ILLINOIS

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

High p_T Jets in a Viscous Charged Medium

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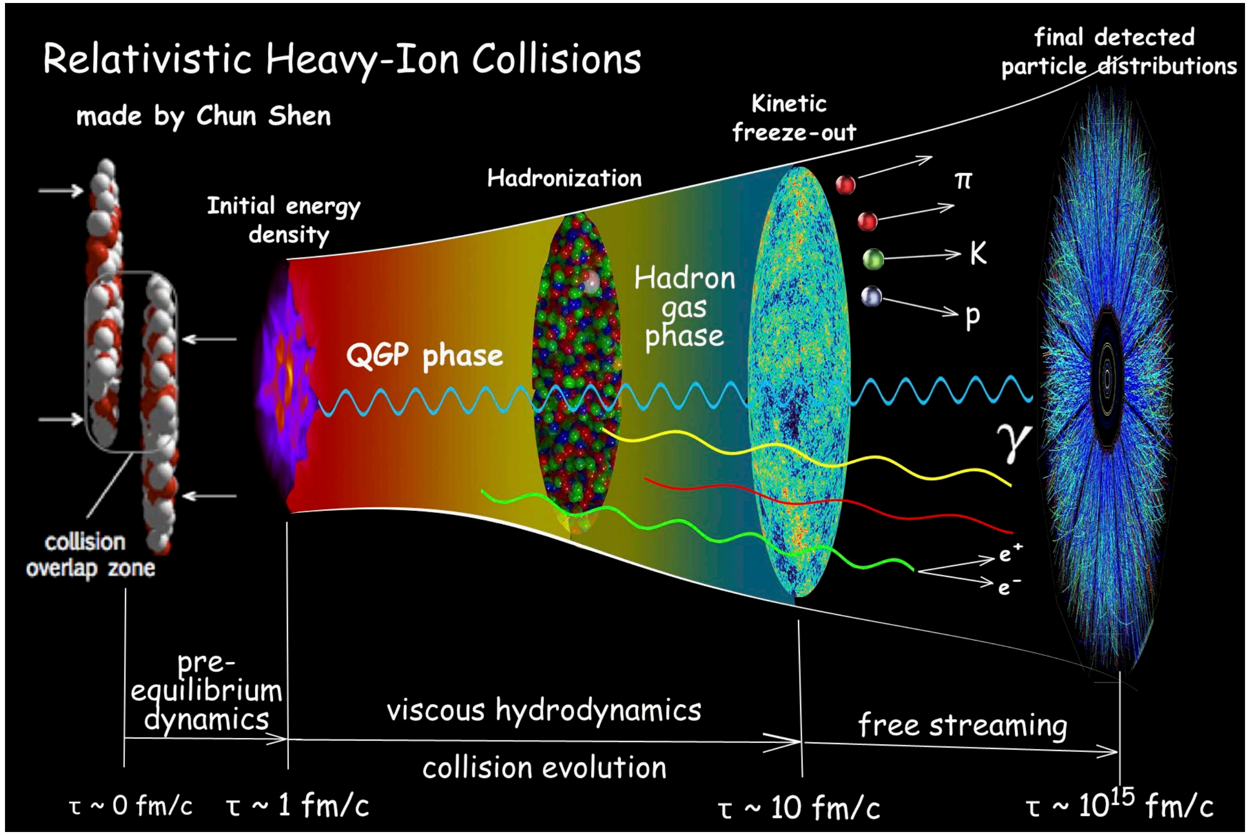
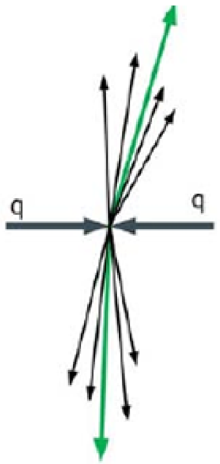
Hot Jets

(Jan 08- Jan 10, 2025)

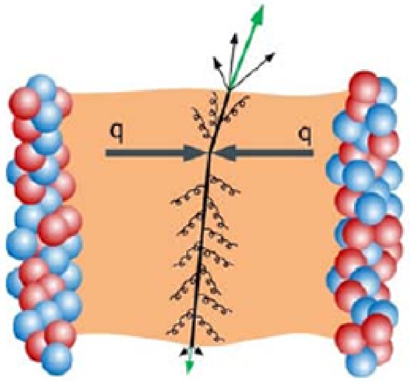
Illinois Center for Advanced Studies of the Universe

Jets in high energy collisions





p+p
proton-proton (pp) collision
No QGP created

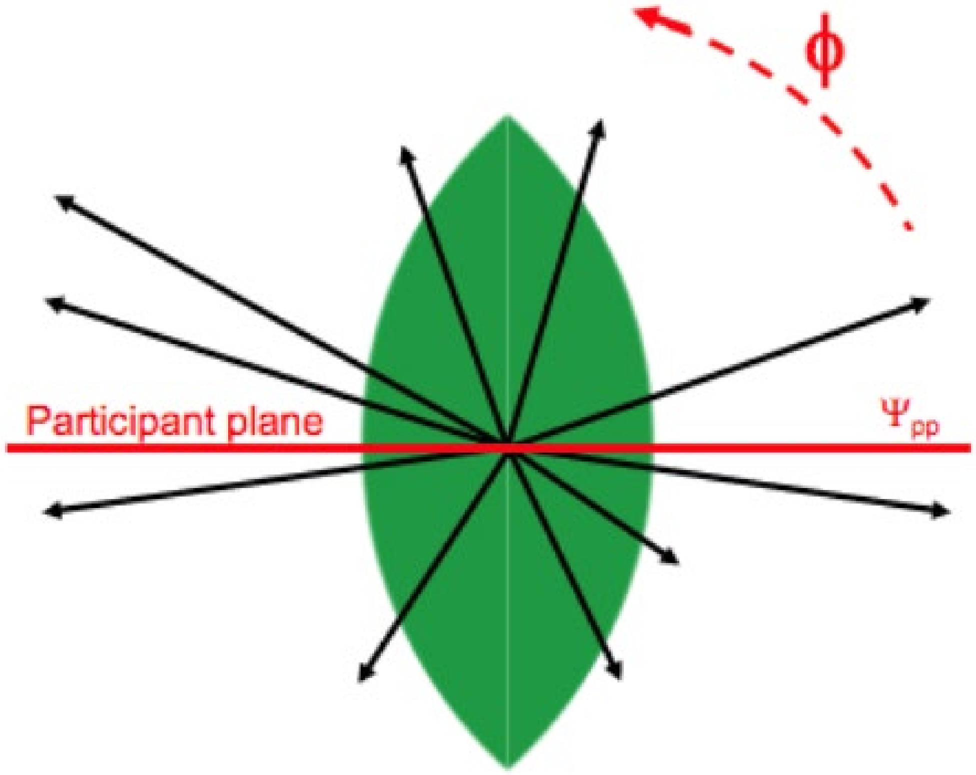


Heavy-ion collision
QGP created
→ additional gluon radiation
wrt pp collisions

How does the medium impact a jet’s energy loss, and ultimately what does that lost energy do to the dissipative medium?

Jet effects on the medium

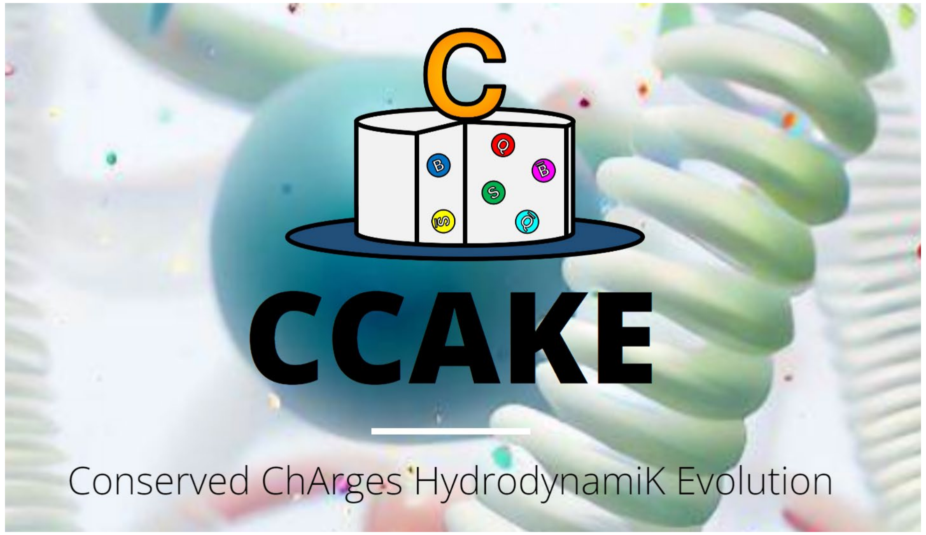
- Jets in a QGP deposit some of their energy as they travel
- The energy of these jets affects the suppression of whatever type of particle you are interested in
- The collective flow of the QGP is mostly defined from the soft sector, low momentum particles, but high momentum jets affect the collective flow, especially away from the event plane



CCAKE Framework

CCAKE **Conserved ChArges HydrodynamiK Evolution**

- Smoothed Particle Hydrodynamics simulation with charge fluctuations
- First implementation of lattice QCD EoS at finite BSQ charge density
- Open Source Code based on vUSPhydro with NEW upgrades

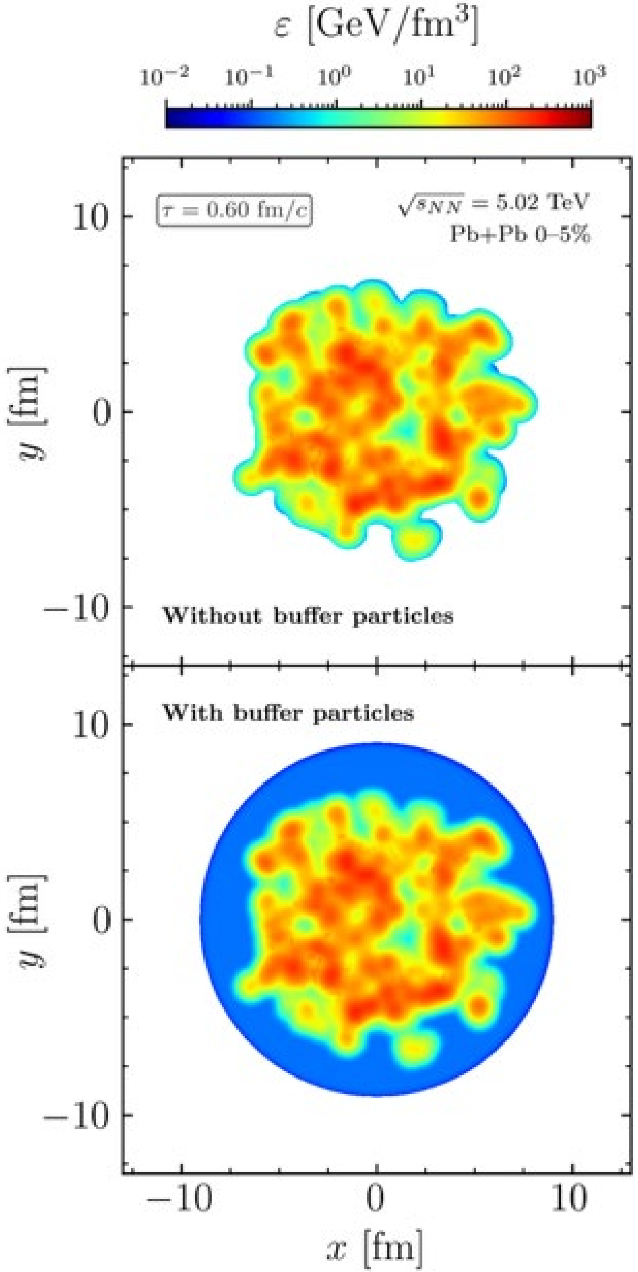


For more information about CCAKE, see Kevin Pala's talk Thursday!

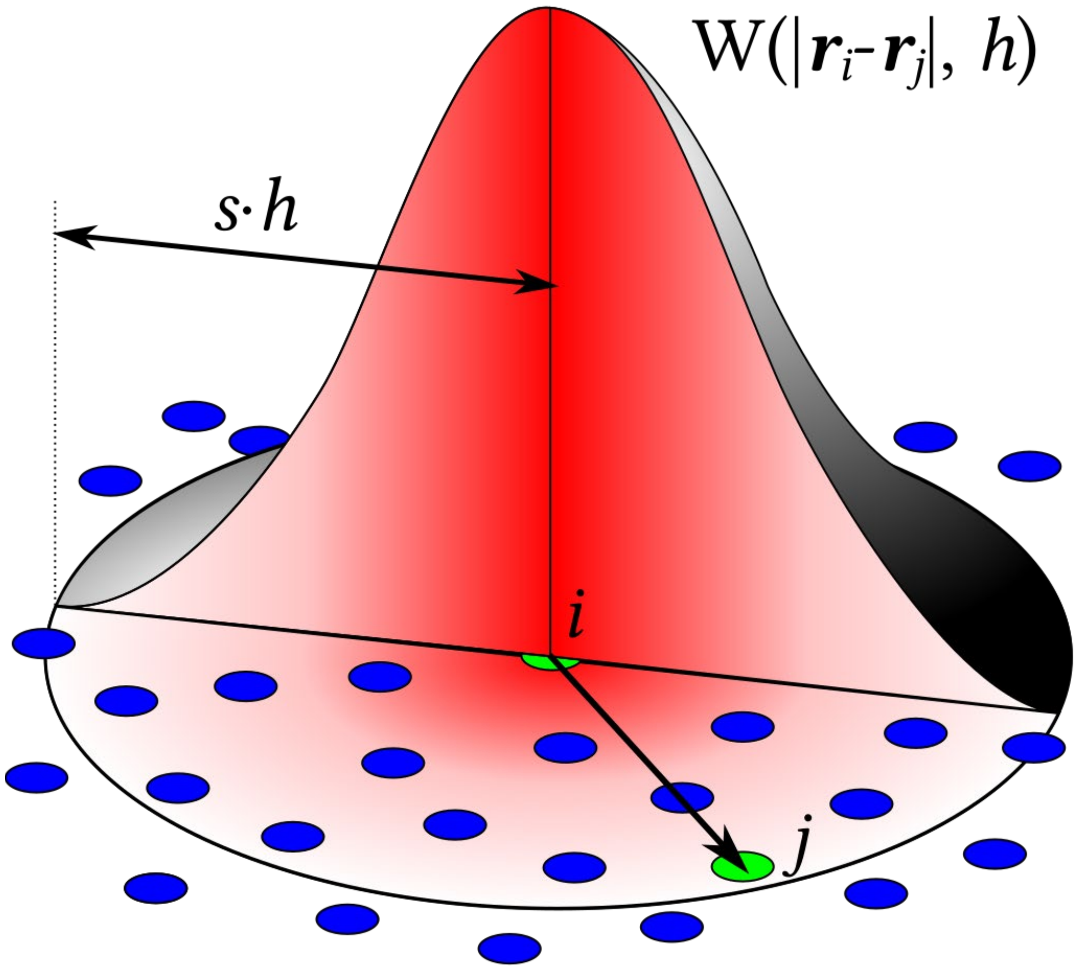
For my event(s)

$$\tau_0 = 0.6\, fm$$
$$\frac{\eta}{s} \geq 0.10$$
$$\sqrt{s_{NN}} = 2.76\, TeV$$

CCAKE is an efficient hydro code to propagate jets on



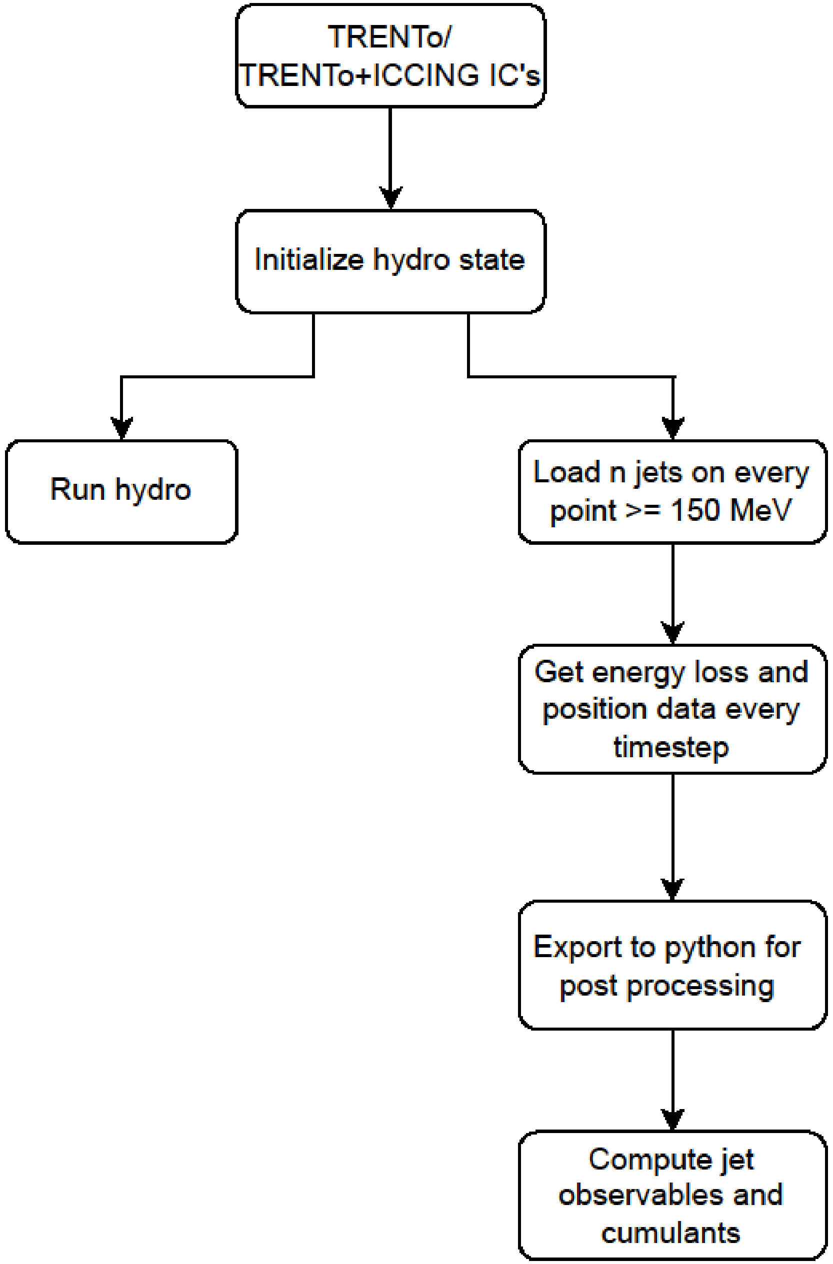
Smoothed Particle Hydrodynamics (SPH)



- Lagrangian hydrodynamics formalism
- Easily adjustable due to initial conditions

Default CCAKE+BBMG

- Currently, 7 back-to-back pairs on each sph particle above freeze out
- Each jet is evolved independently each timestep
- Removal routine to speed up each timestep after jets reach freeze-out


TRENTo/ TRENTo+ICCING IC's

Initialize hydro state

Run hydro

Load n jets on every point >= 150 MeV

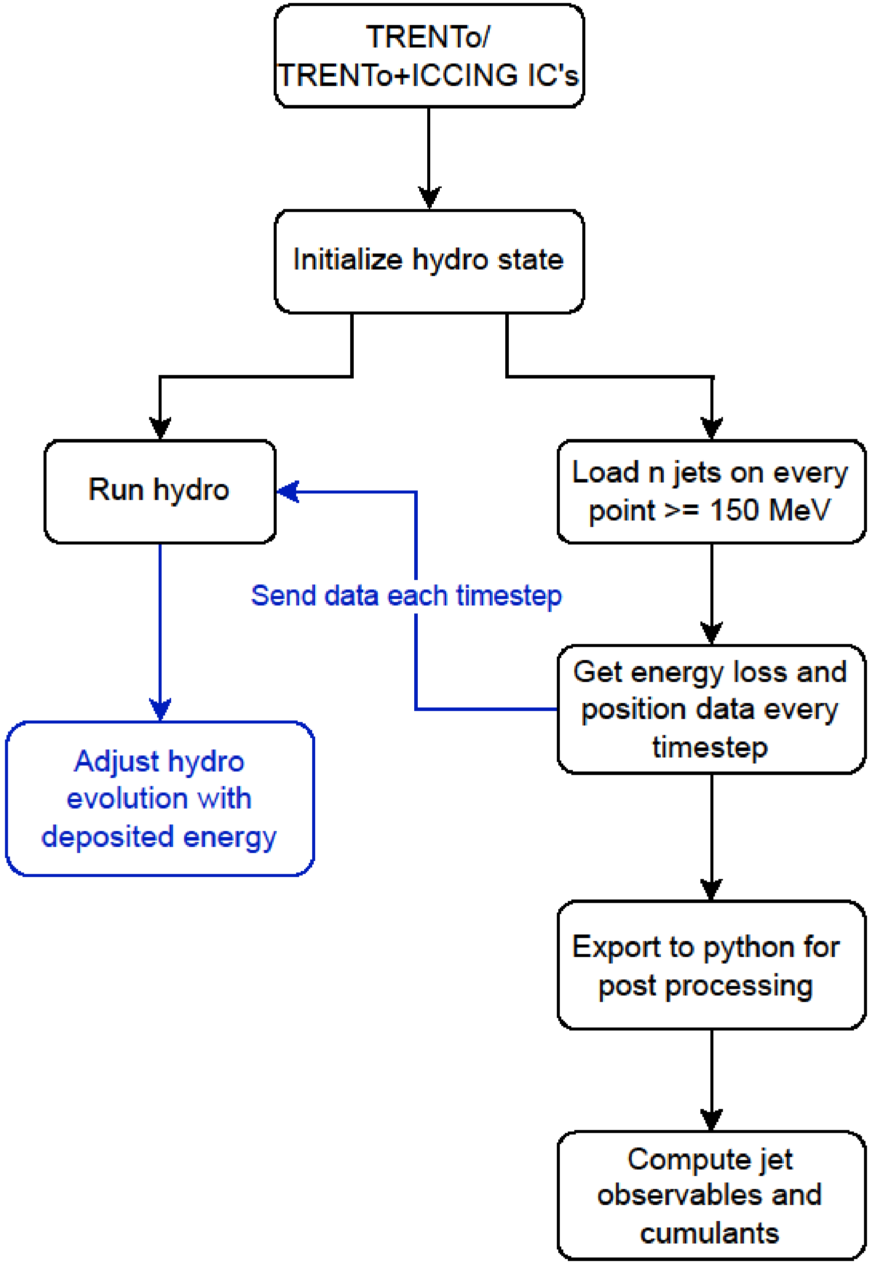
Get energy loss and position data every timestep

Export to python for post processing

Compute jet observables and cumulants

CCAKE+BBMG+Source Term

- Currently, 7 back-to-back pairs on each sph particle above freeze out
- Each jet is evolved independently each timestep
- Removal routine to speed up each timestep after jets reach freeze-out
- Use position and energy loss data to determine path jet takes, and what that energy does to the medium



Jet Quenching Models

pQCD Based

- Weaker coupling
  - $\frac{dE}{dL} \propto L$
- Higher twist, AMY, ASW, GLV

A. Adare, et. al (PHENIX Collaboration) Phys. Rev. C 87, 034911 (2013)

D. Molnar and D. Sun, arXiv:1305.1046

Holography Based

- Stronger coupling
  - $\frac{dE}{dL} \propto L^2$
- AdS-CFT

W. Horowitz and M. Gyulassy 2011 J. Phys. G 38 124114

There are many jet quenching models that all work and I am building a framework that can mimic results from all of them

B. Betz and M. Gyulassy, Nucl. Phys. A 931, 410 (2014)

BBMG Energy Loss Model

We are using a model that has an adjustable energy loss:

$$\frac{dE}{dL} = -\kappa E^{a}(L) L^{z} T^{c} \zeta_{q} \Gamma_{flow} \quad \rightarrow \quad \frac{dP}{d\tau} = -\kappa P^{a}(\tau) \tau^{z} T^{c} \zeta_{q} \Gamma_{flow}$$

arXiv:1512.07443

We have tunable exponents a, z, c, and tunable fluctuations q

$$c = 2 + z - a$$

Our initial jet momenta can be extracted now as

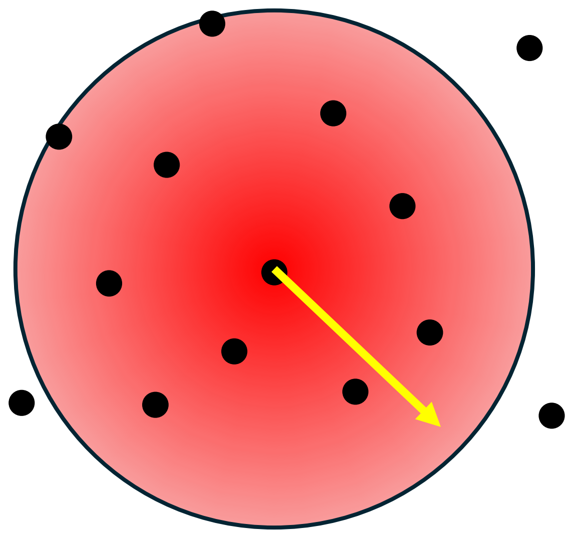
$$P_0^r(P_f, \phi) = \left[P_f^{1-a} + C_r \int_{\tau_0}^{\tau_f} \kappa\, \tau^{z} T^{c} \zeta_{q} \Gamma_{flow} d\tau \right]^{\frac{1}{1-a}}$$

Setting z=1 or z=2 can produce pQCD-like or Holography-like results respectively

Parameter a is seemingly between 0 and 1, yet to have any intuition on how this exponent affects the model largely

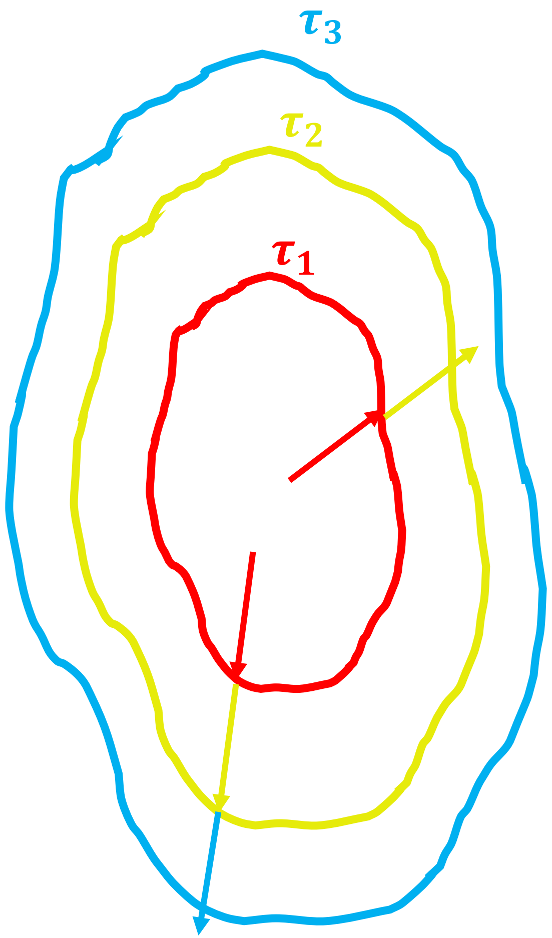
Kernel Function for Jets

- Issue with jets in any hydro code is that they can land between fluid cells
    - If not on a specific particle, T=0 and our energy loss breaks down
- SPH allows us to resolve that issue easily, where we use the kernel function to interpolate around each particle and create a temperature field for jets to propagate through



Tracking Jets

- I record position and energy loss data each timestep
- Most jets exit the medium before freeze-out of sph particles around them
- Some jets last until freeze-out, usually the ones propagating across the entire medium
- Important for back-reaction of jets on medium



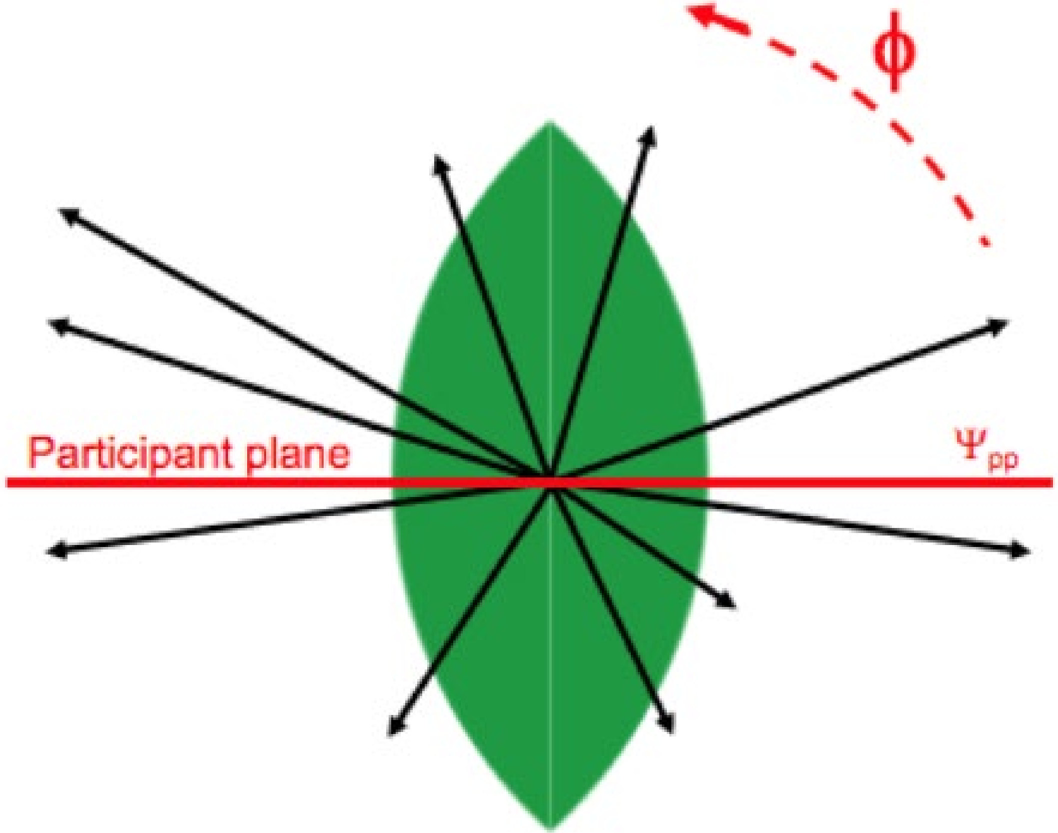
Observables

Once we calculate the initial jet energy for all the jets in our hydro events, we can use these to collect a few high-statistics observables

- Nuclear Modification Factor, R_{AA}
- Hard sector flow coefficients, v_n^{hard}
- Total flow coefficients, v_n^{exp}

The goal is to calculate higher order cumulants, found in

A. Holtermann et. al, Phys. Rev. C 108 (2023) 6, 064901



R_{AA} in the BBMG Model

$$R^{\pi}_{AA}(p_\pi,\phi) = \frac{\left[\sum_{\alpha=q,g}\int_{zmin}^{1}\frac{dz}{z}\, d\sigma_\alpha\left(\frac{p_\pi}{z}\right) R^{\alpha}_{AA}\left(\frac{p_\pi}{z},\phi\right) \mathrm{D}_{\alpha\to\pi}\left(\mathrm{z},\frac{\mathrm{p}_\pi}{\mathrm{z}}\right)\right]}{\left[\sum_{\alpha=q,g}\int_{zmin}^{1}\frac{dz}{z}\, d\sigma_\alpha\left(\frac{p_\pi}{z}\right) \mathrm{D}_{\alpha\to\pi}\left(\mathrm{z},\frac{\mathrm{p}_\pi}{\mathrm{z}}\right)\right]}$$

Distribution taken from PYTHIA8

Partonic R_{AA}: $R^{\alpha}_{AA}(P_f,\phi) = \frac{g_\alpha(P_0)}{g_\alpha(P_f)}\frac{dP_0^2}{dP_f^2}$

Jet invariant distribution: $g_\alpha(P) = \frac{dN_\alpha^{jet}}{dyd^2P}$

KKP Fragmentation Function, taken from:

B. Kniehl, G. Kramer and B. Potter, Nucl. Phys. B 597, 337 (2001)

Flow Coefficients

Calculating any v_n^{hard} from R_{AA} is rather straight forward, but first we need a hard sector event plane

$$\psi_n^{hard}(p_T) = \frac{1}{n}\tan^{-1}\frac{\int_0^{2\pi} d\phi \sin(n\phi)\, R_{AA}(p_T,\phi)}{\int_0^{2\pi} d\phi \cos(n\phi)\, R_{AA}(p_T,\phi)}$$

From which we immediately get

$$v_n^{hard}(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\phi \cos[n\phi - n\psi_n^{hard}(p_T)]\, R_{AA}(p_T,\phi)}{R_{AA}(p_T)}$$

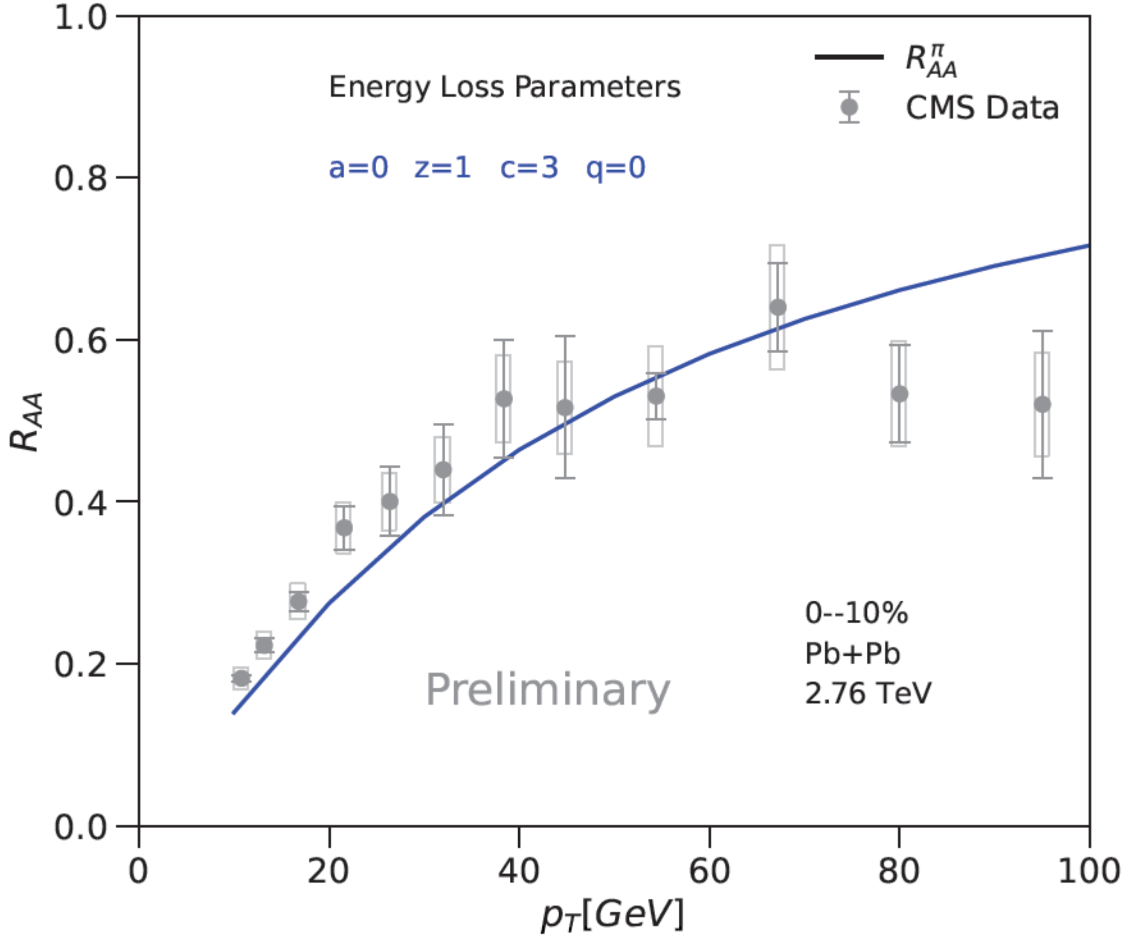
This isn't enough to compare with experimental flow values, we need to combine with the soft sector

$$v_n^{exp}(p_T) = \frac{< v_n^{soft} v_n^{hard} \cos[n(\psi_n^{soft} - \psi_n^{hard})] >}{\sqrt{< (v_n^{soft})^2 >}}$$

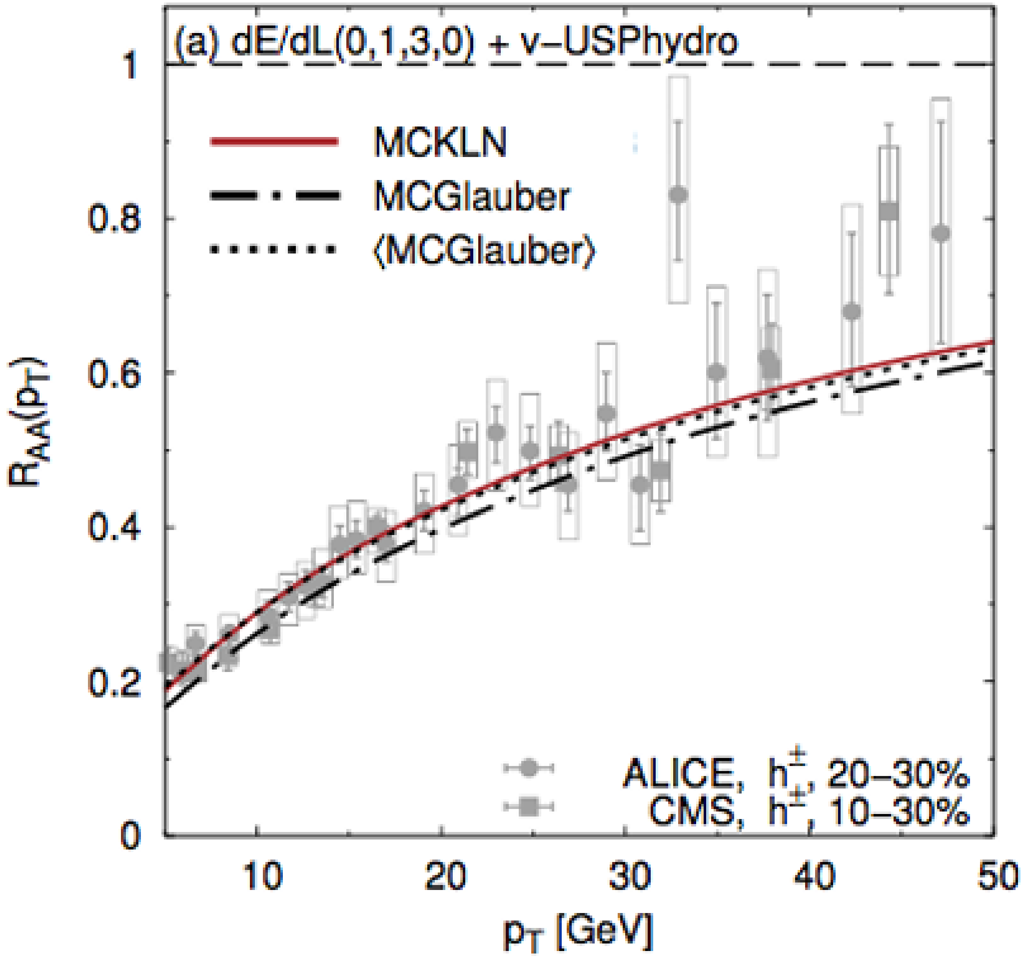
Note this is only one POI that I will be calculating for, I will be doing multiple POI and reference particle calculations eventually

X.N. Wang, Phys.Rev.C 63 (2001) 054902

R_{AA} compared to CMS data

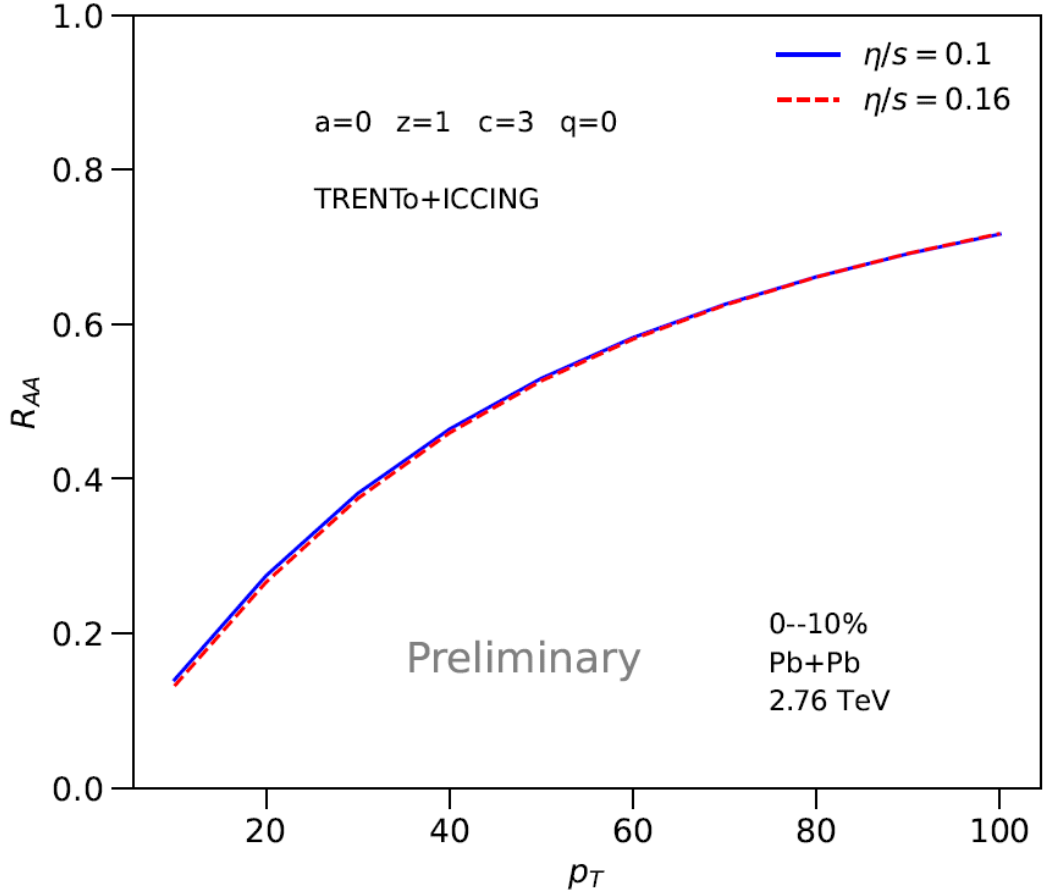


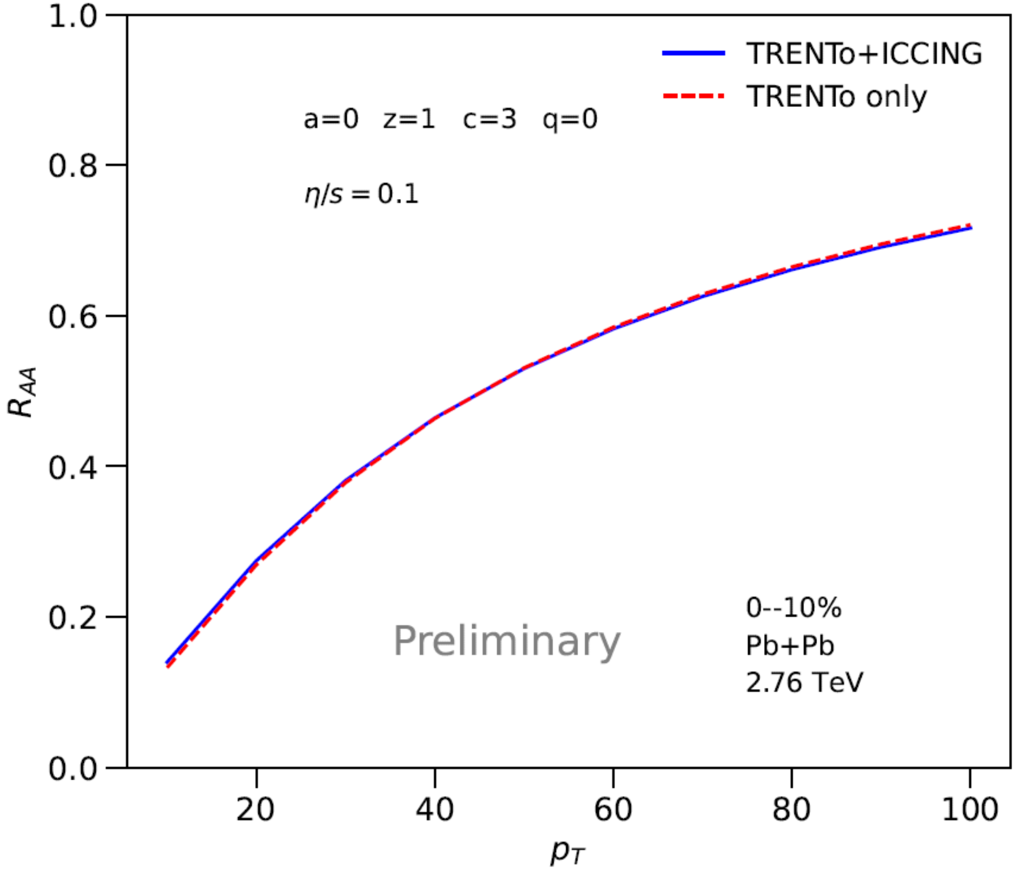
CMS Collaboration, Eur.Phys.J.C 72 (2012) 1945, 2012



B. Betz, et. al, Phys. Rev. Lett. 116, 252301

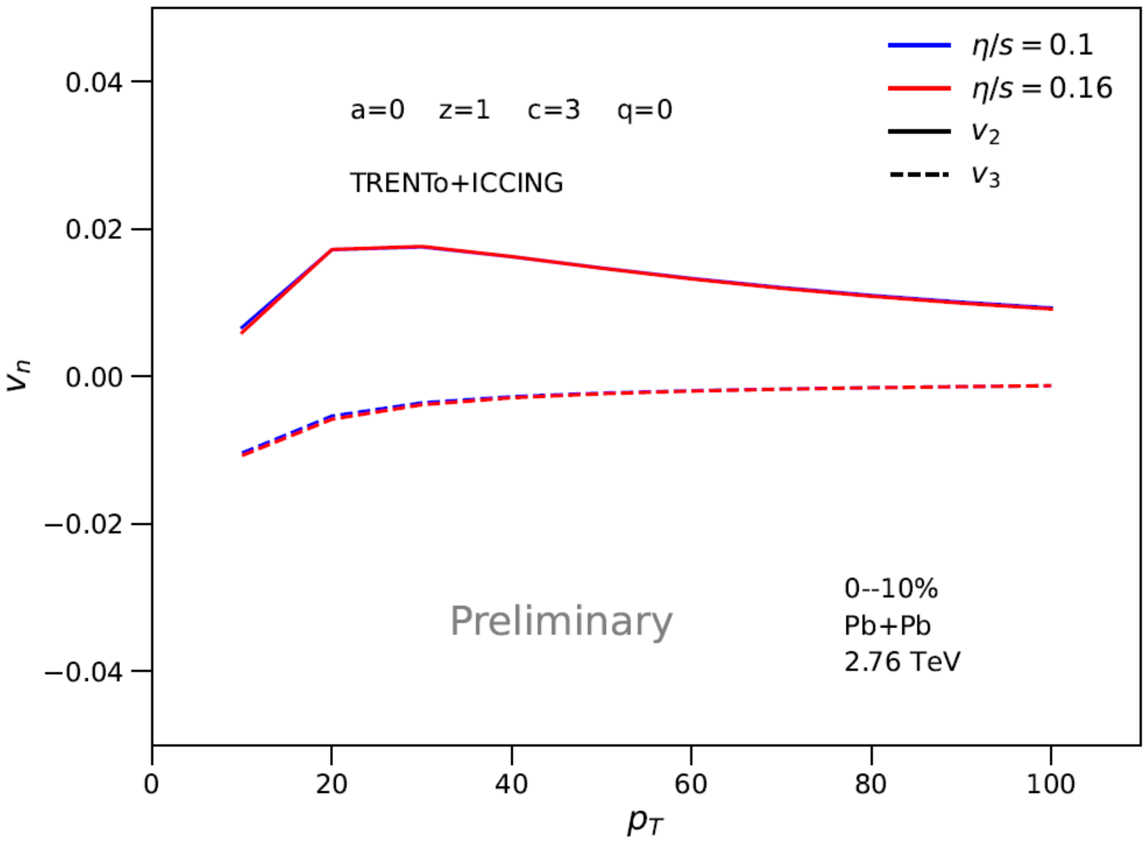
Changing viscosities and initial conditions

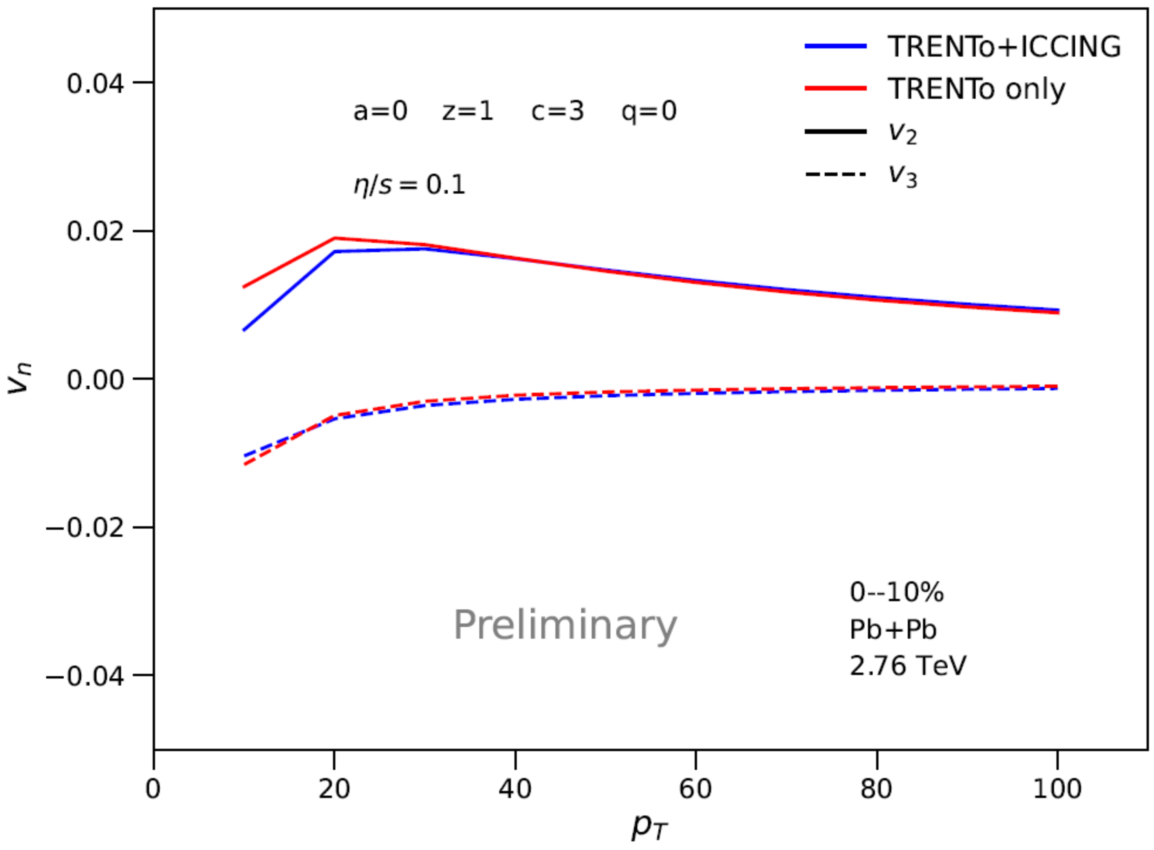




Changing conditions of hydro slightly doesn't seem to have drastic effects on R_{AA}

Changing viscosities and initial conditions





Changing viscosities doesn't have an effect on v_n but the lack of conserved charges may affect v_n at lower p_T

Future

We have much more we can look at, and will once we finish hydro runs for 0-10%, 20-30%, and 40-50%

- Examining R_{AA} to see if my model follows the trend for smaller systems
- Calculating n-particle correlations, flow vectors, and higher order cumulants from statistically significant v_n's
- Expand my code from 2+1D to 3+1D

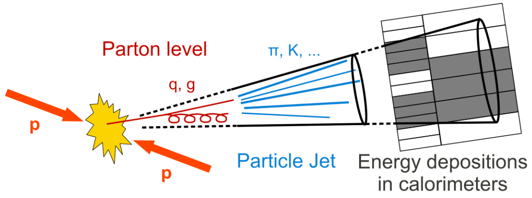
Include a source term in the hydro code for jets to backreact on the medium, and create a conical instead of linear propagation

- See Kevin's talk tomorrow for more information!

Conclusions

- The viscous medium has the expected suppression of high p_T particles resulting from jets
- Changing the shear viscosity doesn't have much affect on the R_{AA} and v_n
- Allowing for BSQ charges doesn't affect R_{AA} much, but had a noticeable shift in the v_2 of the low end of high p_T jets
- The effect of jets on the medium is not yet known, but we come closer to that information each day

Appendix



cms.cern/news/jets-cms-and-determination-their-energy-scale