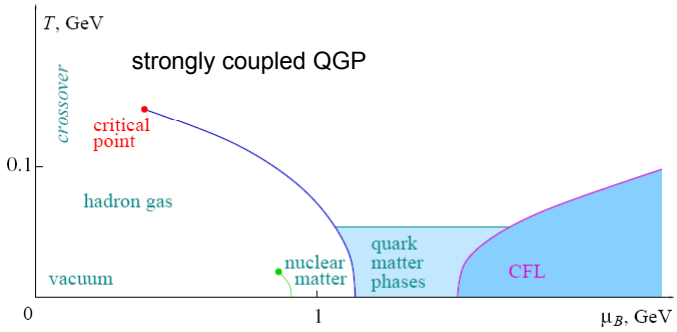
High-pt probes of the quark-gluon plasma: STAR/PHENIX results at RHIC

Craig Ogilvie, Iowa State University

1. What happens to a high-pt parton as it travels through a quark-gluon plasma (QGP)?
2. What does this tell us about the QGP?
3. Not much time on how QGP responds to the hard parton.

QCD Phase Diagram



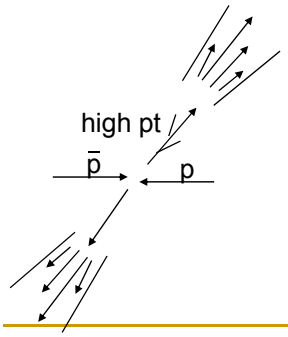
Within sQGP, momentum transfers ~ T ~ few 100 MeV/c
=> coupling large

Non-peturbatively interacting plasma of quarks and gluons
far from an ideal gas

One way to probe the sQGP

hard-scattered parton:
calc. with perturbative QCD

jet of hadrons

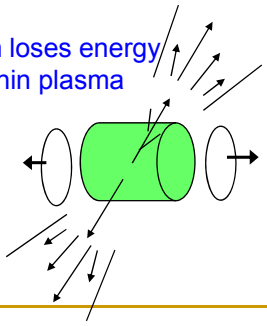


hard-scattered parton during Au+Au

Hadron distribution changed
- singles spectra
-2-particle correlations
- jet-structure

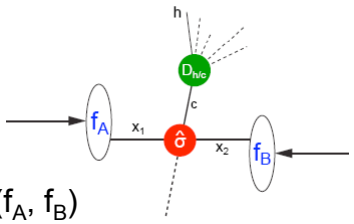
Information on the plasma?

parton loses energy within plasma



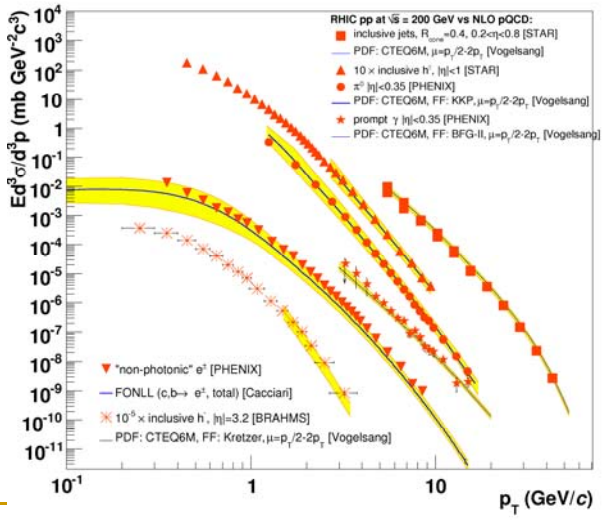
Hard-scattering as a calibrated probe

- Large scale that makes perturbative QCD applicable:
  - high momentum transfer Q^2
- Assume factorization between
  - perturbative hard part σ
  - universal, non-perturbative
    - parton distribution functions (f_A, f_B)
    - fragmentation ($D_{h/c}$) functions
  - from $e^+ + e^-$, p+p….

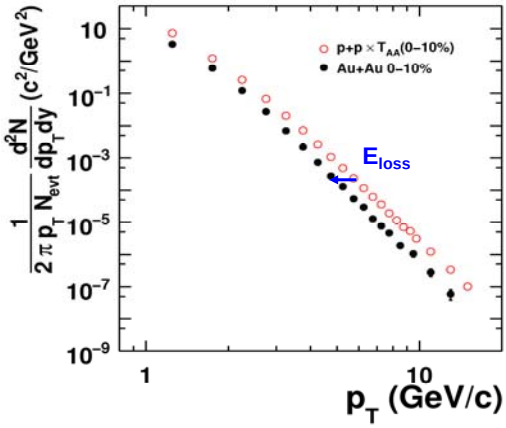


√s=200 GeV, p+p => x
NLO QCD agrees well with data

D. d'Enterria
nucl-ex/0611012



Partons lose energy as they travel through QGP

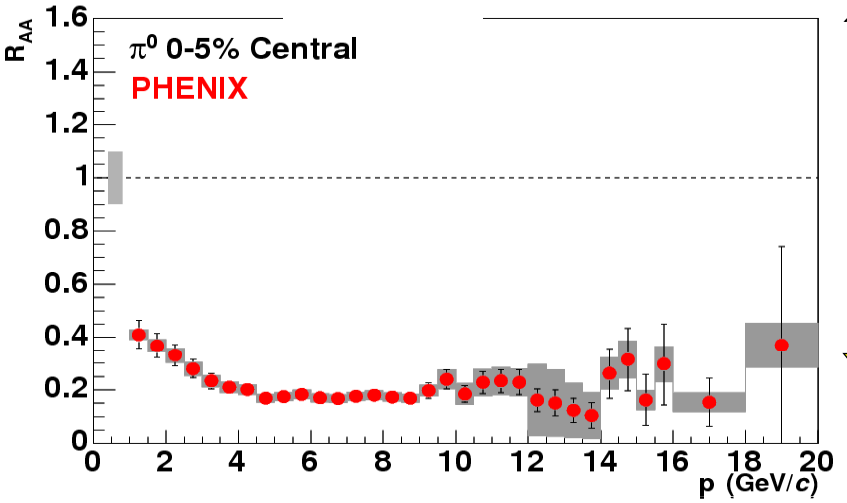


π⁰ spectra at √s=200 GeV
Phys.Rev.C76:034904,2007
PHENIX

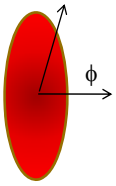
- p+p cross-section scaled by # of nucleon collisions in Au+Au
- Fewer high-pt π^0 in Au+Au
  - Energy-lost by parton => info on opacity, density of QGP

Au+Au π^0 R_{AA}

$$R_{AA} = \frac{dN / dp_\perp (Au + Au)}{< N_{coll} > dN / dp_\perp (p + p)}$$

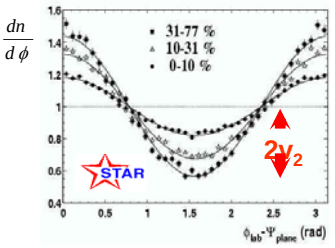


Elliptic asymmetry at high-pt



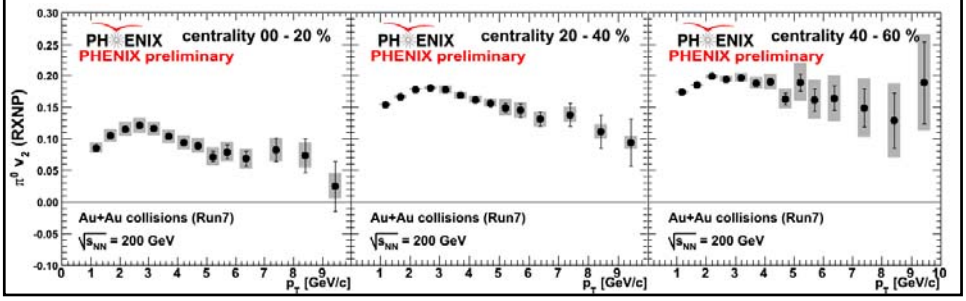
Overlap zone is elliptical:

More energy-lost if parton travels through long-direction of ellipse

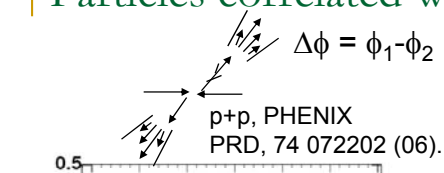


Fewer high-pt hadrons out-of-plane

Asymmetry, v_2, $dN/d\phi = A(1+2v_2 \cos(2\phi))$

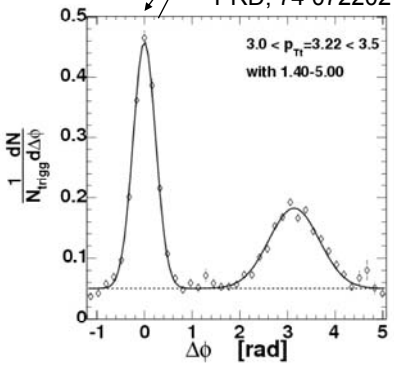


Particles correlated with high-pt trigger



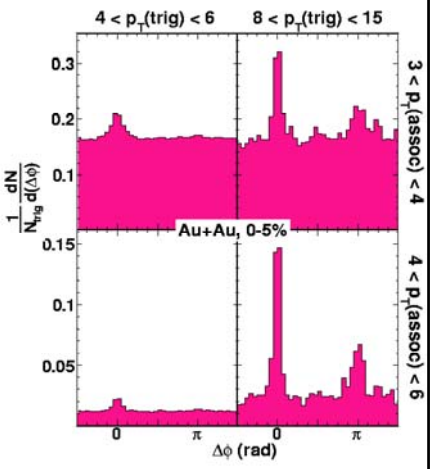
$\Delta\phi = \phi_1 - \phi_2$

p+p, PHENIX
PRD, 74 072202 (06).



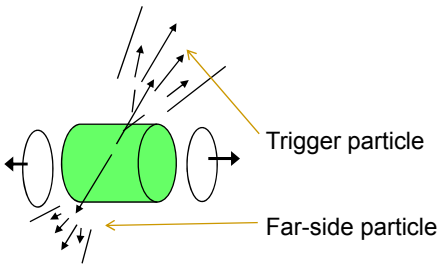
A+A

STAR PRL **97** (2006) 162301

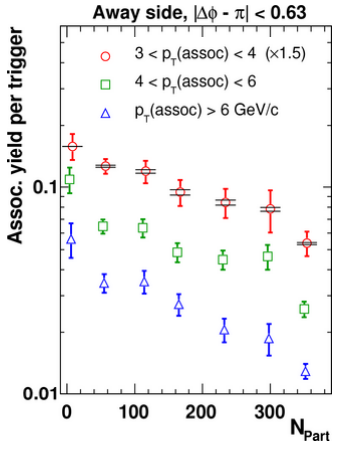


- Correlation survives high-multiplicity environment of A+A

Suppression of far-side hadrons



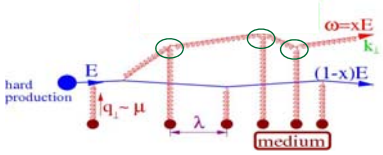
8 < ptrig <15 GeV/c



STAR PRL **97** (2006) 162301

Far-side yield per trigger
sensitive to relative energy lost by both partons
=> Alphabet of observables, $D(z_T)$, I_{AA}, J_{AA}, …

Use measurements to learn about QGP



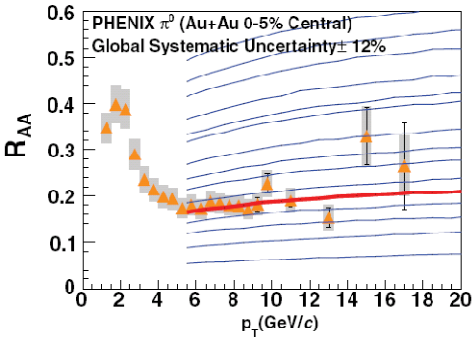
$$\hat{q} = \frac{\mu^2}{\lambda} = \frac{\text{momentum transferred}}{\text{mean free path}}$$

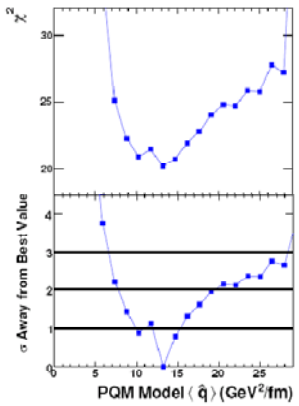
Scattering power of the QCD medium:

- Wiedermann: models of gluon radiation, transport parameter $\hat{q}$
- Note
  - Hard-scattering takes place throughout collision volume
    - Data and models average over wide range pathlengths…
  - Medium expands rapidly $<\hat{q}>$
    - Parton travels through a medium whose density decreases

Comparison data + models (e.g. PQM)

Vary transport parameter $<\hat{q}>$





$$\tilde{\chi}^2(\epsilon_b, \epsilon_c, p) = \left[\sum_{i=1}^{n} \frac{(y_i + \epsilon_b \sigma_{b_i} + \epsilon_c y_i \sigma_c - \mu_i(p))}{\tilde{\sigma}_i^2} + \epsilon_b^2 + \epsilon_c^2\right]$$

PRC 77, 064907 (2008)

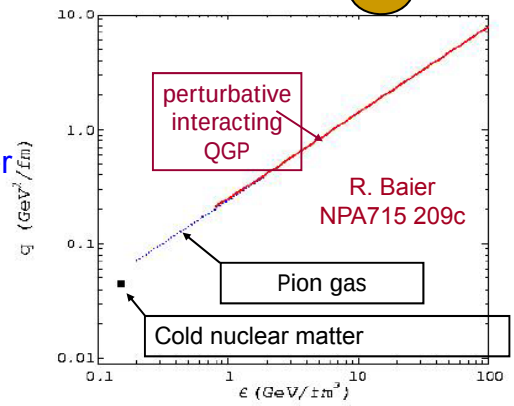
$<\hat{q}>=13.2 \pm^{2.1}_{3.2} \frac{\text{GeV}^2}{\text{fm}}$ But no model uncertainty yet

Strong energy-loss

RHIC data

Large <q>

=> high momentum transfer
=> strong QGP coupling

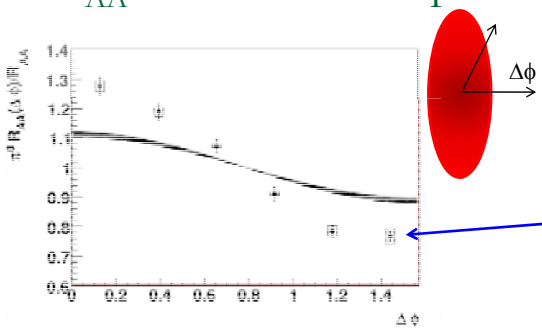


Experimentalist's reaction:

1) Reduce averaging over path-length

2) Other observables to check understanding of energy-loss

Change average over path-length: R_{AA} versus reaction plane



Overlap zone is elliptical:

More energy-lost as parton travels through long-direction of ellipse

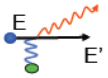
R_{AA} smaller out-of-plane

Model T. Renk, vary E_{loss}
PHENIX prelim centrality 20-30%
π^0 6<pt<7 GeV/c

This and other models fail, yet reproduce R_{AA} vs pt

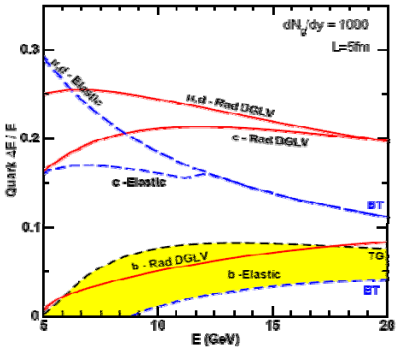
1. Need stronger variation of E_{loss} for different paths, or
2. Sharper early spatial distribution of energy density, or
3. More rapid variation of q with ε, or ……

Test for other mechanisms of energy-loss:



Radiation
due to scattering

Elastic collision,
energy re-distribution



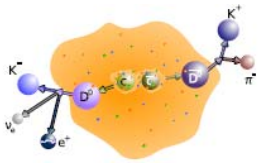
Many calcs on relative importance

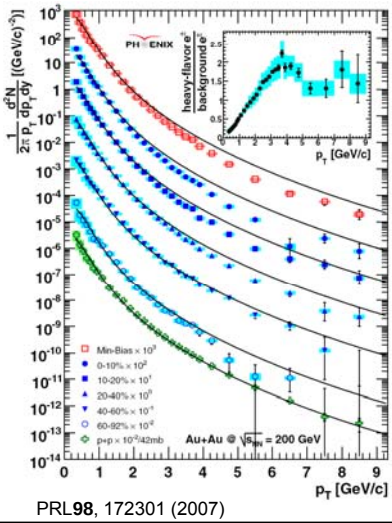
Probe via high-pt heavy-quarks
- smaller energy loss after elastic collision
- gluon radiation also reduced
  - interference during radiation
  - dead-cone effect

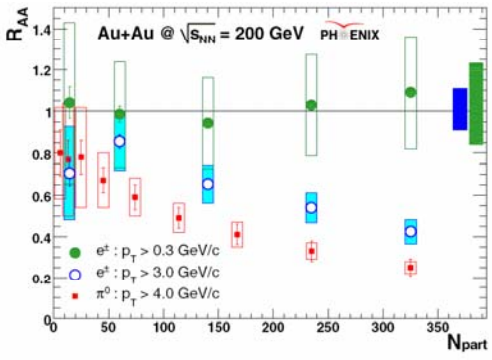
S.Wicks, W. Horowitz, M. Djordjevic M. Gyulassy (**WHDG**) nucl-th/0512076

Heavy-Quark Energy-loss

Semi-leptonic decays of charm
beauty mesons, R. Averbeck





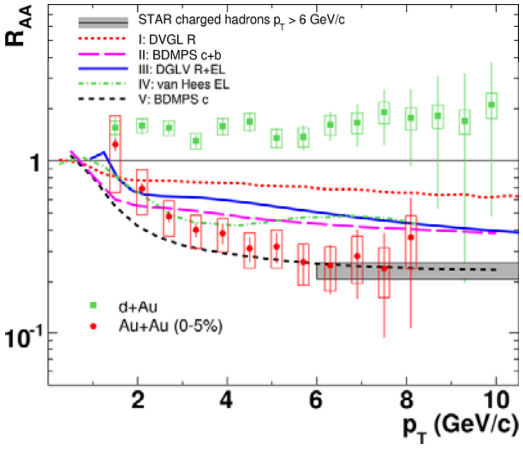


Strong suppression of high-pt charm

PRL**98**, 172301 (2007)

Radiative+collisional energy-loss models struggle

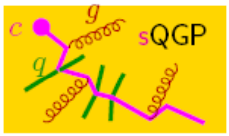
STAR Phys. Rev. Lett. **98** (2007) 192301

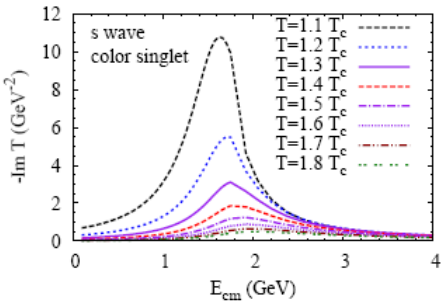


Note, ------
BDMPs charm only, may not be realistic to remove beauty

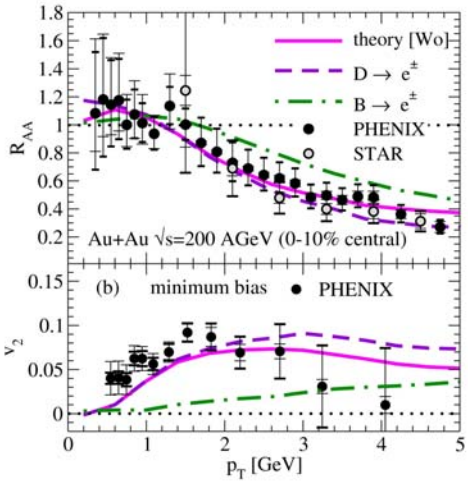
Strong resonance interaction in-medium

Heavy-quarks may form resonances in sQGP near T_c

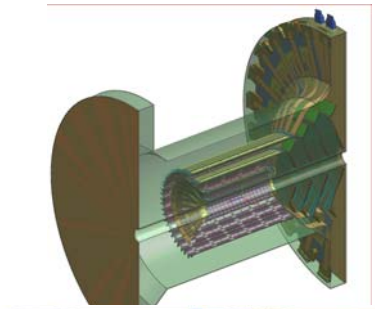


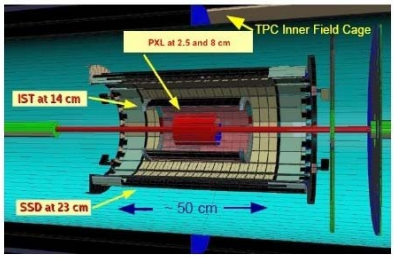


H. van Hees et al, PRL 100, 192301 (2008)

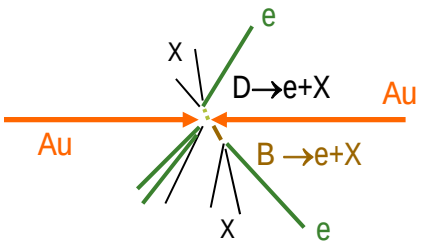


Separation charm/beauty
PHENIX VTX, STAR HFT





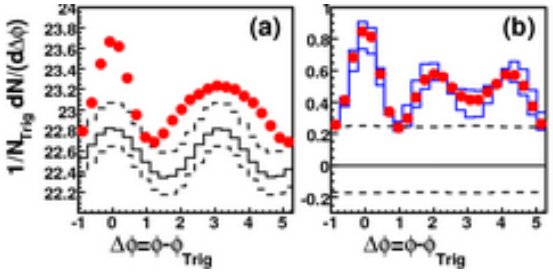
silicon pixel+strip detectors
Tracks extrapolate back to collision
Displaced vertices
=> charm (D), beauty (B)
Requires ~ 50 μm precision

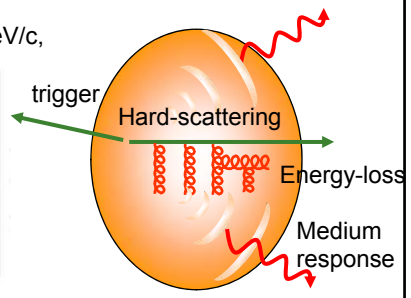


Great hardware opportunity for post-docs

Medium Response: Low-pt far-side

Trigger: $3 < p_T < 4$ GeV/c Assoc: $1 < p_T < 2$ GeV/c,





STAR arXiv:0805.0622v1, PHENIX PRL 98, 232302 (2007)

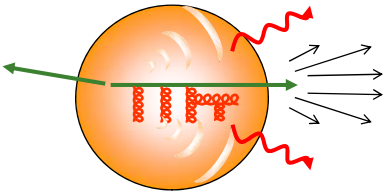
Growing evidence for conical medium response

STAR: 3-particle correlations

PHENIX :angle of conical emission independent of pt

=> not bremstrahlung

No clean separation between medium-response and fragmentation?



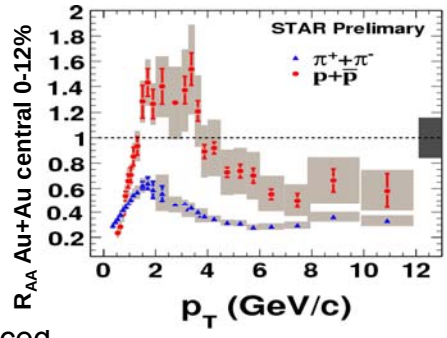
Shocked medium contributes to fragmentation

e.g. coalescence of protons from shower+medium partons

=> Additional high-pt protons
R. Hwa

Protons

More protons than pions at high-pt, even out to 10 GeV/c

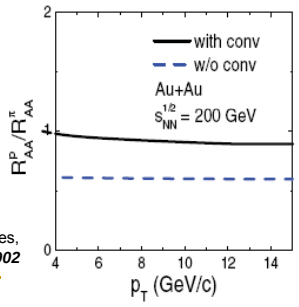


- Fragmentation to protons enhanced by combining with shocked medium?

and/or

- As parton propagates in medium it can change flavor => energy-loss comparable for gluons and quarks,

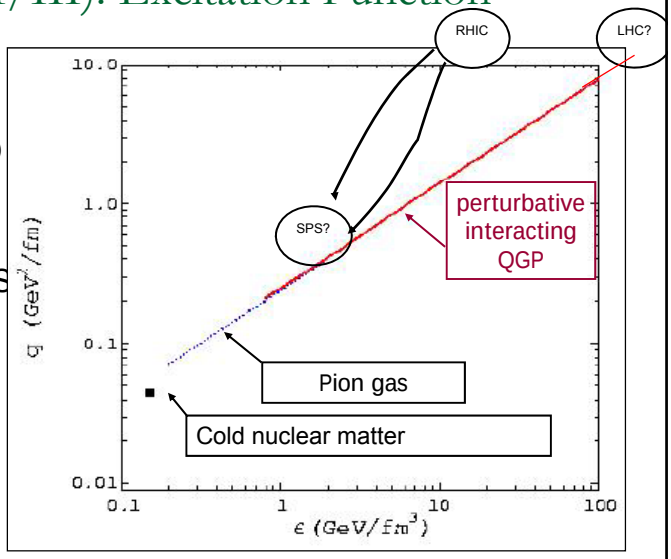
Liu, W. and R.J. Fries, *PRC 2008. **77 054902***



Conclusion

Next Steps (I/III): Excitation Function

- Does q return to perturbative QCD at LHC?
- Evaluate q at SPS (in progress)
- Low-E RHIC, onset of strong opacity?



Other values for qhat: Stefan Bass

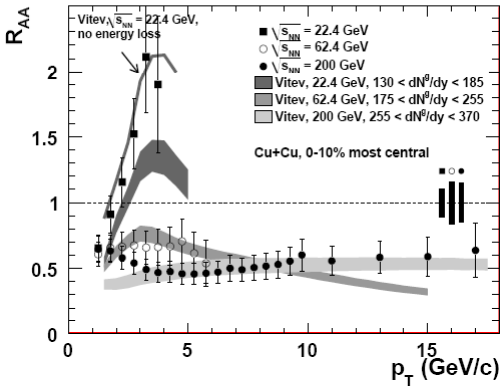
define local transport coefficient along trajectory ξ for all three approaches and compare initial maximum value q_0:

q_0 [GeV²/fm]	ASW	HT	AMY
T	10	2.3	5.5
ε	20	4.5	X
s		3.4	X

(all values quoted for a gluon jet)

different medium scaling can affect q by a factor of 2
need higher precision data and theory advances to provide guidance for *proper* medium scaling

$\sqrt{s_{NN}}$ Dependence: p_T Dependence of π^0 R_{AA} in Cu+Cu

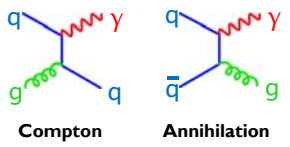


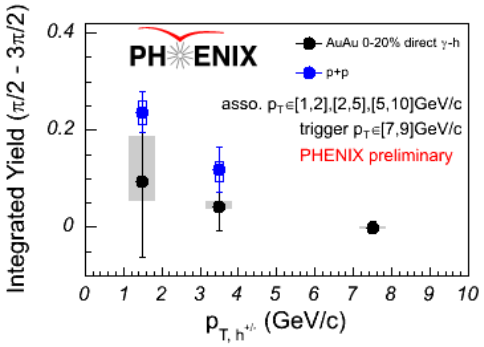
PHENIX, arXiv:0801.4555 [nucl-ex]

- 62.4, 200 GeV:
  - Suppression consistent with parton energy loss for p_T > 3 GeV/c
- 22.4 GeV:
  - No suppression
  - Enhancement consistent with calculation that describes Cronin enhancement in p+A
- Parton energy loss starts to prevail over Cronin enhancement between 22.4 and 62.4 GeV

Next Steps (II/III) Measure ΔE directly

- Direct γ to tag energy

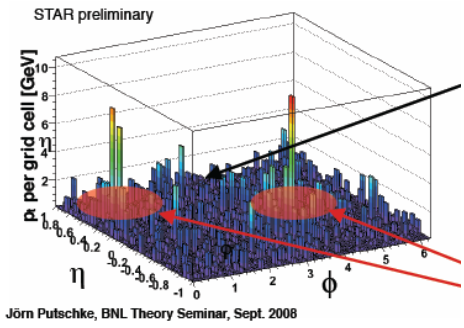


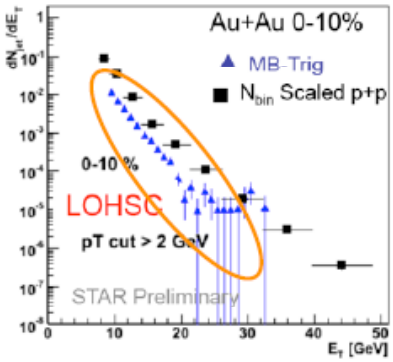


- RHIC-II, LHC

Next Steps (III/III): Fragmentation within jet

- Jets with pt-cut off





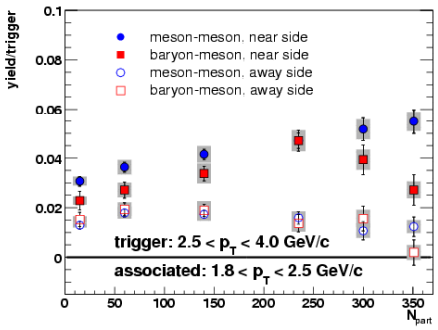
- Higher-pt => LHC, RHIC-II

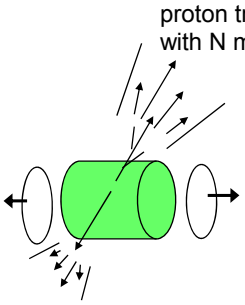
Conclusion

- Energy-loss as high-pt parton travels through QGP
  - Opaqueness parameter, momentum transferred/length $< \hat{q} >$
  - $< \hat{q} >$ larger than expected pQCD, => strongly coupled QGP
- Puzzles
  - R_{AA} vs ϕ, modeled E_{loss} too flat => stronger spatial variation?
  - Large heavy-flavor E_{loss} => quasi-resonances near T_c?
  - Proton R_{AA} closer to 1 => shocked medium recombining?
- Next steps
  - Excitation function of $< \hat{q} >$, LHC, SPS, low-E RHIC
  - E_{loss} via γ-h and reconstructed jets

Backup

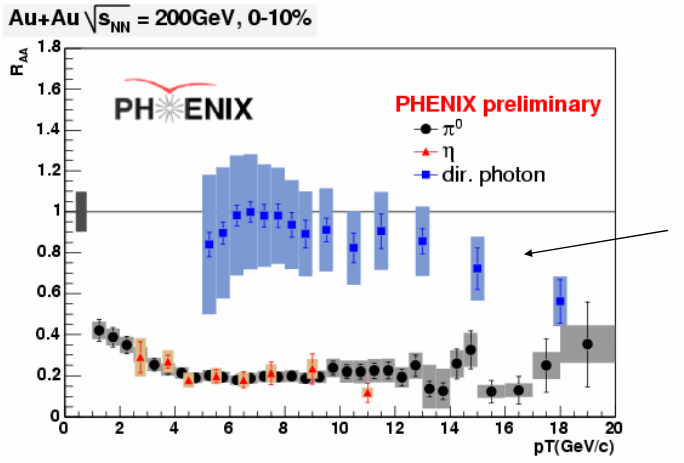
Protons in jets





- For each proton trigger, number of mesons starts to decrease
  - Additional source of protons, e.g. from medium response

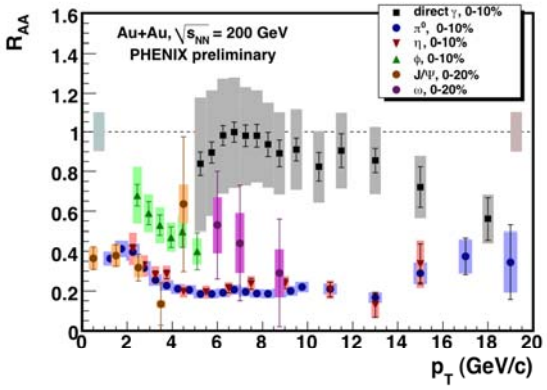
Ratio of (Au+Au)/(scaled p+p spectra)



Drop possibly due to isospin difference p+p and A+A

- Mesons suppressed × 5 → energy-lost in QGP
- γ scale with parton flux

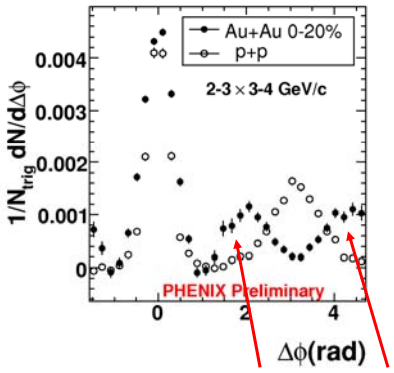
RAA π^0, η, ϕ, J/ψ, ω Mesons and Direct γ

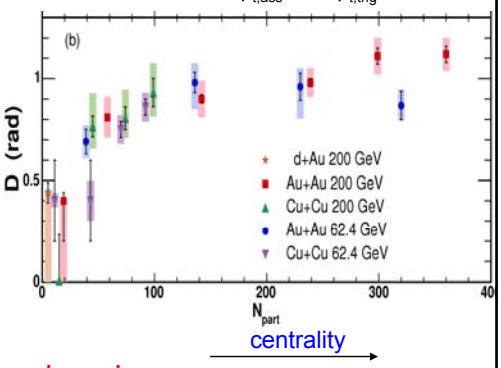


- Same suppression pattern for π^0 and η:
  - parton energy loss and fragmentation in the vacuum
- R_{AA} for ϕ's larger than π^0 R_{AA} for $2 < p_T < 5$ GeV/c

Far-side Production of Particles

PHENIX preliminary
nucl-ex/0611019
$1<p_{t,ass}<2.5<p_{t,trig}<4$ GeV/c





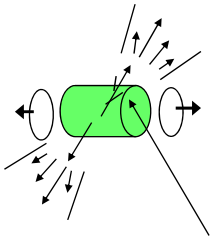
centrality

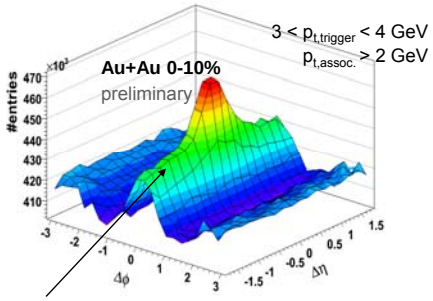
Observation of particles produced
~1 radian away from back-to-back!

Fit with 2 Gaussians, each D radians away from π
D scales with system size

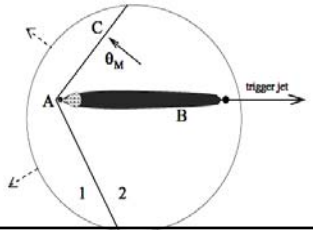
=> emission consistent with medium's response to jet

Response of medium to passage of high-pt parton



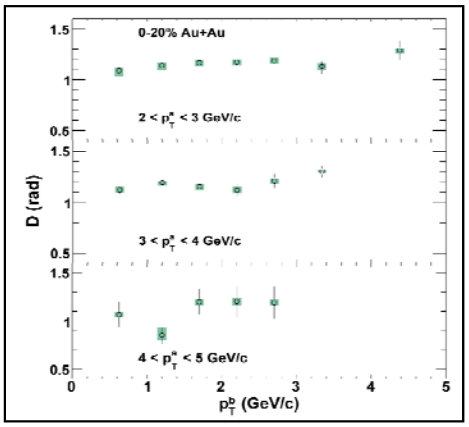


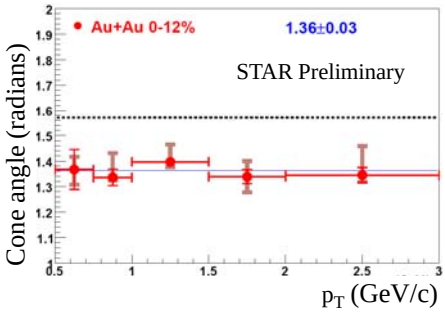
- Near-side, generation of ridge => strength large $\Delta\eta$ (STAR talk)
- Far-side: does super-sonic parton generate a mach-cone ?



hep-ph/0410067;
H.Stocker…
Jorge Casalderry-Solana

Conical? flow – QM08: B. Cole

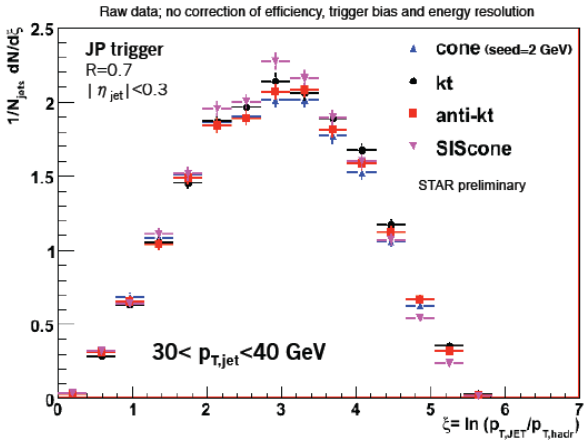




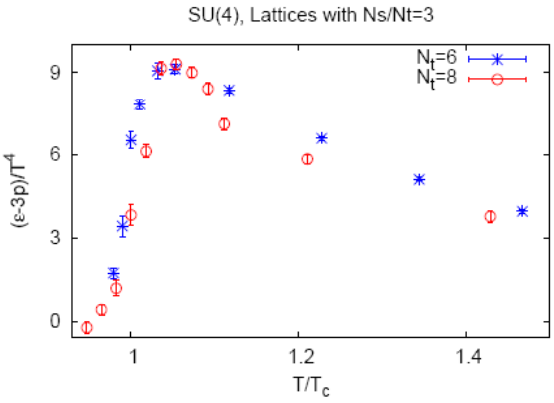
Beware: PHENIX measurement from 2 particle, STAR 3 particle

- Cone? angle does not change appreciably as a function of p_T of trigger or associated hadron.
  - Or centrality, or angle *wrt* reaction plane

Fragmentation within jet: J. Putschke



Strongly Interacting QGP



S. Gupta QM08

LHC predictions: Xin-Nian Wang