Recent advances in the calculation of two-point energy correlators in heavy ion collisions

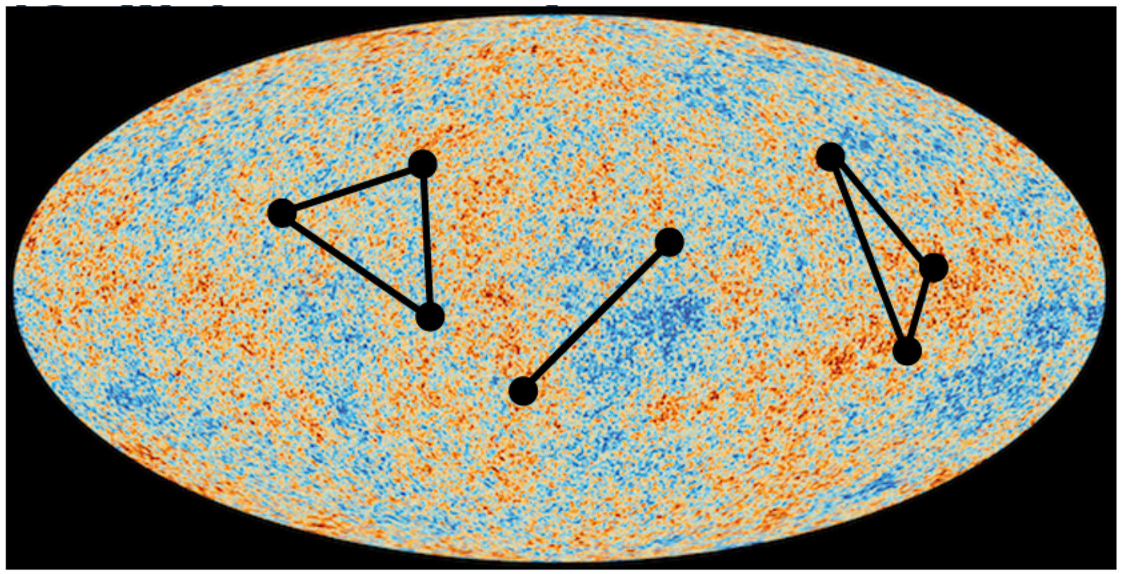
Fabio Dominguez
IGFAE, Universidade de Santiago de Compostela

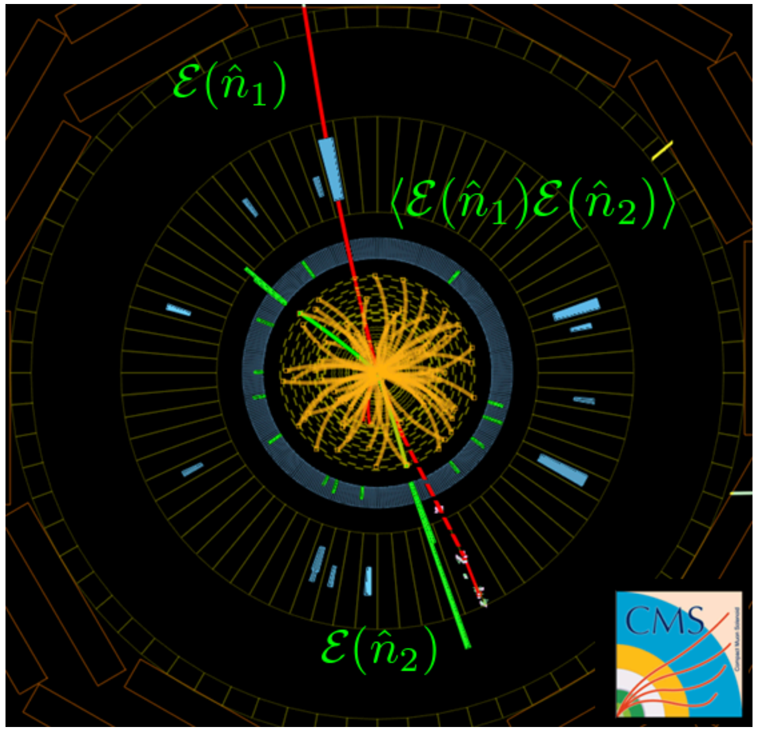
New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions,
ECT*, Trento, Italy,
February13th, 2024.

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2307.15110

IGFAE
Instituto Galego de Física de Altas Enerxías
USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
XUNTA DE GALICIA

Energy flux operators

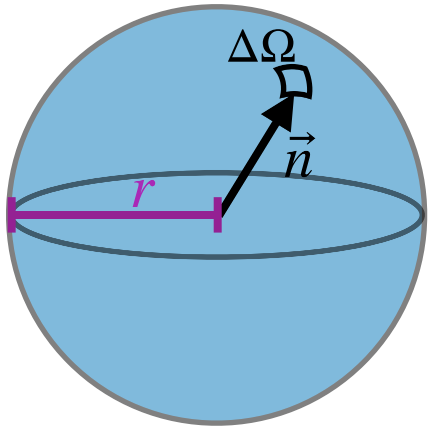




- Correlations of asymptotic energy flux provide valuable information about the underlying theory

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

$$\mathcal{E}(\vec{n})|X\rangle = \sum_a E_a \delta^{(2)}(\Omega_{\vec{p}_a} - \Omega_{\vec{n}})\, |X\rangle$$



Energy correlators

- 2-point function

$$\frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i - \vec{n}_1)\delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

Energy correlators

- 2-point function

Inclusive cross section to produce two particles

$$\frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i - \vec{n}_1)\delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

Energy correlators

- 2-point function

$$\frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i - \vec{n}_1)\delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

Inclusive cross section to produce two particles

Hard scale of the process

Energy correlators

- 2-point function

Inclusive cross section to produce two particles

$$\frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i - \vec{n}_1)\delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

Hard scale of the process

- Due to rotational symmetry, the only relevant variable is the opening angle

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

Energy correlators

- 2-point function

Inclusive cross section to produce two particles

$$\frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i - \vec{n}_1)\delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

Hard scale of the process

- Due to rotational symmetry, the only relevant variable is the opening angle

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

- Can be expressed as a weighted average of the double-inclusive cross-section

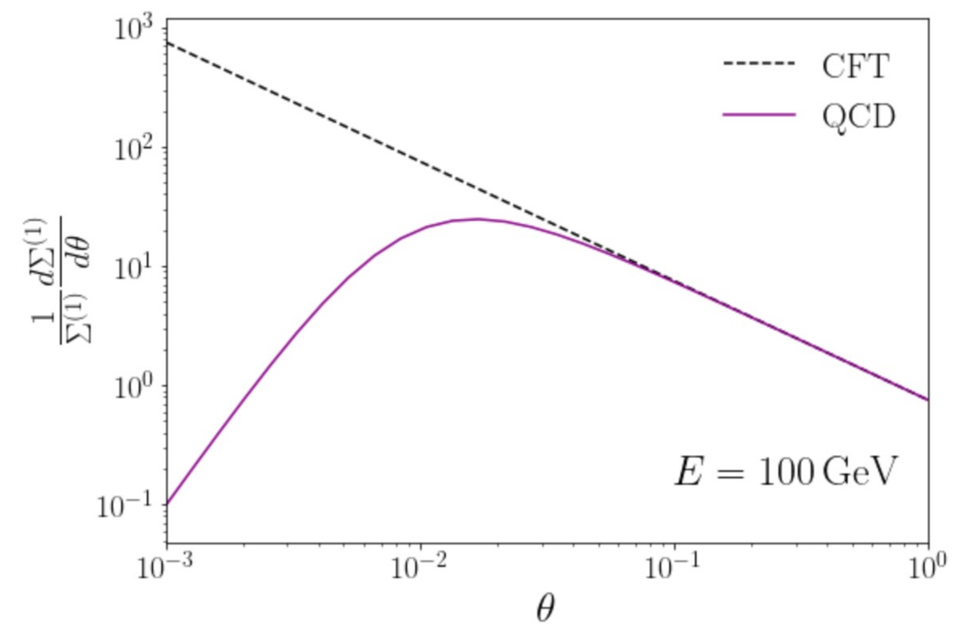
$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma}\sum_{i,j}\int dE_{i,j}\,\frac{d\sigma}{d\theta dE_i dE_j}\,\frac{E_i^n E_j^n}{Q^{2n}}$$

Energy correlators in vacuum

P. T. Komiske, I. Moult, J. Thaler, H. X. Zhu 2201.07800

- In the perturbative region it behaves as a power law

- Confinement scale brakes power law behavior at angles below Λ_{QCD}/E
  - Small angles correspond to large times, where hadronization is dominant
  - Larger angles correspond to early times

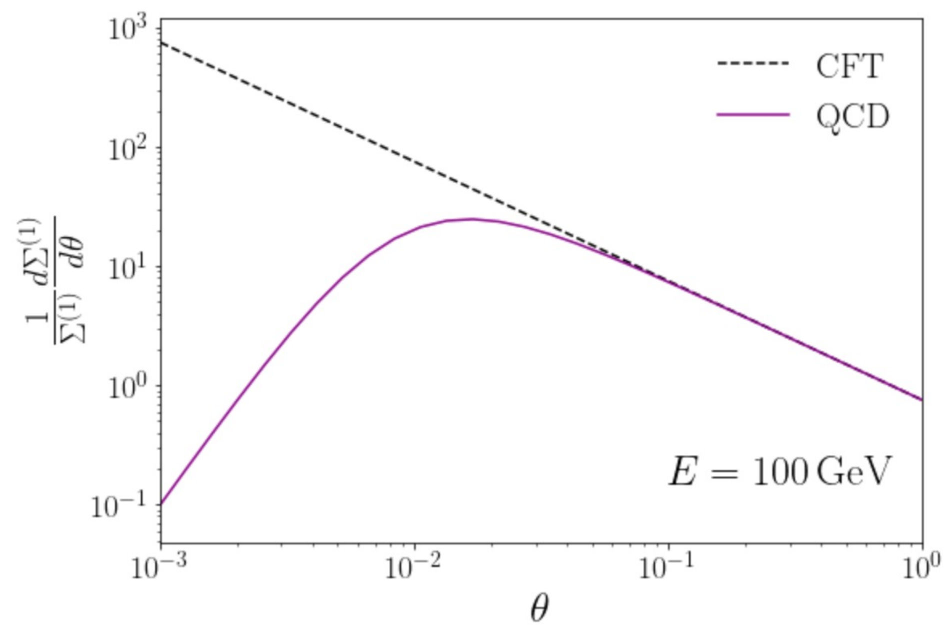


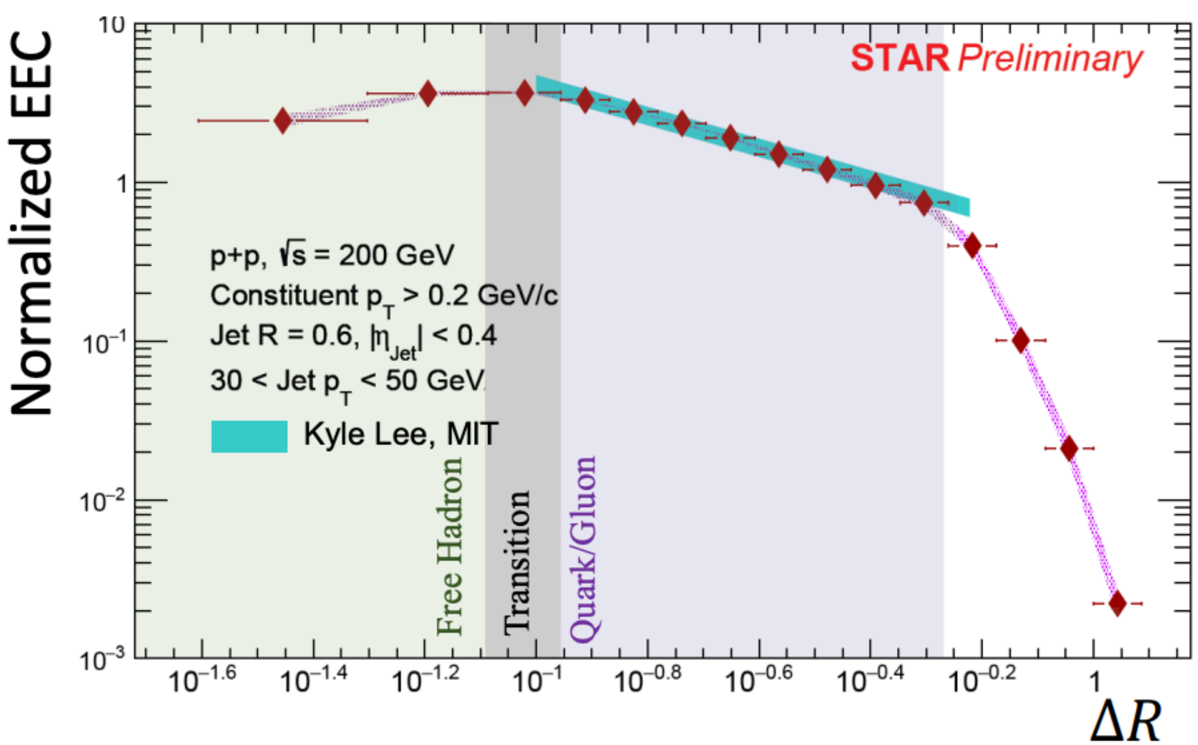
Energy correlators in vacuum

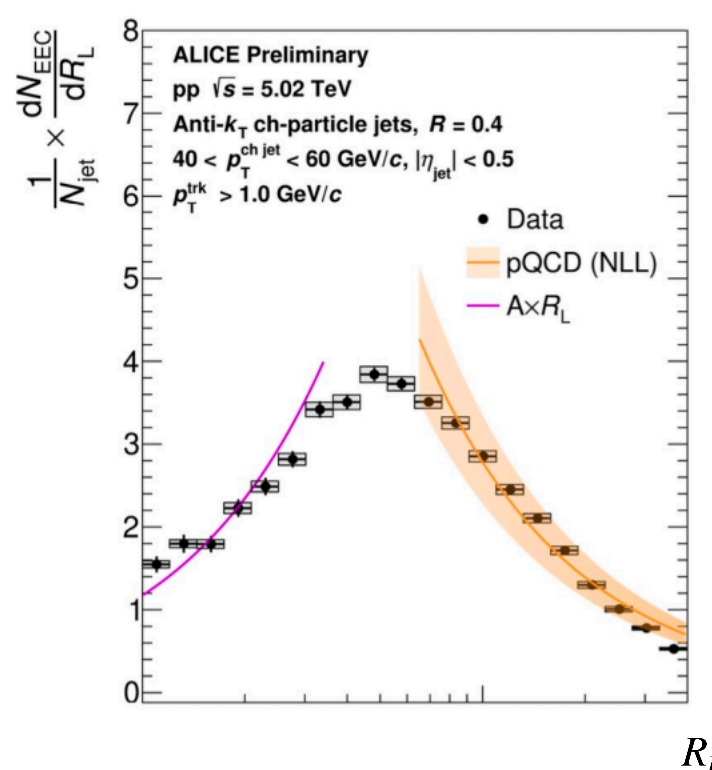
P. T. Komiske, I. Moult, J. Thaler, H. X. Zhu 2201.07800

- In the perturbative region it behaves as a power law

- Confinement scale brakes power law behavior at angles below Λ_{QCD}/E
  - Small angles correspond to large times, where hadronization is dominant
  - Larger angles correspond to early times







Energy correlators in HIC

General advantages:

- Vacuum baseline is understood to a high degree of accuracy in the perturbative regime
- Low sensitivity to soft physics
- Does not require detector information at the particle level
- Alternative to de-clustering observables

Energy correlators in HIC

General advantages:

- Vacuum baseline is understood to a high degree of accuracy in the perturbative regime
- Low sensitivity to soft physics
- Does not require detector information at the particle level
- Alternative to de-clustering observables

From a theorist perspective:

- Insensitive to large logs from soft divergences
- Collinear resummation needed, but medium contributions do not have collinear divergences
- Calculable in pQCD
- Distinct physical phenomena appears at different angular scales

Energy correlators in HIC

General advantages:

- Vacuum baseline is understood to a high degree of accuracy in the perturbative regime
- Low sensitivity to soft physics
- Does not require detector information at the particle level
- Alternative to de-clustering observables

From a theorist perspective:

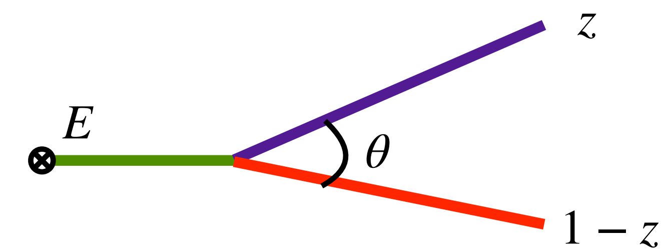
- Insensitive to large logs from soft divergences
- Collinear resummation needed, but medium contributions do not have collinear divergences
- Calculable in pQCD
- Distinct physical phenomena appears at different angular scales

Potential to disentangle effects from different dynamics

Proof of principle of EEC in HIC

- Quark-initiated jet with known initial energy E (γ/Z-jet)
  - In this case energy loss effects are subleading and there is no need for resummation of soft emissions

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left(\frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} + \frac{d\sigma_{qg}^{\text{med}}}{d\theta dz} \right) z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

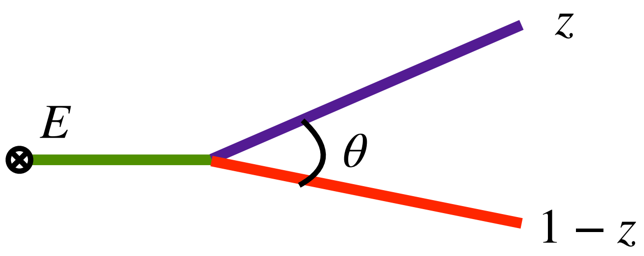


Proof of principle of EEC in HIC

- Quark-initiated jet with known initial energy E (γ/Z-jet)
  - In this case energy loss effects are subleading and there is no need for resummation of soft emissions

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left(\frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} + \frac{d\sigma_{qg}^{\text{med}}}{d\theta dz} \right) z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

Includes collinear resummation



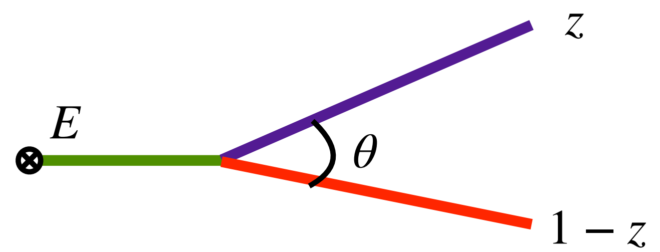
Proof of principle of EEC in HIC

- Quark-initiated jet with known initial energy E (γ/Z-jet)
  - In this case energy loss effects are subleading and there is no need for resummation of soft emissions

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left(\frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} + \frac{d\sigma_{qg}^{\text{med}}}{d\theta dz} \right) z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

Includes collinear resummation (vac term)

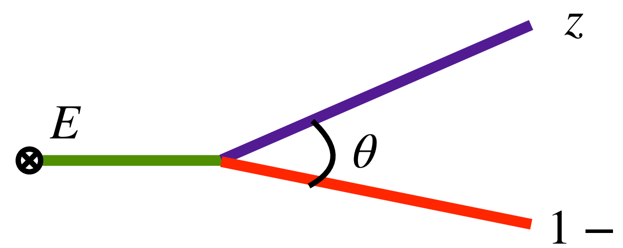
Leading order in the number of emissions (med term)



Proof of principle of EEC in HIC

- Quark-initiated jet with known initial energy E (γ/Z-jet)
    - In this case energy loss effects are subleading and there is no need for resummation of soft emissions

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma_{qg}} \int dz \left(\frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} + \frac{d\sigma_{qg}^{\text{med}}}{d\theta dz} \right) z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$



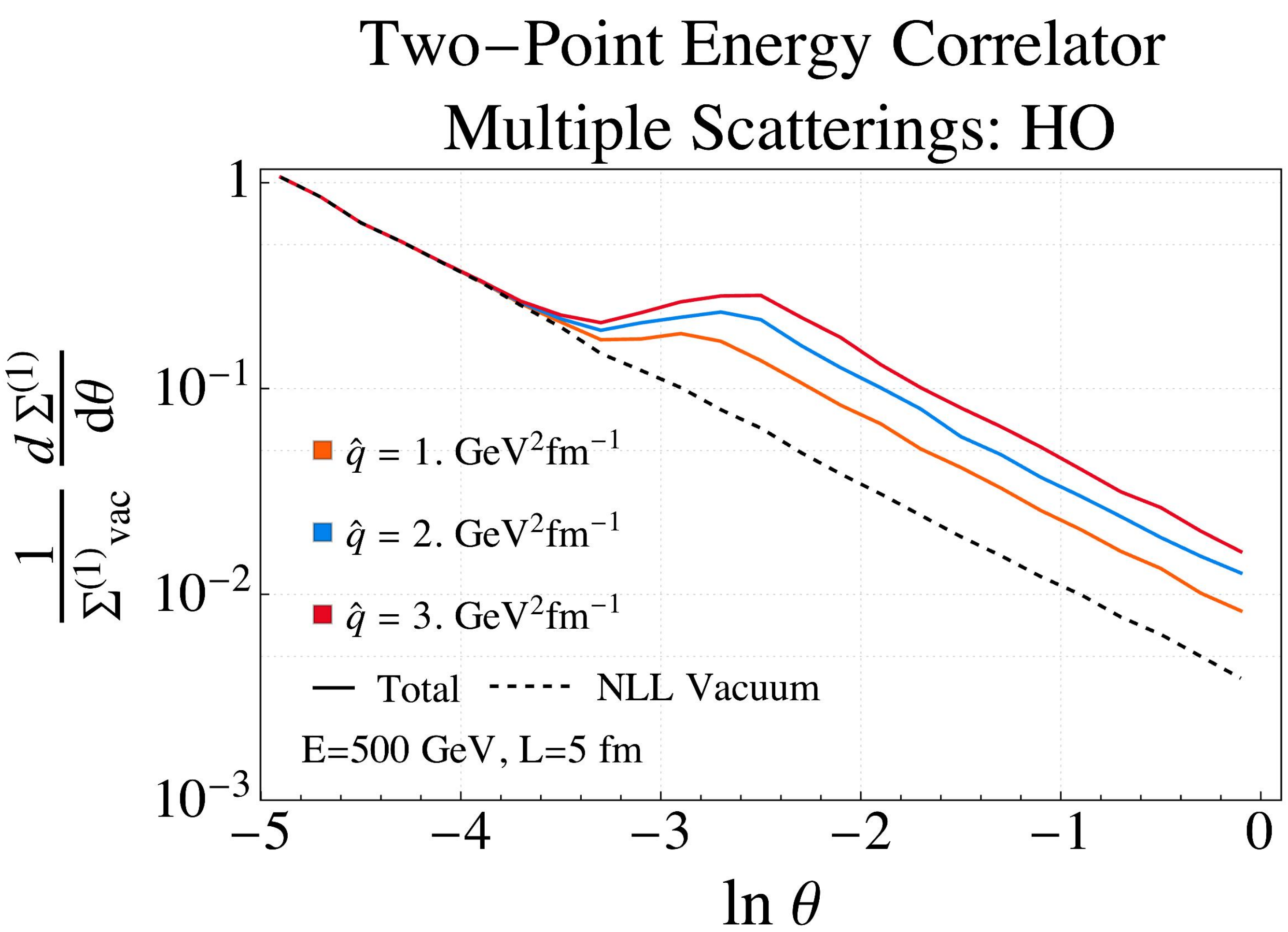
Includes collinear resummation

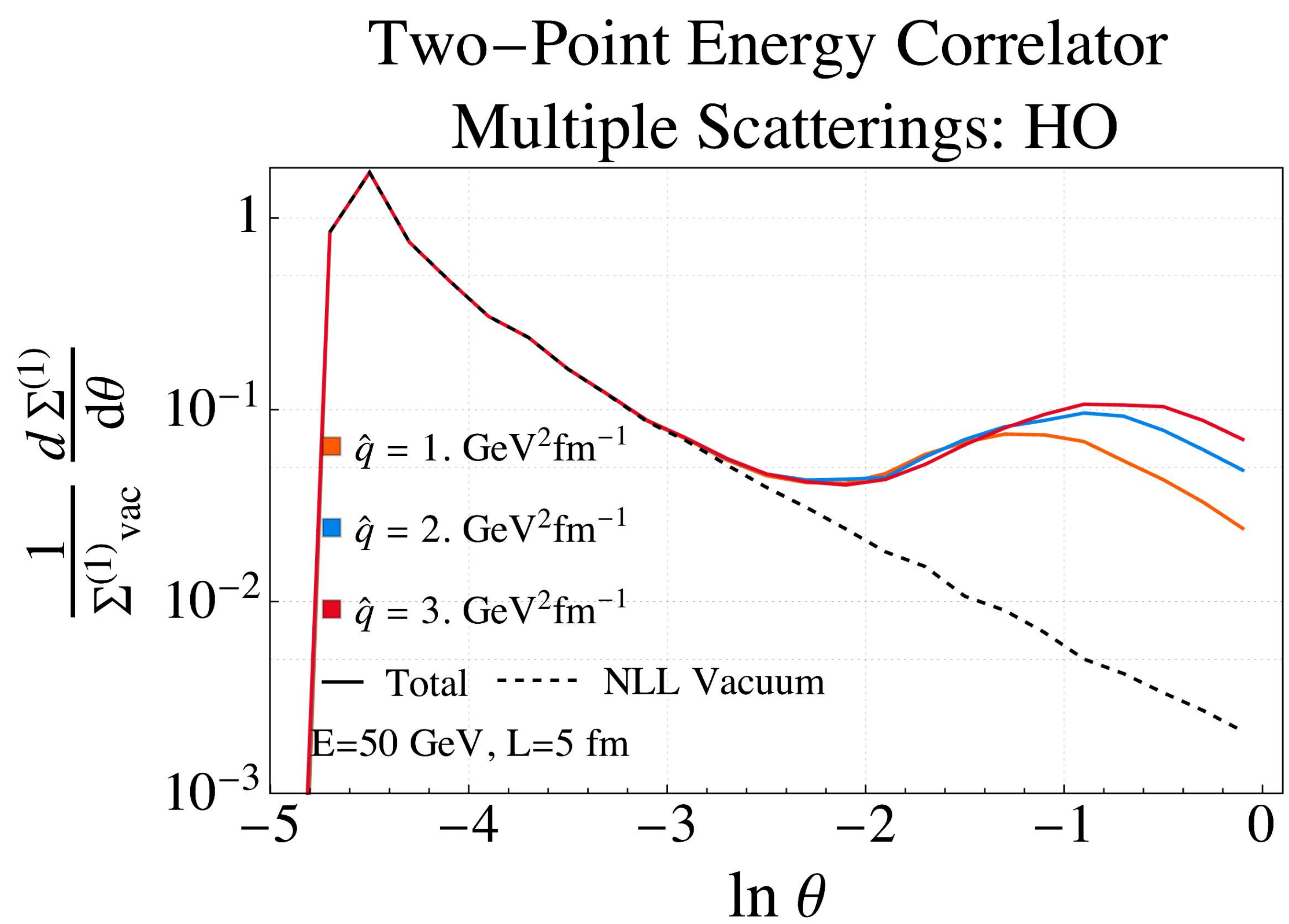
Leading order in the number of emissions

- Medium-splittings calculated on a brick
- Soft approximation ($z \to 0$, keeping zE finite) not suitable
- Two available approximations:
    - Semi-hard approximation: resums multiple scatterings, ignores momentum broadening in an eikonal approach FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653 Isaksen, Tywoniuk 2107.02542
    - Opacity expansion (GLV): possible unitarity issues, no eikonal assumptions involved

Sievert, Vitev 1807.03799

Results in the semi-hard approximation

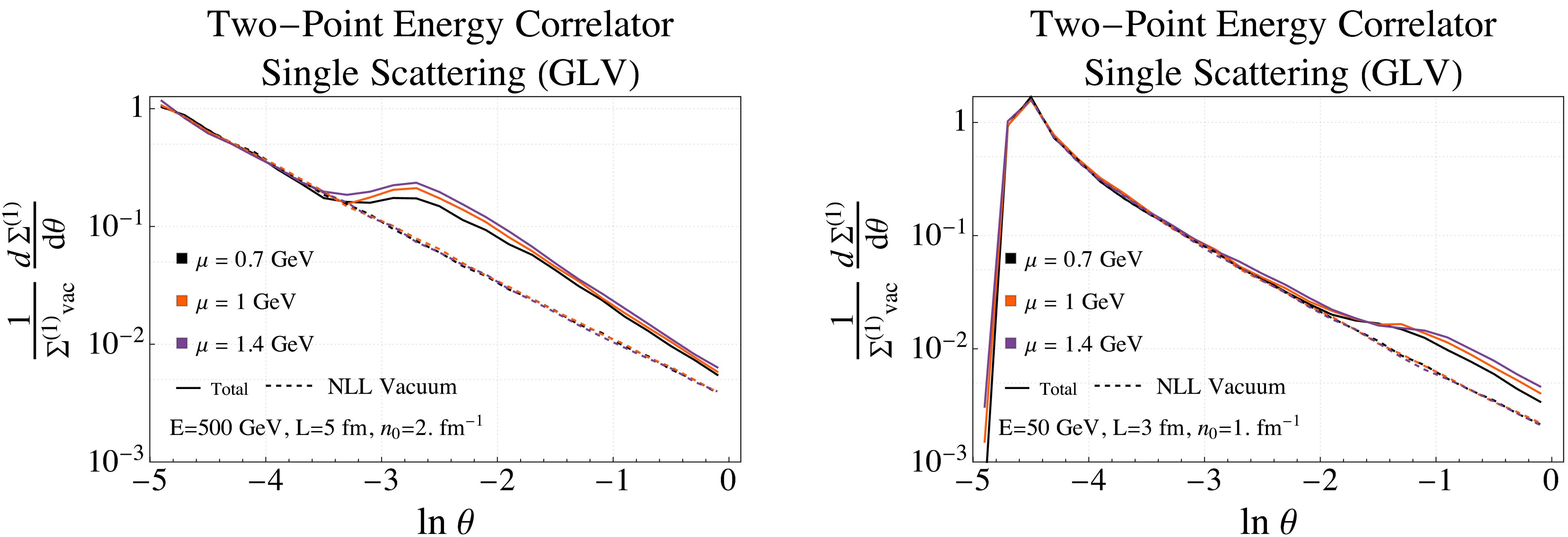




- No modification at small angles
- Transition towards medium-induced enhancement at larger angles
- Varying $\hat{q}$ has different effects depending on medium resolution

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413

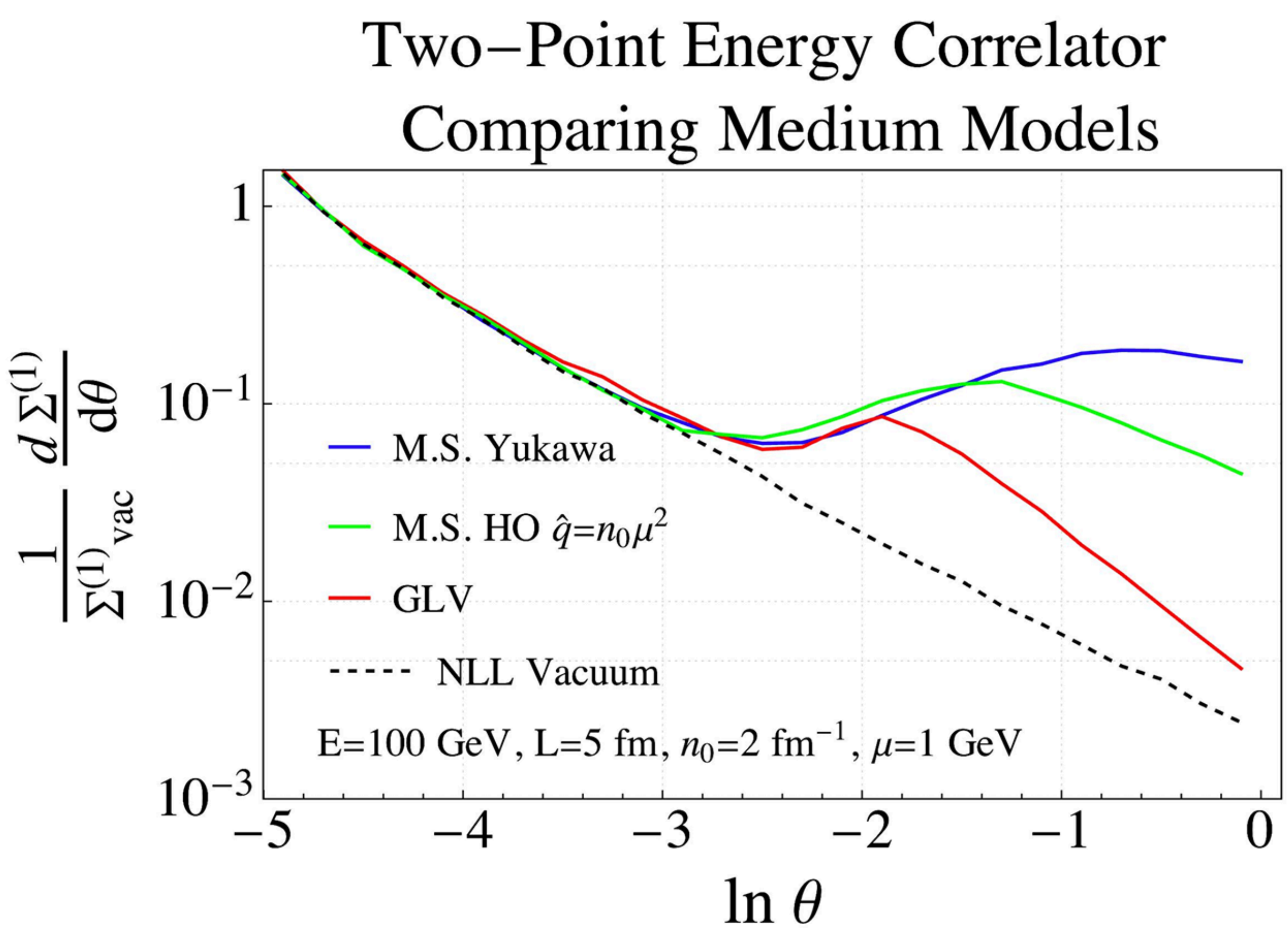
Results for first order in opacity



- Similar qualitative features compared to the semi-hard approach
- Transition towards medium-enhancement not so well defined
- Enhancement at large angles has a much smaller amplitude

C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413

Model comparison



- Small angle behavior and transition towards medium-enhancement common to all cases shown

- No information can be extracted from amplitude of enhancement at large angles

Moving away from the simplest scenario

- Improve the calculation for in-medium splittings
- Include an evolving medium
  - Brick calculations allow us to build some intuition
  - Any meaningful comparison to data must account for medium evolution effects
- Consider energy-loss effects, which will be important for inclusive jet measurements

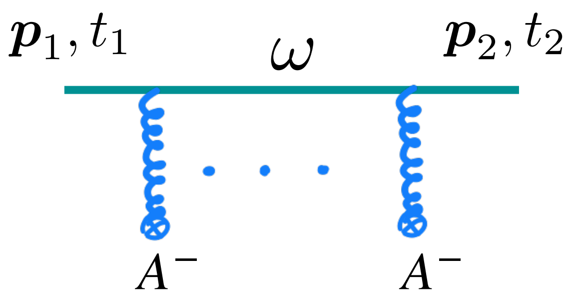
Calculation of in-medium splittings

- Collinear (high-energy) limit: All particles have a large longitudinal momentum compared to their transverse momenta (small angles, DGLAP limit)

- Decoupling of transverse and longitudinal dynamics: Effects coming from the transverse (with respect to the direction of the jet) structure of the medium are suppressed by powers of the energy

See talks by Joseph Bahder and Xoán Mayo on Wed morning for advances towards relaxing this approximation

- Medium interactions are resummed through in-medium propagators



$$= \mathcal{G}_R(\boldsymbol{p}_2, t_2; \boldsymbol{p}_1, t_1; \omega)$$

- Cross section are expressed in terms of medium averages of products of propagators

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653 Isaksen, Tywoniuk 2107.02542

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653   Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653 Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

$$\mathcal{G}_R(t_2, \boldsymbol{x}_2; t_1, \boldsymbol{x}_1; \omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r} \exp\left\{ \frac{i\omega}{2} \int_{t_1}^{t_2} d\xi \, \dot{\boldsymbol{r}}^2(\xi) \right\} \underbrace{\mathrm{P} \exp\left\{ ig \int_{t_1}^{t_2} d\xi \, A_R^-(\xi, \boldsymbol{r}(\xi)) \right\}}_{V_R(t_2, t_1; [\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2, \boldsymbol{x}_2; t_1, \boldsymbol{x}_1; \omega) \, V_R(t_2, t_1; [\boldsymbol{x}_{\mathrm{cl}}])$$

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653   Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

$$\mathcal{G}_R(t_2, \boldsymbol{x}_2; t_1, \boldsymbol{x}_1; \omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r} \exp\left\{ \frac{i\omega}{2} \int_{t_1}^{t_2} d\xi \, \dot{\boldsymbol{r}}^2(\xi) \right\} \underbrace{\mathrm{P}\exp\left\{ ig \int_{t_1}^{t_2} d\xi \; A_R^-(\xi, \boldsymbol{r}(\xi)) \right\}}_{V_R(t_2, t_1; [\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2, \boldsymbol{x}_2; t_1, \boldsymbol{x}_1; \omega) \, V_R(t_2, t_1; [\boldsymbol{x}_{\mathrm{cl}}])$$

- Neglect additional transverse momentum broadening

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653 Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\, \exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\, \dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\, A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\mathrm{cl}}])$$

- Neglect additional transverse momentum broadening

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653 Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\, \exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\, \dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\, A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\mathrm{cl}}])$$

- Neglect additional transverse momentum broadening

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

- The harmonic approximation (HO) is usually employed when using this approach but it is not necessary

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653 Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\,\exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\,\dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\, A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\rm cl}])$$

- Neglect additional transverse momentum broadening

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

- The harmonic approximation (HO) is usually employed when using this approach but it is not necessary

- Angular and time scales are easily identifiable from the analytic formulas

Semi-hard approximation

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653   Isaksen, Tywoniuk 2107.02542

- Take in-medium propagators in the extreme eikonal limit where they can be written as a Wilson line in a straight trajectory in coordinate space

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)=\int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2}\mathcal{D}\boldsymbol{r}\,\exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2}d\xi\,\dot{\boldsymbol{r}}^2(\xi)\right\}\underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2}d\xi\,A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to\mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\,V_R(t_2,t_1;[\boldsymbol{x}_{\rm cl}])$$

- Neglect additional transverse momentum broadening

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega)\to e^{-i\frac{\boldsymbol{p}_2^2}{2\omega}(t_2-t_1)}\int_{\boldsymbol{x}}e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\,V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to(2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\,e^{-i\frac{\boldsymbol{p}_2^2}{2\omega}(t_2-t_1)}V_R(t_2,t_1;[\boldsymbol{n}t])$$

- The harmonic approximation (HO) is usually employed when using this approach but it is not necessary

- Angular and time scales are easily identifiable from the analytic formulas

- Numerical evaluations are straightforward in the large-N_c limit

Relaxing approximations

Relaxing approximations

- Corrections due to momentum broadening can be easily included

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- In the large-N_c limit, eikonal approximation can also be relaxed, with increased complexity in the formulas and higher computational cost for numerical evaluations

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- In the large-N_c limit, eikonal approximation can also be relaxed, with increased complexity in the formulas and higher computational cost for numerical evaluations

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\, \exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\; \dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\; A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\rm cl}])$$

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)}\, V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- In the large-N_c limit, eikonal approximation can also be relaxed, with increased complexity in the formulas and higher computational cost for numerical evaluations

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\, \exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\, \dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\, A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\rm cl}])$$

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- In the large-N_c limit, eikonal approximation can also be relaxed, with increased complexity in the formulas and higher computational cost for numerical evaluations

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\,\exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\; \dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\; A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\mathrm{cl}}])$$

Blaizot, FD, Iancu, Mehtar-Tani 1209.4585

Apolinario, Armesto, Milhano, Salgado 1407.0599

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} \int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}} V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- In the large-N_c limit, eikonal approximation can also be relaxed, with increased complexity in the formulas and higher computational cost for numerical evaluations

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r} \exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2} d\xi\, \dot{\boldsymbol{r}}^2(\xi)\right\} \underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2} d\xi\, A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\, V_R(t_2,t_1;[\boldsymbol{x}_{\mathrm{cl}}])$$

Blaizot, FD, Iancu, Mehtar-Tani 1209.4585

Apolinario, Armesto, Milhano, Salgado 1407.0599

- Going beyond the large-N_c limit requires a much more complex setup where a system of coupled differential equations must be numerically solved

Isaksen, Tywoniuk 2303.12119

Relaxing approximations

- Corrections due to momentum broadening can be easily included

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)}\int_{\boldsymbol{x}} e^{-i(\boldsymbol{p}_1-\boldsymbol{p}_0)\cdot\boldsymbol{x}}\, V_R(t_2,t_1;[\boldsymbol{x}+\boldsymbol{n}t])$$

$$\to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)}V_R(t_2,t_1;[\boldsymbol{n}t])$$

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- In the large-N_c limit, eikonal approximation can also be relaxed, with increased complexity in the formulas and higher computational cost for numerical evaluations

$$\mathcal{G}_R(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2}\mathcal{D}\boldsymbol{r}\exp\left\{\frac{i\omega}{2}\int_{t_1}^{t_2}d\xi\,\dot{\boldsymbol{r}}^2(\xi)\right\}\underbrace{\mathrm{P}\exp\left\{ig\int_{t_1}^{t_2}d\xi\,A_R^-(\xi,\boldsymbol{r}(\xi))\right\}}_{V_R(t_2,t_1;[\boldsymbol{r}])}$$

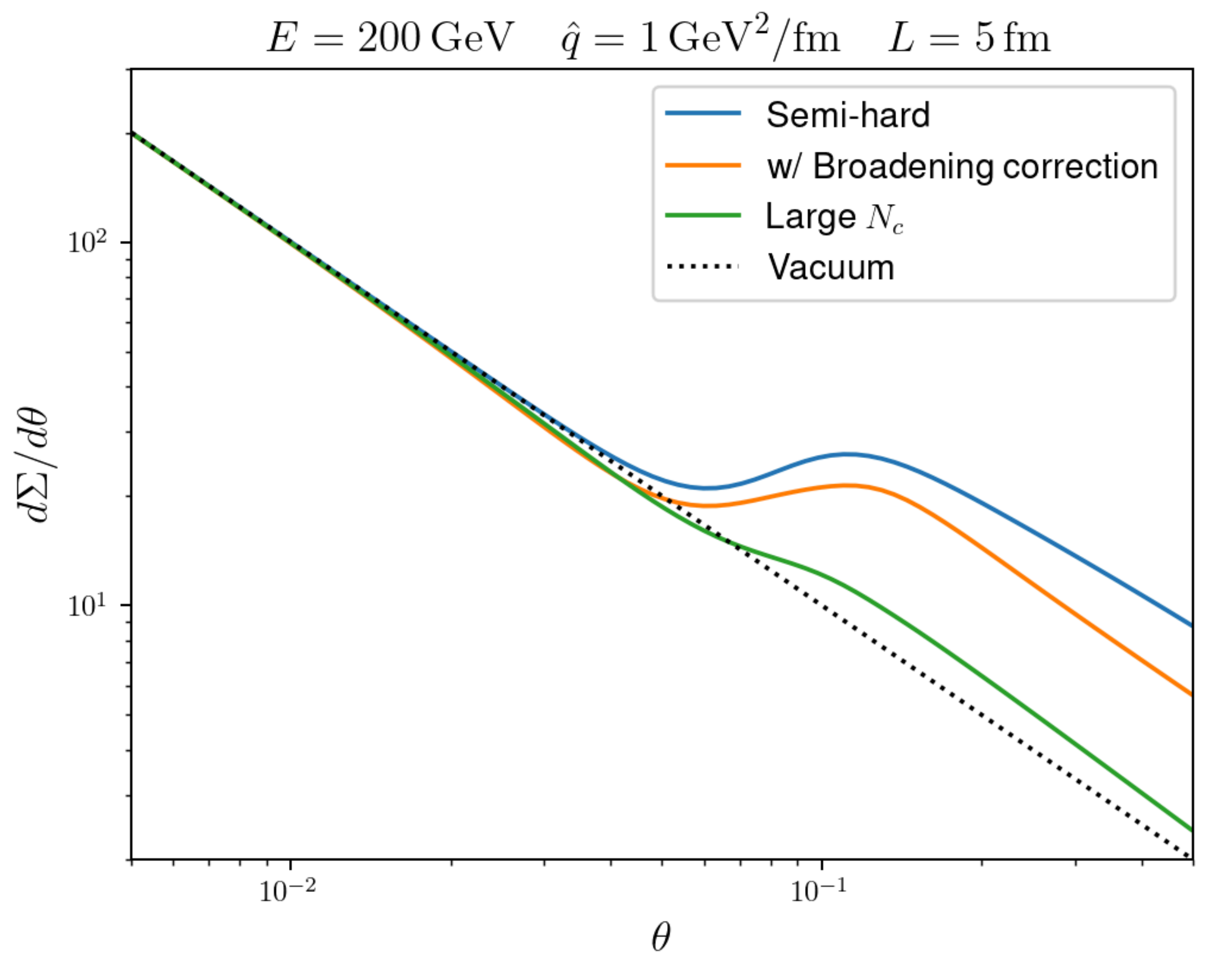
$$\to \mathcal{G}_{0,R}(t_2,\boldsymbol{x}_2;t_1,\boldsymbol{x}_1;\omega)\,V_R(t_2,t_1;[\boldsymbol{x}_{\rm cl}])$$

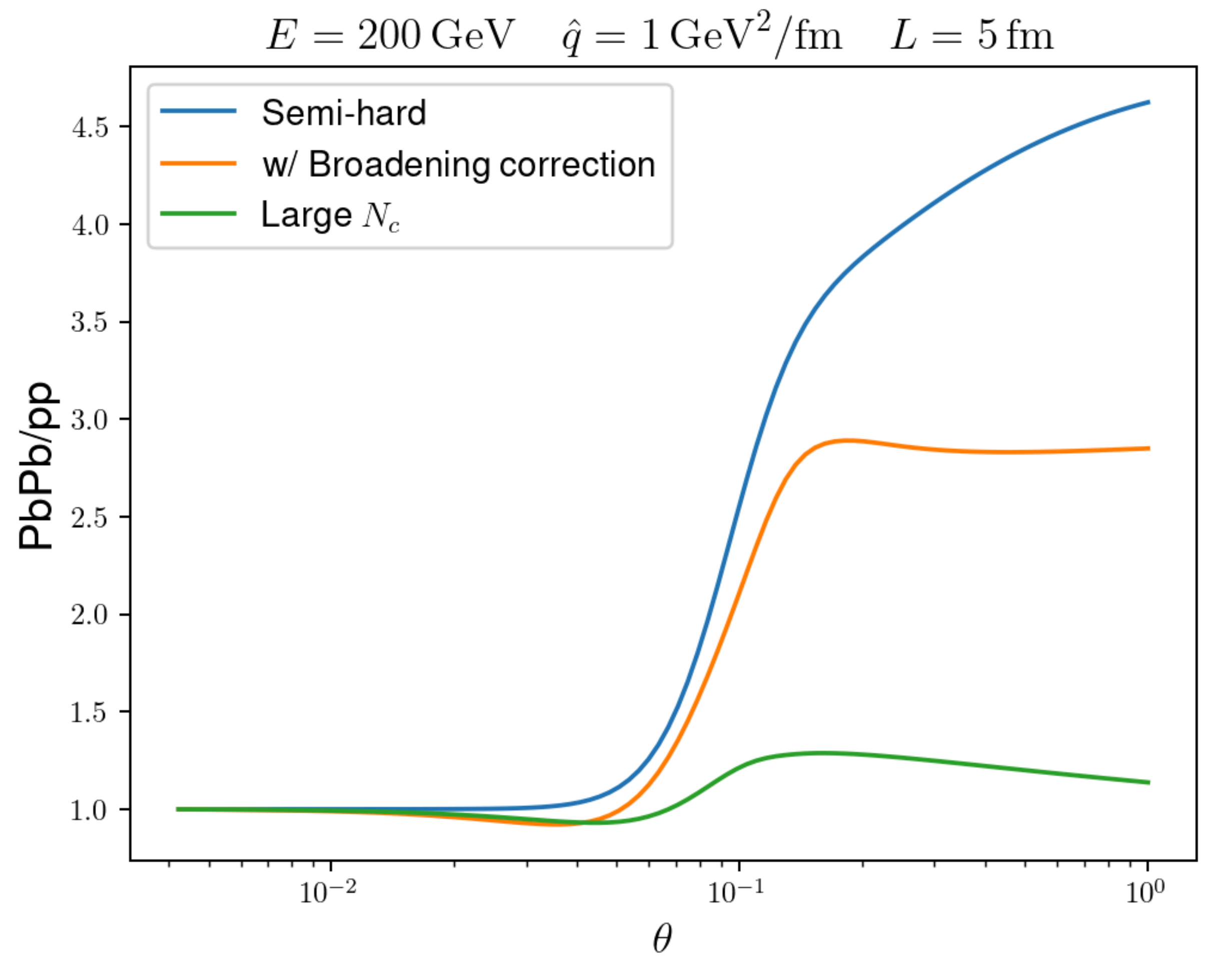
Blaizot, FD, Iancu, Mehtar-Tani 1209.4585
Apolinario, Armesto, Milhano, Salgado 1407.0599

- Goin ... tup
whe ... ally
solve ... 03.12119

Done only for $\gamma \to q\bar{q}$ and the code for this solution has stability problems beyond a restricted area in parameter space and will not be used for this talk

Results for a brick with the harmonic approximation



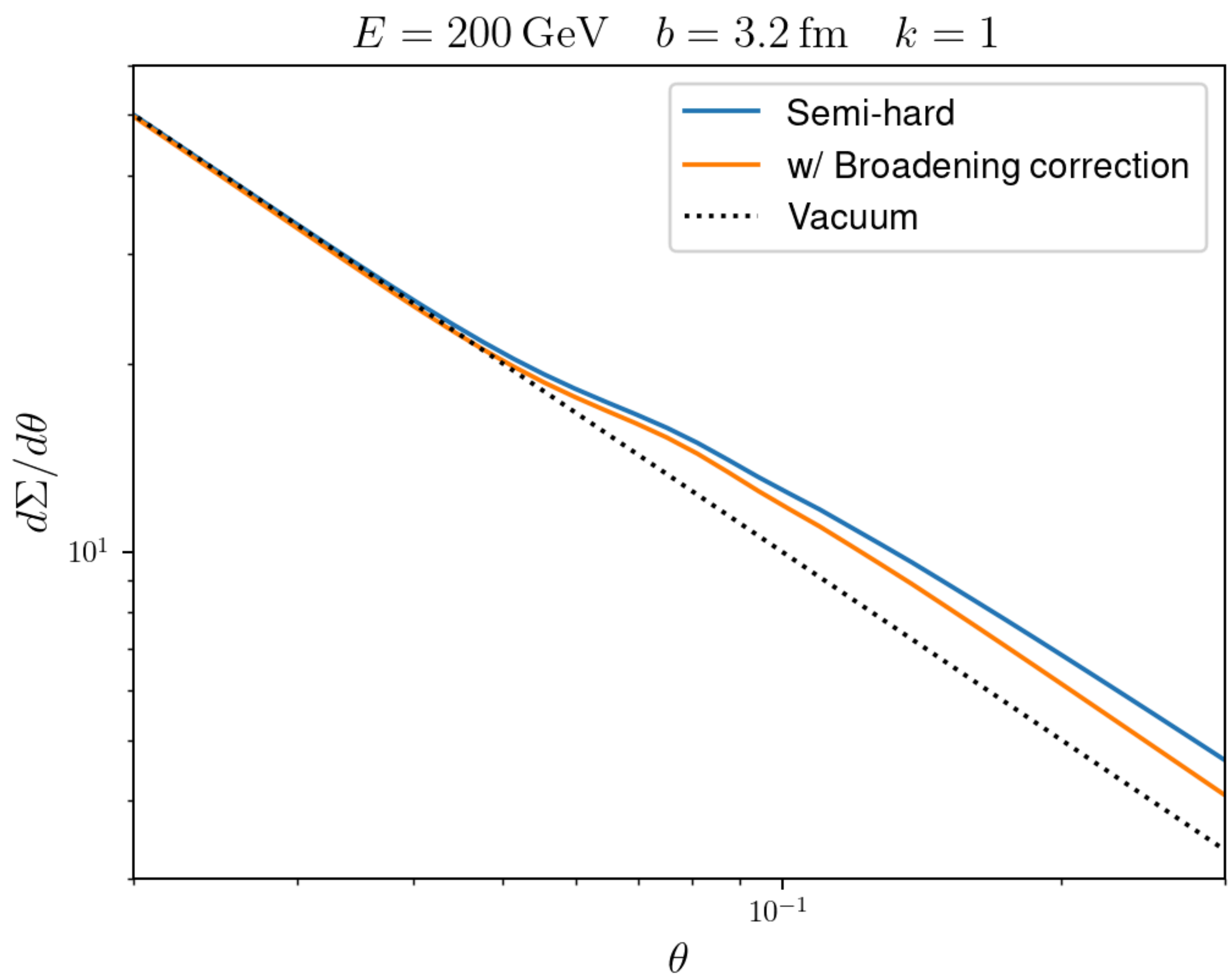


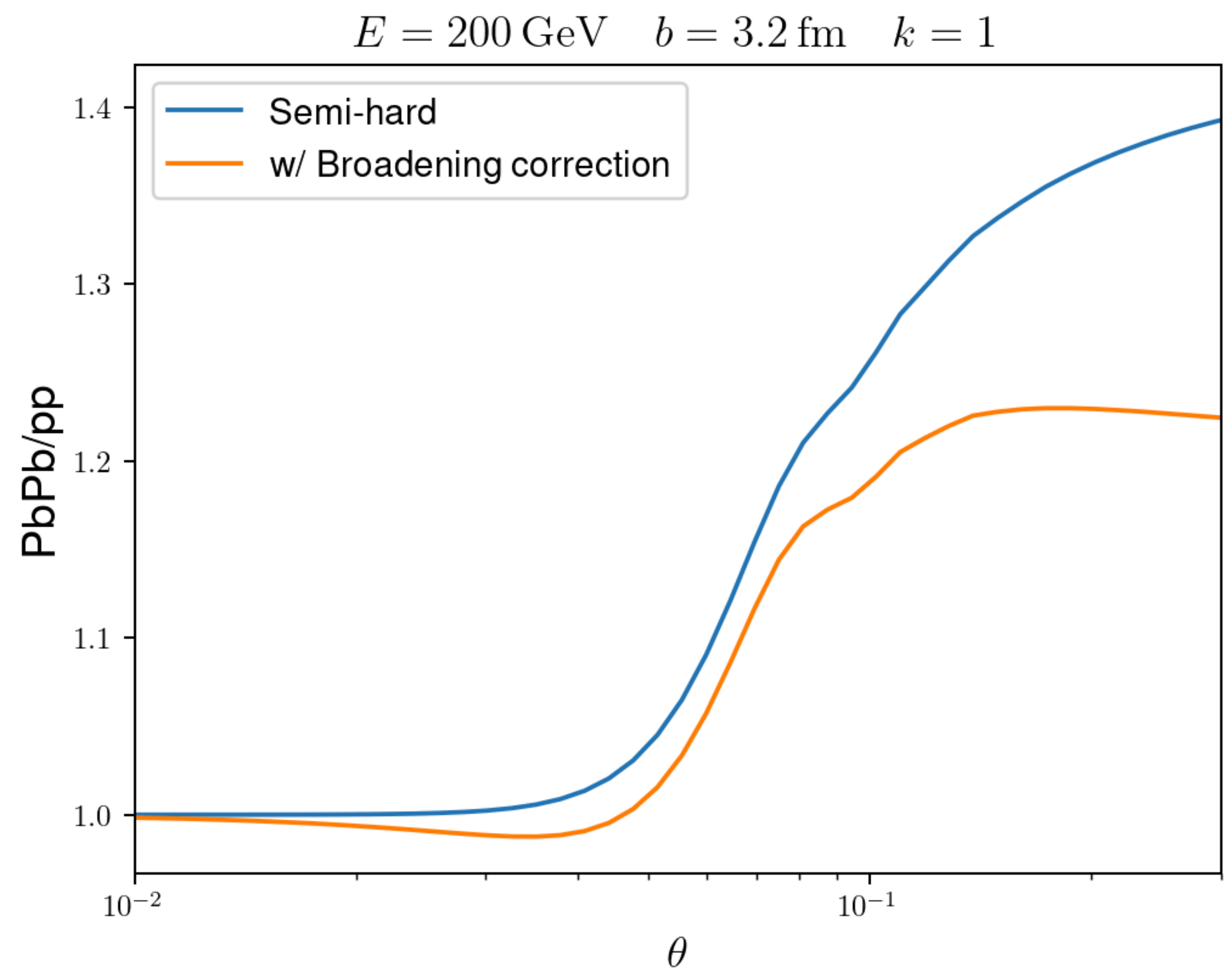
- Large reduction of the enhancement amplitude
- Small dip before transitioning to medium-enhancement, already present when the broadening correction is included
- Overall picture of no modification at small angles followed by a transition to medium-enhancement at large angles still valid

Beyond brick calculations

- Essential if we want to understand anything about how geometry affects our observables
- Repeat the previous calculations with a varying $\hat{q}$
- It is straightforward when eikonal propagation has been assumed (semi-hard, broadening correction)
- Becomes a lot more involved when eikonal approximation is relaxed (large-N_c, will not be shown in this talk)

Results using a hydro simulation





- We assume $\hat{q} \propto T^3$ and take the temperature from trajectories extracted from a smooth-averaged hydro simulation

Luzum, Romatschke 0804.4015 0901.4588

- Qualitative behavior similar to brick case
- Dependence on geometry can be explored

Beyond the harmonic approximation

- Theorists like the harmonic approximation because it allows us to perform analytical calculations when resumming multiple scatterings

- But, the harmonic approximation misses the rare large momentum transfer scatterings characteristic of point-like particles (Molière)

- These rare hard scatterings can be straightforwardly implemented in the semi-hard approximation and the broadening correction, but not clear the approximations are compatible

- When eikonal approximation is relaxed (large-N_c), going beyond the harmonic approximation has not yet been done but feasible to generalize from progress achieved for spectrum in the soft-limit

Andres, Apolinario, FD 2002.01517

Summary of available calculations

	Brick	Evolving media	High-momentum tails
Semi-hard	✓	✓	✓ But…
Broadening correction	✓ ✓	✓ ✓	✓ But…
Large-Nc	✓ ✓ ✓	✗ Feasible	✗ Computationally costly
Isaksen, Tywoniuk $\gamma \to q\bar{q}$	?	Straightforward	Straightforward

Energy loss

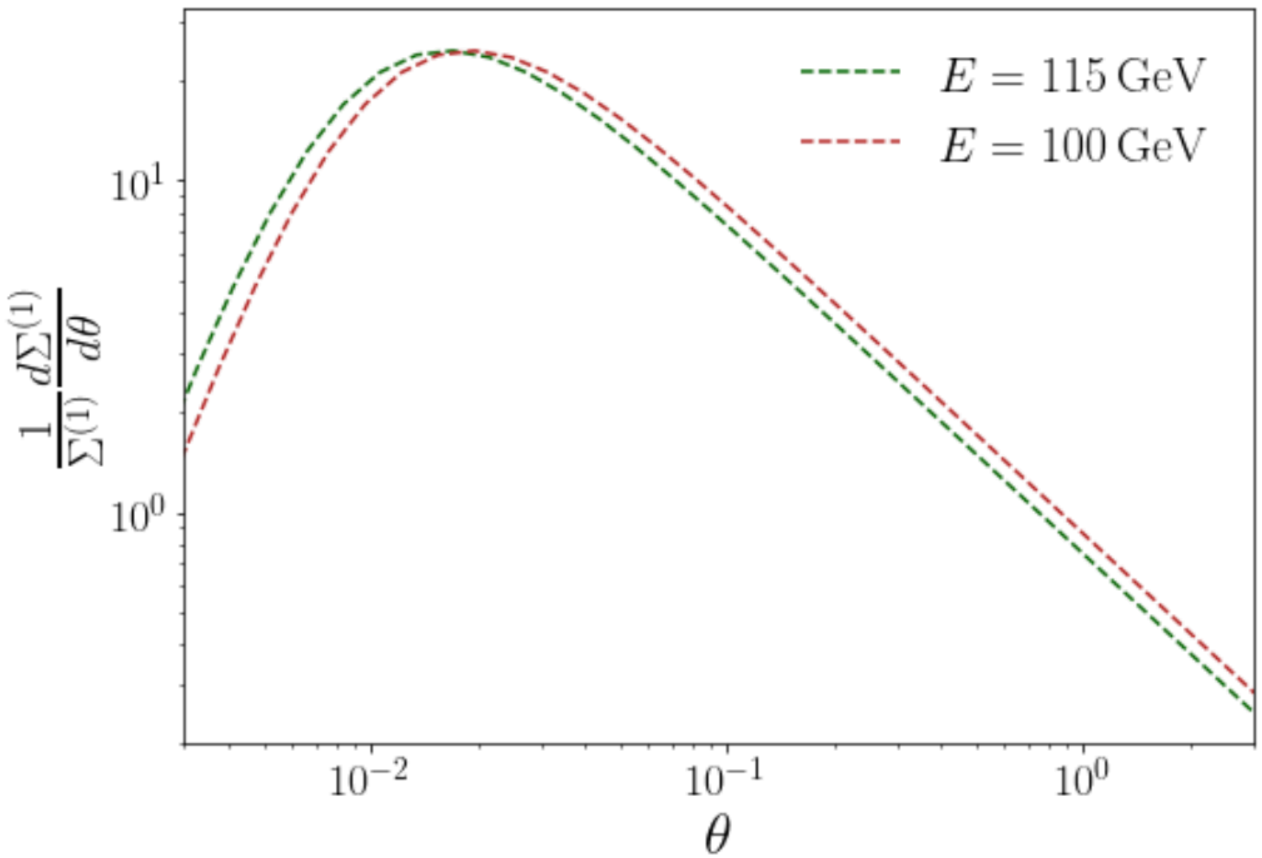
- If we don't know the initial energy of the initial hard parton we cannot neglect the effects of energy loss due to multiple soft emissions

- This is the case for inclusive jet measurements, which will be the first heavy ion measurements of energy correlators

- Energy loss effects on the EECs were studied recently in a simplified model with a resolution scale finding very small modifications

  Barata, Caucal, Soto-Ontoso, Szafron 2312.12527

- Nevertheless, coherent energy loss from the whole jet shifts the jet energy scale resulting in a shift in the vacuum baseline

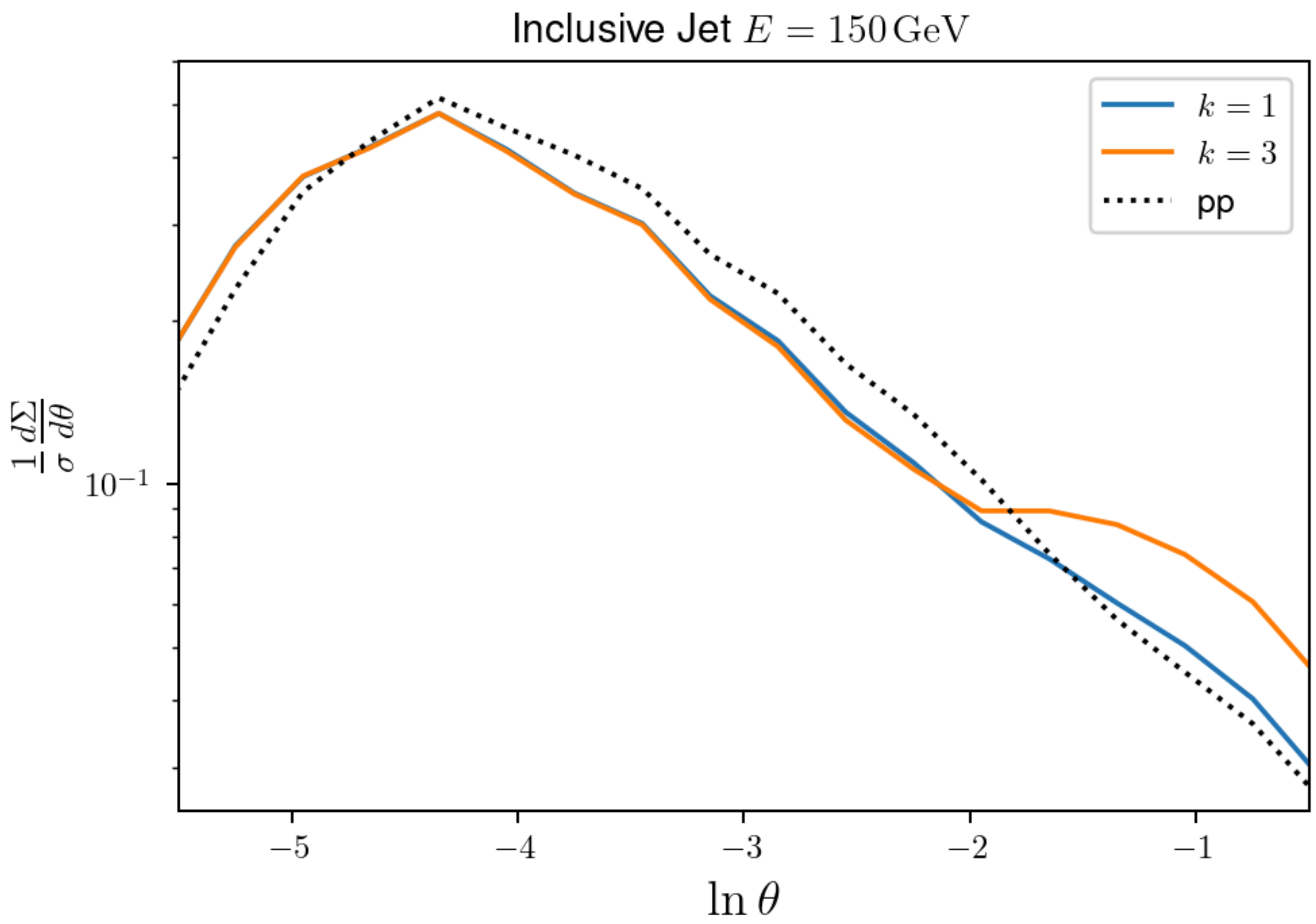


Results for inclusive jets

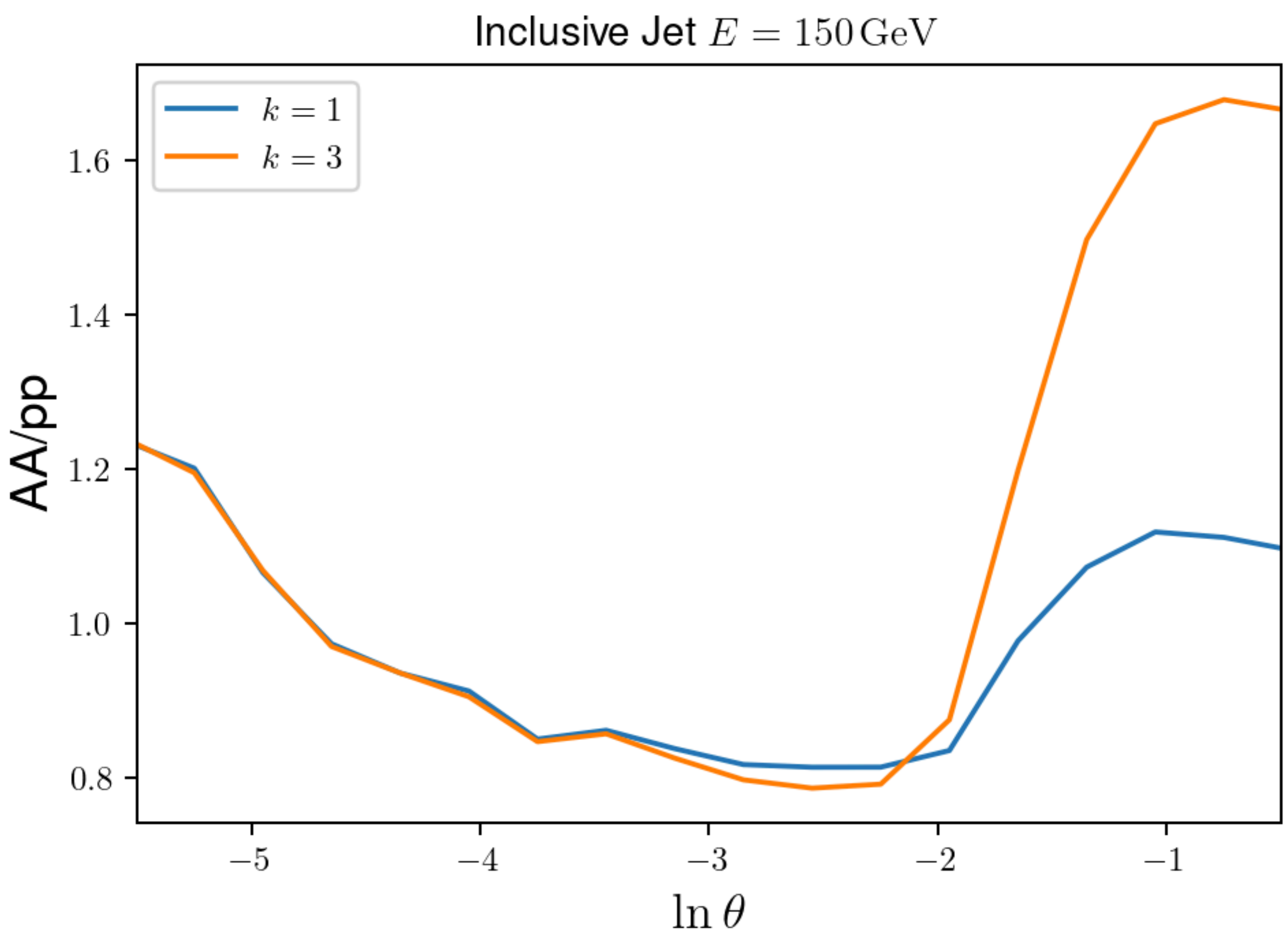
- In order to account for the shift in the energy scale we convolute our results for known initial energies with quenching weights accounting for the energy carried away by an arbitrary number of soft emissions

Salgado, Wiedemann hep-ph/0302184

- We use our calculations done with a expanding medium (modeled by a smooth-averaged hydro simulation) with the semi-hard approximation with the broadening correction



Results for inclusive jets



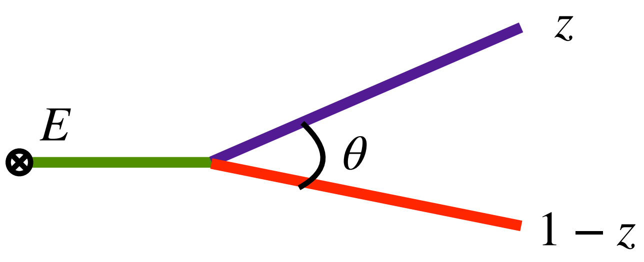
- All structure seen at small angles due to shift in energy scale, independent of fitting parameter
- Transition to medium-enhancement still present
- Amplitude of medium-enhancement at large angles largely overestimated

Outlook

- Steady progress towards meaningful comparisons with data
- Plenty of room for improvement from the theory side
  - Fully relaxing the eikonal approximations for expanding media
- In order to use this observable to extract information from the QGP we must consider variations in centrality, jet energy, center of mass energy, etc.
- Time to start thinking about more differential observables?

Thank you!

Energy correlators in vacuum

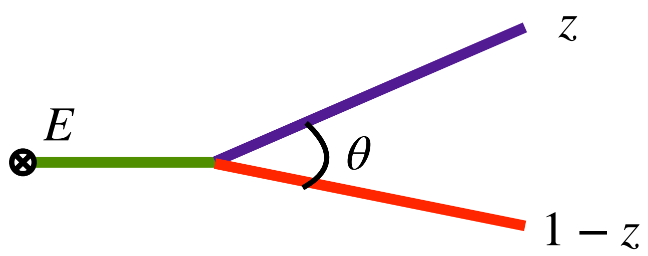


- At leading order

$$\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} = \frac{\alpha_s C_{\rm F}\sigma}{\pi}\frac{1+(1-z)^2}{z\ \theta} \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

Energy correlators in vacuum



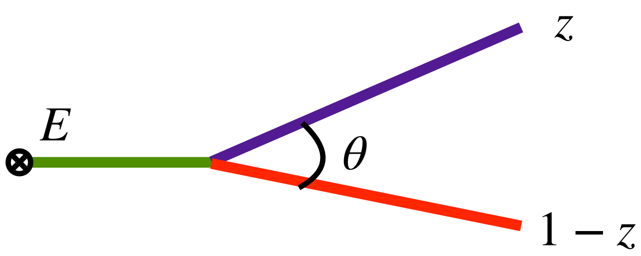
- At leading order

$$\frac{d\sigma_{qg}^{\mathrm{vac}}}{d\theta dz} = \frac{\alpha_s C_{\mathrm{F}} \sigma}{\pi} \frac{1+(1-z)^2}{z\ \theta} \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- For jets we are interested in the collinear (or OPE) limit

D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

Energy correlators in vacuum



- At leading order

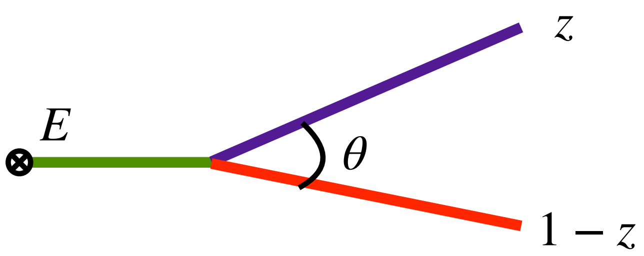
$$\frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} = \frac{\alpha_s C_{\text{F}} \sigma}{\pi} \frac{1+(1-z)^2}{z\ \theta} \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- For jets we are interested in the collinear (or OPE) limit

$$\mathcal{O}(x)\mathcal{O}(y) \xrightarrow{x\to y} \sum_i |x-y|^{\gamma_i} c_i\, \mathcal{O}_i$$

D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

Energy correlators in vacuum



- At leading order

$$\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} = \frac{\alpha_s C_{\rm F}\sigma}{\pi}\frac{1+(1-z)^2}{z\ \theta} \Rightarrow \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

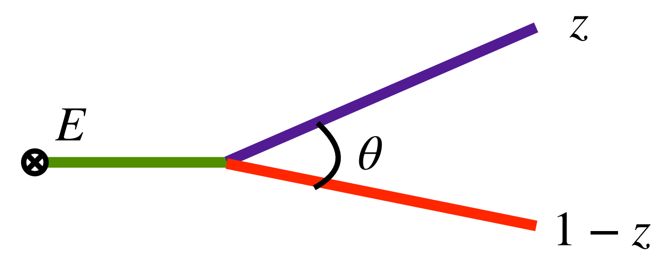
- For jets we are interested in the collinear (or OPE) limit

Light-ray OPE

$$\mathcal{O}(x)\mathcal{O}(y) \xrightarrow{x\to y} \sum_i |x-y|^{\gamma_i} c_i\, \mathcal{O}_i \Rightarrow \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \xrightarrow{\theta\to 0} \sum_i \theta^{\tau_i - 4}\, \mathbb{O}_i(\vec{n}_1)$$

D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

Energy correlators in vacuum



- At leading order

$$\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} = \frac{\alpha_s C_{\rm F}\sigma}{\pi}\frac{1+(1-z)^2}{z\ \theta} \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- For jets we are interested in the collinear (or OPE) limit

Light-ray OPE

$$\mathcal{O}(x)\mathcal{O}(y) \xrightarrow{x\to y} \sum_i |x-y|^{\gamma_i} c_i\, \mathcal{O}_i \quad \Rightarrow \quad \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \xrightarrow{\theta\to 0} \sum_i \theta^{\tau_i-4}\,\mathbb{O}_i(\vec{n}_1)$$

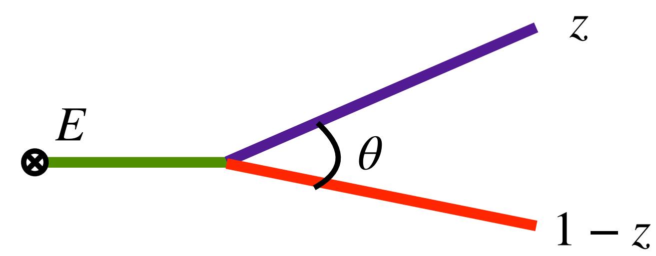
In a CFT:

$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

$\gamma(3)$ is the twist-2 spin-3 QCD anomalous dimension

D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

Energy correlators in vacuum



- At leading order

$$\frac{d\sigma_{qg}^{\rm vac}}{d\theta dz} = \frac{\alpha_s C_{\rm F}\sigma}{\pi}\frac{1+(1-z)^2}{z\ \theta} \Rightarrow \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- For jets we are interested in the collinear (or OPE) limit

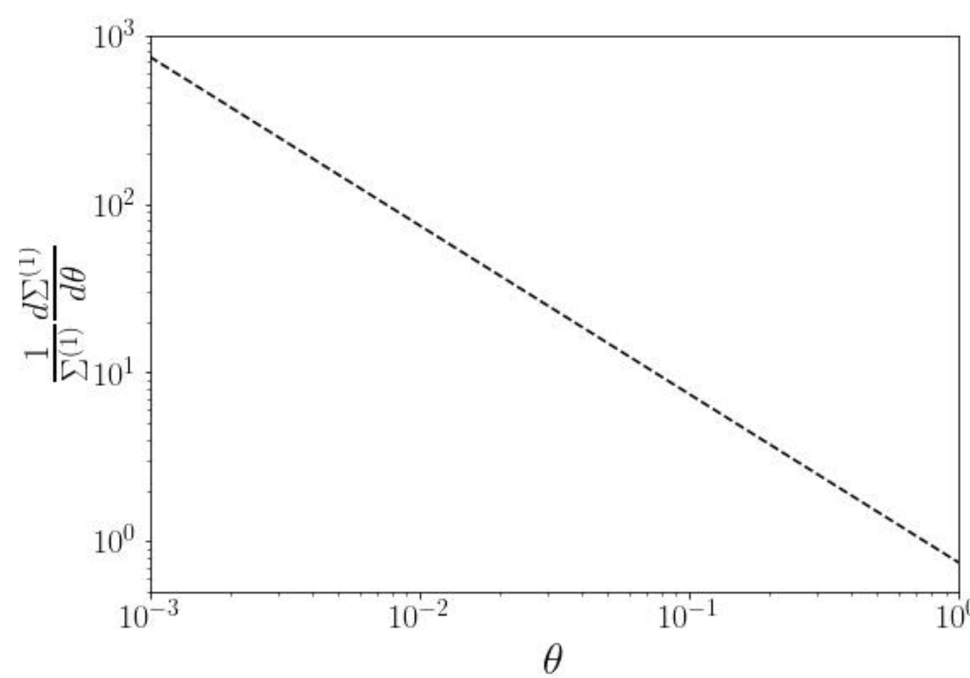
Light-ray OPE

$$\mathcal{O}(x)\mathcal{O}(y) \xrightarrow{x\to y} \sum_i |x-y|^{\gamma_i} c_i\, \mathcal{O}_i \Rightarrow \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \xrightarrow{\theta\to 0} \sum_i \theta^{\tau_i-4}\, \mathbb{O}_i(\vec{n}_1)$$

In a CFT:

$$\frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

$\gamma(3)$ is the twist-2 spin-3 QCD anomalous dimension



D. Hoffman, J. Maldacena 0803.1467
H. Chen , I. Moult, J. Sandor, H. X. Zhu 2202.04085

EECs from massive jets

- Dead-cone effect: radiation from heavy quarks is suppressed at small angles

$$\frac{d\sigma_M^{\text{vac}}}{d\theta dz} \sim \frac{\theta^3}{(\theta^2 + \frac{\theta_0^2}{1-z})^2} \frac{d\sigma^{\text{vac}}}{d\theta dz}$$

Dead-cone angle!

$$\theta_0 = \frac{M}{E}$$

E. Craft, K. Lee, B. Meçai, I. Moult 2210.09311

EECs from massive jets

- Dead-cone effect: radiation from heavy quarks is suppressed at small angles

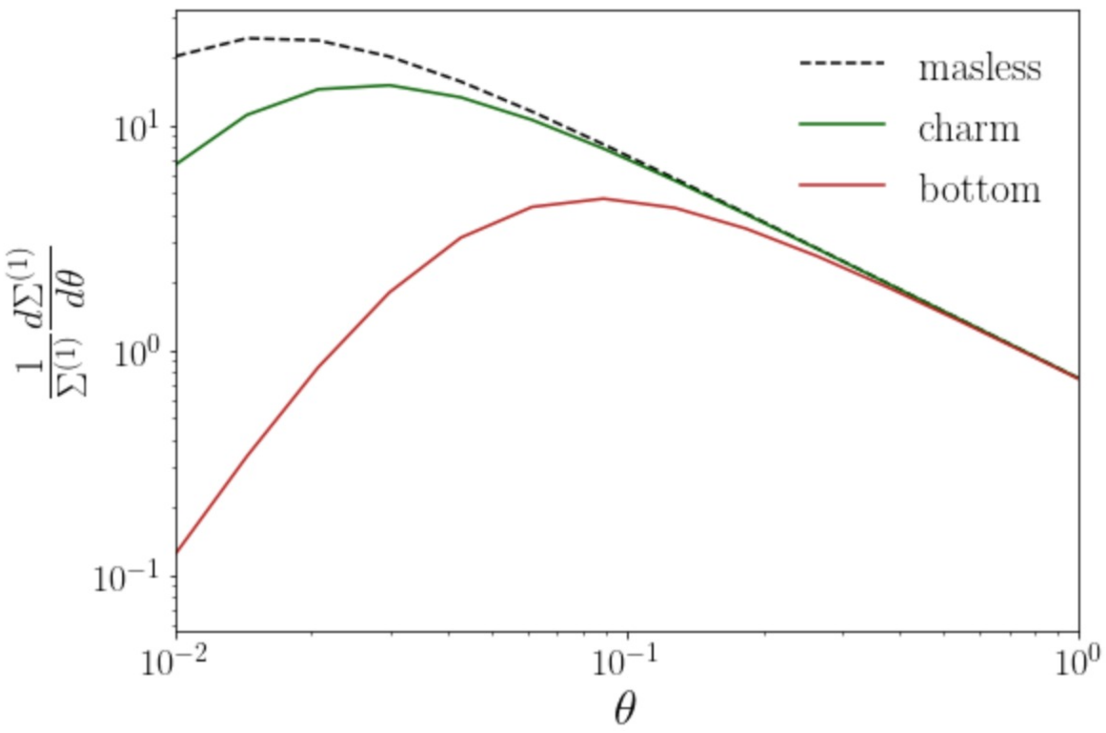
$$\frac{d\sigma_M^{\mathrm{vac}}}{d\theta dz} \sim \frac{\theta^3}{(\theta^2 + \frac{\theta_0^2}{1-z})^2} \frac{d\sigma^{\mathrm{vac}}}{d\theta dz}$$

Dead-cone angle!

$$\theta_0 = \frac{M}{E}$$

- Deviation from power-law behavior occurs at the dead-cone angle in the perturbative regime

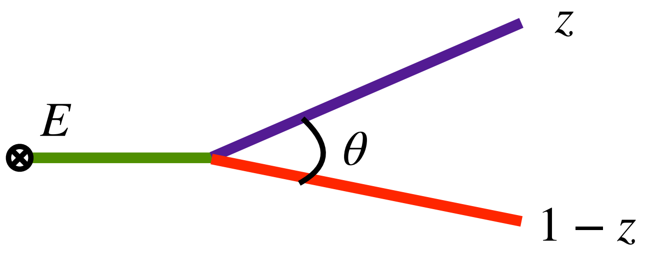
- In the massless case, the transition to the non-perturbative regime can be modeled by putting a gluon mass



E. Craft, K. Lee, B. Meçai, I. Moult 2210.09311

Time and angular scales

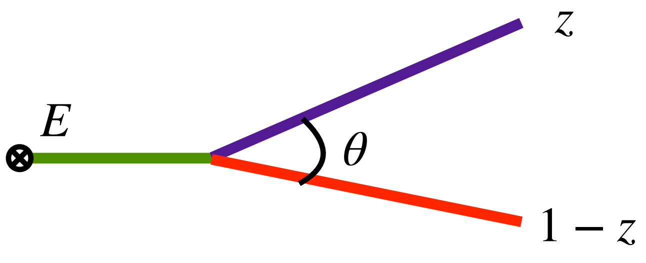
FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653



Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

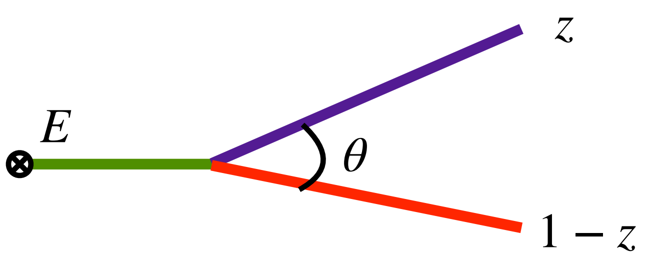
- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



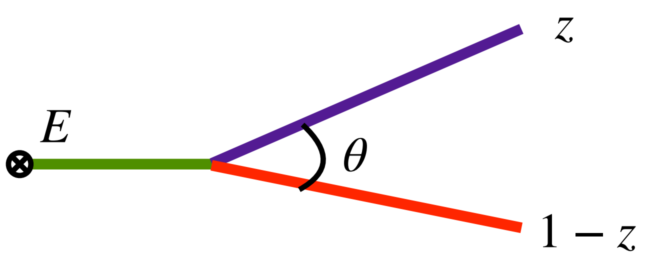
  - (Vacuum) formation time:

$$t_f = \frac{2}{z(1-z)E\theta^2}$$

Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



  - (Vacuum) formation time:

$$t_f = \frac{2}{z(1-z)E\theta^2}$$

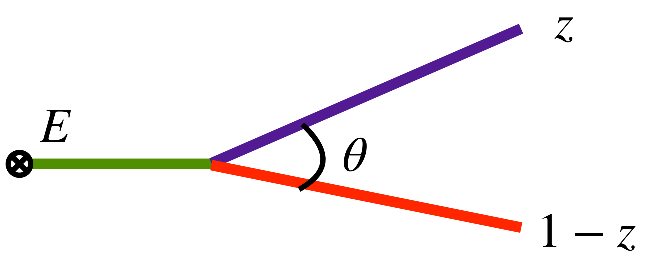
$$\theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



  - (Vacuum) formation time:

$$t_f = \frac{2}{z(1-z)E\theta^2}$$

$$\theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

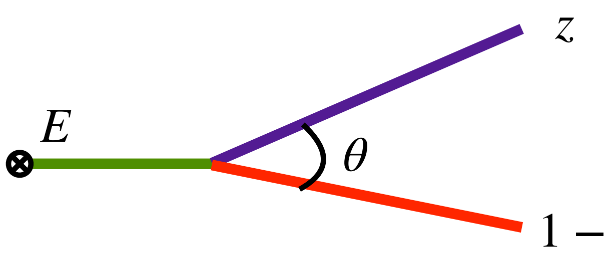
  - Decoherence time:

$$t_d \sim (\hat{q}\theta^2)^{-1/3}$$

Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



  - (Vacuum) formation time:

$$t_f = \frac{2}{z(1-z)E\theta^2}$$

$$\theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

  - Decoherence time:

$$t_d \sim (\hat{q}\theta^2)^{-1/3}$$

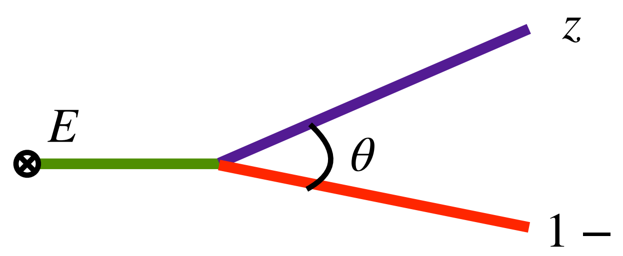
$$\theta_c \sim (\hat{q}L^3)^{-1/2}$$

Below θ_c splittings do not lose color coherence and the medium does not resolve them

Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



  - (Vacuum) formation time:

$$t_f = \frac{2}{z(1-z)E\theta^2}$$

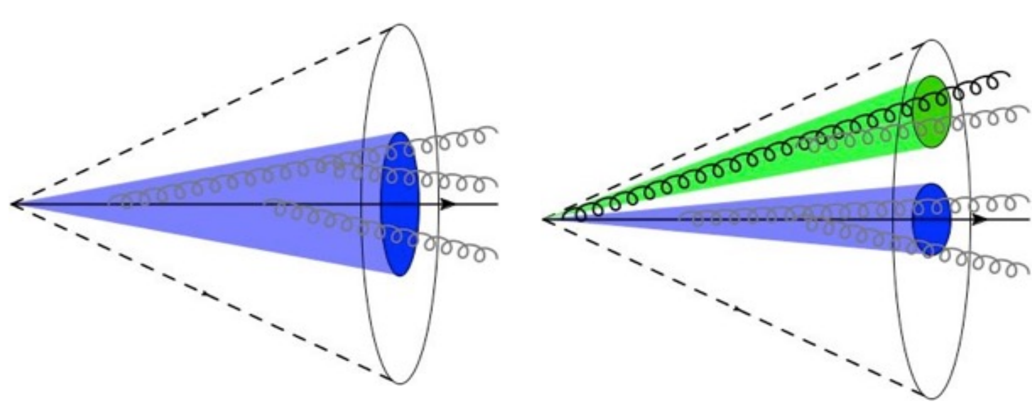
$$\theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

  - Decoherence time:

$$t_d \sim (\hat{q}\theta^2)^{-1/3}$$

$$\theta_c \sim (\hat{q}L^3)^{-1/2}$$

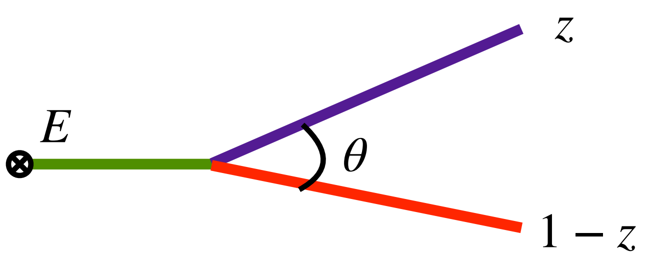


Below θ_c splittings do not lose color coherence and the medium does not resolve them

Time and angular scales

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653

- For a static medium of length L within the harmonic approximation with jet quenching parameter $\hat{q}$ one can read off the relevant scales directly from the formulas



  - (Vacuum) formation time:

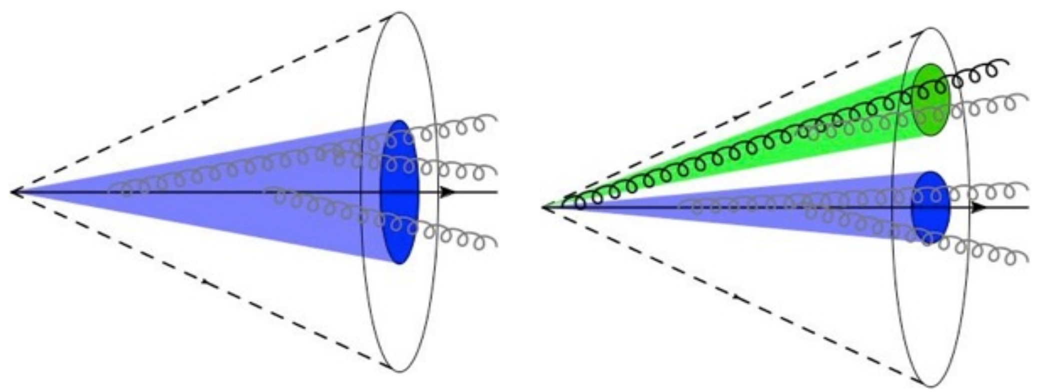
$$t_f = \frac{2}{z(1-z)E\theta^2}$$

$$\theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

  - Decoherence time:

$$t_d \sim (\hat{q}\theta^2)^{-1/3}$$

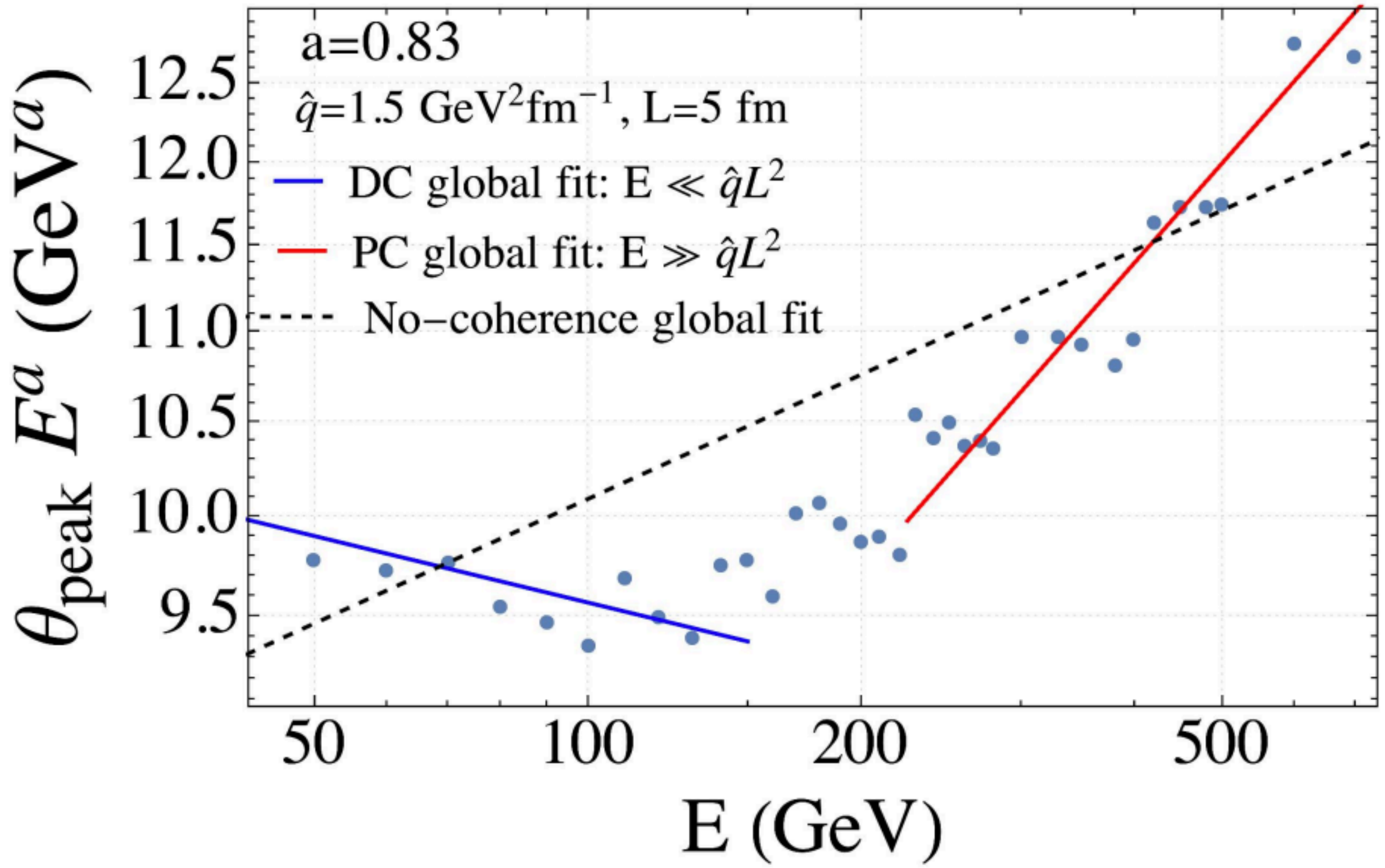


$$\theta_c \sim (\hat{q}L^3)^{-1/2}$$

Below θ_c splittings do not lose color coherence and the medium does not resolve them

If $\theta_L > \theta_c$ then θ_c becomes irrelevant

Coherence transition



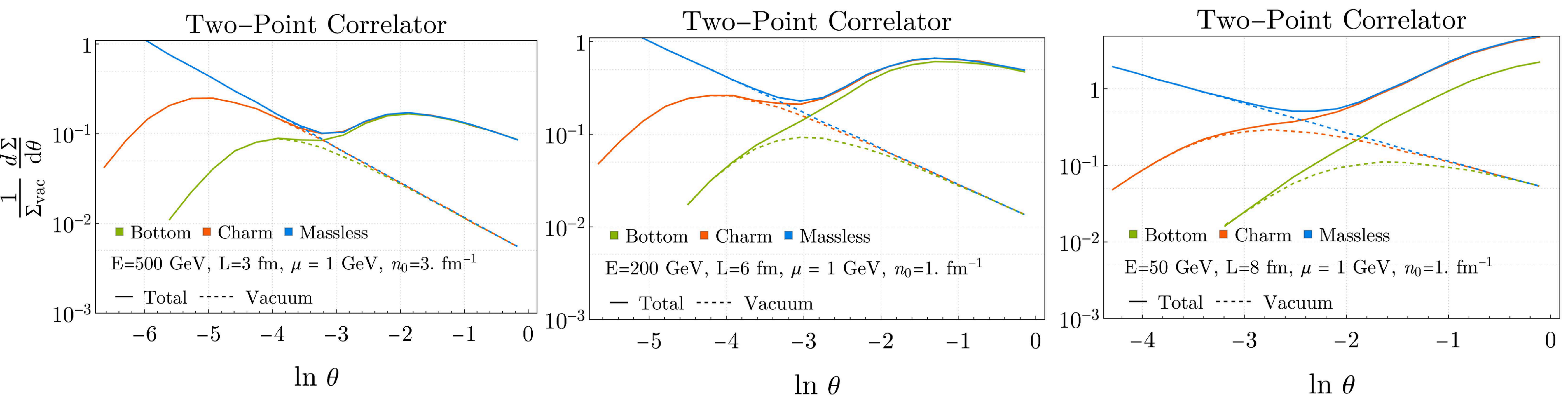
- Extracted the peak angle $\theta_{\rm peak}$ for 332 sets of parameters with $E \in [50{,}700]$ GeV, $L \in [0.2{,}10]$ fm, $\hat{q} \in [1{,}3]$ GeV^2/fm

- Performed separate fits in the two different regions for the scaling behavior of the peak angle with respect to the 3 parameters

C. Andres, FD, R. K. Elayavalli, J. Holguin, C. Marquet, I. Moult, arXiv:2209.11236
C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2303.03413

Massive EEC in HIC

Including mass in medium-induced calculations is straightforward



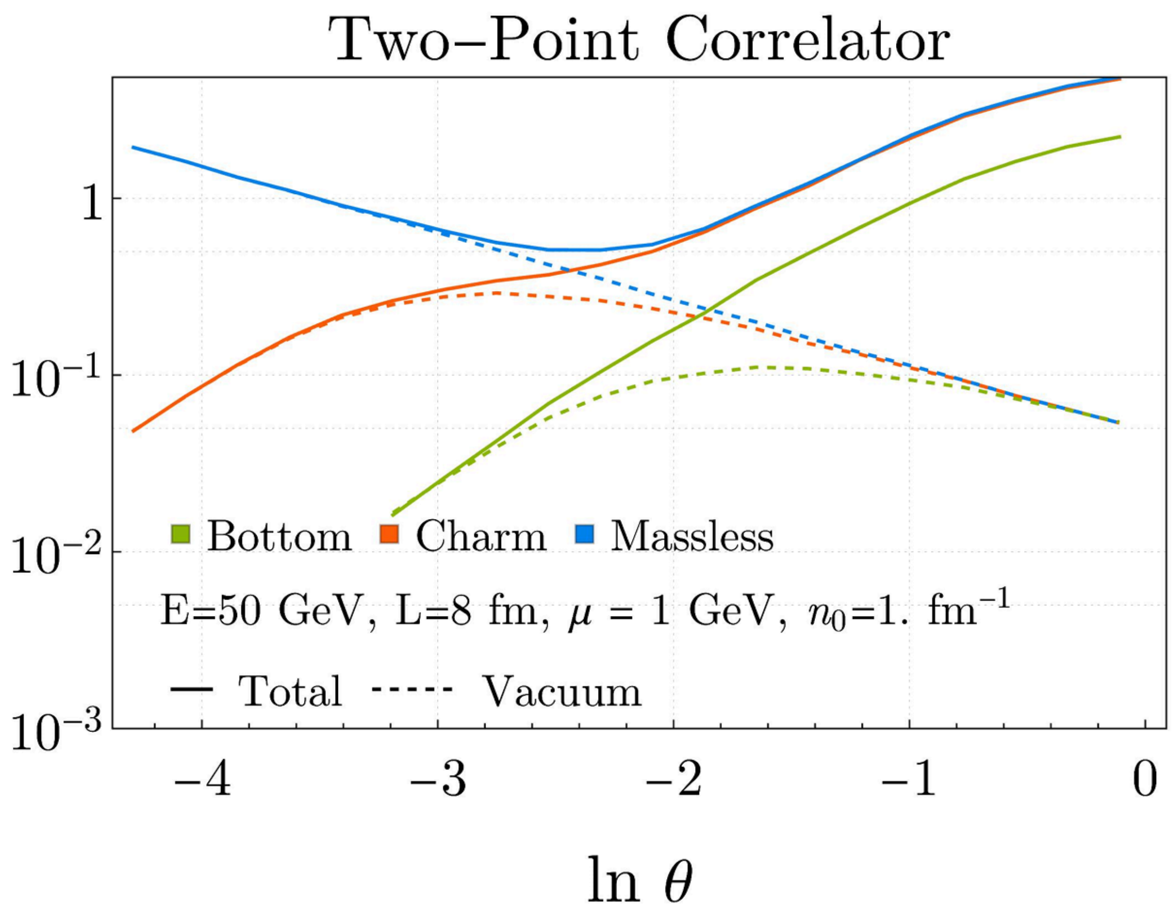
- Dead-cone is filled for lower energy jets

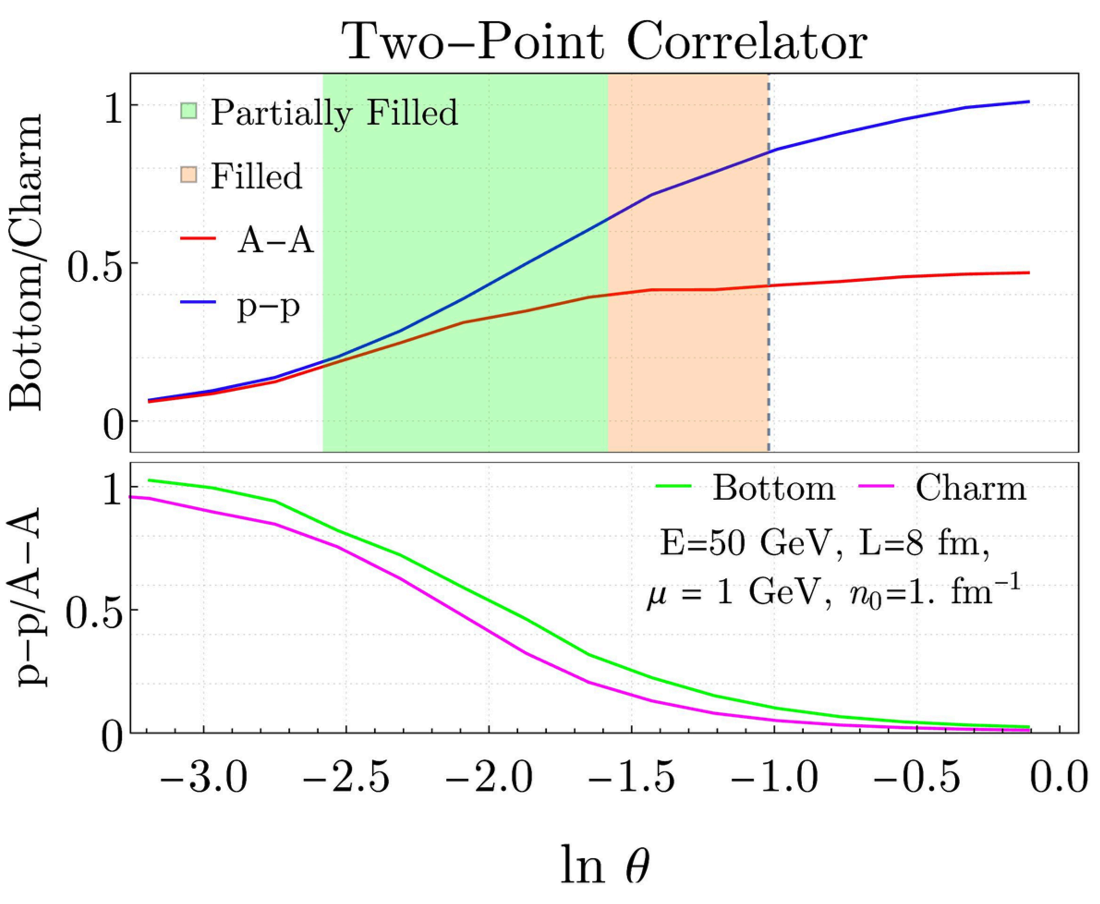
- When dead-cone is filled the mass changes also the large angle behavior

C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2307.15110

Massive EEC in HIC

- Experimentally, the cleanest observable would be the b/c ratio

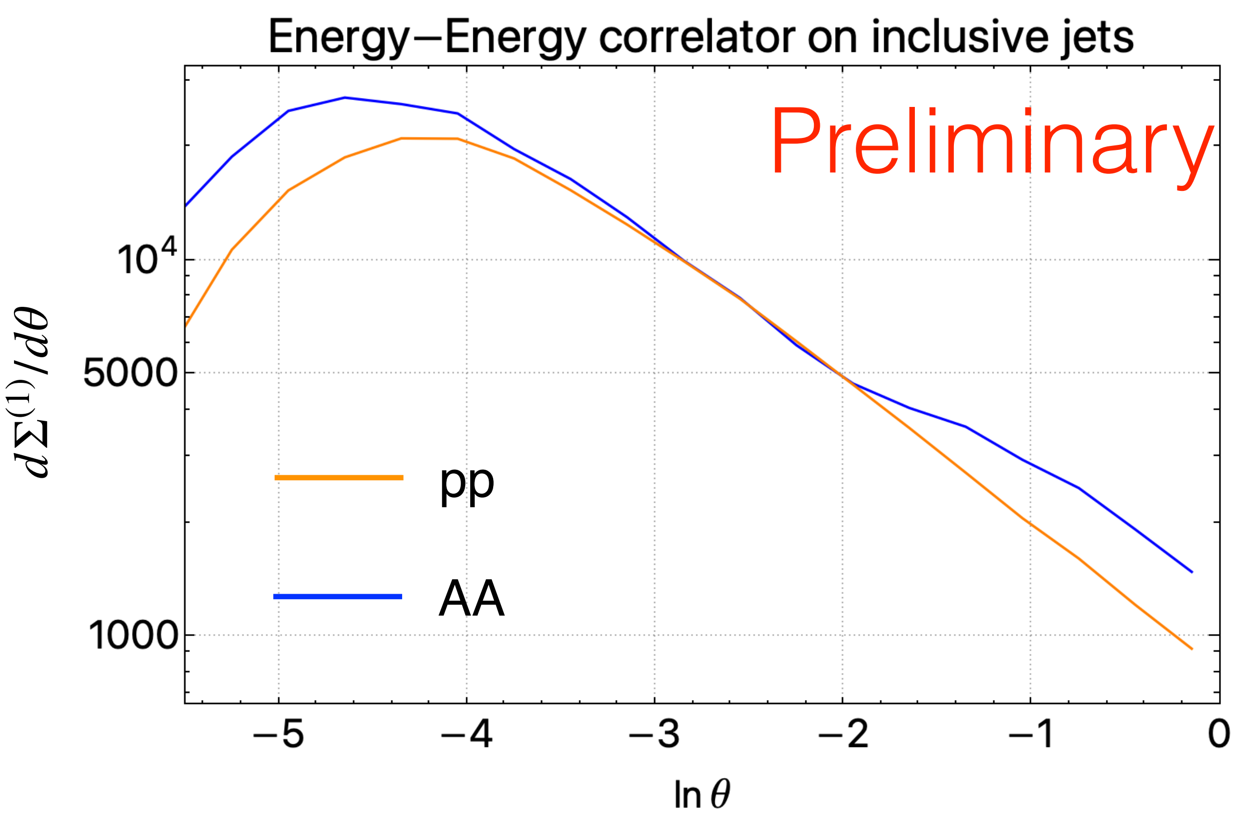


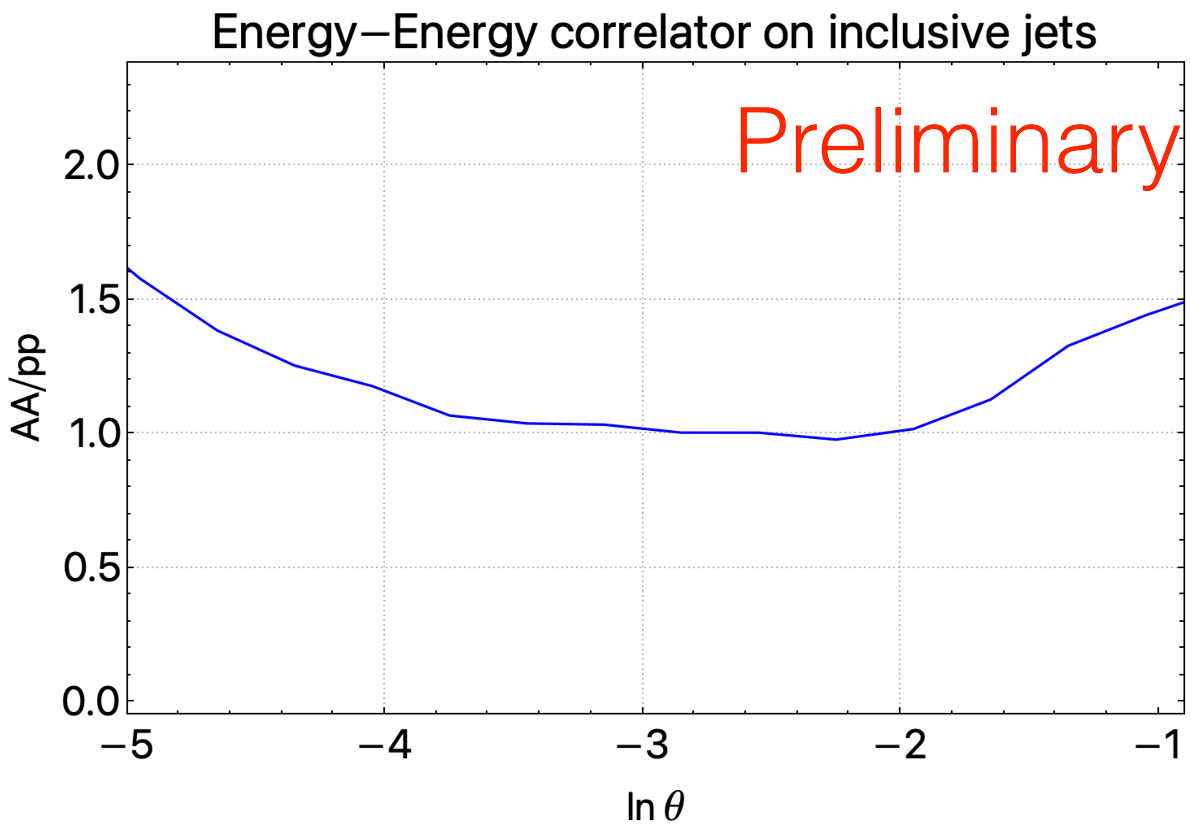


C. Andres, FD, J. Holguin, C. Marquet, I. Moult, arXiv:2307.15110

EECs for inclusive jets

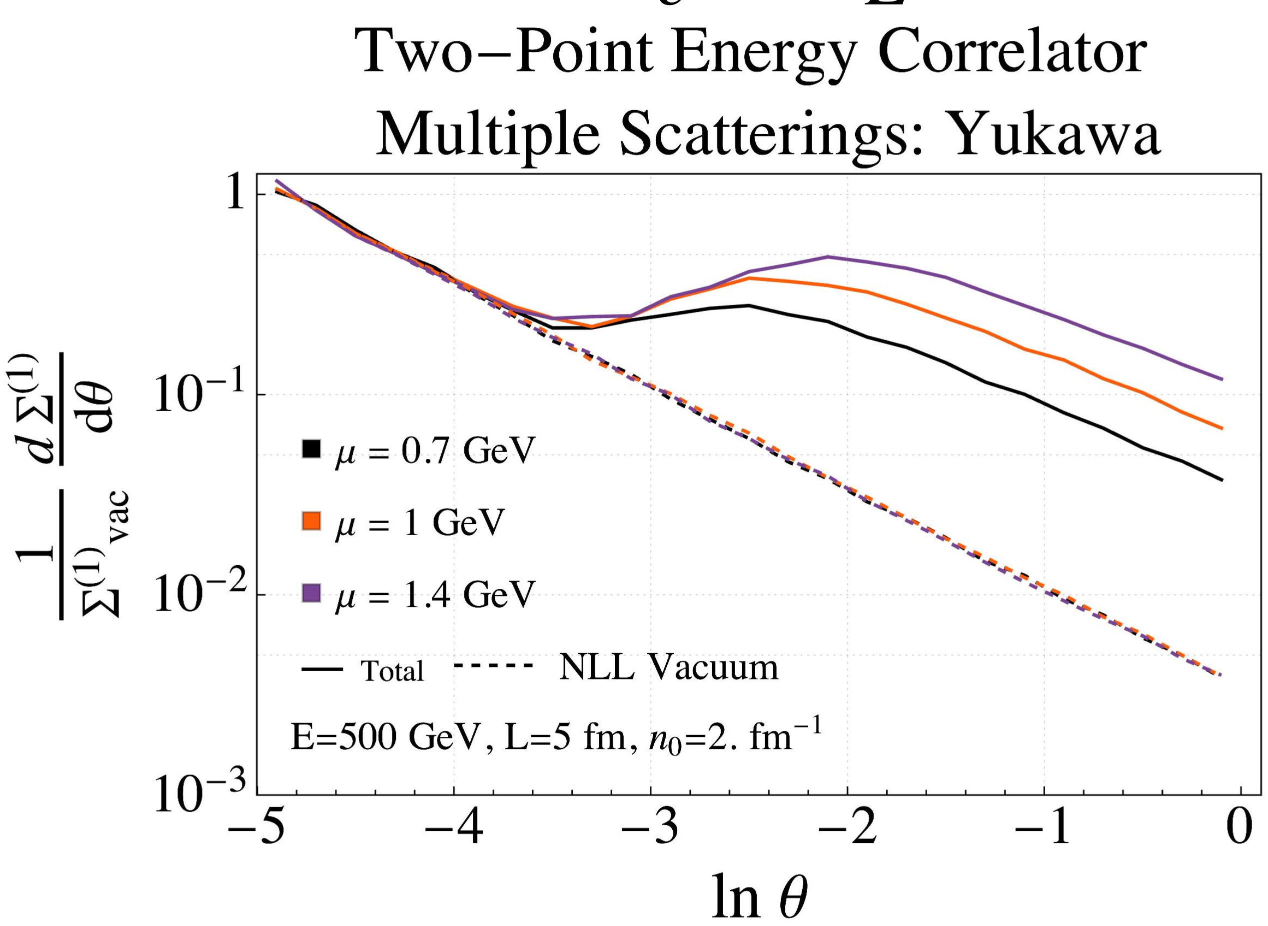
- First measurements will be performed for inclusive jets
- In this case we do not know the energy of the initial parton and therefore energy loss becomes important
- HI-jets have a higher initial energy than pp-jets and therefore the transition to NP regime happens at smaller angles



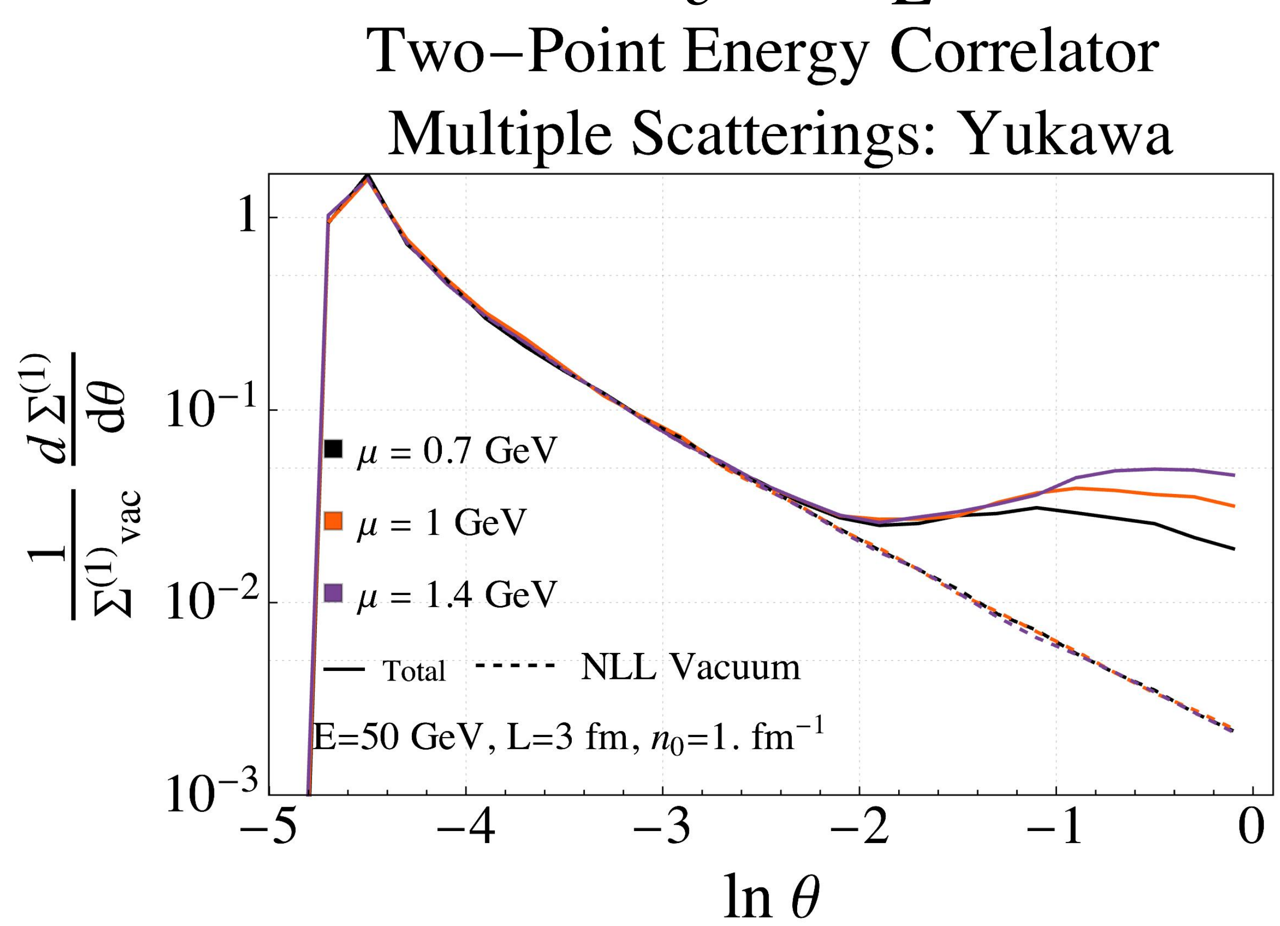


Results with Yukawa interaction

$\theta_c > \theta_L$

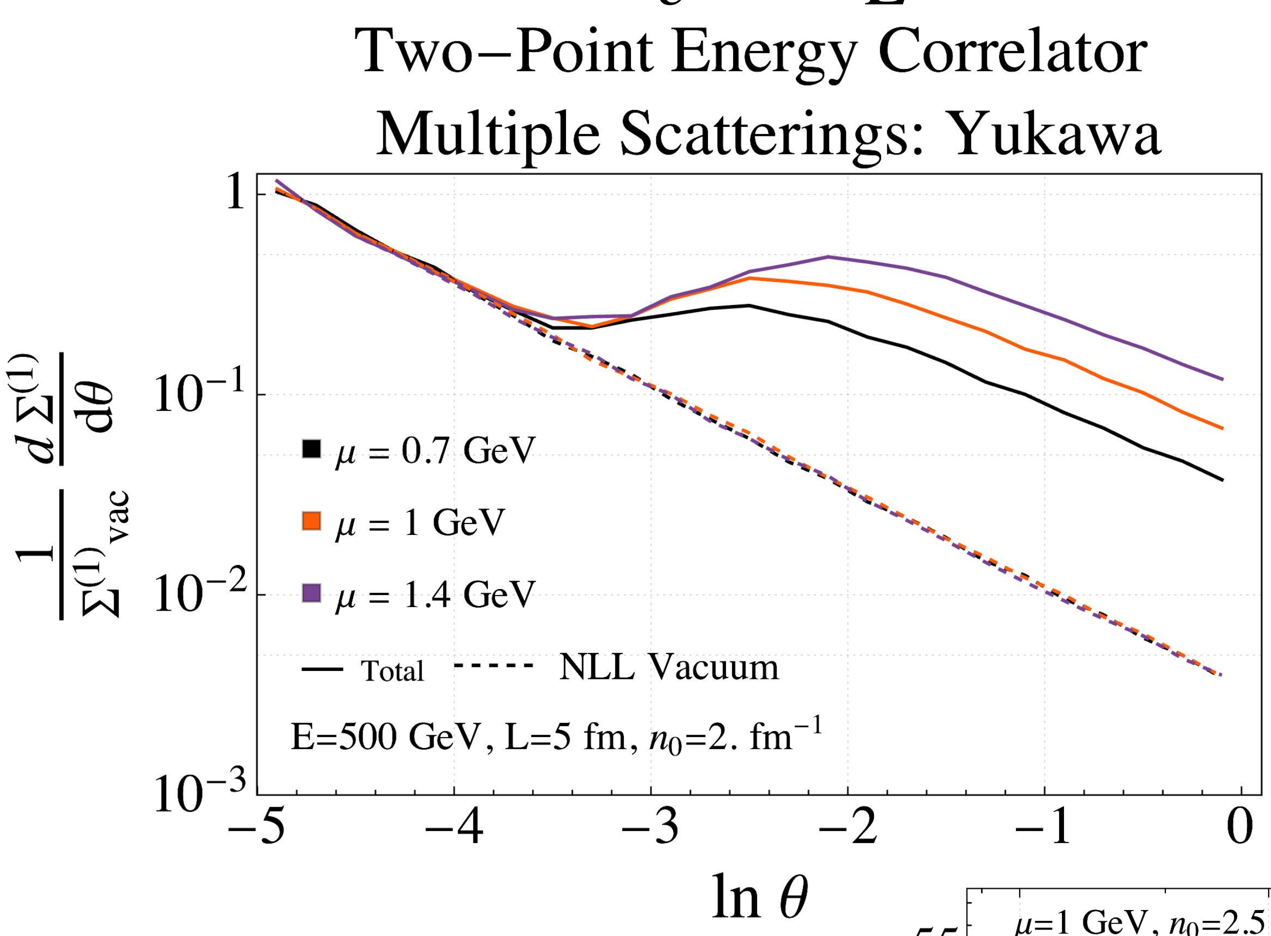


$\theta_c < \theta_L$

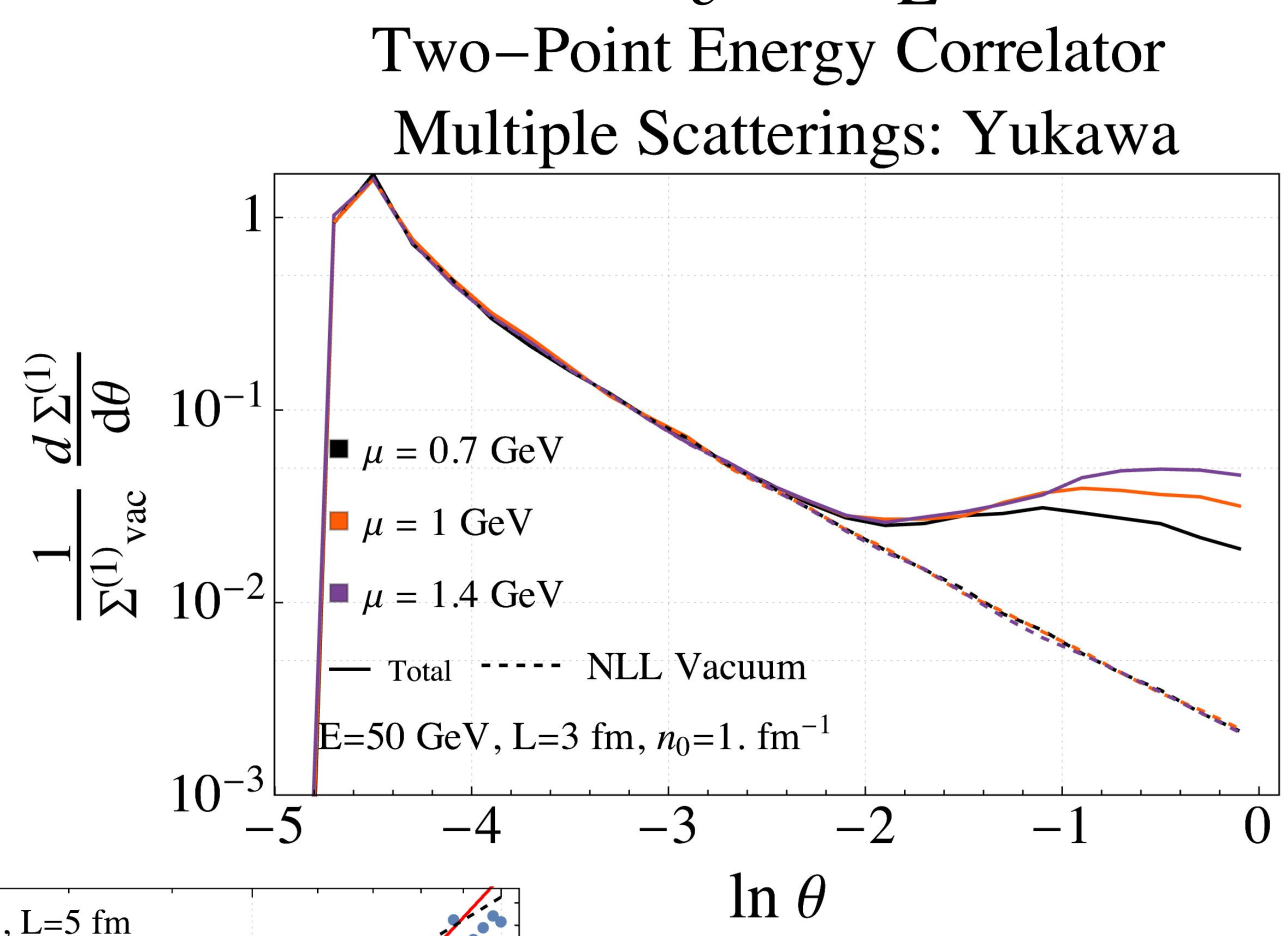


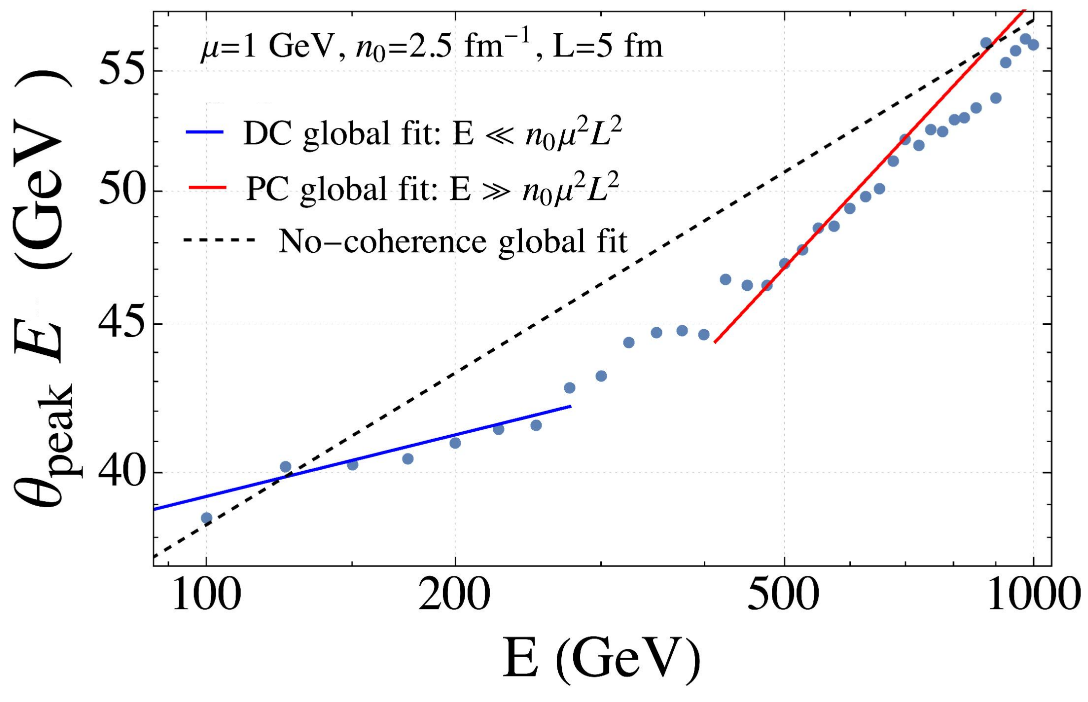
Results with Yukawa interaction

$\theta_c > \theta_L$



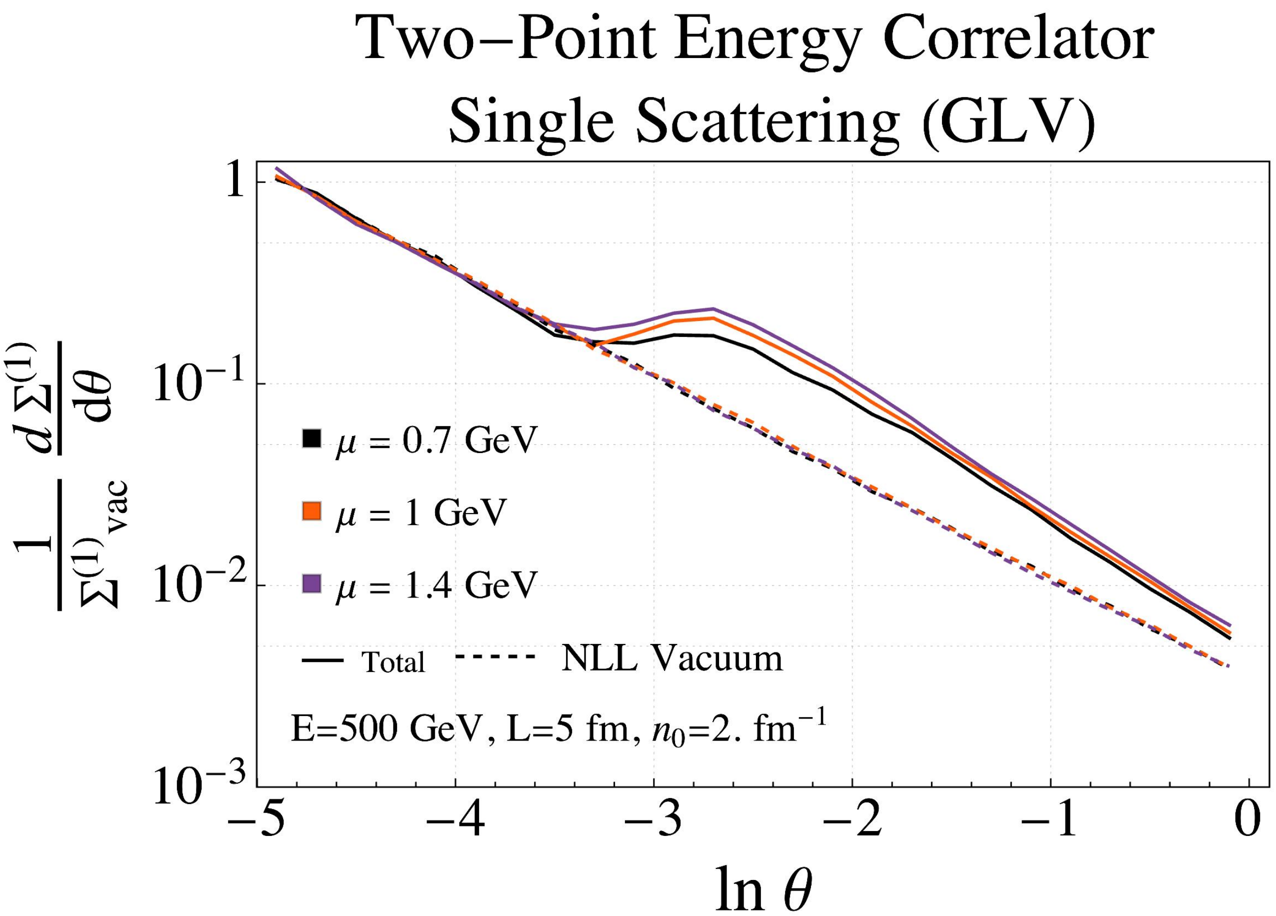
$\theta_c < \theta_L$



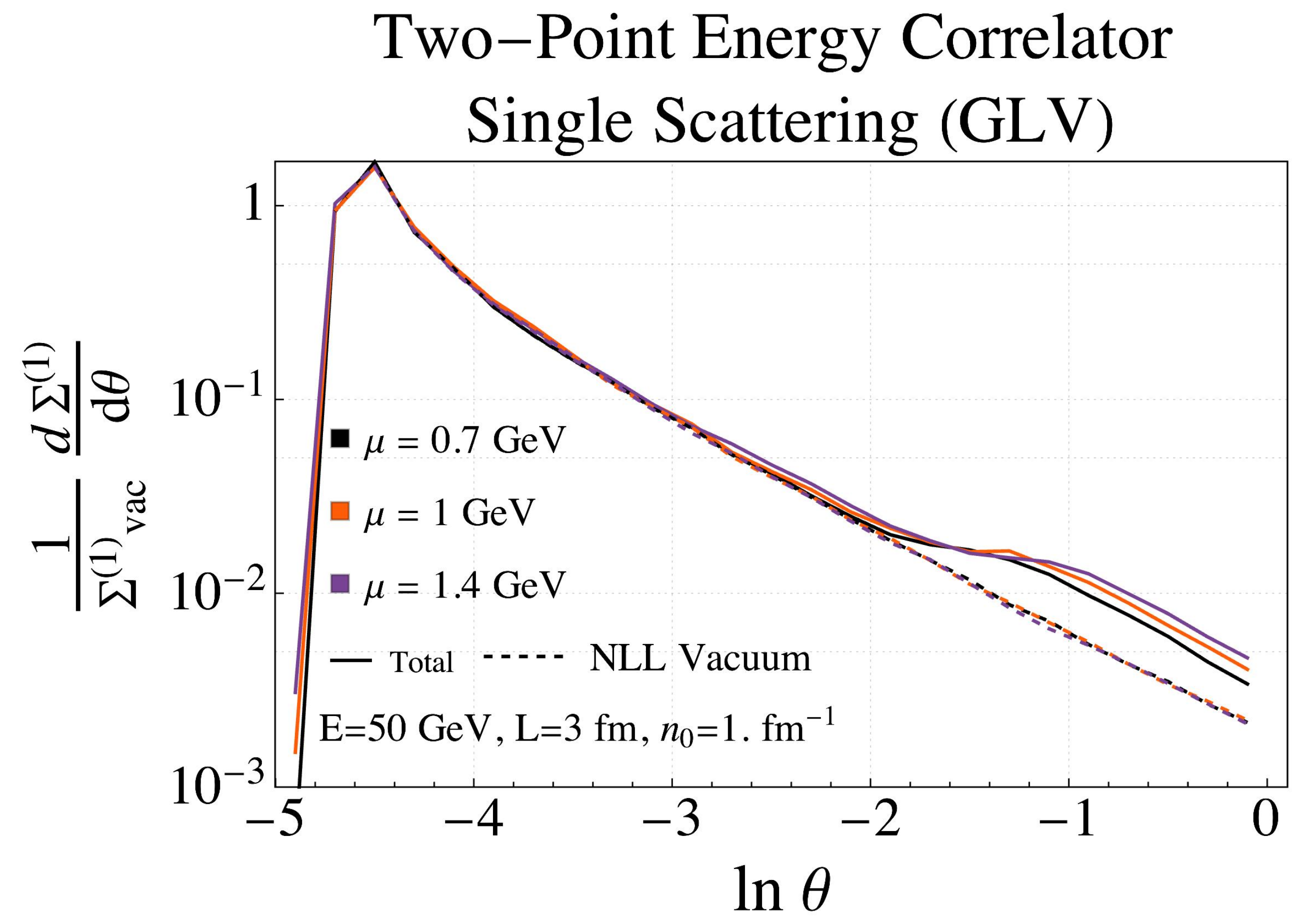


Results with single scattering (GLV)

$\theta_c > \theta_L$

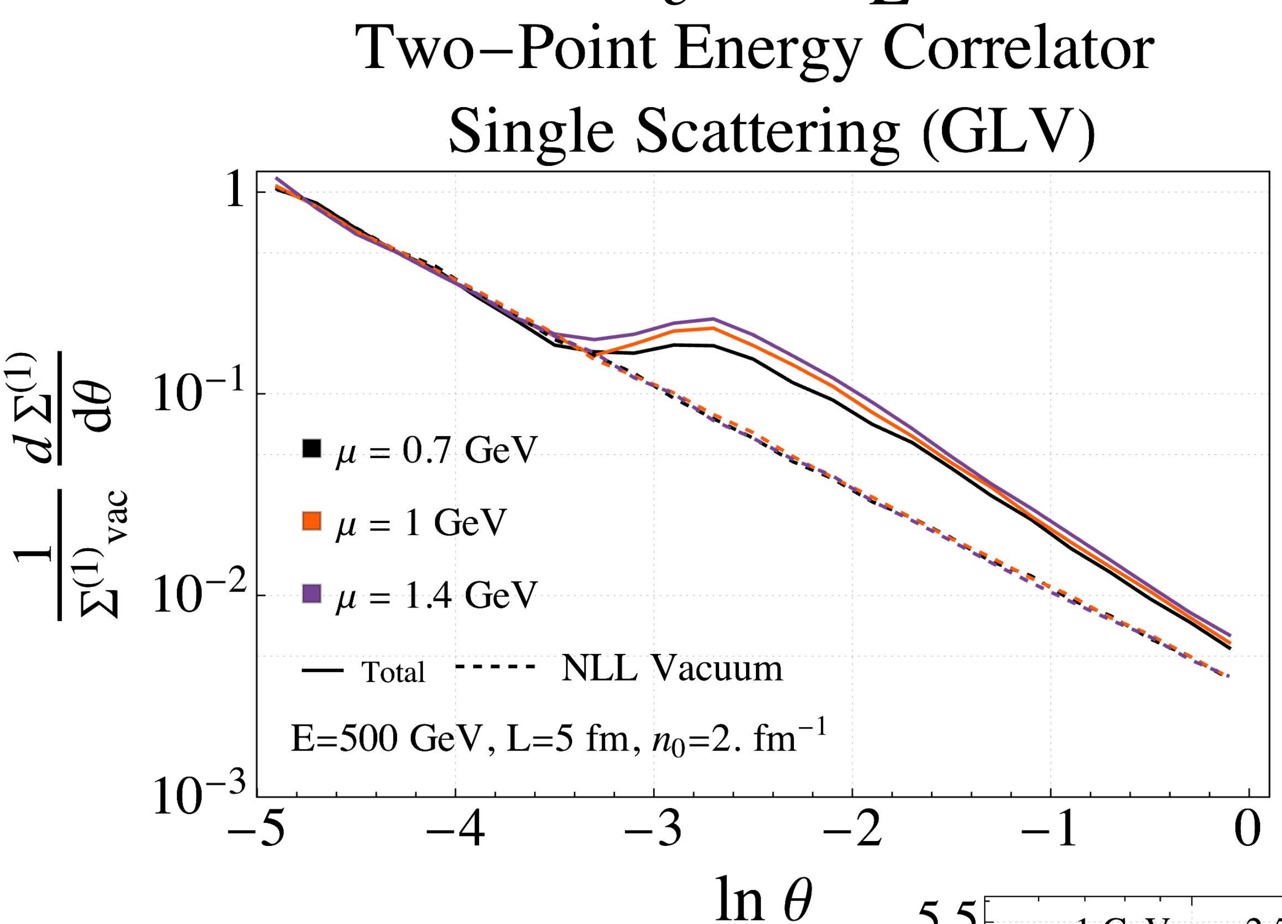


$\theta_c < \theta_L$

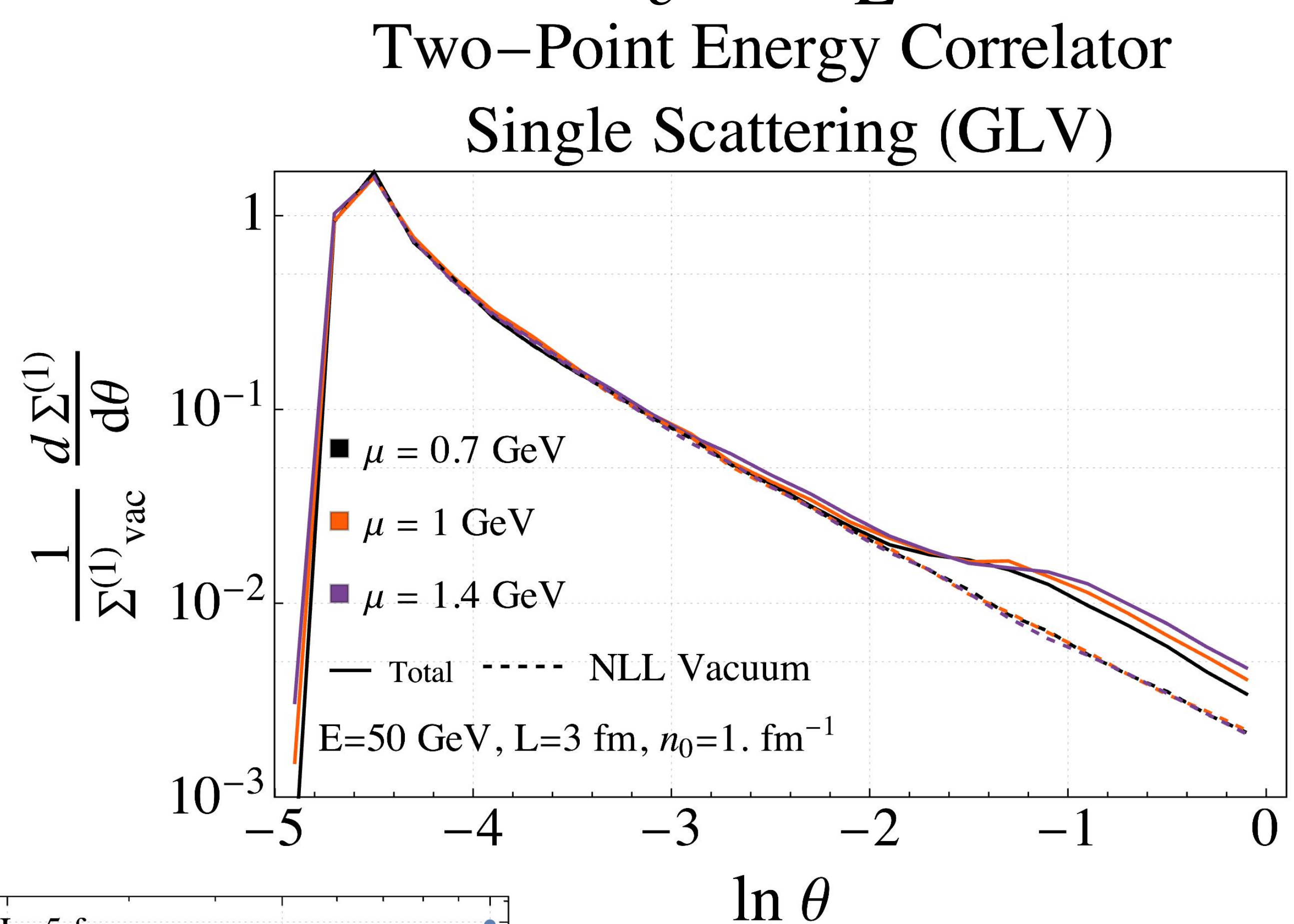


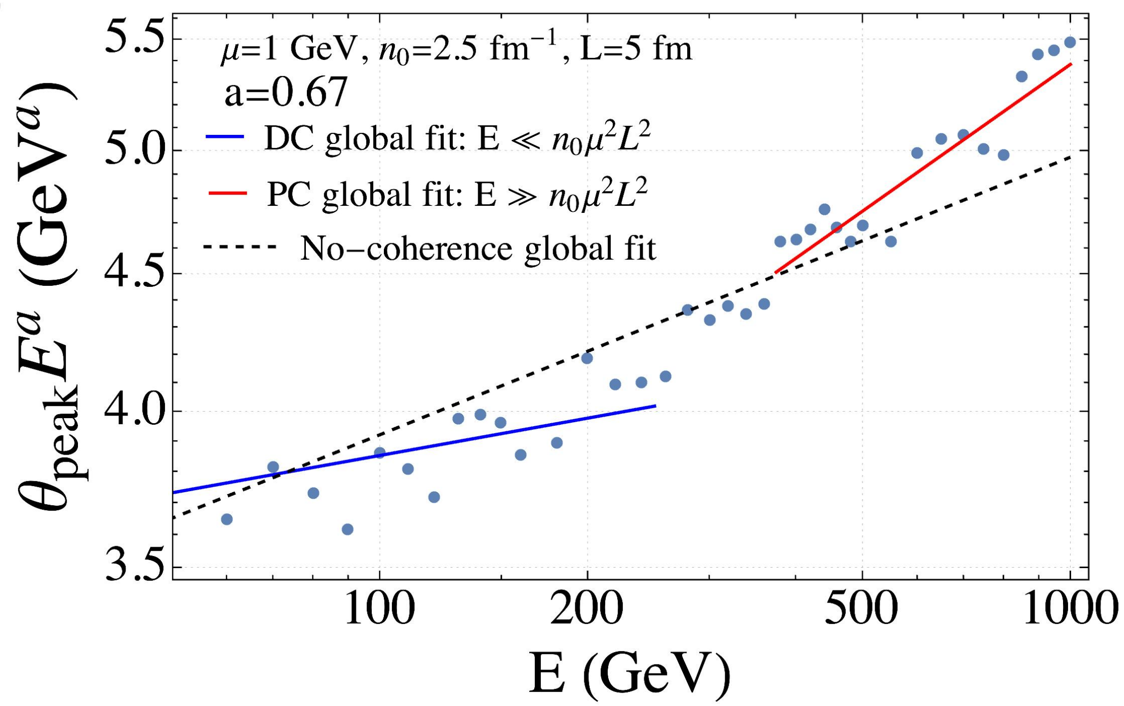
Results with single scattering (GLV)

$\theta_c > \theta_L$

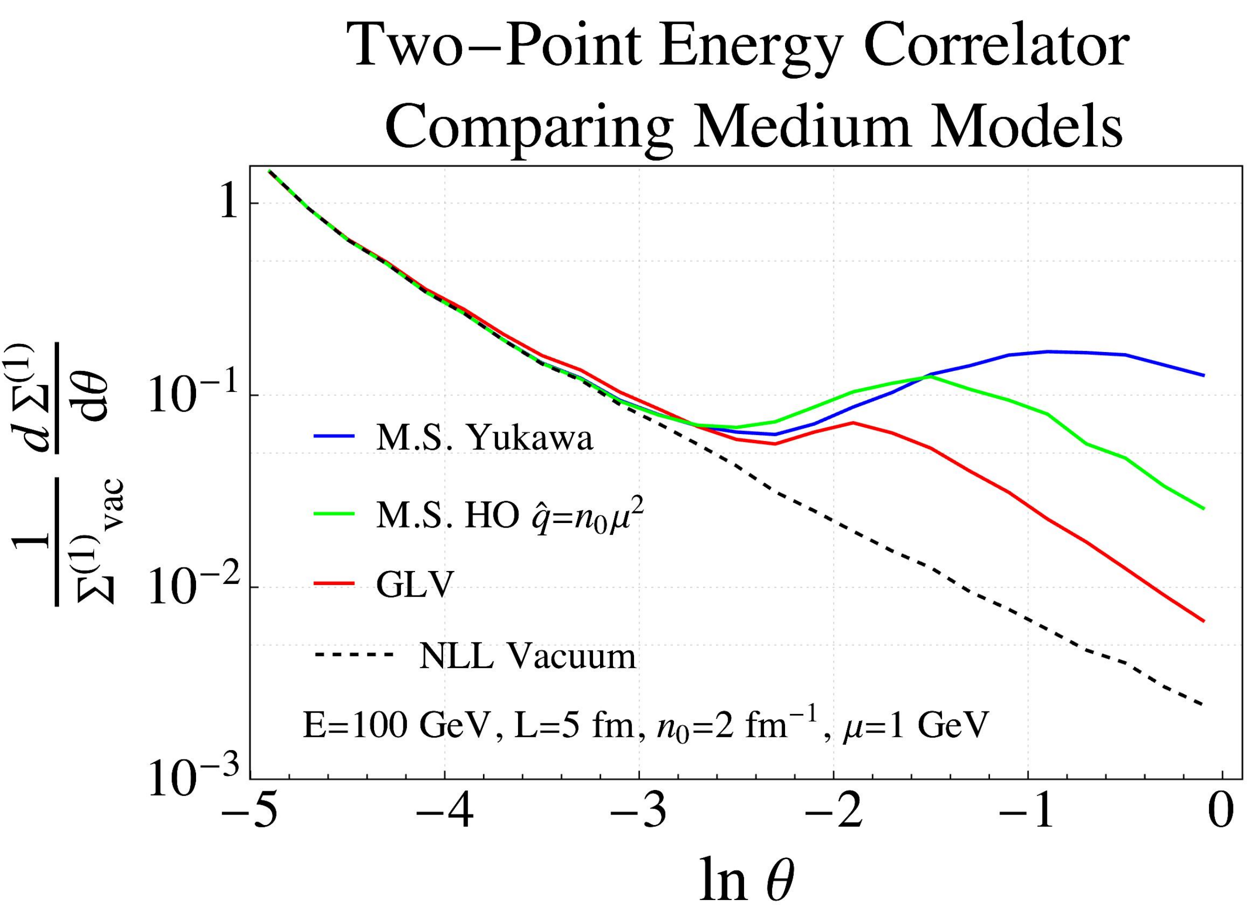


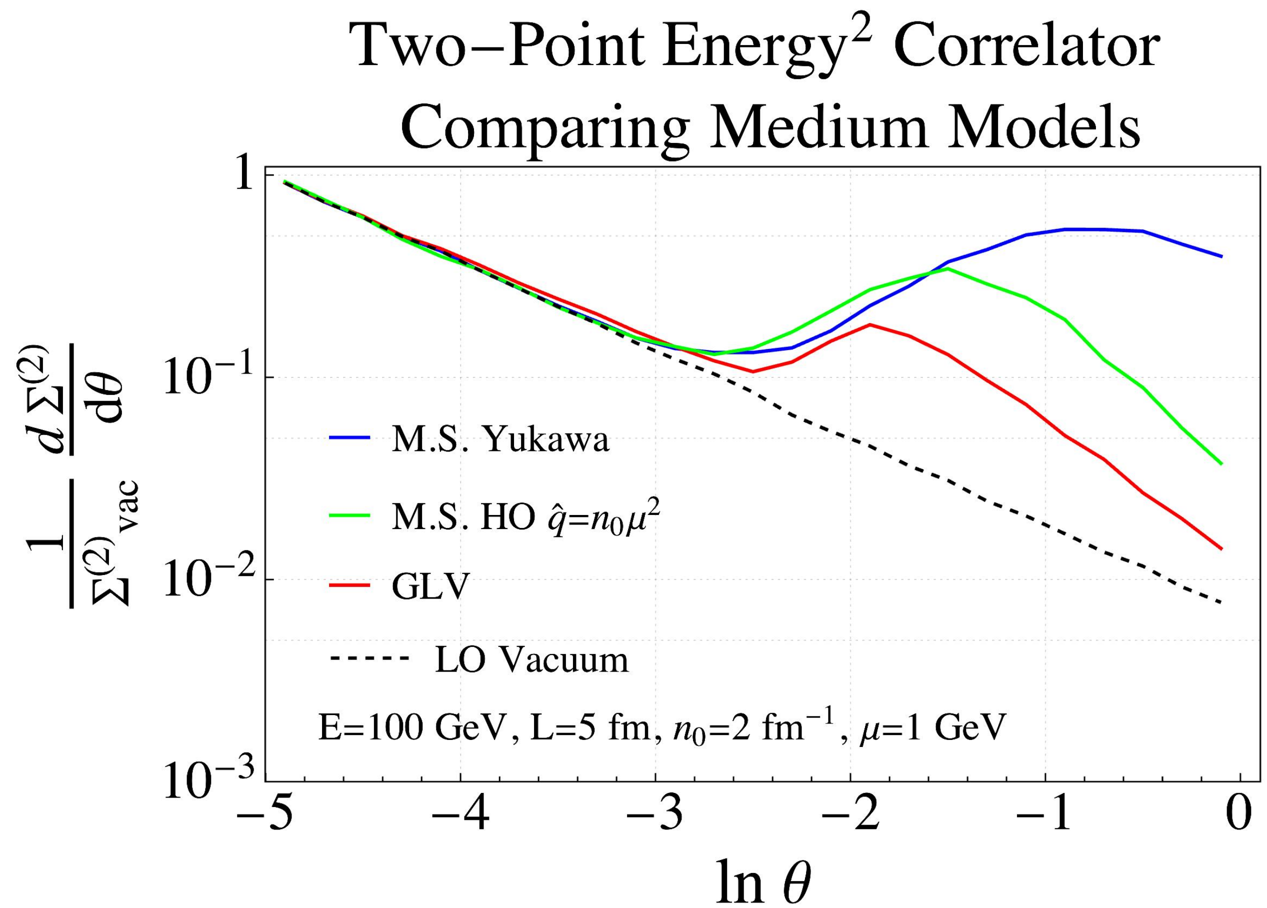
$\theta_c < \theta_L$





Higher energy power





Tilted Wilson lines

FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653
Isaksen, Tywoniuk 2107.02542

- Use high-energy limit of propagators: vacuum propagator times a Wilson line in the classical trajectory

$$\mathcal{G}_R(t_2, \boldsymbol{p}_2; t_1, \boldsymbol{p}_1; \omega) \to (2\pi)^2 \delta^{(2)}(\boldsymbol{p}_2 - \boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2 - t_1)} V_R(t_2, t_1; [\boldsymbol{n}t])$$

- Calculate averages of Wilson lines in the large-N_c limit (calculations also available for finite N_c). All averages can be expressed in terms of fundamental dipoles and quadrupoles

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger \right\rangle = S_{12} \qquad \frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger \right\rangle = Q$$

Tilted Wilson lines

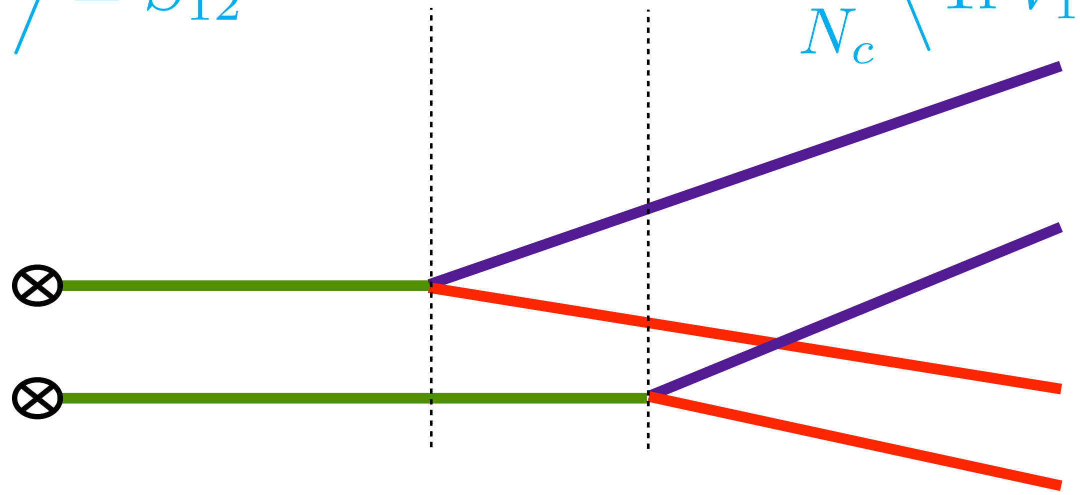
FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653
Isaksen, Tywoniuk 2107.02542

- Use high-energy limit of propagators: vacuum propagator times a Wilson line in the classical trajectory

$$\mathcal{G}_R(t_2, \boldsymbol{p}_2; t_1, \boldsymbol{p}_1; \omega) \to (2\pi)^2 \delta^{(2)}(\boldsymbol{p}_2 - \boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2, t_1; [\boldsymbol{n}t])$$

- Calculate averages of Wilson lines in the large-N_c limit (calculations also available for finite N_c). All averages can be expressed in terms of fundamental dipoles and quadrupoles

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger \right\rangle = S_{12} \qquad \frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger \right\rangle = Q$$



Tilted Wilson lines

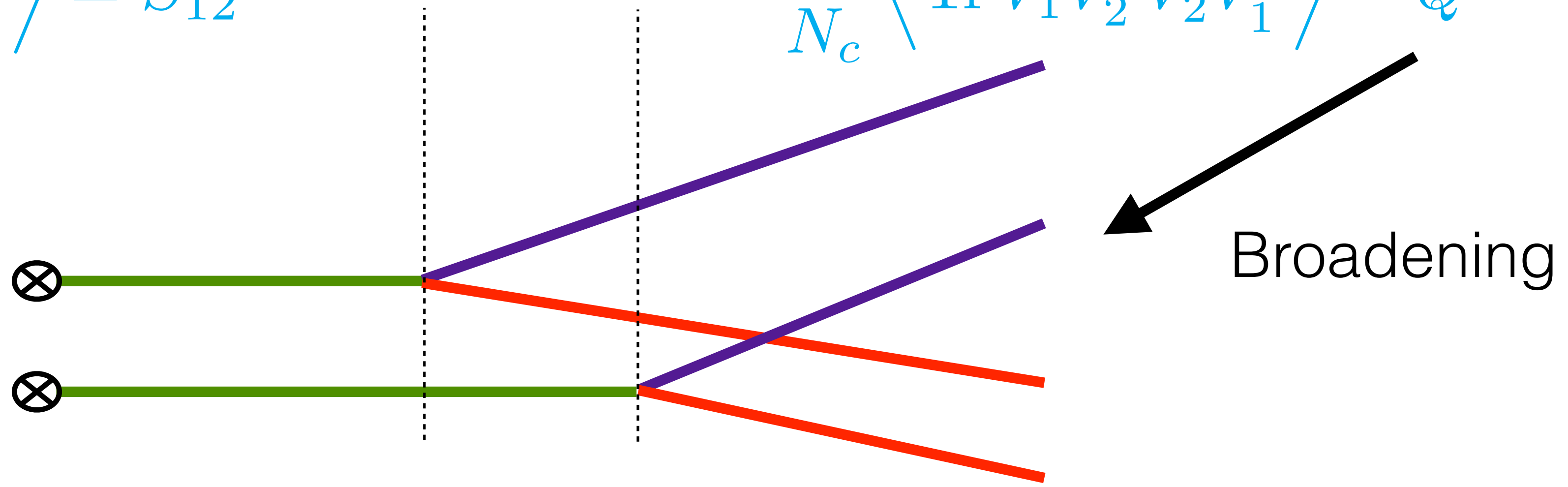
FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653
Isaksen, Tywoniuk 2107.02542

- Use high-energy limit of propagators: vacuum propagator times a Wilson line in the classical trajectory

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)} V_R(t_2,t_1;[\boldsymbol{n}t])$$

- Calculate averages of Wilson lines in the large-N_c limit (calculations also available for finite N_c). All averages can be expressed in terms of fundamental dipoles and quadrupoles

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger \right\rangle = S_{12} \qquad \frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger \right\rangle = Q$$



Tilted Wilson lines

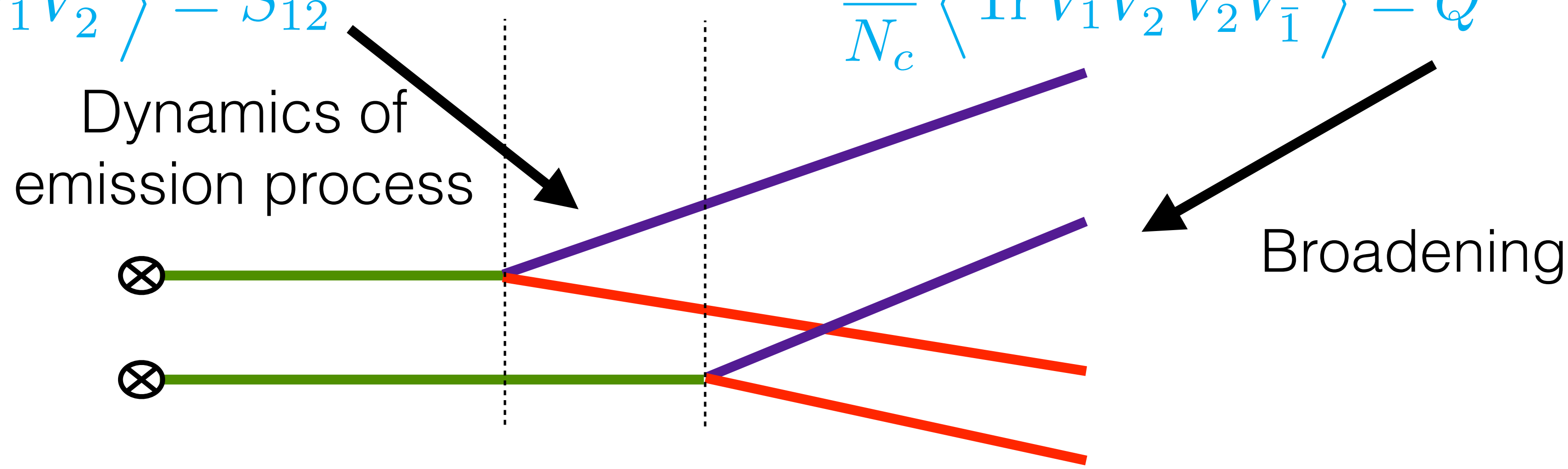
FD, Milhano, Salgado, Tywoniuk, Vila 1907.03653
Isaksen, Tywoniuk 2107.02542

- Use high-energy limit of propagators: vacuum propagator times a Wilson line in the classical trajectory

$$\mathcal{G}_R(t_2,\boldsymbol{p}_2;t_1,\boldsymbol{p}_1;\omega) \to (2\pi)^2\delta^{(2)}(\boldsymbol{p}_2-\boldsymbol{p}_1)\, e^{-i\frac{p_2^2}{2\omega}(t_2-t_1)}V_R(t_2,t_1;[\boldsymbol{n}t])$$

- Calculate averages of Wilson lines in the large-N_c limit (calculations also available for finite N_c). All averages can be expressed in terms of fundamental dipoles and quadrupoles

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger \right\rangle = S_{12} \qquad \frac{1}{N_c}\left\langle \mathrm{Tr}\, V_1 V_2^\dagger V_{\bar{2}} V_{\bar{1}}^\dagger \right\rangle = Q$$



EECs and color coherence