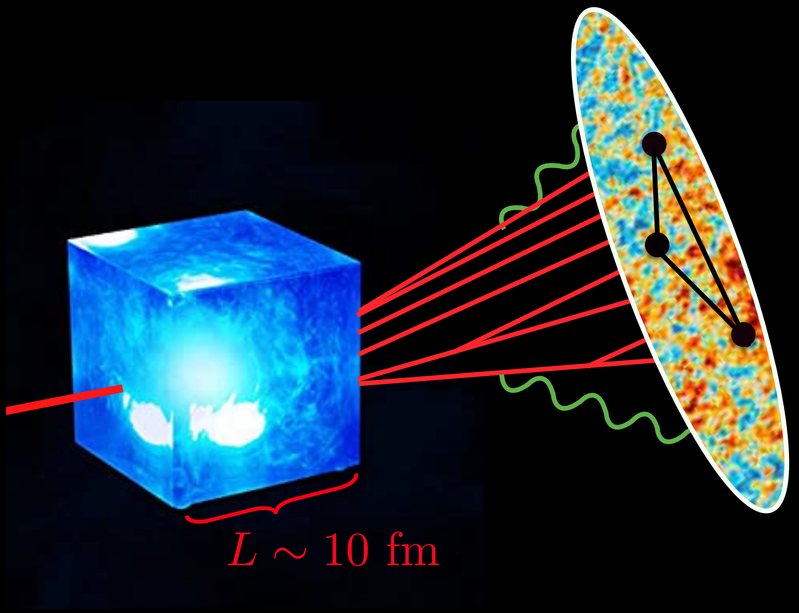
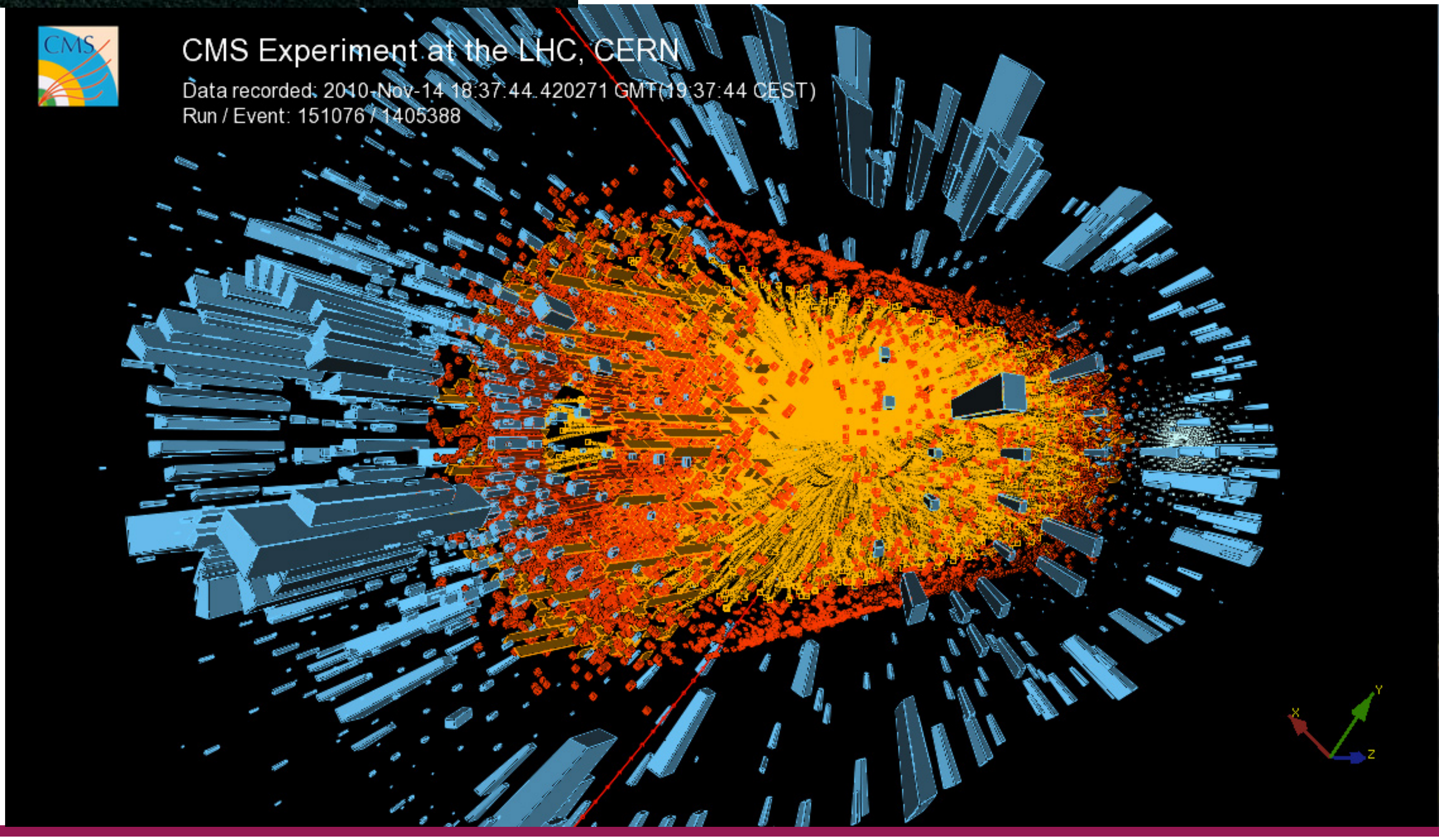
Jet substructure in heavy-ion collisions through energy correlators



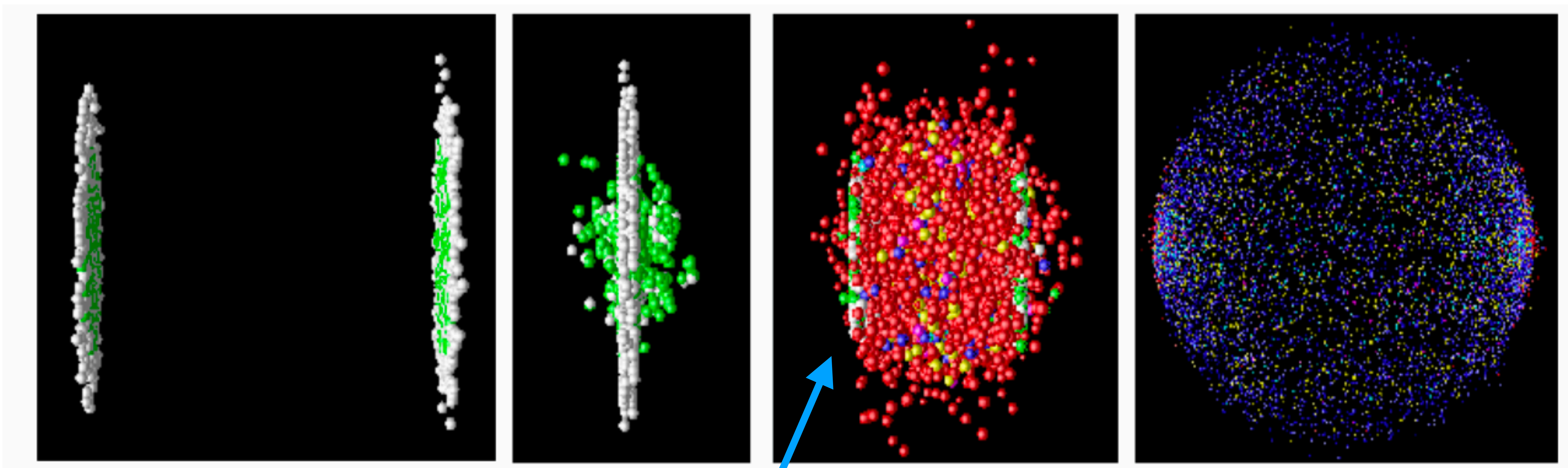
Carlota Andrés
CPHT, École polytechnique
LLR seminar, May 15th 2023


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388

Heavy-ion collisions

- 20 years of HICs at the Relativistic Heavy Ion Collider (**RHIC,** BNL, USA) and 10 years of HICs at the Large Hadron Collider (**LHC, CERN,** Geneva)

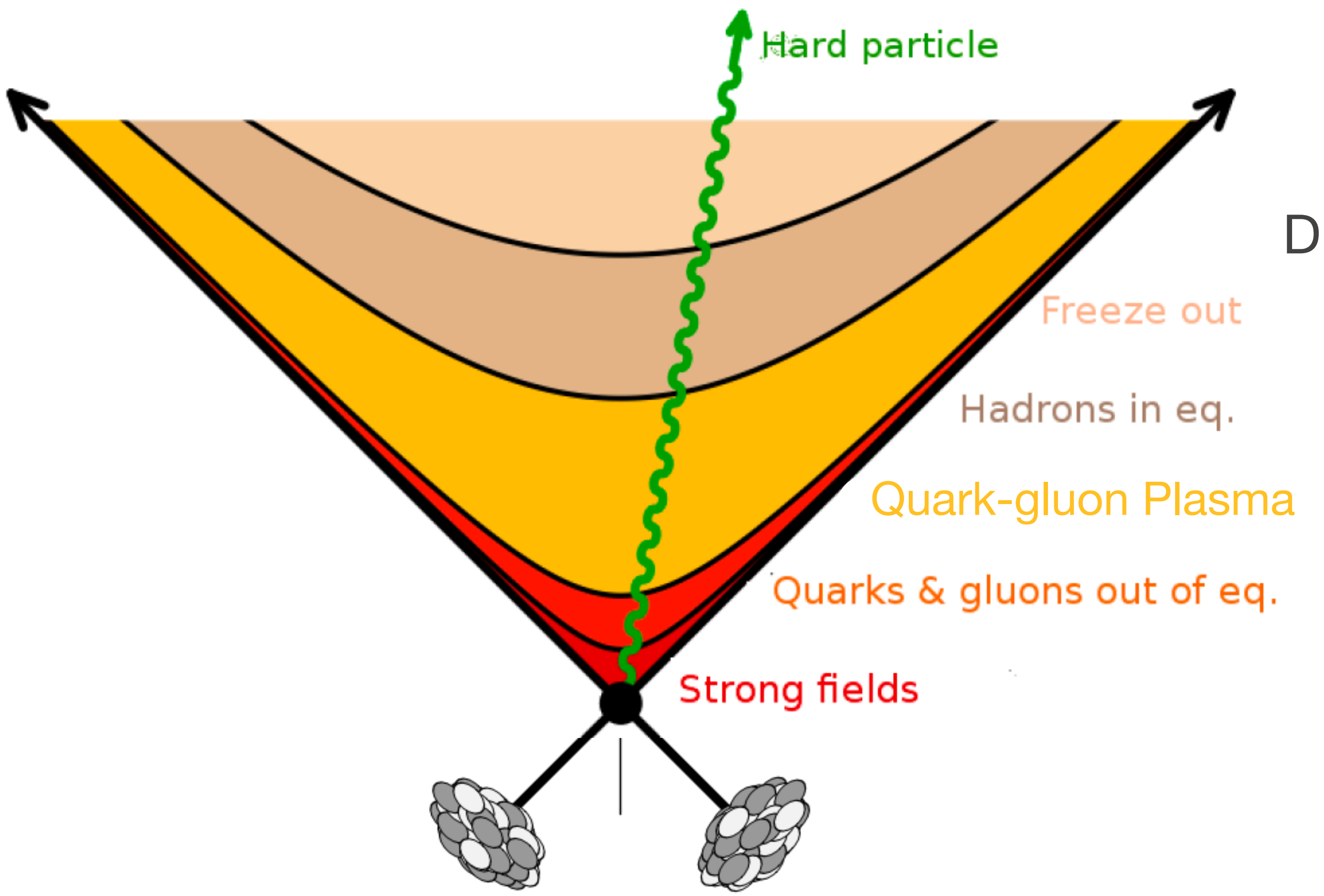


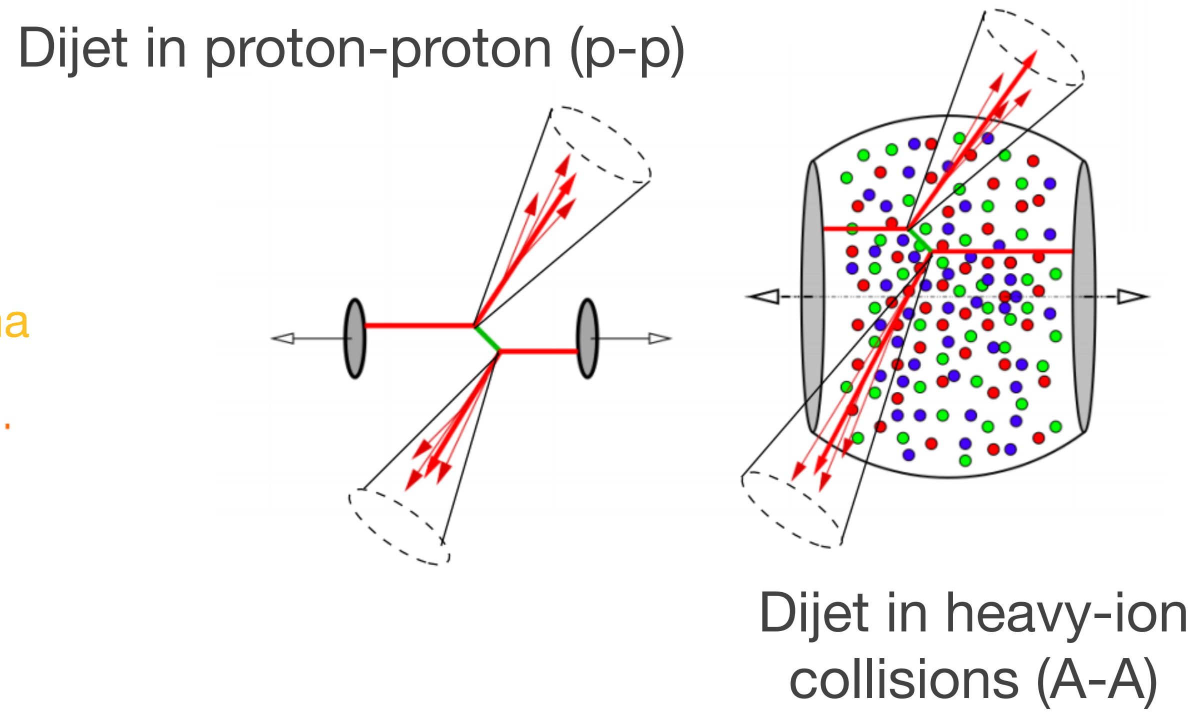
- New state of matter is produced: **quark-gluon plasma (QGP)**!
  - Formed by <u>deconfined quarks and gluons</u>
  - Behaves as a liquid (very well described by relativistic hydrodynamics)
  - Hottest liquid in the Universe (T~3 trillion ºC)

Hottest problem in Quantum Chromodynamics (**QCD**)!

HICs and jets

- How to study the QGP? Using **probes sensitive to it, such as jets**
- High-p_T hadrons/jets are produced with the initial collision

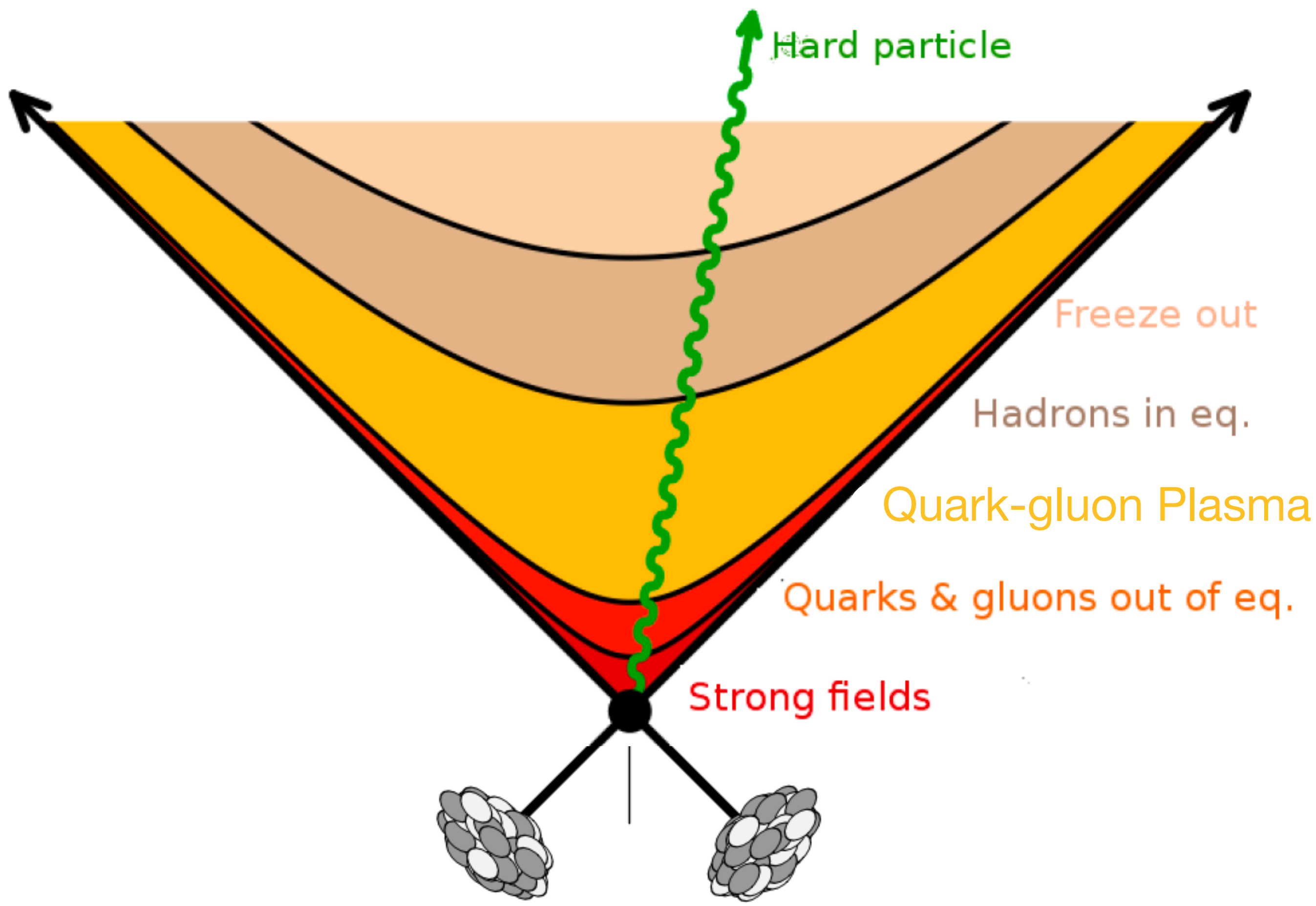


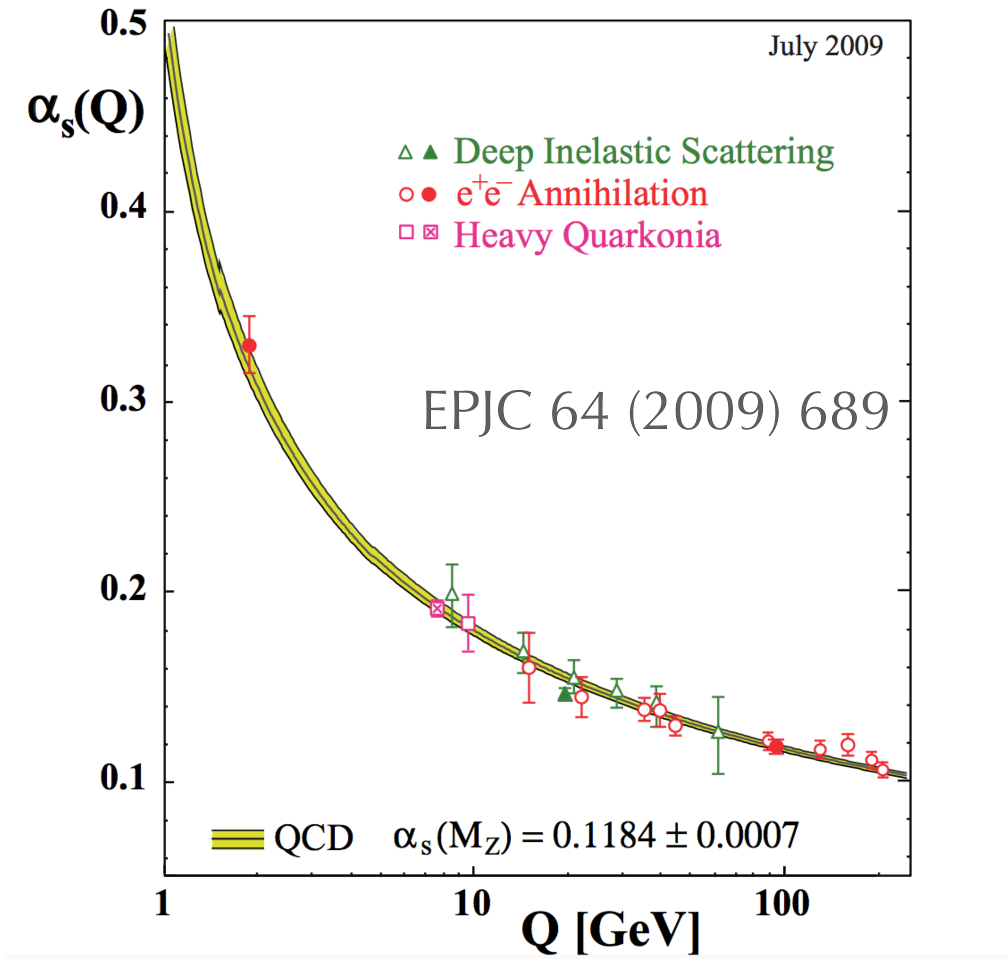


- They traverse the QGP experiencing **jet quenching**
- Large energy ⟶ We can use **perturbative QCD**

HICs and jets

- How to study the QGP? Using **probes sensitive to it, such as jets**
- High-p_T hadrons/jets are produced with the initial collision



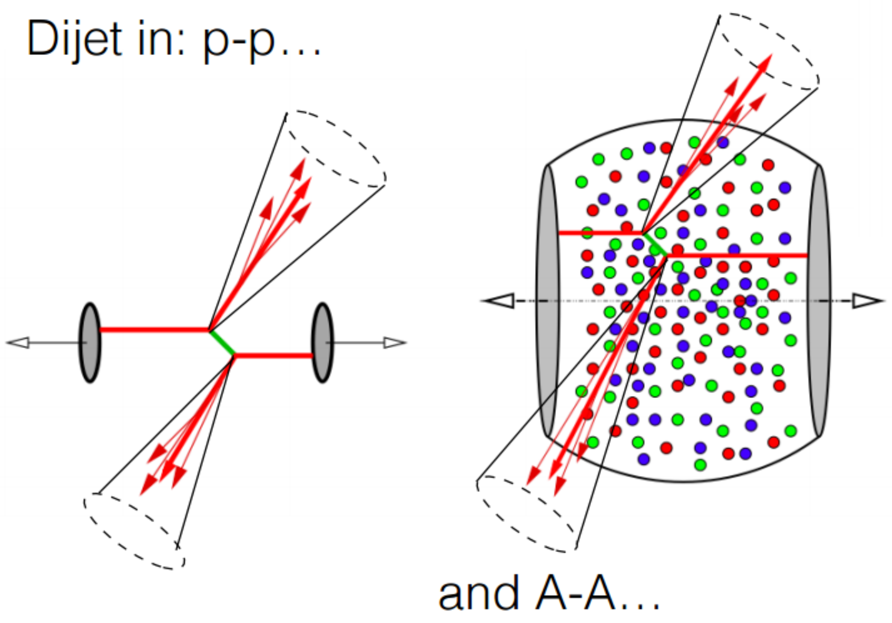


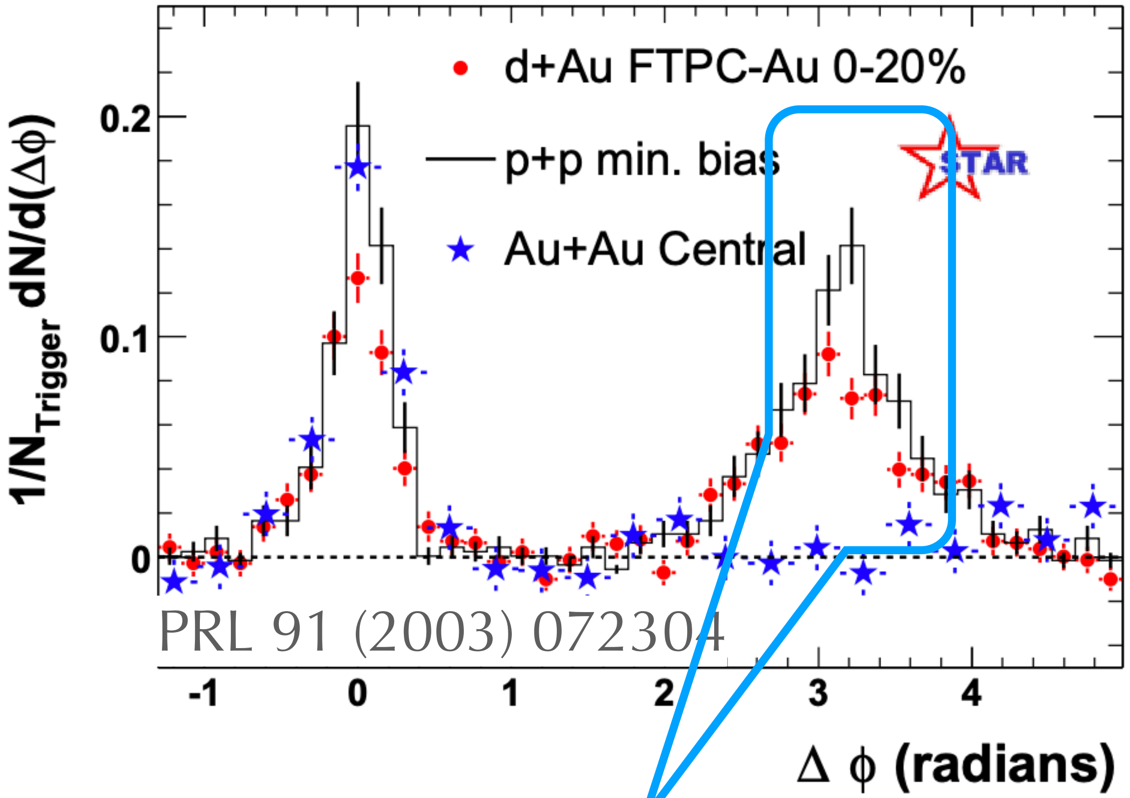
Asymptotic freedom

- They traverse the QGP experiencing **jet quenching**
- Large energy ⟶ We can use **perturbative QCD**

Energy loss

High-p_T hadrons and jets lose energy when interacting with the QGP

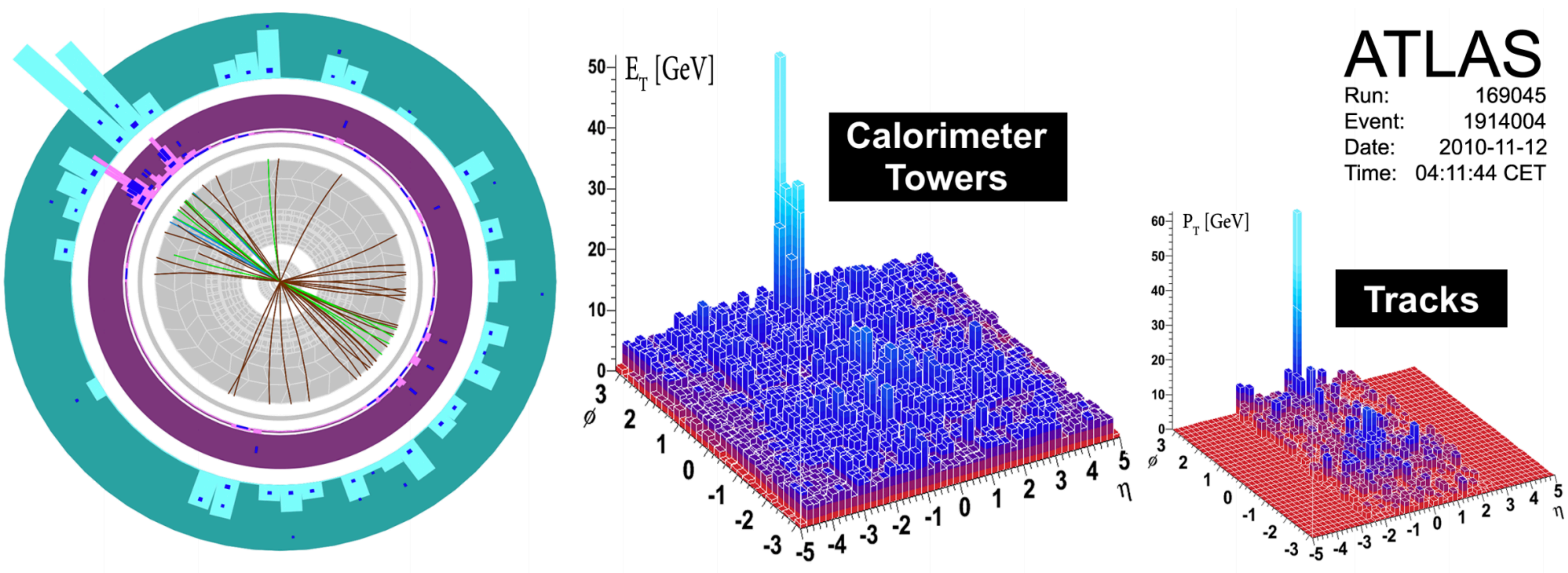




The correlation at 180º in HICs disappears!

Energy loss

High-p_T hadrons and jets lose energy when interacting with the QGP

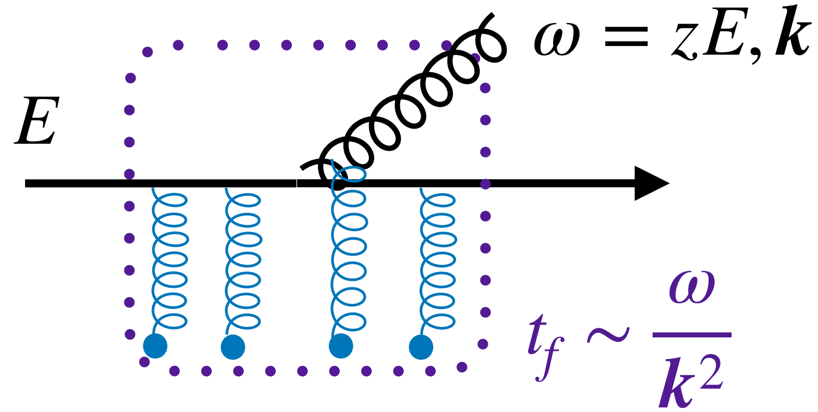


Medium-induced radiation

- Colored particles lose energy (mainly) due to medium-induced radiation

LPM effect

Landau, Pomeranchuk, Migdal



- Multiple scatterings formally resummed in the soft limit ($z \ll 1$ with zE finite) within the **BDMPS-Z formalism**

  Baier, Dokshitzer, Mueller, Peigné, Schiff (96)
  Zaharov (97)

- Single gluon emission spectrum understood very well in the soft limit

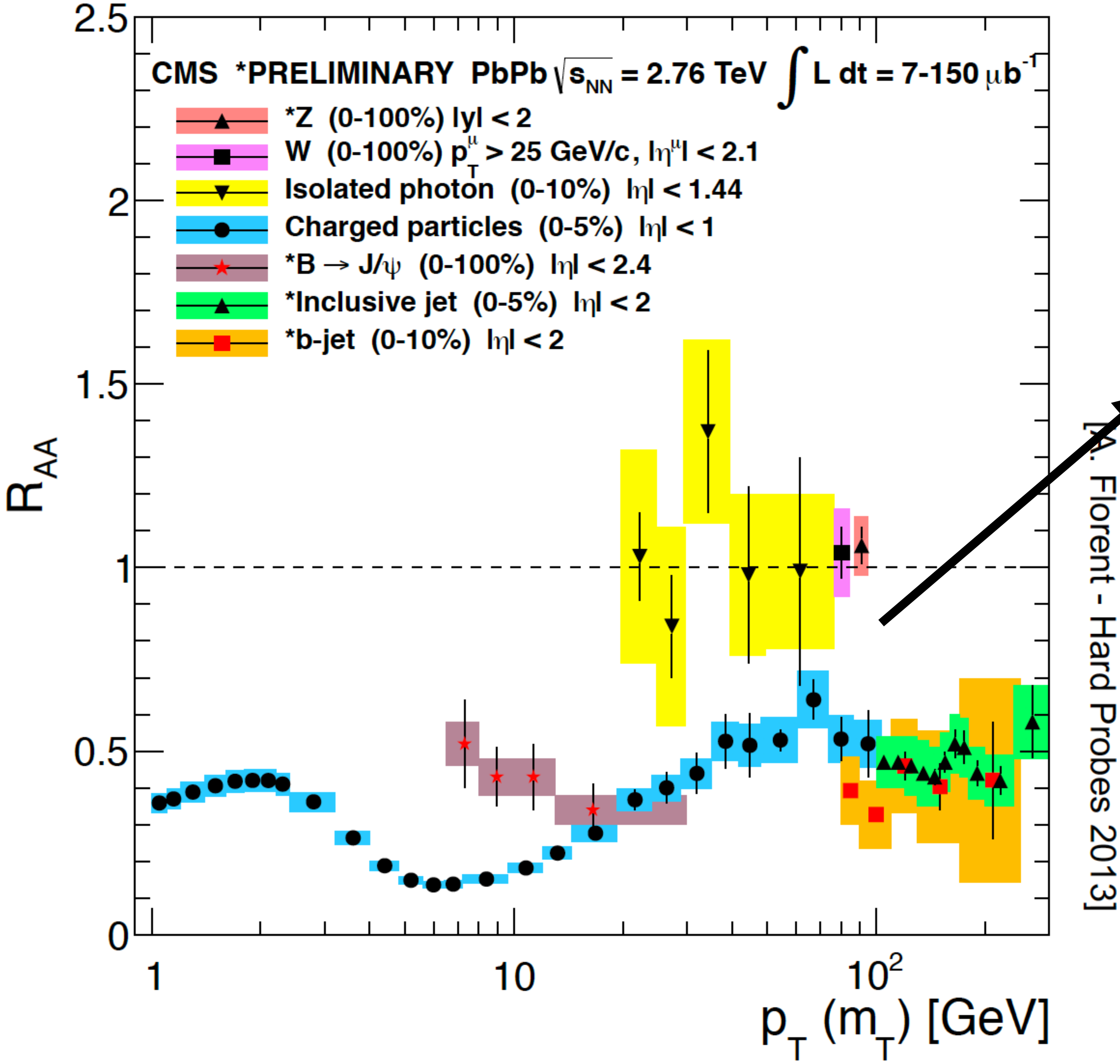
  Classical approximations: Harmonic oscillator, AMY, GLV

  New approaches: Full solution — Improved opacity expansion (IOE)

  Full solution: CA, Apolinário, Dominguez 2002.01517

  Improved opacity expansion (IOE): Mehtar-Tani, Barata, Soto-Ontoso, Tywoniuk, 1903.00506, 2004.02323, 2106.07402

Energy loss



Nuclear modification factor

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

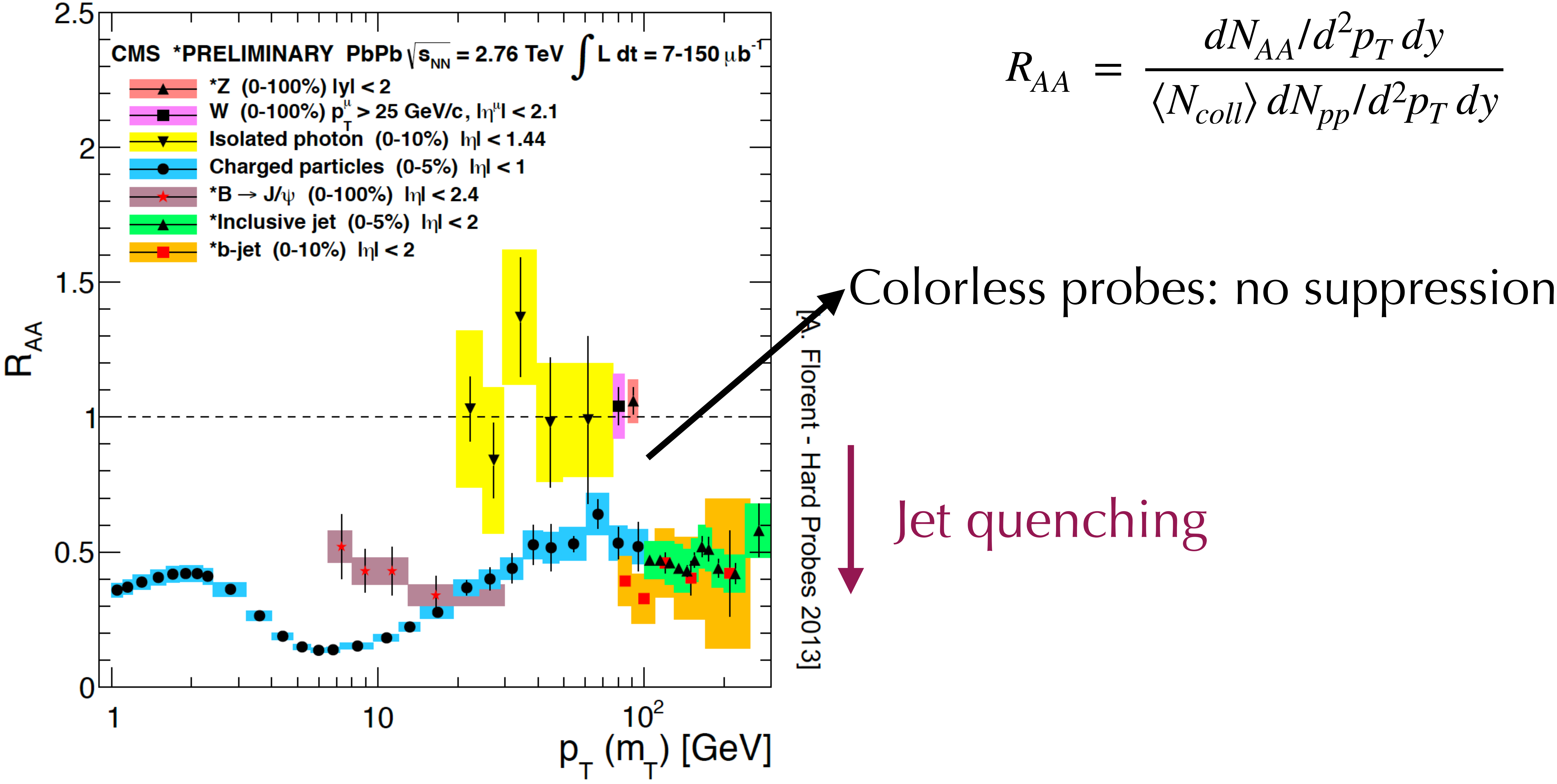
Colorless probes: no suppression

Jet quenching

Energy loss

Nuclear modification factor

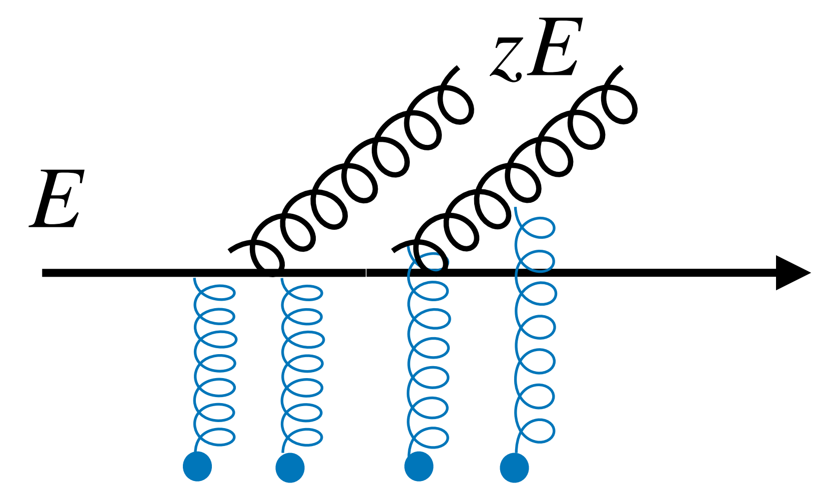
$$R_{AA} = \frac{dN_{AA}/d^2p_T\,dy}{\langle N_{coll}\rangle\, dN_{pp}/d^2p_T\,dy}$$



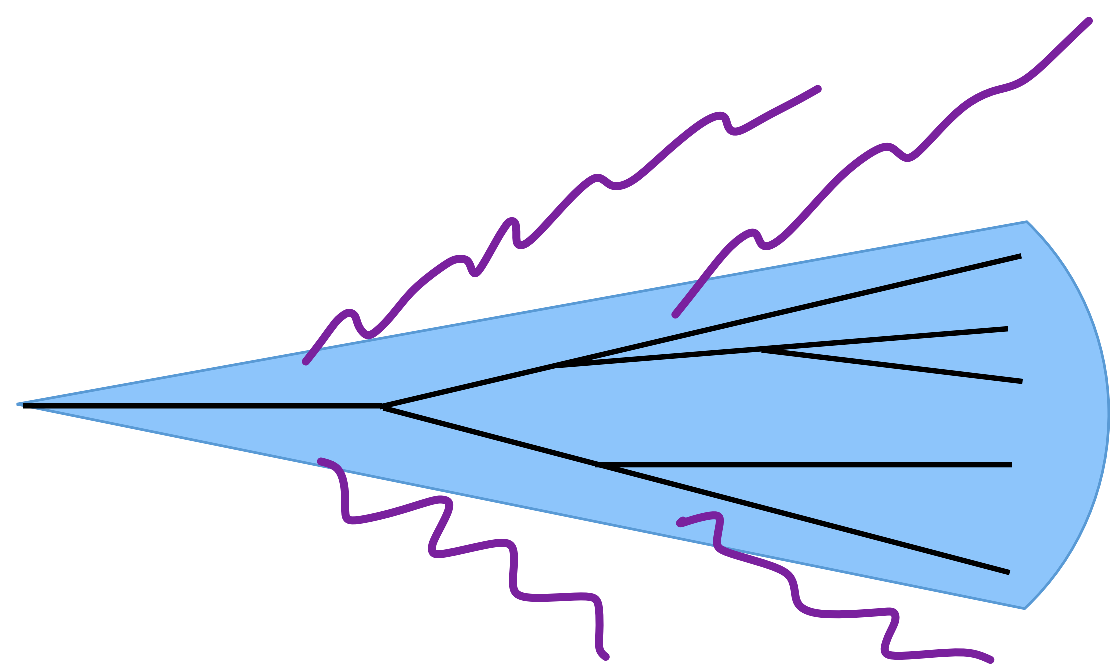
Jet inner structure also expected to be modified by the QGP

From energy loss to jet substructure

- For the **energy loss** calculation we **only need the soft limit** $z \ll 1$
  - Soft divergence of the vacuum vertex



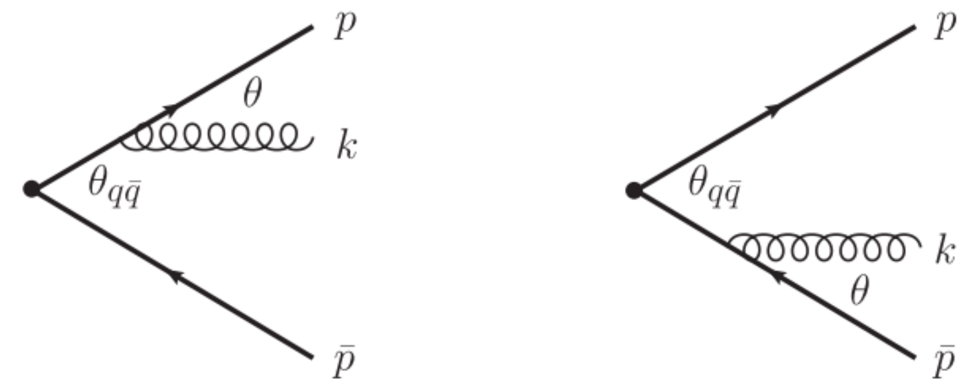
- For jet substructure
  - Emissions from multiple sources
  - Harder vertices



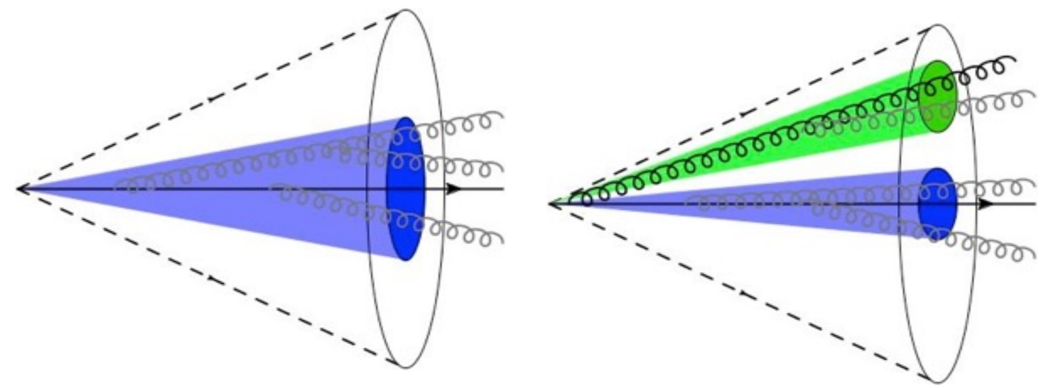
Color coherence in jet quenching

- Antenna calculations show that medium interactions can break angular ordering

  Mehtar-Tani, Tywoniuk, Salgado (2010)
  Casalderrey-Solana, Iancu (2011)

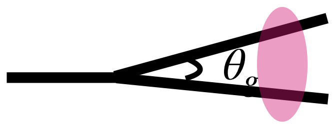


- Emergence of a resolution scale θ_c

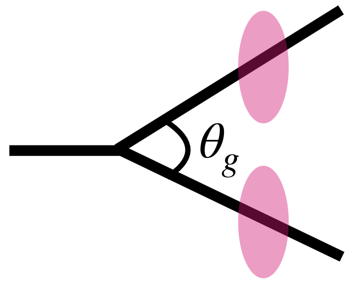


- Can this be seen at the level of one splitting?

$\theta_g < \theta_c$



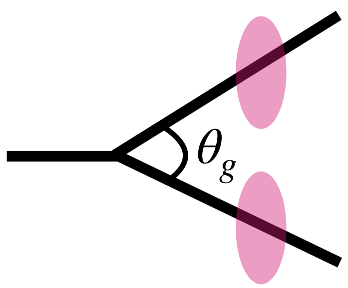
$\theta_g > \theta_c$



From energy loss to jet substructure

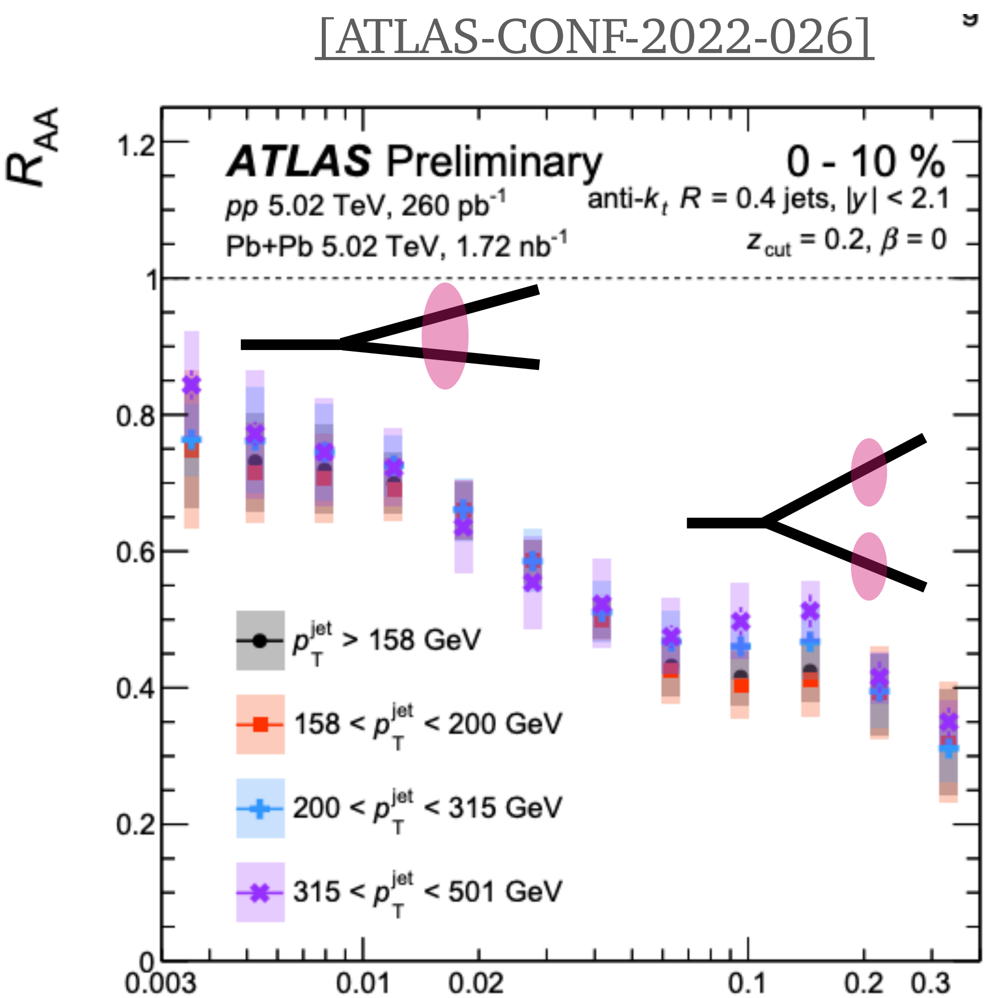
- Grooming techniques to isolate prongs corresponding to a **hard splitting**

$\theta_g > \theta_c$

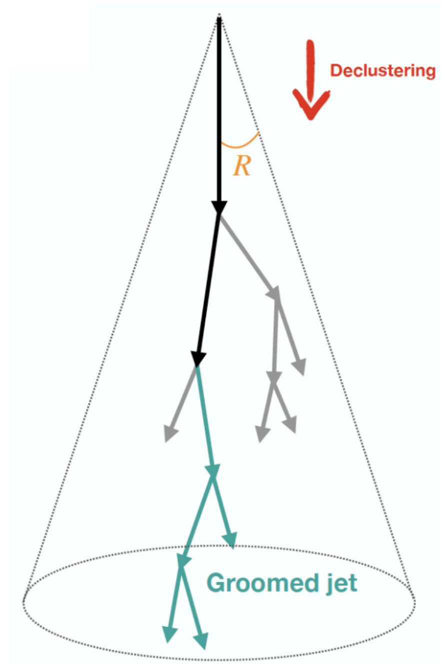


$\theta_g < \theta_c$

[ATLAS-CONF-2022-026]



$r_g = \theta_g R$



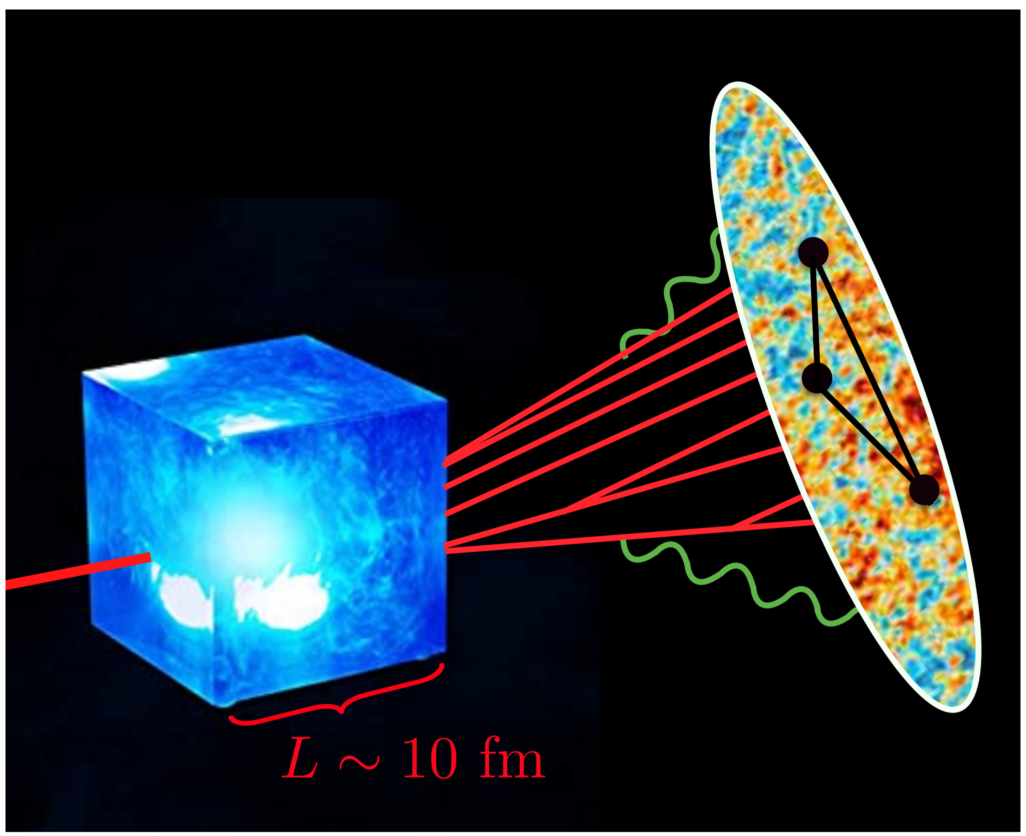
Sketch by Rey Torres

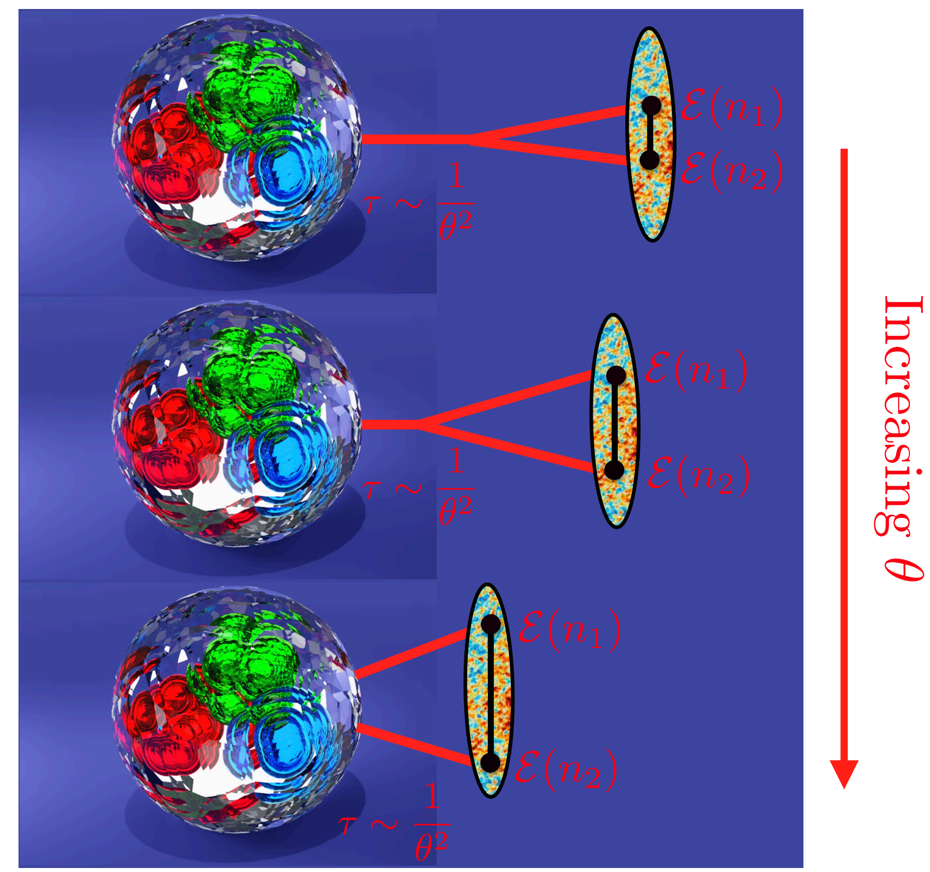
- Obtain θ_g and z_g distributions

Sensitivity of the θ_g-distribution to θ_c Caucal, Soto-Ontoso, Takacs, 2111.14768

Significant missidentification due to the large background in HI found Mulligan, Ploskon 2006.01812

Energy Correlators





CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, arXiv:2209.11236
CA, Dominguez, Holguin, Marquet, Moult, arXiv:2303.03413

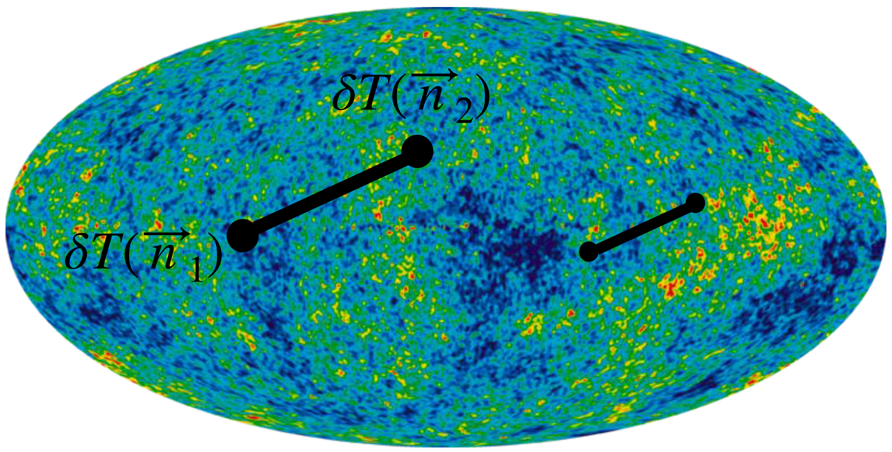
Correlation functions

- What are they?

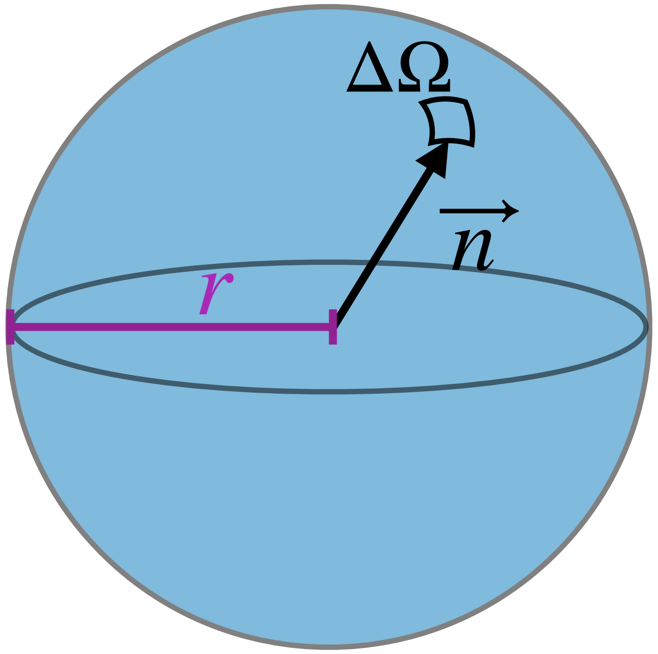
$$\text{Corr}_2(X, Y) = \langle XY \rangle - \langle X \rangle \langle Y \rangle$$

$$\text{Corr}_3(X, Y, Z) = \langle XYZ \rangle - \langle X \rangle \langle YZ \rangle - \langle Y \rangle \langle XZ \rangle - \langle Z \rangle \langle XY \rangle + 2\langle X \rangle \langle Y \rangle \langle Z \rangle$$

- In physics: usually $\langle X_i \rangle = 0 \Rightarrow \langle X_1, X_2, \ldots X_n \rangle$ is the *n*-point correlator



Energy correlators



- Correlators $\langle \varepsilon(\vec{n}_1)\varepsilon(\vec{n}_2)\cdots\varepsilon(\vec{n}_k)\rangle$ of the energy flux:

$$\varepsilon(\vec{n}) = \lim_{r\to\infty}\int \mathrm{d}t\, r^2 n^i\, T_{0i}(t, r\vec{n})$$

They naturally remove the soft physics with NO grooming!

- 1-point correlator: $\langle \varepsilon(\vec{n})\rangle \propto \sum_i E_i$ Total energy flux through an area element

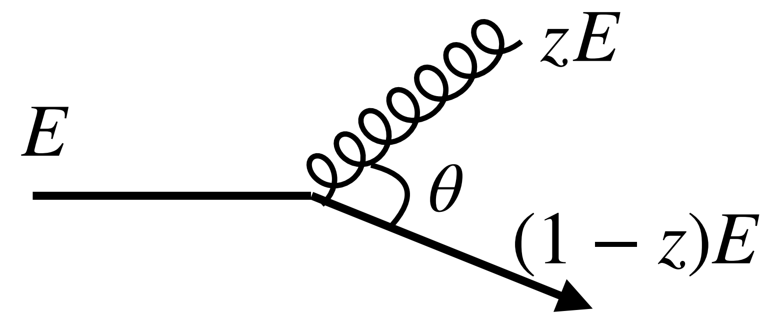
- 2-point correlator:

Inclusive cross section to produce two particles *i* and *j*

$$\frac{\langle \varepsilon^n(\vec{n_1})\varepsilon^n(\vec{n_2})\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\frac{\mathrm{d}\sigma_{ij}}{\mathrm{d}\vec{n}_i\mathrm{d}\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i - \vec{n}_1)\delta^{(2)}(\vec{n}_j - \vec{n}_2)$$

Hard scale of the process

2-point correlator



- As function of the relative angle only:

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

  - Infrared and collinear safe for $n = 1$
  - For divergences $1 < n \leq 2$ can be absorbed into track or fragmentation functions

- 2-point correlator for a quark jet: $Q = E$

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

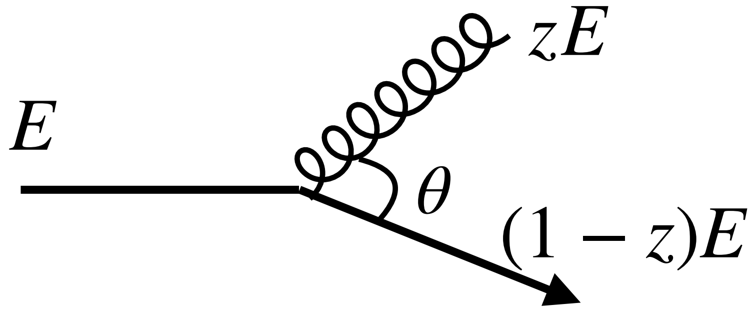
Inclusive cross section

μ_s a softer scale over which the cross section is inclusive

  - Additional energy loss ($E_q + E_g \neq E$) is subleading
  - qq and gg contributions are higher order

EEC in p-p

(In the perturbative regime)



- EEC for a massless quark jet in vacuum at LO:

$$\frac{d\sigma_{qg}^{\text{vac}}}{dz\,d\theta} = \frac{\alpha_s C_F\,\sigma}{\pi}\,\frac{1+(1-z)^2}{z\,\theta} + \mathcal{O}\left(\alpha_s^2, \theta\right) \quad \Rightarrow \quad \frac{d\Sigma^{(1)}}{d\theta} \sim \frac{1}{\theta}$$

- EEC for a massless quark jet in vacuum at NLO + NLL resummation:

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

Power-law behavior

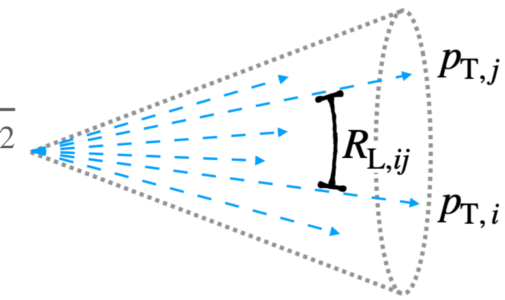
$\gamma(3)$ is the twist-2 spin-3 QCD anomalous dimension

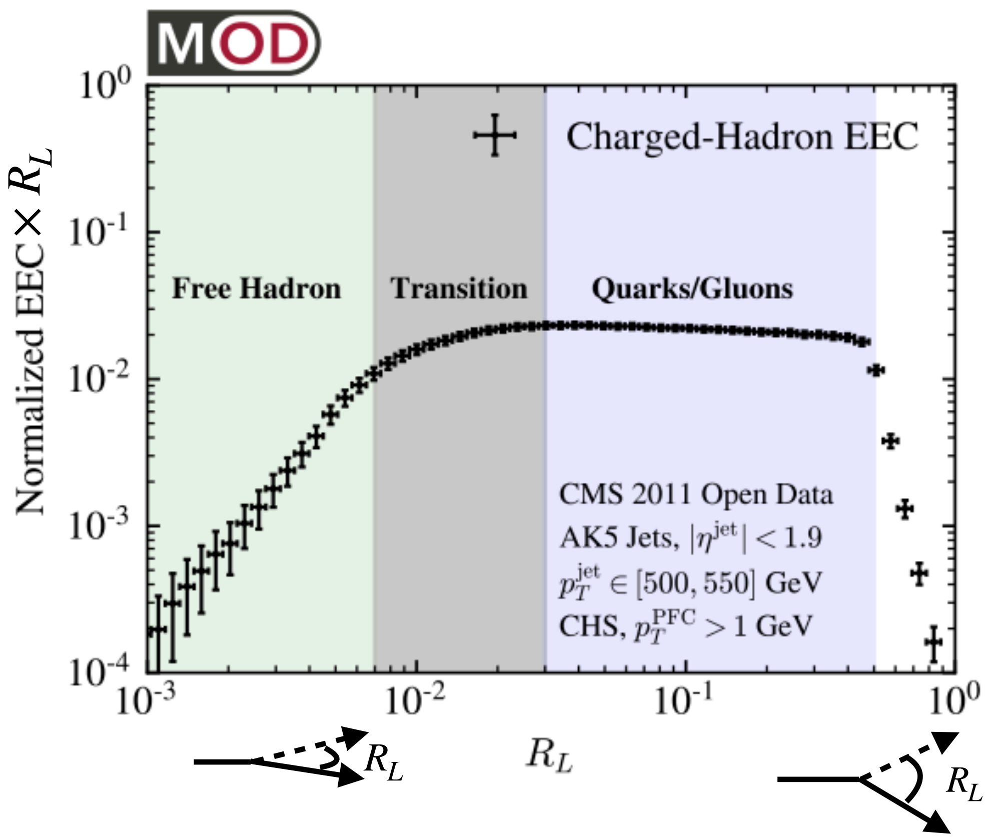
Hoffman, Maldacena, 0803.1467
Chen, Moult, Sandor, Zhu, 2202.04085

- Higher-orders, soft physics, quark/gluon ratios can change the overall normalization but not the power-law behavior

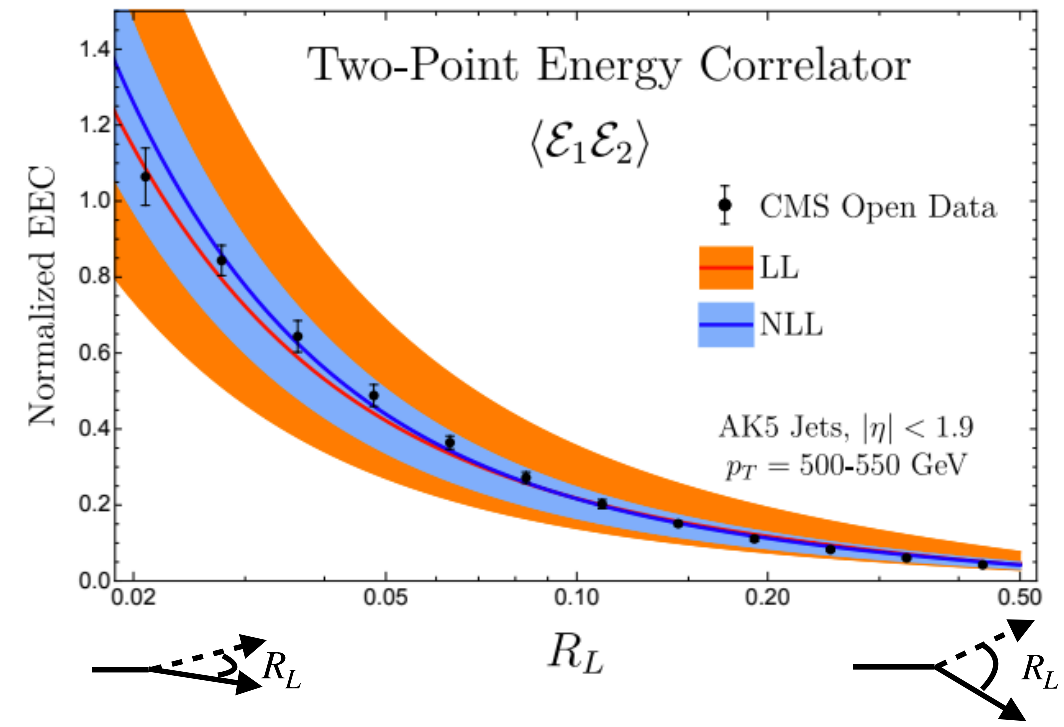
EEC in p-p

$R_L = \sqrt{\Delta\phi^2 + \Delta\eta^2}$





Komiske, Moult, Thaler, Zhu 2201.07800



Lee, Meçaj, Moult 2205.03414

EEC in p-p

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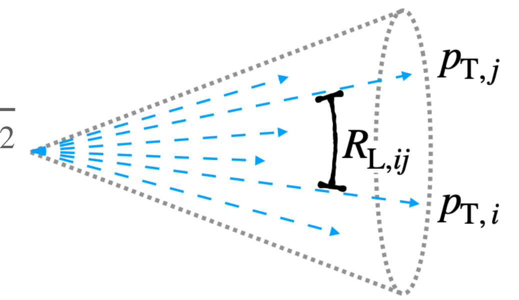

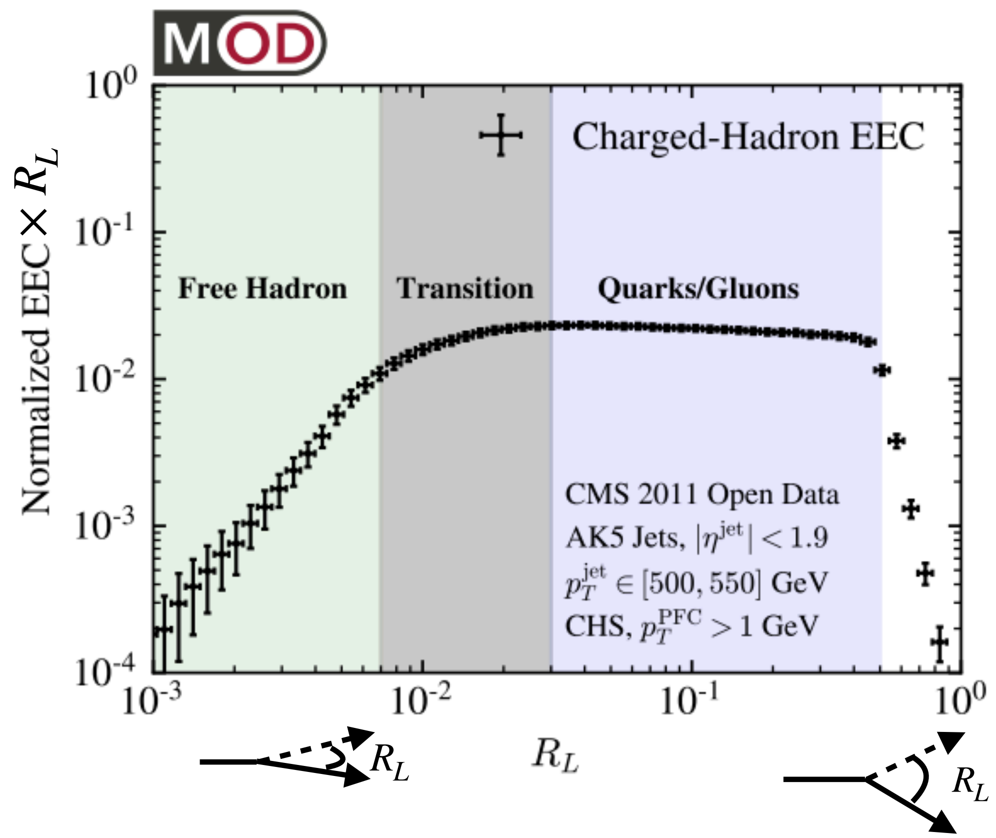

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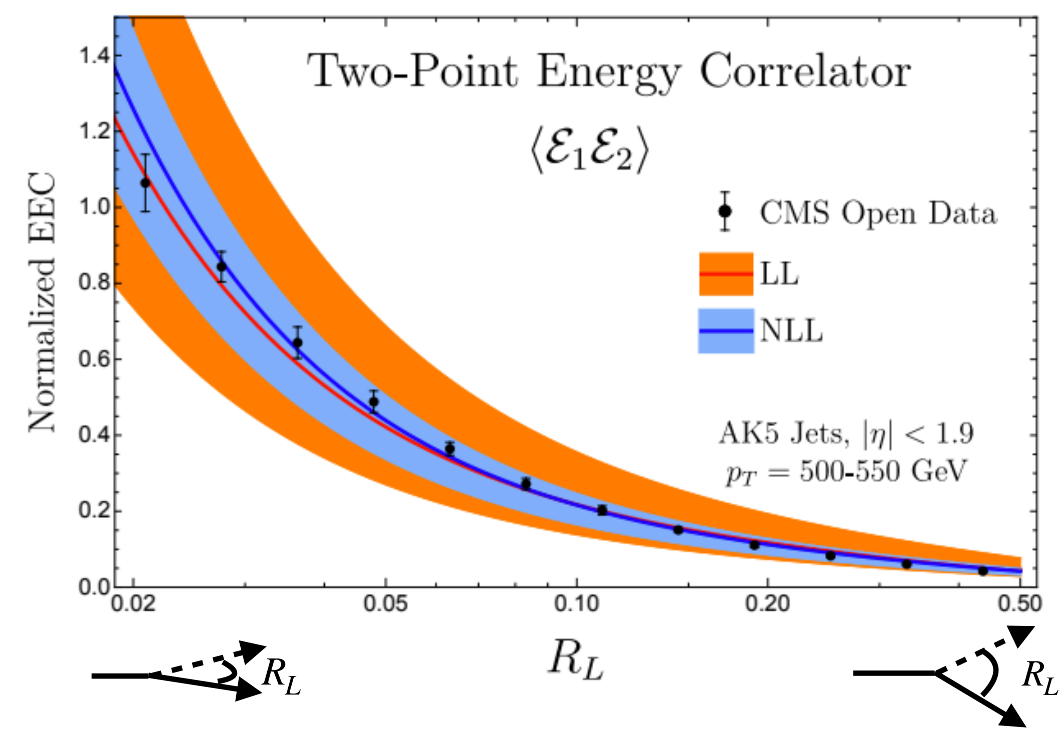


Lee, Meçaj, Moult 2205.03414

- Clear separation between perturbative and non-perturbative regimes
- p-p baseline under control
- Reduced sensitivity to soft physics

Energy correlators in HICs

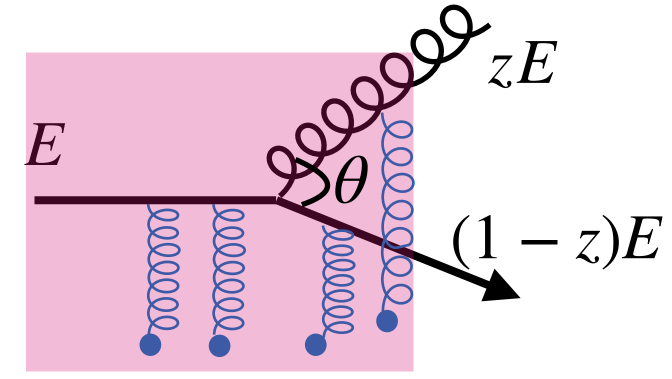
- **Background** is expected **to be less of an issue**
  - **Energy weighting** removes most of the soft physics, specially if one increases the power in the energy weighting
  - **Uncorrelated background** does not **affect** the shape of the correlations, **only** the **normalization**

- Observables are **not event-by-event**
  - Fluctuations are less important
  - Requires large statistics
  - Cannot be used to tag events

EEC in HICs

- EEC for a massless quark **heavy-ion** jet:

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



- We can always define F_{med} such as

$$\frac{d\sigma_{qg}}{d\theta dz} = \left(1 + F_{\text{med}}(z,\theta)\right) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz} \qquad F_{\text{med}}(z,\theta) \xrightarrow{\theta<\theta_L} 0$$

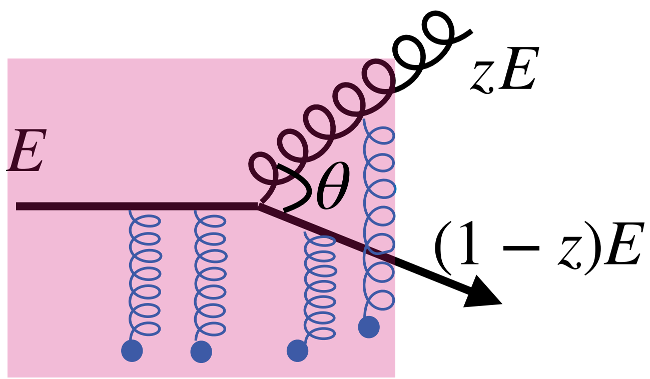
- We do not expect medium modification at small angles, thus vacuum collinear resummation should still be valid

$$\frac{d\Sigma^{(n)}}{d\theta} = \left(\frac{1}{\sigma_{qg}} \int dz \, \left(g^{(n)}(\theta,\alpha_s) + F_{\text{med}}(z,\theta)\right) \frac{d\sigma^{\text{vac}}}{d\theta dz} z^n (1-z)^n\right)\left(1 + \mathcal{O}\left(\frac{\bar{\mu}_s}{Q}\right)\right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{\theta Q}\right)$$

$$g^{(1)}(\theta,\alpha) = \theta^{\gamma(3)} + \mathcal{O}(\theta) \quad \Longrightarrow \quad \frac{d\Sigma^{(1)\,\text{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

Evaluation of the in-medium splitting

$$\frac{d\sigma_{qg}}{d\theta dz} = \left(1 + F_{\text{med}}(z,\theta)\right) \frac{d\sigma_{qg}^{\text{vac}}}{d\theta dz}$$



- Well understood in the soft limit $z \to 0$ or when all transverse momenta are integrated over, thus losing the angle dependence

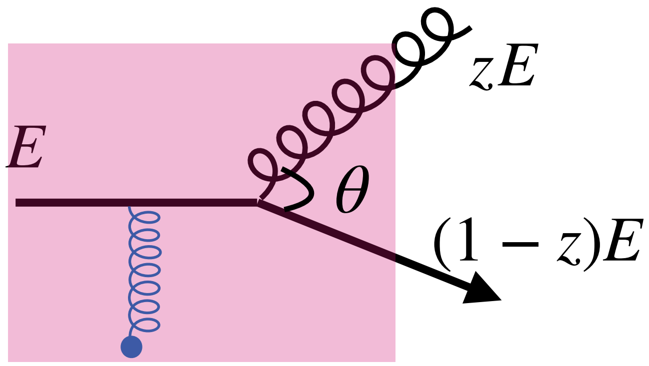
- For the energy correlator calculation is is crucial to **keep z finite and also the angle dependence**

- **Complete (multiple scatterings)** medium-induced emission spectrum **keeping z** and **θ not yet available**

Recent results for the $\gamma \to q\bar{q}$ case (computationally costly) Isaksen, Tywoniuk, 2303.12119

Beyond the soft limit

- Two available approaches:
  - **Opacity expansion:**



    - $N = 1$ result

      Ovanesyan, Vitev 1103.1074, 1109.5619

    - Highly complicated recursive relations to go to all orders

  - ***Tilted* Wilson lines (multiple scatterings resummed):**
    - Assumes *semi-hard* splittings (z not too small)
    - All partons propagate along straight line trajectories

Dominguez, Milhano, Salgado, Tywoniuk, Vila, 1907.03653

Isaksen, Tywoniuk 2107.02542

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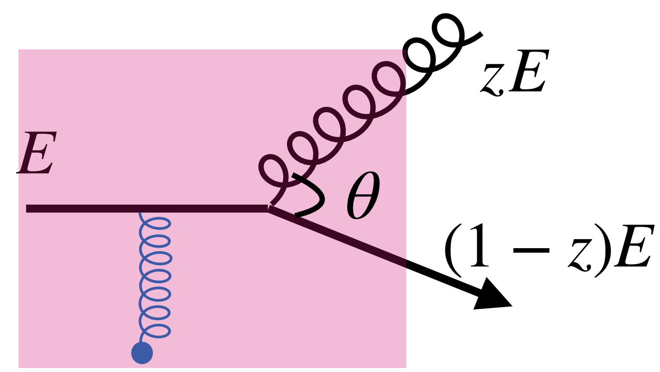
      Ovanesyan, Vitev 1103.1074, 1109.5619



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Dominguez, Milhano, Salgado, Tywoniuk, Vila, 1907.03653

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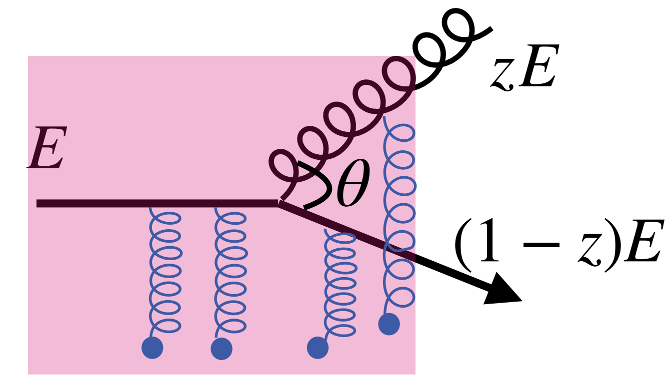
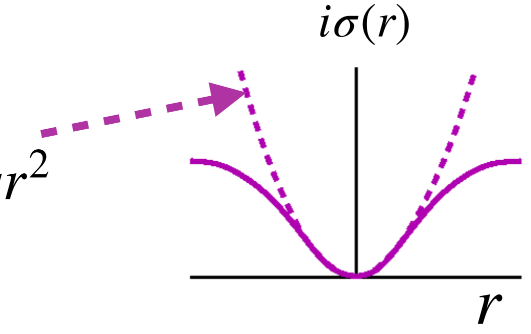
Our model



- Medium is assumed to be **static and uniform**, with length L
- **Harmonic oscillator** (HO) approximation employed $n\sigma(r) \approx \frac{1}{2}\hat{q}r^2$



- The strength of the interactions is encoded in the **jet quenching paramete**r $\hat{q}$, which measures the average transverse momentum transferred per unit length
- Emissions with a long formation time are not sensitive to the medium and therefore are emitted as in vacuum
- Multiple medium scatterings destroy the color coherence between the daughter partons

Time and angular scales (HO)

- For a static medium of length L within the HO one can read off the relevant scales directly from the formulas:

  2 competing angular scales: θ_L and θ_c

  - (Vacuum) formation time:

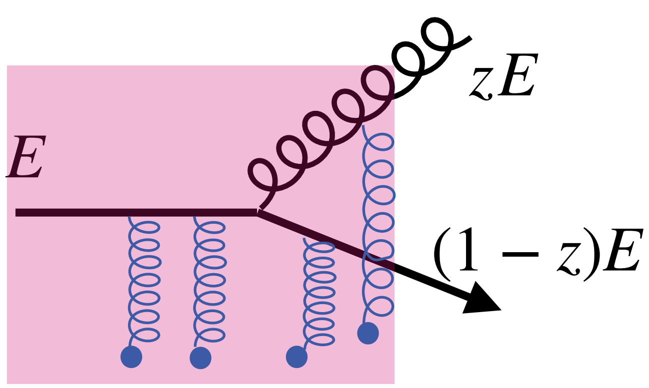
$$t_f = \frac{2}{z(1-z)E\theta^2} \xrightarrow{t_f \leq L} \theta_L \sim (EL)^{-1/2}$$

Below θ_L all emissions have a formation time larger than L

  - Decoherence time:

$$S_{12}(\tau) = e^{-\frac{1}{12}\hat{q}(1+z^2)\theta^2\tau^3} \qquad t_d \sim (\hat{q}\theta^2)^{-1/3} \xrightarrow{t_d \leq L} \theta_c \sim (\hat{q}L^3)^{-1/2}$$

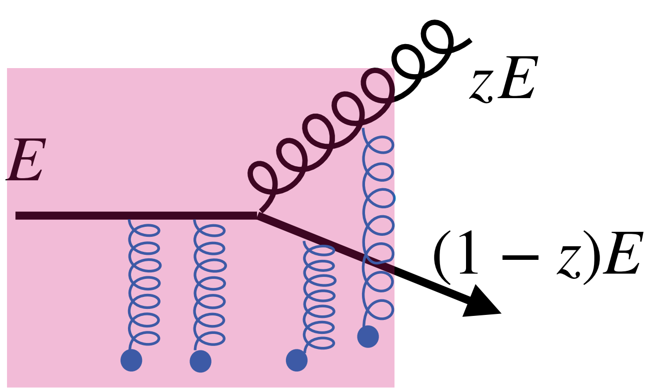
Below θ_c splittings do not color decohere and the medium does not resolve them



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

Time and angular scales (HO)

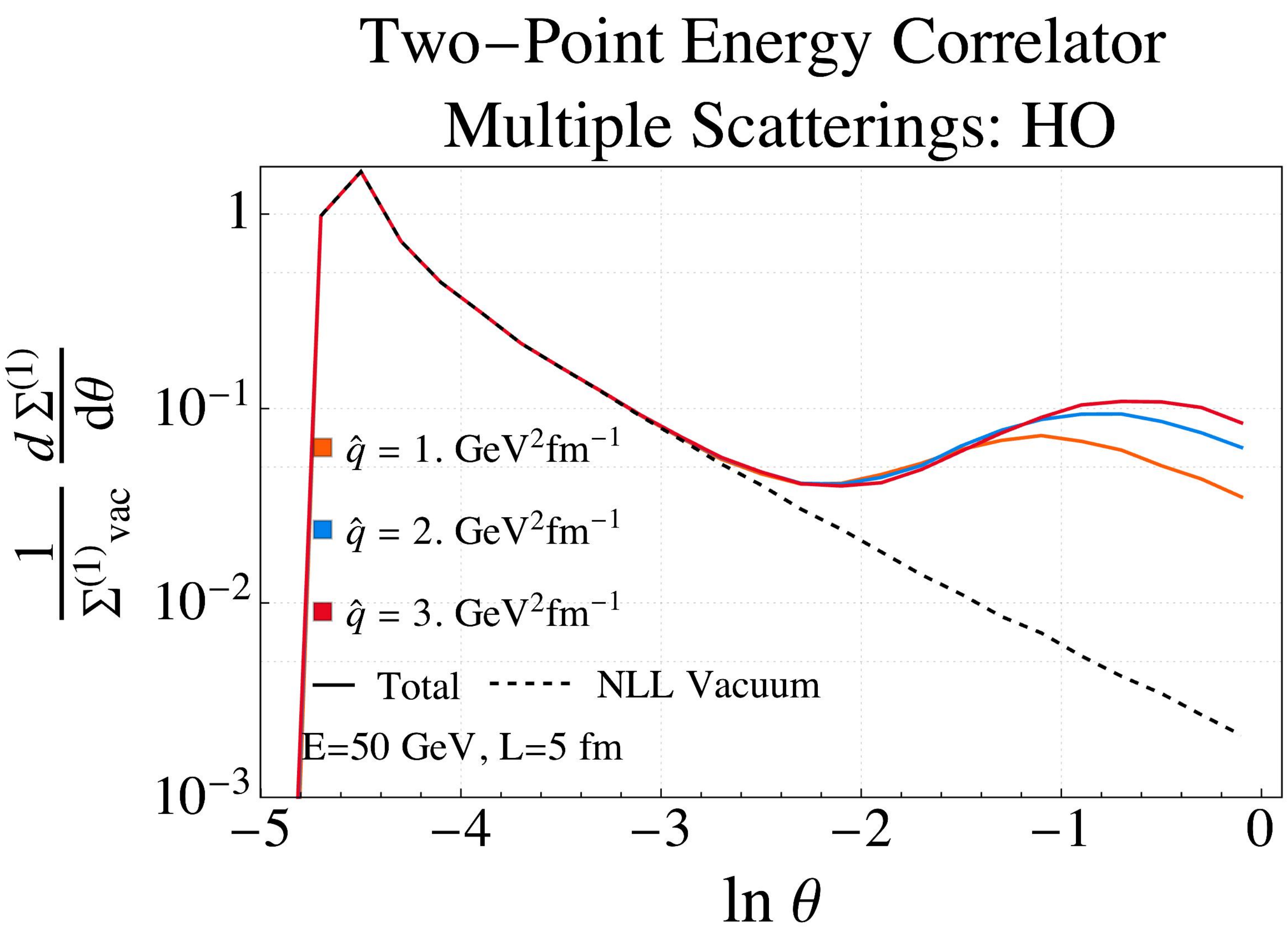
Can be extended to include a more **realistic interactions or expanding media**, but then we would not know the scales directly from the equations



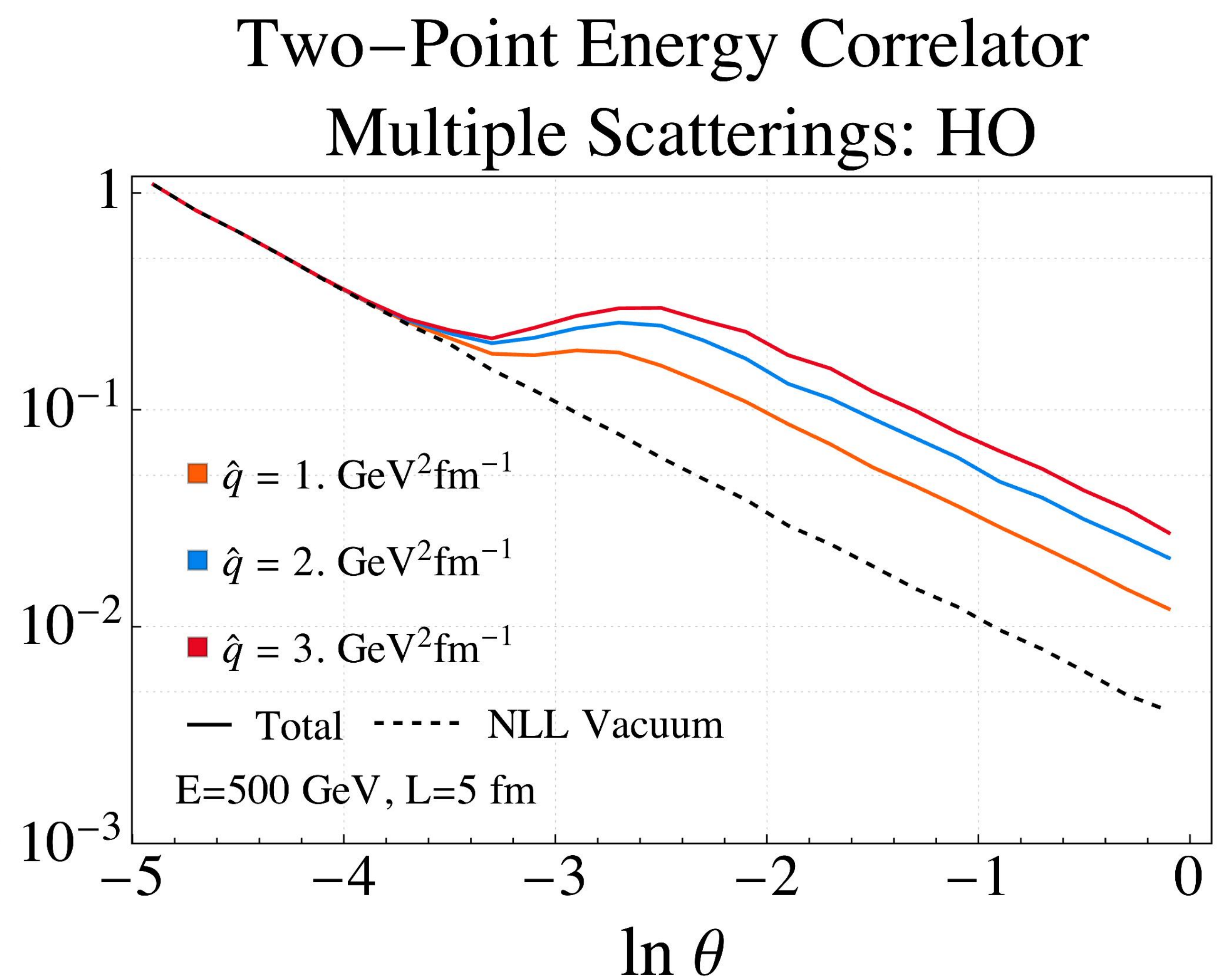
If $\theta_L > \theta_c$: θ_c becomes irrelevant

Results HO

$\theta_L \gg \theta_c \left(E \ll \hat{q}L^2\right)$



$\theta_L \ll \theta_c \left(E \gg \hat{q}L^2\right)$



Results HO

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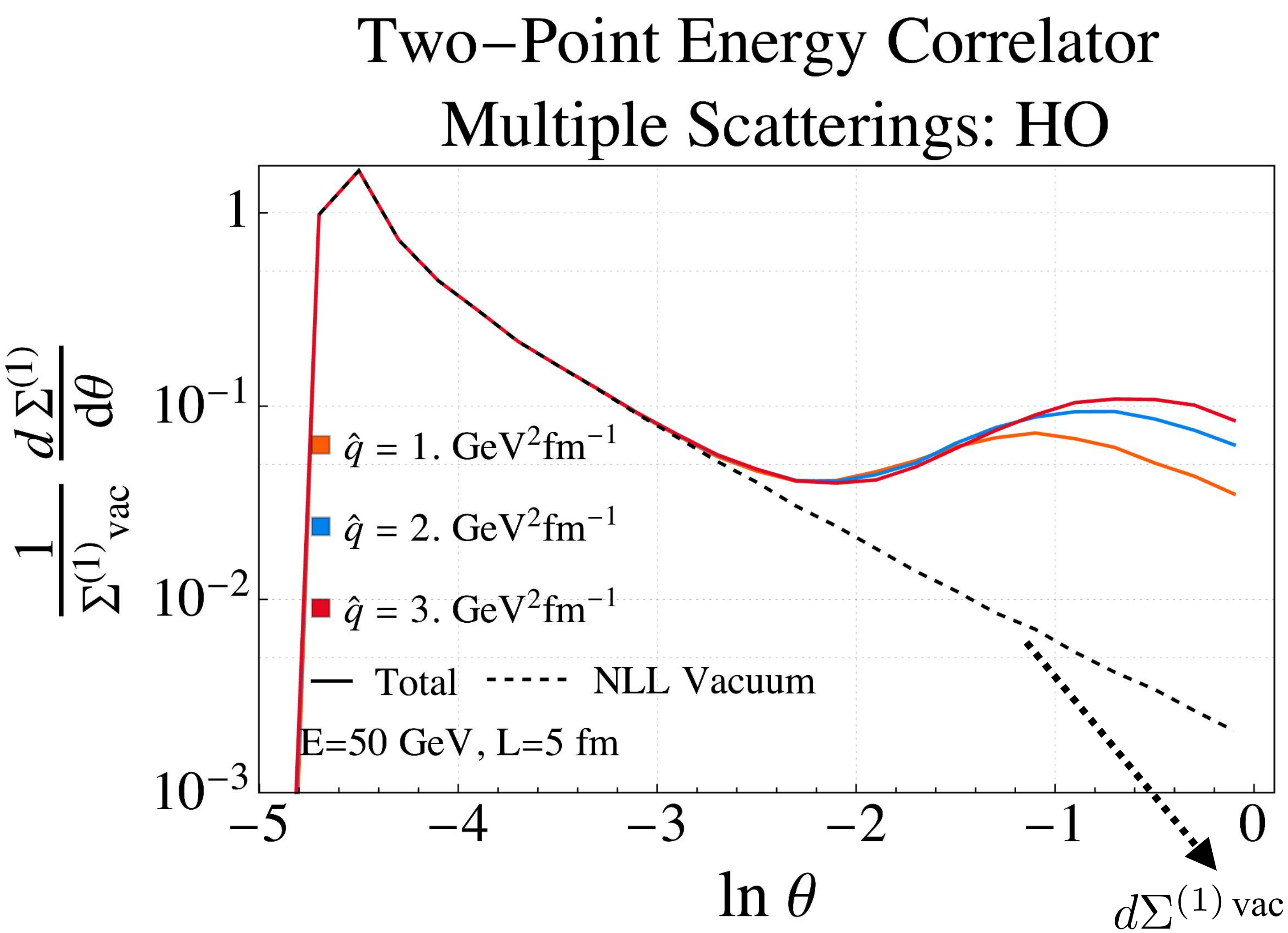
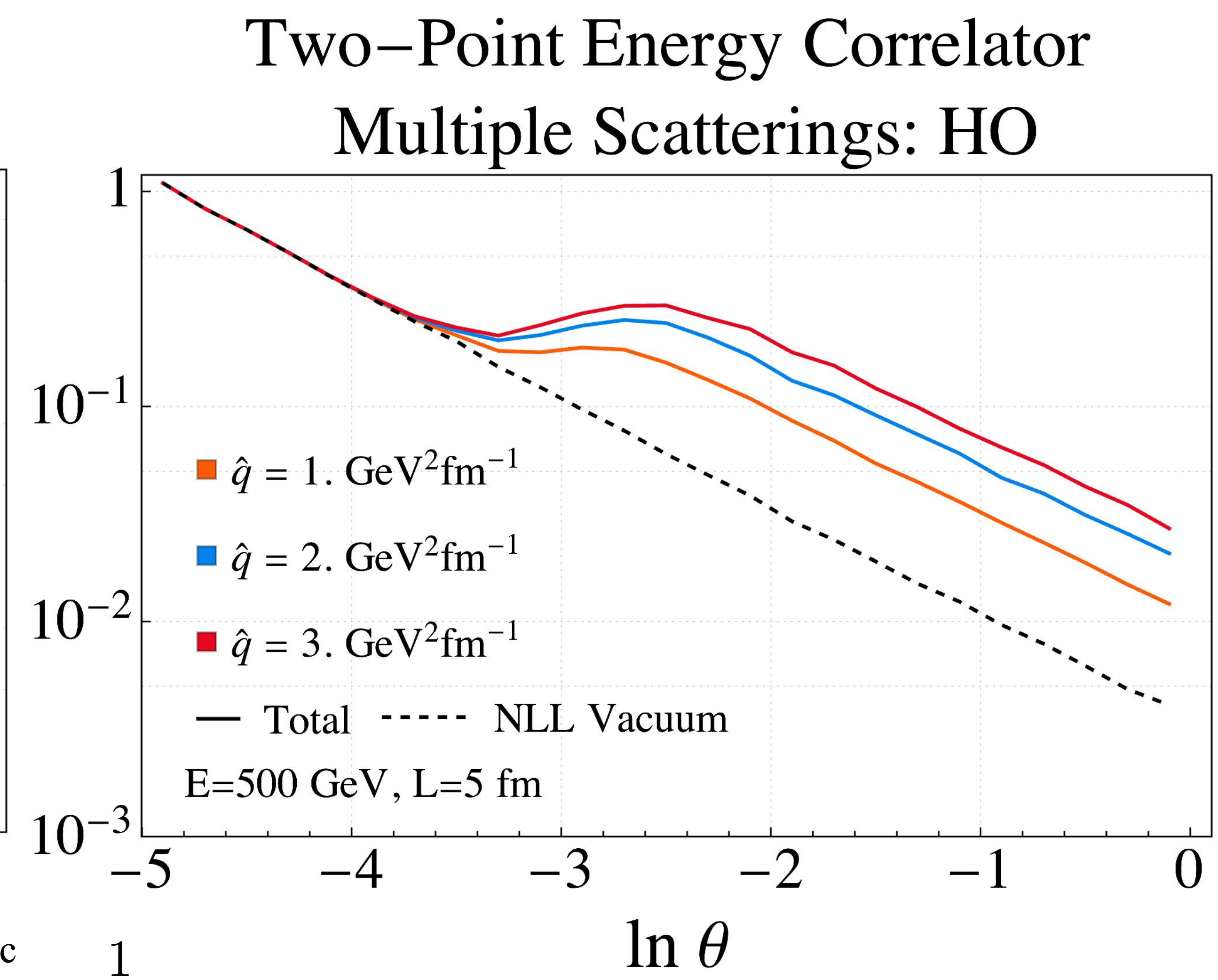


$$\frac{d\Sigma^{(1)\,\rm vac}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

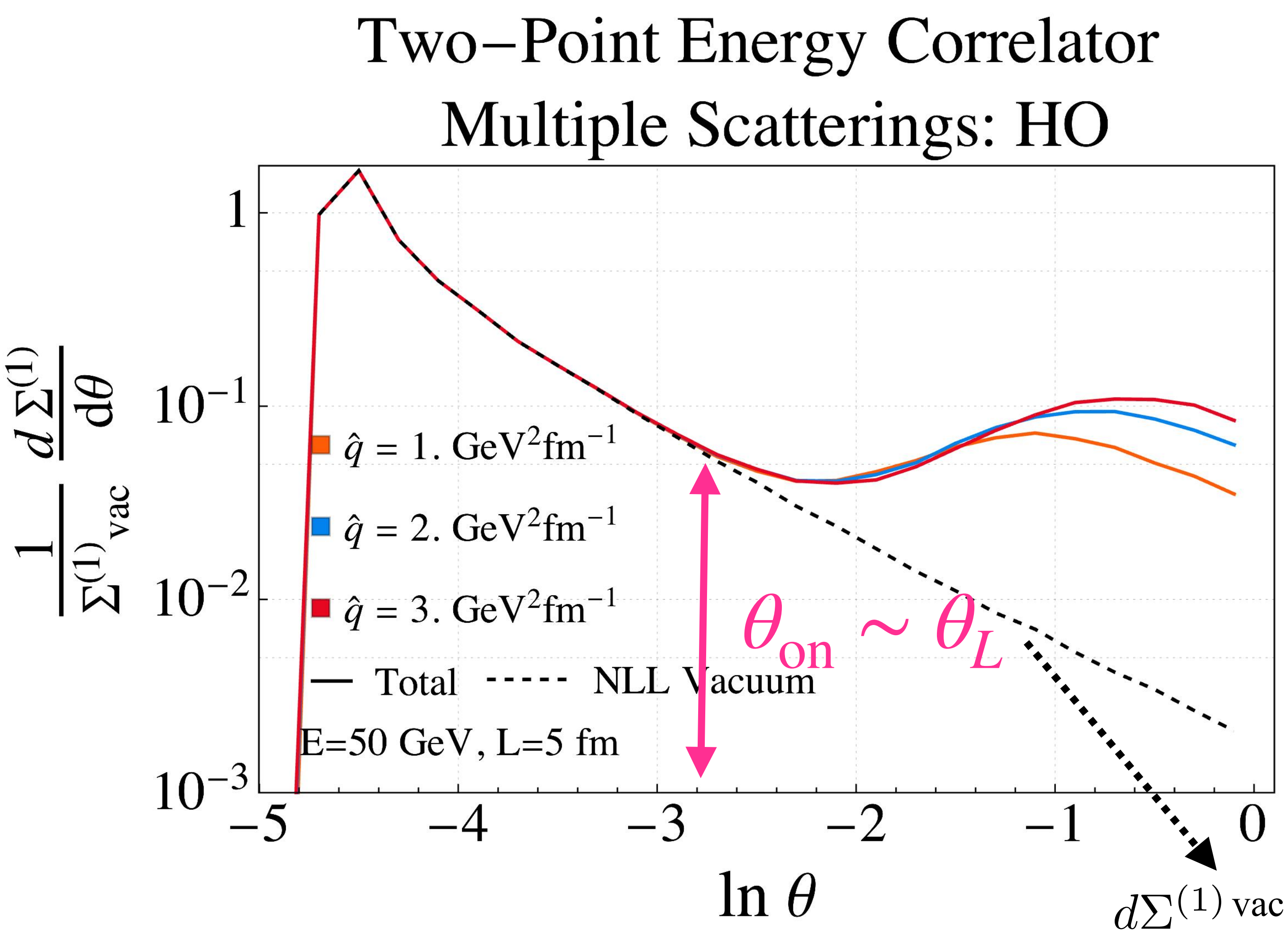
$\theta_L \ll \theta_c \left(E \gg \hat{q}L^2\right)$



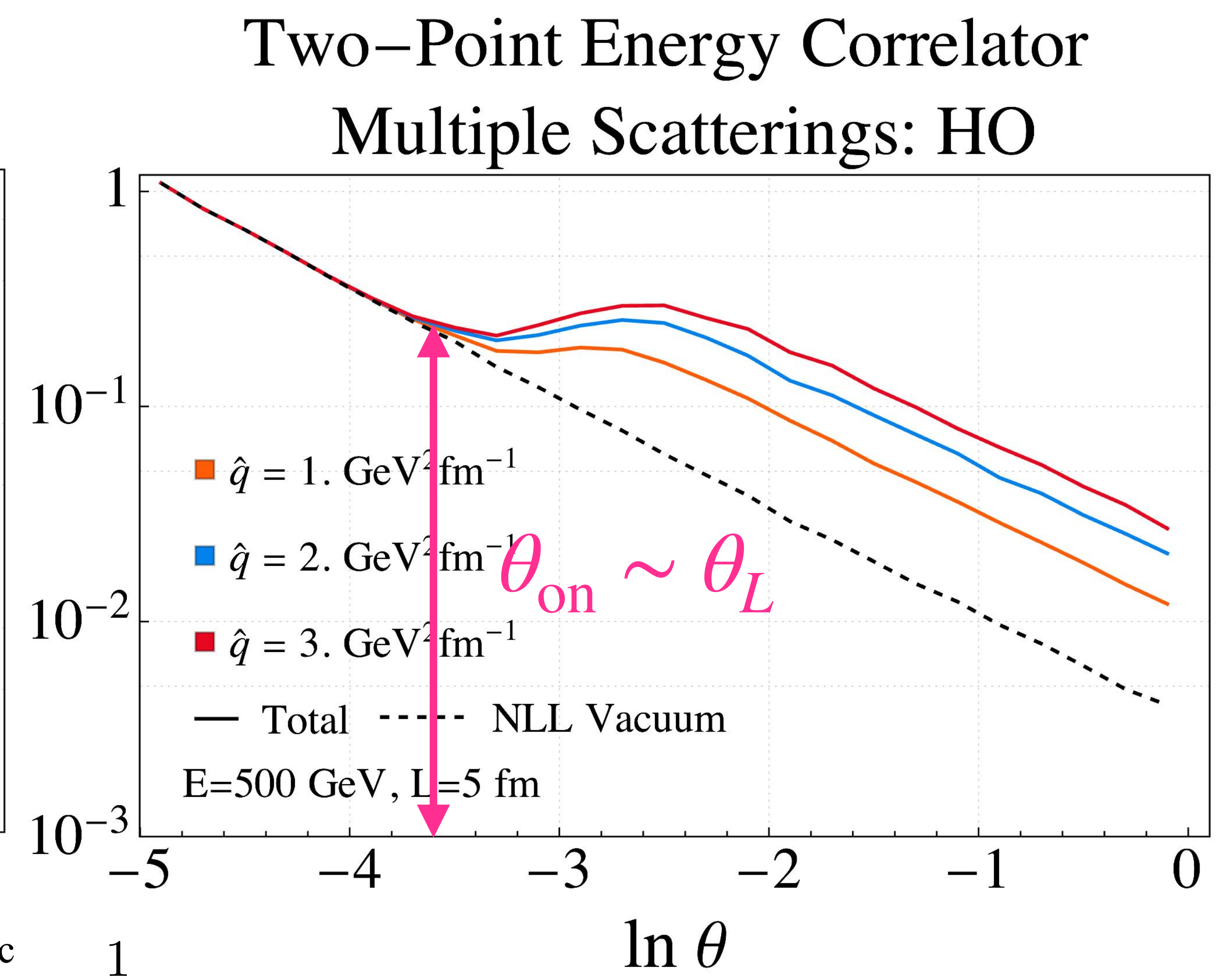
- **No** medium-induced enhancement at **small angles**

Results HO

$\theta_L \gg \theta_c \left(E \ll \hat{q}L^2\right)$



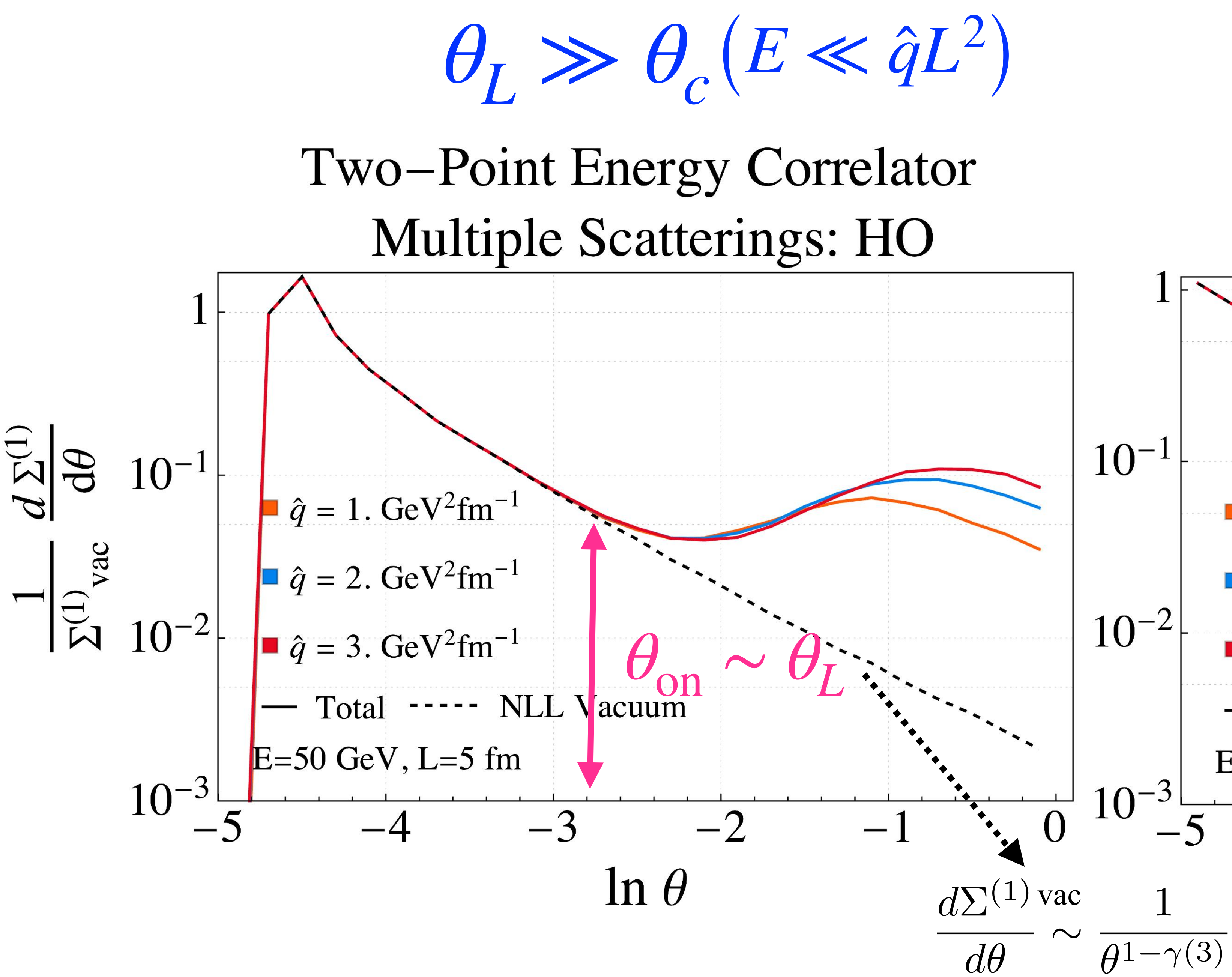
$\theta_L \ll \theta_c \left(E \gg \hat{q}L^2\right)$

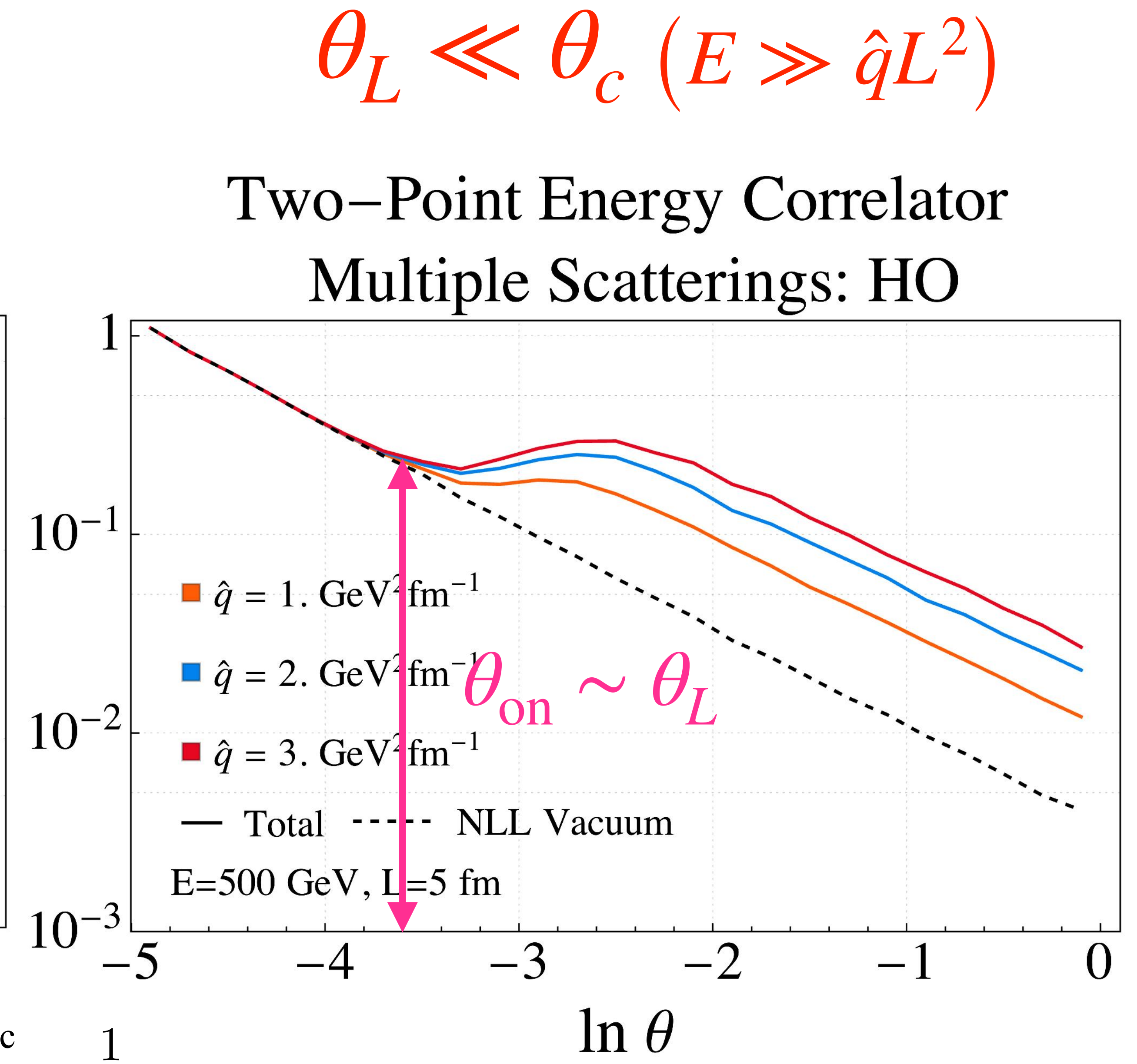


$$\frac{d\Sigma^{(1)\,\mathrm{vac}}}{d\theta} \sim \frac{1}{\theta^{1-\gamma(3)}}$$

- **No** medium-induced enhancement at **small angles**
- Onset angle seems to be independent of $\hat{q}$

Results HO

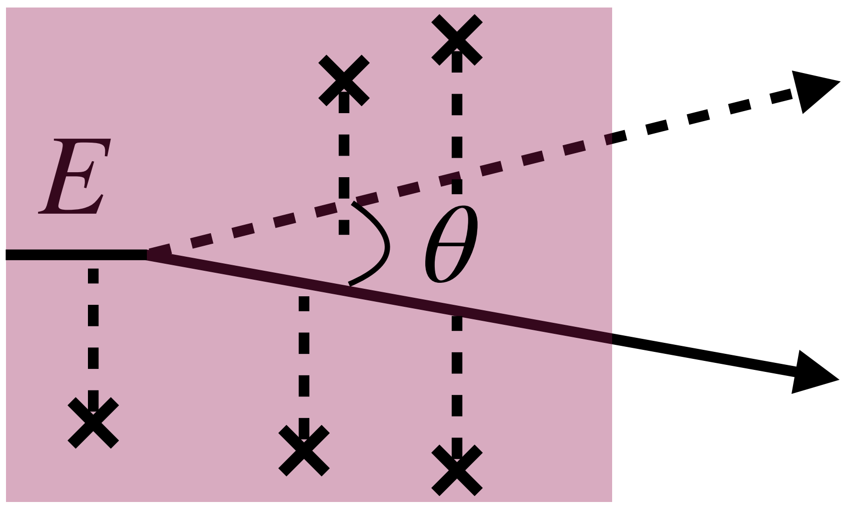




- **No** medium-induced enhancement at **small angles**
- Onset angle seems to be independent of $\hat{q}$
- Varying $\hat{q}$ has different effects in the two regimes

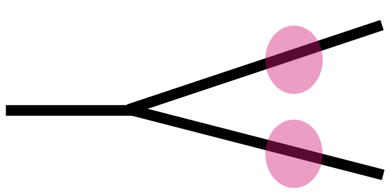
Interpretation

$\theta_L \gg \theta_c \quad (E \ll \hat{q}L^2)$

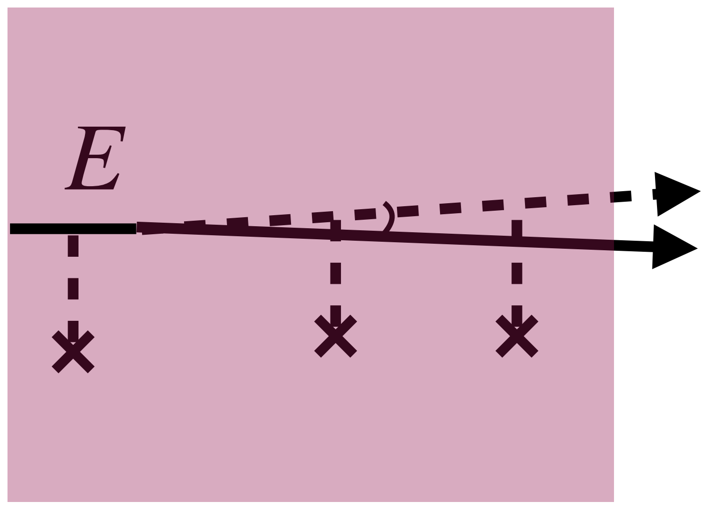


For $\theta \gg \theta_L \Rightarrow \theta \gg \theta_c$

The medium resolves the emission

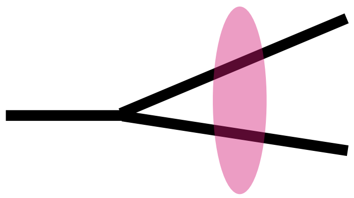


$\theta_L \ll \theta_c \quad (E \gg \hat{q}L^2)$

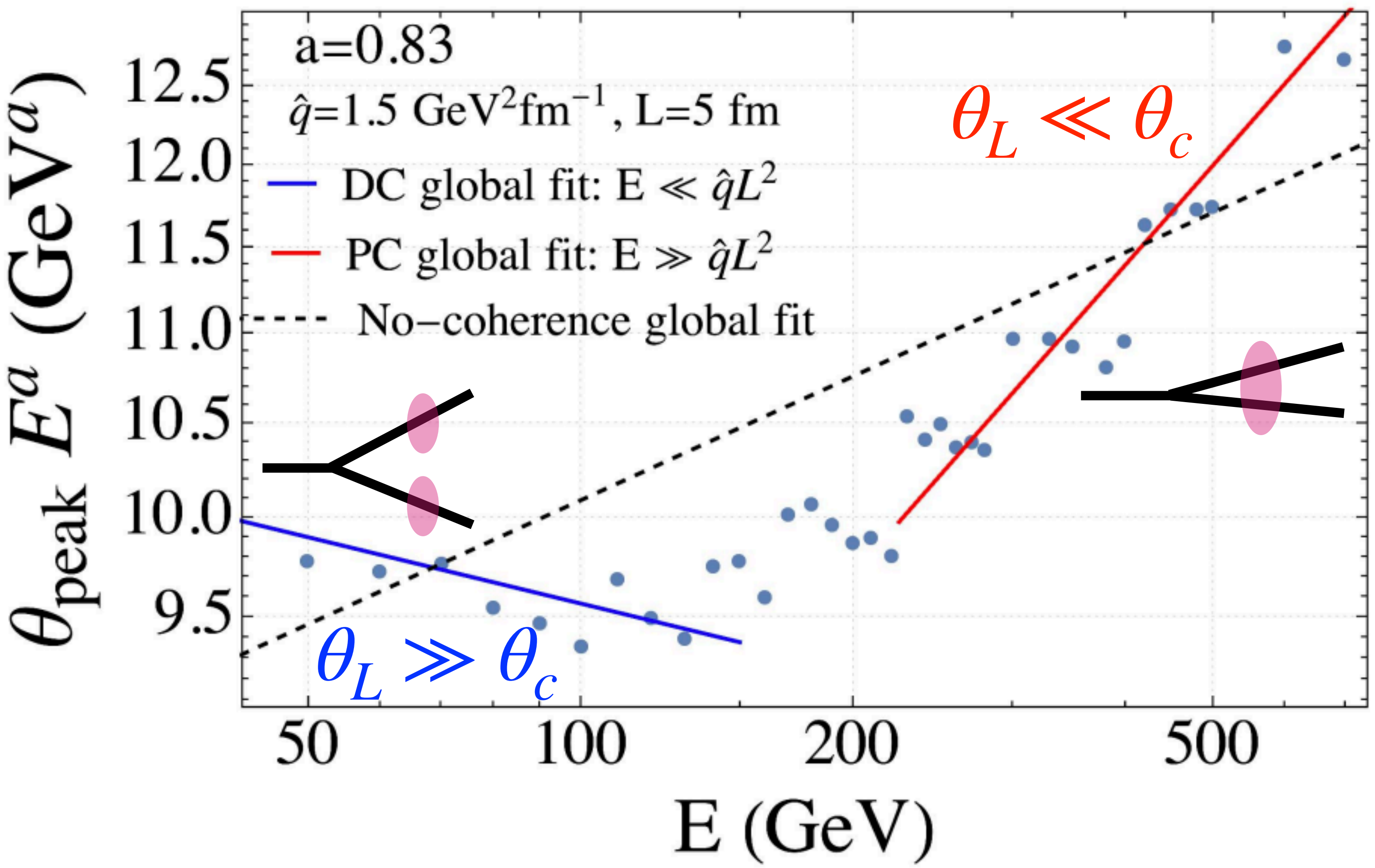


For $\theta_c \gg \theta \gg \theta_L$:

The medium does NOT resolve the emission



Coherence transition

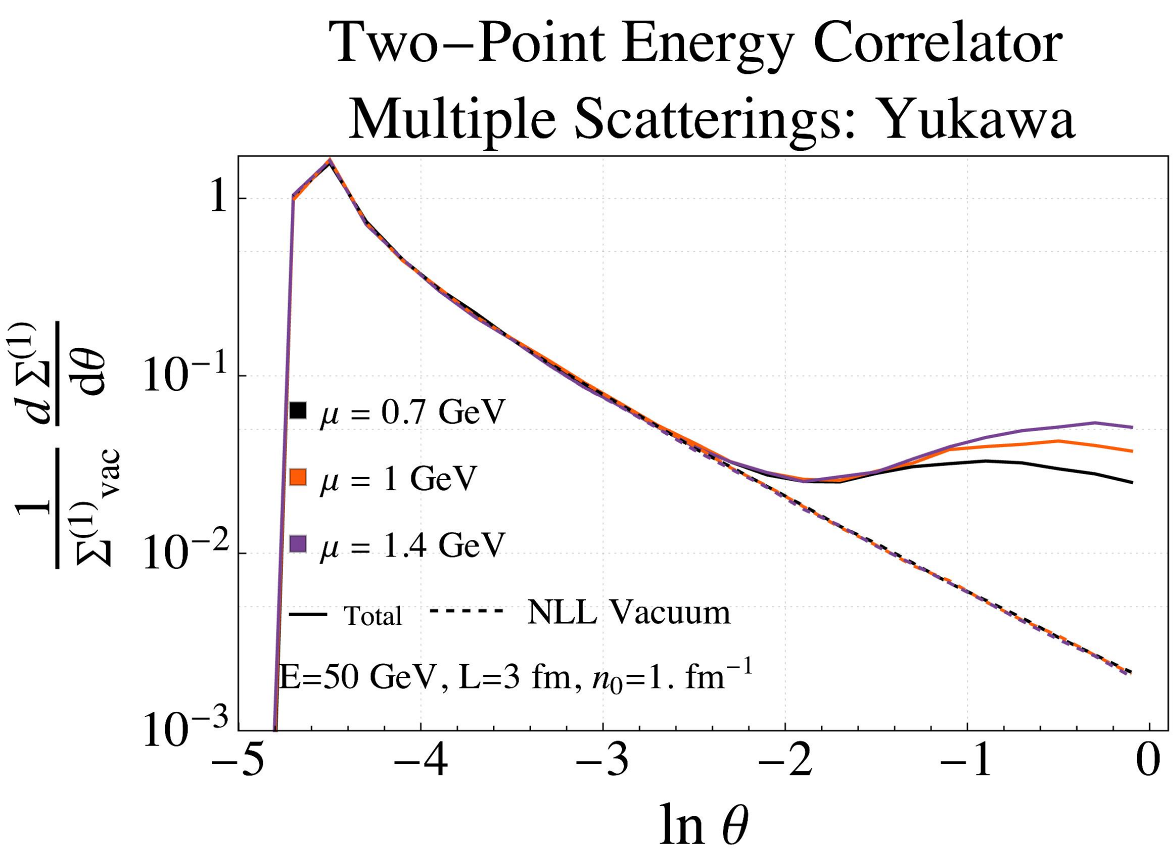


- Extracted the peak angle θ_{peak} for 332 sets of parameters with $E \in [50,700]$ GeV, $L \in [0.2,10]$ fm, $\hat{q} \in [1,3]$ GeV^2/fm

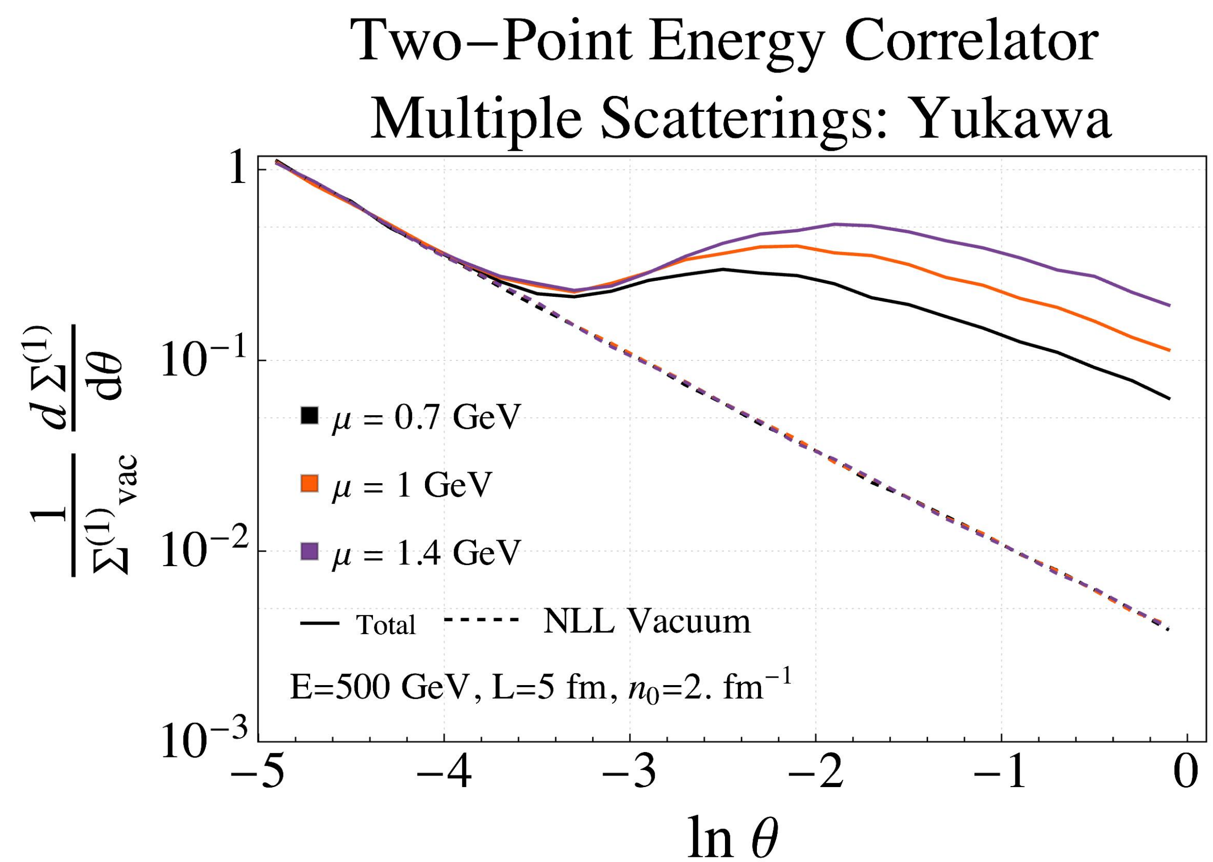
- Performed separate fits in the two different regions for the scaling behavior of the peak angle with respect to the 3 parameters

Results with a Yukawa interaction

$\theta_L \gg \theta_c$



$\theta_L \ll \theta_c$



$$V_{\text{yuk}}(\boldsymbol{q}) = \frac{8\pi\mu^2}{\left(\boldsymbol{q}^2+\mu^2\right)^2}$$

$$\sigma(\boldsymbol{q}) \equiv -V(\boldsymbol{q}) + (2\pi)^2\delta^2(\boldsymbol{q})\int_l V(\boldsymbol{l})$$

Results with a Yukawa interaction

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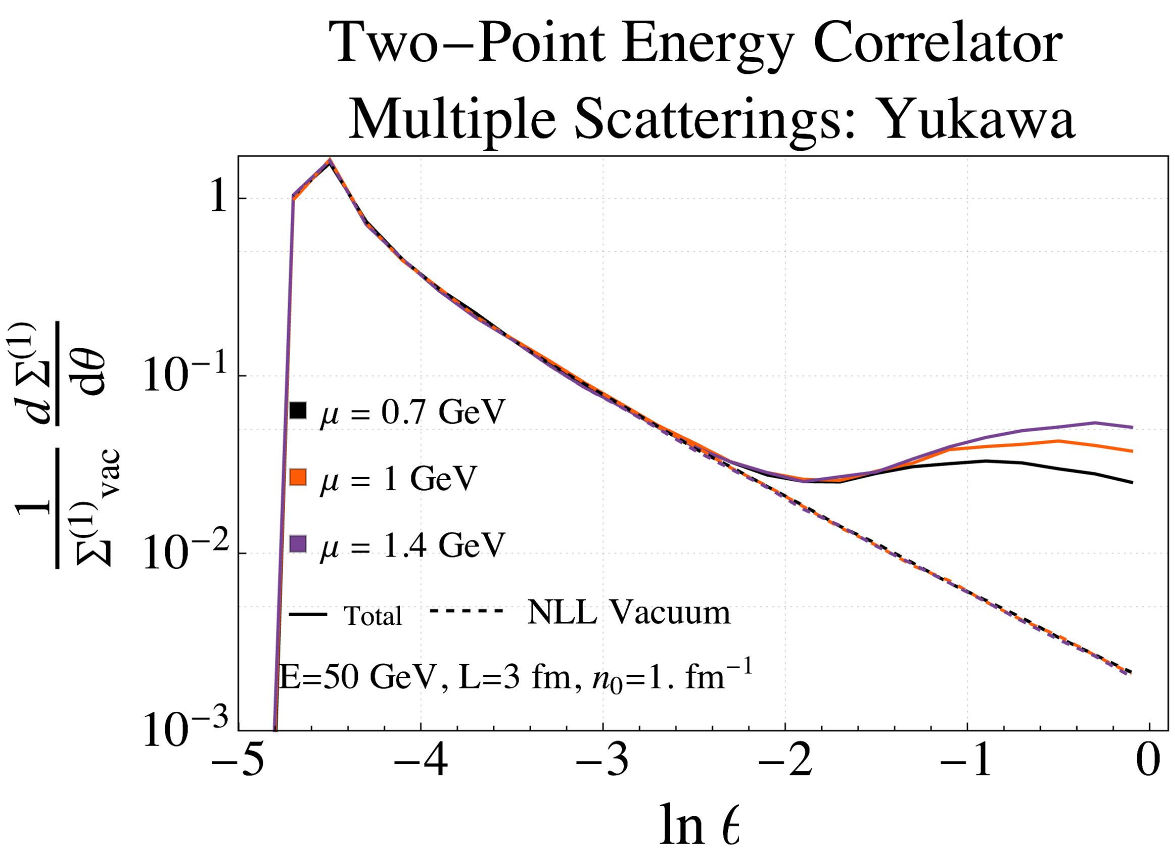
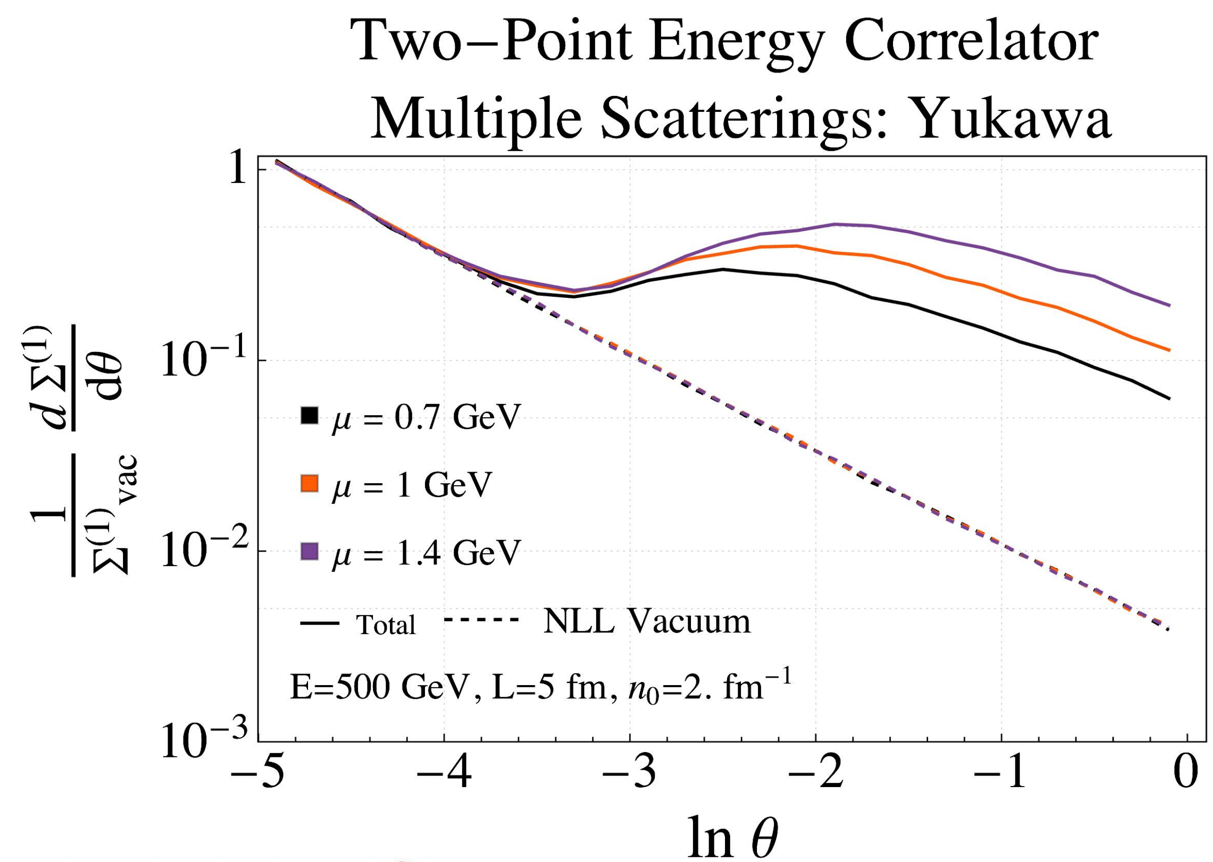


$\theta_L \ll \theta_c$



$$V_{\rm yuk}(\boldsymbol{q}) = \frac{8\pi\mu^2}{\left(\boldsymbol{q}^2 + \mu^2\right)^2}$$

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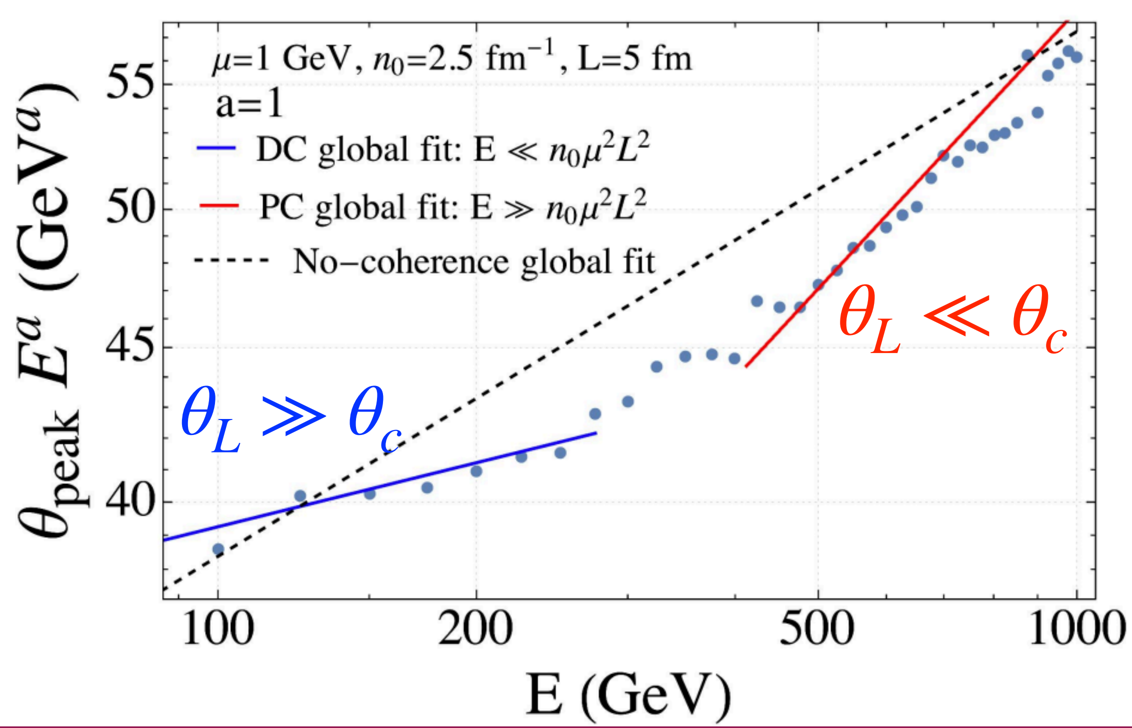
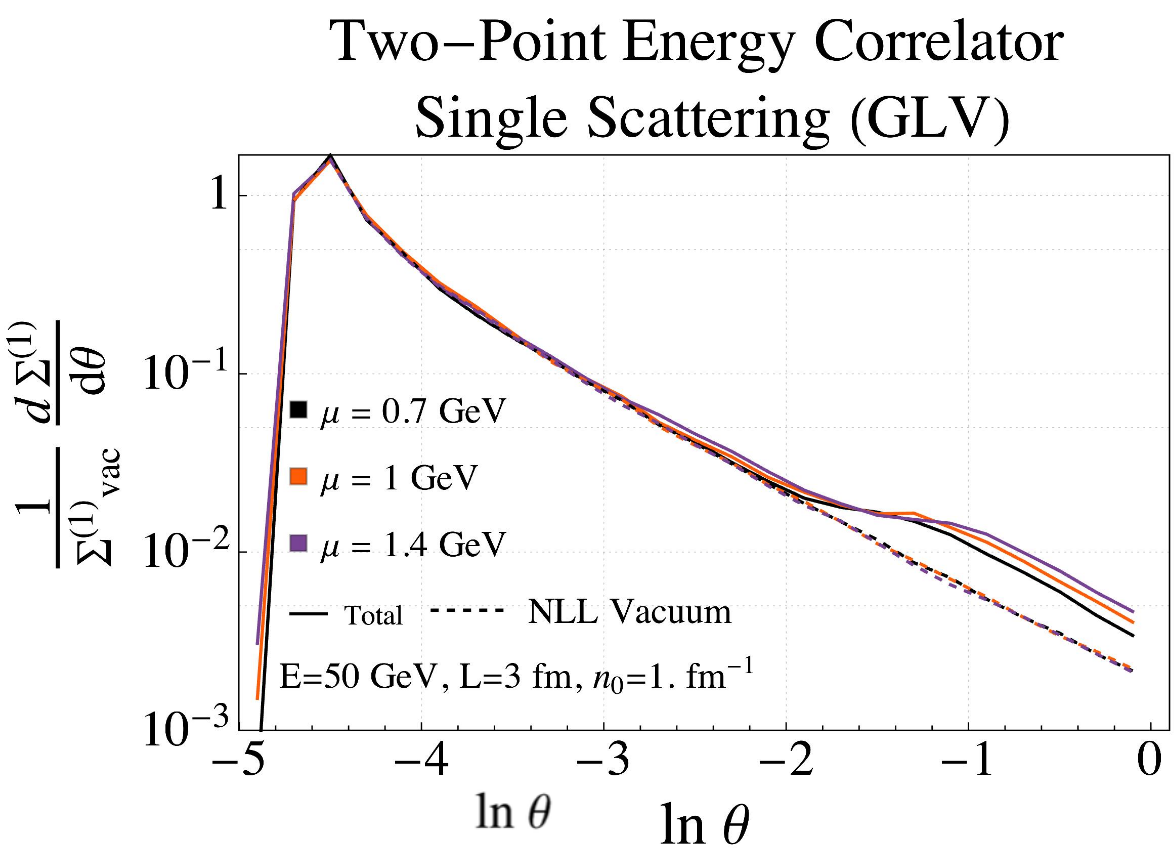


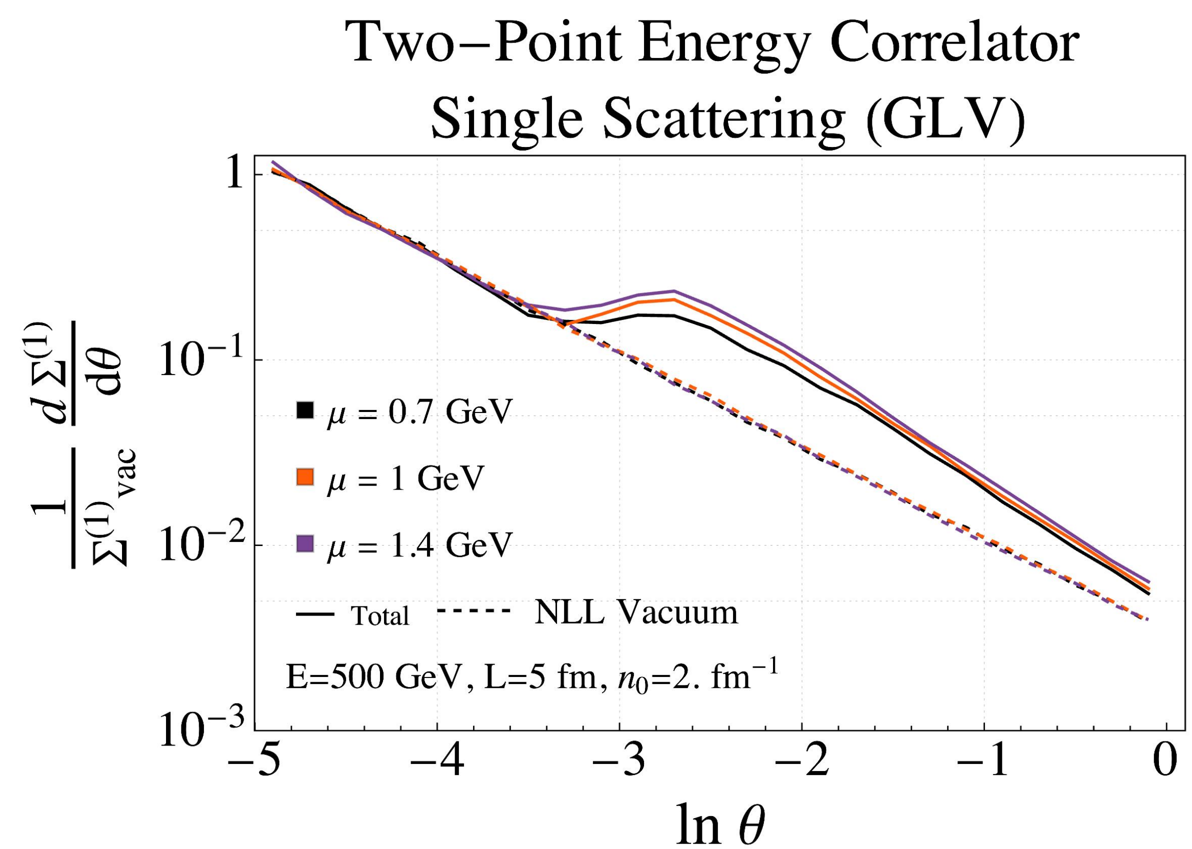
Onset of color **coherence is NOT a feature of the HO** approximation

Results GLV

$\theta_L \gg \theta_c$

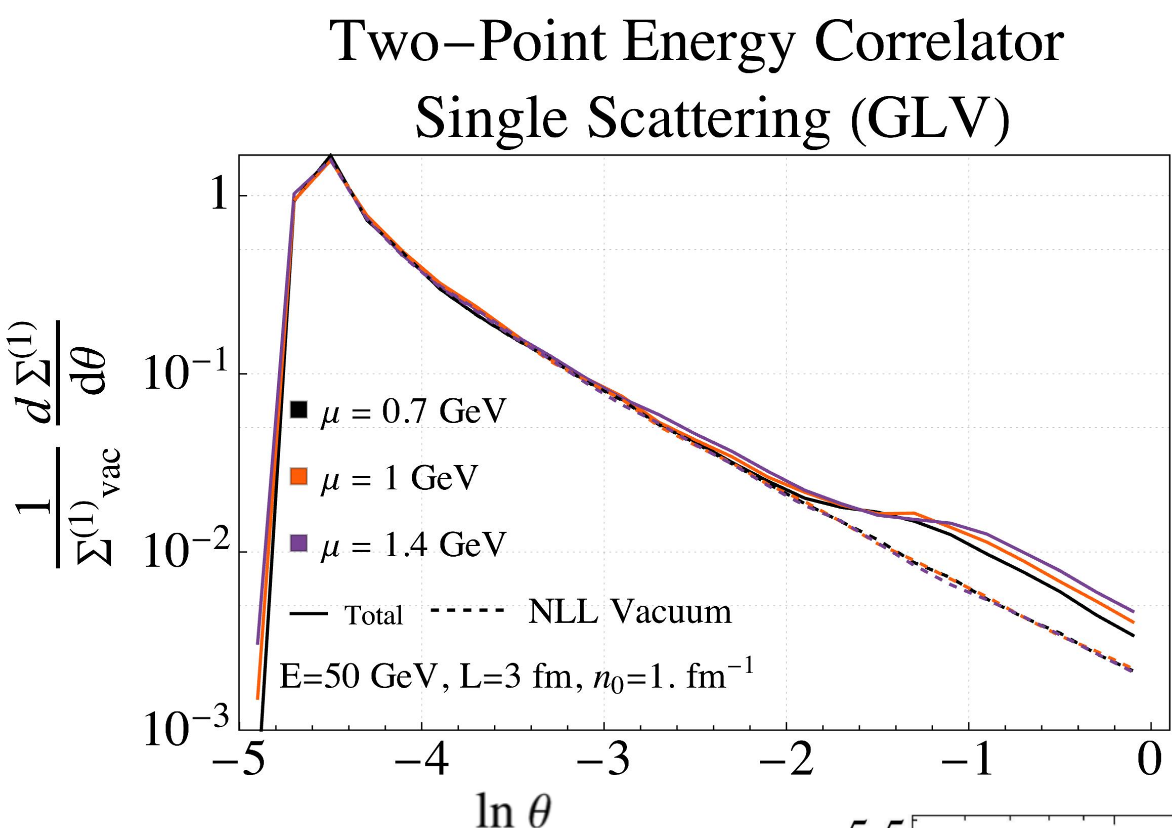


$\theta_L \ll \theta_c$

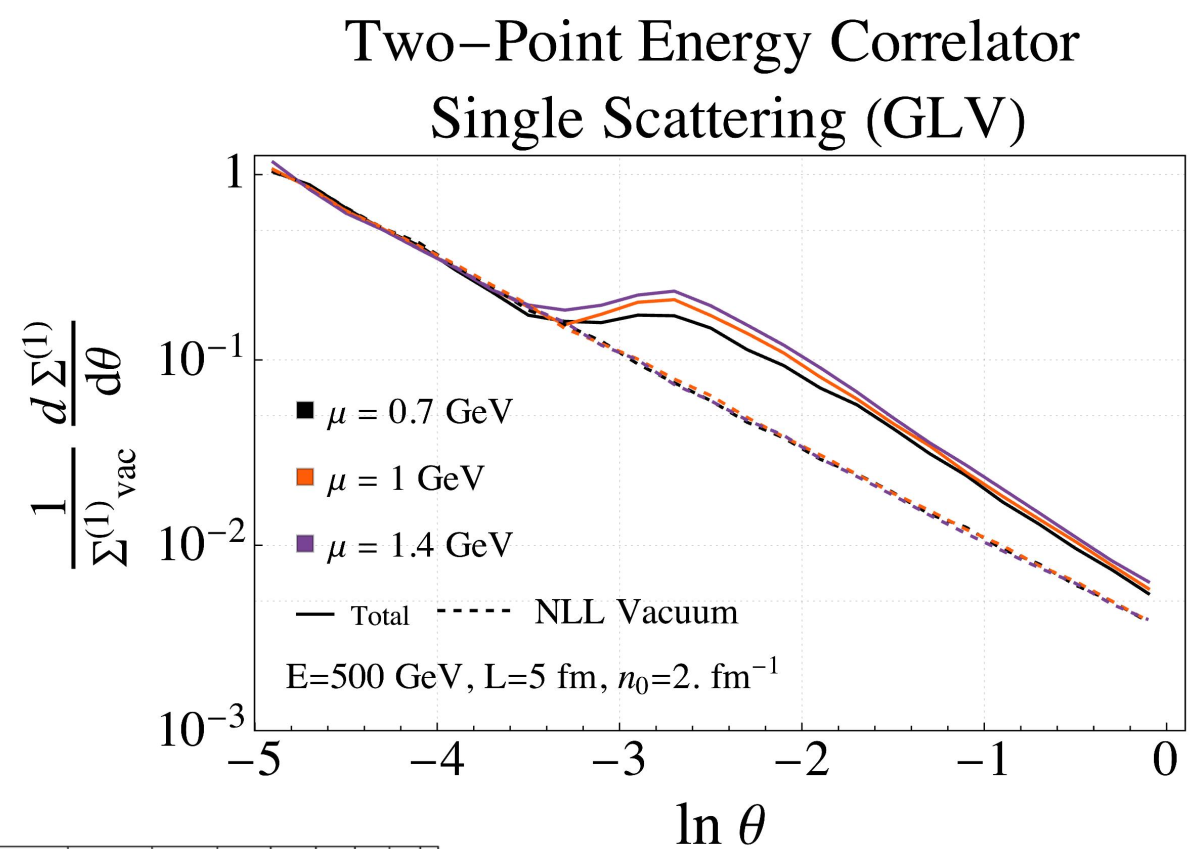


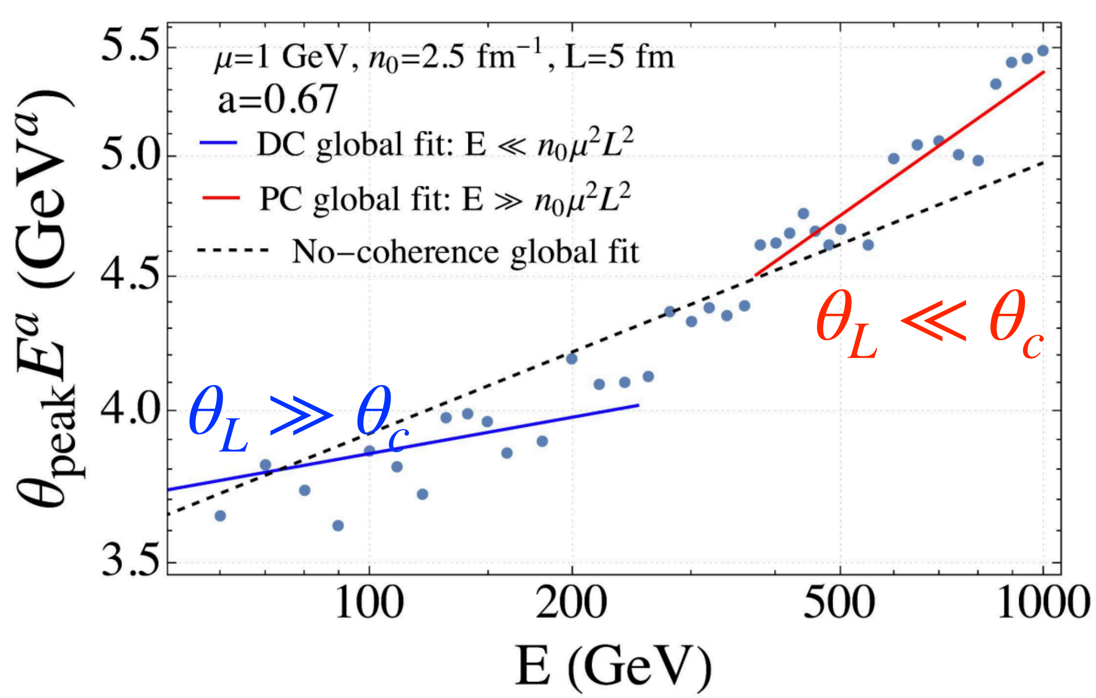
Results GLV

$\theta_L \gg \theta_c$



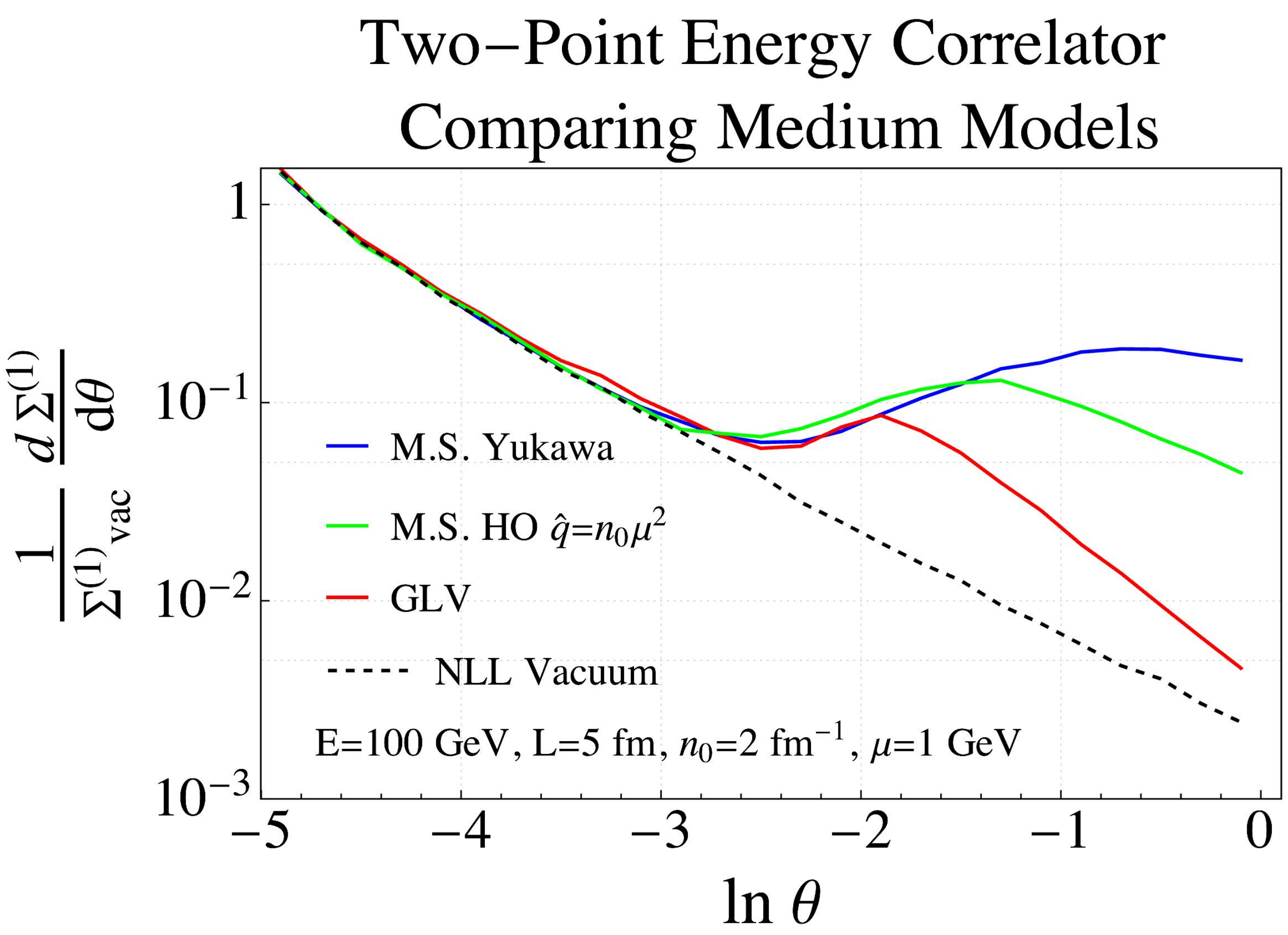
$\theta_L \ll \theta_c$

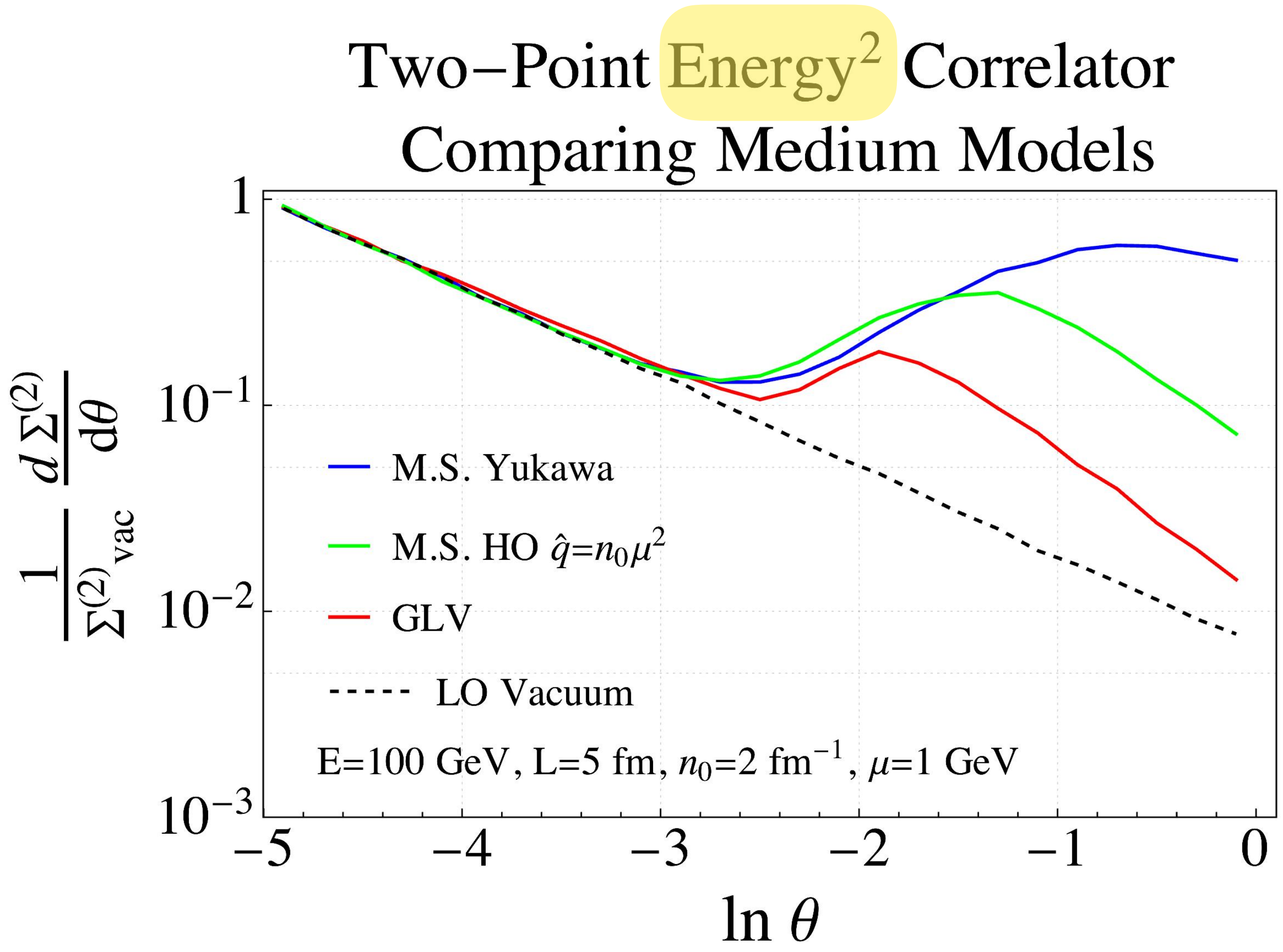




Onset angle is **not as sharply** defined **as** in the **multiple scattering** case

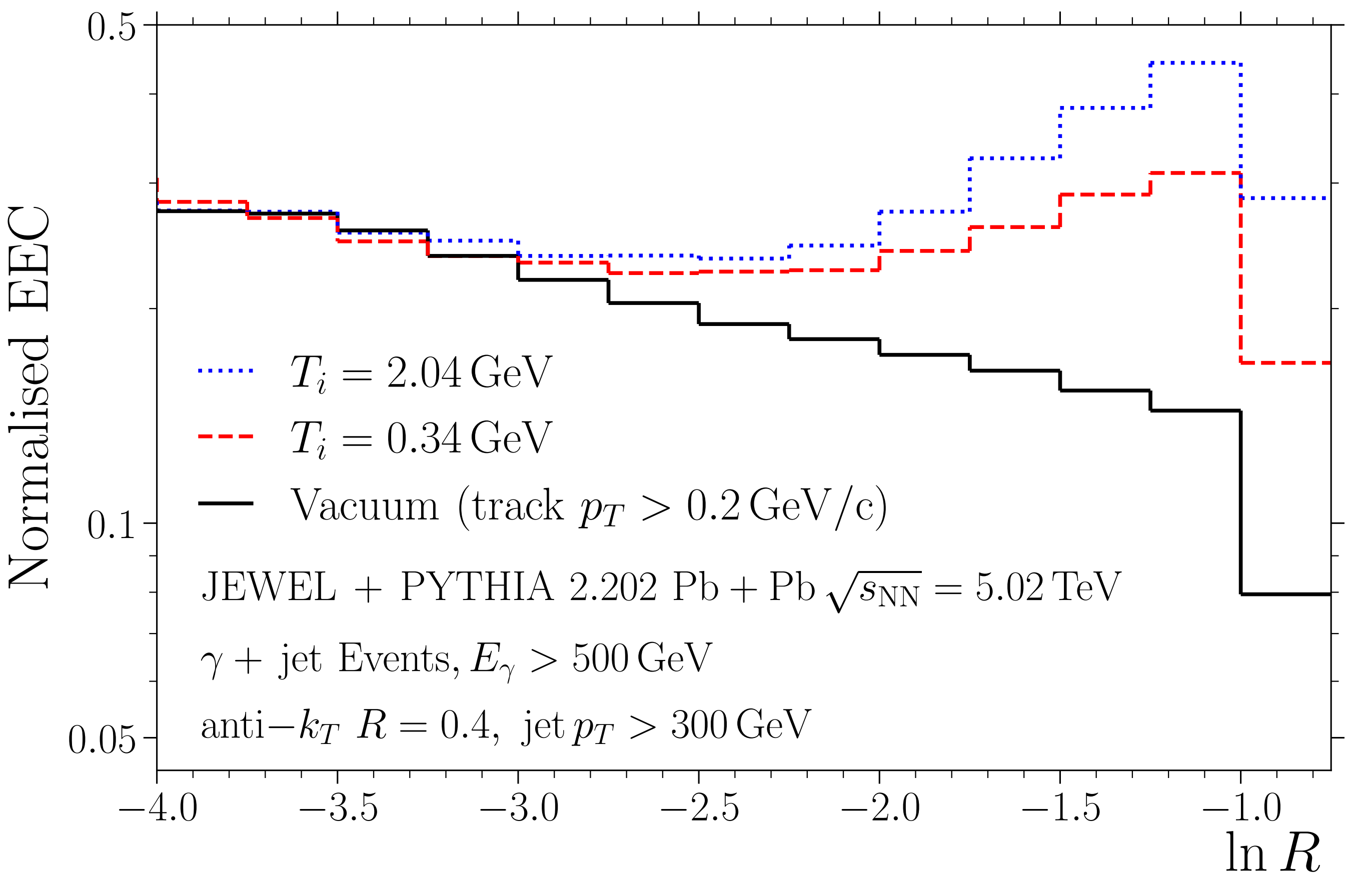
Higher point correlators

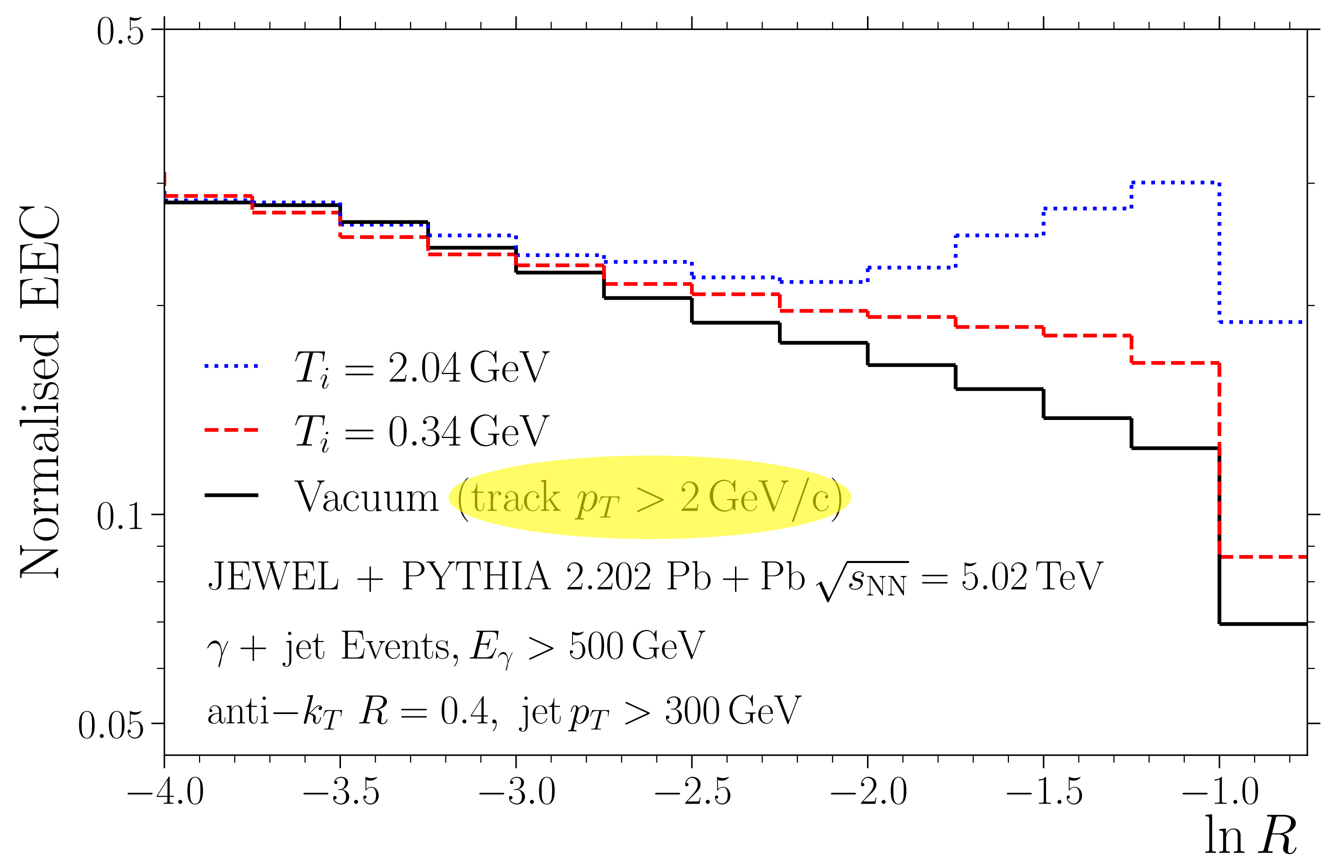




Results from JEWEL

- An analysis on JEWEL is on the way





Features in the curves seem resilient against a hadron cut $p_T \gtrsim 2\,\mathrm{GeV}$

Conclusions

- Energy Correlators provide a powerful tool to understand jets in HICs
  - Broadly insensitive to soft physics: hadronization, and background are usually subleading
  - Can be computed perturbatively
  - Experimentally accessible
- Characteristic features of the calculation of the in-medium splittings are clearly imprinted in these observables
- 2-point correlator provides a robust angular variable that can be used to probe color coherence in jets in the QGP
  - Main features seem to be model independent, though transitions between regions are less sharp for the GLV case

Outlook

- Lots of new exciting developments!
- **Expanding** media
  - Using energy correlators to find the relevant angular scales
- **Heavy quarks**
  - Can be used to measure the dead-cone
- **Monte Carlo studies**
  - Test resilience to background
  - Test the effects of having the full parton shower

Merci pour votre attention