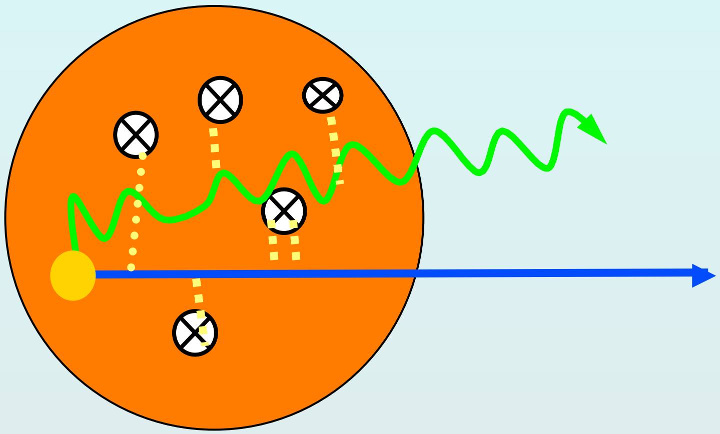
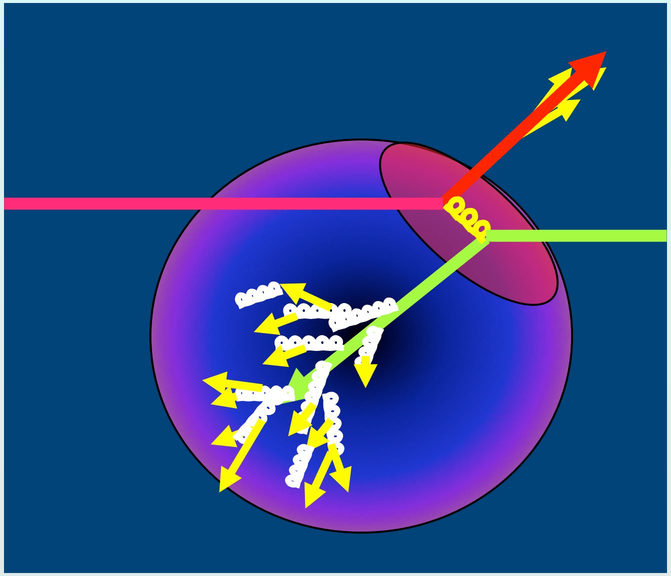
Lecture 1
Energy Loss and Opacity in the Quark Gluon Plasma



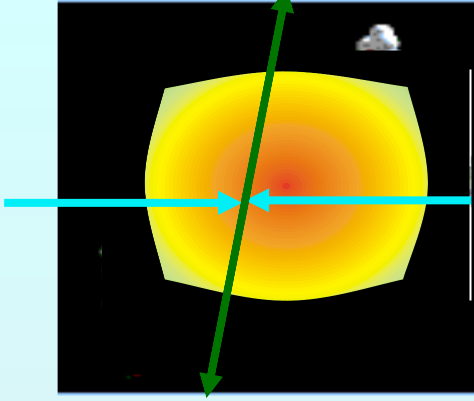


Barbara Jacak
UC Berkeley/ LBNL
June 25, 2015

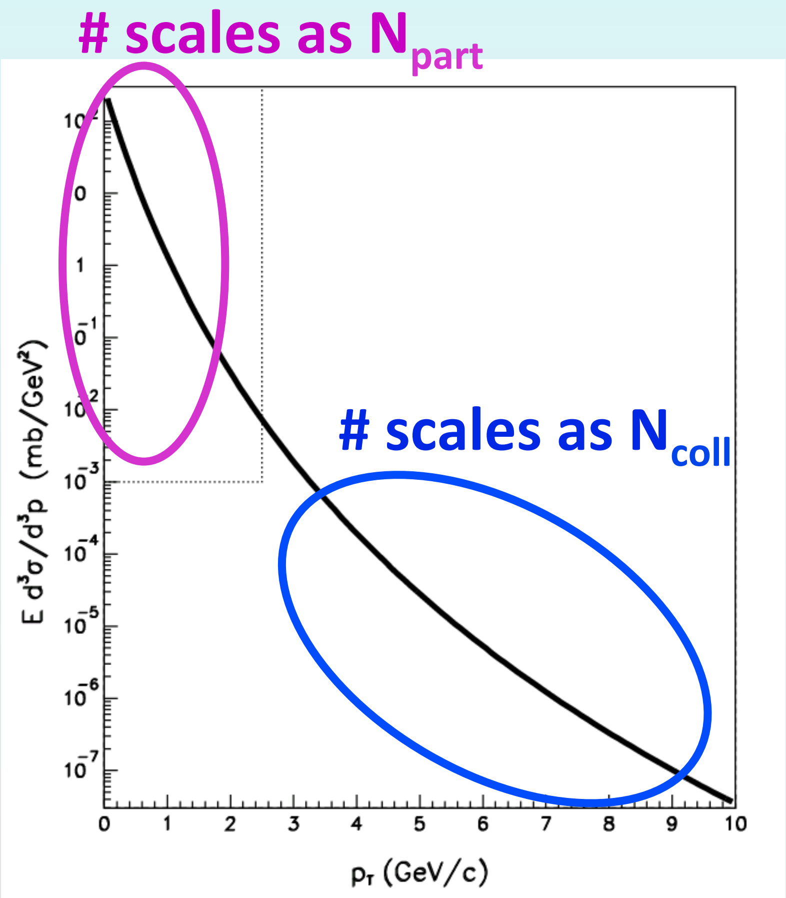
Outline

- Partonic probes of quark gluon plasma
  and how to generate them
- Opacity of the plasma
- Energy loss in pQCD
- Looking inside jets in heavy ion collisions
- The fate of heavy quarks in QGP

study plasma with radiated & “probe” particles



- as a function of transverse momentum
  - 90° is where the action is (max T, ρ)
  - p_L between the two beams: midrapidity
- p_T < 1.5 GeV/c
  - “thermal” particles
  - radiated from bulk medium
  - “internal” plasma probes
- p_T > 3 GeV/c
  - large E_{tot} (high p_T or M)
  - set scale other than T(plasma)
  - autogenerated “external” probe
  - describe by perturbative QCD
- control probe: photons
  - EM, not strong interaction
  - produced in Au+Au by QCD
    - Compton scattering



Step 1: heat nuclei to >150 MeV

Large Hadron Collider

CERN in Geneve

Pb+Pb @ 2.76 TeV/A

Relativistic Heavy Ion Collider

Brookhaven in New York

Au+Au @ 200 GeV/A

Collide heavy ions for max temperature & volume

p+p and p/d+A for comparison

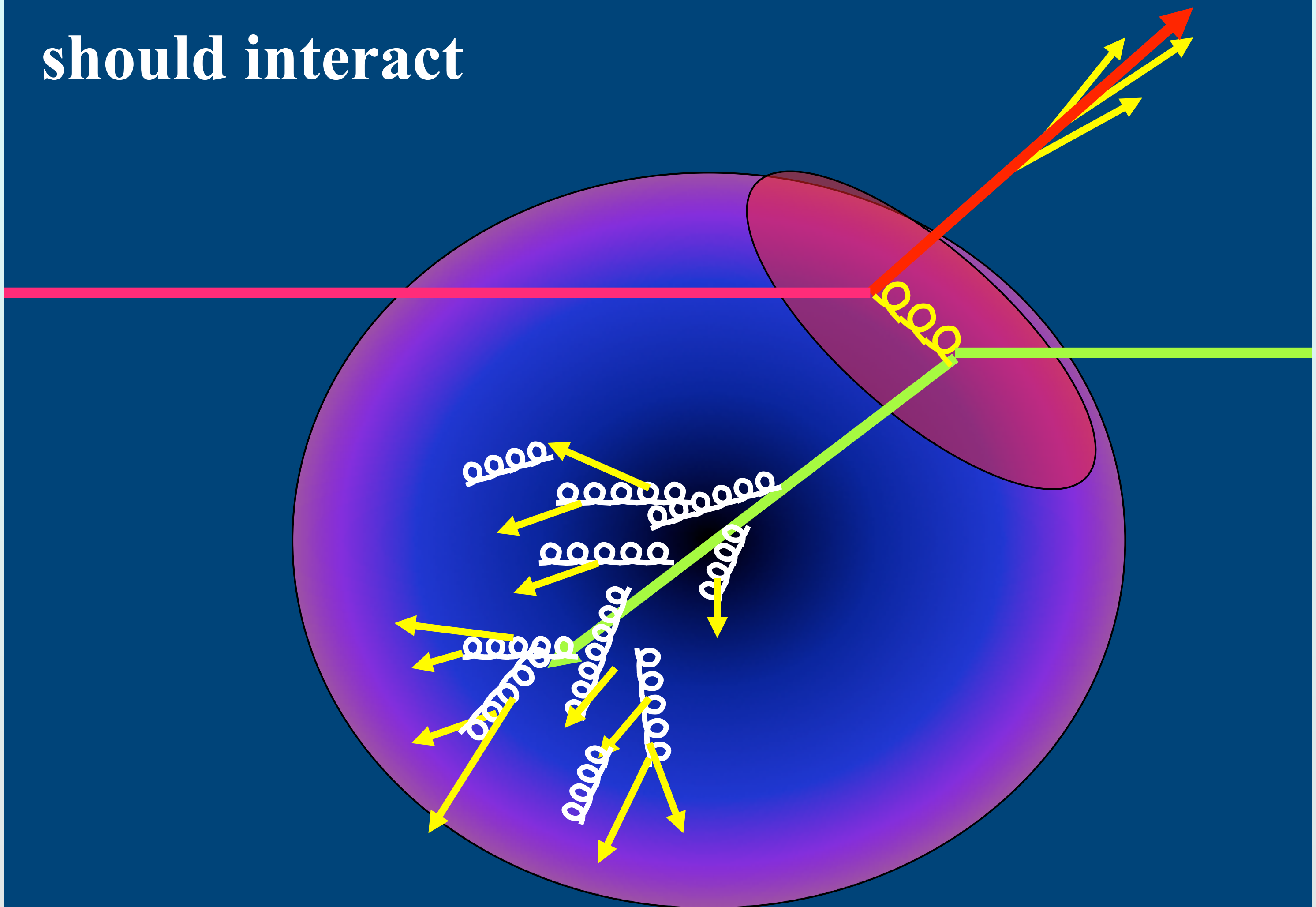
Experiments at RHIC

At LHC they are even bigger!

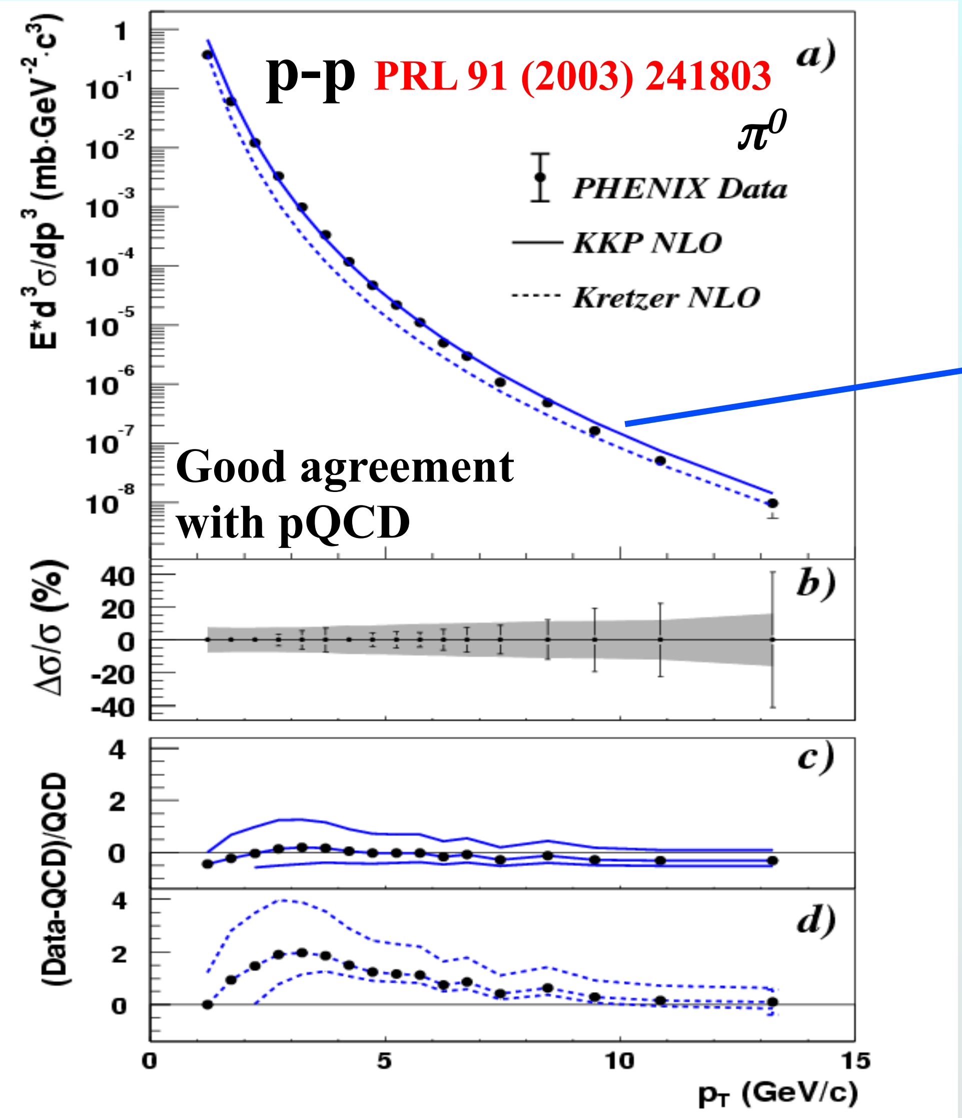
ALICE + ATLAS + CMS

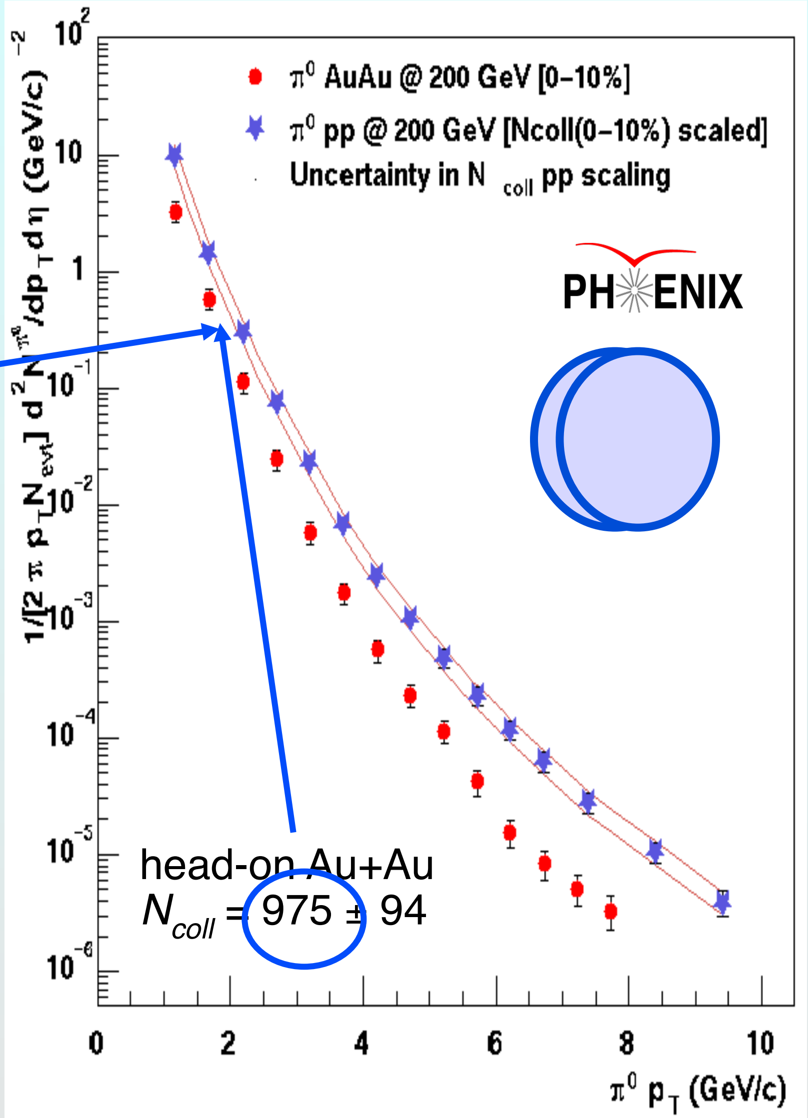
Do fast quarks & gluons escape the plasma?

They feel the strong interaction, so they should interact

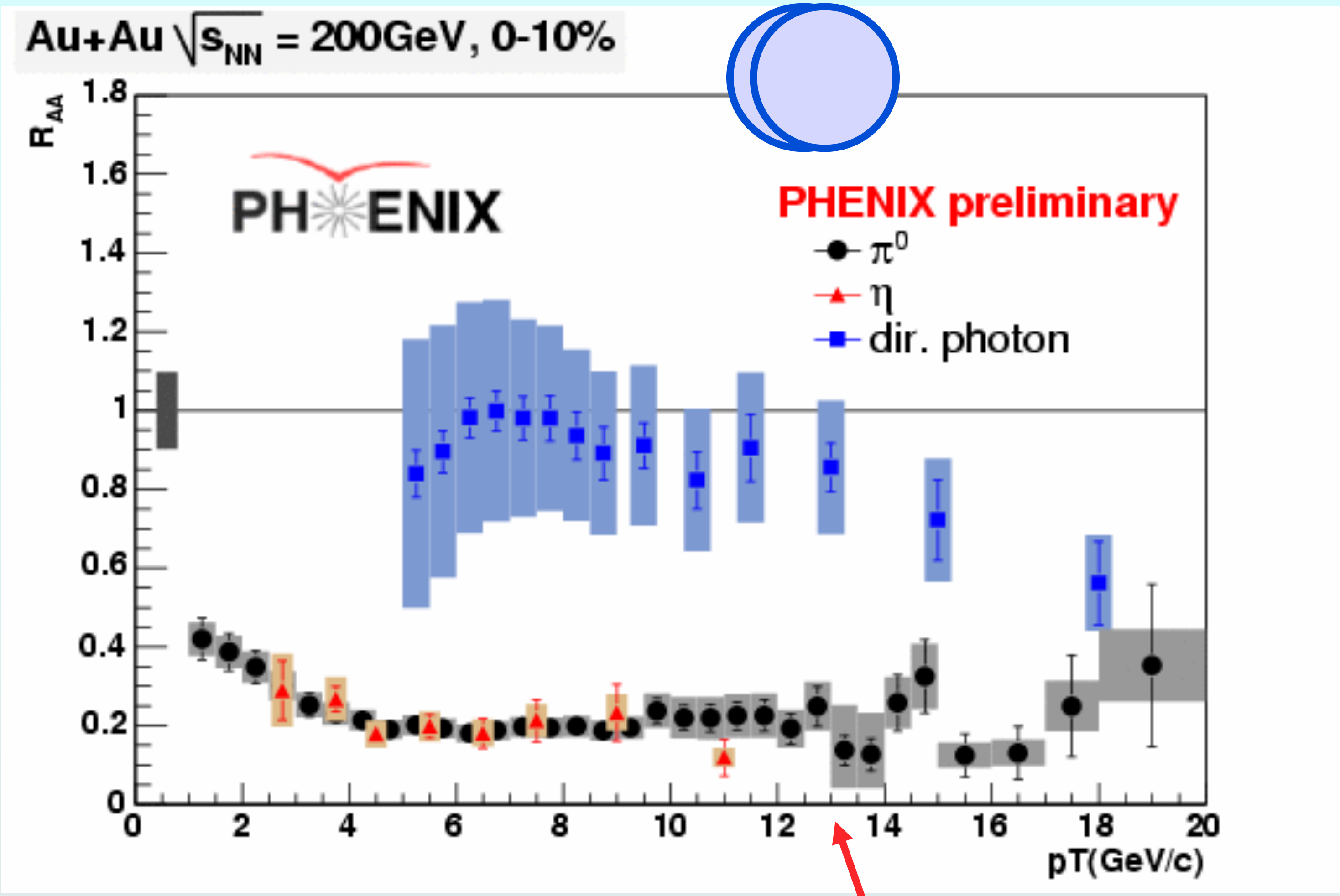


Measuring QGP opacity to quarks & gluons





colored objects lose energy, photons don't

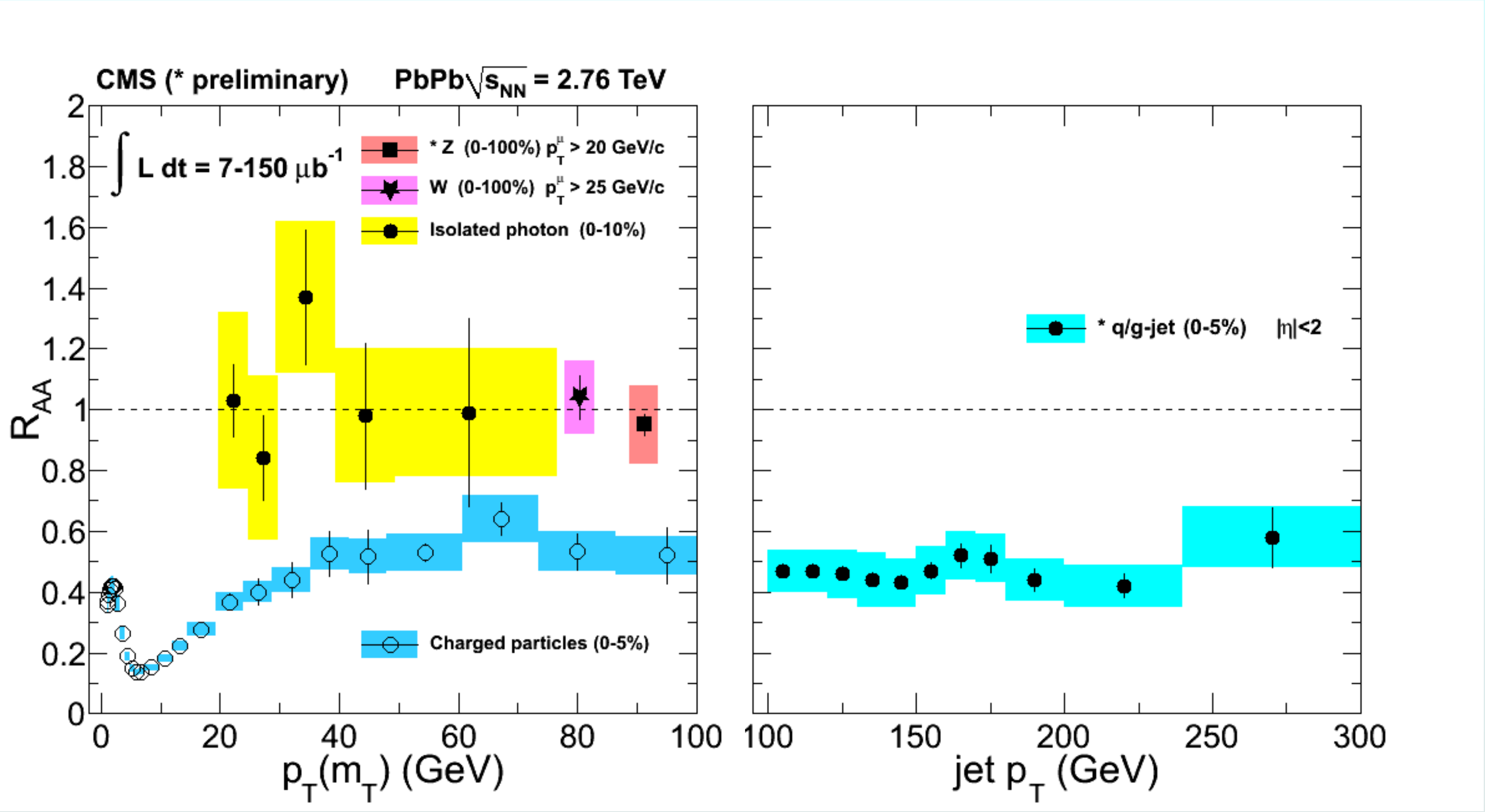


Nuclear modification factor:

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

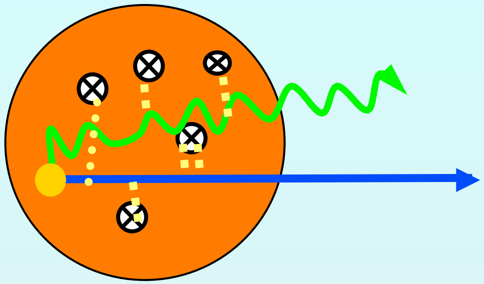
VERY opaque! Lots of gluon radiation (bremsstrahlung)

Energy loss even by very energetic q & g



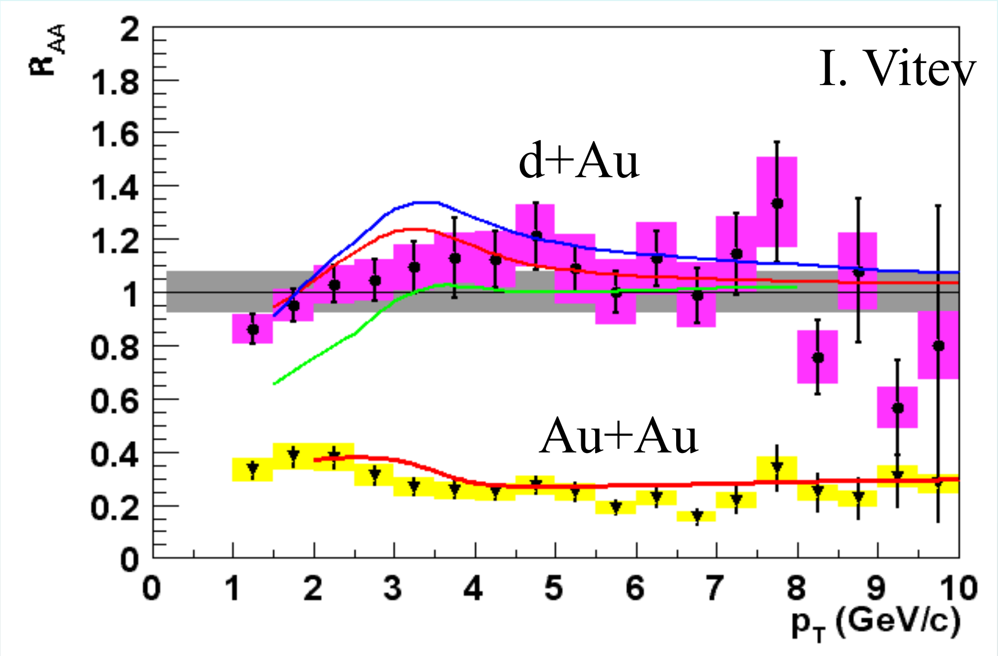
- LHC experiments reach to 300 GeV!

QCD: medium induces gluon bremsstrahlung



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

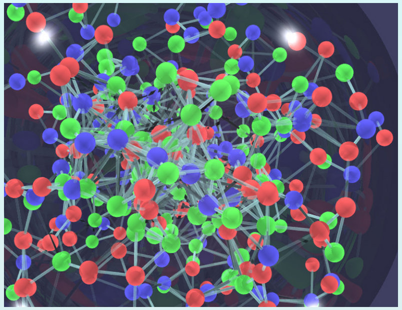
interaction of radiated gluons with gluons in the plasma greatly enhances the amount of radiation



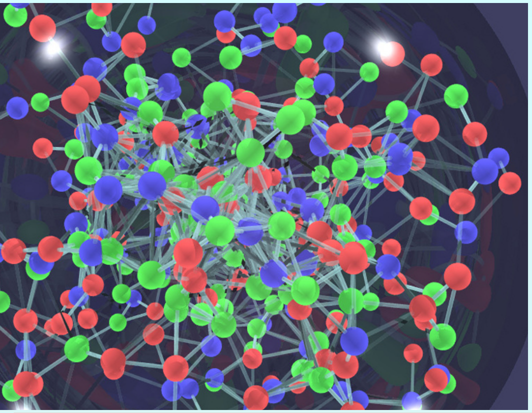
Radiation is coherent, rather than incoherent

Energy loss depends on medium density

- **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 $n = L/\lambda$, μ=typical p_T transfer in 1 scattering
    - λ,μ 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!

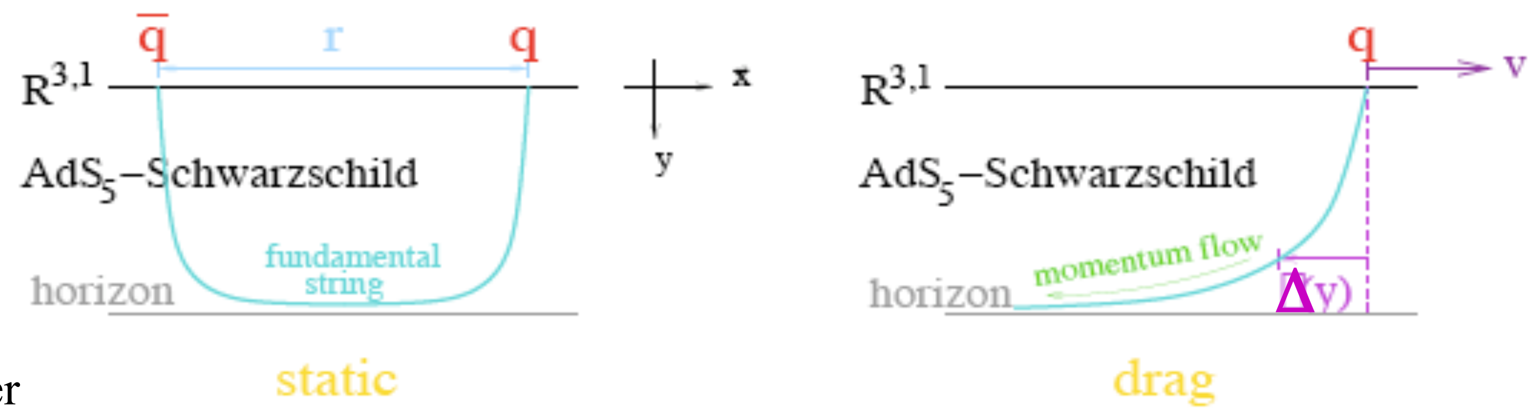


What else could happen?

- radiation (bremsstrahlung)
- collisional energy loss

In plasma: interactions among charges of multiple particles
charge is spread, screened in characteristic (Debye) length, λ_D
also the case for strong, rather than EM force

- AdS/CFT says QGP is a strongly interacting field
  Interact with this QGP as with a tiny black hole
  No particles to hit, none can survive inside. Eloss ➔ collective excitations



S. Gubser

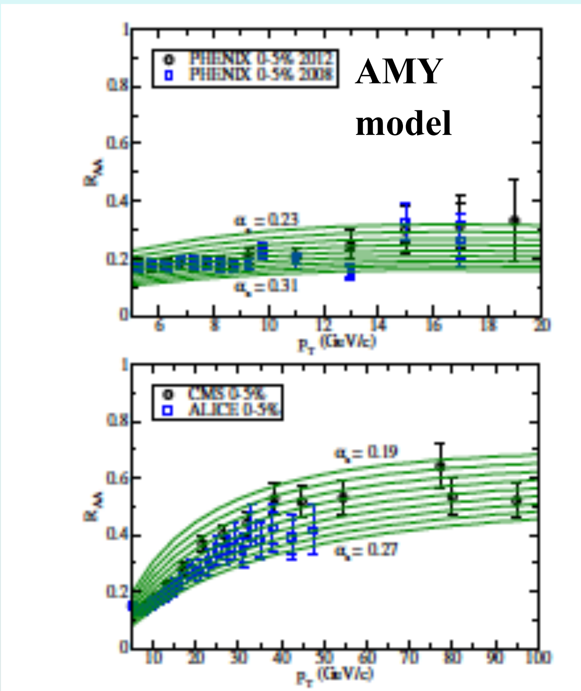
Figure 2: *Left: a screened attraction between static quark arises from a string dipping into AdS_5-Schwarzschild. Right: a drag force arises from a string tailing behind a moving quark.*

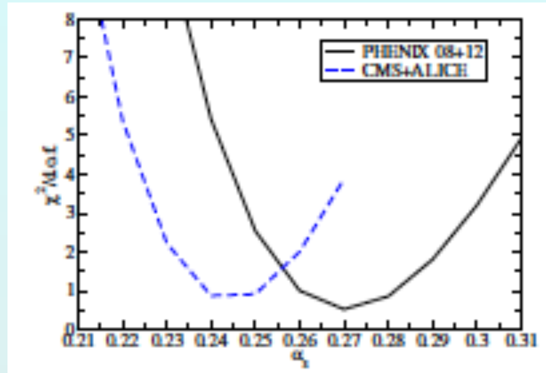
Fit R_{AA} at different $\sqrt{s}$

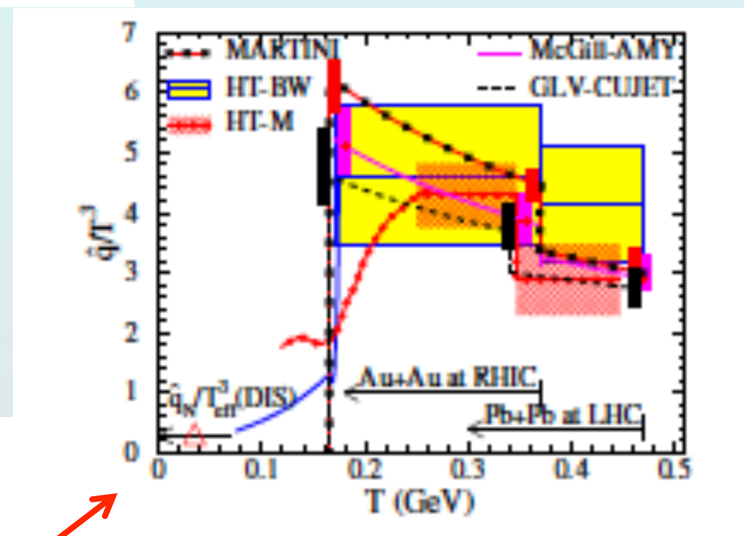
arXiv:1312.5003

JET collaboration fit all data with multiple calculations

minimize $\chi 2$ for best fit to strong coupling parameter or $\hat{q}$

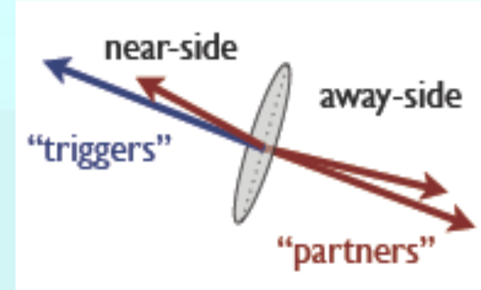




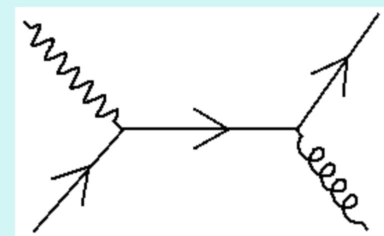


Put together all the calculations

More jet probes = more insight



- **Hadrons**
  - Single high p_T hadrons (leading jet fragments)
  - di-hadron correlations
- **Reconstructed jets** (*reconstructed jets depend on algorithm)*
  - Single jets
  - <di-jets> or jet-h correlations
- **Gamma-jet correlations** (*photon tags jet energy)*
  - γ-h correlations
  - <γ-reconstructed jet>



- **Construct the variables: R_{AA}, I_{AA}, A_J, q-hat**

Nuclear modification:

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

$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

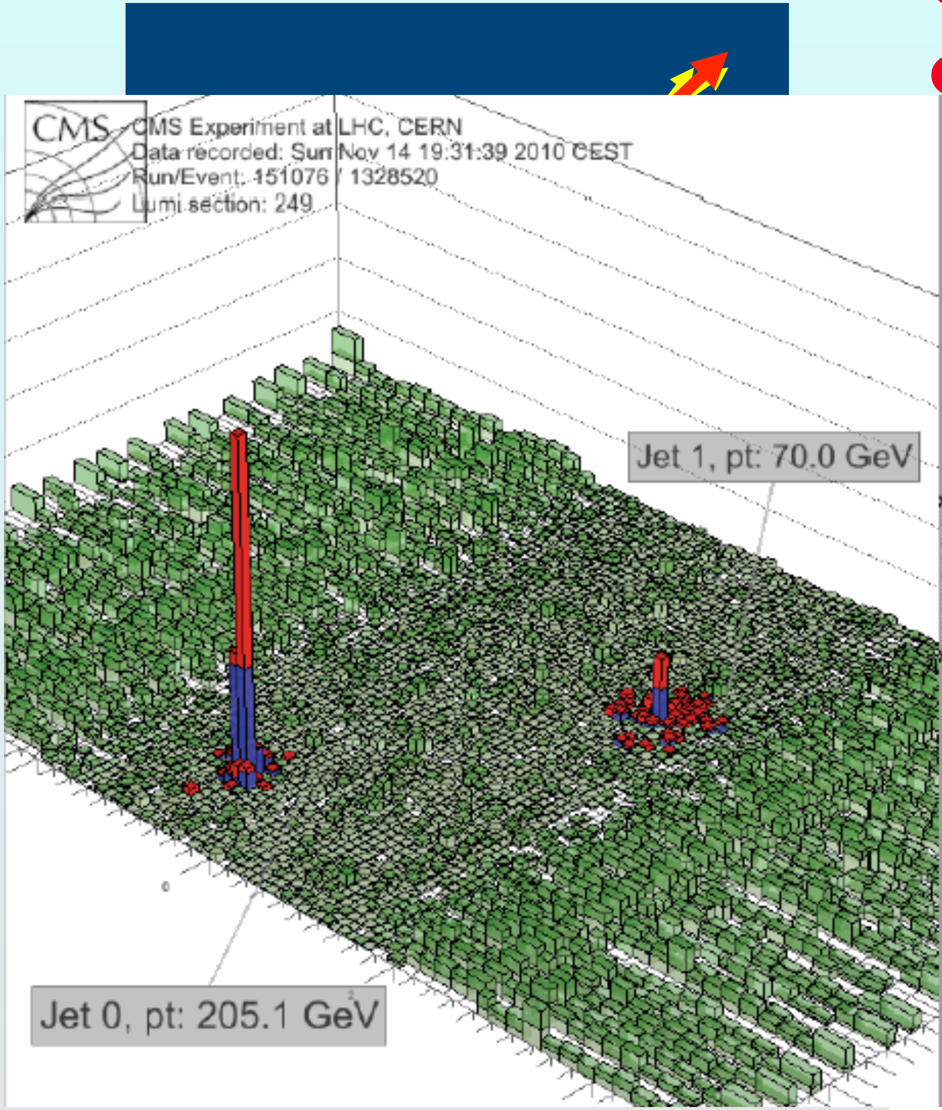
Jet asymmetry:

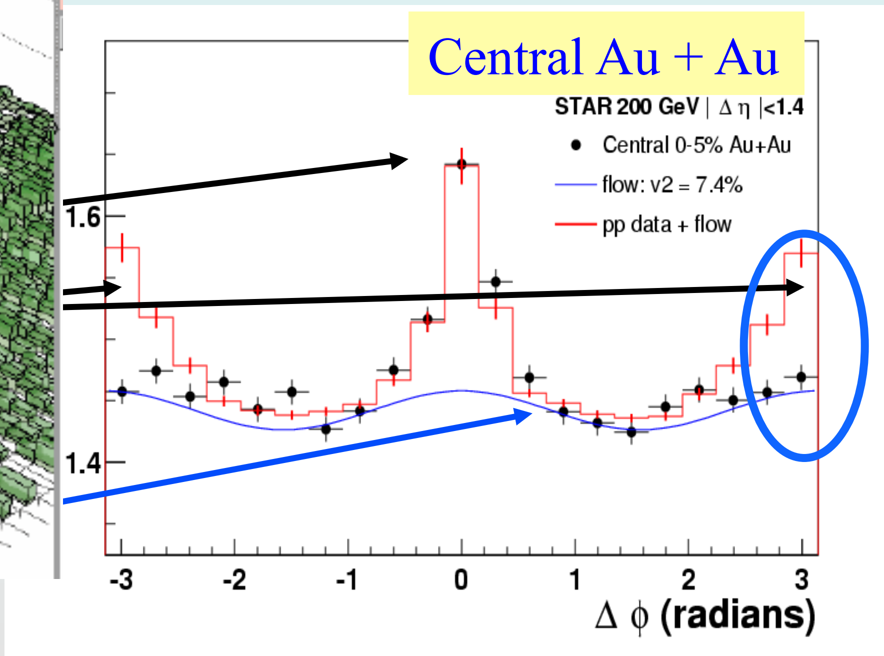
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Jet transport coefficient: $\hat{q} = \mu^2/\lambda$; μ = <p_T transfer> in 1 scattering

Just how opaque IS the plasma?

- Use jet *pairs*
- high p_T trigger to tag hard scattering
- second particle to probe the medium
- answer: VERY opaque!

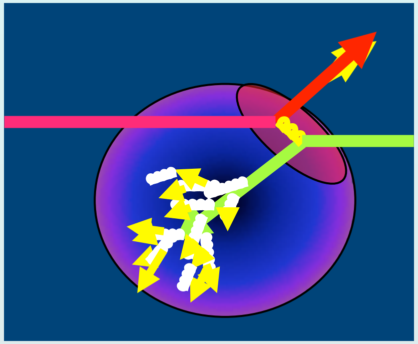




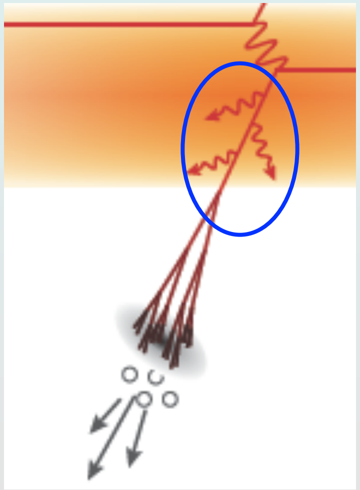
Where does the lost energy go?

- We don't know yet!
- Medium enhances gluon radiation/splitting:

extra gluons at small angles (in/near jet cone)

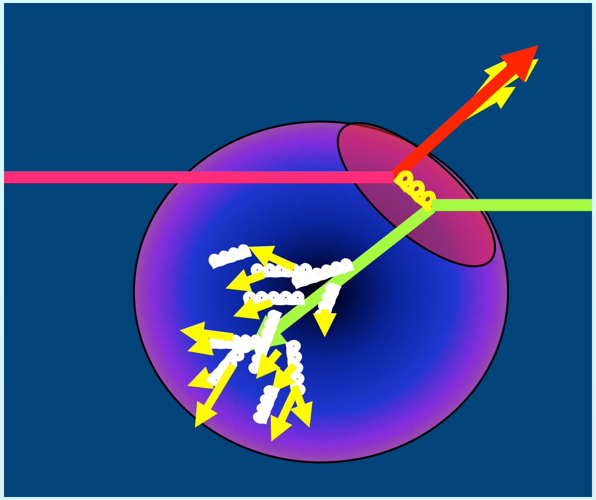


radiated gluons thermalize in medium (i.e. they're gone!)



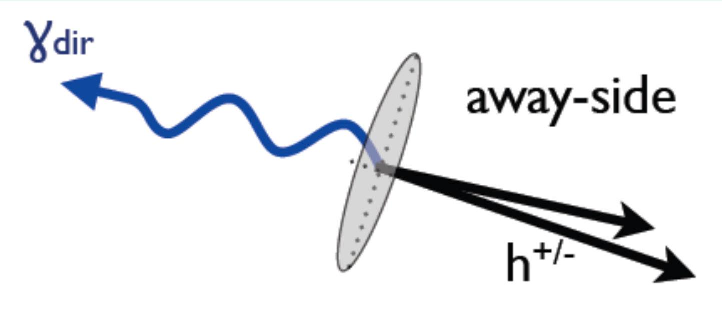
remain correlated with leading parton, but broaden/change jet

Jet Fragmentation function



$D(z) = 1/N_{jet}\, dN(z)/dz;\; z = p_{had}/p_{jet}$

Measure: count partners per trigger as fraction of trigger momentum



$z_T = p_{Ta}/p_{Tt} \sim z$ **for γ trigger**

$\xi = \ln(1/z_T)$

Modification factor similar to R_{AA}:

$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

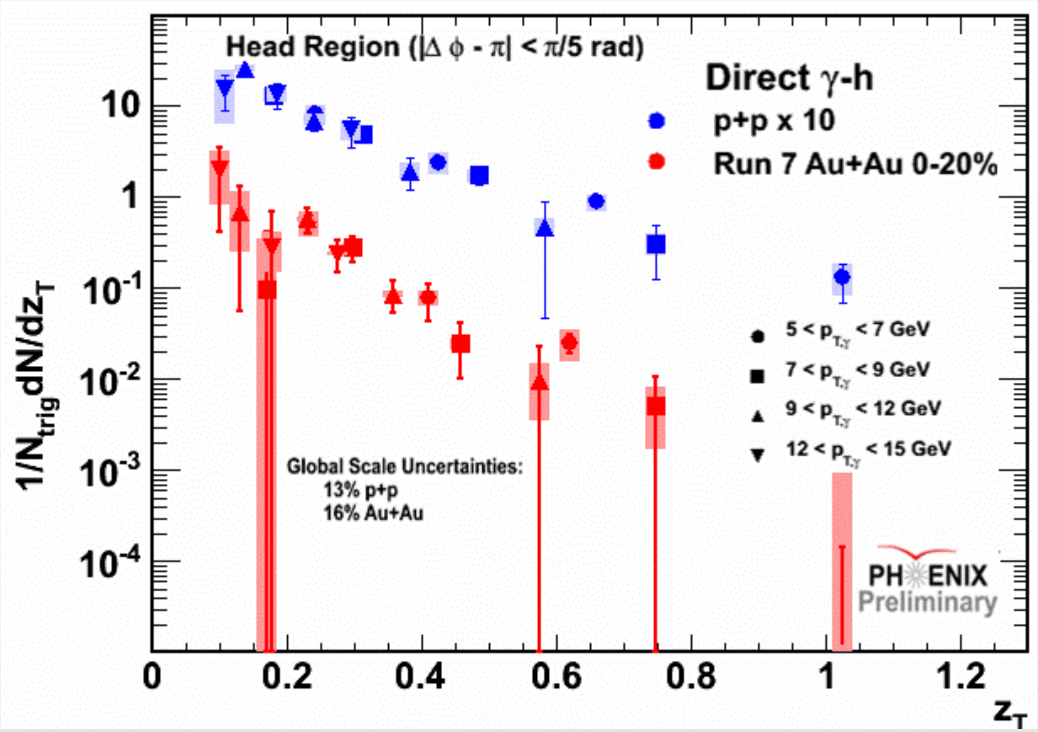
FFn experimental challenge:

measure the parton p

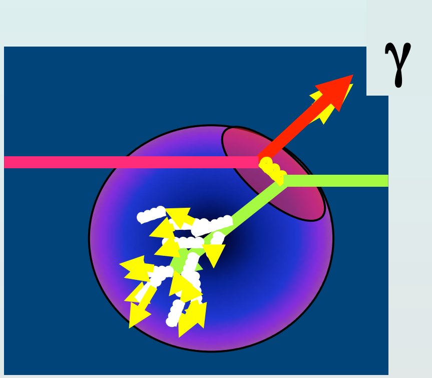
Use trigger γ or jet

What happens to the lost energy?

- **First step: tag the jet's energy**
  - **qg -> qγ**
  - **Is fragmentation of the quark into the jet of hadrons modified?**



Calibrate the probe energy: use QCD Compton process



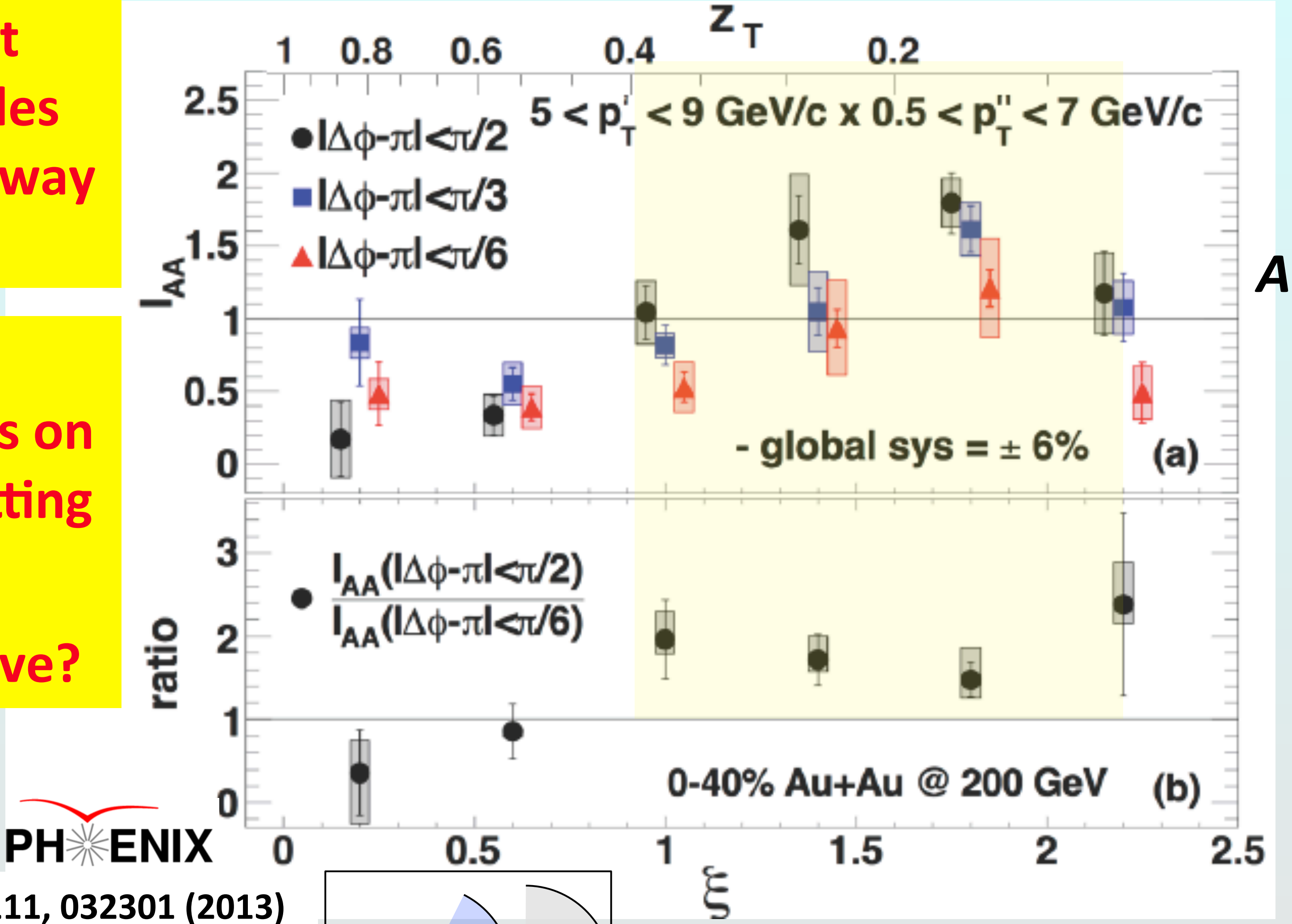
PHENIX: FFn via γ-h correlation

γ: parton energy, h: fragmentation fn.

"Extra" soft particles at larger angles near the away side jet

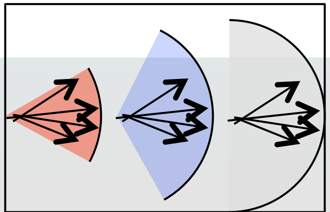
Provide constraints on gluon splitting

Perturbative?

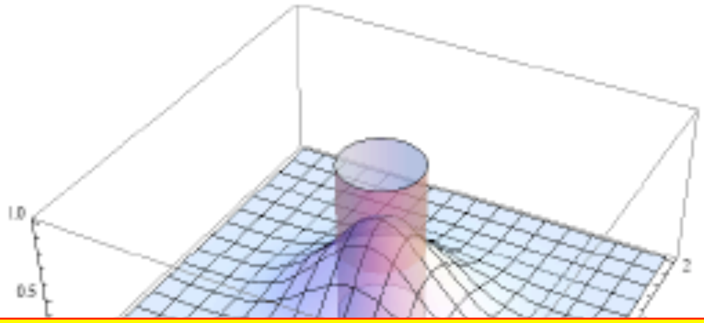


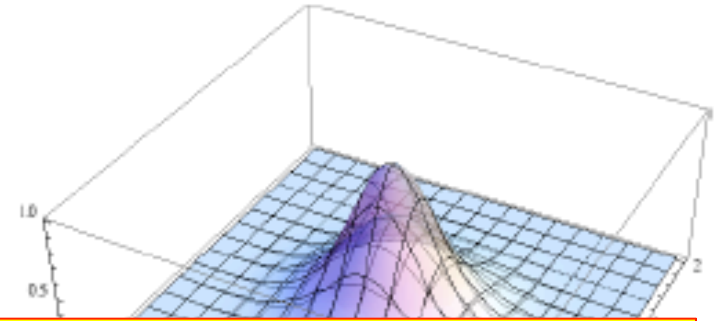
Au+Au/ p+p

PRL 111, 032301 (2013)



Jet energy collection

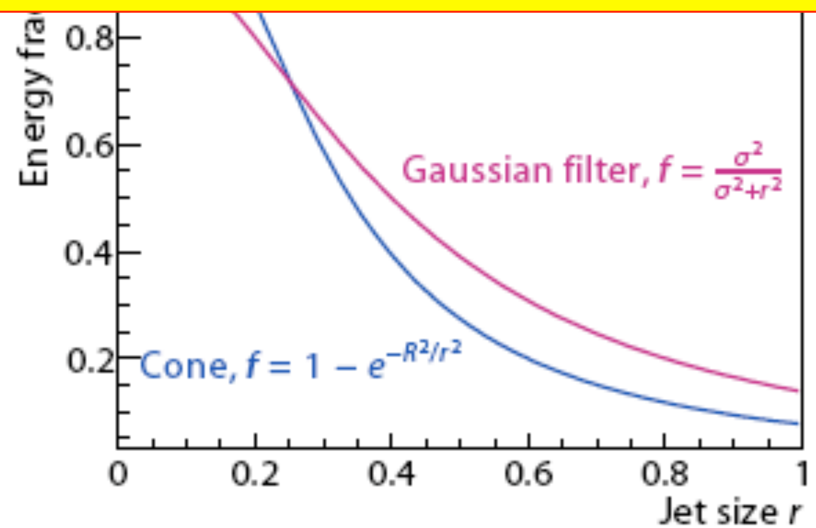




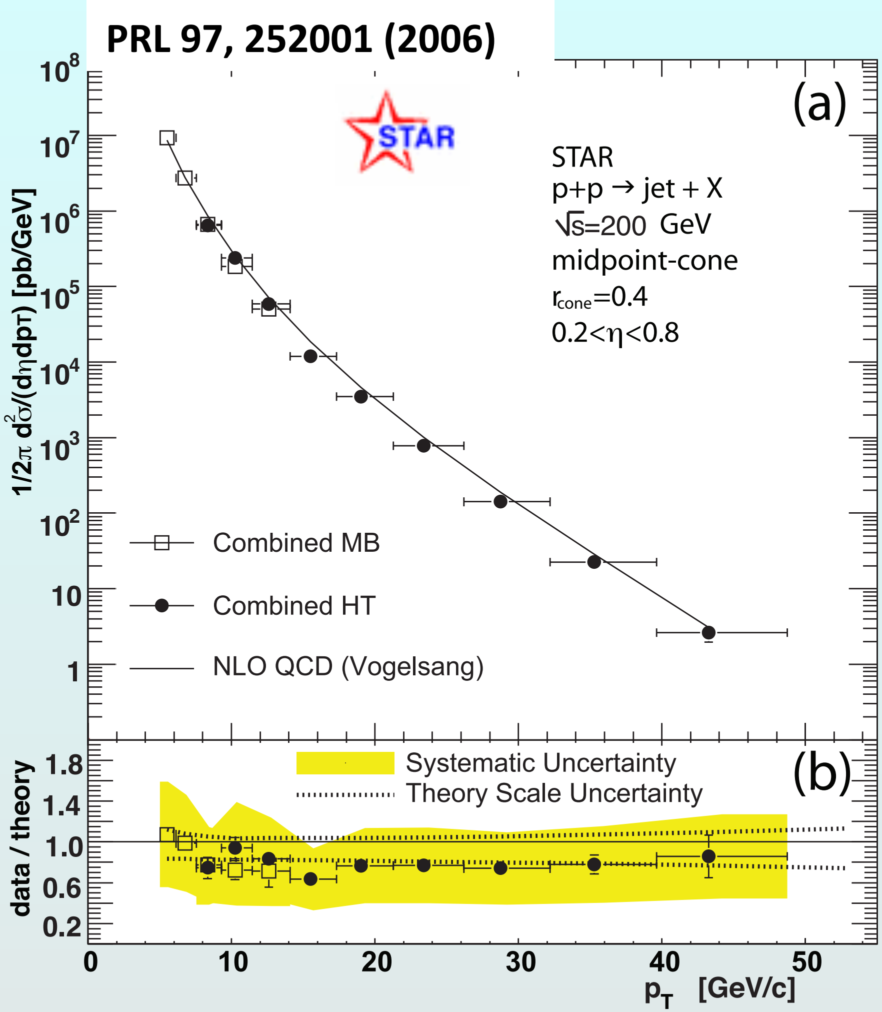
Anti-k_T algorithm: $d_{1i} = \min(1/k_{T1}^2, 1/k_{Ti}^2)\, \Delta_{1i}^2/R^2$

Distance between hard particle 1 and soft particle i is determined by the p_T of the hard particle and the separation distance

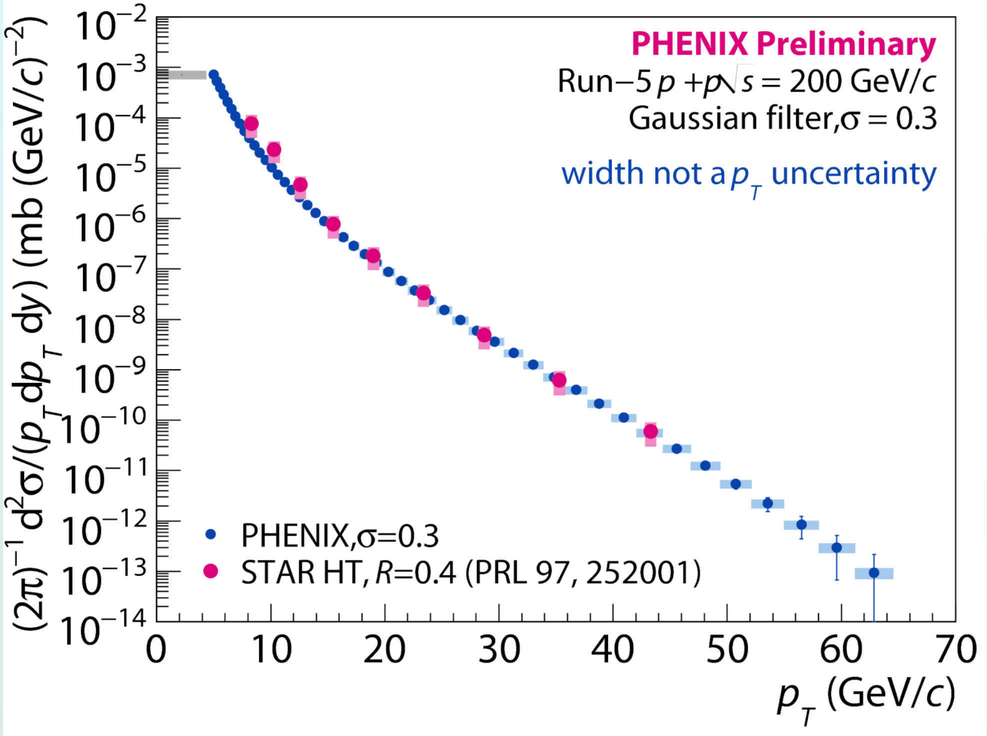
Soft particles don't modify jet shape – algorithm is infrared safe



Reconstructed jets in p+p collisions at RHIC



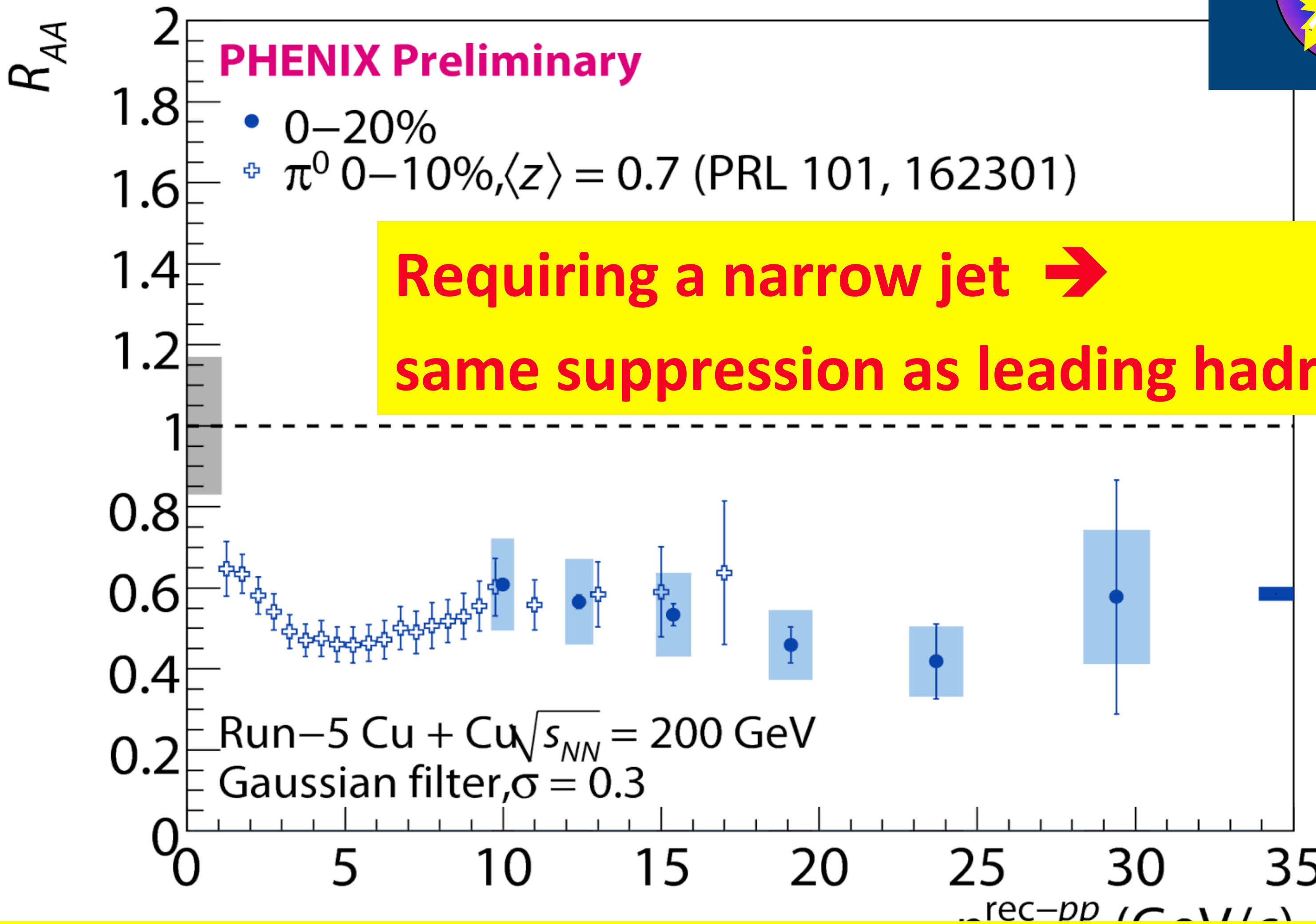
*** STAR uses reconstructed jets in p+p for a beautiful spin measurement!**

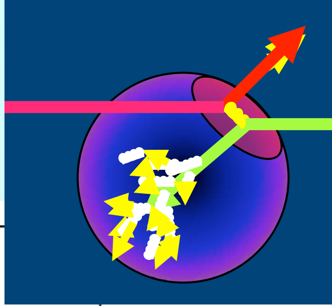


STAR jets using cone algorithm; PHENIX with Gaussian Filter

$\sigma = 0.3$ not the same as $R = 0.4$ midpoint cone, but apparently close

Reconstruct jets in heavy ion collisions



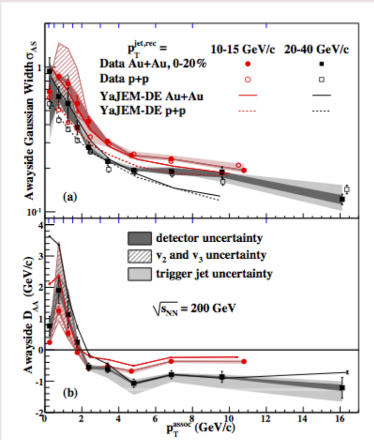


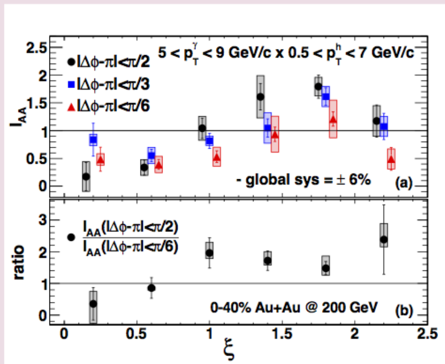
Requiring a narrow jet ➔ same suppression as leading hadron

Hard to reconcile if eloss = splitting *inside* jet cone

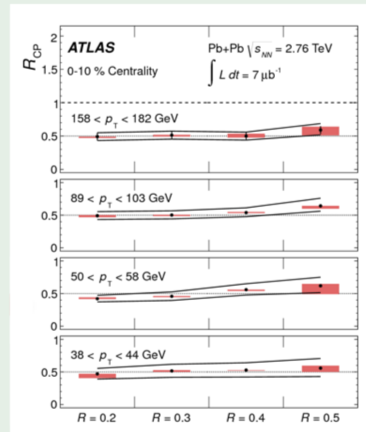
So far, we see

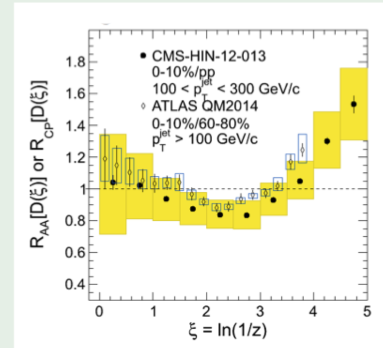
Jets @ RHIC

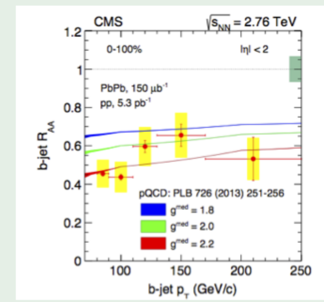


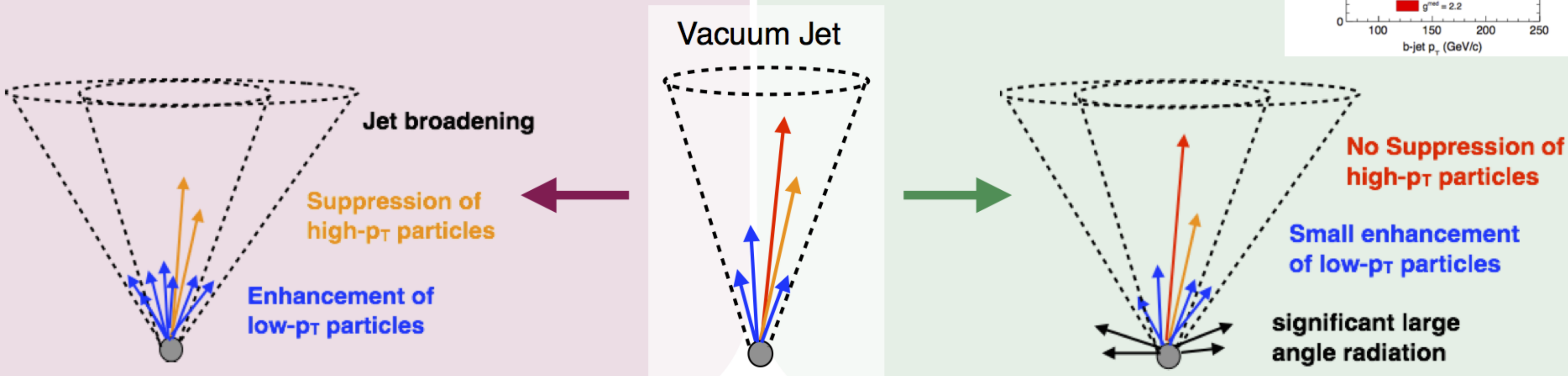


Jets @ LHC





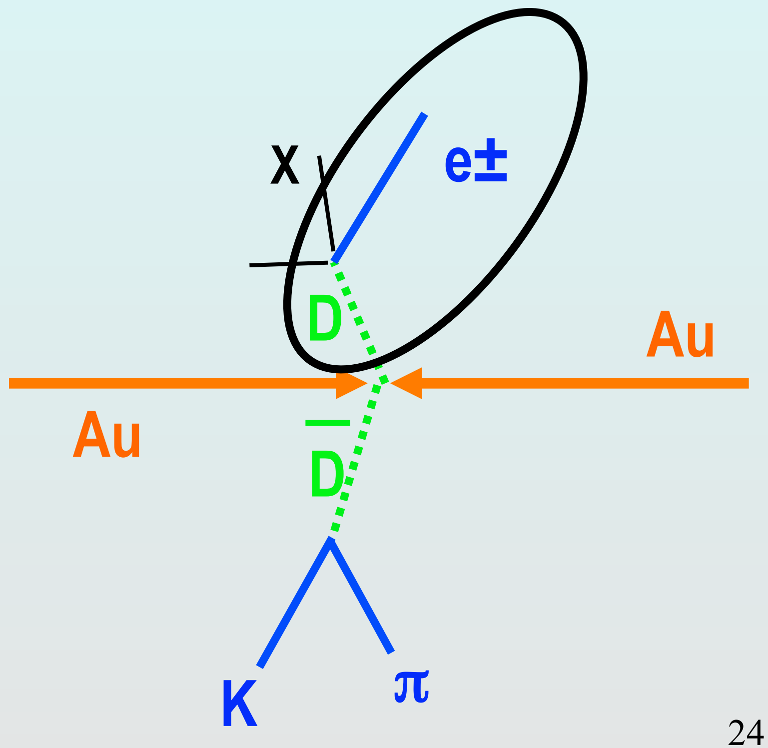




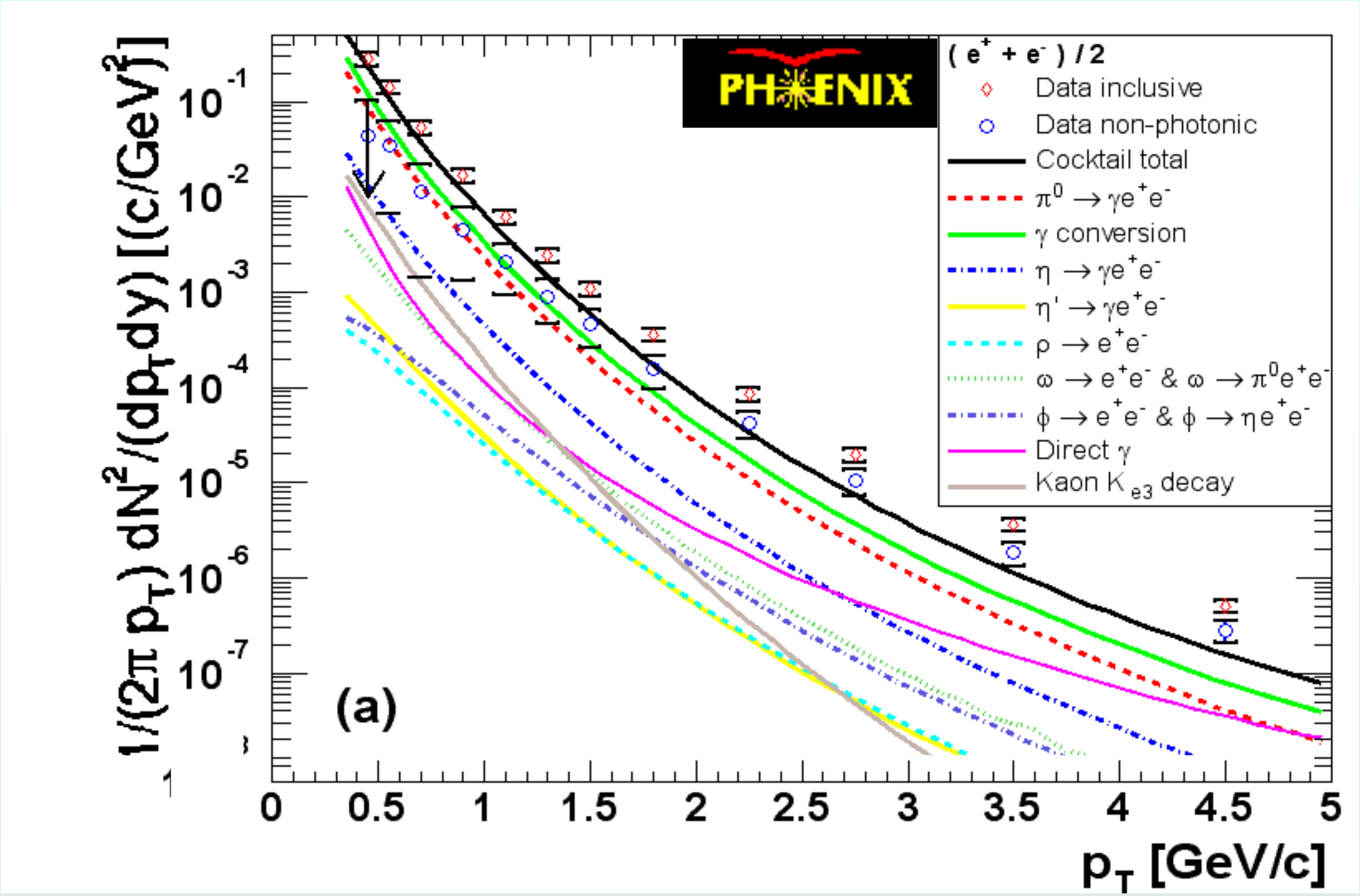
What happens to more massive probes?

- Diffusion of heavy quarks traversing QGP
  M_c ~ 1.3 GeV/c^2
- Prediction: less energy loss than light quarks
  large quark mass reduces phase space for radiated gluons
  how many collisions with light quarks???

- Measure via semi-leptonic decays of mesons containing charm or bottom quarks



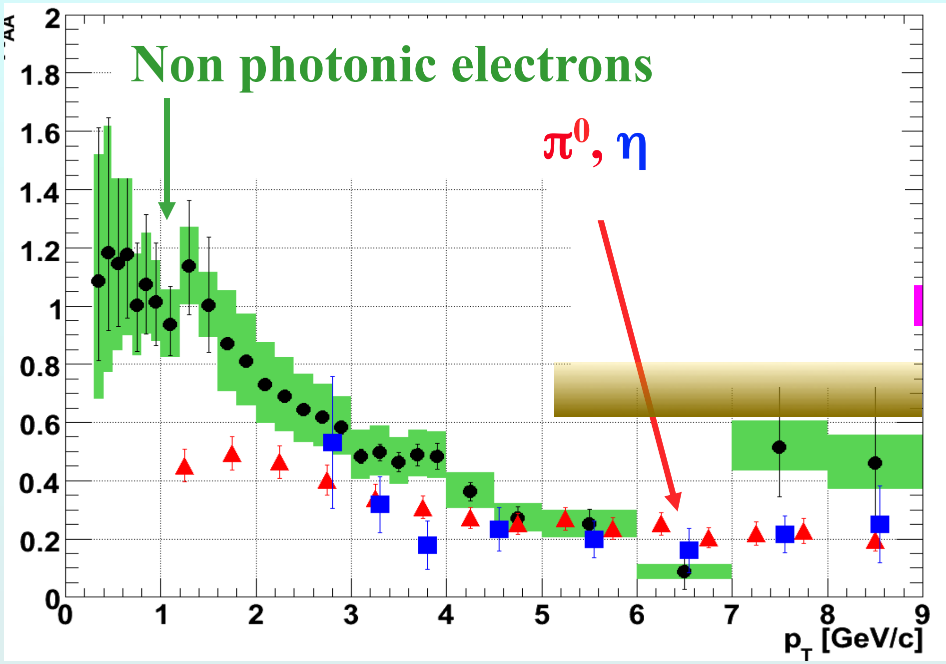
c,b decays via single electron spectrum

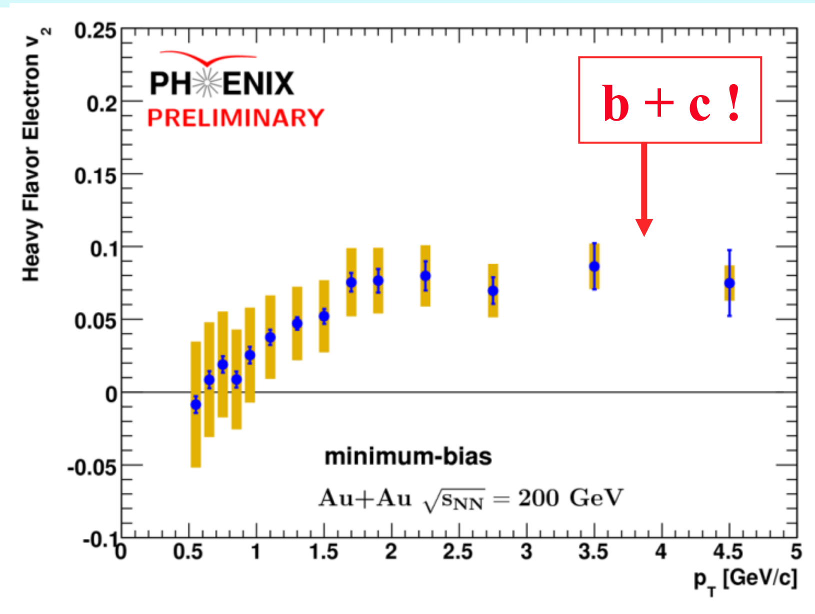


compare data to "cocktail" of (measured) hadronic decays

PRL 96, 032301 (2006)

Surprise: large heavy quark energy loss!



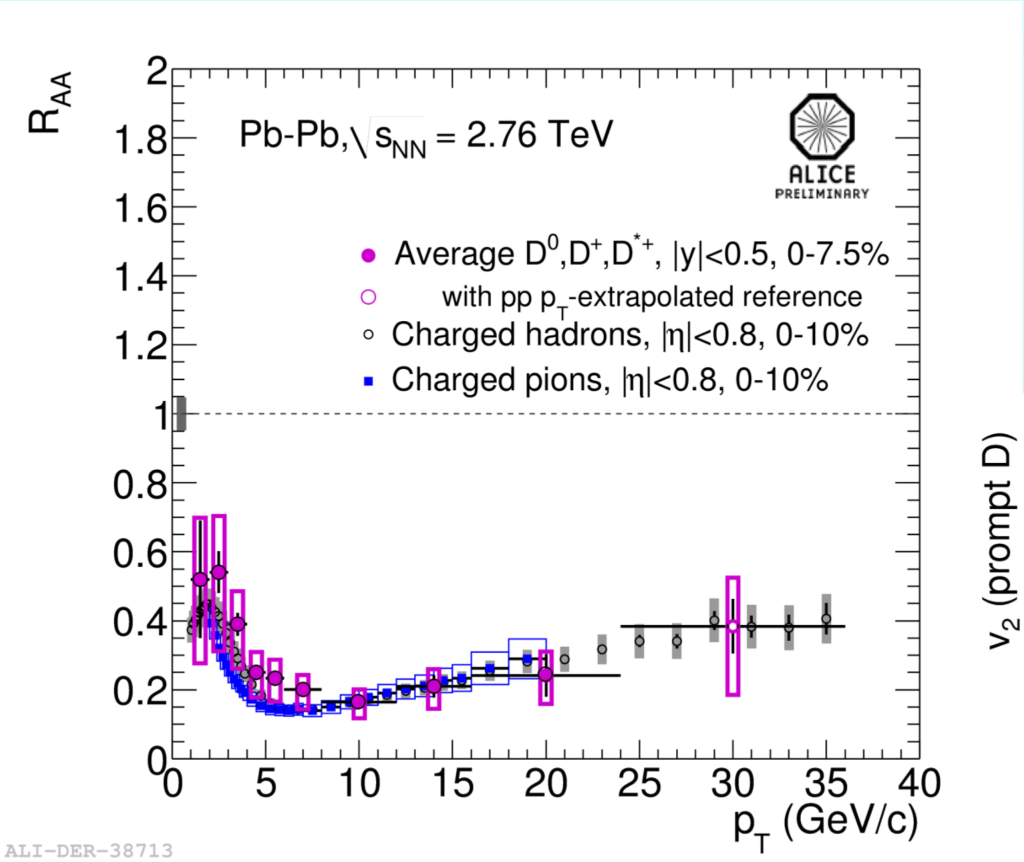


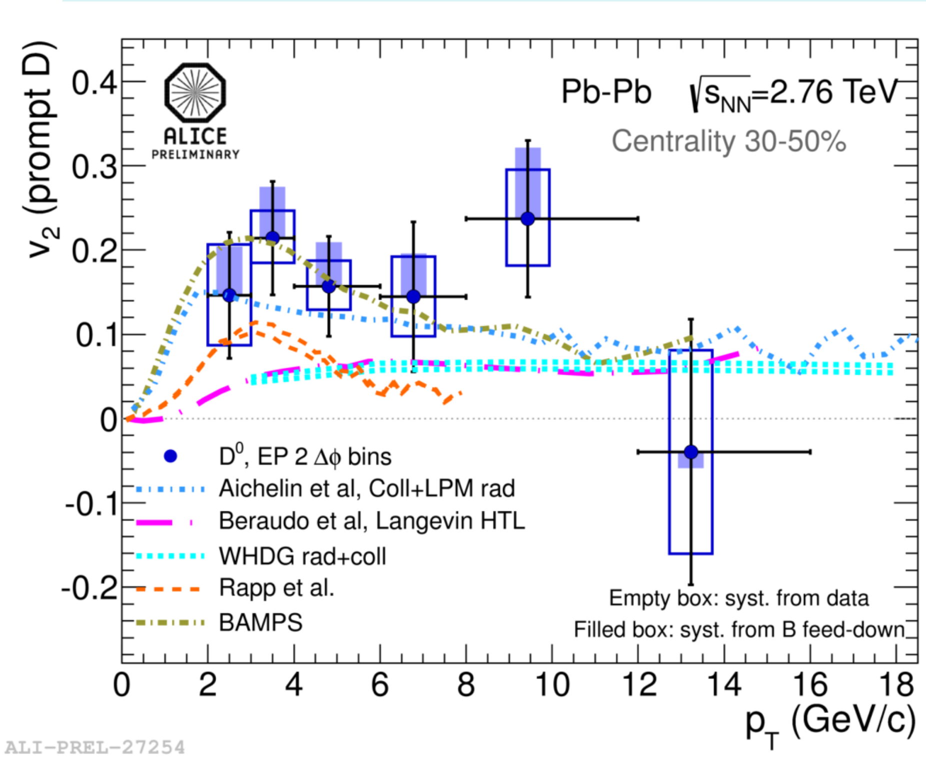
► more energy loss than gluon radiation can explain!
► charm quarks flow along with the liquid

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

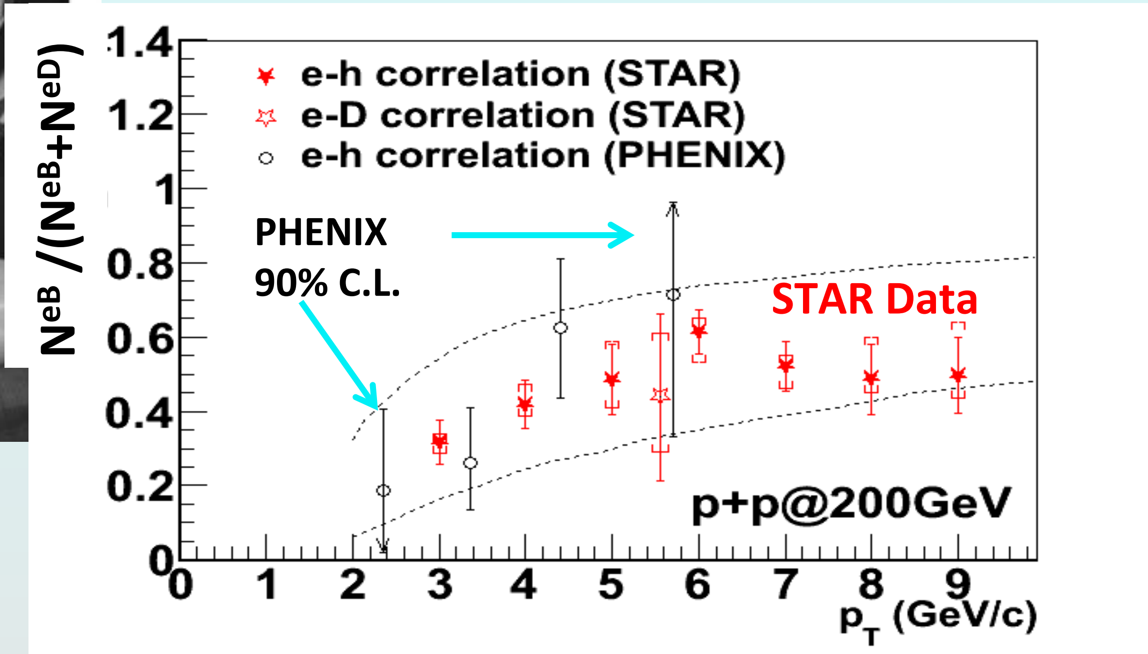




- Can reproduce energy loss and flow at both energies
- Charm quarks diffusing through strongly coupled QGP

An astounding result!

Even more surprising than you might think…



Significant fraction must be b quarks!

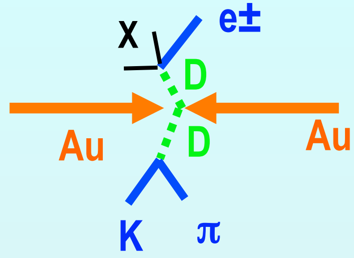
Reconstruct D and B decays to find out

- **Silicon detector arrays around beam pipe**

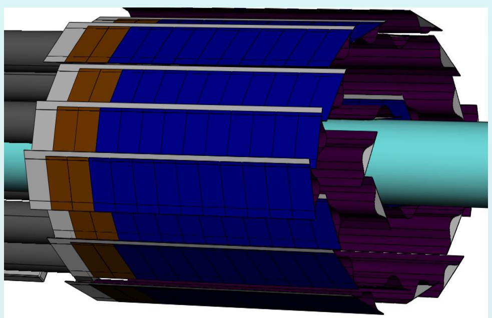
  STAR, ALICE, PHENIX

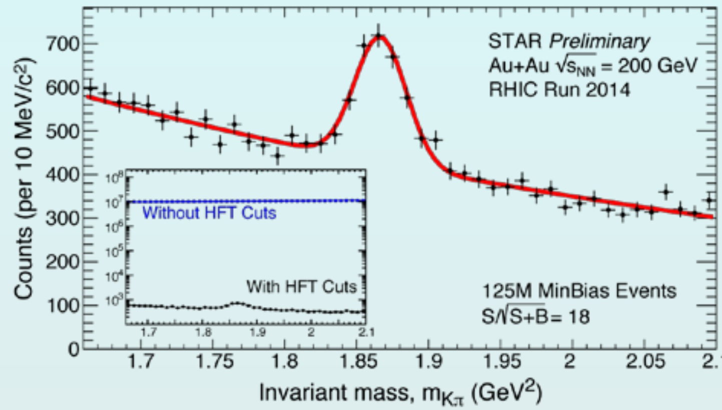
  Tag displaced vertex to separate c,b

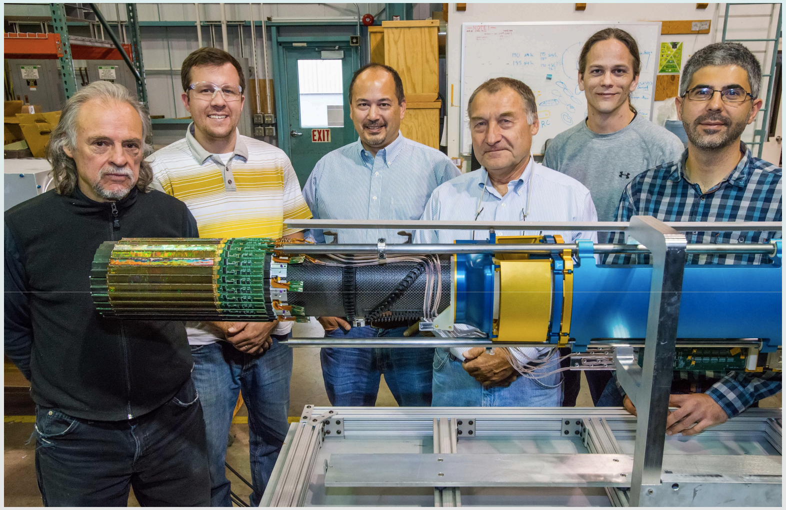
  Reconstruct D & B mesons from their decay hadrons

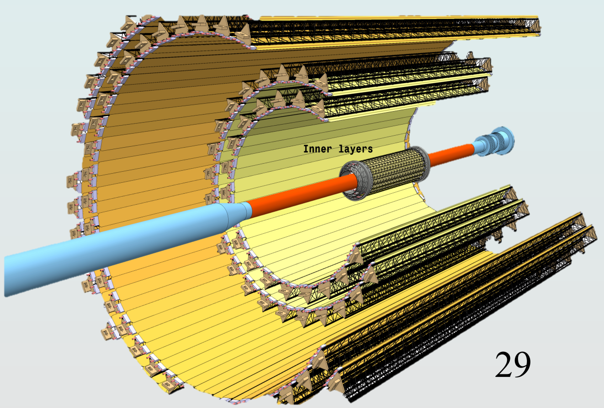


$D^{\pm}\ c\tau = 310\ \mu$









small viscosity/entropy was a surprise

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"

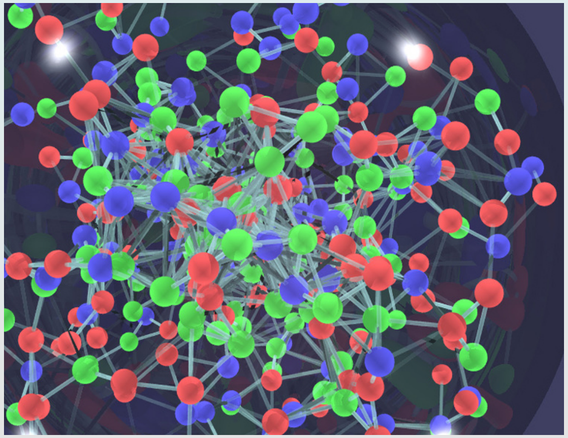
Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

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



High $m_{eff} \rightarrow$ large collisional energy loss

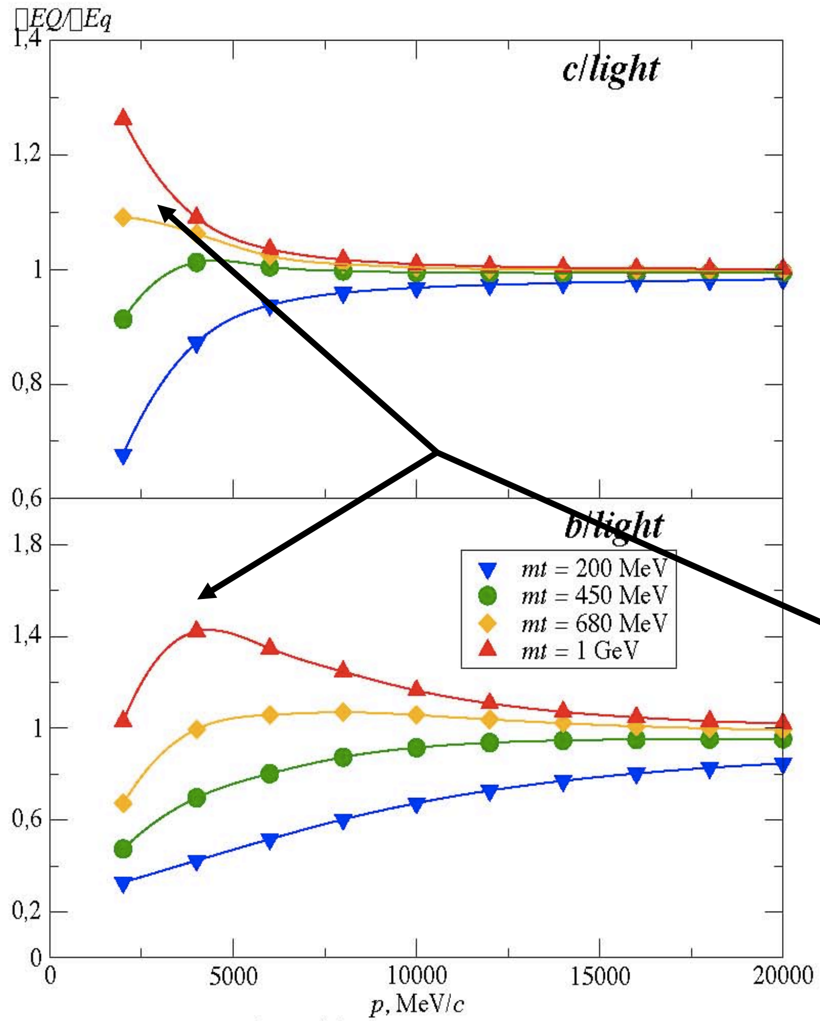


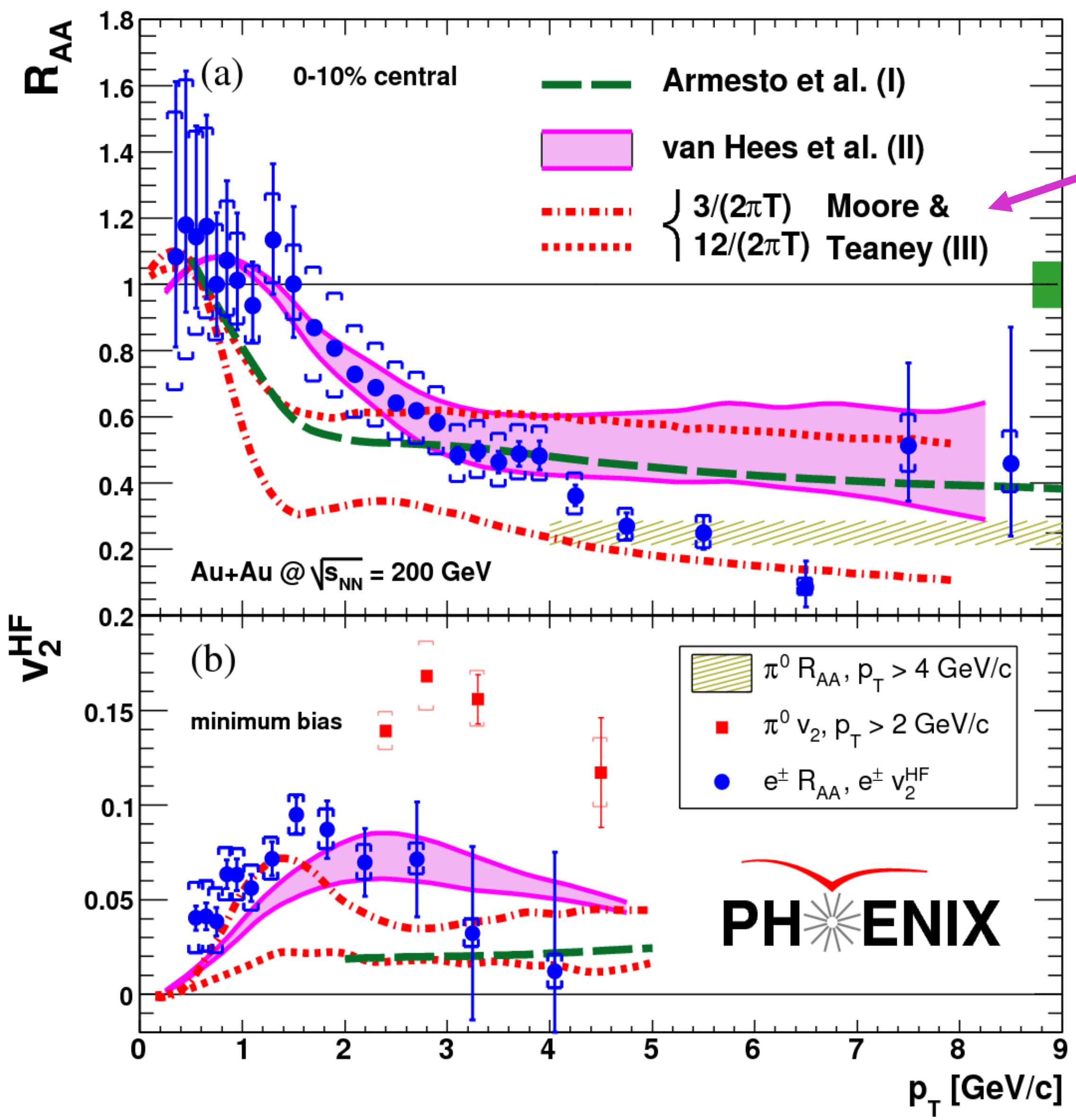
Fig. 3. The heavy-to-light ratio $\Delta E_Q/\Delta E_q$ of collisional energy loss for charm quarks (upper panel) and bottom quarks (lower panel), compared to that of light quarks (m_q = 200 MeV). The results for the numerator ΔE_Q and the denominator ΔE_q are the same as used for plotting Fig. 2.

R. Kolevatov &
U.A. Wiedemann
arXiV:0812.0270

- The "clumps"?
- b/c separation allows to test!

an independent measure of viscosity

PRL98, 172301 (2007)



Heavy quark diffusion (Langevin equation)

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

~ agrees with data
charm relaxation is fast

D ~ 4-6/(2πT)

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

→ η/S = (1.3 – 2.0)/ 4π

- **backup slides**

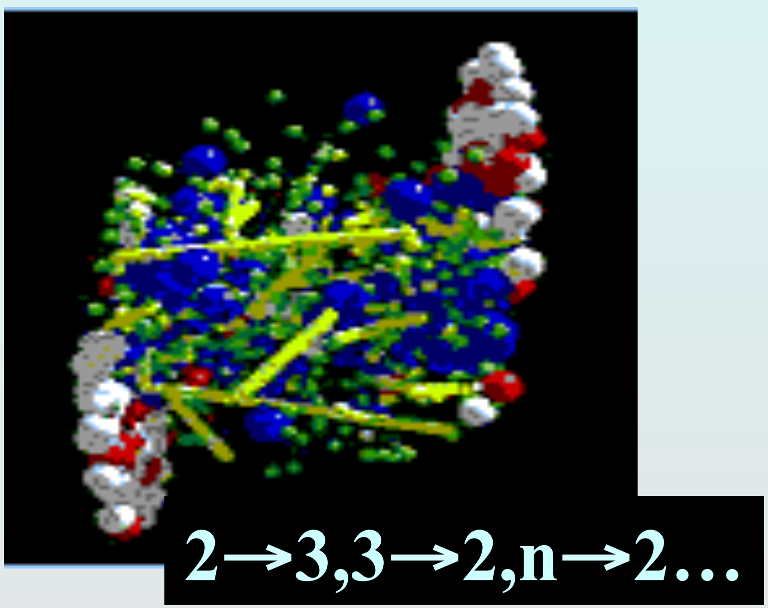
Calculating transport in QGP

weak coupling limit

perturbative QCD

kinetic theory, cascades

interaction of particles

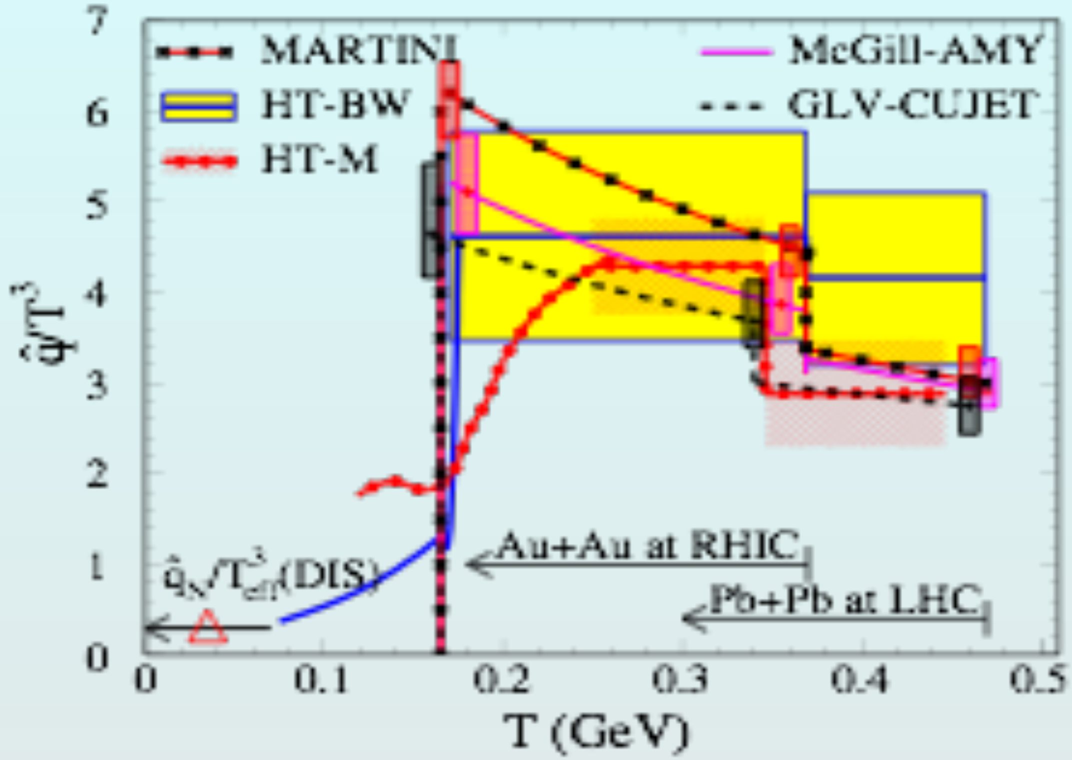


∞ strong coupling limit

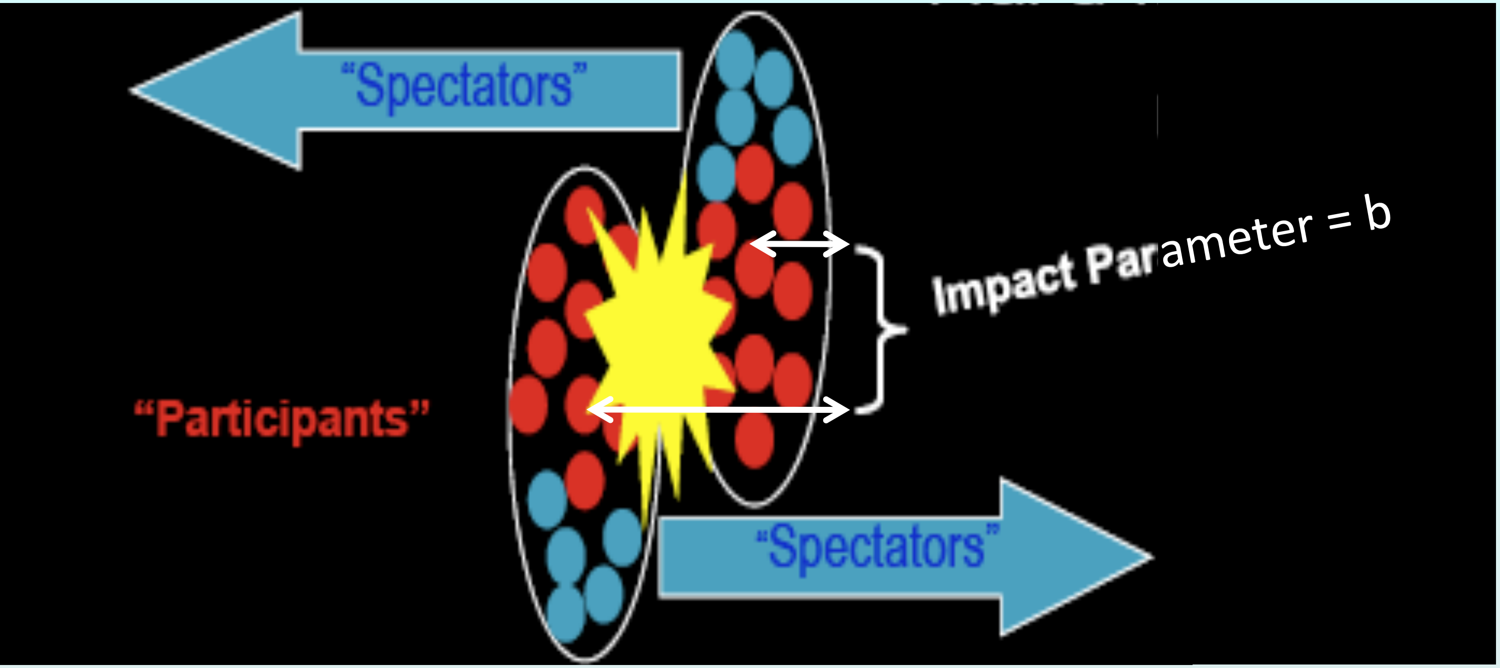
not easy! Try a pure field…

gravity ↔ supersym 4-d

(AdS/CFT)


MARTINI
HT-BW
HT-M
McGill-AMY
GLV-CUJET
$\hat{q}/T^3$
T (GeV)
$\hat{q}_N/T^3_{eff}$(DIS)
Au+Au at RHIC
Pb+Pb at LHC
0
1
2
3
4
5
6
7
0
0.1
0.2
0.3
0.4
0.5

Geometry



Use Glauber model of nucleons in the nucleus

calculate # of participant nucleons N_{part}

# of binary NN collisions N_{coll}

Using the duality

Anti de-Sitter/Conformal Field Theory Correspondence

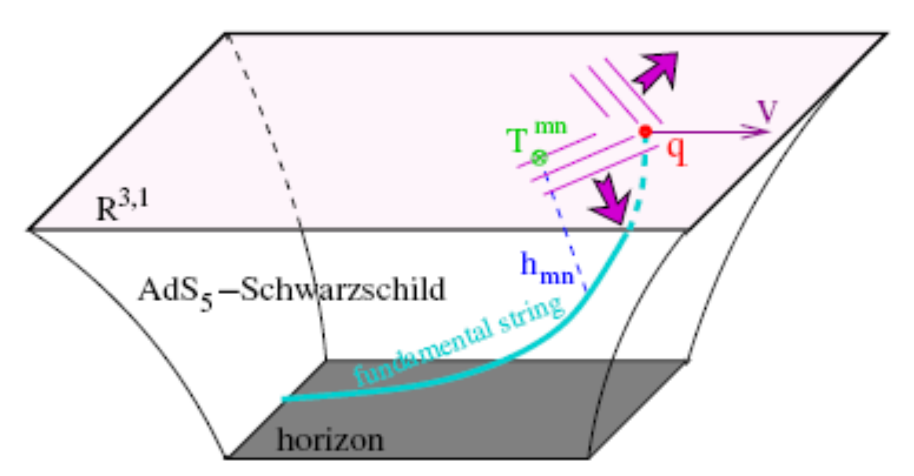
N=4 Supersymmetric Yang-Mills theory - a field theory similar to QCD ⟷ **Weakly coupled type IIB on AdS_5xS^5 Dual to gravity near a black hole**

Maldacena

Predict properties of strongly coupled systems ($\eta/s \geq 1/4\pi$) & non-equilibrium processes (e.g. energy loss)

"easy" to calculate evolution of stress-energy tensor

Applied to strongly correlated electron systems, too



Son, Policastro, Starinets; Gubser