What can we learn from/about QCD energy loss?

(From an experimentalists point of view)

Marco van Leeuwen,
Utrecht University

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Universiteit Utrecht

What can we expect to learn?

- Understand in-medium fragmentation
- Use this understanding to measure medium proporties (density, temperature)

WARNING: This is not applied physics

NO need to 'model everything' – Need to address fundamental questions about QCD

- 'perturbative': radiation, coupling between hard partons and medium
- 'strongly coupled': fundamental insights about bulk matter and confinement (poss. including hadronisation)

Parton energy loss – generic interpretation

Parton spectrum | Energy loss distribution | Fragmentation (function)

$$\left.\frac{dN}{dp_T}\right|_{hadr} = \left.\frac{dN}{dE}\right|_{jets} \otimes P(\Delta E) \otimes D(p_{T,hadr}/E_{jet})$$

known pQCDxPDF | extract | \`known' from e^+e^-

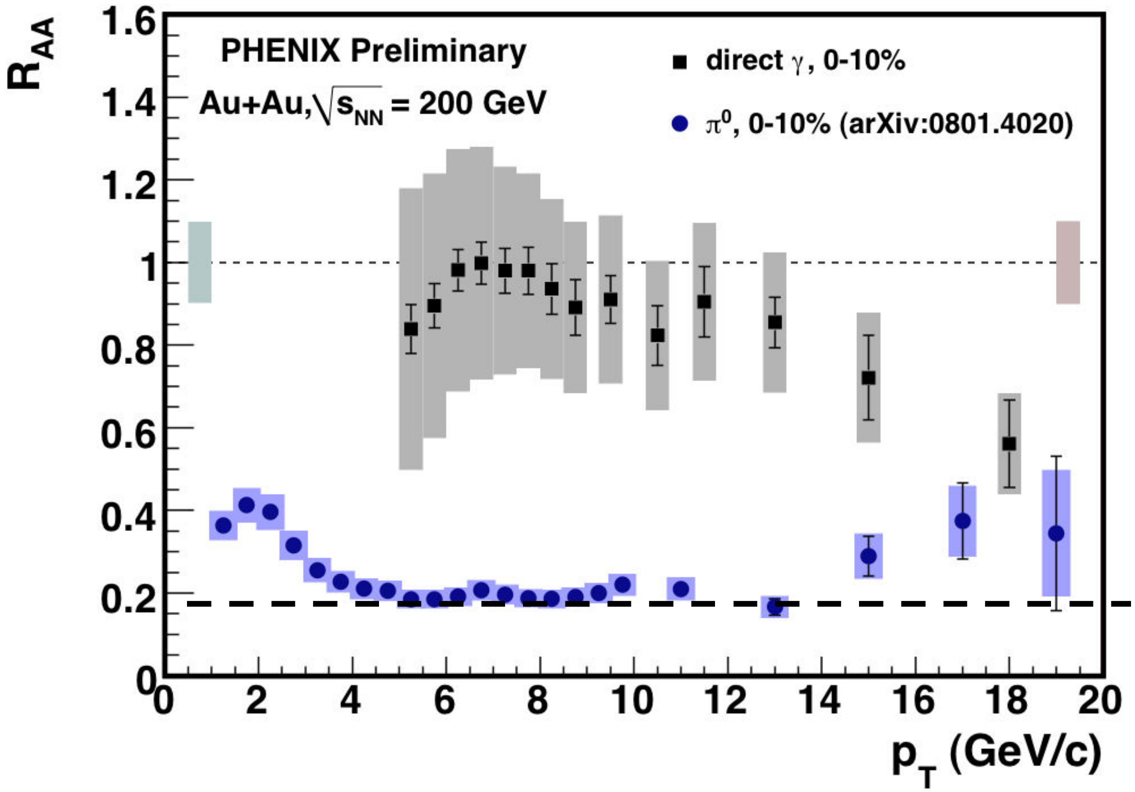
This is what we are after

P(ΔE) combines geometry with the intrinsic process – Unavoidable for many observables

Notes:

- This formula is the simplest ansatz – Test this one first unless good counter-arguments
- Analogous 'formulas' exist for other observables, e.g. di-hadrons, jet broadening, γ-jet

Some things we learned from R_{AA}



Suppression large $\Rightarrow$ dense medium

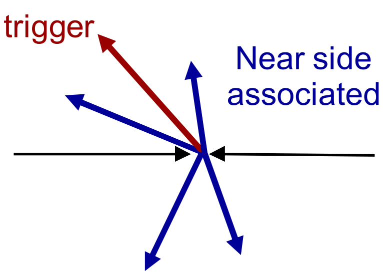
R_{AA} ~ independent of p_T at RHIC
Important fact, or coincidence?

Black-white scenario, power-law+constant fractional loss, or complicated interplay?

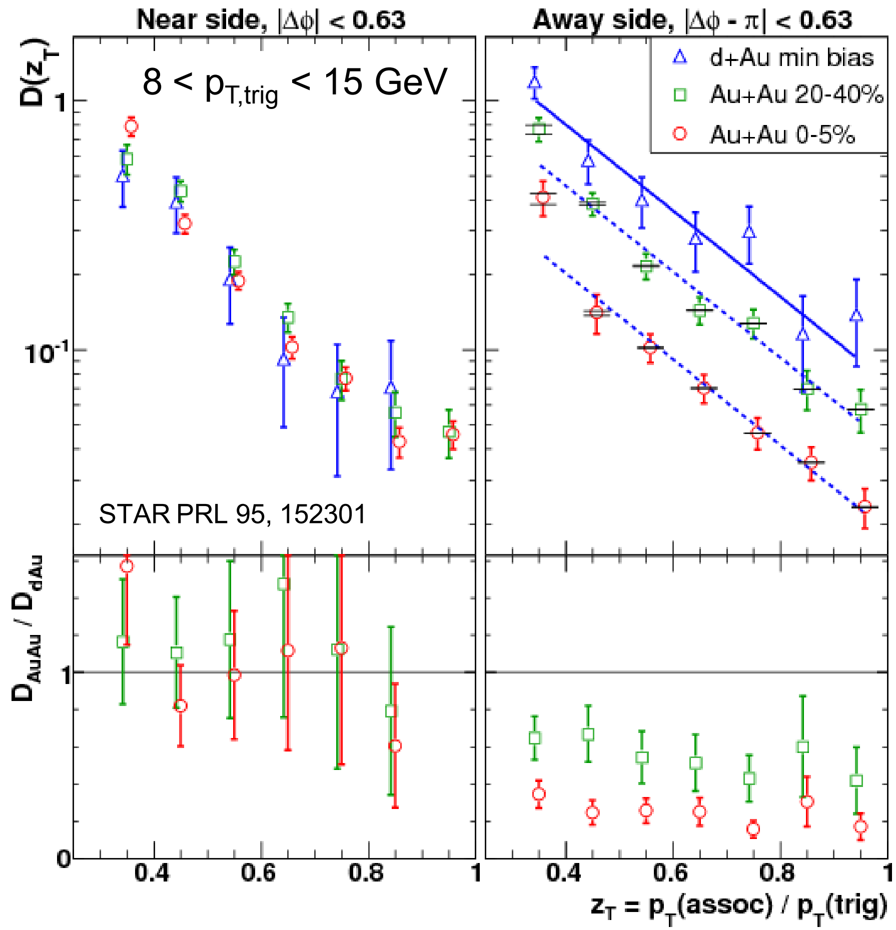
Some things we learned from I_{AA}

Near side

Yield of additional particles in the jet

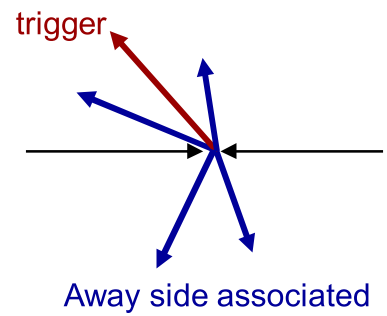


No suppression



Away side

Yield in balancing jet, after energy loss



Suppression by factor 4-5 in central Au+Au

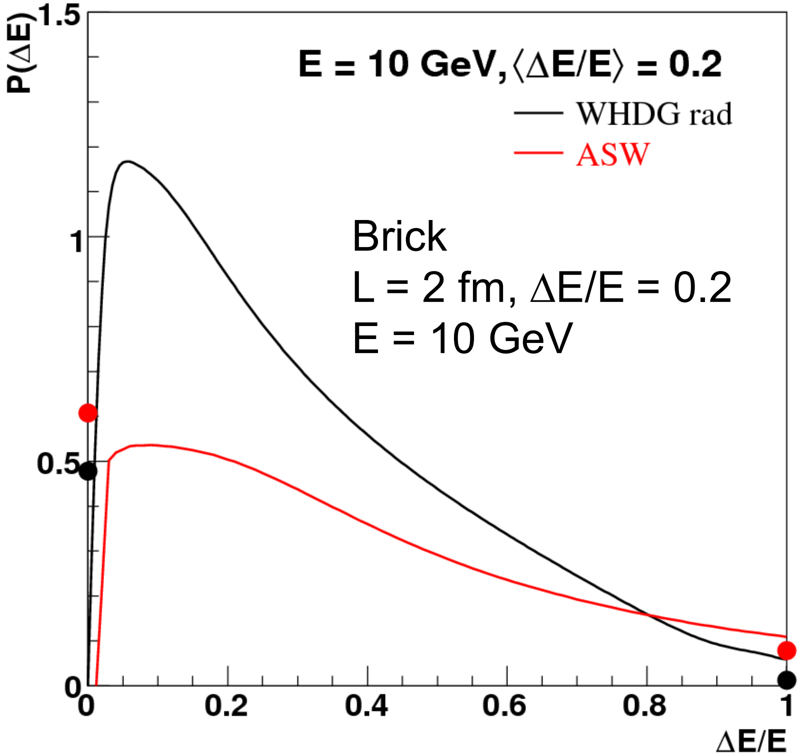
Near side: No modification ⇒ Fragmentation outside medium?

Away-side: Suppressed by factor 4-5 ⇒ large energy loss

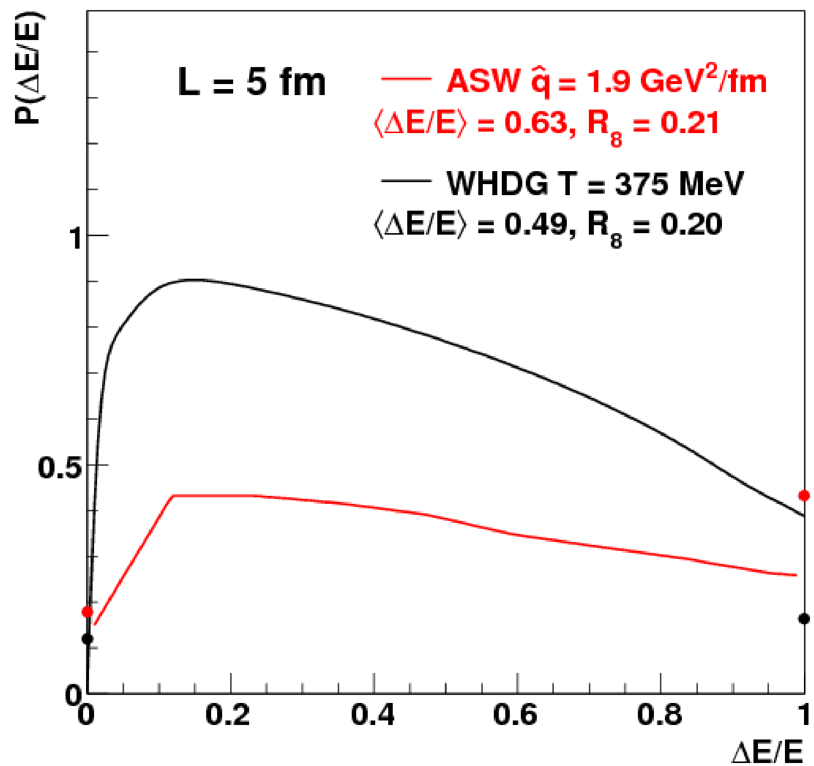
Black-white scenario, insensitive to E-loss, or complicated interplay?

Some things we learned from theory

First-guess for RHIC: ⟨ΔE/E⟩ ~ 0.2



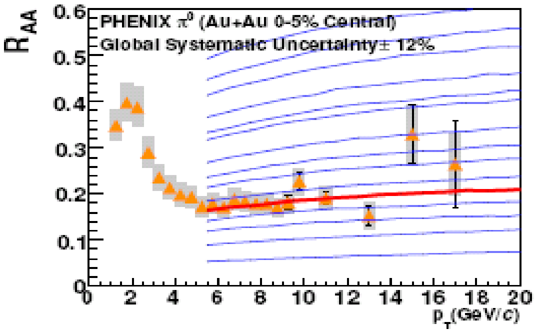
Typical for RHIC: R_8 ~ 0.2

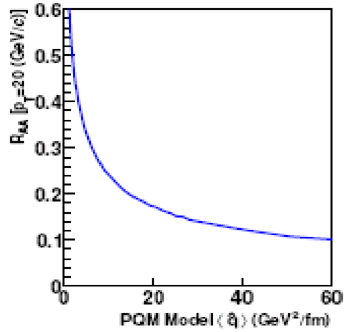


Expect P(0) + broad distribution out to large E-loss
⇒ Effectively black-white?

Round I: measure R_{AA} and extract medium properties

PHENIX, arXiv:0801.1665,
J. Nagle WWND08





PQM $\langle\hat{q}\rangle = 13.2^{+2.1}_{-3.2}$ GeV^2/fm

WHDG $dN_g/dy = 1400^{+200}_{-375}$

ZOWW $\varepsilon_0 = 1.9^{+0.2}_{-0.5}$ GeV/fm

AMY $\alpha_s = 0.280^{+0.016}_{-0.012}$

GLV, AMY: T = 300-400 MeV BDMPS: T ~ 1000 MeV

Clearly, we do not understand parton energy loss well enough to learn about the medium

Intermezzo: need a common scale

To discuss medium properties, need a common scale
Obvious choice: *T*
+ scheme to calculate relevant variables μ, λ

e.g. gluon gas, Baier scheme:

$$\mu = gT = \sqrt{4\pi\alpha_s}\,T \qquad \lambda = \frac{1}{\rho\sigma} \qquad \rho = \frac{16\cdot 1.202}{\pi^2}T^3 \qquad \sigma = \frac{9\pi\alpha_s^2}{\mu^2}$$

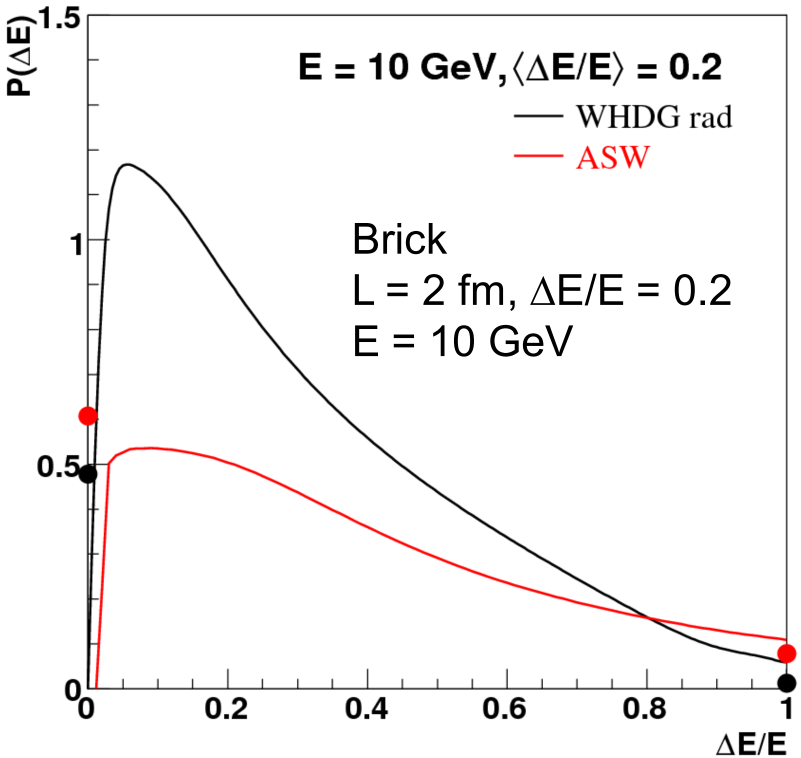
$$\hat{q} = \frac{72\cdot 1.202\,\alpha_s^2}{\pi}T^3$$

However, HTL: $\hat{q} = 3\alpha_s m_D T \ln\left(\frac{\Lambda^2}{m_D^2}\right) = 1.37\ \mathrm{Baier}\ \ln\left(\frac{\Lambda^2}{m_D^2}\right)$

Please specify exactly how you calculated!
Note: the ‘details’ are important, but common to all calculations
– a separate discussion

Find the differences...

First-guess for RHIC: ⟨ΔE/E⟩ ~ 0.2



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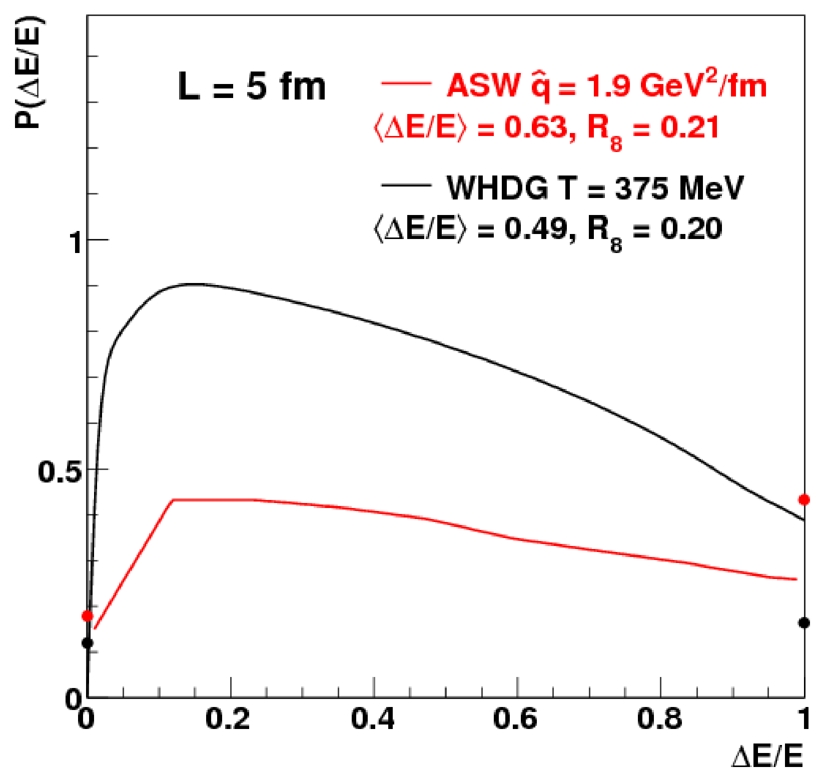


Differences not restricted to T, ρ only

For example: BDMPS, GLV give different P(ΔE)

Good: provides handle to discriminate models/theories

But how?

How to progress

Two approaches, in parallel (experiment, theory):
1) Perform new measurements to test energy loss theories
2) Identify differences between models/theories and devise tests

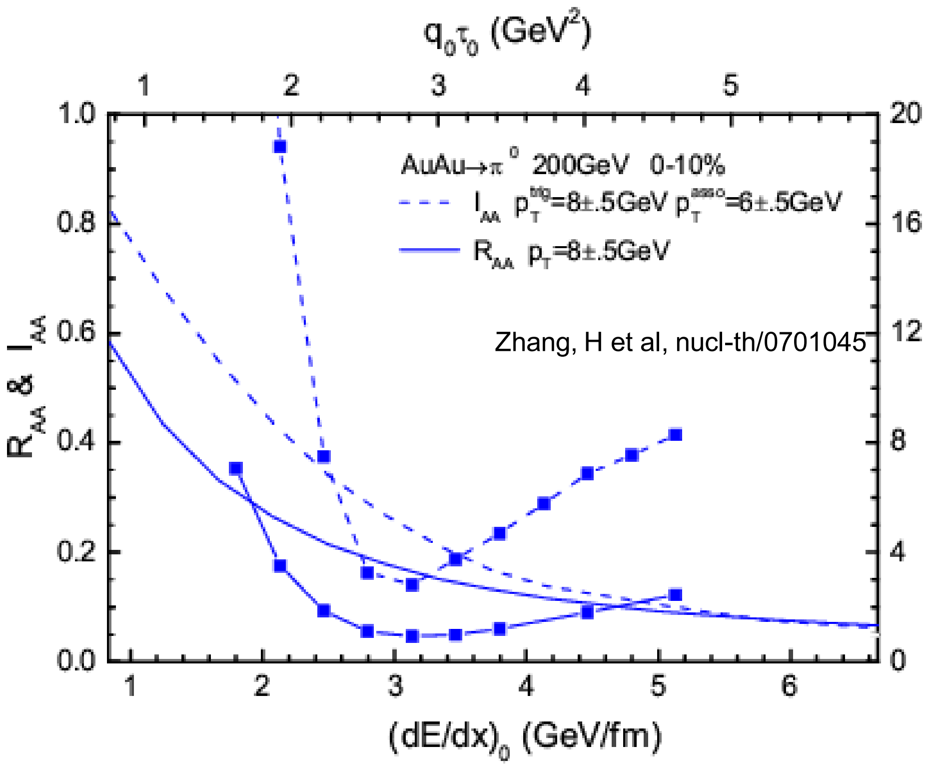
Note: complicated calculations, important to have ongoing discussion between theory and experiment

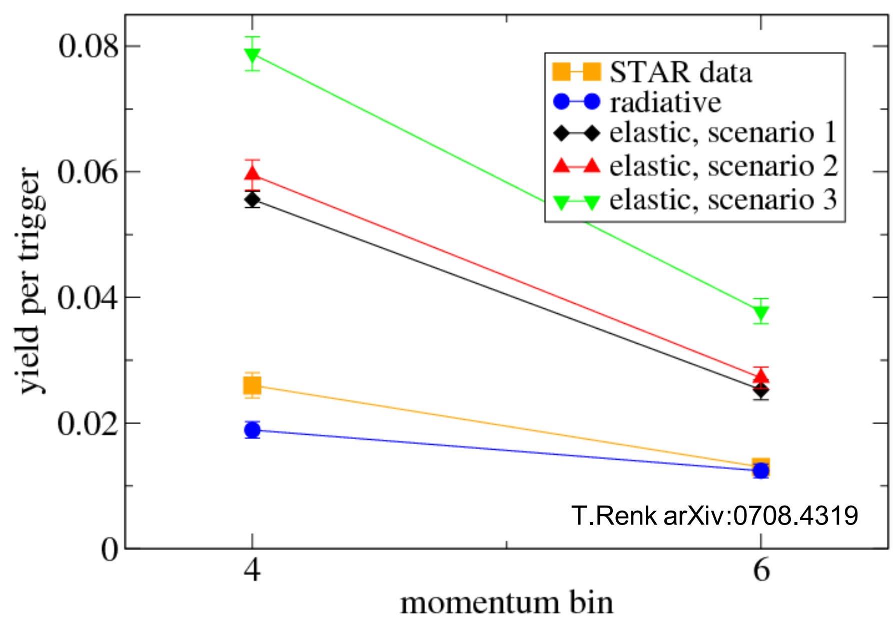
Examples:
- I_{AA}: change average over medium
- γ-hadron: mono-chromatic partons
- v_2, R_{AA} vs reaction plane: check geometry/path length dependence
- Jet-finding: change sensitivity to many aspects of E-loss

One obvious way to progress: calculate all of the above in all formalisms to see whether there is sensitivity to the differences

(somewhat brute-force…)

Round IIa: using R_{AA} and I_{AA} together





Di-hadrons provide stronger constraint on density?

N.B. update by Nagle, WWND08

Renk: elastic ∝ L does not fit R_{AA} and I_{AA} together

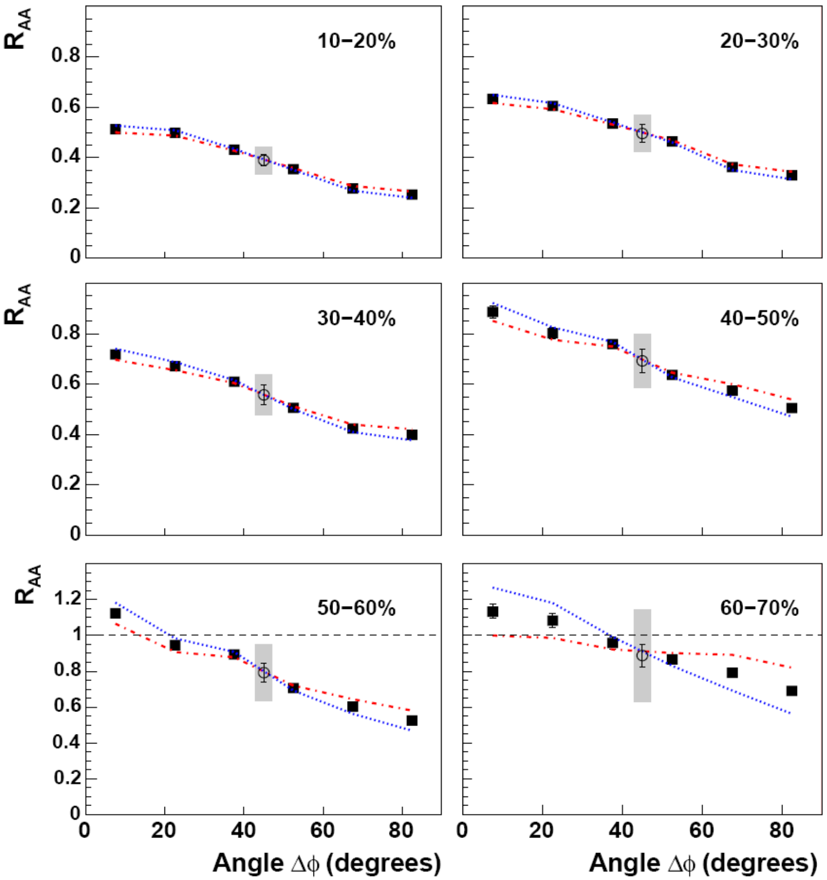
Are R_{AA} and I_{AA} consistent with one E-loss scenario?

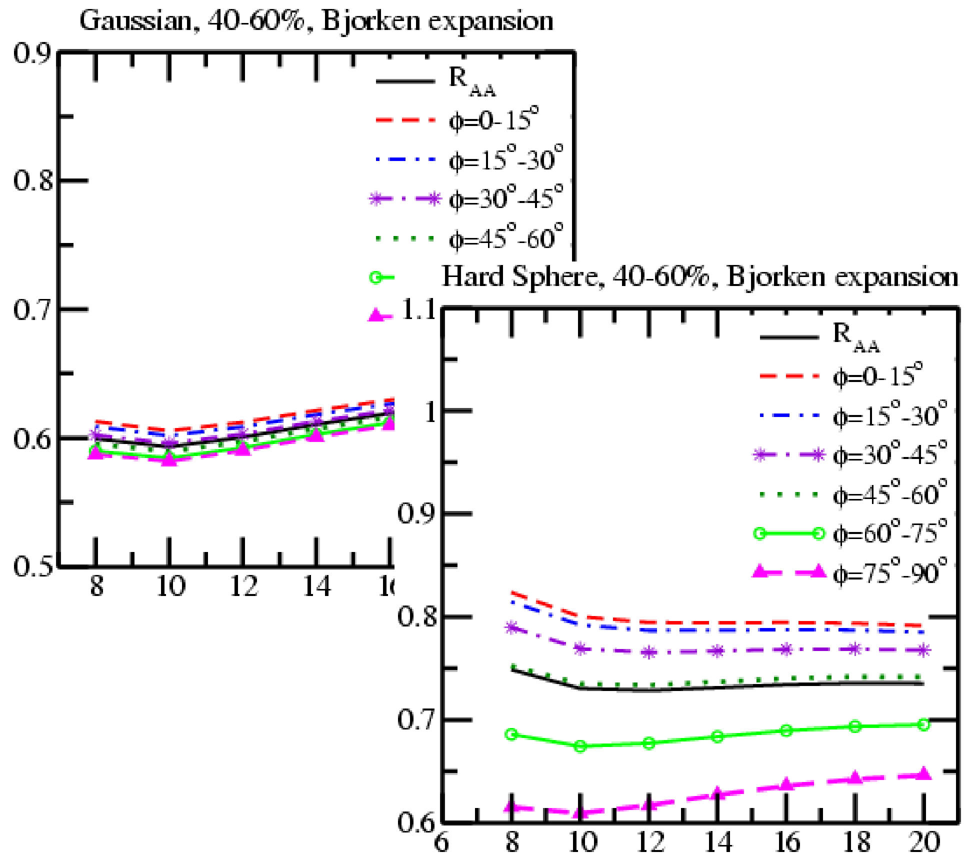
+ γ-jet?

Round IIb: measuring geometry

e.g. R_{AA} vs reaction plane

PHENIX, PRC 76, 034904





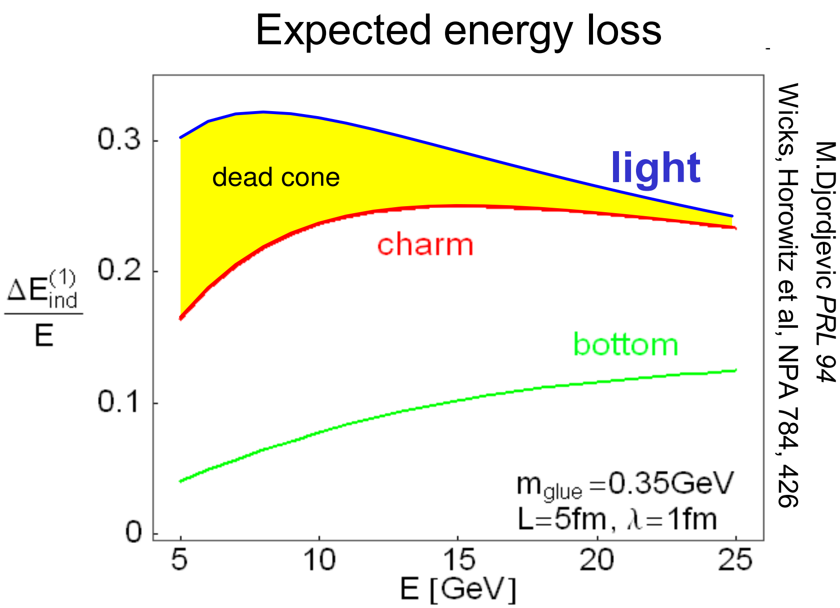
A. Majumder, PRC75, 021901

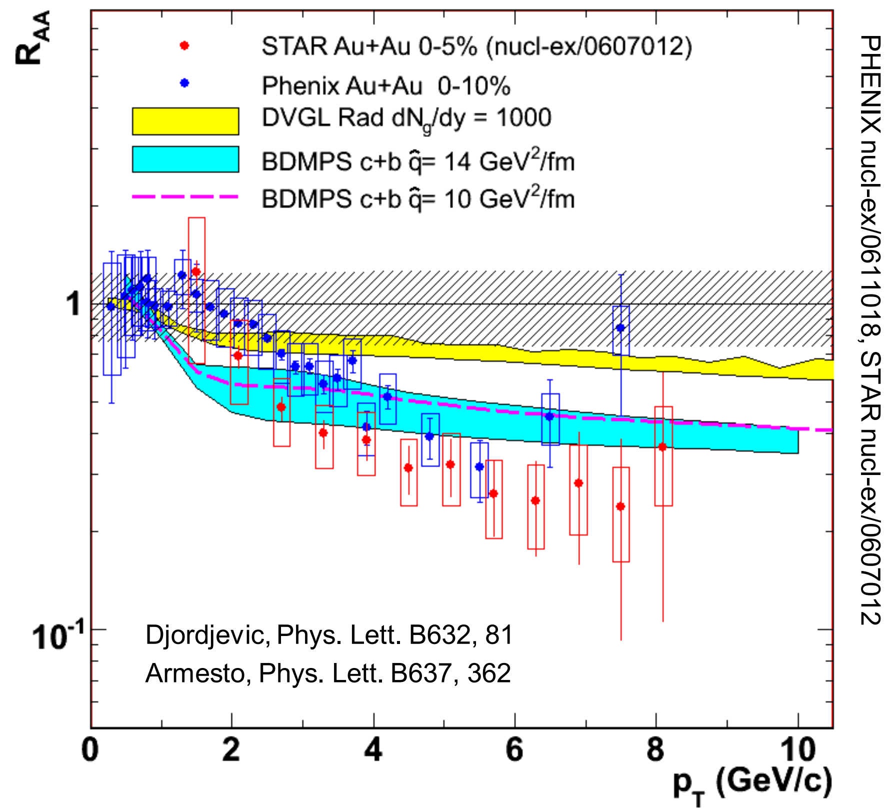
‘Measurement is done’

Module caveats about reaction plane, non-flow?

R_{AA} vs reaction plane sensitive to geometry model

Round X: heavy flavour





Idea:

Dead-cone effect: heavy quarks lose less energy

- Different probe, different sensitivity
- Important cross-check

Measured suppression larger than expected

Many items under discussion: experimental results (STAR-PHENIX discrepancy)
B/D ratio, etc

Need to understand this one before claiming victory

Too much details to discuss for this talk

Thoughts about black-white scenario

Or: Hitting the wall with P(ΔE)

- At RHIC, we might have effectively a ‘black-white scenario’
  - Large mean E-loss
  - Limited kinematic range
- Different at LHC?
  - Mean E-loss not much larger, kinematic range is?
  - Or unavoidable: steeply falling spectra

In addition: the more monochromatic the probe,
the more differential sensitivity γ-jet, jet-reco promising!

The request from experiment

Measure-everything approach not very efficient, nor satisfying

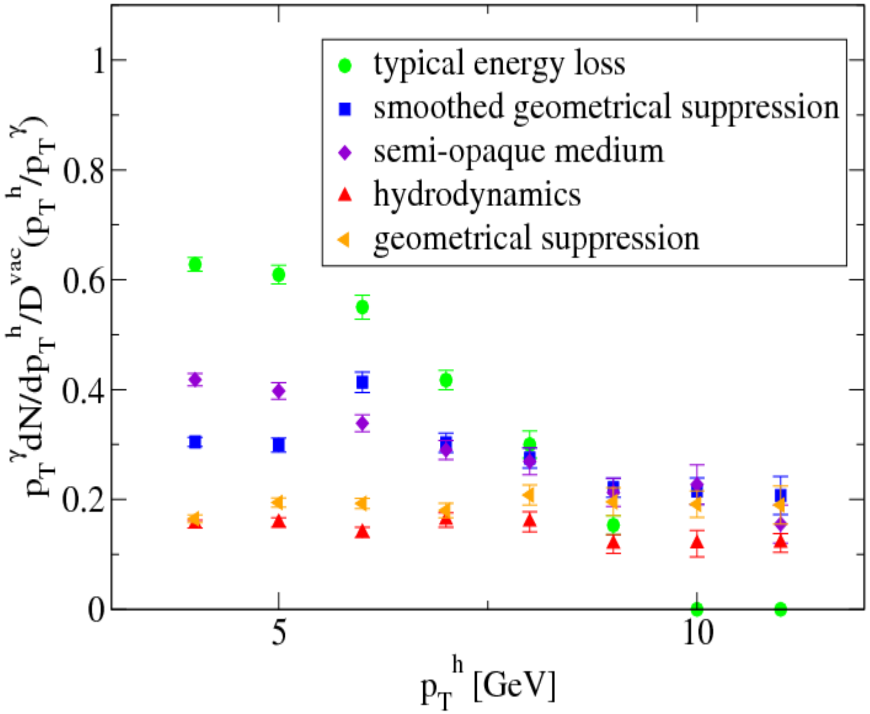
Can we narrow down the model-space?
Which observables are sensitive?

`Tell us what to measure (and how precise)’

Example of killer plot

OK, just for illustration – this one has caveats

Recoil suppression I_{AA} for γ-hadron



T. Renk

Measurement sensitive to energy loss distribution $P(\Delta E)$

Unfortunately: most scenarios in the plot already 'ruled out'

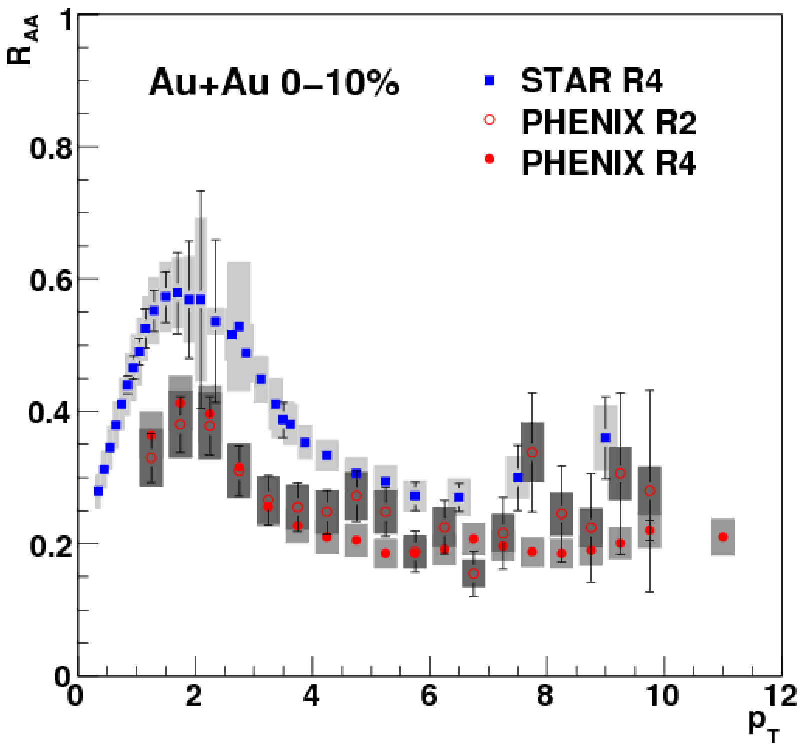
Can we come up with other candidates?

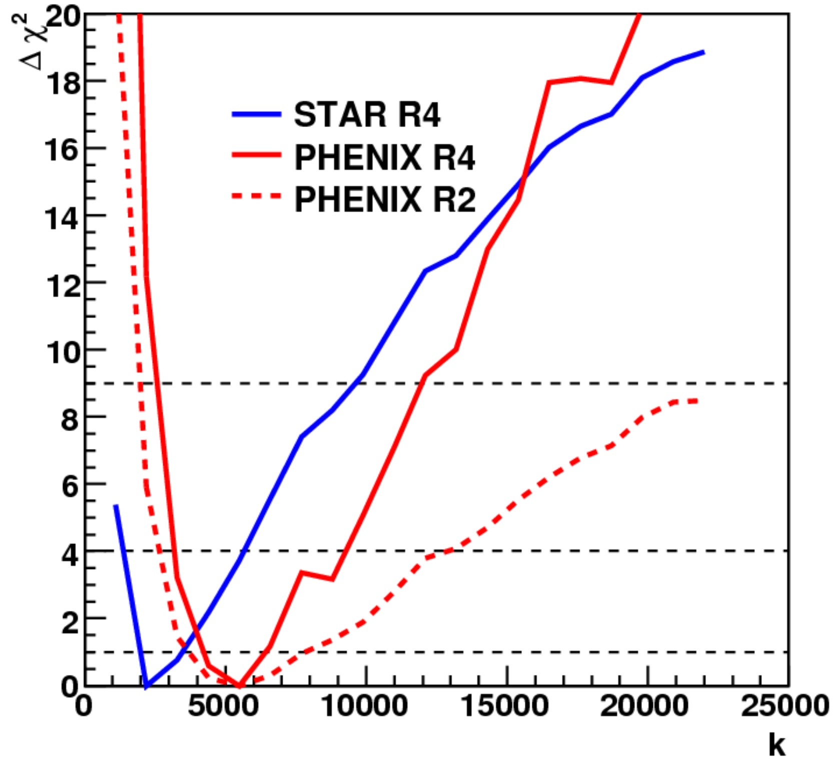
Summary

- Possible goals of energy loss measurements:
  - Understand in-medium fragmentation energy loss
  - Infer medium density
    (with specified caveats, if necessary)
- Need common scale to compare theories/models
  - Reference problem: TECHQM brick
  - Need to agree on reference scale T
- Conclusion so far: Large differences between models
  - T = 500 – 1000 MeV (my estimate, without expansion?)
- Need to identify observables that test energy loss models in more than one way
  - I_{AA}: indicates $\Delta E \propto L$ – More precise data desirable and achievable
  - γ-jet: data still fresh, limited precision
  - R_{AA} vs reaction plane, v_2: mostly test geometry (details?)
  - Jet measurements: next talks

Extra slides

Critical look at pion R_{AA} from RHIC

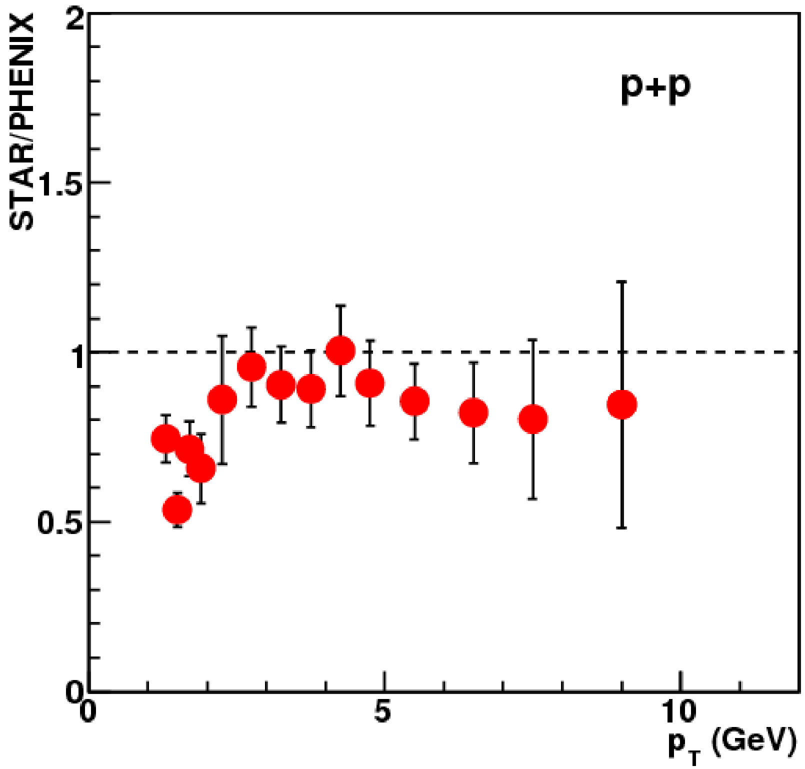


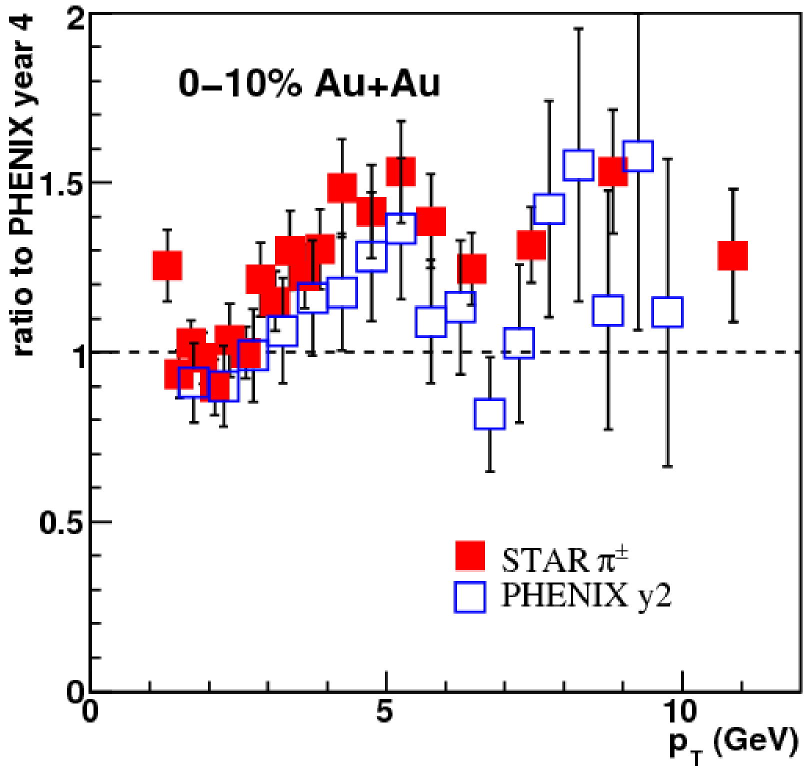


Sizable differences between STAR, PHENIX R_{AA}

Taking stat+sys together, deviation is ~2 sigma for $5.25 < p_T < 20$

STAR/PHENIX comparison

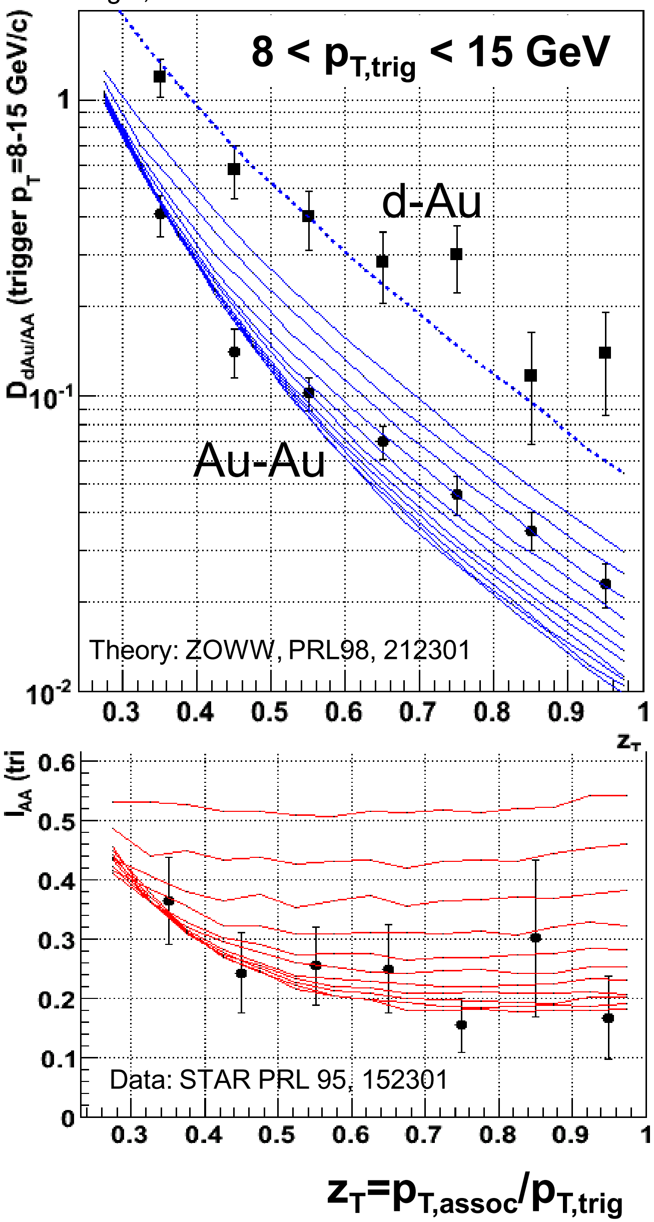


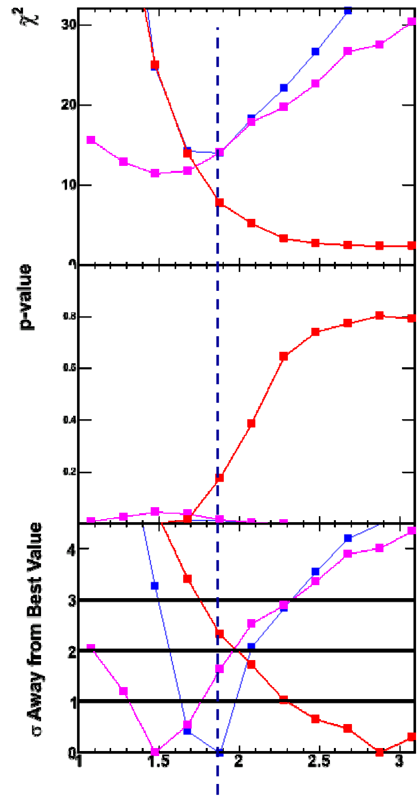


Difference sits in Au+Au result…

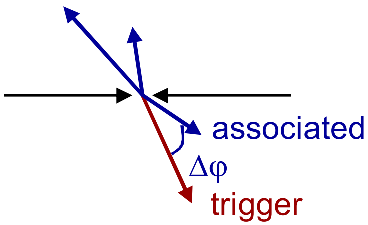
Medium density from di-hadron measurement

J. Nagle, WWND2008





ε_0=1.9 GeV/fm
single hadrons

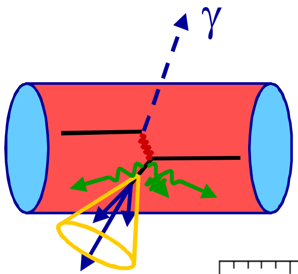


- I_{AA} constraint
- D_{AA} constraint
- D_{AA} + scale uncertainty

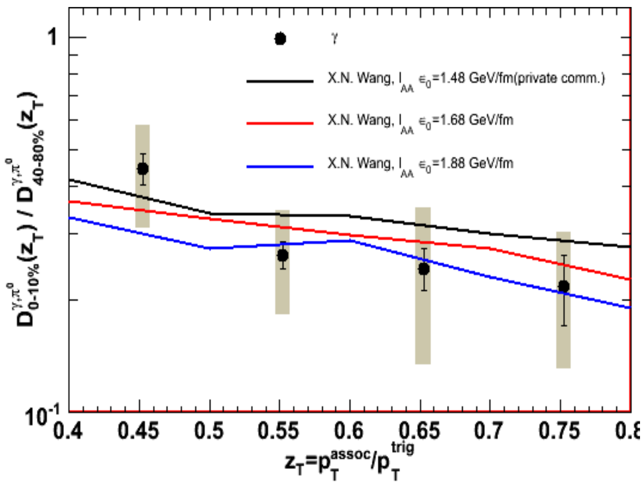
R_{AA} and I_{AA} give similar medium density in HT

What about other formalisms?

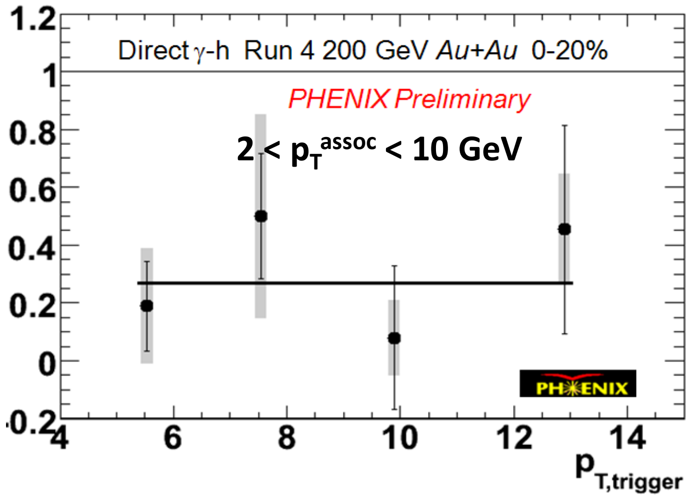
Outlook for γ-jet at RHIC



$8 < E_{T,\gamma} < 16$ GeV

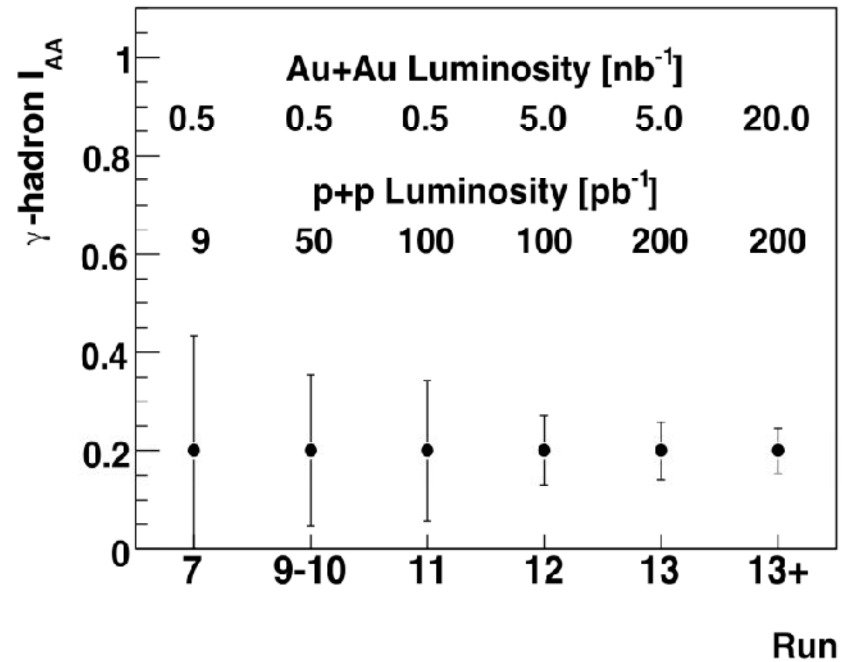


A. Hamed, Hard Probes 2008



J. Frantz, Hard Probes 2008

Projected performance for γ-hadron measurement



Current uncertainties large, improvements expected

Transport and medium properties

Transport coefficient

$\hat{q} =$ 2.8 ± 0.3 GeV²/fm

(model dependent)

$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} = 0.08 - 0.10$$

(Majumder, Muller, Wang)

pQCD: $\hat{q} \approx 2 \cdot \varepsilon^{3/4}$

(Baier)

$\varepsilon \approx 23 \pm 4$ GeV/fm³

T ≈ 400 MeV

$\varepsilon \sim 5$ - 15 GeV/fm³

T ~ 250 - 350 MeV

Viscosity

$$\frac{\eta}{s} < 0.1$$

From v_2

(see previous talk: Steinberg)

Lattice QCD: $\eta/s < 0.1$ (Meyer)

$\tau_0 = 0.3$-1fm/c

$$\varepsilon = \frac{E}{V} \approx \frac{1}{\pi R^2 \tau_0} \frac{dE_T}{dy}$$

(Bjorken)

Total E_T

$$\frac{dE_T}{dy} = 580 \text{ GeV}$$

Broad agreement between different observables, and with theory

A quantitative understanding of hot QCD matter is emerging

Some pocket formula results

GLV/WHDG: $dN_g/dy = 1400$

$$\rho(\tau) = \frac{dN_g}{dy}\frac{1}{\tau\pi R^2} \qquad \rho(\tau_0 = 1\ \mathrm{fm}) = 12.4\ \mathrm{fm}^{-3} \qquad \rho = \frac{16\cdot 1.202}{\pi^2}T^3$$

$T(\tau_0) = 366$ MeV

PQM: $\hat{q} = 13.2\ \mathrm{GeV}^2/\mathrm{fm}$ (parton average)

$$\hat{q} = \frac{72\cdot 1.202\ \alpha_s^2}{\pi}T^3$$

T = 1016 MeV

AMY: T fixed by hydro (~400 MeV), $\alpha_s = 0.297$

Large difference between models ?