Highlights from RHIC

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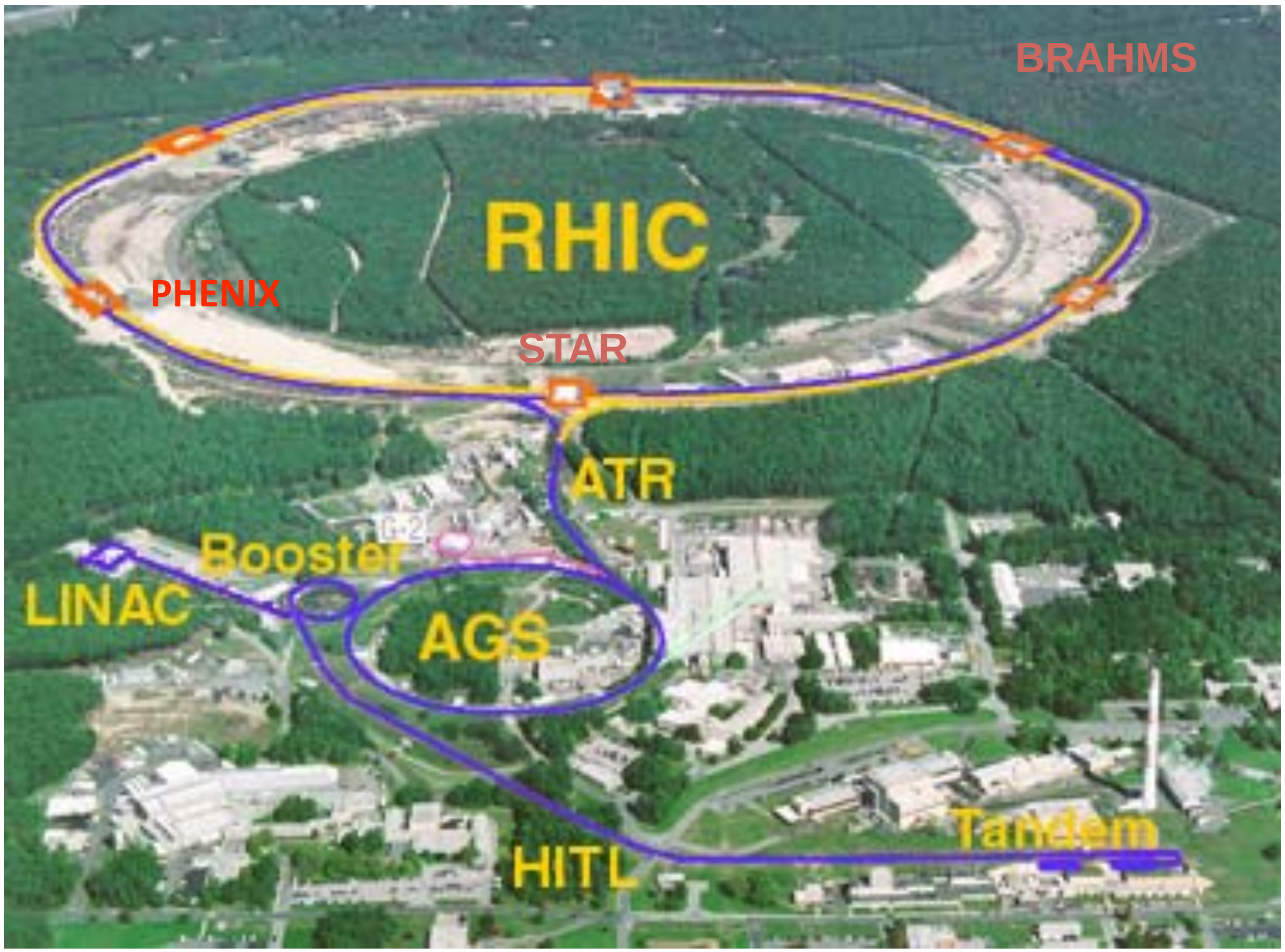
LANL

Latest News from Quark Matter 2009

The **R**elativistic **H**eavy **I**on **C**ollider
at Brookhaven National Laboratory



R-HI
New state of matter
QGP
De-confinement
…

polarized proton
Nucleon Spin Structure
Spin Fragmentation
pQCD
…

RHIC is a QCD lab

The PHENIX detector

Philosophy:

High rate capability to measure rare probes, limited acceptance.

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes

$|\eta| < 0.35$

$90^\circ + 90^\circ$ azimuth

- 2 forward muon spectrometers
  - Identify and track muons

$1.2 < |\eta| < 2.4$

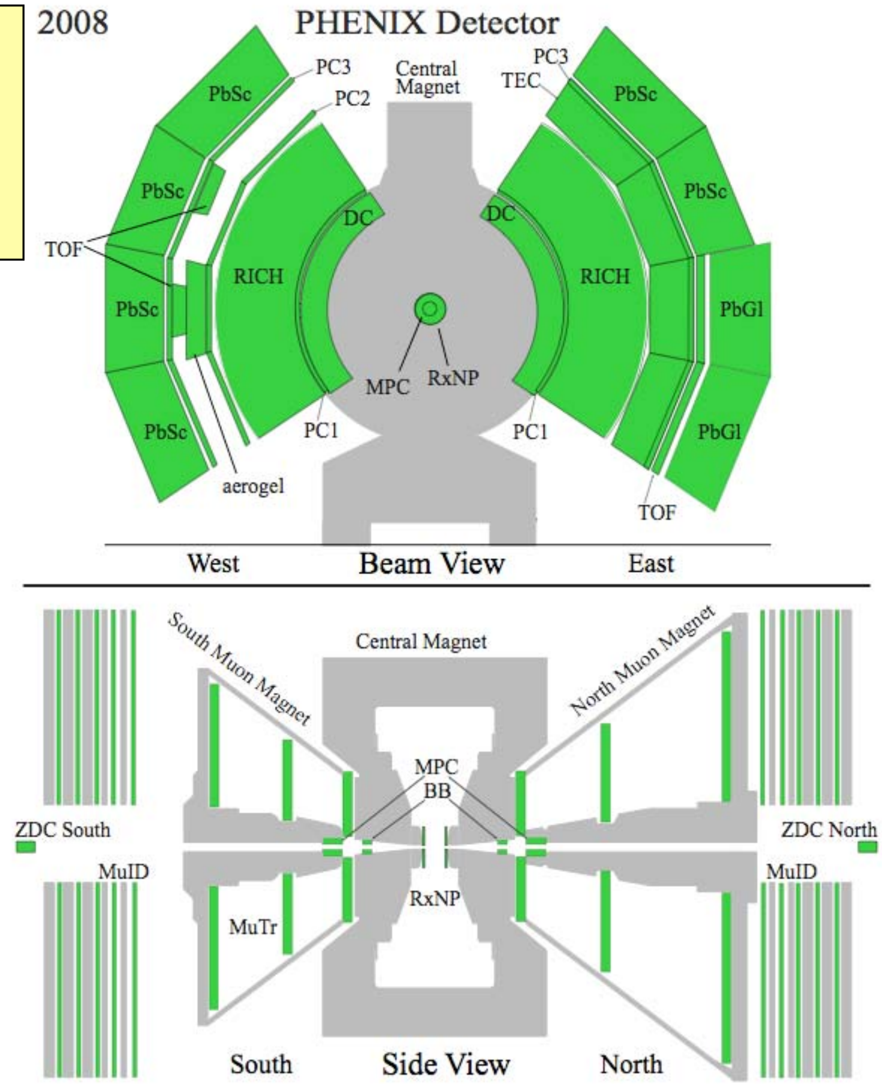
2π azimuth

- 2 forward calorimeters (as of 2007!)
  - Measure forward pions

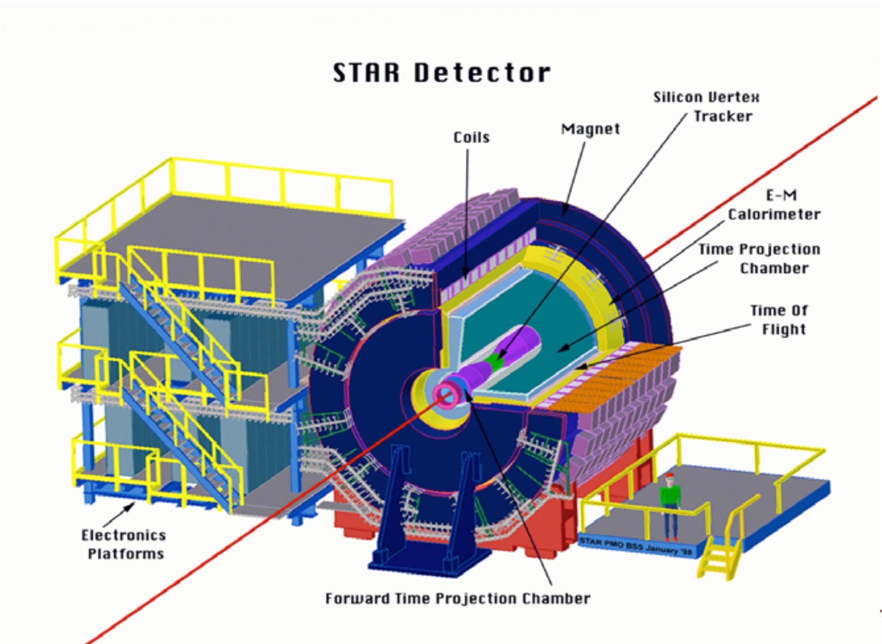
$3.1 < |\eta| < 3.7$

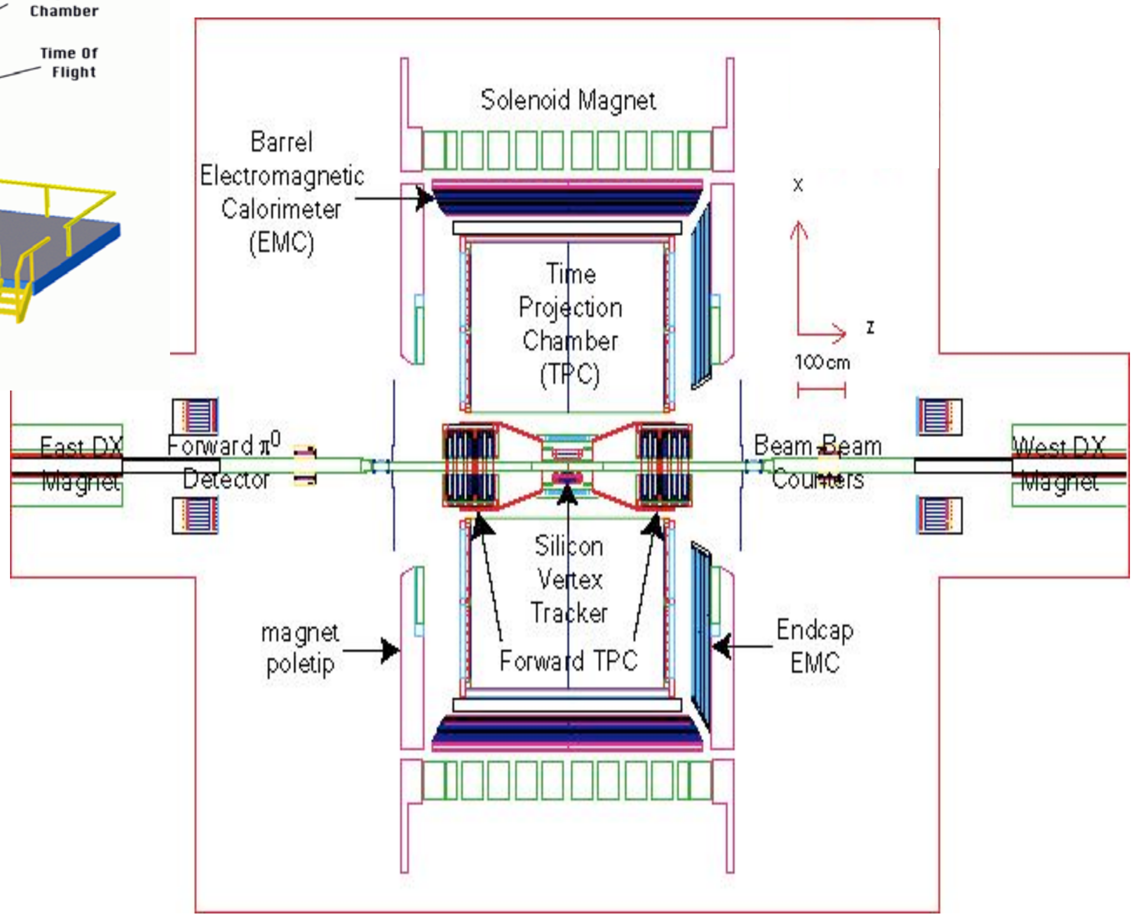
2π azimuth

- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)



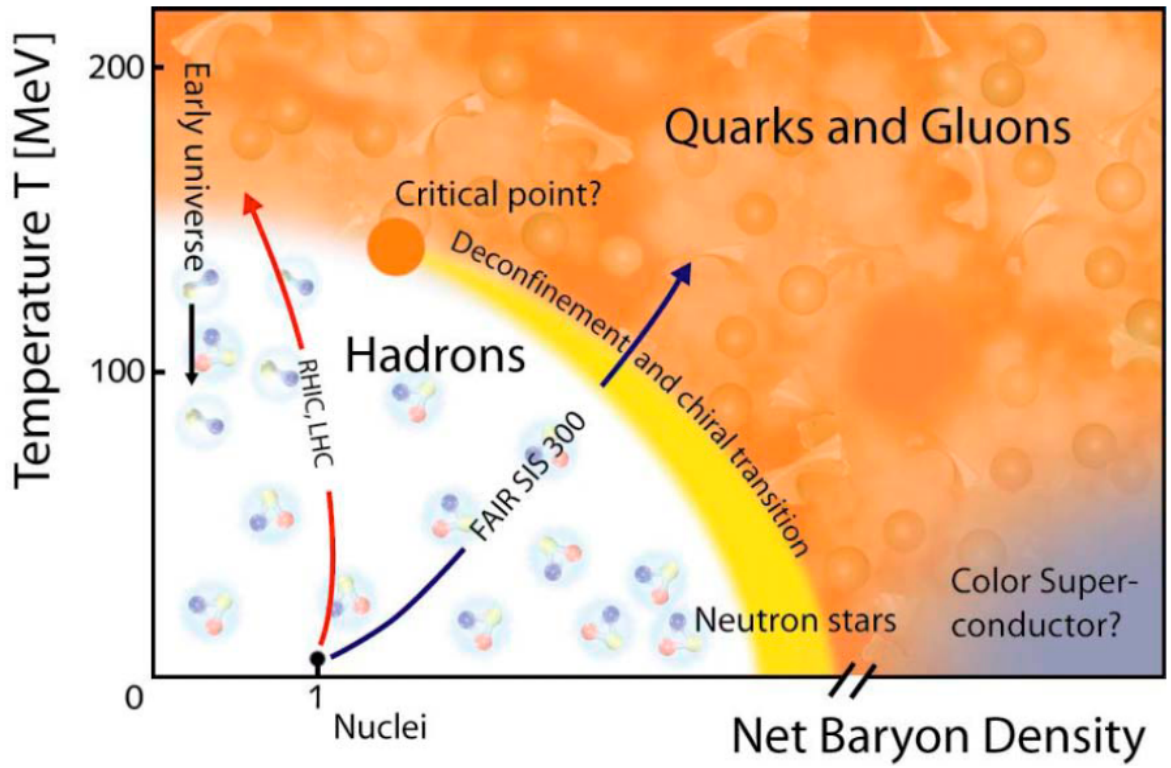
The STAR Detectors



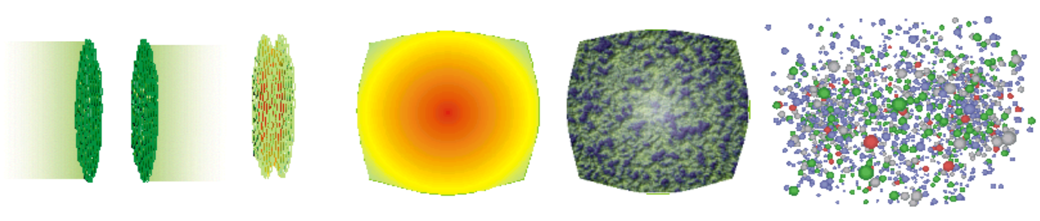


- Time Projection Chamber $|\eta|<1.6$
- Forward TPC $2.5<|\eta|<4.0$
- Silicon Vertex Tracker $|\eta|<1$
- Barrel EMC $|\eta|<1$
- Endcap EMC $1.0< \eta <2.0$
- Forward Pion Detector $3.3<|\eta|<4.1$

Phase Diagram

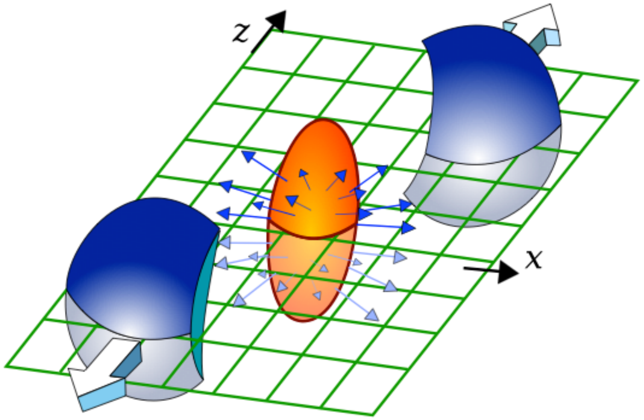


Phase diagram of nuclear matter

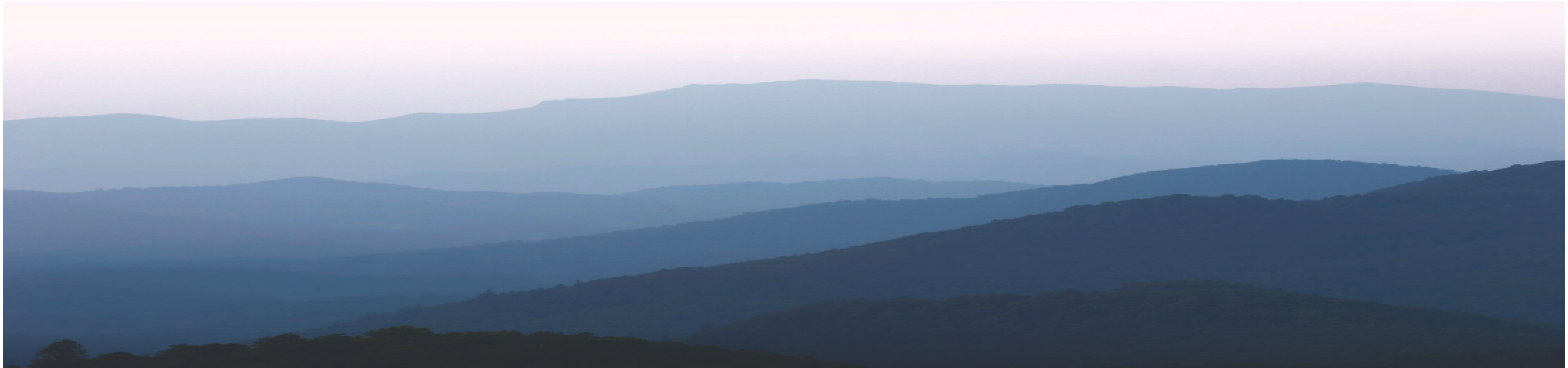


Selected Topics on Heavy Ion Physics

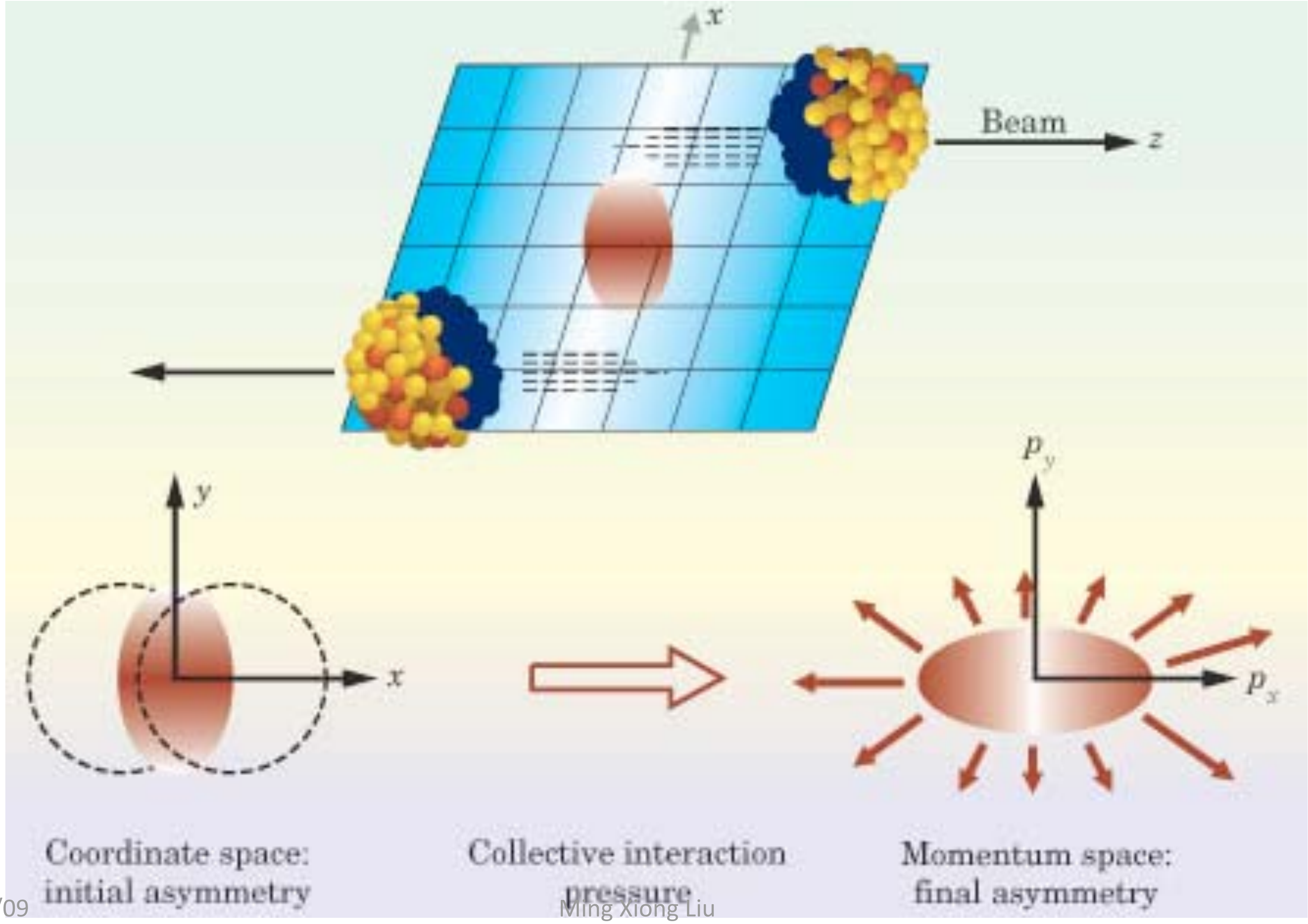
- QGP Bulk Property and Soft Physics
  - Parton Collective Motion and “Perfect Liquid”
  - Blackbody Thermal photons
- Medium Interaction and Hard Probes
  - Jet energy loss
  - Direct photons
- QGP Screening and Heavy Quarkonia Produciton
  - J/Psi
  - Upsilon



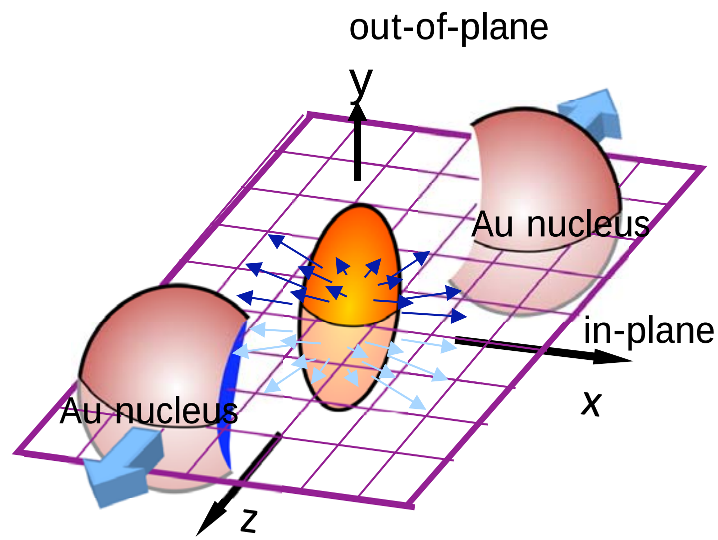
Elliptic flow and scaling properties



Reaction Plane in AuAu Collisions



What is Flow?



- initial state of non-central collision
  - large asymmetric pressure gradients
  - → hydrodynamic flow of partons
  - control parameters: ε_s, η, c_s
- translates into
  - final state momentum anisotropy

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$

$$v_{2n} = \left\langle \cos\left(2n\left[\varphi - \Psi_R\right]\right)\right\rangle$$

- hydrodynamic flow exhibits scaling properties which can be validated (or invalidated), e.g.:

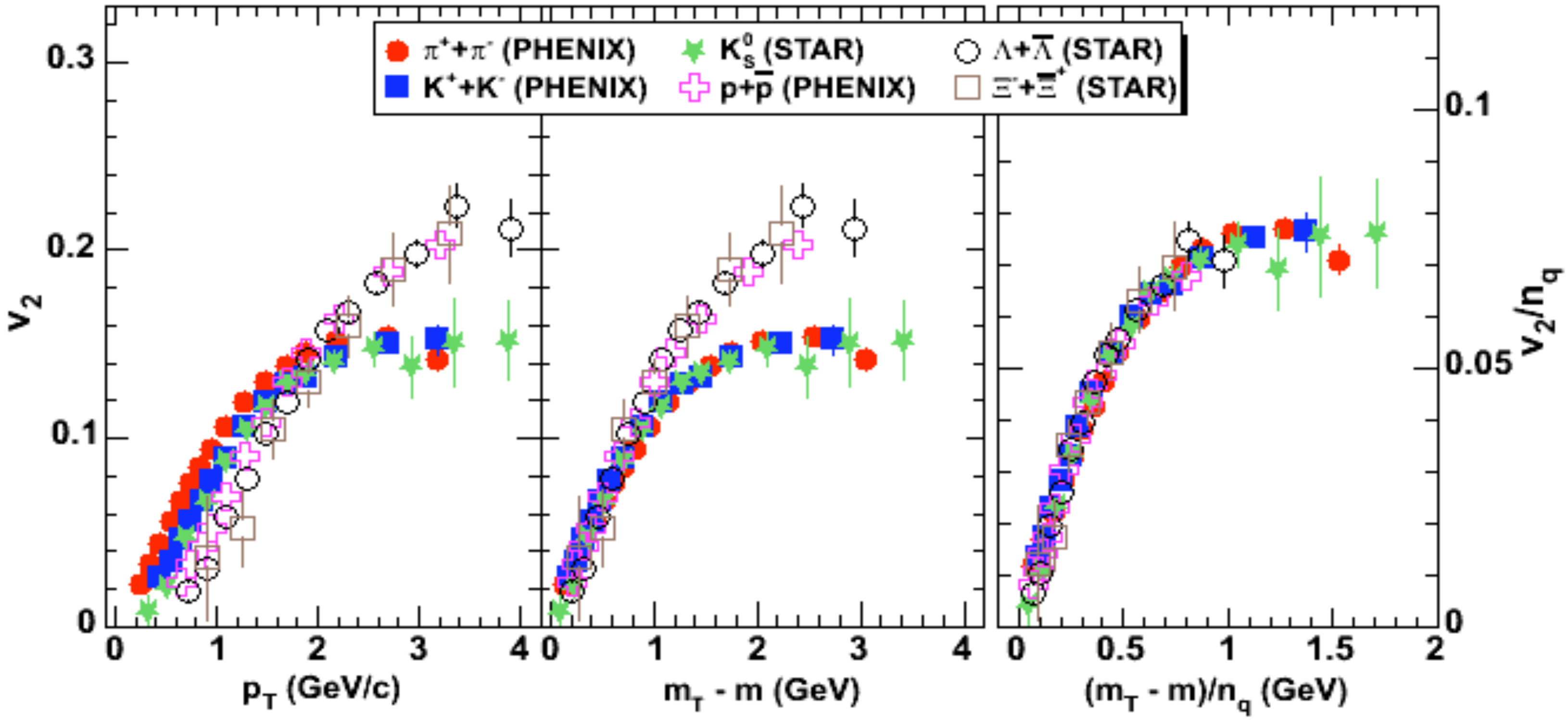
$$\frac{v_{4,M}(2p_T)}{v_{2,M}^2(2p_T)} \approx a\left(\frac{1}{4} + \frac{1}{2}\times\frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}\right) \qquad \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)} \approx \frac{1}{2}$$

$$\frac{v_{4,B}(3p_T)}{v_{2,B}^2(3p_T)} \approx a\left(\frac{1}{3} + \frac{1}{3}\times\frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}\right) \qquad a \approx 1.8$$

→ $v_4/v_2 2 \approx 0.9$

Quark number + KE_T scaling (AuAu 200 GeV)

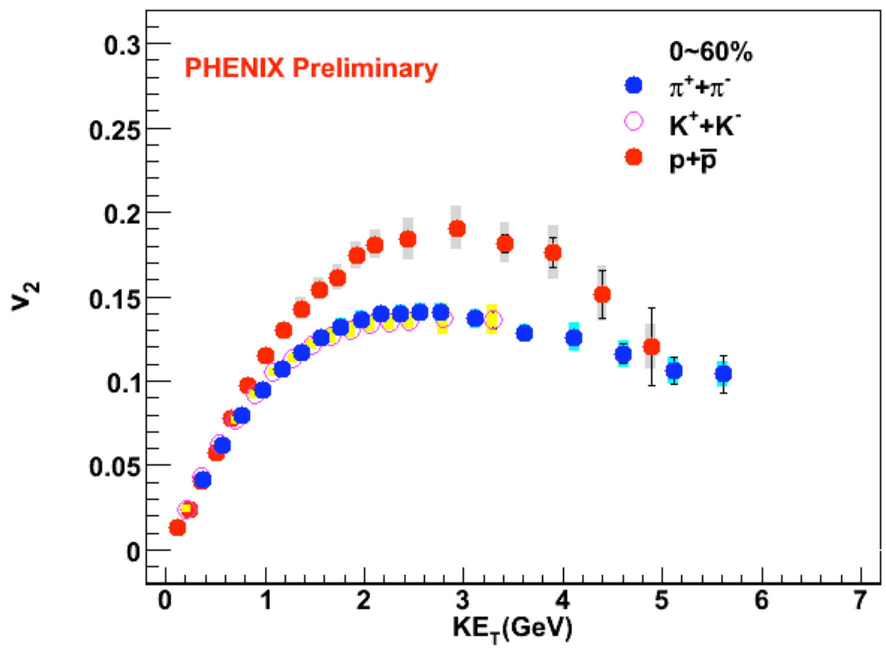
PHENIX PRL. 98, 162301 (2007)

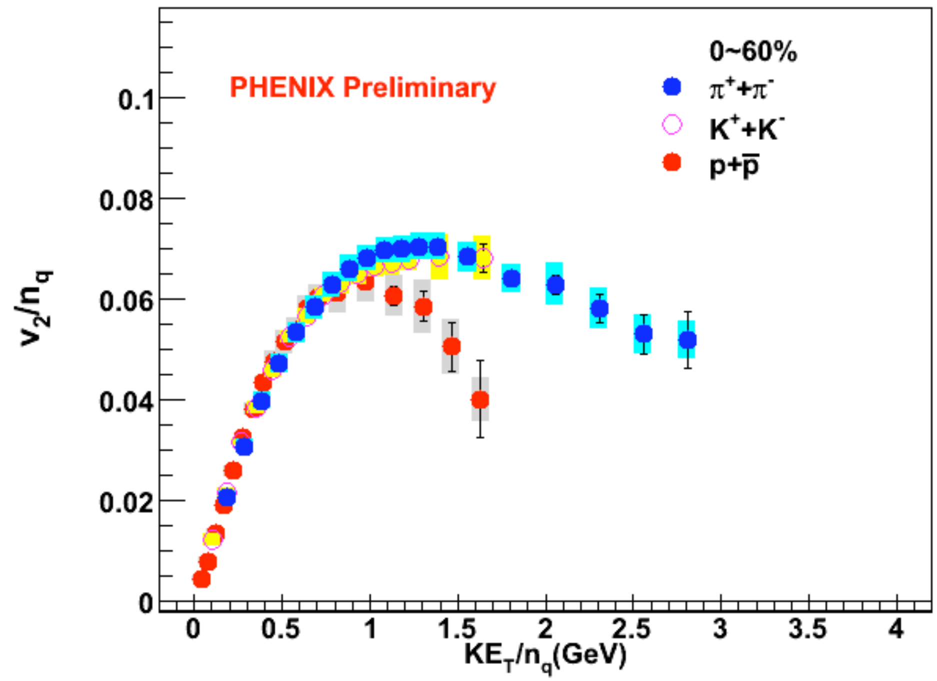


Transverse kinetic energy: $KE_T \approx m_T - m$, where $m_T^2 = p_T^2 + m^2$

$v_2(p_T)/n_{quark}$ vs. KE_T/n_{quark} becomes one curve independent of particle species.

KE_T and NCQ scaling
Parton Collective Motion





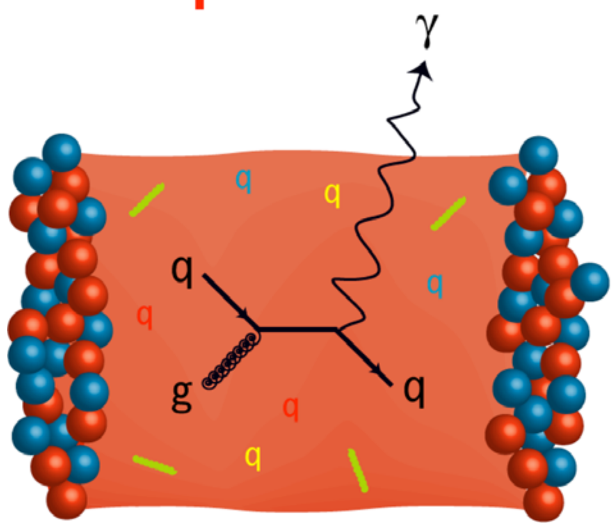
KE_T scaling works for baryons and mesons separately at moderate p_T

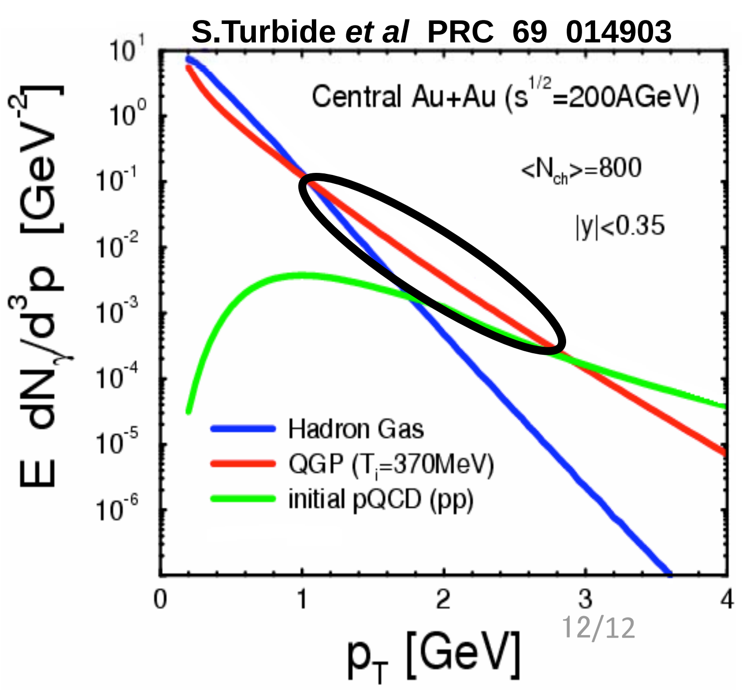
At low p_T KE_T/n_q scaling suggests flow established at partonic level; breaks down at KE_T/n_q>1 GeV

At p_T/n_q~1.5 GeV/c^2, PID v_2 start to deviate from NQ scaling, in particular for protons.

Thermal Radiation and Direct photon

- Photons emitted from every stage of collisions
  → Carry the thermodynamic information about the matter when they are generated.
  - Low pT region (**1~3 GeV/c**)
    – **Thermal radiation from QGP**
  - Intermediate pT region (**3~5 GeV/c**)
    – **jet-medium interactions**
      - jet-photon conversion
      - in-medium bremsstrahlung
- Nuclear matter/PDF effects may enhance/decrease photon yield at low pT.
  - Cronin effect, nuclear shadowing
- Measurement of direct photon is very challenging due to a large background from hadron decays.



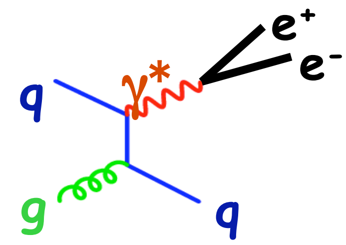


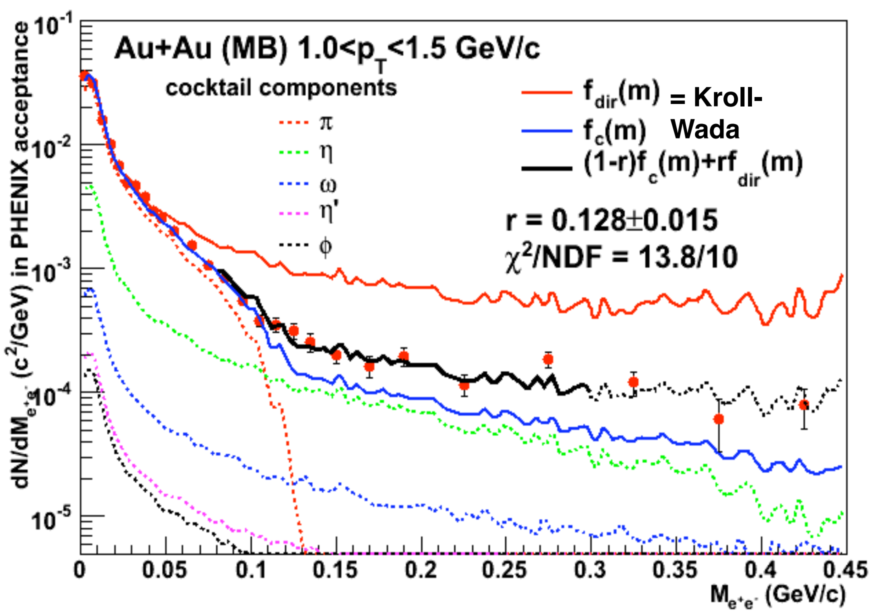
Direct γ in AuAu via Internal Conversion

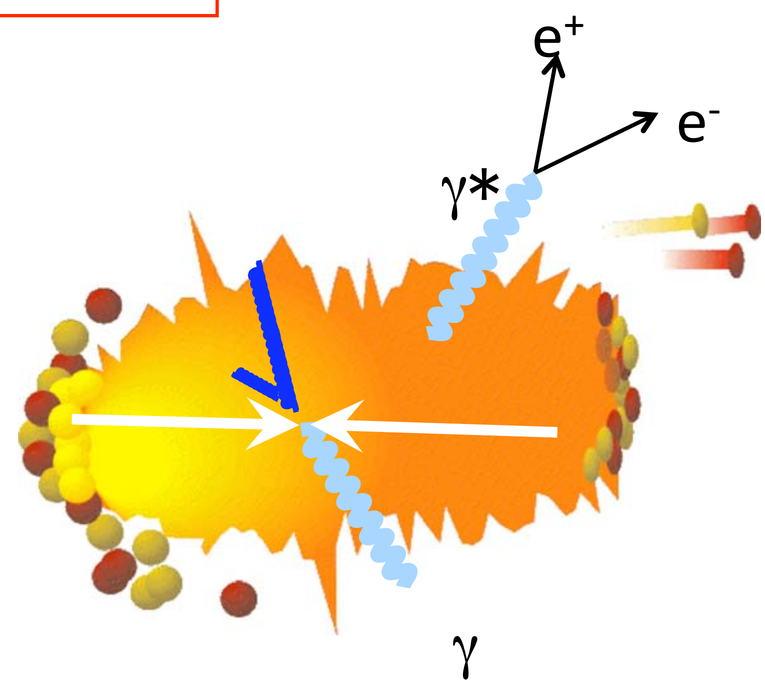
Kroll Wada PR**98**(1955) 1355

PHENIX NPA**774**(2006)403

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\left(1-\frac{m_{ee}^2}{M^2}\right)^3 \mid F(m_{ee}^2)\mid^2 \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)$$



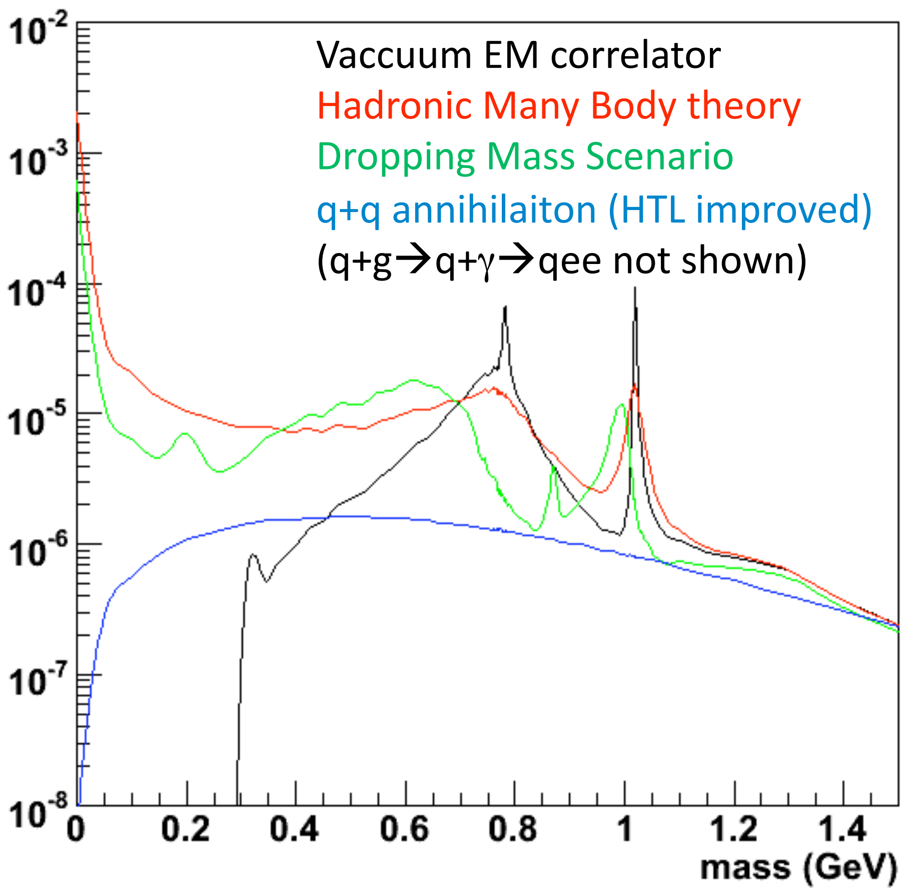




Eliminating the π^0 background by going to $0.2<m_{ee}<0.3$ GeV enables direct γ signal to be measured for $1<p_T<3$ GeV/c in Au+Au. It is exponential, does that mean it is thermal. We must see whether p-p direct γ turns over as $p_T \rightarrow 0$ as in Drell-Yan or exponential like for π^0

Theory Prediction of Dilepton Emission

$$\frac{dN_{ee}}{p_t dp_t dM dy}$$ at y=0, pt=1.025 GeV/c



Theory calculation by Ralf Rapp

Usually the dilepton emission is measured and compared as dN/dptdM

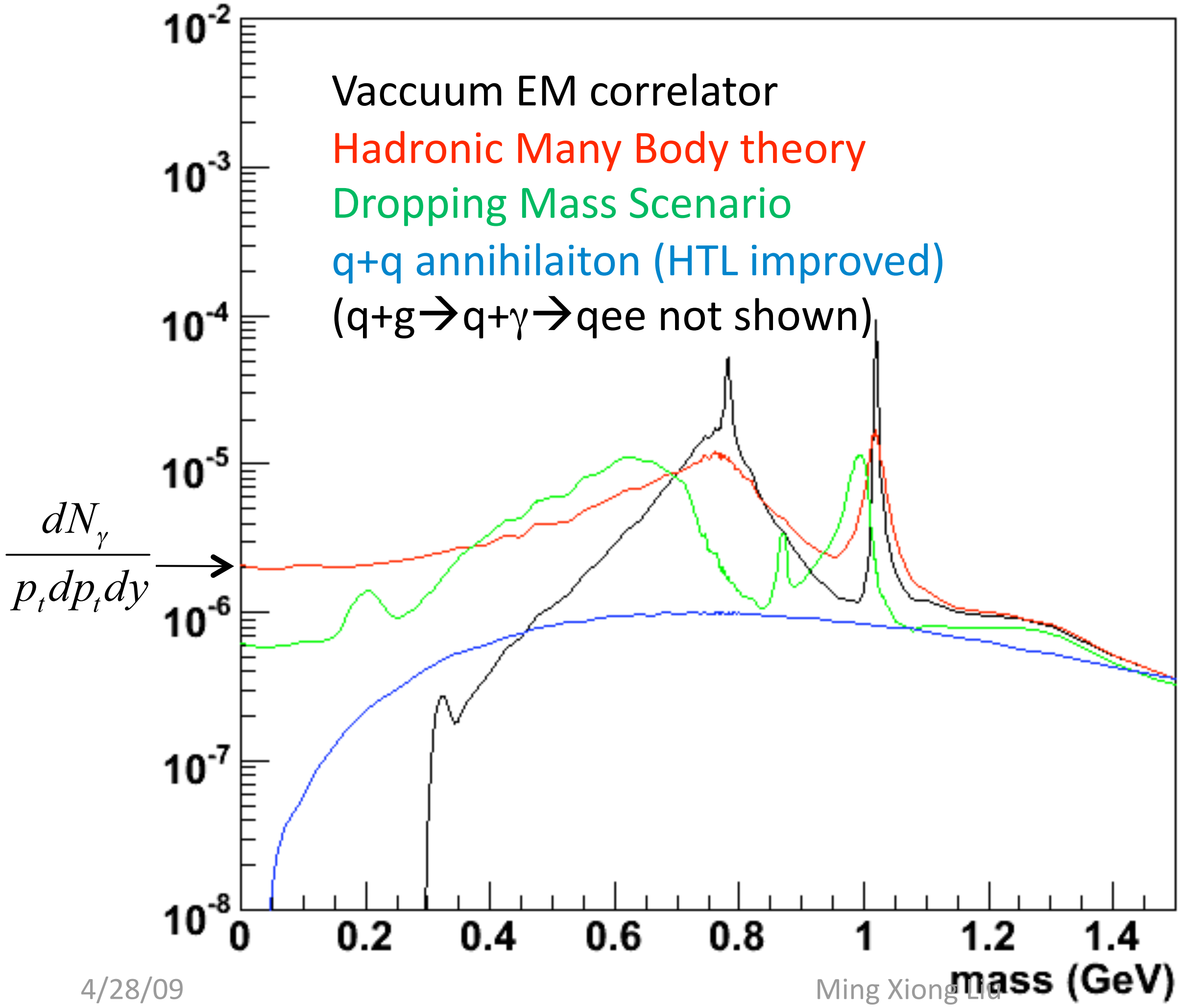
The mass spectrum at low pT is distorted by the virtual photon→ee decay factor 1/M, which causes a steep rise near M=0

qq annihilaiton contribution is negligible in the low mass region due to the m**2 factor of the EM correlator

In the caluculation, partonic photon emission process q+g→q+γ→qee is not included

Virtual photon emission rate

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



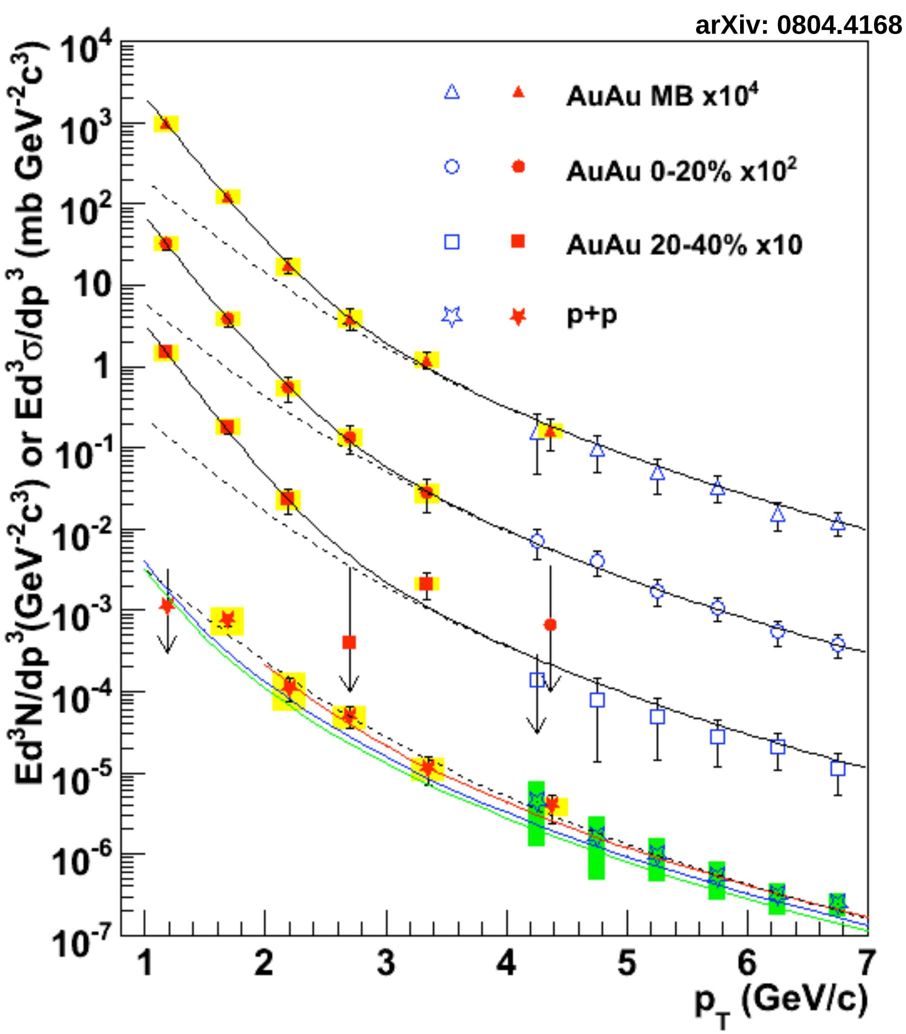
The same calculation, but shown as the virtual photon emission rate.

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

When extrapolated to M=0, the real photon emission rate is determined.

q+g→q+γ* is not shown; it is similar size as HMBT at this pT

Evidence of Thermal Radiation?



p+p

- First measurement in 1-3GeV/c
- Consistent with NLO pQCD

→ **Serves as a crucial reference**

Au+Au

- Significant excess over binary-scaled p+p result for pT<3GeV/c.

→ Inverse slope of exponential fit is related to temperature of matter

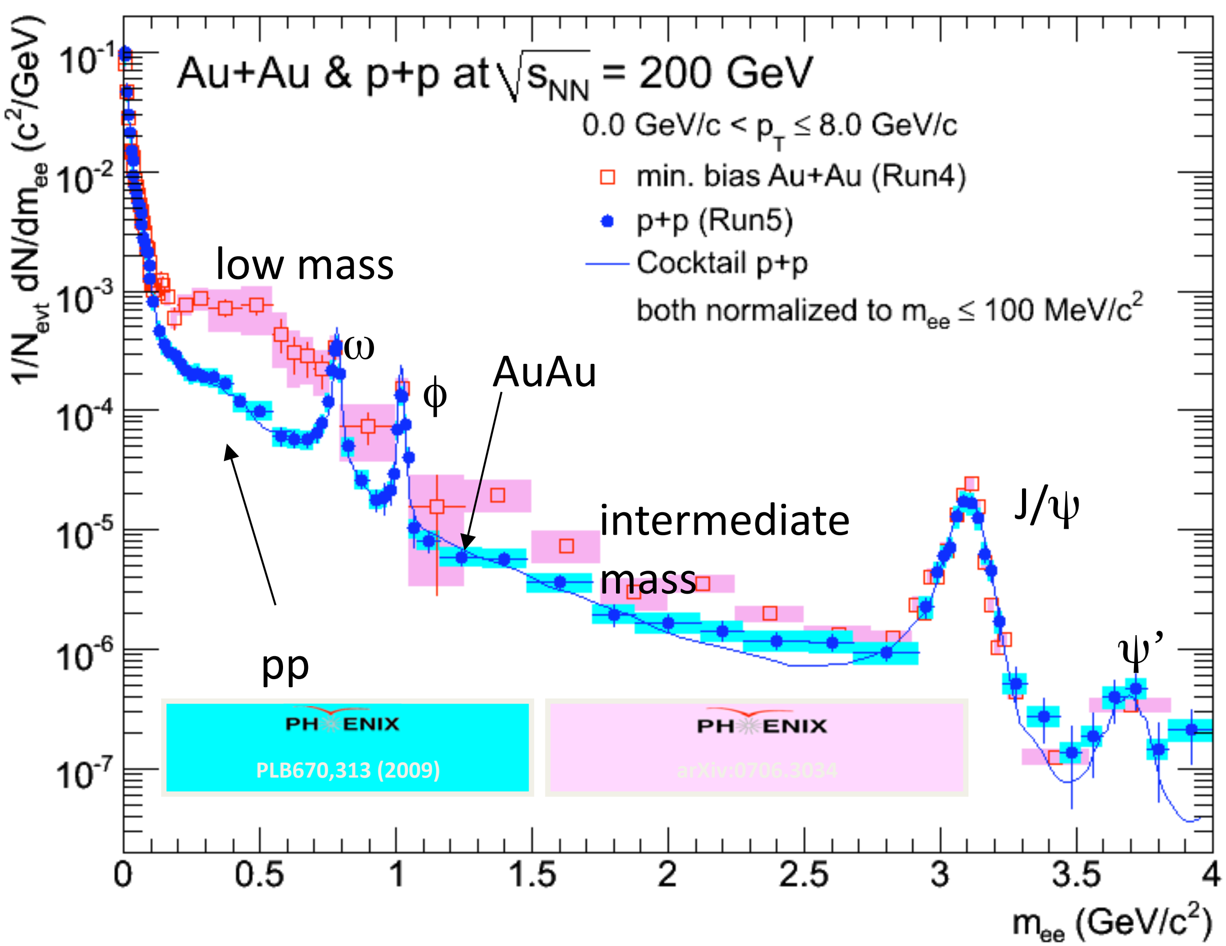
Inverse slope

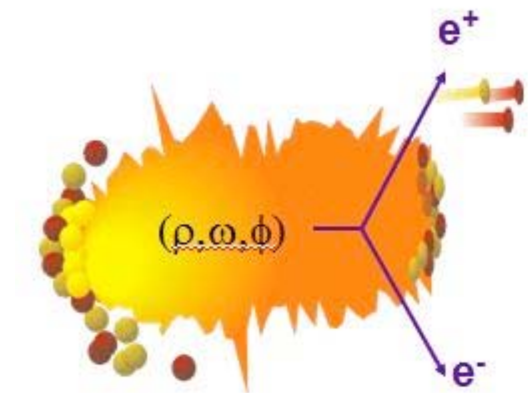
$$\underbrace{A\exp(-p_T/\boxed{T})}_{\text{Exponential part}} + \underbrace{T_{AA} \times A_{pp}(1+p_T^2/b)^{-n}}_{\text{Binary-scaled p+p result}}$$

centrality	$dN/dy(p_T > 1\mathrm{GeV}/c)$	$T(\mathrm{MeV})$
0-20%	$1.10 \pm 0.20 \pm 0.30$	$221 \pm 23 \pm 18$
20-40%	$0.52 \pm 0.08 \pm 0.14$	$215 \pm 20 \pm 15$
MB	$0.33 \pm 0.04 \pm 0.09$	$224 \pm 16 \pm 19$

PHENIX Low Mass Dielectrons

p+p NORMALIZED TO m_{ee}<100 MeV





pp and AuAu normalized to p^0 Dalitz region (~ same # of particles)

p+p: agree with the expected background from hadron decays

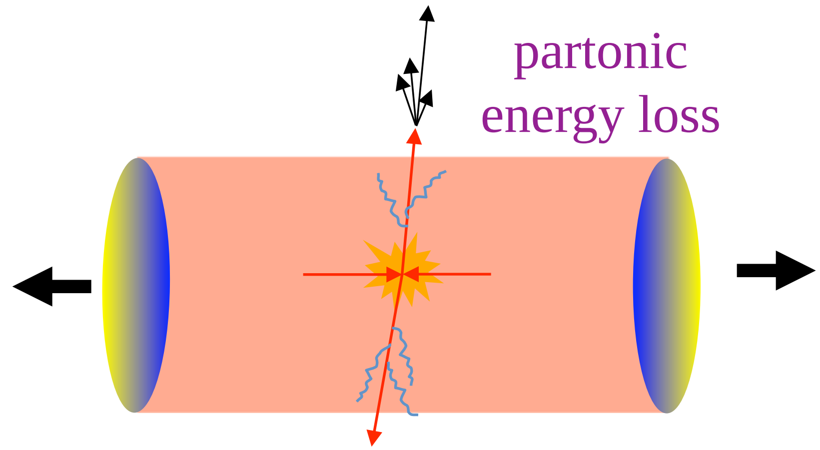
Au+Au: large Enhancement in 0.15-0.75 GeV/c^2

What Have We Learned about the Bulk Properties?

- **What is the ultimate say on partonic collectivity for the matter ?**
  - **Yes. Case Closed. (A. Tang, QM2009)**
- **What is the limit of NQ scaling of V_2?**
  - **NQ Scaling studied works in lower energy, smaller system and at forward region. Signs of deviation from NQ scaling has been observed at large pt in AuAu collisions at 200 GeV.**
- **In Au+Au collisions, significant excess of direct photon over binary-scaled p+p result is seen, is this thermal radiation?**
  - Nuclear matter effect to direct photon yield should be evaluated in order to extract net signal of thermal photons.
  - Run8 d+Au result is promising and will come in near future

The Hard Probes

- Hard scattering & Jet
  - Multiple scattering
  - Energy loss
  - Jet suppression
  - Leading particle
- Heavy Quarkonium
  - Debye screening
  - J/Psi suppression



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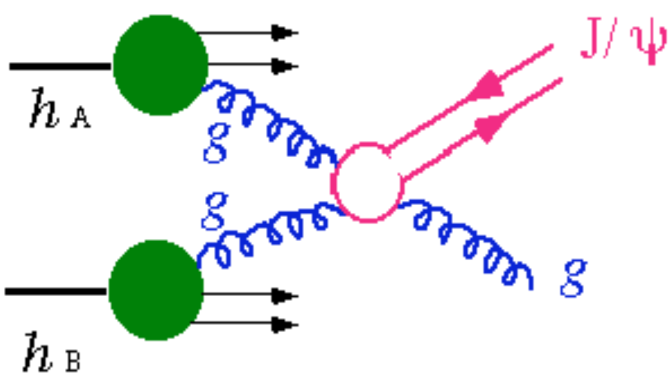
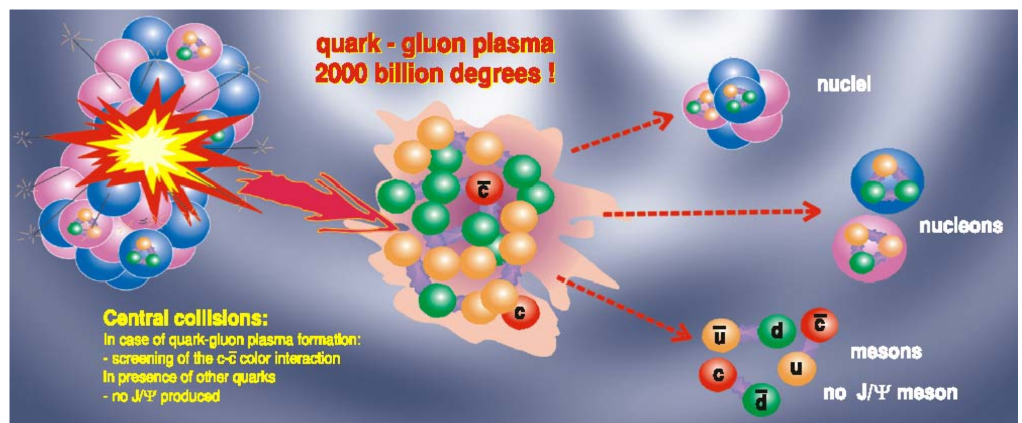
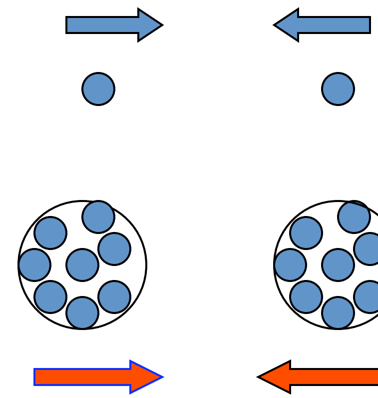


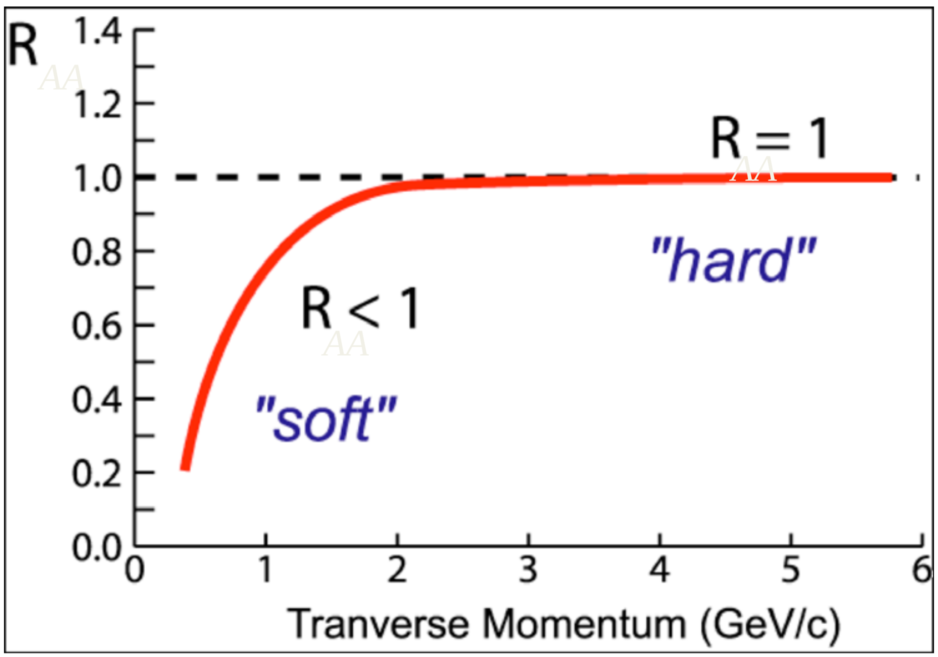


Energy loss
from single particles

Nuclear Modification Factor: R_{AA}

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





If no "effects":

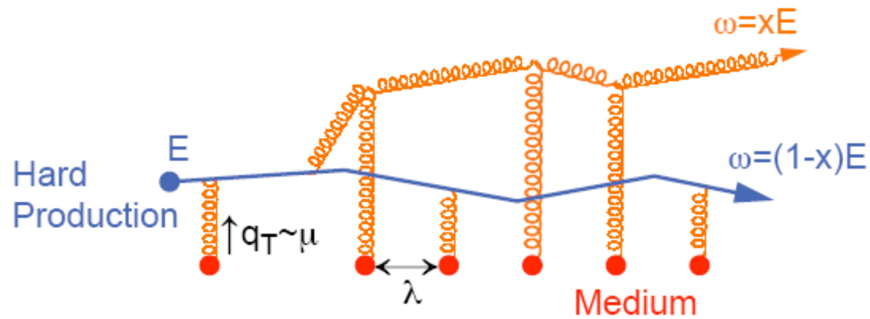
R_{AA} = 1 at high-p_T where hard scattering dominates

Suppression:

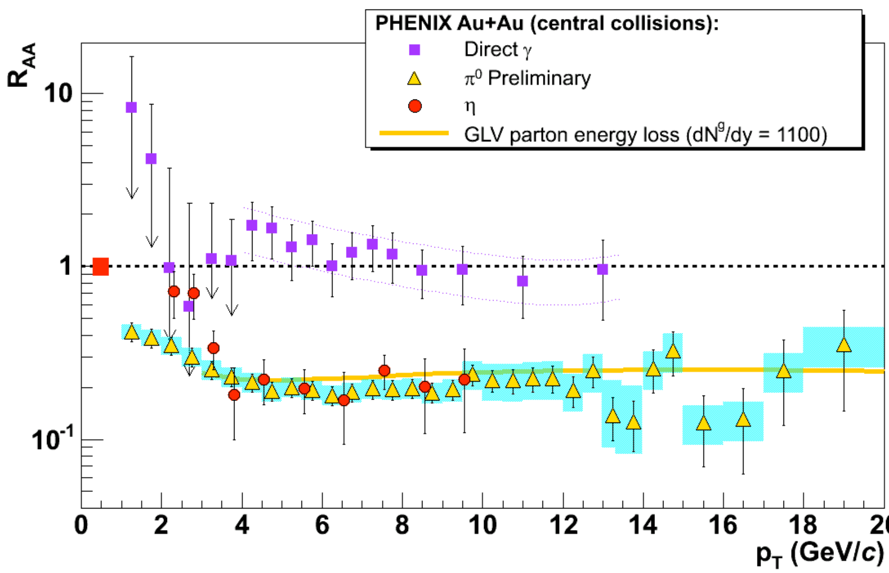
R_{AA} < 1 at high-p_T

Jet Quenching at RHIC

- Energy loss of partons from hard scattering through re-scattering in the hot & dense medium
  - nuclear modification factor $R_{AA} << 1$ at high p_T

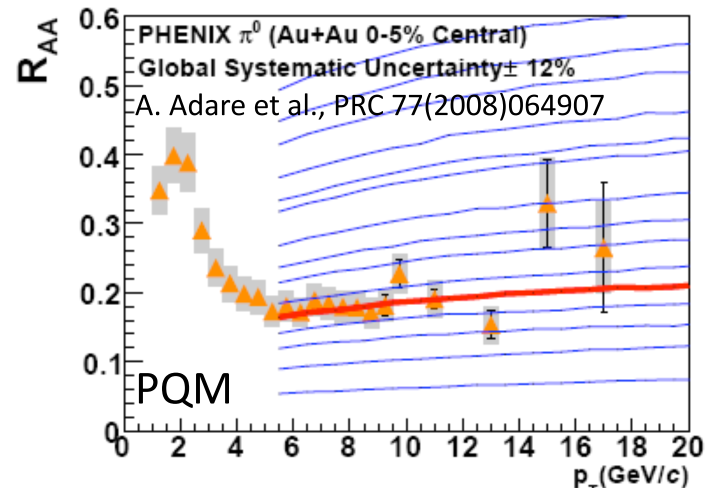


$$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\mathrm{Yield}_{pp}}$$



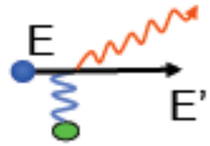
Huge opacity of the medium

- Access medium properties through statistical analysis
  - example: transport coefficient in PQM model

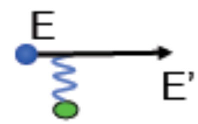


$\rightarrow \langle \hat{q} \rangle = 13.2^{+2.1}_{-3.2}\ \mathrm{GeV}^2 / \mathrm{fm}$

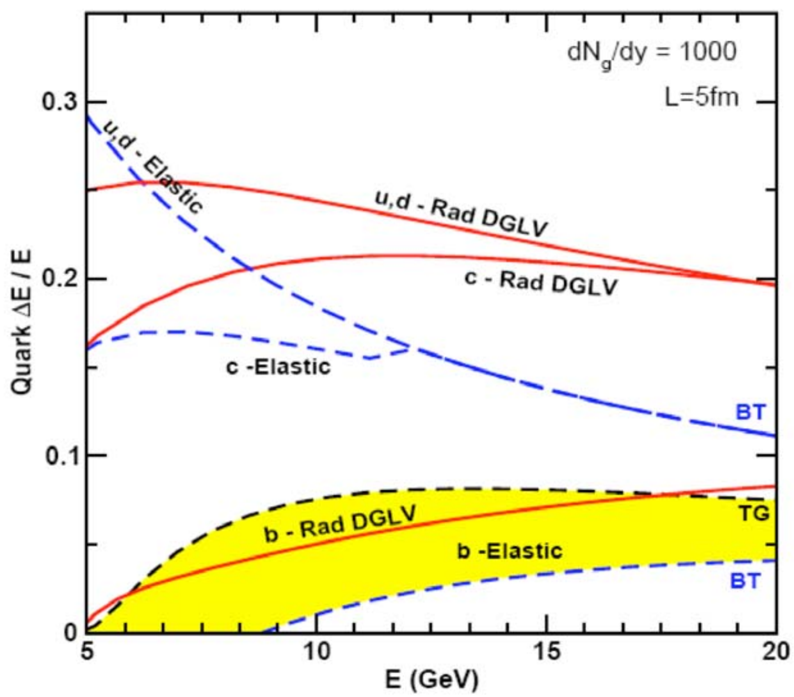
Other Mechanisms of Energy-loss:



Radiation
due to scattering



Elastic collision,
energy re-distribution



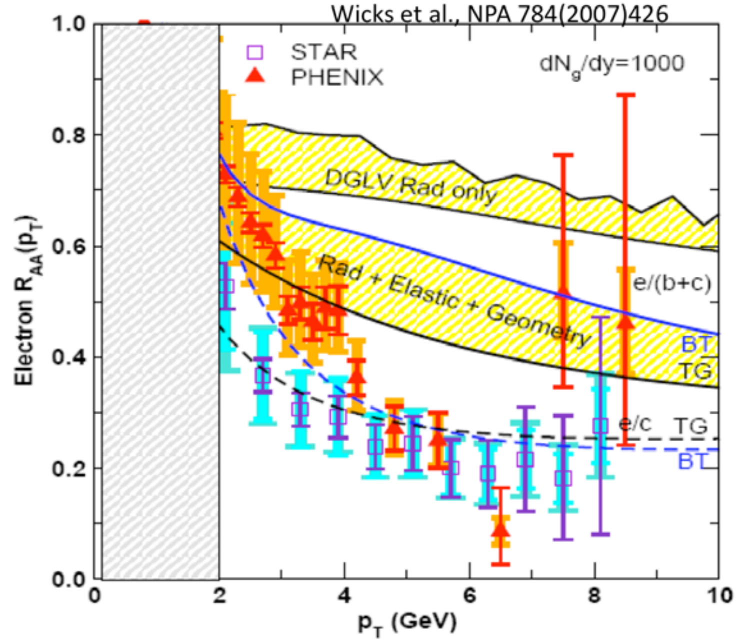
S.Wicks, W. Horowitz, M. Djordjevic M. Gyulassy (**WHDG**) nucl-th/0512076

Many calcs on relative importance

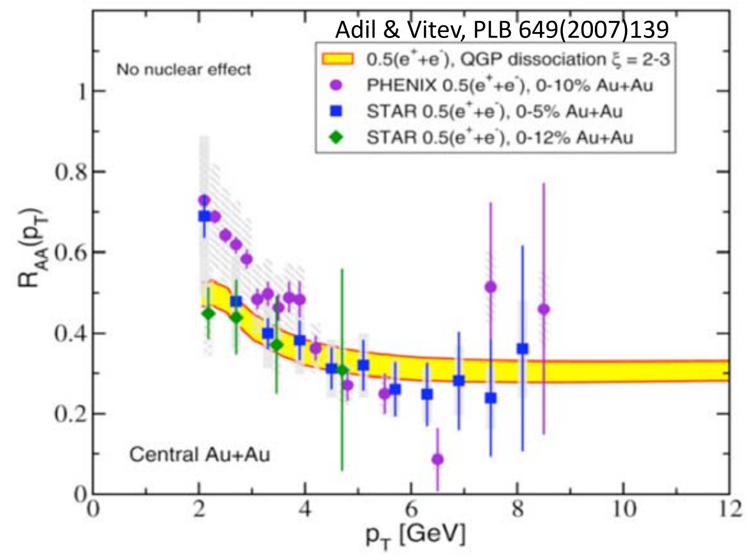
Probe via high-pt heavy-quarks
- smaller energy loss after elastic collision
- gluon radiation also reduced
    - interference during radiation
    - dead-cone effect

$e^{\pm}$ R_{AA}: a Challenge for Models

- Testing ground for various parton energy loss (ΔE) models
  - radiative ΔE only
    - Djordjevic et al., PLB 632(2006)81
    - Armesto et al., PLB 637(2006)362)
  - collisional ΔE included
    - Wicks et al., NPA 784(2007)426
    - van Hees & Rapp, PRC 73(2006)034913)

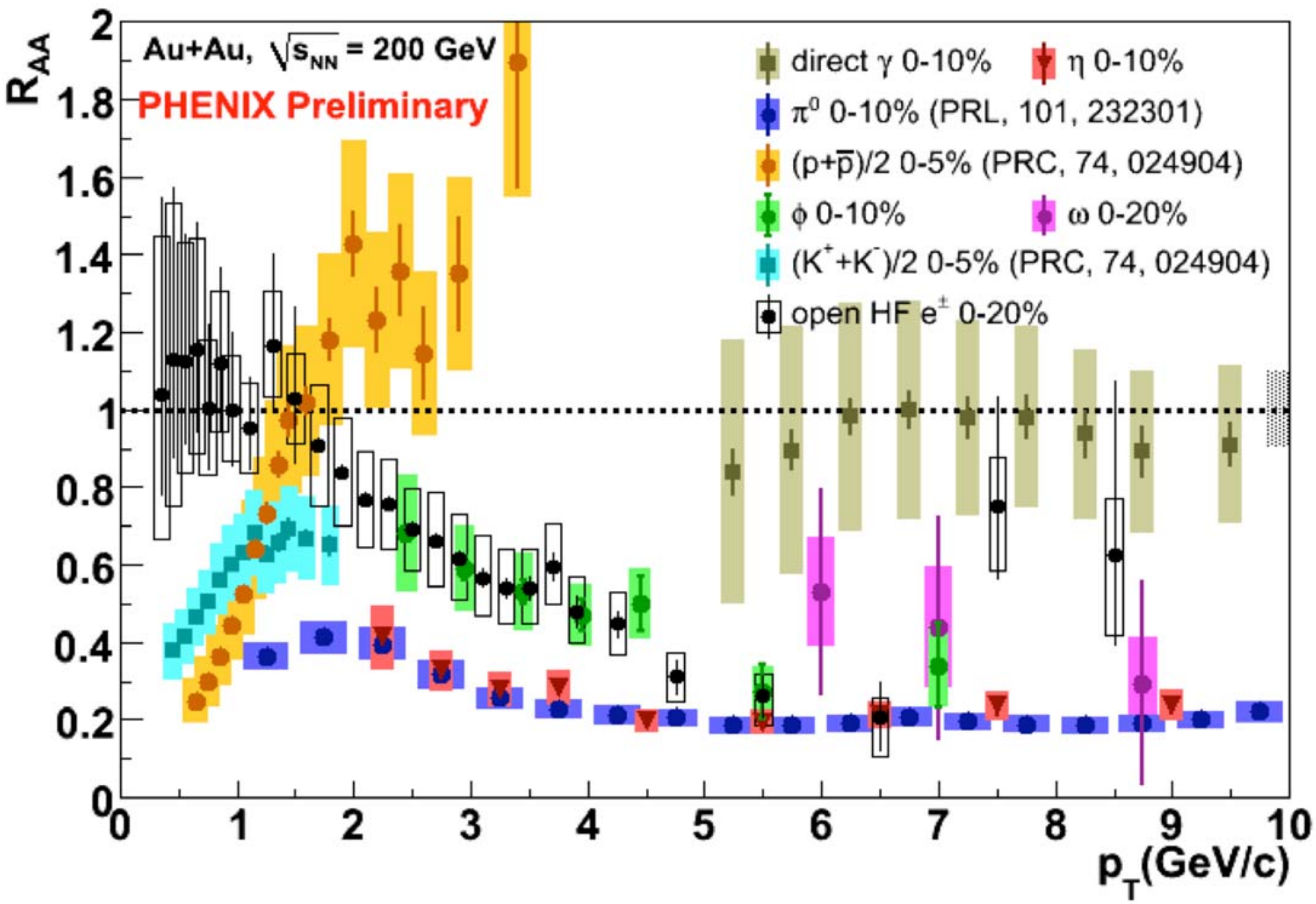


- Alternative approaches to interpret the suppression
  - collisional dissociation of heavy mesons (charm and bottom!)
    - Adil & Vitev, PLB 649(2007)139
  - contribution from baryon enhancement
    - Sorensen & Dong, PRC 74(2006)024902



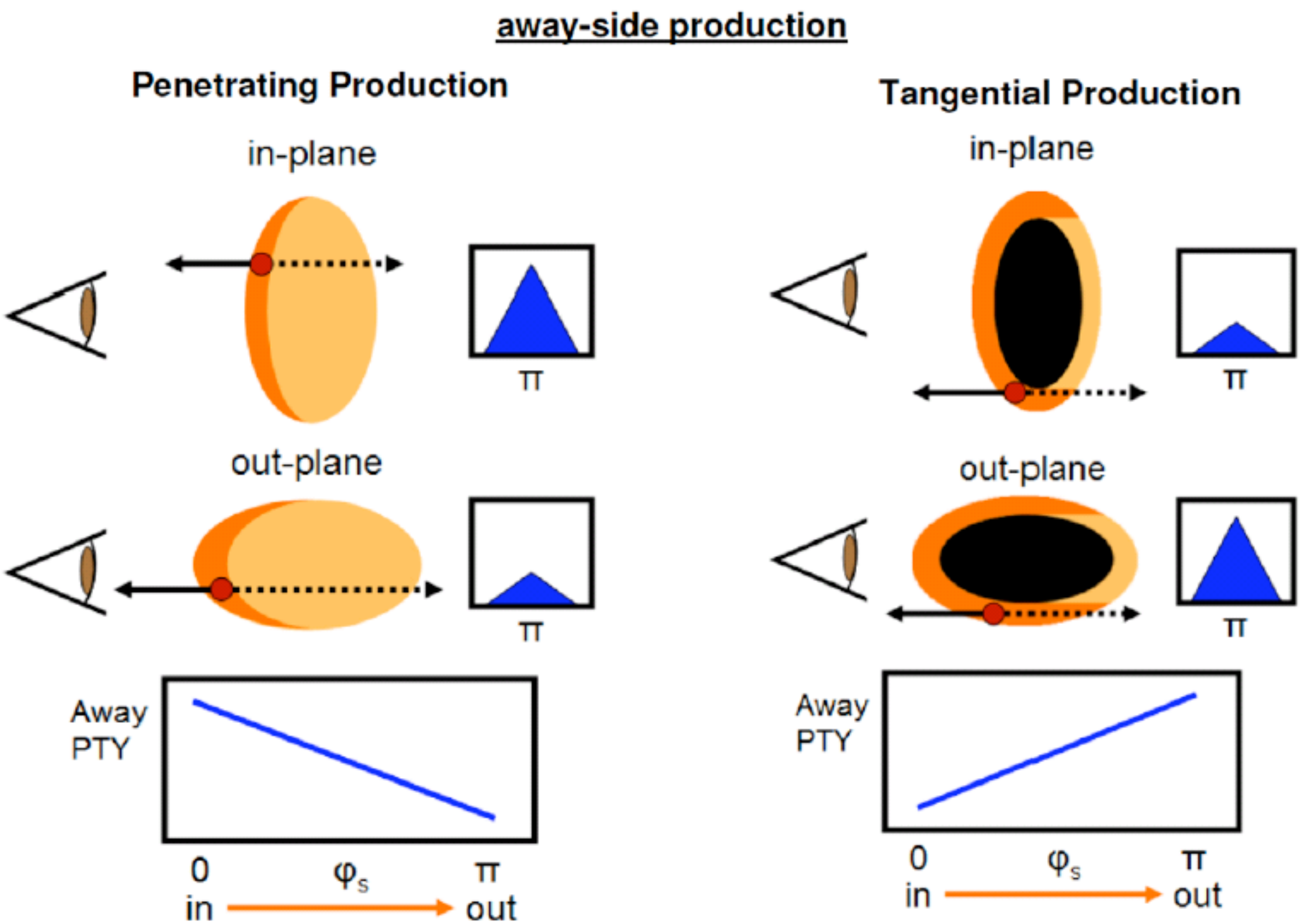
Sample of R_{AA} in PHENIX

$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\text{Yield}_{pp}}$$



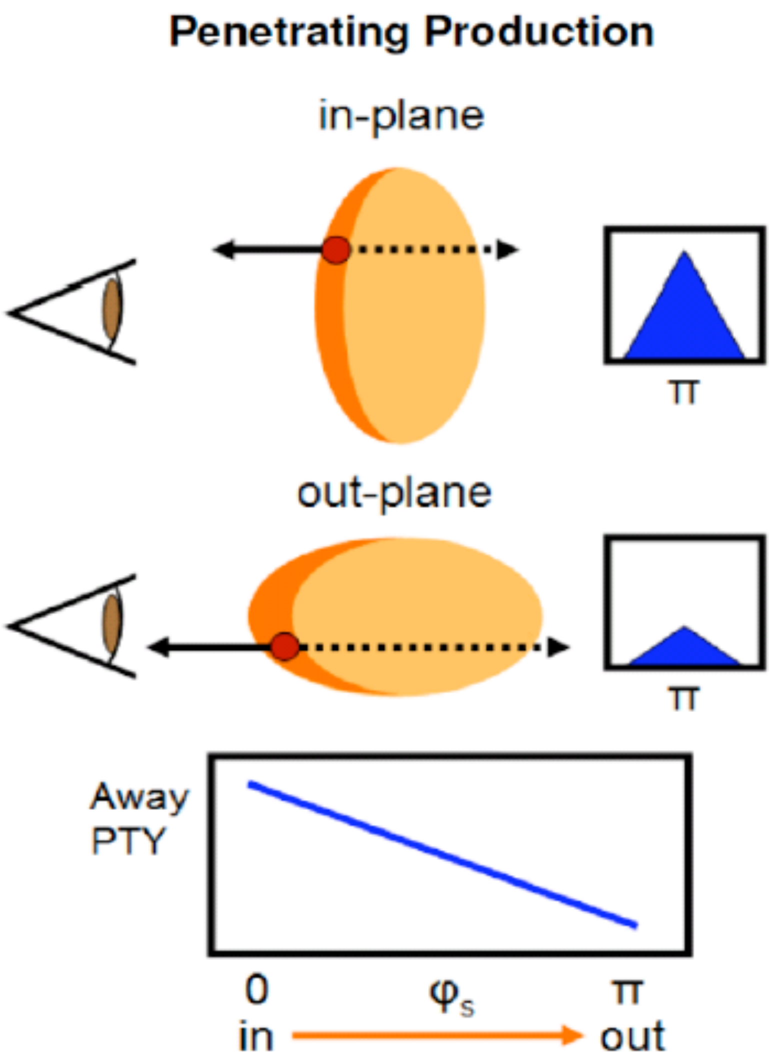
Energy loss and two particle correlation

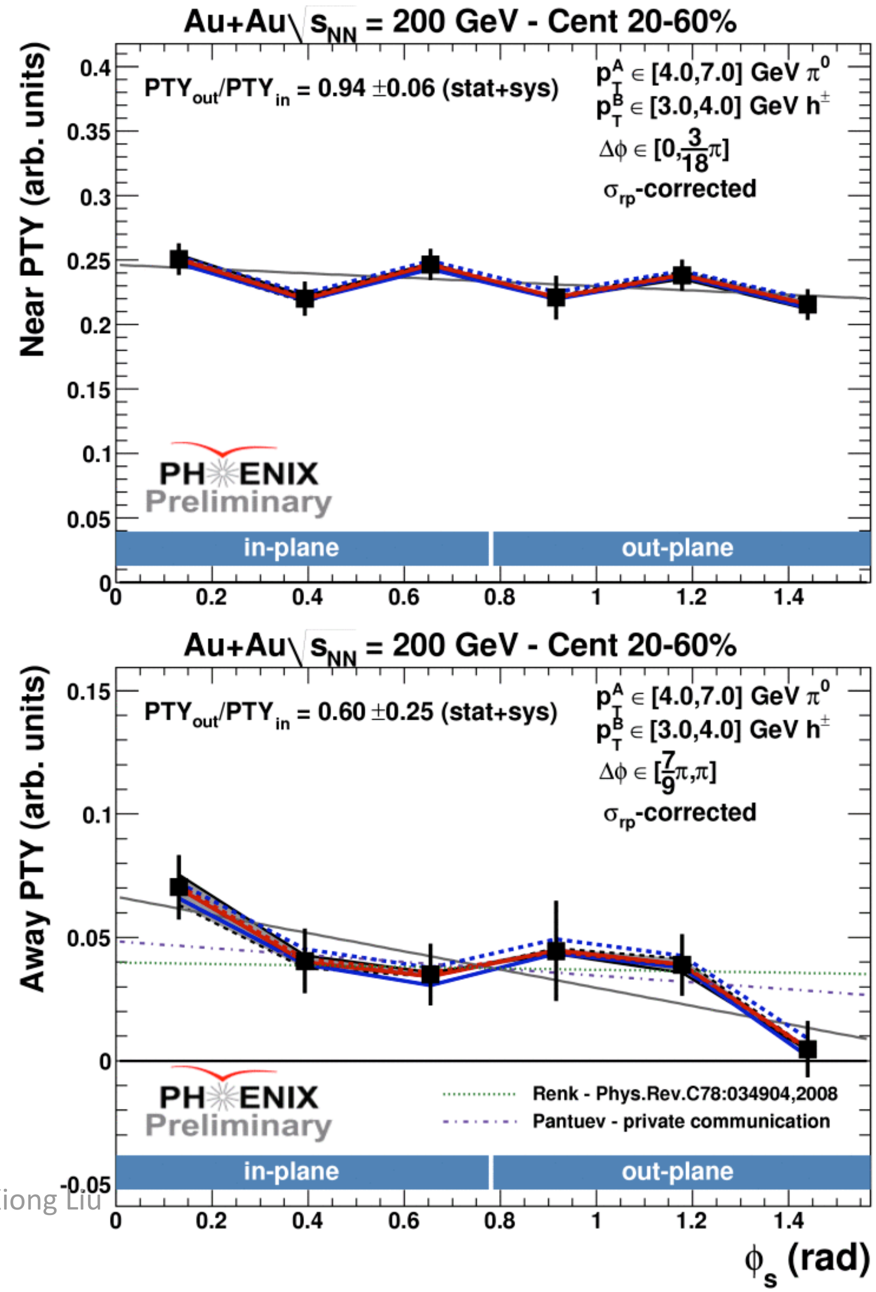
How Opaque is the medium?



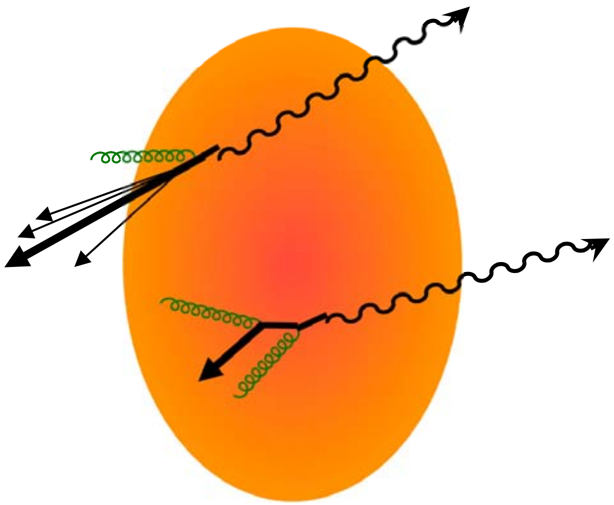
The rp-dependence of away-side PTY can discriminate between models.

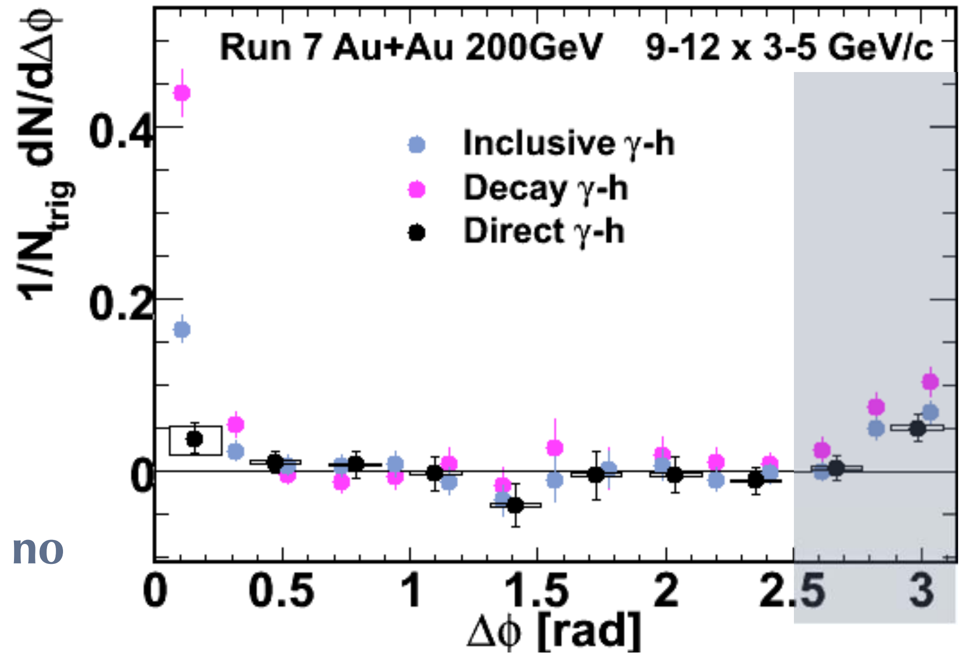
Near/Away Side Particle Yield vs ϕ_s (π^0-h)



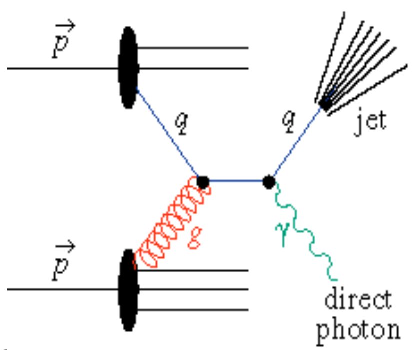


A Better Probe: Direct γ-jet



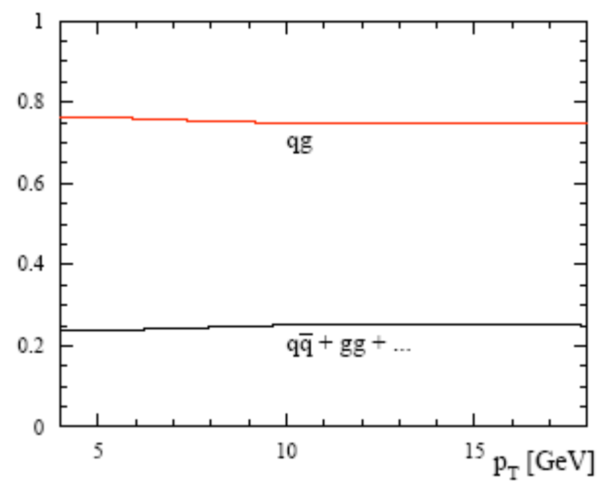


- γ not affected by strong interaction ⇒ no surface bias, can probe the entire geometry
- well calibrated, $E_\gamma \sim E_{jet}$

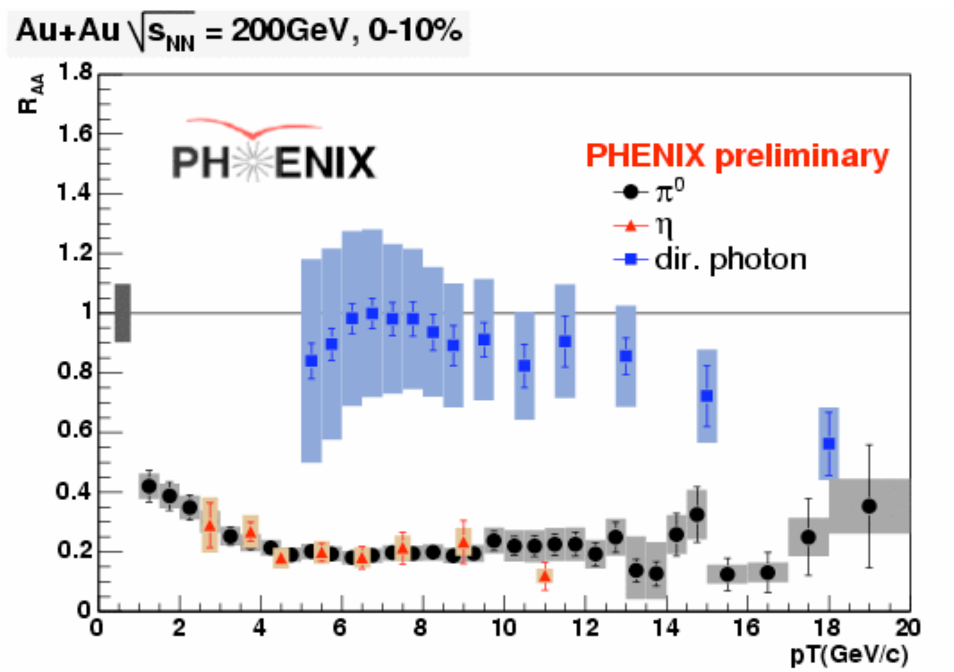


Quark-Gluon Compton scattering

$$\vec{p} + \vec{p} \to \gamma(+\,jet) + X$$



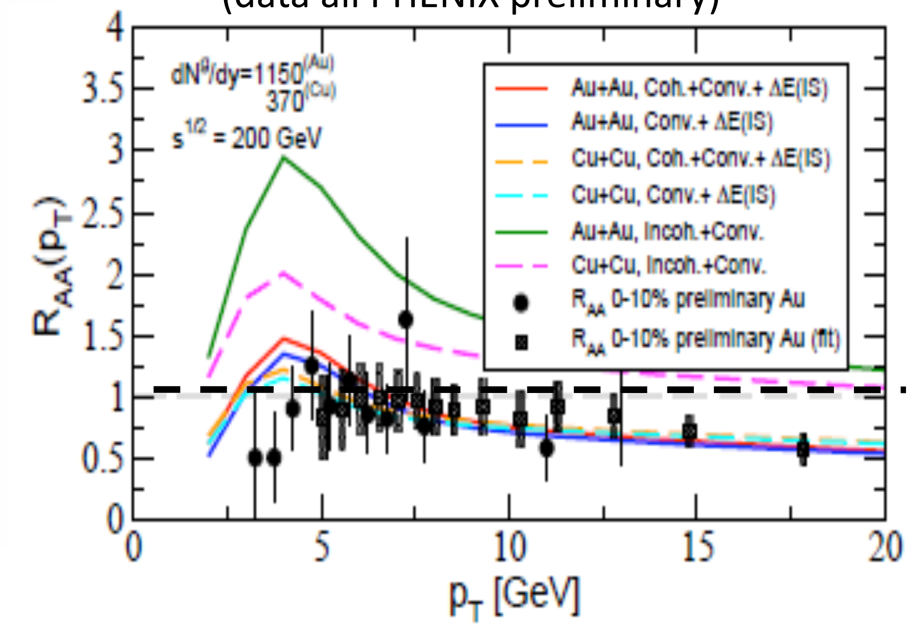
No Suppression in Direct Photons



Isospin, Cronin, shadowing, dE/dx

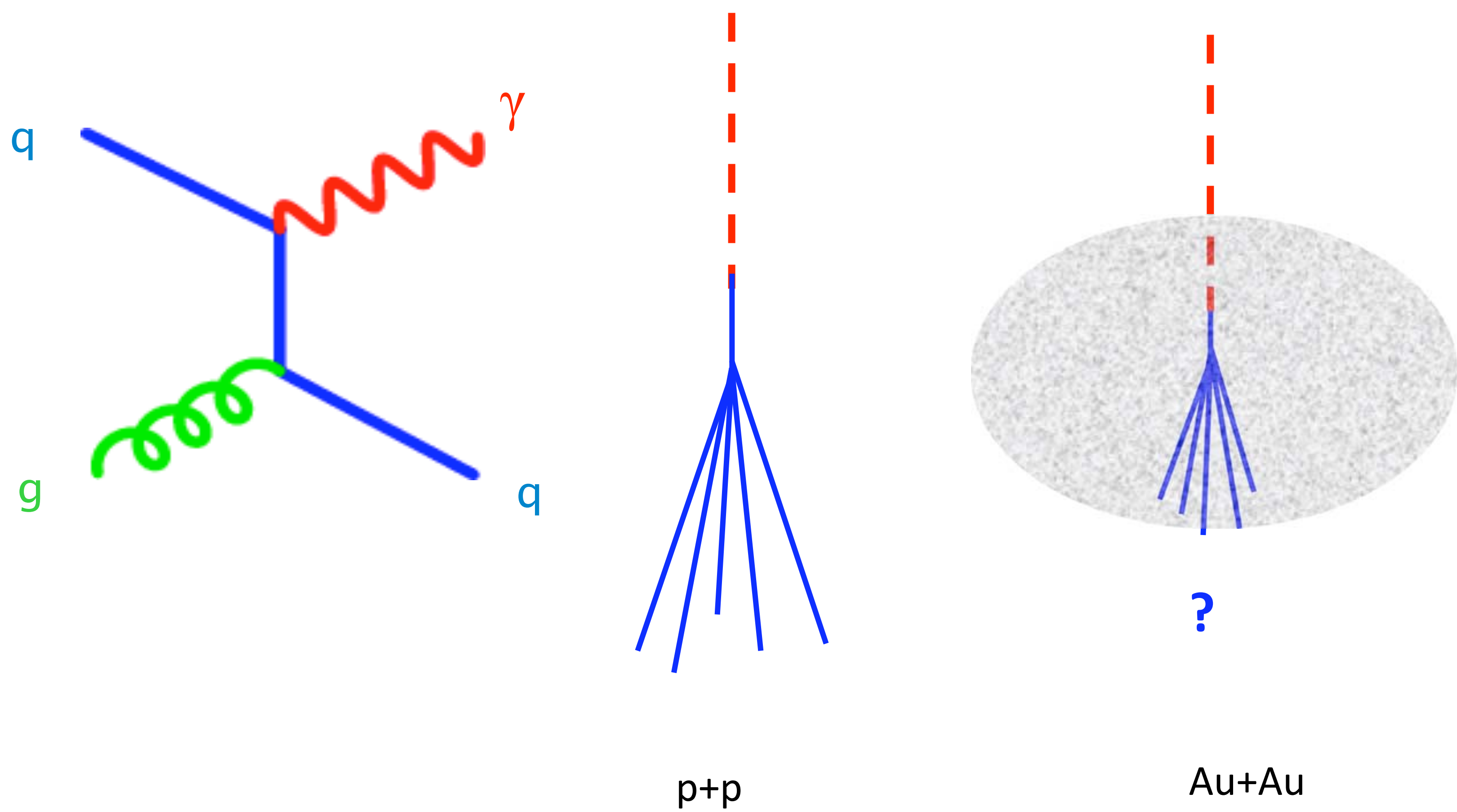
Vitev, nucl-th/0810.3194v1

(data all PHENIX preliminary)

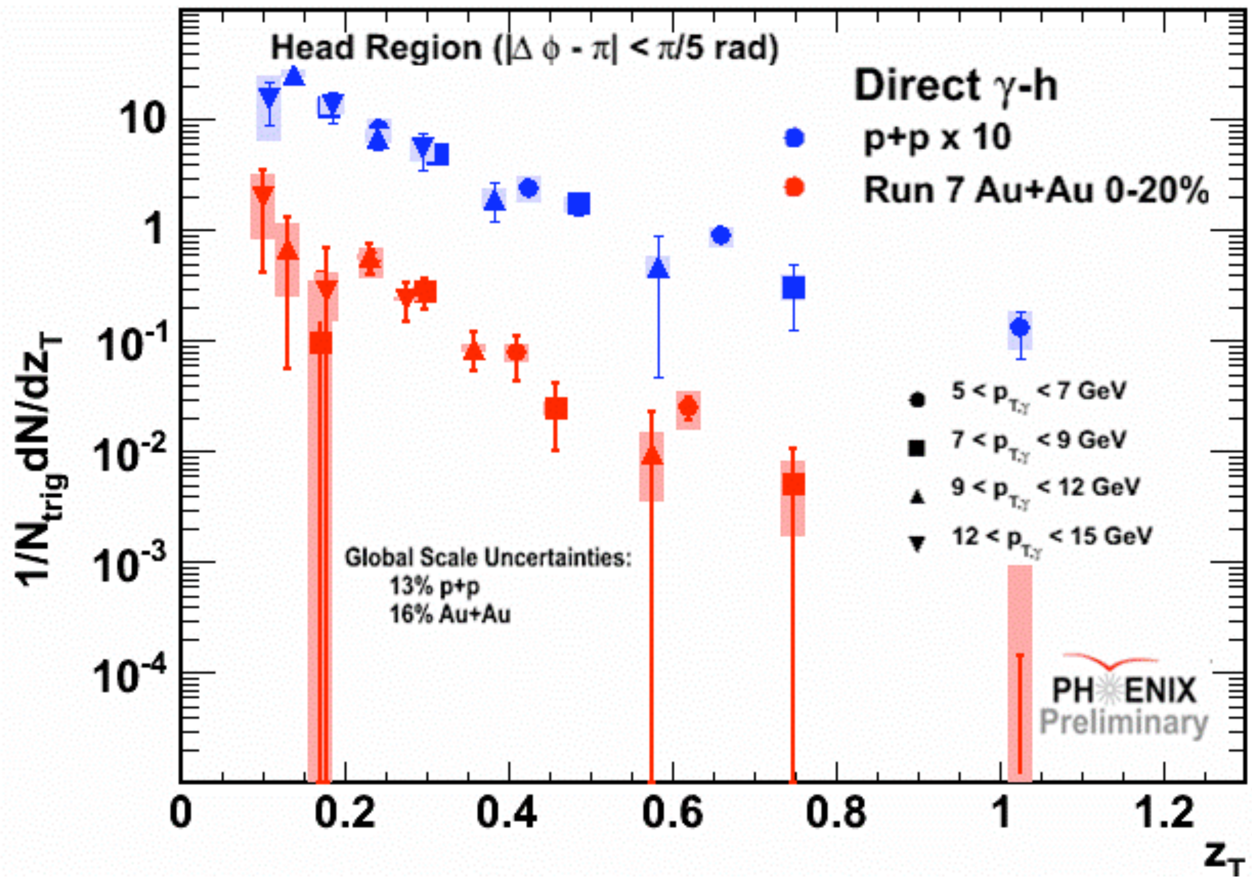


Au+Au photons have some modification at high p_T, but may be just CNM effects – i.e. Cronin & neutron vs proton (isospin/ charge) effects

γ-jet Correlations



Fragmentation function in p+p and Au+Au



$$z_T = \frac{p_T^{hadron}}{p_T^{trigger}}$$

$$D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(z_T)}{dz_T}$$

p+p slope:

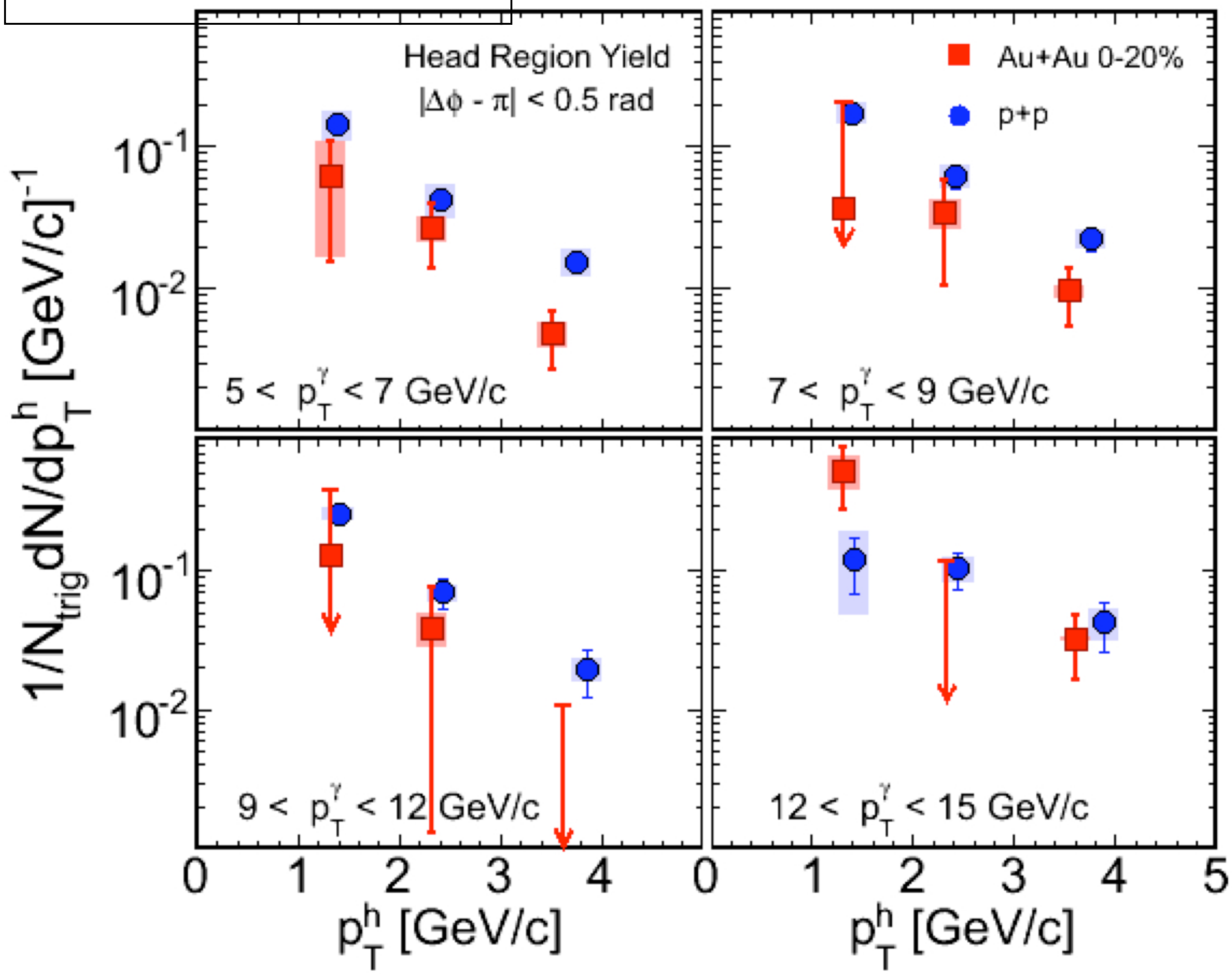
6.89 ± 0.64

Au+Au slope:

9.49 ± 1.37

Away Side Jet Suppression

arXiv:0903.3399



$$z_T = \frac{p_T^{hadron}}{p_T^{trigger}}$$

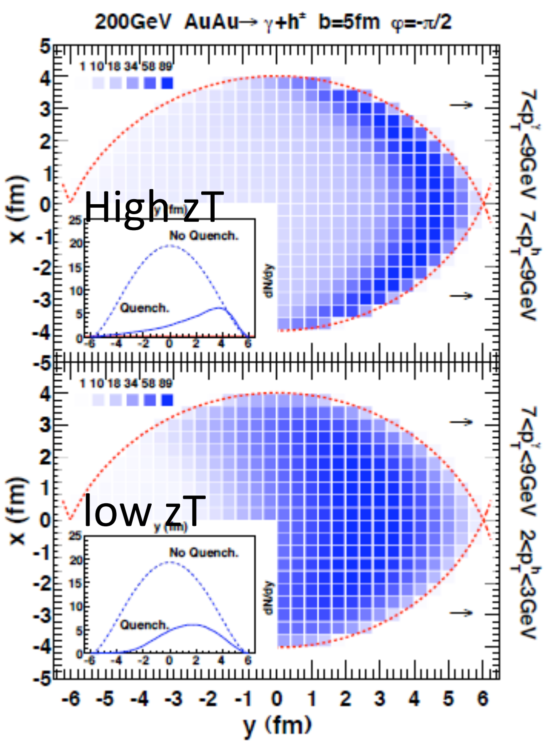
Fragmentation function:

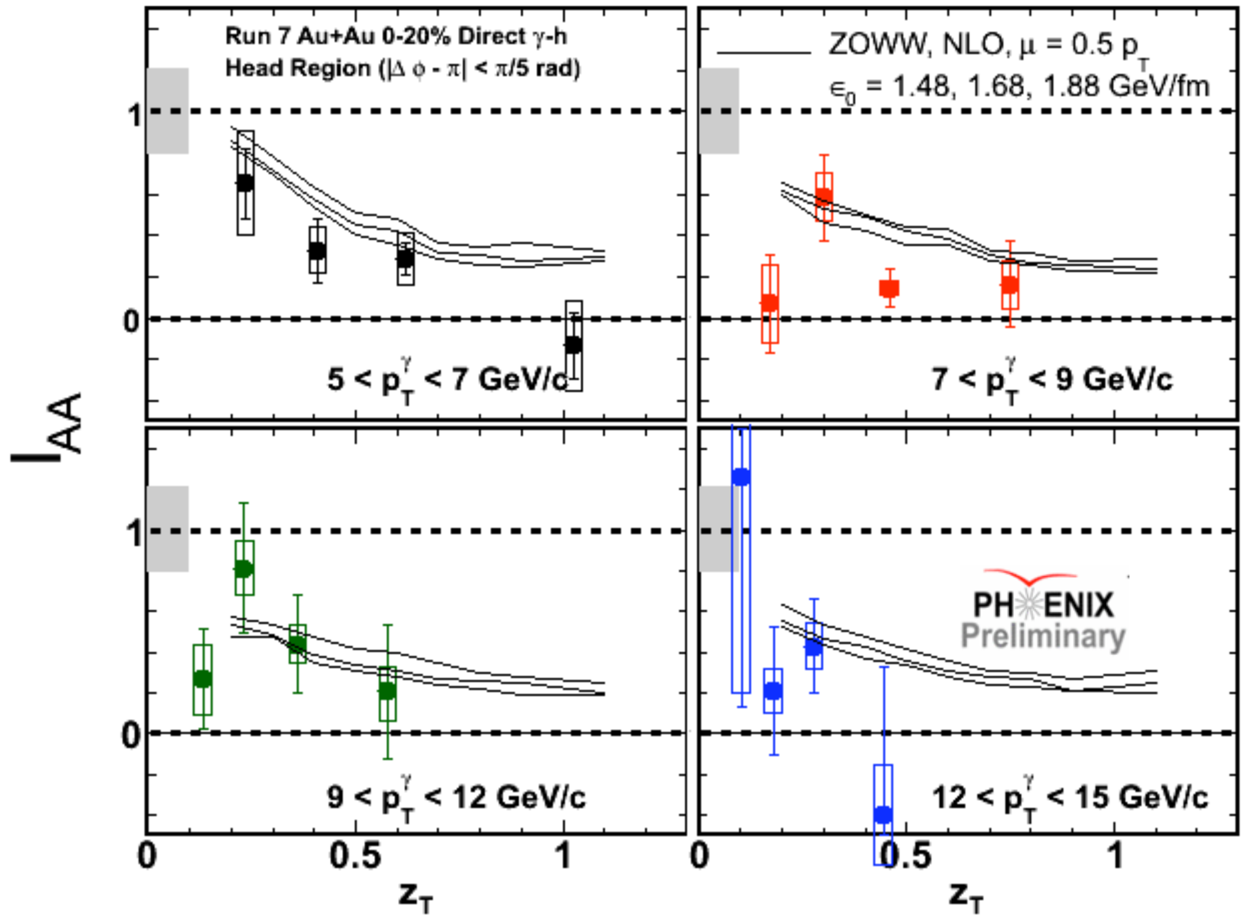
$$D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(z_T)}{dz_T}$$

$$I_{AA} \approx D_{AA}(z_T) / D_{pp}(z_T)$$

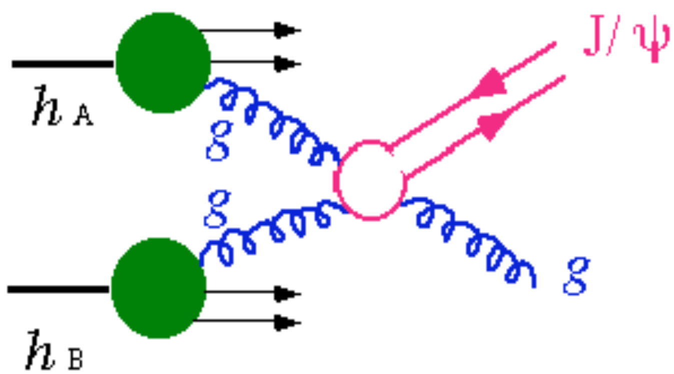
Surface emission?

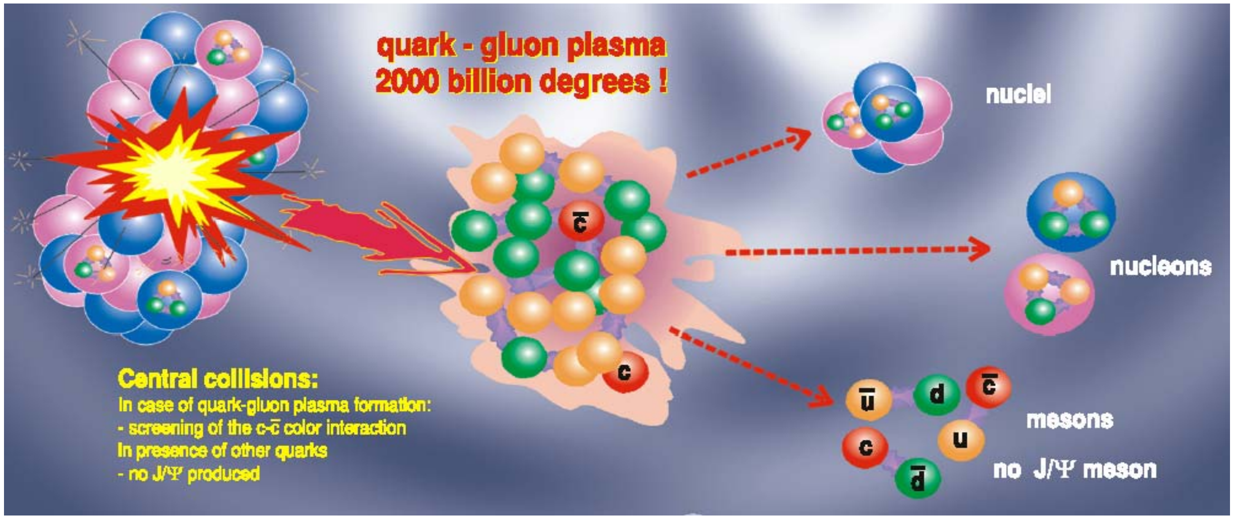
- Modification at low z_T and suppression at high z_T
- arXiv:0902.4000v1





Heavy Quarkonia

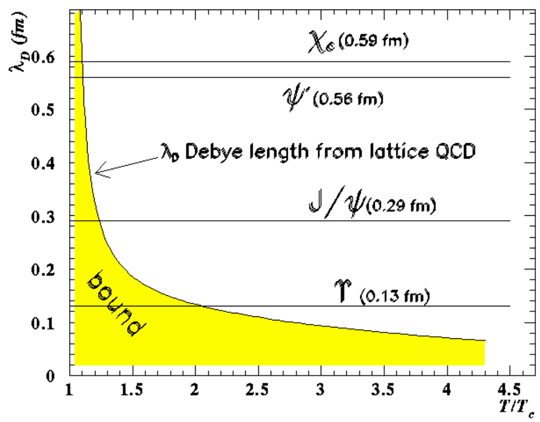




Deconfinement and Quarkonia

For the hot-dense medium (QGP) created in A+A collisions at RHIC:

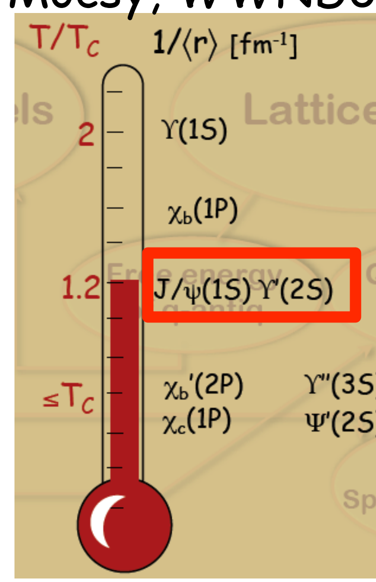
- Large quark energy loss in the medium implies high densities
- Flow scales with number of quarks – partonic flow
- Is there deconfinement? → look for Quarkonia screening



Debye screening predicted to destroy J/ψ's in a sQGP with other states "melting" at different temperatures due to different sizes or binding energies.

RHIC: T/T_C ~ 1.9 or higher

Mocsy, WWND08



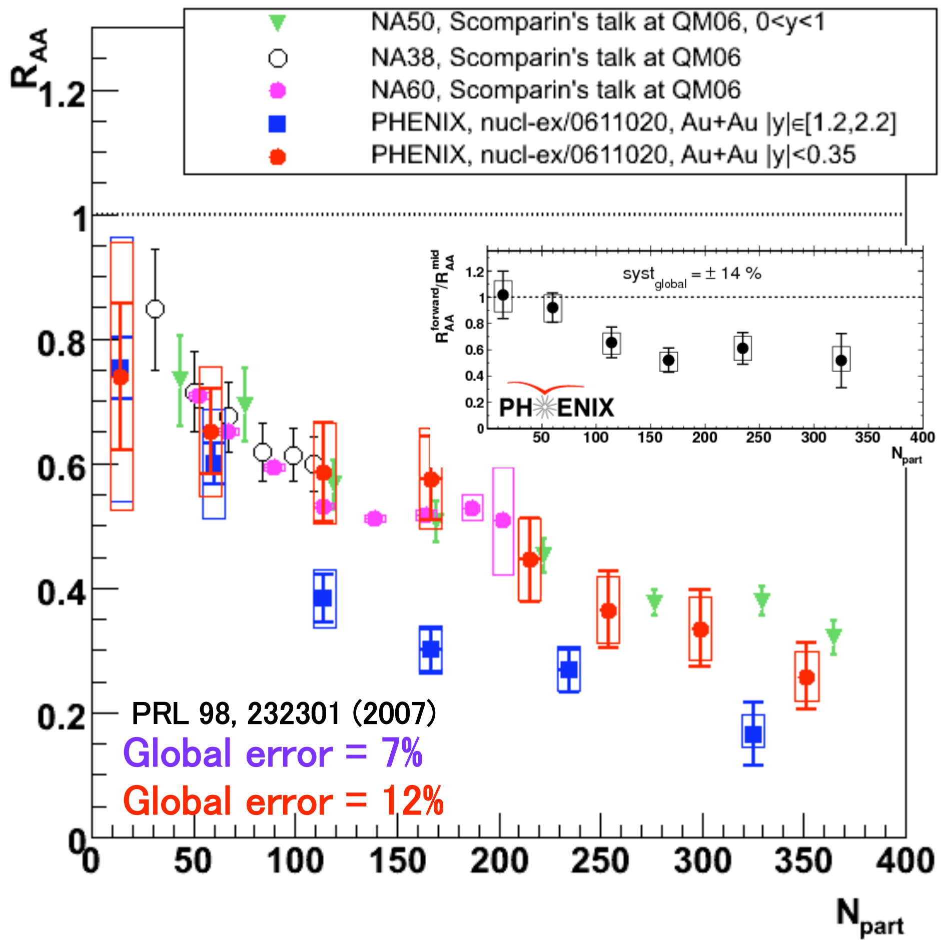
Different lattice calculations do not agree on whether the J/ψ is screened or not – measurements will have to tell!

Satz, hep-ph/0512217

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

The RHIC J/ψ "puzzle"

- Suppression doesn't increase with local density
  - R_{AA} (RHIC, $|y|<0.35$) ≈ R_{AA} (SPS)
  - R_{AA} ($|y|<0.35$) > R_{AA} ($1.2<|y|<2.2$)
- Possible candidates
  - Regeneration compensating for strong suppression
  - Temperature both at RHIC & SPS not sufficient to melt J/ψ, only excited states melt
  - Gluon saturation models predict stronger charm production at mid rapidity



E. Scomparin (proc. QM06) : nucl-ex/0703030

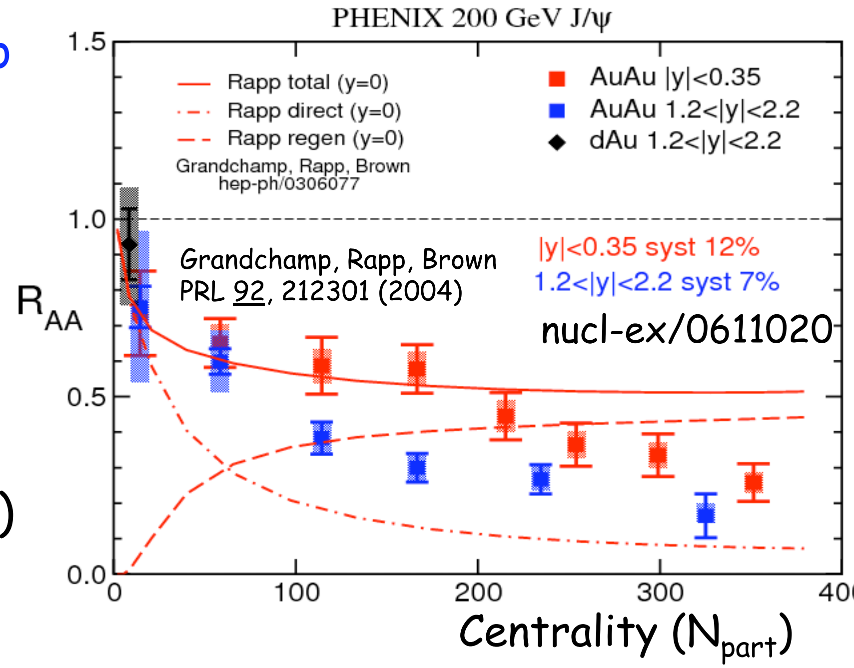
QGP effects on Quarkonia
Regeneration – Compensating for Screening

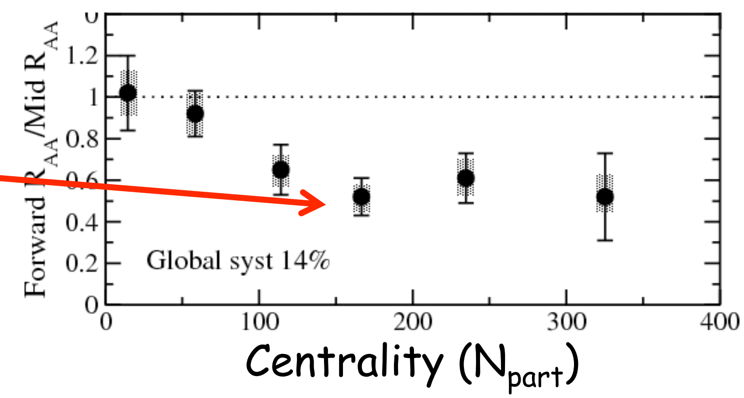
- larger gluon density at RHIC expected to give stronger suppression than SPS
- but larger charm production at RHIC gives larger regeneration

- forward rapidity lower than mid due to smaller open-charm density there
- very sensitive to poorly known open-charm cross sections (FVTX will help here)

- expect inherited flow from open charm
- regeneration would be HUGE at the LHC!

- *can the two compensating components (screening & regeneration) which may have diff. centrality dependences, give a flat forward/mid-rapidity R_{AA}?*



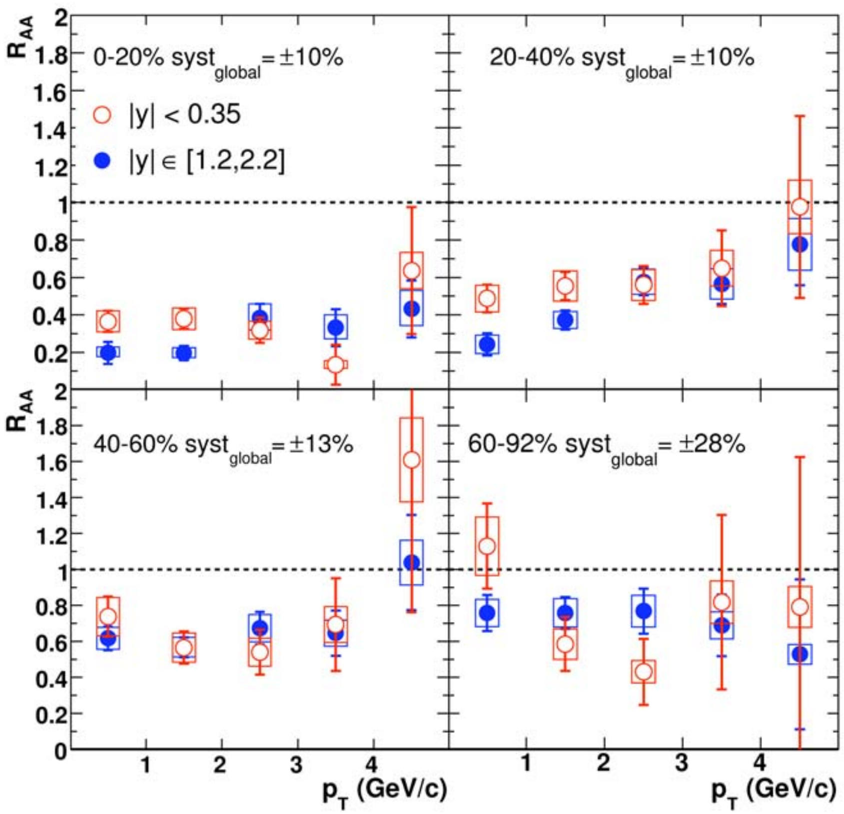


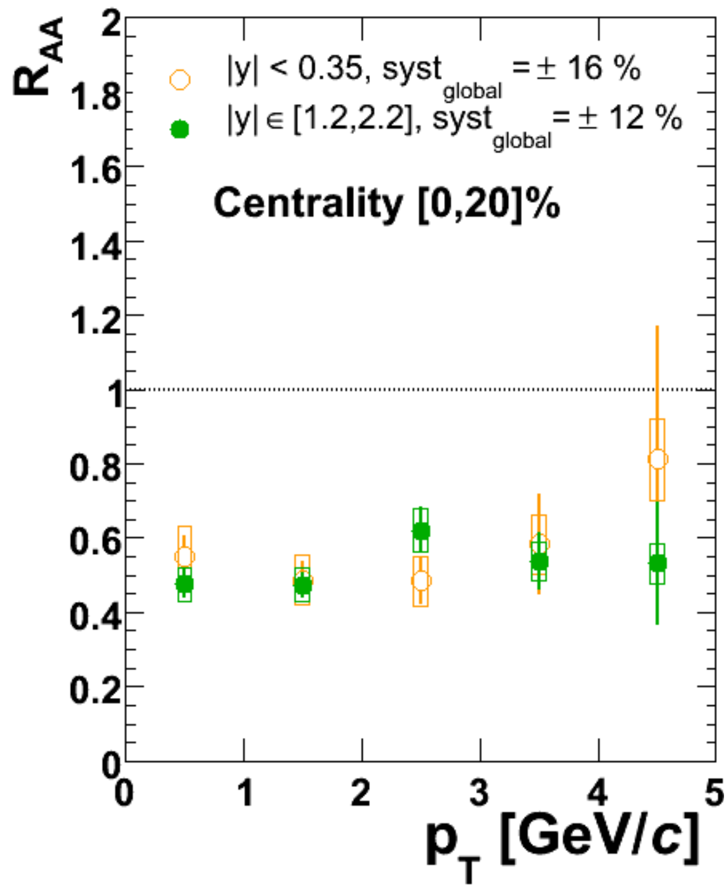
Experimental Approaches to Solve the Puzzle

- Higher energies (LHC)
  - Regeneration => Spectacular increase in R_{AA}
  - Sequential melting => Onset at start of J/ψ melting
- Higher masses (ψ', Υ(1S,2S,3S))
  - Better understanding of sequential melting
- Other observables
  - Momentum dependence
  - Rapidity dependence
  - Elliptic flow
- Better CNM constraints

Momentum Dependence

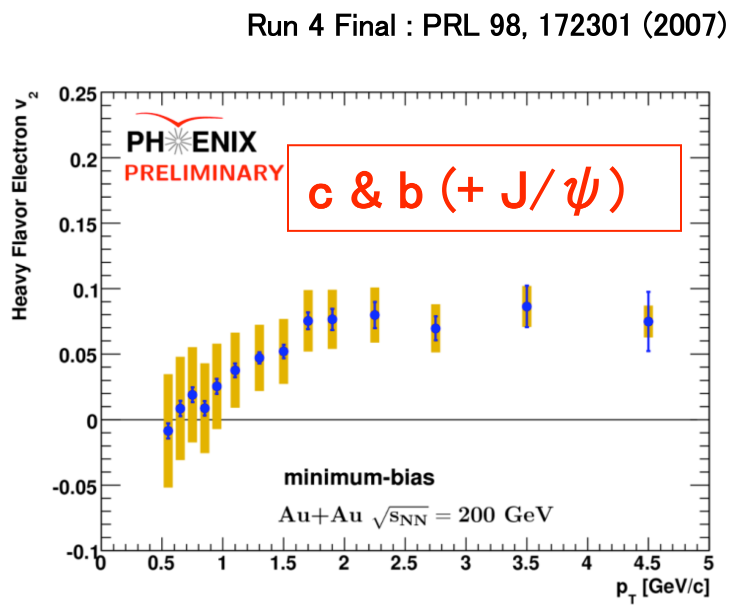
- In Au+Au (left) and central Cu+Cu (right)
  - Momentum distribution is rather flat up to 5 GeV/c





J/ψ Elliptic Flow

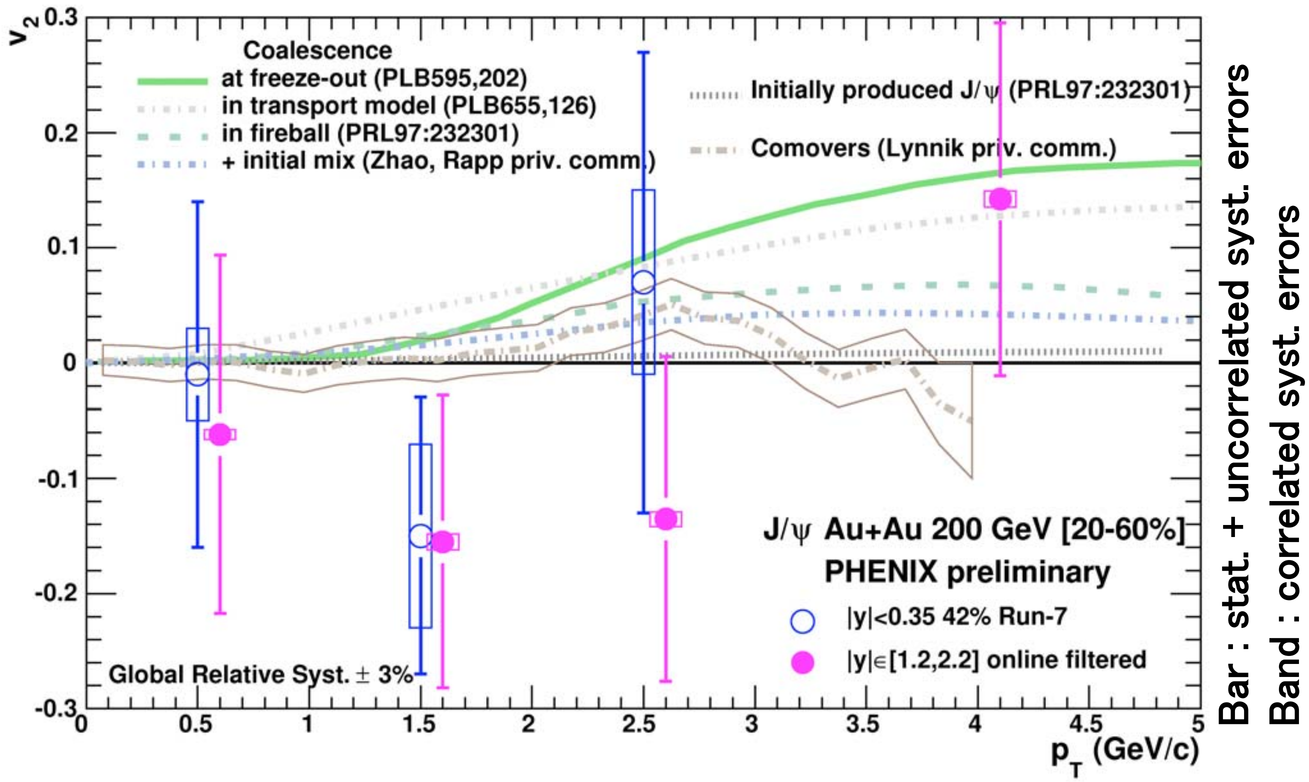
- J/ψ flow : possible test of regeneration
  - **Electrons from open c and b semileptonic decays show nonzero elliptic flow**
  - J/ψ regenerated from c quarks should inherit their flow



- Main criticisms
  - Flow is seen at NA50 and NA60 where net charm yield is not that high
    - Indication of other causes that induce J/ψ flow
- But then…
  - Absence of J/ψ elliptic flow would weigh against regeneration models which all predict substantial flow

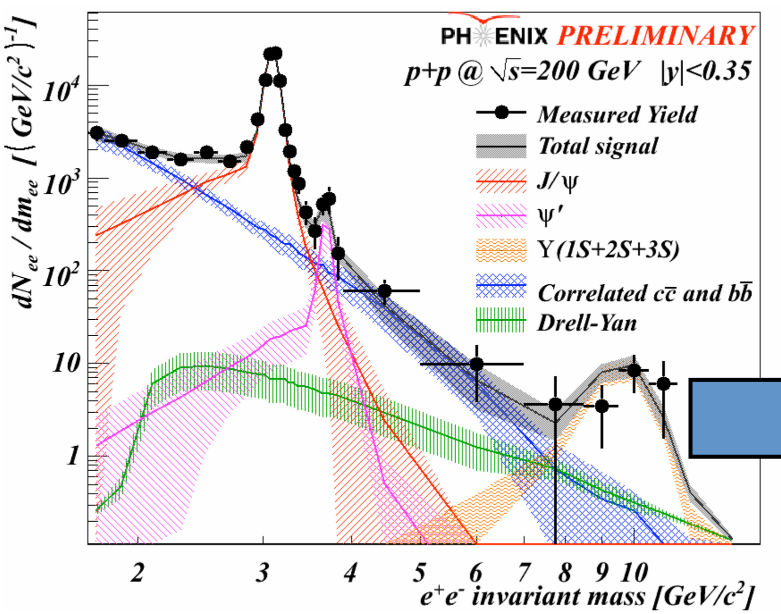
J/ψ Elliptic Flow

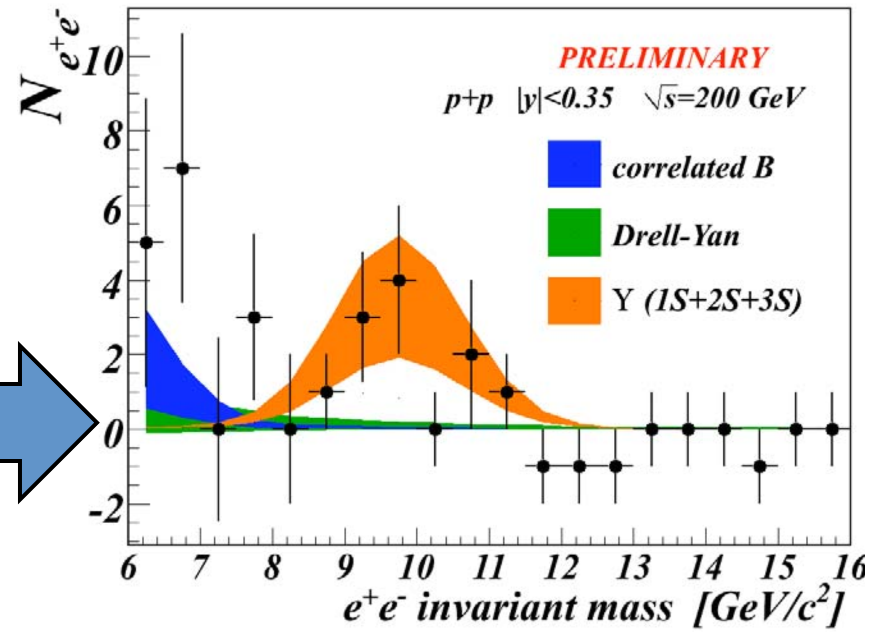
p_T integrated v_2 = (−10±10)% @ |y|<0.35 and (−9.3 ± 9.2)% @ −1.2<|y|<1.2



Probability of positive v_2 from p_T integrated values ≈ 15%, and 8% if two rapidities are combined

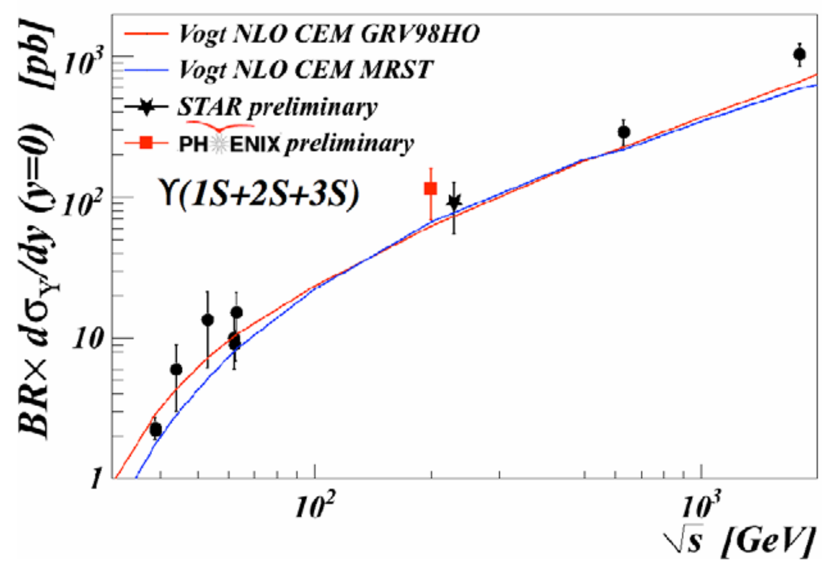
Quarkonia Production & Suppression – Upsilons in p+p



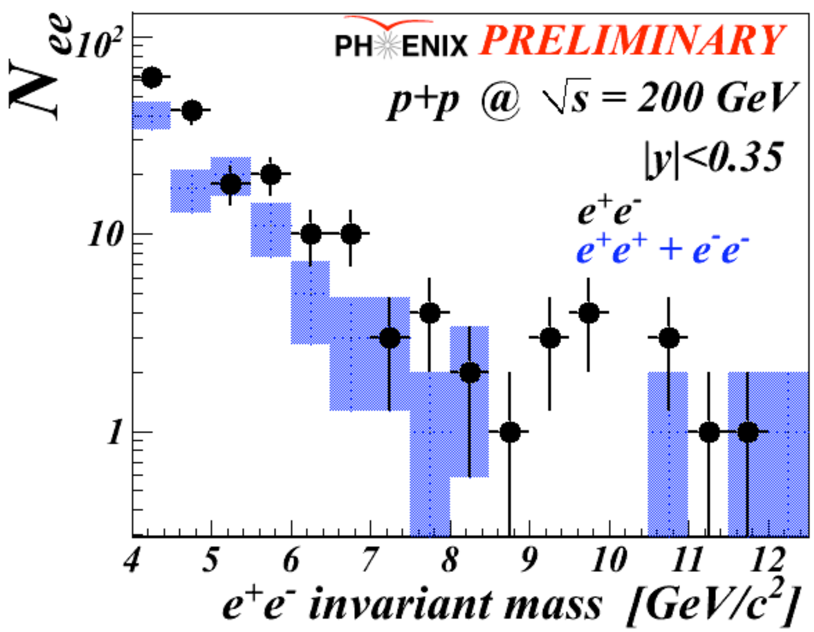


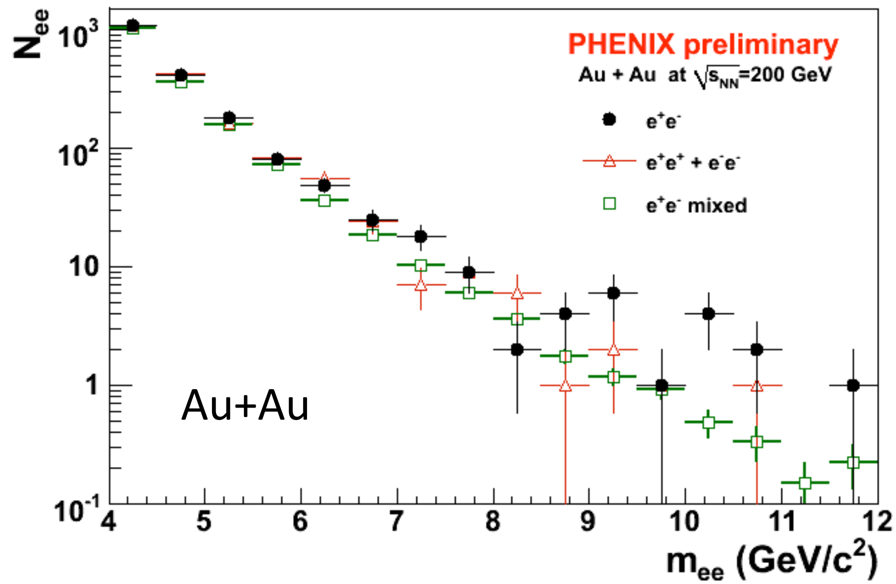
- Cross section follows world trend
- Baseline for Au+Au

$$BR * \frac{d\sigma}{dy}\bigg|_{|y|<0.35} = 114^{+46}_{-45}\, pb$$

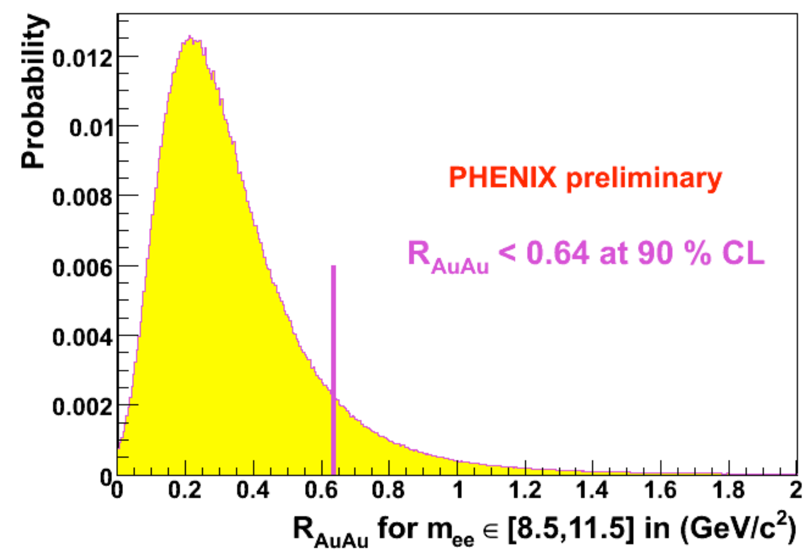


Quarkonia – Upsilons Suppressed in Au+Au



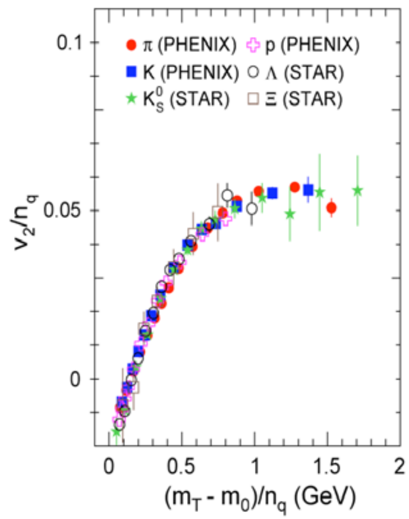


	p+p	Au+Au
N[8.5,11.5]	10.5(+3.7/-3.6)	11.7(+4.7/-4.6)
$N_{J/\Psi}$	2653 ±70±345	4166 ±442 (+187/-304)
$R_{AA}(J/\Psi)$	---	0.425 ±0.025±0.072

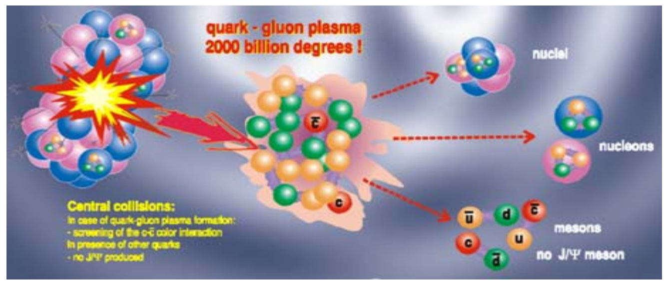


R_{AuAu} [8.5,11.5] < 0.64 at 90% C.L.

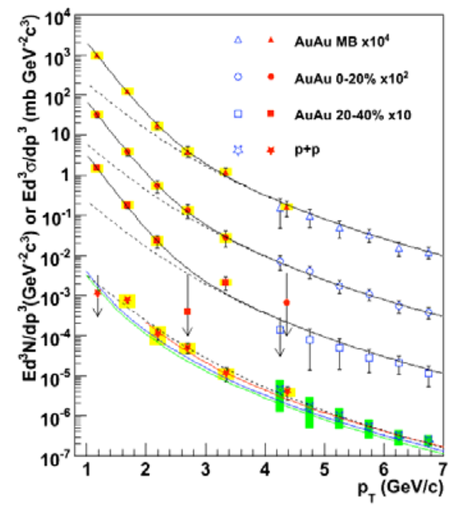
Summary



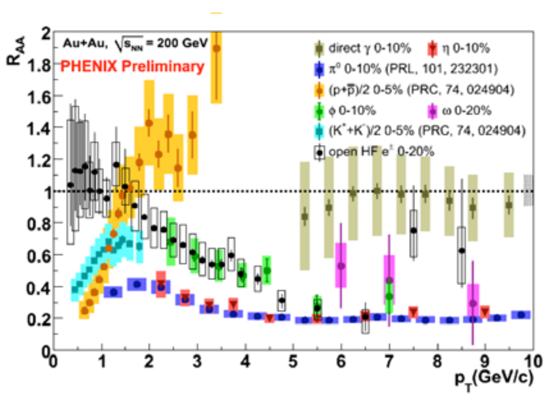
π (PHENIX)
p (PHENIX)
K (PHENIX)
Λ (STAR)
K^0_S (STAR)
Ξ (STAR)
v_2/n_q
$(m_T - m_0)/n_q$ (GeV)



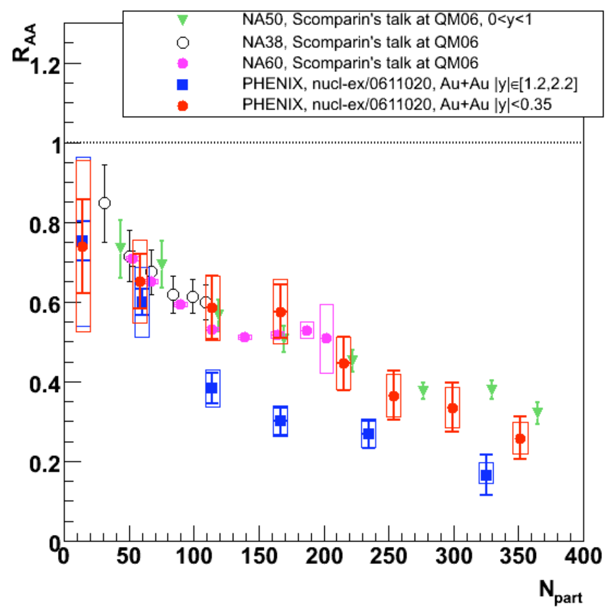
quark - gluon plasma
2000 billion degrees !
nuclei
nucleons
mesons
no J/Ψ meson
Central collisions:



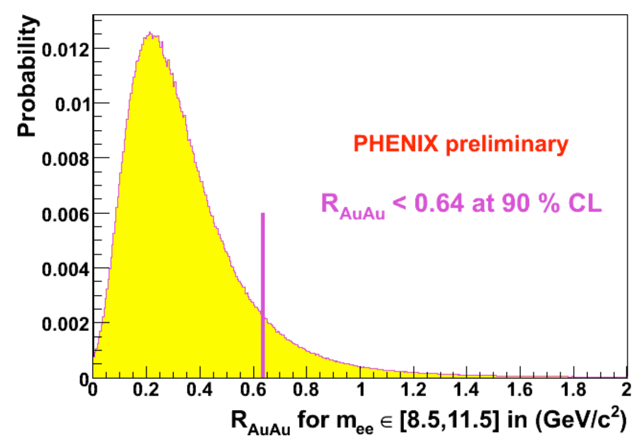
AuAu MB x10^4
AuAu 0-20% x10^2
AuAu 20-40% x10
p+p
p_T (GeV/c)



Au+Au, $\sqrt{s_{NN}}$ = 200 GeV
PHENIX Preliminary
direct γ 0-10%
η 0-10%
π^0 0-10% (PRL, 101, 232301)
$(p+\bar{p})/2$ 0-5% (PRC, 74, 024904)
φ 0-10%
ω 0-20%
$(K^+ + K^-)/2$ 0-5% (PRC, 74, 024904)
open HF $e^\pm$ 0-20%
R_{AA}
p_T(GeV/c)



NA50, Scomparin's talk at QM06, 0<y<1
NA38, Scomparin's talk at QM06
NA60, Scomparin's talk at QM06
PHENIX, nucl-ex/0611020, Au+Au |y|∈[1.2,2.2]
PHENIX, nucl-ex/0611020, Au+Au |y|<0.35
R_{AA}
N_{part}



PHENIX preliminary
R_{AuAu} < 0.64 at 90 % CL
Probability
R_{AuAu} for $m_{ee} \in [8.5,11.5]$ in (GeV/c^2)

backup

Should Υ's be Suppressed?

Υ's long touted as a standard candle for quarkonia melting
- but what should we really expect?

	$R_{AuAu}(y=0)$
J/Ψ	0.425 ± 0.025 ± 0.072
M_{e+e-}= [8.5,11.5 GeV]	< 0.64 at 90% C.L.

- σ_{abs} of Υ probably ~1/2 of that for J/Ψ – E772 (*PRL 64, 2479 (1990)*)
    - E772 Υ nuclear dependence corresponds to R_{AuAu} = 0.81

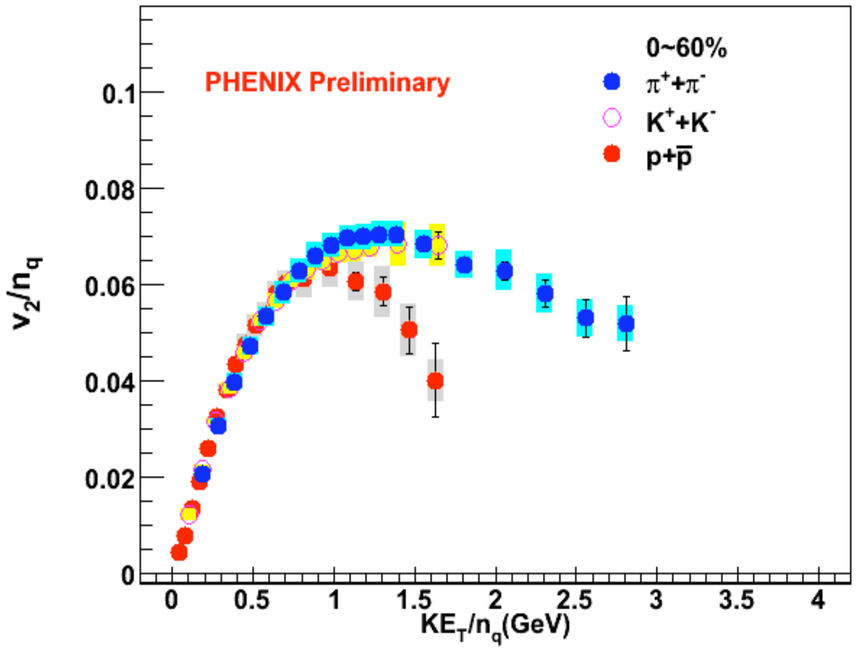
- Lattice expectations in Au+Au - Υ_{2S+3S} suppressed: R_{AuAu} = 0.73

- **absorption x lattice ~ 0.73 x 0.81 ~ 0.60 ??? – but need serious theory estimate instead of this naïve speculation!**
    - e.g. Grandchamp et al. hep-ph/0507314

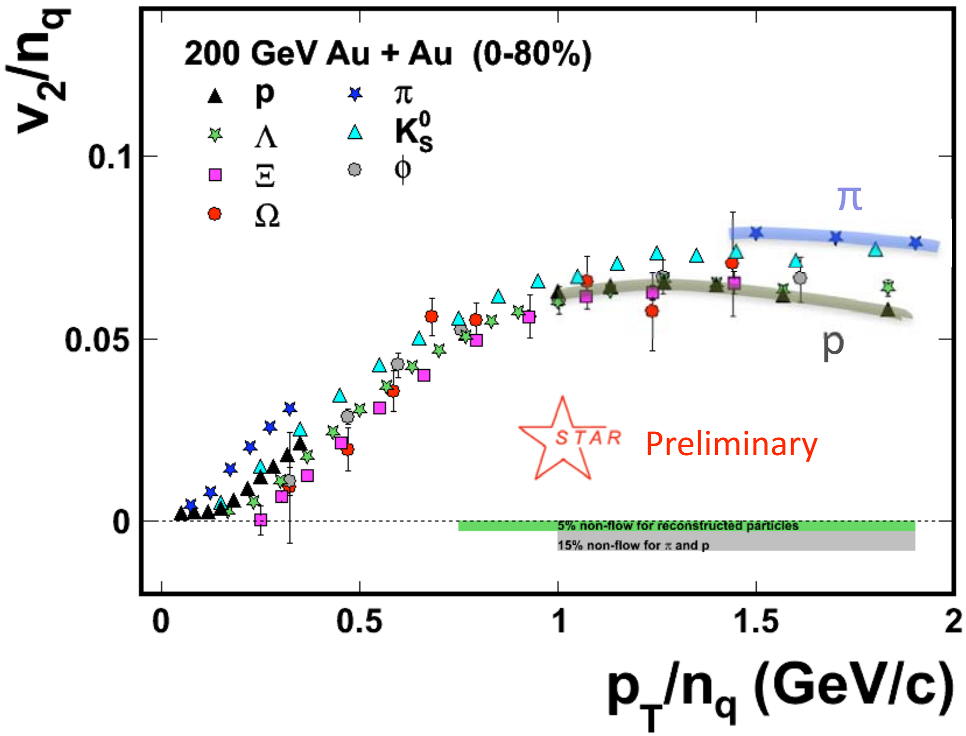
Other considerations:
- Υ in anti-shadowing region (for mid-rapidity)

- CDF: 50% of Υ from χ_b for p_T>8 GeV/c - but less (25%?) at our p_T
    - *PRL84 (2000) 2094, hep-ex/9910025*

NQ Scaling, MSH and Large p_t



See talk by M. Shimomura



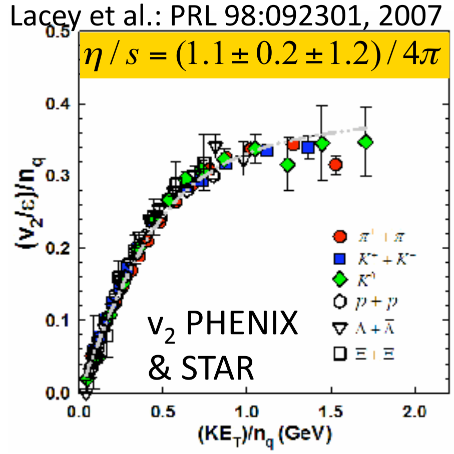
See talk by S. Shi

At p_T/n_q~1.5 GeV/c^2, PID v_2 start to deviate from NQ scaling, in particular for protons.

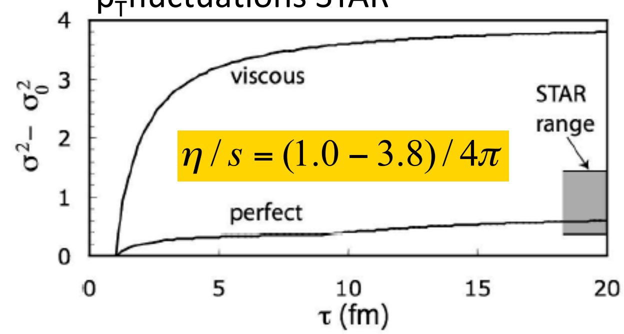
η/s measurements

- need observables that are sensitive to shear stress
- damping ~ η/s
- flow
- fluctuations
- heavy quark motion

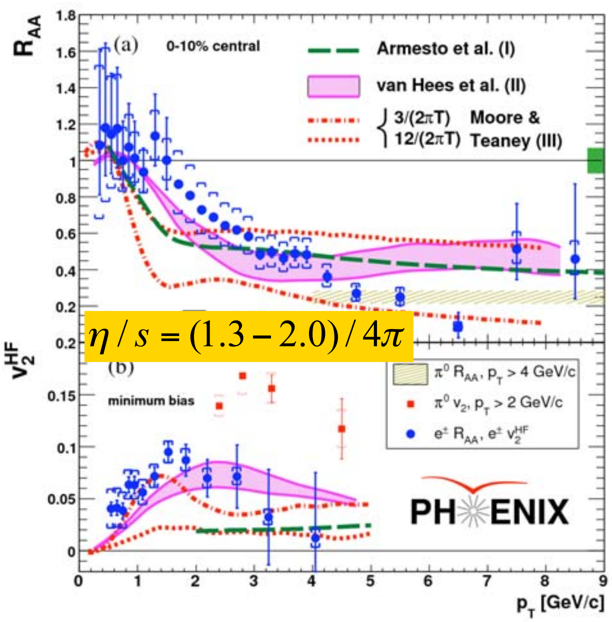
R. Lacey et al.: PRL 98:092301, 2007



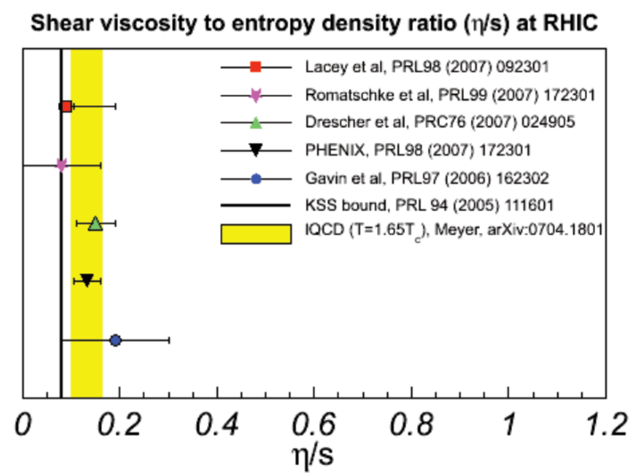
S. Gavin and M. Abdel-Aziz:
PRL 97:162302, 2006
p_T fluctuations STAR



A. Adare et al.: PRL 98:092301, 2007



- top RHIC energy
  - η/s close to conjectured minimum $1/4\pi$



Virtual photon method

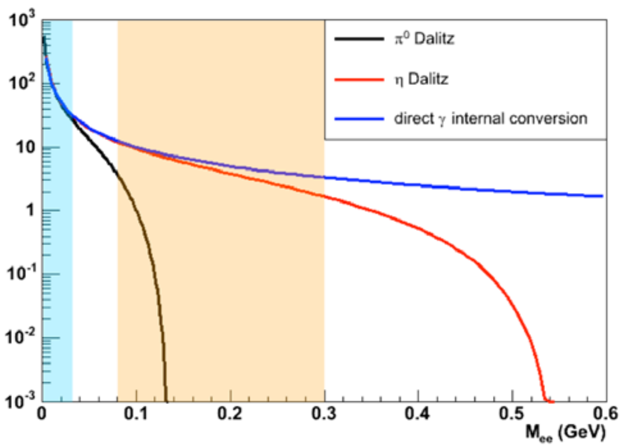
- Any source of real γ can emit γ^* with very low mass.
- Convert direct γ^* fraction to real direct photon yield

$$\frac{\gamma_{direct}}{\gamma_{inclusive}} = \frac{\gamma^*_{direct}}{\gamma^*_{inclusive}}$$

Kroll-Wada formula

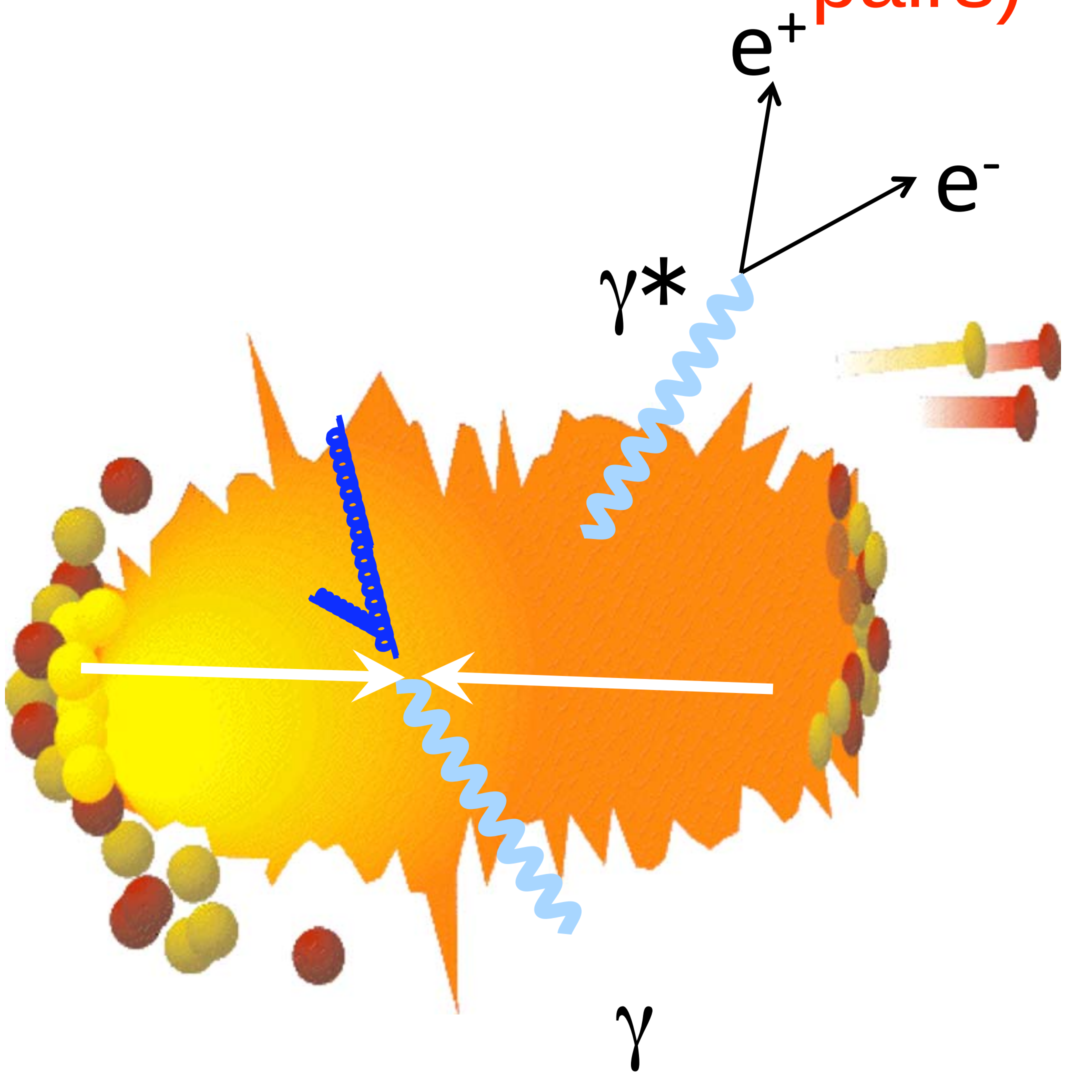
$$\frac{d^2N}{dM_{ee}dN_\gamma} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{M_{ee}^2}}\left(1+\frac{2m_e^2}{M_{ee}^2}\right)\frac{1}{M_{ee}}S$$

S **: Process dependent factor**



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

Electromagentic probes (photon and lepton pairs)



- Photons and lepton pairs are cleanest probes of the dense matter formed at RHIC
- These probes have little interaction with the matter so they carry information deep inside of the matter
  - Temperature?
  - Hadrons inside the matter
  - Matter properties

What we can learn from lepton pair emission

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

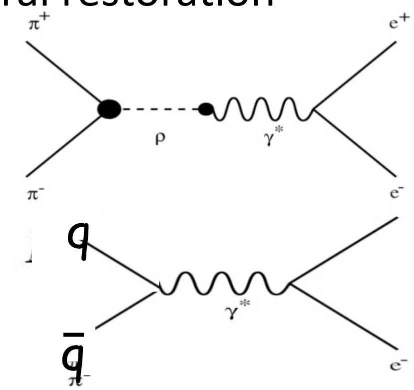
EM correlator
Medium property

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.