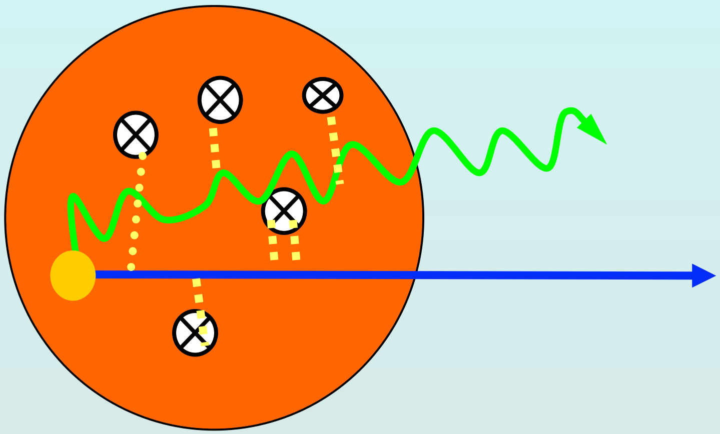
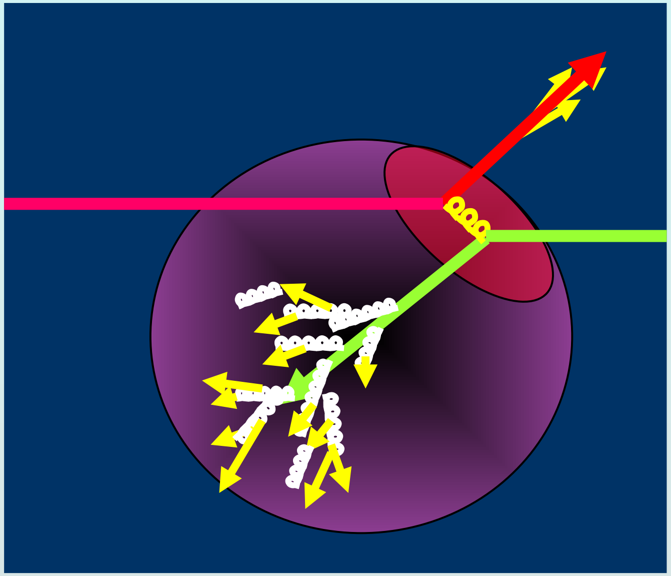
# Lecture 2
# Thermalization, Energy Loss and Heavy Quarks in Quark Gluon Plasma

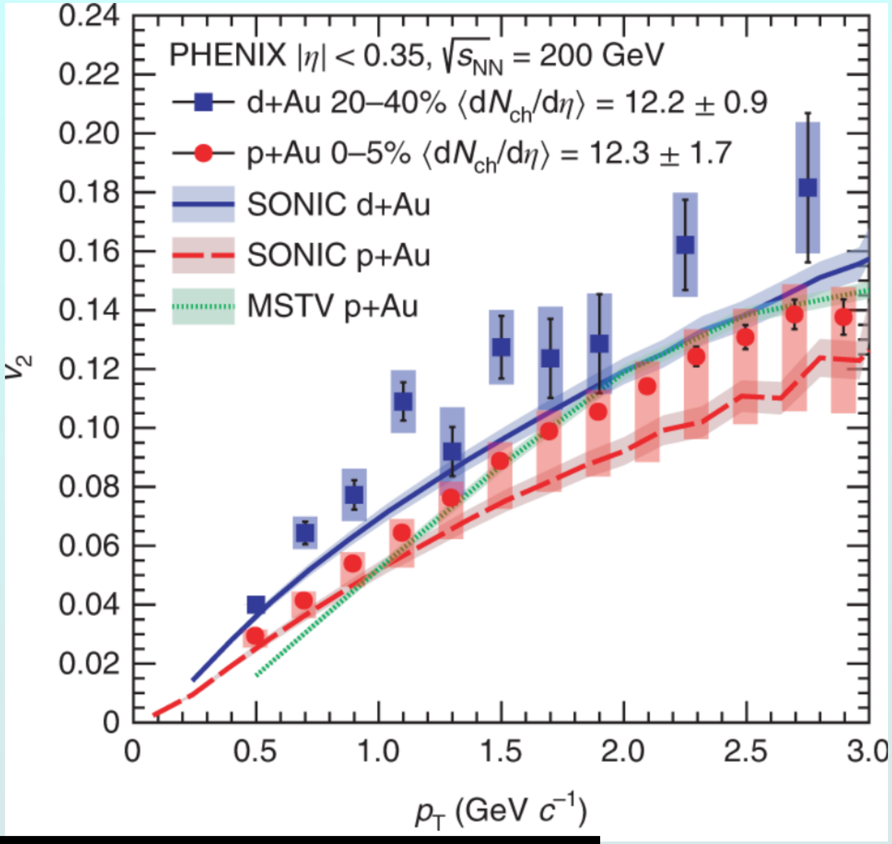




*Barbara Jacak*
*UC Berkeley & LBNL*
*June 12, 2023*

# Eeek! Hydrodynamics in small systems!

*PHENIX Collaboration*
*Nature Physics (2018)*

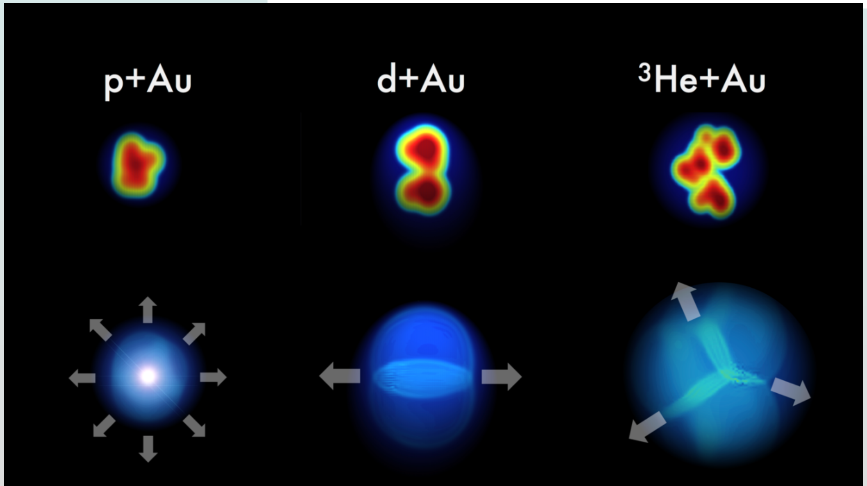



***Not big & dense***

***But, we see collective flow!***

***Seeded by the initial geometry***

***A small droplet of QGP?!***



# Mechanism for fast thermalization?

- Must be thermalized in < 1 fm/c!

  Otherwise (viscous) hydro $v_2$ smaller than in data

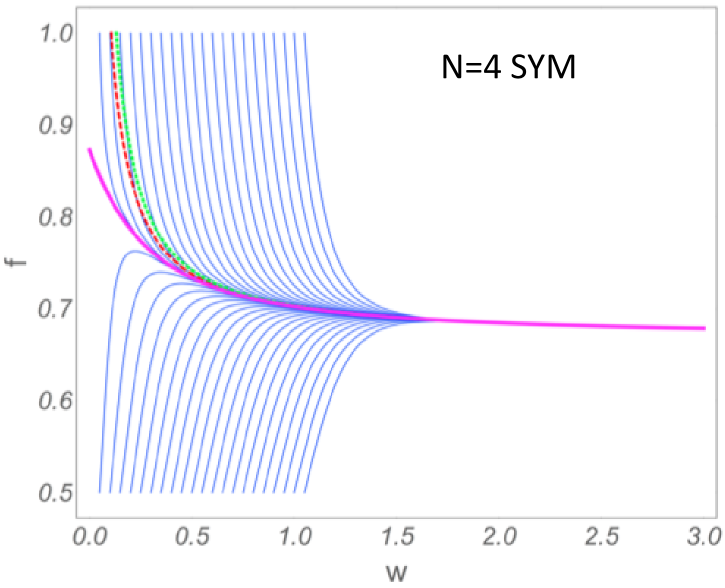
- Can this be achieved with gg, qg, and qq binary scatterings?

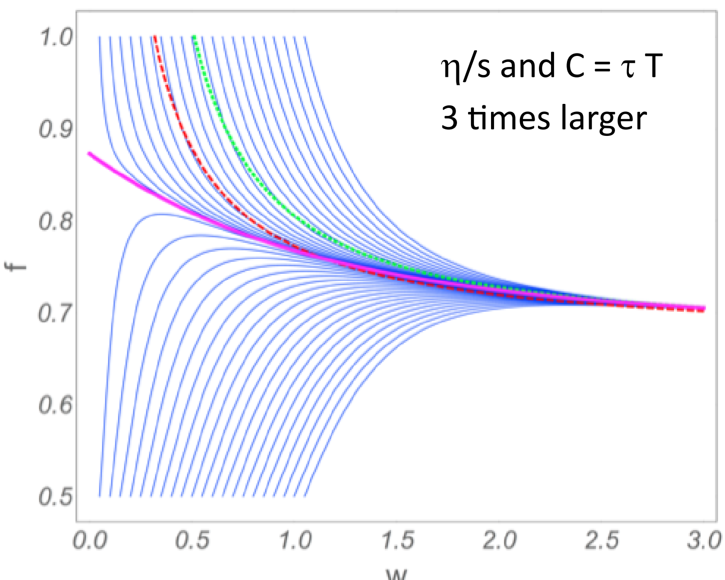
  NO!

  Making this picture yield sufficient $v_2$, requires boosting the pQCD gg, qg,qq cross sections by a factor of ~50!

- Many-body interactions can do just that!
- But, can hydro set in before thermal equilibrium?

# Hydrodynamic attractor




arXiv:1503.07514

*Numerical solutions of viscous hydro*

*For conformal fluid*

***Lines = various initial conditions***

***Red & green = 1st and 2nd order hydrodynamics***

***Can consider hydro as a systematic gradient expansion in powers of w***

***$\tau$ = relaxation time***

***T = temperature***

***w = T x time***

***Since non-hydro modes decay exponentially, system relaxes to an attractor***

***Driven by fast longitudinal expansion & competition of free streaming vs. dissipation***

***Attractor is present for larger $\eta/s$, but it takes longer for system to reach it***

# Impact of hydrodynamic attractor

- Hydro works even before there is time for equipartition of the momenta of quarks and gluons
  - The requirement of equilibration for hydrodynamics is relaxed in rapidly expanding systems!
  - Mathematical feature appears to be there also in real life

- Can explain hydrodynamic behavior of very small systems
  - *Could still make a hot spot and QGP droplet*

- Now use hydro to describe the plasma expansion dynamics and add probes & their interactions to make a complete model of the collision

# Part 2: Energy loss & fate of heavy quarks

*quarks and gluons are called "partons"*

*hadrons are quark-containing particles that we detect*

*leptons, such as electrons, do not feel the strong interaction*

- **Partonic probes of quark gluon plasma**
  **Measure high momentum hadrons + hadron jets**
- **Opacity of the plasma to gluons and light quarks**
- **Energy loss in pQCD**
- **Heavy quarks as probes, and their fate in QGP**

# From last lecture

Viscosity: inability to transport momentum & sustain a wave

low viscosity → absorbs particles & transports disturbances

Viscosity/entropy near 1/4π limit from quantum mechanics!

∴ liquid at RHIC is "perfect"

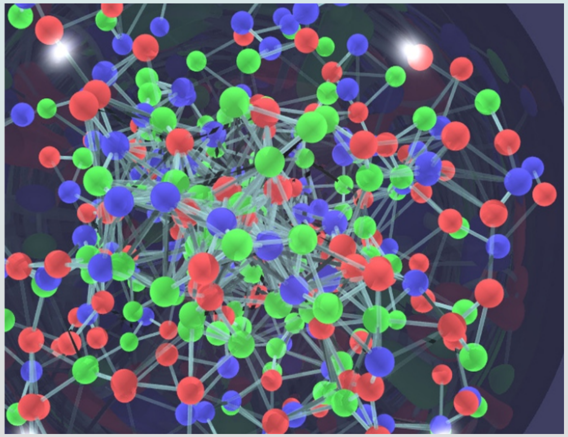
Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Good momentum transport: neighboring fluid elements "talk" to each other

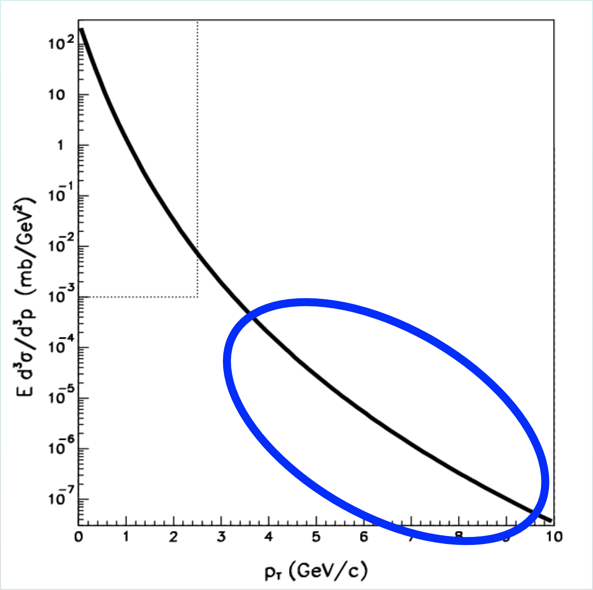
→ QGP is strongly coupled

Should affect opacity :

e.g. q,g collide with "clumps" of gluons, not individuals

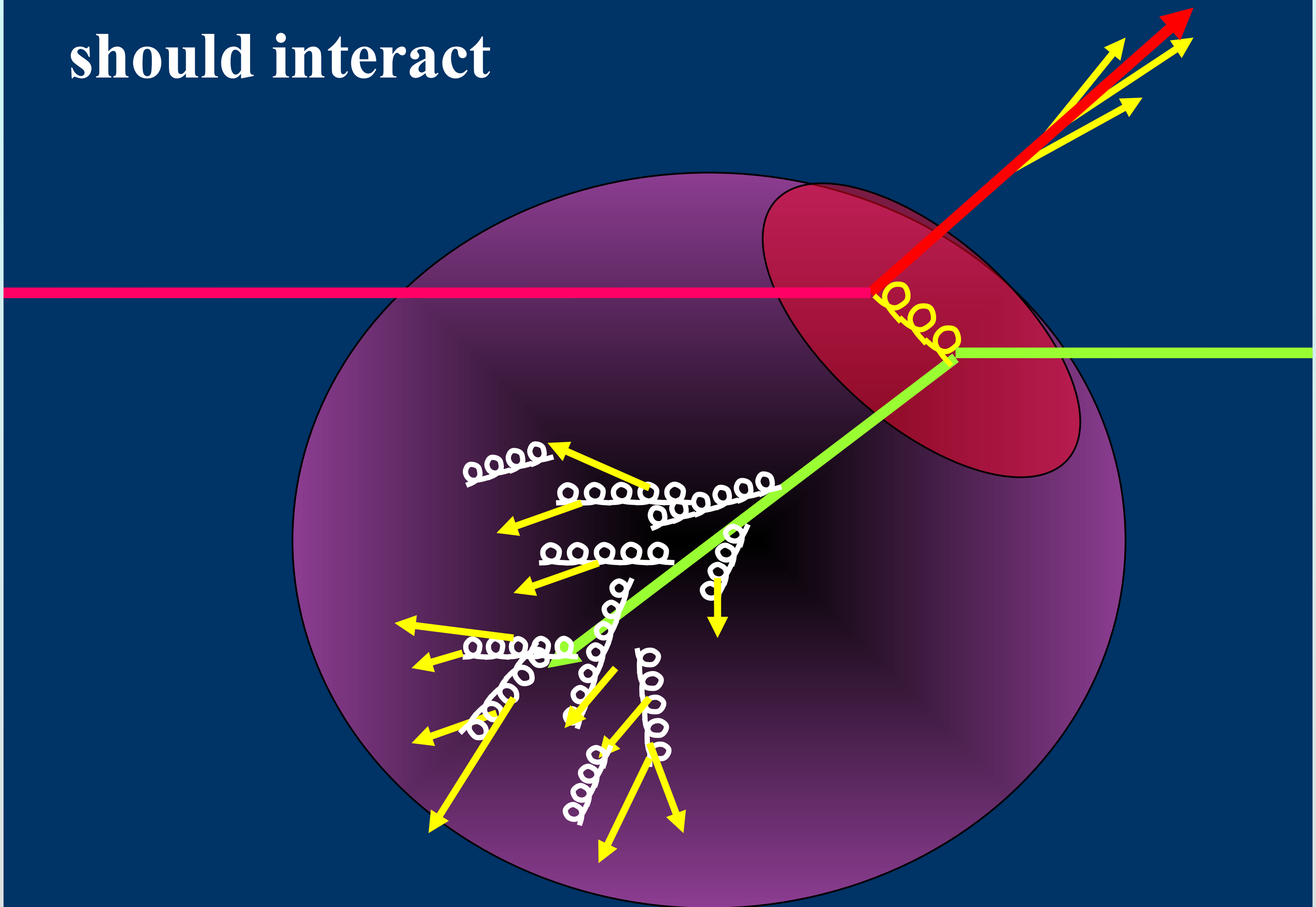


# How does the QCD plasma transport energy?



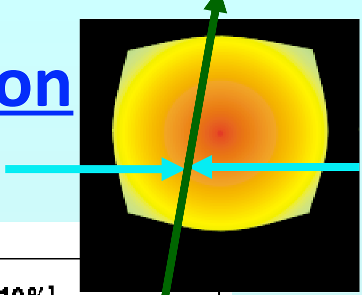
# Do fast quarks & gluons escape the plasma?

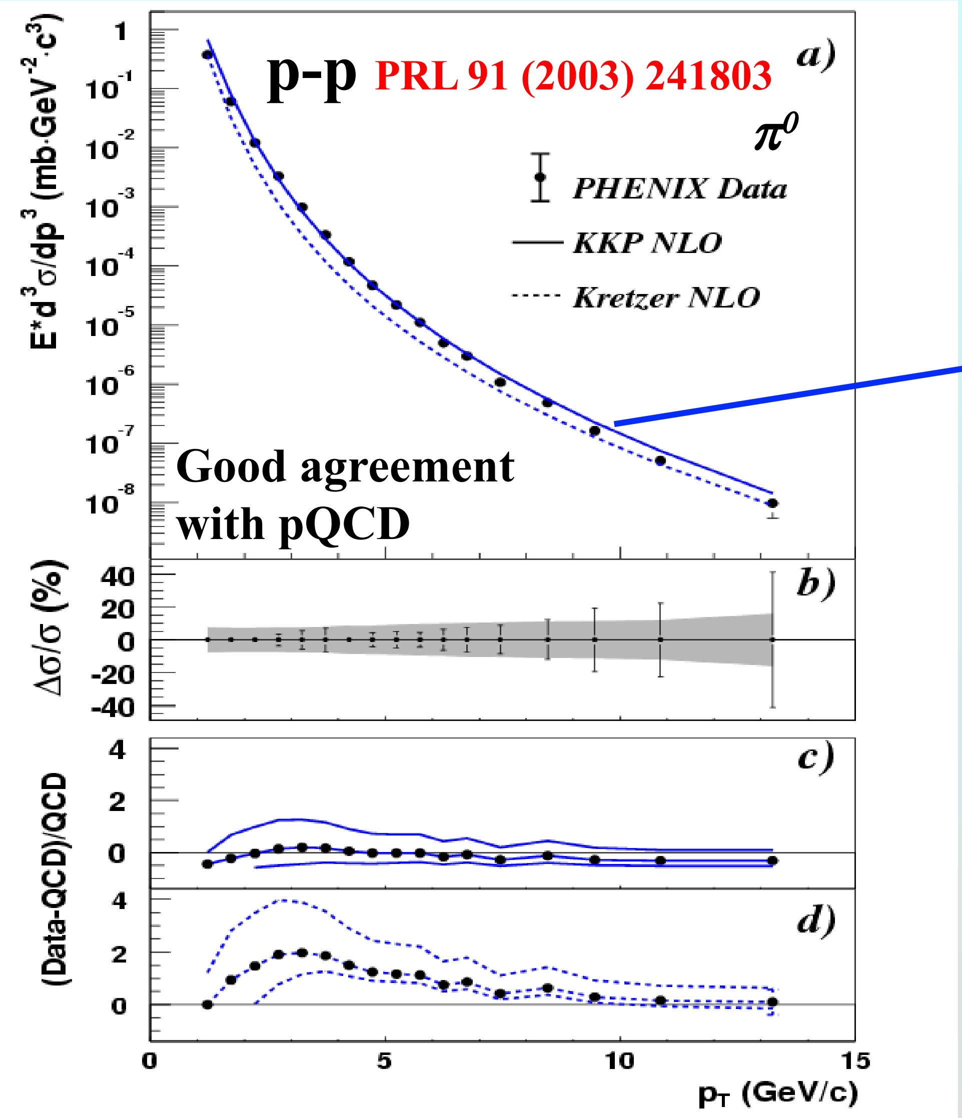
**They feel the strong interaction, so they should interact**

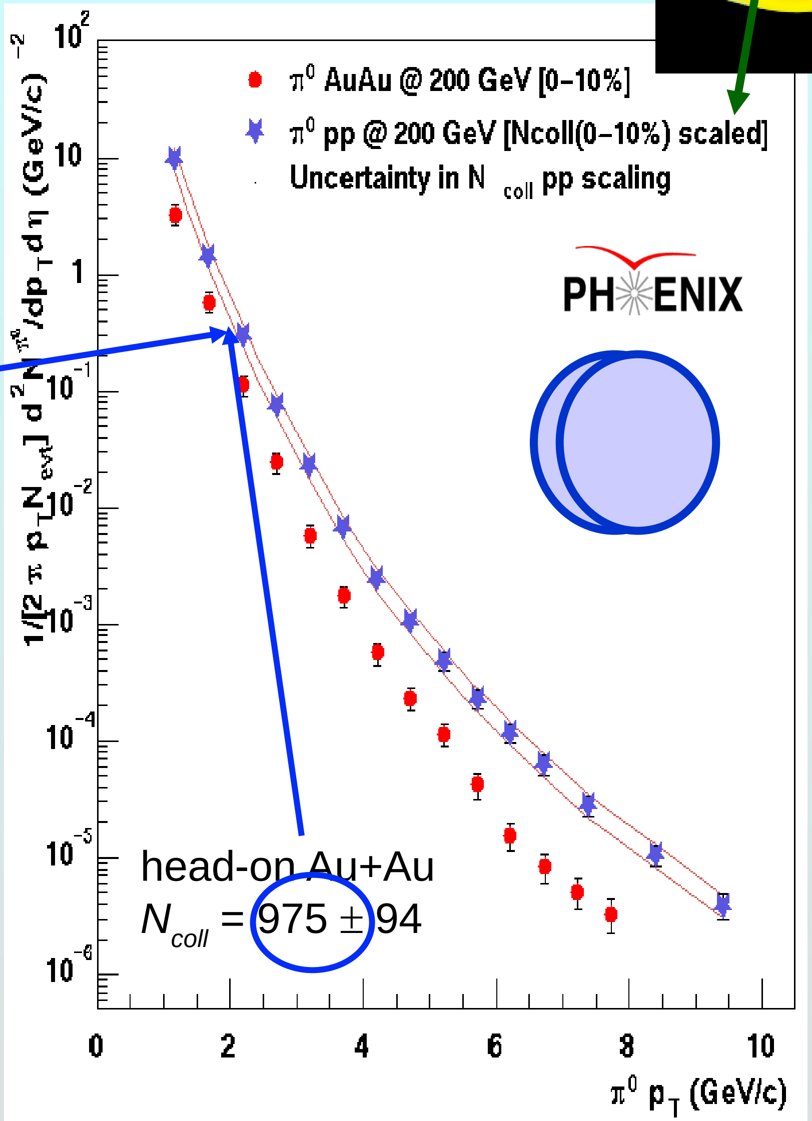


# Energy loss in plasma

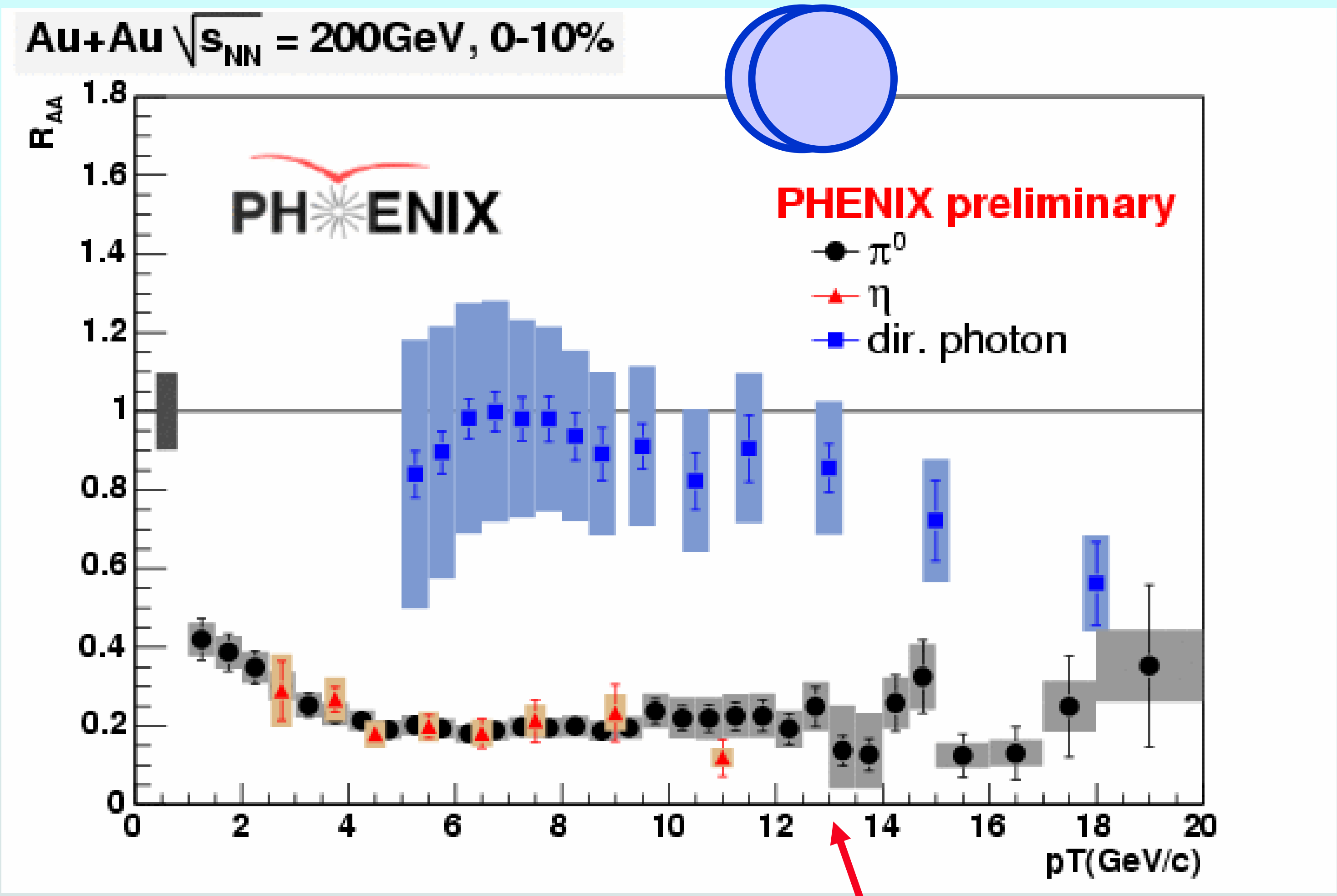
# Opacity? Probe must feel strong interaction





# colored objects lose energy, photons don't

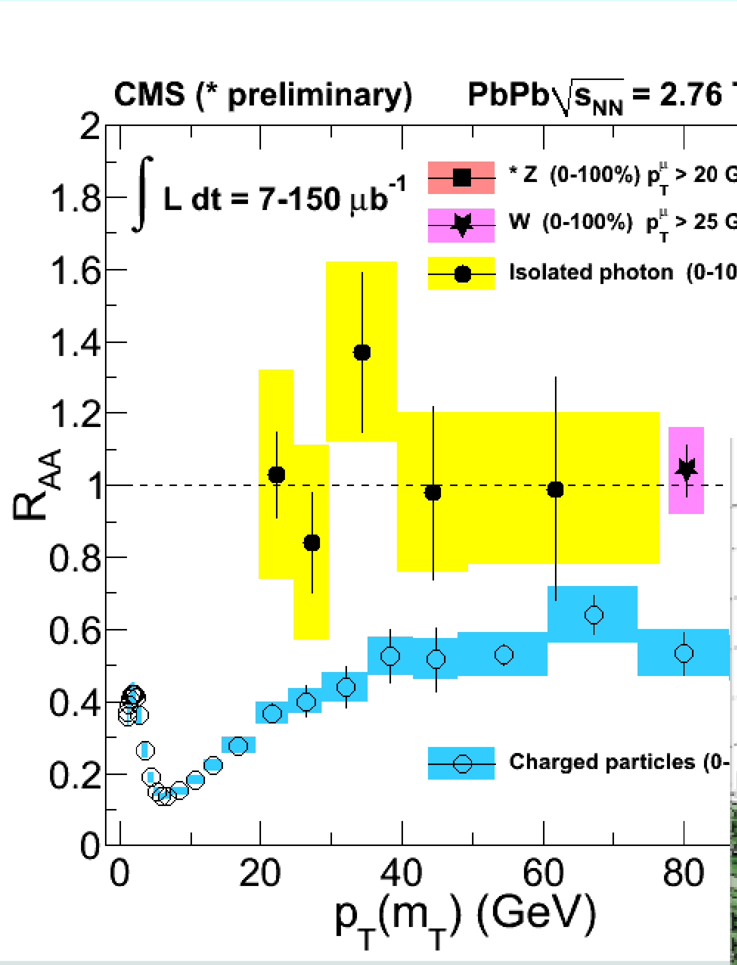


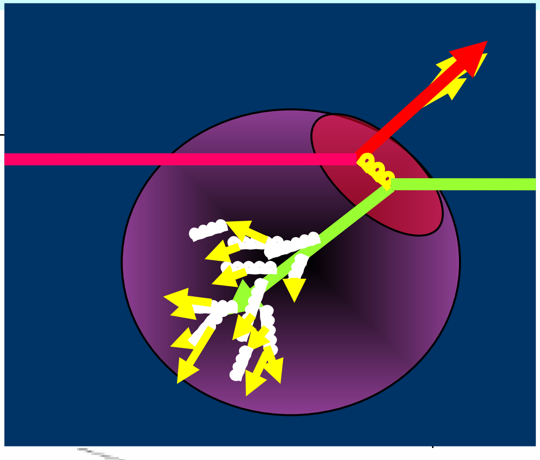

*Nuclear modification factor:*

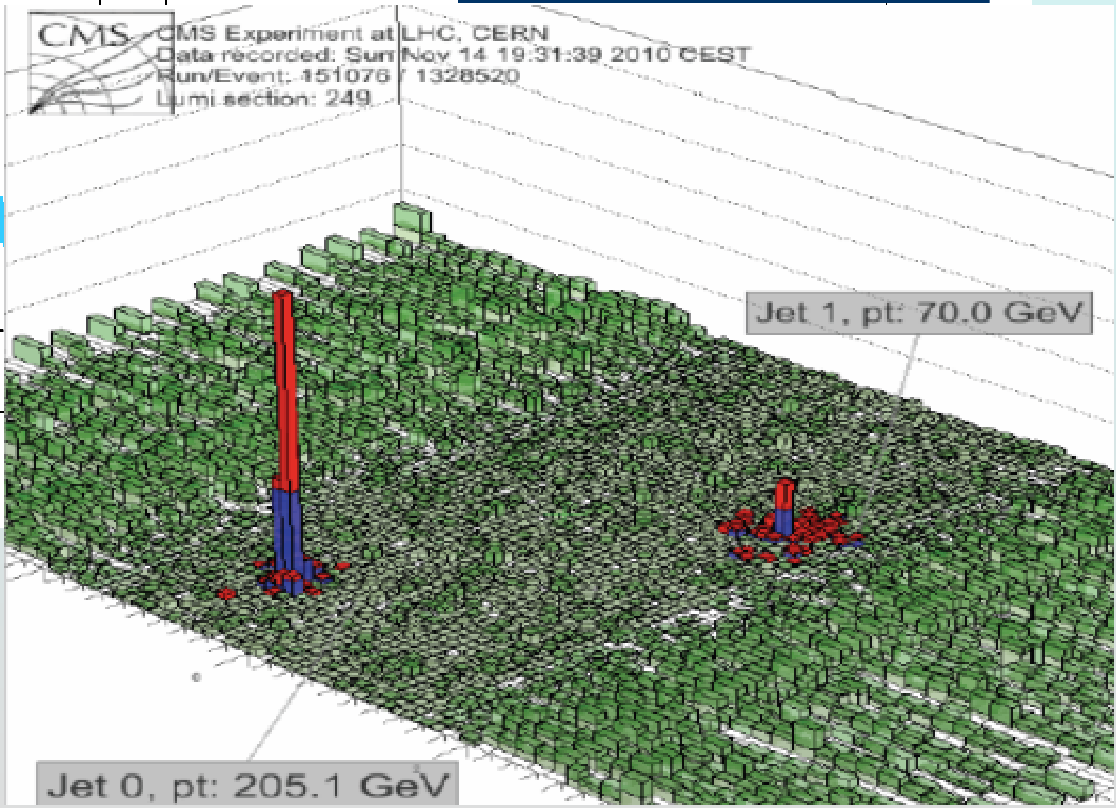
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

*VERY opaque! Gluon radiation (bremsstrahlung) induced*

# Energy loss even by very energetic q & g

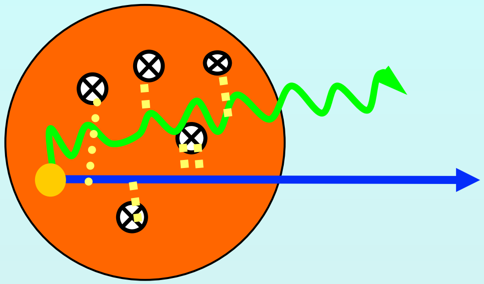


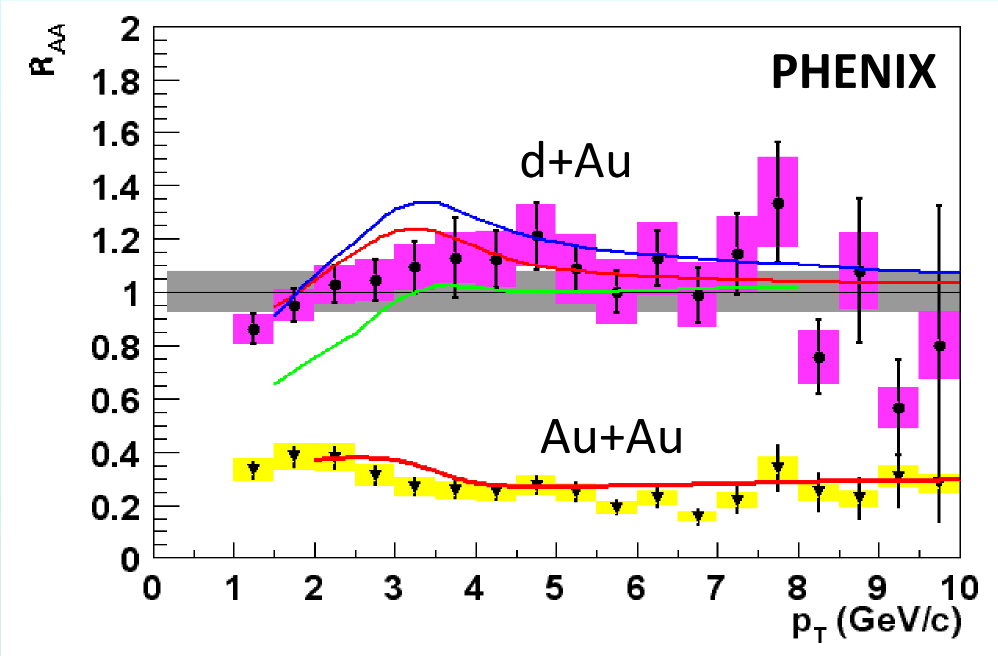



- LHC experiments reac

# Suppression seen in Au+Au but not d+Au



interaction of radiated gluons with gluons in the plasma greatly enhances the amount of radiation




Calculations: I. Vitev

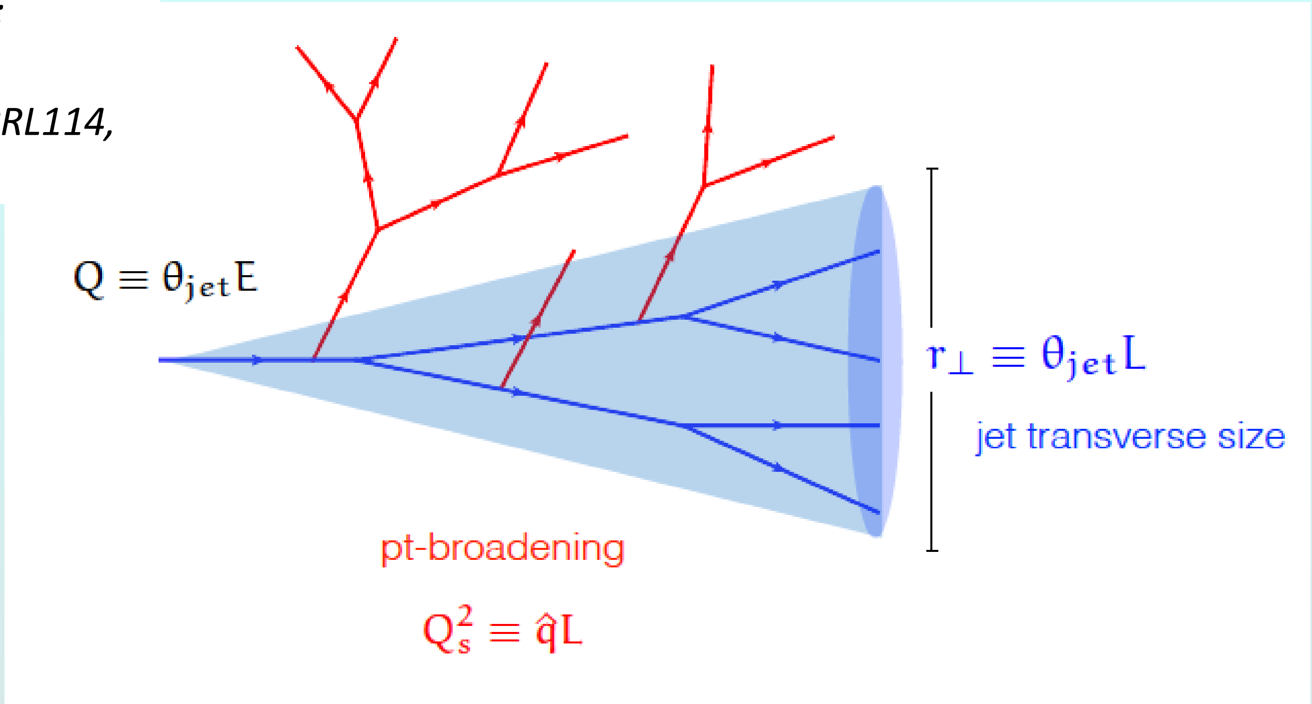
Radiation is coherent, rather than incoherent

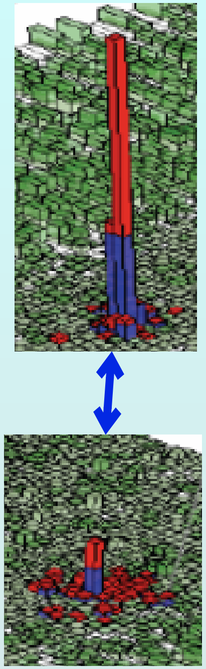
**Large energy loss should be absent if no large volume of plasma**

# Connect observations to QCD

*Y. Mehtar-Tani: 1602.01047*

*Blaizot, et al, PRL114, 222002 (2015)*



***Can't see a single quark or gluon in the detector***

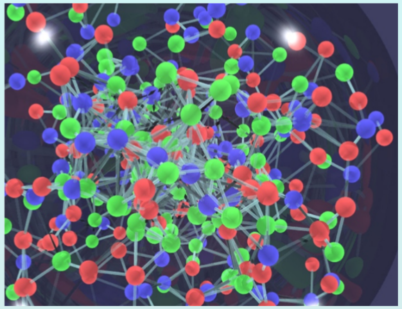
***Partons radiate gluons, which collect into final state hadrons (which we call "fragmentation")***

***The hadrons are co-moving and boosted by quark's momentum***

***We detect them as jets of hadrons***

# The medium density matters

- **In dilute medium:**
  - Independent processes: bremsstrahlung & scattering
  - Calculate probabilities and add them up
  - Independent radiations follow Bethe-Heitler



- **In dense medium:**
  - Mean free path is short: $\lambda = \sigma/\rho$
  - Formation time of radiated gluon: $\tau = \omega/k_T^2$
  - Transverse momentum of radiated gluon: $k_T^2 = n\mu^2$
    - # of collisions $n=L/\lambda$, $\mu$=typical $p_T$ transfer in 1 scattering
    - $\lambda,\mu$ are properties of the medium, combine to $\hat{q} = \sqrt{\mu^2/\lambda}$
- **Coherence in the dense medium!**
  - Next scattering takes place faster than gluon formation
  - Add amplitudes for all multiple scatterings
  - In QCD this increases the energy loss!

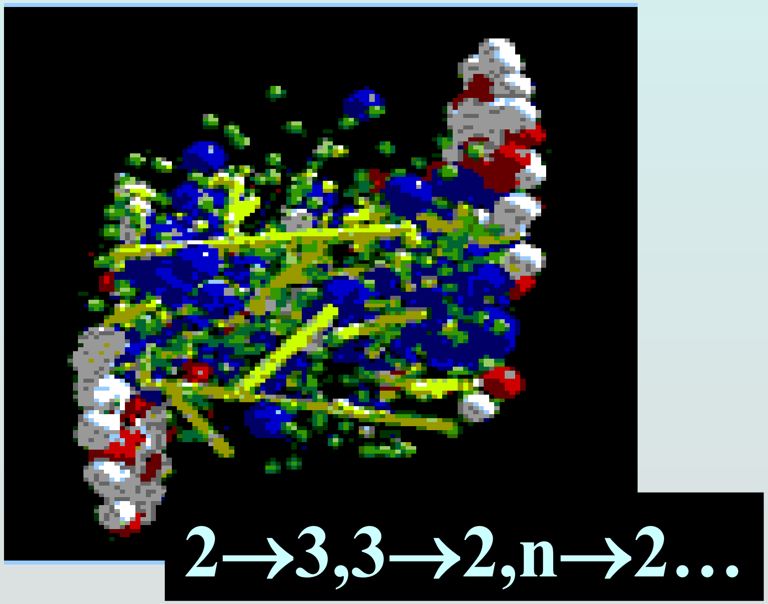
# Calculating transport in QGP

**weak coupling limit**

*perturbative QCD*

*kinetic theory, cascades*

*interaction of particles*



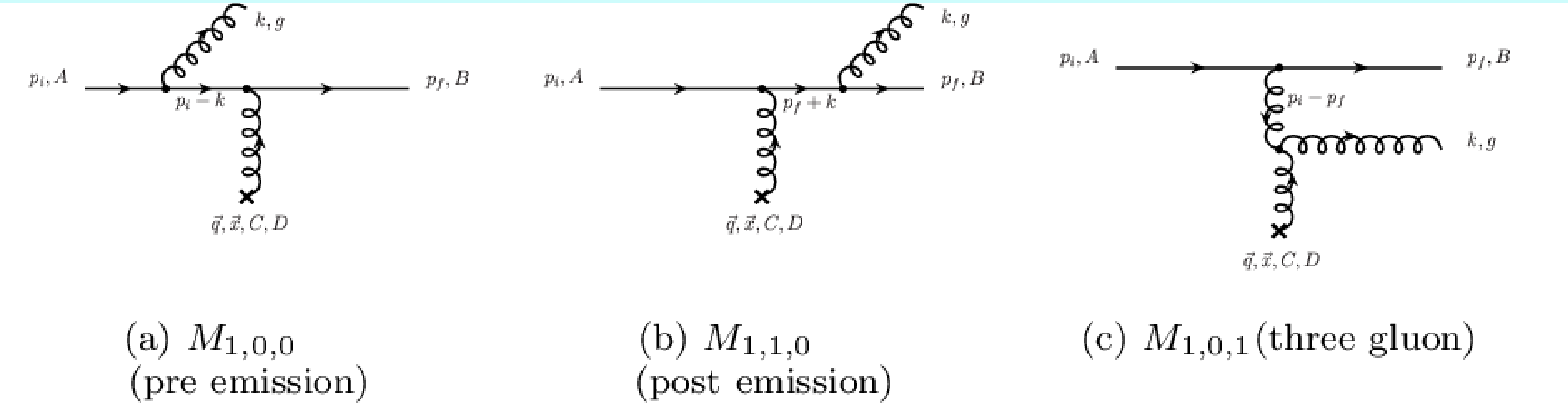

**∞ strong coupling limit**

*not easy! Try a pure field…*

*gravity ↔ supersym 4-d*

*(AdS/CFT)*

# pQCD: Color interactions with plasma



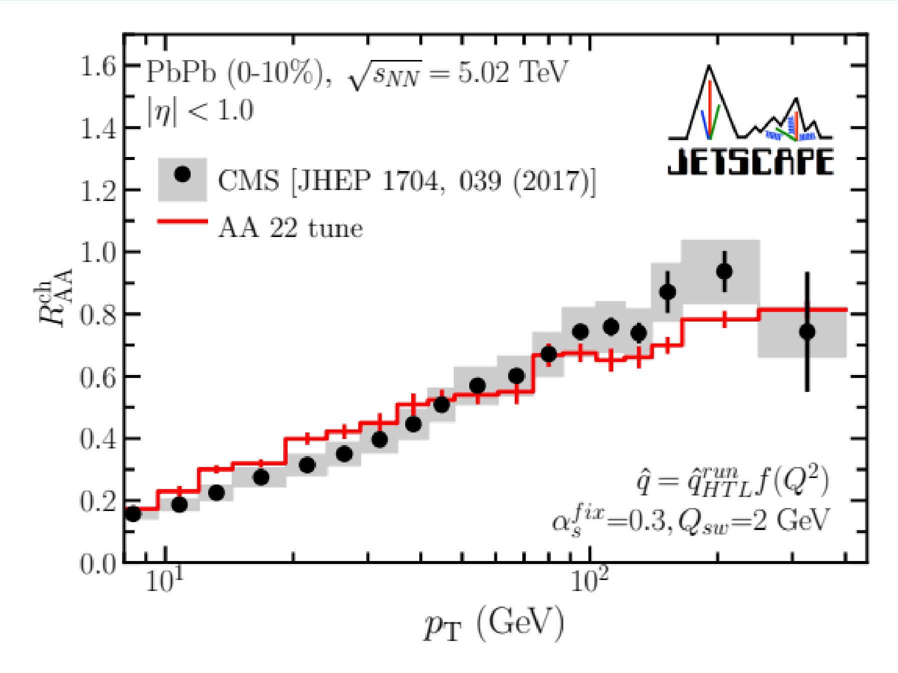

- pQCD to several orders (emit increasing numbers of gluons)
  - Opacity expansion (avoid calculating each possible emission)
  - Higher twist approximation
  - Hard thermal loops & resummation, etc.
- Goal: learn transport properties (qhat) from the data
- Recall: Transverse momentum of radiated gluon: $k_T^2 = n\mu^2$

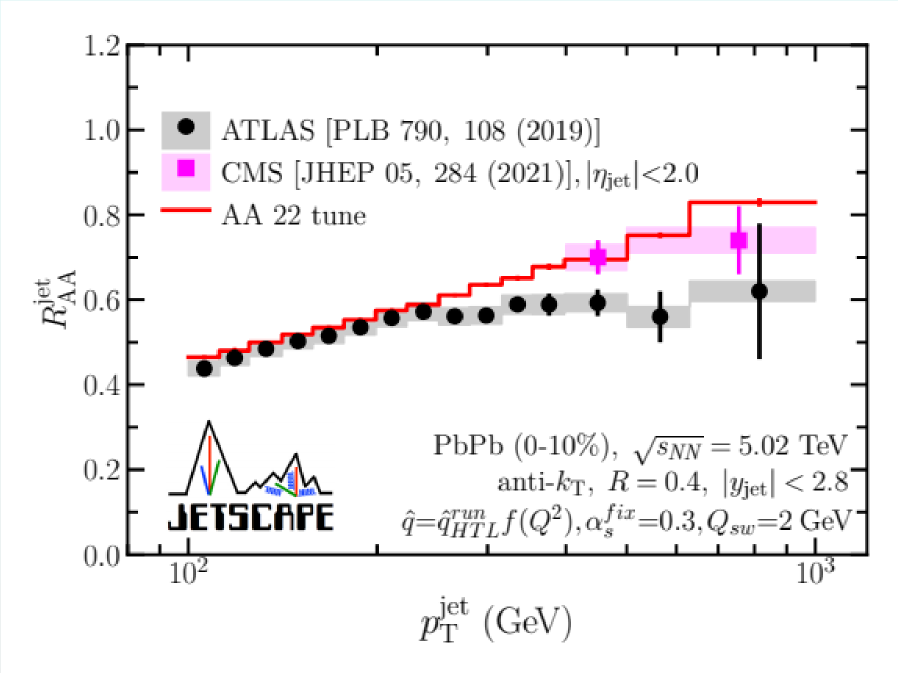
  # of collisions $n = L/\lambda$, $\mu$=typical $p_T$ transfer in 1 scattering

  qhat= $\sqrt{\mu^2/\lambda}$

# How to quantify q-hat?

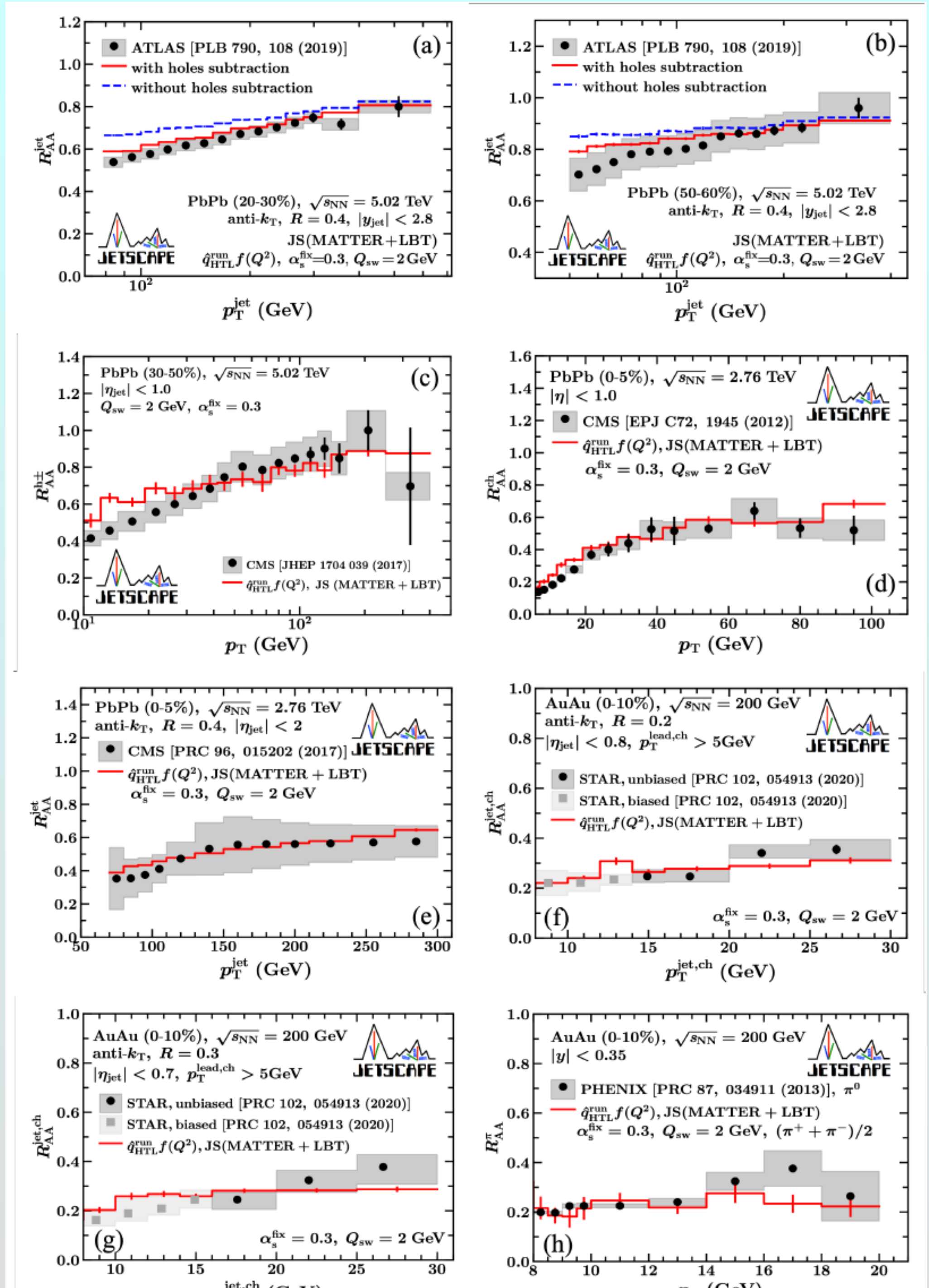
- Measure $R_{AA}$ for high $p_T$ hadrons & jets
- Begin with realistic initial conditions (with fluctuations)
- Model collision & expansion dynamics with hydro*
- Add energy loss mechanism(s)
- Constrain combined model with data *



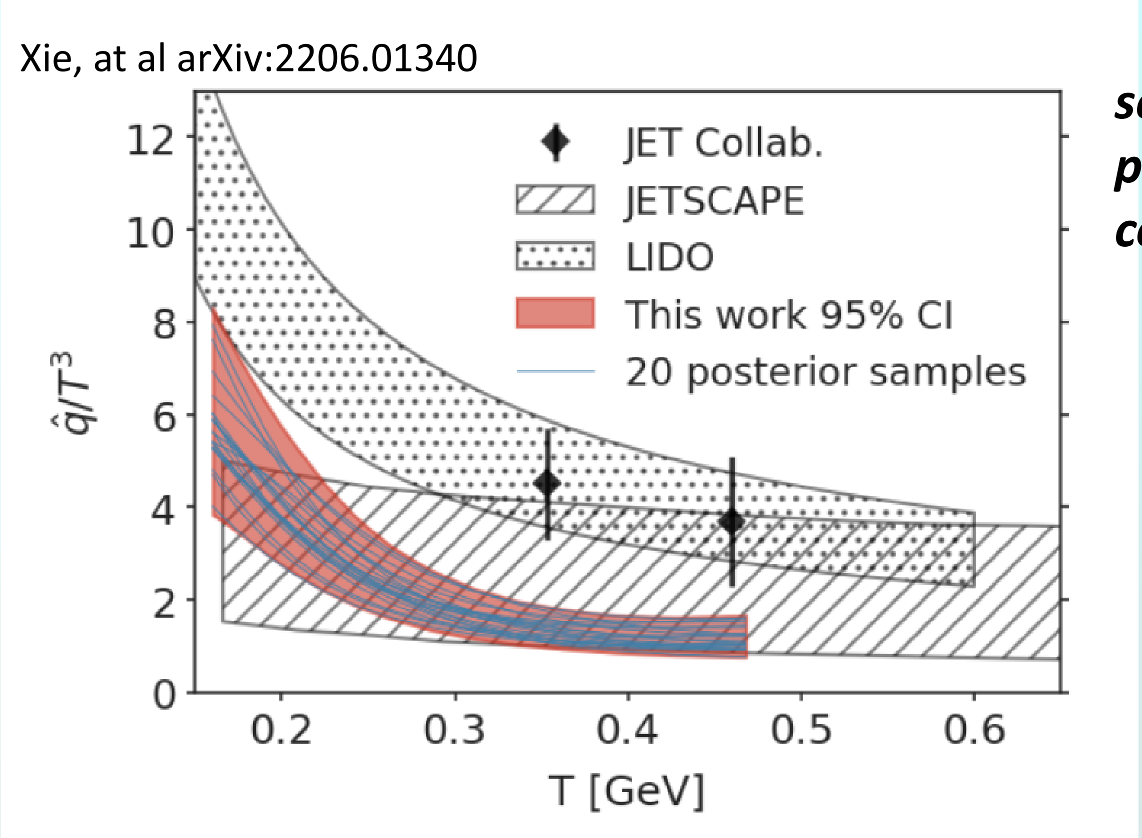




** Ensure consistency with flow & other data*

# Fit as much data as you can get your hands on



# Extract q-hat from models




***several phenomenological collaborations***

***$\hat{q}/T^3 \sim 2 - 4$***

**Red band using global Bayesian inference + all data**

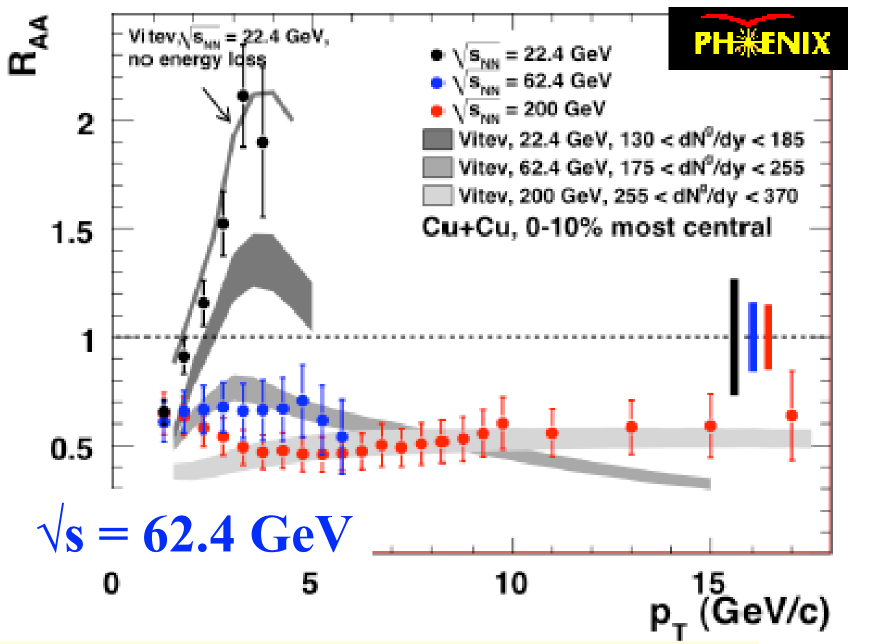
**NB: qhat grows near phase transition temperature**

***should expect this from min $\eta/s$ (max interaction $\sigma$)***

# the opacity sets in between 20 & 39 GeV √s

*Cu+Cu*

$\sqrt{s}$ = 20 GeV

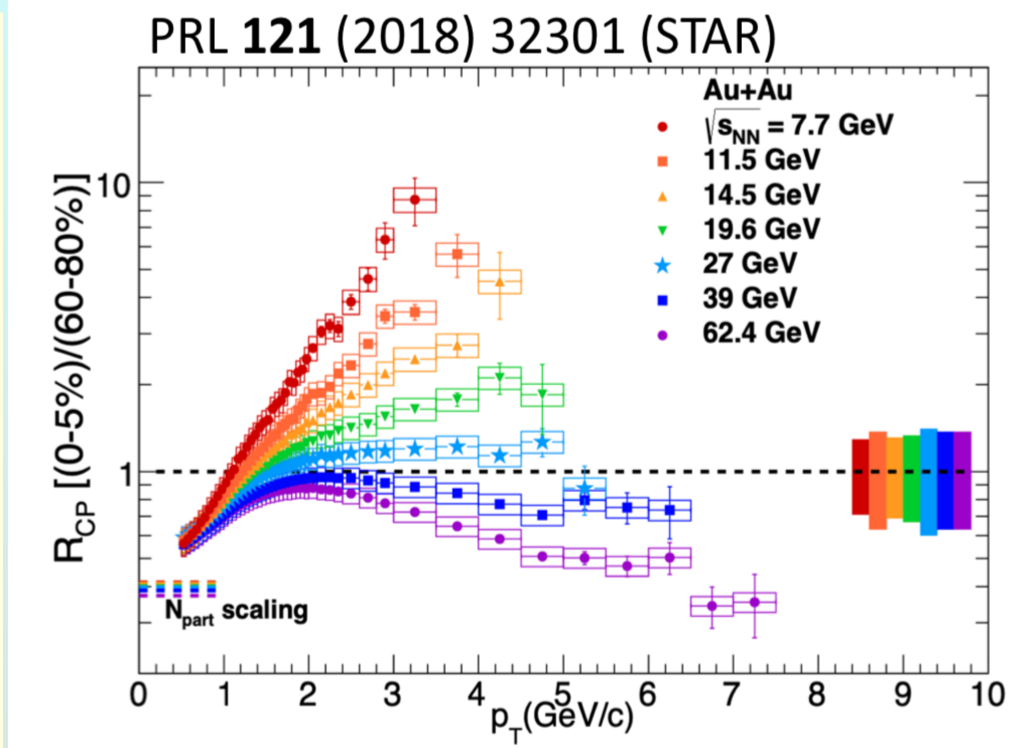



$\sqrt{s}$ = 62.4 GeV

PRL 101, 162301 (2008)

$\sqrt{s}$ = 200 GeV

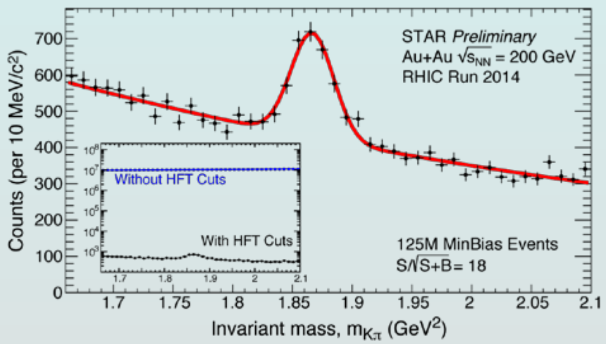
*Au+Au*



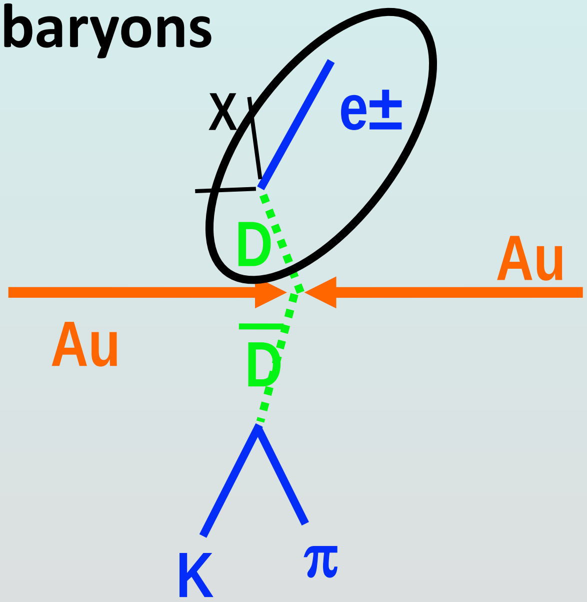
# Heavy Quarks

# What happens to more massive probes?

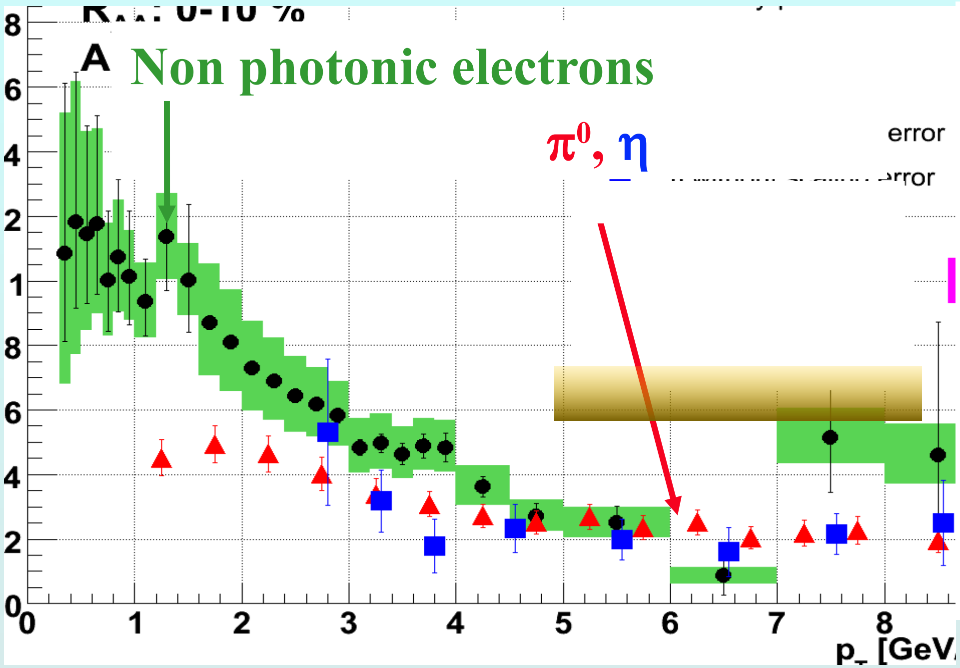
- **Diffusion of heavy quarks traversing QGP**
  **$M_c \sim 1.3\ GeV/c^2$, $M_b \sim 4.2\ GeV/c^2$**
- **Prediction: less energy loss than light quarks**
  ***large quark mass reduces phase space for radiated gluons***
  ***"dead cone" effect***
  ***collisions with light quarks don't change c,b much***
- **Measure hadrons containing charm or bottom quarks**
  **e.g. D & B mesons, $\Lambda_c$, $\Xi c$, $\Sigma_c$ baryons**

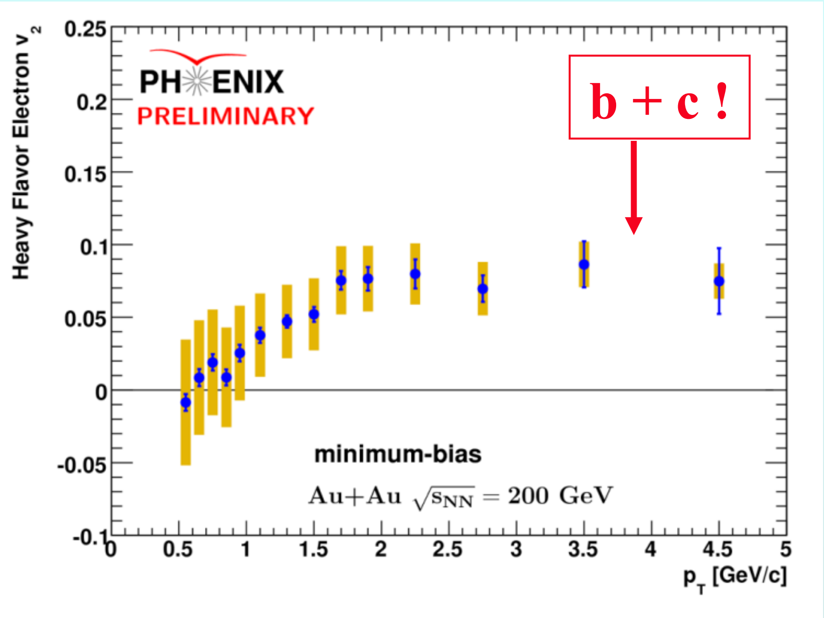



D-> Kπ invariant mass



# Surprise: large heavy quark energy loss!




► **more energy loss than gluon radiation can explain!**

► **charm quarks flow along with the liquid**

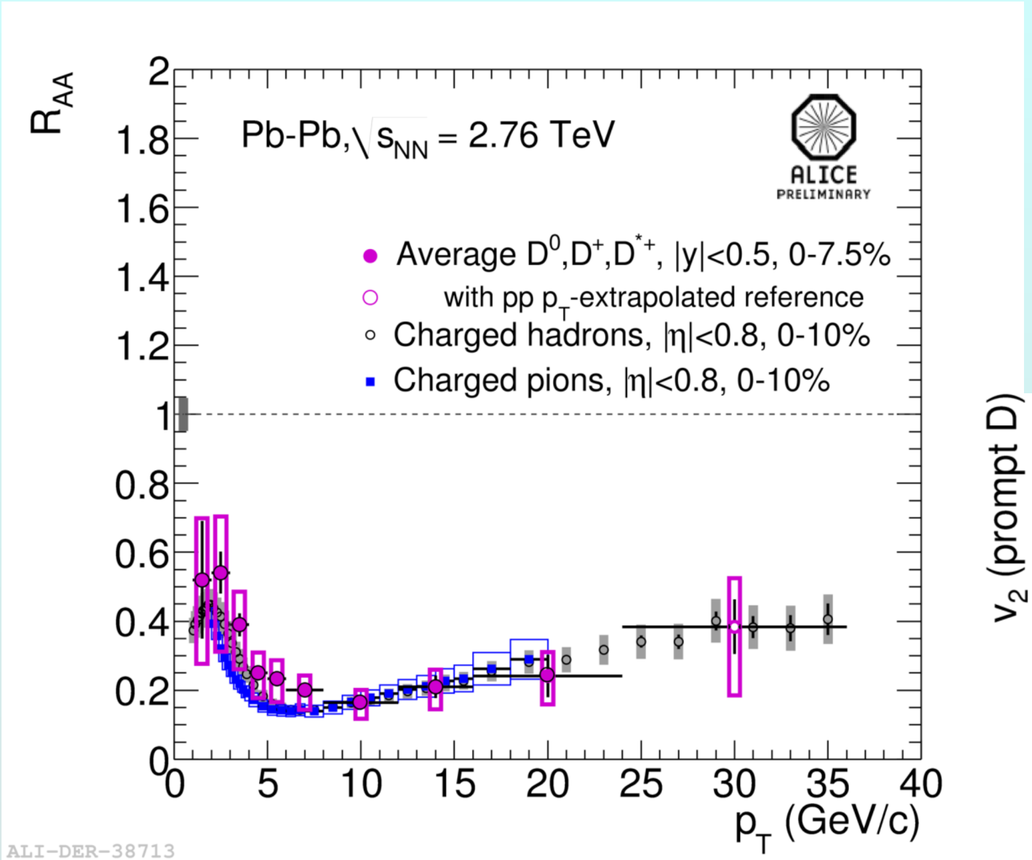
***Who ordered that?***

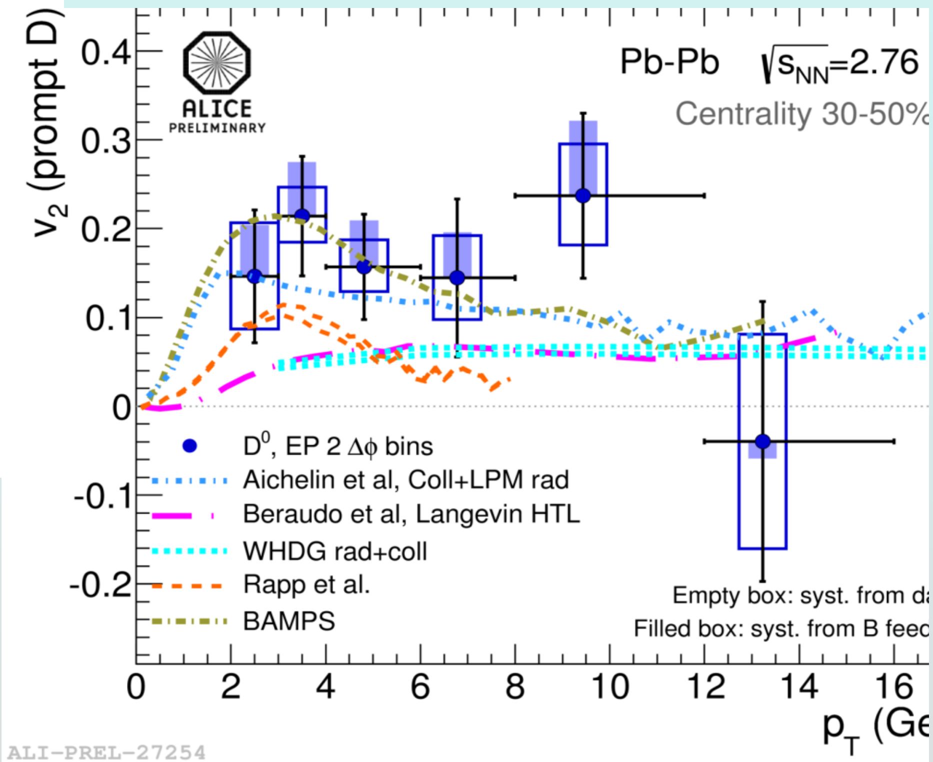
***Mix of radiation + collisions (diffusion)***

***but collisions with what?***

***Drag force of strongly coupled plasma on moving quark?***

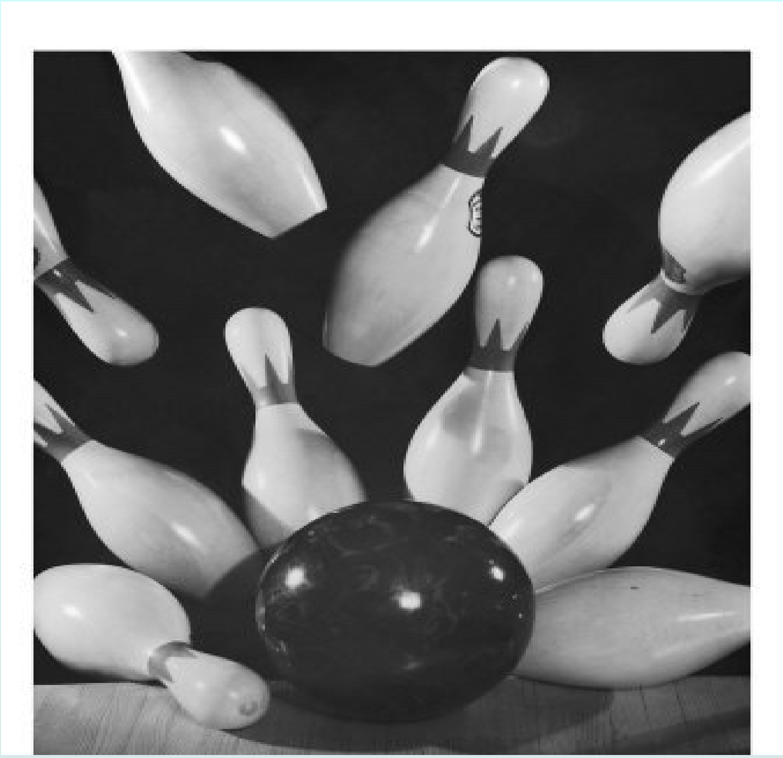
# Same behavior in QGP at LHC



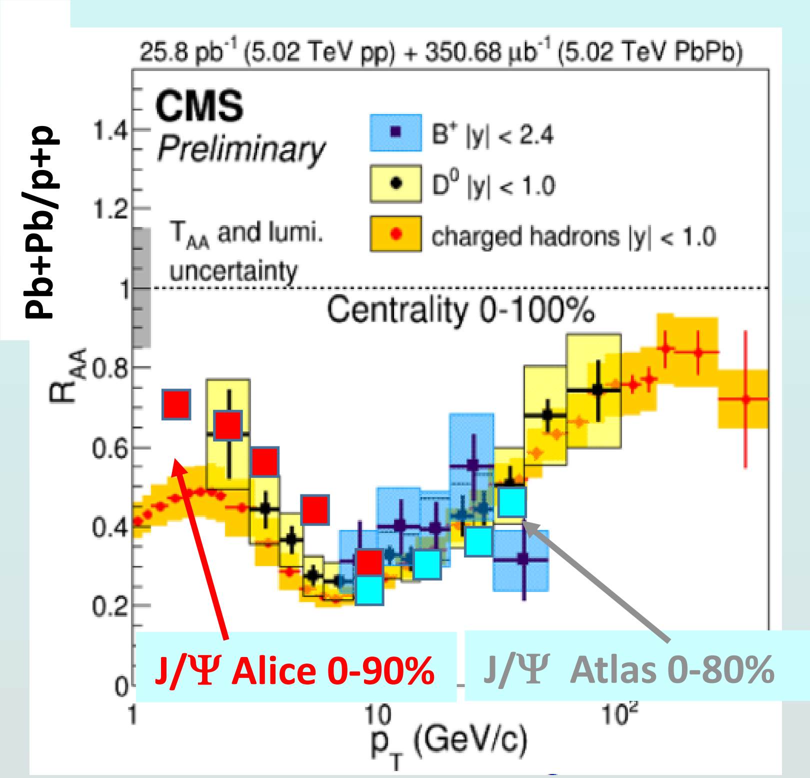




- Can understand energy loss and flow at both energies
- Charm quarks diffusing through strongly coupled QGP

# An astounding result!

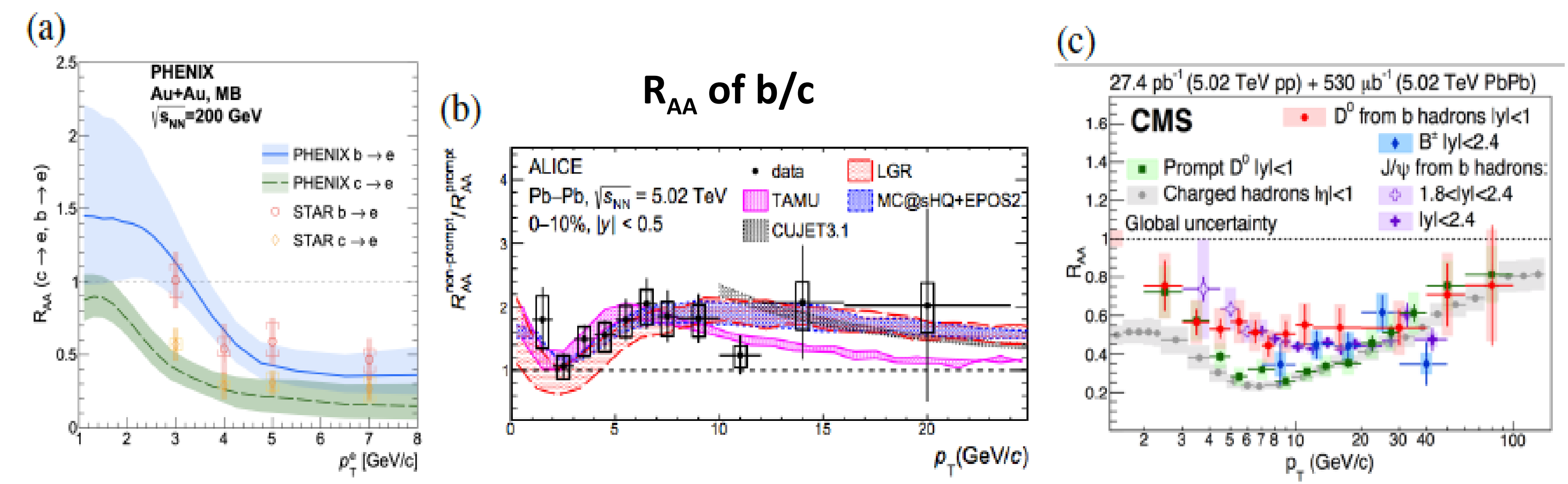


Even more surprising than you might think…




*Even b quarks lose energy!*

# In more detail




- *Why are c and even b quarks affected?*
- **Collide with something heavy?**

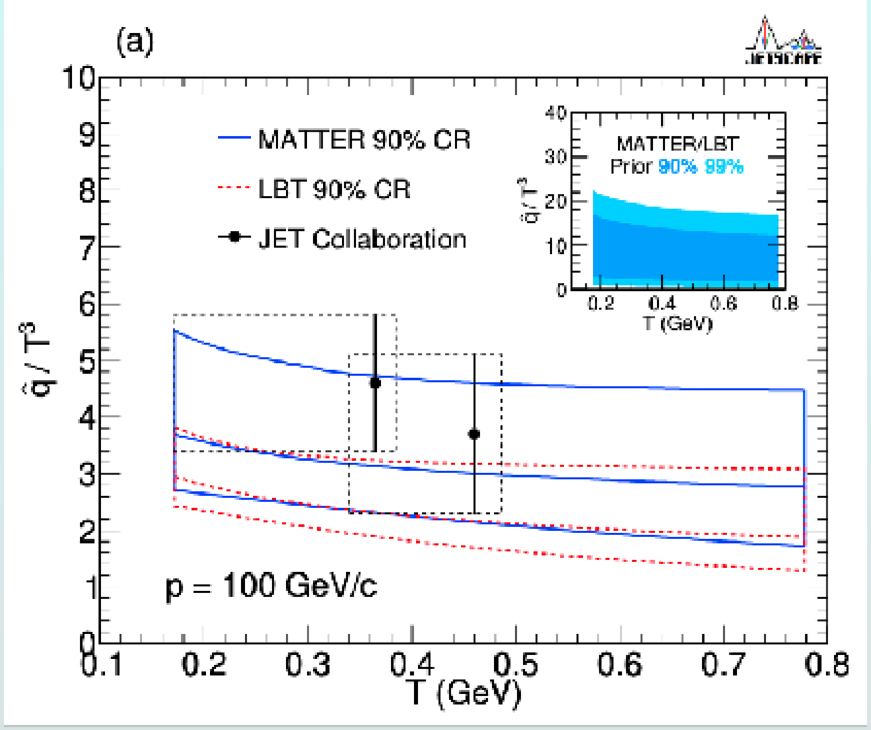
  **Gluons get a thermal mass**

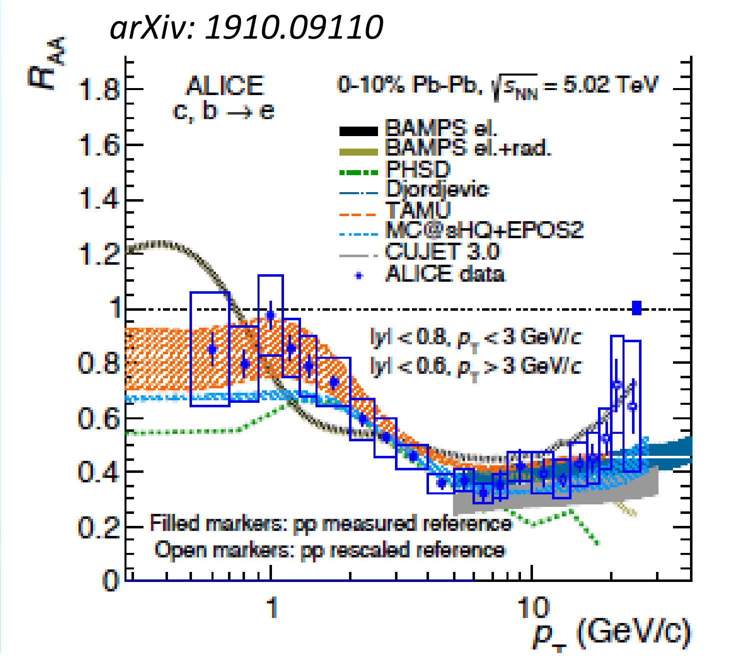
  **Perhaps we have multi-gluon quasiparticles**
- **Strong coupling makes the plasma opaque to all objects with color charge**

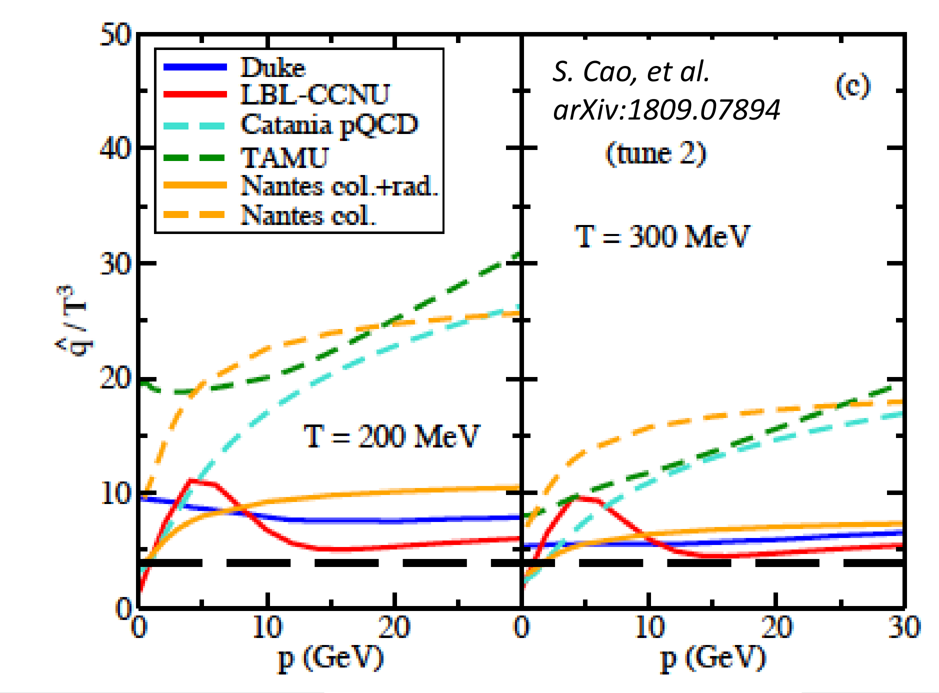
# Data + theory = transport

***Heavy quark energy loss dominated by collisions at low $p_T$, radiation at high $p_T$.***

***Light + heavy: precision***



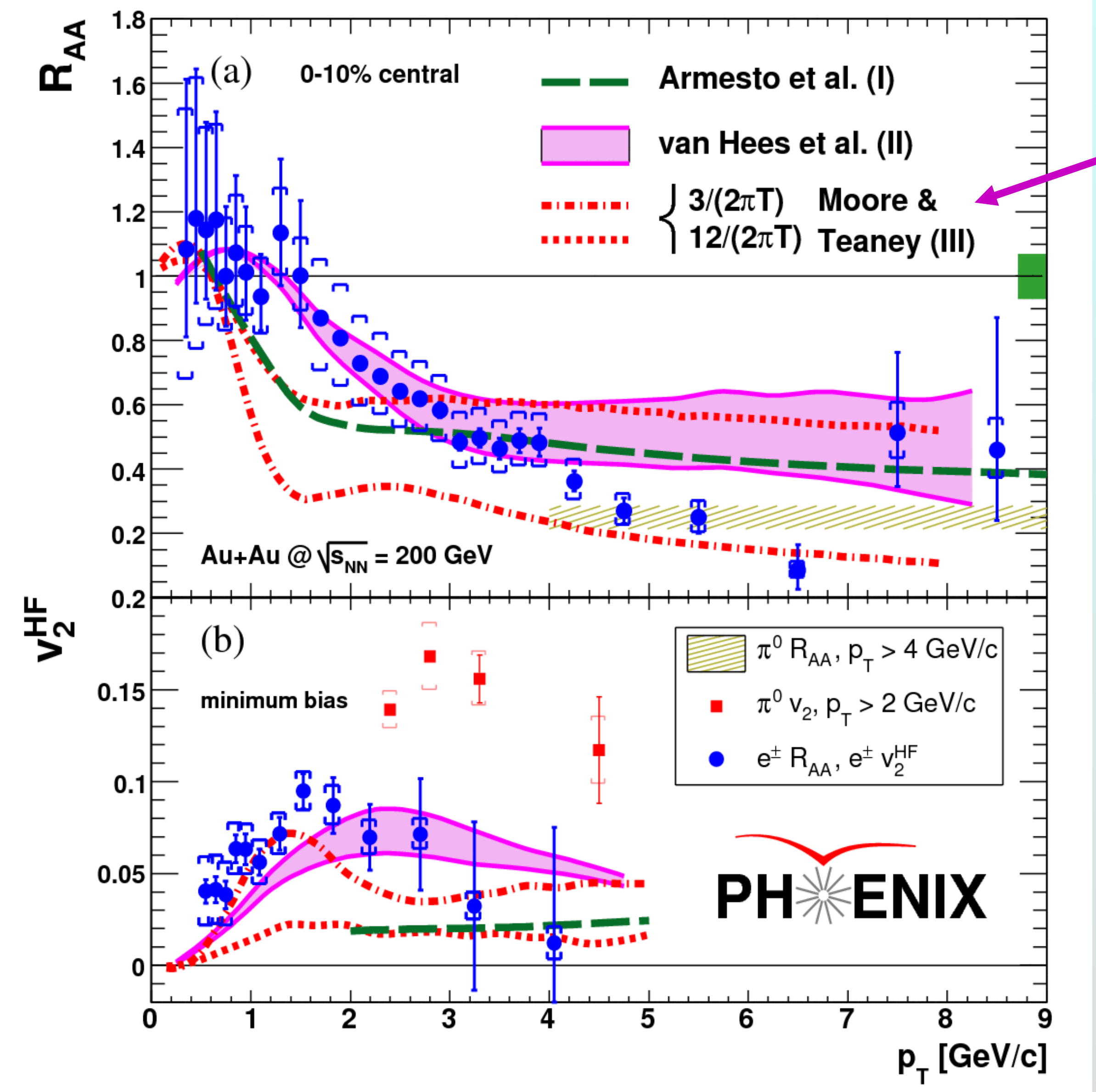

RHIC and LHC data analyzed by JETSCAPE collaboration:

S. Cao et al., arXiv: 2102.11337

**Heavy quark $R_{AA}$ fits**

# an independent measure of viscosity

PRL98, 172301 (2007)




**Heavy quark diffusion & drag (Langevin equation)**

drag force ↔ random force
↔ $<\Delta p_T^2>$/unit time ↔ D*

**~ agrees with data**
**slow relaxation ruled out**

***D ~ 4-6/(2πT)***

$\eta = 1/3\ \rho <v> \lambda$
$D = <v>/\ 3\rho s$
$D = \eta/\rho \sim \eta/S$

**→ η/S = (1.3 – 2.0)/ 4π**

# approaches to heavy quark diffusion

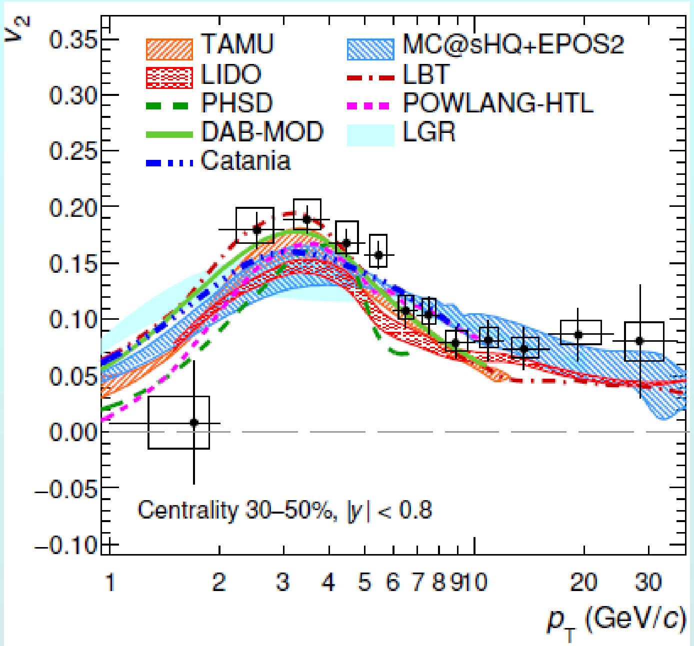
- **Perturbatively**
- **Non-perturbatively using AdS/CFT**
- **Non-perturbatively using lattice QCD**
- **From data using Bayesian analysis**

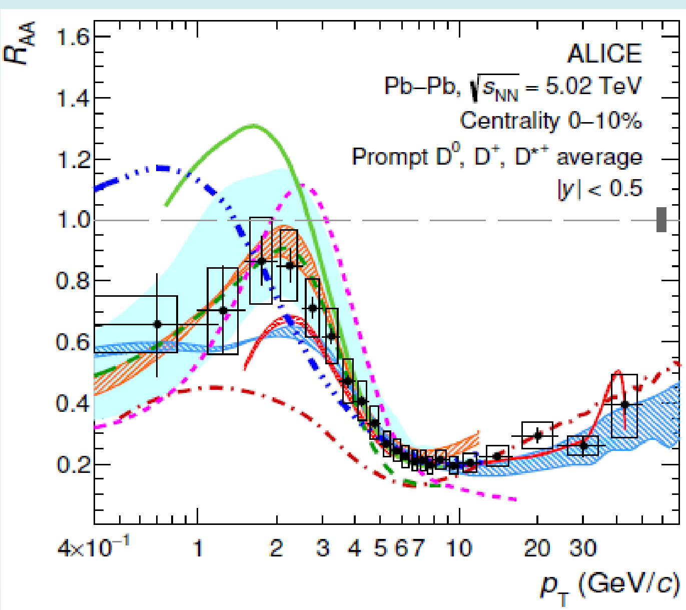
- **Lattice: in the heavy quark limit, can extract the diffusion coefficient from spectral function of the chromoelectric field strength correlator**

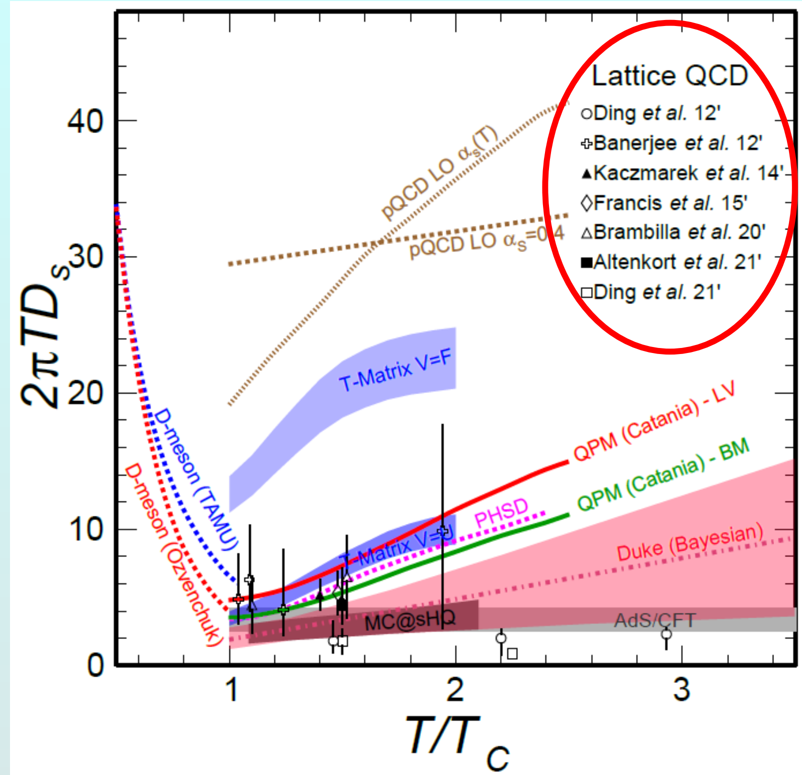
$$\kappa_{\rm fund} = \frac{g^2}{3N_c} {\rm Re} \int dt \, \langle {\rm Tr}_c [U(-\infty, t) E_i(t) U(t,0) E_i(0) U(0, -\infty)] \rangle_T \,,$$

(U is a timelike Wilson line)

# Heavy quark diffusion from D meson $v_2$ and $R_{AA}$



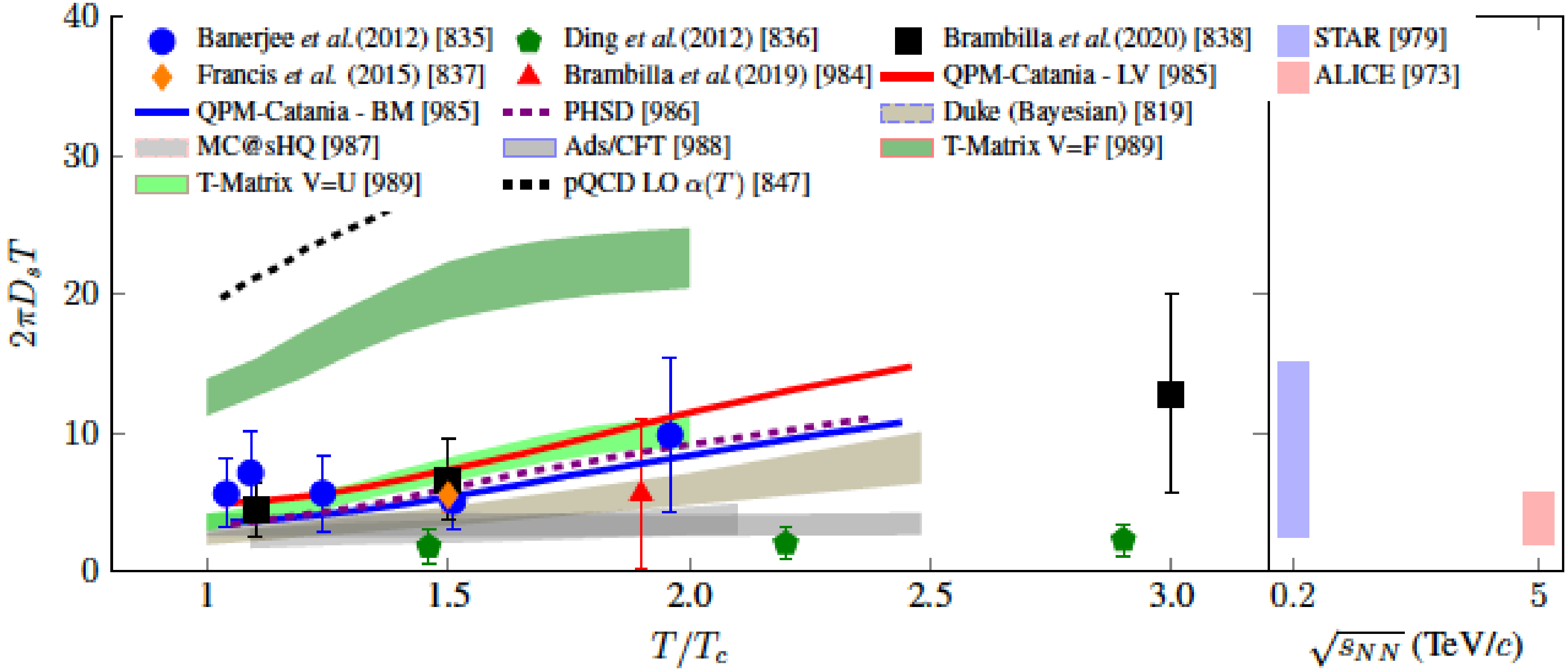




***Again use data + models together:***
***radiation, collisions, medium evolution***

***$D_s(2\pi T)$ = 1.5 - 4.5 near $T_c$***
***per models with $\chi^2$/DOF < 5 (2)***
***for $R_{AA}$ ($v_2$)***

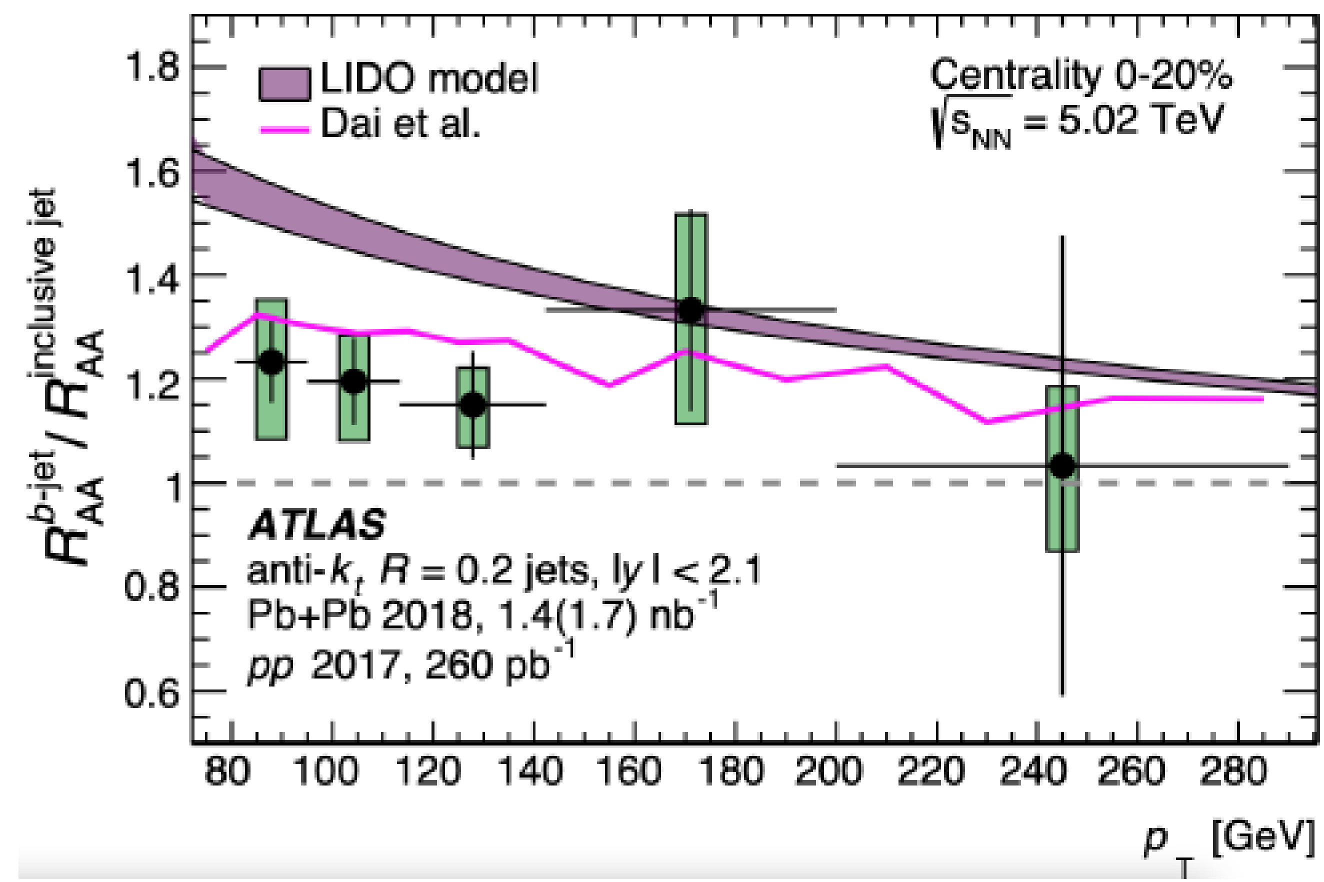
# Compare diffusion models to data extraction



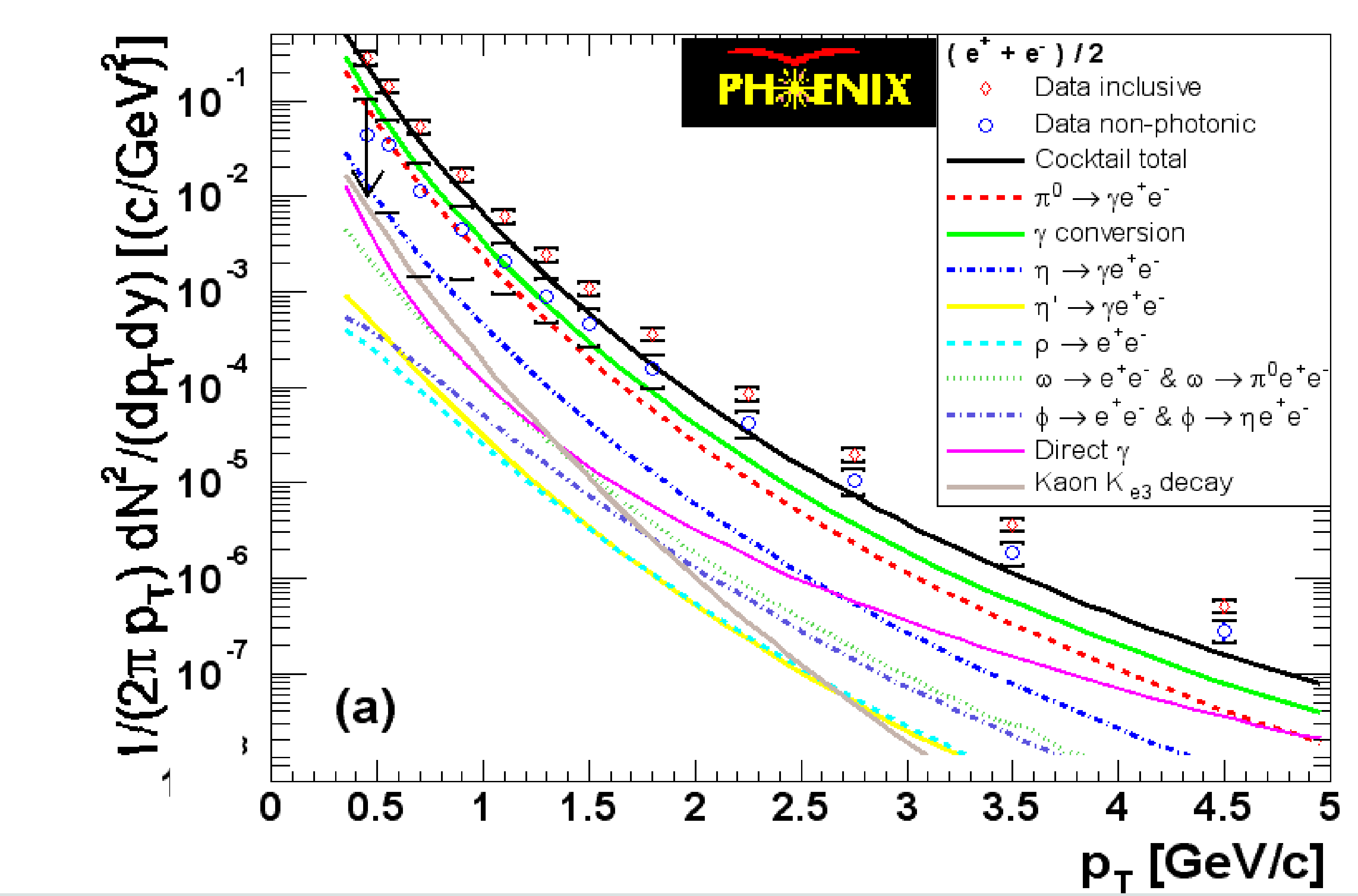
# Take aways

- Even small systems show collective flows
  - Likely due to fast longitudinal expansion driving relaxation to hydrodynamic attractor
  - non-hydro modes decay exponentially so pre-equilibrium dynamics relax very quickly
- We observe a large energy loss for partons transiting the plasma
  - Compare the data to hydro + interaction models
  - We find that $\hat{q}/T^3 \sim 2 – 4$
- Heavy quarks also lose energy in QGP
  - Charm quarks like light quarks (!) bottom slightly less
  - q-hat consistent with that from light quarks for $p_T > 10\text{-}15$ GeV/c
  - Low $p_T$ dominated by collisional energy loss
- Charm mesons also flow
  - Charm diffusion coefficient: $D_s(2\pi T) = 1.5 - 4.5$ near $T_c$

- **backup slides**


LIDO model
Dai et al.
Centrality 0-20%
√sNN = 5.02 TeV
ATLAS
anti-kt, R = 0.2 jets, |y| < 2.1
Pb+Pb 2018, 1.4(1.7) nb-1
pp 2017, 260 pb-1
R_AA^b-jet / R_AA^inclusive jet
pT [GeV]
1.8
1.6
1.4
1.2
1
0.8
0.6
80
100
120
140
160
180
200
220
240
260
280

# c,b decays via single electron spectrum

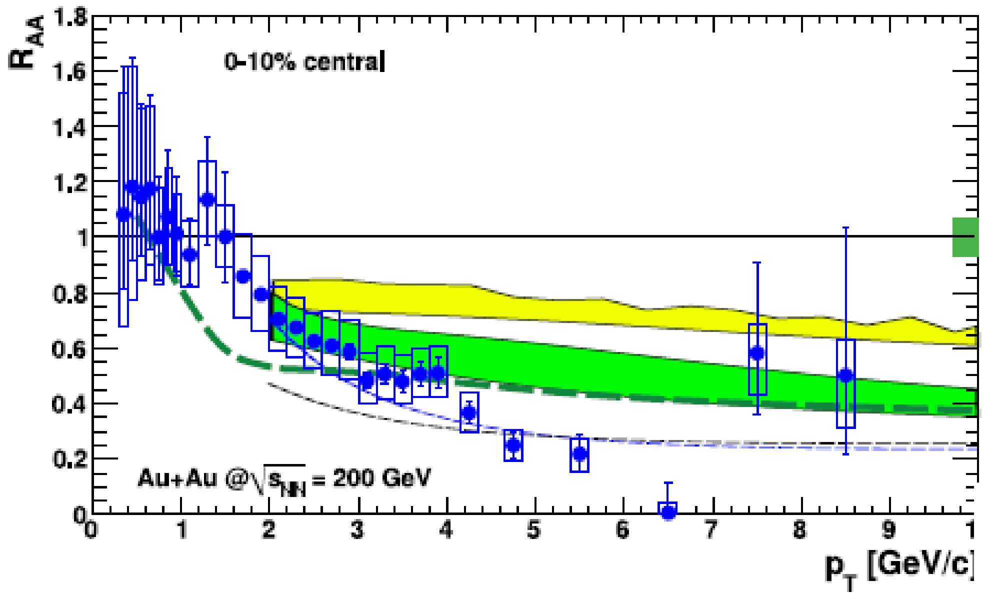



**compare data to "cocktail" of (measured) hadronic decays**



PRL 96, 032301 (2006)

# heavy quark suppression & flow?



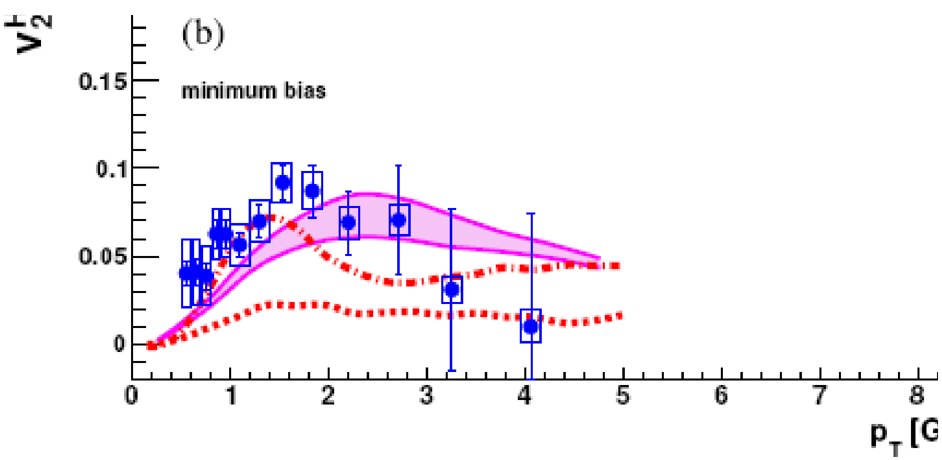

*PRL.98: 172301,2007*

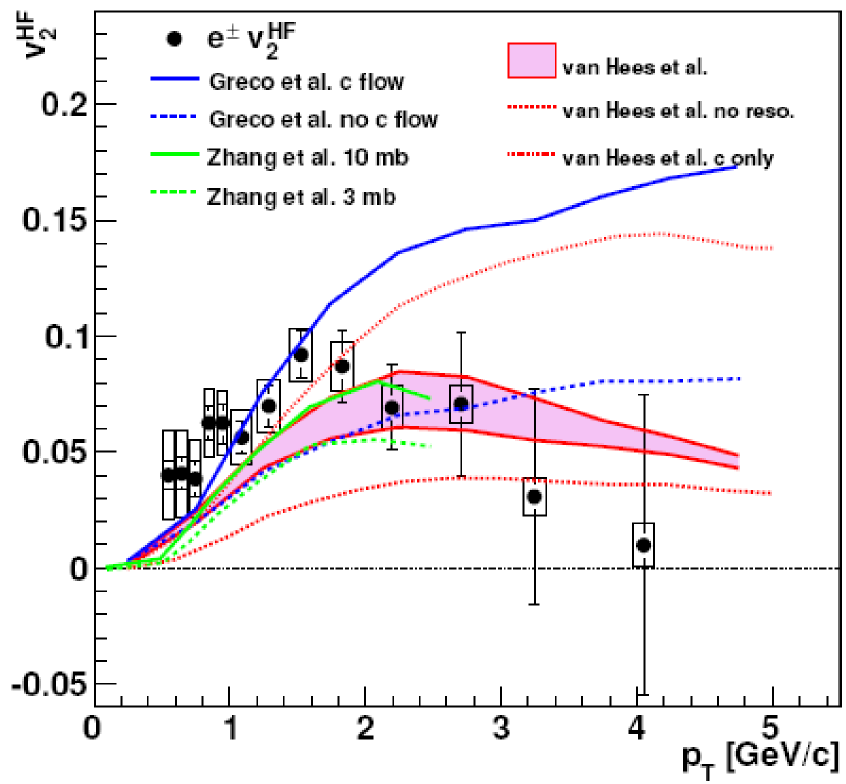
*arXiV: 1005.1627*

**Collisional energy loss?**

**$v_2$ decrease with $p_T$?**

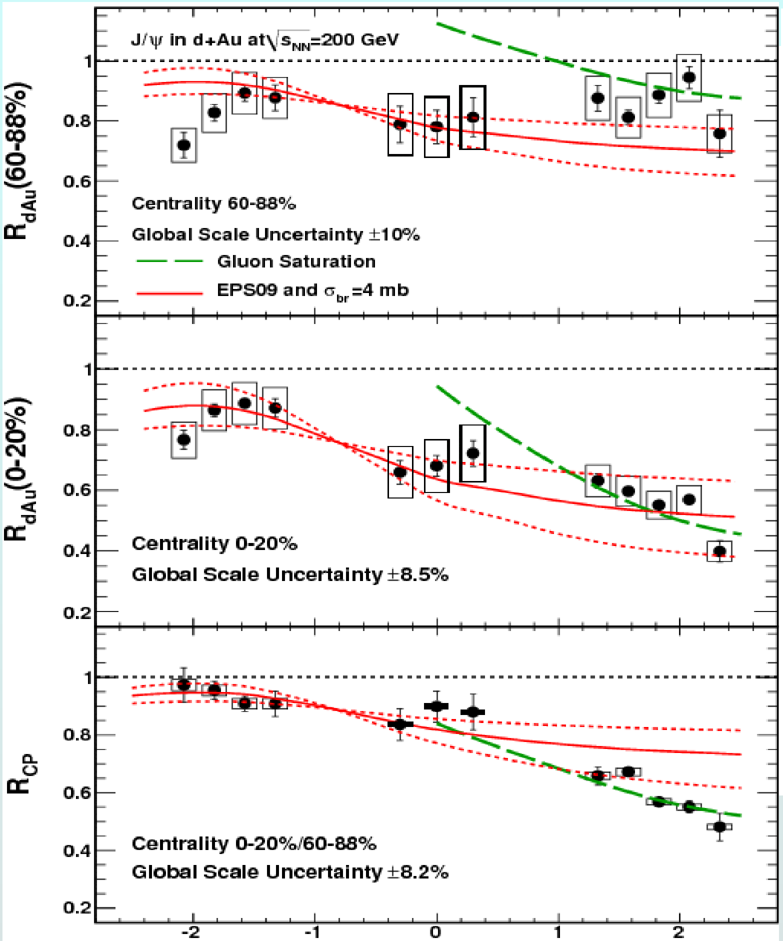
**role of b quarks?**



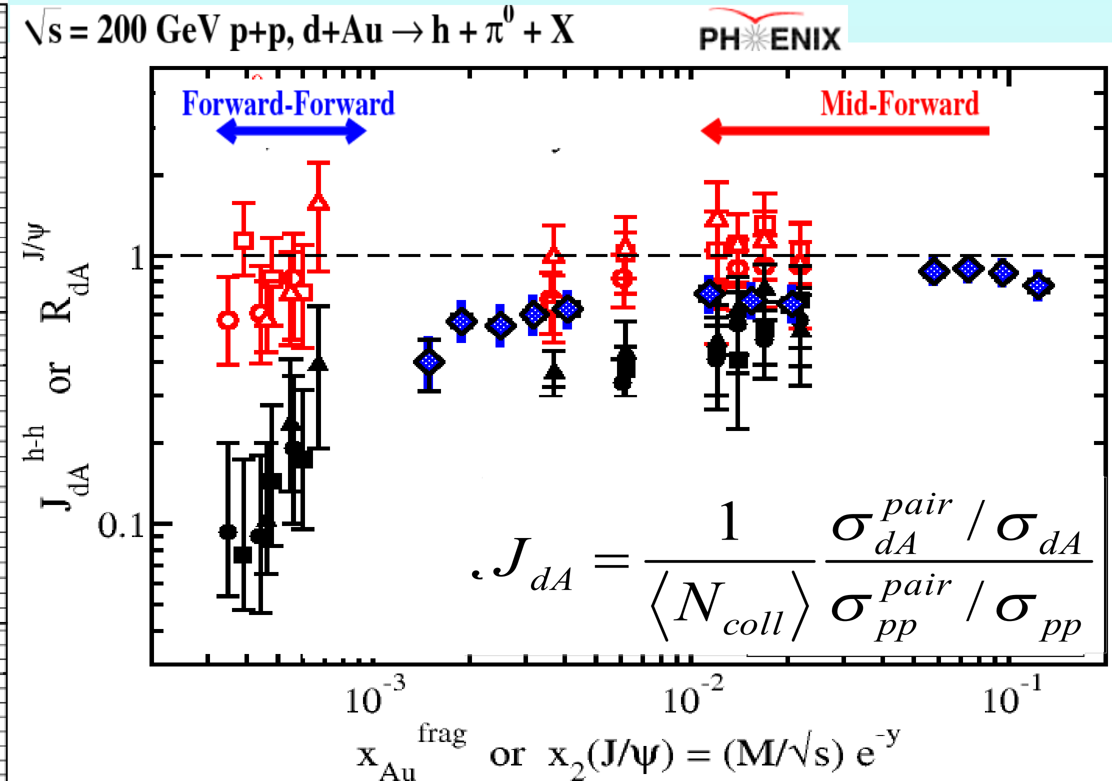



# Dense gluonic matter (d+Au, forward y): large effects observed

arXiv:1010.1246




arXiv:1105.5112




Di-hadron suppression at low x

pocket formula (for 2➔2):

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

Shadowing/absorption stronger than linear w/nuclear thickness

trend as, e.g. in CGC …