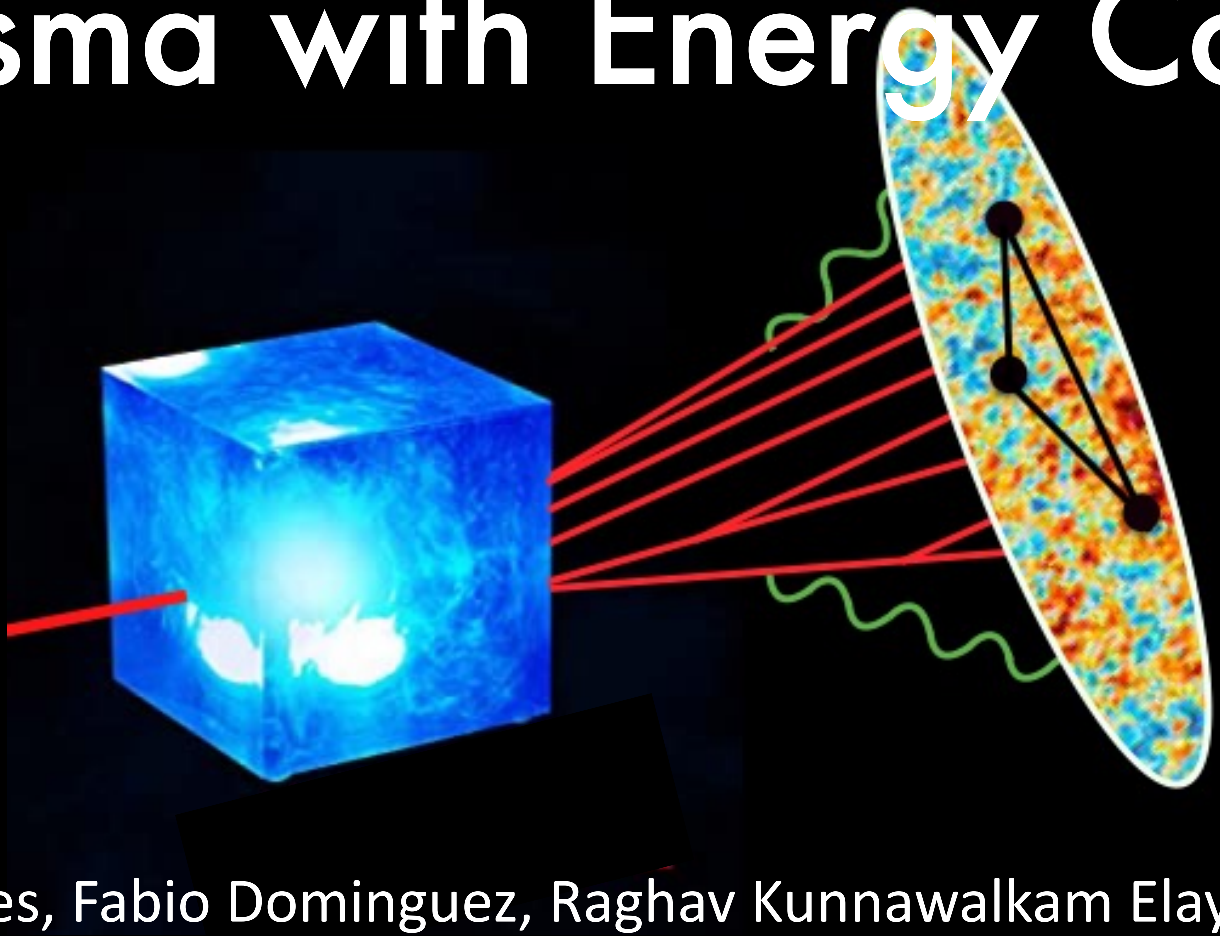
Resolving the Scales of the Quark-Gluon Plasma with Energy Correlators



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Cyrille Marquet, and Ian Moult

Gluodynamics
P2IO Physique des 2 Infinis et des Origines
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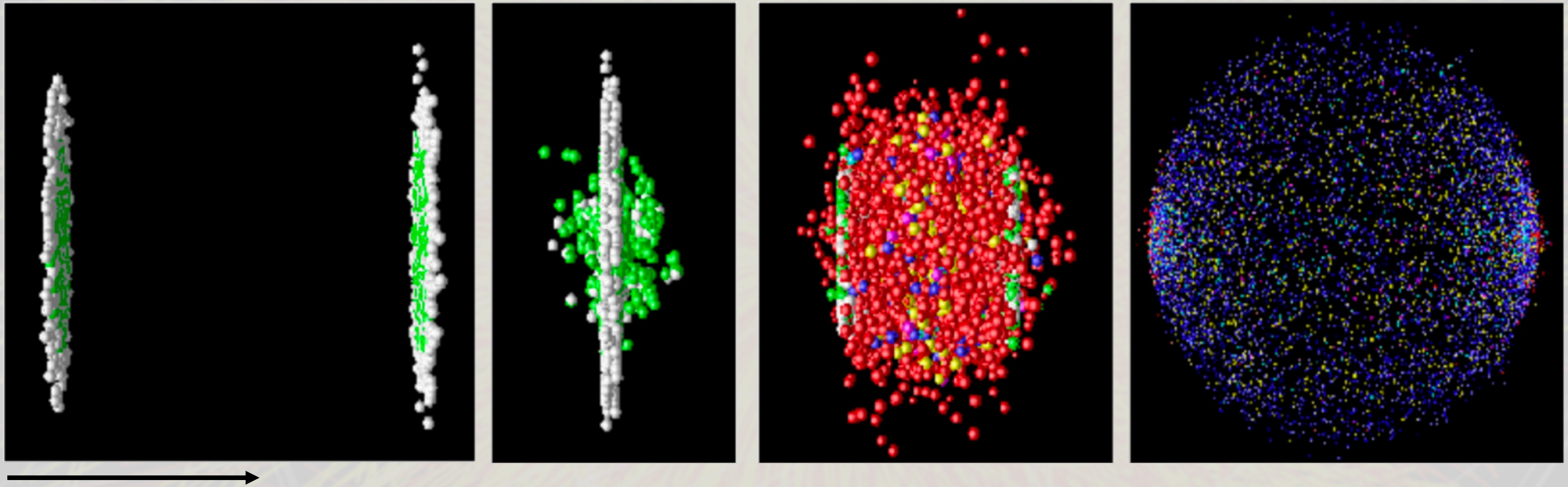
Introduction



We want to study the QGP in HIC.
– 20 years of HIC at RHIC, 10 years of HIC at the LHC, sPHENIX coming soon.

We need to study the QGP with sensitive QCD probes with good theoretical control…

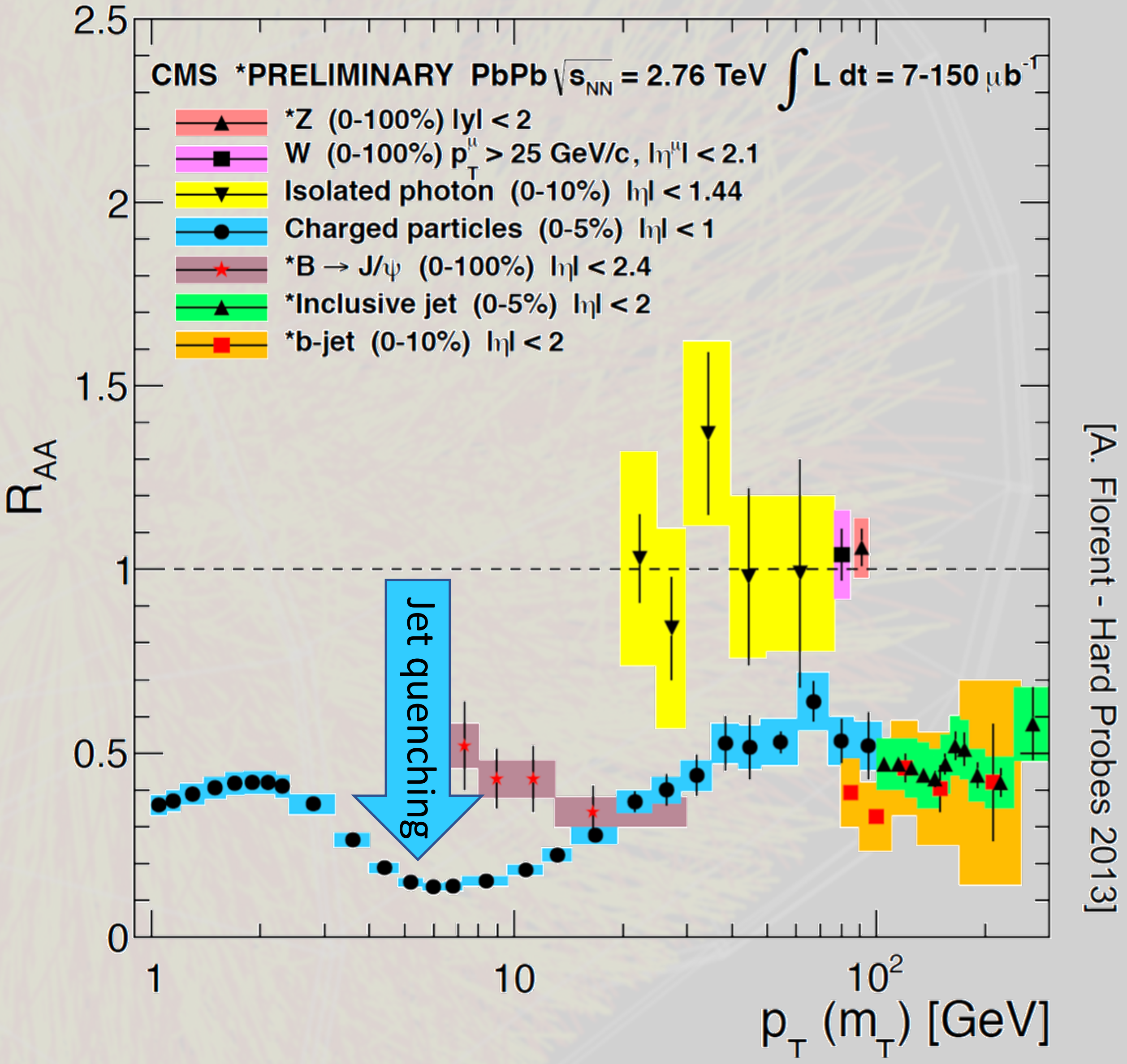
Introduction

Prototypical observable:

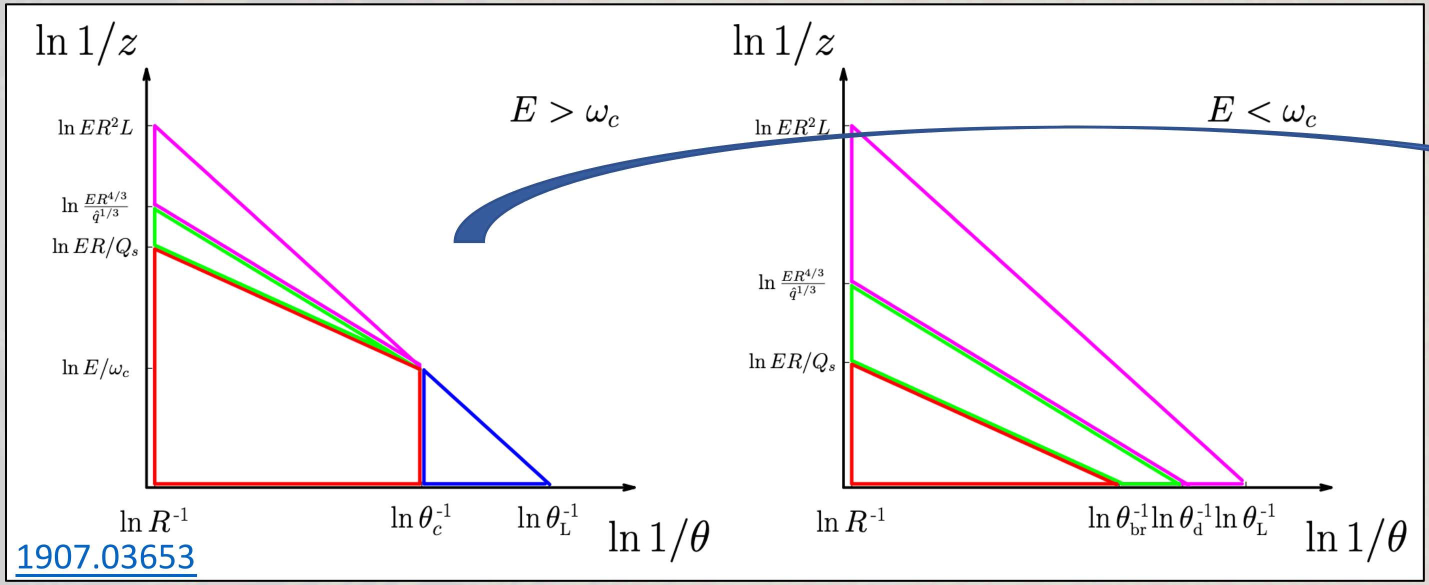
$$R_{AA} = \frac{dN_{AA}/d^2p_T\,dy}{\langle N_{coll}\rangle\, dN_{pp}/d^2p_T\,dy}$$

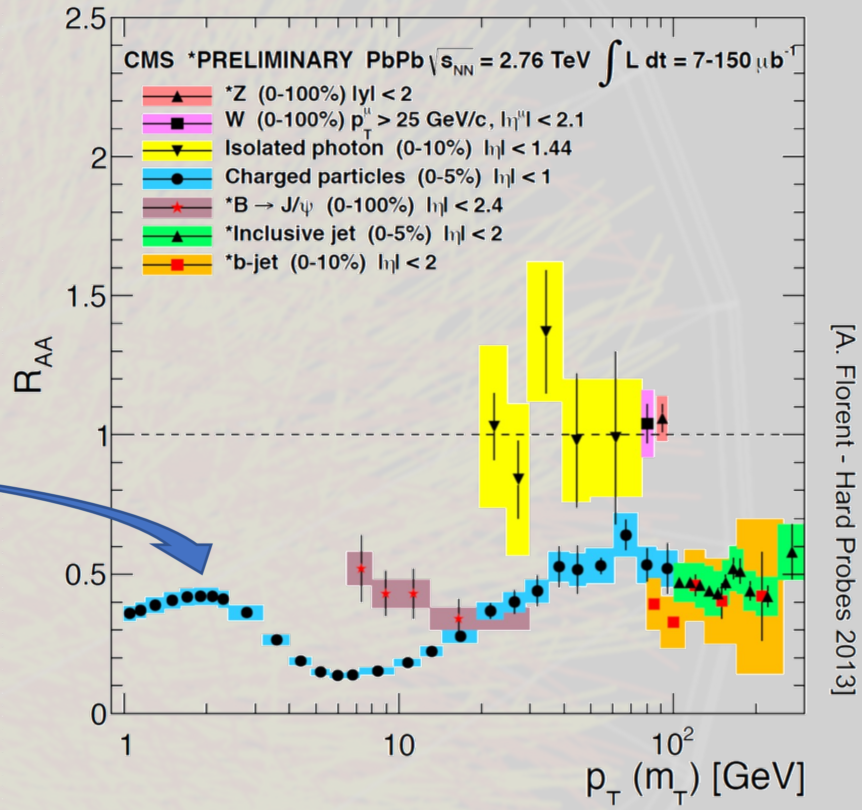
$R_{AA} \neq 1$ for coloured probes.

Principle mechanism is energy loss due to medium induced radiation.



Introduction

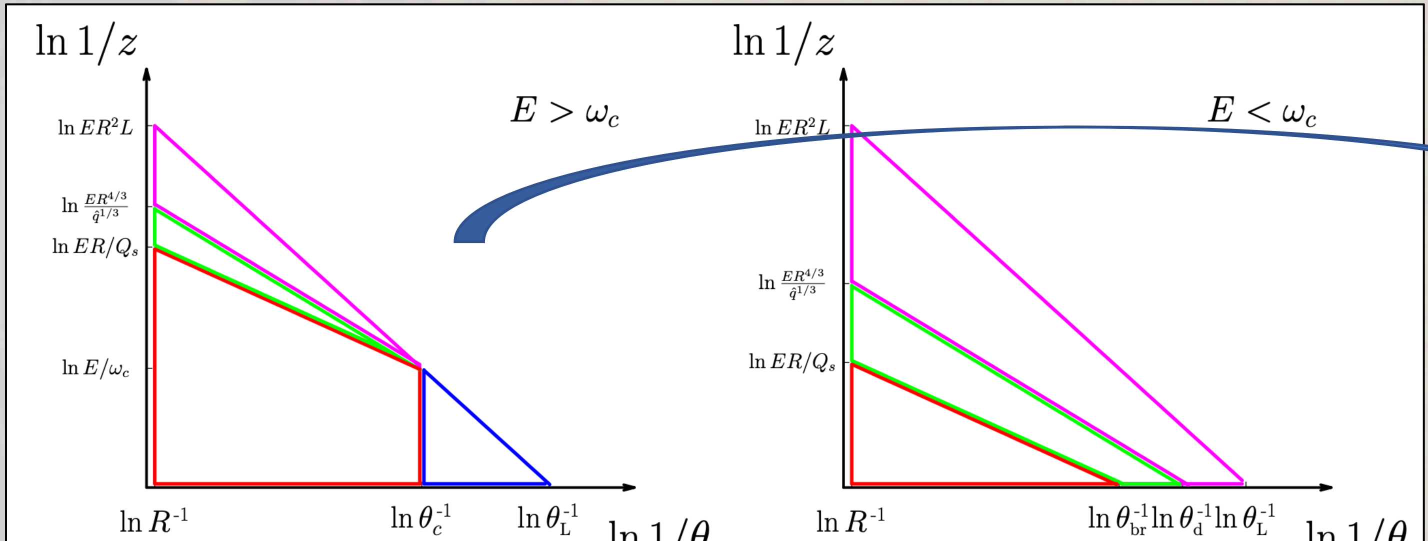




Problem:

Jet quenching is a multi-scale process. It is difficult to unambiguously resolve the scales/properties of the QGP involved within current approaches.

Introduction



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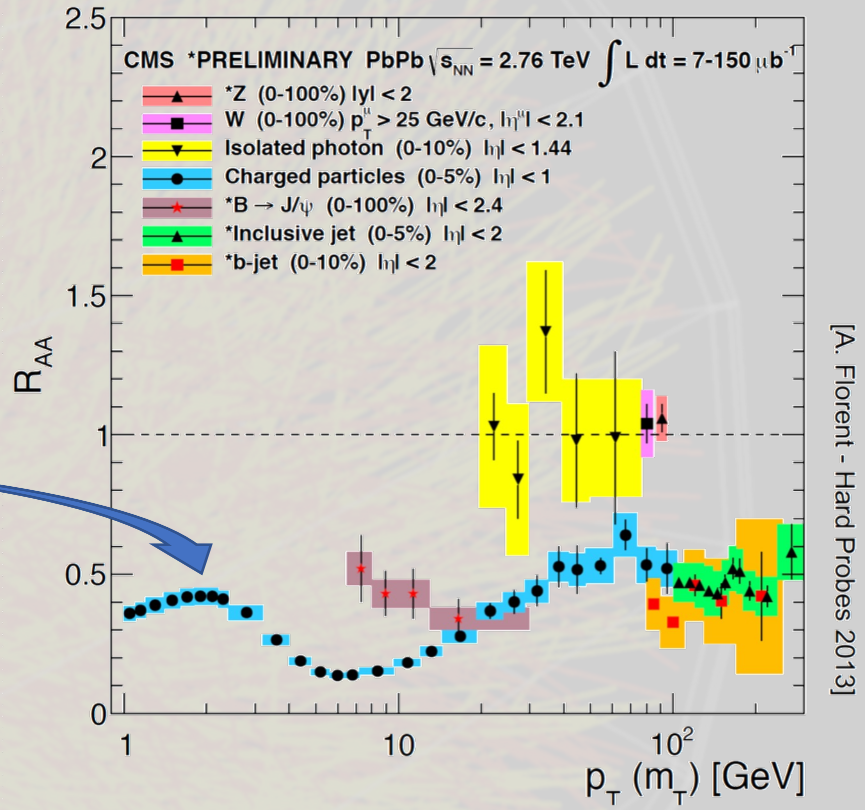
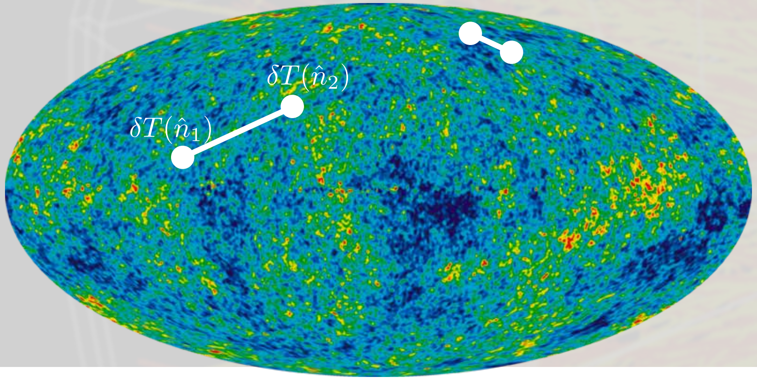


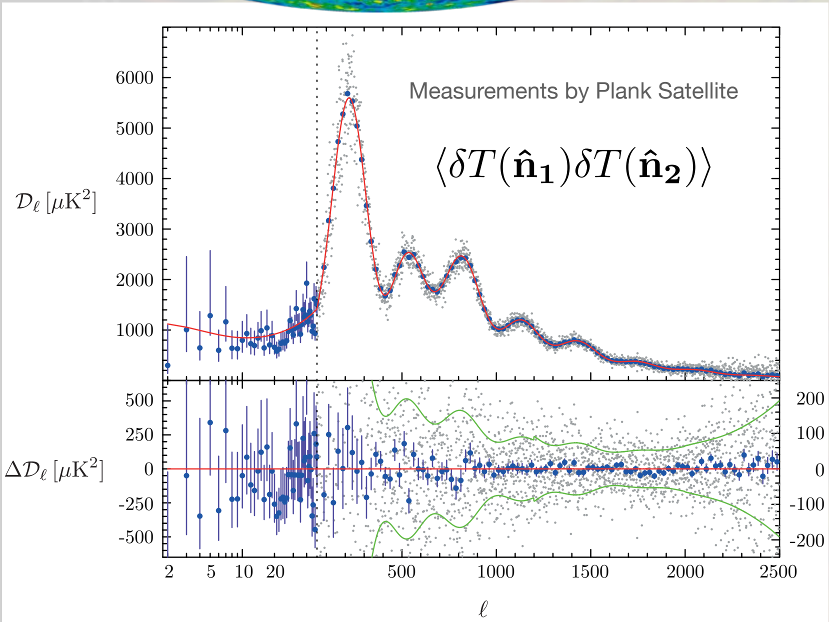
There has been a lot of work introducing observables.

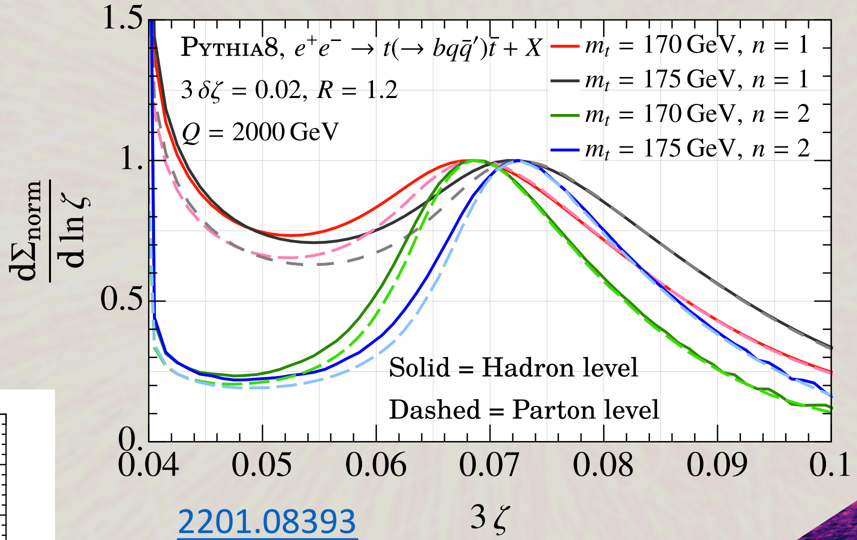
1512.08107, 1710.03237, 1812.05111, 2010.00028, and more

We would like to present a new approach to add to this body of work.

Part 2: Correlation functions of $\mathcal{E}(\vec{n})$







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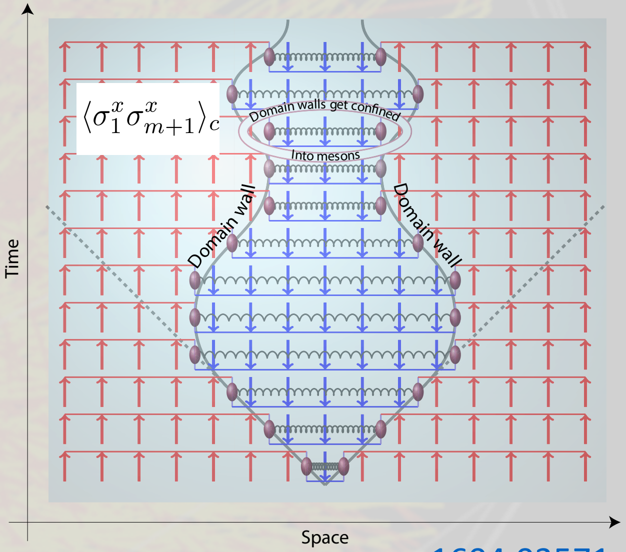

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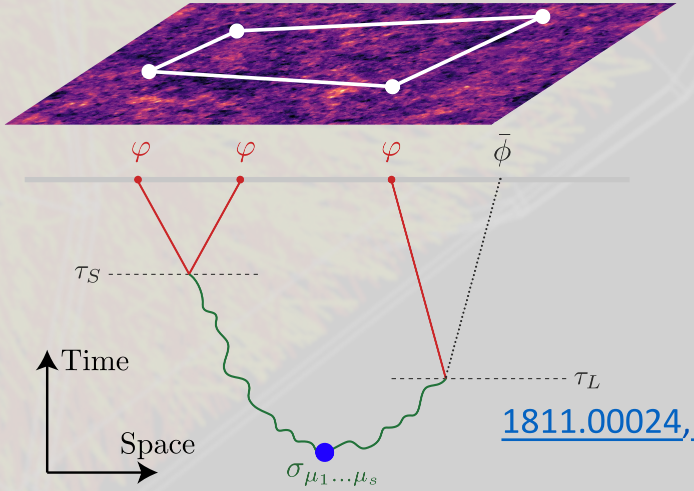


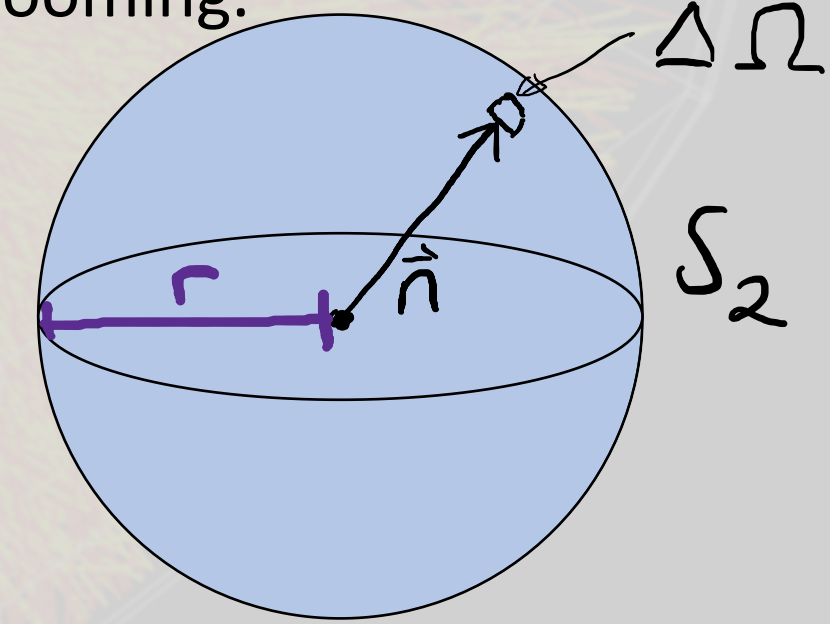
1811.00024, 1503.08043

Correlation functions of $\mathcal{E}(\vec{n})$

- Generally one can define correlators of any quantum charge or conserved quantity.
- For QCD, correlators of energy flux are usually of most interest – these naturally remove soft physics without grooming.

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} \int_0^\infty dt\, r^2 n^i T_{0i}(t, r\vec{n})$$

$$\mathcal{E}(\vec{n}) \simeq \int_0^\infty dt\; E_{\text{flux through } \Delta\Omega}(t)$$



[0803.1467](0803.1467)

Correlation functions of $\mathcal{E}(\vec{n})$

Which correlation function is the one for us?

- In the previous slide the 2-point correlator gives a sentive pobe of hadronisation.
- In 2201.08393 the 3-point provided a sentive probe to the top mass.

Look to what is currently done and sucessful.

- R_{AA} can be expressed as a function of one-point correlators + corrections:
  - $R_{AA} = \langle N_{AA} \rangle / (\langle N_{\text{Coll}} \rangle \langle N_{pp} \rangle)$. $\langle N \rangle$ is the one point correlator of the number opertator and due to momentum conservation $\langle N \rangle \approx \langle \mathcal{E} \rangle / \langle Q \rangle$.
- In effect, R_{AA} gives access to the simplest but also least sensitive correlator. Let us increase the sentivity (at the expense of a little more complexity) by looking directly at the 2-point correlator.

The observable analytically

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \int \mathrm{d}\vec{n}_{1,2} \frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} \delta(\vec{n}_2 \cdot \vec{n}_1 - \cos\theta).$$

The observable analytically

Equiv. to $t_f \lesssim L$

Vacuum $\theta \ll 1$ resummation

$$\frac{\mathrm{d}\Sigma^{(1)}}{\mathrm{d}\theta} \sim \frac{1}{\theta^{1-\gamma(3)}} + \mathcal{O}(\theta^0)$$

$\theta \gtrsim (EL)^{-1/2}$ Medium induced quenching

$$\left.\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta}\right|_{\theta \gtrsim \theta_L} = \frac{1}{\sigma_{qg}} \int \mathrm{d}z \frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta \mathrm{d}z} z^n (1-z)^n$$
$$\times \left(1 + \mathcal{O}(\alpha_s \ln \theta_L^{-1}) + \mathcal{O}\left(\alpha_s \frac{\mu_s^n}{E^n}\right)\right)$$

$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta \mathrm{d}z} = \frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}z}(1 + F_{\mathrm{med}}(z, \theta, \hat{q}, L))$$ 1907.03653, 2107.02542

$$\frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta \mathrm{d}z} \approx \frac{\alpha_s C_F \sigma}{\pi} \frac{1 + (1-z)^2}{z\ \theta} + \mathcal{O}(\alpha_s^2, \theta^0)$$

The observable numerically

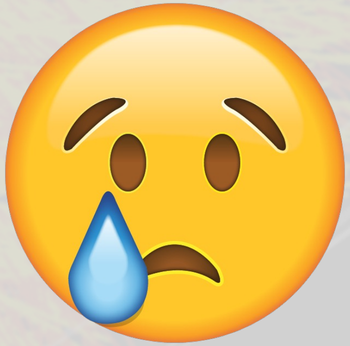
$$F_{\mathrm{med}} = 2\int_0^L \frac{\mathrm{d}t_1}{t_\mathrm{f}}\left[\int_{t_1}^L \frac{\mathrm{d}t_2}{t_\mathrm{f}}\cos\left(\frac{t_2-t_1}{t_\mathrm{f}}\right)\mathcal{C}^{(4)}(L,t_2)\mathcal{C}^{(3)}(t_2,t_1) - \sin\left(\frac{L-t_1}{t_\mathrm{f}}\right)\mathcal{C}^{(3)}(L,t_1)\right]$$

$$\mathcal{C}^{(3)}_{gq}(t_2,t_1) = \frac{1}{N_c^2-1}\left\langle \mathrm{tr}[V_2^\dagger V_1]\,\mathrm{tr}[V_0^\dagger V_2] - \frac{1}{N_c}\mathrm{tr}[V_0^\dagger V_1]\right\rangle .$$

$$\mathcal{C}^{(3)}_{gq}(t_2,t_1) = \mathrm{e}^{-\frac{1}{2}\int_{t_1}^{t_2}\mathrm{d}s\, n(s)[N_c(\sigma_{02}+\sigma_{12})-\frac{1}{N_c}\sigma_{01}]}$$
$$= \mathrm{e}^{-\frac{1}{12}\hat{q}(t_2-t_1)^3\theta^2\left(1+z^2+\frac{2z}{N_c^2-1}\right)} .$$

$$\mathcal{C}^{(4)}_{gq}(L,t_2) = \frac{1}{N_c^2-1}\left\langle \mathrm{tr}[V_{\bar{1}}^\dagger V_1 V_2^\dagger V_{\bar{2}}]\,\mathrm{tr}[V_{\bar{2}}^\dagger V_2] - \frac{1}{N_c}\mathrm{tr}[V_{\bar{1}}^\dagger V_1]\right\rangle ,$$

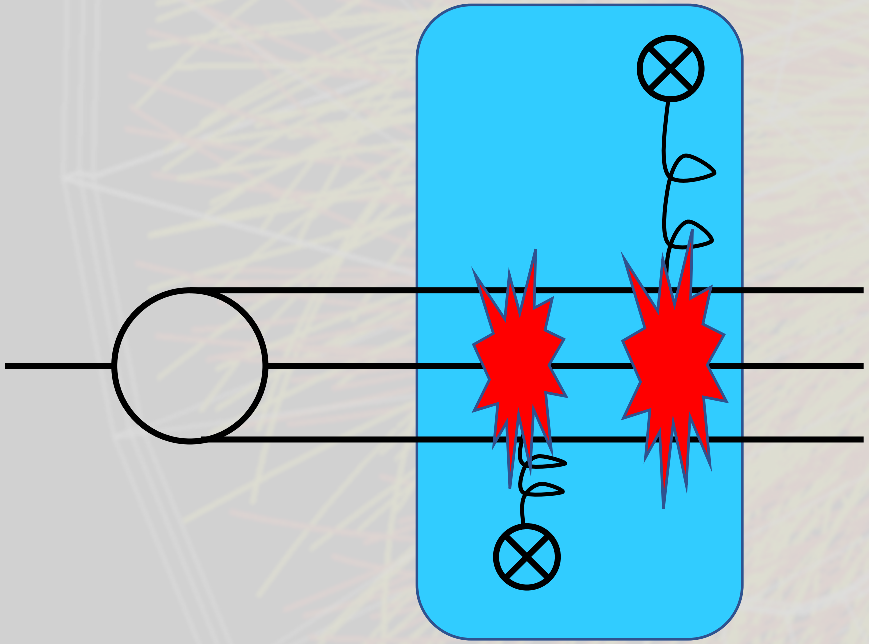
$$\frac{1}{N_c^2}\langle \mathrm{tr}[V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger]\,\mathrm{tr}[V_2 V_{\bar{2}}^\dagger]\rangle \simeq \mathrm{e}^{-\frac{1}{4}\hat{q}\theta^2(t-t_2)(t_2-t_1)^2(1-2z+3z^2)}$$
$$\times\left(1-\frac{1}{2}\hat{q}\theta^2 z(1-z)(t_2-t_1)^2\int_{t_2}^t \mathrm{d}s\,\mathrm{e}^{-\frac{1}{12}\hat{q}\theta^2[(s-t_2)^2(2s-3t_1+t_2)+6z(1-z)(s-t_2)(t_2-t_1)^2]}\right)$$



The observable numerically

$\theta_{\mathrm{c}} \gg \theta_{\mathrm{L}}$

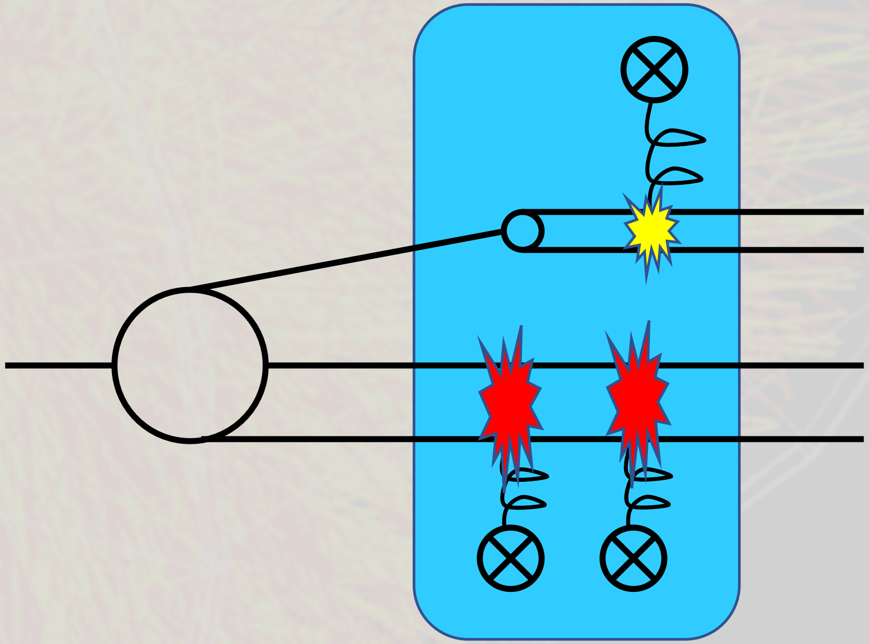
$E \gg \hat{q}L^2$



For angles $\theta_{\mathrm{c}} \gg \theta \gg \theta_{\mathrm{L}}$, the quark jet undergoes some energy loss but the substructure is not resolved.

$\theta_{\mathrm{c}} \ll \theta_{\mathrm{L}}$

$E \ll \hat{q}L^2$



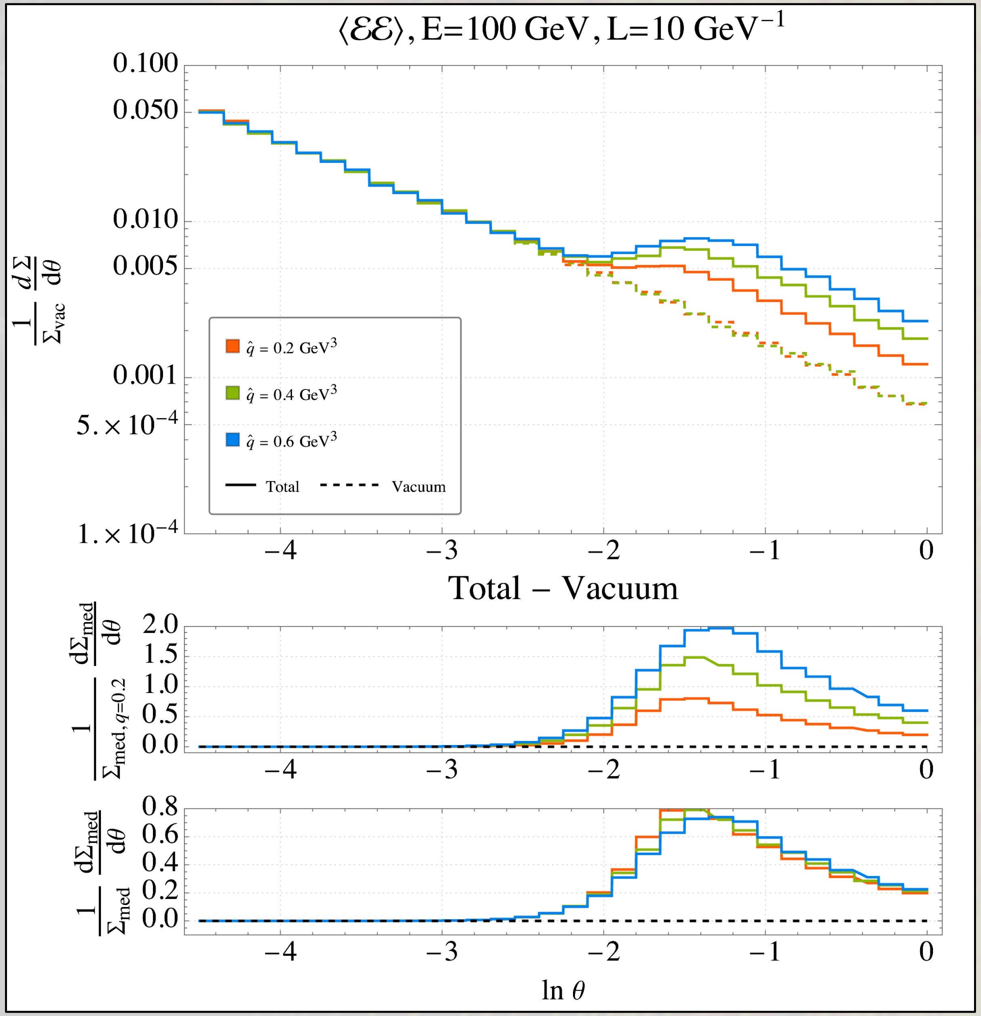
Initial splitting can be resolved by the medium when $\theta \gg \theta_{\mathrm{L}}$. Broadening and energy loss occur.

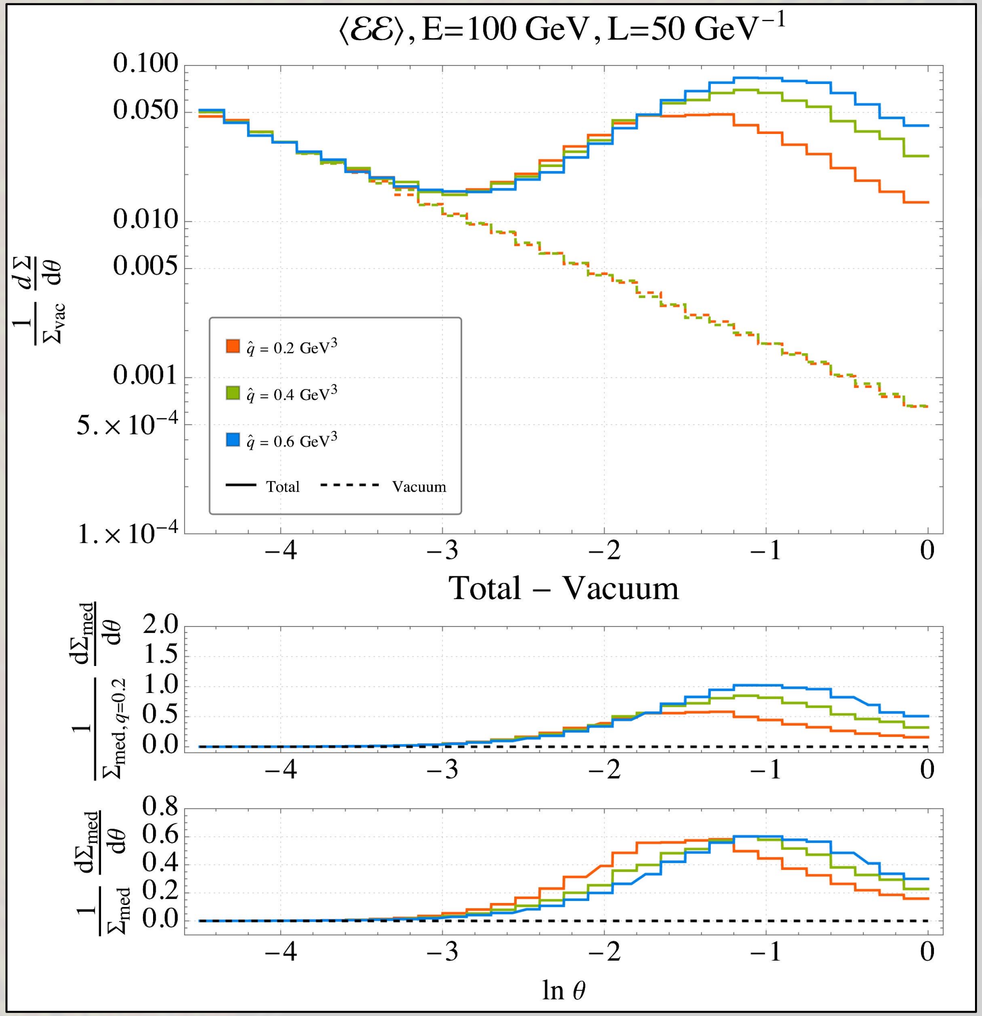
The observable numerically

$\theta_c \gg \theta_L$

$L = 10\ \mathrm{GeV}^{-1} \equiv 2\ \mathrm{fm}$

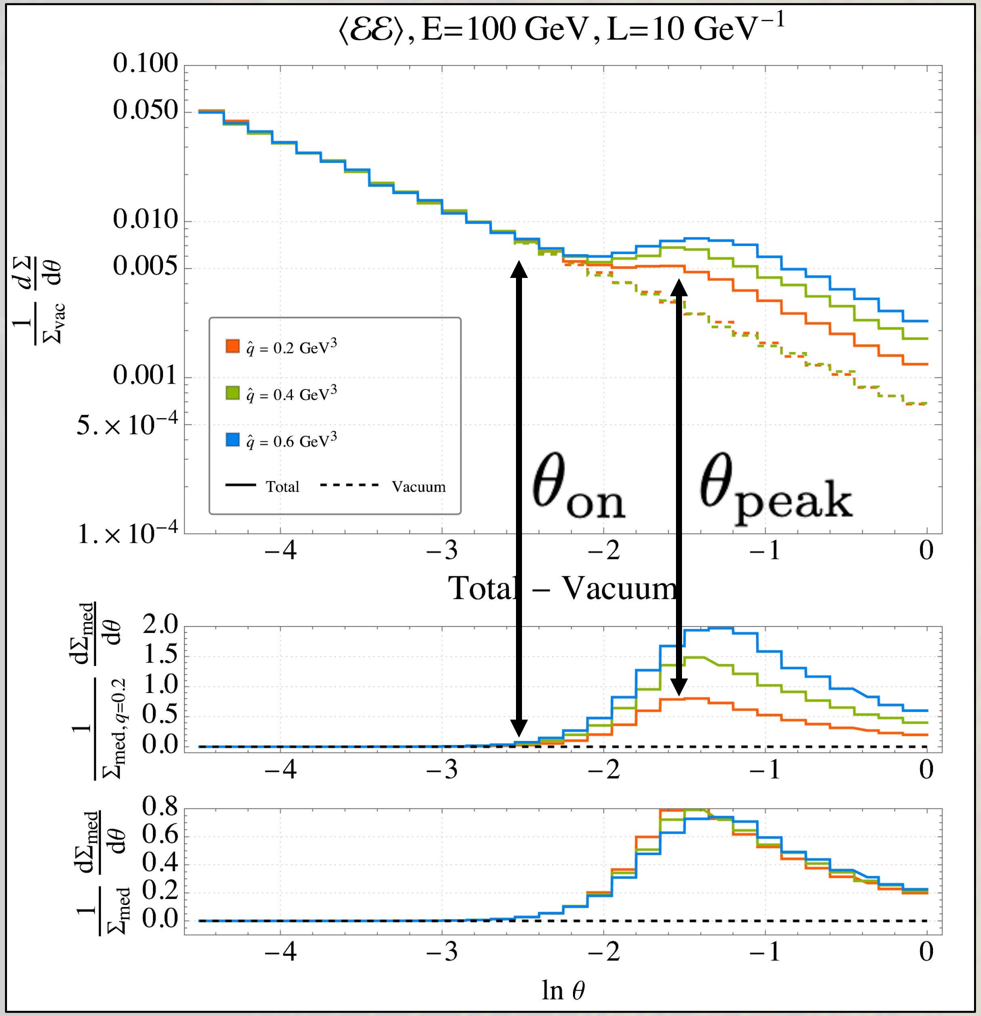
$\theta_c \ll \theta_L$

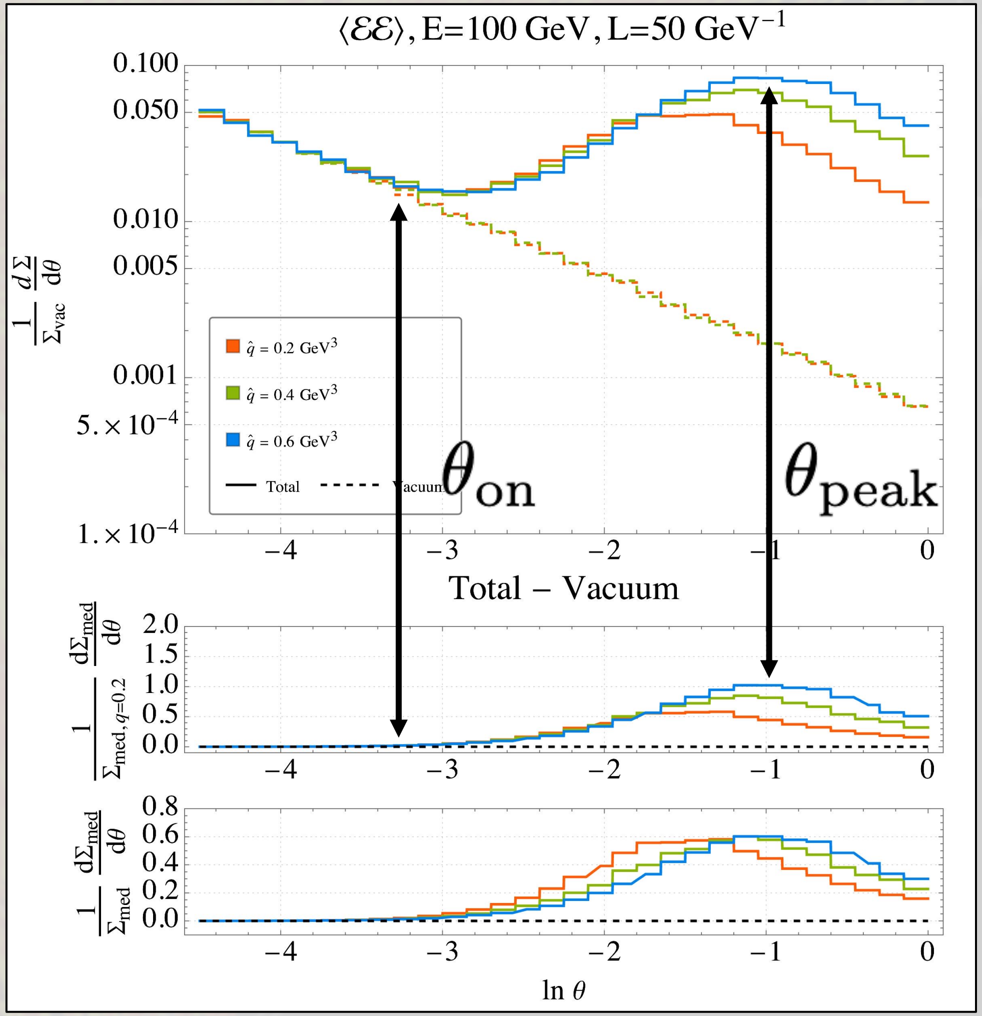




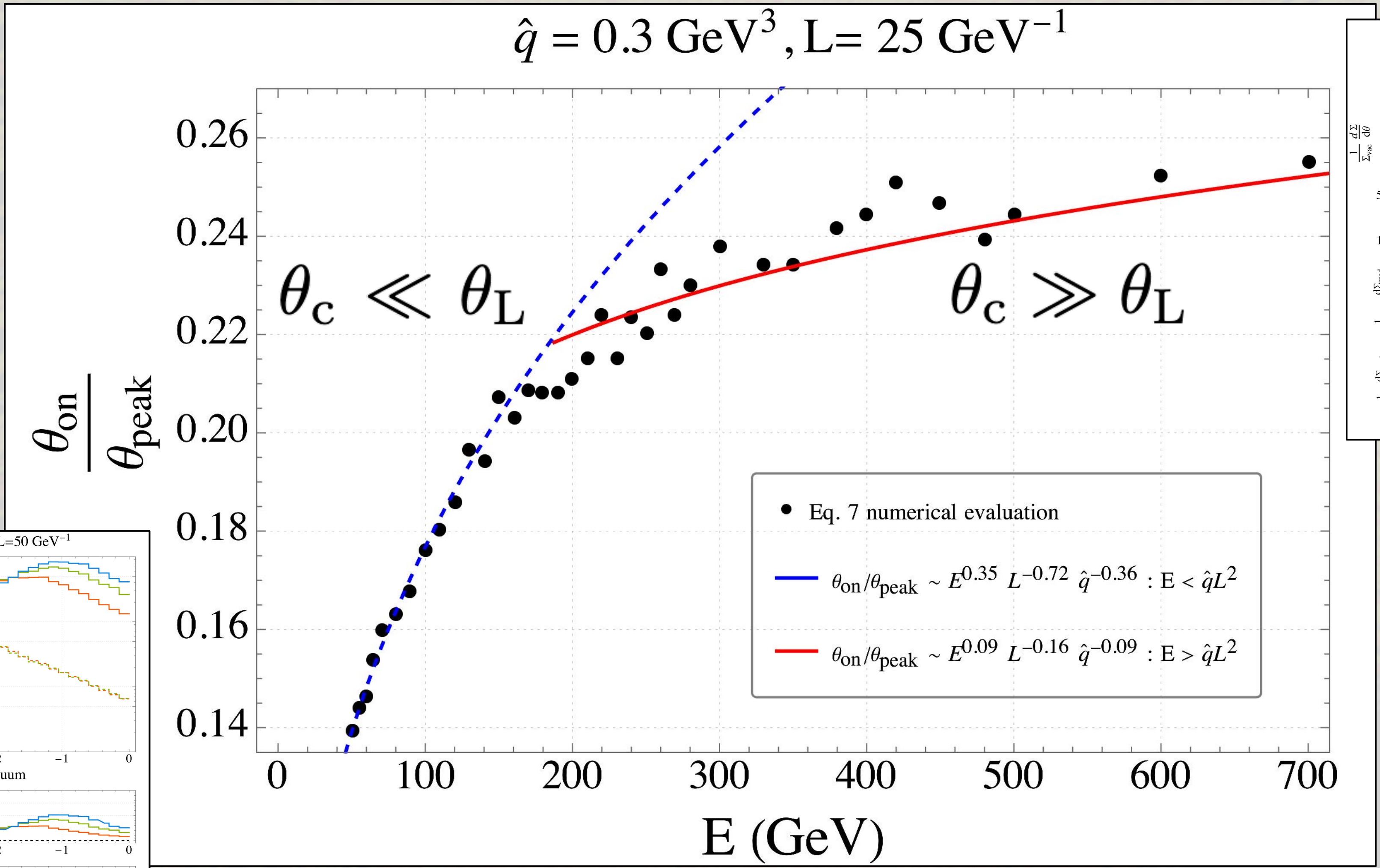
The observable numerically

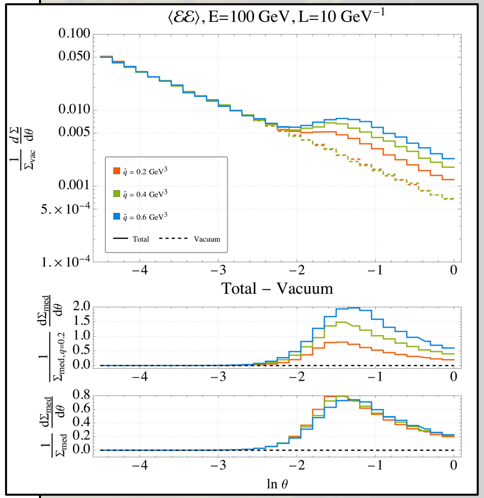
$\theta_c \gg \theta_L$ $\qquad L = 10\ \text{GeV}^{-1} \equiv 2\ \text{fm}$ $\qquad \theta_c \ll \theta_L$

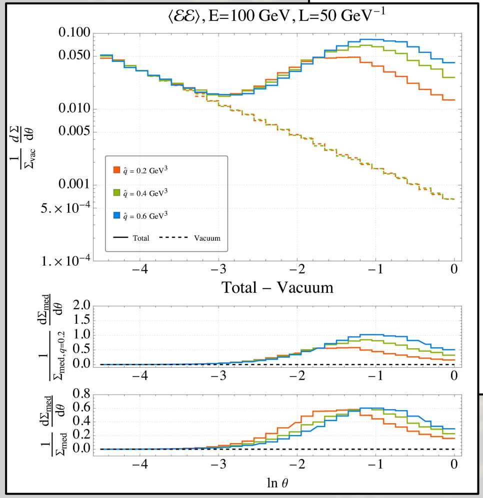




The observable numerically





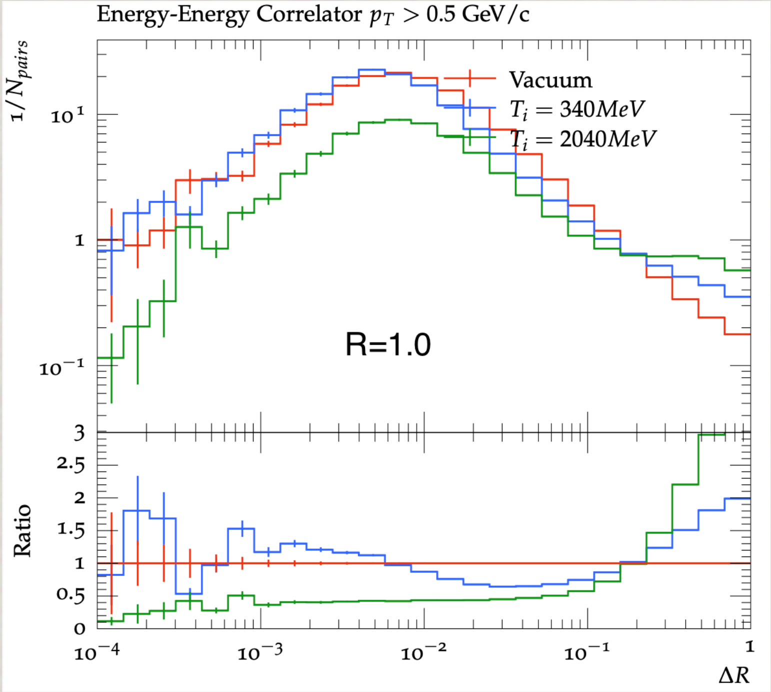


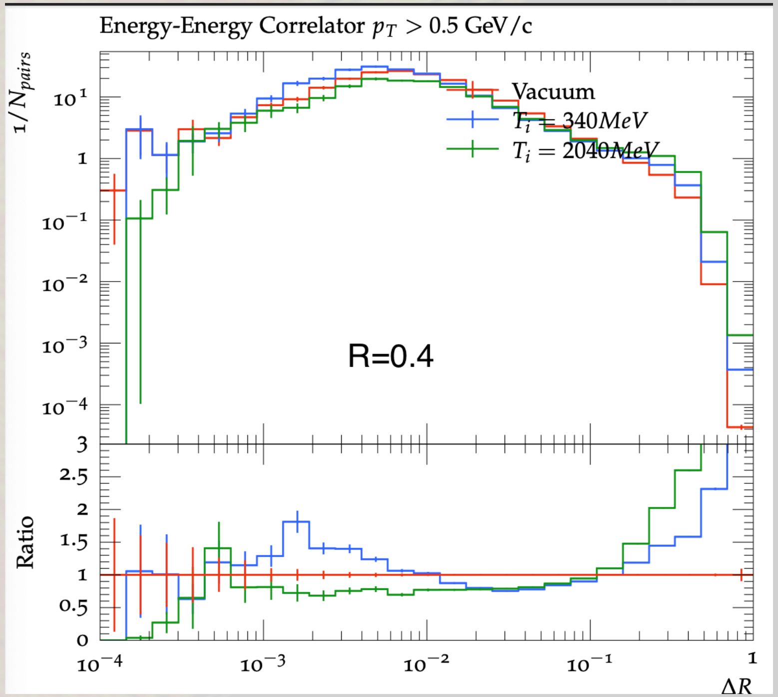
The observable numerically

An analysis in JEWEL is now also under way.

Early results indicate the main features of the curves are resilient against a hadron pt cut $p_t \gtrsim 2$ GeV.

Complimentarity between be measurement at sPHENIX and LHC.





Conclusions

Energy Correlators are cool and fun! 😁

- Our early results suggest properties of the QGP can be resolved by using energy correlators for jet substructure.
- Our initial analysis uses the BDMPS-Z model for the numerics. However, the basic features should be model independent, they are set by formation times and uncertainty relations. Could not be explained by changing q/g fraction.
- Correlators are naturally insentive to low scale physics – hadronisation, background amd soft corrections typically are sub-leading.
- We are optimistic for a future measurement at STAR and sPHENIX, and we are studying feasibility in JEWEL.

Part N/A: Supplemental Material

$$\mathcal{M}_{\gamma\to q\bar{q}} = \frac{e}{E}\mathrm{e}^{i\frac{\boldsymbol{p}_1^2}{2zE}L+i\frac{\boldsymbol{p}_2^2}{2(1-z)E}L}\int_0^\infty \mathrm{d}t\,\int_{\boldsymbol{k}_1,\boldsymbol{k}_2}\left[\mathcal{G}(\boldsymbol{p}_1,L;\boldsymbol{k}_1,t|zE)\,\bar{\mathcal{G}}(\boldsymbol{p}_2,L;\boldsymbol{k}_2,t|(1-z)E)\right]_{ij}$$
$$\times\,\gamma_{\lambda,s,s'}(z)\boldsymbol{k}\cdot\boldsymbol{\epsilon}_\lambda^*\,\mathcal{G}_0(\boldsymbol{k}_1+\boldsymbol{k}_2,t|E)$$

$$\mathcal{G}(\boldsymbol{p}_1,t_1;\boldsymbol{p}_0,t_0) = \int_{\boldsymbol{x}_1,\boldsymbol{x}_2}\mathrm{e}^{-i\boldsymbol{p}_1\cdot\boldsymbol{x}_1+i\boldsymbol{p}_0\cdot\boldsymbol{x}_0}\mathcal{G}(\vec{x}_1,\vec{x}_0)$$

$$\mathcal{G}(\vec{x}_1,\vec{x}_0) = \int_{\boldsymbol{r}(t_0)=\boldsymbol{x}_0}^{\boldsymbol{r}(t_1)=\boldsymbol{x}_1}\mathcal{D}\boldsymbol{r}\,\exp\left[i\frac{E}{2}\int_{t_0}^{t_1}\mathrm{d}s\,\dot{\boldsymbol{r}}^2\right]V(t_1,t_0;[\boldsymbol{r}])$$

$$V(t_1,t_0;[\boldsymbol{r}]) = \mathcal{P}\exp\left[ig\int_{t_0}^{t_1}\mathrm{d}t\,\mathbf{t}^a A^{-,a}(t,\boldsymbol{r}(t))\right]$$

$$\frac{\mathrm{d}N^{\mathrm{med}}}{\mathrm{d}z\mathrm{d}\boldsymbol{p}^2} = \frac{1}{4(2\pi)^2\,z(1-z)}\langle|\mathcal{M}_{\gamma\to q\bar{q}}|^2\rangle = \frac{1}{4(2\pi)^2\,z(1-z)}\langle\left|\mathcal{M}^{\mathrm{in}}_{\gamma\to q\bar{q}}+\mathcal{M}^{\mathrm{out}}_{\gamma\to q\bar{q}}\right|^2\rangle$$

Part N/A: Supplemental Material

$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta\mathrm{d}z} = \frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta\mathrm{d}z}(1 + F_{\mathrm{med}}(z,\theta,\hat{q},L))$$

$$F_{\mathrm{med}} = 2\int_0^L \frac{\mathrm{d}t_1}{t_\mathrm{f}}\left[\int_{t_1}^L \frac{\mathrm{d}t_2}{t_\mathrm{f}}\cos\left(\frac{t_2-t_1}{t_\mathrm{f}}\right)\mathcal{C}^{(4)}(L,t_2)\mathcal{C}^{(3)}(t_2,t_1) - \sin\left(\frac{L-t_1}{t_\mathrm{f}}\right)\mathcal{C}^{(3)}(L,t_1)\right]$$

$$\mathcal{C}_{gq}^{(3)}(t_2,t_1) = \frac{1}{N_c^2-1}\left\langle \mathrm{tr}[V_2^\dagger V_1]\,\mathrm{tr}[V_0^\dagger V_2] - \frac{1}{N_c}\,\mathrm{tr}[V_0^\dagger V_1]\right\rangle .$$

$$\begin{aligned}\mathcal{C}_{gq}^{(3)}(t_2,t_1) &= \mathrm{e}^{-\frac{1}{2}\int_{t_1}^{t_2}\mathrm{d}s\,n(s)[N_c(\sigma_{02}+\sigma_{12})-\frac{1}{N_c}\sigma_{01}]}\\ &= \mathrm{e}^{-\frac{1}{12}\hat{q}(t_2-t_1)^3\theta^2\left(1+z^2+\frac{2z}{N_c^2-1}\right)} .\end{aligned}$$

$$\mathcal{C}_{gq}^{(4)}(L,t_2) = \frac{1}{N_c^2-1}\left\langle \mathrm{tr}[V_{\bar{1}}^\dagger V_1 V_2^\dagger V_{\bar{2}}]\,\mathrm{tr}[V_{\bar{2}}^\dagger V_2] - \frac{1}{N_c}\,\mathrm{tr}[V_{\bar{1}}^\dagger V_1]\right\rangle ,$$

$$\begin{aligned}&\frac{1}{N_c^2}\langle \mathrm{tr}[V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger]\,\mathrm{tr}[V_2 V_{\bar{2}}^\dagger]\rangle \simeq \mathrm{e}^{-\frac{1}{4}\hat{q}\theta^2(t-t_2)(t_2-t_1)^2(1-2z+3z^2)}\\ &\times\left(1-\frac{1}{2}\hat{q}\theta^2 z(1-z)(t_2-t_1)^2\int_{t_2}^{t}\mathrm{d}s\,\mathrm{e}^{-\frac{1}{12}\hat{q}\theta^2\left[(s-t_2)^2(2s-3t_1+t_2)+6z(1-z)(s-t_2)(t_2-t_1)^2\right]}\right)\end{aligned}$$