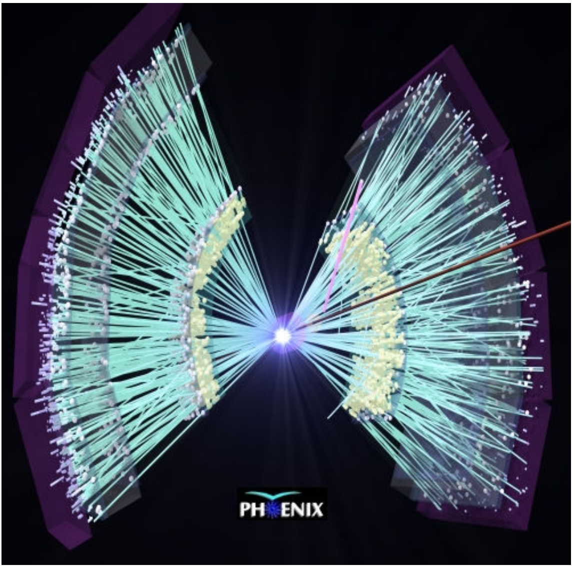
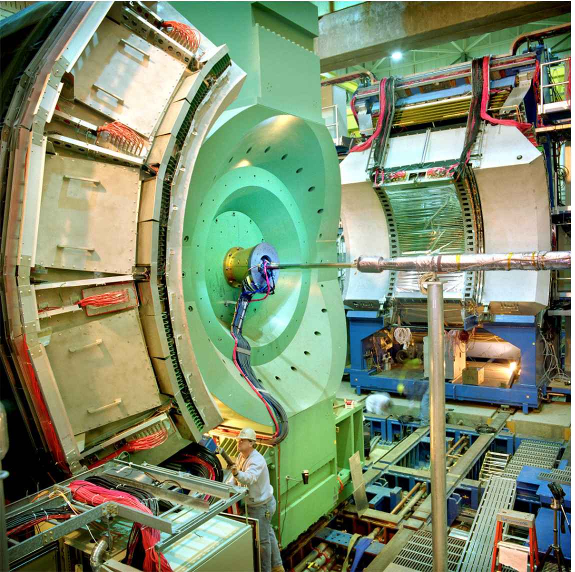
Hot QCD Matter: An Experimenter's Dream and Nightmare

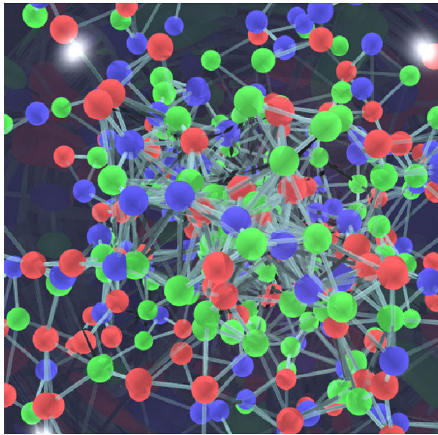




B. Jacak

Stony Brook

October 25, 2009



Hot QCD Matter

- **Exciting and surprising results from RHIC**
  - What *IS* the coupling in the plasma?
  - What are the degrees of freedom - point particles? pure fields? composite quasiparticles?

- **What are the physical properties of the plasma?**
  - Thermal: T, ρ, EOS
    - opacity, fluidity
  - Dynamic: viscosity, diffusion, energy transport
    - color screening, correlations inside

- **Measure the above in a system lasting <10 fm/c!**
  - Nature does the time integral, whether we like it or not

Today (results from PHENIX)

- Exciting and surprising results from RHIC
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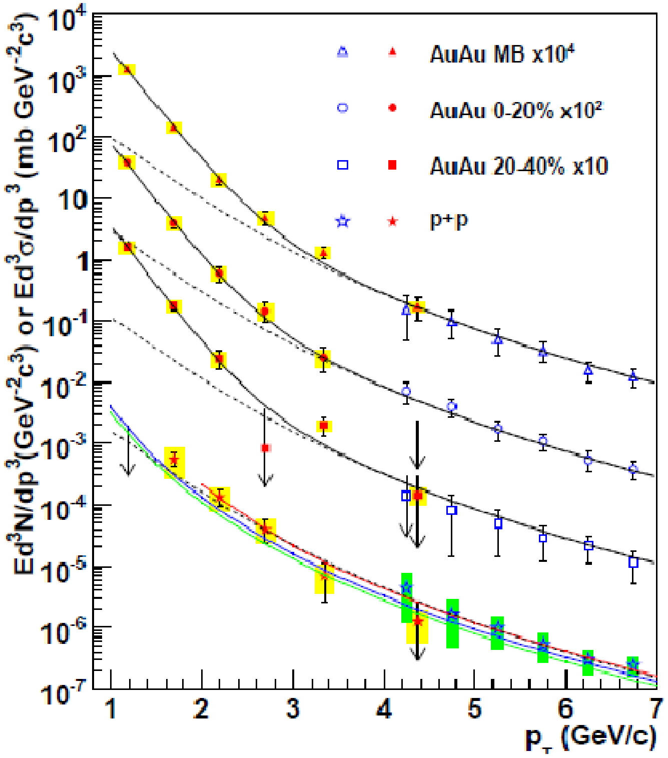
  - Nature does the time integral, whether we like it or not

Initial State Temperature: direct photons



arXiv:0804.4168v1 [nucl-ex]

Low mass, high p_T e^+e^- →

nearly real photons

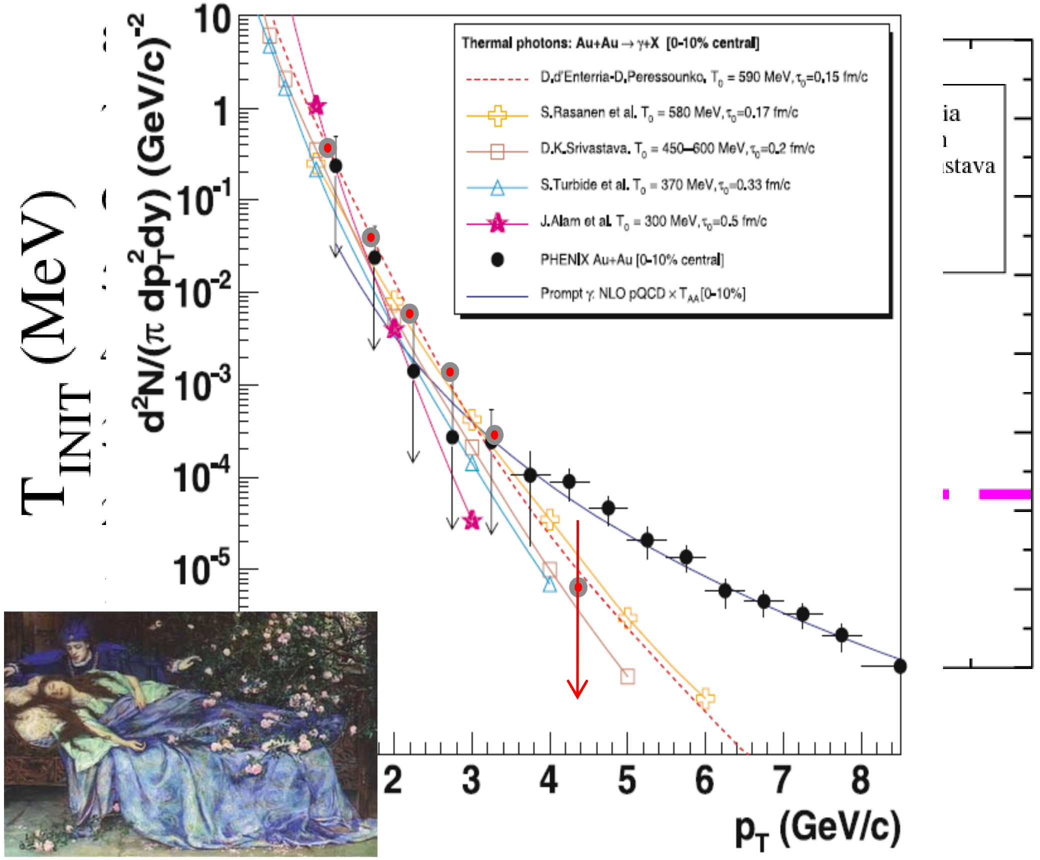
Large enhancement above p+p in the thermal region

- Exponential fit in p_T:

T_{avg} = 221 ±23 ±18 MeV

- Multiple hydro models reproduce data

•$T_{init} \geq 300$ MeV



Lepton pair emission ↔ EM correlator

e.g. Rapp, Wambach Adv.Nucl.Phys 25 (2000)

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

$\gamma^*\rightarrow ee$ decay

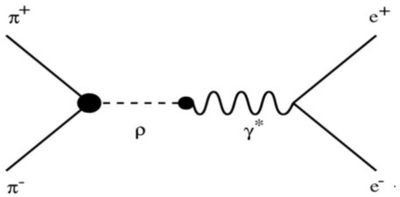
EM correlator
Medium property

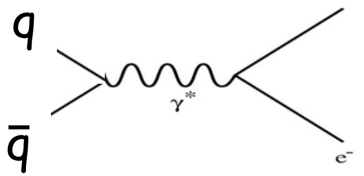
Boltzmann factor
temperature

Hadronic contribution
Vector Meson Dominance

Medium modification of meson
Chiral restoration

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M) & , \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right) N_c \sum_{q=u,d,s}(e_q)^2 & , \end{cases}$$





qq annihilation

Thermal radiation from
partonic phase (QGP)

From emission rate of dilepton, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

Dilepton emission

Calculation: R. Rapp

Dilepton

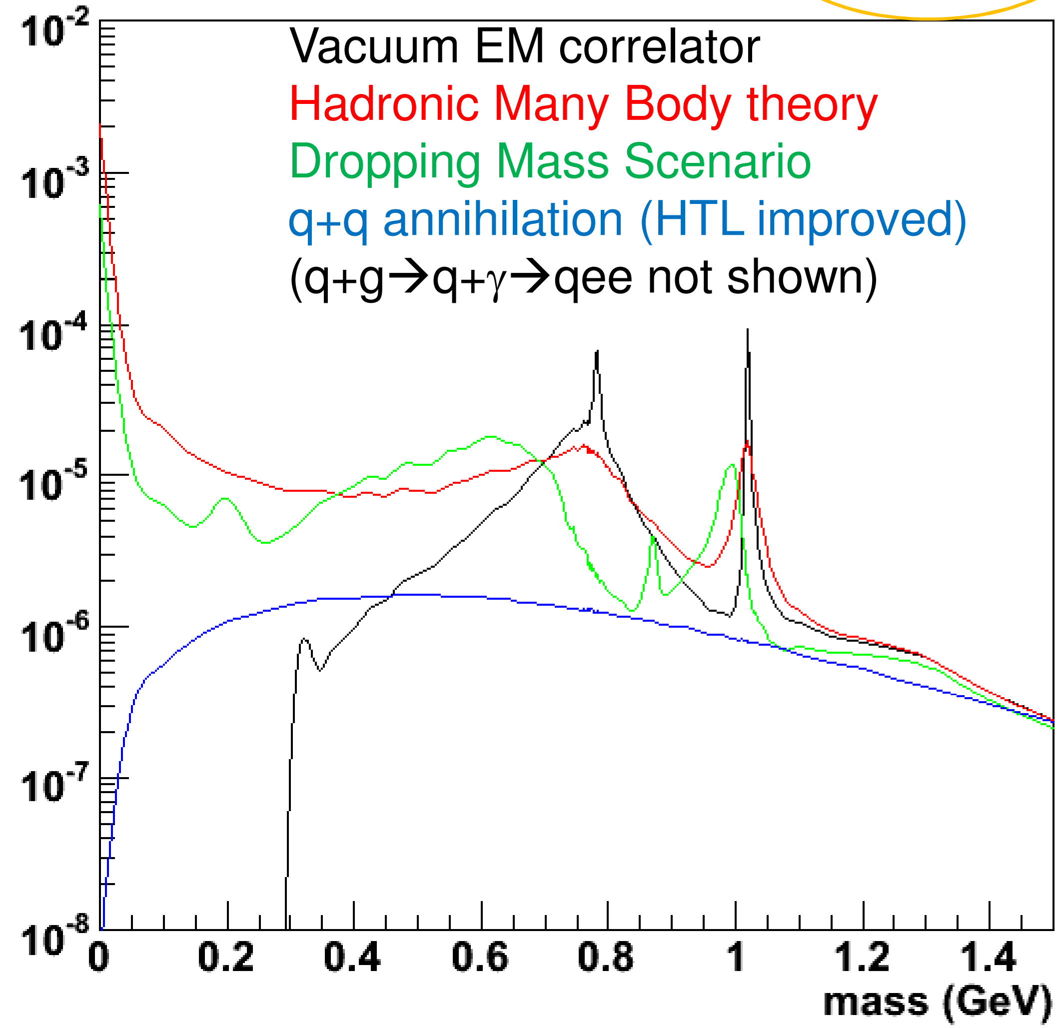
Prob. $\gamma^* \rightarrow l^+l^-$

$$q_0 \frac{dR_{ll}}{dM^2 d^3q} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}\, q_0 \frac{dR_{\gamma^*}}{d^3q}$$

virtual photon

$$\frac{dN_{ee}}{p_t dp_t dM dy}$$

y=0, pt=1.025 GeV/c



Normally: dilepton emission as spectrum $dN/dp_T dM$.

Mass spectrum at low p_T is distorted by virtual photon→ee decay factor 1/M: steep rise as $M \rightarrow 0$

*qq annihilation contribution negligible at low mass due to m**2 factor of the EM correlator*

NB: calculation omits partonic photon emission process $q+g \rightarrow q+\gamma \rightarrow q+e^+e^-$

Relation of dileptons and virtual photons

Emission rate of dilepton per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

Emission rate of (virtual) photon per volume

$$q_0\frac{dR_{\gamma^*}}{d^3q} = -\frac{\alpha}{2\pi^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T).$$

Relation between them

Prob. $\gamma^* \rightarrow l^+l^-$

$$q_0\frac{dR_{ll}}{dM^2d^3q} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2}q_0\frac{dR_{\gamma^*}}{d^3q}$$

Dilepton

virtual photon

This relation holds for the yield after space-time integral

Virtual photon emission rate can be determined from dilepton emission rate

$$\begin{aligned} q_0\frac{dn_{\gamma^*}}{d^3q} &\simeq \frac{3\pi}{\alpha}M^2 q_0\frac{dn_{ll}}{d^3q\,dM^2} \\ &= \frac{3\pi}{2\alpha}M q_0\frac{dn_{ll}}{d^3q\,dM}. \end{aligned}$$

M x dNee/dM gives Virtual photon yield

For M→0, n_γ^* → n_γ(real) so real photon emission rate can also be determined

Virtual photon emission rate

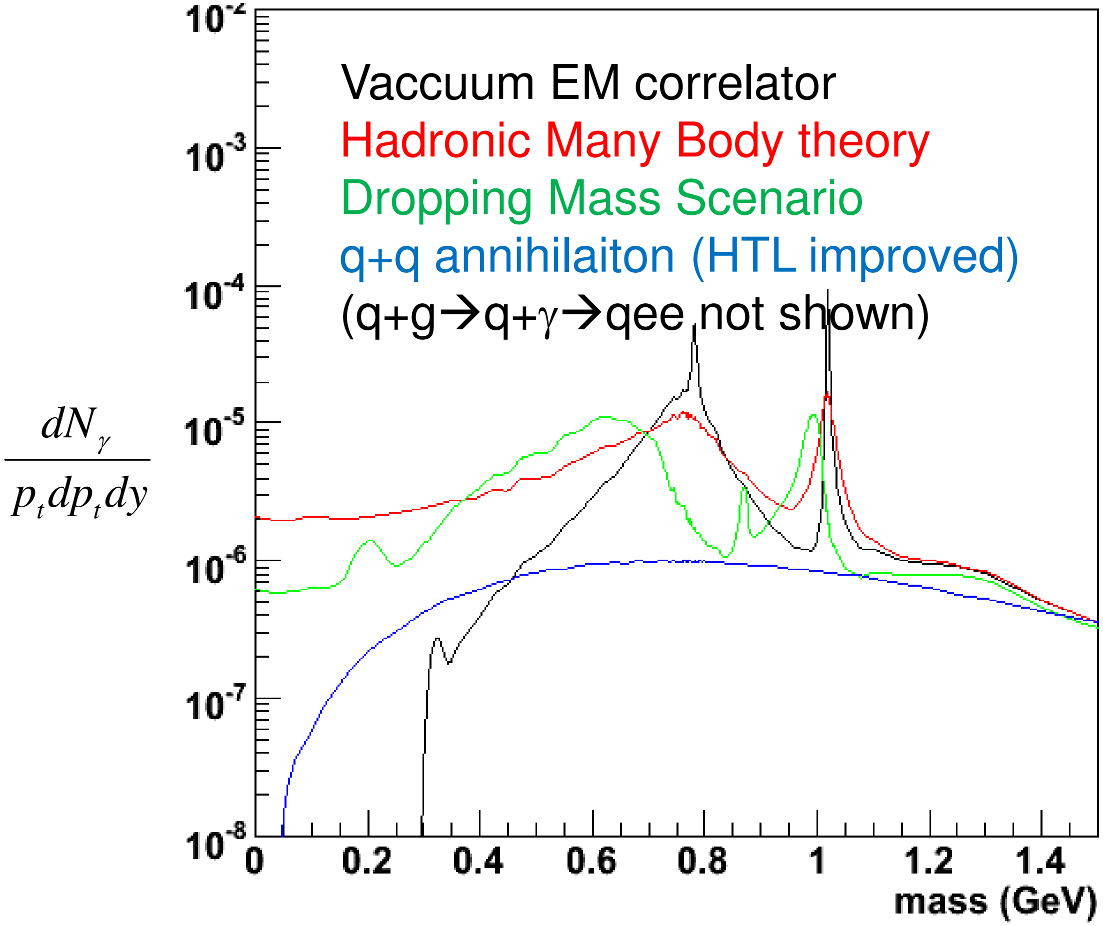
Dilepton

Prob. $\gamma^* \rightarrow l^+l^-$

$$q_0 \frac{dR_{ll}}{dM^2 d^3q} = \frac{1}{2}\frac{dR}{d^4q} = \frac{\alpha}{3\pi}\frac{L(M)}{M^2} q_0 \frac{dR_{\gamma^*}}{d^3q}$$

virtual photon

$$M \times \frac{dN_{ee}}{p_t dp_t dM dy} \propto \frac{dN_{\gamma^*}}{p_t dp_t dy}$$ at y=0, pt=1.025 GeV/c



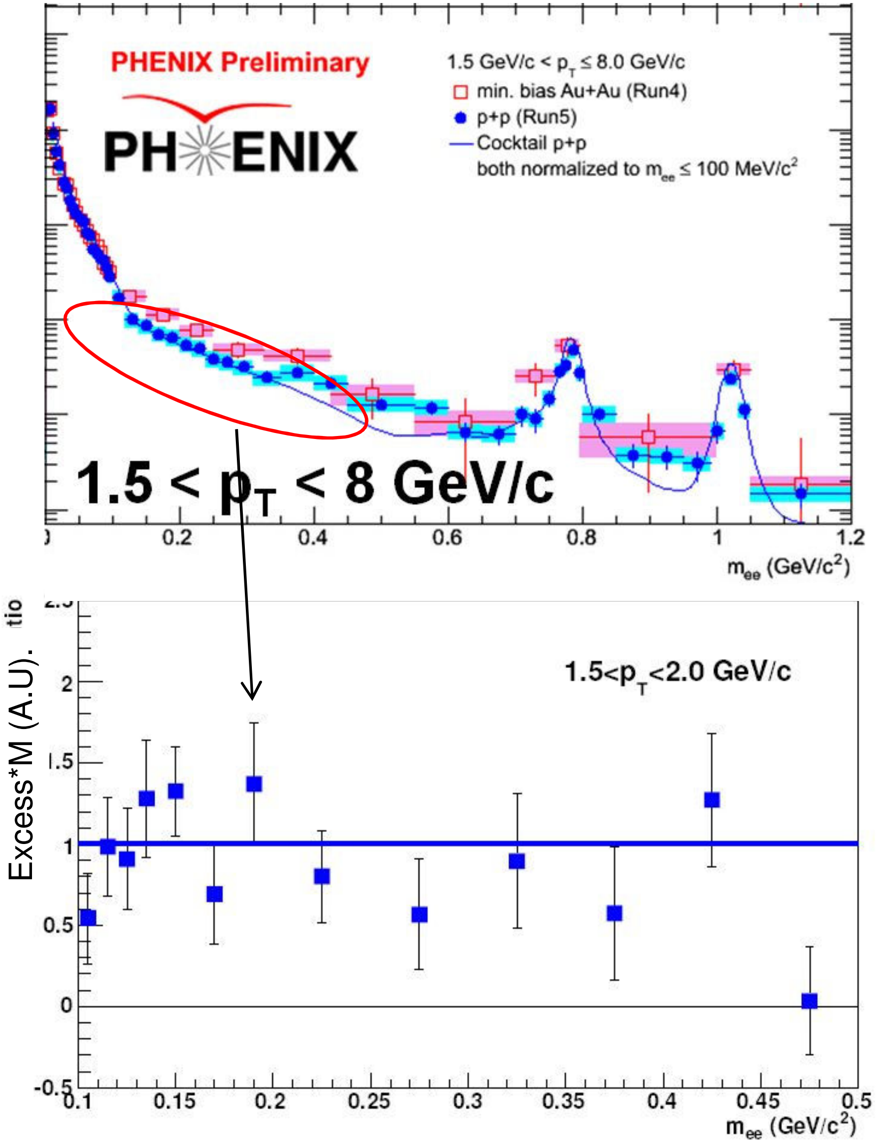
Same calculation shown as virtual photon emission rate.

Note: steep rise at M=0 is gone, and the virtual photon emission rate is more directly related to the underlying EM correlator.

For M→0, n_γ → n_γ(real)*

q+g→q+γ is not shown; is similar to HMBT at this p_T*

Excess of virtual photon



Excess over cocktail ~ constant with mass at high p_T.

Convert to virtual photon yield by 1/M factor from the virtual photon decay.
→ distribution is ~flat over 0.5 GeV/c^2

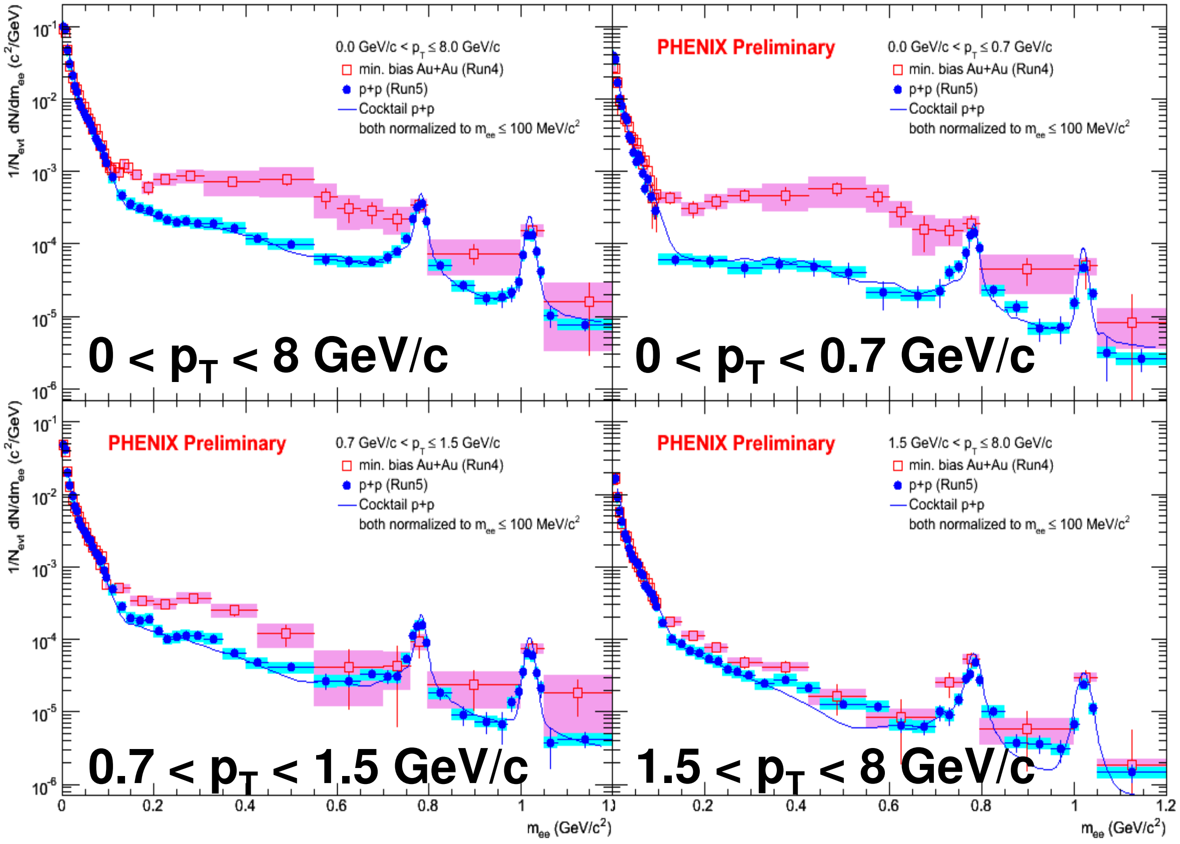
Extrapolation to M=0 should give the real photon emission rate.

No indication of strong modification of EM correlator at high p_T !

presumably the virtual photon emission is dominated by processes

e.g. $\pi+\rho \rightarrow \pi+\gamma^*$ or $q+g \rightarrow q+\gamma^*$

How about low p_T ?



QuickTime™ and a
decompressor
are needed to see this picture.

Excess*M (A.U).

Low p_T shape incompatible with constant virtual photon emission rate…

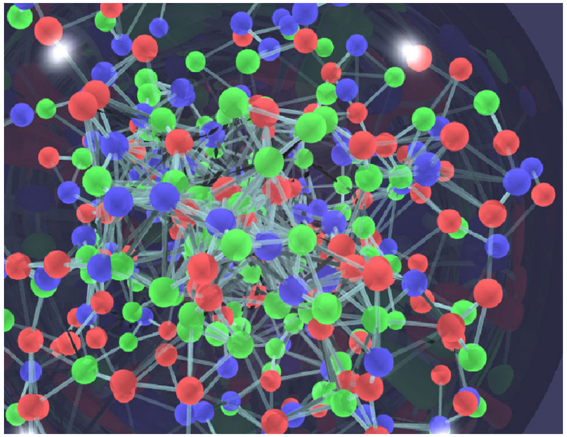
Enhancement of EM correlator at low mass, low p_T?

NEED HELP FROM THEORY!!

NEW DATA COMING IN 2010

Interactions within the plasma

- Experimentalist’s simple minded picture

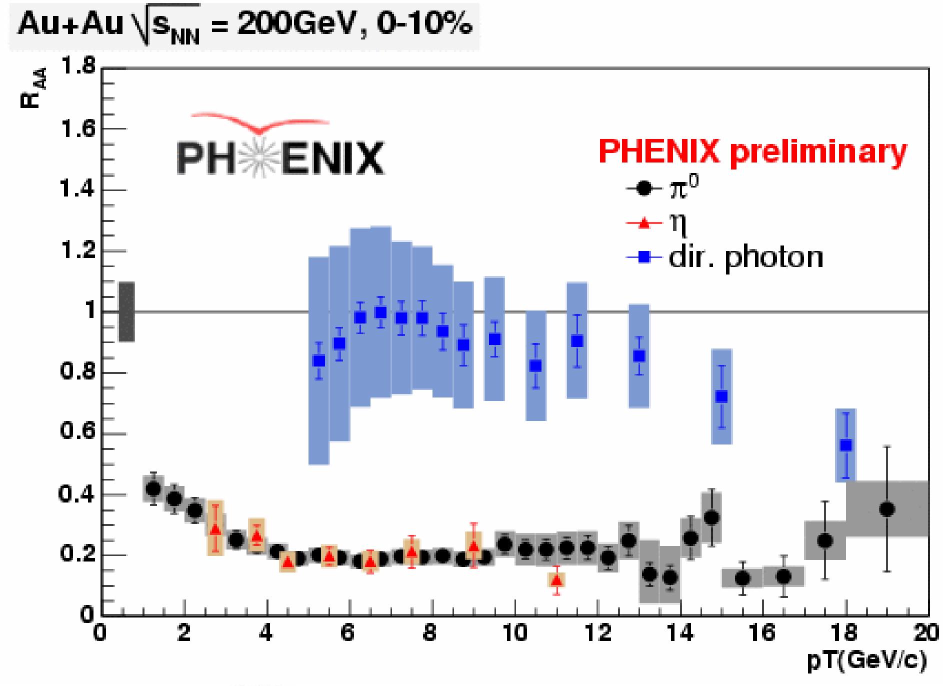


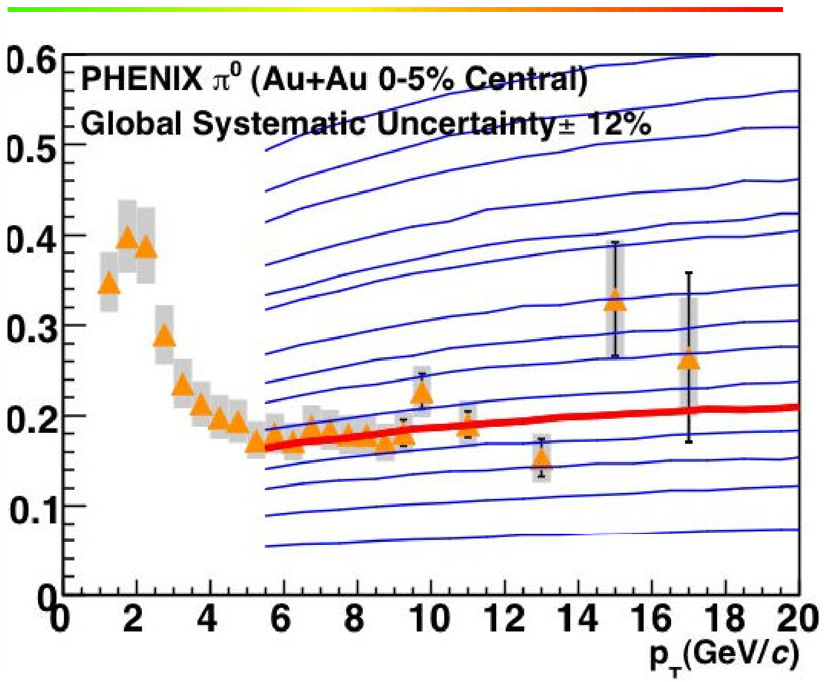
Strong coupling =
interactions among multiple neighbors

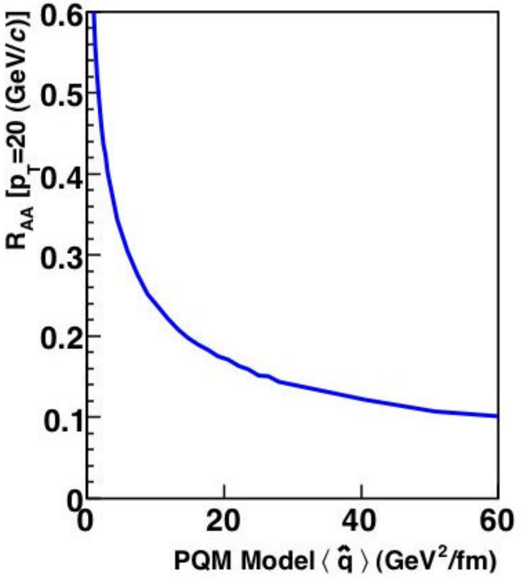
- Of course this must cause correlations within plasma
also increases opacity

how is the energy loss mechanism affected?
is the quark gluon plasma “black”?

Iconic jet quenching (opacity) result







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Insights somewhat unsatisfying

S. Bass, et al.
Phys.Rev.C79:024901,2009

Put 3 different energy loss schemes into common, realistic hydrodynamic calculation

QuickTime™ and a
decompressor
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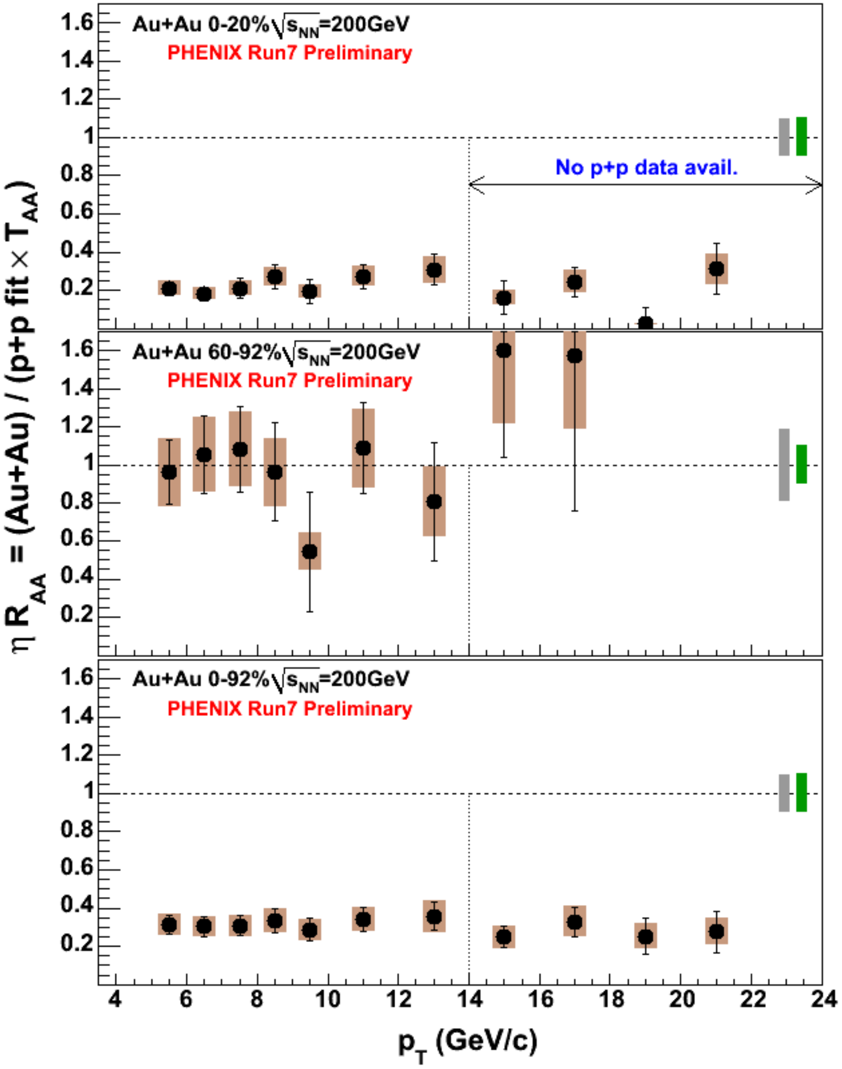
QuickTime™ and a
decompressor
are needed to see this picture.

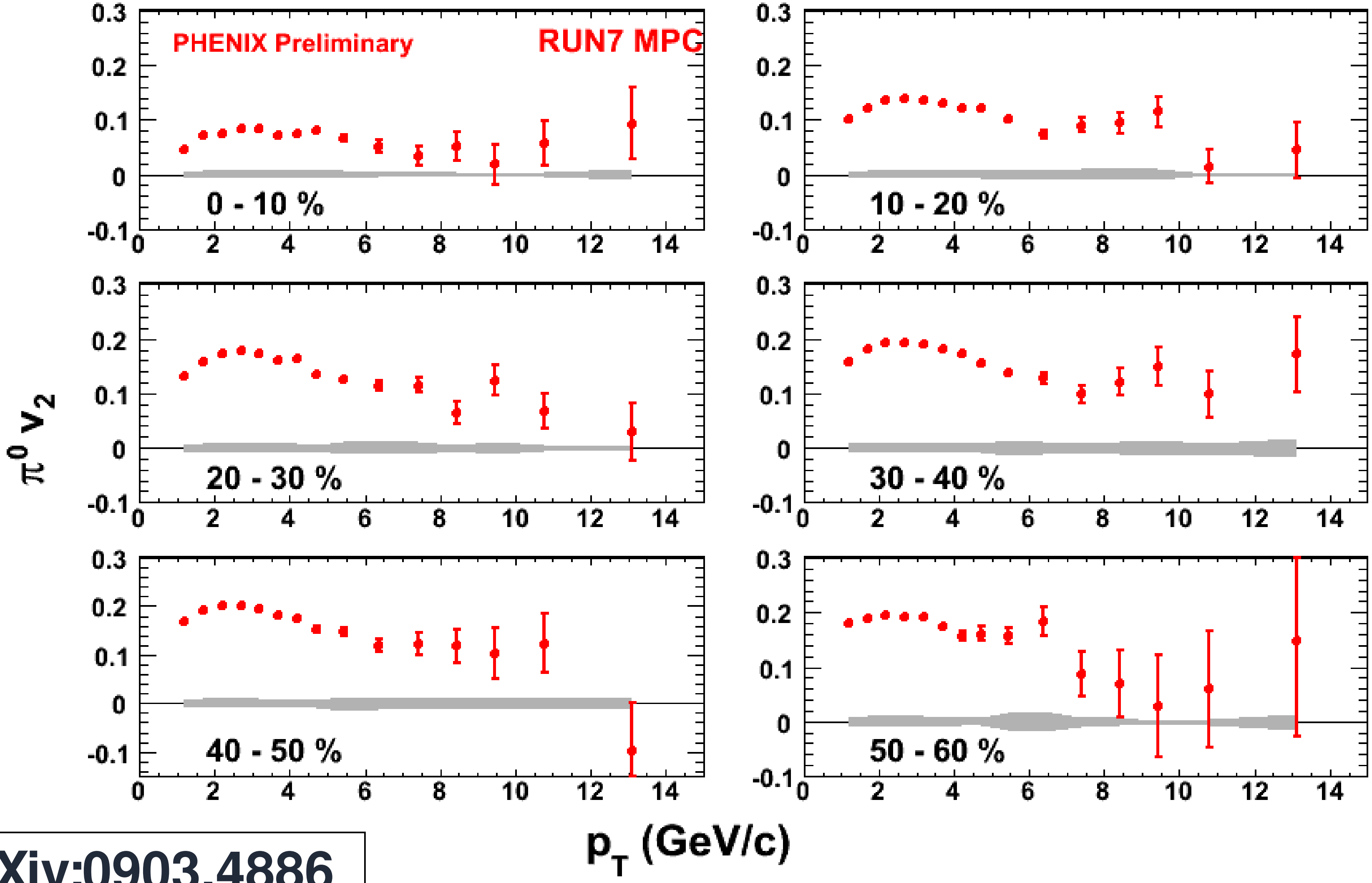
We can do better!

- **Extend the p_T range**
  Difficult for π^0 because decay γ's merge in the calorimeter
- ***Measuring η instead of π^0 is the solution***

R_{AA} remains flat to at least 22 GeV/c!



Next step: constrain geometry: high-p_T v_2

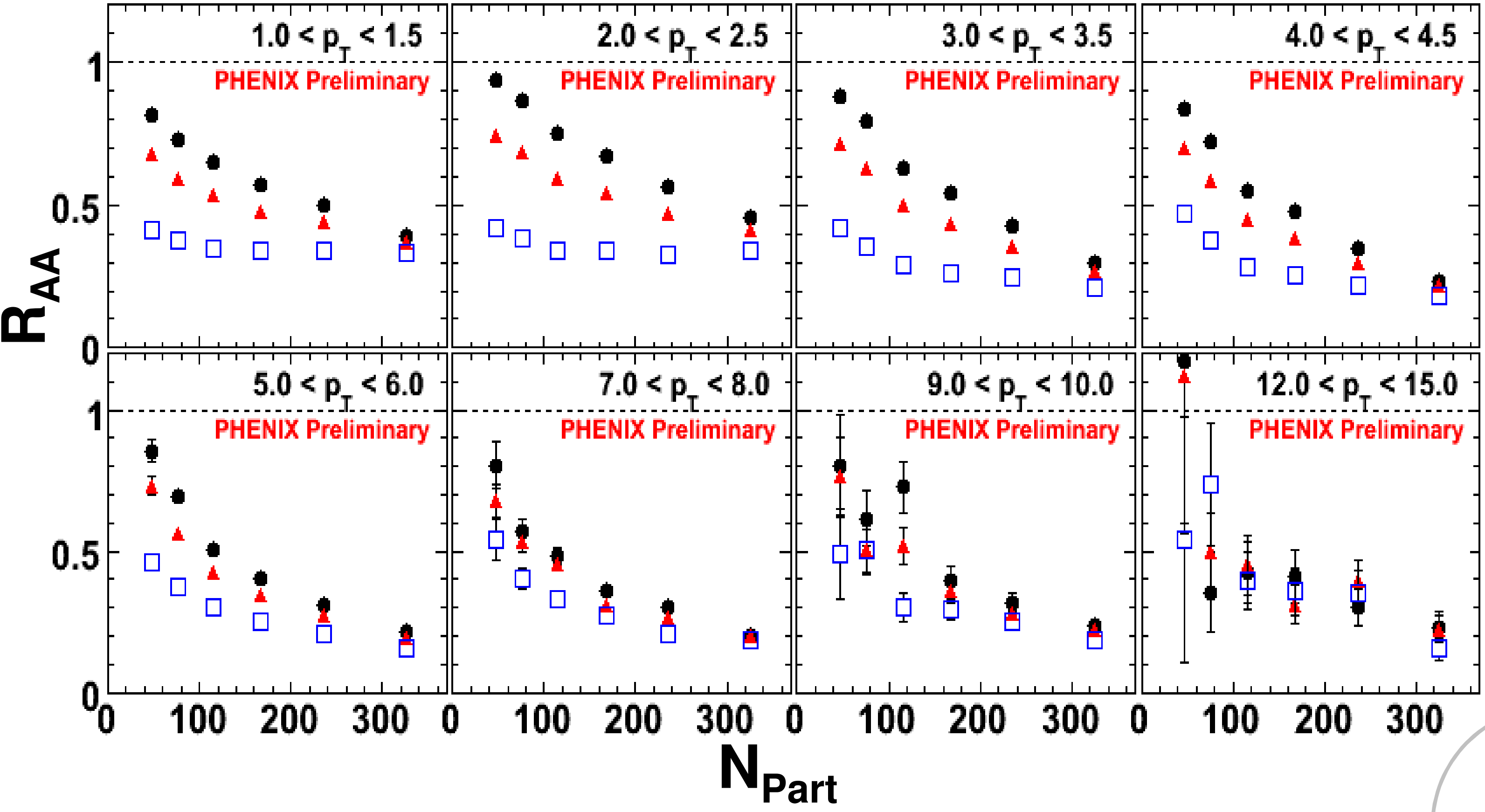


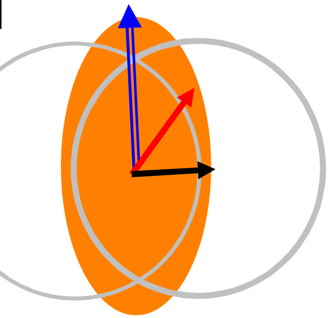
arXiv:0903.4886 (Run-4 data)

Out-of-plane vs. in-plane

p_T

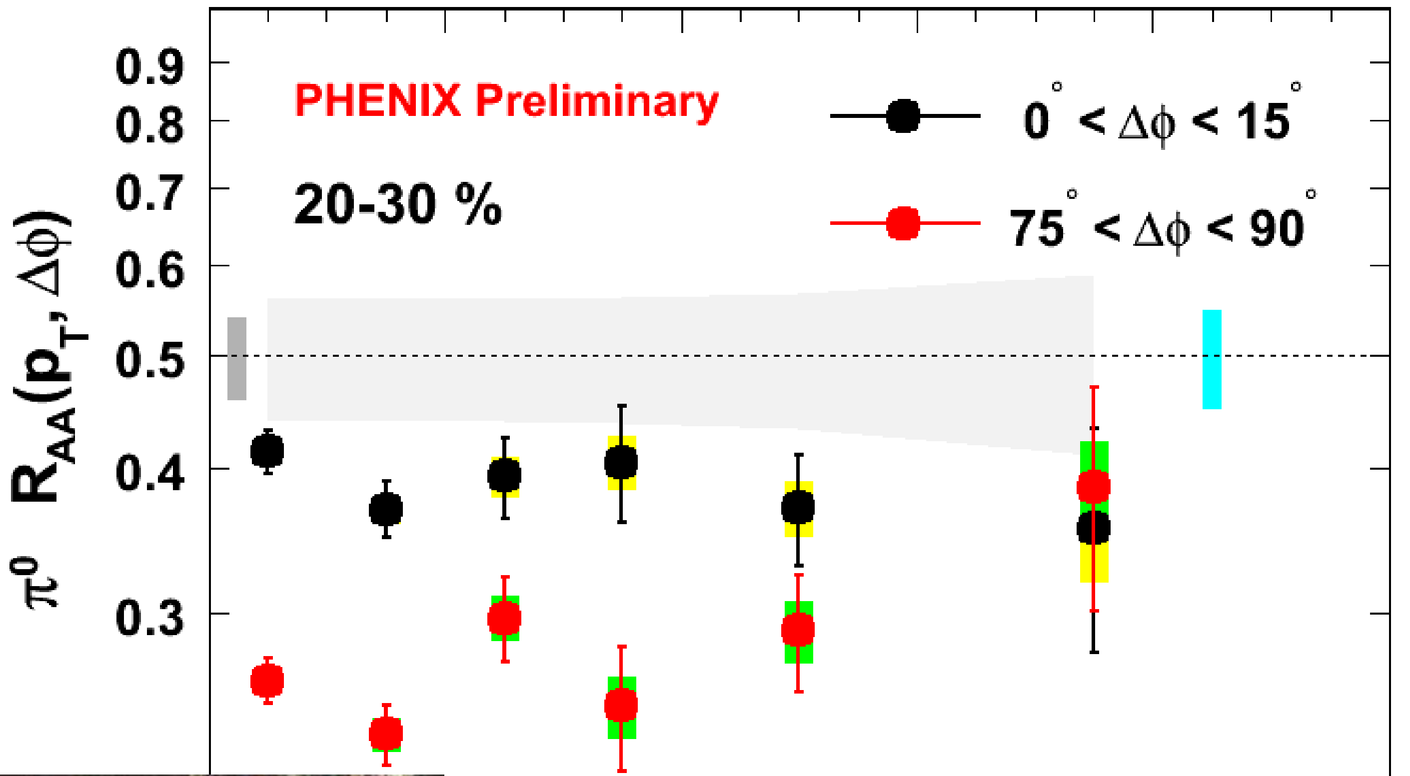
Run-7





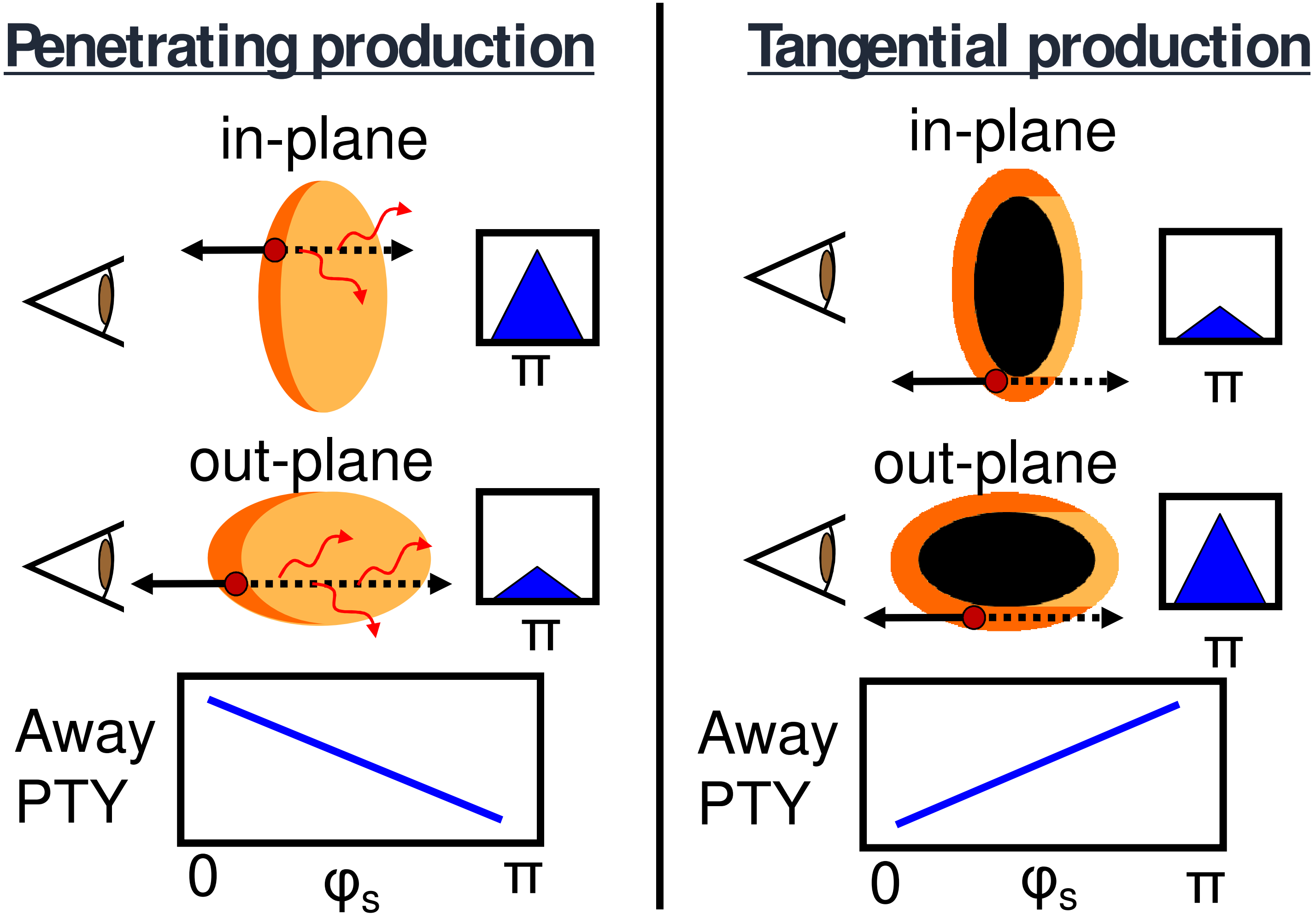
- Out-of plane R_{AA} nearly flat with centrality at low p_T
- In- and out-of-plane converge at high-p_T (~10GeV/c)

Differentiate among energy loss models!



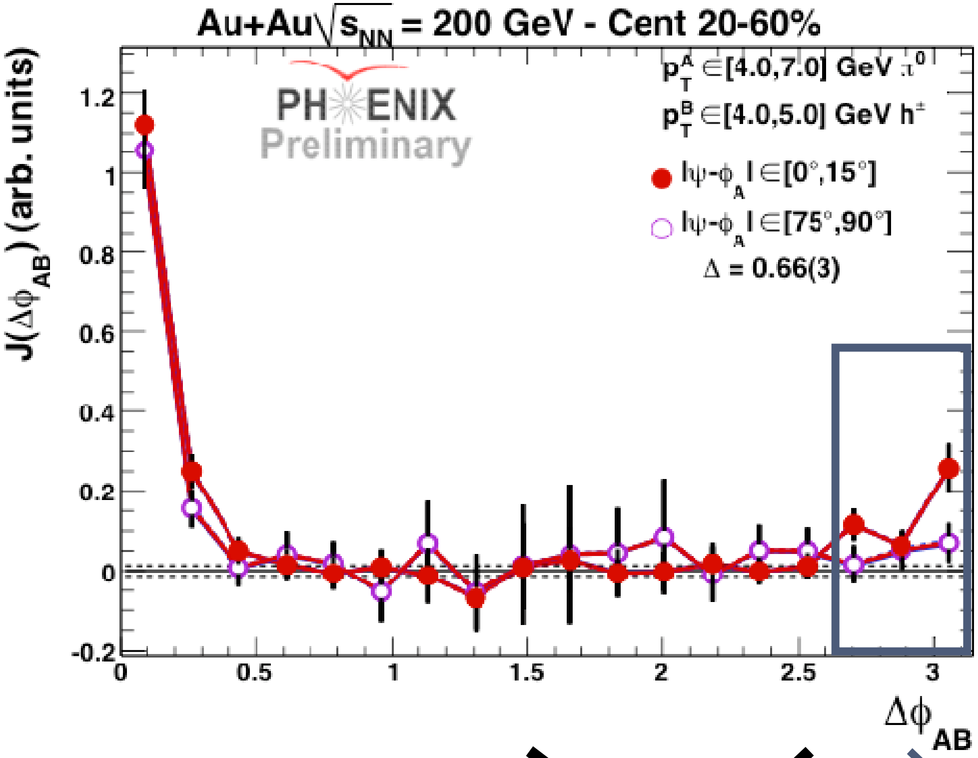
culations by S.Bass *et al* in *arXiv:0808.0908*

More differential yet:
dijet reaction plane dependence

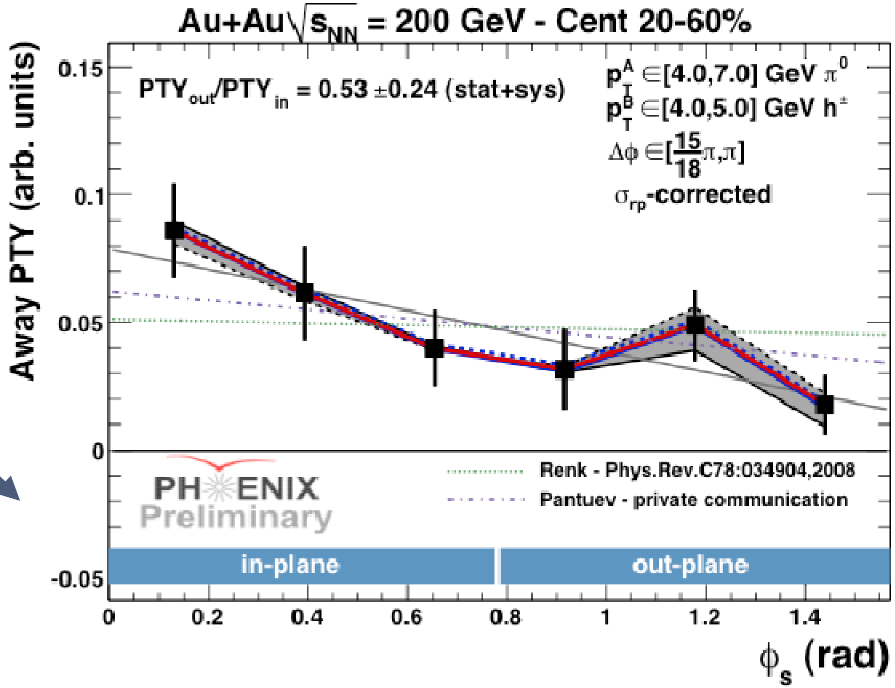


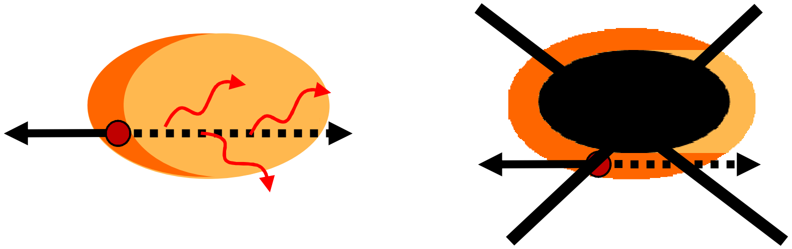
PTY = per-trigger yield

Away side yield



Away side yields drop from in-plane to out-of-plane: jets do penetrate medium

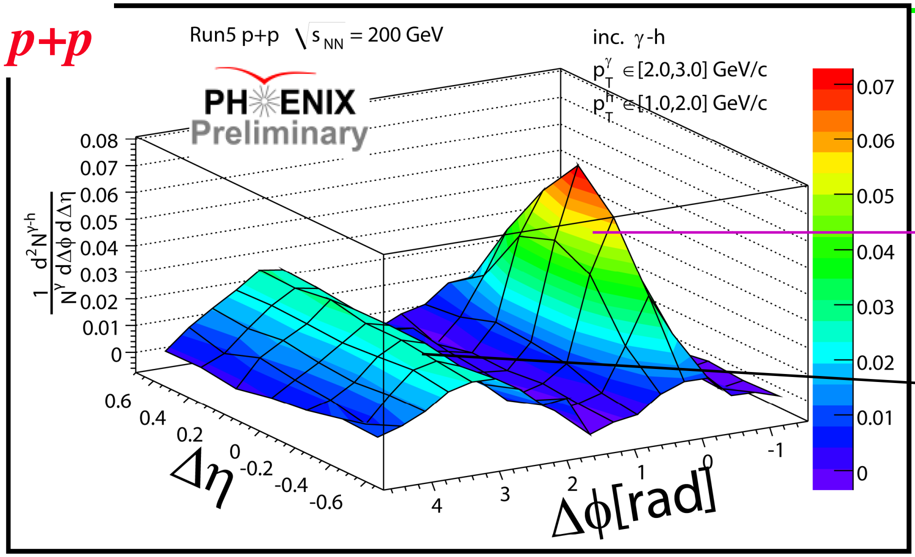




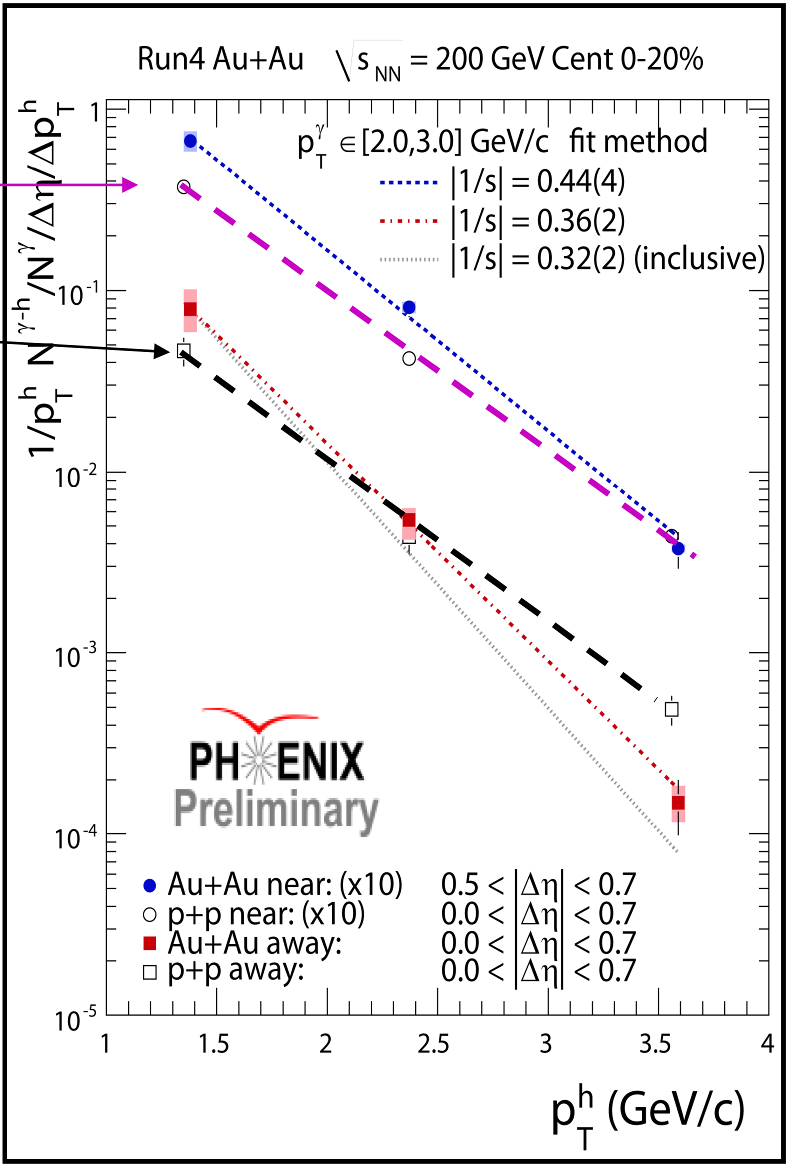
Medium is not totally opaque

Shocks? Medium spectrum

p+p



Harder than inclusive, softer than jet

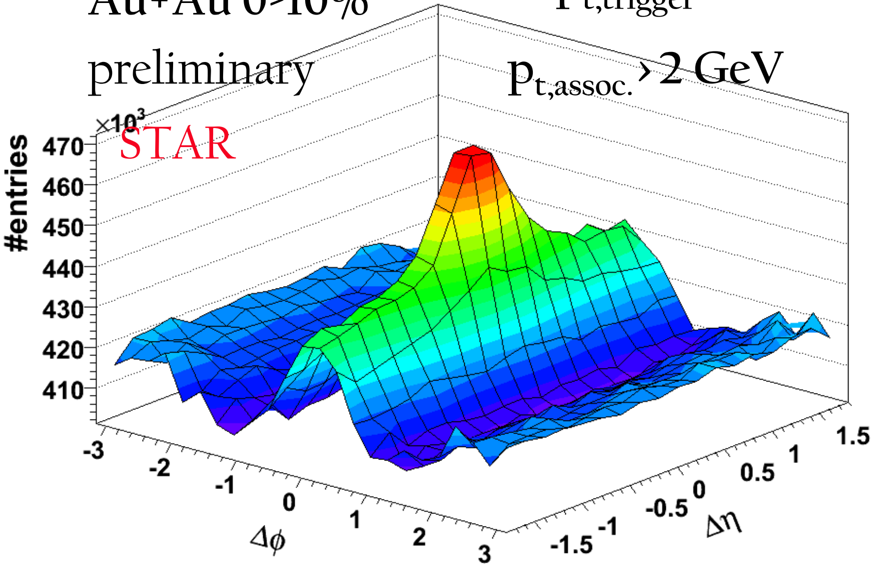


Au+Au 0-10%

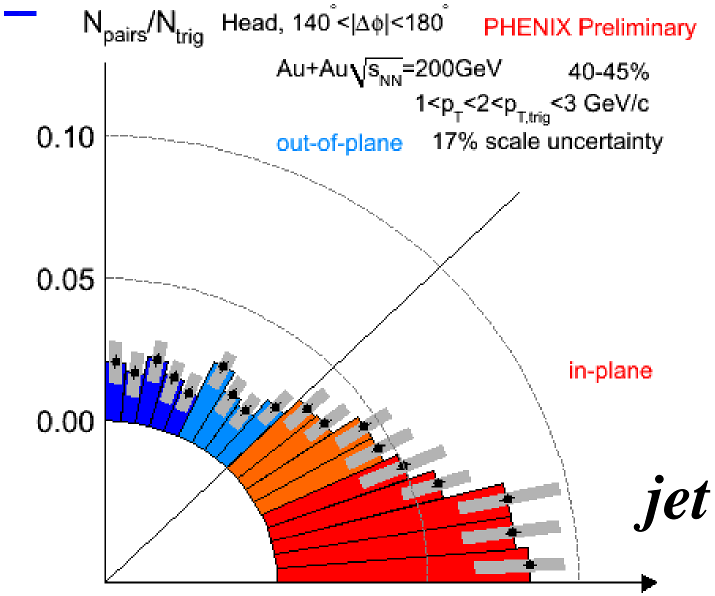
preliminary

$3 < p_{t,trigger} < 4$ GeV

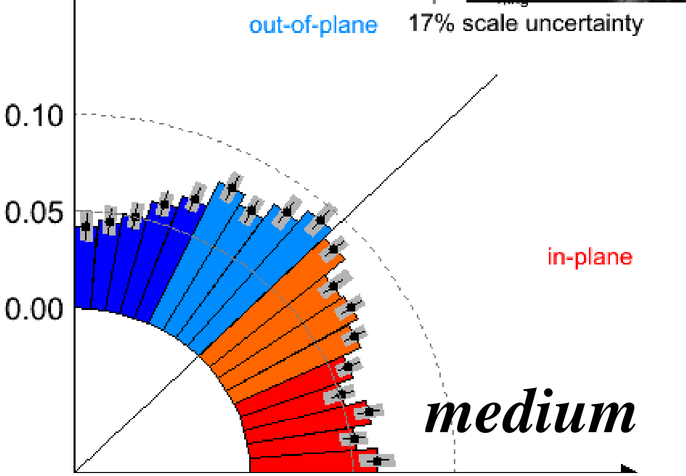
$p_{t,assoc.} > 2$ GeV

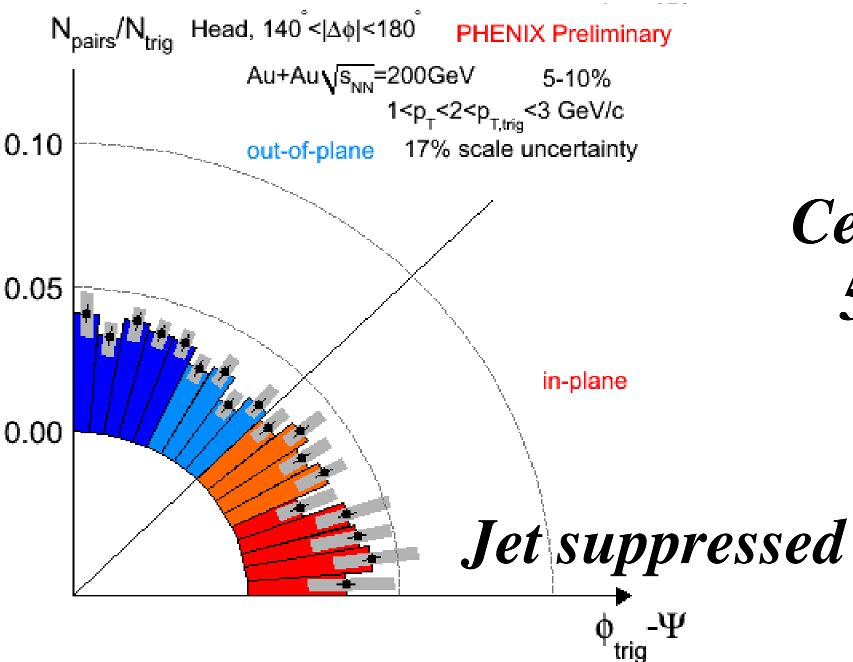


Jet-medium interaction

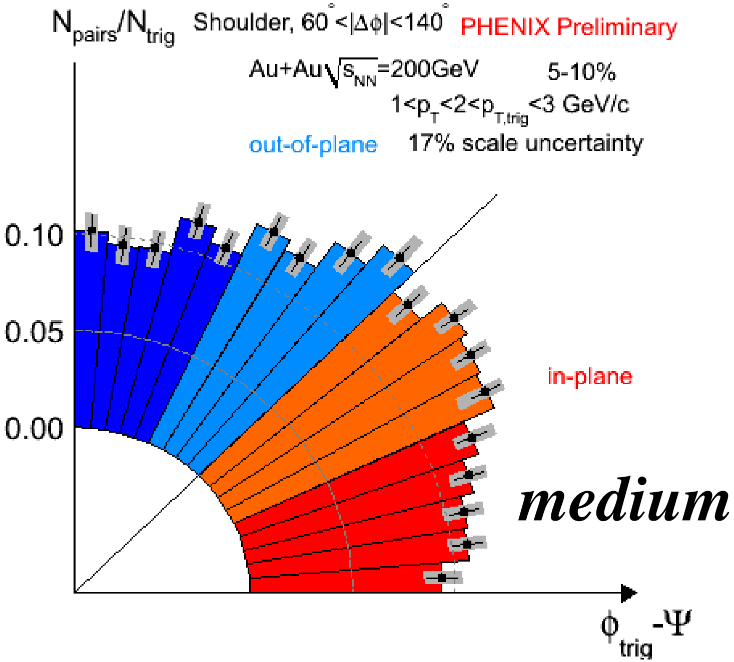


Centrality:
40-45%



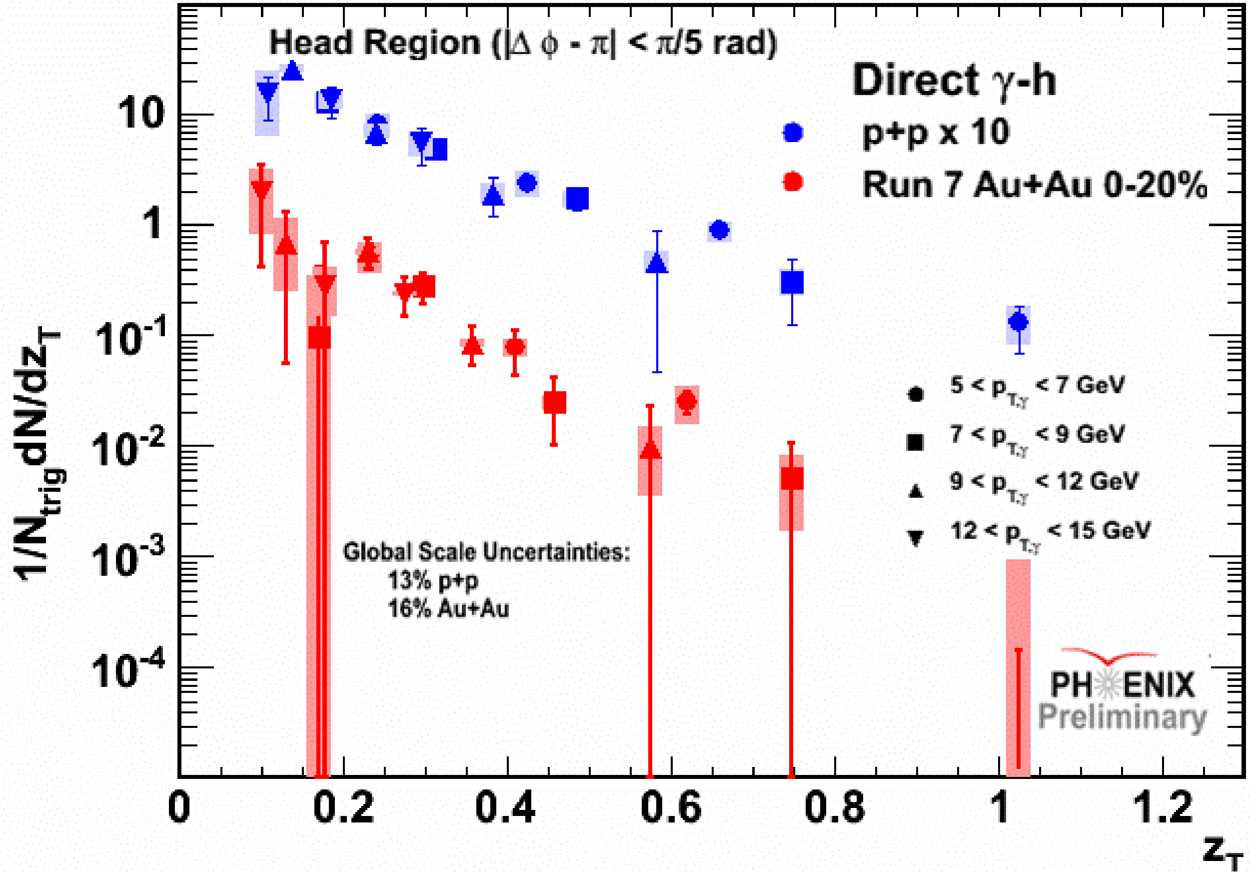


Central:
5-10%



γ-jet (γ-h) correlation: calibrated probe

fragmentation of γ tagged jets in/out of medium

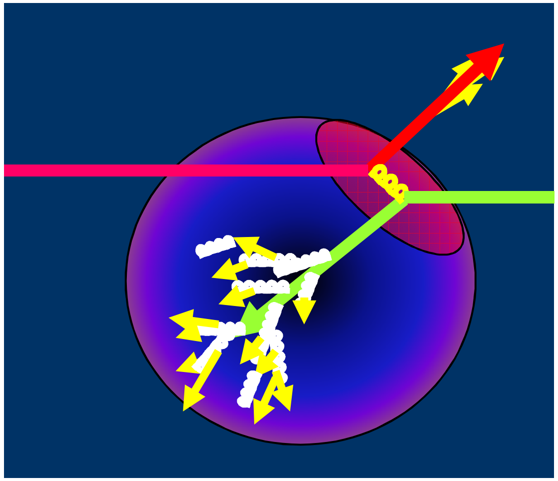


p+p slope:

6.89 ± 0.64

Au+Au slope:

9.49 ± 1.37



Challenge: understand energy transfer to/from the medium! Coupling properties…

Next step: full jet reconstruction

Gaussian filter algorithm

optimize signal/background by focusing on jet core

stabilizes jet axis in presence of background

QuickTime™ and a
decompressor
are needed to see this picture.

σ

QuickTime™ and a
decompressor
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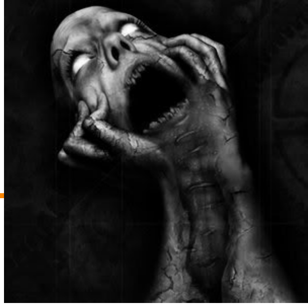
In ion collisions life is tougher



signal

background

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decompressor
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In Cu+Cu

π

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decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
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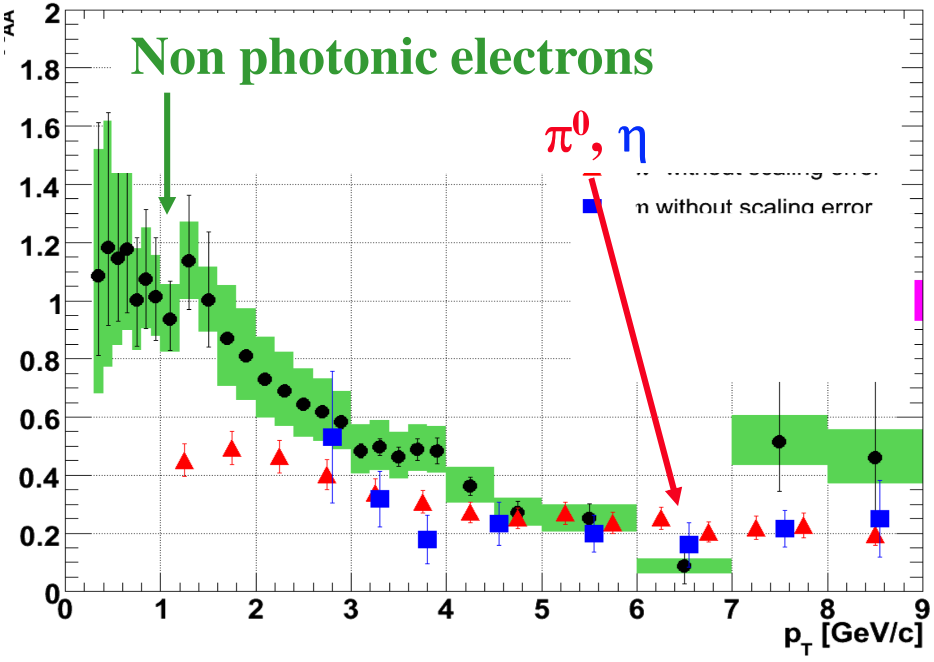
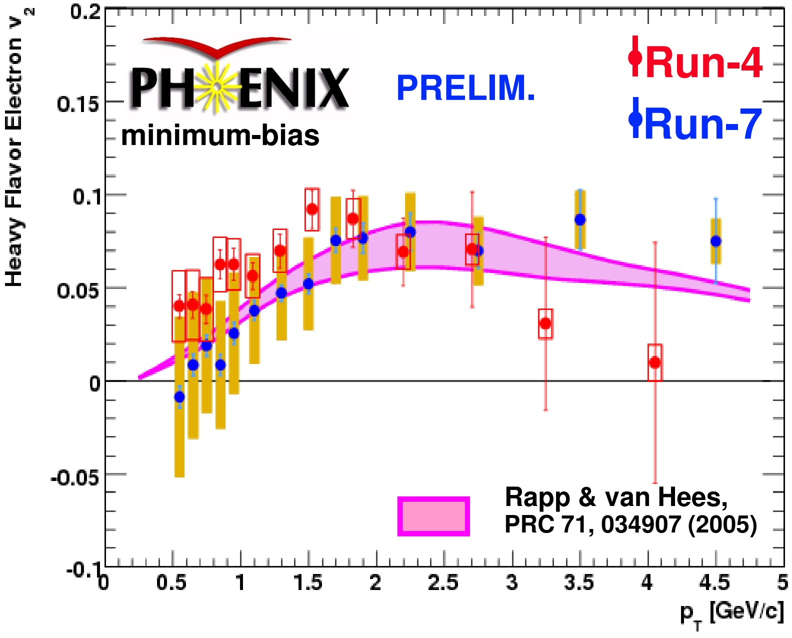
σ

Yikes! R_{AA} flat to > 30 GeV/c p_T

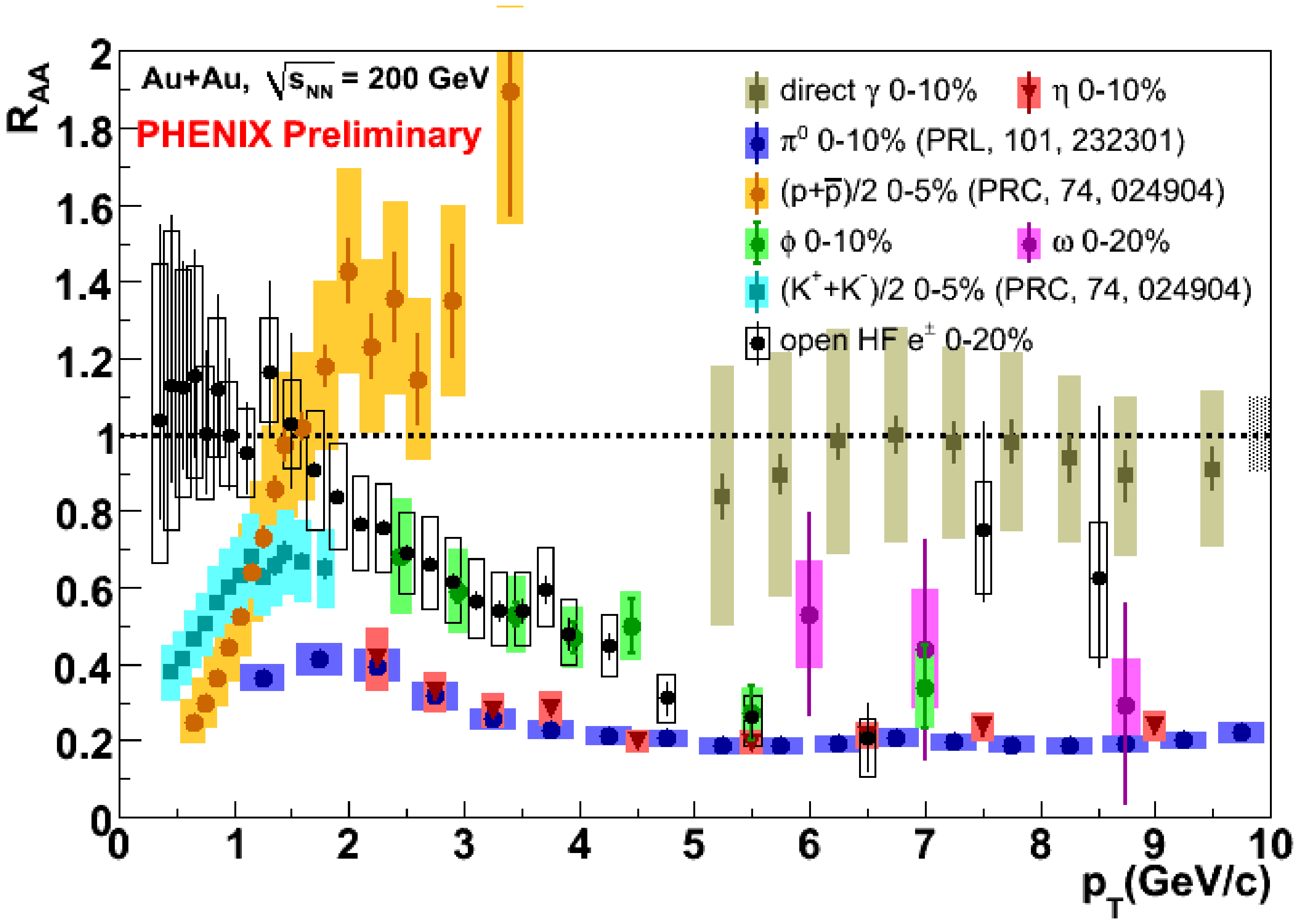
Heavy quark energy loss (large!)





Who ordered that?
Mix of radiation + collisions (diffusion)
but collisions with what?
AdS/CFT provides an answer, but…

Not all energy loss is created equal!



High m_{eff} → large collisional energy loss

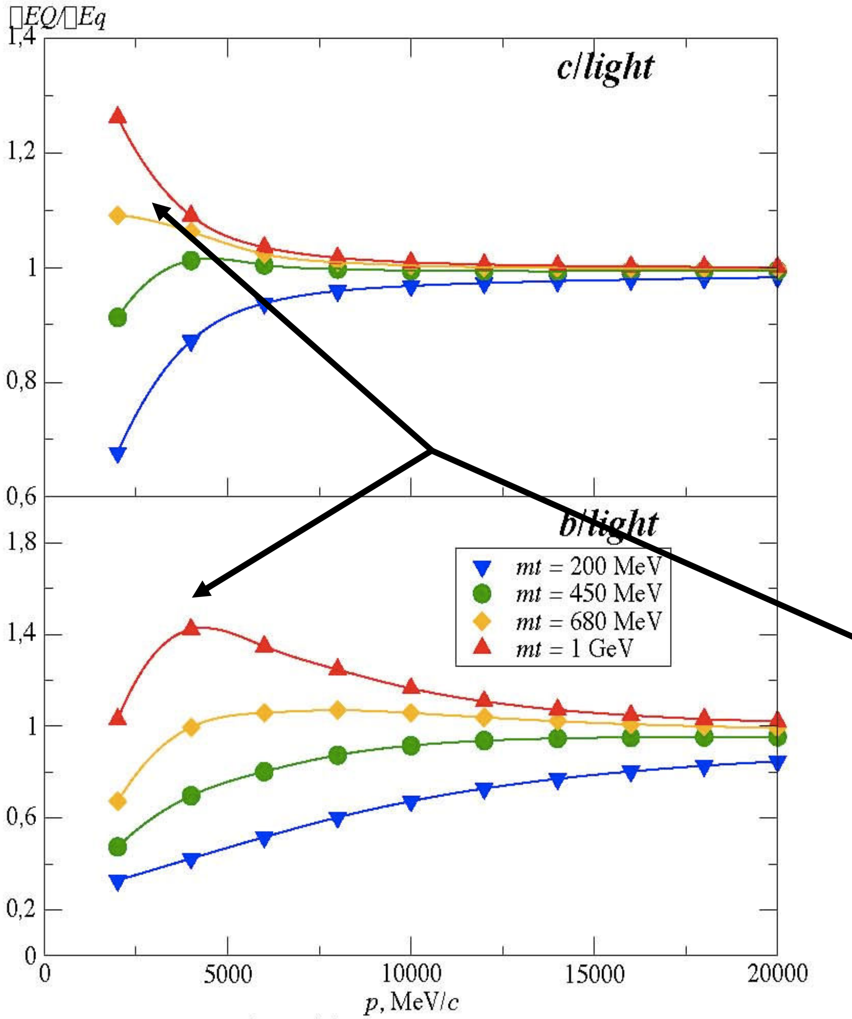
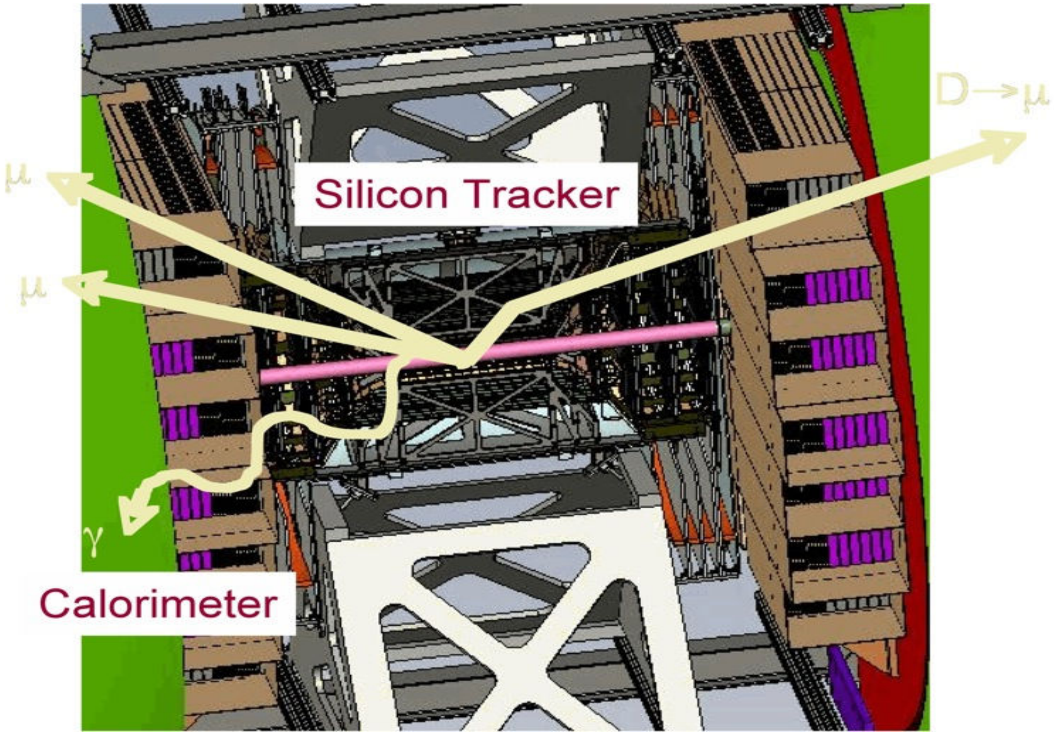


Fig. 3. The heavy-to-light ratio $\Delta E_Q/\Delta E_q$ of collisional energy loss for charm quarks (upper panel) and bottom quarks (lower panel), compared to that of light quarks (m_q = 200 MeV). The results for the numerator ΔE_Q and the denominator ΔE_q are the same as used for plotting Fig. 2.

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

- **The “clumps”?**
- **b/c separation allows to test!**

Upgrades over next ~3 years



PHENIX Upgrades

Forward Calorimeter

γ, π^0 at η= 1-3

Correlate with mid-y $h^\pm$

Silicon VTX, FVTX

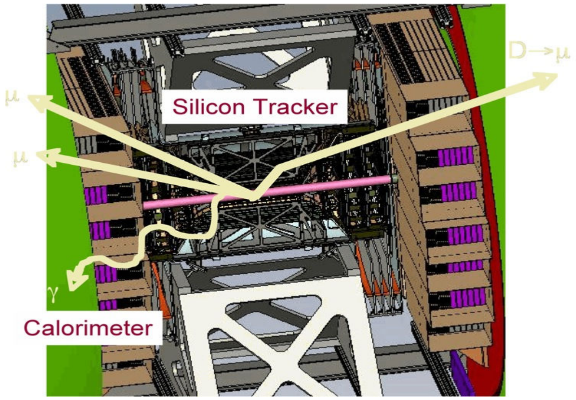
Tag displaced vertex for heavy quark decays

Track charged hadrons in large acceptance

***In addition to RHIC-II luminosity upgrade x8**

Over next decade: entirely new questions

- **Precision jet probes of energy transport in medium**
  - **What degrees of freedom?**
  - **Heavy quark fragmentation modified?**
  - **Theory + dynamics: qualitative → quantitative**
- **What is the screening length in strongly coupled QCD matter?**
  - **Experiment: onium spectroscopy in pp, dAu, AuAu**
  - **Theory: understand production & cold matter effects**



Supplement silicon tracker to enhance momentum resolution

Enhance electron ID capabilities inner barrel compact calorimeter?

Conclusion:

- It could be that theorists' dreams make for the experimenters' nightmares…

  The really interesting stuff is hard to measure

- Experimenters' dream results are *definitely* the stuff of the theorists' nightmares

  We really want to pin you down

  Extract properties of hot QCD matter by constraining theory + phenomenology with data!

- But for Al - we wish very sweet dreams!

  We'll work hard for those sugarplums

HAPPY BIRTHDAY

- **backup slides**

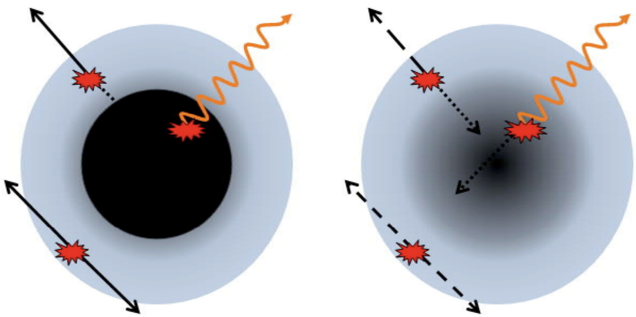
Tag jet energy with direct photon

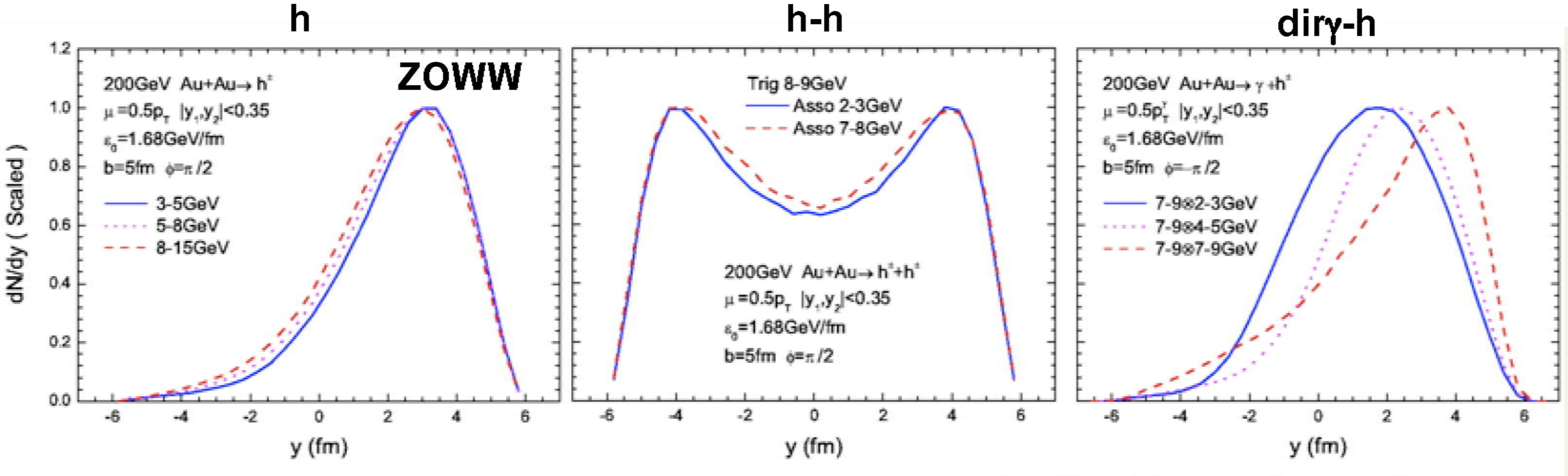
black core
γ-h $I_{AA} \approx$ h R_{AA}

penetrating
γ-h probes a different set of path lengths through the medium than either h or h-h suppression

the direct γ better constrains the parton energy

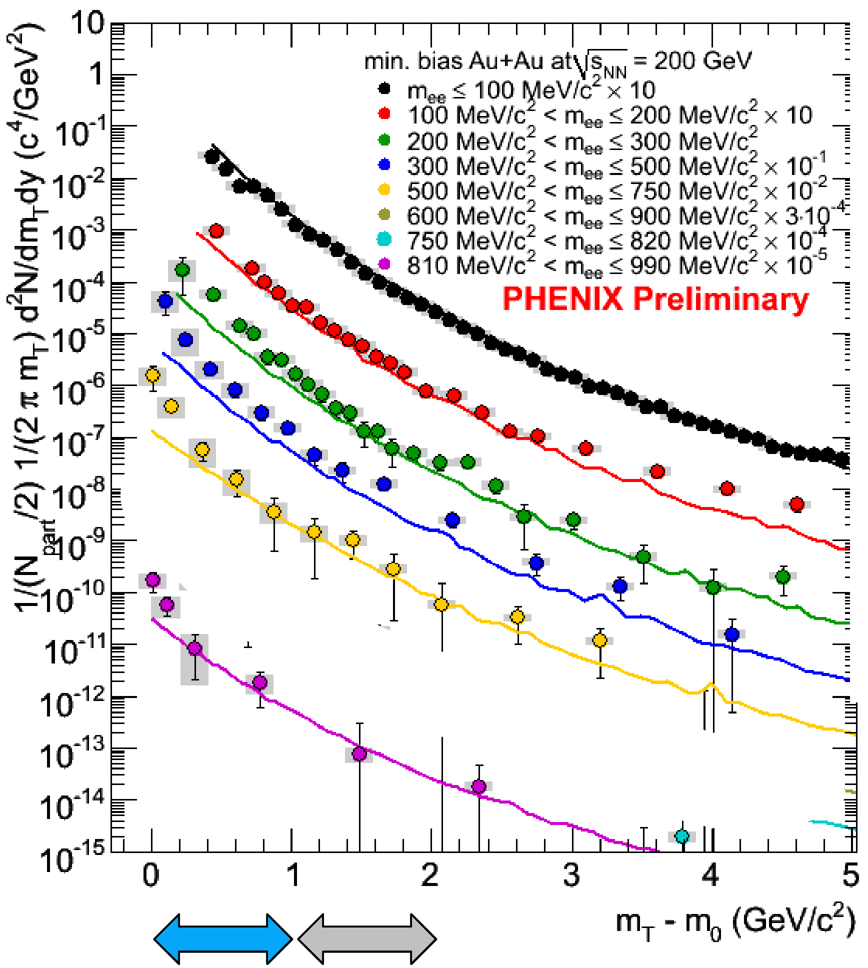
Black Core / Corona vs. Diffuse Medium

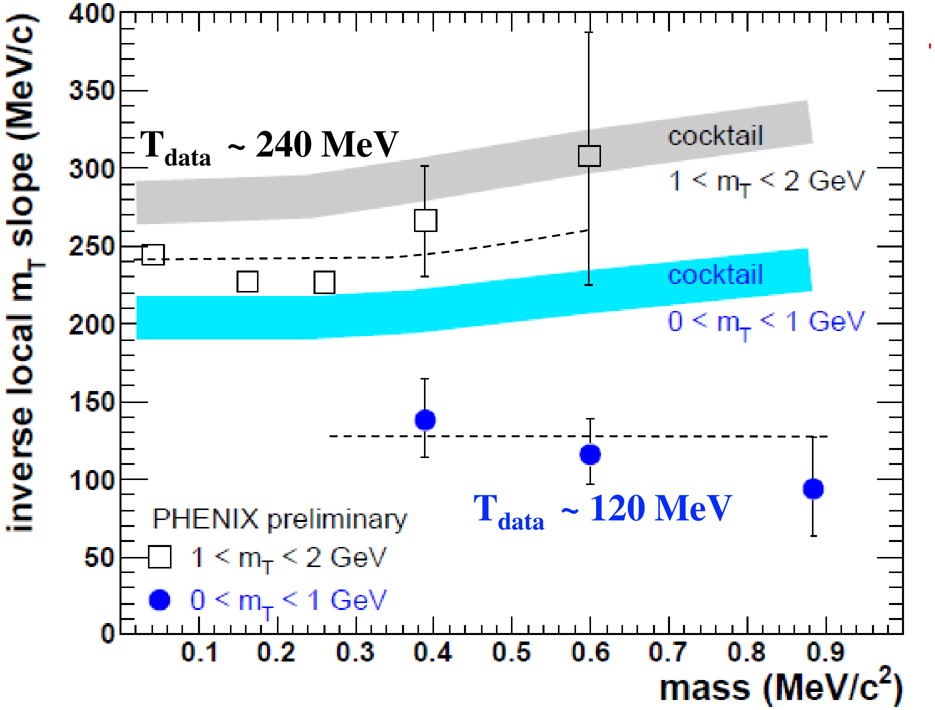




EPJC (2008) + ref's therein

Local Slopes of Inclusive m_T Spectra





- Data have soft m_T component not expected from hadron decays
- Note: Local slope of all sources! need more detailed analysis

Soft component below m_T ~ 500 MeV:

T_{eff} < 120MeV independent of mass

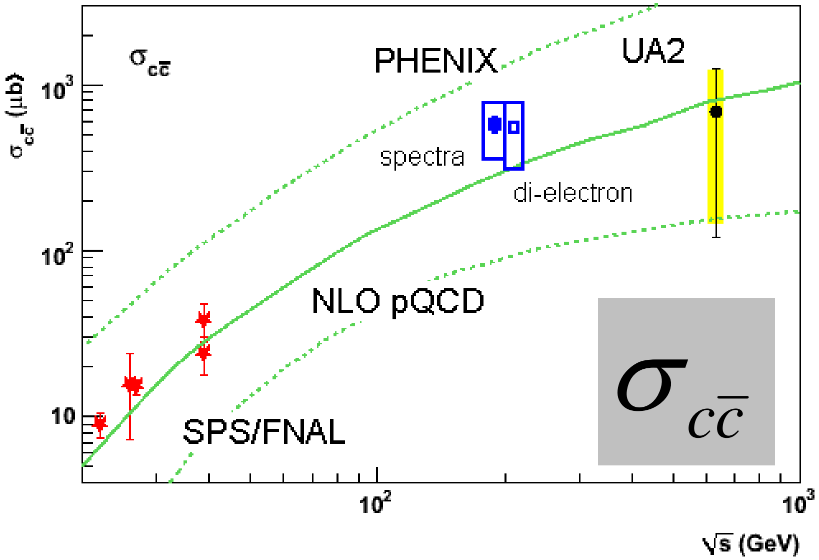
more than 50% of yield

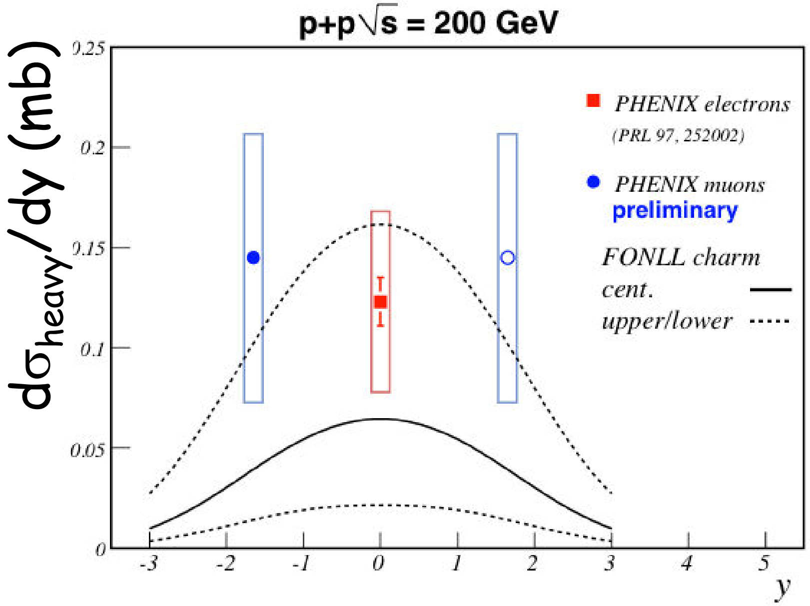
Open Heavy Flavor

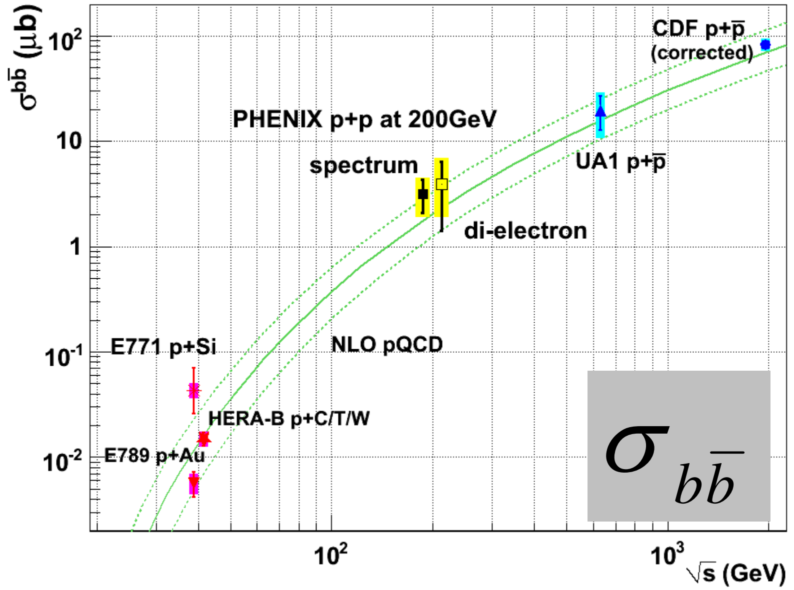
σ determined three different ways:

- **single electron spectra methods:**
  - **cocktail subtraction**
  - **converter**
- **di-electrons**

Muon measurement at forward rapidity is consistent

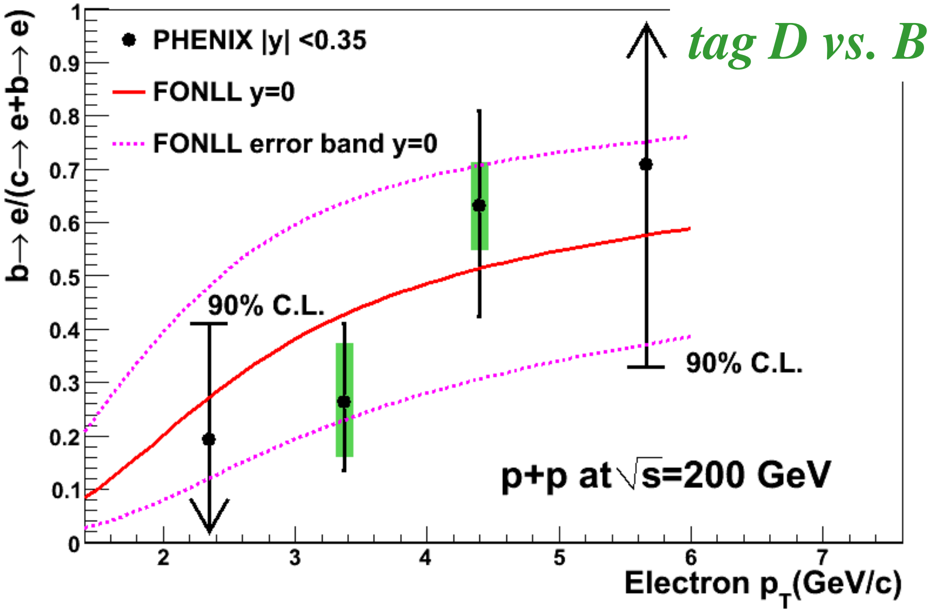




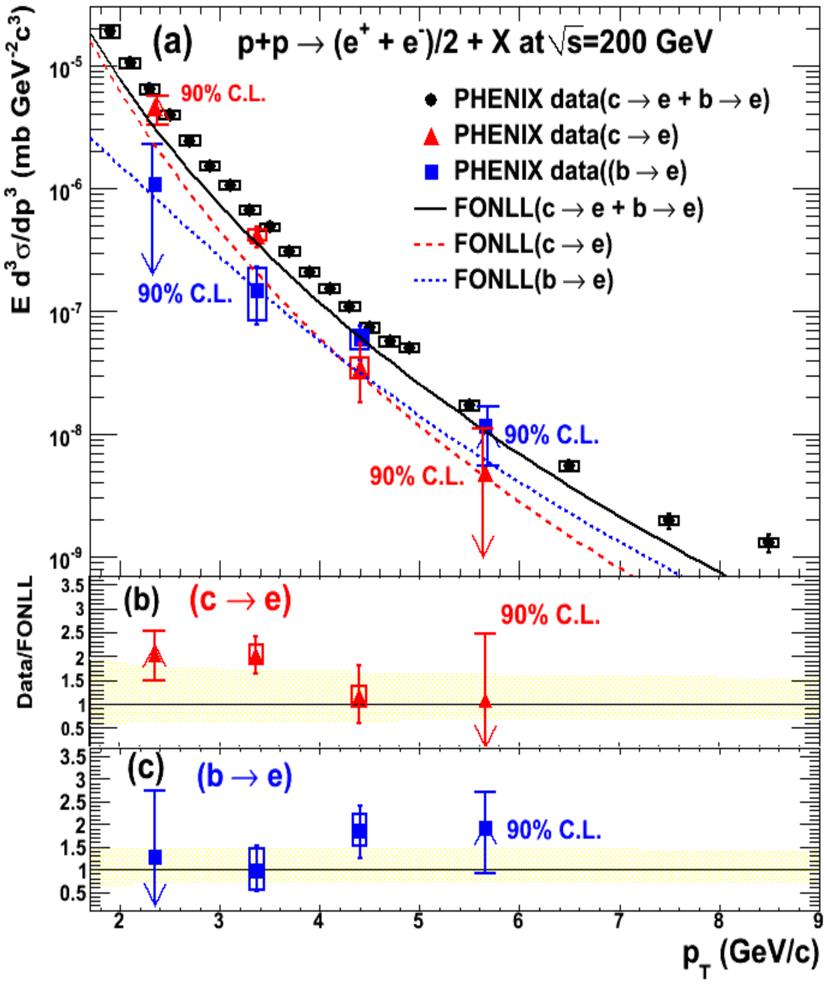


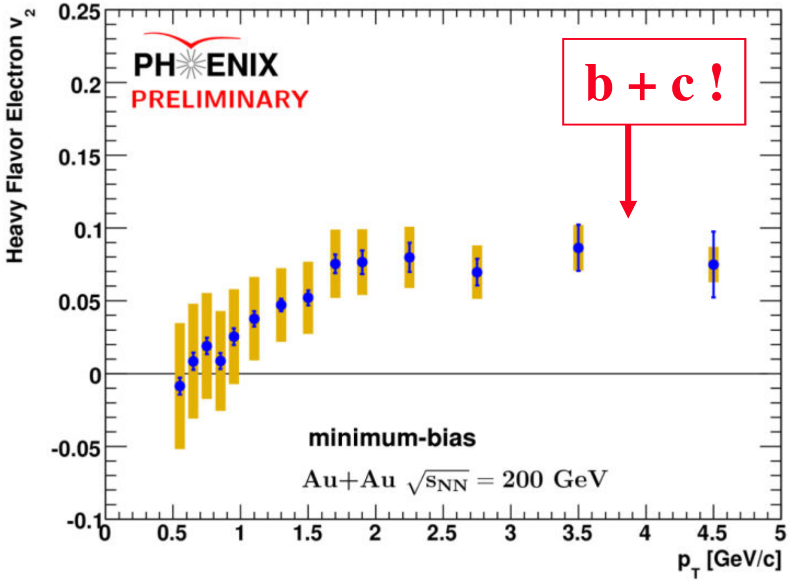
b quarks and medium effects…

e-h correlations to tag D vs. B decays



B meson spectra



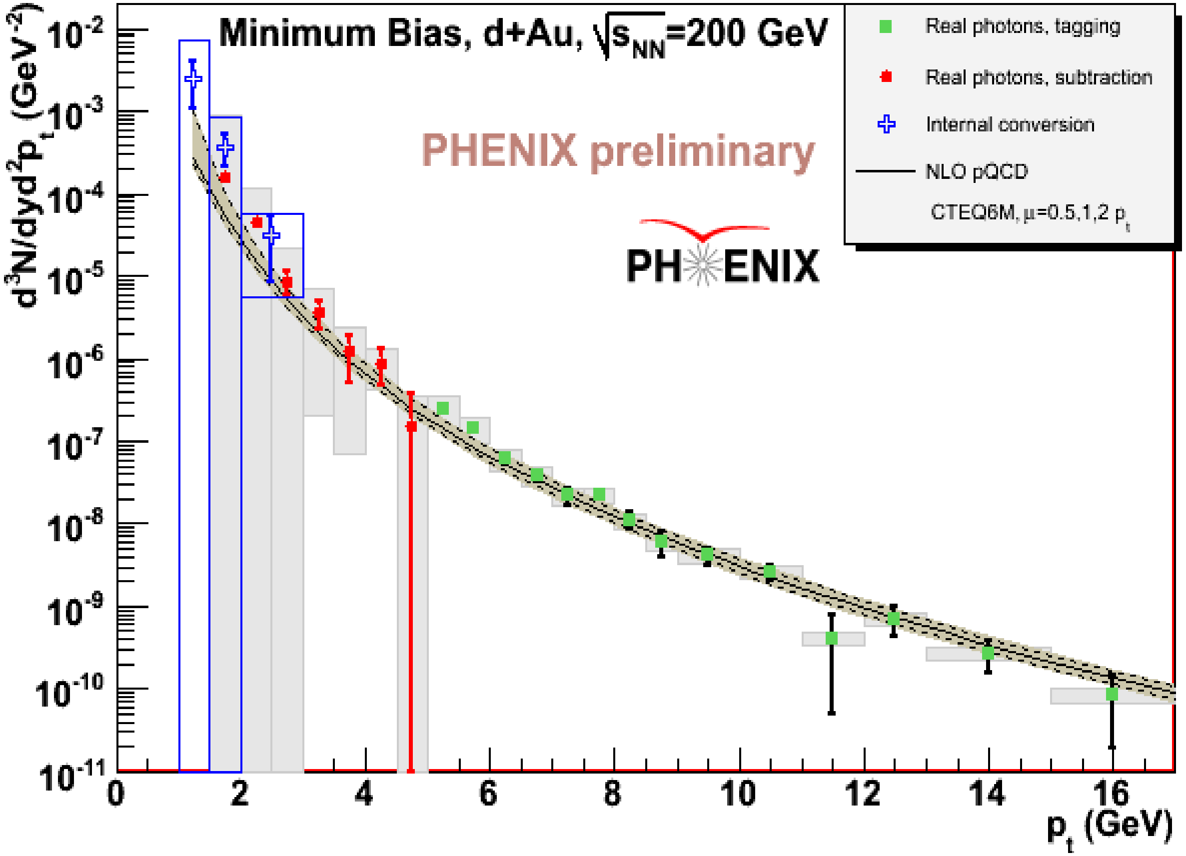


b + c !

Oh oh!

Nuclear Effects

Should modify low p_T direct γ yield
→ Evaluate using d+Au data.



☐ Systematic errors on Run3 d+Au results are still large.

☐ At 2-3 GeV/c, data looks in agreement with pQCD calculation.

→ No modification of direct γ yield by nuclear effects?

☐ **Run 8 analysis underway: x30 statistics**

Both ridge & shoulder yields grow

QuickTime™ and a
decompressor
are needed to see this picture.

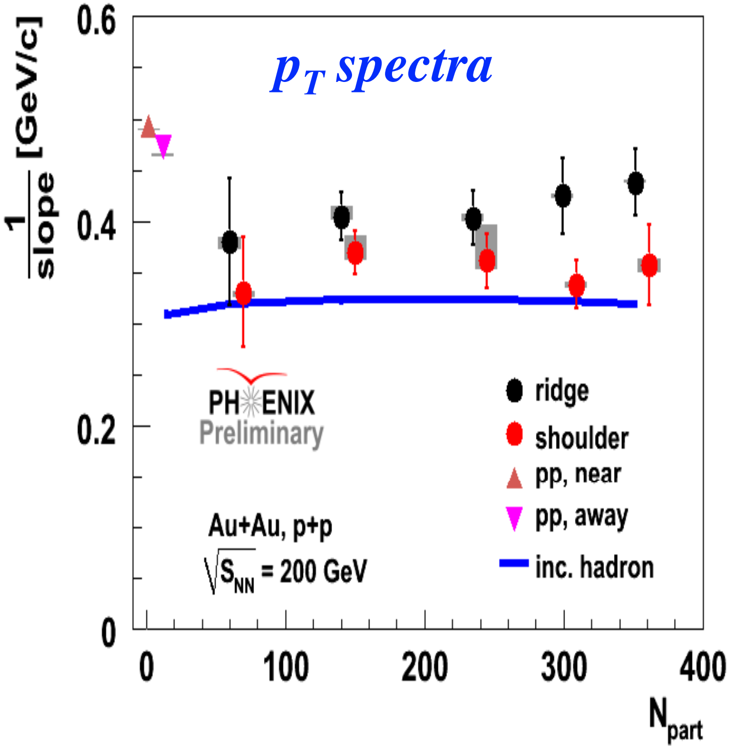
Away/near to ~ cancel acceptance

QuickTime™ and a
decompressor
are needed to see this picture.

Shoulder and ridge have the same physics!

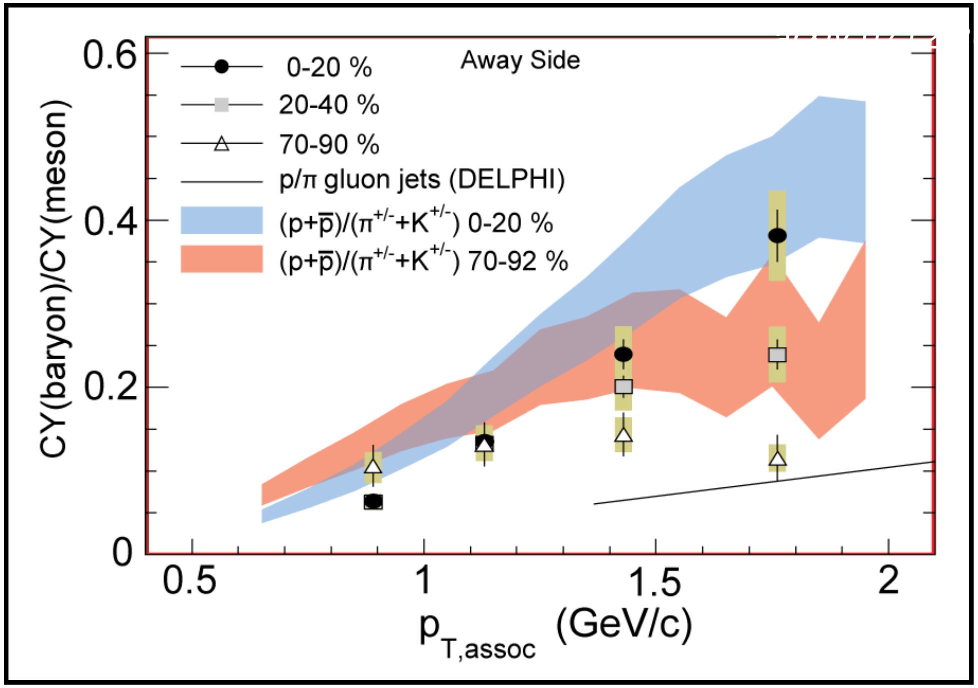
See also Rudy Hwa, Jiangyong Jia recent talks

From the bulk or jet-like?


p_T spectra

Particle content

PHENIX PRL 101, 082301 (2008)



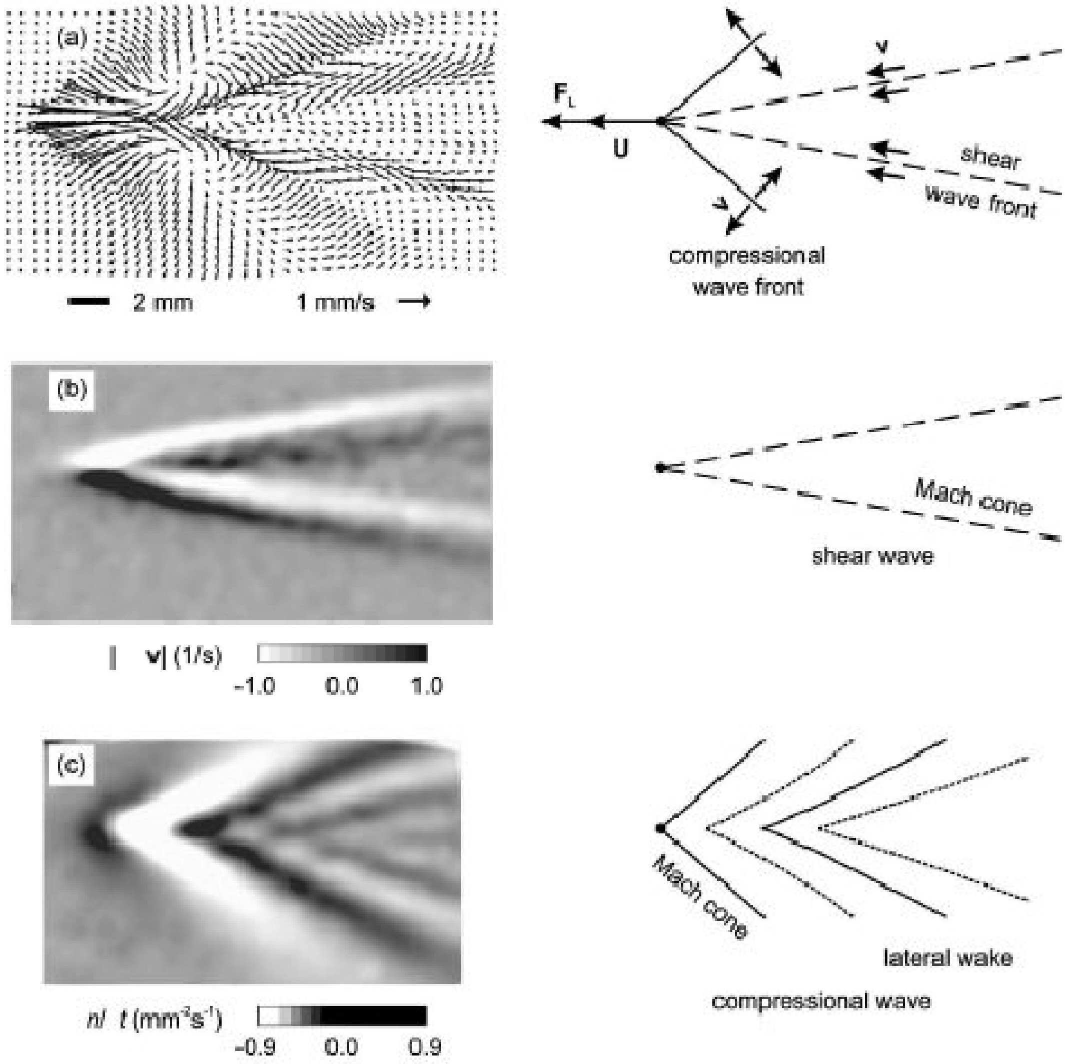
Answer:

it's more like the bulk!

∴QGP-like

Compressional and shear wakes in a two-dimensional dusty plasma crystal

NOSENKO *et al.* PHYSICAL REVIEW E 68, 056409 (2003)



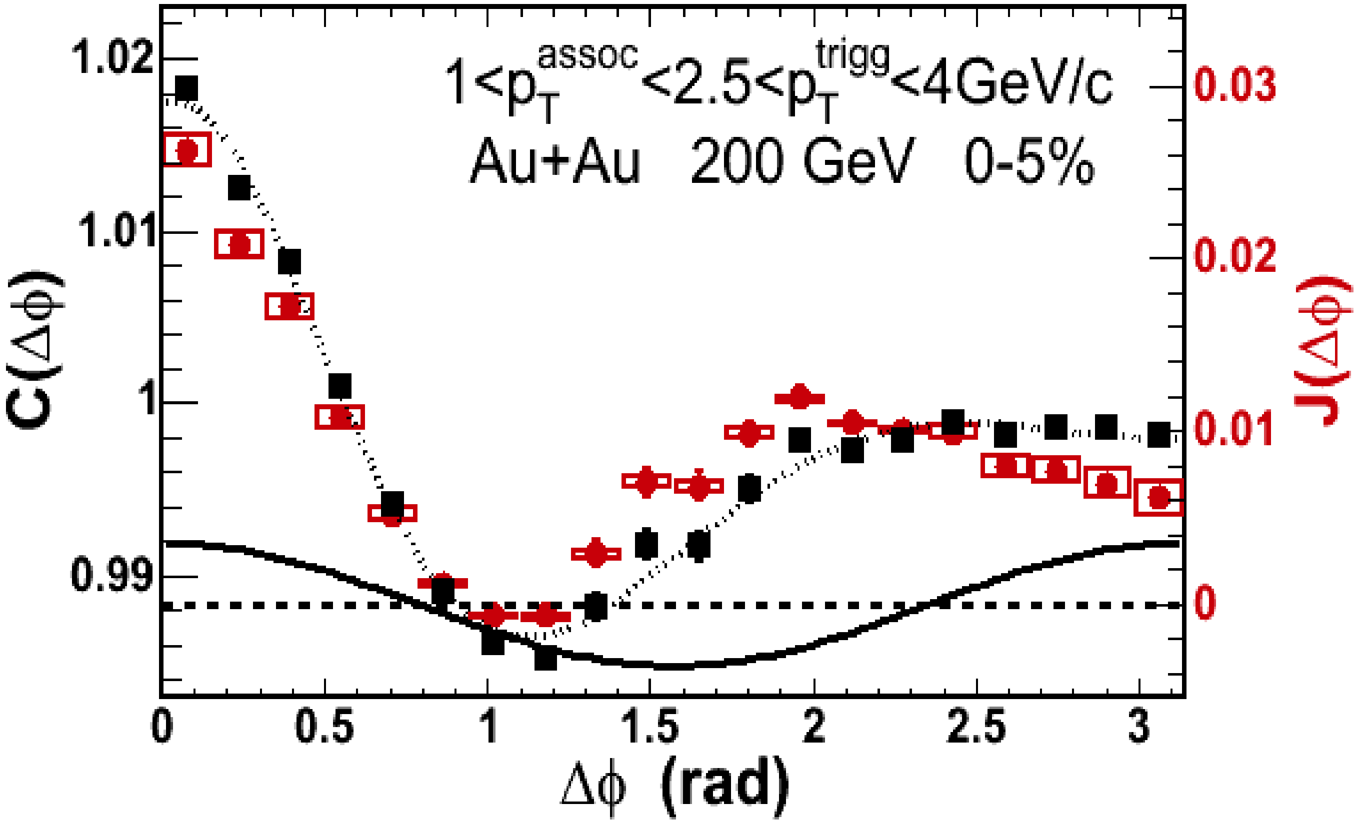
Are shocks in strongly coupled EM plasma. So sQGP could also support shockwaves

(shear generally a phenomenon in crystals but not liquids)

FIG. 4. The compressional- and shear-wave Mach cones, excited simultaneously. The scanning speed U is higher than the sound speed for both the compressional and shear waves. Maps are shown for (a) particle velocity v, (b) vorticity $|\nabla \times \mathbf{v}|$, and (c) $\partial n/\partial t$, where n is the particle areal number density.

QuickTime™ and a
decompressor
are needed to see this picture.

In the most central collisions



Quantifying the viscosity

Need:

- **3-d viscous hydro calculations**
- **Precision data**
- **Mass dependence of v_2**

$$\eta \sim n\,\bar{p}\,\lambda_{mfp}$$

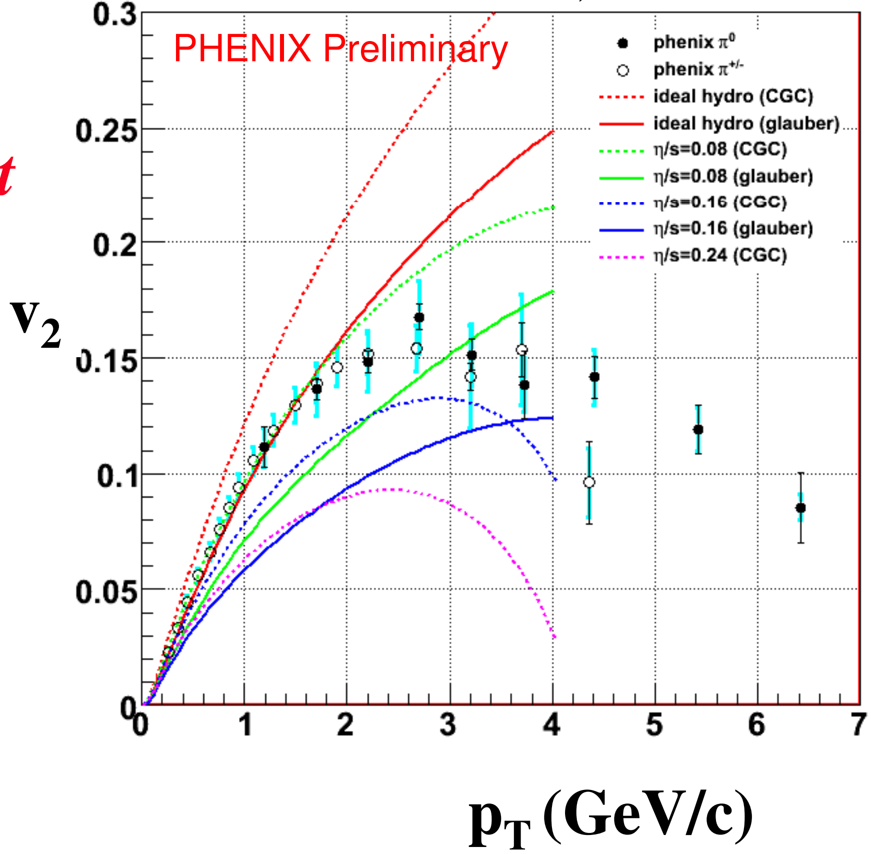
+ other observables for p_T transport

<u>$\eta/s \sim 0 - 0.8$</u>

Recall: in ideal hydro $\lambda_{mfp}=0$

<u>Conjectured η/s bound: $1/4\pi$</u>

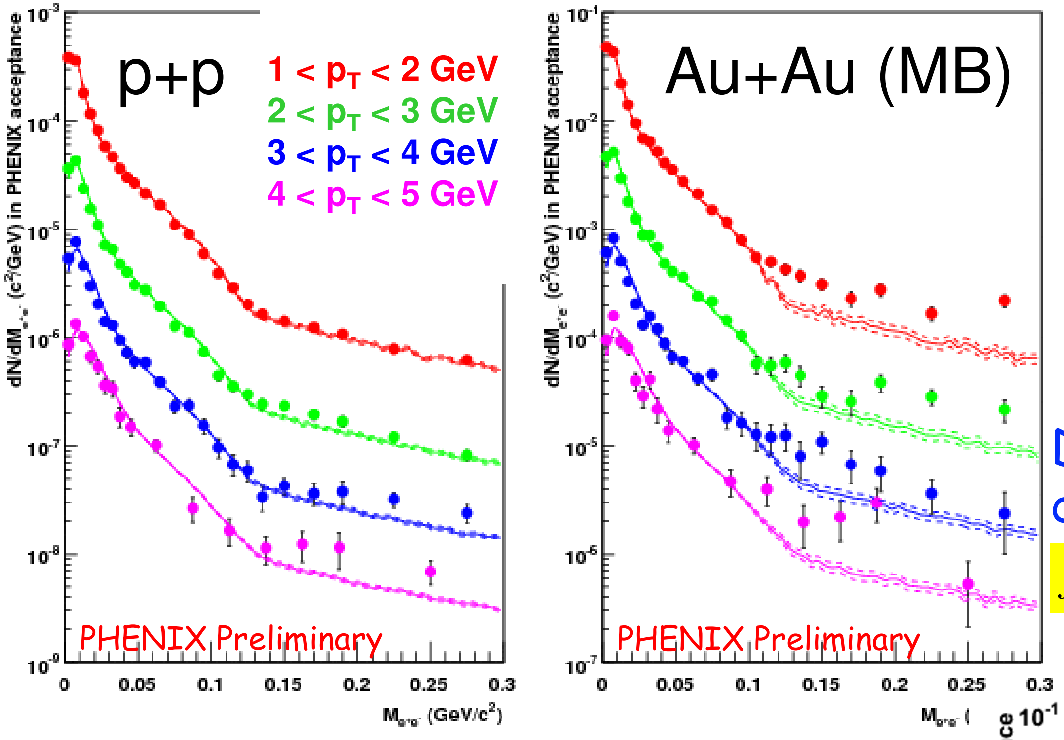
Romatschke & Romatschke, arXiv:0706.1522

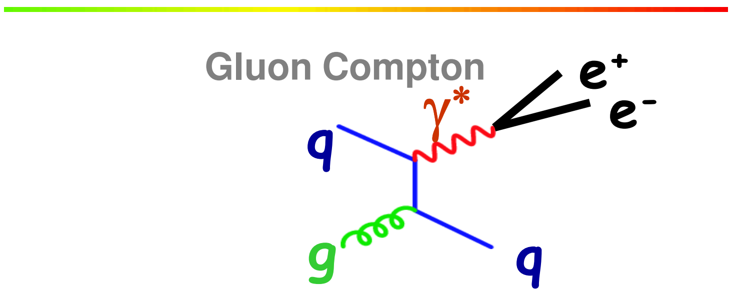


Work is underway to control:

- ***initial state geometry***
- ***gluon distribution***

Dileptons at low mass and high p_T

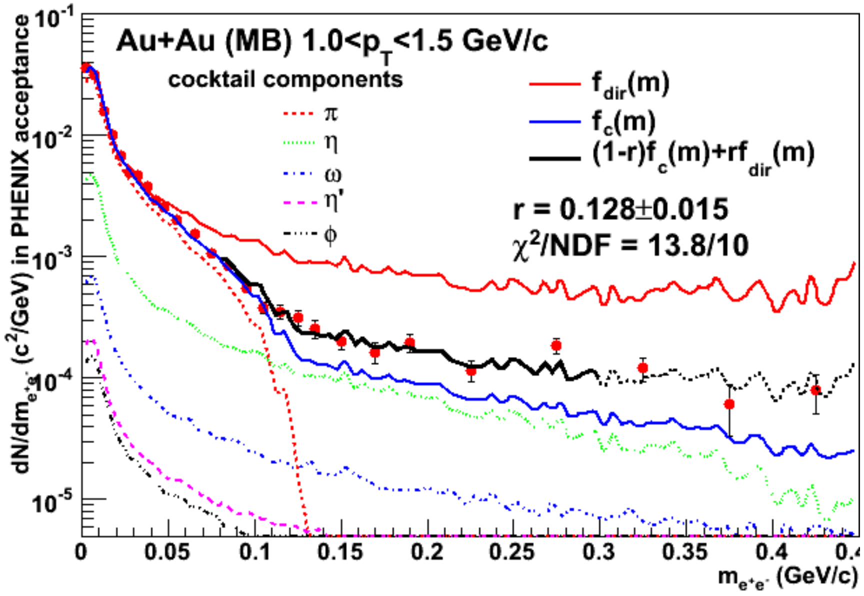




Direct γ^*/Inclusive γ^* determined by fitting each p_T bin

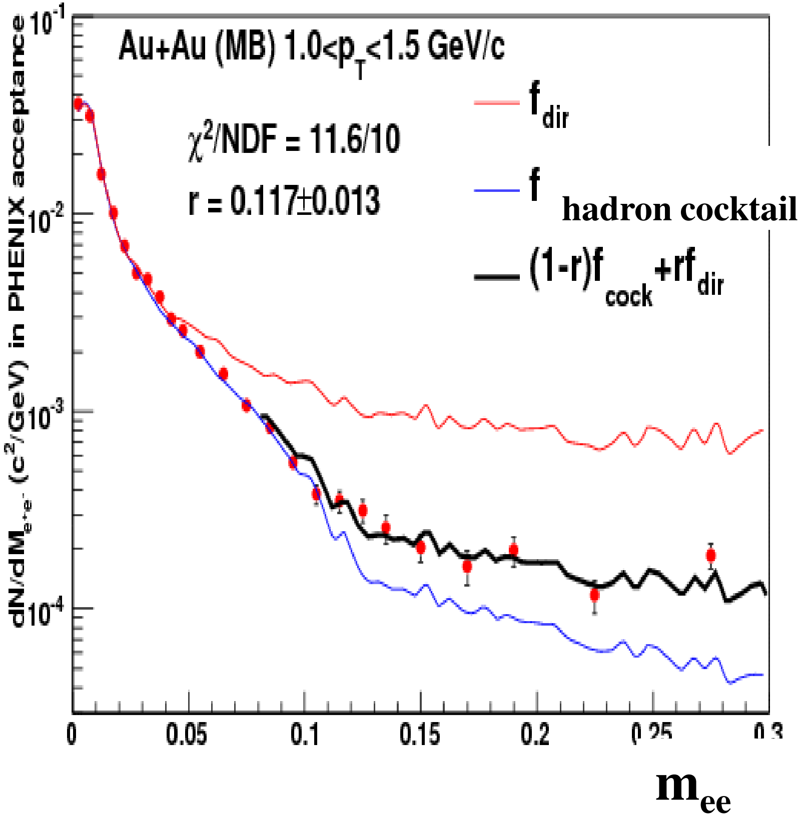
$$f_{data}(M_{ee}) = (1-r)\cdot f_{cocktail}(M_{ee}) + r\cdot f_{direct}(M_{ee})$$

r : direct γ^*/inclusive γ^*

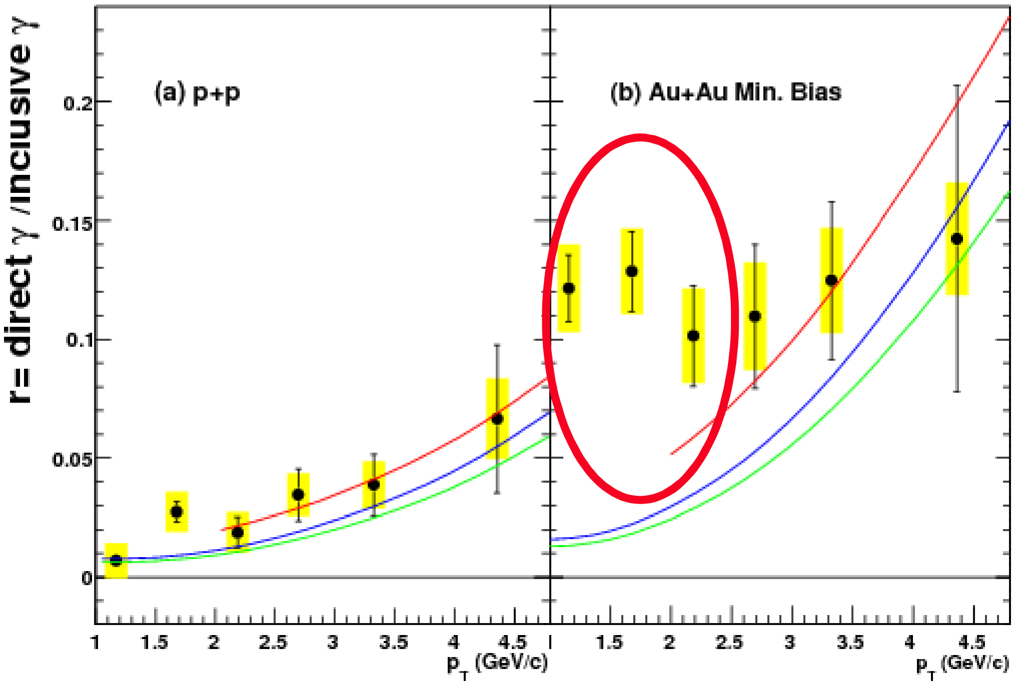


- m<2π only Dalitz contributions
  - p+p: no enhancement
  - Au+Au: large enhancement at low p_T
- A *real* γ source → *virtual* γ with v. low mass
- We assume internal conversion of direct photon → extract the fraction of direct photon

direct photons via e+e-



for low mass, $p_T > 1$ GeV/c
direct γ* fraction of inclusive γ*
(mostly π^0, η) is ≈ real γ fraction
of γ (mostly π^0, η)



low mass and $p_T >> m_{ee}$
dominated by decay of γ*

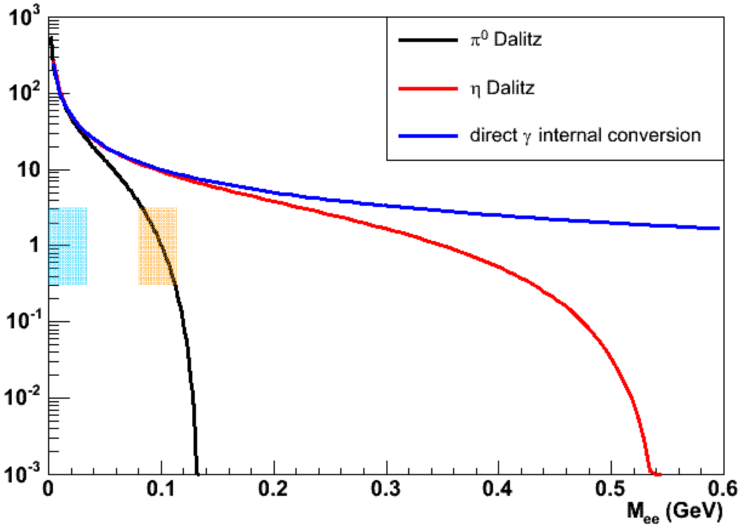
Virtual Photon Measurement

- Any source of real γ can emit γ^* with very low mass.
- Relation between the γ^* yield and real photon yield is known.

$$\frac{d^2N}{dM_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}SdN_{\gamma}$$

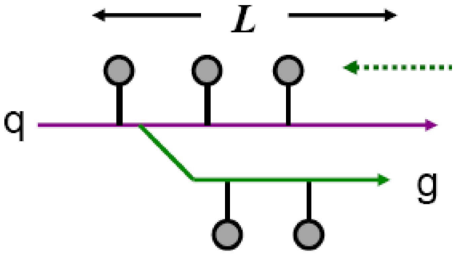
Eq. (1)

***S*: Process dependent factor**

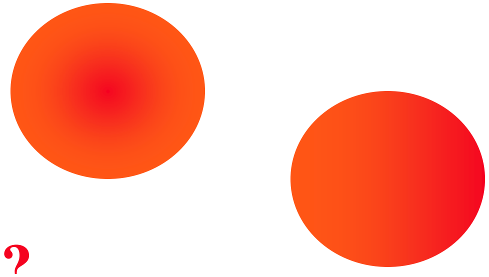


- Case of Hadrons
  - $S = \left|F\left(M_{ee}^2\right)\right|^2\left(1-\frac{M_{ee}^2}{M_{hadron}^2}\right)^3$
  - Obviously *S* = 0 at $M_{ee} > M_{hadron}$
- Case of direct γ^*
  - If $p_T^2 >> M_{ee}^2$
  - $S = 1$
- Possible to separate hadron decay components from real signal in the proper mass window.

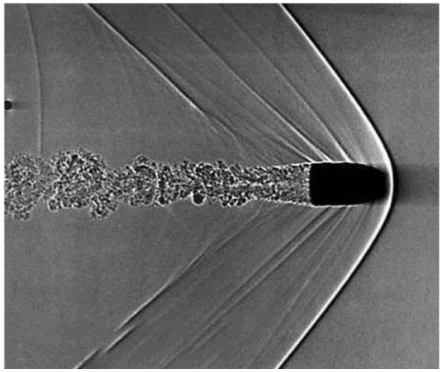
Where does the lost energy go?



- Radiated particles still correlated with the jet



- Completely absorbed by plasma
  Thermalized?
  Collective conservation of momentum?



- Excites collective response in plasma
  Shocks or sound waves?
  Wakes in the plasma?