Sensitivity of jet observables to the presence of quasi-particles in the QGP

Zach Hulcher

in collaboration with D. Pablos and K. Rajagopal

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Stanford University

Why Moliere?

- QGP, at length scales of $O(T^{-1})$ is best described as a strongly coupled liquid.

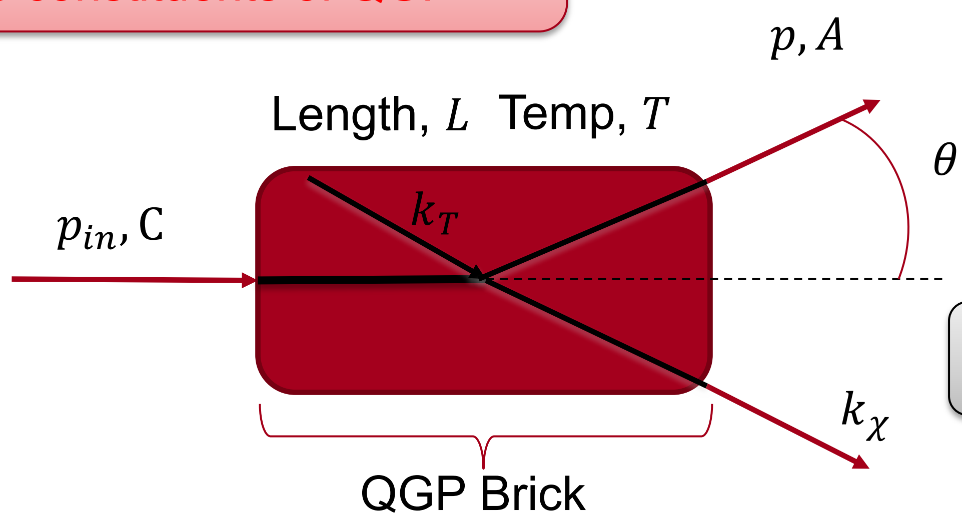
- At shorter length scales, and thus high exchanged-momentum, asymptotic freedom → quasi-particle behavior.

- High energy partons have the potential to probe the particulate nature of QGP.

Moliere Scattering in QGP

Power-law-rare medium kicks which can probe particle constituents of QGP

Other implementations in JEWEL, LBT, MARTINI…



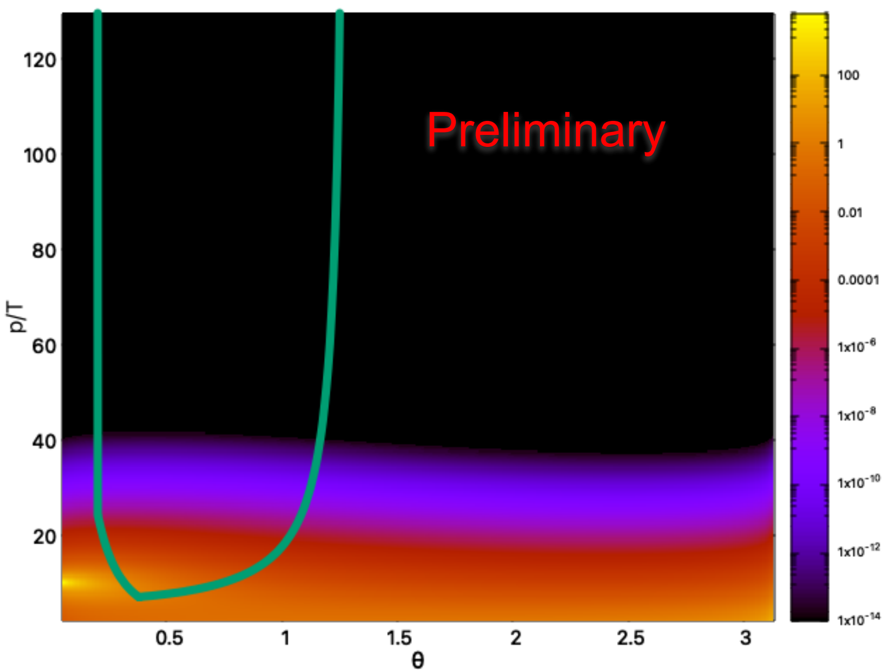
D'Eramo et al., 2019

- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium (hole).

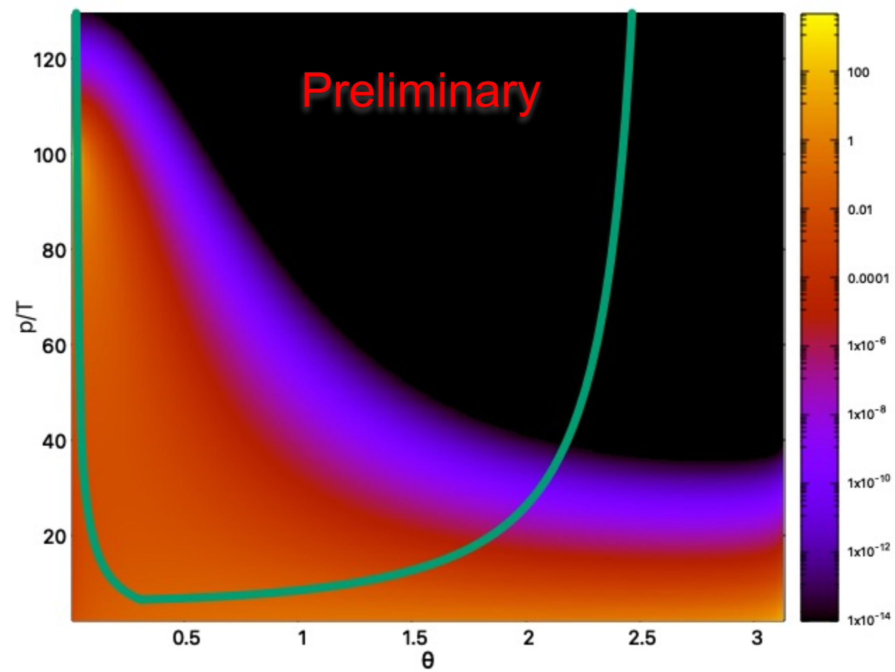
Tree-Level 2-2 massless scattering amplitudes

$$F^{C\to A}(p,\theta;p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C\to A}}{2(4\pi)^3}\left(\frac{p\sin(\theta)}{p_{in}|\boldsymbol{p}-\boldsymbol{p_{in}}|T}\right)\int_{k_{min}}^{\infty} dk_T\, n_D(k_T)\left[1 \pm n_B(k_\chi)\right]\int_0^{2\pi}\frac{d\phi}{2\pi}\frac{\left|M^{(n)}\right|^2}{g_s^4}$$

Results and Allowed Phase Space



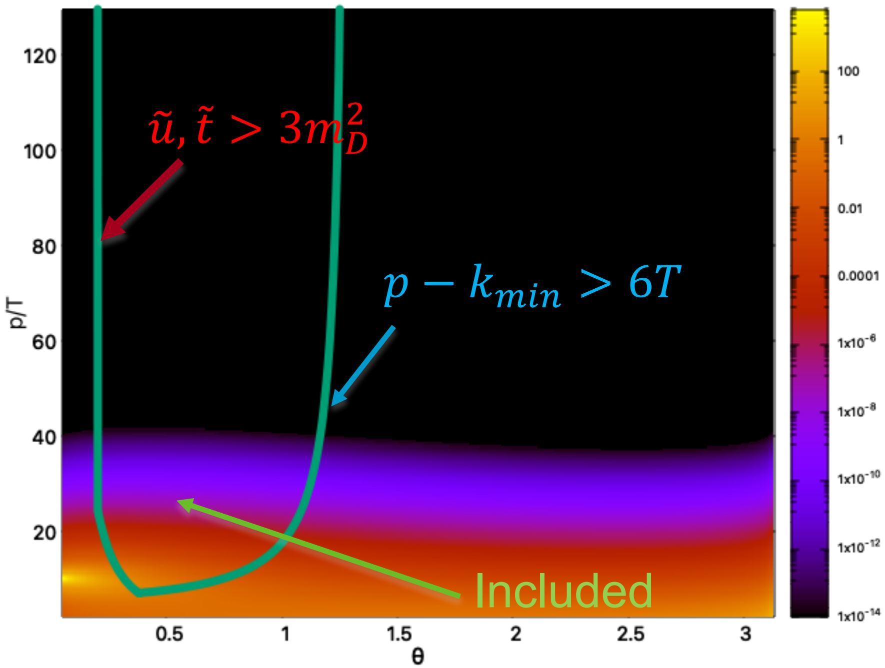
Incoming gluon, $p_{in} = 10T, \Delta t = 15/T$



Incoming gluon, $p_{in} = 100T, \Delta t = 15/T$

- Analytical results → fast with inverse CDF sampling.
- Accounts for full kinematics (no small angle approximation)

Results and Included Phase Space



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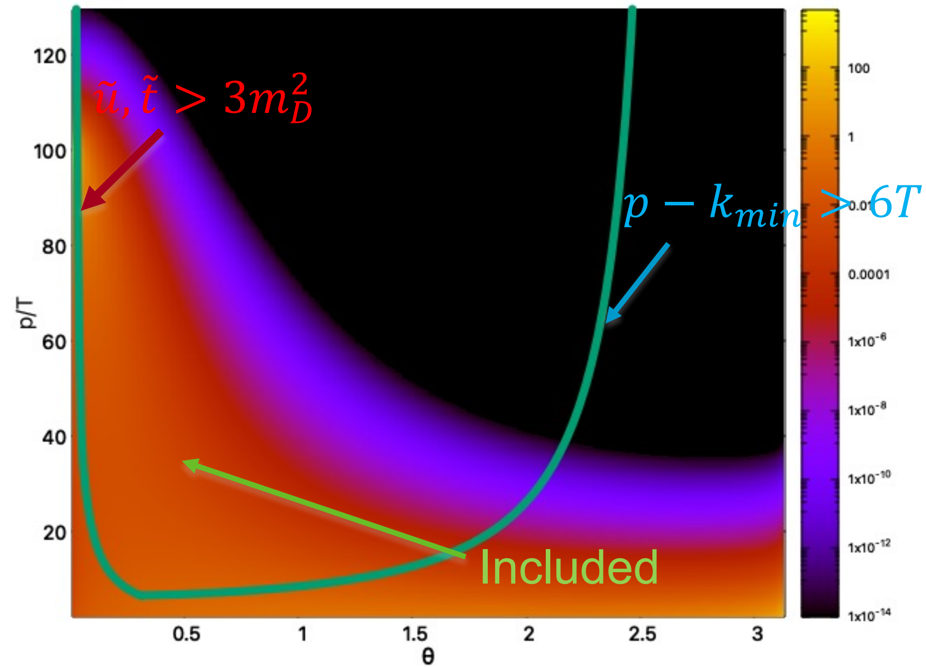


Incoming gluon, $p_{in} = 100T, \Delta t = 15/T$

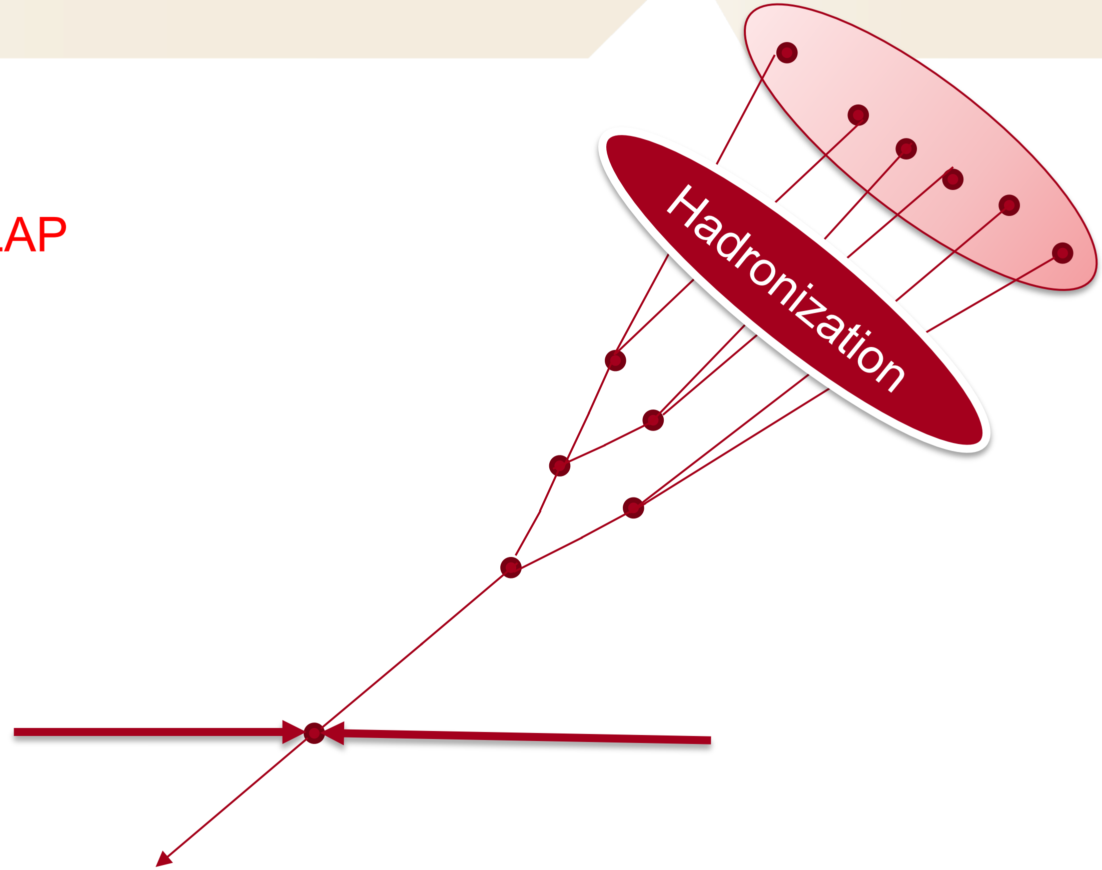
Restrict to high momentum transfer $\longrightarrow$ $\tilde{u}, \tilde{t} > c \cdot m_D^2$

- Excludes low energy, non perturbative scatterings.
- Justifies massless assumption in amplitudes.

Now we need a jet Monte Carlo that includes soft interactions with the medium to put this into…

The Hybrid Model

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).



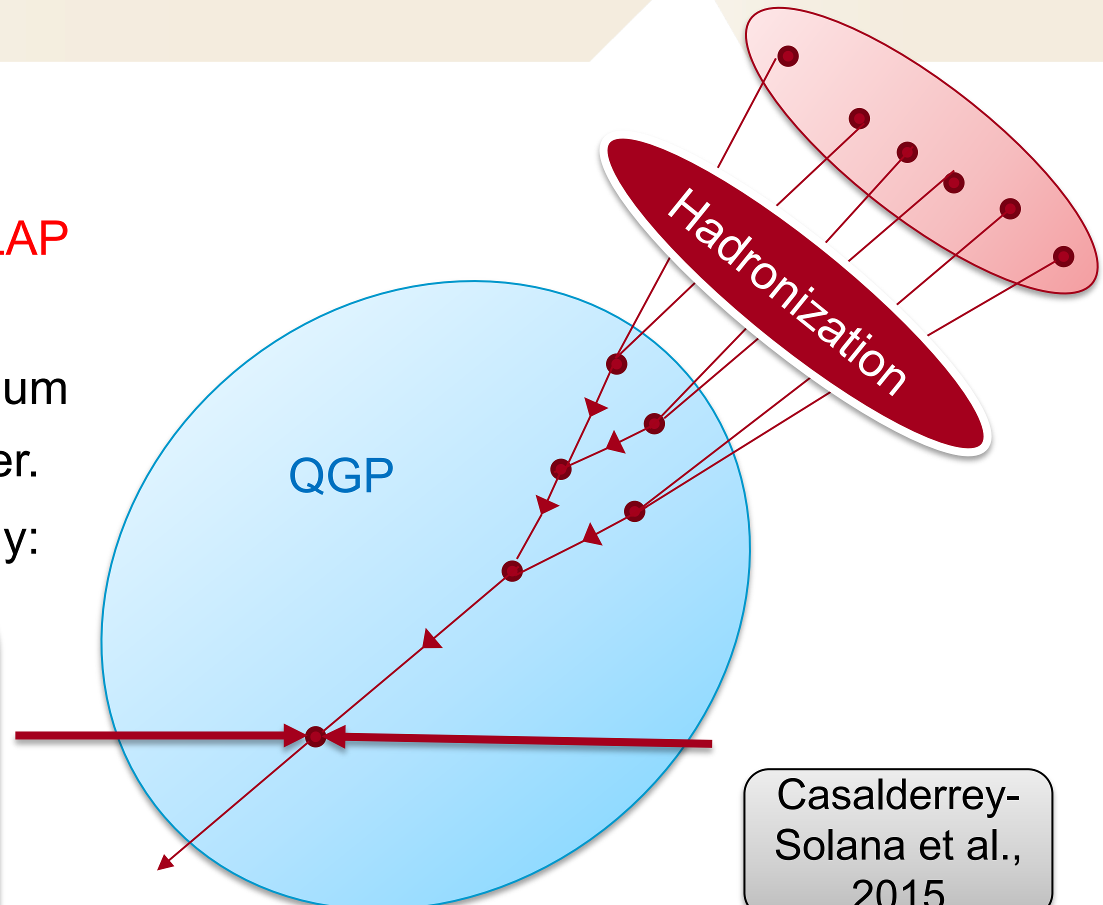
A Perturbative Event … Living in a Holographic World

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

O(1) fit const.

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}} \qquad \tau = \frac{2E}{Q^2}$$



Casalderrey-Solana et al., 2015

…That's Also Approximately a Hot Plasma

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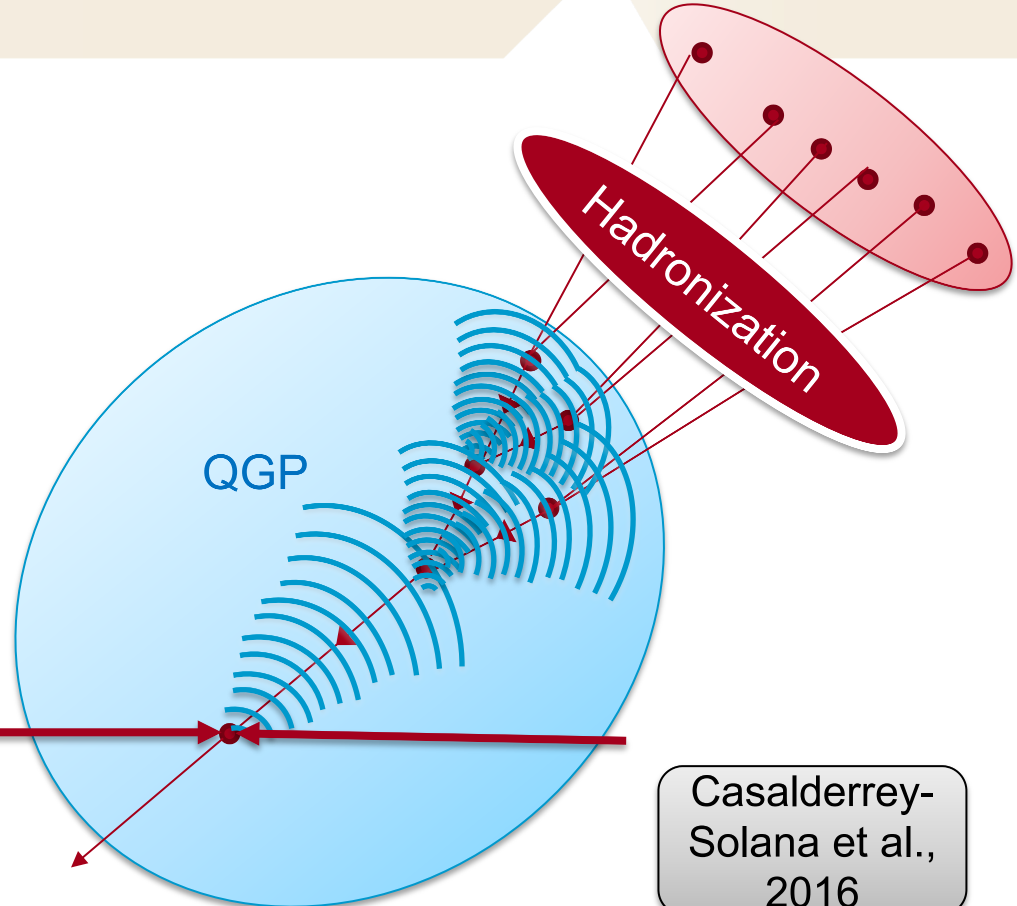

Casalderrey-Solana et al., 2016

Energy and momentum conservation $\longrightarrow$ activate hydrodynamic modes of plasma.

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Moliere in Hybrid Model

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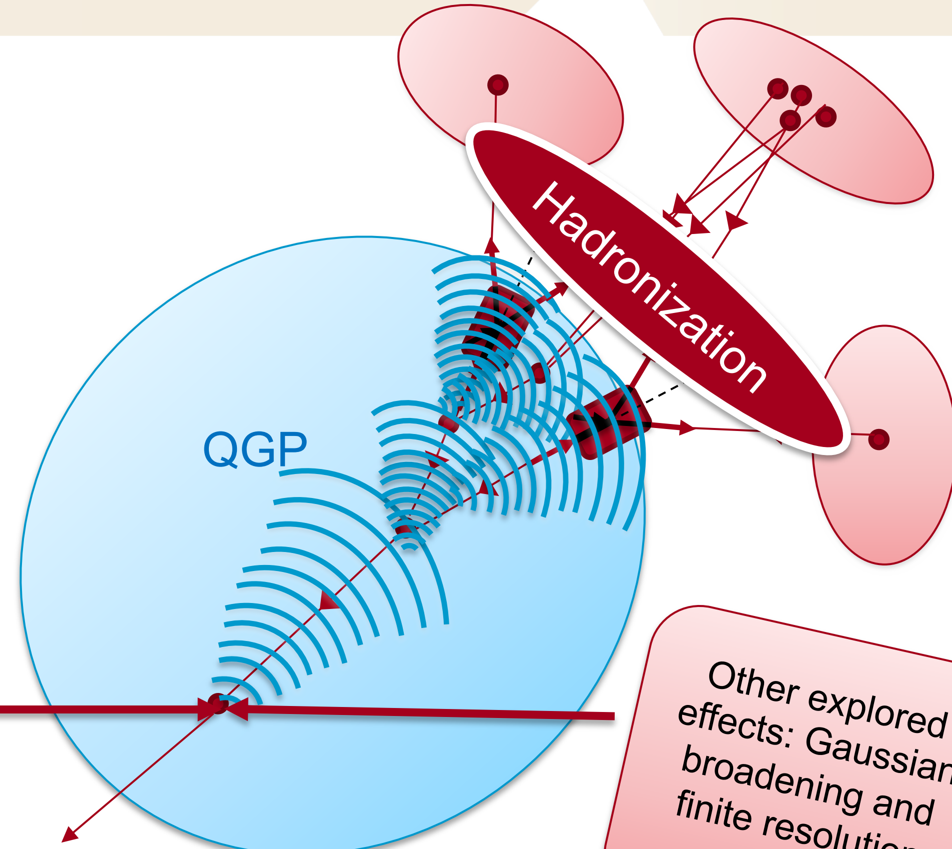


Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation $\longrightarrow$ activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Gaussian Broadening vs Large Angle Scattering

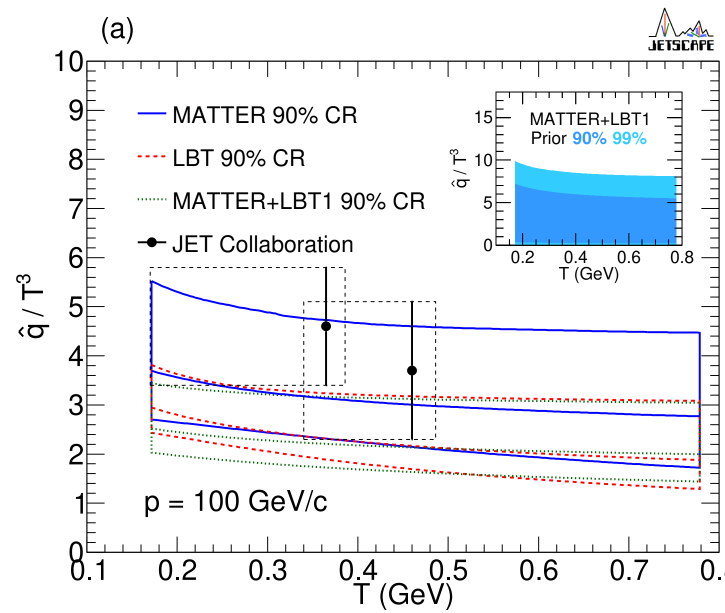
- Elastic scatterings of exchanged momentum $\sim m_D$

  ⟶ Gaussian broadening due to multiple subscattering
- At strong coupling, holography predicts Gaussian broadening without quasi-particles (ex: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

- Restricting momentum exchanges $\gg m_D$

  ⟶ perturbative regime separate from Gaussian broadening, with a power law distribution



D'Eramo et al., 2011
+
Mehtar-Tani et al., PRD 2021

Jet R_{AA}

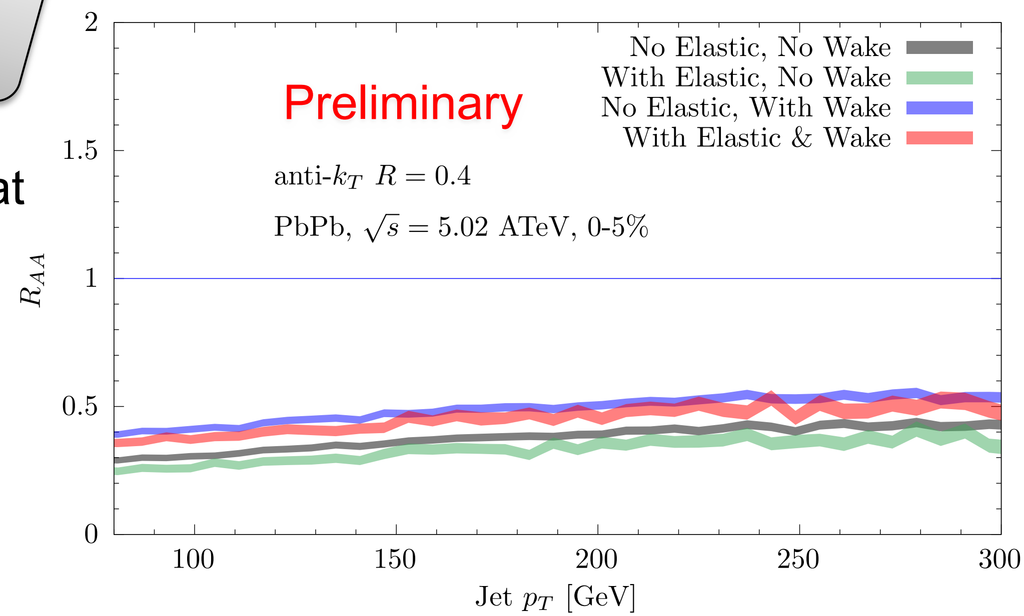
Casalderrey-Solana et al. 2019

- κ_{sc} previously fit with jet+hadron suppression data from ATLAS+CMS at 2.76+5.02 TeV

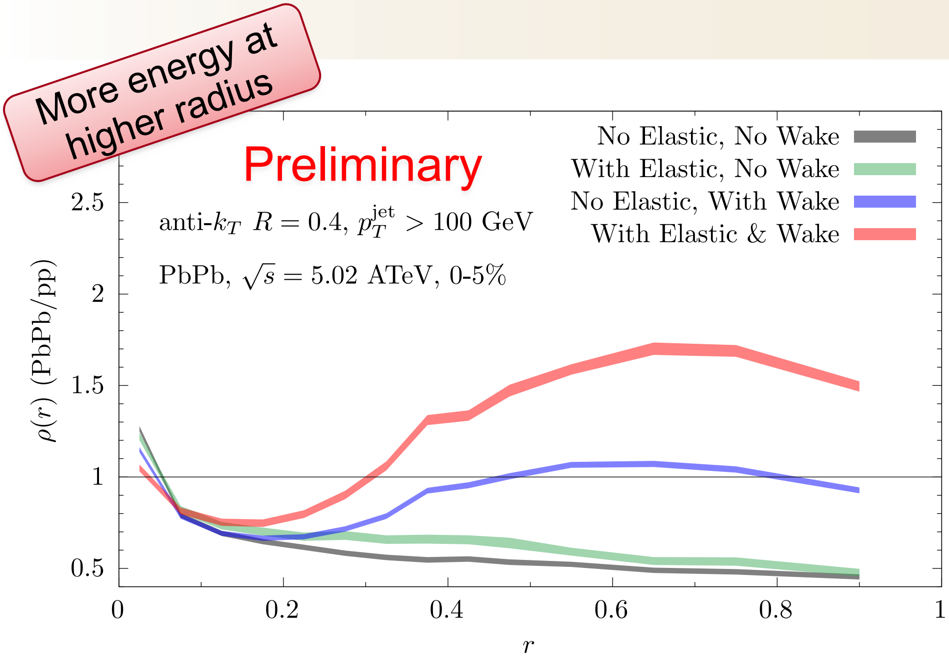
- Elastic scatterings lead to additional suppression.

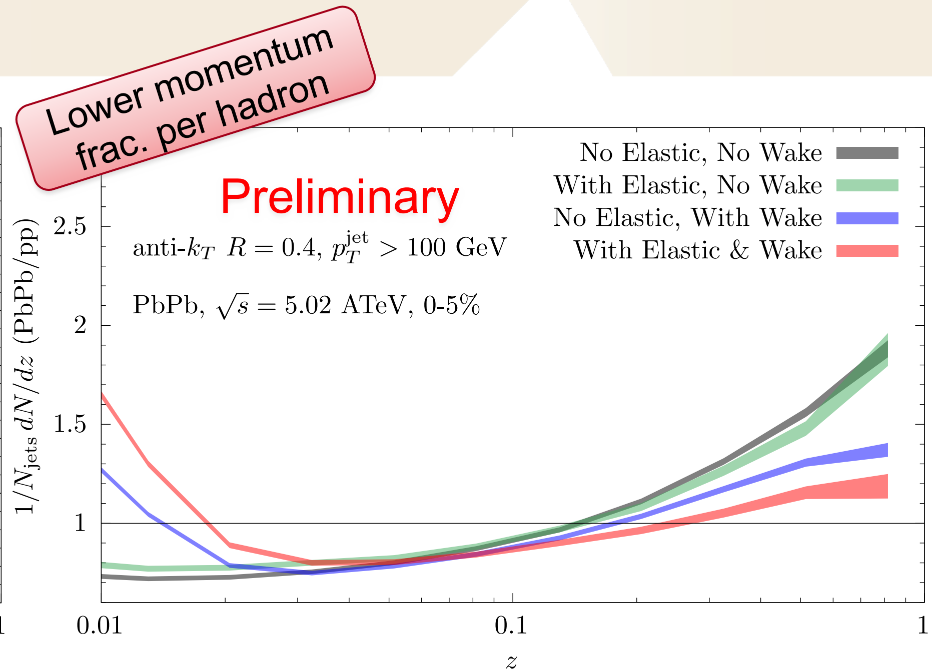
- Adding the hadrons from the wake allows the recovery of part of the energy within the jet cone.

- Very small change to value of κ_{sc} with addition of elastic scatterings.



Jet Shapes and FF





→ Elastic scattering effects only visible after accounting for wakes.

- A given elastic scattering transfers jet energy to high angle and lower momentum fraction partons, which are the most easily suppressed.
- Their depositions in hydrodynamic modes live on.
- Moliere scattering followed by strongly coupled energy loss turns elastic scattering effects into wake effects. Moliere changes shape of wake.
- More energy at higher radius and lower mom. fractions, but only with wake.

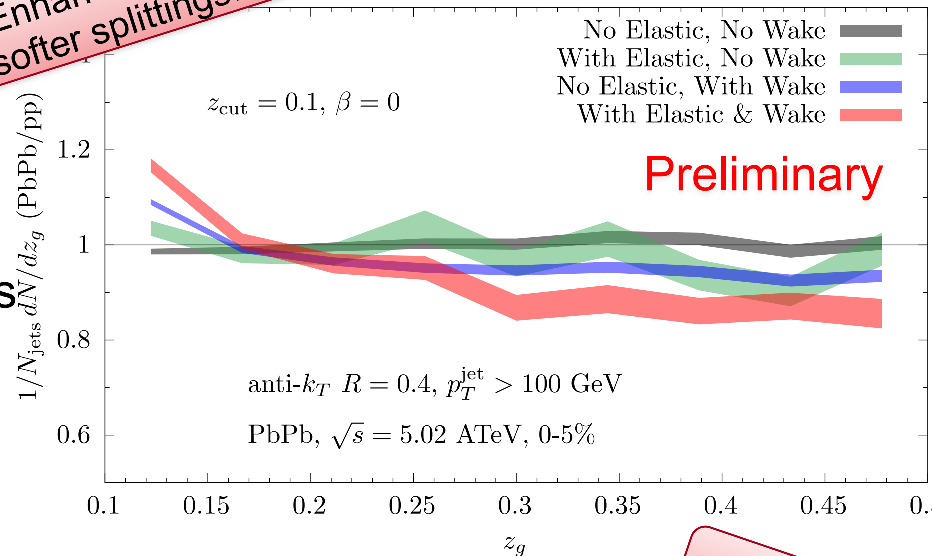
z_g and Groomed Radius

Soft Drop ($\beta = 0$)

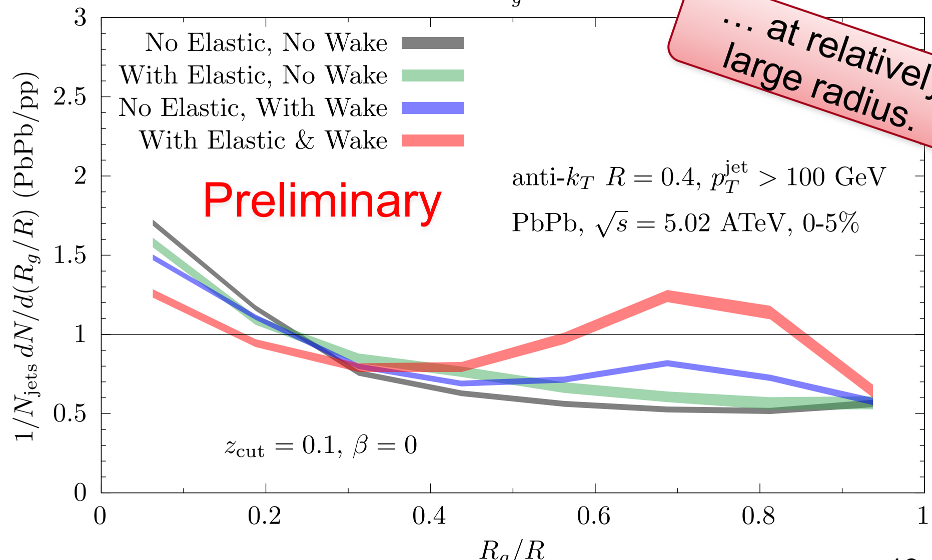
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. If $\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then the original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Same message: Elastic scattering effects show up as modified wake effects.

Enhancement of softer splittings…



… at relatively large radius.



Leading k_T

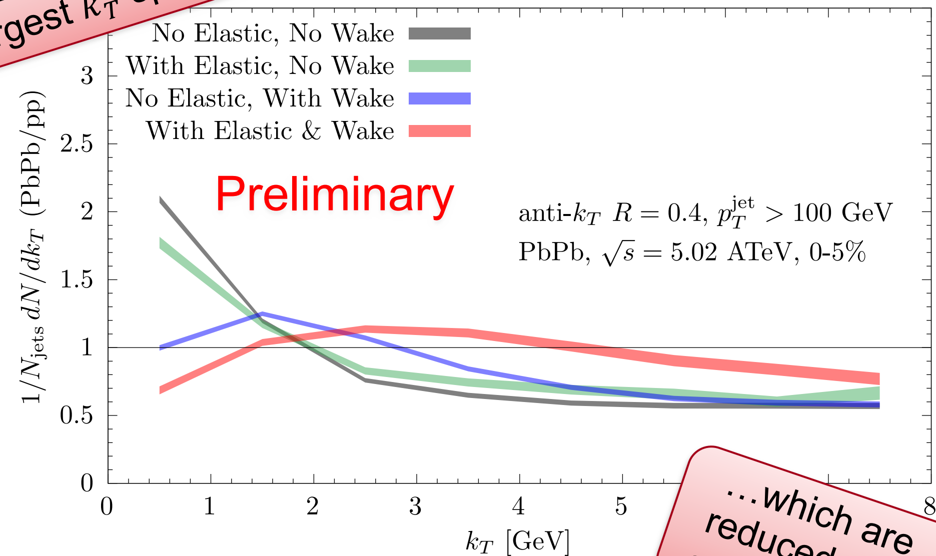
1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

$$k_T = \min(p_{T1}, p_{T2})\sin(R_g)$$

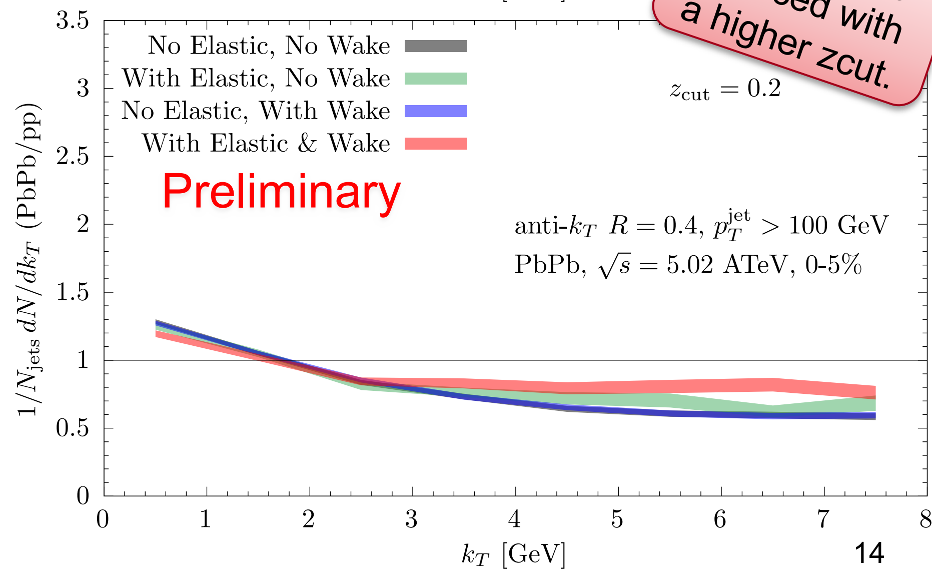
Similar message: Elastic scattering effects show up as modified wake effects.

However, these effects can be reduced by some necessary cuts for background subtraction.

Enhancement of largest k_T splittings…

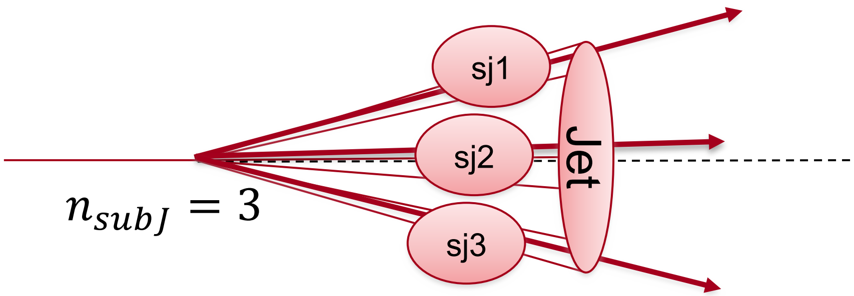


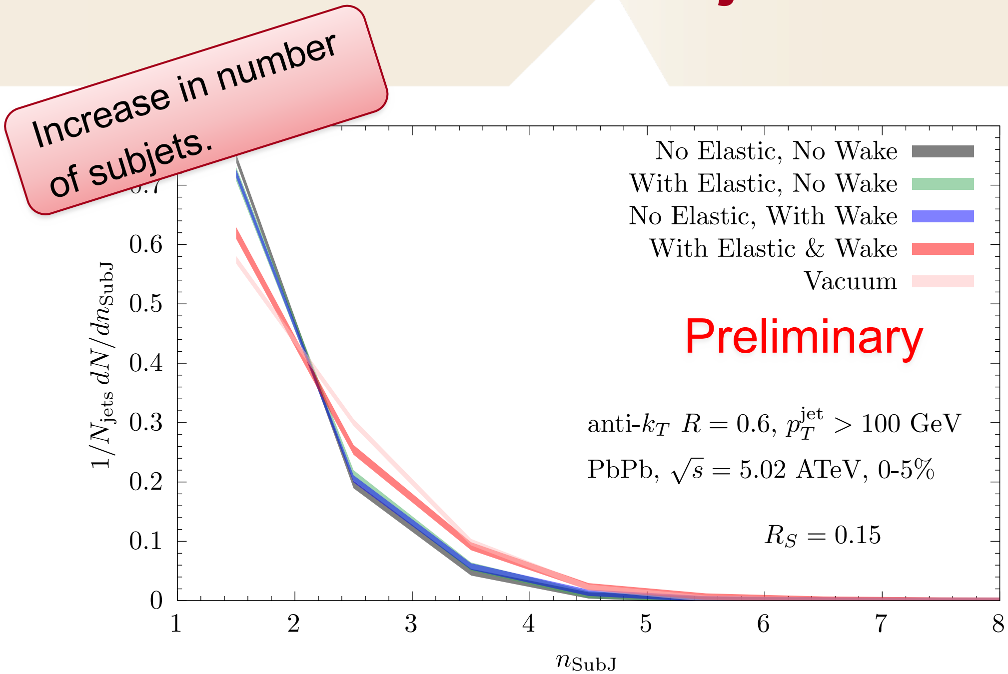
…which are reduced with a higher zcut.



Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15



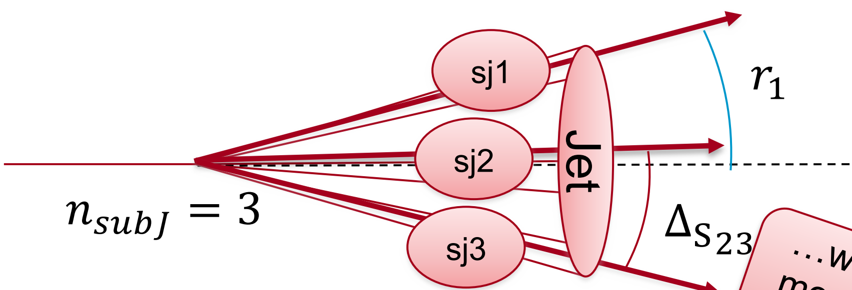


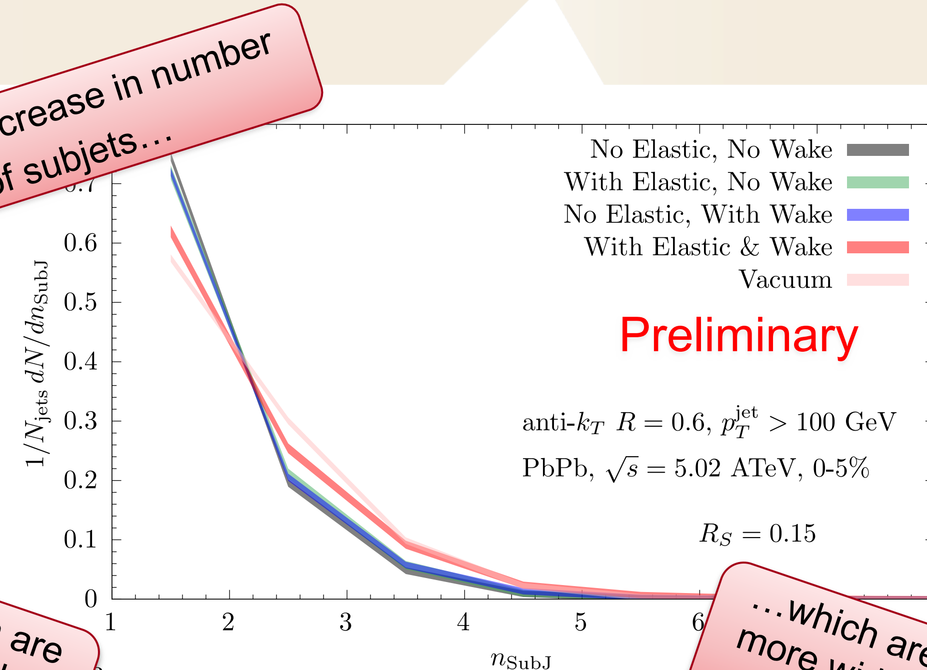
Refined message: Effect only visible when including the wake, but, clearly different from simply having a larger wake.

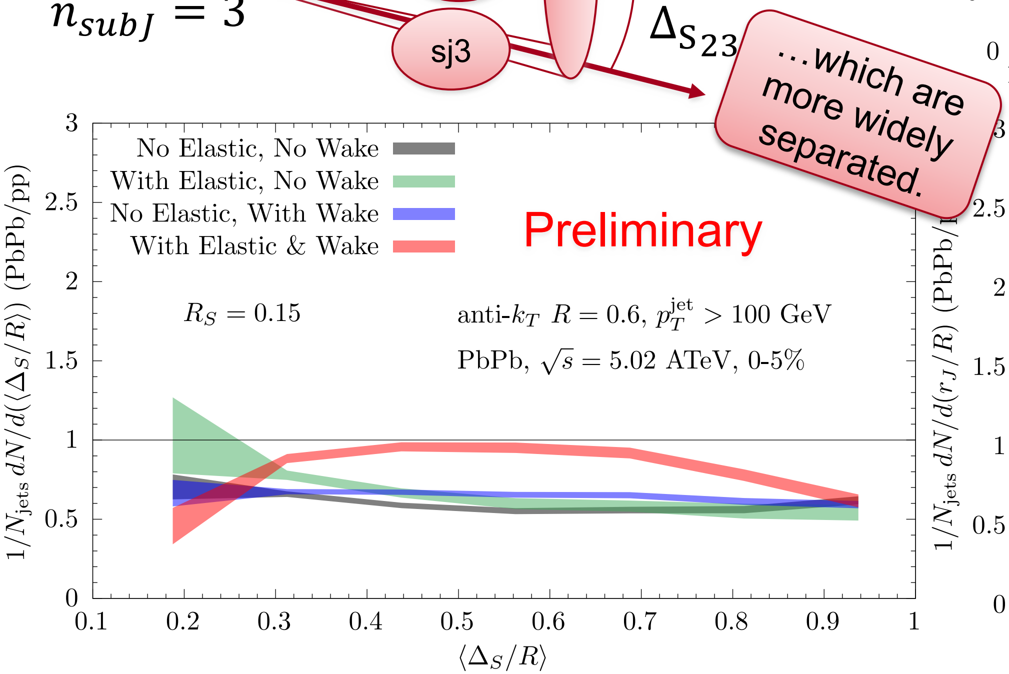
Adding the wake did not increase the number of subjets in the absence of elastic scatterings. Moliere gives the wake more prongs, and the jet more subjets. Moliere changes the shape of the wake.

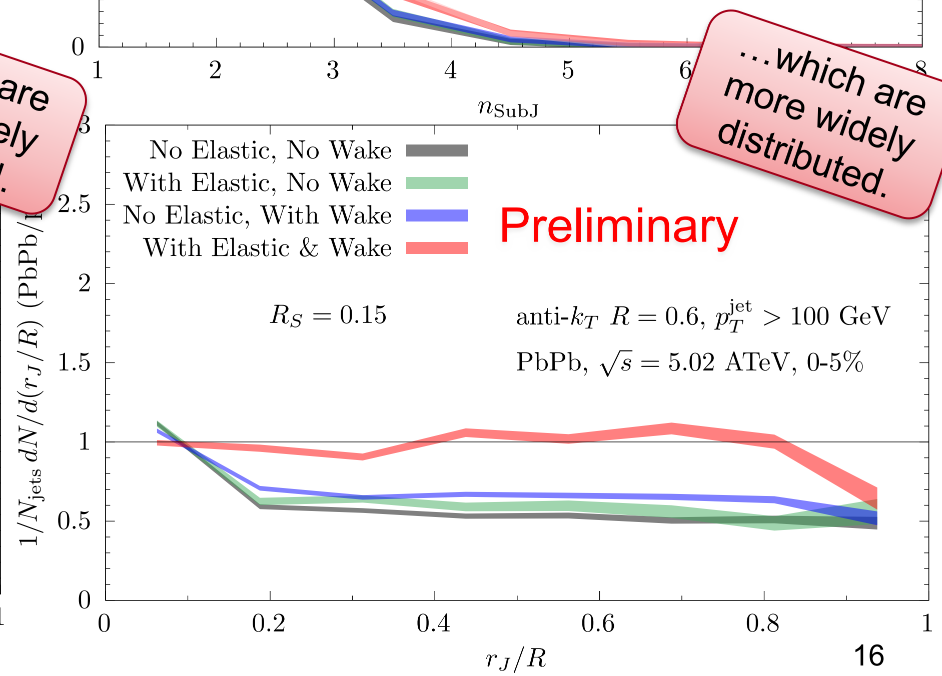
Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15

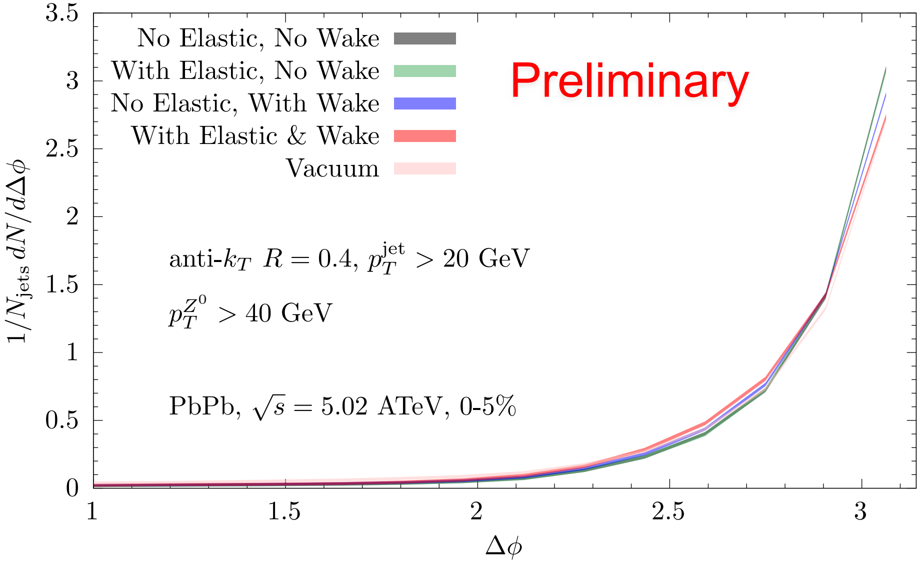


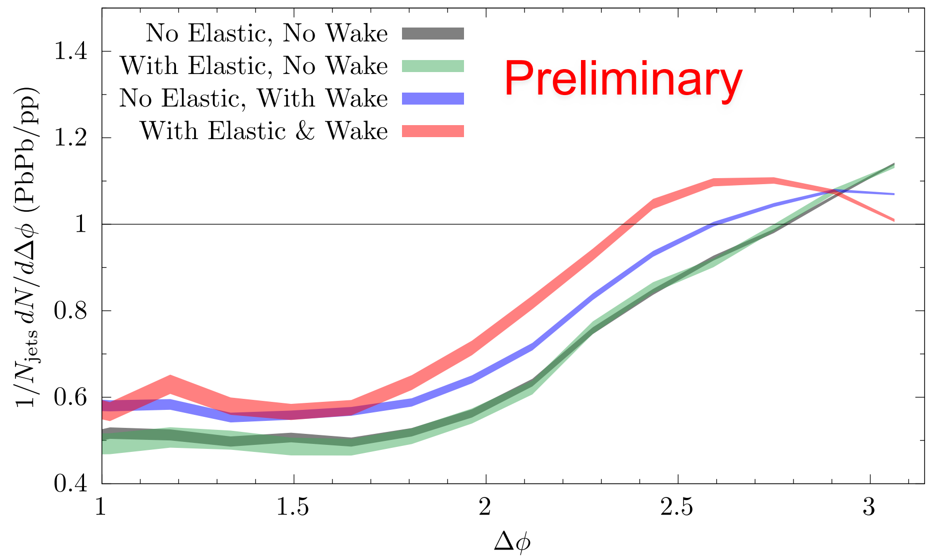






Z-Jet Acoplanarity





- Study acoplanarity in boson-jet system: Z-jet.
- Small effect due to elastic scatterings. Same message: small effect is due to modification of the wake.
- Desirable to look into acoplanarities at even lower p_T , perhaps via single hadron correlations (Gamma-D, $D\overline{D}$ correlations…).

Conclusions

- Studied the effect of power-law-rare large-angle scattering on jet observables in the perturbative regime.

- Moliere scattering followed by strongly coupled energy loss turns elastic scattering effects into wake effects. Moliere changes shape of wake.

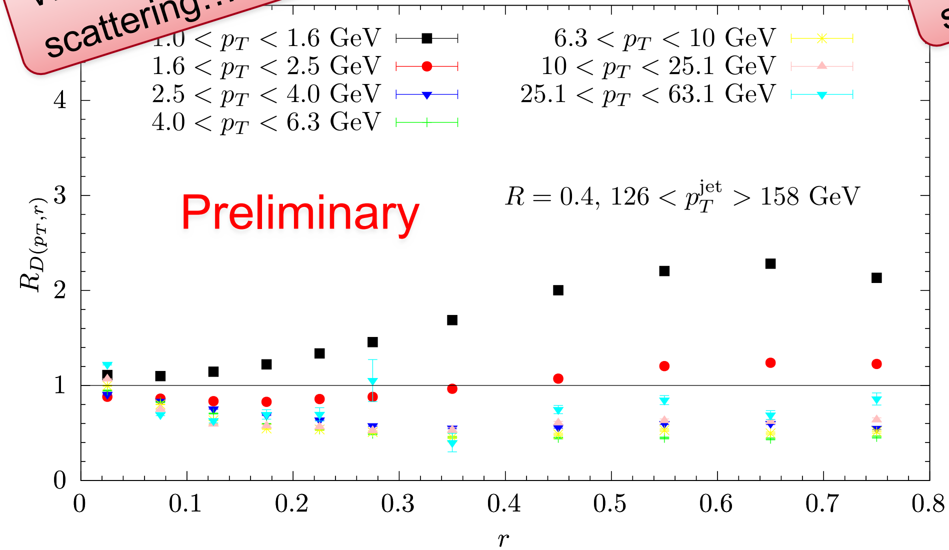
- Effects of Moliere scattering on observables are predominantly wake effects.

- Inclusive subjet observables are especially sensitive to the presence of elastic scatterings. They are unaffected by the wake in the absence of Moliere scattering.

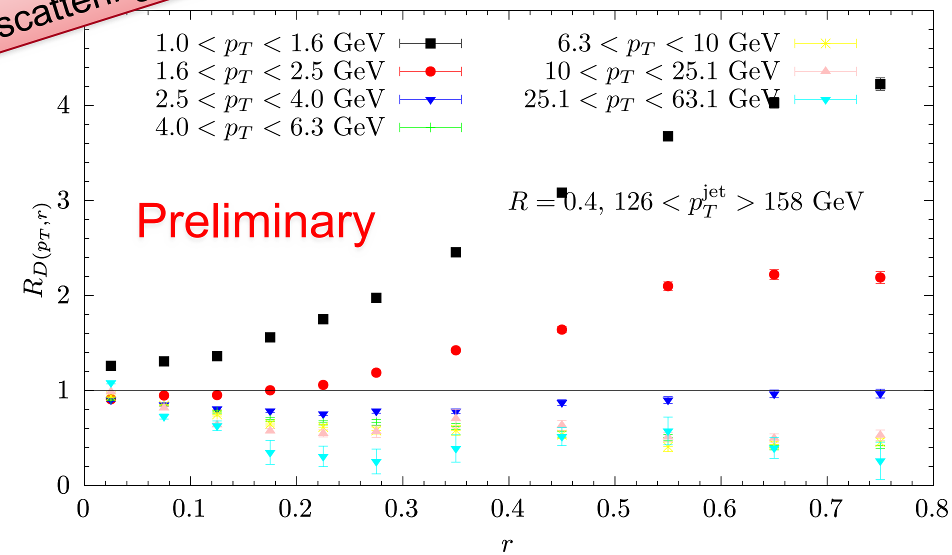
- Future: studying charm observables (gamma-D, $D\bar{D}$, D within jets …)

ATLAS Jet Shapes

Without elastic scattering…

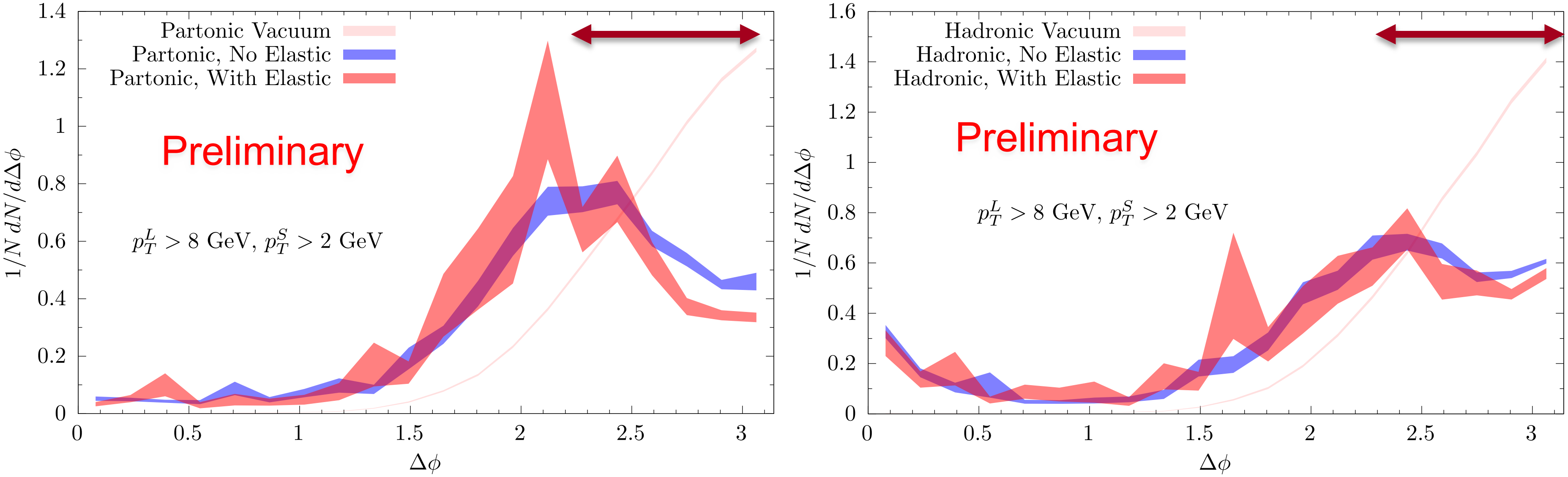


With elastic scattering…



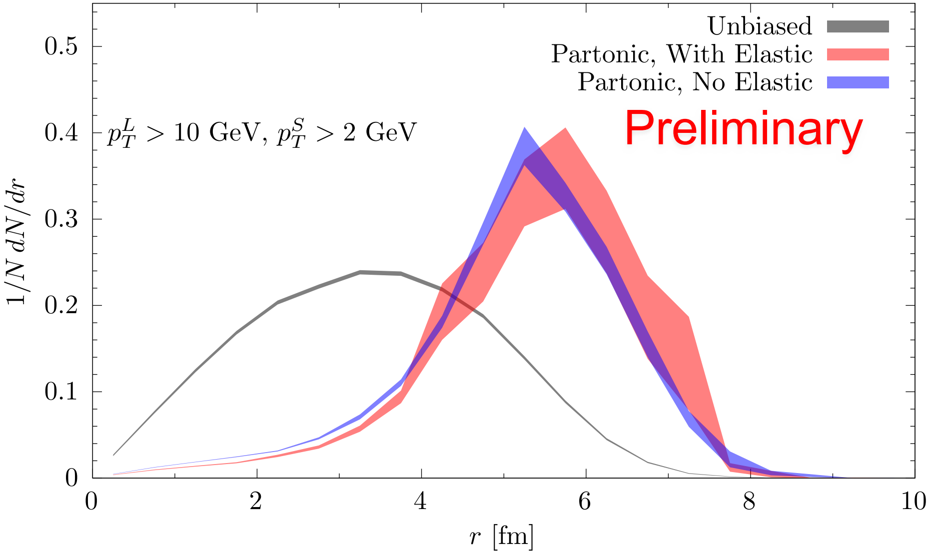
- Elastic scattering leads to more low p_T particles
- Increased separation of p_T with elastic scattering, as higher p_T partons more likely to interact, losing more energy, and separating the previously stacked higher p_T points.

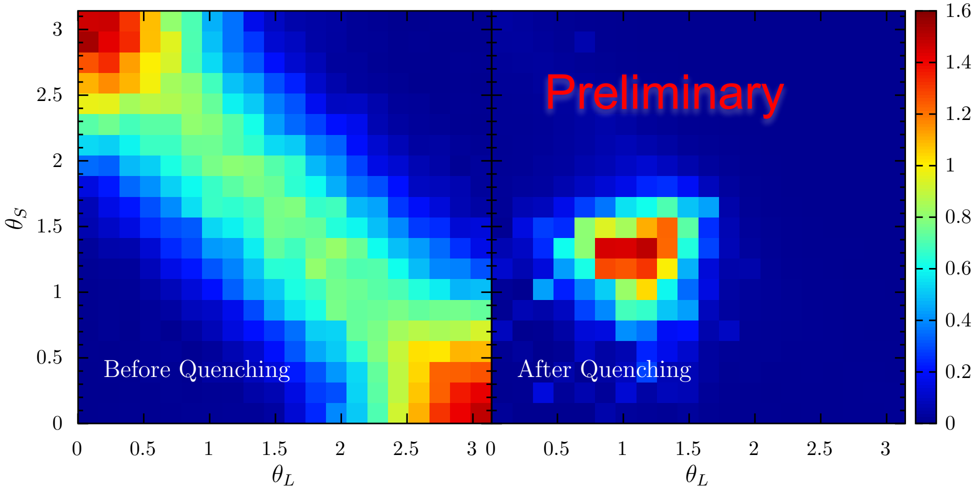
C-$\bar{\text{C}}$ Acoplanarity



Broadened distribution even in the absence of Gaussian broadening or elastic scattering

Biases



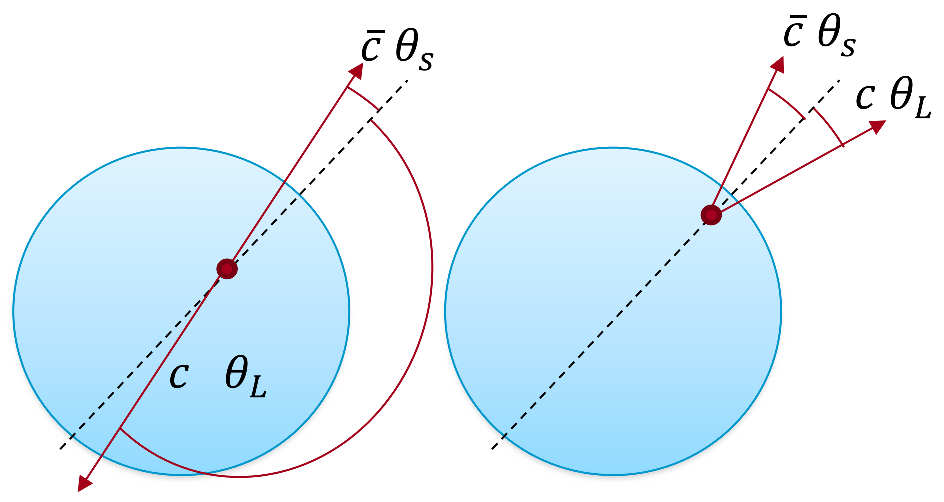


- Creation point moved to periphery of QGP

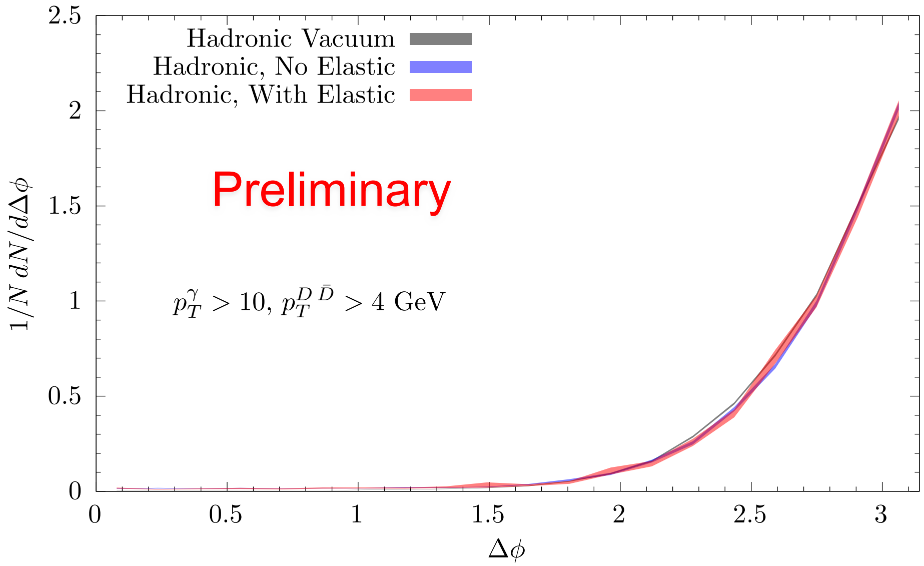
  → Surface bias

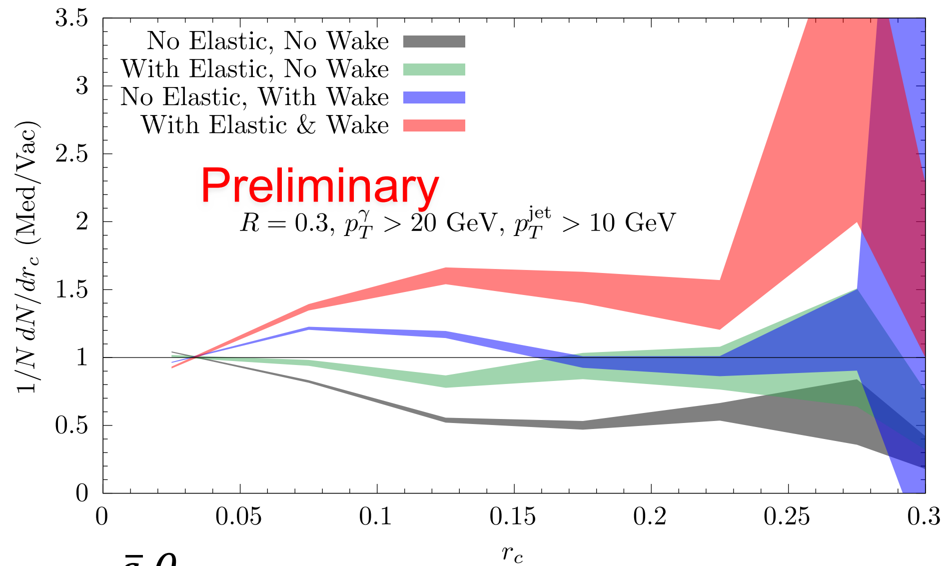
- Preferred orientation of surviving c $\bar{c}$ pairs after quenching. Tendency to point outwards with less angular separation

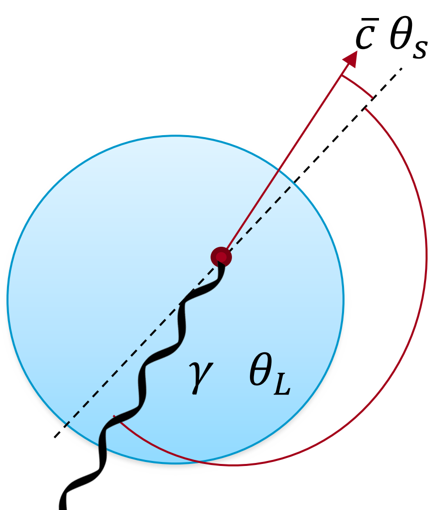
  → Orientation bias



Gamma-c

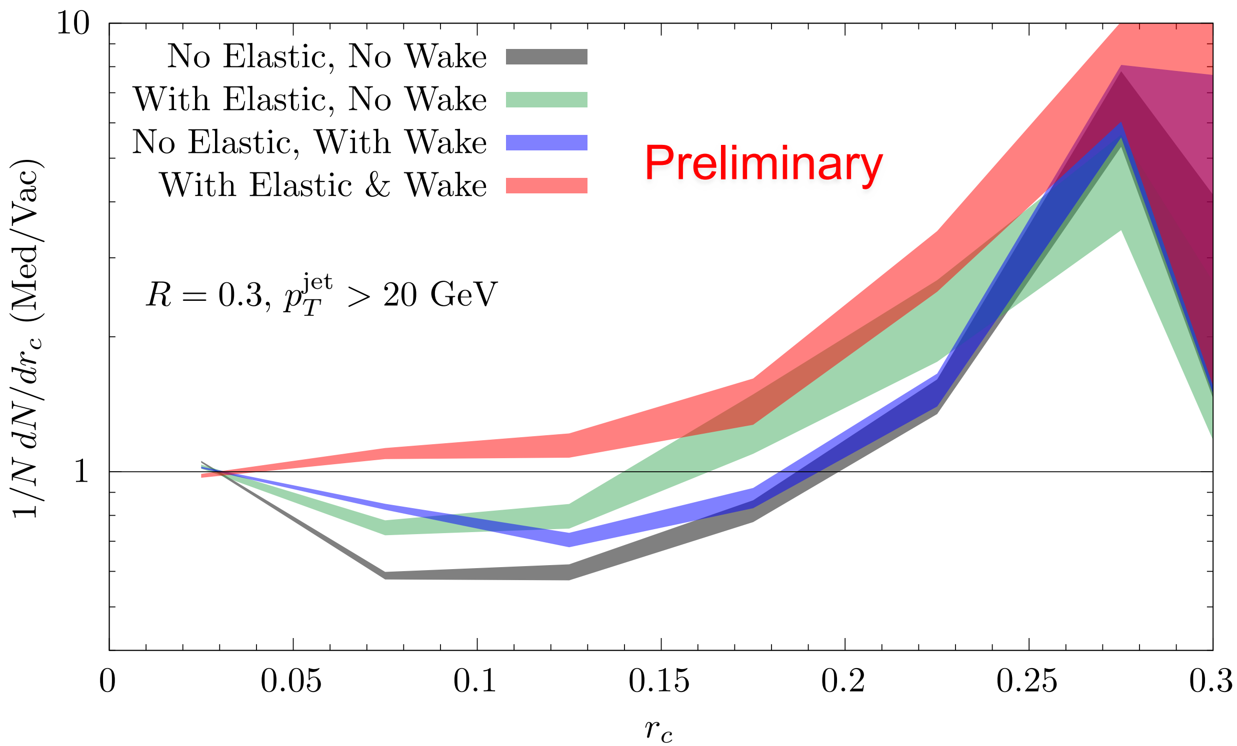




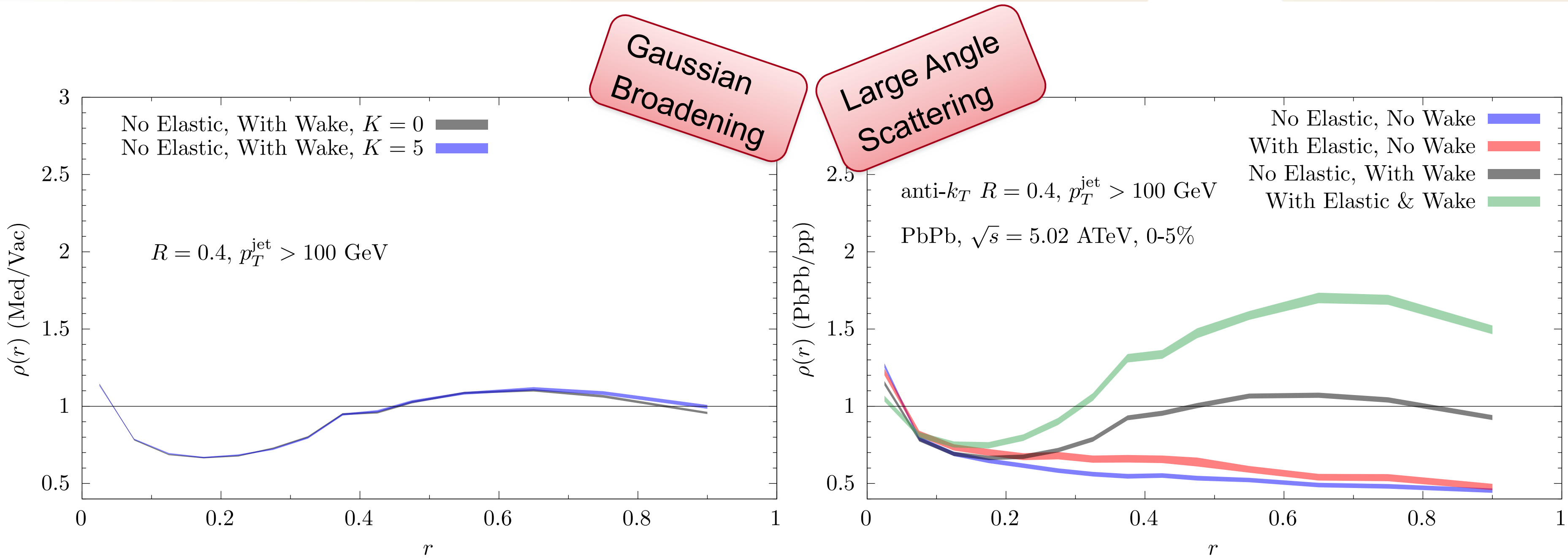


No bias as γ not quenched

Inclusive D Jets



Effect of Gaussian Broadening



- Multiple soft scattering can only significantly broaden a particle when it has lost most of its energy to the QGP.
- Effect of broadening with wake isolatable from large angle scattering with wake