Vision on Key Measurements Past, Present and Future

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Massachusetts Institute of Technology

Heavy-ion Jet Substructure Workshop
13-17 May 2019, University of Bergen, Norway

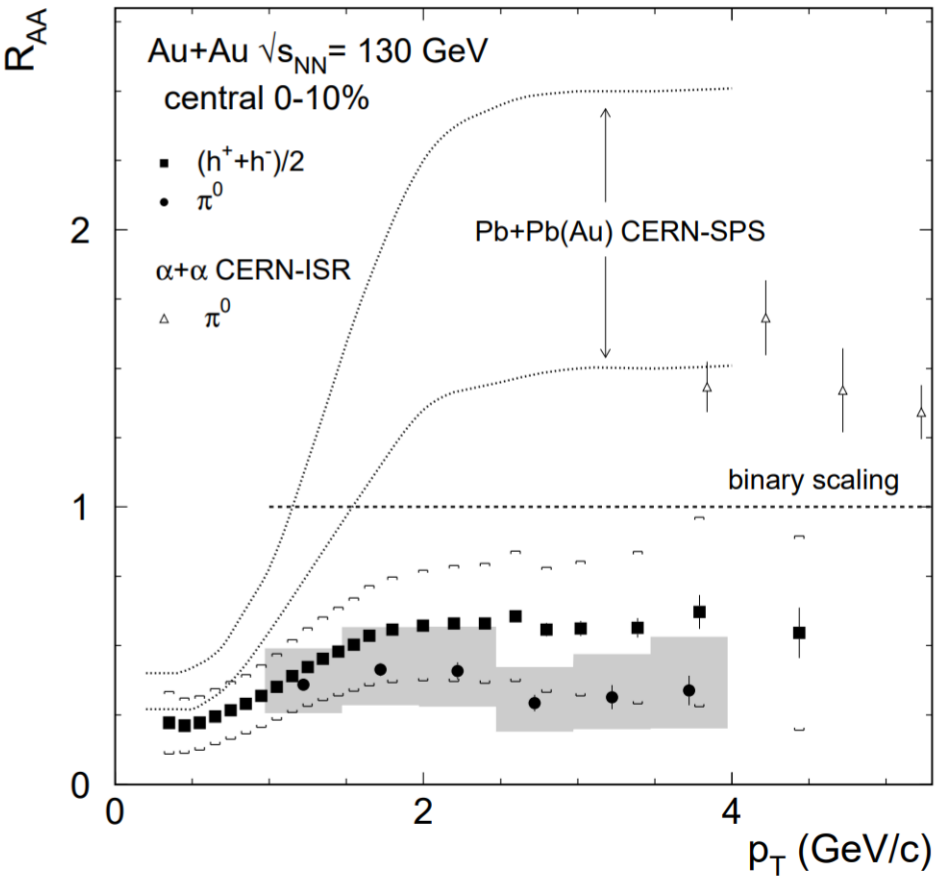
MIT Group efforts are supported by US DOE NP and DOE Early Career Award

Early Key Measurements at RHIC (2001-3)

PHENIX

PRL 88 (2002) 022301

(1033 citations)



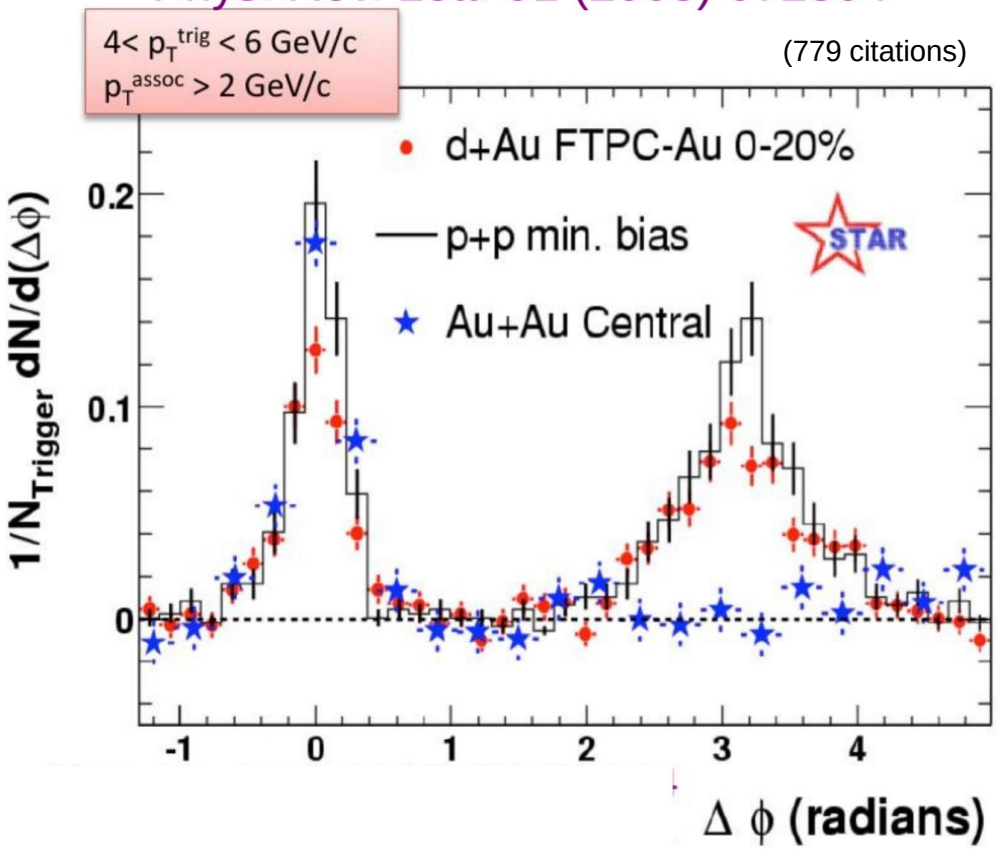
Strong suppression of high p_T hadrons

Modification of the leading fragment

Di-hadron Correlation

Phys. Rev. Lett. 91 (2003) 072304

(779 citations)



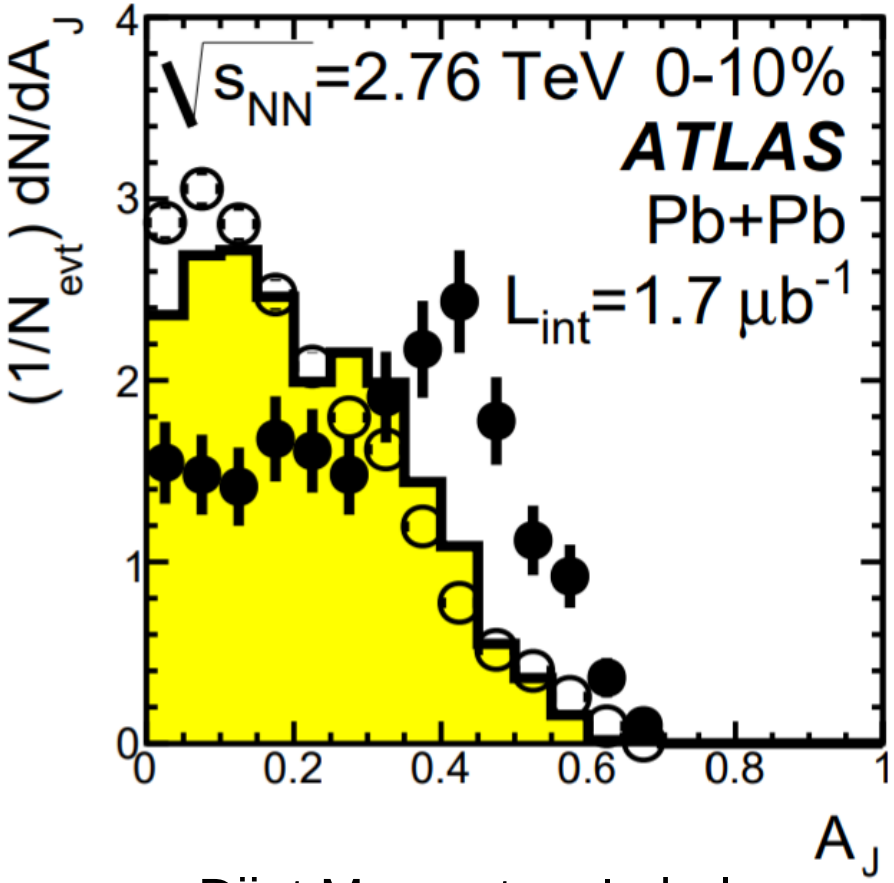
Disappearance of the away-side peak

Fate of associated hadron in the near- and away-side

Early Key Measurements at LHC (2010)

PRL 105 (2010) 252303

(731 citations)

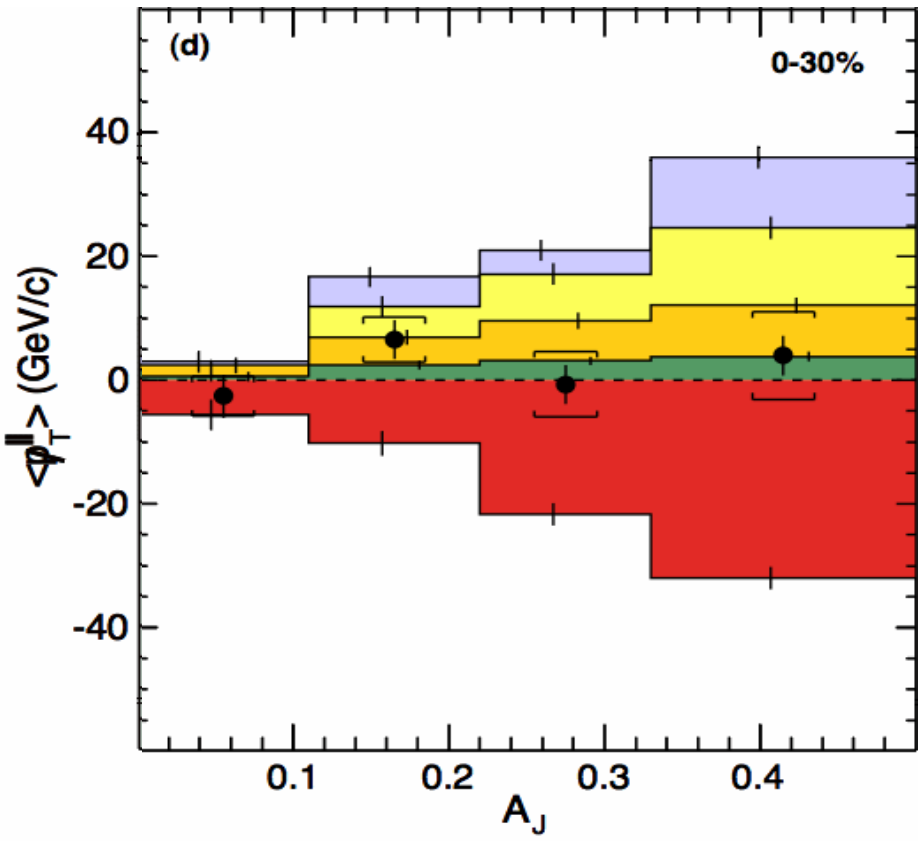


Dijet Momentum Imbalance

Jet quenching with jet
Energy flow out of the jet cone

PRC 84 (2011) 024906

(690 citations)

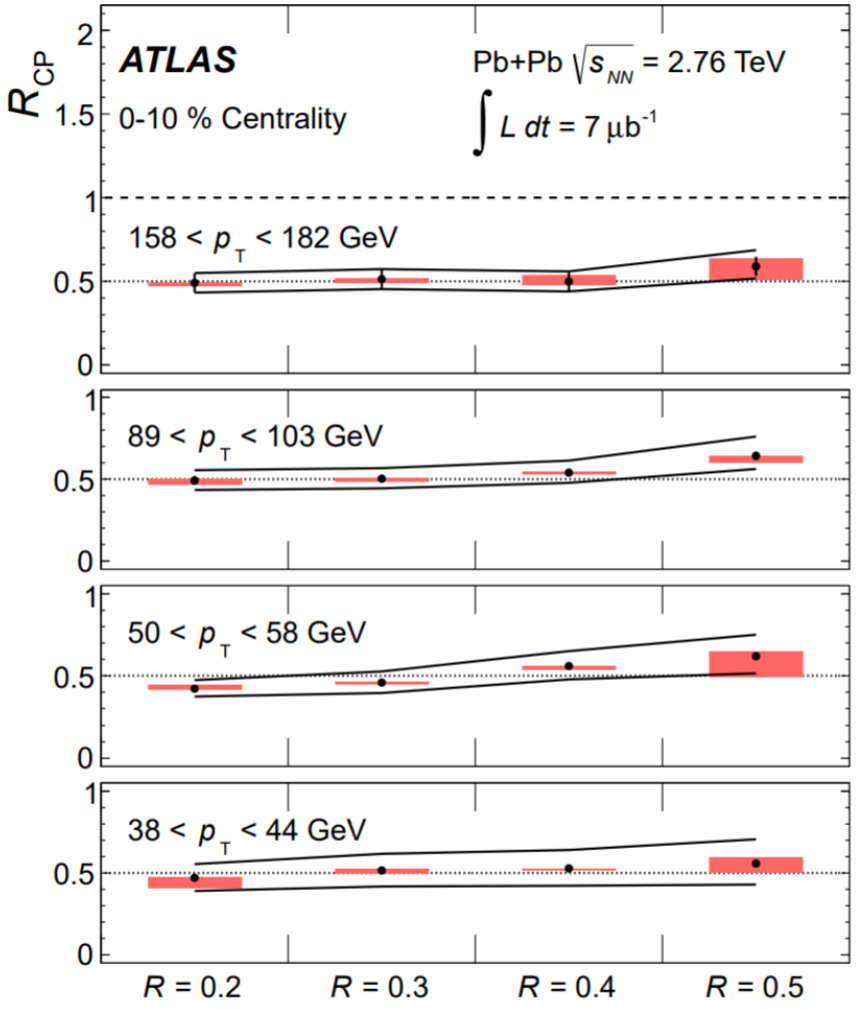


Missing Transverse Momentum

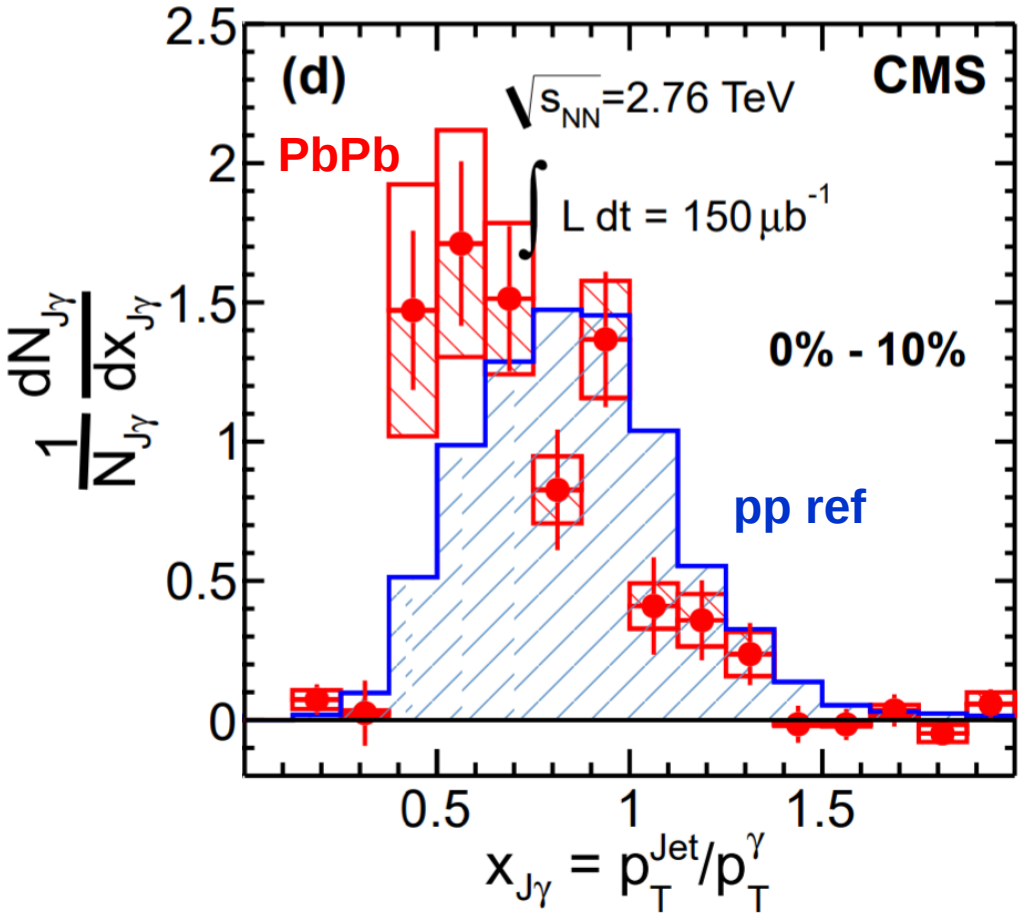
Quenched energy carried by low p_T particle out of the jet cone

Key Results on Jet Energy Loss (2013)

PLB 719 (2013) 220-241



PLB 718 (2013) 773-794

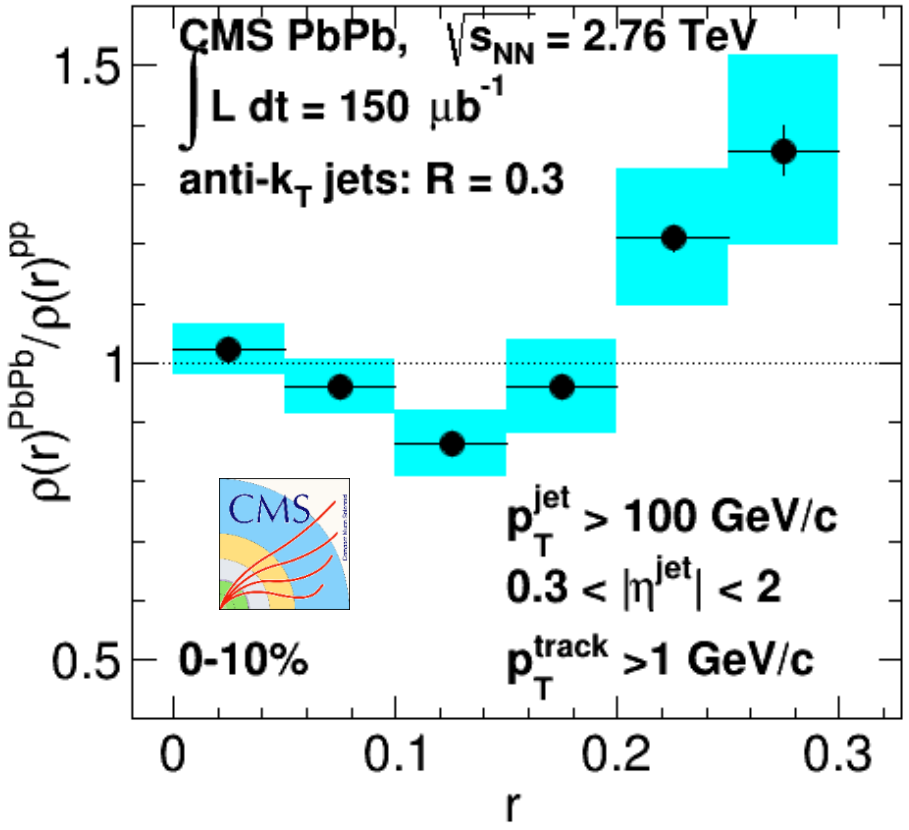


Slow recovery of the quenched energy

"Absolute Energy Loss"

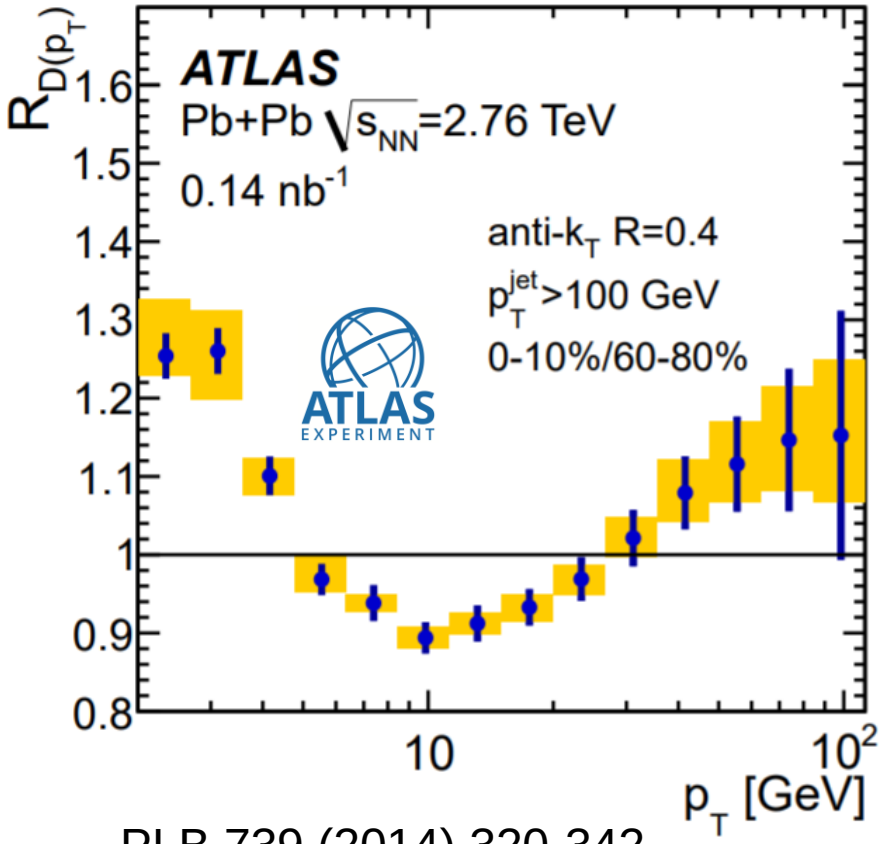
Key Results on Jet Structure (2014)

Jet Transverse Structure



PLB 730 (2014) 243-263

Jet Longitudinal Structure



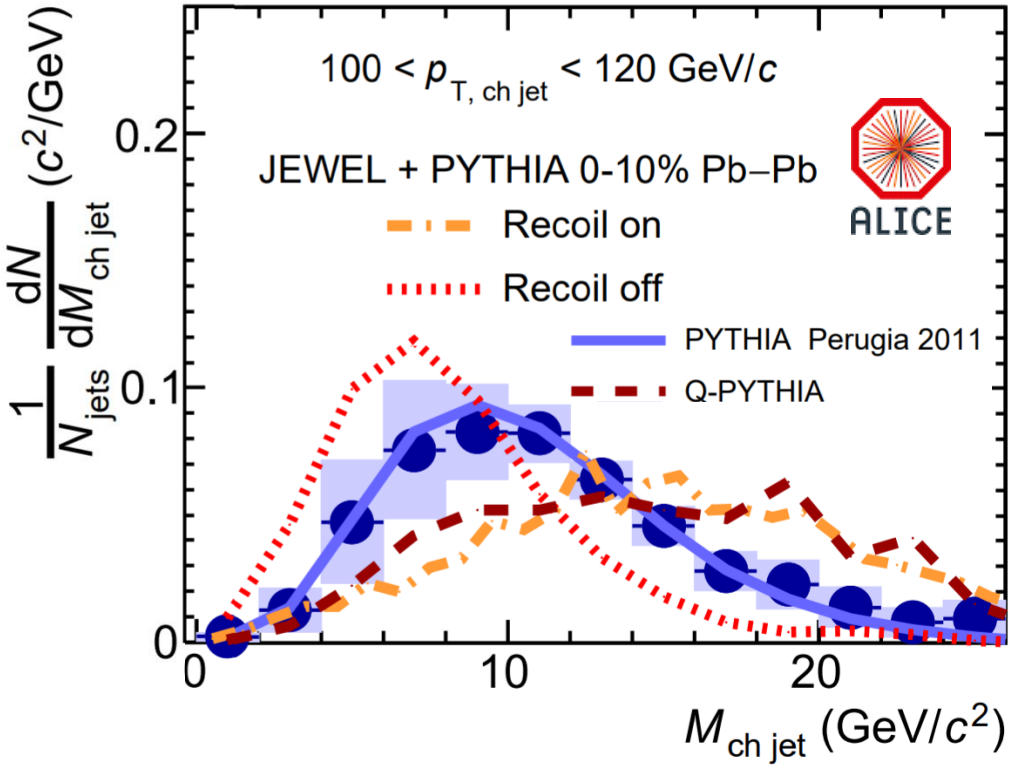
PLB 739 (2014) 320-342

- Significant modification of average jet substructure when compared the jets in PbPb to the pp reference at the same p_T
- Jet structures, defined by clustering and background subtraction algorithms, are modified in PbPb collisions

Jet Substructure Dependent Eloss (2017)

Ungroomed Charged Jet Mass

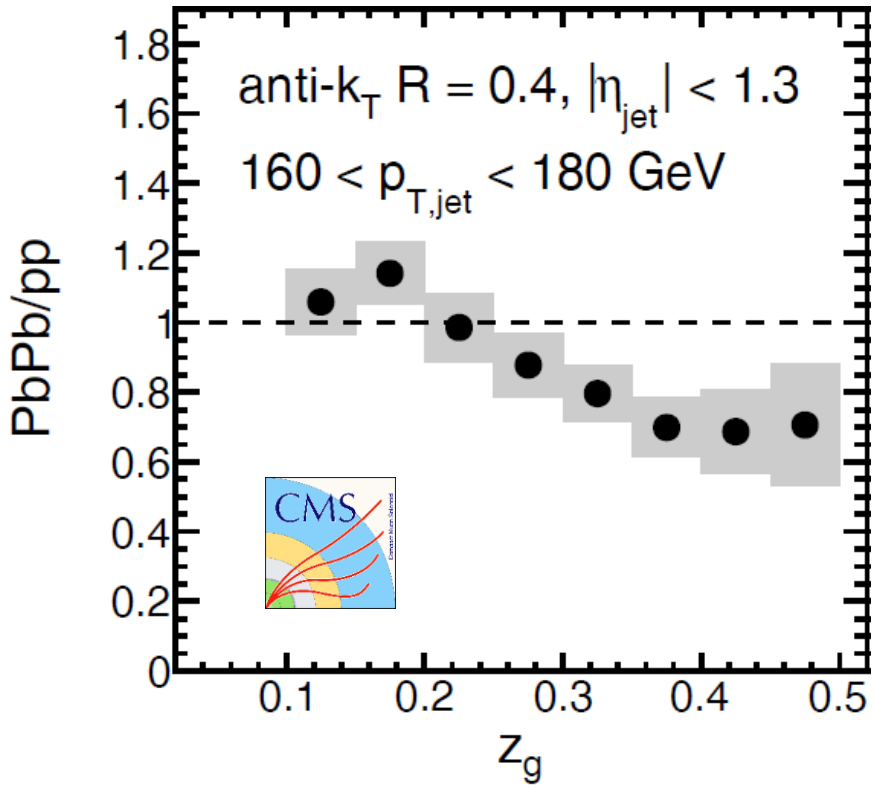
PLB 776 (2018) 249-264



No significant modification of jet mass with respect to PYTHIA

Groomed Subjet p_T Sharing

PRL 120 (2018) 142302

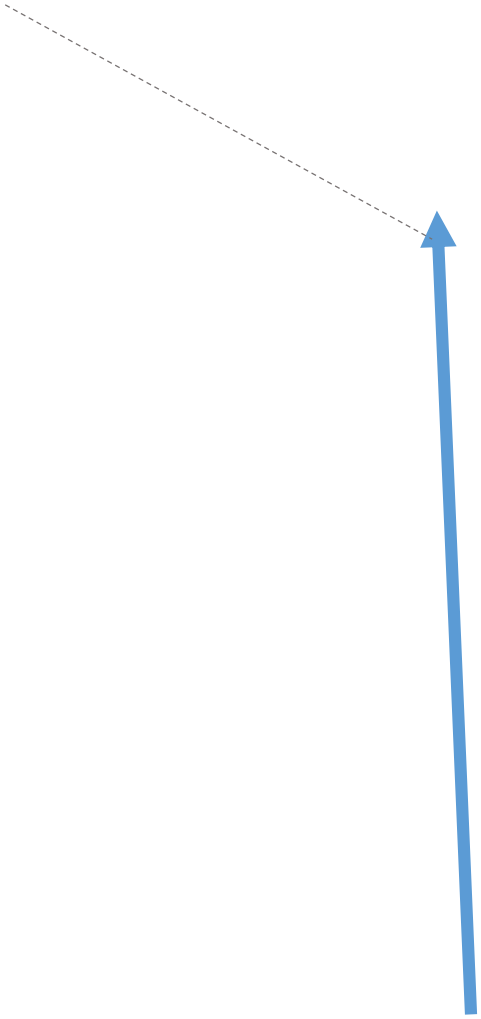


Significant modification of Z_g at LHC

No significant modification Z_g at RHIC
(See Raghav's talk)

Progress Over the Last ~18 Years

2001 Leading Fragment



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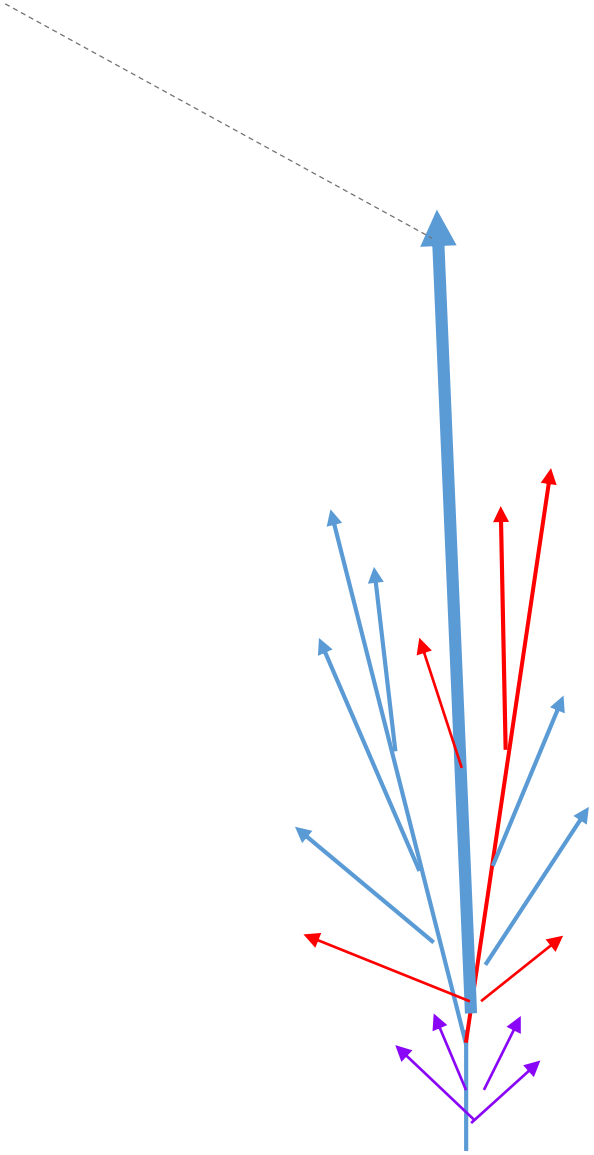

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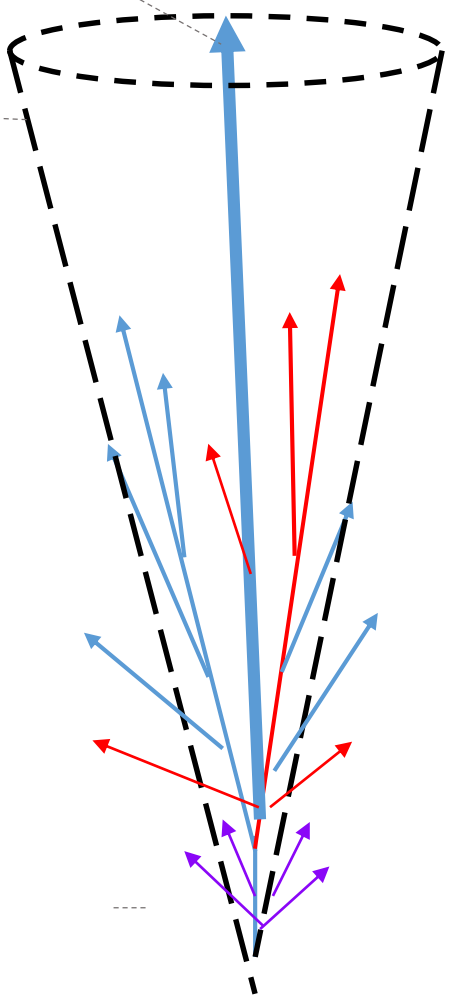

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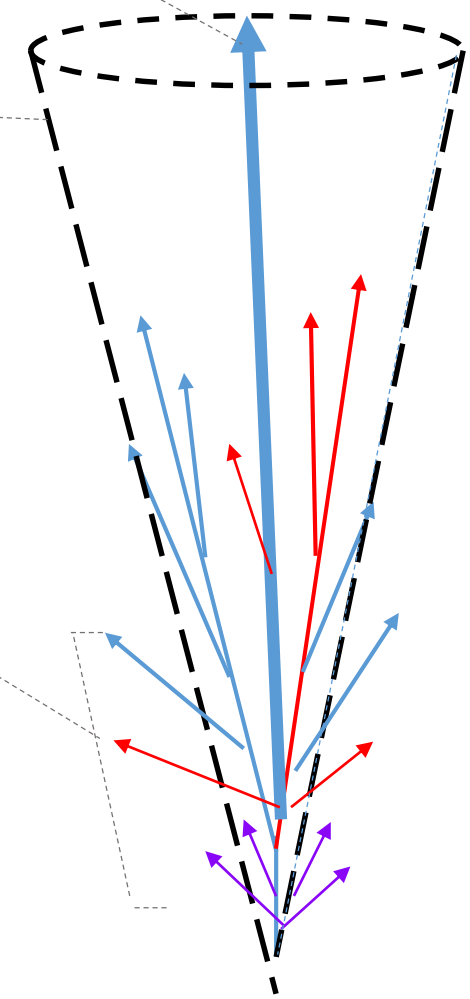

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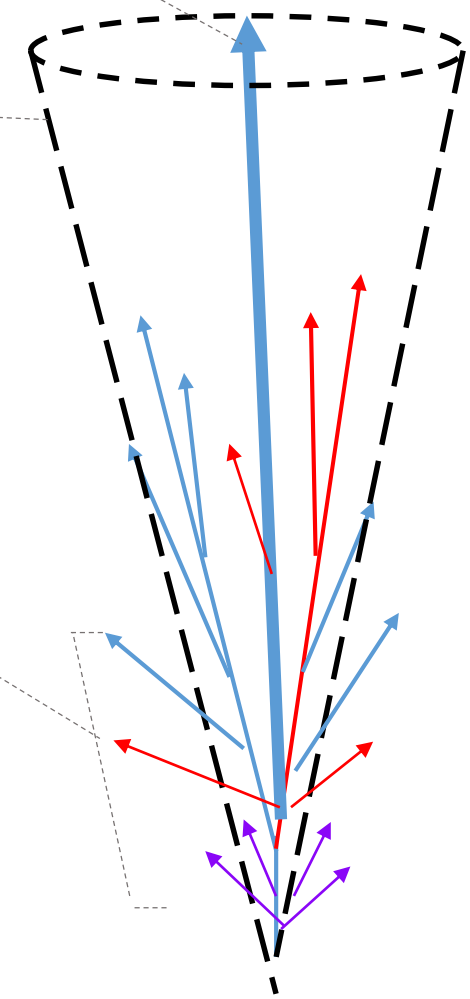

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-2014 Parton Flavor Dependence of Eloss

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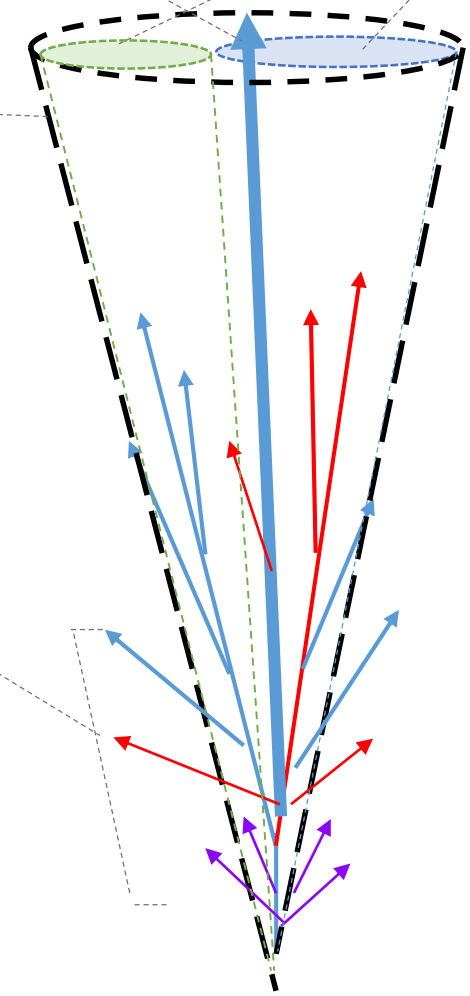
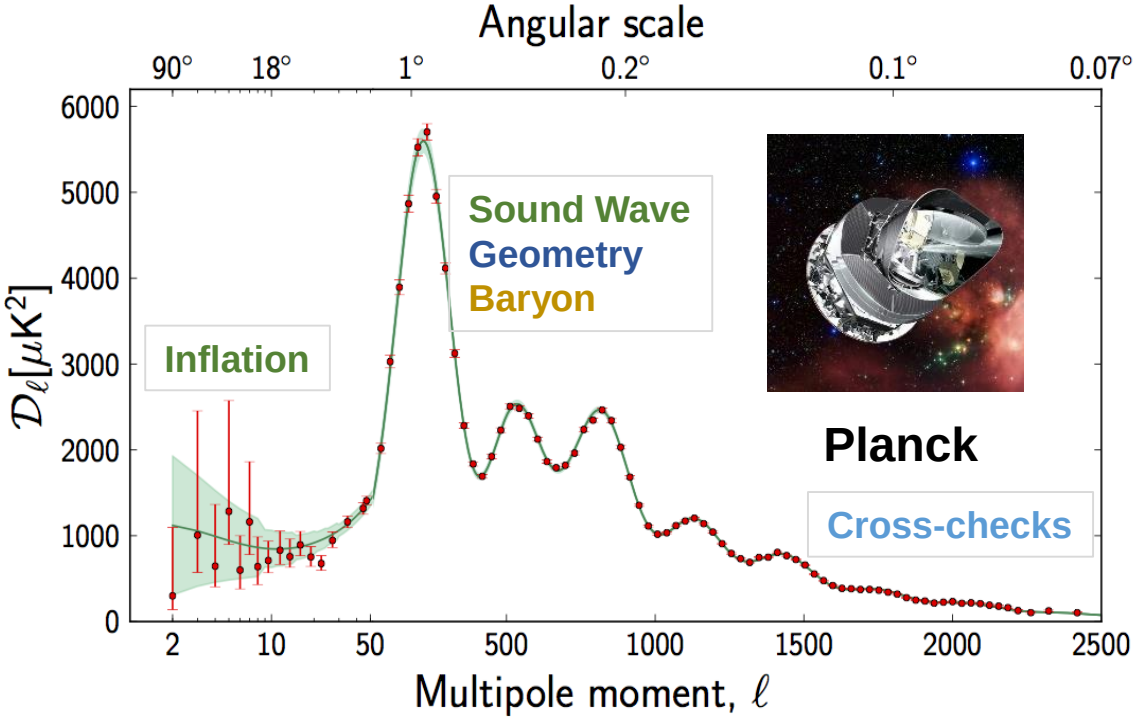
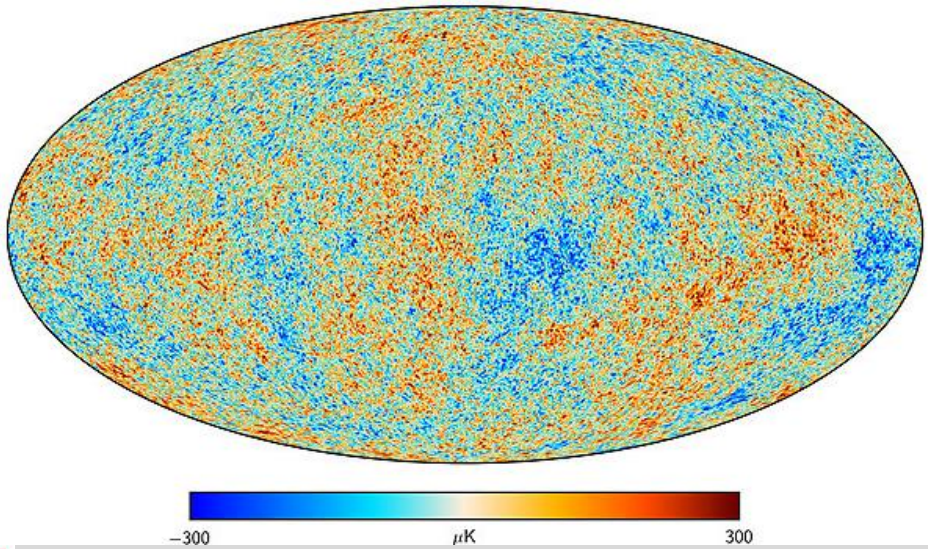


2019
Present Status

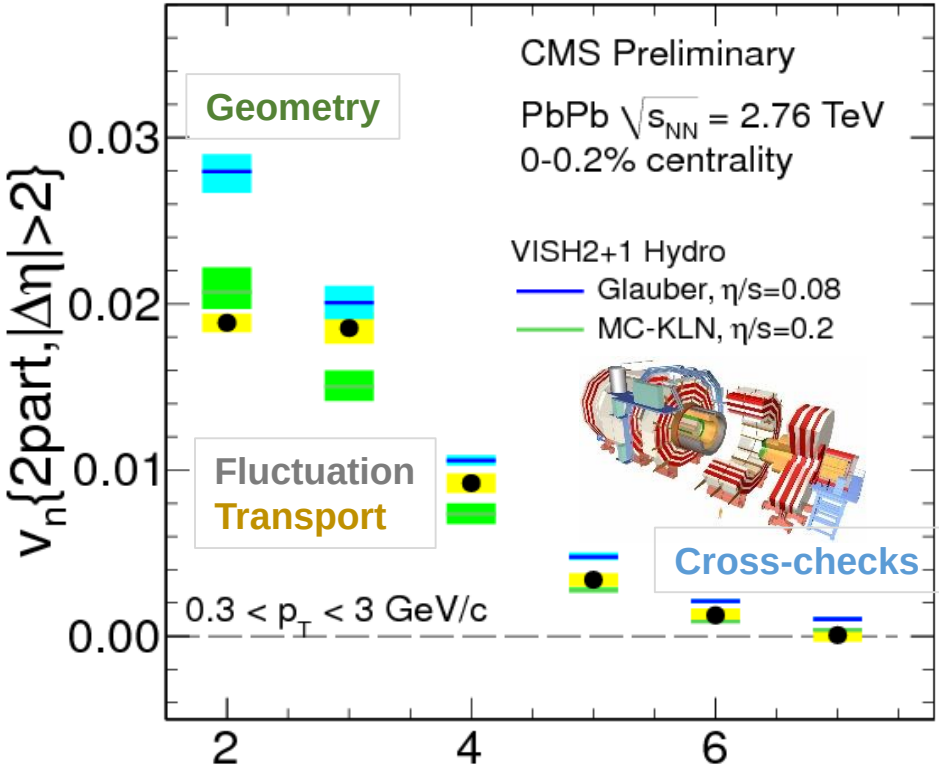
Density Fluctuation of CMB and QGP

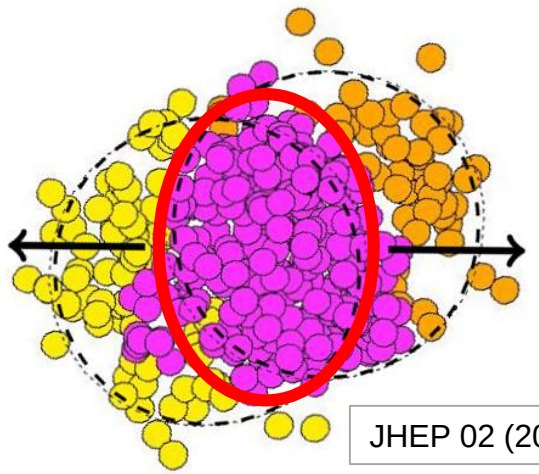
Power spectrum of the Big Bang





Fourier analysis of many little bangs



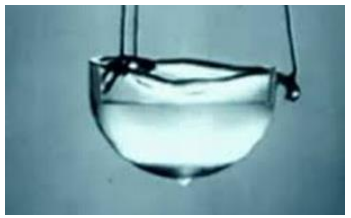


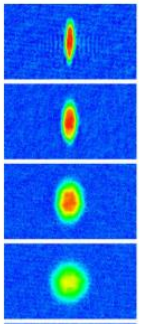
JHEP 02 (2014) 088

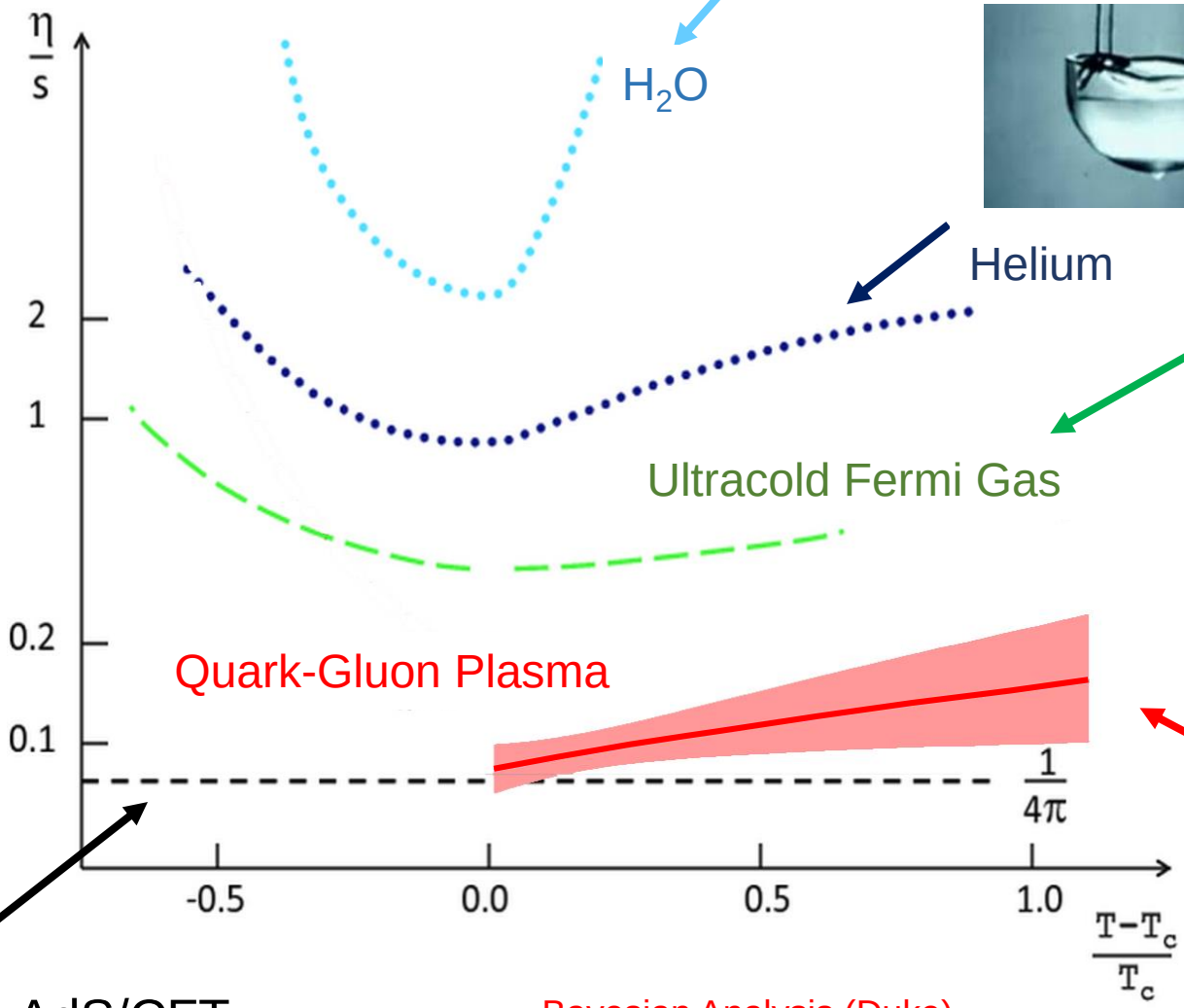
Near Perfect Fluid

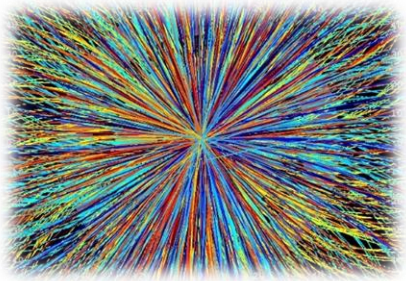
Shear viscosity to entropy ratio

Cartoon









Temperature

Calculation from AdS/CFT

Bayesian Analysis (Duke)
PRC94 (2016) no.2, 024907

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Shear viscosity to entropy ratio

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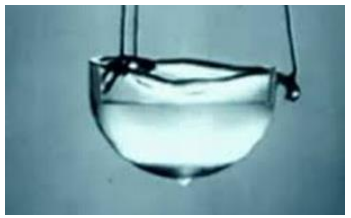

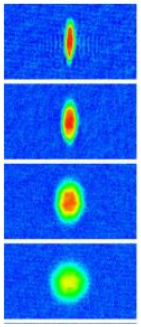

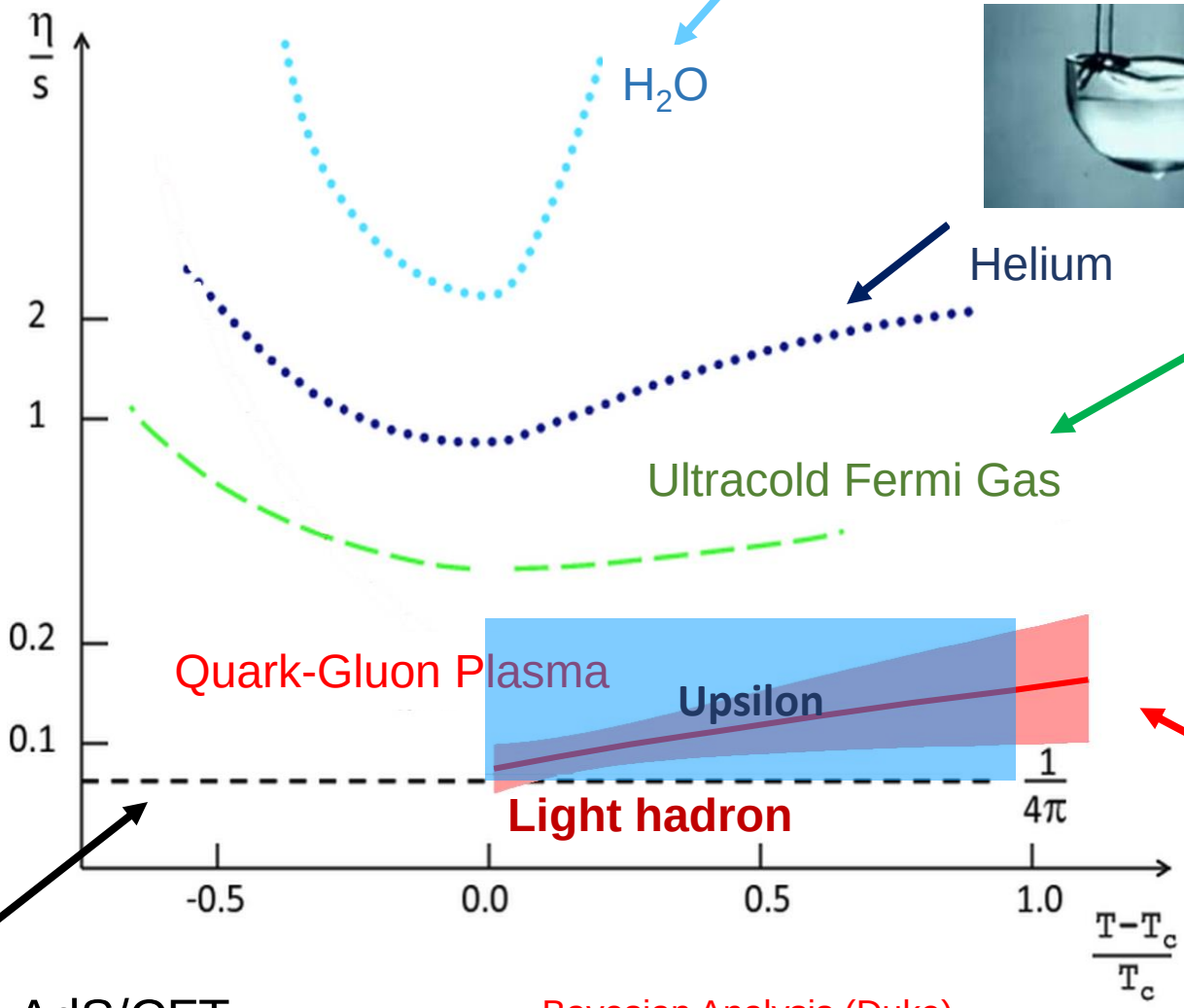

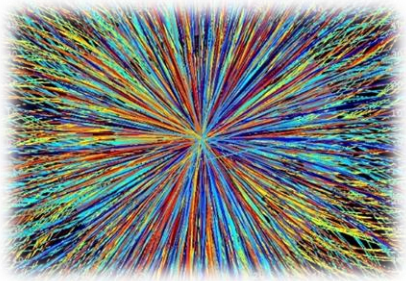

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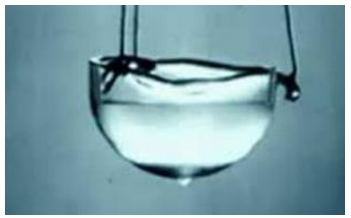
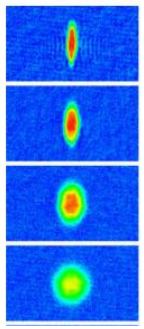
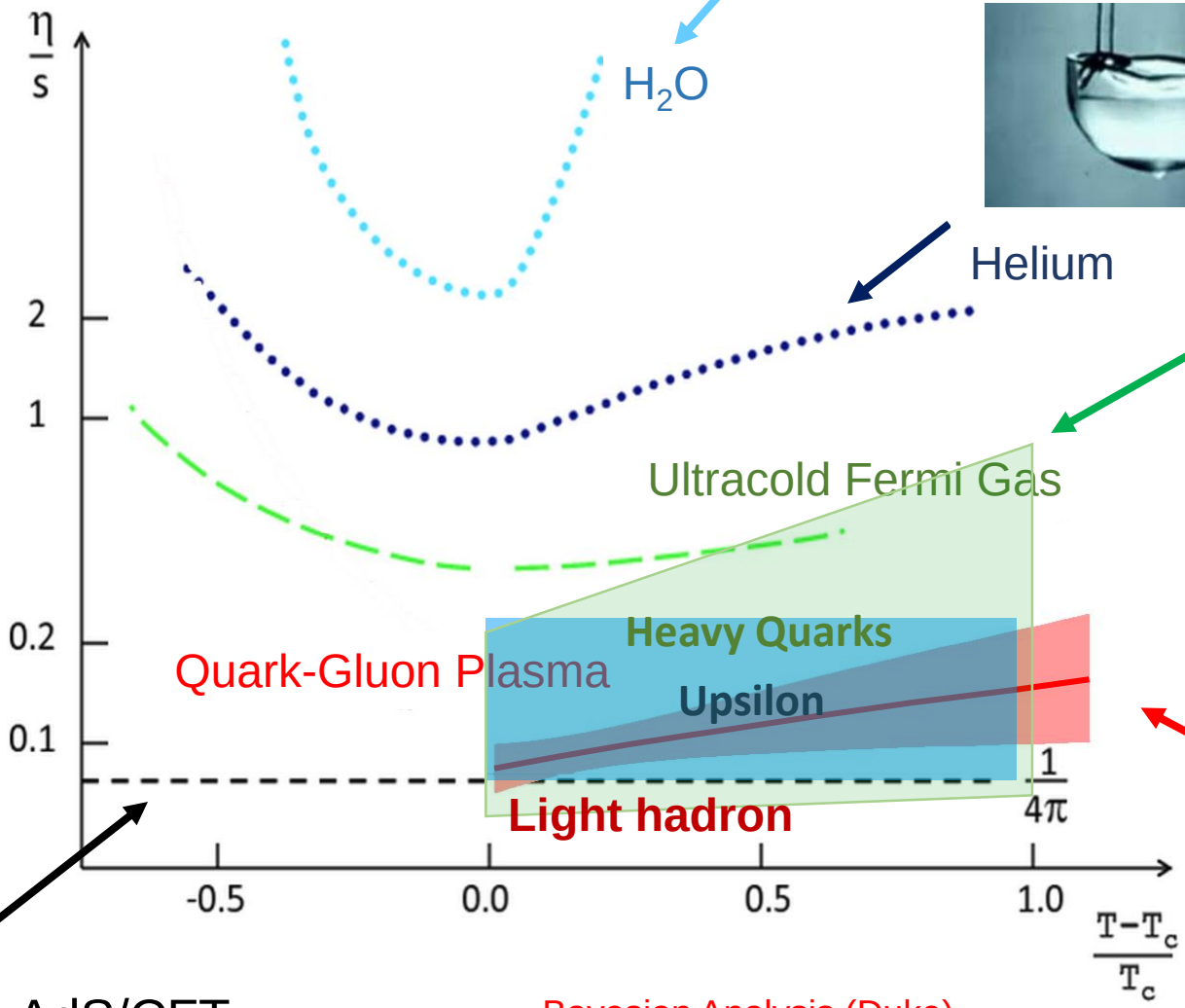
Agreement between Hard and Soft Probes

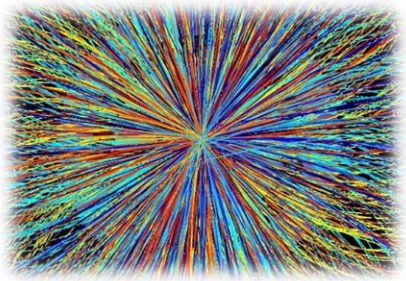
Shear viscosity to entropy ratio

Cartoon









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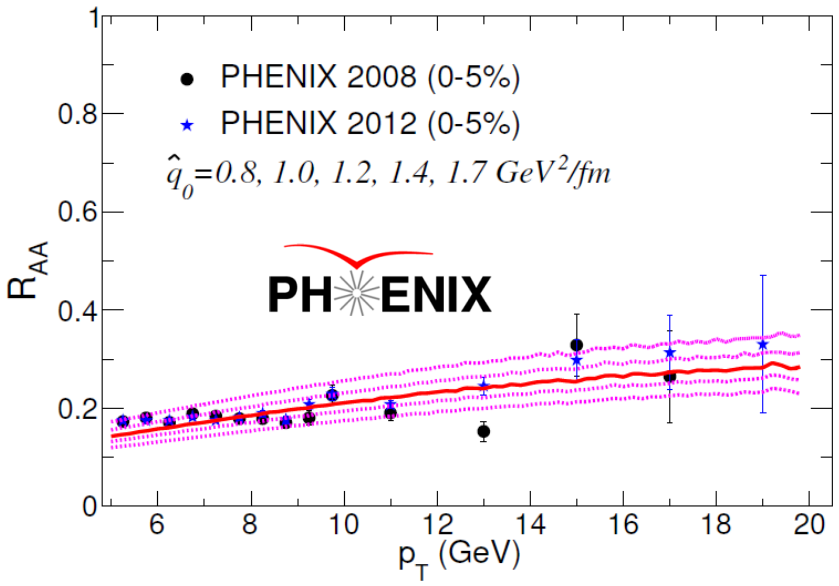
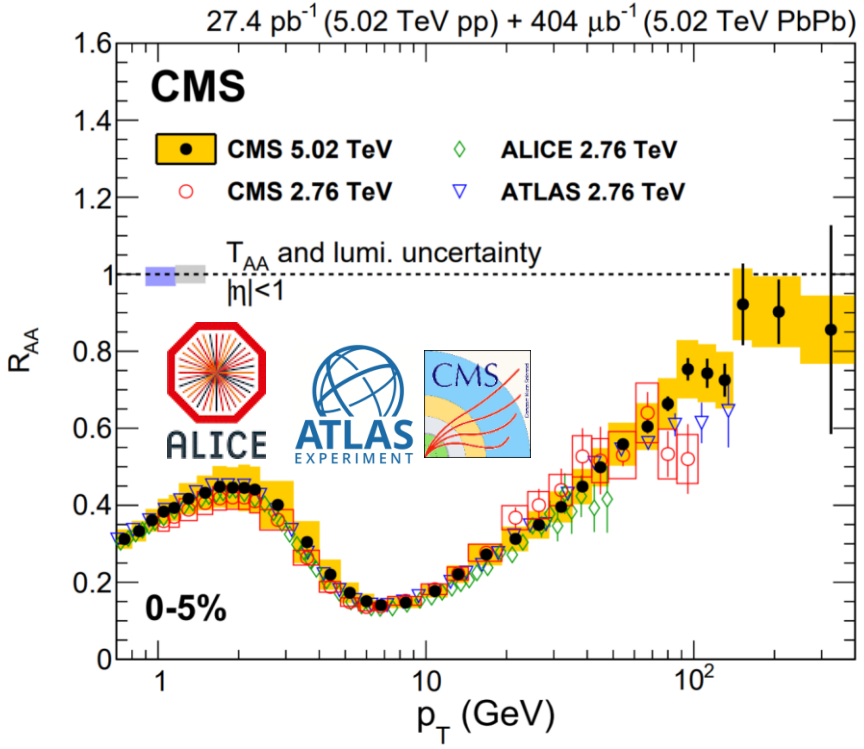
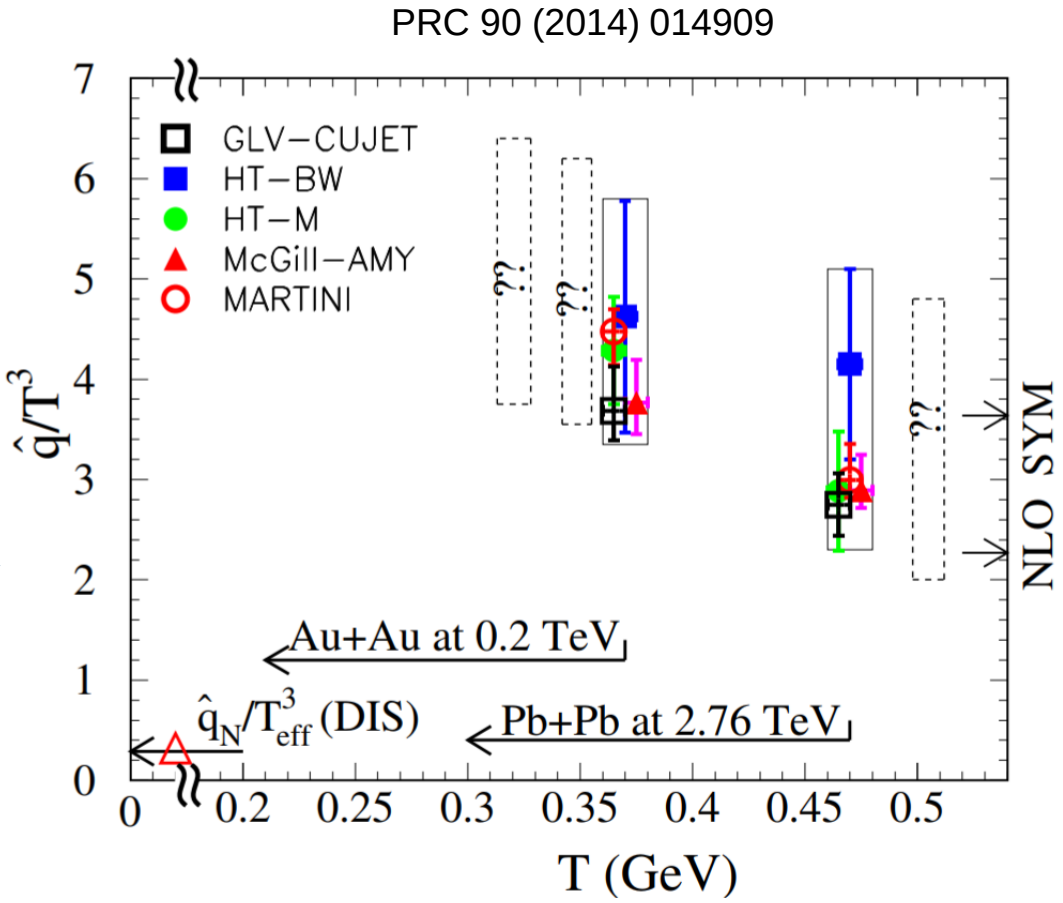
Precision Measurement of Hadron R_{AA}



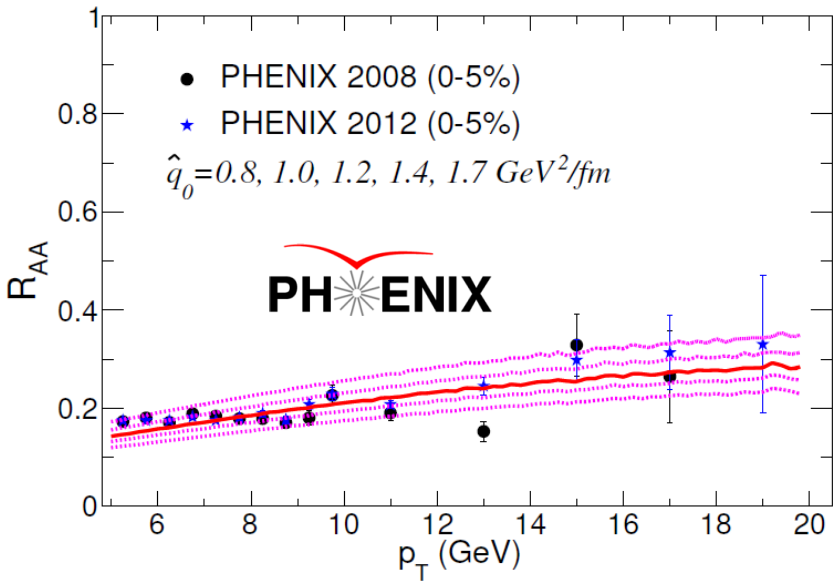


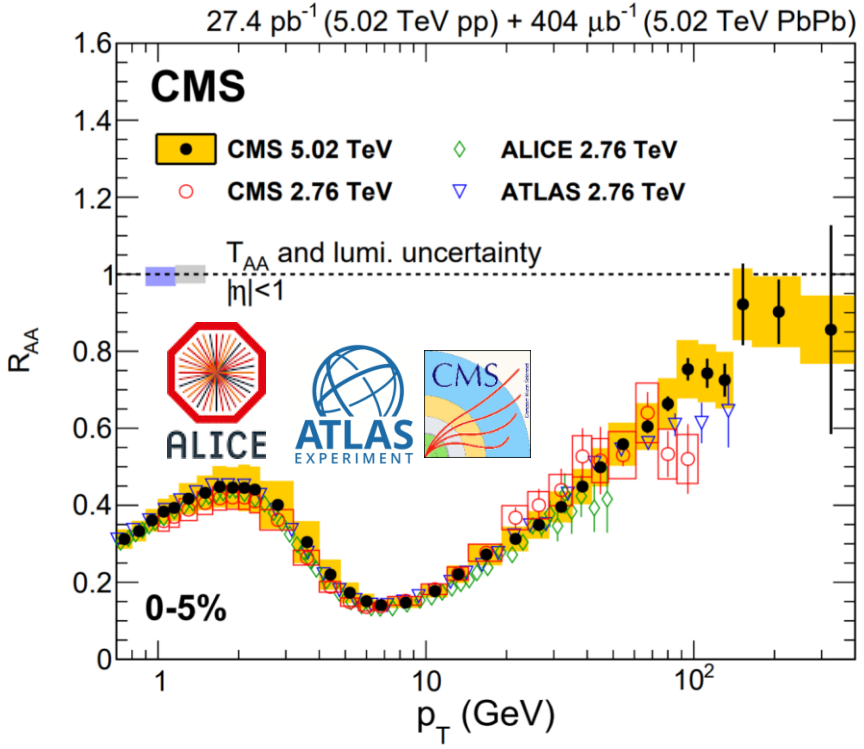
PRC 90 (2014) 014909



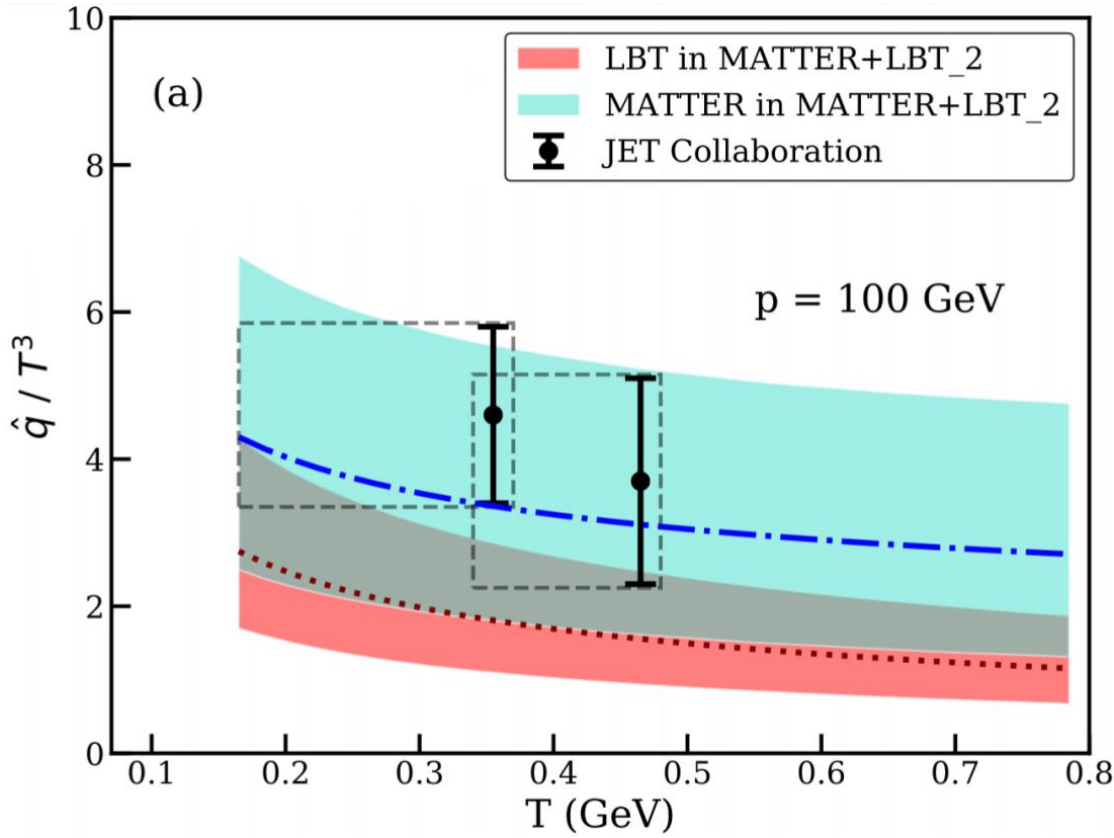
- Extraction of jet quenching parameters from hadron spectra
- Large uncertainty from model dependence

Precision Measurement of Hadron R_{AA}





JETSCAPE Collaboration Preliminary



- Extraction of jet quenching parameters from hadron spectra
- Large uncertainty from model dependence

Jet Quenching Mechanism

Extraction with hadron spectra can not provide a full picture

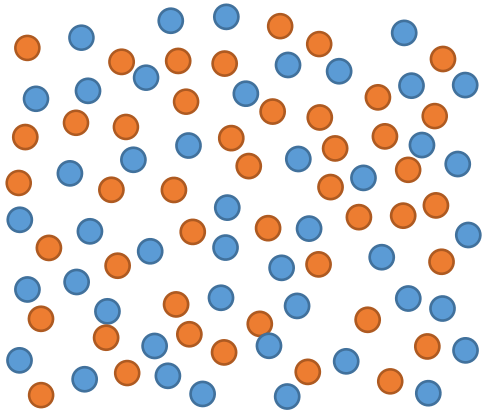
To fully utilize the jet as a probe of the QGP:

Need the full understanding of the jet quenching mechanism which include: how the medium modifies the jets and how the jets modify the medium

Q: Why do we need more accuracy?

Quark Gluon Plasma Substructure

Quarks and Gluons



QGP Fluid
“Quark Soup”

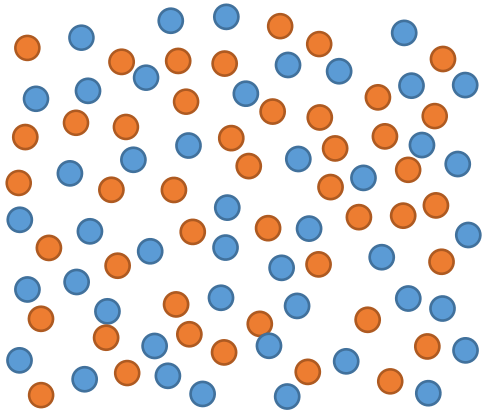
AdS/CFT low viscosity goo

Short Wavelength

Long Wavelength

Quark Gluon Plasma Substructure

Quarks and Gluons



QGP Fluid
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Short Wavelength

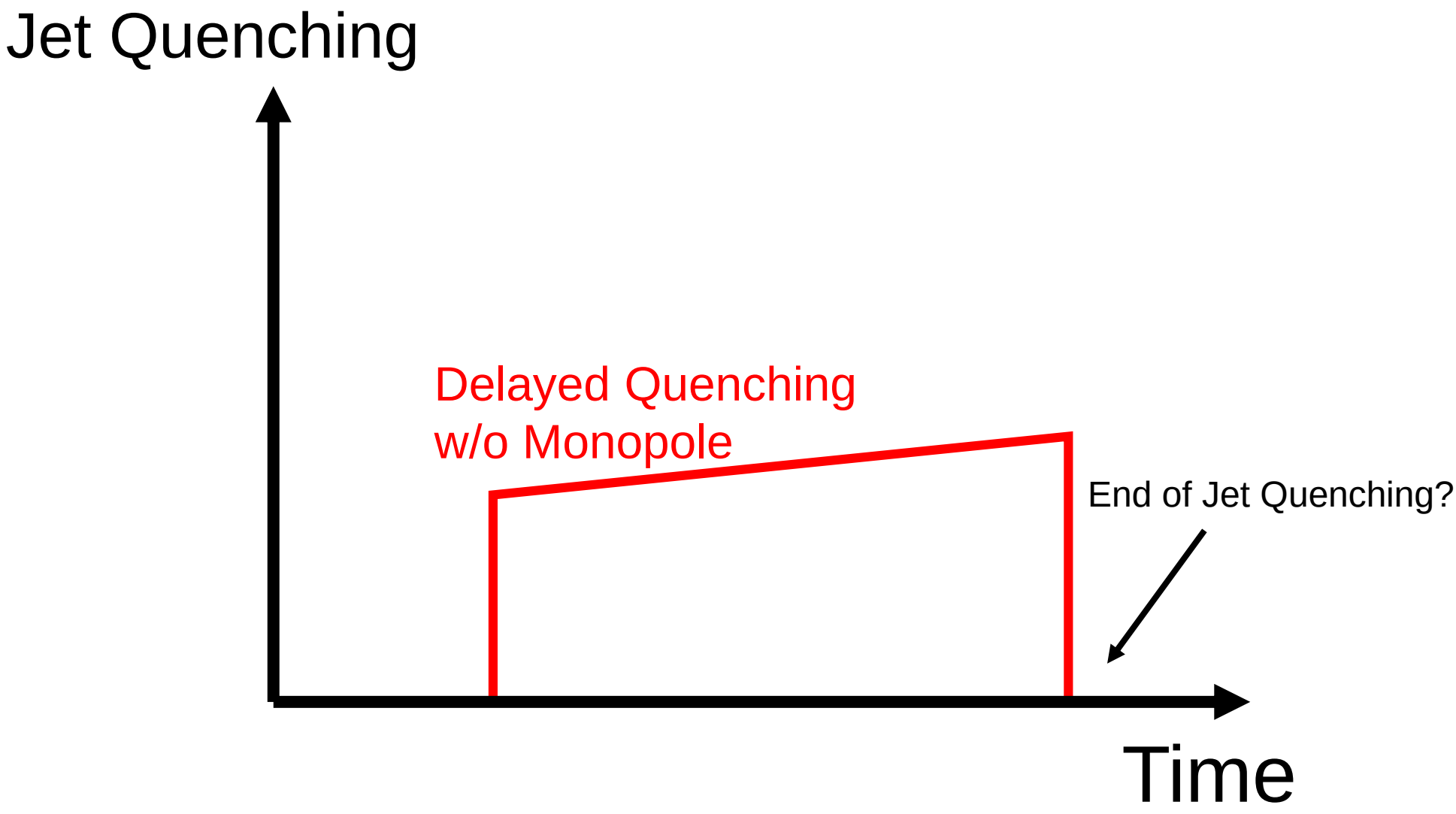
What is the structure of QGP at intermediate length scale ?

Long Wavelength

Can we come out with concrete observables and an estimated size of the effects from the jet tool workshop?

Jet Quenching vs. Time

Cartoon



Contribute to the understanding of starting time of the jet quenching (QGP)

Jet Quenching vs. Time

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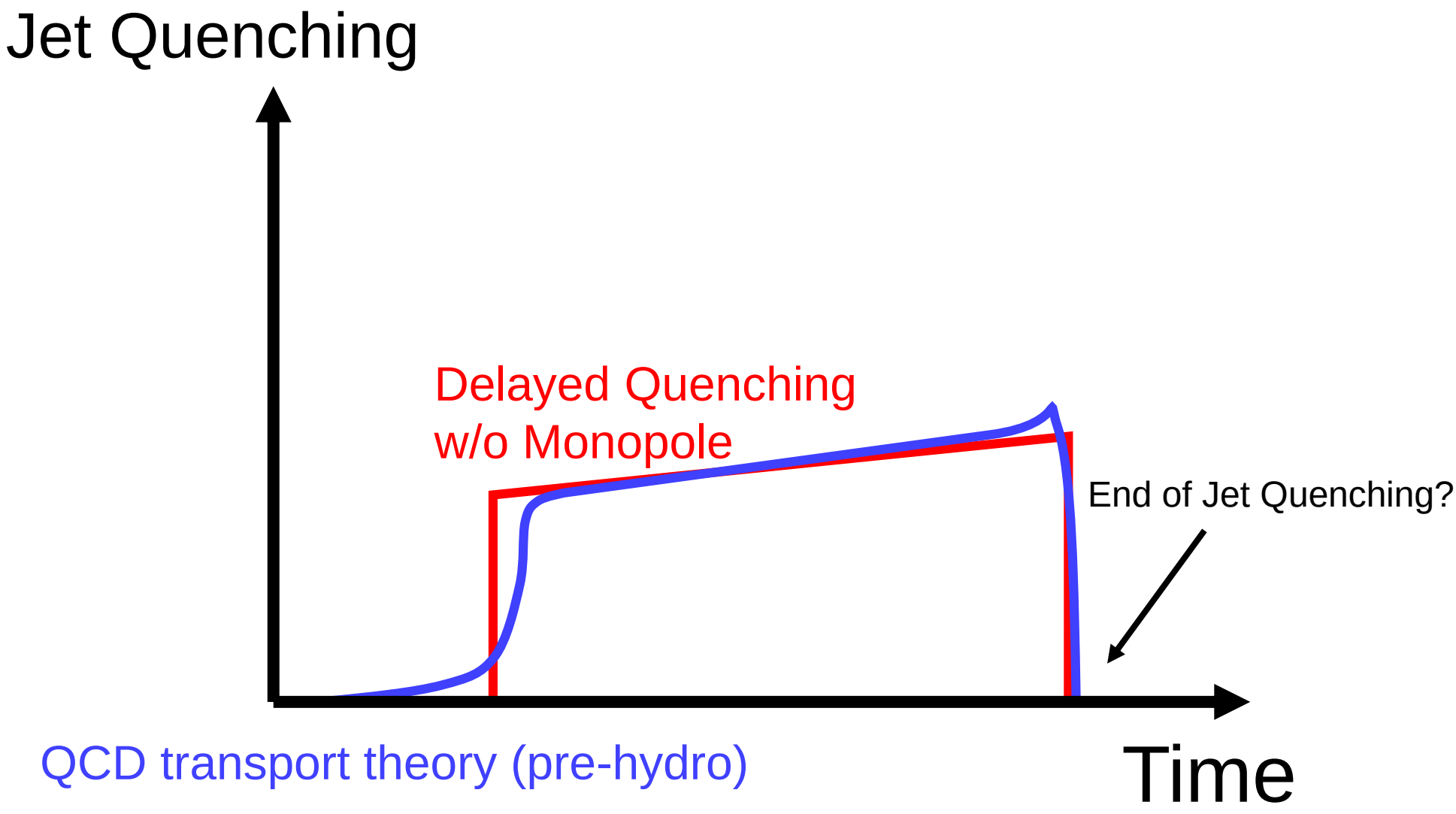

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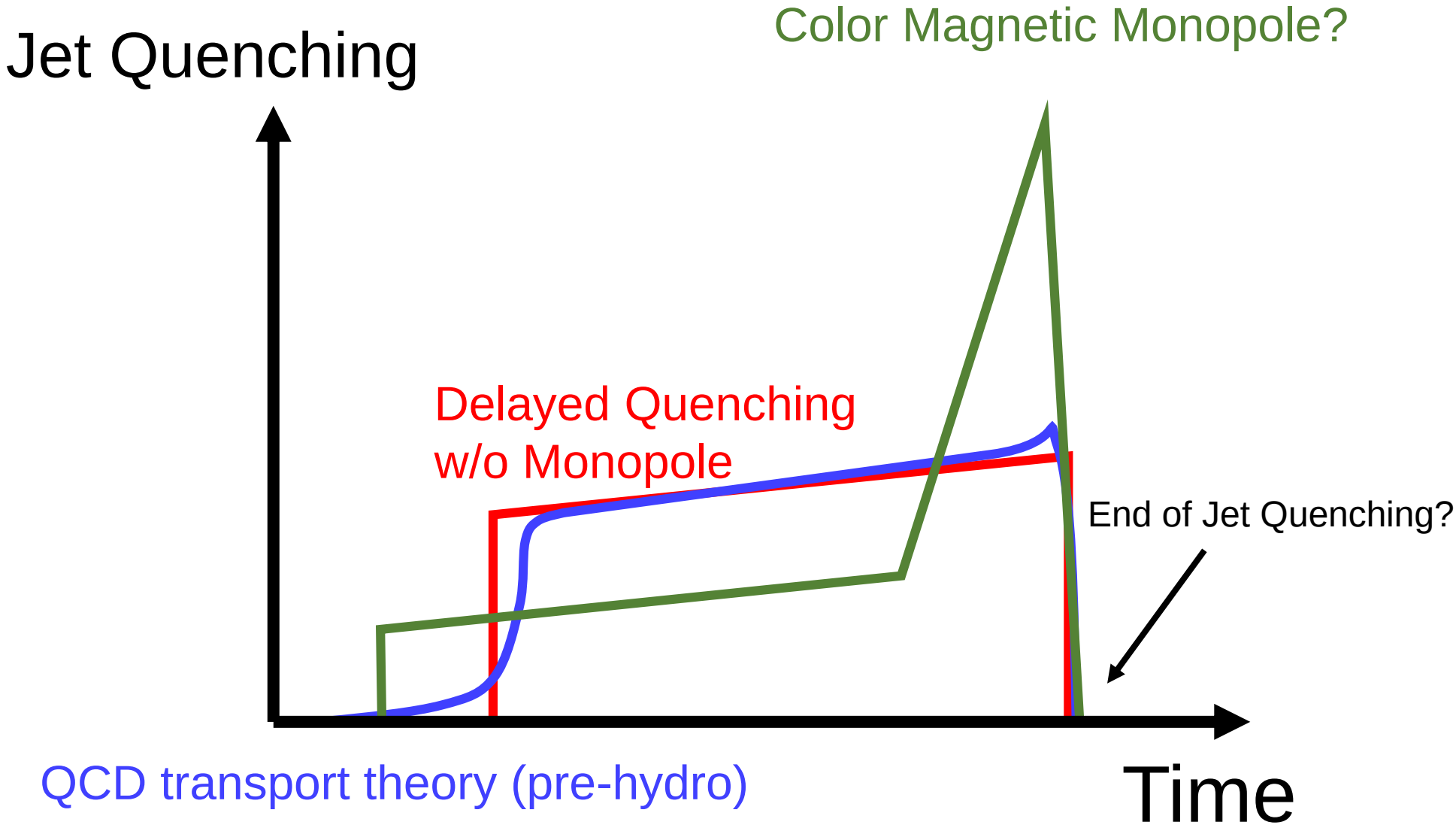


Currently, we can not separate the three curves using hadron R_{AA} and v_2

Jet substructure involving partons with different formation time could help

Future Measurements

Jet Substructure and QGP Properties

Can we extract QGP properties from jet substructures?

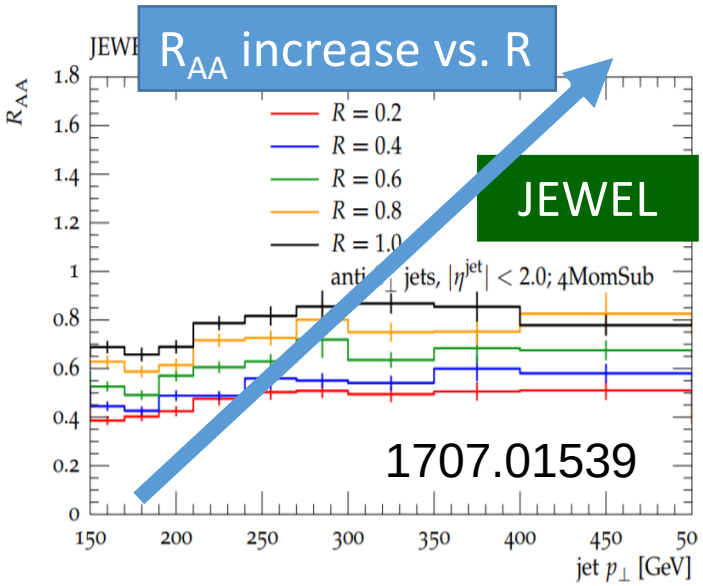
To make an organized effort toward success:

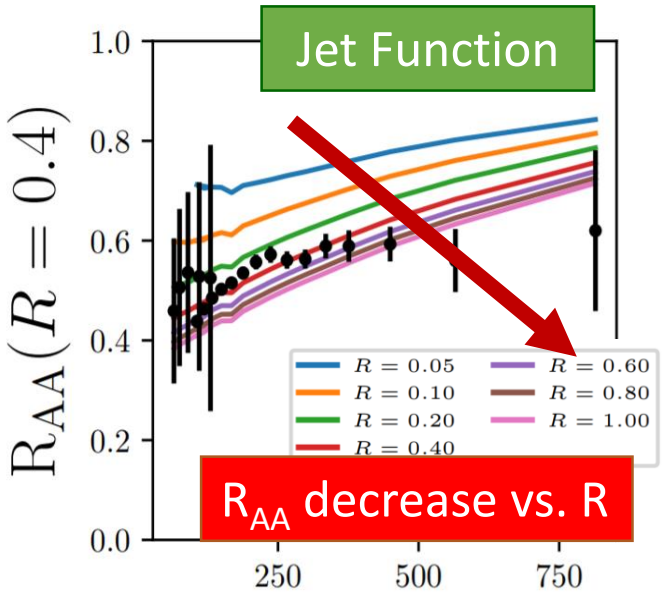
1. Make a complete survey on jet spectra and substructure (choose the basis wisely)

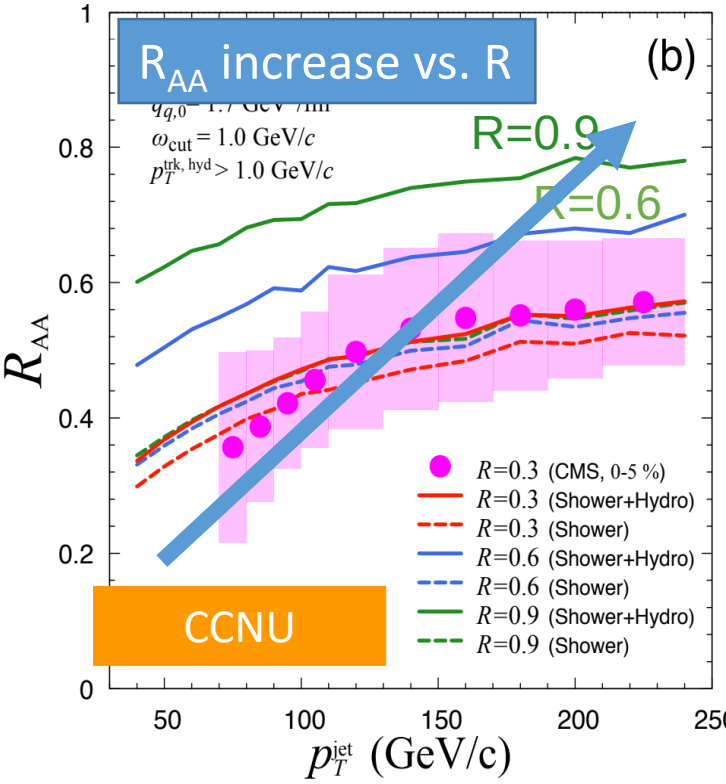
2. Make human understandable measurements which are sensitivity to one dominant effect

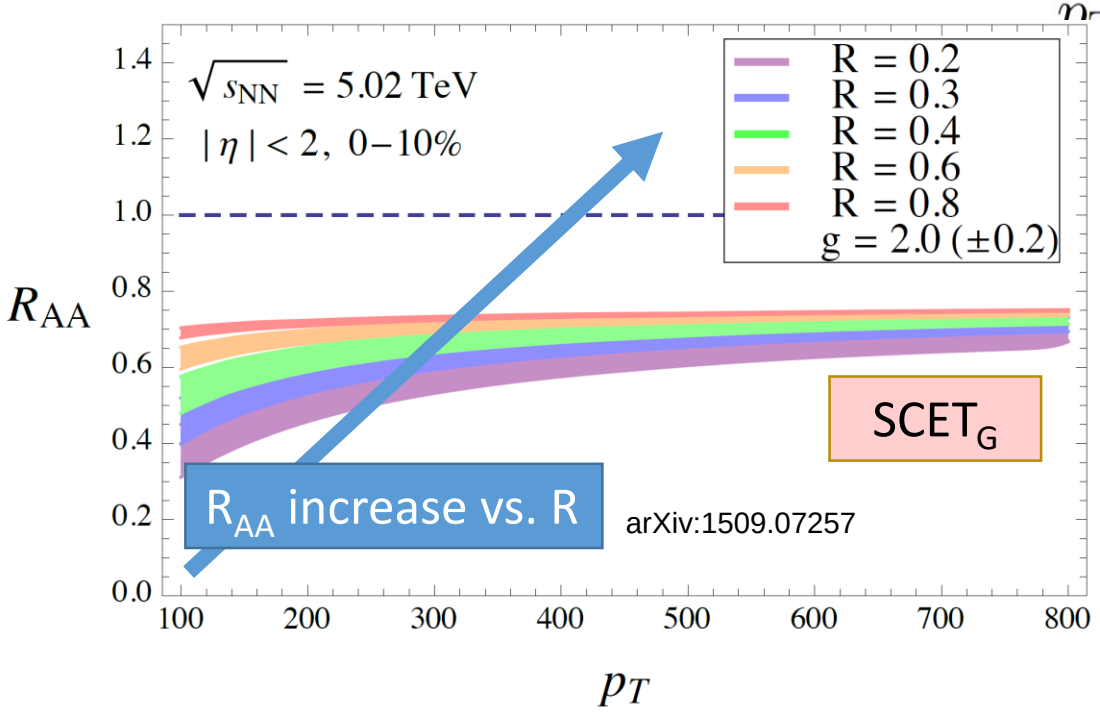
3. Need direct (or a concrete strategy) comparisons between the expectations from RHIC and LHC energies

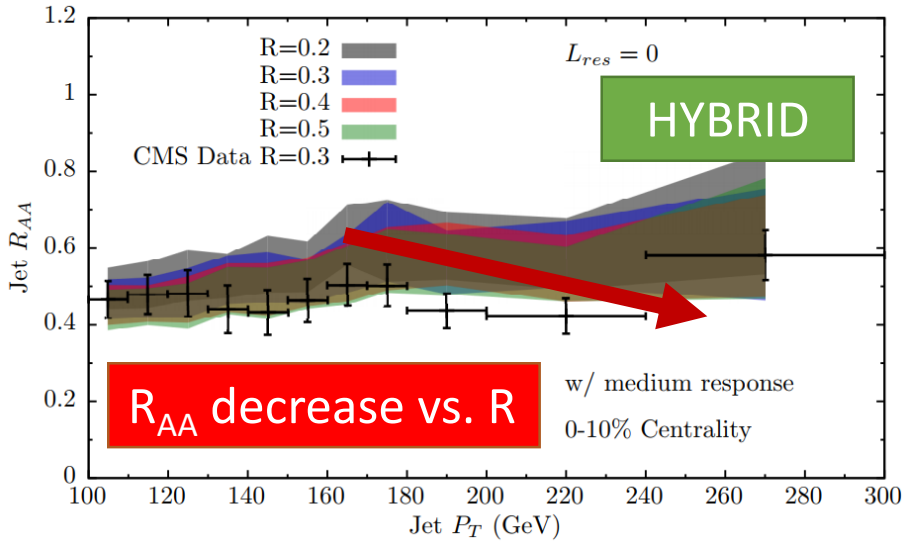
Example 1: Jet R_{AA} vs. R





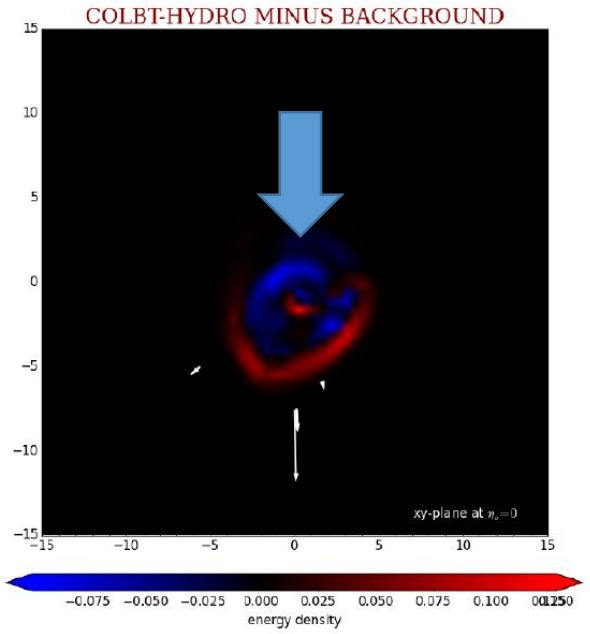


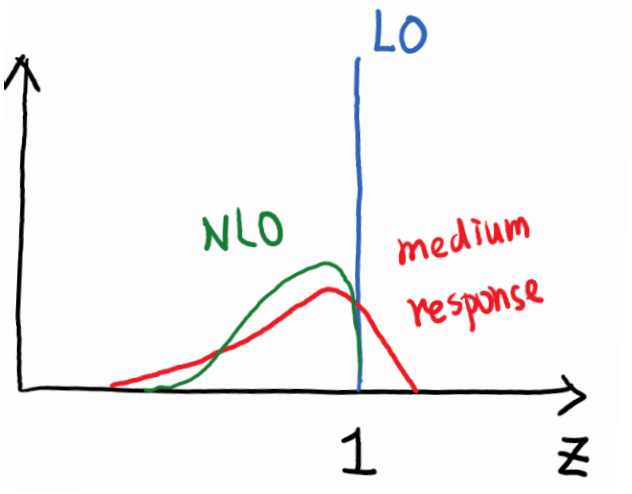


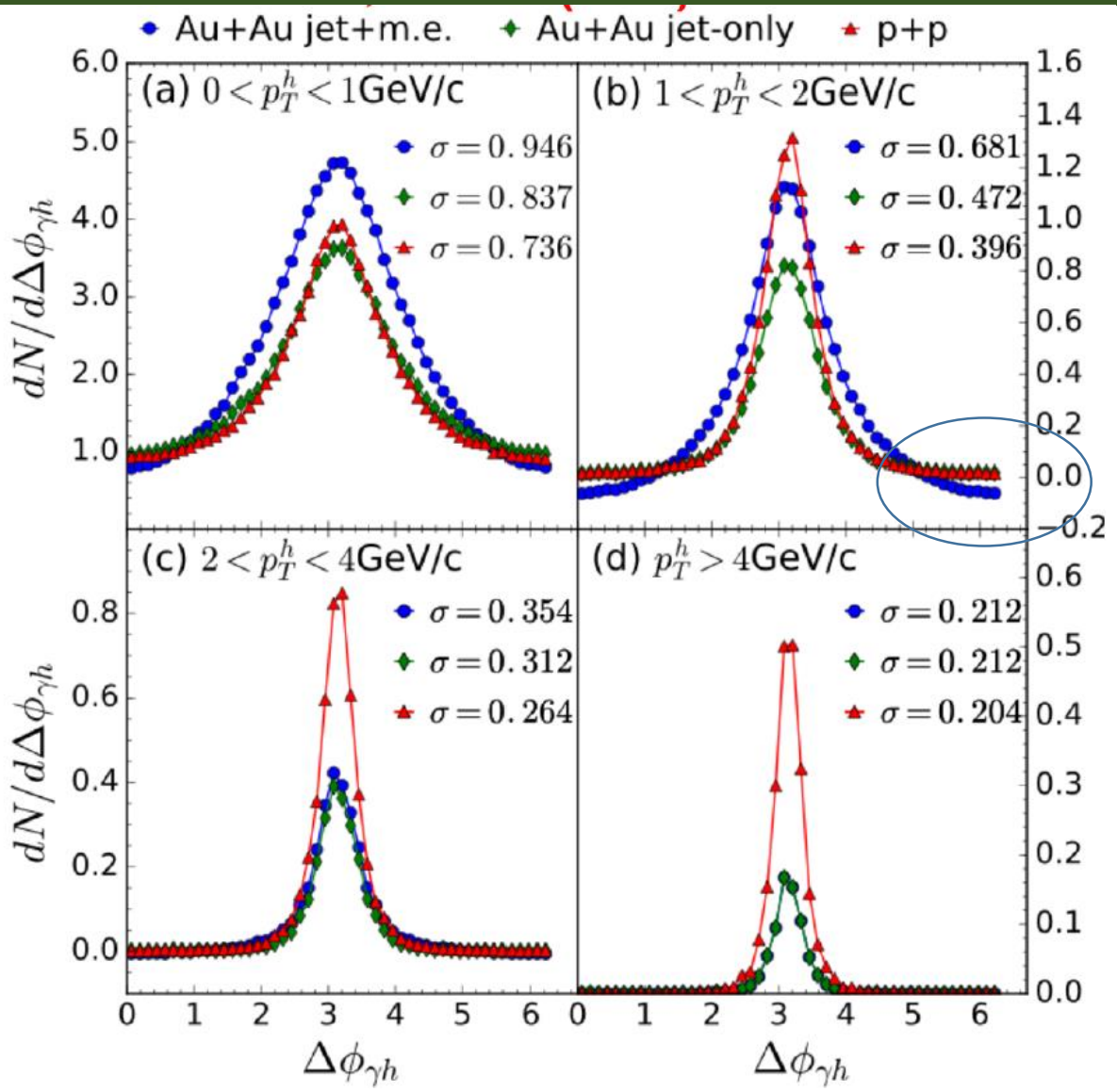


Example 2: Medium Response

Tan Luo, Xin-Nian Wang







Measure the **near-side associated yield** with photon-jet and Z-jet

Ex: Z-hadron correlation, "Z fragmentation function"

3. Complementarity between RHIC & LHC

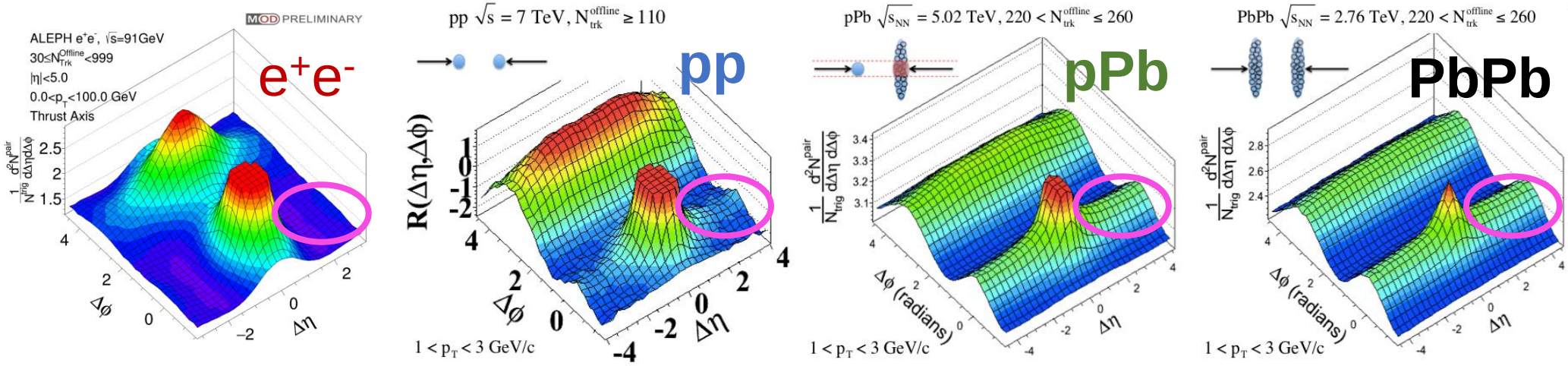
Change the initial temperature by 100-200 MeV

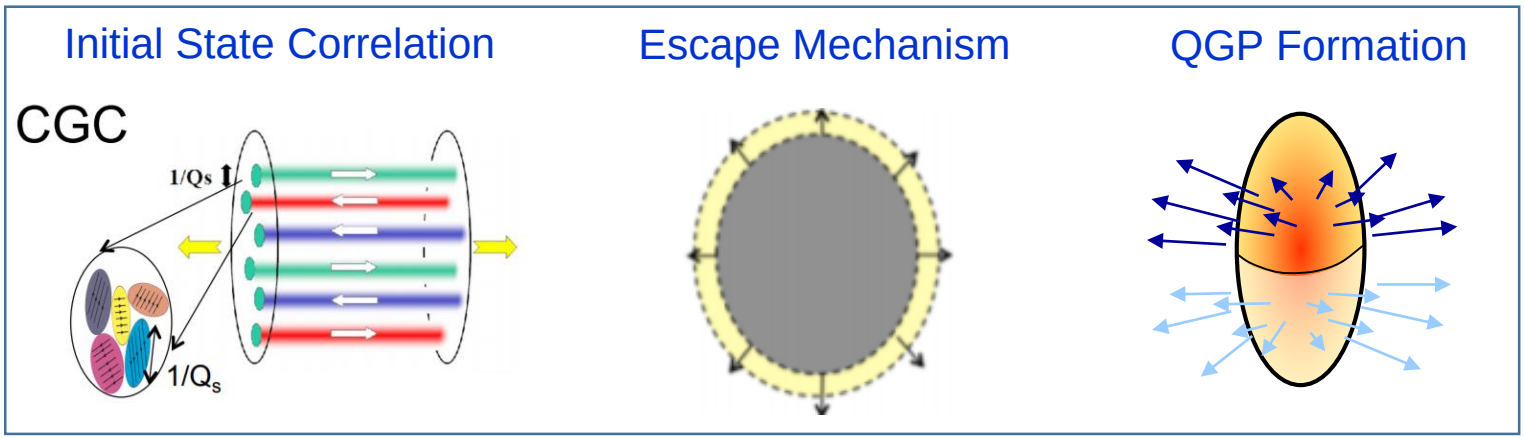
- Exciting opportunity to extract properties of QGP vs. Temperature
- Could simultaneously vary the QGP geometry by centrality selection

Complications (or opportunity):

- **Spectra slope**: Steeper jet p_T Spectra at RHIC (larger sensitivity to quenching)
- Smaller **initial state radiation** at RHIC at LHC (larger sensitivity at RHIC to dijet / photon-jet azimuthal decorrelation)
- Sampling different part of **nPDF:** led to different quark/gluon composition (RHIC has more quark jets) and purity of photons (RHIC isolated photon has less fragmentation contamination)
- **Larger nuclei passing time** at RHIC than LHC: possible complications from cold nuclear effects at RHIC
- **Au+Au vs. Pb+Pb** (seriously, what's the point?)

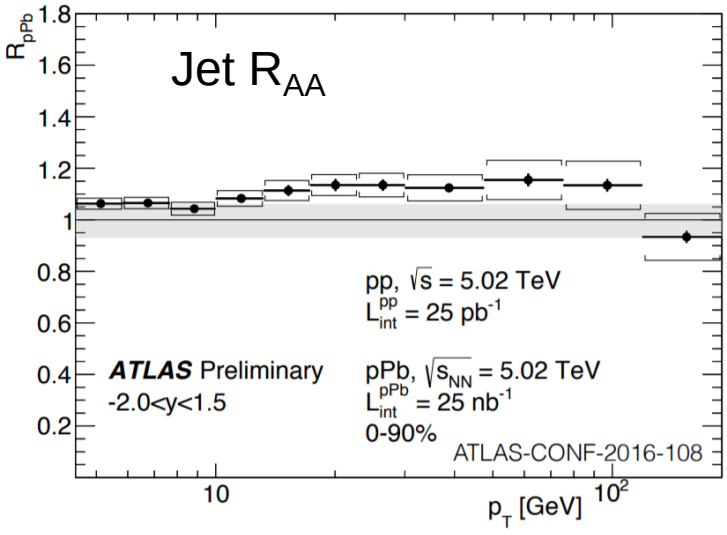
Jet Quenching in Small System

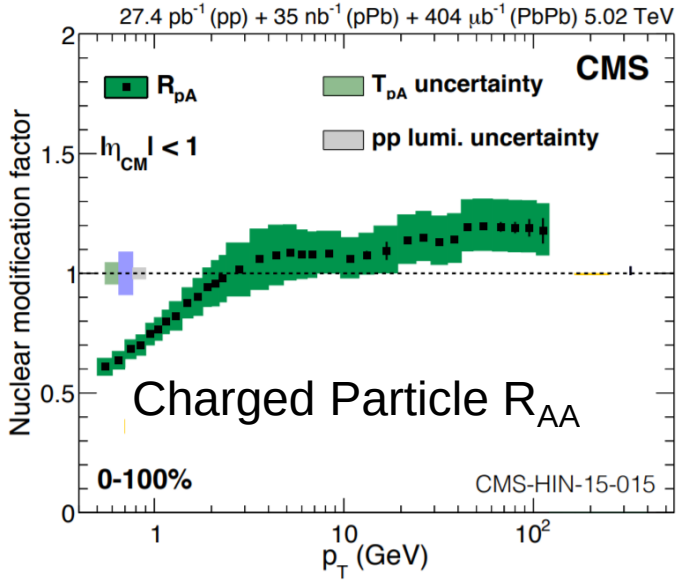


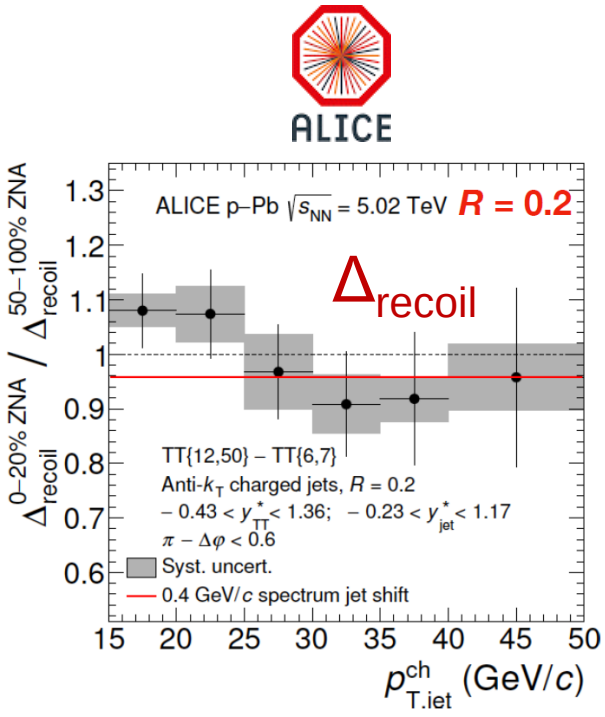


- Collective behavior is observed in small systems down to pp
- Not observed (yet) in high multiplicity e^+e^-
- Have we detected jet quenching in small system?

Jet Quenching in Small System

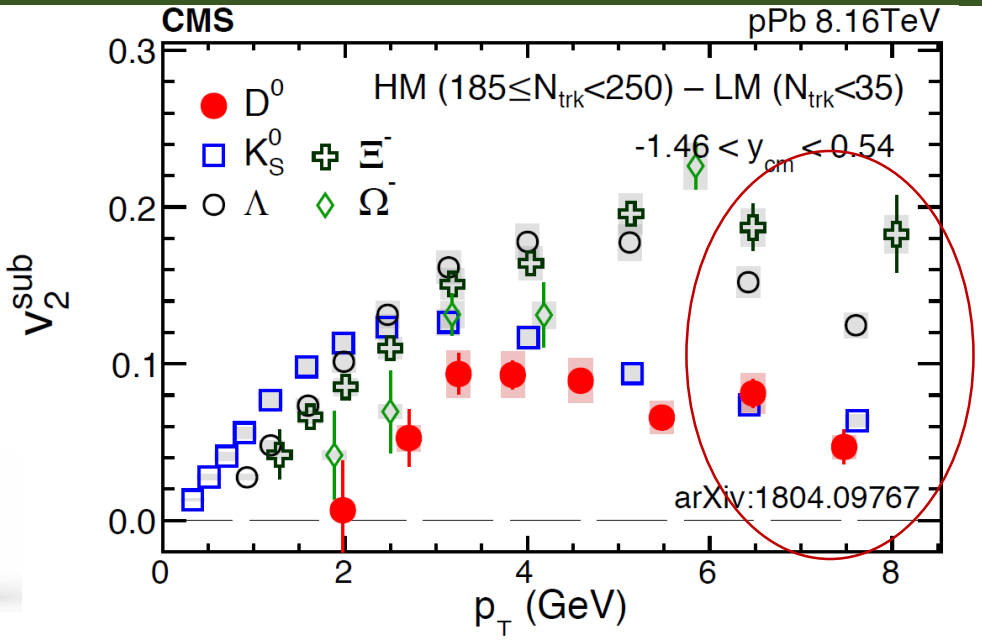


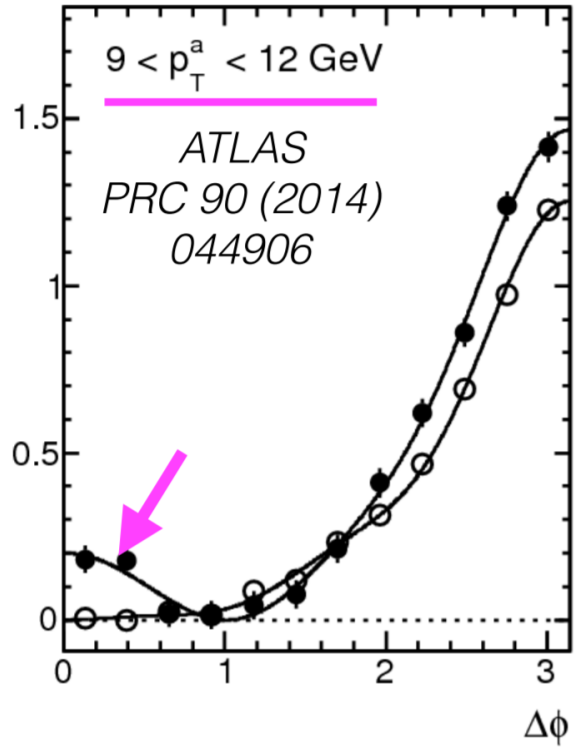




- No suppression observed in pPb collisions from those observables
- Also centrality / activity dependent results:
  Charged Particle Q_{pPb} from ALICE, R_{dAu} in PHOBOS and CMS dijet:
  need higher accuracy and better event classification

Jet Quenching in Small System





Sizable v_2 at high p_T in identified hadrons!

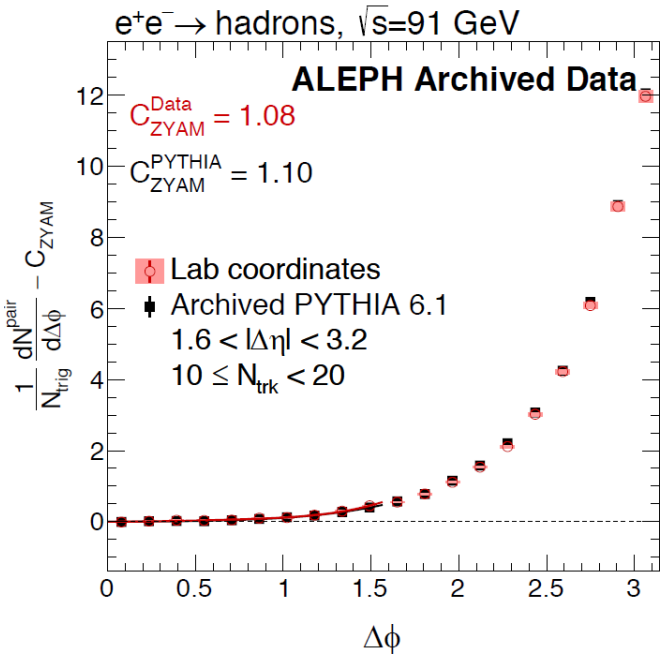
- Effect of residual non-flow? Selection bias?
- Indication that CGC and/or Escape Mechanism effects in pPb?

Crucial elements:

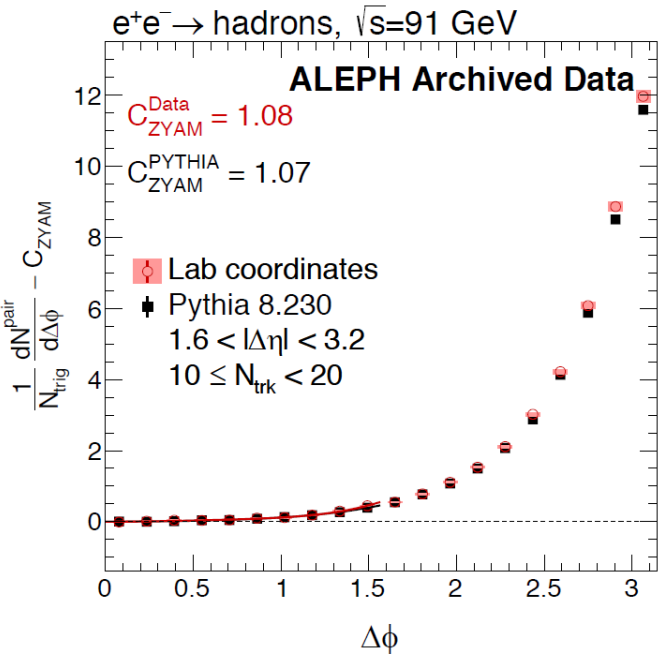
- Exp: How can we do better in centrality classification?
- Theory: what do we expect? How big is the modification in R_{AA} , photon-jet asymmetry and jet substructure in 0.001% pPb collisions?
- What is a good reference?
  Ex: ref from event generators which are tuned to describe e^+e^- well

Archived ALEPH e^+e^- Data

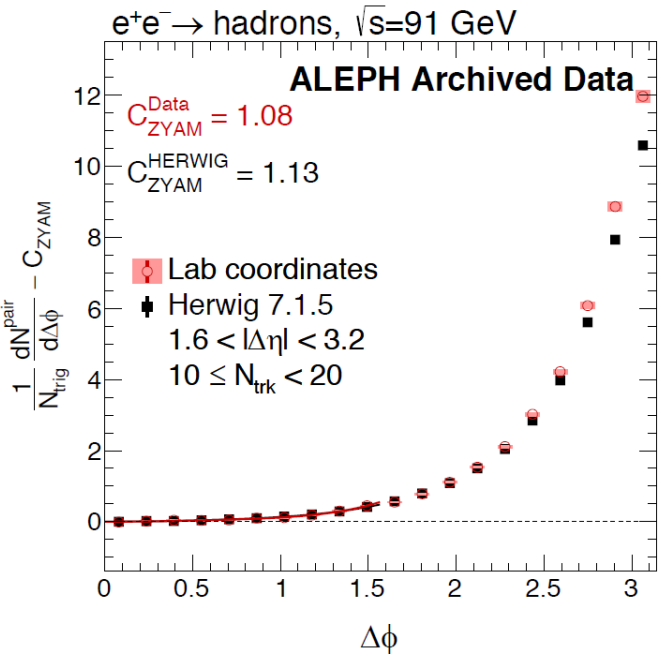
$10 \leq N_{trk} < 20$ Good agreement between **data** and **generators**



Pythia 6



Pythia 8



Herwig 7

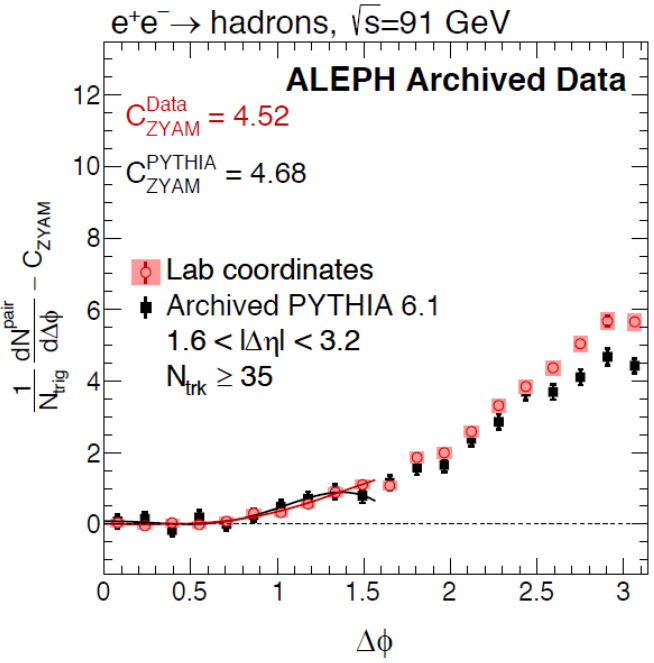
- In addition, e^+e^- data are the best testing ground for the new jet substructure observables proposed in the jet tool workshop

- Could serve as a validation of the theoretical approach in vacuum and a reference to pp, pA and AA collisions

Archived ALEPH e^+e^- Data

$N_{trk} \geq 35$

Bad description from Herwig 7



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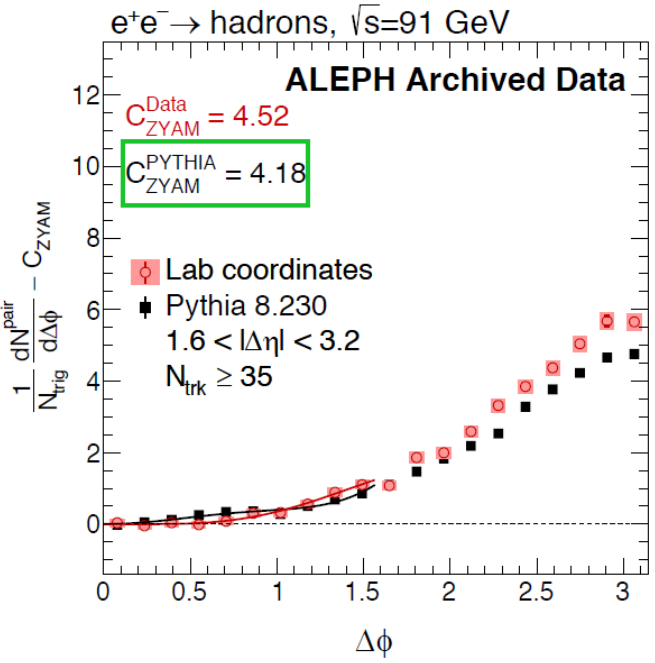

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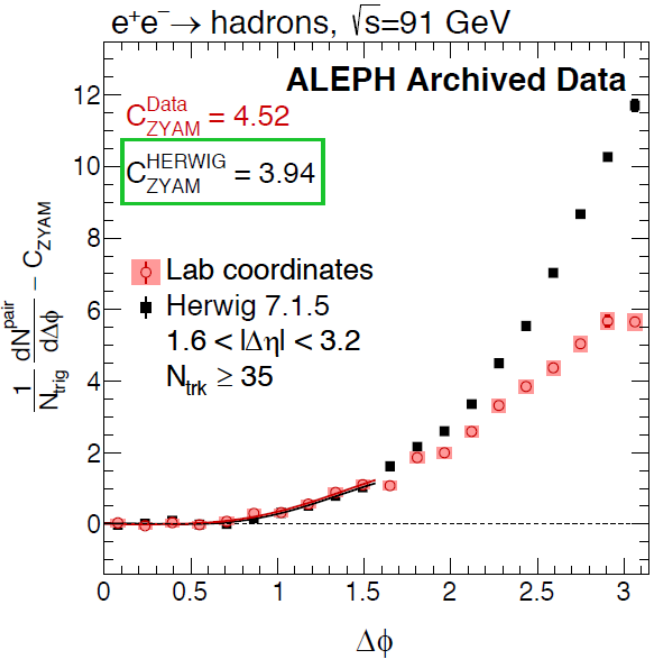

Herwig 7

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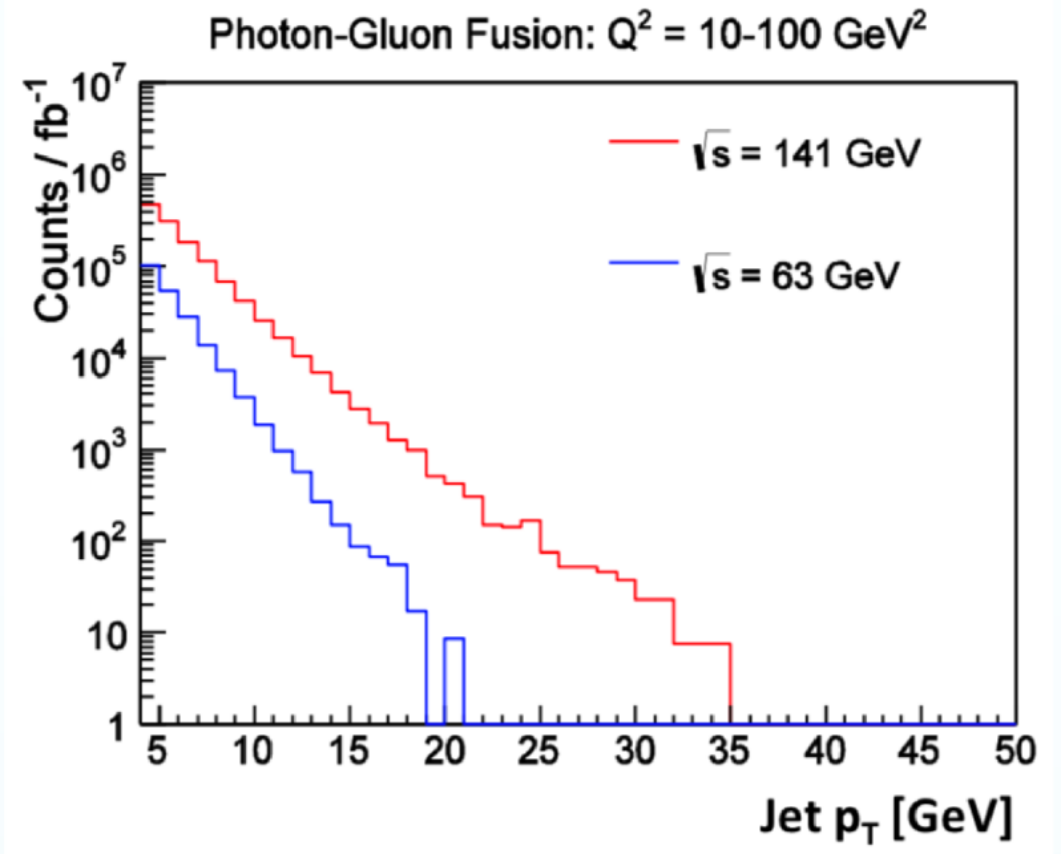
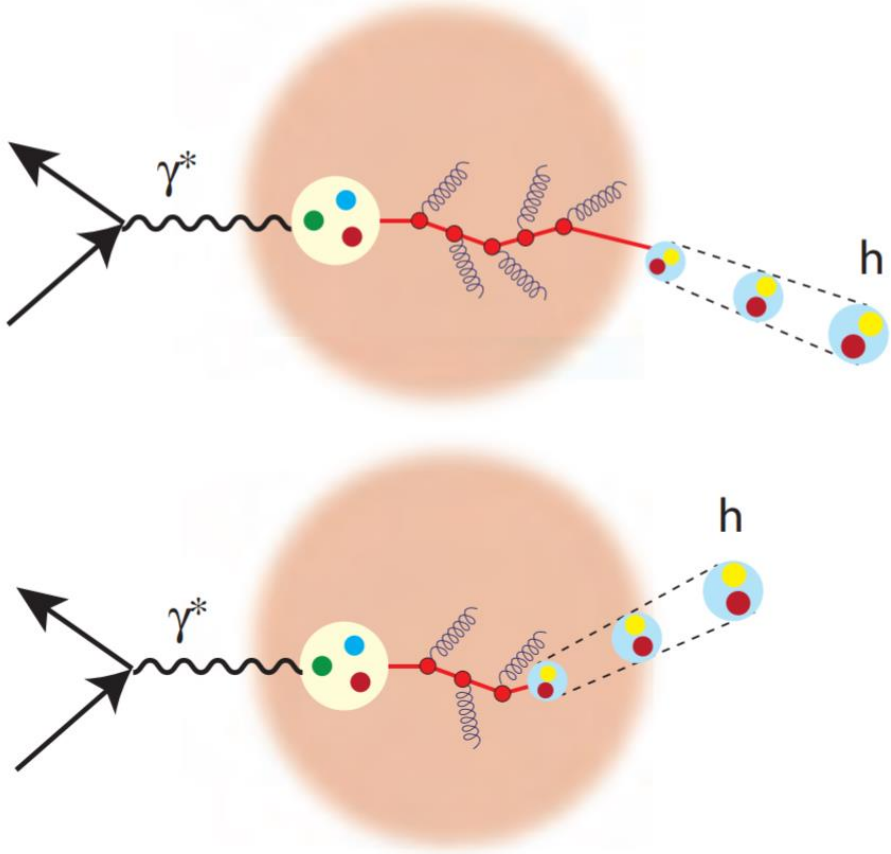
Connection to Electron Ion Collider



Hadronization effect due to the presence of cold nuclear matter



- Full extraction of parton distribution functions and the origin of spin
- Eloss in cold nuclear matter: **O(10)** smaller effect than hot QCD
- Very clean environment in e+A
  Probably hadronization is the main non-perturbative effect
- Difficulty: relatively lower jet p_T reach

Summary

- Jet tool workshop:
  - Show that jet substructure observable could be sensitive to QGP properties
  - Agree on how to do a complete survey on jet spectra and jet substructure measurements
  - Design “smoking gun” observables which are sensitive to a dominant mechanism
  - Show how to utilize the RHIC and LHC data to extract QGP properties vs. Temperature

- Efforts on archived e^+e^- data:
  - Validation of the event generators vs. event multiplicity
  - A testing ground for new ideas from the jet tools workshop
  - Potentially a new reference to the hadron-hadron collisions

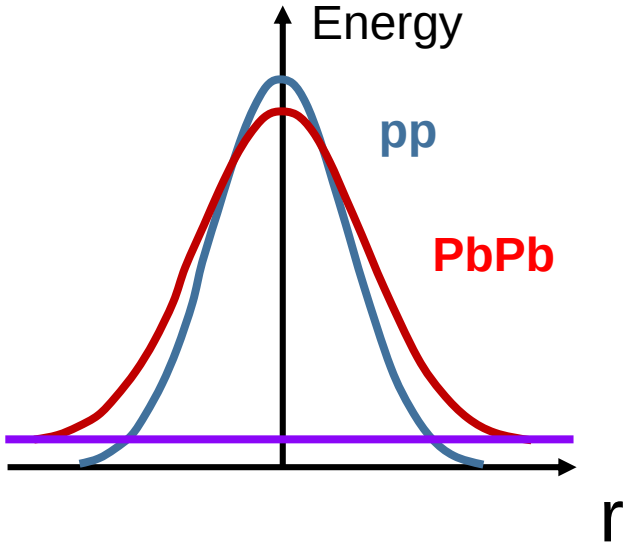
- Connection to EIC:
  - Hot QCD experience could help for the extraction of cold QCD matter properties
  - Understanding of cold QCD could help refine the interpretation of hot QCD results

- Backup slides

Jet Longitudinal Structure

Jet shape

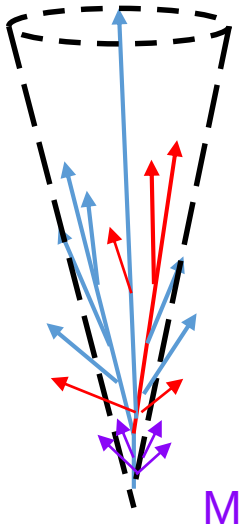
"the jet energy distribution" vs. r



$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0 < r < r_f} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$

Jet Fragmentation function

how transverse momentum is distributed inside the jet cone



Jet Quenching

Medium Response

$$\xi^{\text{jet}} = \ln \frac{|\mathbf{p}^{\text{jet}}|^2}{\mathbf{p}^{\text{trk}} \cdot \mathbf{p}^{\text{jet}}}$$