Jet substructure and its utility in small and large systems

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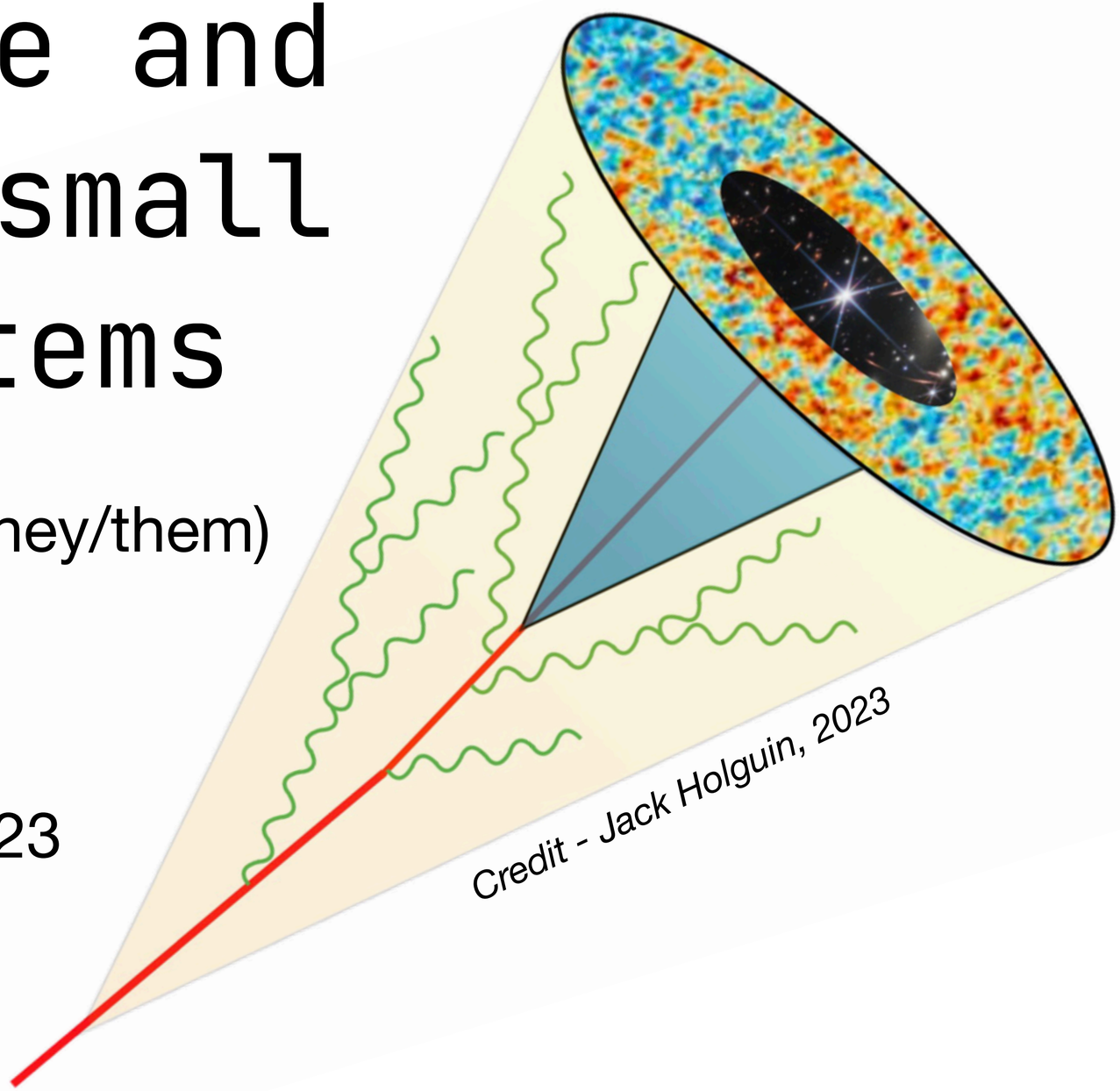
raghavke.me

GHP Meeting April 13th 2023
@ Minneapolis



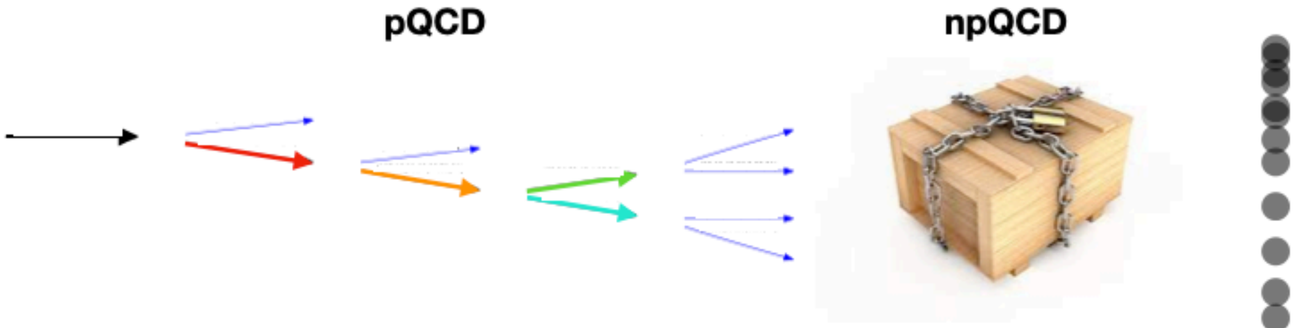
Jet substructure - WHY, WHAT, HOW

Small Systems pQCD to npQCD

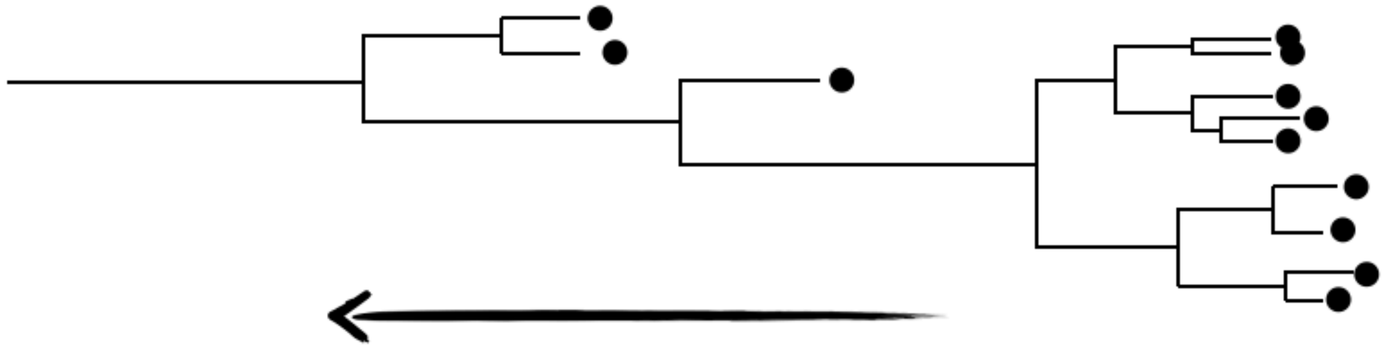
Large Systems QGP Space time structure

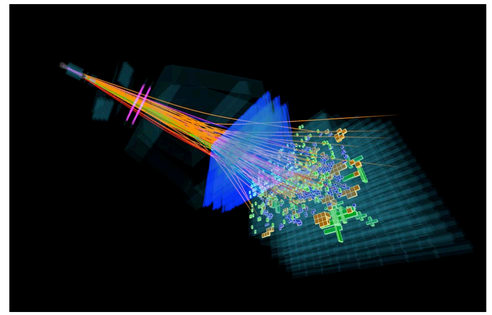
Looking ahead

Conceptual picture of jets



τ_f

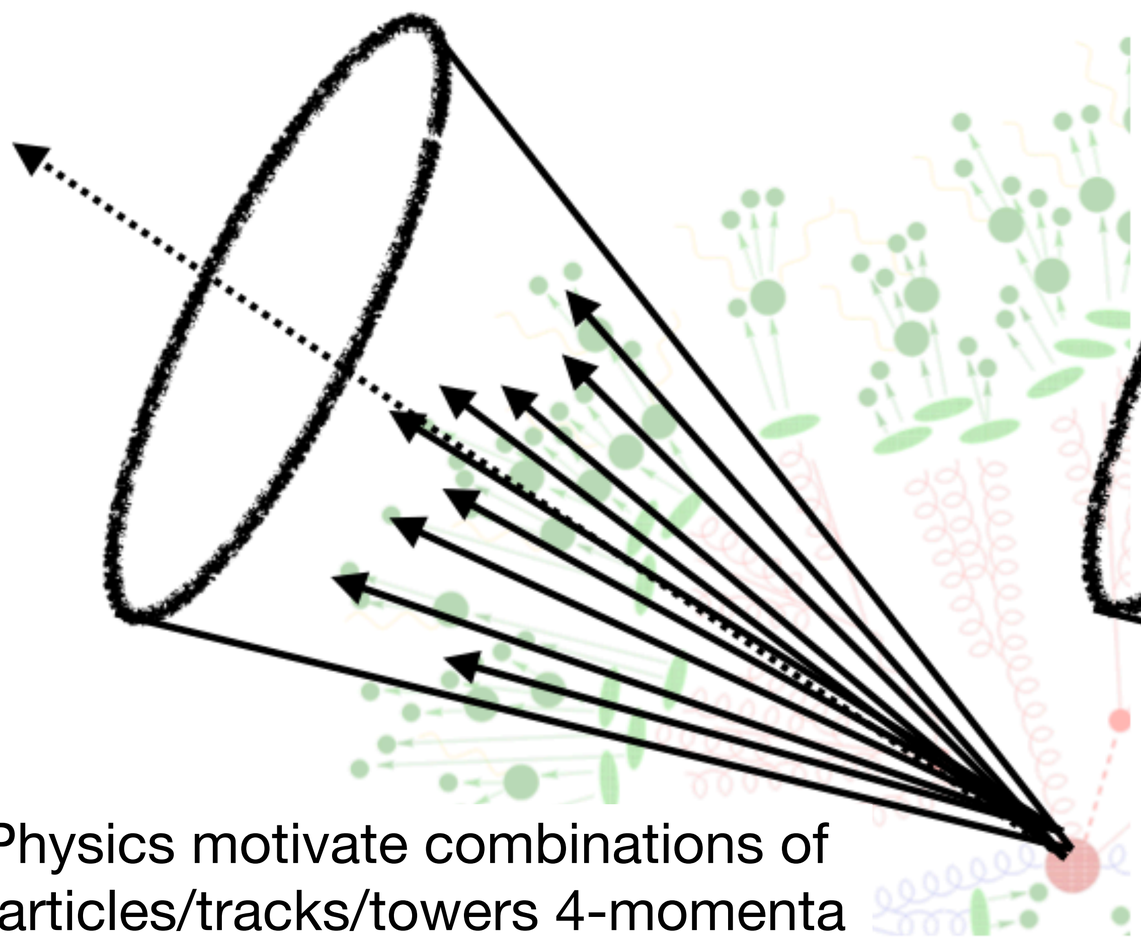




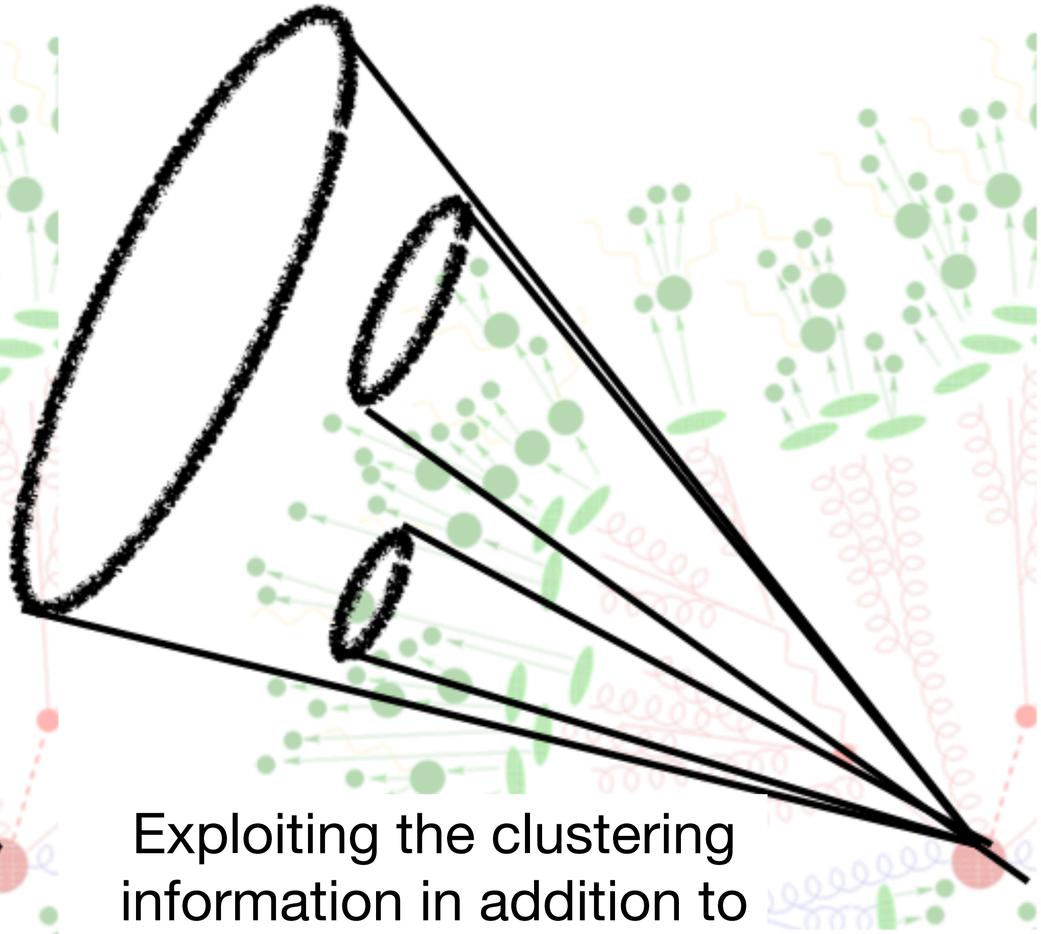
Jet Clustering

What is jet substructure?

A useful way to tag jet populations



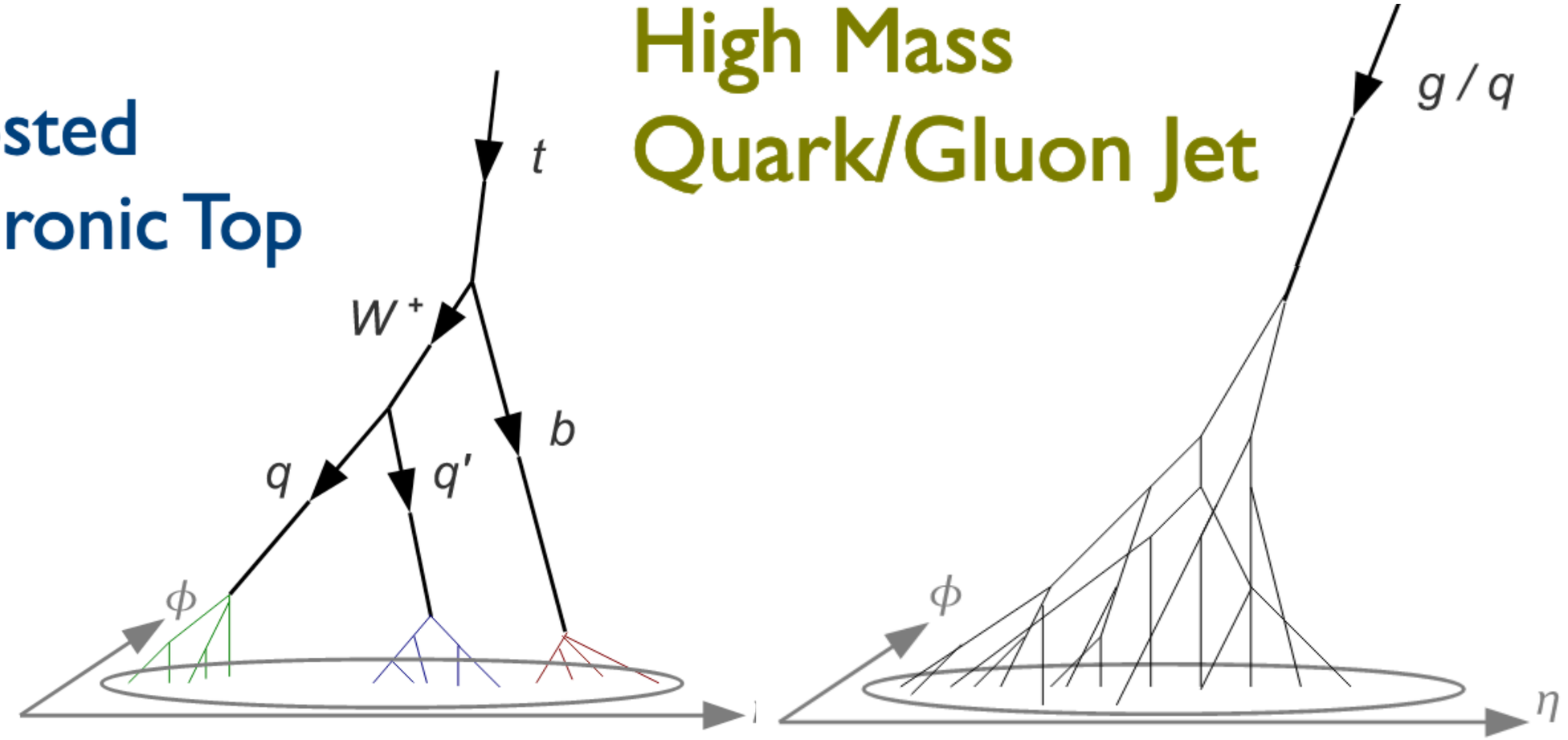
Physics motivate combinations of particles/tracks/towers 4-momenta



Exploiting the clustering information in addition to measured 4-momenta

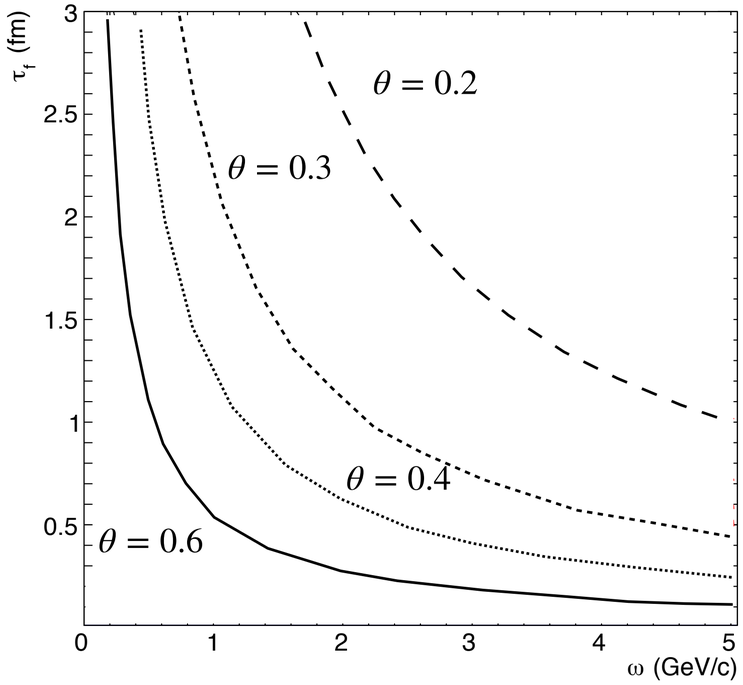
What is jet substructure?

Origins - HEP use case

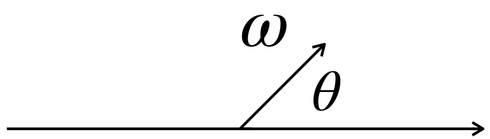


Credit - Jesse Thaler, 2011

Splittings in theory

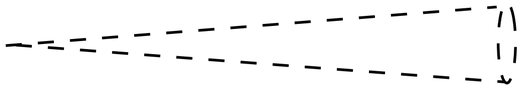


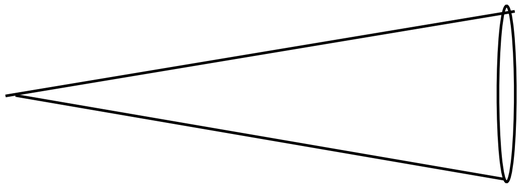
DGLAP Functions!



$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

Narrow emission - late time





wide emission - early time

- Two fundamental scales involved in jet evolution - opening angle and energy
- Narrow emissions occur at later times
- Early time emissions correspond to wider angle
- At fixed emission energy - angle of emission determines the time scale!

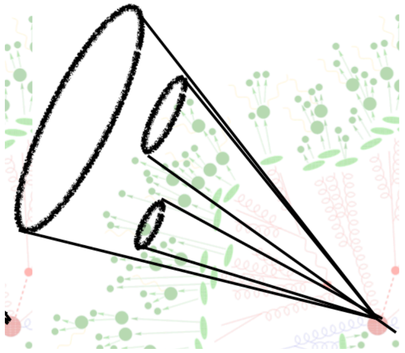
Jet substructure - WHY, WHAT, HOW

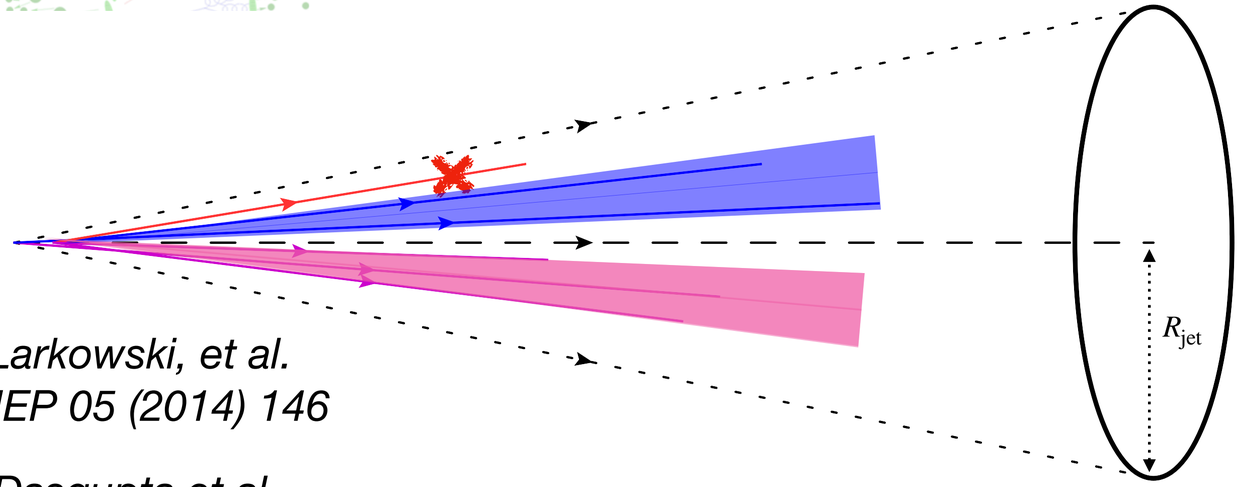
Small Systems pQCD to npQCD

Large Systems QGP Space time structure

Looking ahead

Splittings in experiment

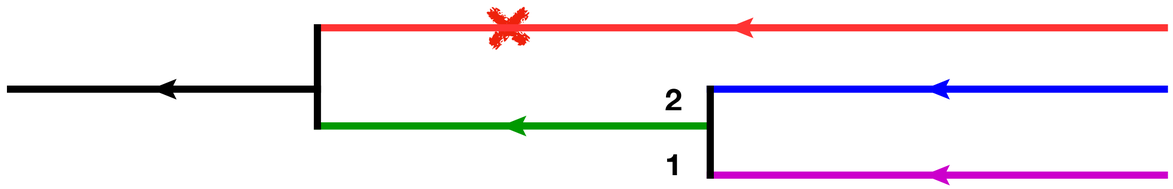


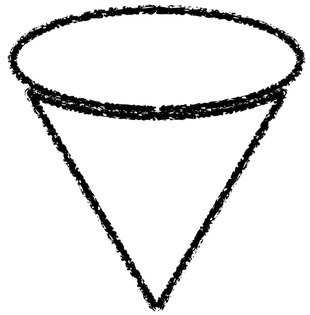


Larkowski, et al.
JHEP 05 (2014) 146

Dasgupta et al.
JHEP 09 (2013) 029

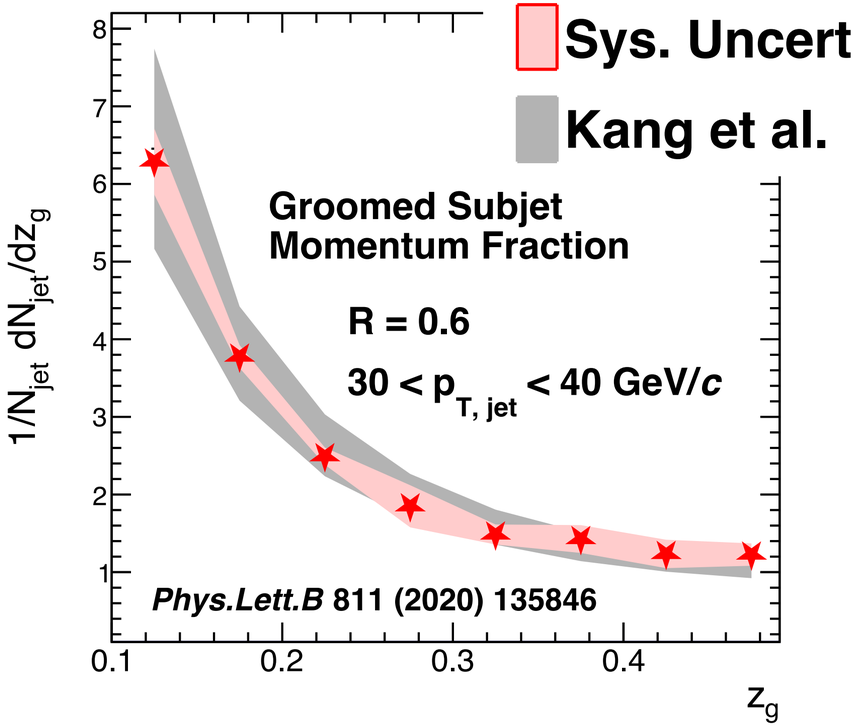
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1$$





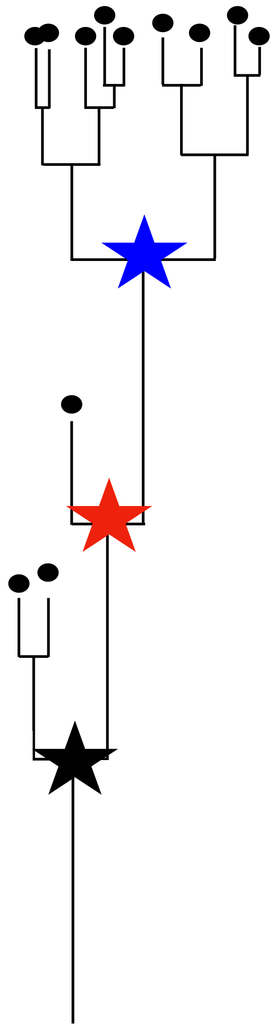
$30 < p_T^{jet} < 40$ GeV/c

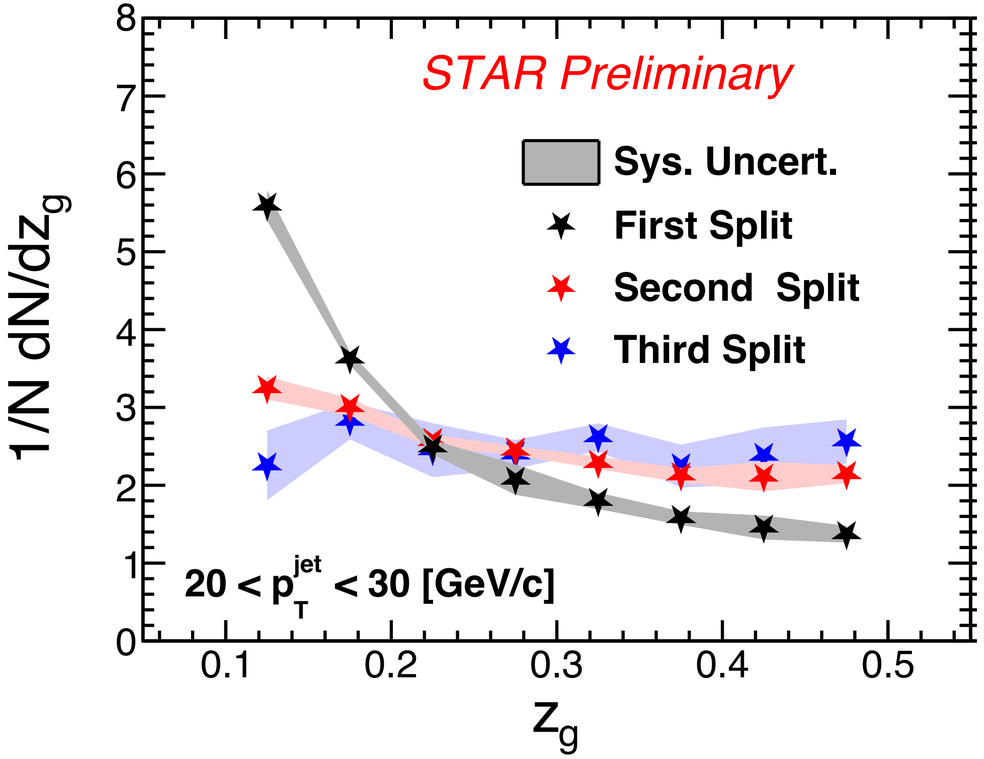
$R = 0.6$ anti $-$ k_T



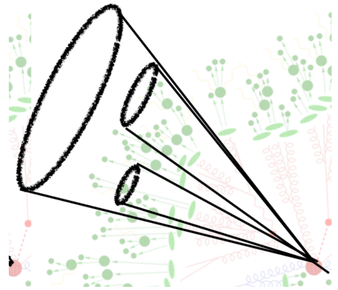
First SoftDrop splittings can be described by pQCD

Delving further into the jet substructure

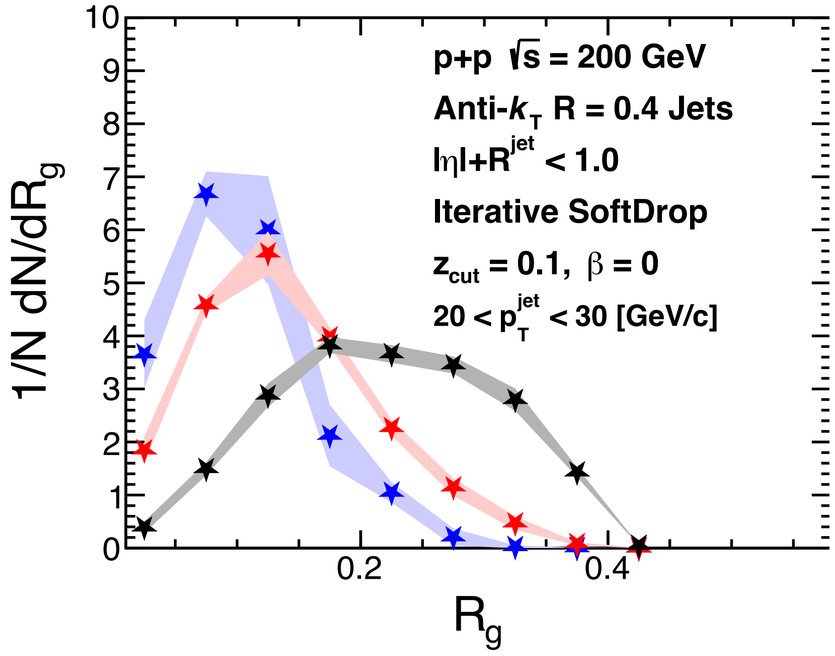




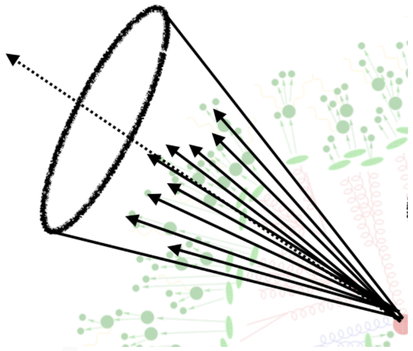
- **Flat z_g distribution and smaller $\langle R_g \rangle$** for the third split, where we observe collinear emissions



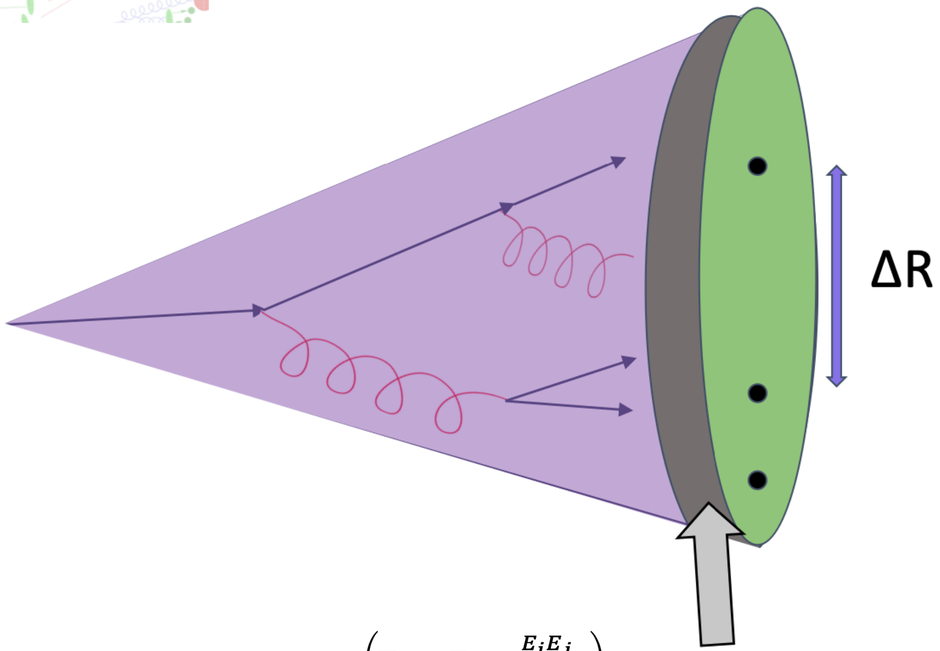
- Measured in 3 dimensions - p_T vs $z_g(R_g)$, split #
- Defines a time axis!



See talk by Monika Robotkova (CTU) @ HP 2023



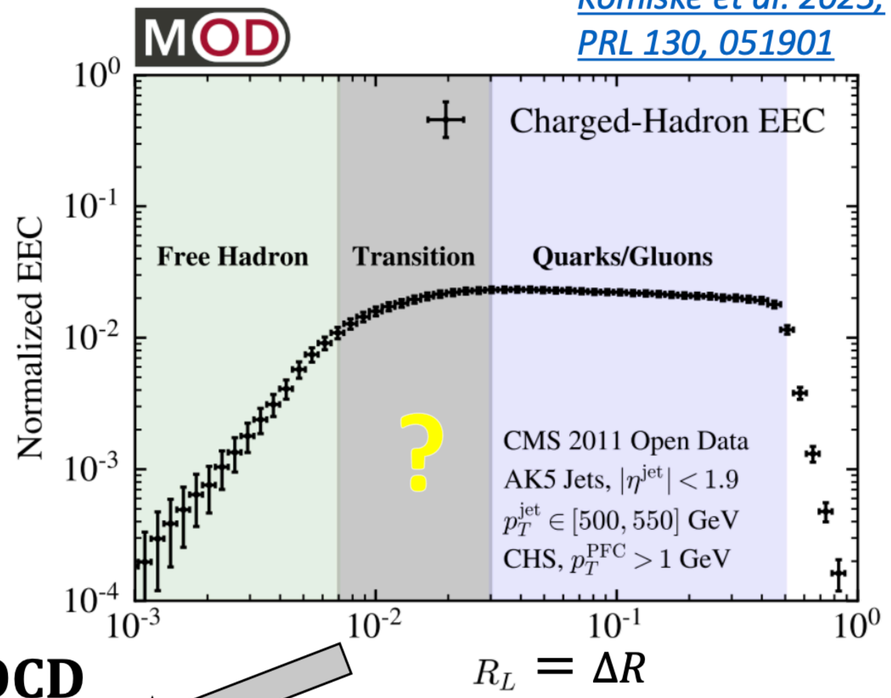
Energy-Energy Correlators



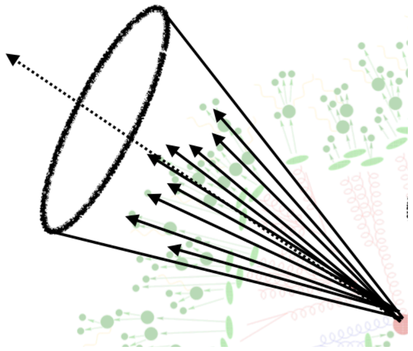
Normalized EEC = $\frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{{p_{T,Jet}}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{{p_{T,Jet}}^2}\right)}{d\,(\Delta R)}$

Turnover $\propto \frac{\Lambda_{QCD}}{{p_T}^{Jet}}$

Komiske et al. 2023, PRL 130, 051901



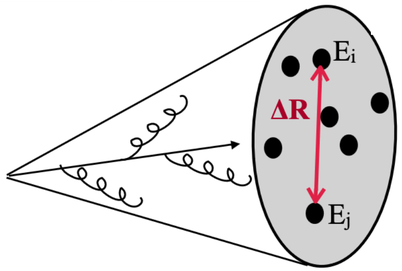
- Behavior at low ΔR corresponds to a random distribution of hadrons, while behavior at high ΔR is influenced by parton shower– **Study Transition Region**



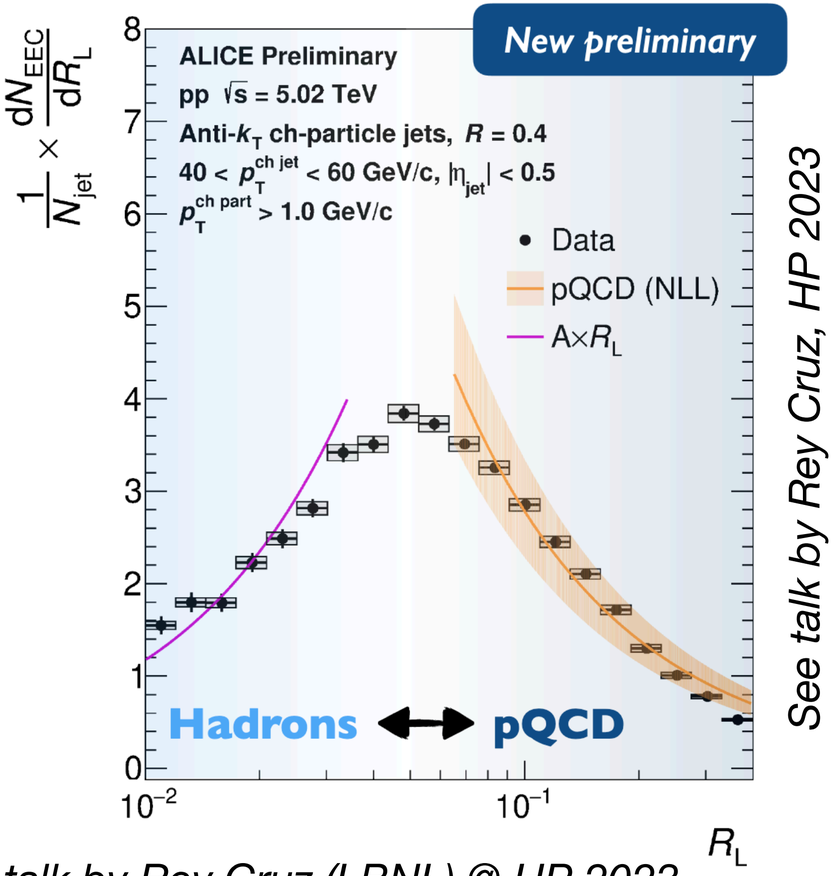
Evidence for transition

"field theory faces reality"

arXiv:2205.03414 , 2209.11236

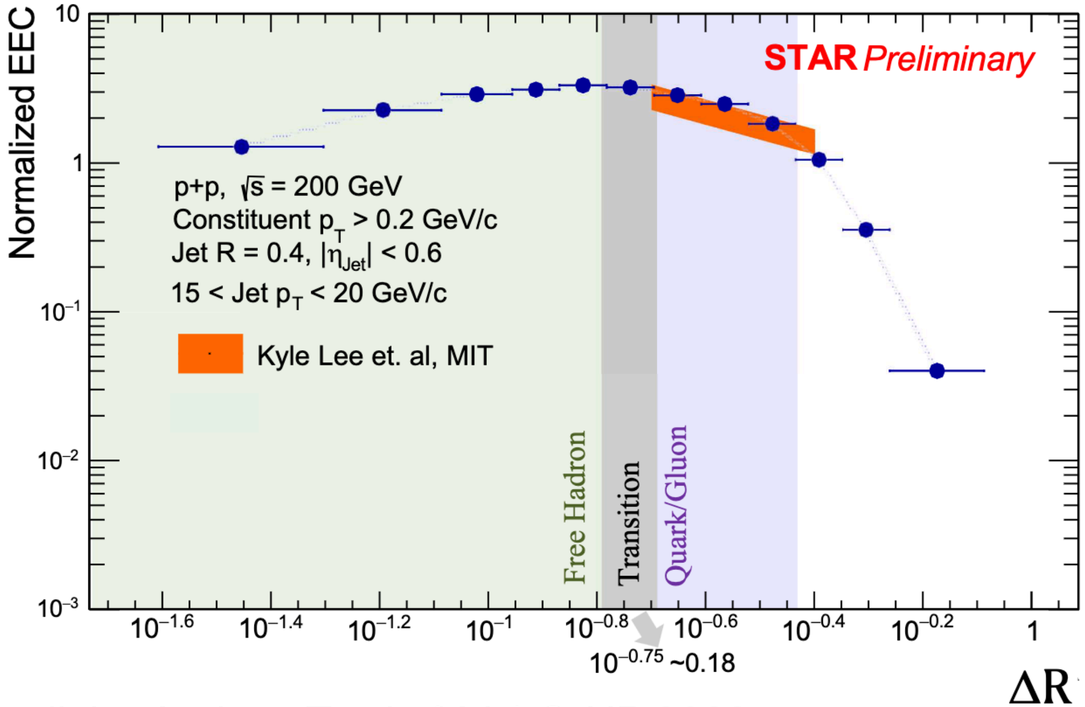


- Transition indicated as a function of the opening angle - which we know is related to the time scale!



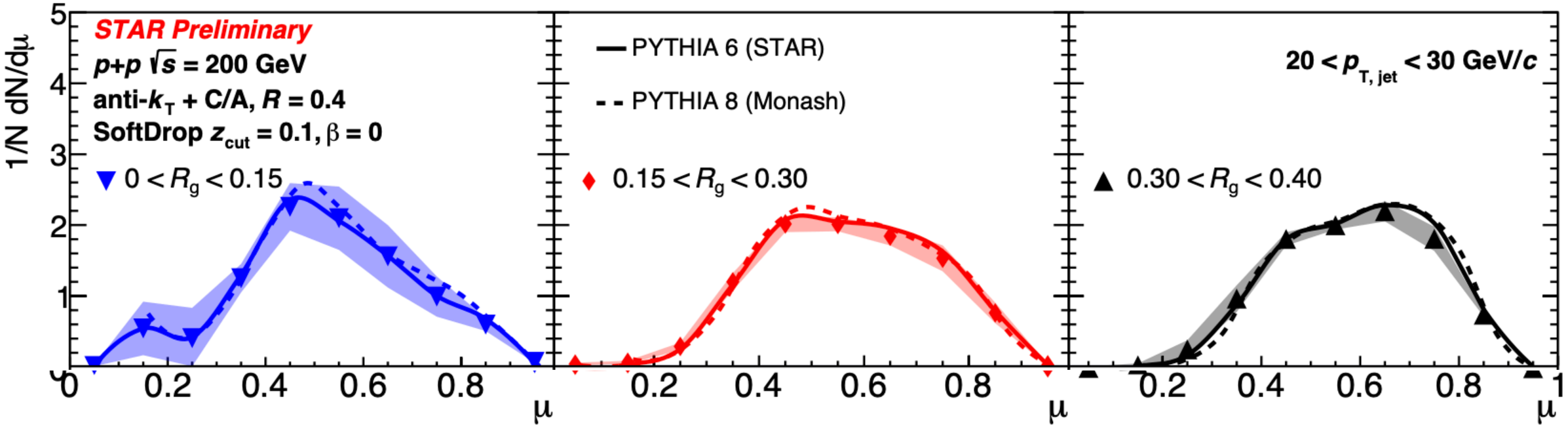
See talk by Rey Cruz, HP 2023

See talk by Rey Cruz (LBNL) @ HP 2023



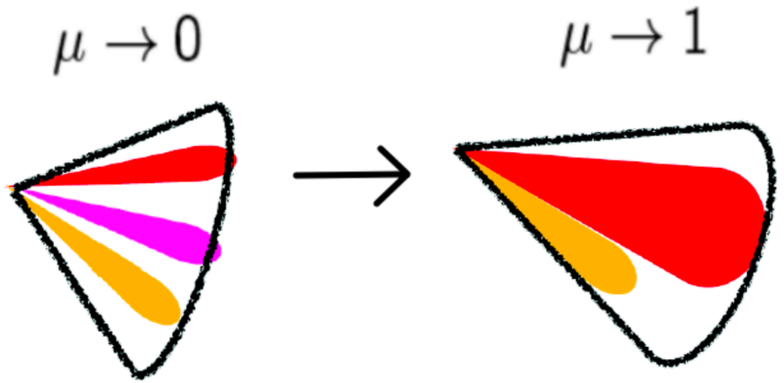
See talk by Andrew Tamis (Yale) @ HP 2023

Virtuality evolution within jets



Monika Robotkova (CTU) @ HP 2023

Dasgupta et. al.
JHEP09 (2013) 029



- Narrower splittings result in a faster reduction of virtuality!

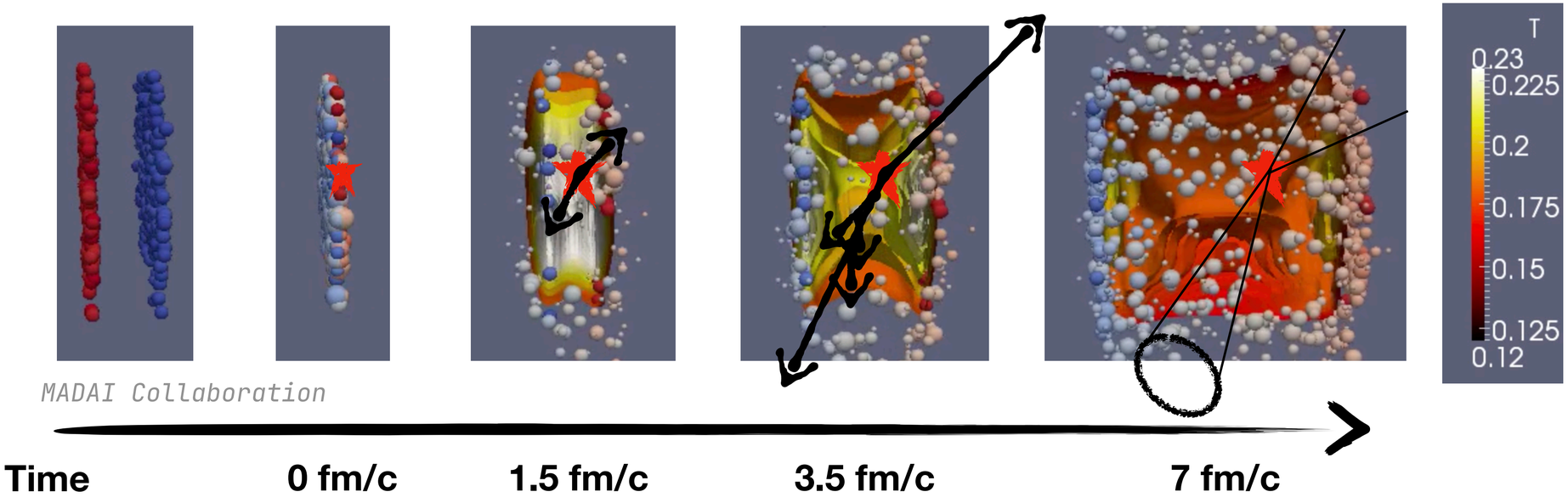
Jet substructure - WHY, WHAT, HOW

Small Systems pQCD to npQCD

Large Systems QGP Space time structure

Looking ahead

Jets and the QGP



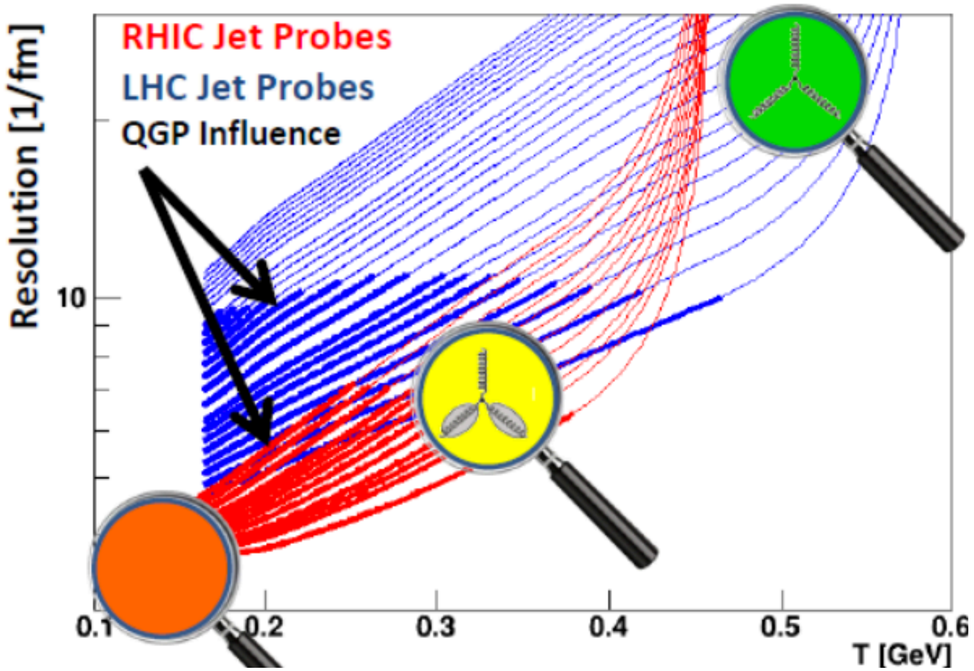
0 - 5 fm/c

Concurrent evolution of jet shower and QGP

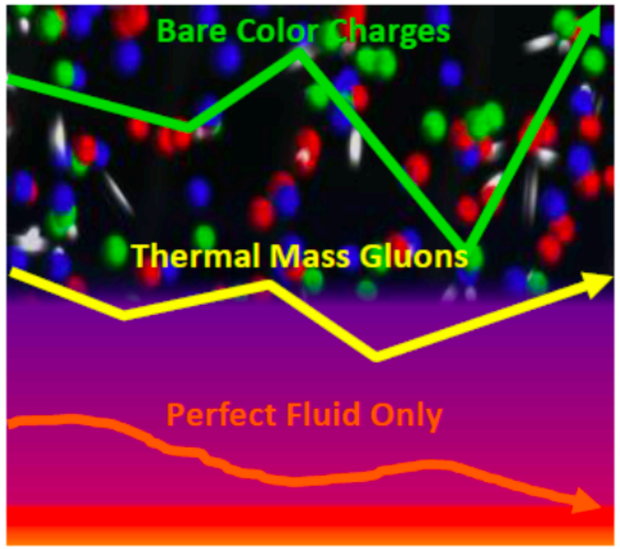
> 10 fm/c

Resulting modification to jet observables offers clue to medium properties

Jets in Heavy Ions - probe of parton energy loss



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

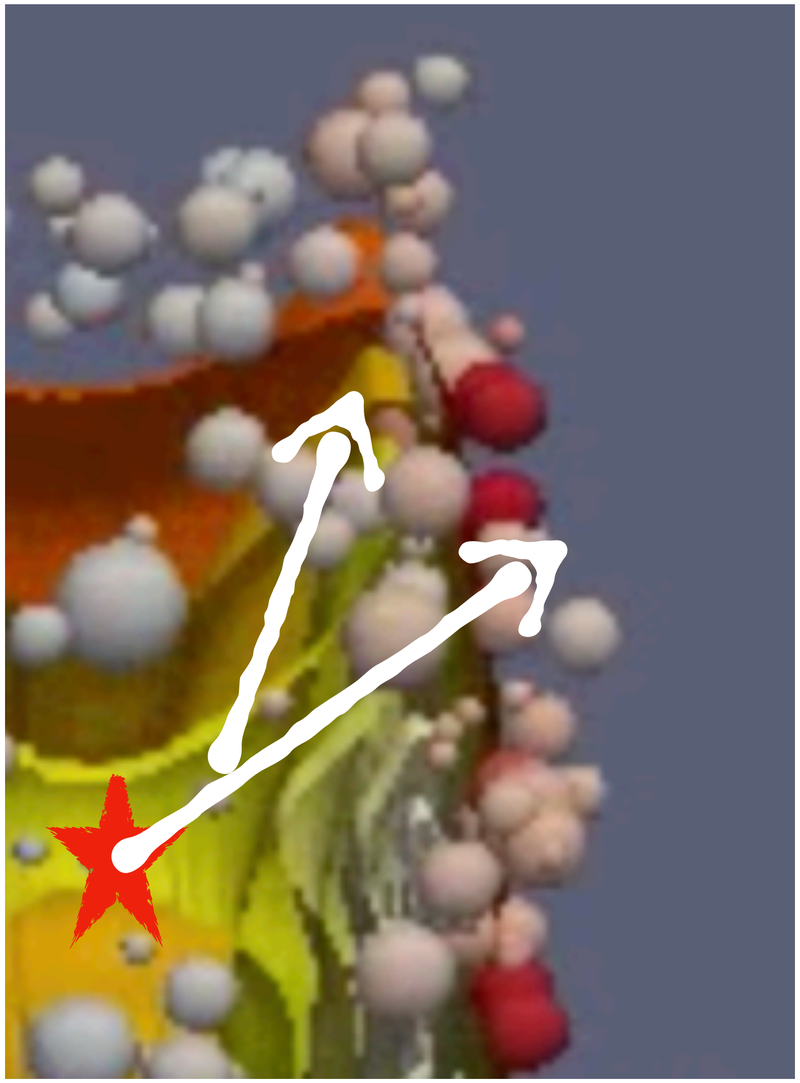


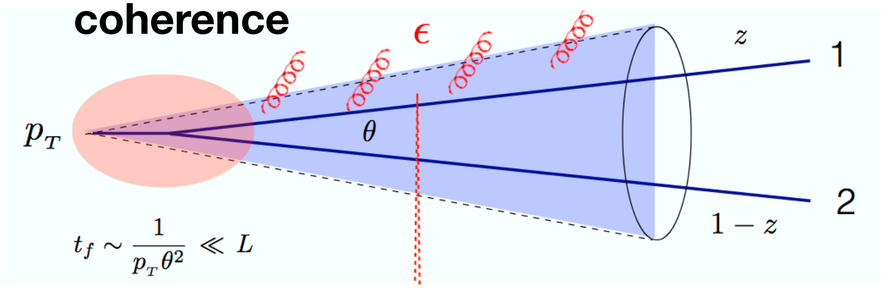
Microscopic properties of the QGP Medium -
structure at varying scales

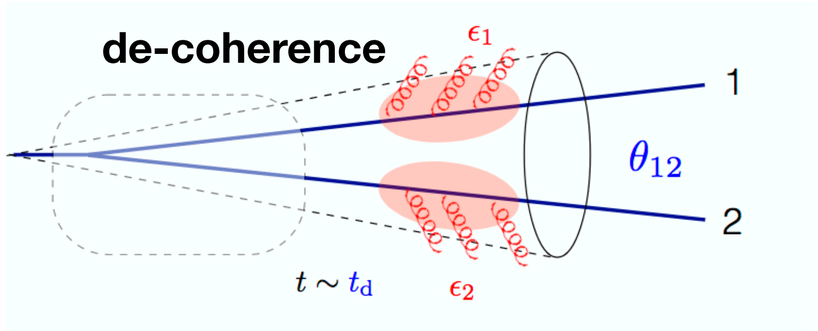
This is inherently a two step process that is not mutually exclusive

Understand jet energy loss → Extract medium properties

Is jet quenching dependent on the angular scale?







$\lambda_\perp$

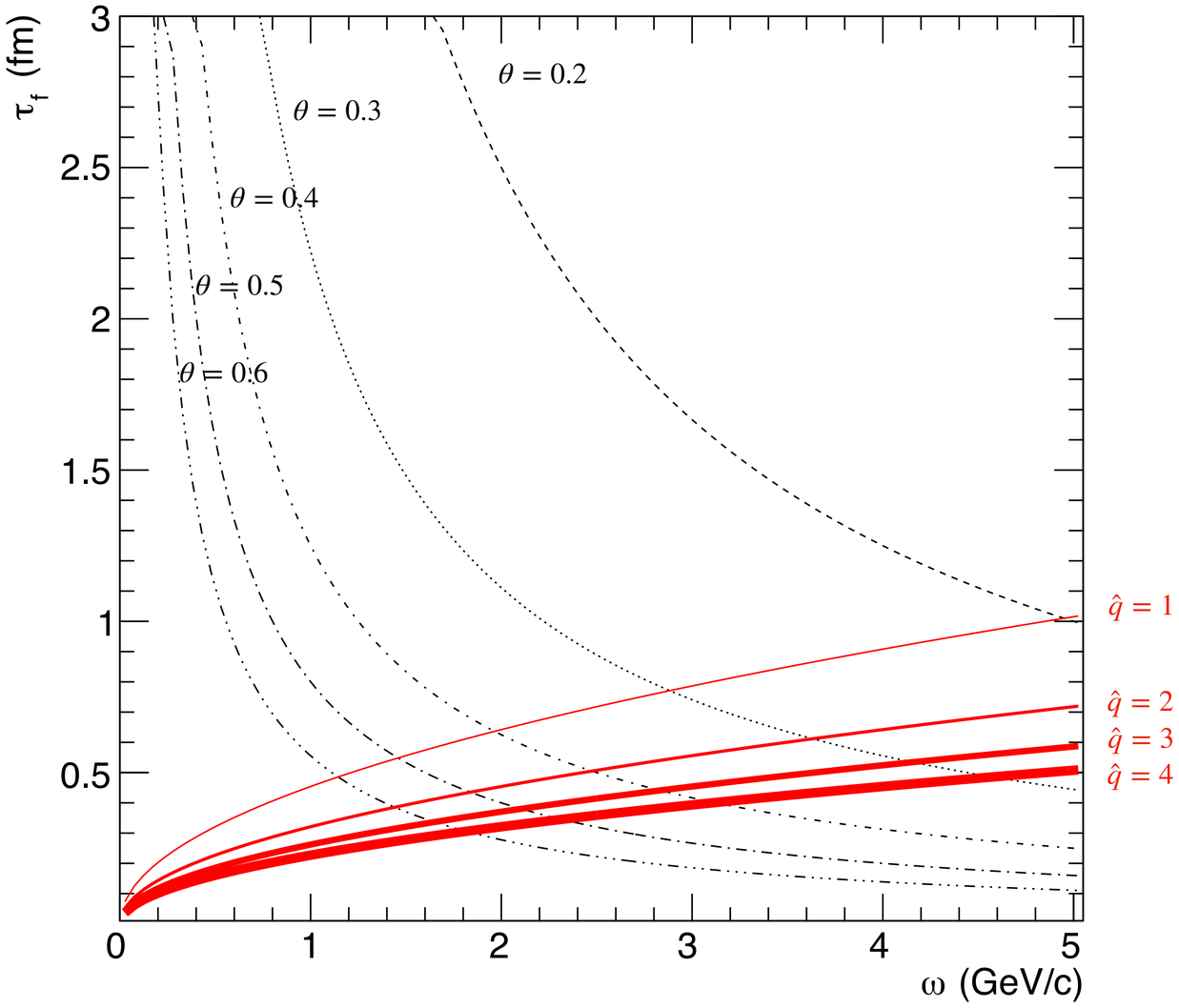
$\lambda_\perp$ sensitive to QGP's transport properties

Early splits probe the coherence length

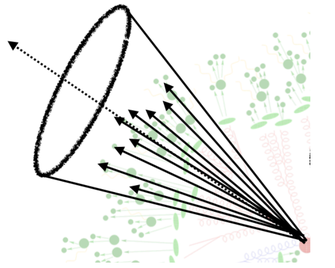
Mehtar-Tani, Tywoniuk, Phys. Rev. D 98, 051501 (2018)
Barata et. al. JHEP 09 (2021) 153

Mehtar-Tani, Pablos, Tywoniuk,
Phys. Rev. Lett. 127 (2021) 25, 252301

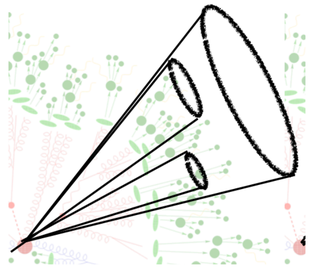
First steps in space-time differential energy loss



$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$



$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

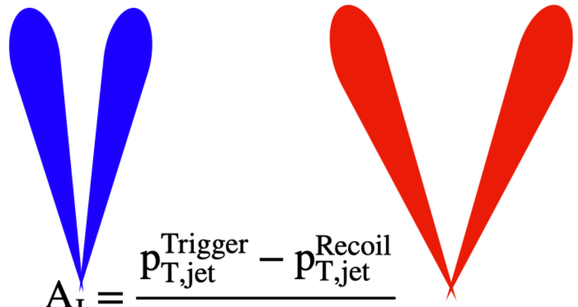


$$\hat{q} \equiv \frac{d\langle k_\perp^2 \rangle}{dL}$$

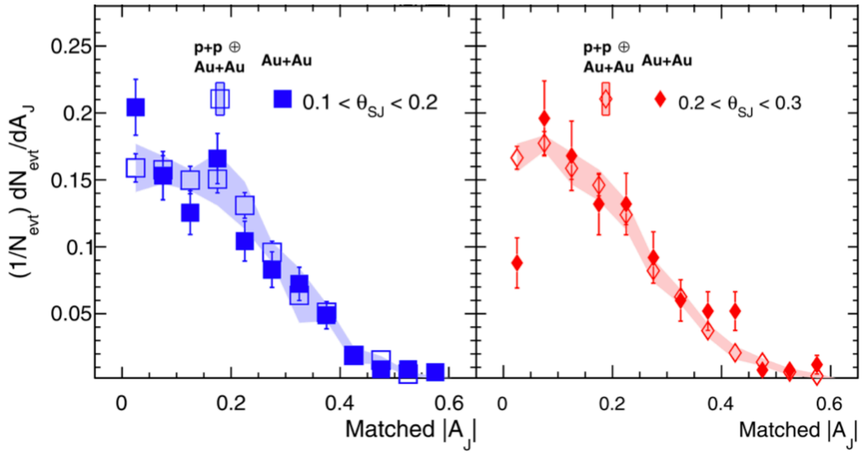
Transport parameter
average energy lost to the medium per distance traversed

STAR Phys. Rev. C 105, 044906 (2022)

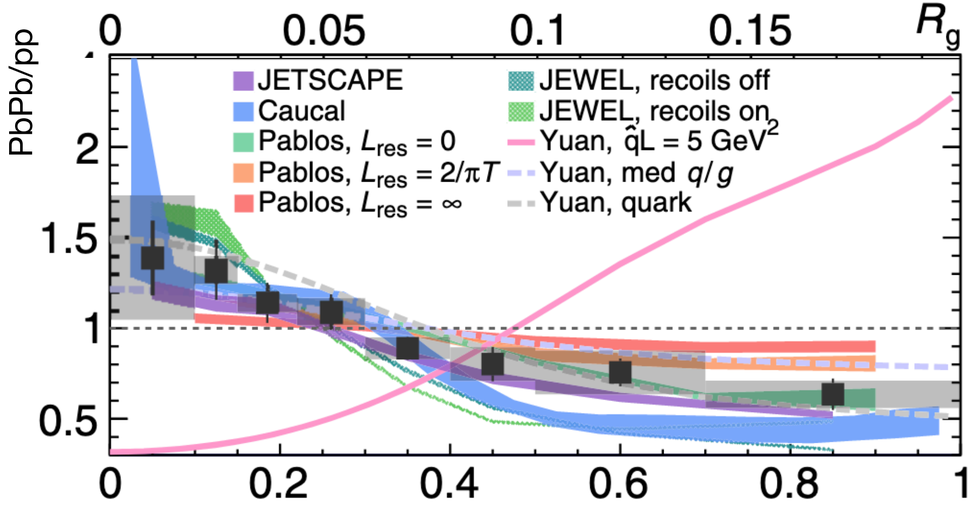
$0.1 < \theta < 0.2$ $0.2 < \theta < 0.3$

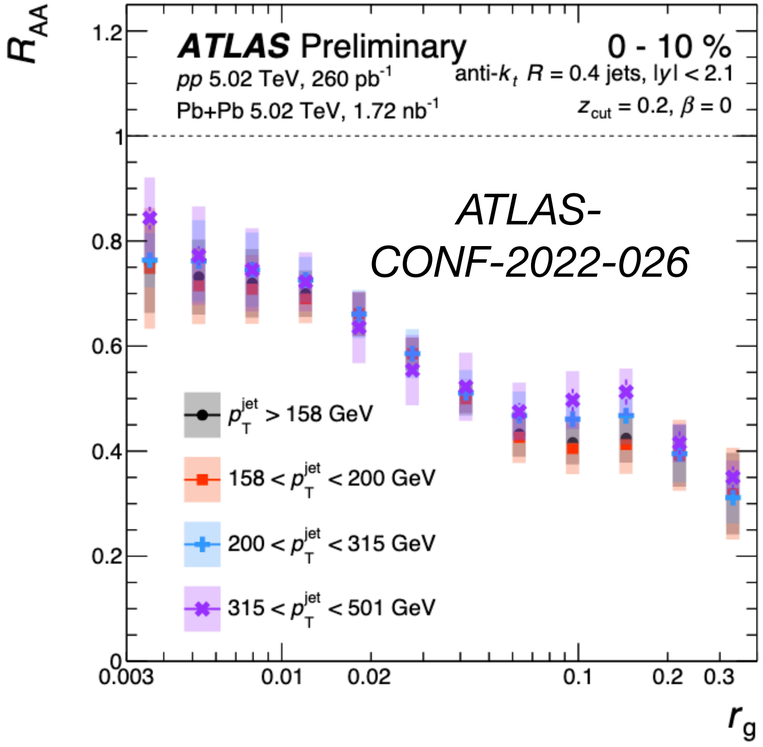


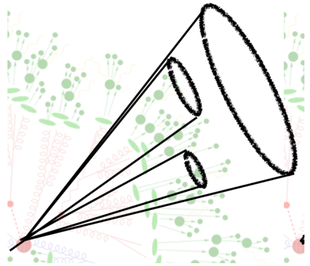
$$A_J = \frac{p_{T,jet}^{Trigger} - p_{T,jet}^{Recoil}}{p_{T,jet}^{Trigger} + p_{T,jet}^{Recoil}}$$



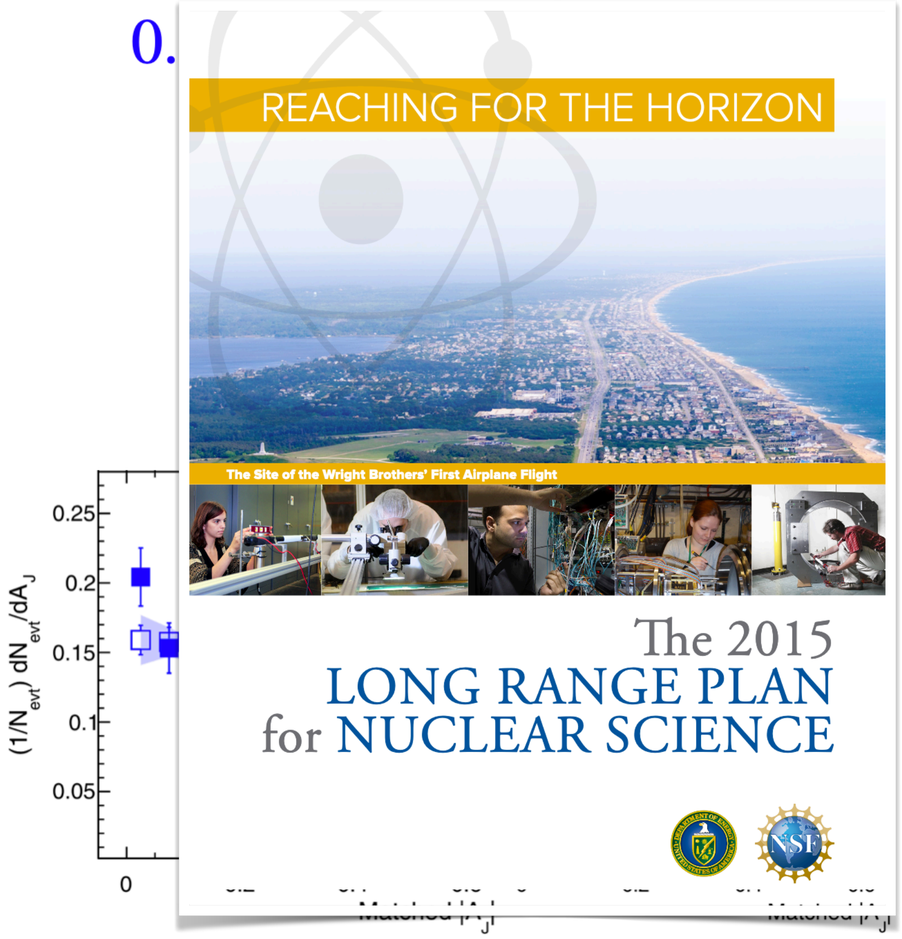
ALICE Phys. Rev. Lett. 128, 102001

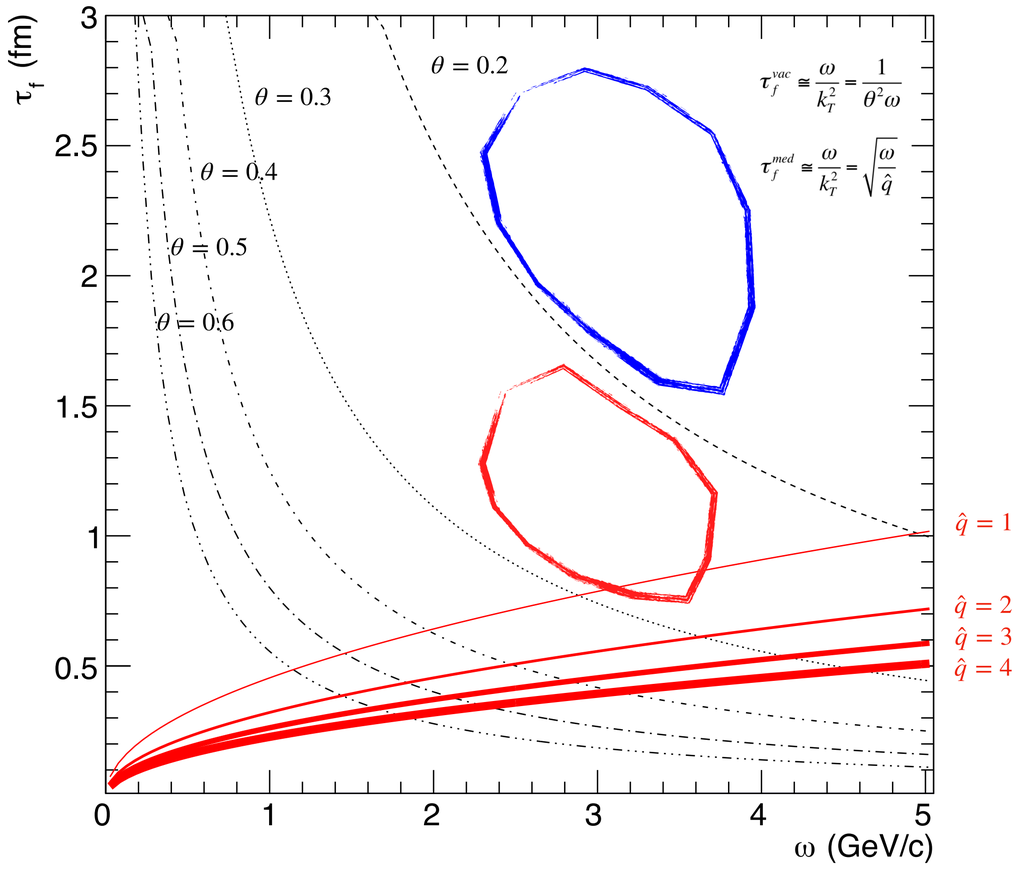






- Different methods of estimating angular dependence of quenching - subjets vs harder prongs!





- Energy loss for these dijets is an experimental observation of soft radiation from a single color charge!

- Potential upper limit on the coherence length

$$\lambda_\perp \sim \frac{1}{\hat{q} t_f} \leq 0.1$$

Jet substructure - WHY, WHAT, HOW

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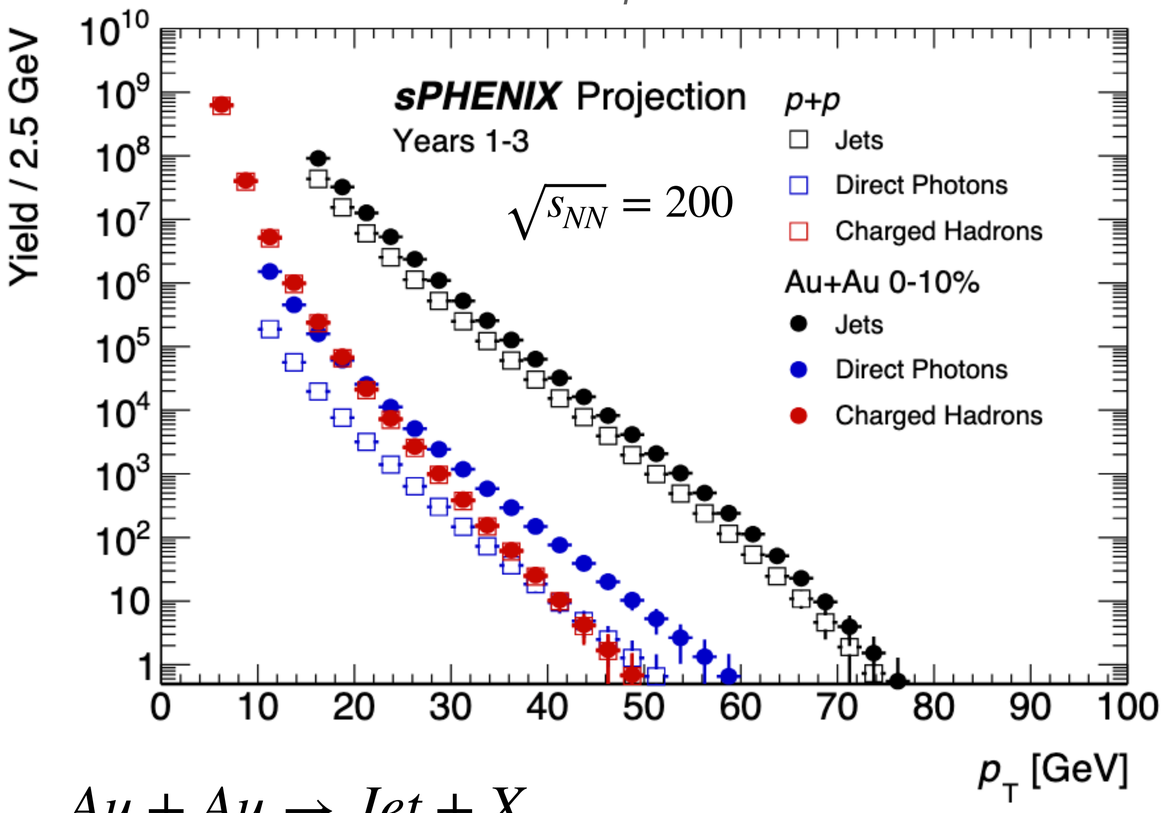
Large Systems QGP Space time structure

Looking ahead

sPHENIX

sPHENIX Beam Use Request Document 2021



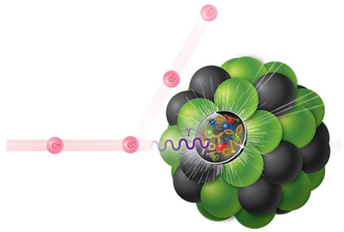
$$Au + Au \rightarrow Jet + X$$

$$Au + Au \rightarrow \gamma + Jet + X$$

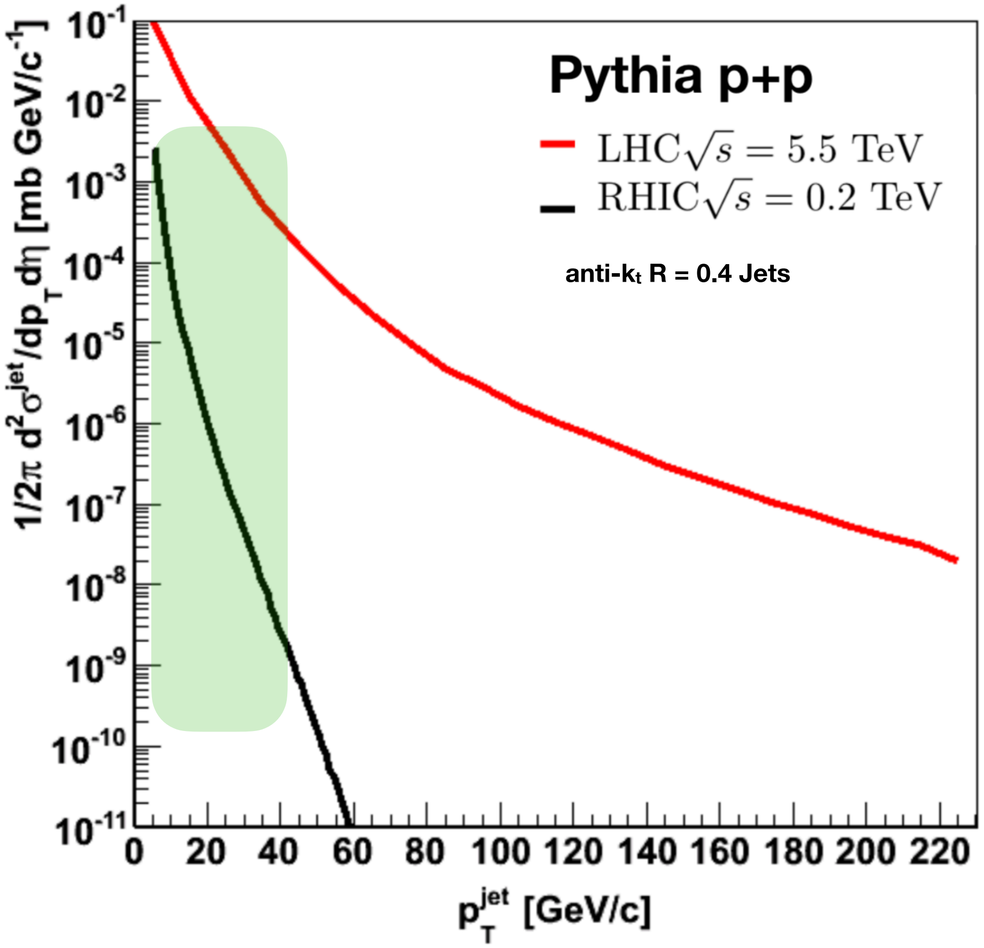
$$Au + Au \rightarrow h^{\pm,0} + X$$

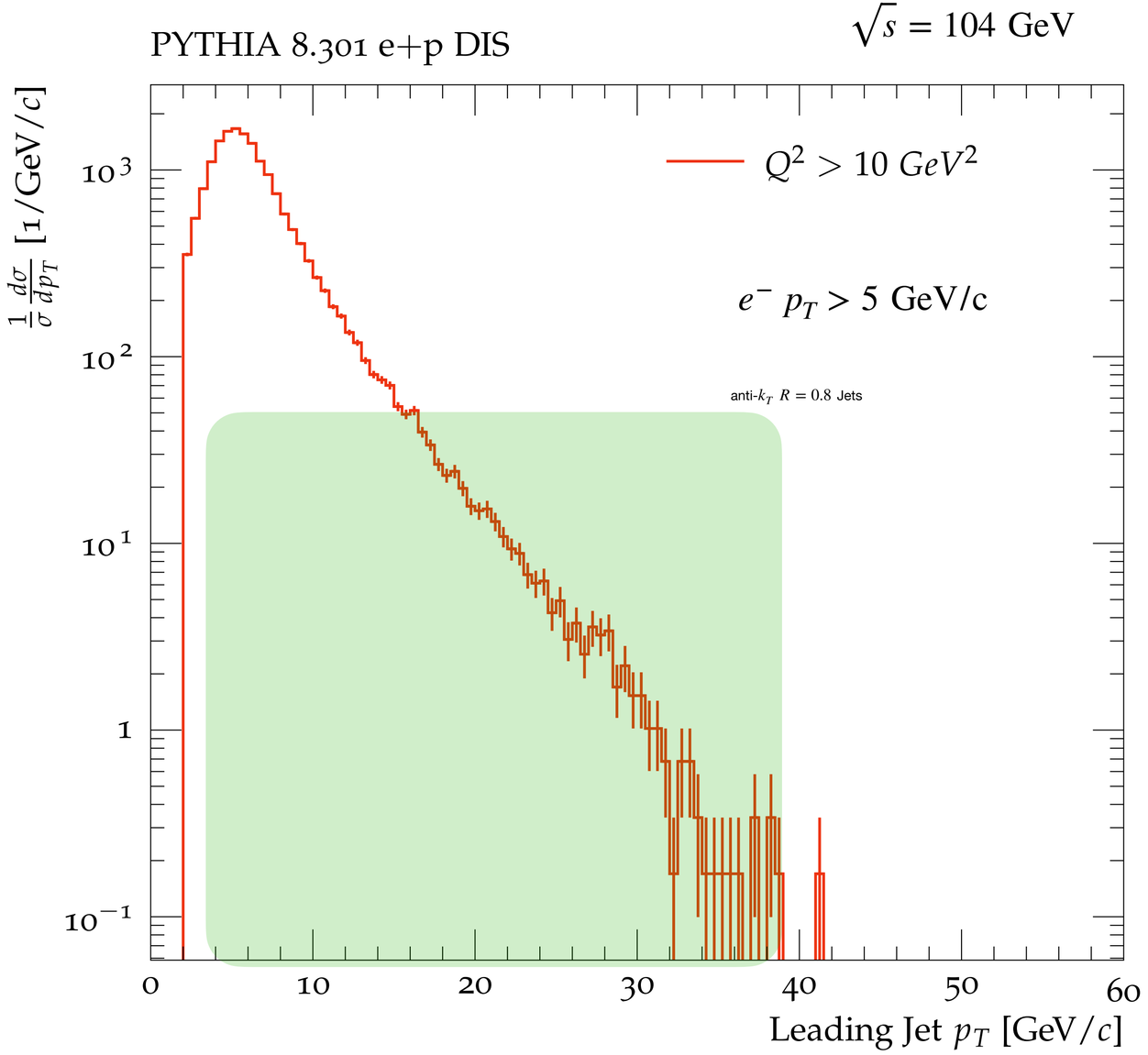
- Streaming readout allows high data-taking rate enabling slicing and dicing across phase-space
- Factor of 30 increase in data comparison to previous measurement on opening angle

Jets at the EIC

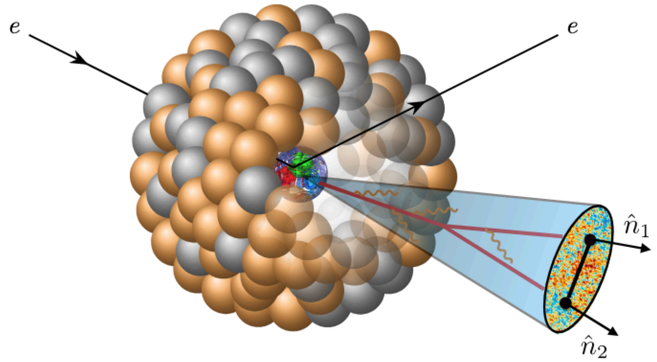


Similar jet kinematics with varied flavor composition and interaction scales

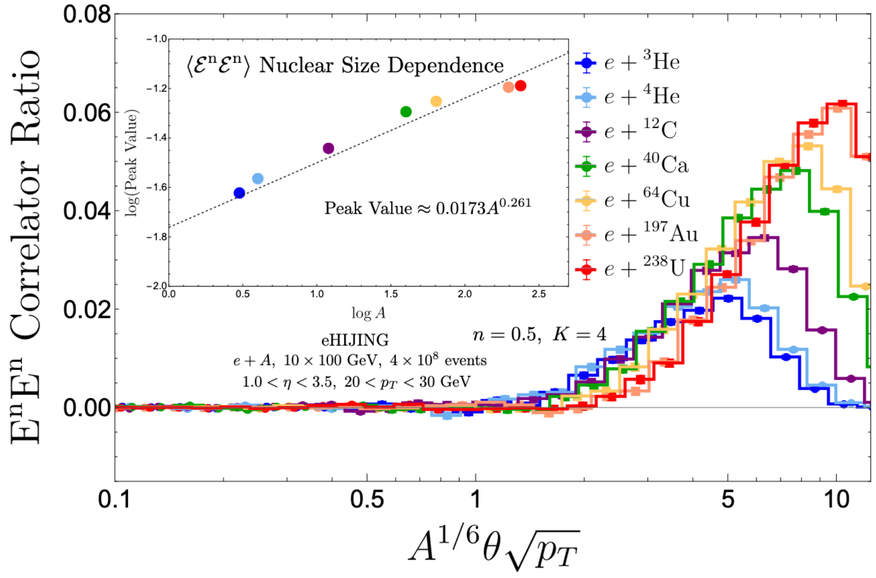




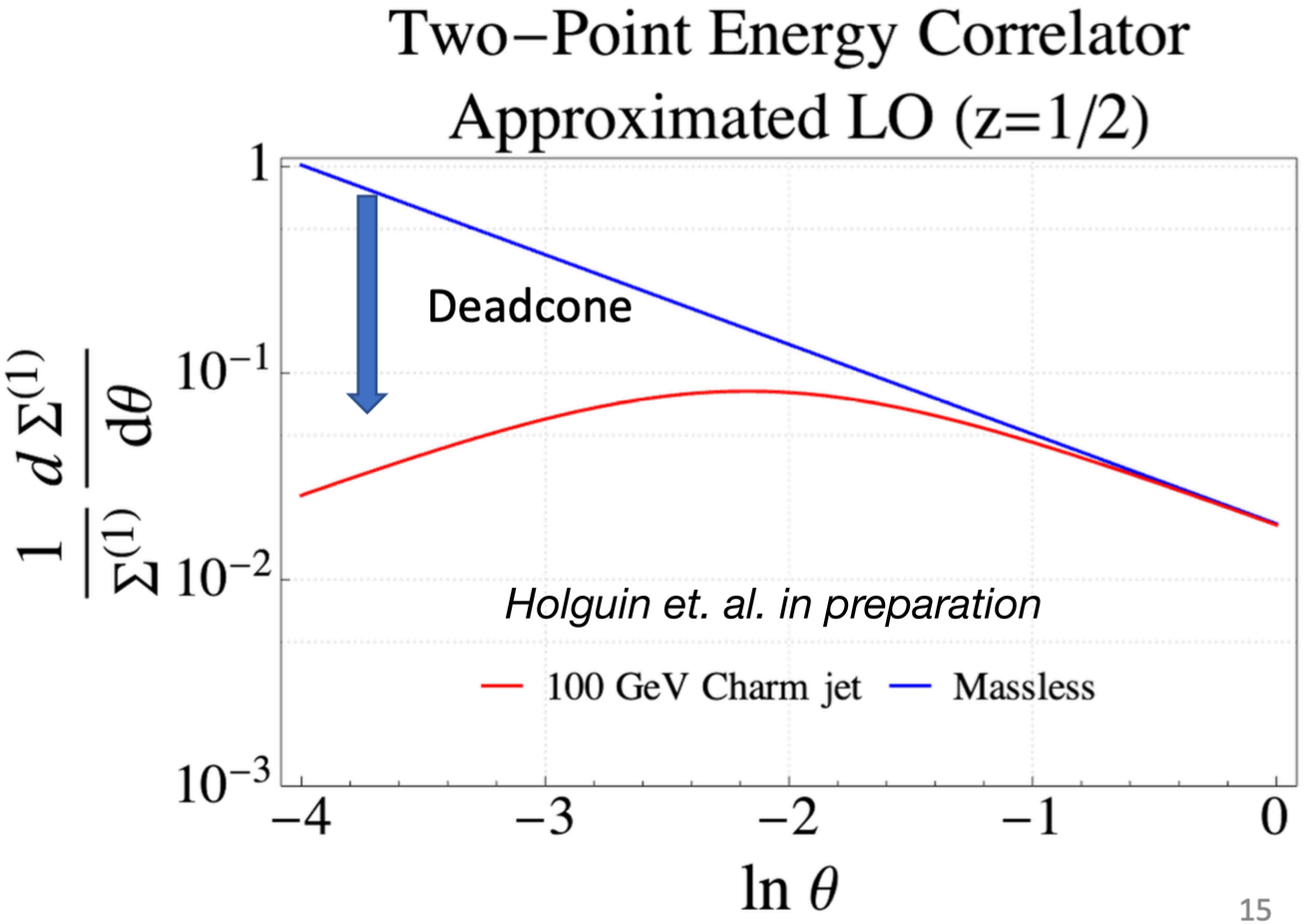
Extracting physics via the angular structure of particle distribution within jets



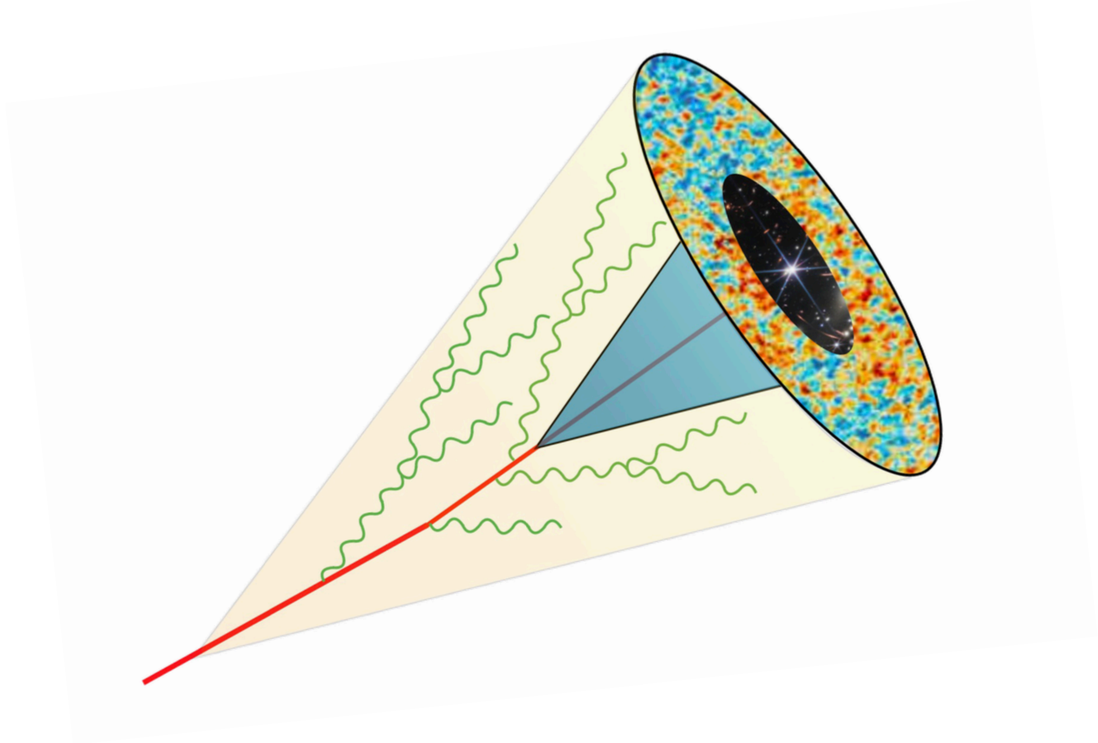
Devereaux et. al arXiv:.2303.08143



See talk by Jack Holguin (Ecole) @ HP 2023

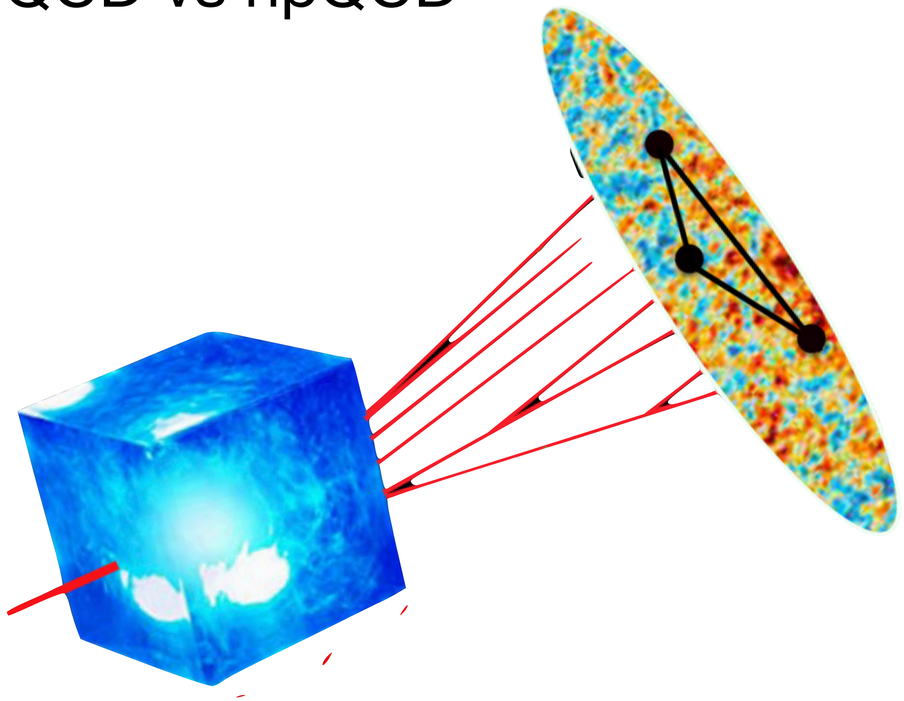


RKE (Vanderbilt) @ GHP 2023



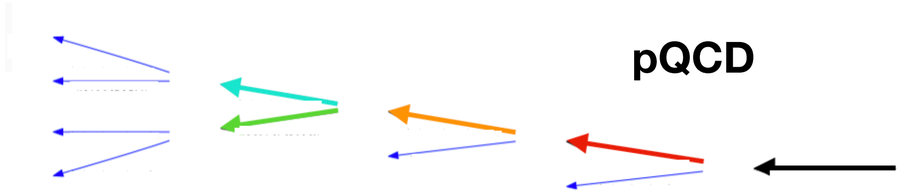
- Track the space-time evolution of fundamental particles
- Interactions with a ‘medium’ are imprinted on the angular structure of jets

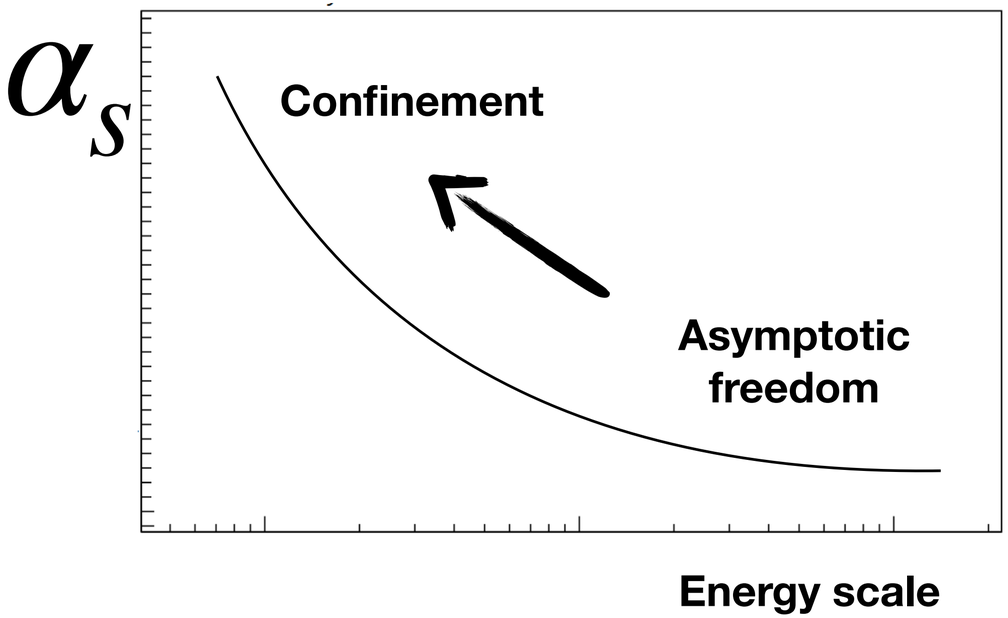
- The era of precision jet substructure is upon us!
- Tools available that allow us to separate scape dependent physics - pQCD vs npQCD

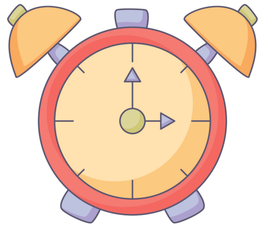


Bonus slides

Lets look inside jets!

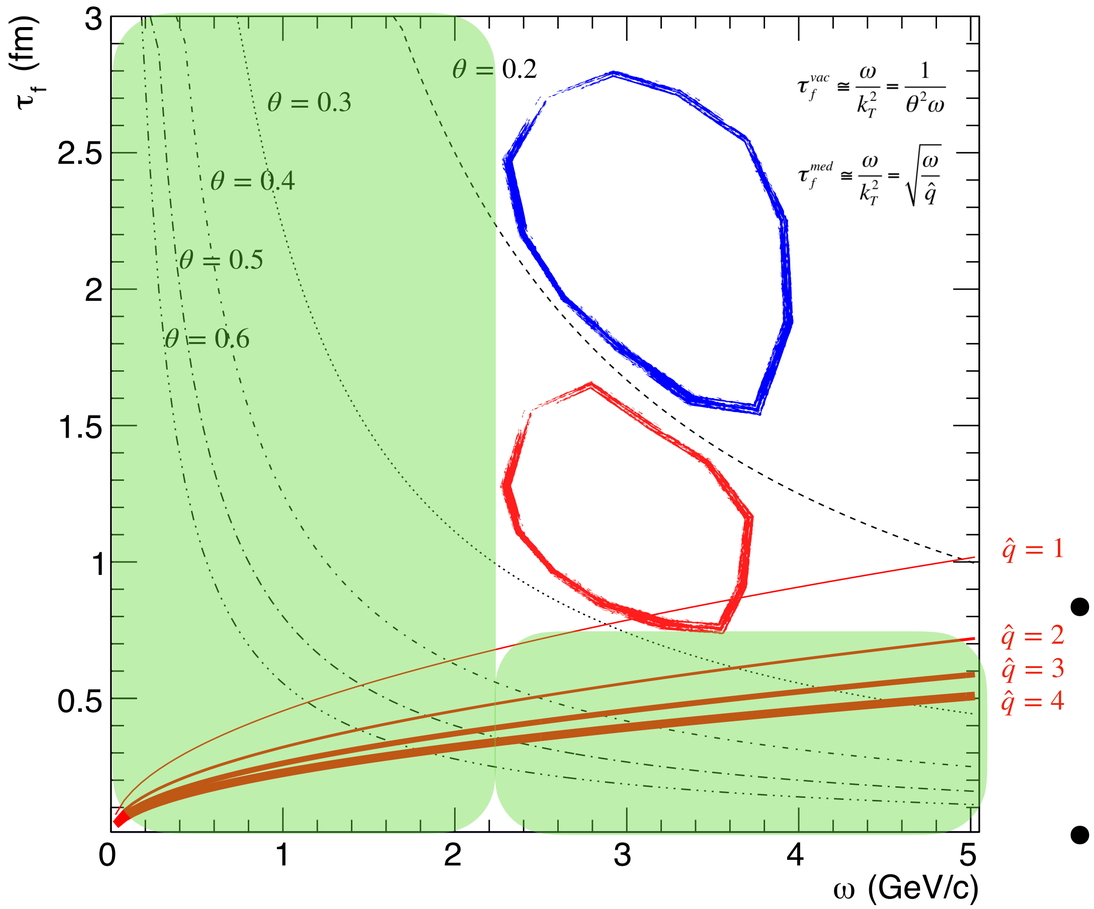


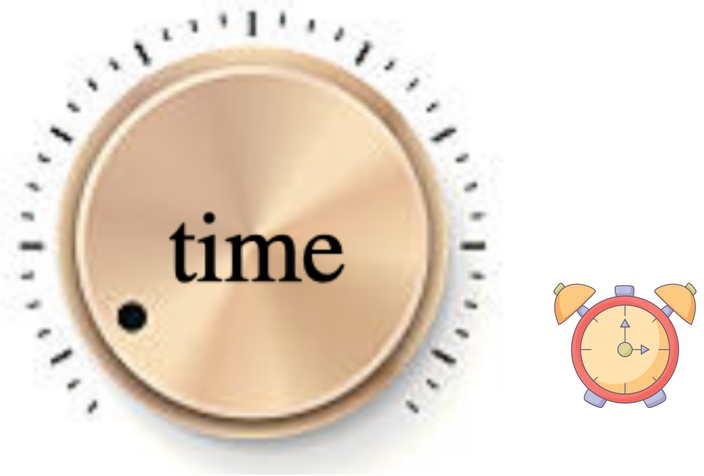




- What is the evolution of the substructure within a jet?
- Is the splitting kinematics dependent on the available phase-space?

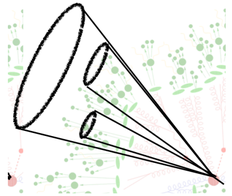
Multi-dimensional exploration of fundamental QCD and QGP transport properties





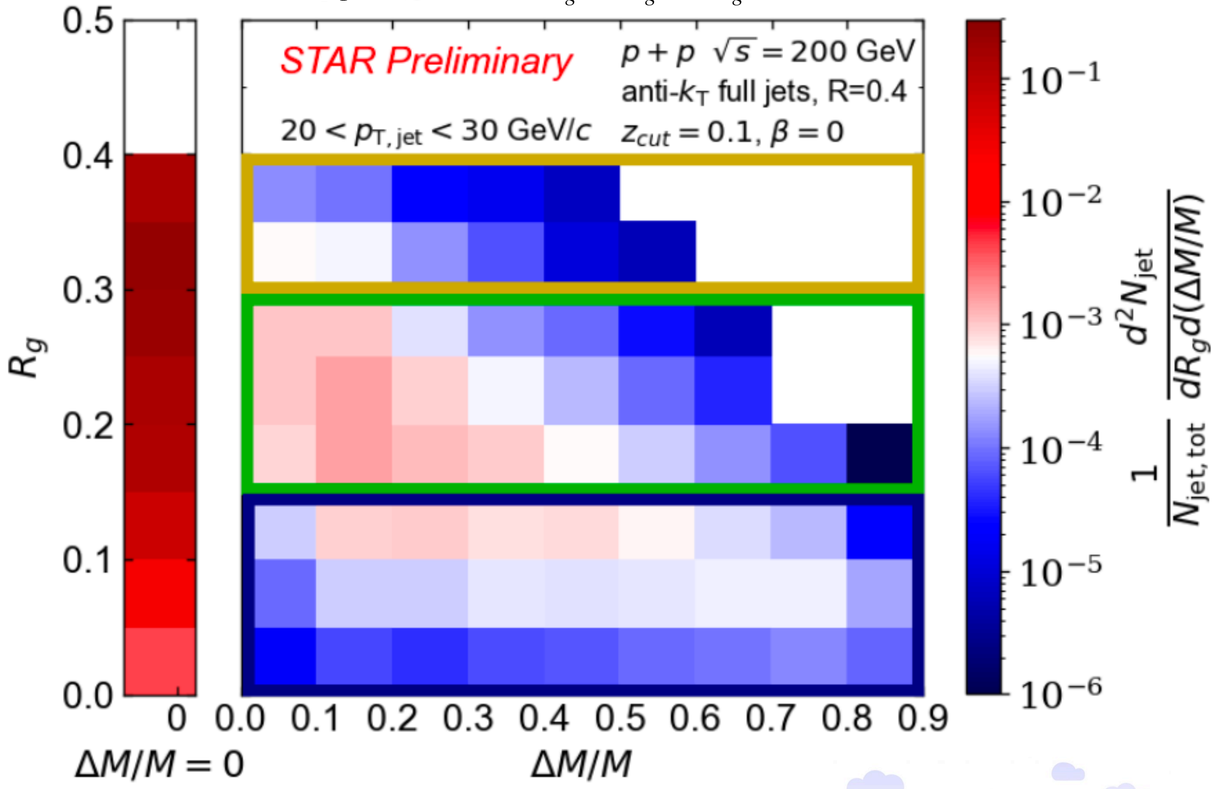
- Scan across emission phase-space with the large statistics dataset
- Space-time tomography of the QGP

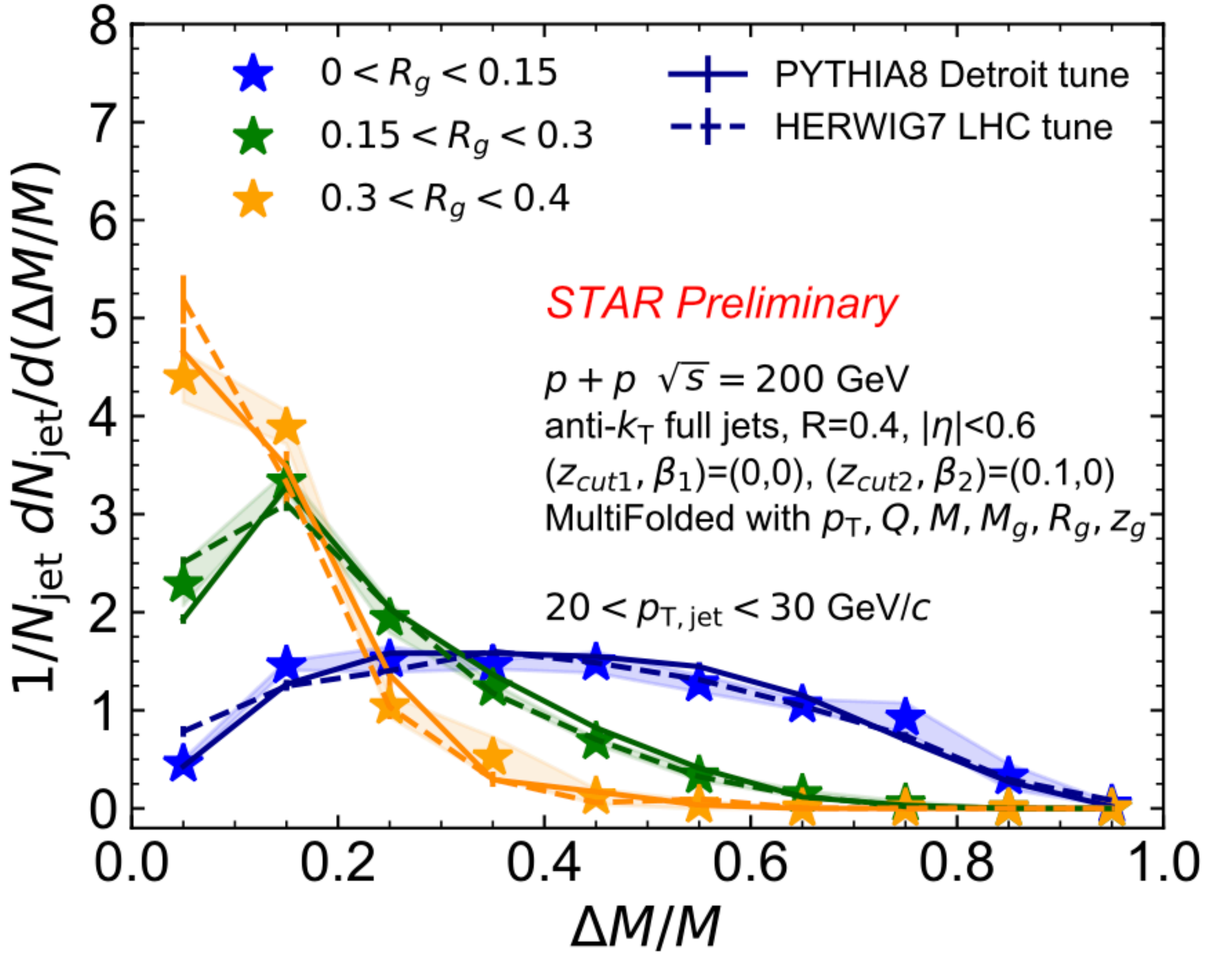
Multi-dimensional structure of jet evolution



6D unfolded simultaneously
via MultiFold machine learning technique

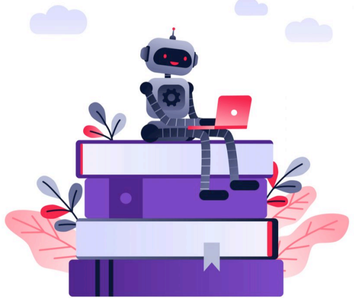
p_T *vs* Q *vs* M *vs* z_g *vs* R_g *vs* M_g



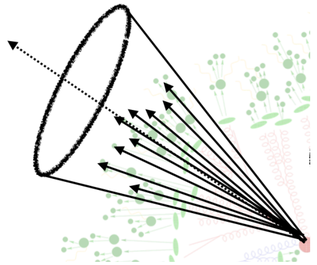


Youqi Song (Yale) @ DIS 2023

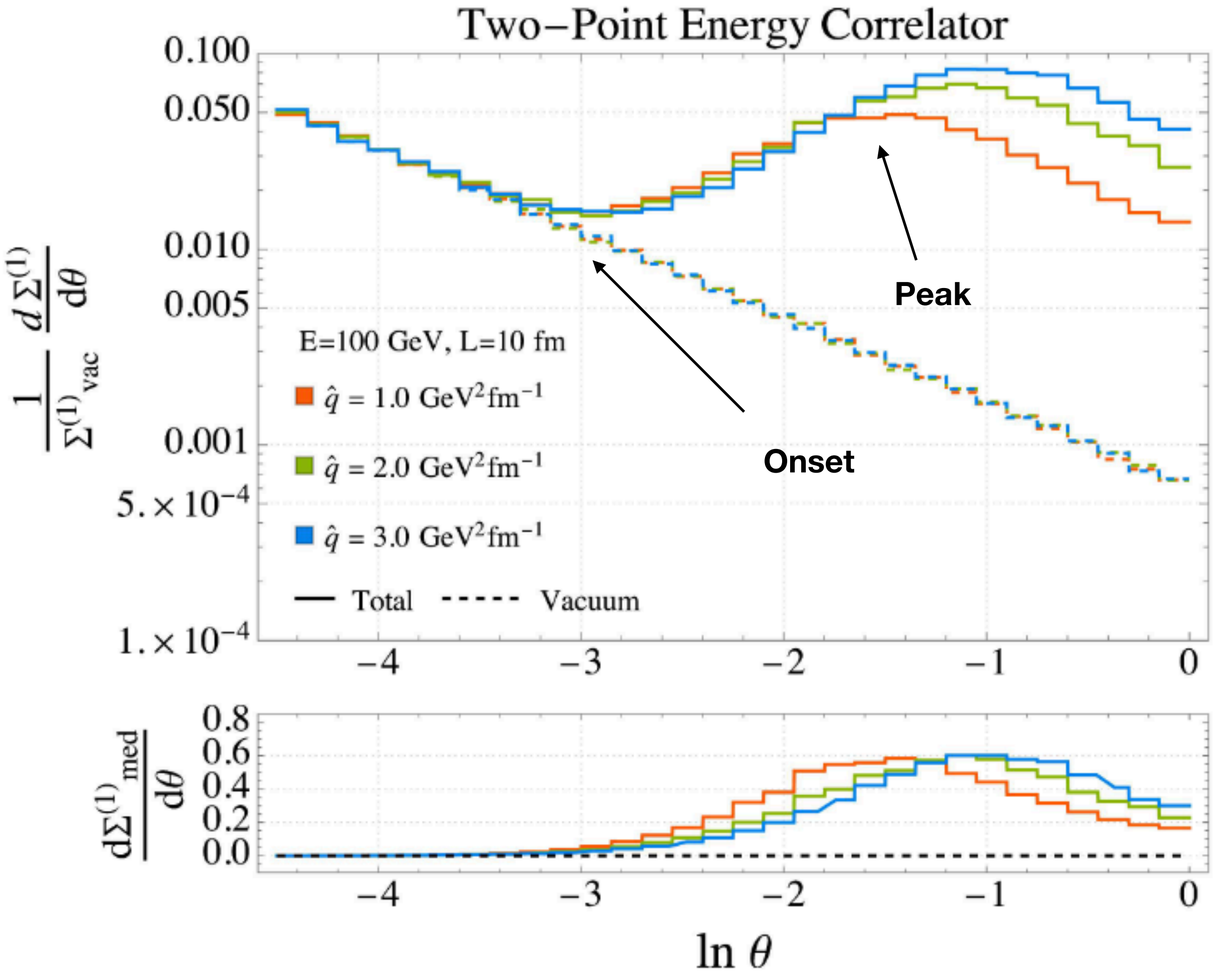
Andreassen et.al
Phys. Rev. Lett. 124, 182001 (2020)



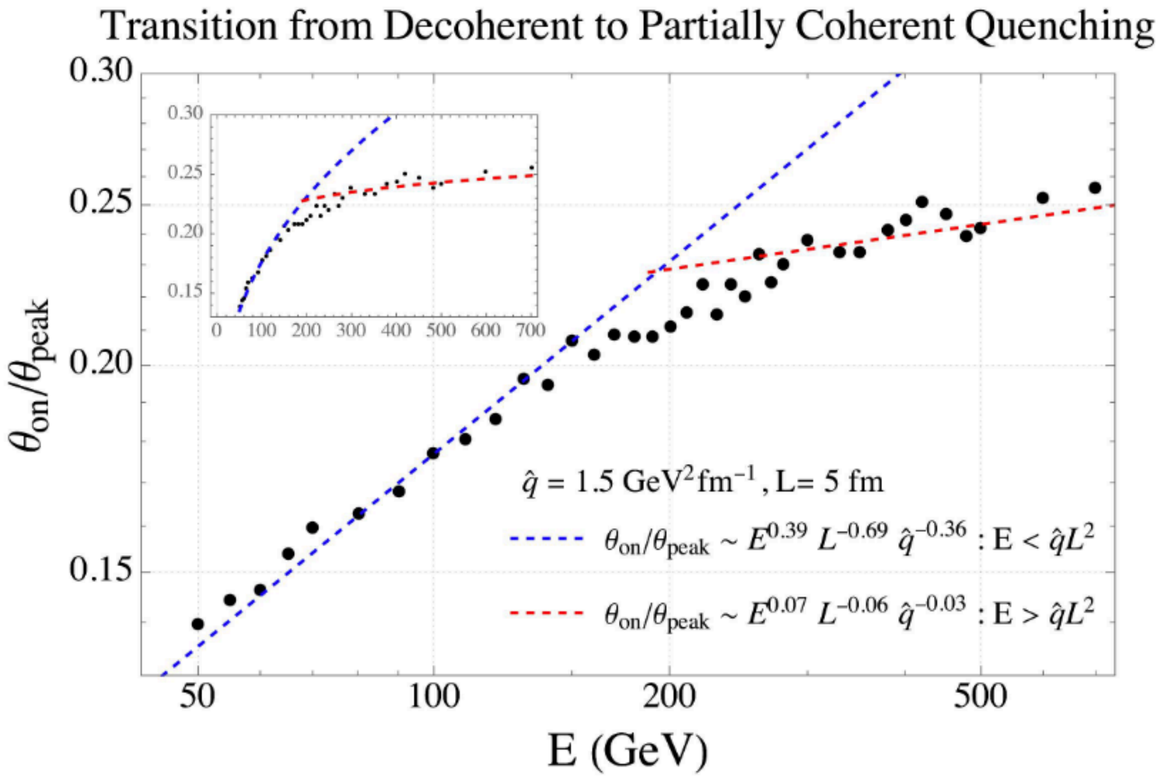
- The more you groom, the further along the shower you go!



EECs in Heavy Ions



- Larger the $\hat{q}$ -> peak shifted to the right



Moult, et.al 2201.07800

Andres, RKE, et.al 2209.11236