Hard Probes: Past, Present and Future

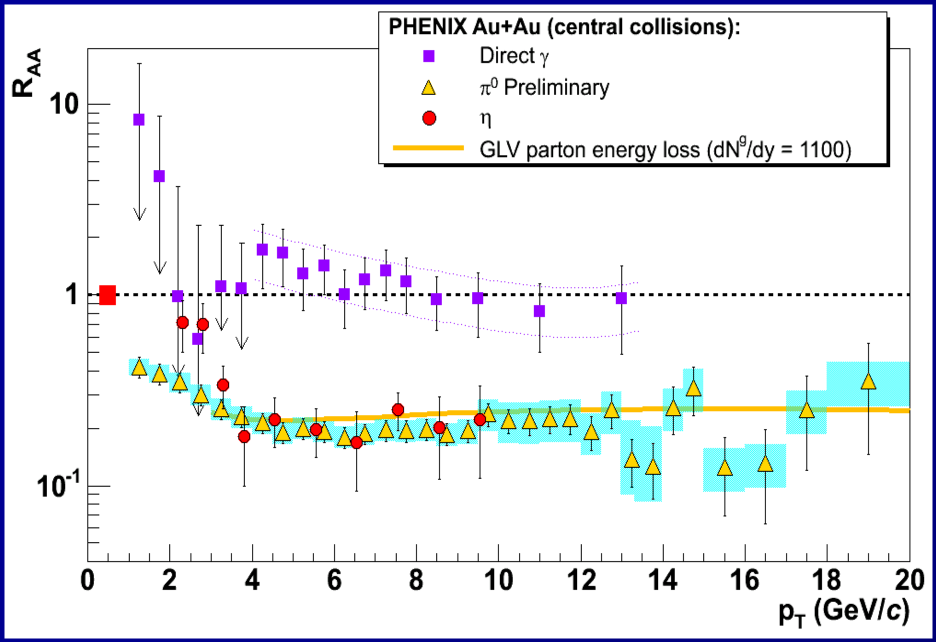
Prof. Brian A. Cole
Columbia University

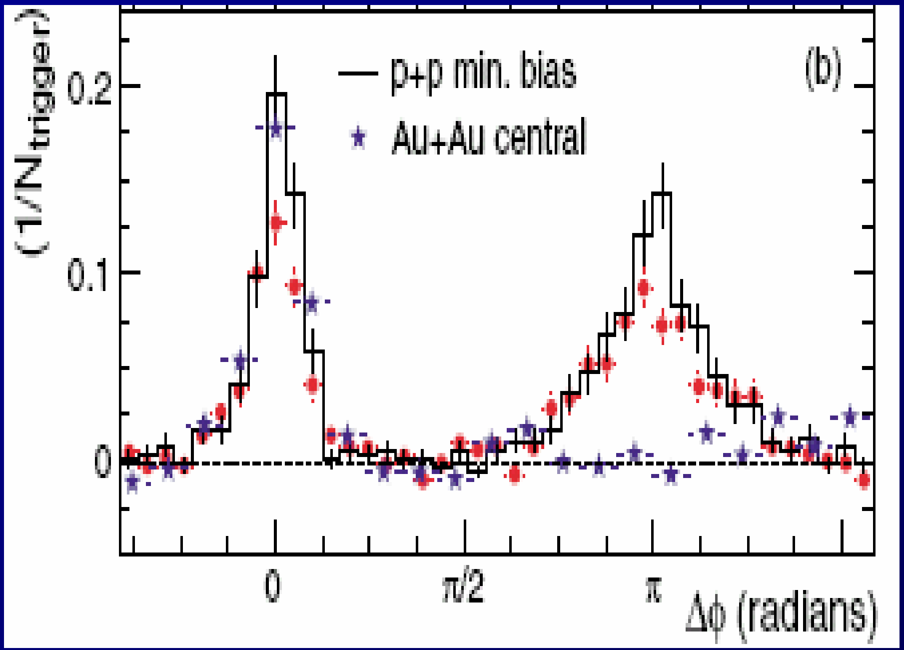
Disclaimer:

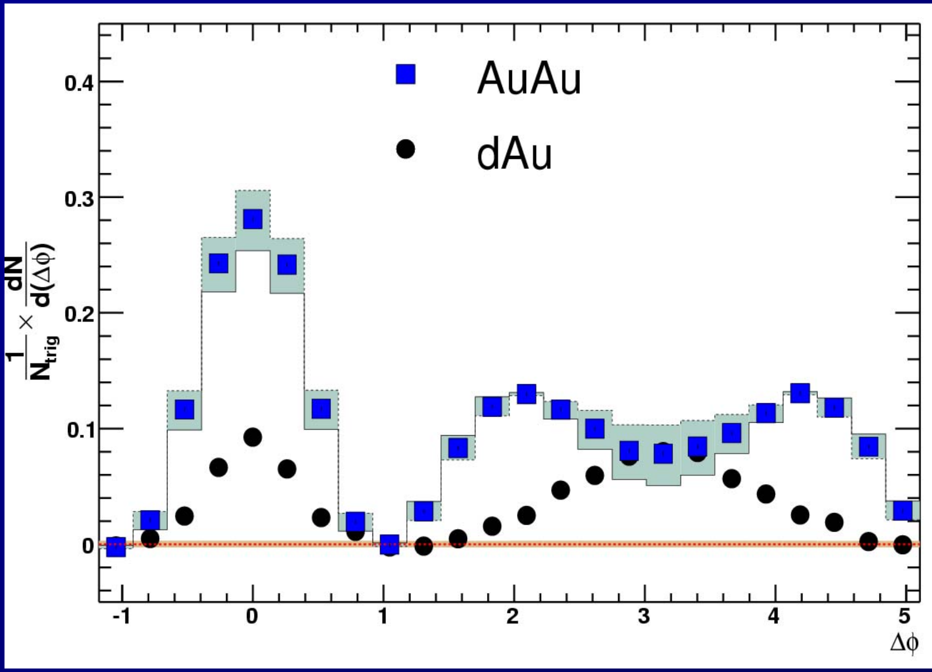
I am a member of both PHENIX and ATLAS collaborations. I will, of course, endeavor to be unbiased *wrt* experiments.

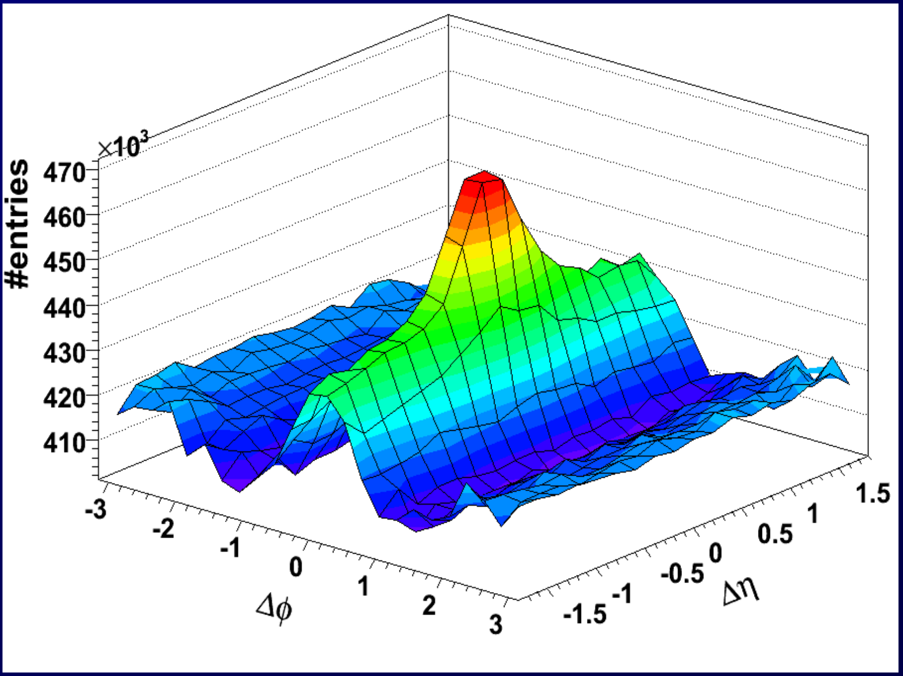
But I have clear prejudices on physics …

An Embarassement of Riches (past)









But what do we really know? (present)

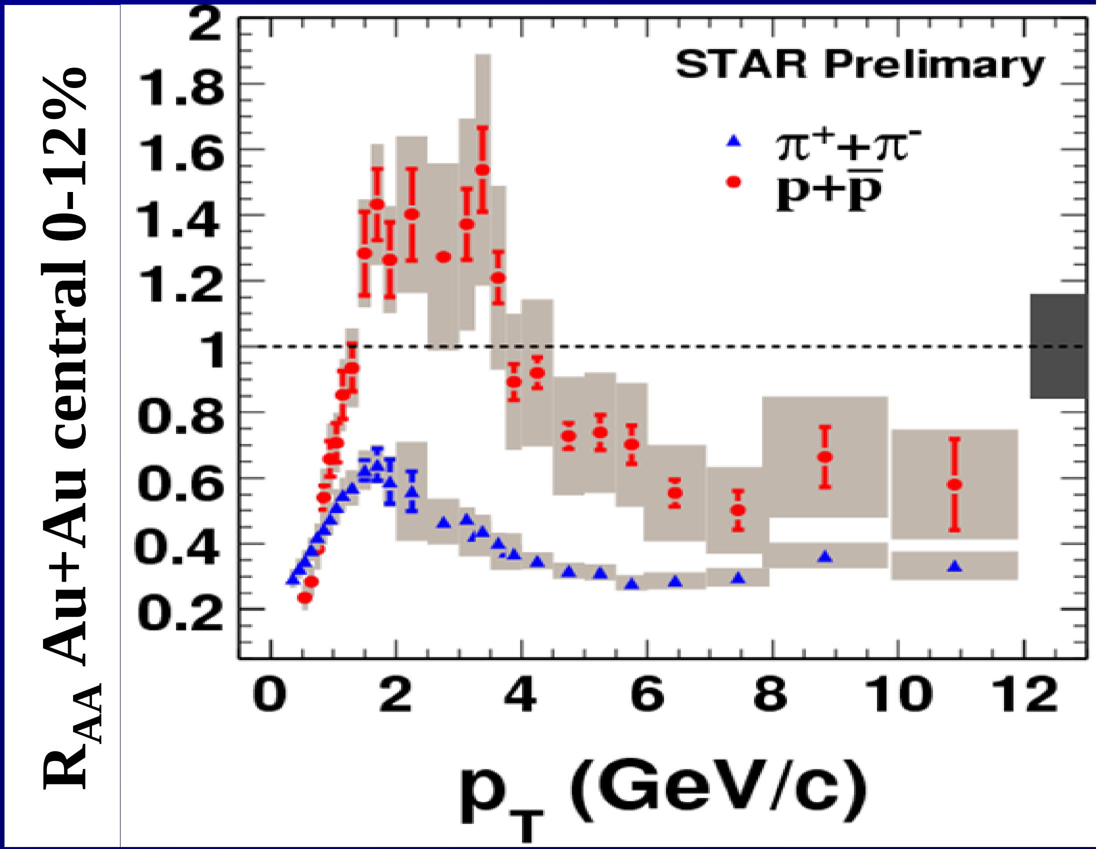
High p_T quarks & gluons are quenched

- Is the energy loss radiative? collisional? both?
- Wrong question – of course it's both
  - But, then, what are relative contributions?
- Unless the partons interact with something other than individual charges in the medium (e.g. chromo-B fields)?
  - or
- Unless the quarks and gluons don't even interact perturbatively (e.g. due to strong coupling)?
- Can we even tell???
  - Unfortunately, this is a question we still have to entertain …
  - Ideally we would answer questions from bottom to top

One Reason to be Suspicious

- Striking result from STAR
  - High p_T protons less suppressed than π.
- But protons tend to come more from gluons.
  - Pions more from quarks.
- But we expect larger energy loss for gluons than quarks?
  - Nominally 9/4.
- No evidence for QCD color factors???

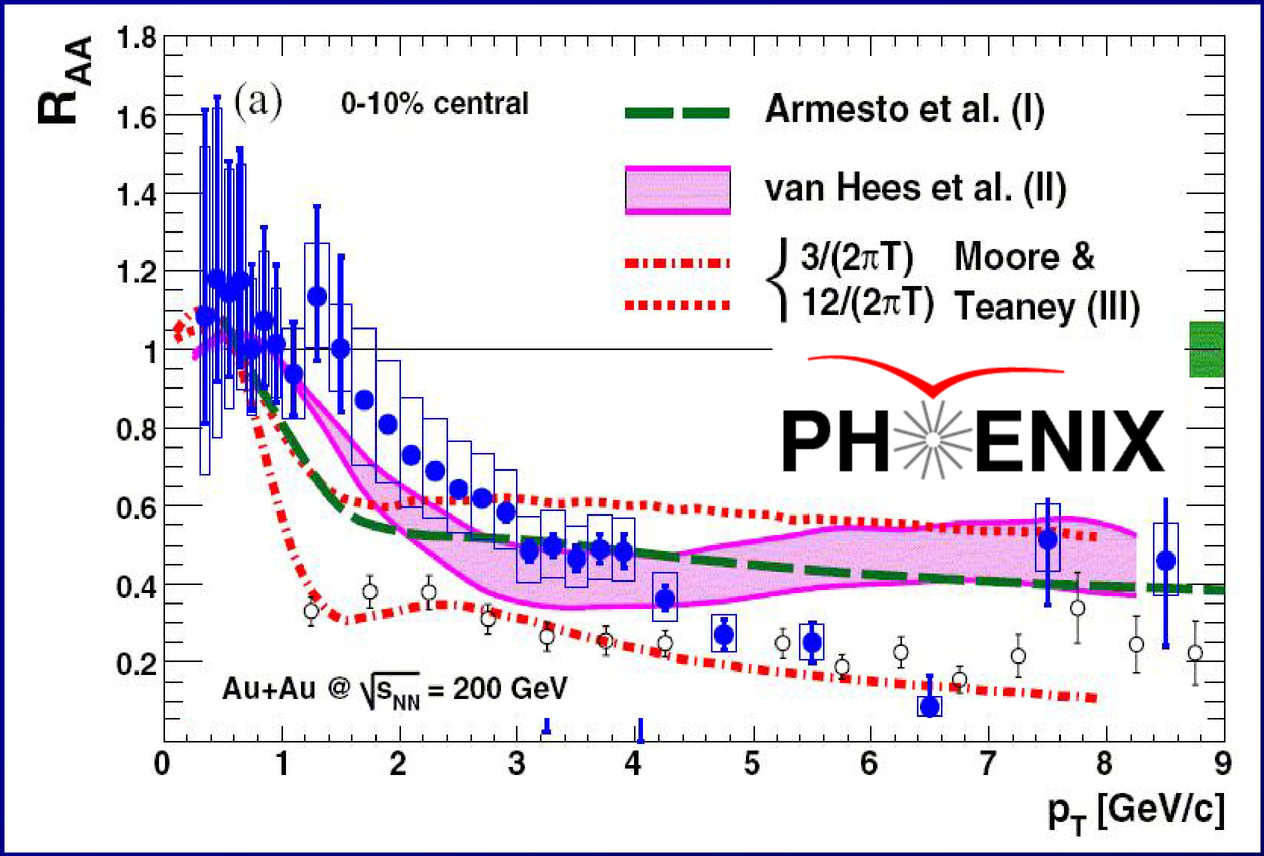
From talk by Bedanga



Needs quantitative, careful evaluation, more knowledge re: baryon FF functions (STAR?)

Another Reason to be Suspicious

Single electron (c, b semi-leptonic decay) R_{AA}



- **Heavy quarks show same suppression as light quarks at high p_T?? With substantial bottom contribution??**
- **Occam's razor: maybe there is some universal suppression mechanism (i.e. not usual energy loss) ??**

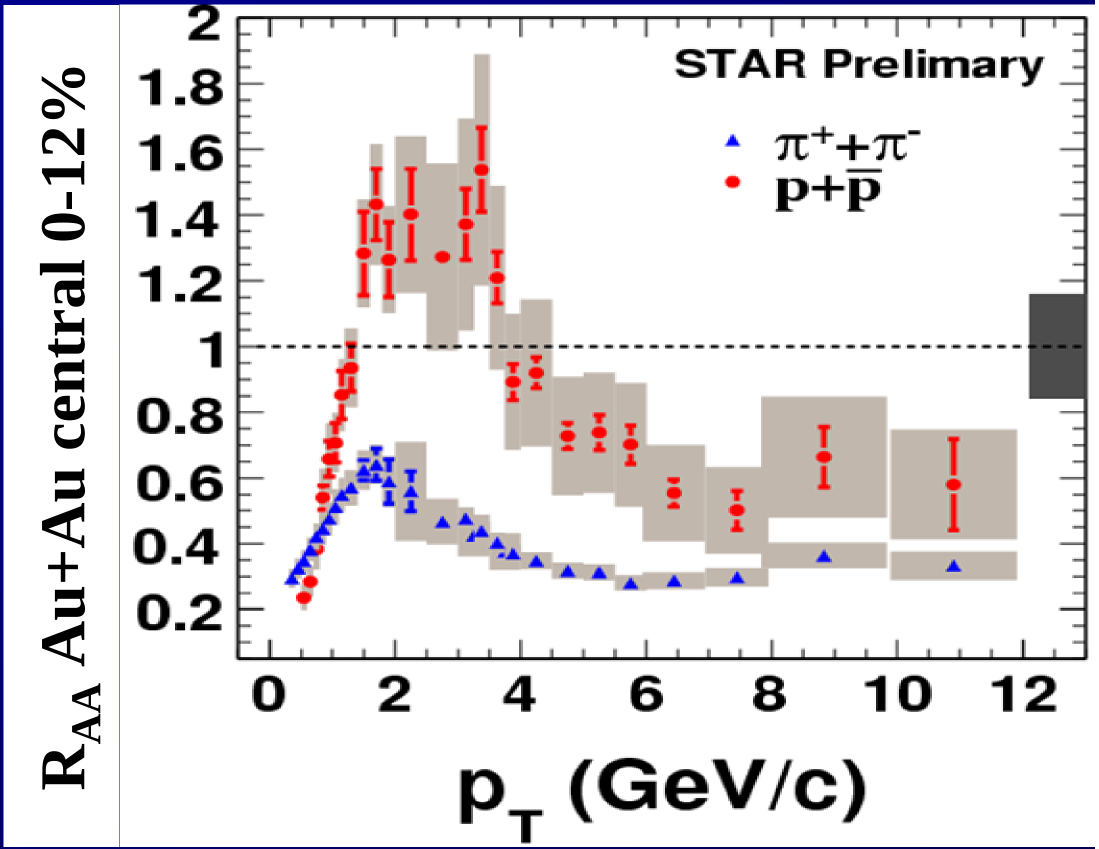
On the other hand …

- This result is very interesting:

$$R_{AA}^{p} > R_{AA}^{\pi}$$

- If protons more sensitive to gluon quenching than pions
  - Naively conclude that gluons lose less energy than quarks???
- Hard to imagine in any quenching scenario!
  - Proton D(Z) modified by quenching/medium?

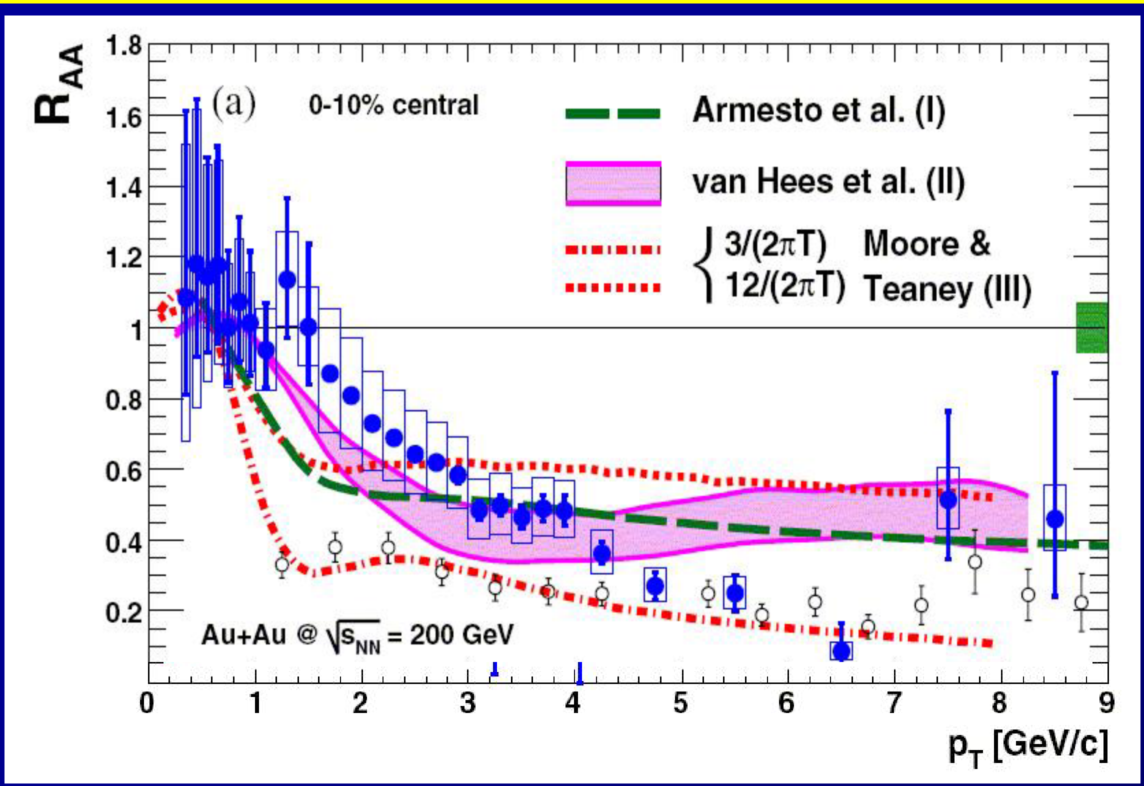
From talk by Bedanga



Yet another surprise from RHIC data – but I don’t think we understand it yet.

Stay tuned (esp. w/ more statistics)

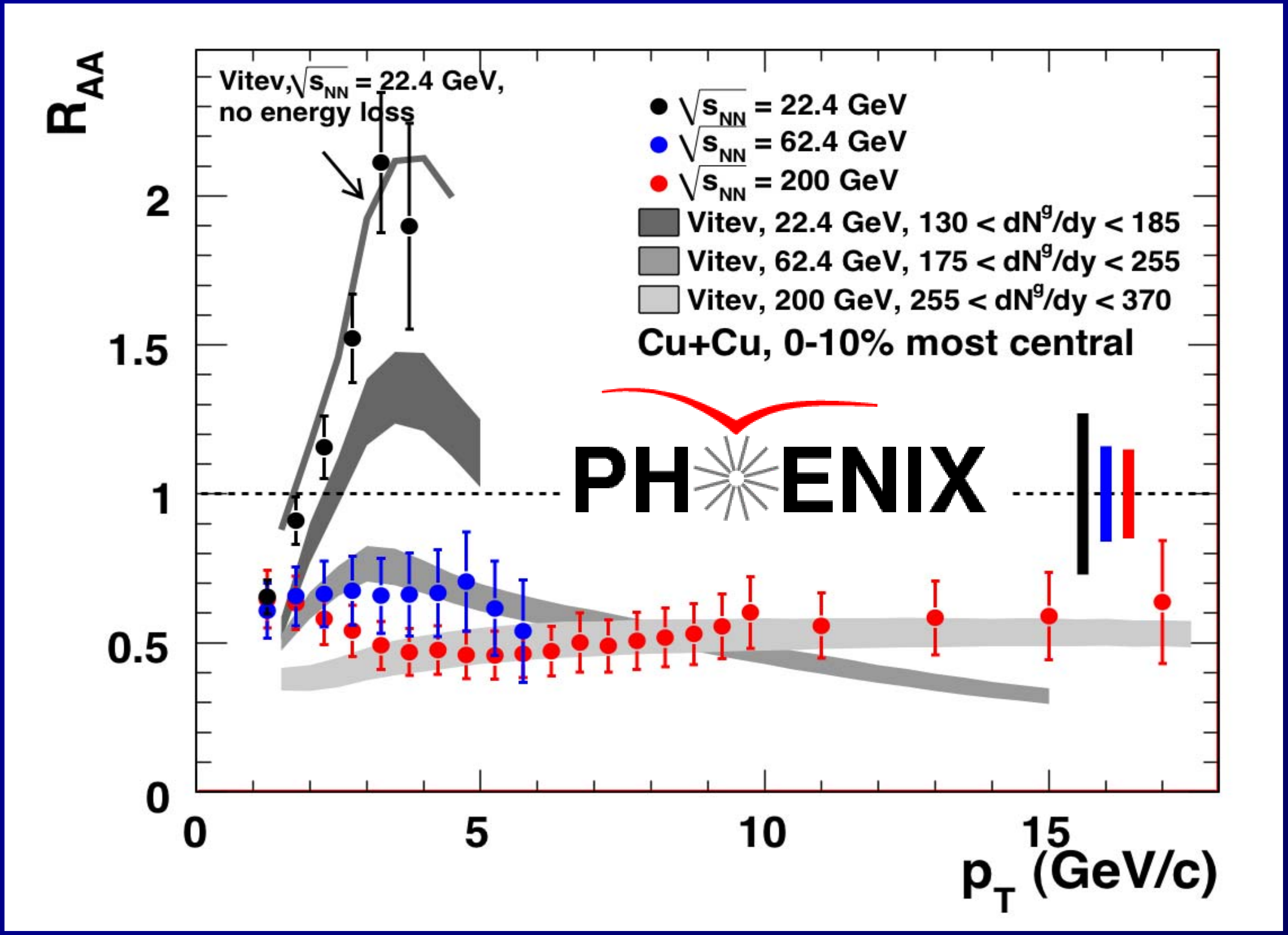
On the other hand …



Not yet clear whether heavy quark suppression kills perturbative energy loss

- **Moore&Teaney, Vitev, van Hees**
  - **Heavy quarks may hadronize inside/interact non-perturbatively in the medium (implication for light quarks?)**
- **Or: AdS/CFT drag (talk by Horowitz w/ test)**
- **Or: heavy quarks lost to baryons**
  - **Measure Λ_c!**

Evidence that we do understand quenching?

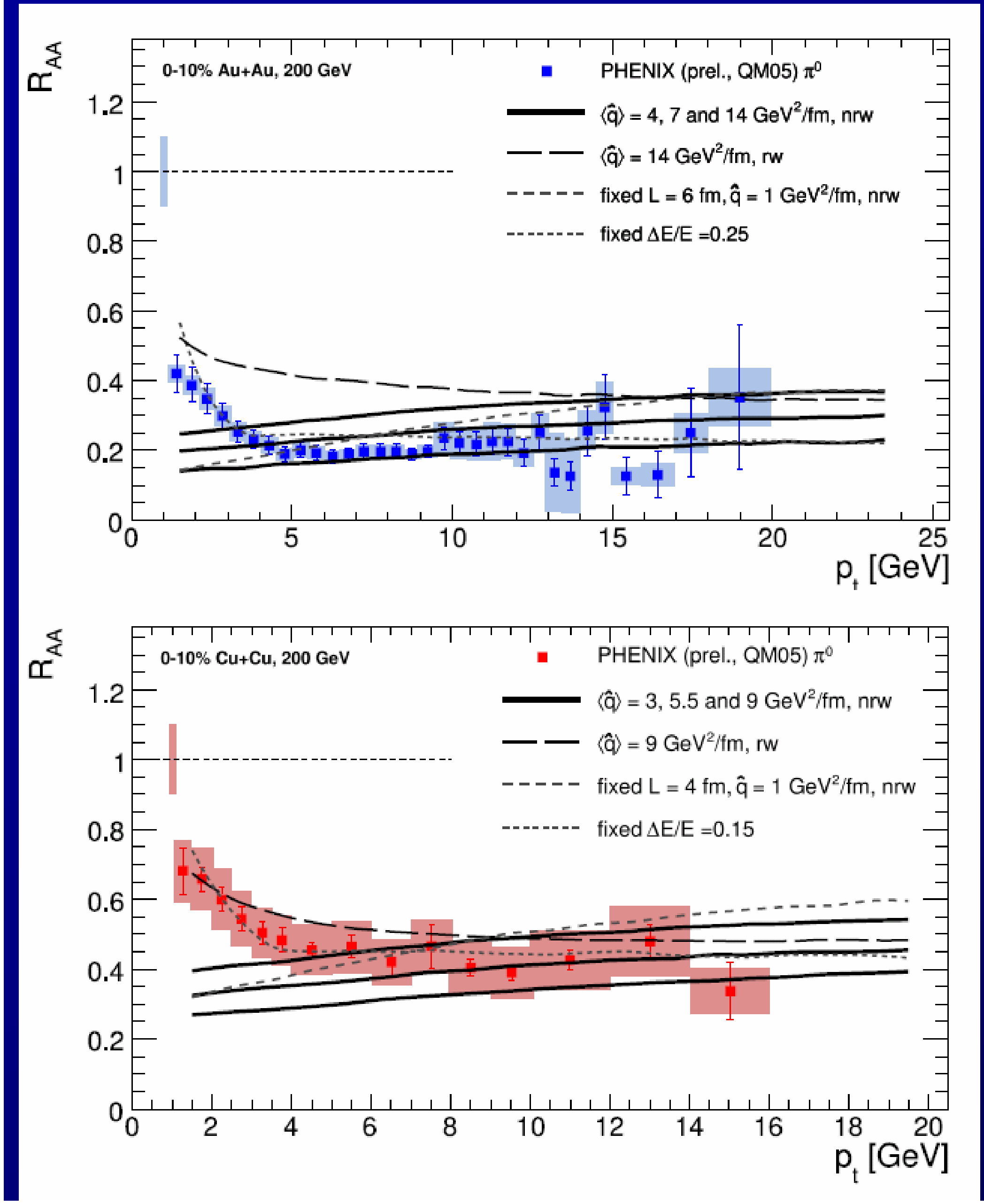


Cu+Cu π^0 R_{AA} for different collision energies

- **Quark/gluon fraction vs p_T changes with $\sqrt{s}$**
- **If quenching didn't depend on color factors, presumably, would not obtain agreement?!**
  - **But, depends on assumption re: medium properties vs $\sqrt{s}$**

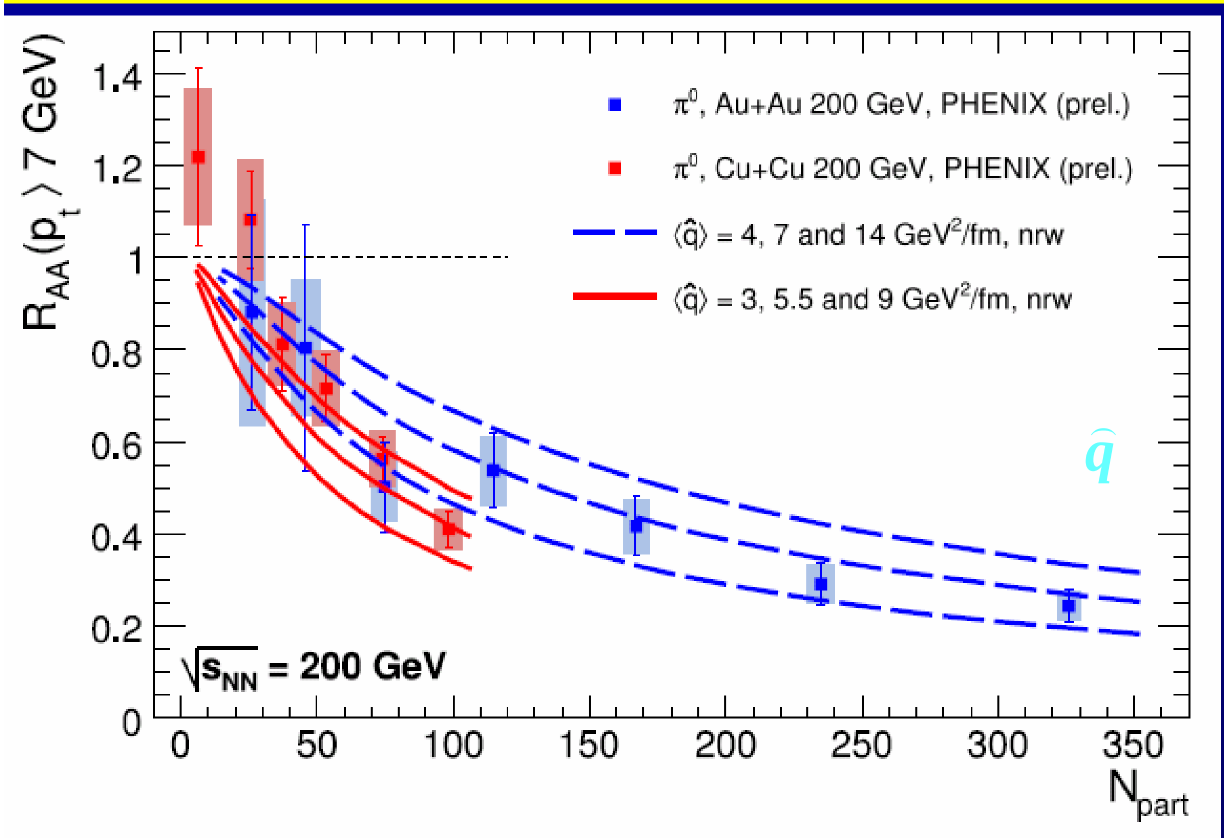
More evidence we understand quenching?

C. Loizides arxiv:



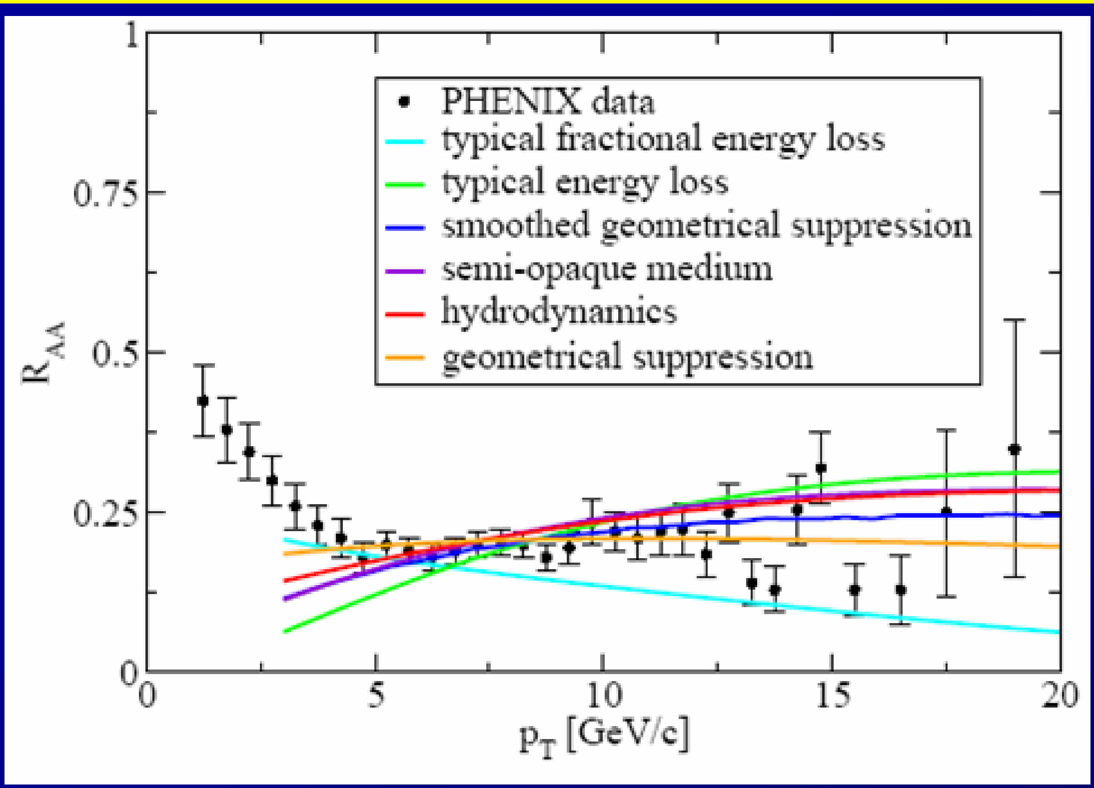
- PQM can describe Au+Au, Cu+Cu data with same calculation
  - Systems w/ different geometry & opacity
- More important (?)
  - Describes slow growth of RAA with p_T
    - ⇒Characteristic feature of radiative energy loss
    - ⇒But sensitive to parton spectrum, shadowing(b), …

Understand quenching (PQM)? Not so fast…



- **Centrality dependence in Au+Au well described**
  - **Provides more sensitivity to medium than central $R_{AA}(p_T)$**
- **But Cu+Cu? Maybe, maybe not.**
  - **Data not precise enough!**
  - **No Cronin in PQM(?). But then Au+Au??**

Single Hadron R_{AA} and Fragility



T. Renk,

Central Au+Au π^0 R_{AA} compared to (dramatically) different energy loss scenarios

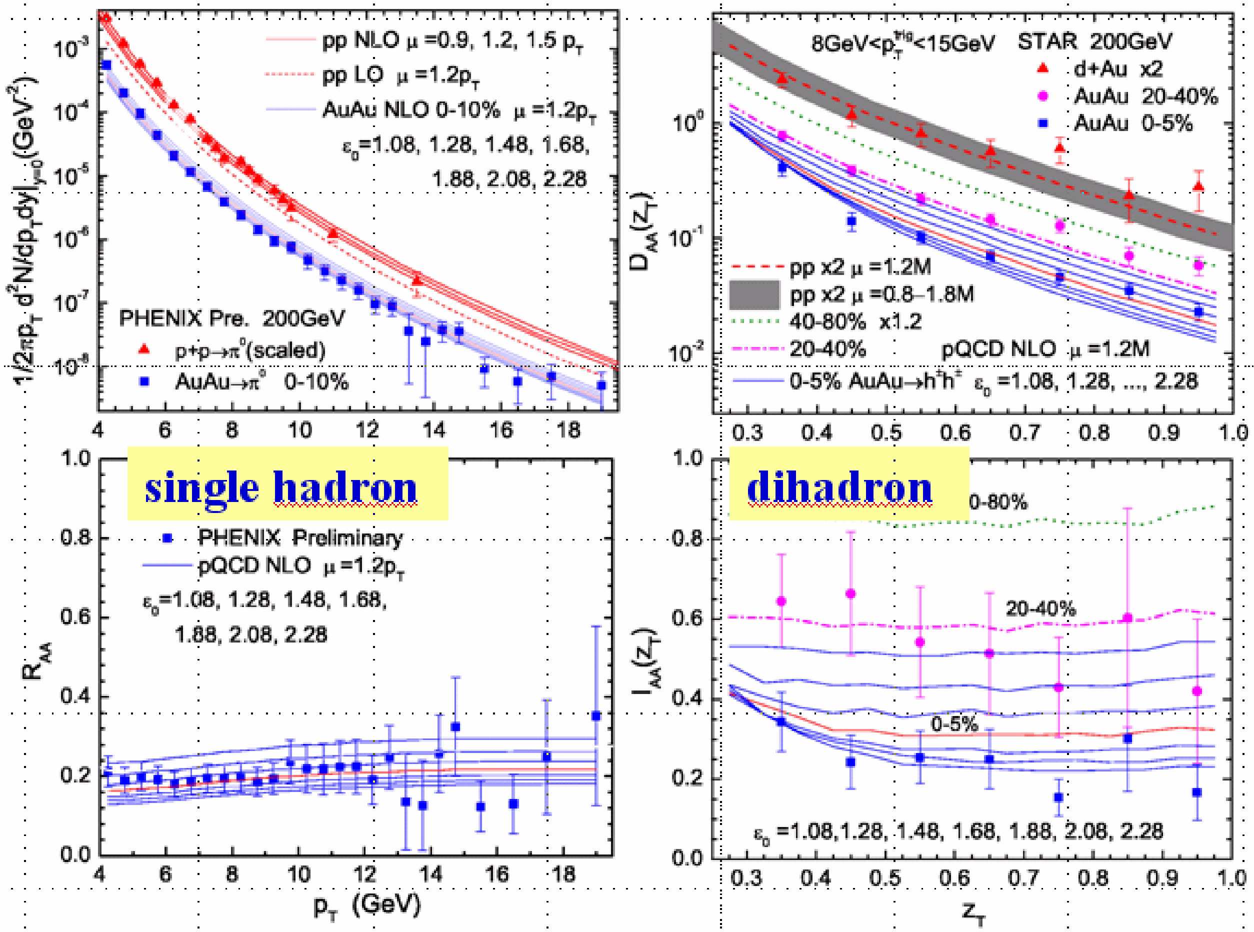
- **I think we can all agree that**
  - **A SINGLE SET OF $R_{AA}(p_T)$ IS NOT SUFFICIENT FOR DETERMINING MEDIUM PARAMETERS, or even CONSTRAINING ENERGY LOSS MODELS**
- **But, models don't describe the data equally well either**
  - **Need quantitative tests against the data!**

Quantitative tests against data

From parallel session talk by H-Z Zhang

II. Fragility of single/dihadron suppression factors

Simultaneous fit of single/dihadron spectra



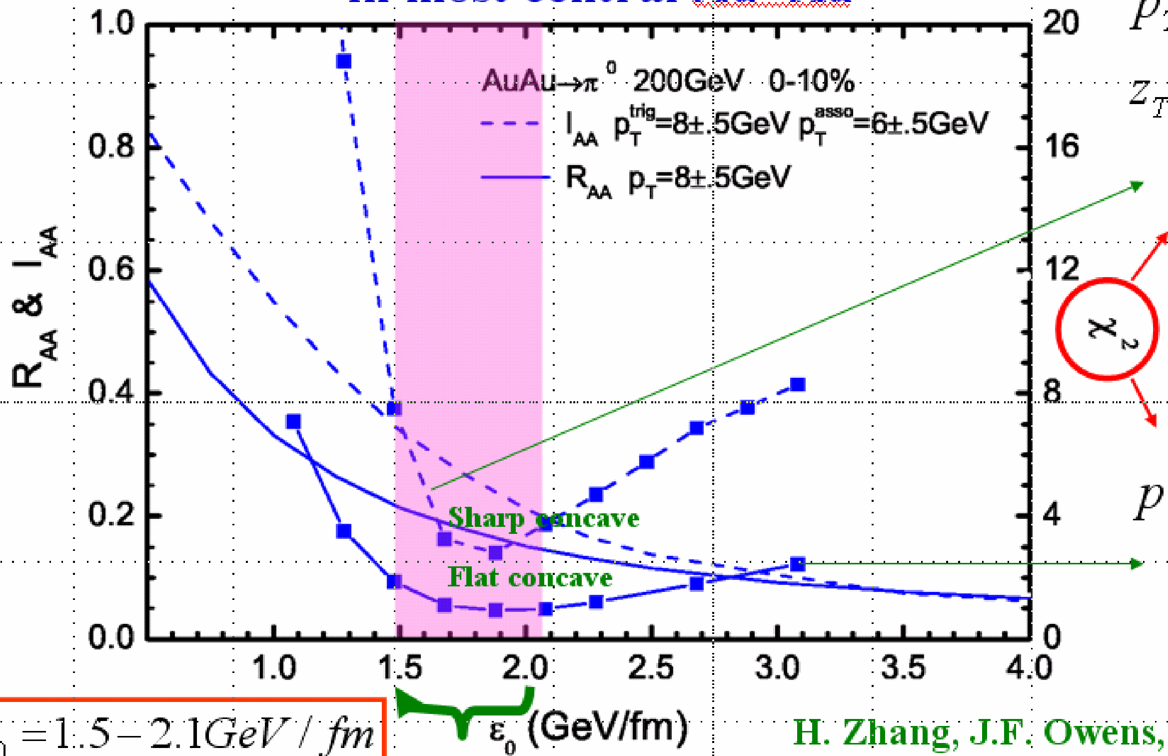
In most central Au+Au

Quantitative tests against data (2)

From parallel session talk by H-Z Zhang

χ^2-fit to both suppression factors

in most central Au+Au



$p_T^{trig} = 8 - 15 GeV$

$z_T = 0.45 - 0.95$

for dihadron

$p_T = 4 - 20 GeV$

for single

$\varepsilon_0 = 1.5 - 2.1 GeV / fm$

H. Zhang, J.F. Owens, E. Wang and X.-N. Wang , PRL 98(2007)212301

Iaa robust when Raa fragile at RHIC

8

- **Exactly what we needed!? Yes, and no.**

First, need to test models

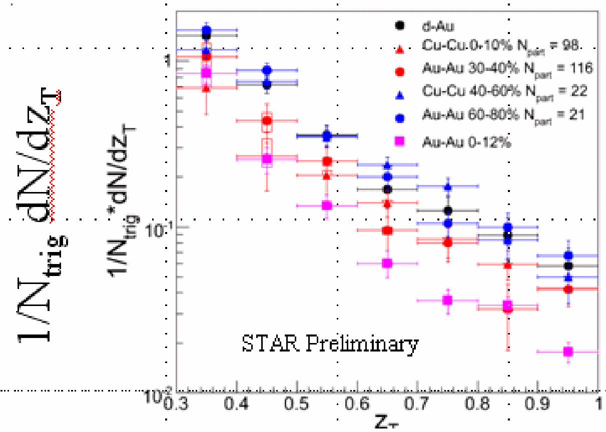
From plenary talk by B. Mohanty, parallel talk by O. Catu

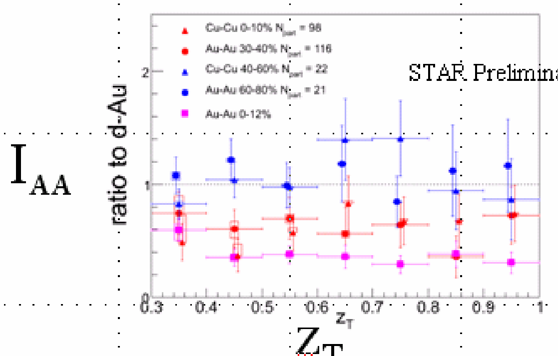
Away-side Di-hadron Fragmentation Function

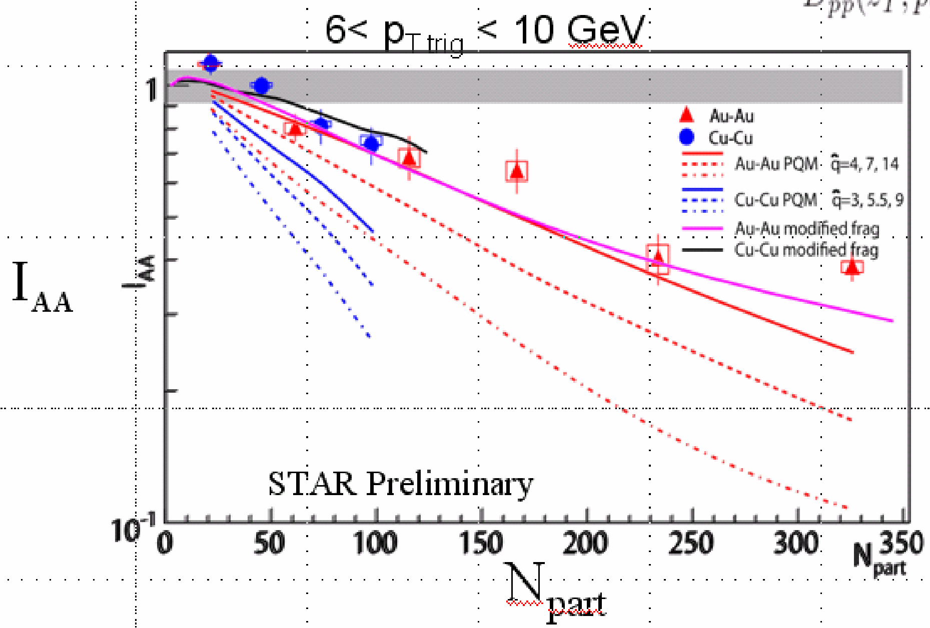
$$D^{h_1h_2}(z_T, p_T^{trig}) = p_T^{trig}\frac{d\sigma_{AA}^{h_1h_2}/dp_T^{trig}dp_T}{d\sigma_{AA}^{h_1}/dp_T^{trig}}$$

$z_T = p_T^{assoc}/p_T^{trig}$

$$I_{AA} = \frac{D_{AA}(z_T, p_T^{trig})}{D_{pp}(z_T, p_T^{trig})}$$







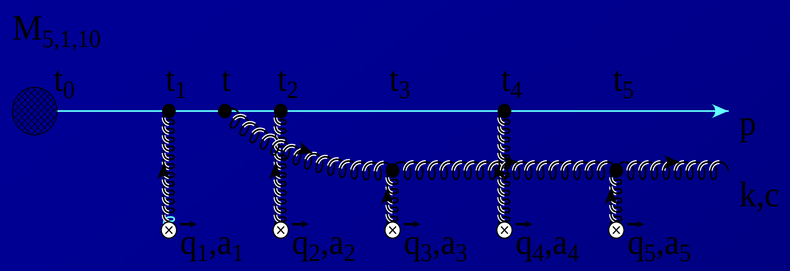
- ✓ Inconsistent with PQM calculations
- ✓ Modified fragmentation model better

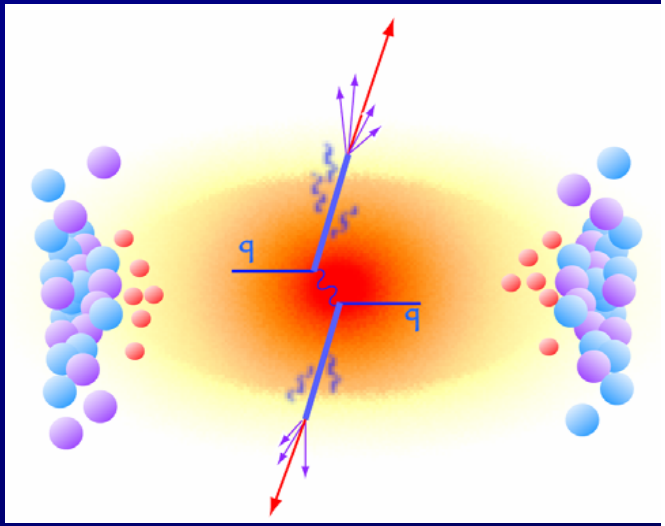
C. Loizides, Eur. Phys. J. C 49, 339-345 (2007)

H. Zhong et al., PRL 97 (2006) 252001

- ✓ Denser medium in central Au+Au collisions compared to central Cu+Cu
- ✓ z_T distributions similar for Au+Au and Cu+Cu for similar N_{part}

Bootstrapping our way to jet tomography (present)





- **Tomography (our goal):**
  - **studying an unknown medium with a well understood & calibrated probe.**
- **Unfortunately, this is not what we are doing**
  - **We have some assumptions/calculations of medium properties.**
  - **And incomplete understanding of how our probe(s) interact with that medium.**

    ⇒ **We must simultaneously test descriptions of the medium and our understanding of energy loss.**

    ⇒ **Only when we have demonstrated that we have consistent description of energy loss & medium can we really start to extract $\hat{q}$ (e.g.)**

What are (some of) the issues?

- **Do we understand energy loss at all?**
  - We <u>must</u> determine whether energy loss is perturbative
  - e.g. determine whether quenching depends on color factors.
    - ⇒Otherwise we're wasting many person-years, many $$$
- **We must come to terms with collisional energy loss**
  - Calculations without it should be viewed as toys.
  - If we don't have sufficient theoretical understanding
    - ⇒Then we have to improve that understanding
    - ⇒Otherwise we're wasting many person-years, many $$$
- **Need to address open issues in (pert.) energy loss**
  - Role of collective flow on energy loss.
  - Thick vs. thin medium, opacity expansion (talk by S. Wicks)
  - Massive gluons, running coupling, non-static charges, …

What are (some of) the issues? (2)

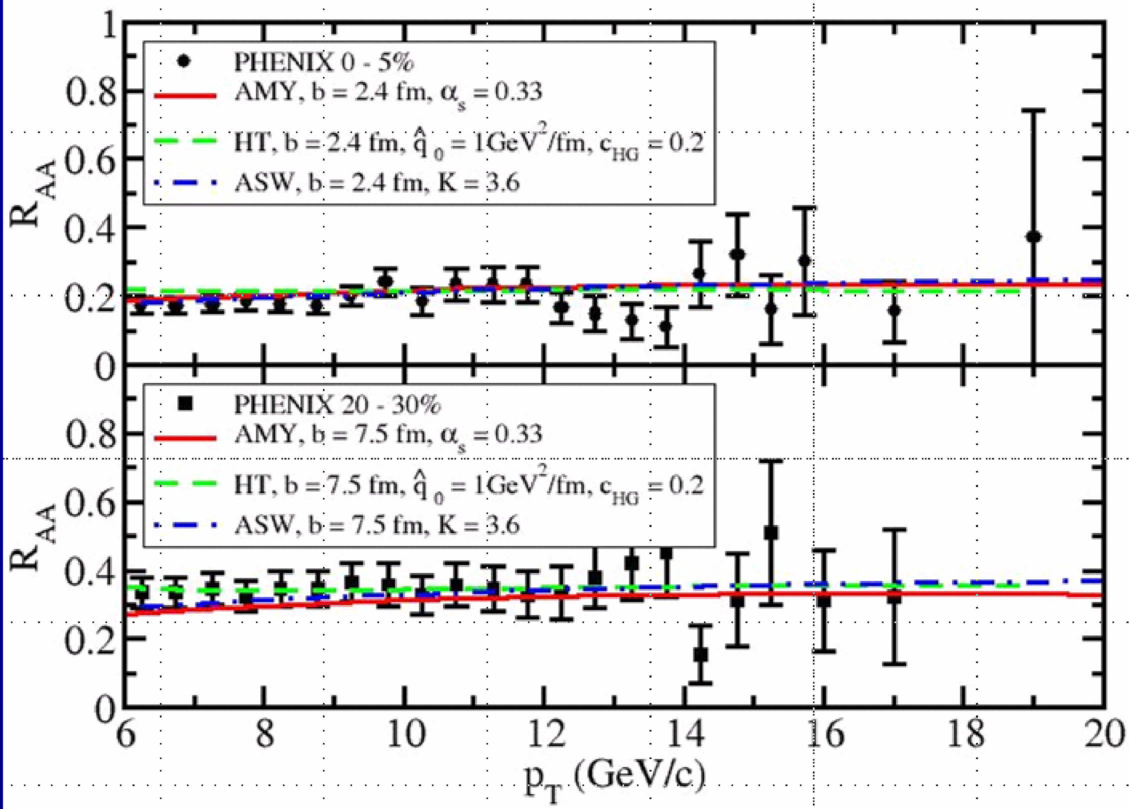
- **When new ideas/solutions to open problems in parton energy loss arise we need to critically test them.**
  - **If they survive the tests, must be incorporated into a "canonical" energy loss model.**
  - **If they don't, they must be rejected or fixed.**
  - **Need to do this in an organized way across community.**

    ⇒Otherwise we're wasting many person-years, many $$$
- **We need to test different, viable energy loss calculations in same, realistic geometry(ies).**
  - **Then quantitative tests against data make sense.**
  - **<u>Toy models no longer suffice except for proof of principle.</u>**
  - **Need to do this in an organized way across community.**

    ⇒Otherwise we're wasting many person-years, many $$$

Signs of progress

Discriminative Power of R_{AA}



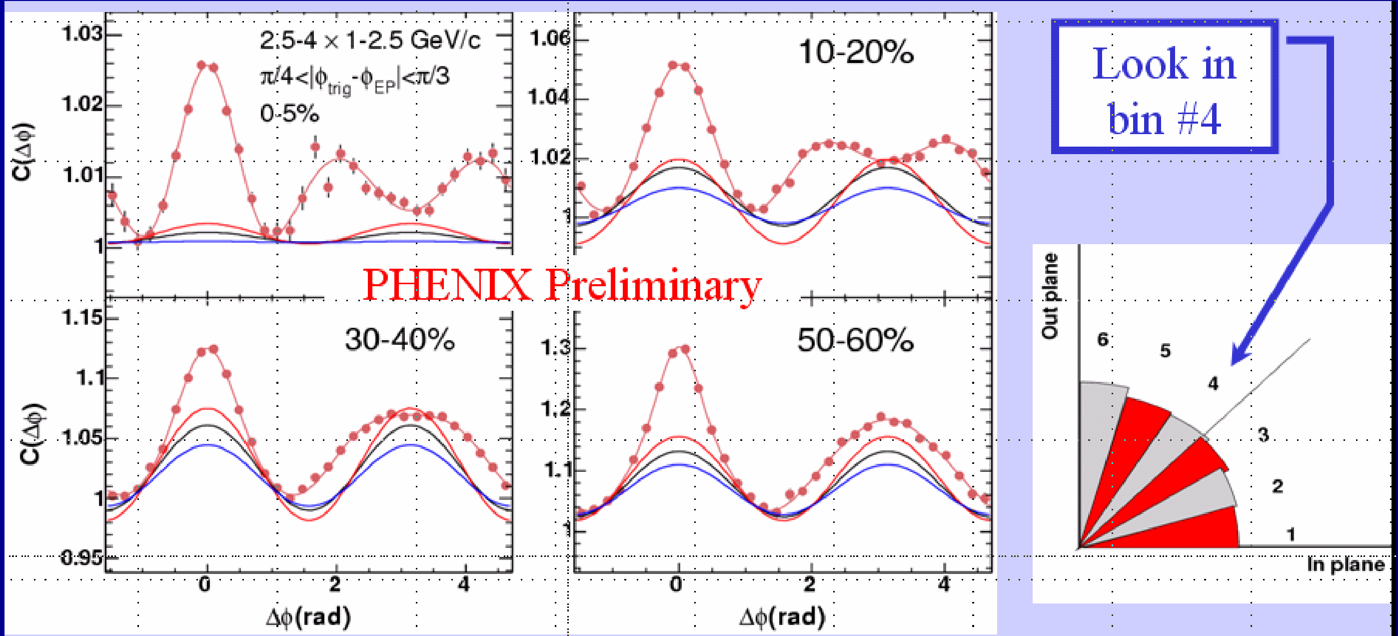
- R_{AA} in (semi-)central collisions is well described by all jet energy-loss schemes
- parameters reflect tuning of medium structure hard-wired into schemes
- do differing medium assumptions have impact on analysis?
- ➢ more sophisticated analysis/observables needed!

ASW	HT	AMY
K=3.6	q_0=1.5	α_s=0.33

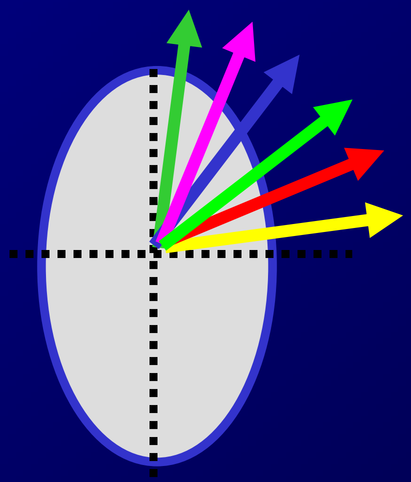
This is just a start – must follow through as community

Medium response: conical? flow

From BAC talk QM 2005

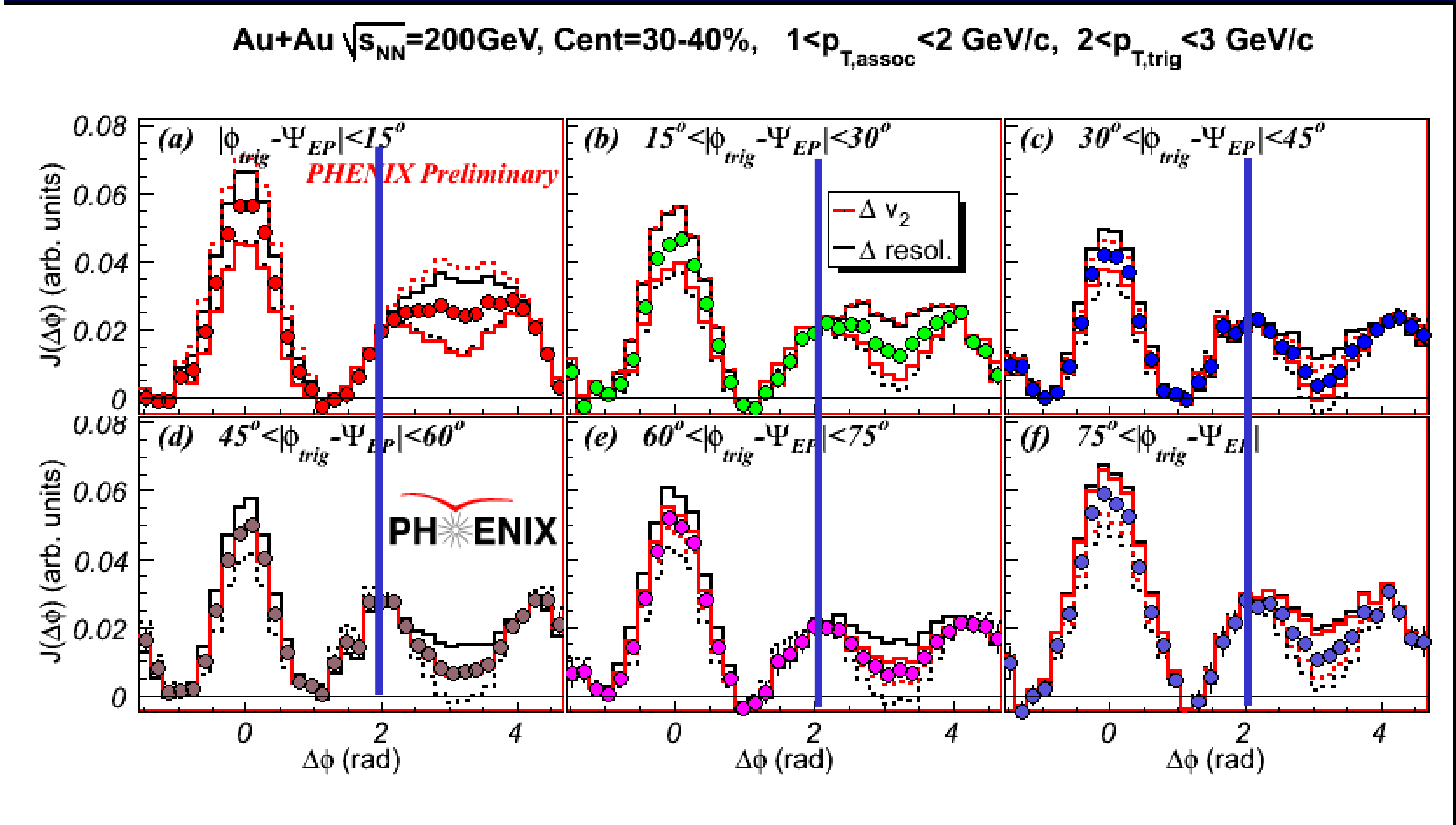


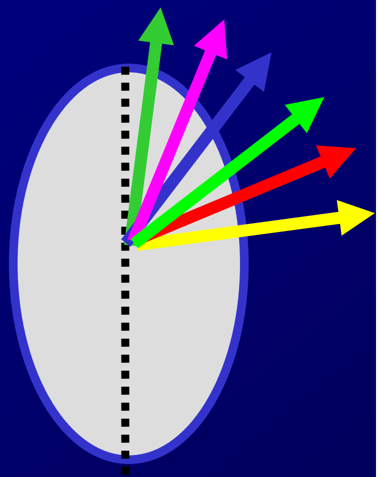
- For PHENIX reaction plane resolution & chosen bin sizes, $\Delta\phi_{trig}$ bin 4 has smallest flow effects.
- Even without subtracting flow contribution, a dip is seen for central collisions.



- **Let's get one thing straight:**
  - **The cones? are not an artifact of background subtraction!**
  - **We should not have to discuss this issue any more …**

Conical? flow – RP dependence



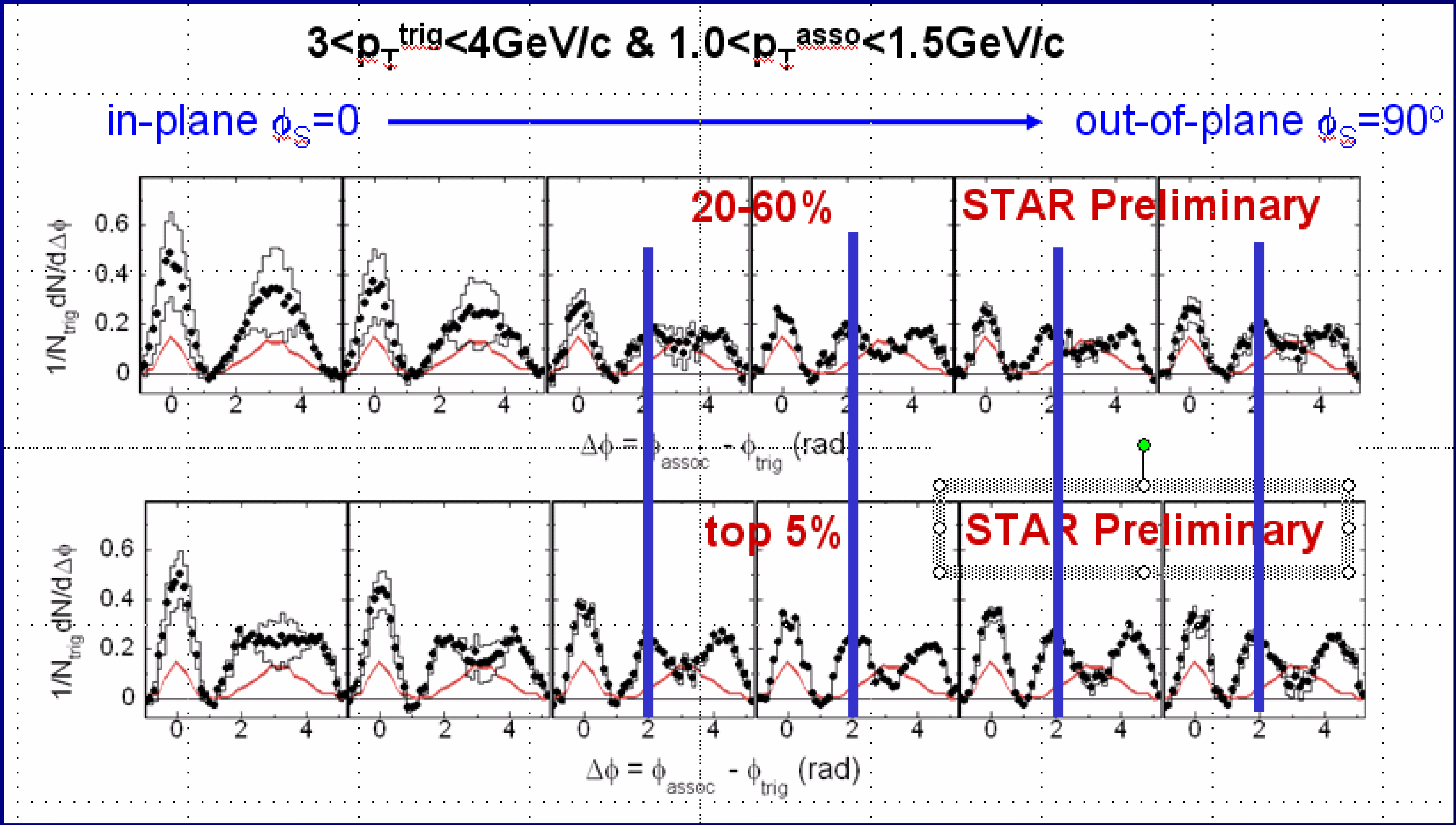


- The position of the cone? does not change with angle of trigger hadron *wrt* reaction plane.
  - But we do see the di-jet remnant behave as expected

    ⇒Decreases as ϕ_t - Ψ_{RP} increases.

Conical? flow – RP dependence (STAR)

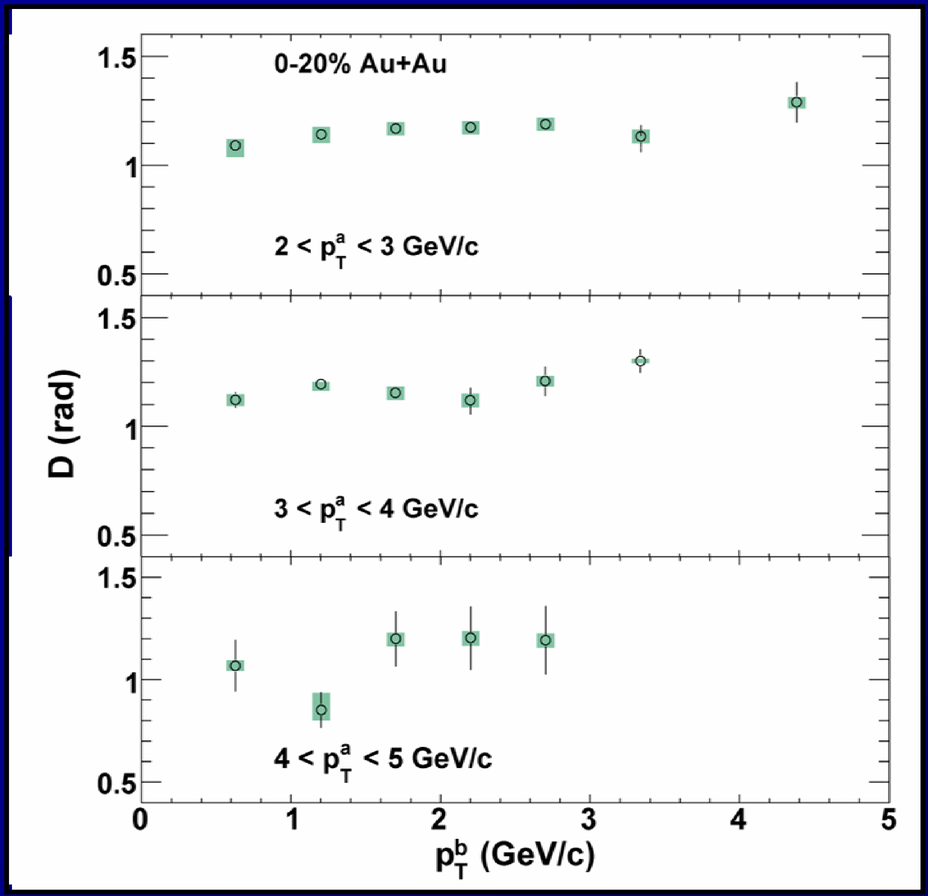
From parallel talk by A. Feng



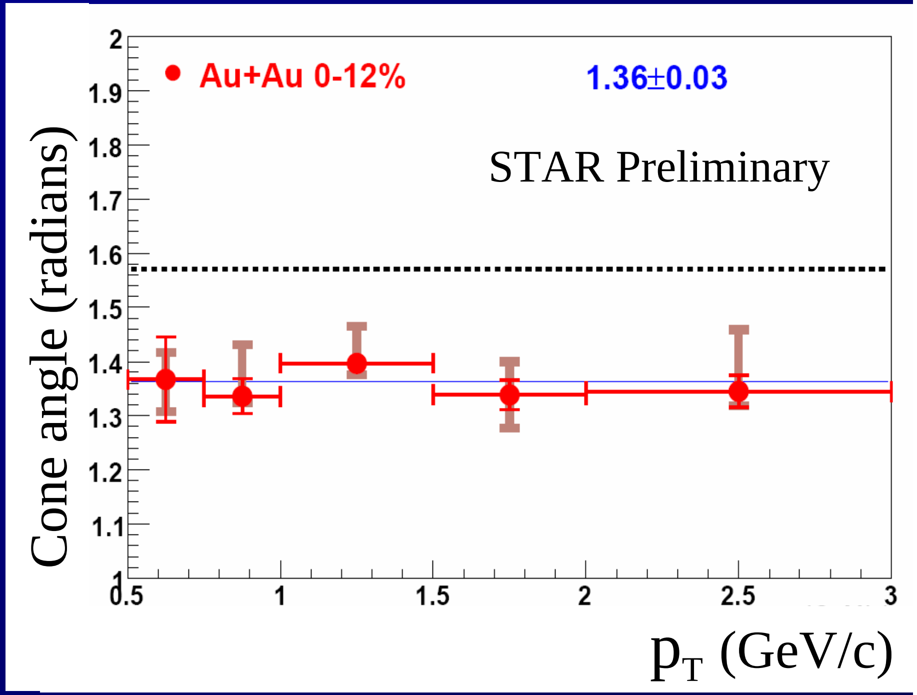
- PHENIX & STAR results on RP dependence in excellent qualitative agreement.

Conical? flow – other results shown this week

From M. McCumber parallel talk



From talk by B. Mohanty



Beware: PHENIX measurement from 2 particle, STAR 3 particle

- **Cone? angle does not change appreciably as a function of p_T of trigger or associated hadron.**
  - Or centrality, or angle *wrt* reaction plane
  - Can you find the pattern here…

Conical? Flow – what is it really?

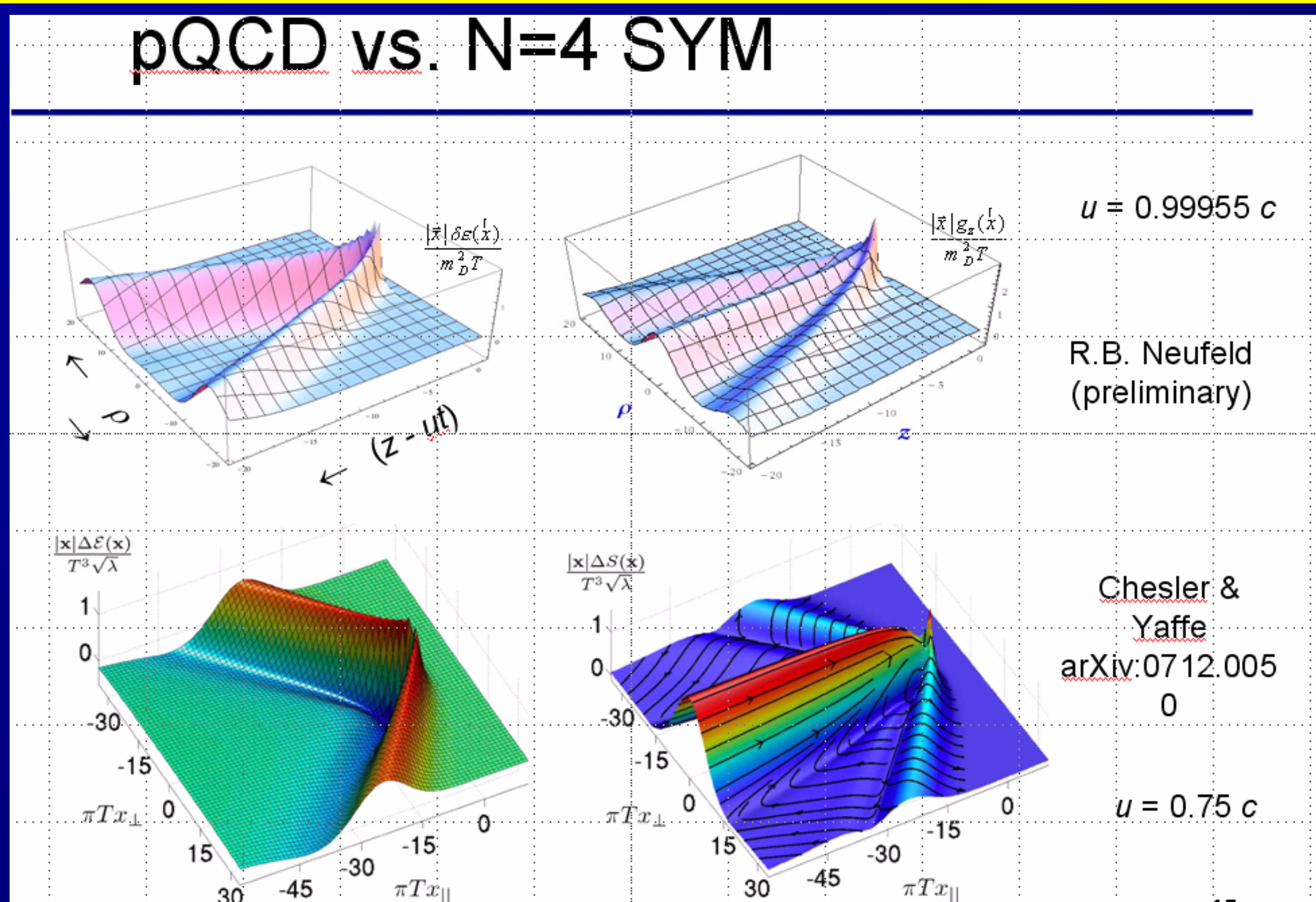
- Other observations from data
  - 3-particle correlations from STAR & PHENIX may suggest conical flow pattern.
  - pT spectrum in the cone? consistent w/ medium not jets.

    ⇒We are developing a large body of data that I believe is difficult to explain via "geometric" effect.
- If we are going to take "bent-jet" as serious candidate for conical? flow, then:
  - We should evaluate using real jet quenching model
  - In a realistic description of medium (e.g. hydro)

    ⇒No free parameters – it will work or not. But ???
- Similarly, if we are going to take gluon radiation as serious candidate for conical? flow, then
  - We need a complete calculation w/ realistic geometry.

Mach Cone?

From talk by
B. Mueller

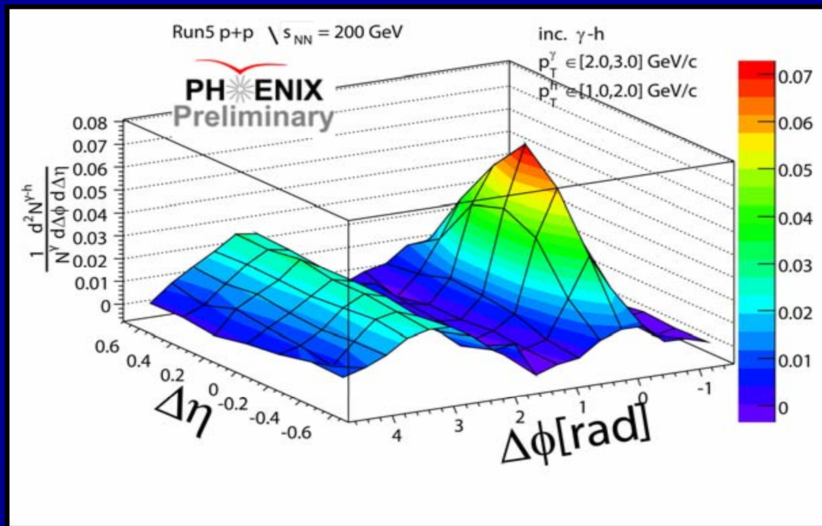


- **We have good reason to think the medium can support, propagate shocks.**
  - **But can they produce the signal we see (not obviously).**
  - **Stay tuned (on the edge of your seat …)**

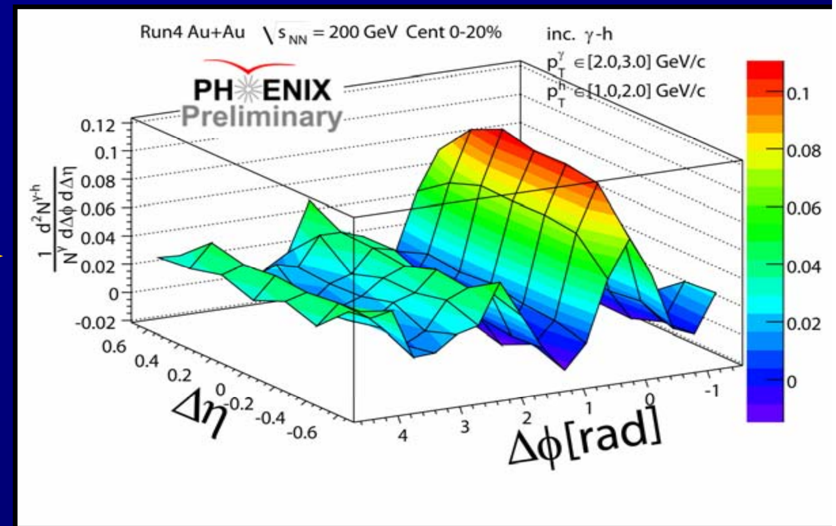
The Ridge: also seen by PHENIX, PHOBOS

Talk by McCumber

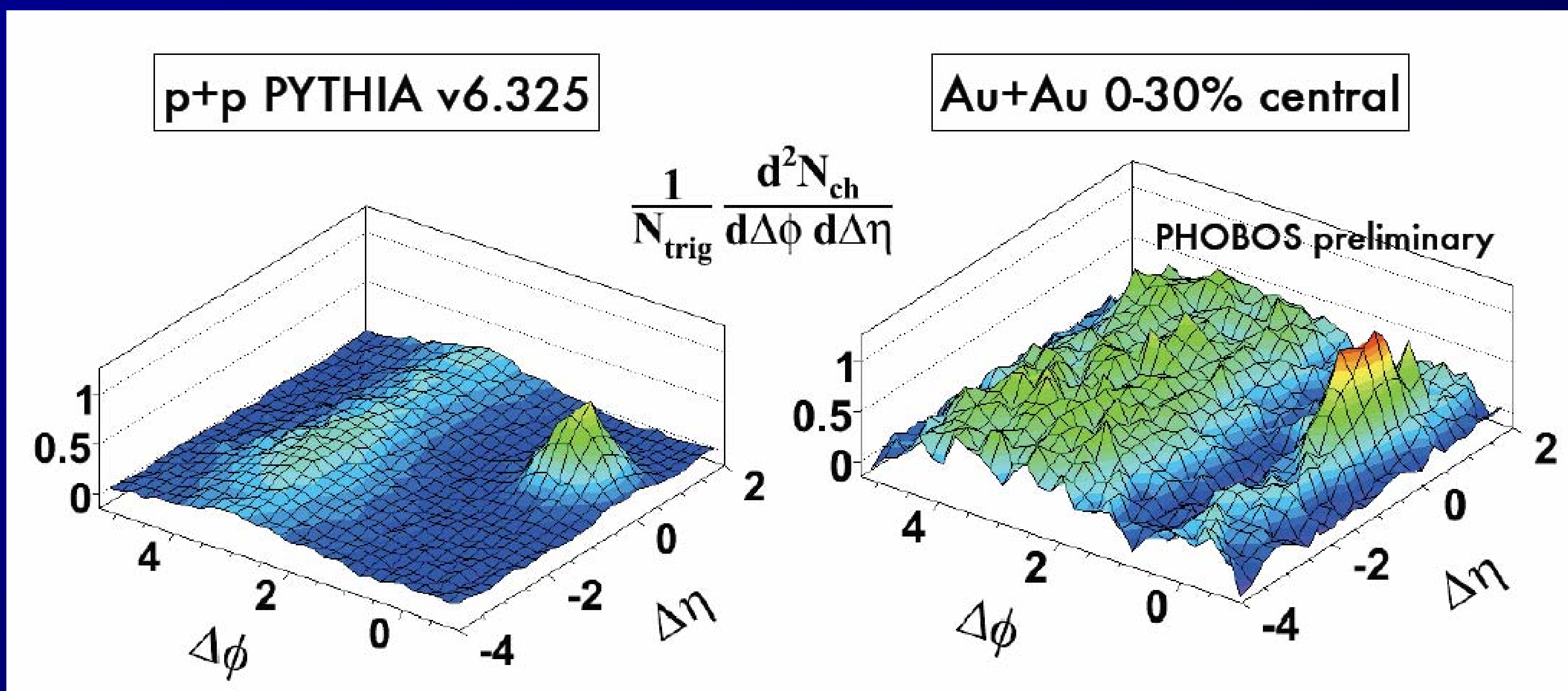
p+p, peripheral Au+Au



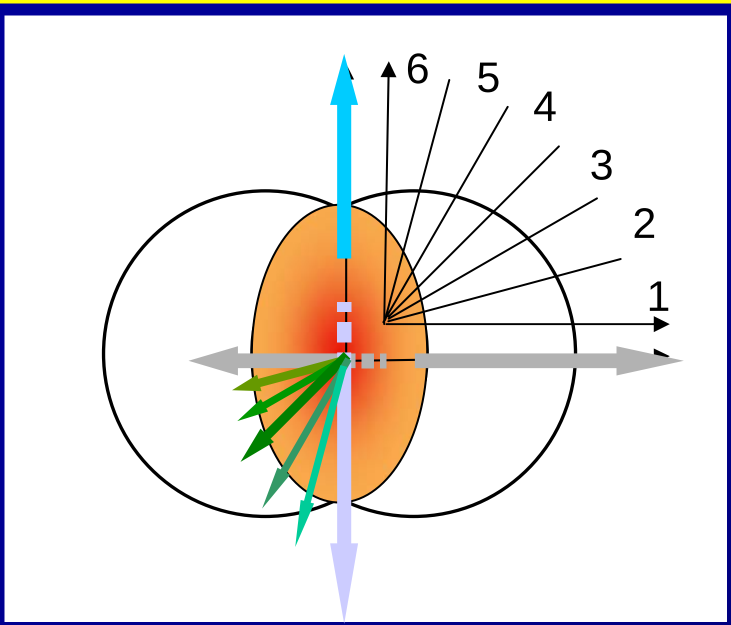
central Au+Au



Talk by E. Wenger



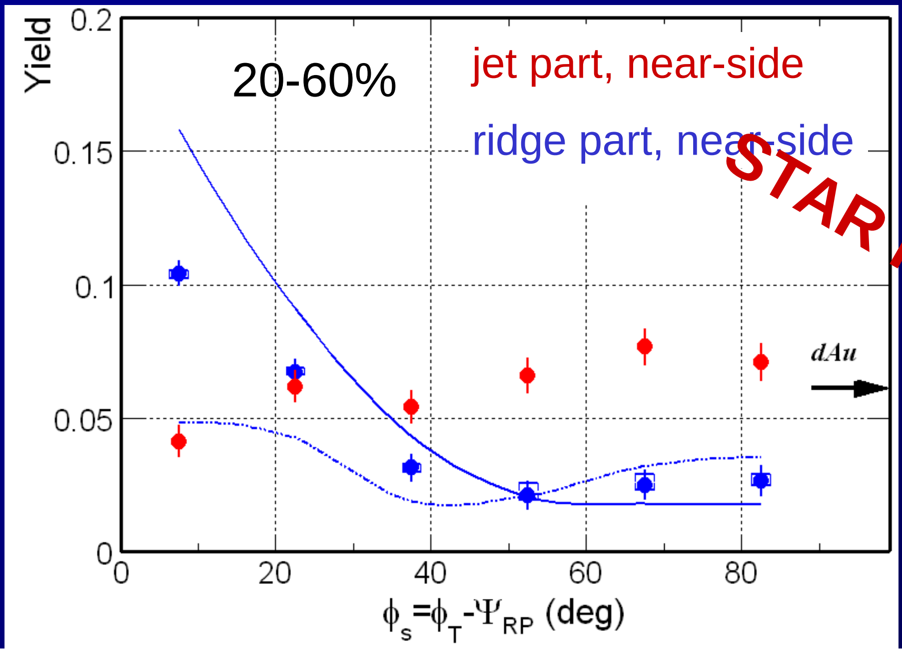
The Ridge: new insights

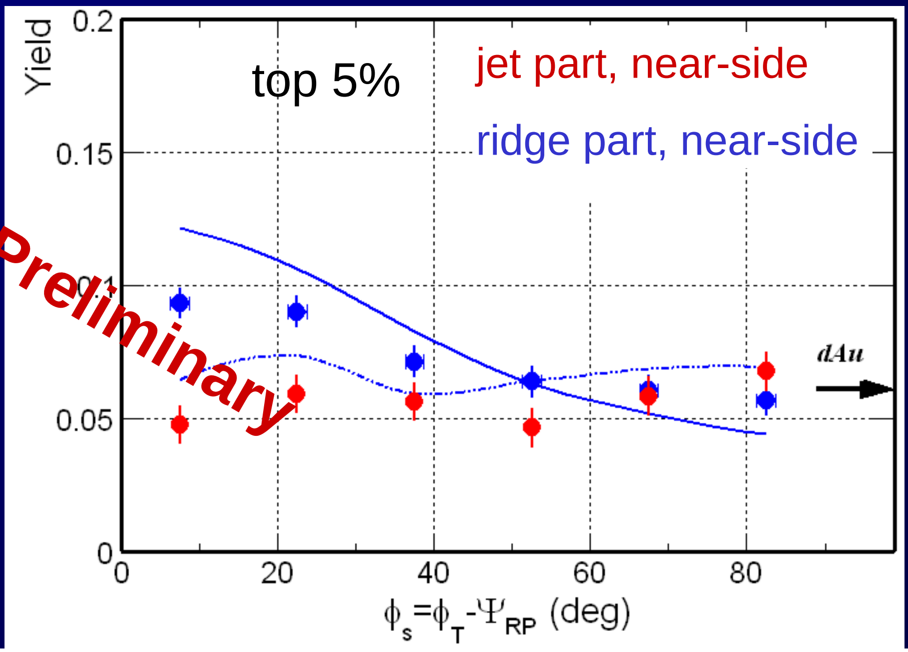


- **Study yield in ridge vs angle of trigger hadron *wrt* reac. plane**
  - **Ridge yield concentrated in the reaction plane (beware sys. err.)**
  - **Flat for larger ϕ_t - Ψ_{RP}**
  - **Non-zero or zero?**

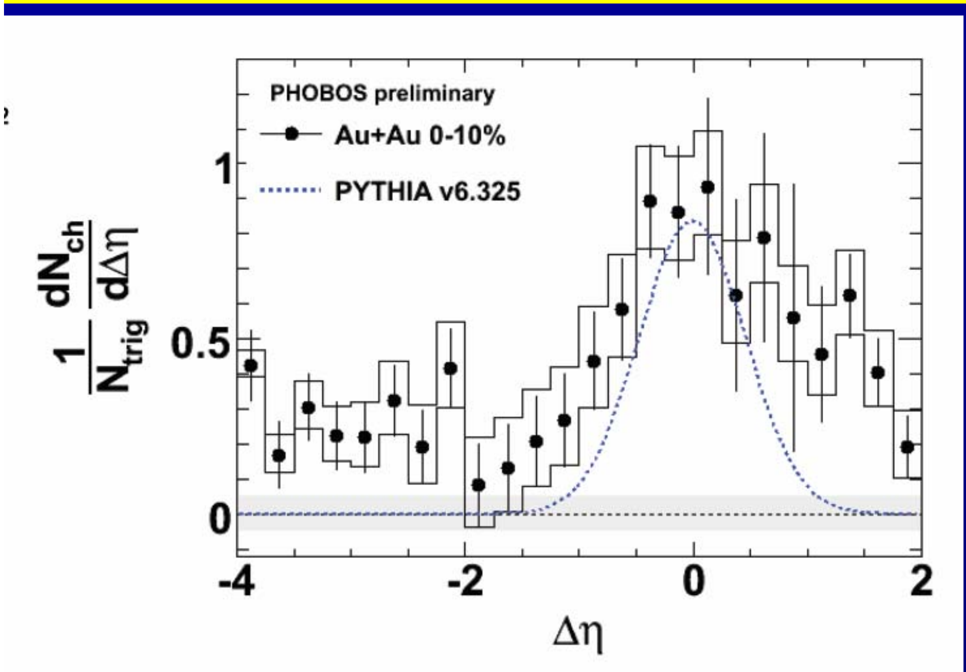
⇒Important to establish!!

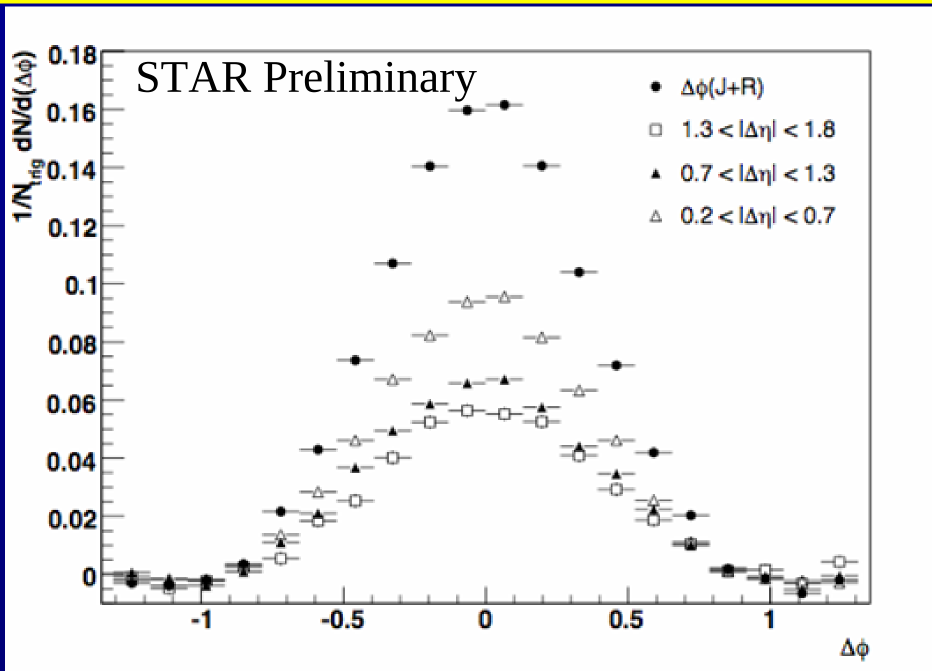
Parallel talk by A. Feng





The Ridge: new insights





- **Ridge extends over loooooong range in Δη.**
- **How close is the Δφ distribution to that of jets?**
  - **A crucial question to be answered (quantitatively)**
- **Momentum and flavor dist. characteristic of medium.**
  - **(data not shown for brevity)**
- **We assembling the data that we need to test models.**

The Ridge: Models

Shamelessly ripped off from Wenger (sincerest form of flattery?)

Theoretical Interpretations of Ridge

Very different proposed mechanisms qualitatively describe "ridge" at $|\Delta\eta|<2$

- Coupling of induced radiation to longitudinal flow
  Armesto et al., PRL 93, 242301
- Recombination of shower + thermal partons
  Hwa, arXiv:nucl-th/0609017v1
- Anisotropic plasma
  Romatschke, PRC 75, 014901
- Turbulent color fields
  Majumder, Muller, Bass, arXiv:hep-ph/0611135v2
- Bremsstrahlung + transverse flow + jet-quenching
  Shuryak, arXiv:0706.3531v1
- Splashback from away-side shock
  Pantuev, arXiv:0710.1882v1
- Momentum kick imparted on medium partons
  Wong, arXiv:0707.2385v2

So far we can't rule any of these out.

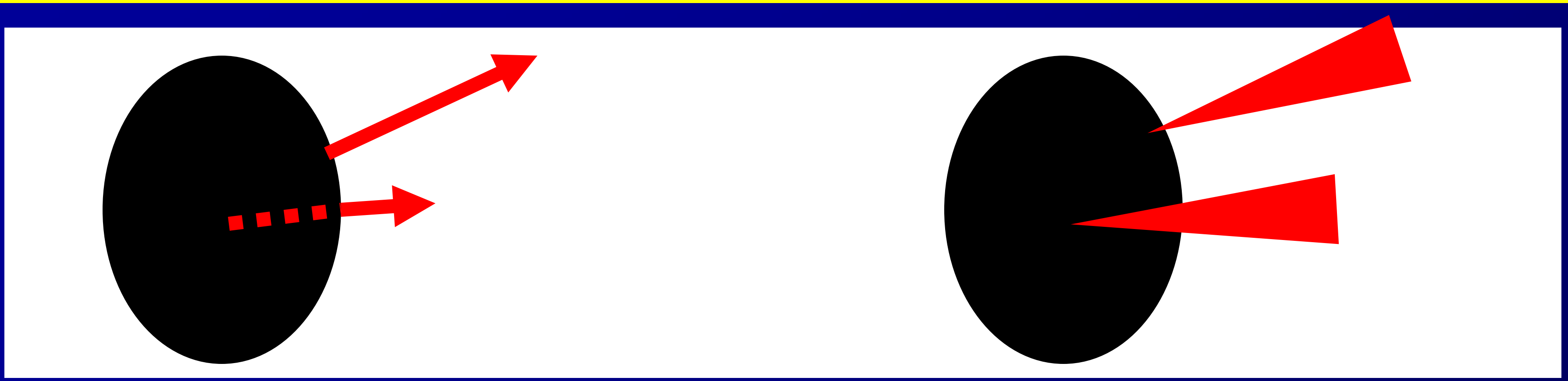
Somehow we must exclude all but 1 (or 0)

- **Theorists: help us kill your model (you know it best!)**
- **Otherwise we're wasting many person-years, many $$$**

Conclusions

- **We desperately need a coherent theory+expt. effort**
  - **To address issues with energy loss models**
  - **To test models against consistent set of realistic geometries**
  - **Examples for how to do this: MRST & CTEQ**
    - **⇒Only then can we really bootstrap our way to tomography**
- **It's time to get past/get over fragility**
  - **Yes, we know already!**
  - **But $R_{AA}(p_T, A, N_{part}, \phi-\Psi)$ absolutely necessary for**
- **It's too early to be trying to determine $\hat{q}$ to 10, 20, 30%**
  - **When there are much larger theoretical uncertainties.**
  - **We experimentalists should be using (and refining our) data to help resolve those theoretical uncertainties.**
- **Exciting data on medium response, but still inconclusive**

The Future: Jets, γ-jet/h



- The ΔE bias is one of the biggest (but not the only) problems that we face in understanding quenching.
  - Simply don't see a large fraction of the jets.
- In principle, full jet measurements fix this problem
  - e.g. 100 GeV jet @ LHC should always be visible.
  - Unless quenching is completely non-perturbative & strong.

    ⇒The data will then at least be definitive.
- Will happen @ LHC within ~2 years.
  - But RHIC experiments also pursuing full jets, γ-h/jet.