RHIC and the QGP at 10: from the "age of discovery" to the "age of exploration"

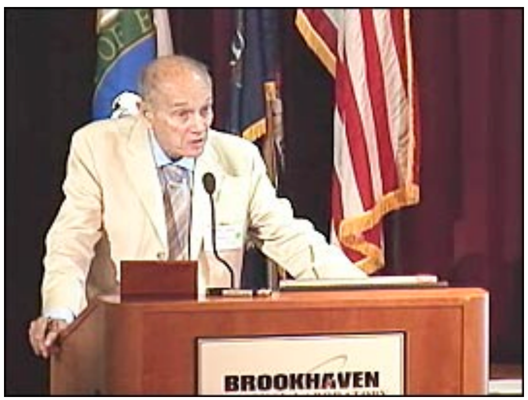
QCHS IX

Madrid - August 2010

Helen Caines - Yale University

”"The beginning of knowledge is the discovery of something we do not understand" - Frank Herbert

“Birthday” celebrations at BNL

James Cronin Nobel Prize -1980	Ernest Courant 90th Birthday	Samuel C.C. Ting Nobel Prize -1976
		
with Val Fitch : proved that K decays break fundamental symmetries	helped formulate the concept of “strong focusing” accelerators	with Burton Richter : discovered the J/Ψ

RHIC NYT headlines from the past decade

Just What Does Happen When 'Worlds' Collide? May 2000

A Coming-Out Party for a Particle Collider Jan 2001

Gauging a Collider's Odds of Creating a Black Hole - April 2008

Trying to Cook a Soup of Free-Range Quarks Jan 2001

In Lab's High-Speed Collisions, Things Just Vanish March 2005

One Trillion Degrees, Even Gold Turns Into the Sloshiest Liquid April 2005

Getting the Most Bang Out of Quarks and Gluon May 2007

Experiments on Dense Matter Evoke Big Bang Jan 2001

In a Lab on Long Island, a Visit to the Big Bang Jan 2003

In Brookhaven Collider, Scientists Briefly Break a Law of Nature Feb 2010

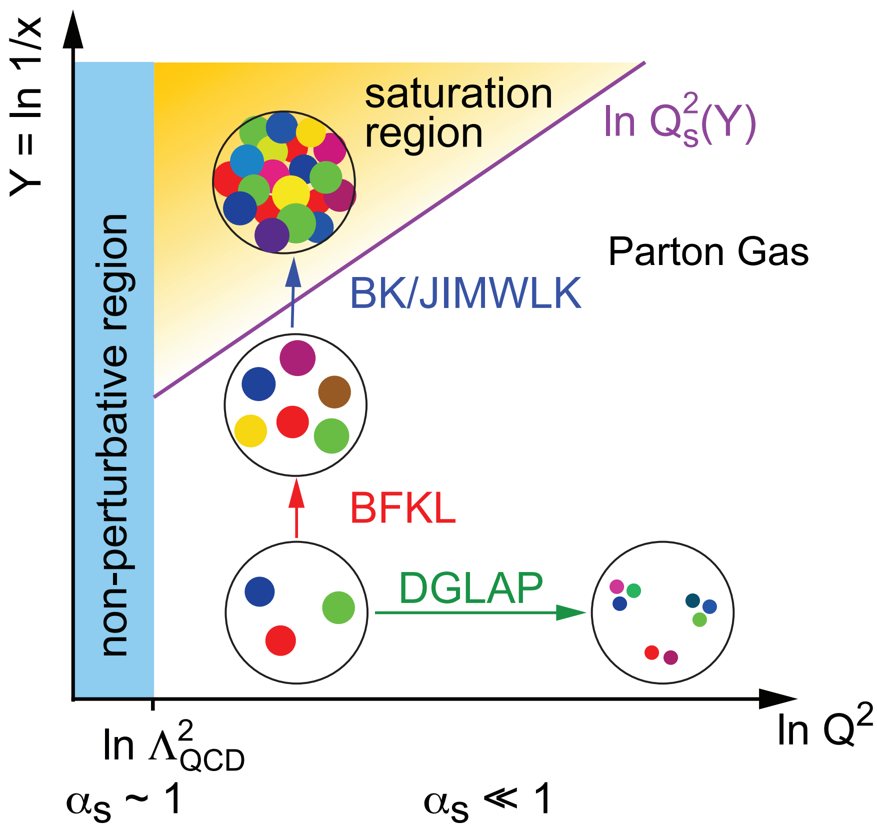
Nuclear Physics: Not Just for Men - May 2007

Scientists Deciphering Atomic Forces Report Hottest, Densest Matter Ever Observed June 2003

Digging Ourselves a Black Hole August 2008

Initial conditions at RHIC - CGC

Gluon density increases with decreasing x
Can't grow continuously must saturate



CGC - Color Glass Condensate
semi-classical effective field theory for low-x gluons in nuclei saturation of gluons at low x

Gluons (color) with long evolution time scales (glass) and high occupation numbers (condensate)

Incoherent sum of partons (A*proton) → thin wall of coherent gluons randomly distributed

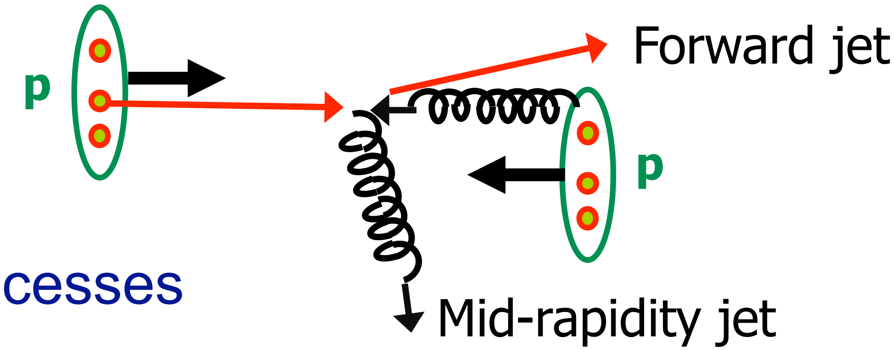
Predicted to occur at low x (10^{-3}) → forward y at RHIC

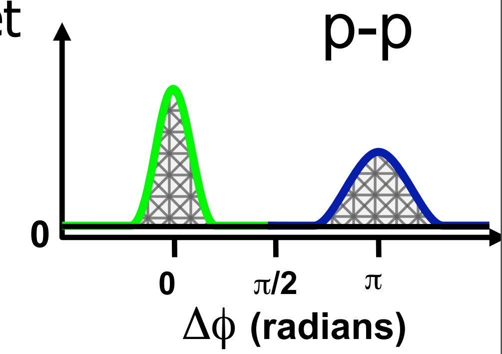
Initial conditions at RHIC - CGC

Scattering:

ΔΦ Correlation

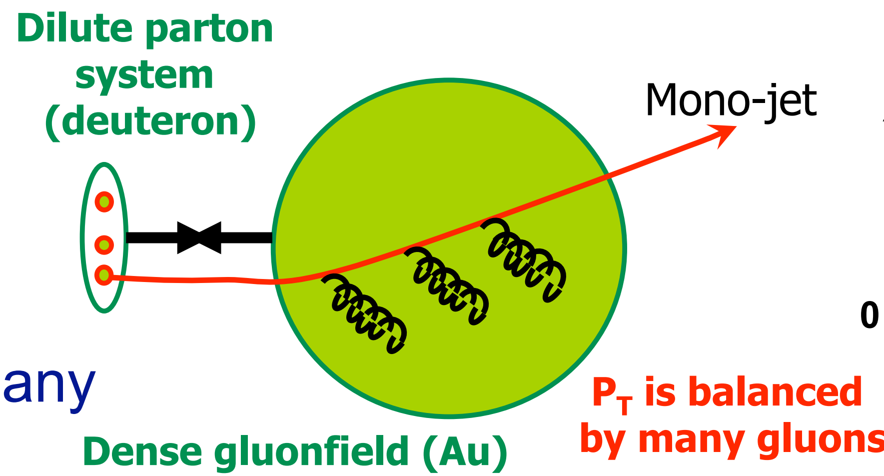
Dilute systems (p-p):

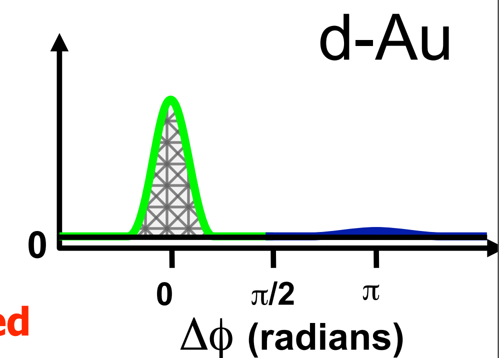




low gluon density
pQCD like 2→2 processes

Saturated (CGC) systems (d-Au):

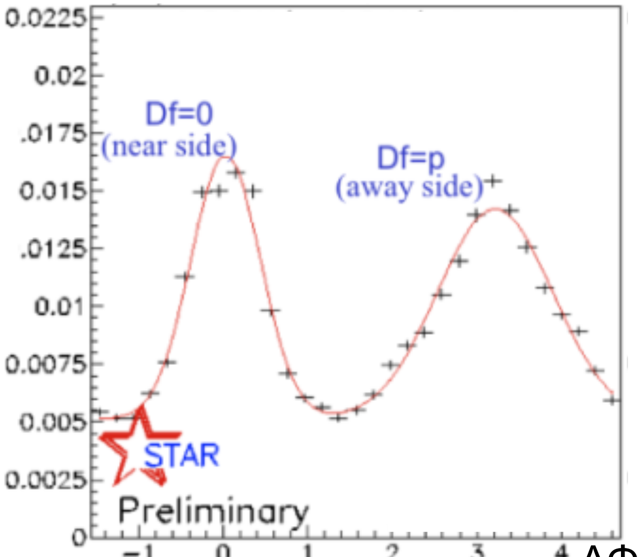




high gluon density
recoil balanced by many soft gluons
mono-jets 2→1 processes

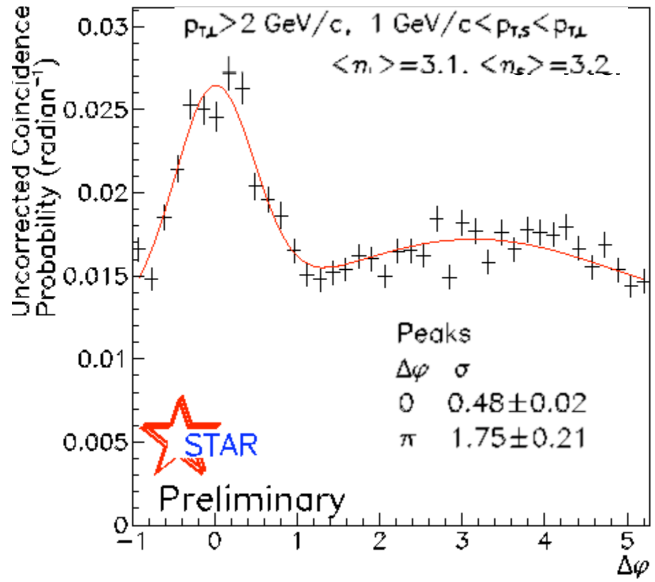
Forward-Forward correlations

p-p



E.Braidot RBRC-Glasma 2010

Central d-Au,⟨b⟩~2.7fm



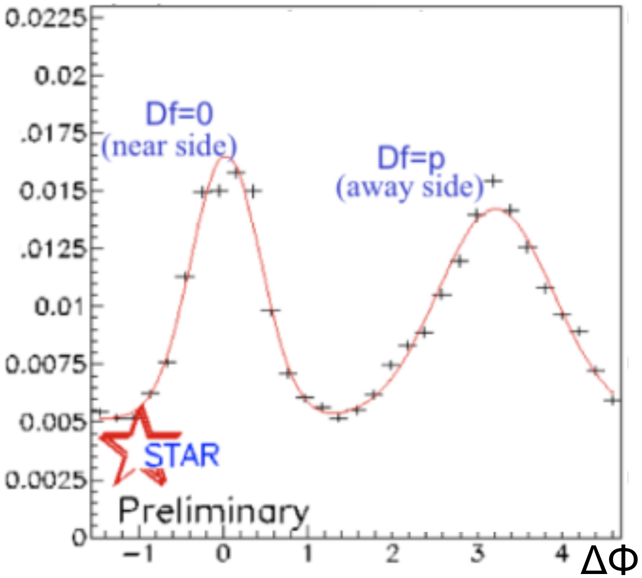
Peripheral:
d-Au ~ p-p

Forward-mid:
d-Au ~ p-p

- Near-side peak (d-Au) = Near-side peak (p-p)
- Away-side peak (d-Au) << Away-side peak (p-p)
- Away-side width (d-Au) >> Away-side width (p-p)

Forward-Forward correlations

p-p



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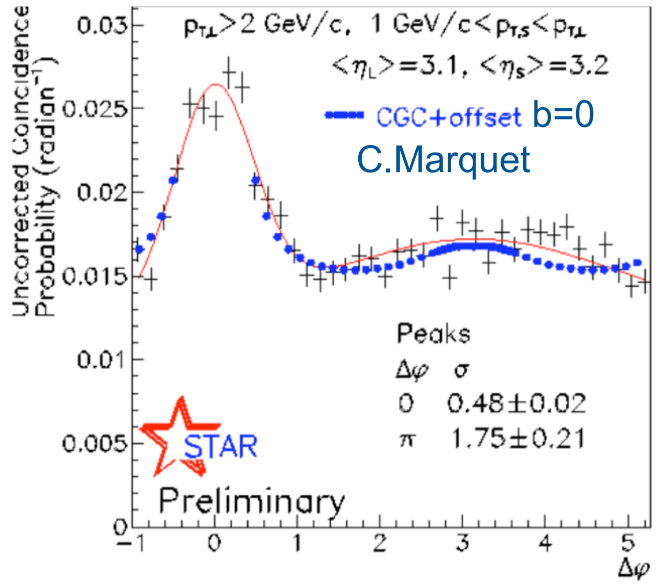

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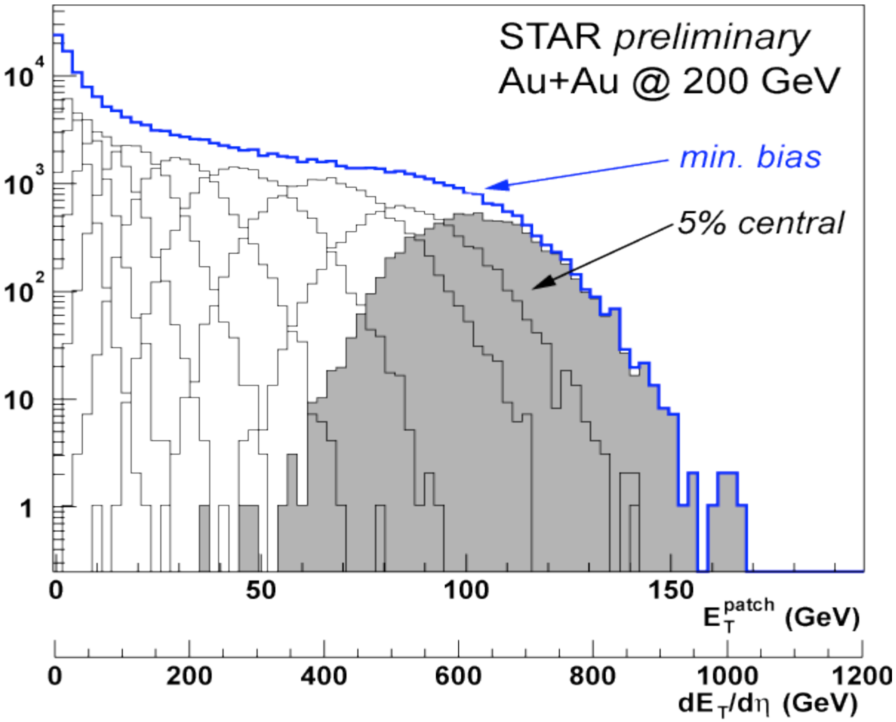
CGC calc:

C.Marquet arXiv:0708.0231, K.Tuchin arXiv:0912.5479

Good agreement with central data
Predict centrality dependence

First hint of CGC at RHIC:
x(Forward y_{RHIC}) ~ x(Mid y_{LHC})

Early conditions at RHIC - ε



Central events: 26 TeV (out of 39.4 TeV) is removed from beam

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system

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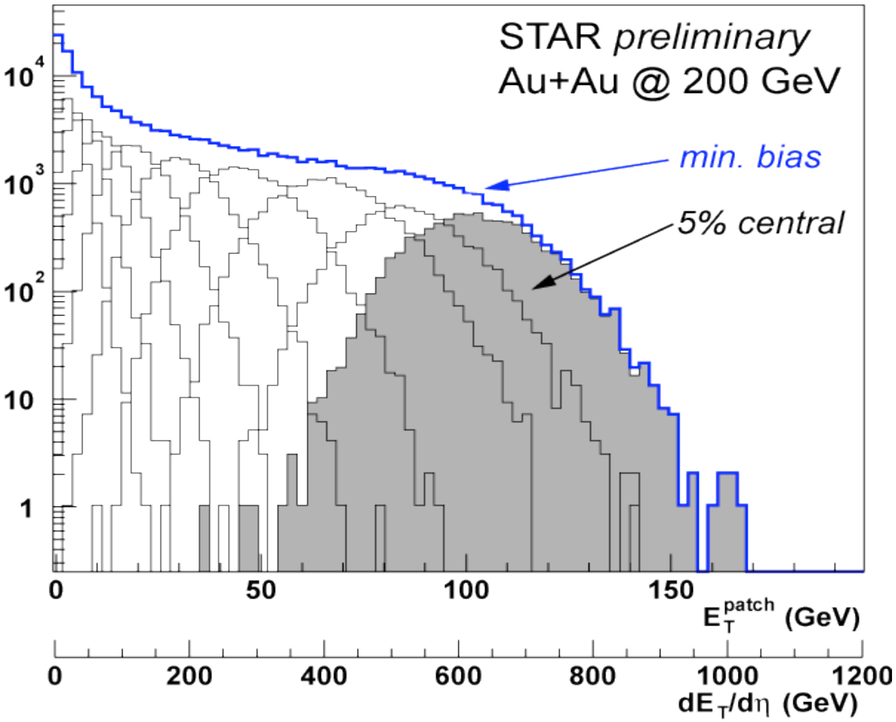

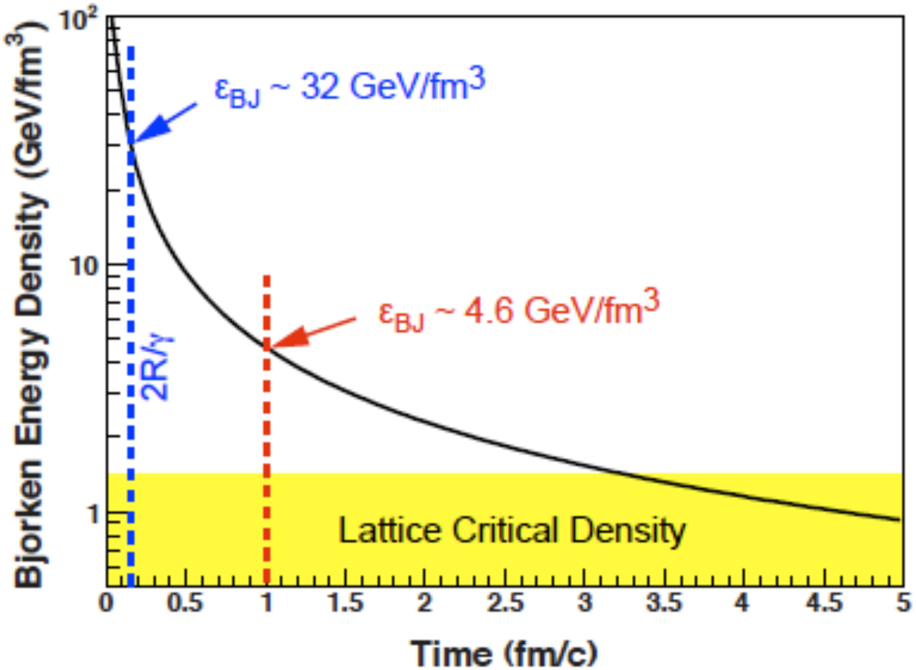

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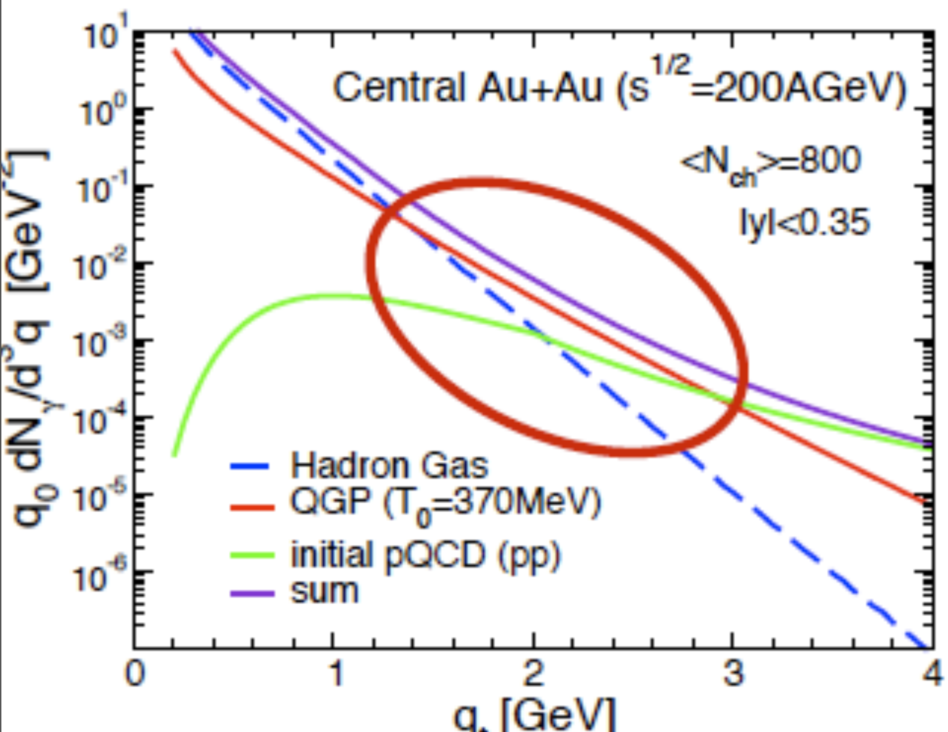
$\varepsilon_{BJ} \approx 5.0$ GeV/fm^3
~30 times normal nuclear density
~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

Early conditions at RHIC - T

Direct Photons:

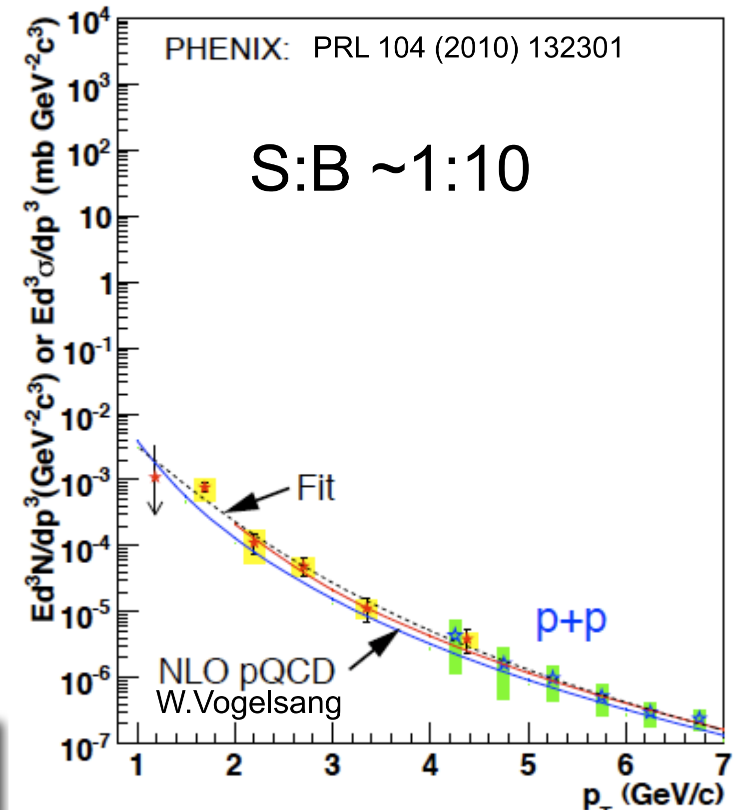
- no charge or color → don't interact with medium
- emitted over all lifetime → convolution of all T

Theory well developed



QGP dominates: $1 < p_T < 3$ GeV/c

Measurement and corrections under control



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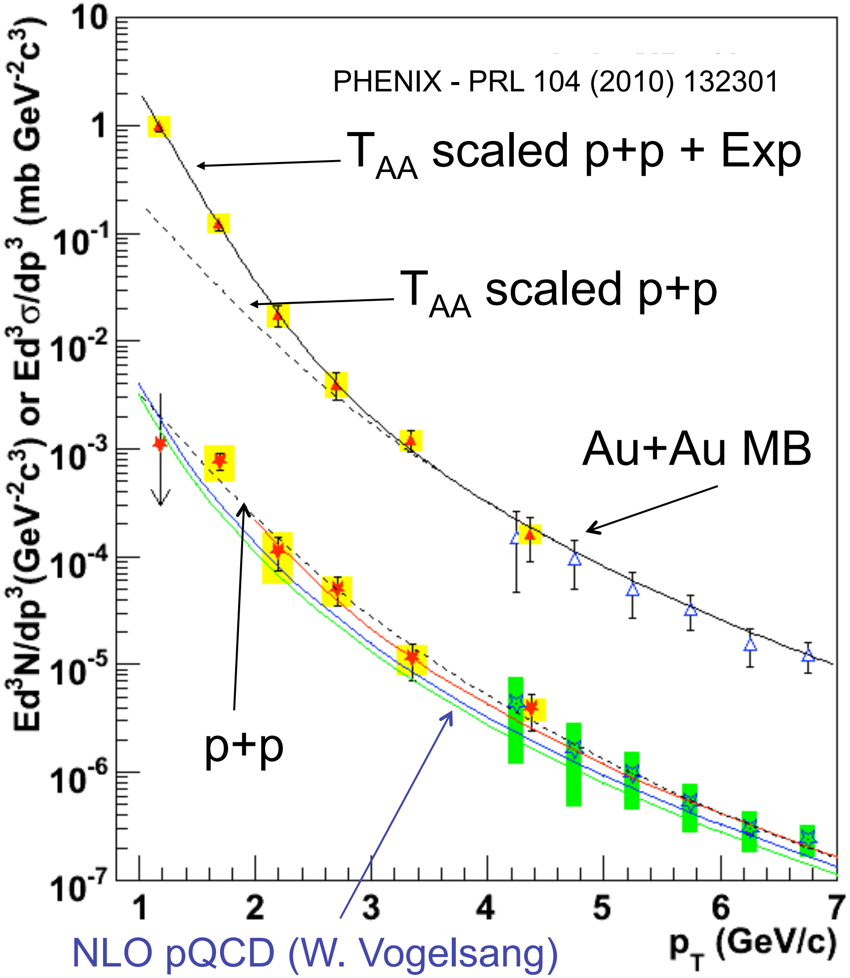

Au-Au:
After background subtraction spectrum well fit by:

T_{AA} scaled p+p + Exp

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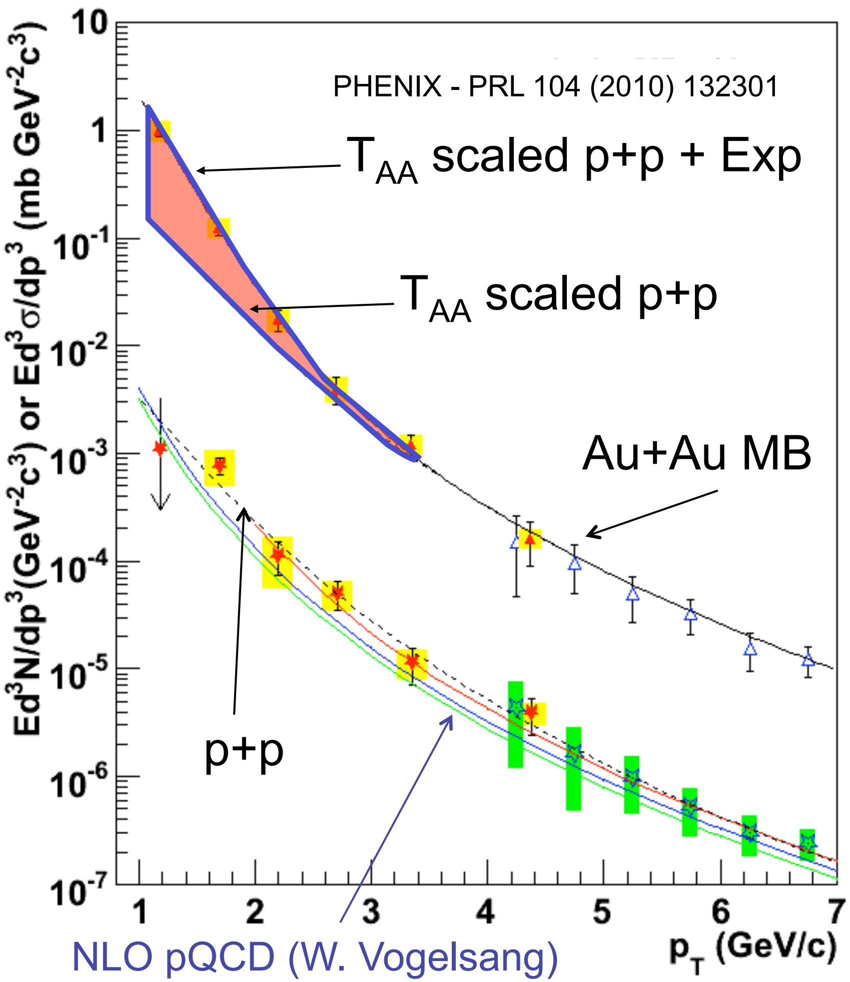

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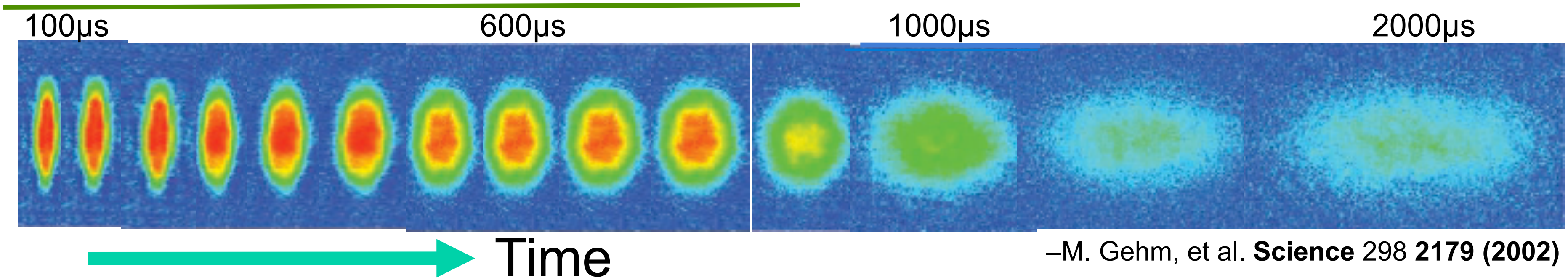
Emission rate and shape consistent with that from a hot thermally equilibrated medium

T = 300 - 600 MeV
> 2* T_C
τ < 1 fm/c

First experimental observation of T > T_c

Flowing like a "Perfect" liquid



–M. Gehm, et al. **Science** 298 **2179 (2002)**

- Very strong elliptic flow → early equilibration

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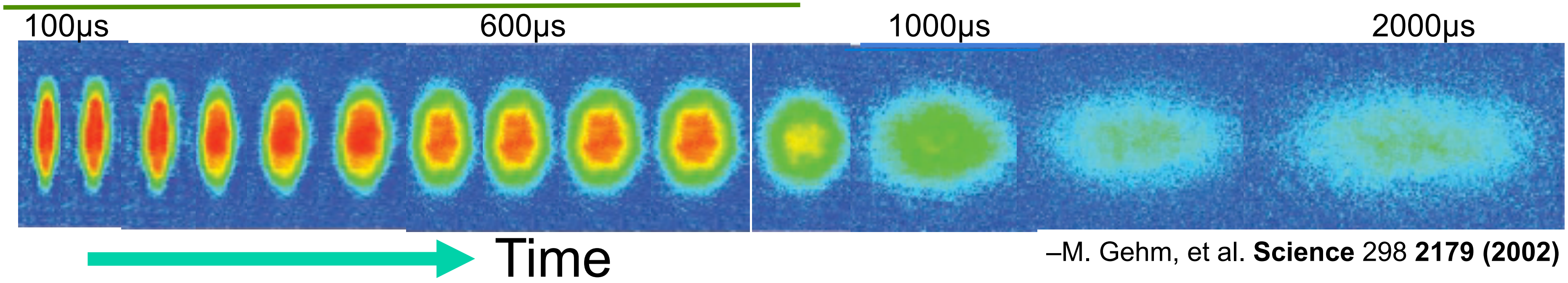

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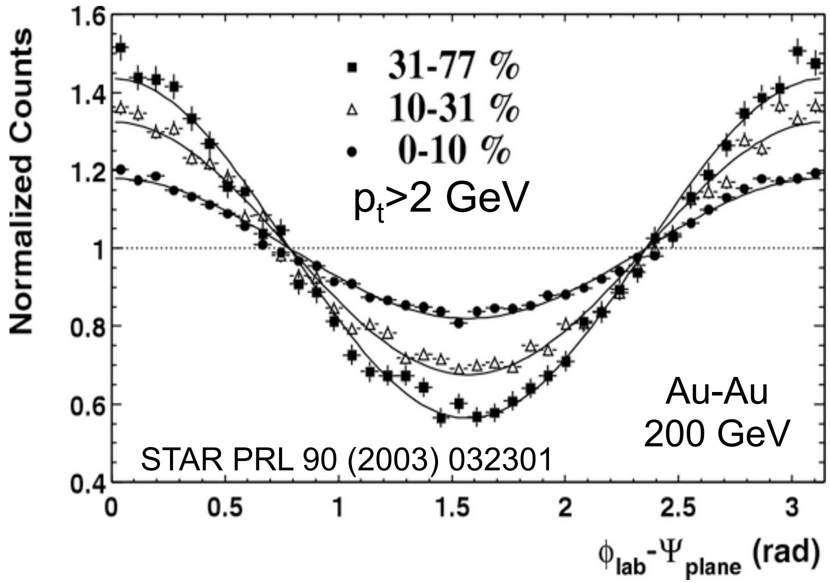

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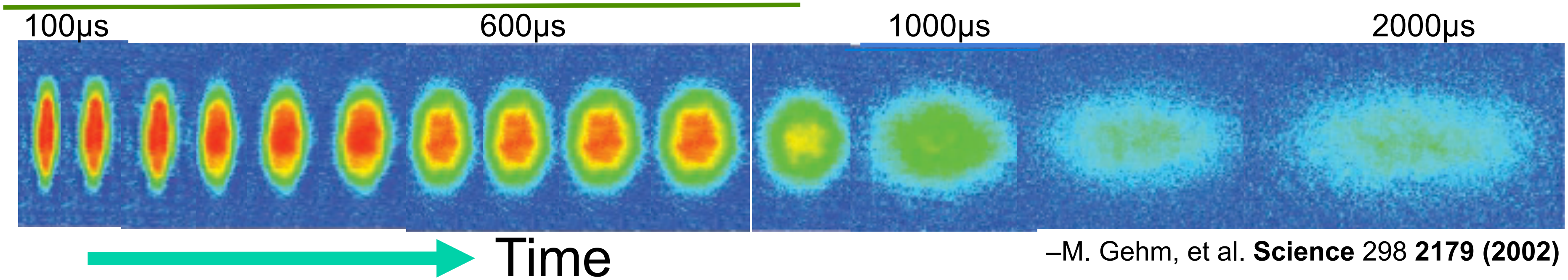

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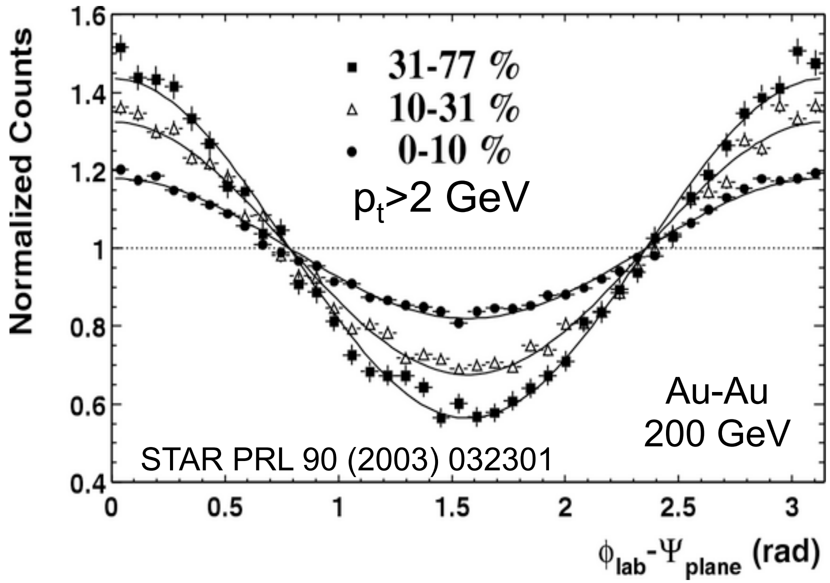
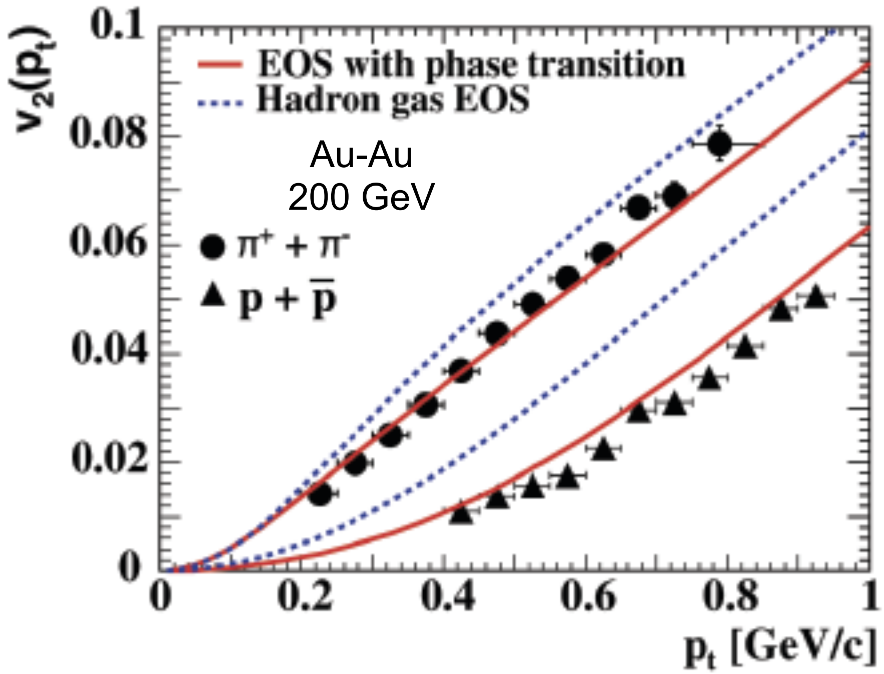




- Pure hydrodynamical models including QGP describe elliptic and radial flow

QGP is a “perfect” fluid

How perfect is the "Perfect fluid"

Viscosity

$$\eta \sim n\bar{p}\lambda = n\bar{p}\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}$$

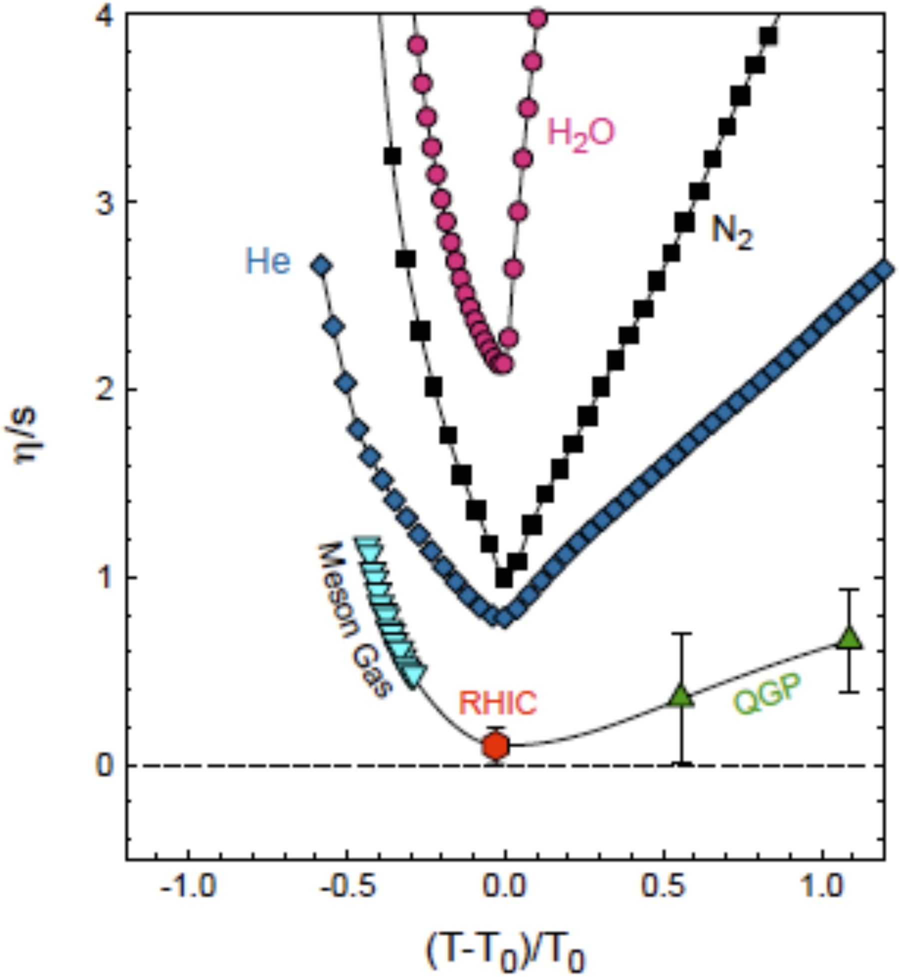
- small η → large coupling

String theory (AdS/CFT) predicts a lower bound:

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$$

The Shear Viscosity of Strongly Coupled N=4 Supersymmetric Yang-Mills Plasma G. Policasto, D.T. Son, A.O. Starinets PRL 87: 081601 (2001).

water under normal condition
η/s ~ 380 ħ/4π



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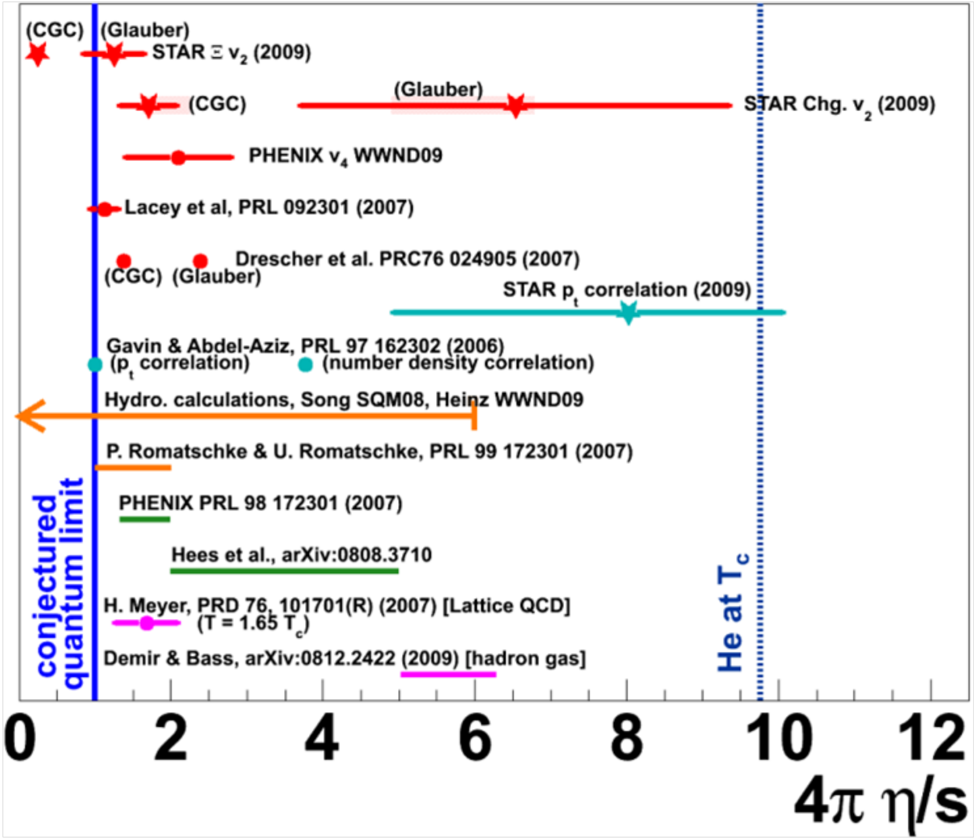
ALL results close to the limit



Many ways have been devised to extract η/s from data

QGP → sQGP

There are partonic degrees of freedom

- Elliptic flow is additive.
- If partons are flowing the *complicated* observed flow pattern in $v_2(p_T)$ for hadrons

$$\frac{d^2N}{dp_T d\phi} \propto 1 + 2 v_2(p_T)\cos(2\phi)$$

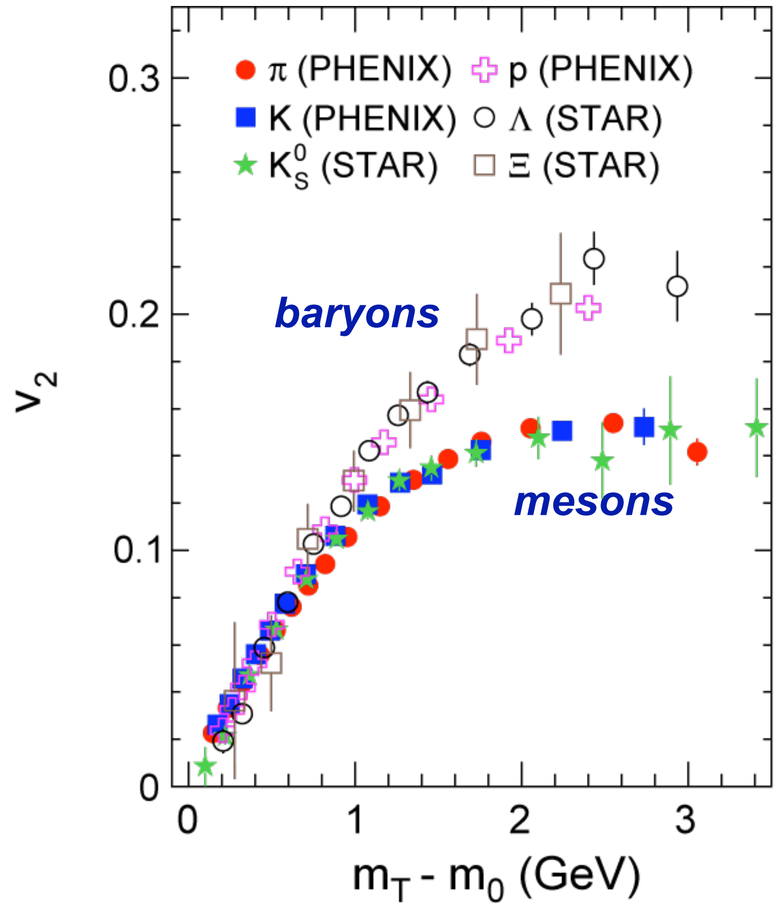
should become *simple* at the quark level

$p_T \rightarrow p_T/n$

$v_2 \rightarrow v_2/n$,

n = (2, 3) for (meson, baryon)

$$m_T = \sqrt{p_T^2 + m_0^2}$$



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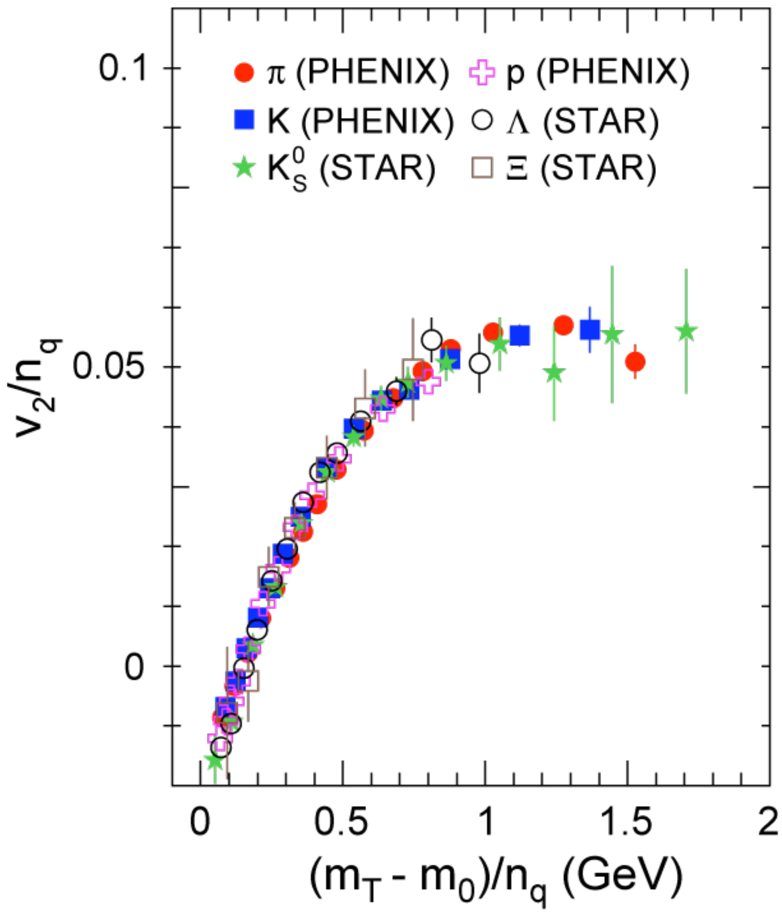
Works for p, π, K^0_s, Λ, Ξ..

$v_2^s \sim v_2^{u,d} \sim 7\%$

$$m_T = \sqrt{p_T^2 + m_0^2}$$



Constituents of QGP are partons

Summary of first decade of RHIC - I

- Energy density in the collision region is way above that where hadrons can exist

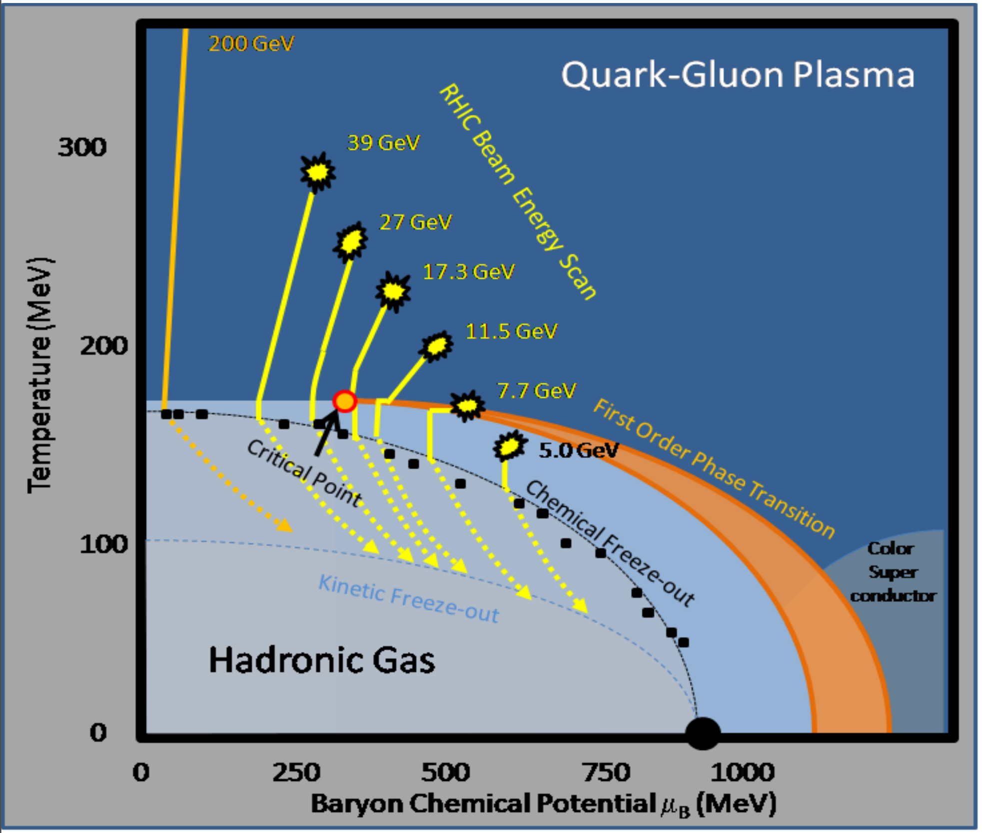
- The initial temperature in the collision region is way above that where hadrons can exist

- The medium has quark and gluon degrees of freedom in initial stages

We have created a new state of matter at RHIC - the sQGP

- A sQGP: flows like an almost "perfect" liquid
  interacts strongly with partons passing through it

RHIC: the Beam Energy Scan



RHIC such a versatile machine need to make good use of it

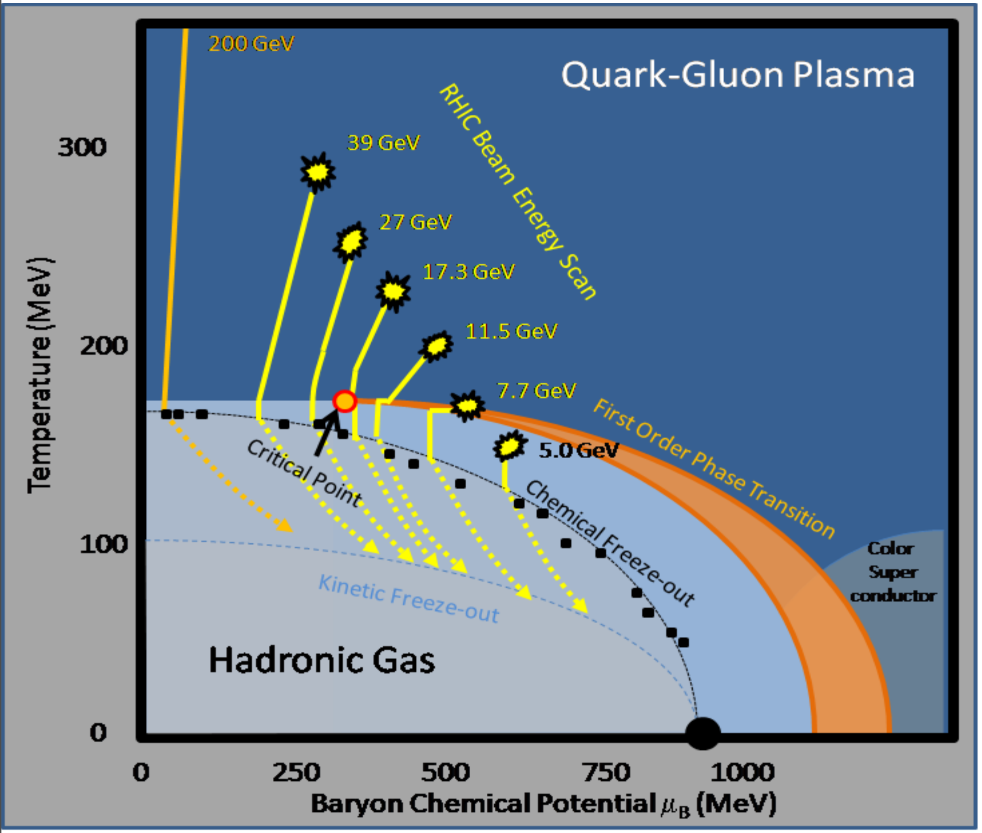
Lattice QCD predicts:

- High T & Low μ_B
  Cross-over
- High μ_B & Low T -
  1st order transition
- Mid μ_B & Mid T -
  Critical Point

Evidence of a critical point and/ or 1st order phase transition?

What √s does sQGP "turn off"?

RHIC: the Beam Energy Scan



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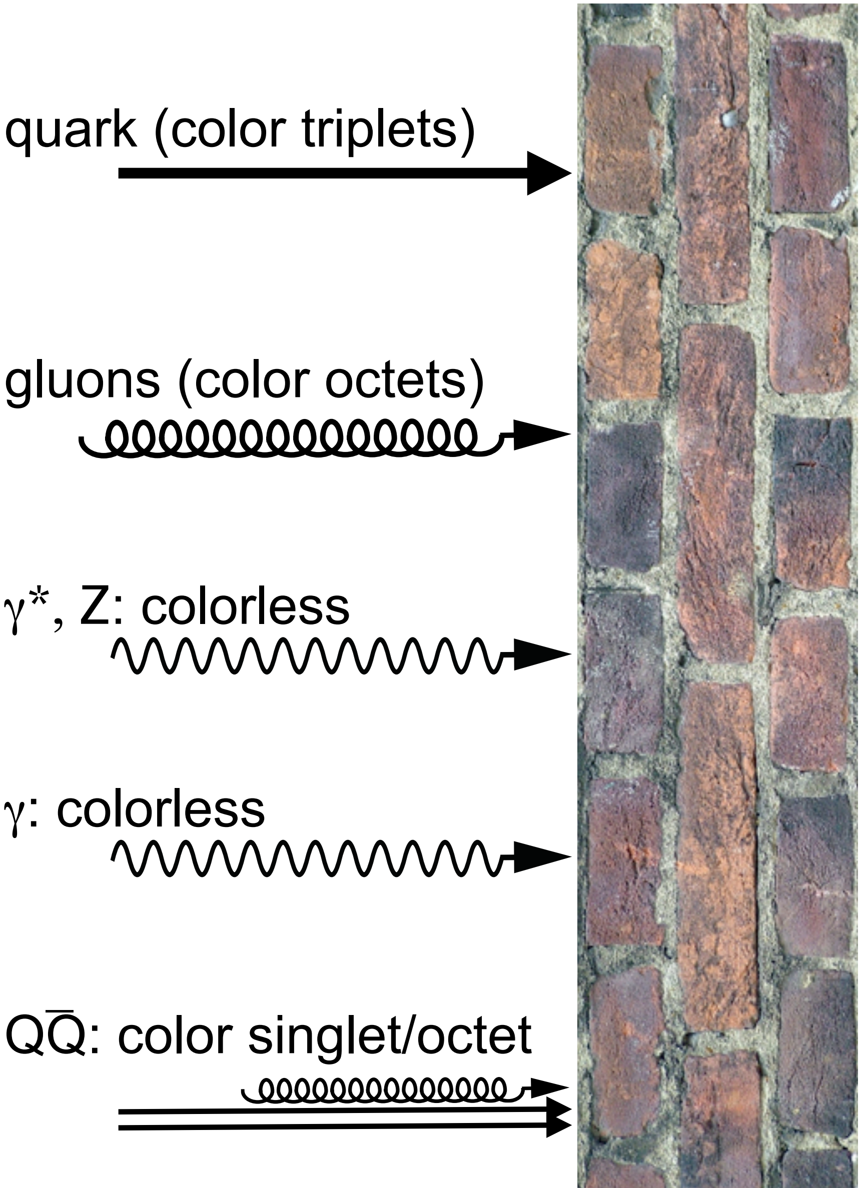
Location of CP not known - experimental search needed

What √s does sQGP "turn off"?

Scan began this year, data at √s = 62, 39, 11.5 and 7.7 GeV data currently being analyzed -watch this space

Hard probes of dense matter (Bricks)



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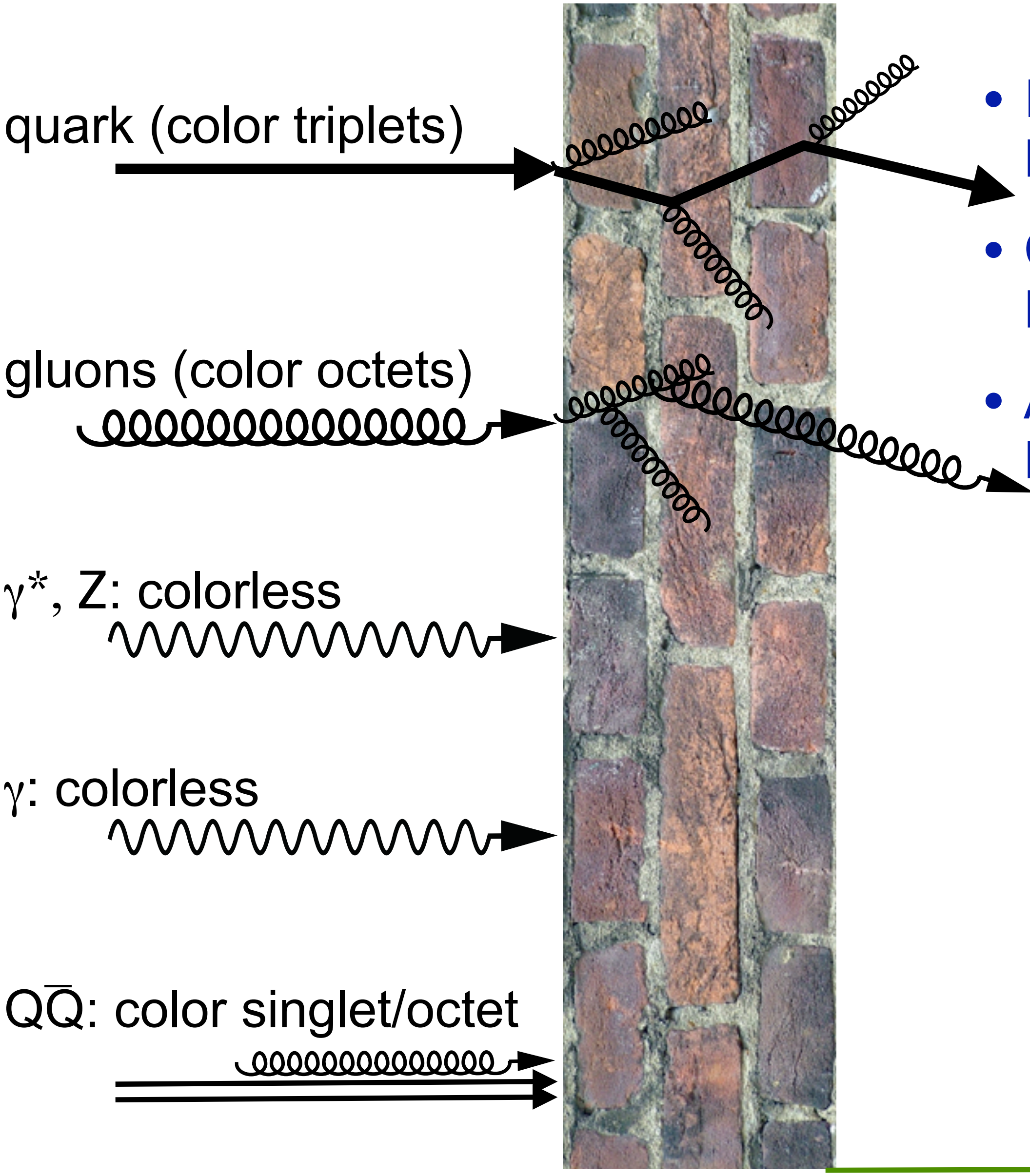

- Induced Gluon Radiation
- Collisional Energy Loss
- Absorption as Pre-Hadrons

Yields:

- transport coefficient
- Gluon Density
- Energy Density

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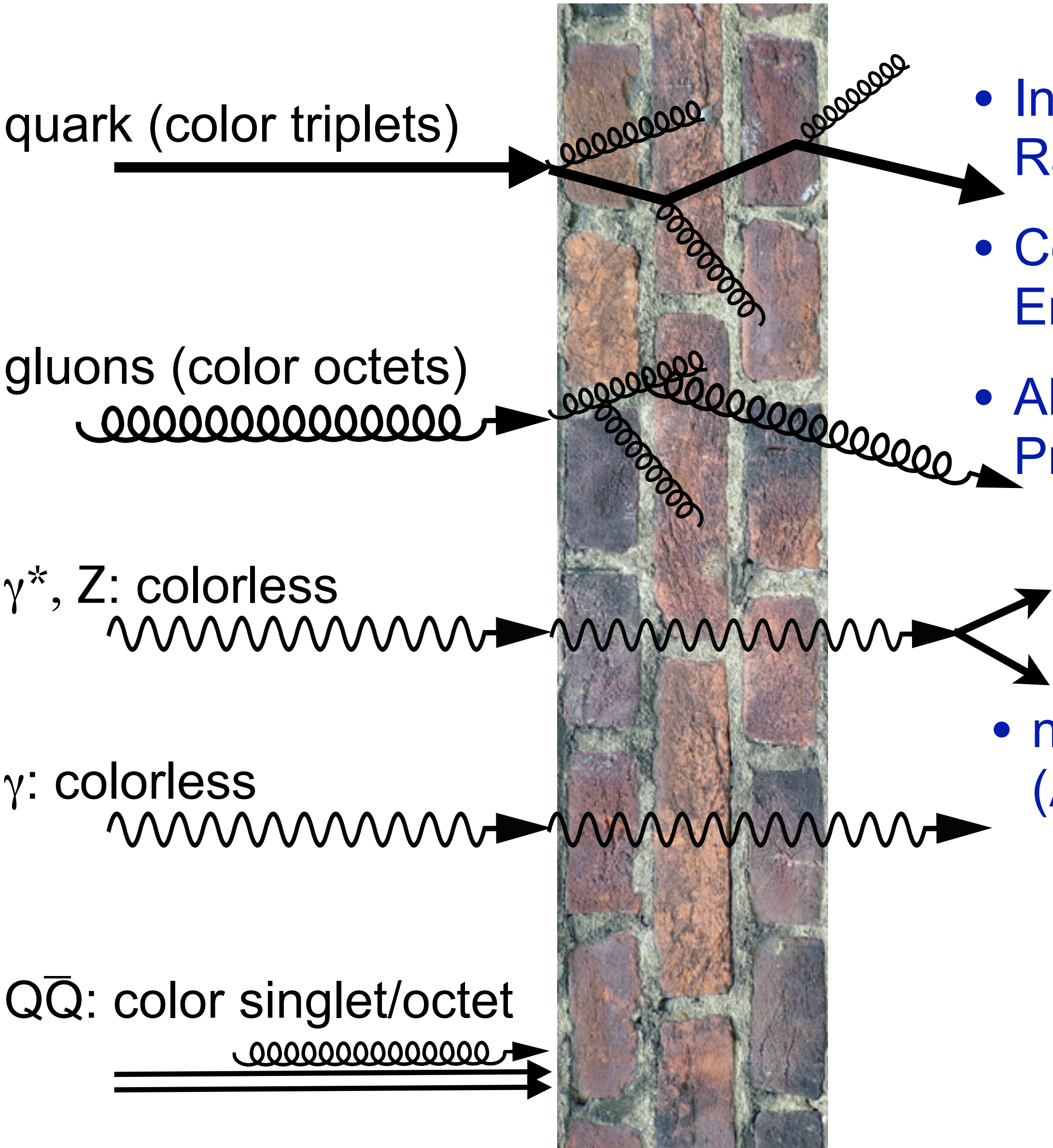

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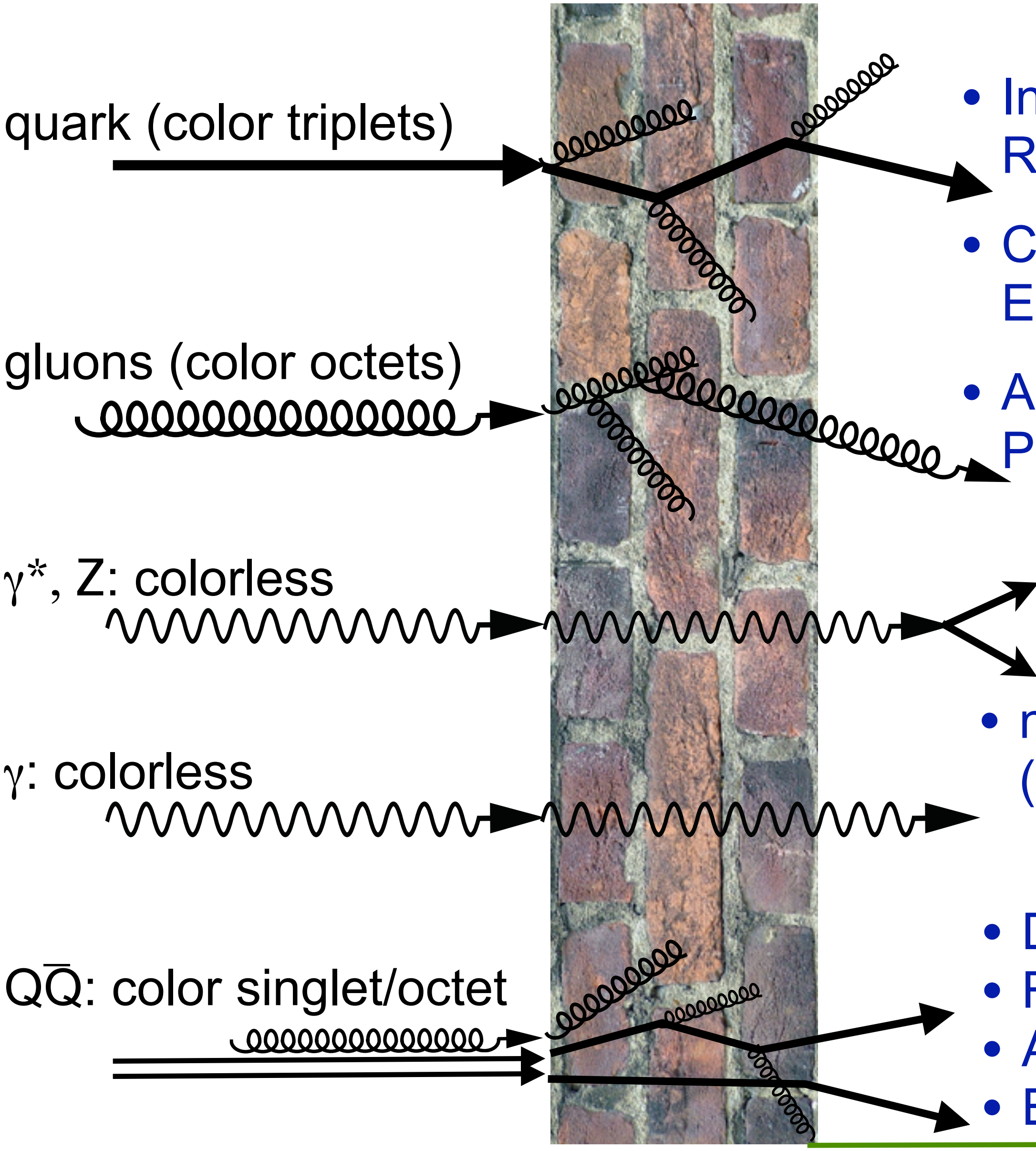

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- Dissociation
- Recombination
- Absorption
- E-loss ?

Yields:
- T_{QGP}
- Probe Deconfinement

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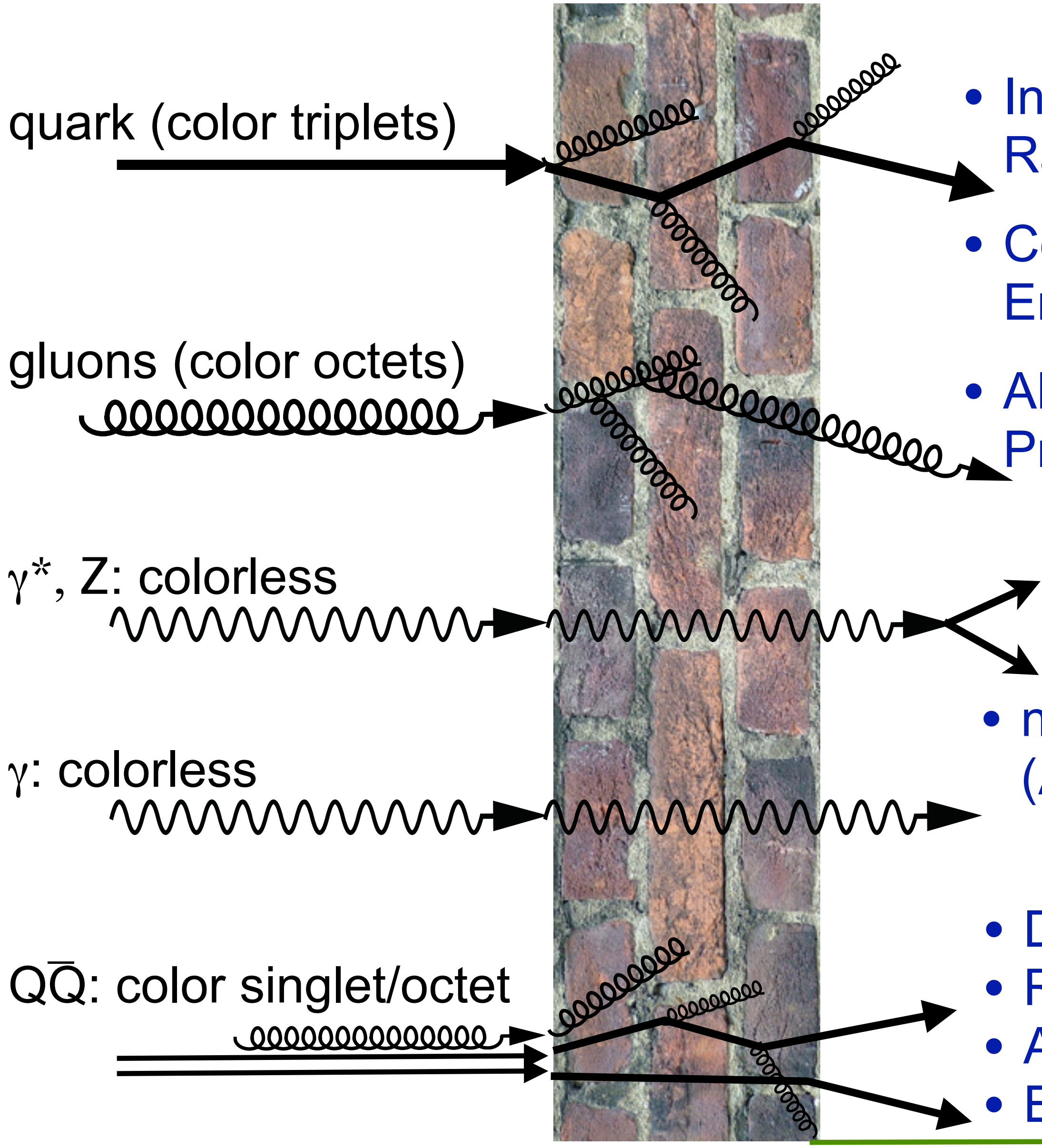

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~~Yields:~~

- ~~T_{QGP}~~
- ~~Probe Deconfinement~~

Probing for the QGP

p-p - No QGP, baseline measure

d-A - No QGP, initial state effects

A-A - QGP created

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Ave. no of p-p collisions in A-A collision

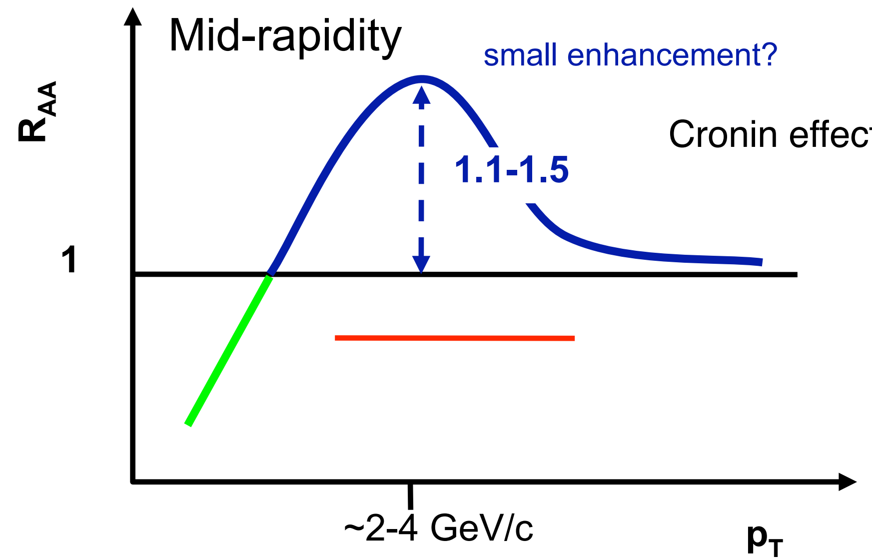
d-A: Cronin enhancement

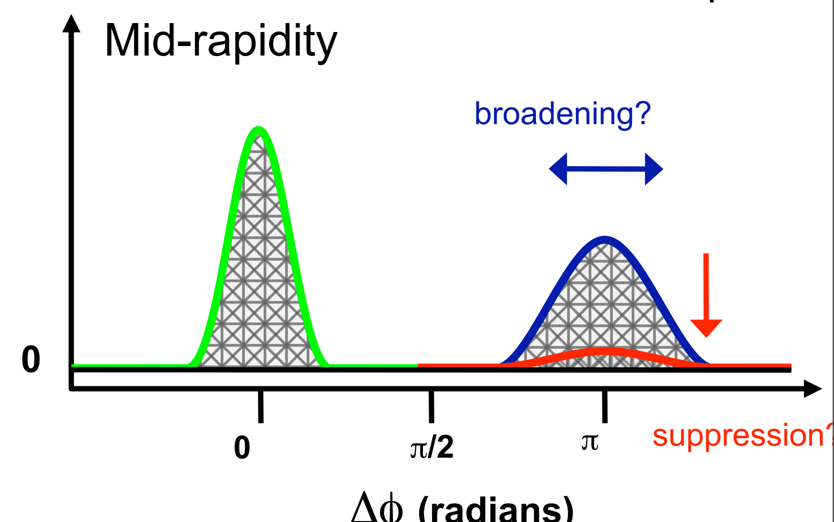
A-A: High p_T suppression

Away-side di-hadron correlations:

d-A: p-p like

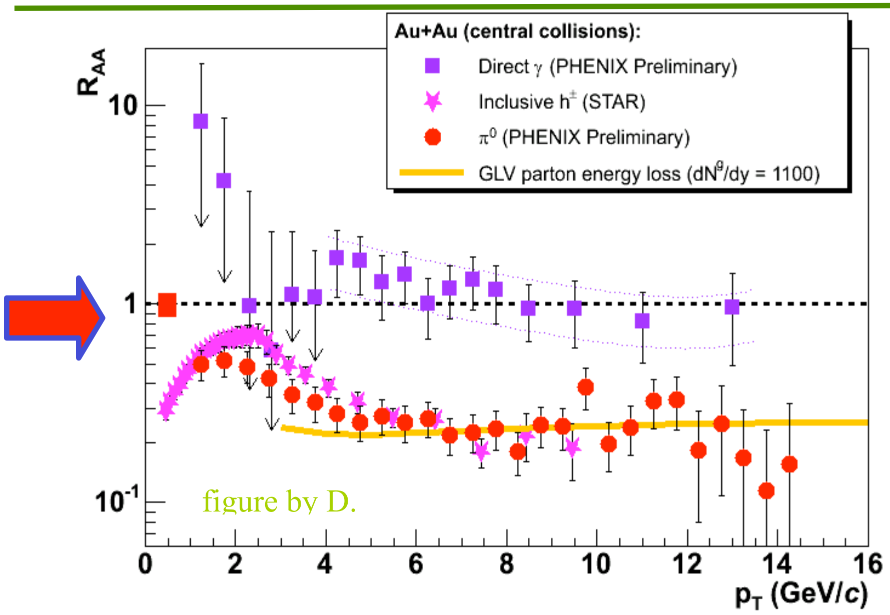
A-A: Strong suppression





Clean separation of initial state (d-Au) and QGP (Au-Au) effects

High-p_T suppression



Observations at RHIC:

1. Photons not suppressed
   - Good! γ don't interact with medium
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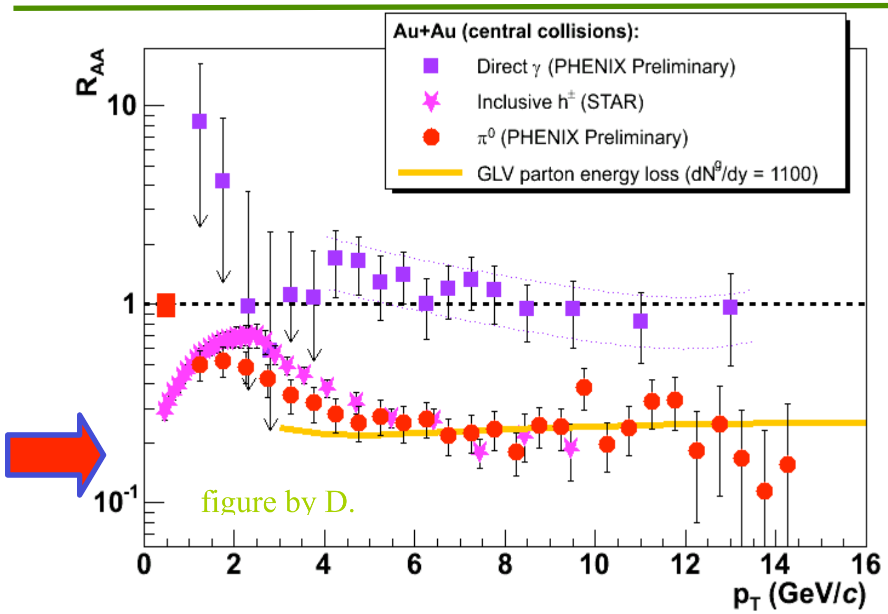
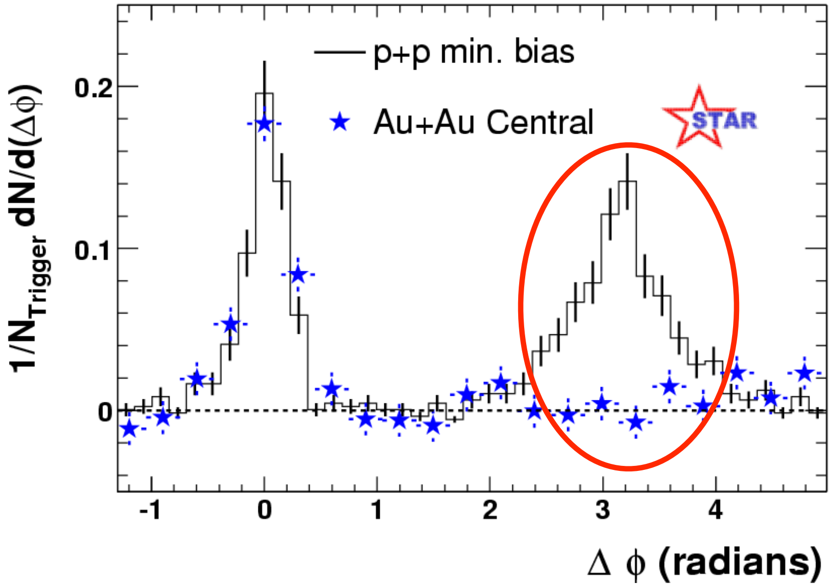
High-p_T suppression





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   - Away-side jet highly quenched

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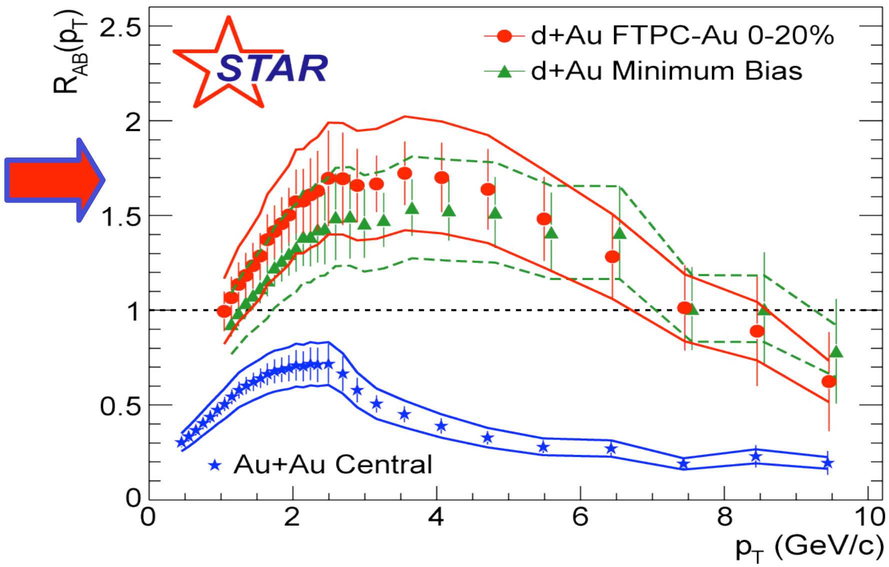

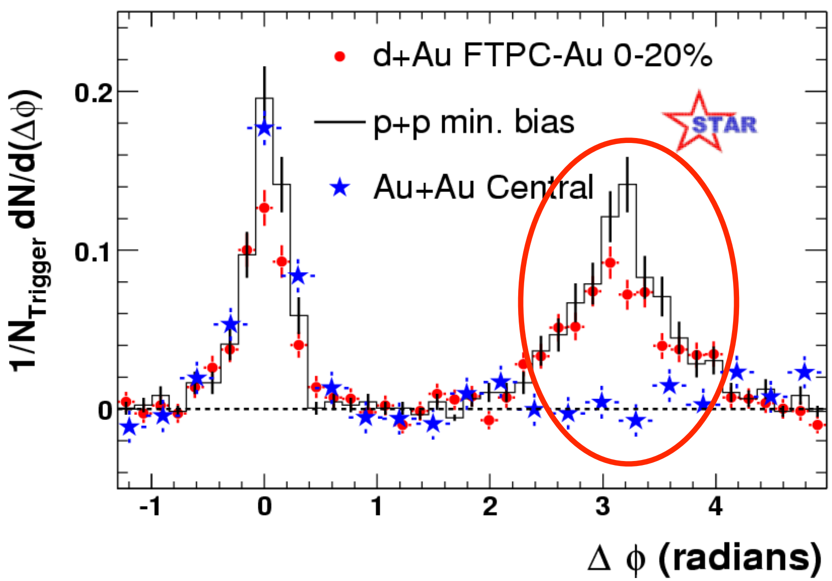

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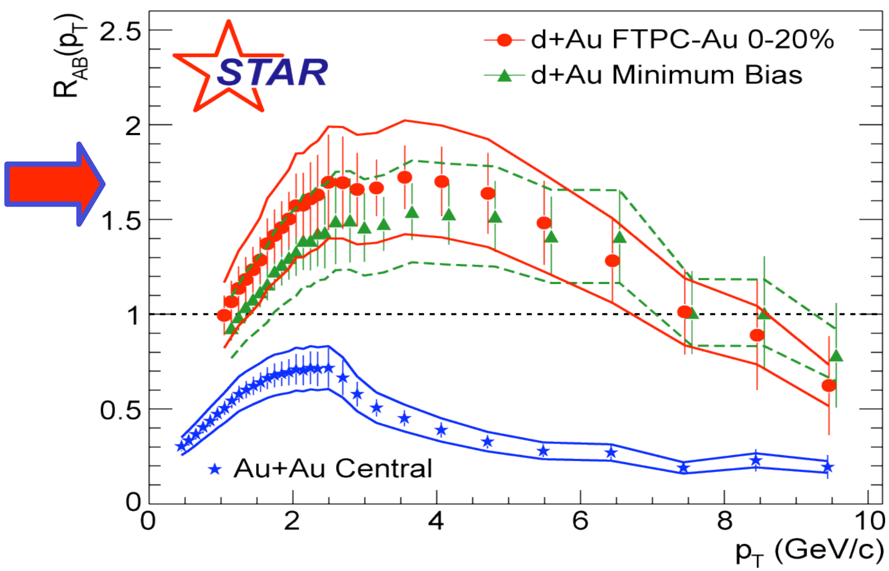

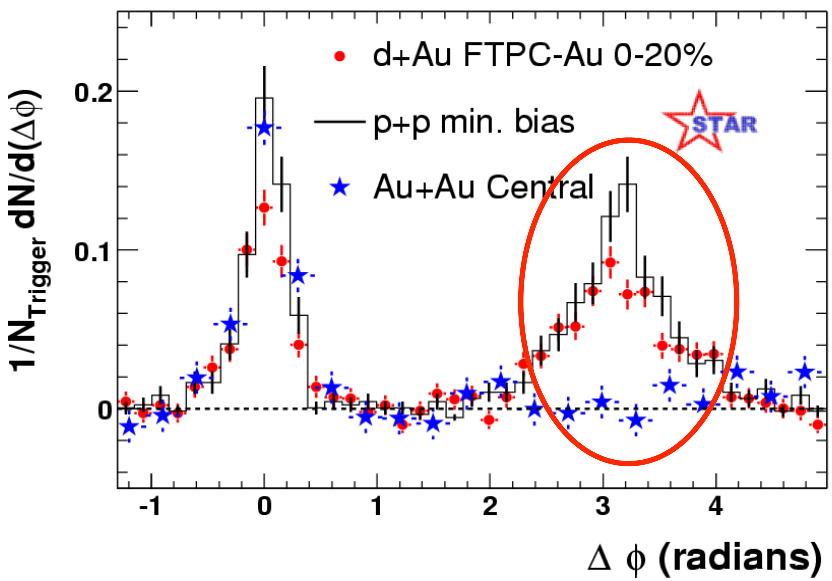

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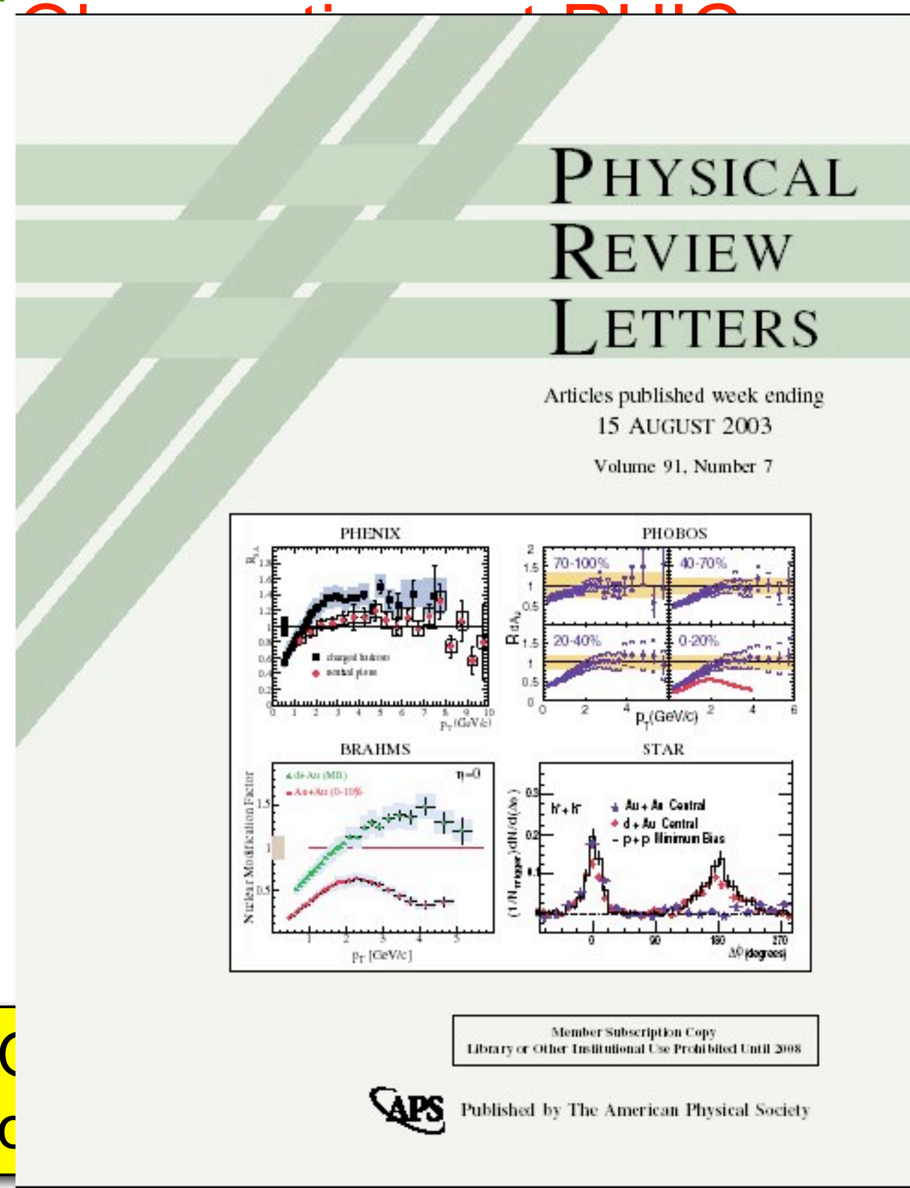
sQGP - strongly coupled: colored objects suffer large E loss

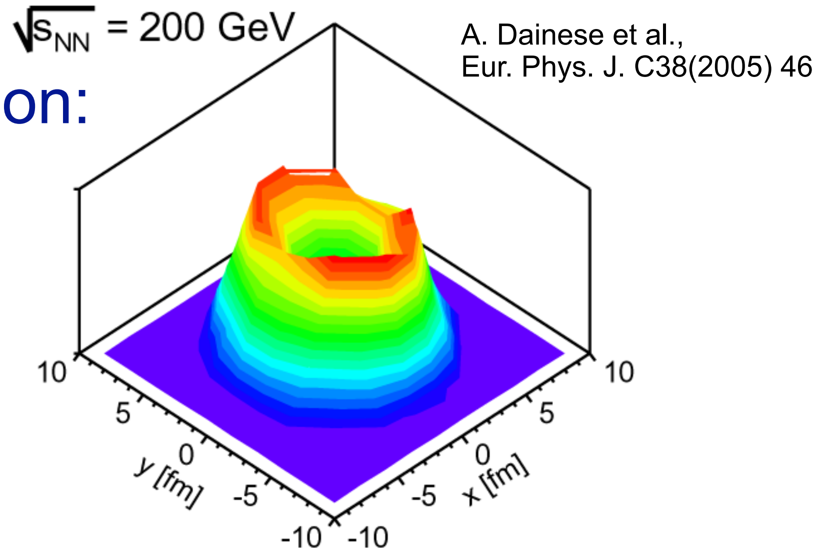
High-p_T suppression



The limitations of R_{AA}

Insensitivity to   due to surface emission:

$\hat{q}$ = $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length



Distributions of parton production points in the transverse plane

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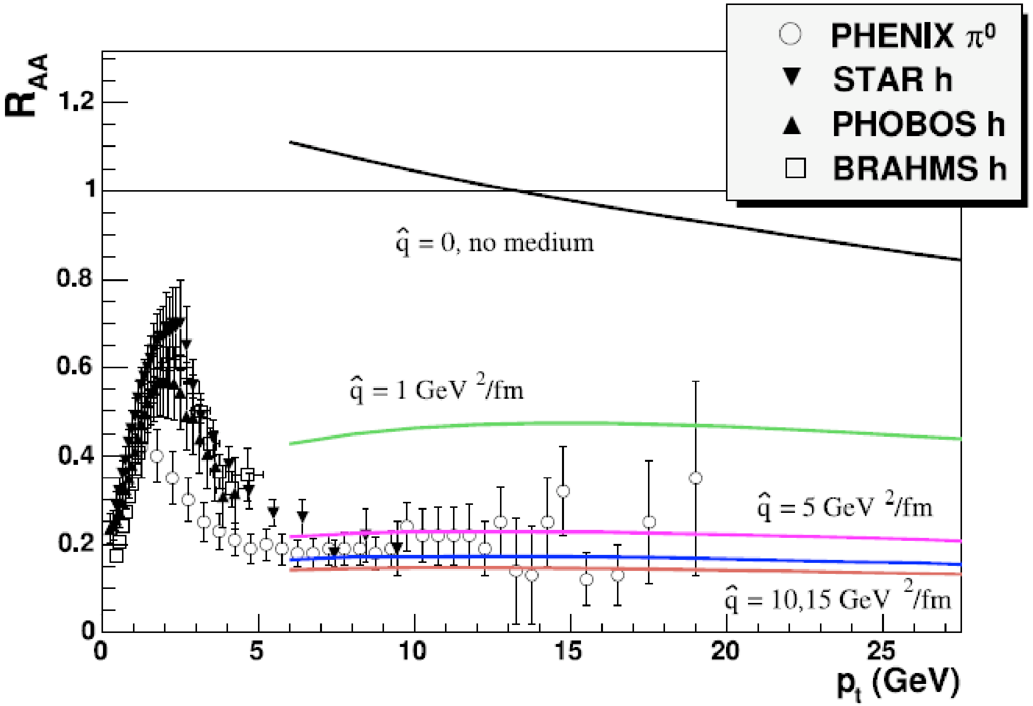
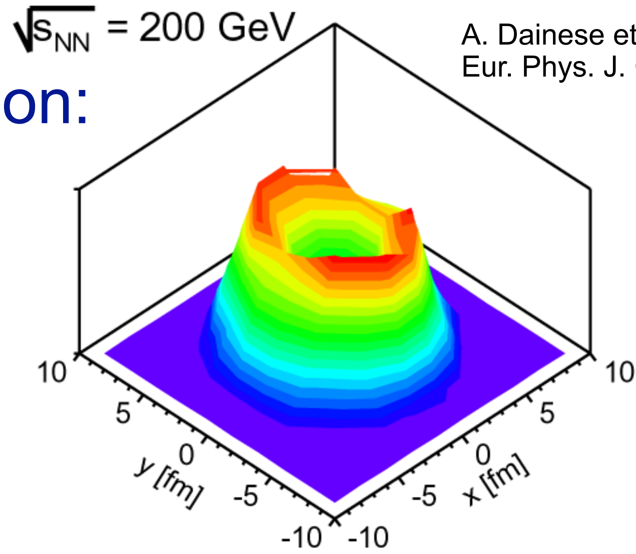
R_{AA} > 0 even for highest densities



[Eskola, Honkanen, Salgado, Wiedemann (2004)]



A. Dainese et al., Eur. Phys. J. C38(2005) 461

Distributions of parton production points in the transverse plane

Rough correspondence:

$$\bar{\hat{q}} = 10\frac{GeV^2}{fm} \Leftrightarrow \frac{dN^g}{dy} \approx 1800$$

$$\bar{\hat{q}} = 5\frac{GeV^2}{fm} \Leftrightarrow \frac{dN^g}{dy} \approx 900$$

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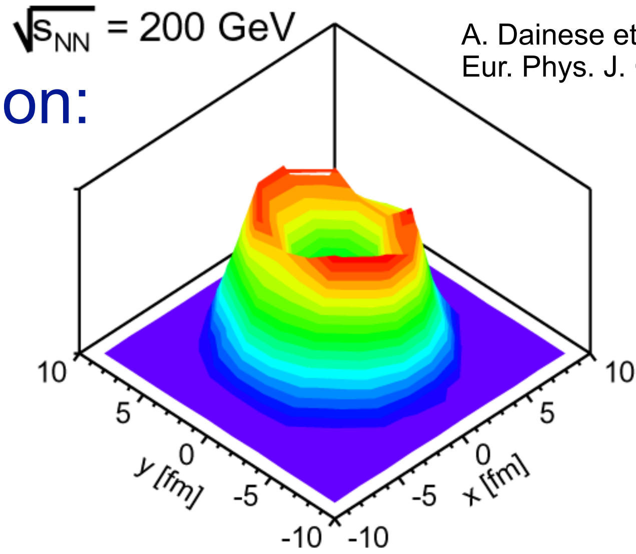

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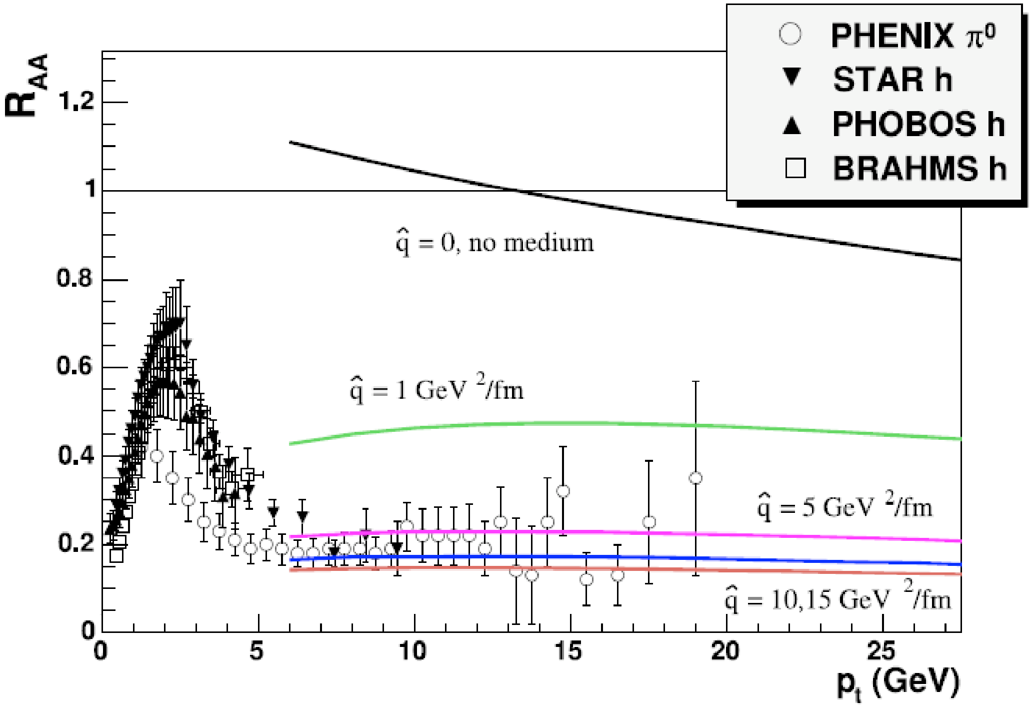

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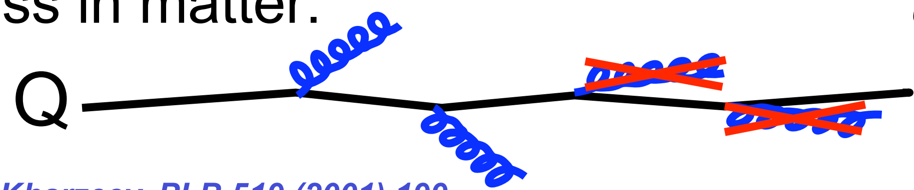
Need more sensitive tool

Heavy quarks are gray probes

Dead cone effect implies lower heavy quark energy loss in matter:



$$\omega \left. \frac{dI}{dw} \right|_{\mathrm{HEAVY}} = \frac{\omega \left. \frac{dI}{dw} \right|_{\mathrm{LIGHT}}}{\left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

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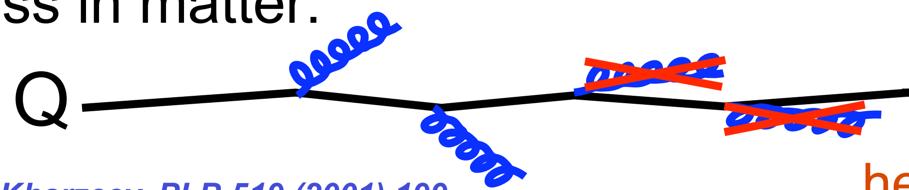

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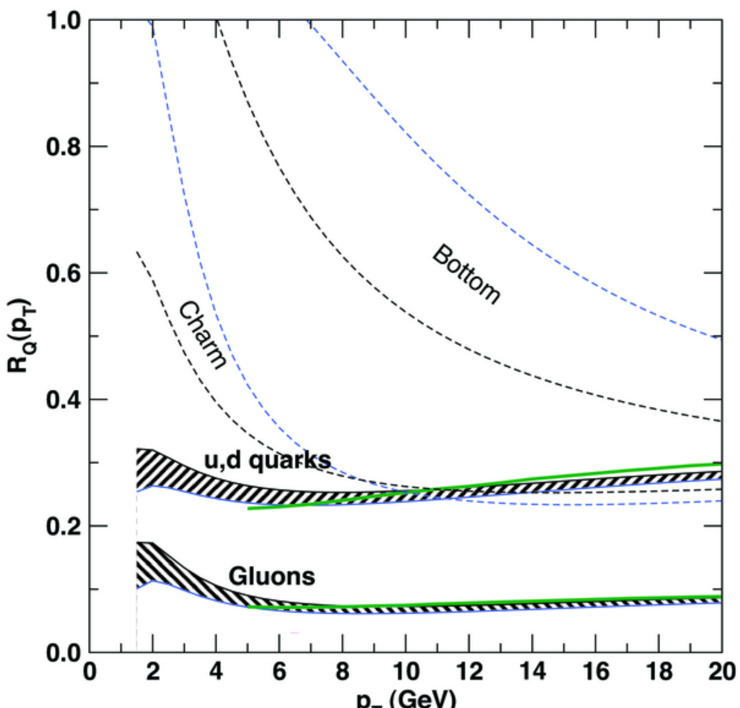
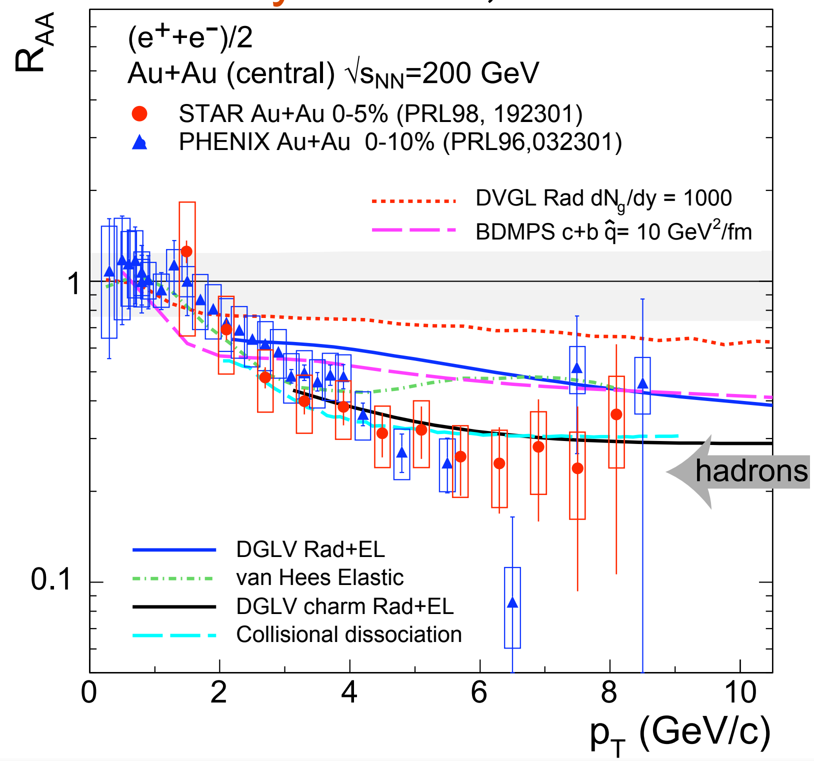
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

heavy flavor c,b → e K ν



Wicks et al, Nucl. Phys. A784 (2007) 426



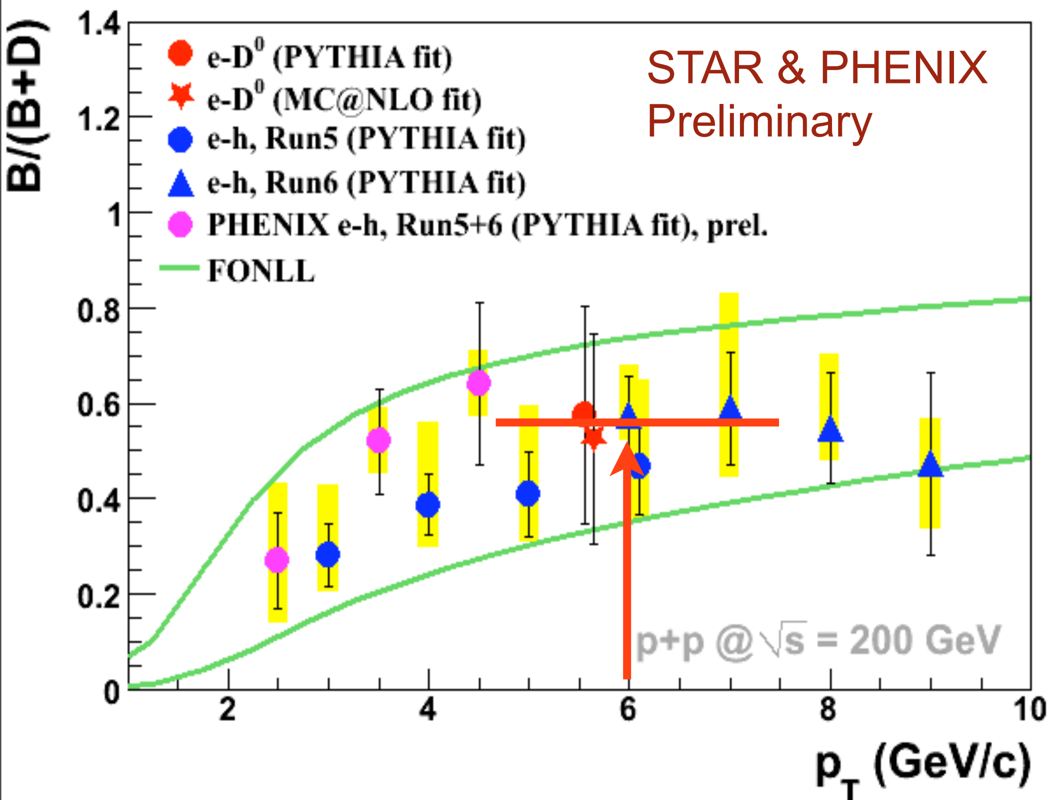
Heavy flavor JUST as suppressed

It gets worse ... bottom not gray either

Can get R_{AA} only if:

include radiation and elastic collisional energy loss

assume **all** non-photonic energy loss comes from c



BUT STAR and PHENIX show b contribution in p+p collisions

⇒ ~55% at p_T^e = 6 GeV/c

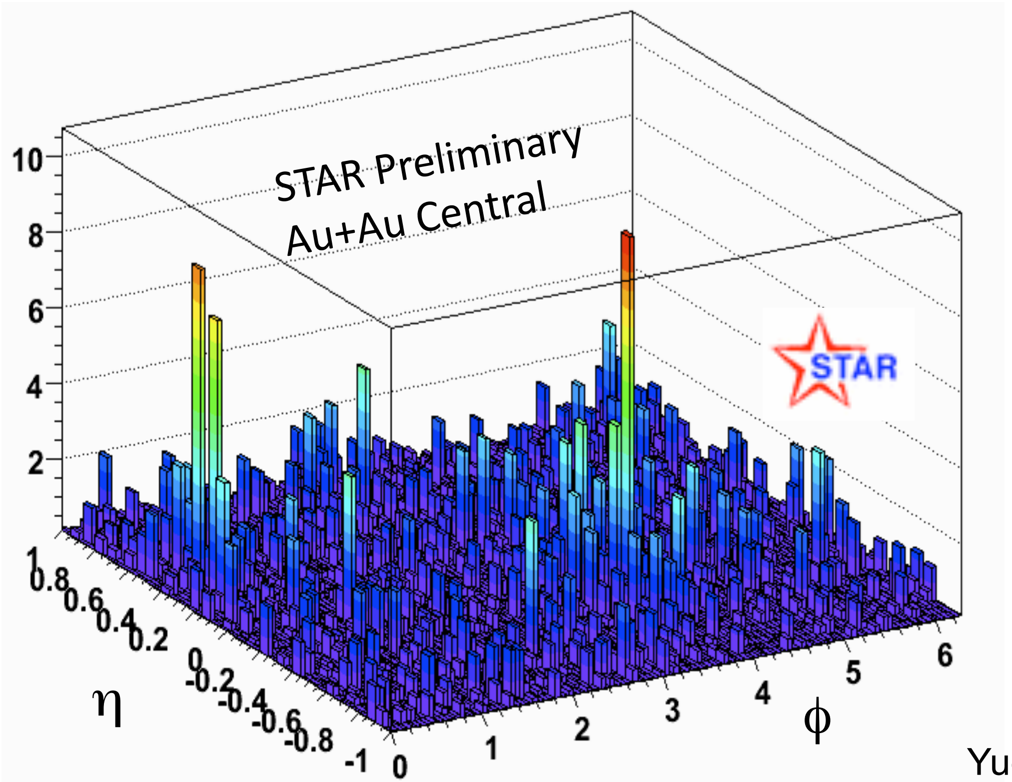
Beauty appears equally suppressed

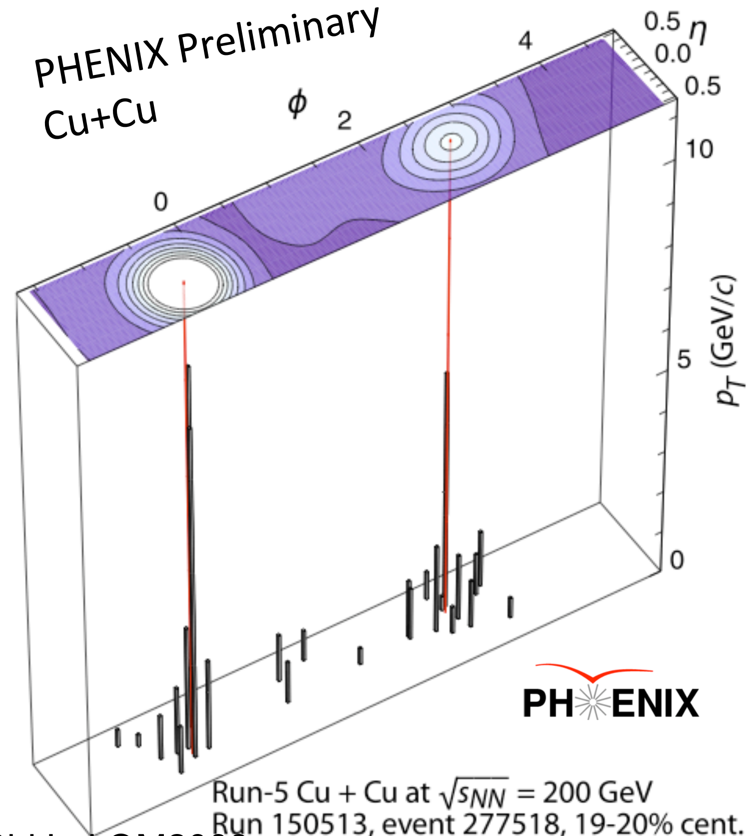
We still don't fully understand energy loss

Needed to measure b and c R_{AA} independently AND accurately

A key measurement for RHIC upgrades and the LHC

Jets at RHIC





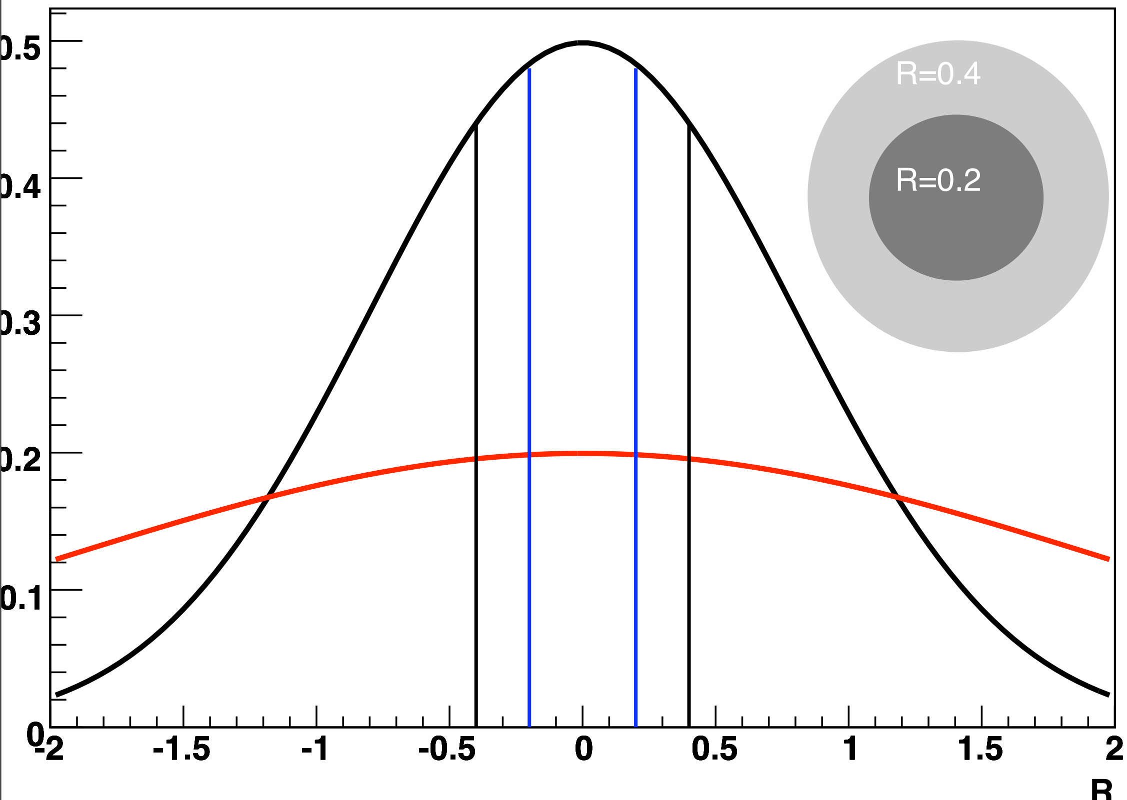
Yue Shi Lai QM2009

Clearly visible above background in both experiments

Underlying event a significant challenge - magnitude & fluctuations

Tools (i.e. FastJet package, gaussian filters) and methods (unfolding) developed to extract and correct the data

Look at the jet energy profile



M. Ploskon QM2009

Calc $N_{jet}(R=0.2)/N_{jet}(R=0.4)$ as function of $p_{T,jet}$

For fixed partonic p_T

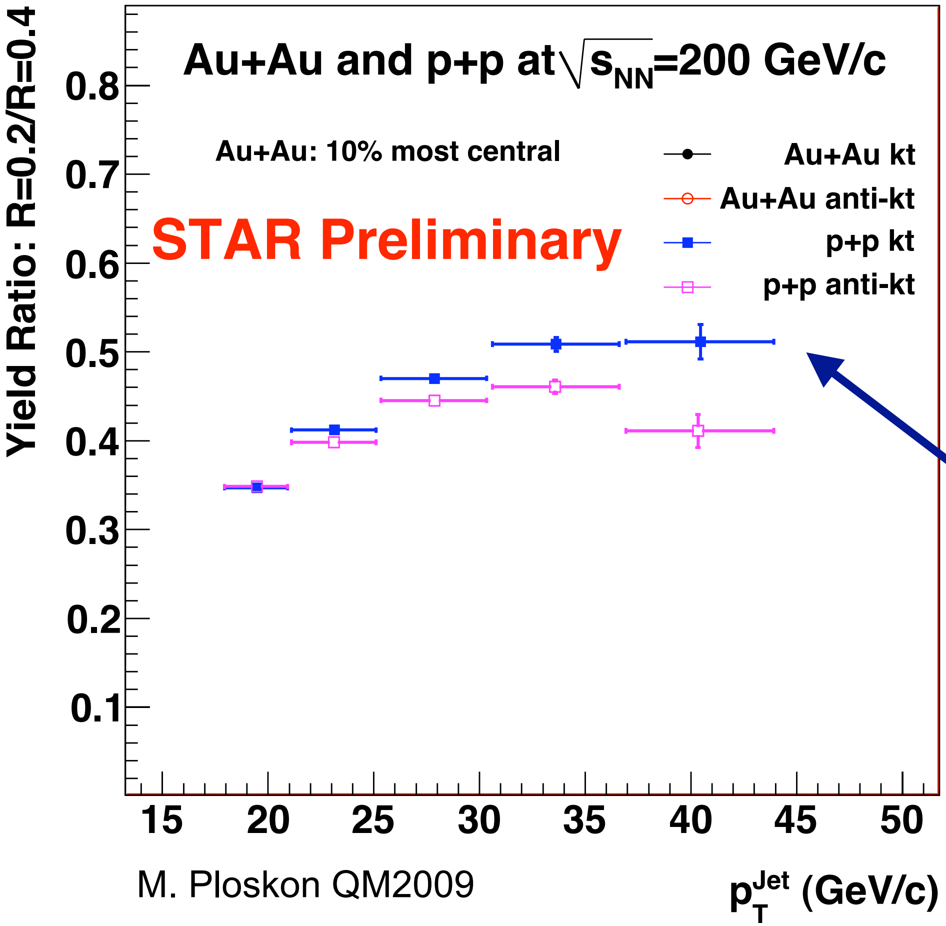
ratio(narrow)>ratio(broad)

i.e.

ratio(p-p) > ratio(Au-Au)

due to QGP interactions

Look at the jet energy profile



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p-p:
"Focussing" of jet with increasing jet energy

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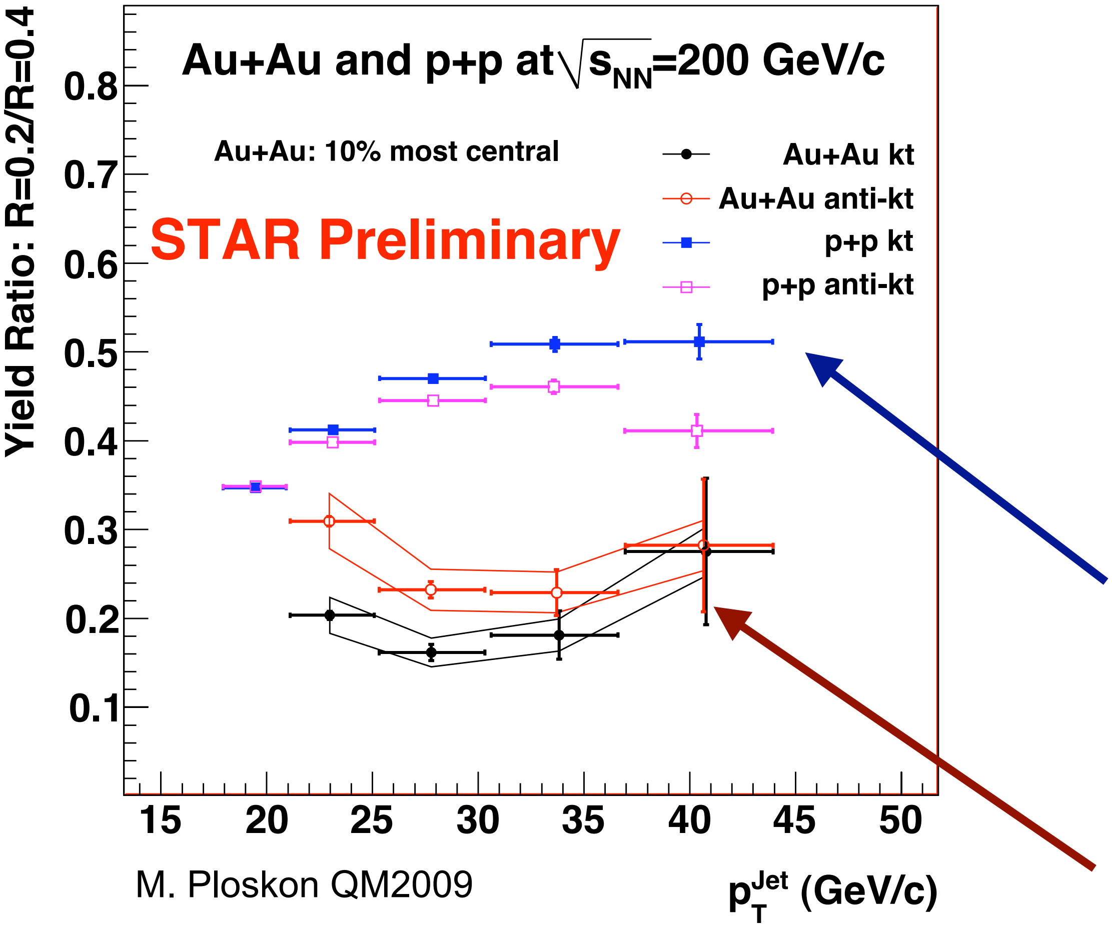


De-focussing of energy profile when jet passes through sQGP

Calc $N_{jet}(R=0.2)/N_{jet}(R=0.4)$ as function of $p_{T,jet}$

For fixed partonic p_T ratio(narrow)>ratio(broad)

i.e.

ratio(p-p) > ratio(Au-Au) due to QGP interactions

<u>p-p:</u>

"Focussing" of jet with increasing jet energy

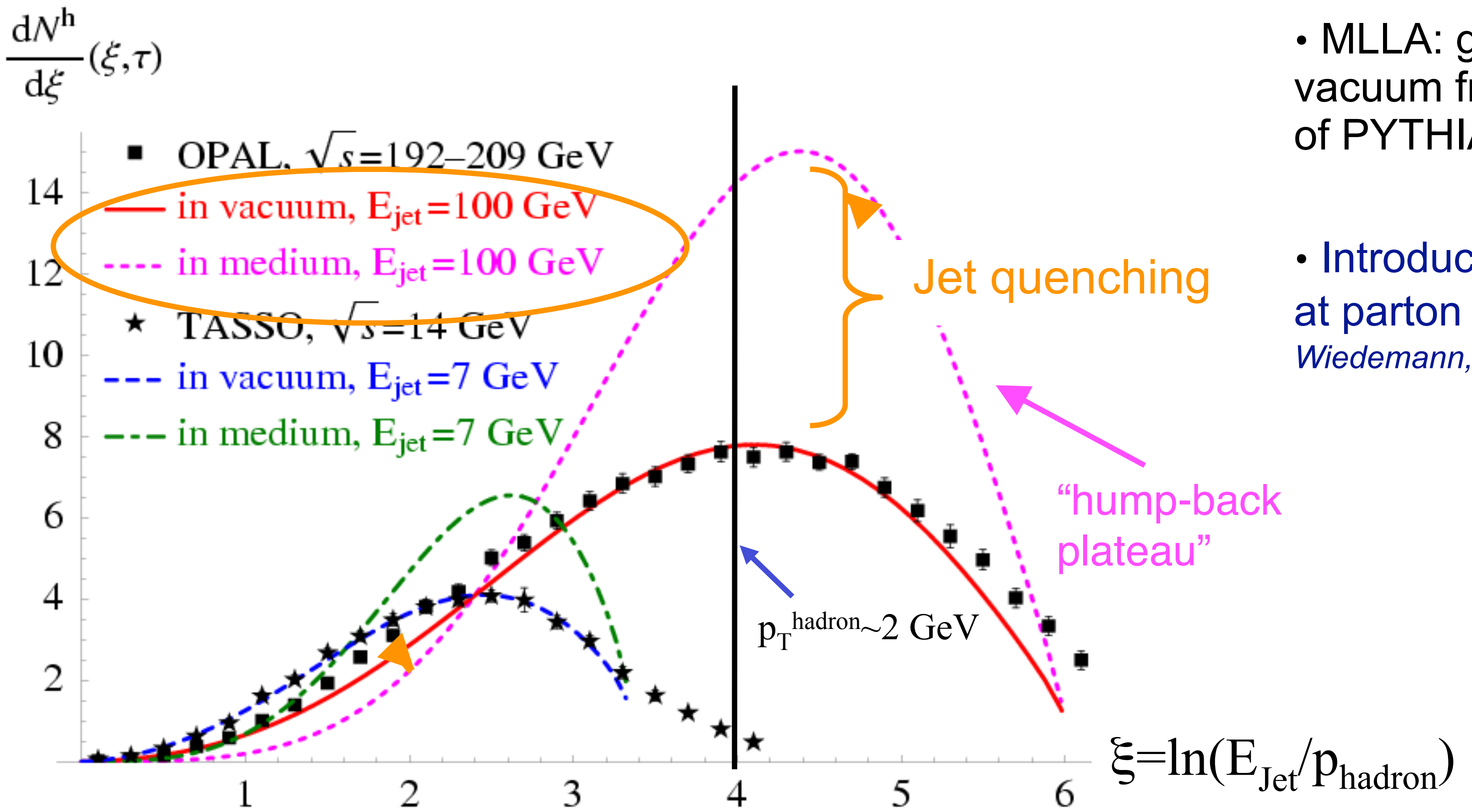
<u>Au-Au:</u>

"Broadening" of jet with increasing jet energy

Modification of the fragmentation

p and E must be conserved so quenched energy must appear somewhere

Prediction that the fragmentation function is modified in the presence of a QGP - more and softer particles produced



- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

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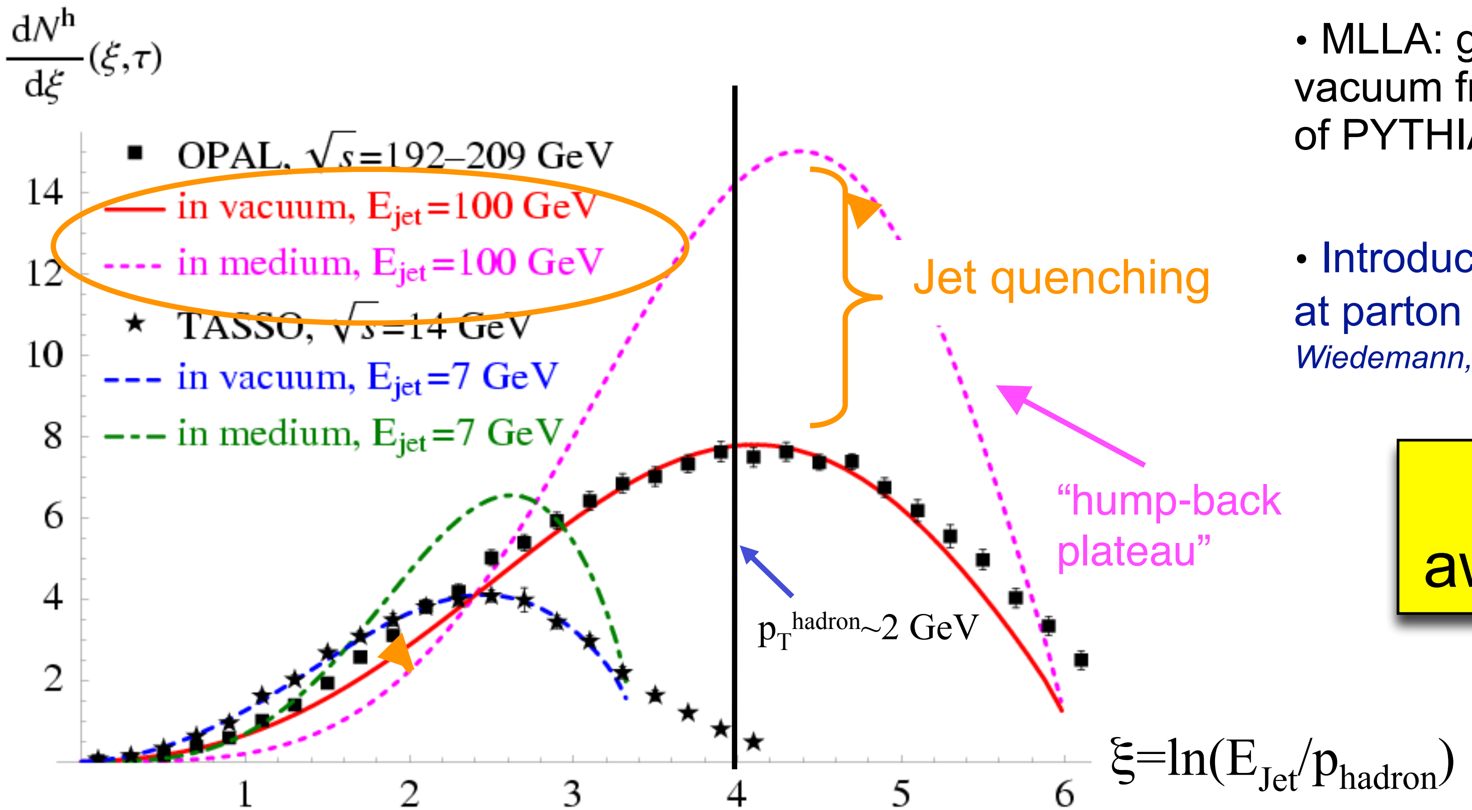

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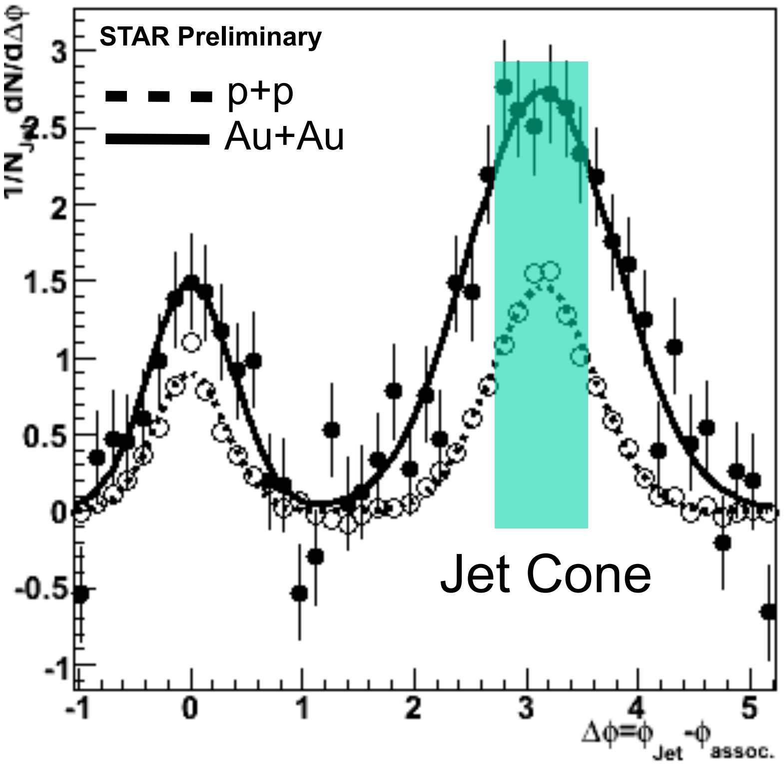
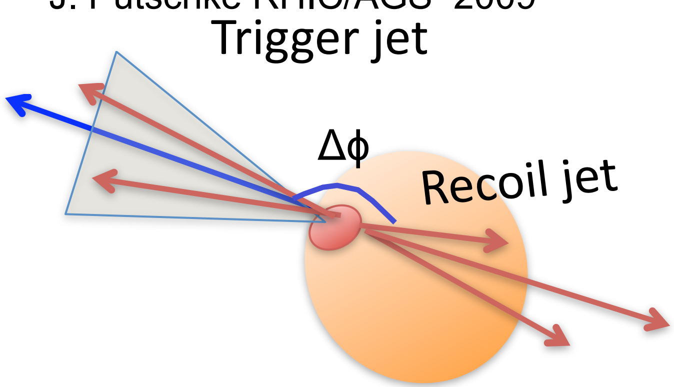
Look at away-side FF

Jet-hadron correlations

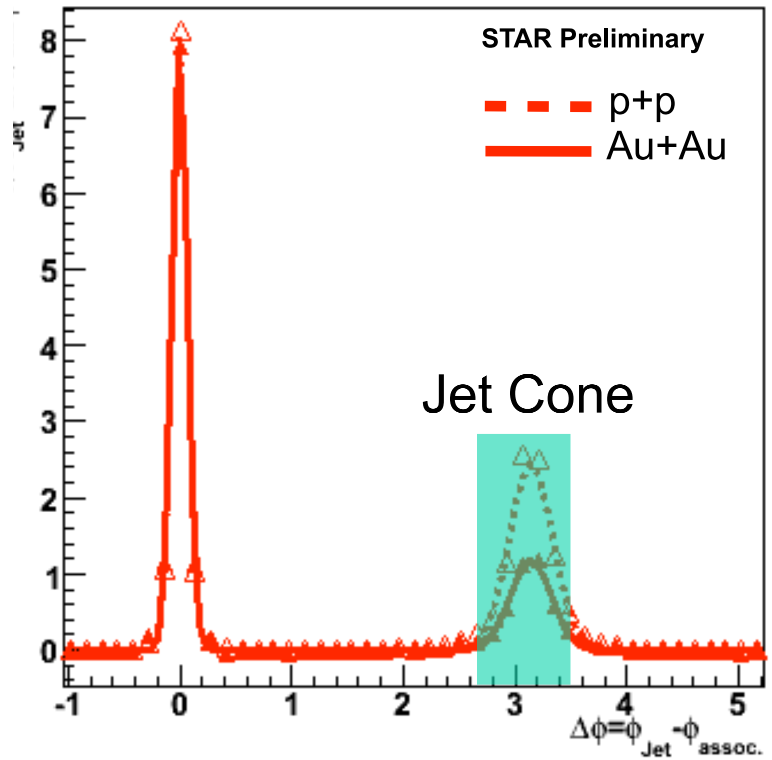
$0.2 < p_{t,assoc} < 1.0$ GeV/c



J. Putschke RHIC/AGS 2009



$p_{t,assoc} > 2.5$ GeV/c



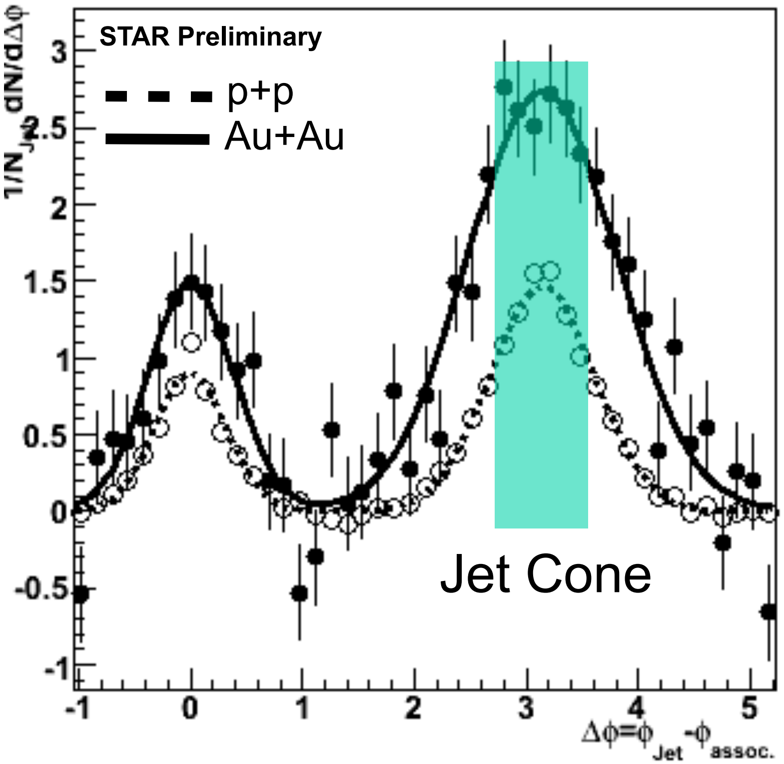
Au+Au 0-20%
High Tower Trigger
1 tower
0.05x0.05 (η x ϕ)
with E_t > 5.4 GeV

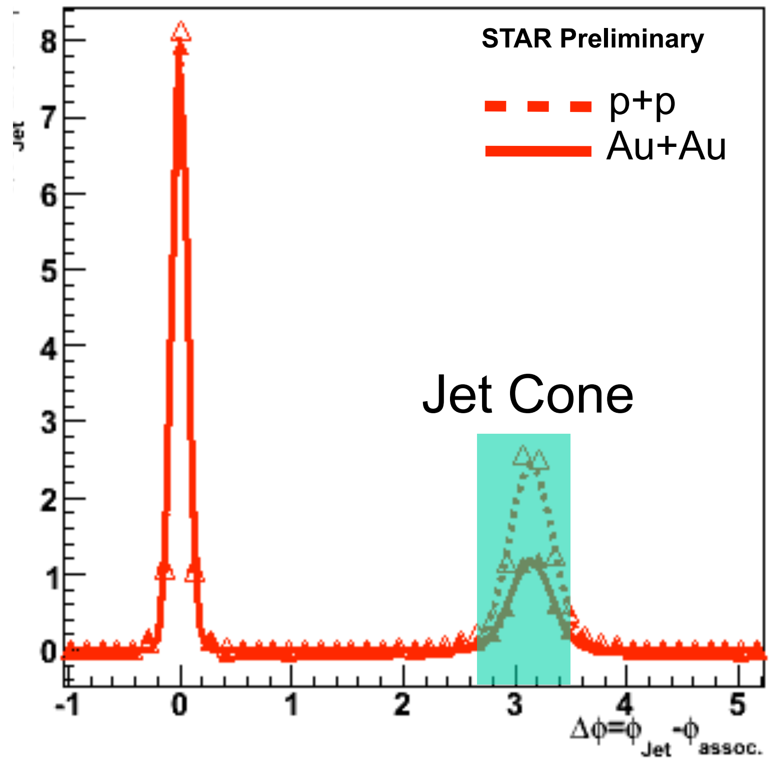
Jet trigger:
Anti-k_T,
R=0.4,
$p_{t,rec}$(jet)>20 GeV
using
$p_{t,}$(particle)>2 GeV

Jet-hadron correlations

$0.2<p_{t,assoc}<1.0$ GeV/c

$p_{t,assoc}>2.5$ GeV/c





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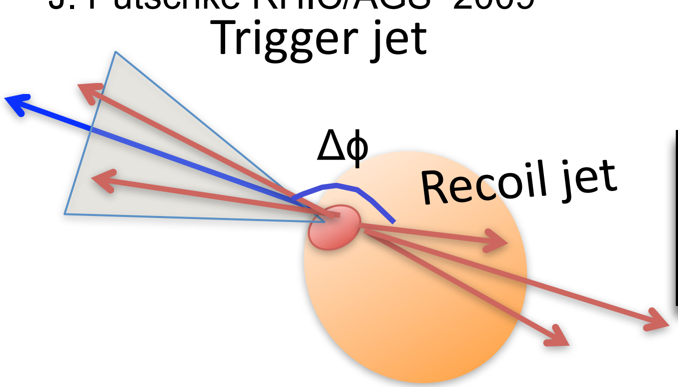


Away-side: Broadening
Softening

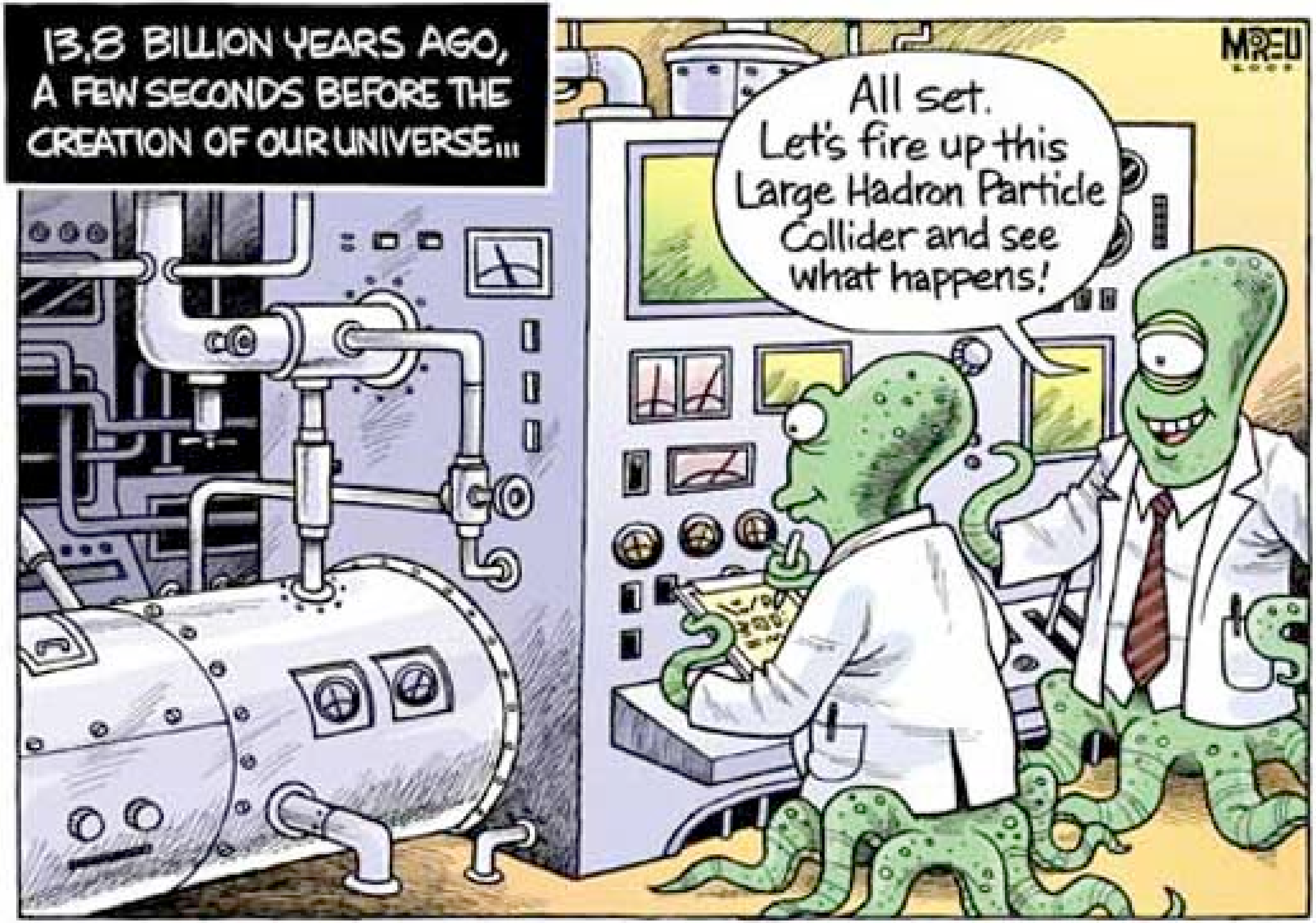
First direct measurement of Modified Fragmentation due to presence of sQGP

Summary of first decade of RHIC - II

- p-p data well described by pQCD calculations at high p_T
- Cold nuclear matter effects are there (d-Au R_{AA} and di-hadron correlations) but cannot explain Au-Au data
- Large suppression of high p_T hadrons in the presence of a sQGP
- c and b quarks interact as strongly as the light quarks and gluons (R_{AA} of non-photonic e)
- no theory yet available to precisely describe all suppression results
- Strong evidence of broadening of the jet energy profile (R=0.2/R=0.4)
- Quenched jet energy reappears as numerous large angle, low p_T, particles (jet-hadron correlations)

Results can be explained as due to significant partonic energy loss in the sQGP before fragmentation - numerous details left to be understood

The LHC continues the investigation...



BACKUP SLIDES