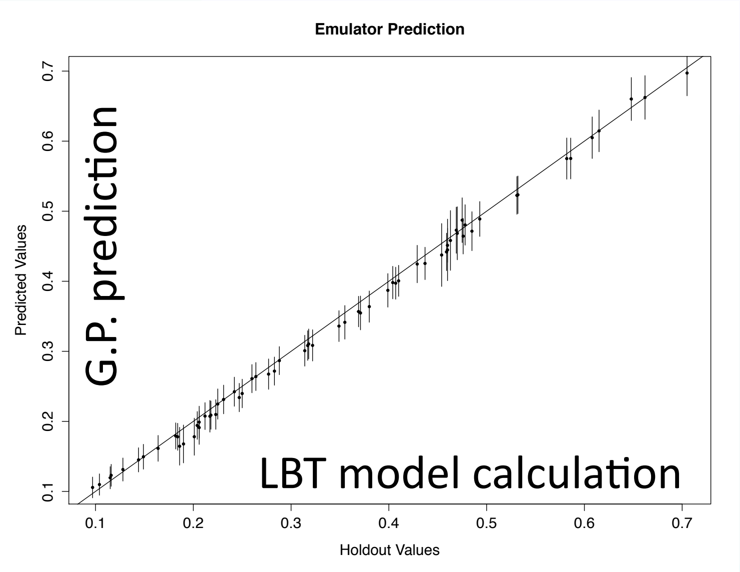




Model to data comparison setup: statistics

Gaussian Process Emulator – Fast Surrogate of model calculation:

Train **Gaussian process emulator** with smartly chosen points (**Latin Hypercube**) in the parameter space (10*dimension points are sufficient)



Gaussian process emulator can reproduce model calculation and serve as fast surrogate – *"model the model"*

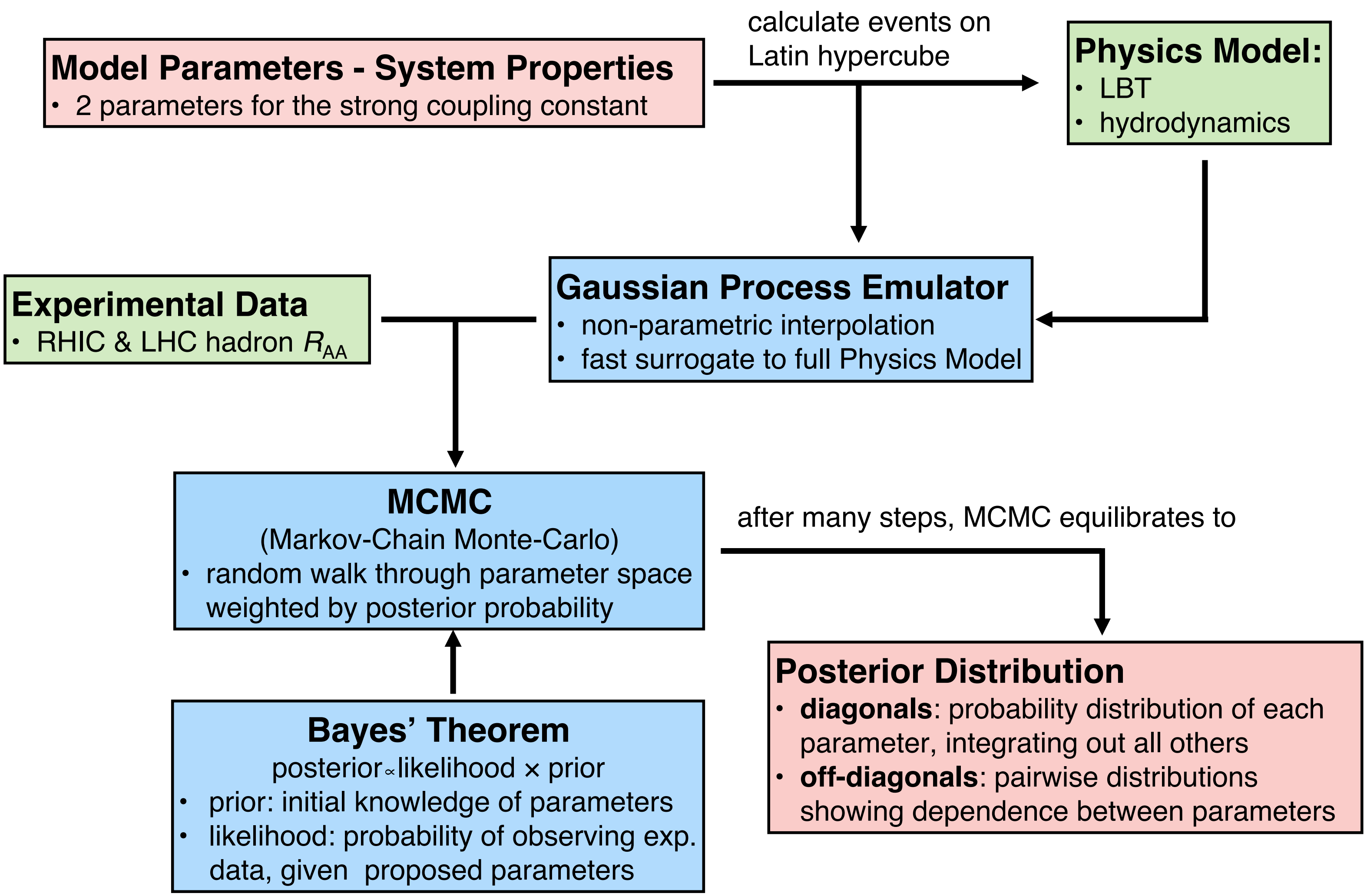
Bayesian Analysis:

Use the emulator to sweep over the parameter space, compare to experimental data, and compute the posterior probability of each set of parameters based on the **Bayes' Theorem**

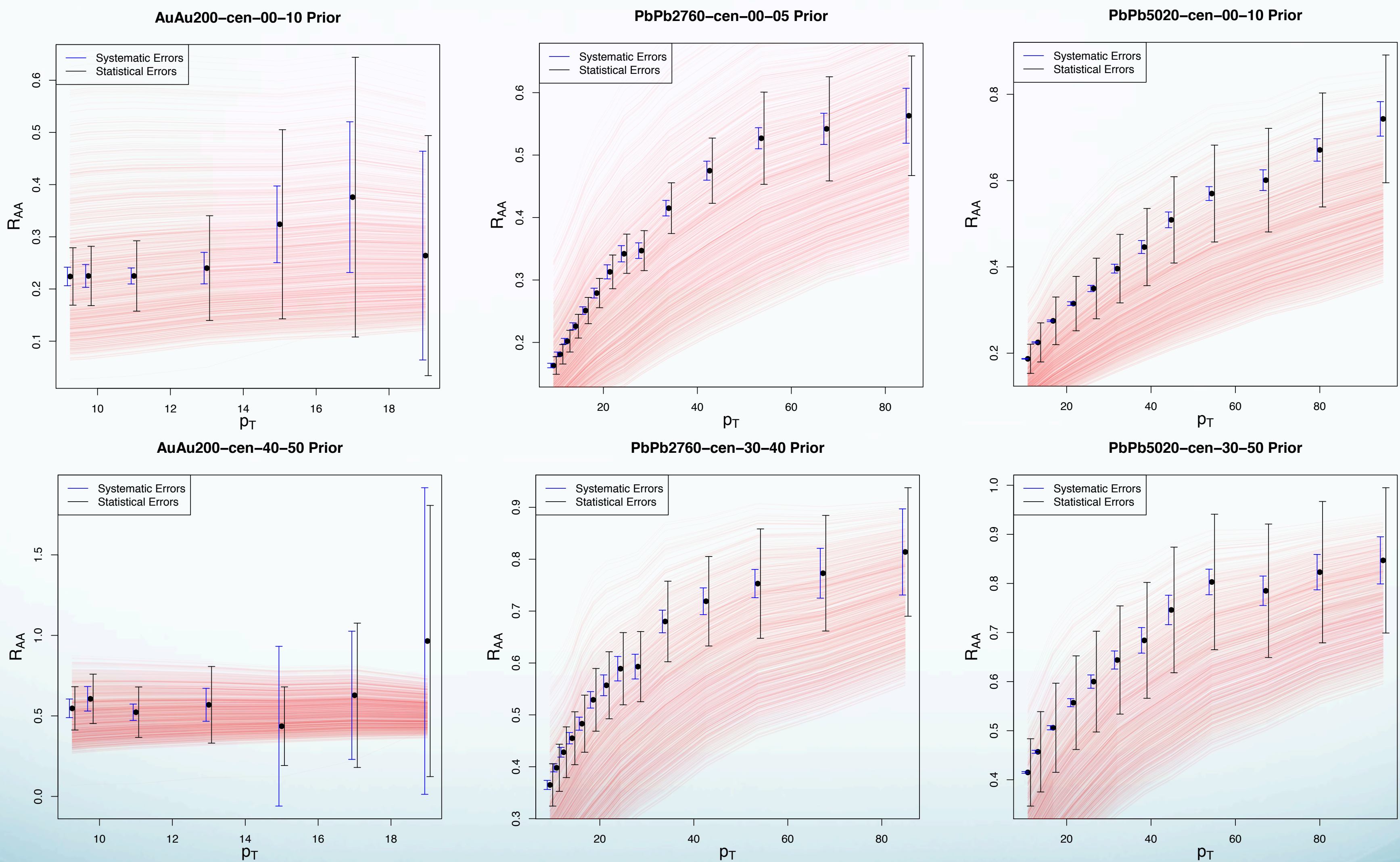
$$P_{\text{post}}(x_*|X,Y,y_{exp}) \propto P_{\text{likelihood}}(X,Y,y_{exp}|x_*)P_{\text{prior}}(x_*)$$

Flow chart of statistics analysis

Extraction of QGP Properties via a Model-to-Data Analysis

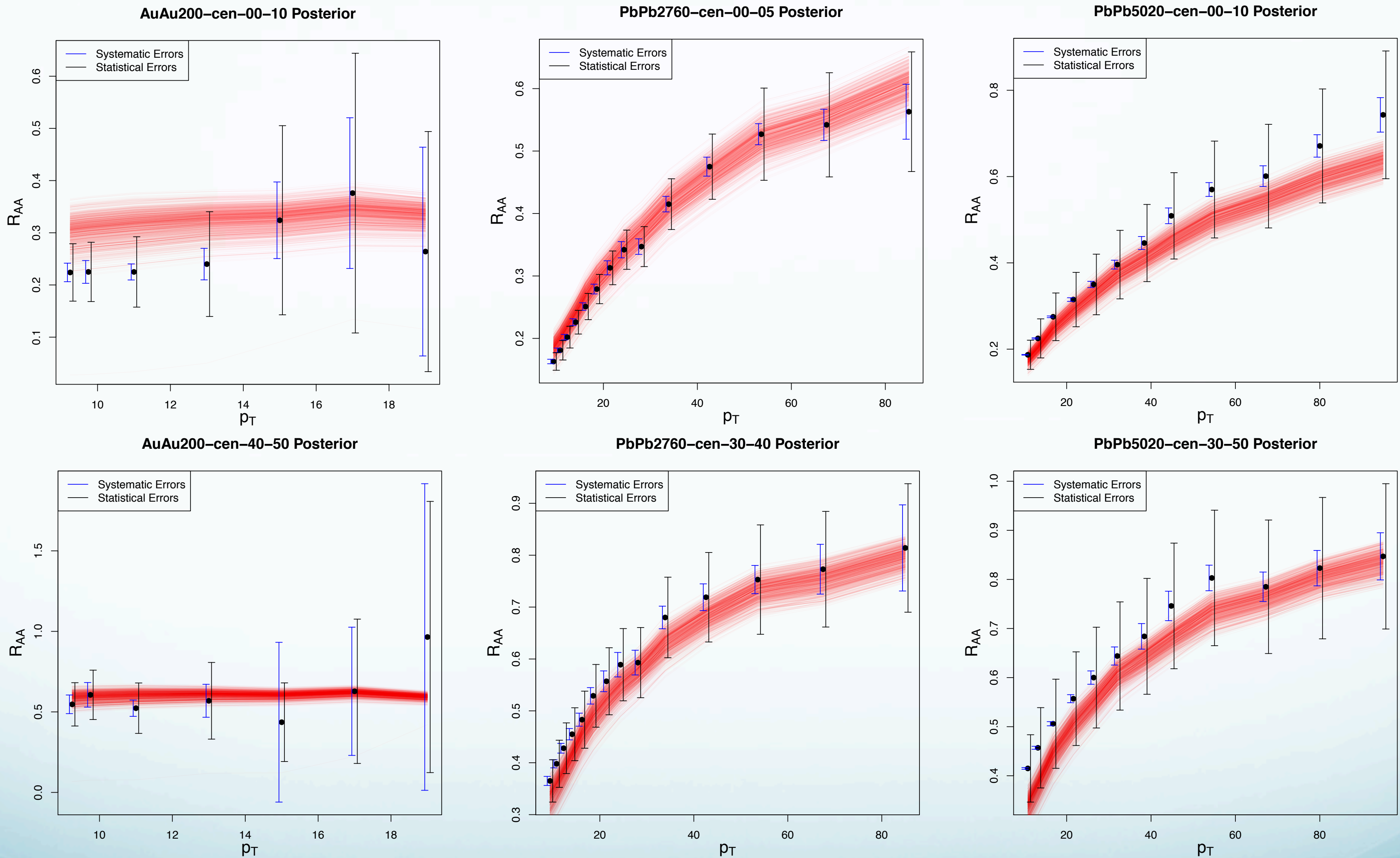


Statistics analysis – preliminary results



Calculation prior to Bayesian analysis (no knowledge of parameter space)

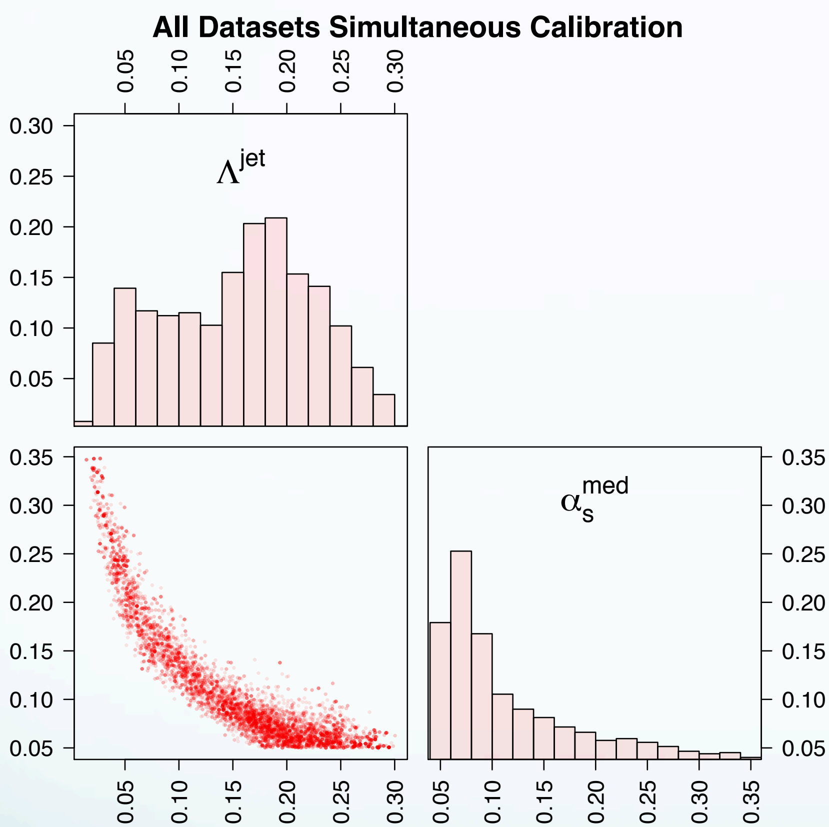
Statistics analysis – preliminary results

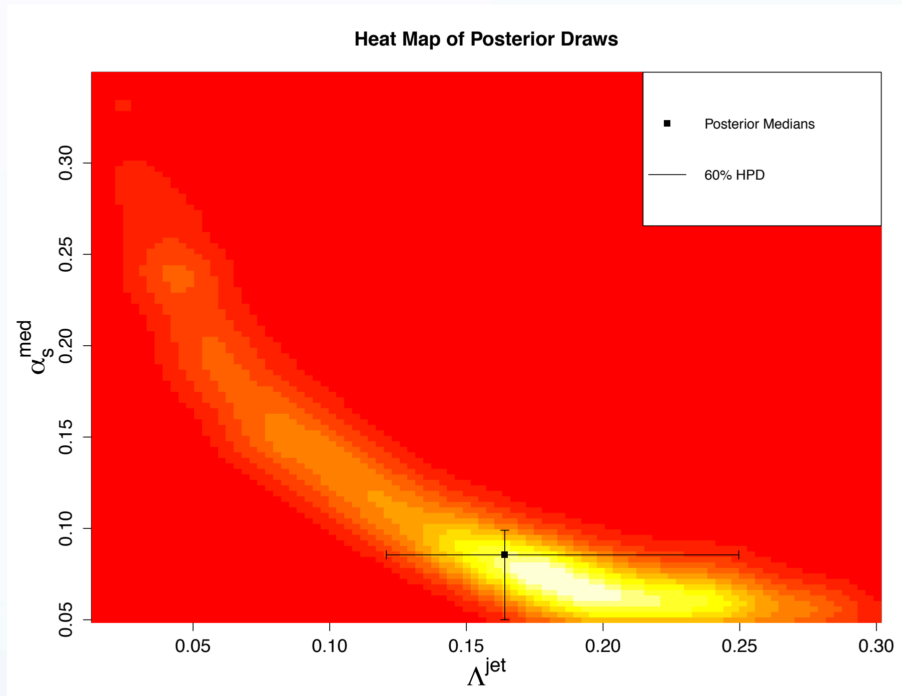


Calculation prior to Bayesian analysis (no knowledge of parameter space)

Calculation with posterior probability distribution given by Bayesian analysis

Constraint of the two input parameters



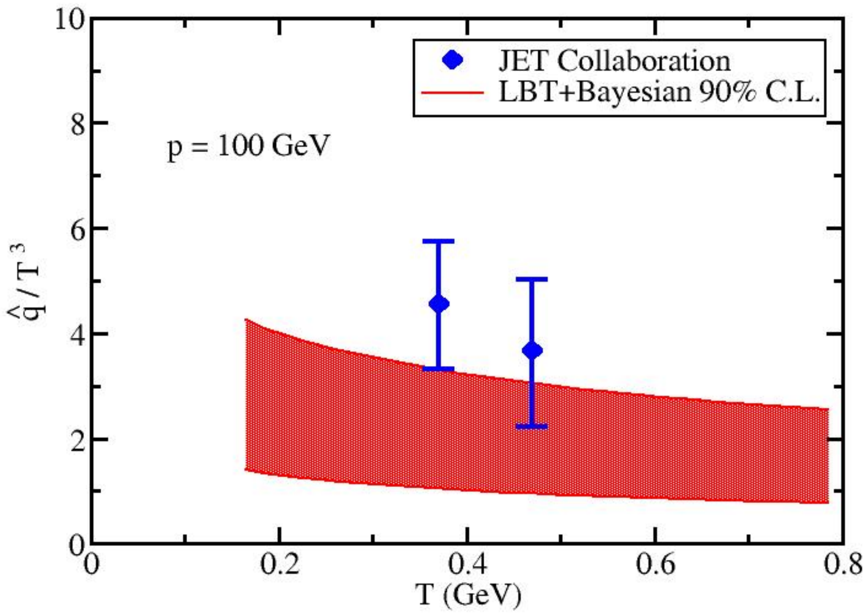


Strong correlation between the two input parameters

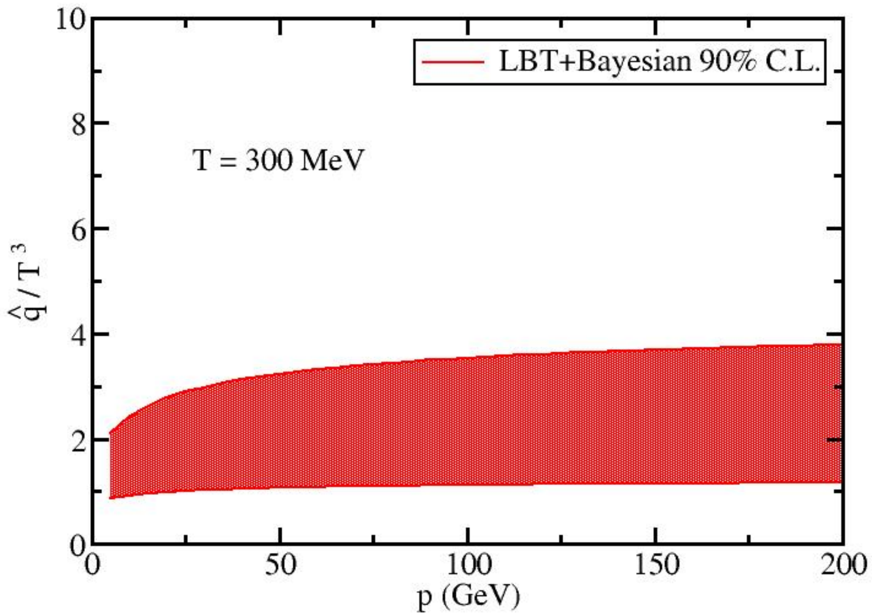
Constraint range with 60% C.L.:

$$\Lambda^{\rm jet} : [0.121, 0.250] \qquad \alpha_s^{\rm med} : [0.050, 0.099]$$

Extracted $\hat{q}$ from LBT + Bayesian analysis



temperature dependence



momentum dependence

Not inconsistent with previous JET collaboration work.

Hint of smaller band for $\hat{q}$

- Full Monte-Carlo implementation vs. semi-analytical calculation
- Inclusion of elastic scattering in LBT
- Need more sophisticated parametrization of the temperature dependence of α_s

Summary and Outlook

- Established a unified approach for multistage jet evolution: applying different jet energy loss theories at different stages of jet evolution (e.g. virtuality ordered DGLAP at high Q + time ordered transport at low Q)
- Established a statistic analysis framework -- Gaussian process emulator + Bayesian analysis -- that helps extract jet transport coefficient from model to data comparison
- Will prepare a user-friendly Monte-Carlo event generator for the heavy-ion community

Thank you!

WAYNE STATE

JETSCAPE

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