# Resolving Spacetime Evolution of QCD Jets Using Energy-Energy Correlators

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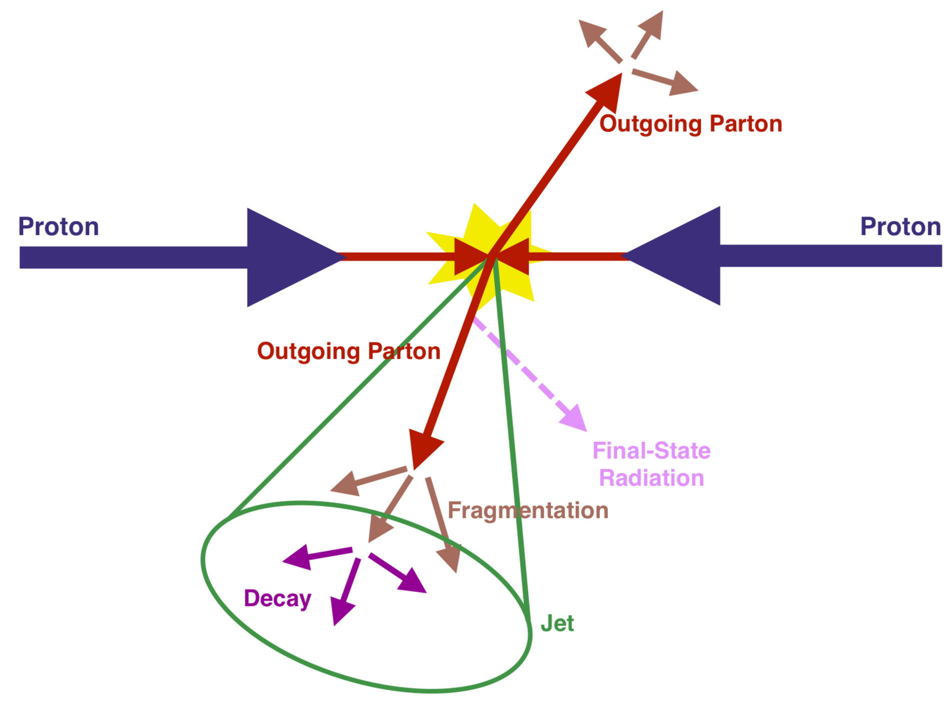
## Motivation

High-energy hadronic collisions allow us to explore **Quantum Chromodynamics (QCD)**. In proton-proton (*pp*) collisions, energetic quarks and gluons shower into jets, which allow the study of the transition from perturbative to non-perturbative regimes, revealing how partons ultimately confine into hadrons.




In heavy-ion collisions, these jets traverse the **Quark-Gluon Plasma (QGP)**, where their structure is modified - a phenomenon known as **jet quenching**.

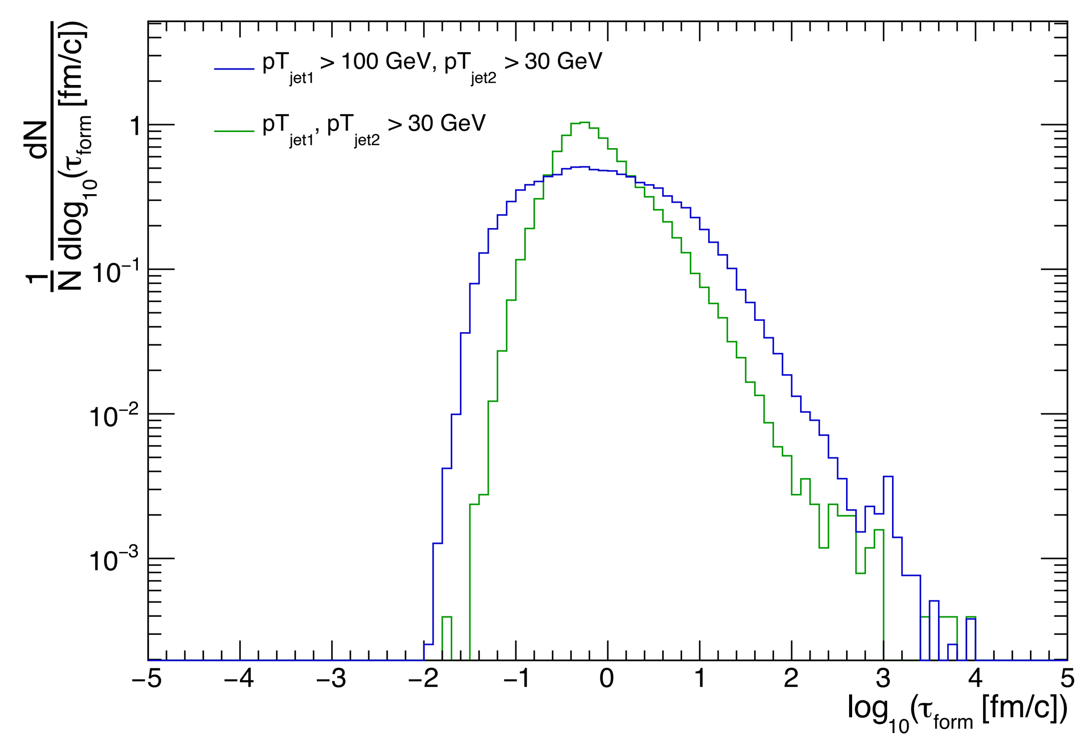
**This work:** we focus on *pp* collisions (vacuum) to establish a solid baseline for future studies in heavy-ion environments.

**Figure 1:** Hard-scattering of **partons** in a *pp* collision and **parton shower**, followed by **hadronization** and hadron decay, with **jet** formation.

## Formation Time

The **formation time of an emission,** $\tau_{form}$, is the time it takes to behave as an independent source of radiation.

$$\tau_{form} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{1,2})}$$




The distribution separates into **three regimes**: **early parton radiation** at short times, **late hadronic decays** at long times, and a consistent **transition** around $\tau_{form} \approx 1$ fm/c, which reflects the characteristic **hadronization timescale** (largely independent of the jet transverse momentum, $p_T$), [1, 2].

**Figure 2:** Statistical distribution of the formation time for two sets of jet $p_T$ configurations

## Energy-Energy Correlator (EEC)

### Angular EEC

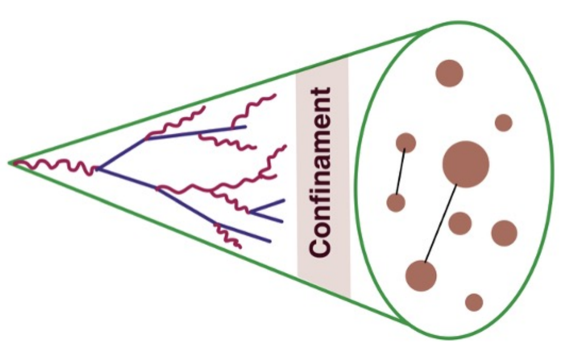
- Measures how energy is distributed at different angular scales within a jet

$$\frac{d\Sigma}{d\log(\Delta R)} = \frac{1}{N_{pairs}}\sum_{i\neq j} E_i E_j \delta(\Delta R - \Delta R_{ij})$$

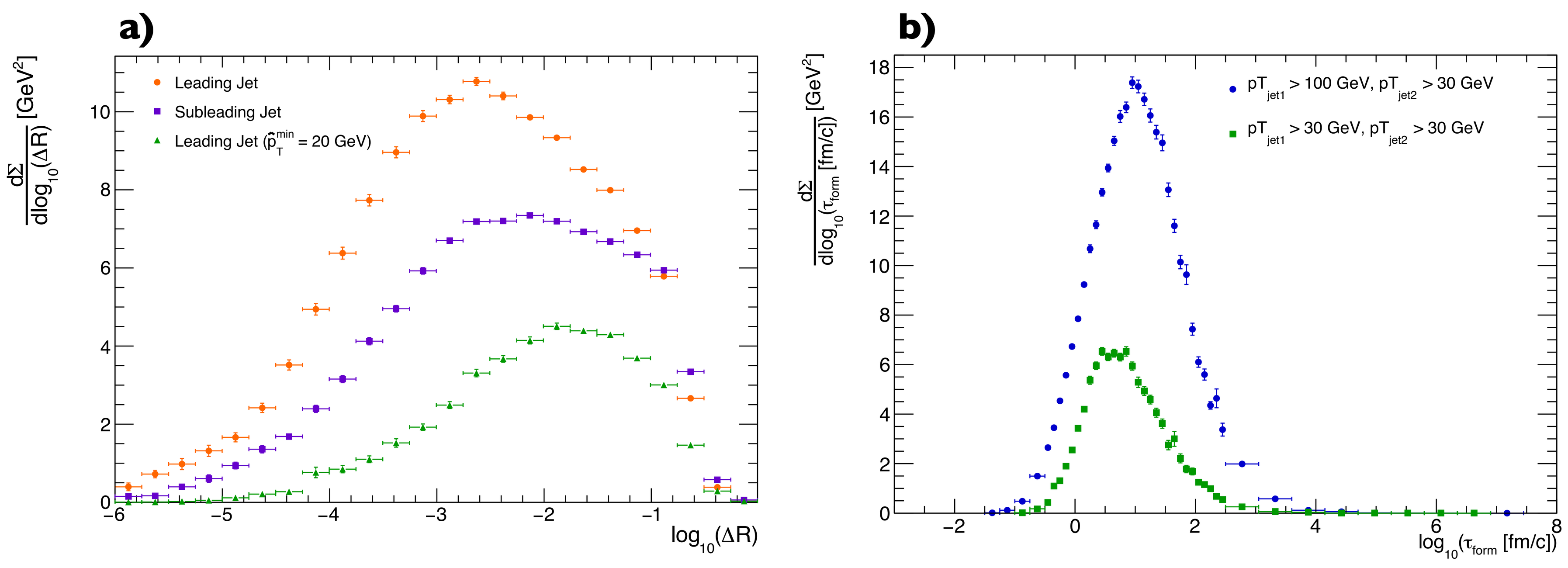
- Shows the transition between perturbative splittings and hadronization regime [3]

### Temporal EEC

- Proposed redefinition of EEC in terms of τ_form between particle pairs
- Reveals characteristic timescales of jet fragmentation




➡ Together they give a **space-time** interpretation of **jet substructure evolution** !

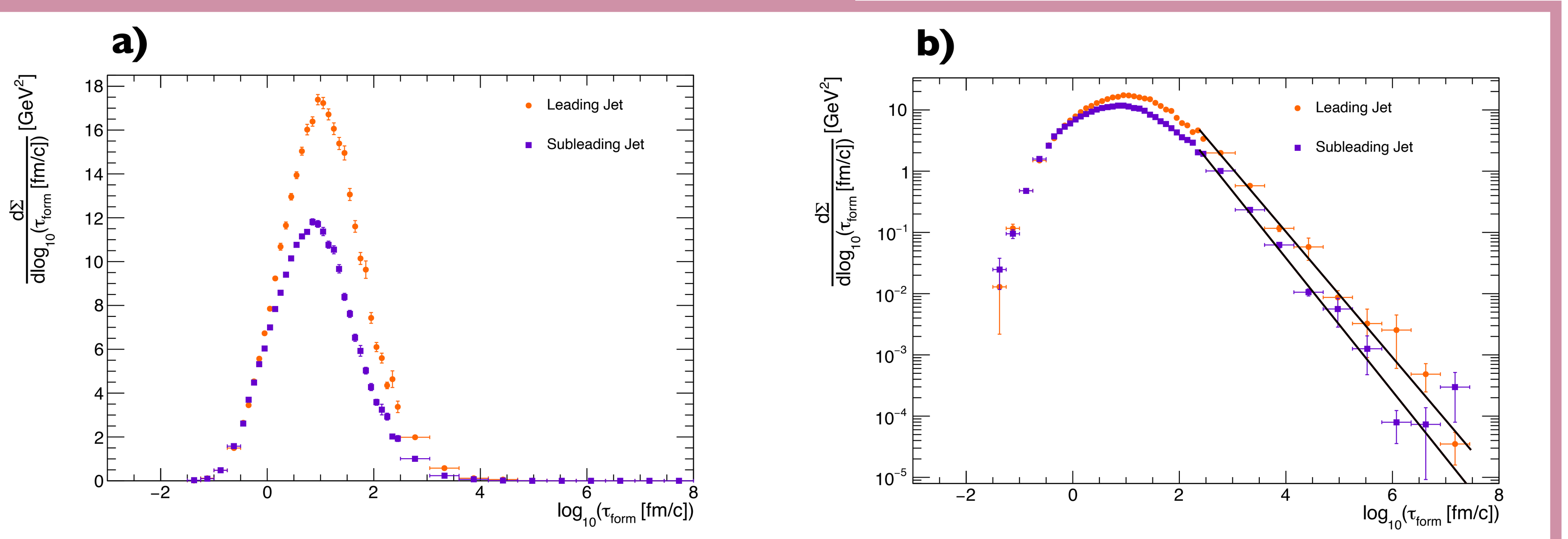



Shift consistent with $\tau \sim \frac{1}{\hat{p}_T(\Delta R)^2}$

Shift consistent with $\Delta R \sim \frac{\Lambda_{QCD}}{\hat{p}_T}$

**Figure 3: a)** Angular EEC distribution for leading and sub-leading jets in different jet $p_T$ configurations **b)** $\tau_{form}$ EEC distribution for leading jets in different jet $p_T$ configurations

## $\tau_{form}$ EEC



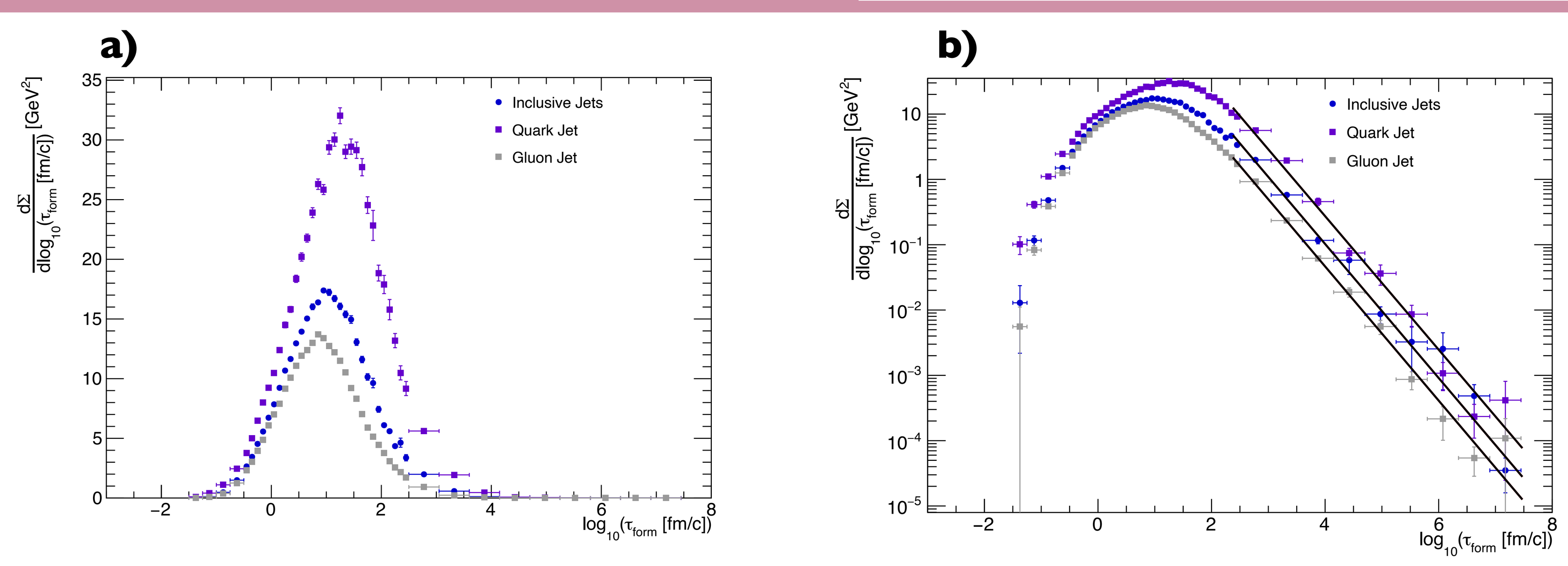

- Universal pQCD up to ~1 fm/c
- Clear transition!
- Non-perturbative power-law fall-off:

$$\log(y) = -\alpha\log(\tau_{form})$$

| Leading Jet | Sub-leading Jet |
|---|---|
| α = 1.03 ± 0.02 | α = 1.09 ± 0.01 |

**Figure 4: a)** $\tau_{form}$ EEC distribution for leading and sub-leading jets **b)** Figure 4.a) in logarithmic scale with fitted lines of the power-law scaling

## Flavour Dependence




| Inclusive Jets | Quark Jets | Gluon Jets |
|---|---|---|
| α = 1.03 ± 0.02 | α = 1.02 ± 0.01 | α = 1.03 ± 0.01 |

Non-perturbative scaling independent of $p_T$ and flavor !

**Figure 5: a)** $\tau_{form}$ EEC distribution for different flavour tagged events **b)** Figure 5.a) in logarithmic scale with fitted lines of the power-law scaling

## Conclusions & Future work

Both angular and temporal EEC show the expected $\hat{p}_T$ dependent shifts

The proposed temporal EEC reveals a **clearer transition** at $\tau_{form} \approx 1$ fm/c than the traditional angular correlator

The results show **universality of non-perturbative power-law scaling** with $\alpha \approx 1.03 \pm 0.02$, independent of jet flavour or $p_T$

This new observable establishes a **baseline for future jet quenching studies** and is a valuable tool for testing hadronization models

## References

[1] L. Apolinário, A. Cordeiro, K. Zapp, Eur.Phys.J.C 81 (2021) 6, 561

[2] L. Apolinário, P. Guerrero-Rodriguez, K. Zapp, Eur.Phys.J.C 84 (2024) 7, 672

[3] C. Andrés, F. Dominguez, R. Elayavalli, J. Holguin, C. Marquet, Phys.Rev.Lett. 130 (2023) 26, 262301