How do quarks and gluons lose energy in the QGP? Introduction

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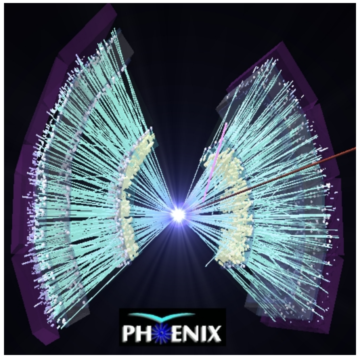
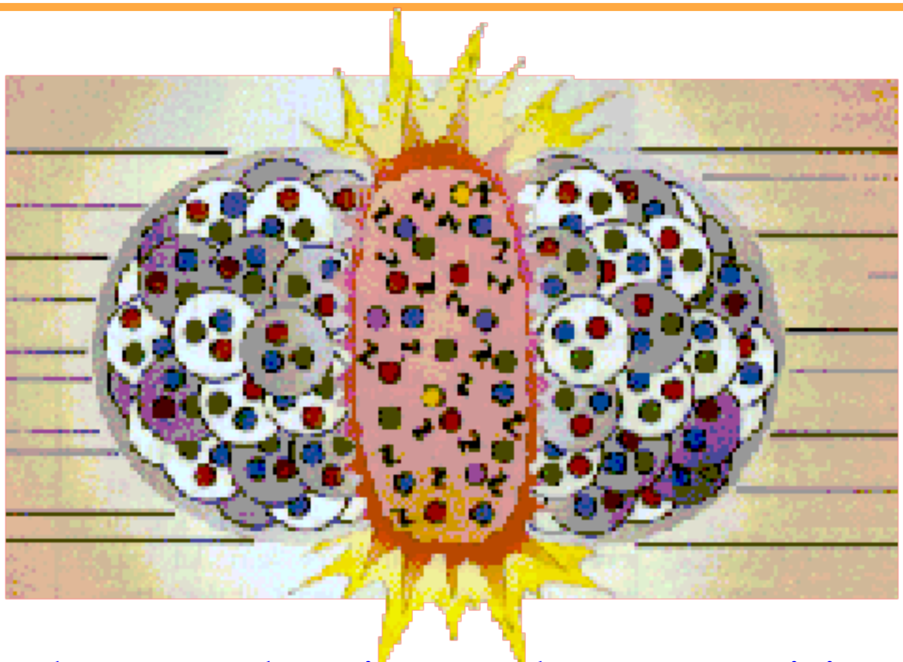
Physics Seminar
Yale University
New Haven, CT
October 29, 2015



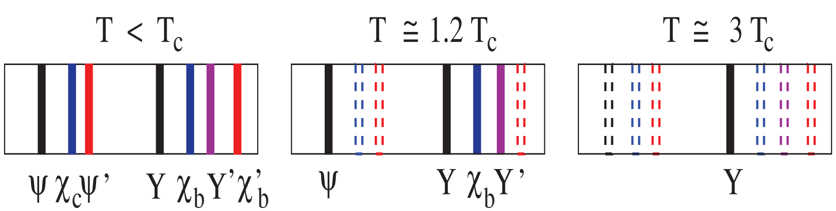
High Energy Nucleus-Collisions provide the means of creating Nuclear Matter in conditions of Extreme Temperature and Density



- At large energy or baryon density, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of "deconfined" (from their individual nucleons) quarks and gluons covering a volume that is many units of the confinement length scale.

The gold-plated signature for the QGP J/ψ Suppression-1986

• In 1986, T. Matsui & H. Satz PL **B178**, 416 (1987) said that due to the Debye screening of the color potential in a QGP, charmonium production would be suppressed since the cc-bar couldn't bind. QGP thermometer



J/Ψ PHENIX design goal 1990-1991
ϒ sPHENIX design goal 2015

Jet Quenching: Parton energy loss by coherent LPM radiative energy loss in the QGP-1997

• In 1997, Baier, Dokshitzer, Mueller Peigne, Schiff also Zakharov, see ARNPS **50**, 37 (2000), said that the energy loss from coherent LPM radiation for hard-scattered partons exiting the QGP would "result in an attenuation of the jet energy and a broadening of the jets"

The energy loss, -dE/dx, of an outgoing parton per unit length (x) of a medium with total length L, due to coherent gluon bremsstrahlung is proportional to the q^2 and takes the form:

$$\boxed{\frac{-dE}{dx} \approx \alpha_s \left\langle q^2(L) \right\rangle = \alpha_s \mu^2 L / \lambda_{mfp} \equiv \alpha_s \hat{q} L}$$

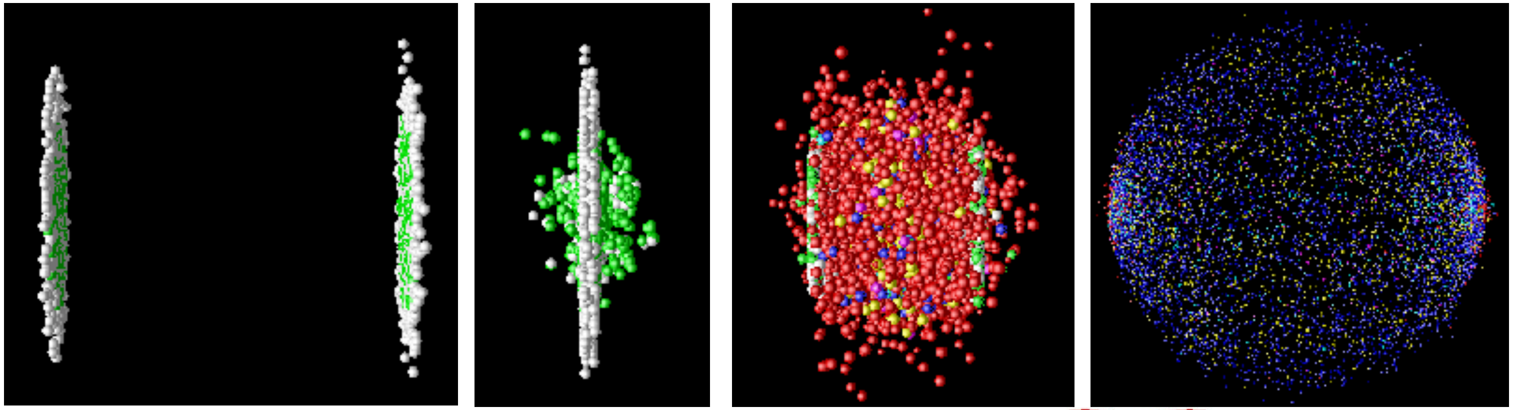
where μ, is the mean momentum transfer per collision (~the Debye screening mass). Thus, the total energy loss in the medium goes like L^2.

"Mike, is there a 'real collider detector' at RHIC?"---J. Steinberger

- **PHENIX is picturesque because it is not your father's solenoid collider detector**
- **Special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities*.**
  - ✓ ***possibility of zero magnetic field on axis***
  - ✓ ***minimum of material in aperture 0.4% X_o***
  - ✓ ***EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger***
  - ***γ π^0 separation up to $p_T \sim 25$ GeV/c***
  - ***EMCAL and precision TOF for $h^{\pm}$ pid***

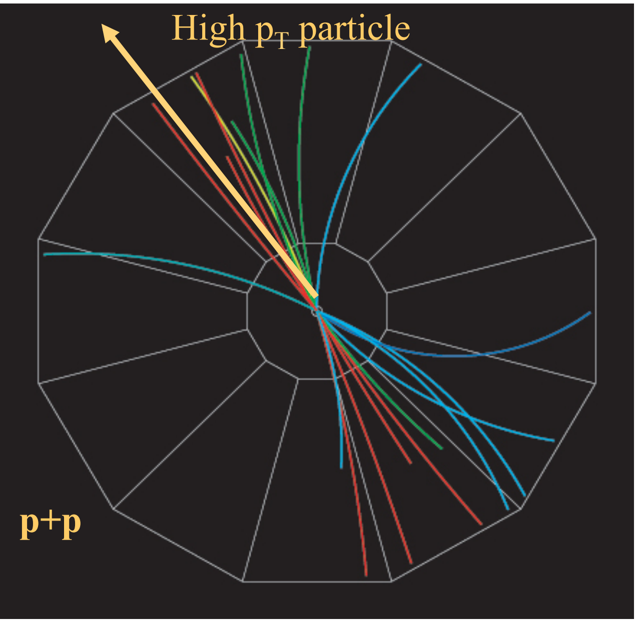
Three things are dramatically different in Relativistic Heavy Ion Physics than in p-p physics

- the multiplicity is ~A~200 times larger in AA central collisions than in p-p ⇒huge energy in jet cone: 300 GeV for R=1 at $\sqrt{s_{NN}}$=200 GeV
- huge azimuthal anisotropies which don't exist in p-p which are interesting in themselves, and are useful, but sometimes troublesome.
- space-time issues both in momentum space and coordinate space are important in RHI : for instance what is the spatial extent of parton fragmentation, is there a formation time/distance?

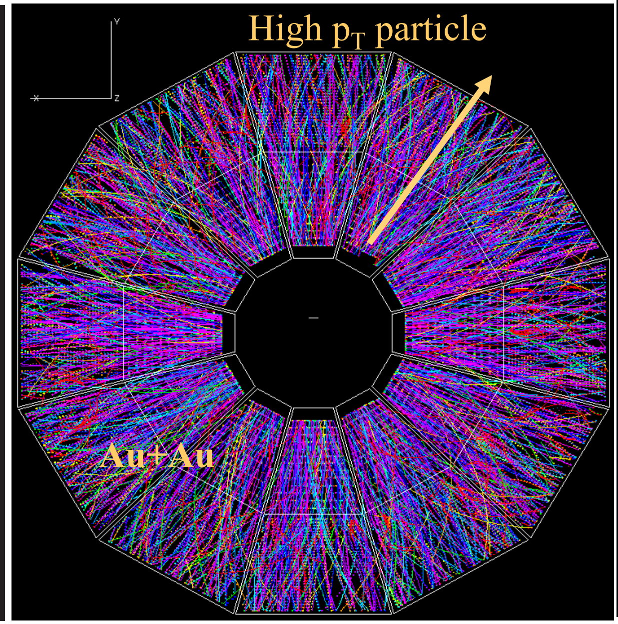


AuAu Central Collisions cf. p-p

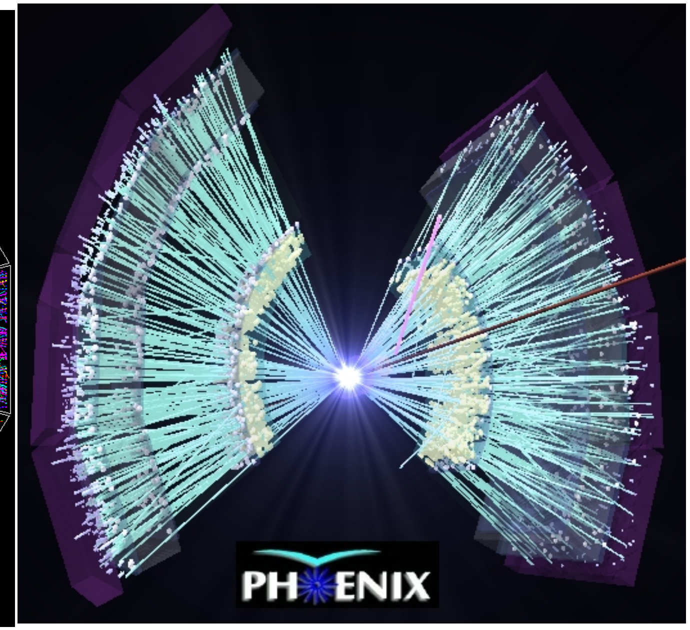
STAR-Jet event in pp

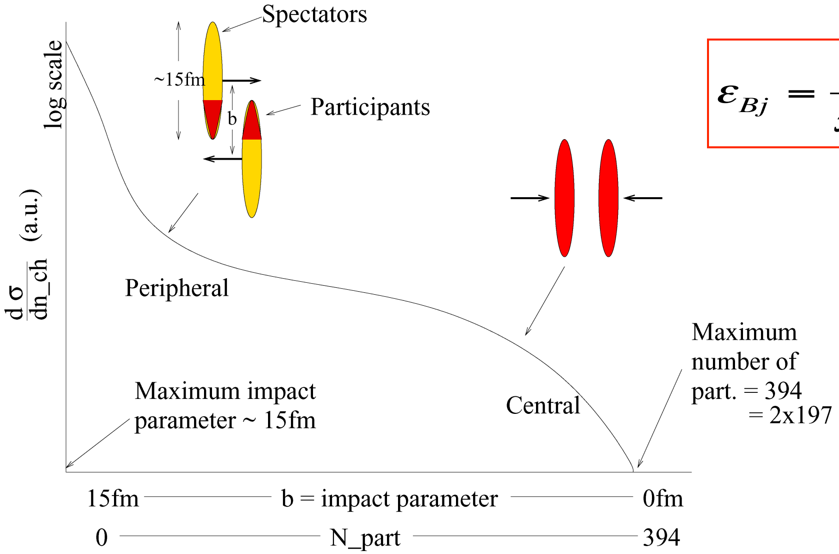


STAR Au+Au central

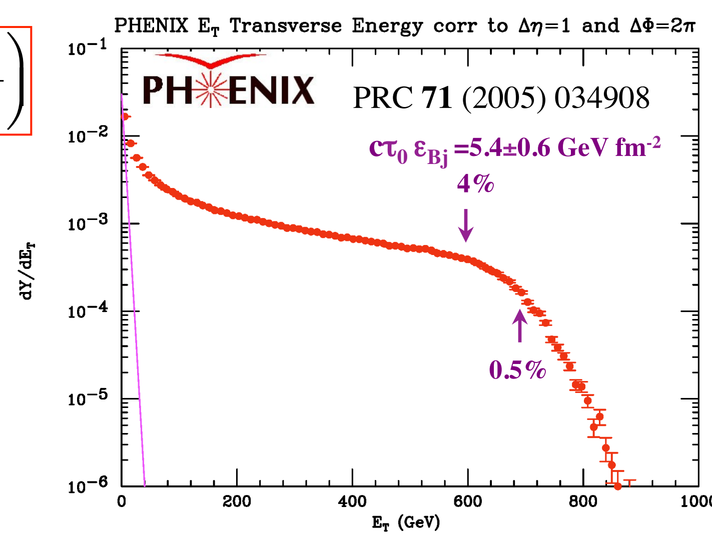


PHENIX Au+Au central

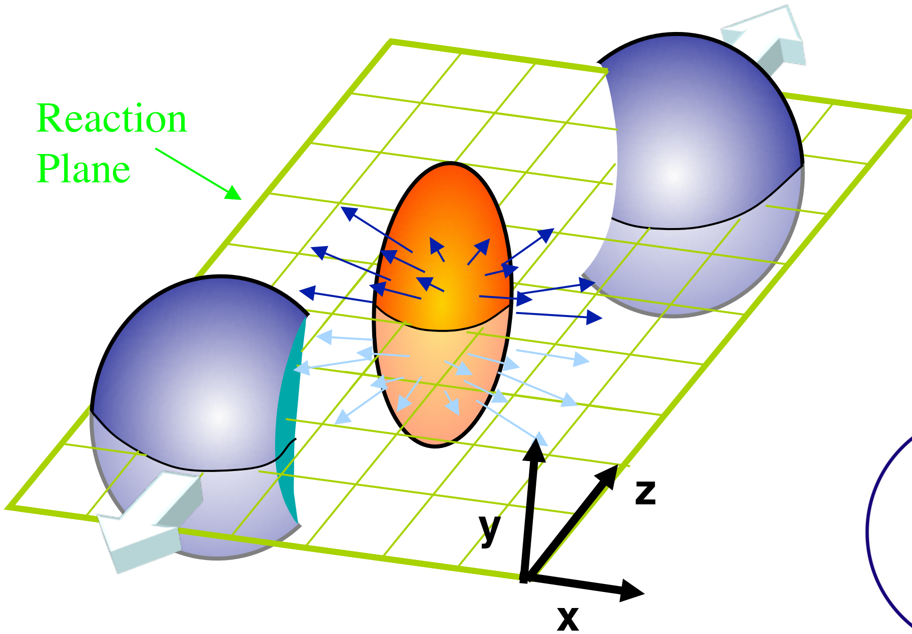




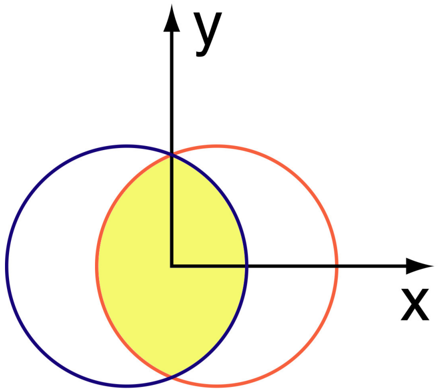
$$\boxed{\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)}$$

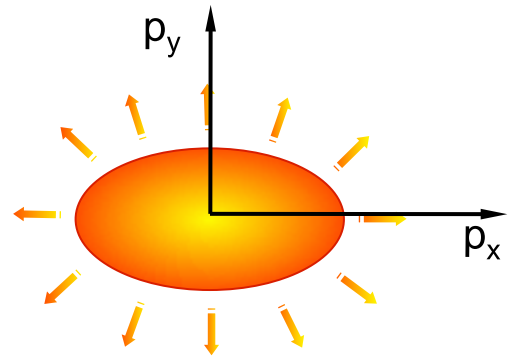


Anisotropic (Elliptic) Transverse Flow--an Interesting complication in AA collisions



- spatial anisotropy⇒ momentum anisotropy





$$\phi = \operatorname{atan}\frac{p_y}{p_x}$$

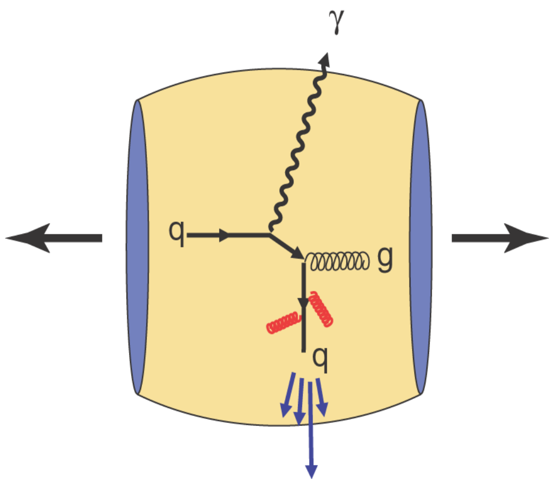
$$\frac{Ed^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^3N}{2\pi\, p_T dp_T dy}[1+2v_1\cos(\phi-\Phi_R)+2v_2\cos 2(\phi-\Phi_R)+\cdots]$$

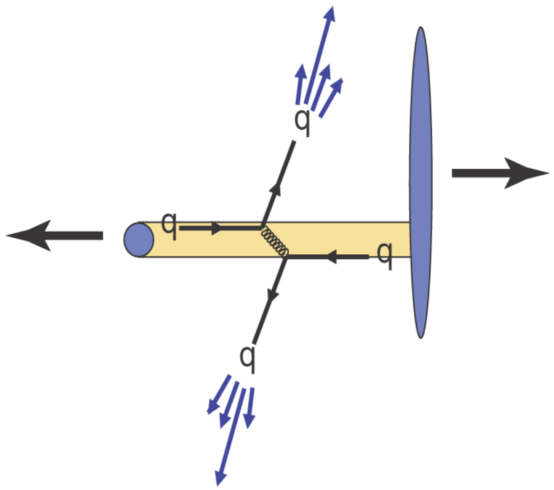
$$v_1 = \langle \cos\phi \rangle \qquad v_2 = \langle \cos 2\phi \rangle$$

Directed flow zero at midrapidity	Elliptical flow dominant at midrapidity

- Perform a Fourier decomposition of the momentum space particle distributions in the x-y plane
  - ✓ v_2 is the 2nd harmonic Fourier coefficient

Hard scattering as a probe of the medium: Hot (AA) vs Cold pA Nuclear Matter Effects





Hard scattering of partons in the initial collision is in-situ internal probe of medium. Do quarks and gluons lose energy in the medium? If so exactly how?

In p+A or d+A, medium is small, (1 nucleon wide) or non-existent. This is baseline for any cold nuclear matter effect in initial collision

- RHIC is versatile
  - ✓ Can collide any nuclear species on any other

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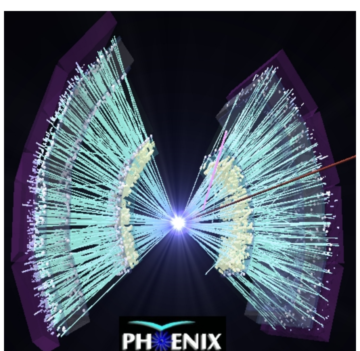


Let's write a Textbook on QGP Physics

QGP

Physics

A Course Given by ENRICO FERMI
at the University of Chicago. Notes Compiled by
Jay Orear, A. H. Rosenfeld, and R. A. Schluter

Revised Edition

CHAPTER I. PROPERTIES OF NUCLEI

CHAPTER II. INTERACTION OF RADIATION WITH MATTER

After 15 years at RHIC and 4 years at LHC, we could do a fair job on chapter 1, Properties of the QGP, but for Chapter 2, the Interaction of quarks and gluons and other radiation with the QGP, I don't know. I have not seen evidence that provides convincing proof of any theory or model. I don't know any valid formula comparable to Bethe-Bloch for ionization loss or Bethe-Heitler for radiation.

How it began (for me)
MJT@Snowmass 1982

STANDARD MODEL GROUP, QCD SUBGROUP - DYNAMICS
ISOLATING AND TESTING THE ELEMENTARY QCD SUBPROCESS*

Michael J. Tannenbaum
Brookhaven National Laboratory, Upton, New York 11973

Introduction

QCD to an experimentalist is the theory of interactions of quarks and gluons. Experimentalists like QCD because QCD is analogous to QED. Thus, following Drell and others[1] who have for many years studied the validity of QED, one has a ready-made menu for tests of QCD. There are the static and long distance tests such as:

- the value of the coupling constant α_s
- the shape of the QCD potential and "onia" spectroscopy in analogy to atomic spectroscopy and tests of Coulomb's law at large distances. (One might try to imagine the QCD analogue of g-2 and the Lamb shift.)
- tests of confinement: i.e., can you break up a proton into 3 quarks?

These topics are covered by Peter LePage in the static properties group. In this report, dynamic and short distance tests of QCD will be discussed, primarily via reactions with large transverse momenta.

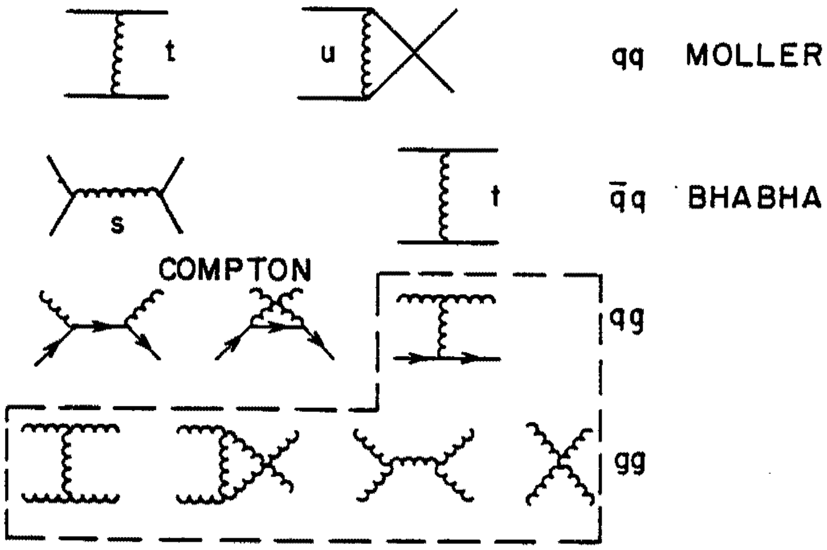
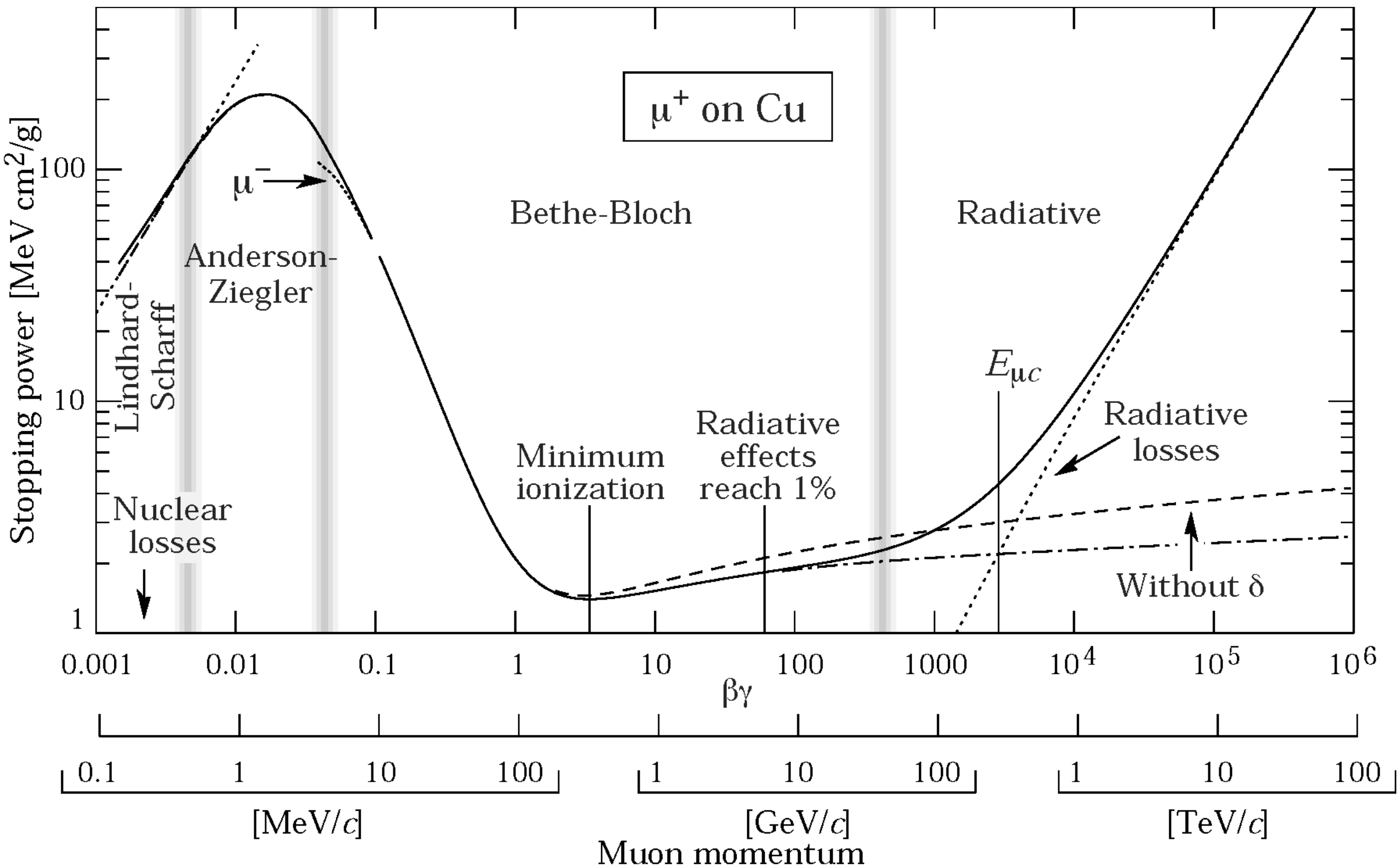


FIGURE 1

i.e. Experimentalists like QCD because QCD is *like* QED.

An example from QED, Muon dE/dx vs E



I would like to see something like this for q and g in QGP

Even this was not straightforward, e.g. see MJT CERN-PPE-94-134.

The gold-plated signature for the QGP c.1986
J/ψ Suppression

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
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and

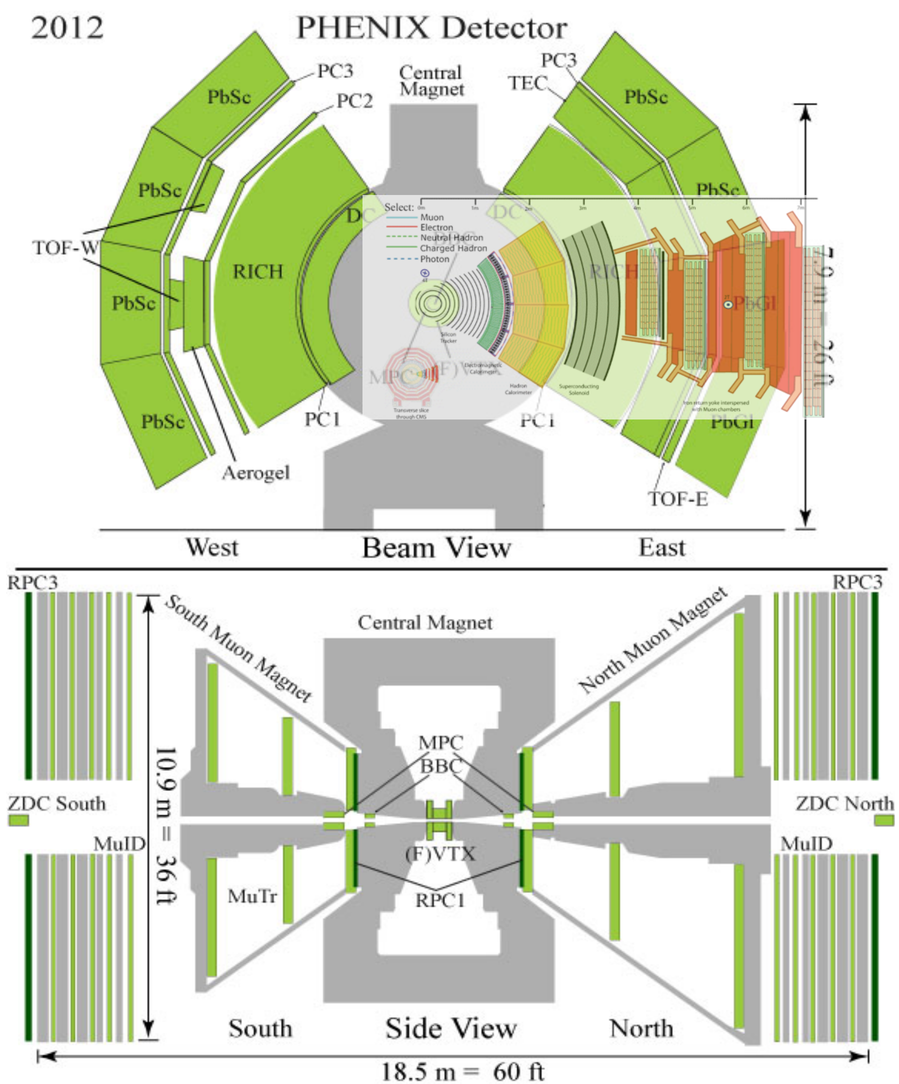
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

$$V = \frac{-4\,\alpha_s}{3\;\;r} + \sigma\, r \Rightarrow \frac{-4\,\alpha_s}{3\;\;r}\, e^{-\mu(T)r} + \sigma\,\frac{(1 - e^{-\mu(T)r})}{\mu(T)}$$

We designed PHENIX explicitly to make this measurement (and lots of others)



- **PHENIX is a special purpose detector designed and built to measure *rare processes* involving *leptons and photons* at the *highest luminosities*.**

✓ *possibility of zero magnetic field on axis*

✓ *minimum of material in aperture 0.4% X_o*

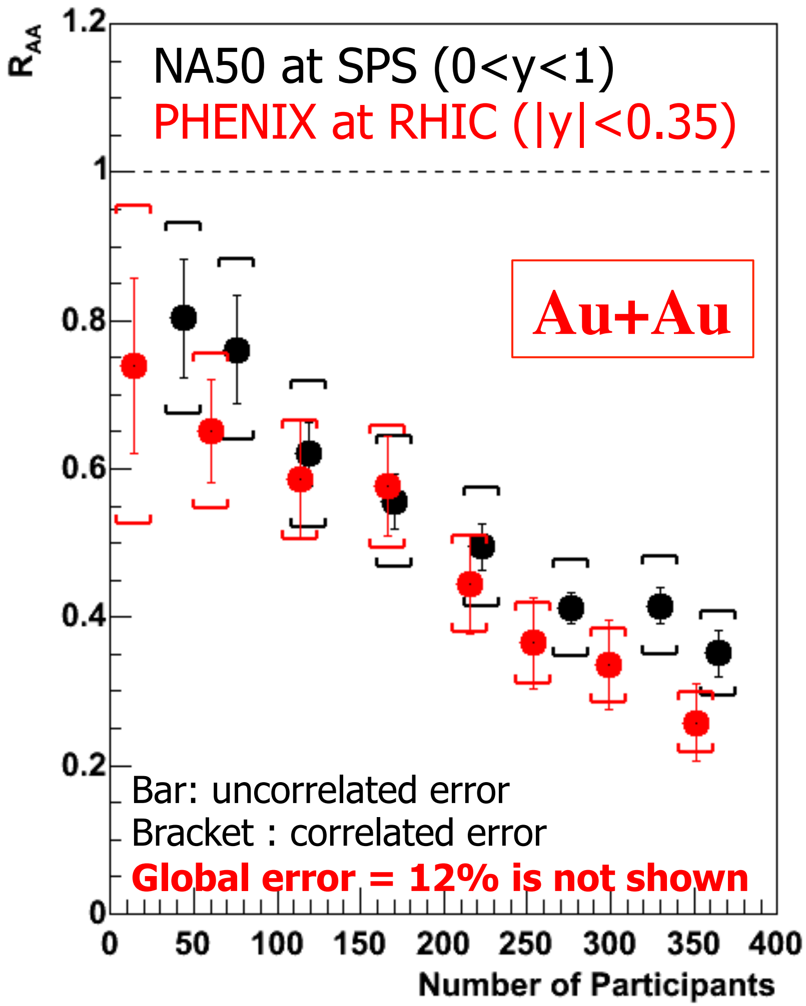
✓ *EMCAL RICH $e^{\pm}$ i.d. and lvl-1 trigger*

- *γ π^0 separation up to $p_T \sim 25$ GeV/c*
- *EMCAL and precision TOF for $h^{\pm}$ pid*

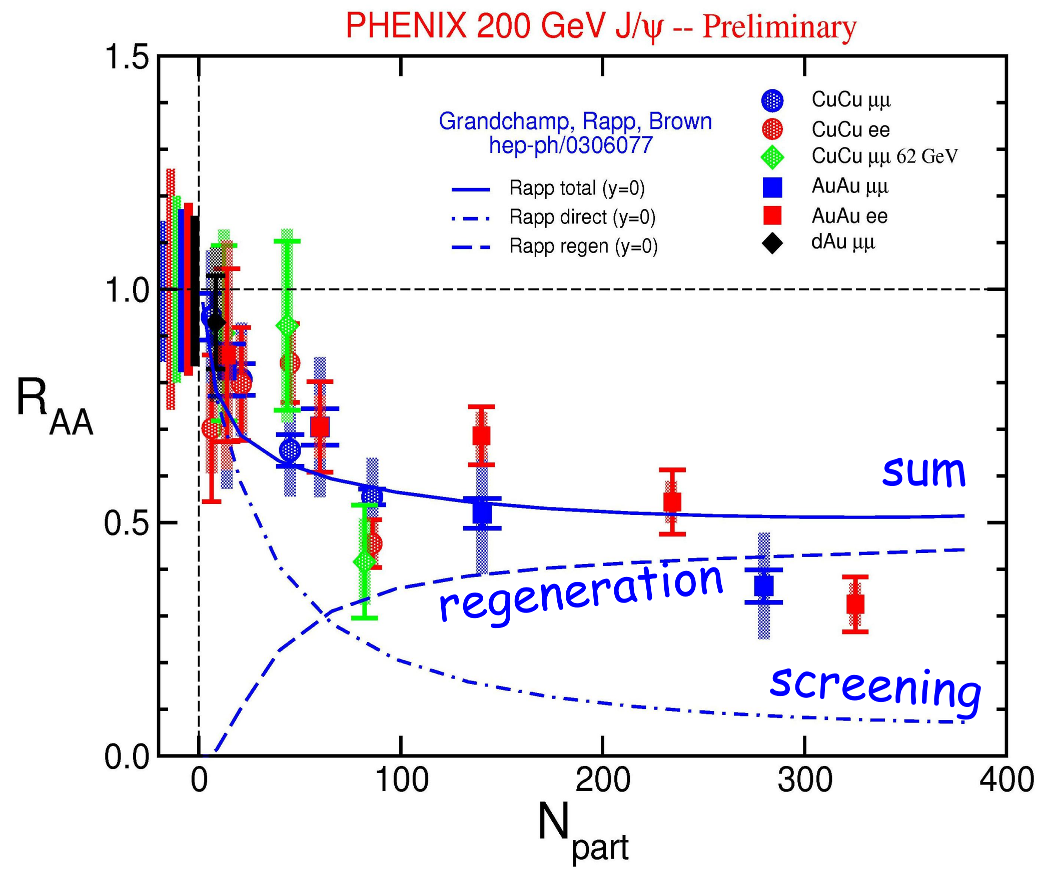
For the record: I was always skeptical of J/ψ suppression for the QGP because it was also “suppressed” in p+A collisions

Comparison to scale with a wedge of CMS

Maybe I was right?



PHENIX PRL **98**, 232301 (2007)



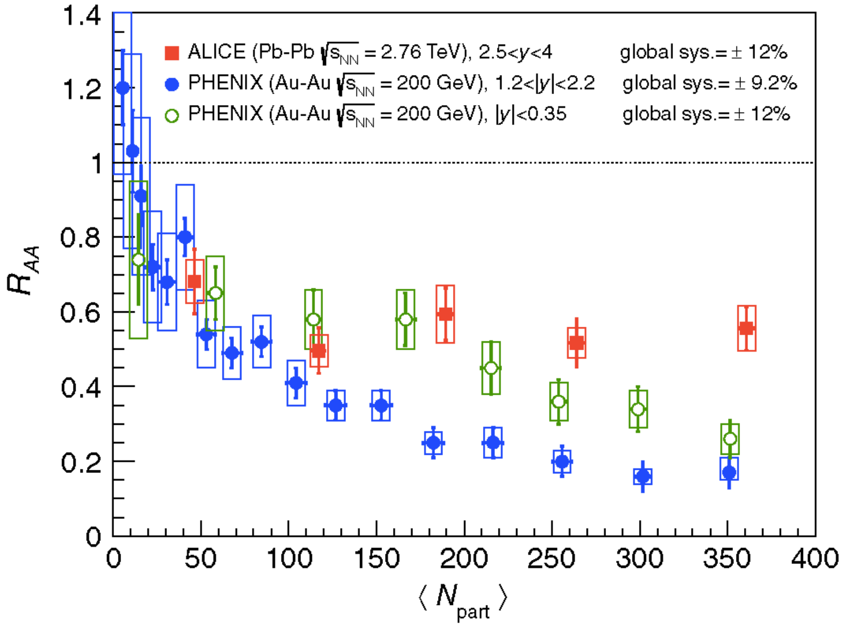
Grandchamp, Rapp, Brown;

- ✓ In-media dissolution
- ✓ Plus regeneration from "off-diagonal" c-cbar pairs

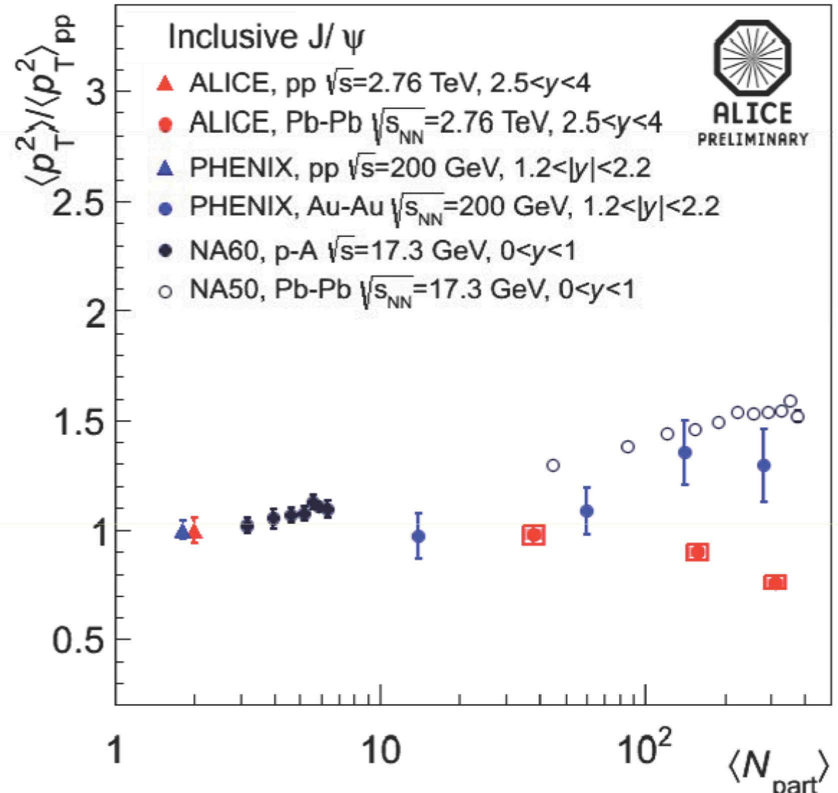
J/ψ suppression same at $\sqrt{s_{NN}}$ =17.2 and 200 GeV ---> the Nightmare Scenario

The Nightmare is that nobody will believe this. Must see J/ψ enhancement to believe⇒LHC result

LHC data ALICE



ALICE PRL **109**, 072301 (2012)



Less J/ψ suppression at $\sqrt{s_{NN}}$ =2.76 TeV than 200 GeV ---clear regeneration but according to H. Satz this is neither J/ψ suppression or enhancement since J/ψ/cc-bar is the same in pp and AA while at RHIC a clear suppression of this ratio.

From P. Giubellino-ISSP2013. He claimed that decrease in $<p^2_T>$ with centrality proved deconfinement. I claim that deconfinement would remove low p_T J/ψ hence increase $<p^2_T>$; MJT thinks coalescence would increase low p_T J/ψ so proves regeneration.

http://www.ift.uni.wroc.pl/~mborn31/Talks/redborn-Satz.pdf

MJT-Strangeness 1996 Budapest

APH N.S., Heavy Ion Physics **4** (1996) 139-148

HEAVY ION PHYSICS
©Akadémiai Kiadó

Charm in PHENIX—a signal or a background?

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Received 26 June 1996

Abstract. Charm, as well as Strangeness, plays an important role in searches for the Quark Gluon Plasma. J/Ψ Suppression and Strangeness Enhancement are two of the earliest proposed QGP signatures. Recent theoretical work on charm in Relativistic Heavy Ion collisions has focussed on dilepton production. However, even before the discovery of the J/Ψ, evidence of open charm was seen in hadron collisions via the observation of prompt **single** leptons "resulting from the semi-leptonic decays of charm particles."[1] The 'copious' yield of

MJT-We designed PHENIX to detect electrons with $p_T \geq 0.5$ GeV/c with 10^{-4} rejection at the trigger level. Should be able to detect prompt-single $e^{\pm}$ from *c* and *b* quark decay with no COMBINATORIC background, so why not look? At the time, theorists only discussed charm as a background to di-lepton production, not a signal. Prompt-single $e^{\pm}$=charm discovered at CERN-ISR by MJT and others: CCRS, Nucl. Phys. B113(1976)189.

First qcd-based model BDMPSZ c. 1997

I don't want to discuss models in detail, since they are nothing like QED or QCD, theories that you can set your watch by (at least QED). I just mention this one example which stimulated the use of hard-probes at RHIC. See Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. **50**, 37.

It is interesting to note that the original STAR Letter of Intent (LBL-29651) in 1990 following Wang and Gyulassy (LBL-29390) did cite as one objective: "the use of hard scattering of partons as a probe of high density nuclear matter... "Passage through hadronic or nuclear matter is predicted to result in an attenuation of the jet energy and broadening of jets. Relative to this damped case, a QGP is transparent and an enhanced yield is expected."

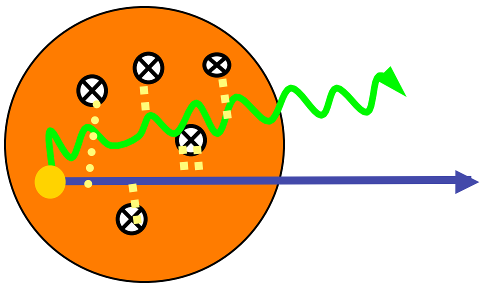
Of course this is precisely the opposite of what was actually discovered at RHIC. For a timely (c. 1990) discussion of High p_T and QGP, see MJT BNL-45696. Frankly, it was known since theoretical explanations of Busza's original p+A measurements (see MJT arXiv: 1309.4678) that in a nucleus, due to relativity and Quantum Mechanics, a struck nucleon can only become an excited nucleon with roughly the same energy, but reduced longitudinal momentum and rapidity, and that it is relatively unaffected by being struck again. It remains in that state inside the nucleus because time dilation and the uncertainty principle prevent it from fragmenting into particles until it is well outside the nucleus. Thus, until the QCD based models, starting with Baier, Dokshitzer, Mueller, Peigné, Schiff [NPB**483**(1997)291], which I found out about only in 1998 at the IV Workshop on QCD when Rolf Baier asked me whether we could measure jets in A+A collisions at RHIC, I described the original WangGyulassy Jet Quenching as "the vanishing of something that doesn't exist in the first place".

BDMPSZ-Energy loss of partons

- A medium effect predicted in QCD---Energy loss by colored parton in medium composed of unscreened color charges with thermal mass μ by gluon bremsstrahlung--LPM radiation-of gluons. I'm not sure whether radiated or target gluons are massive or both.
- The main parameter in the model is the transport parameter $\hat{q}$, the mean 4-momentum transfer^2/collision, $\mu^2=\mu^2_D$ expressed as the mean 4-momentum transfer^2 per elastic scattering mean free path, λ, i.e. $\hat{q}=\mu^2/\lambda$. In various models $\hat{q}\sim$1-20 GeV^2/fm, which corresponds to elastic scattering m.f.p. of $\lambda=\mu^2/\hat{q}\sim 0.5^2/1\text{-}20=0.25\text{-}0.0125$ fm, small enough to explain rapid thermalization. Also coherent LPM --> dE/dx~L.
- MJT thinks that $\mu=\mu_D\sim 0.5$ GeV must imply broadening of di-jet correlation.

- Unfortunately there are no general simple formulas, for instance Vitev, PLB606(2005)303:

$$\frac{\langle \Delta E \rangle}{E} \approx \frac{9 C_R \pi \alpha_s^3}{4} \frac{1}{A_\perp} \frac{dN^g}{dy} L \frac{1}{E} \ln \frac{2E}{\mu^2 L} + \cdots$$



- But this formula says ΔE/L ≈ ln (E/L) --> Doesn't look radiative like BDMPSZ

(soft) BDMPS medium-induced GLUON SPECTRUM

radiation spectrum per unit path length

characteristic behaviour:

- totally incoherent Bethe-Heitler regime:

$\omega \leq \omega_{BH} = \lambda\mu^2$

$$\frac{\omega dI}{d\omega dz} \propto \frac{\alpha_s}{\pi}\frac{1}{\lambda} \quad \rightarrow \quad \frac{\omega dI}{d\omega} \propto \frac{\alpha_s}{\pi}\frac{L}{\lambda}$$

- coherent LPM regime:

$\lambda < t_{coh} < L, \quad N_{coh} >> 1, \quad \omega > \omega_{BH}$

$$\frac{\omega dI}{d\omega dz} \propto \frac{\alpha_s}{\pi}\frac{1}{t_{coh}} \quad \rightarrow \quad \frac{\omega dI}{d\omega} \propto \frac{\alpha_s}{\pi}\sqrt{\frac{\omega_c}{\omega}}$$

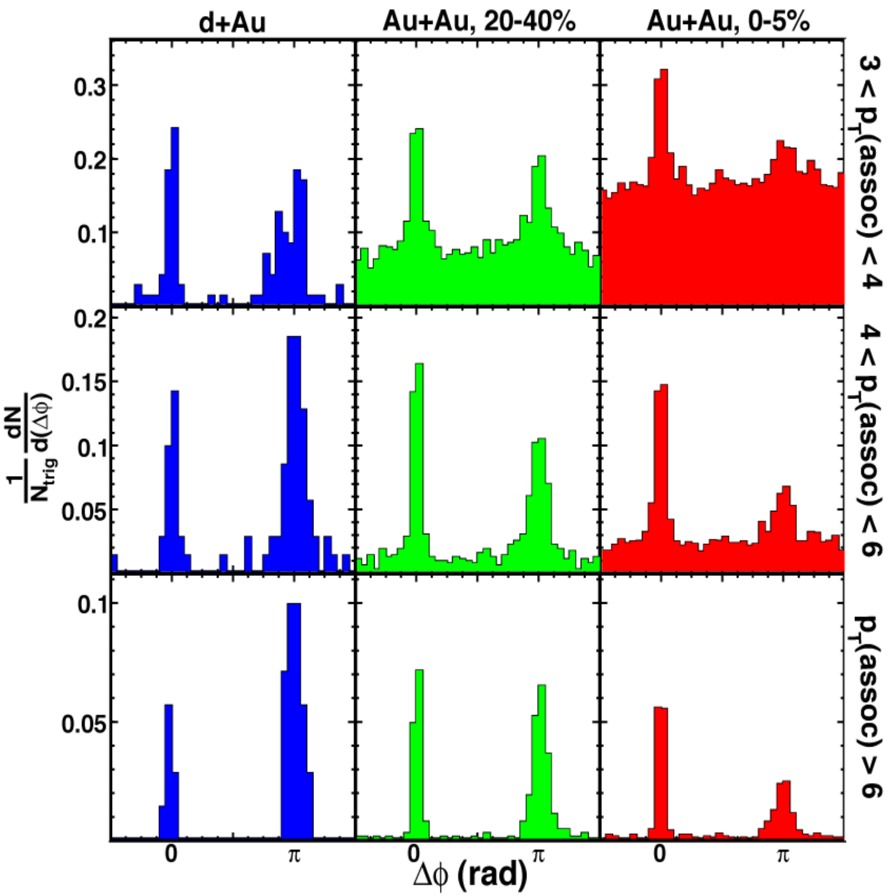
Quenched large $p_\perp$ π^0 spectra – p.10

Why is q-hat not visible in di-jet broadening?

Also, Rolf thinks that it is possible for a parton to emerge from the center of the medium without a large energy loss (i.e. no LPM) , only BH , which Salgado and Wiedemann seem to have ignored and which is the result of multiple scattering with total $Q^2=\mu^2 L/\lambda=\hat{q}L$, where L is the length of the medium traversed. However, this accentuates something that is puzzling to me. Why has nobody ever seen evidence for this?

STAR [Phys. Rev. Lett. **97**, 162301 (2006)] has reported that in events triggered by a charged particle with $p_{T_t} \geq 8$ GeV/c, in Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV, away-side jet correlations with the same width as in p-p (actually d+Au) collisions reappear, or 'punch-thru', for particles with away side $p_{T_a} \geq 3$ GeV/c. However, I expect that since the $Q^2 = \hat{q}L \sim 10-20$ GeV^2 (which corresponds to $5-10$ (GeV/c)^2 smearing in azimuth) is comparable to the $k_T^2 = 7.2 \pm 1.8$ (GeV/c)^2 smearing of the away jet in p-p collisions at $\sqrt{s} = 200$ GeV [PHENIX Phys. Rev. D**74**, 072002 (2006)], it should easily be visible as an azimuthal width of the punch-thru peak in Au+Au central collisions roughly $\sqrt{2}$ times larger than in p-p collisions unless $L \ll 1$ fm, i.e. the events are strongly surface biased, in which case I wonder why the 'punch-thru' depends on p_{T_t}.

STAR data AuAu: PRL 97-Newer data Later



$8 < p_{Tt} < 15$ GeV/c $\langle p_{Tt}\rangle = 9.38$ GeV/c

STAR, J. Adams, D. Magestro, et al
PRL **97**, 162301 (2006)

"For $8 < p_T^{trig} < 15$ GeV/c and $p_T^{assoc} > 6$ GeV/c, a Gaussian fit to the away-side peak finds a width of $\sigma_{\Delta\phi} = 0.24 \pm 0.07$ for d+Au and 0.20 ± 0.02 and 0.22 ± 0.02 for 20%–40% and 0%–5% Au+Au collisions, respectively."

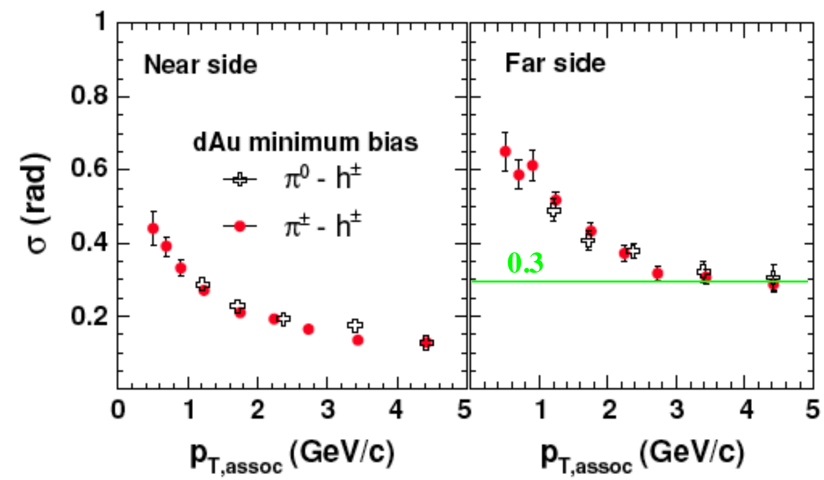
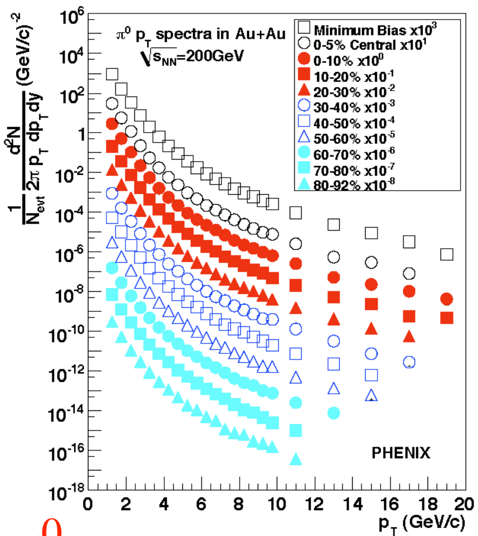


FIG. 16. (Color online) Near- and far-side widths as a function of $p_{T,\mathrm{assoc}}$ from pion-hadron azimuthal correlations for charged pion (closed symbols) and neutral pion (open symbols) triggers from the $p_{T,\mathrm{trig}}$ range of 5–10 GeV/c in minimum-bias d + Au collisions (see text). Bars are statistical errors.

PHENIX ppg039 PRC **73,** 054903 (2006)

The most important innovation at RHIC was the use of hard-scattering as an in-situ probe of the medium in RHI collisions

RHIC Physics is Precision Science

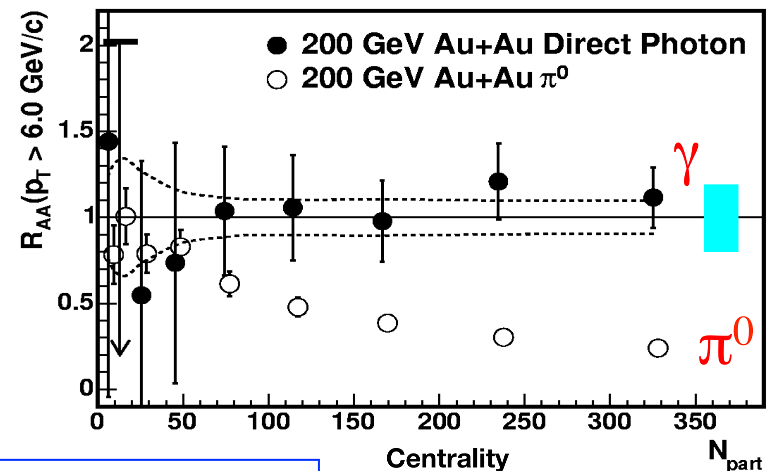


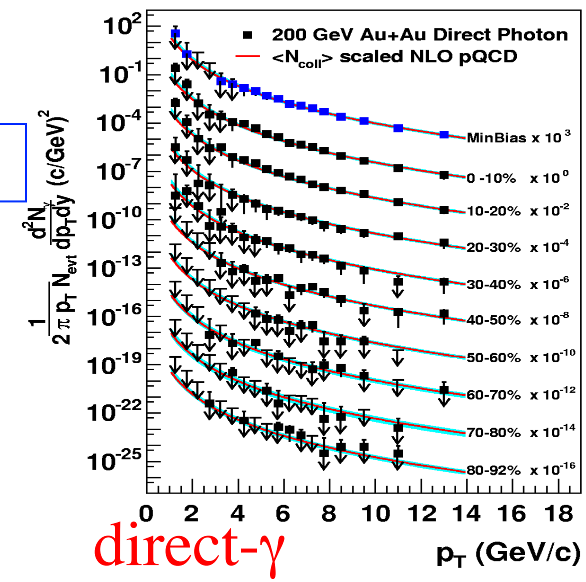
π^0

- This one figure encodes rigorous control of systematics

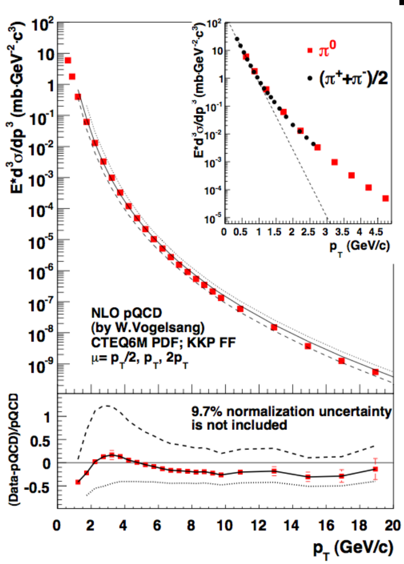
PRL**94** (2005) 232301

PRL**101** (2008) 232301



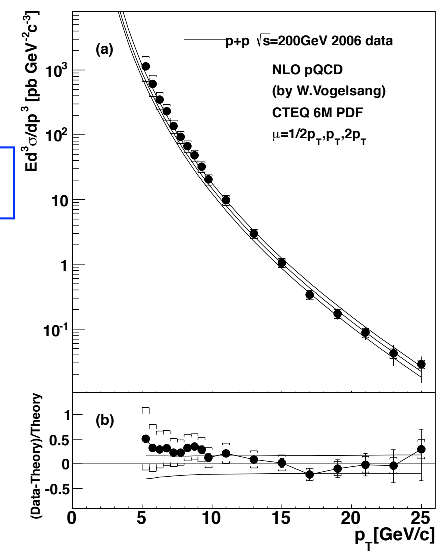


direct-γ



PRL**91** (2003) 241803

PRD **86** (2012) 072008



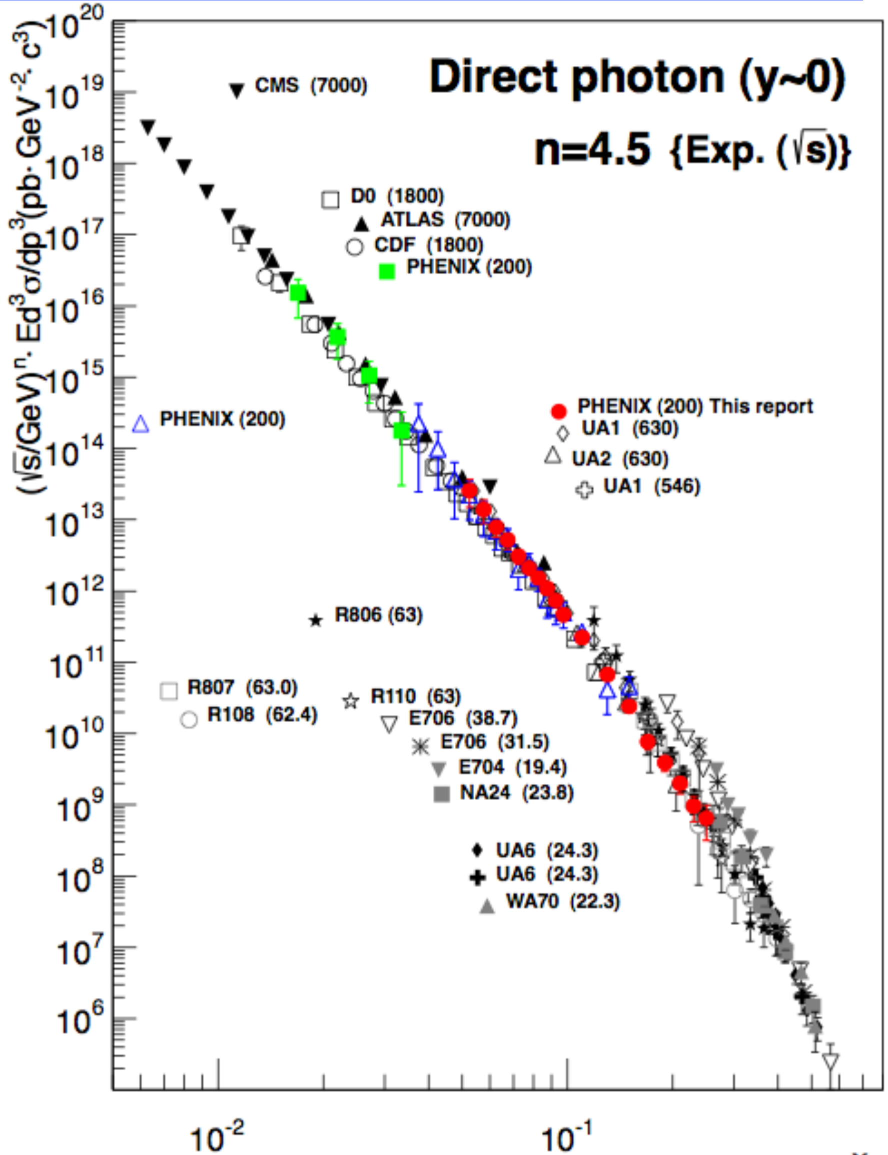
- in four different measurements over many orders of magnitude

Direct photons unaffected by QGP medium in Au+Au →
π^0 suppression is medium effect

QCD in Action 2012 in Direct γ production g+q→γ+q

See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320

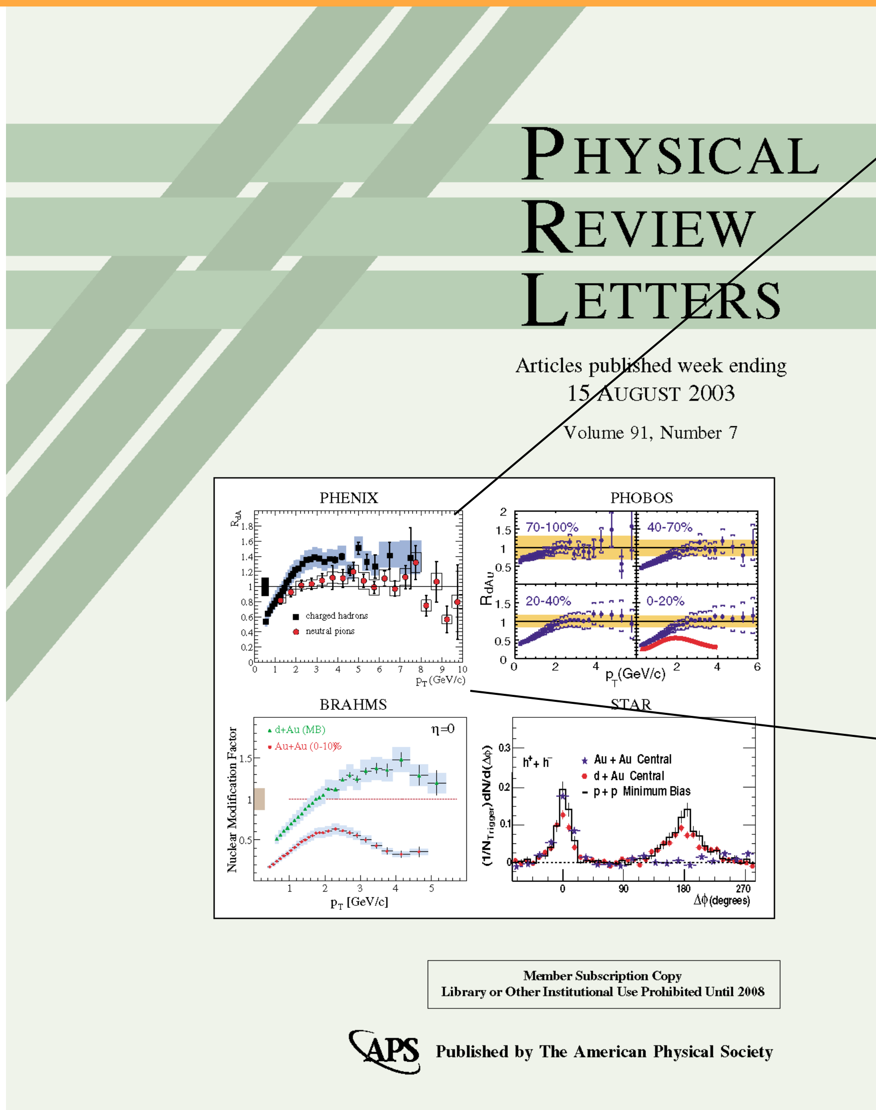
Plot by PHENIX Phys. Rev. D86(2012) 072008

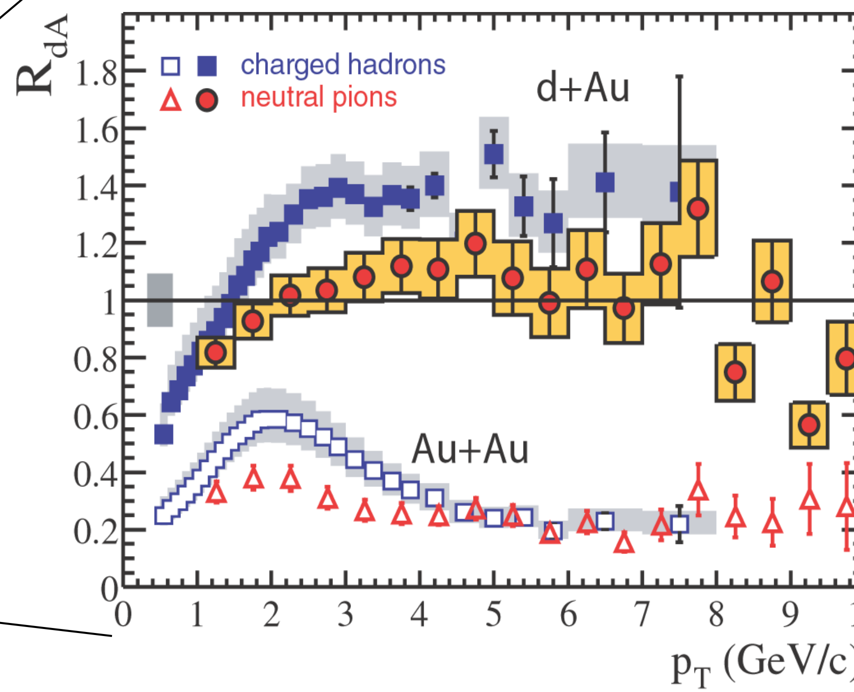


x_T scaling with n_{eff}=4.5 works for direct-γ due to QCD non-scaling

Collection of World's direct-γ measurements in (p+p / p+pbar) including PHENIX low p_T msmt. PRL104(2010)132301and PRC87(2013)054907

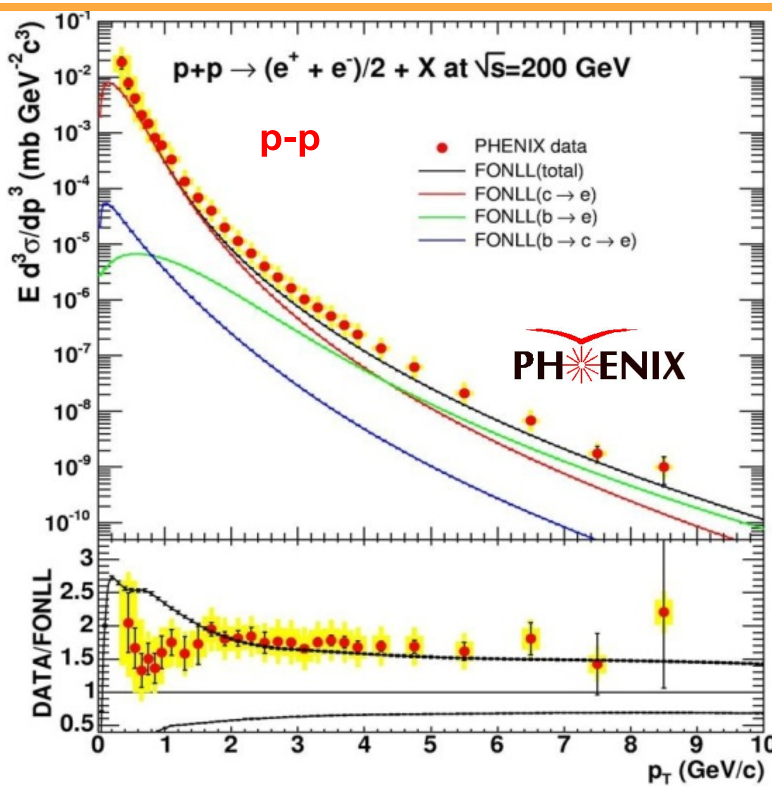
π^0 are suppressed in Au+Au but not in d+Au
$\Rightarrow$ suppression is due to hot matter

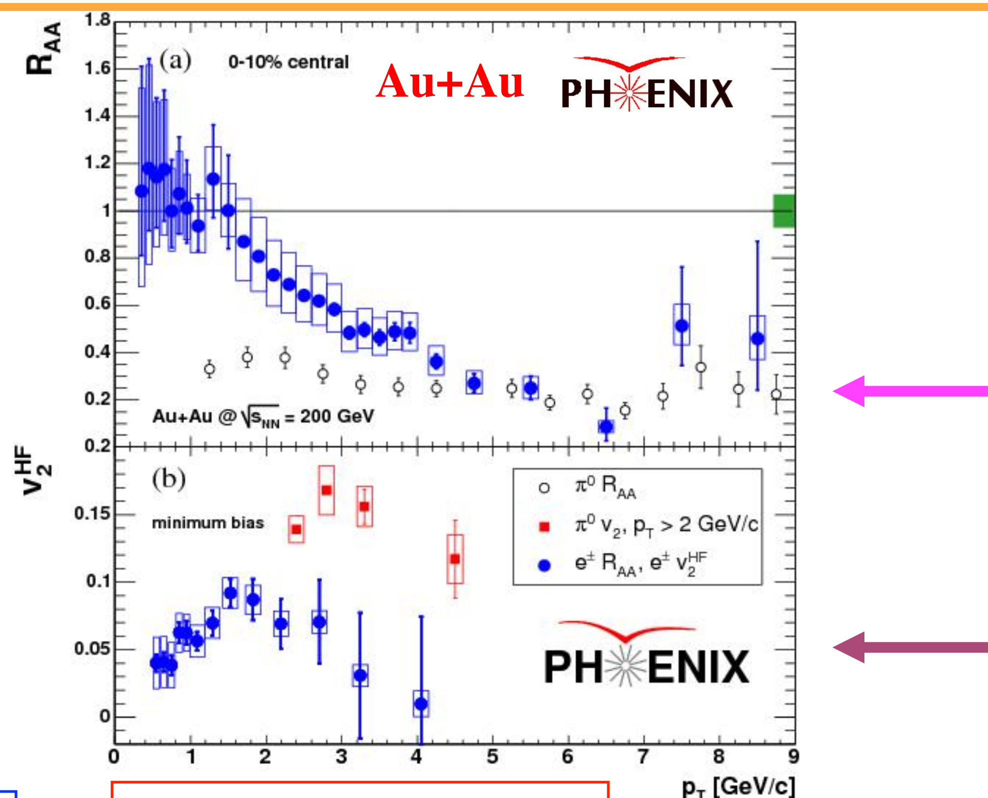




$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA}/dp_T dy N^{inel}_{AA}}{\langle T_{AA}\rangle d^2\sigma^{\pi}_{pp}/dp_T dy}$$

QM2006-Direct e± in Au+Au indicate a theoretical crisis



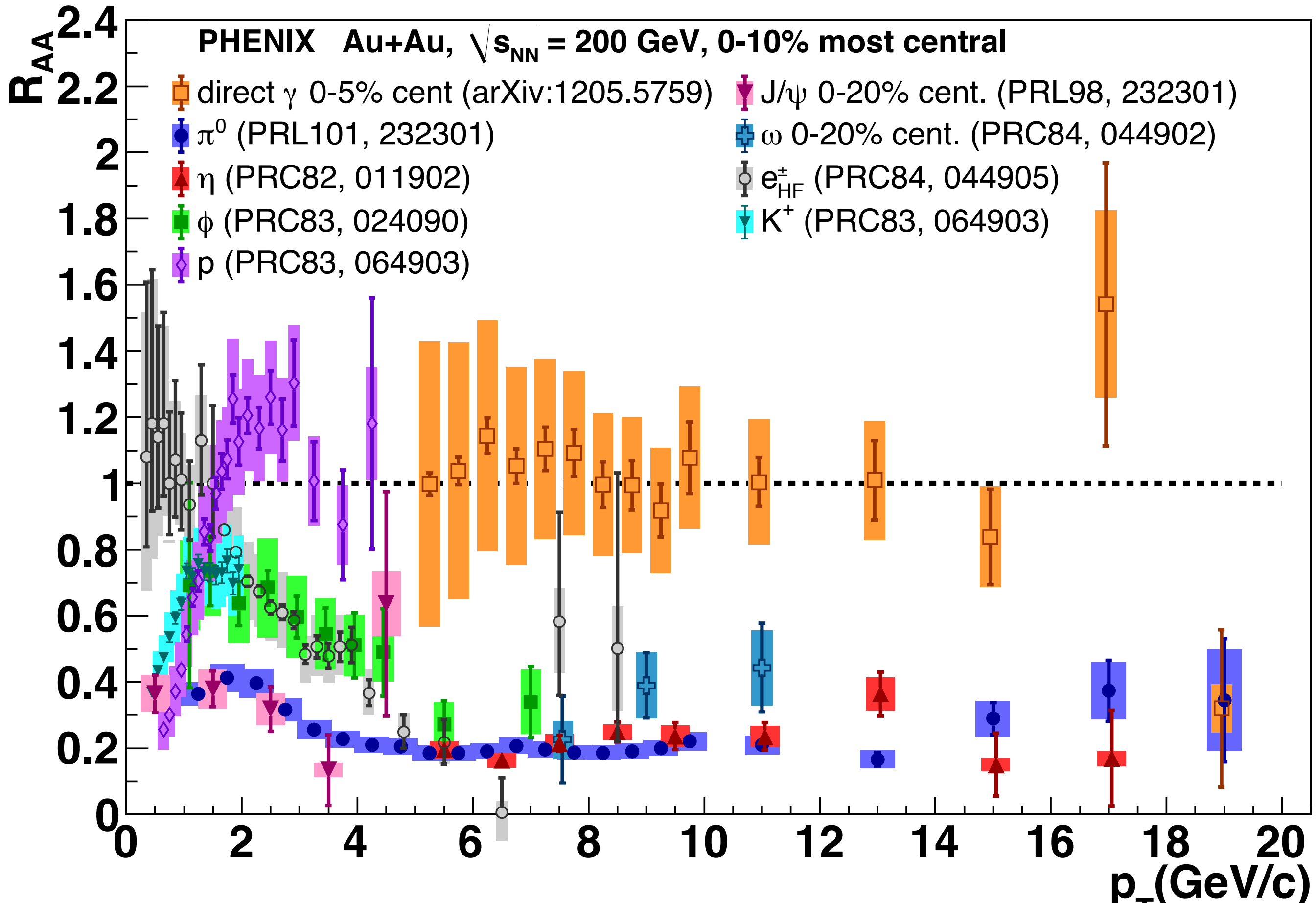


p-p beautiful agreement of e± with *c b* production PHENIX PRL**97**(2006)252002

Au+Au PHENIX
PRL **98** (2007)172301

Heavy quarks suppressed the same as light quarks (opposite of what was predicted) and they flow, but less. This discovery provided a demonstration that heavy quarks were strongly coupled to the medium, with viscosity/entropy density $\eta/s \approx (1.3\text{-}2)/4\pi$, close to the quantum lower bound, reinforcing the `perfect fluid' and stimulating a broad spectrum of possible explanations. See references in IJMPA**29**(2014)1430017.

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV 2013

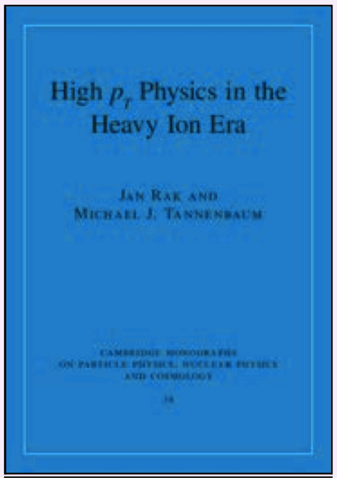


particle ID is crucial: different particles behave differently

Notable are that ALL particles are suppressed for p_T>2 GeV/c (except for direct-γ), even electrons from c and b quark decay; with one notable exception: the protons are enhanced-(baryon anomaly)

If the previous slides went by too fast

- I wrote a book with Jan Rak with all this kind of information, "High p_T physics in the Heavy Ion Era", Cambridge 2013 where you can review this information. It is probably available either in hard cover or as an eBook in the Yale Physics Library.



View larger image

High-pT Physics in the Heavy Ion Era

Jan Rak, University of Jyväskylä, Finland
Michael J. Tannenbaum, Brookhaven National Laboratory, New York

Hardback

Series: Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology(No. 34)

ISBN:9780521190299

396pages
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Dimensions: 247 x 174 mm
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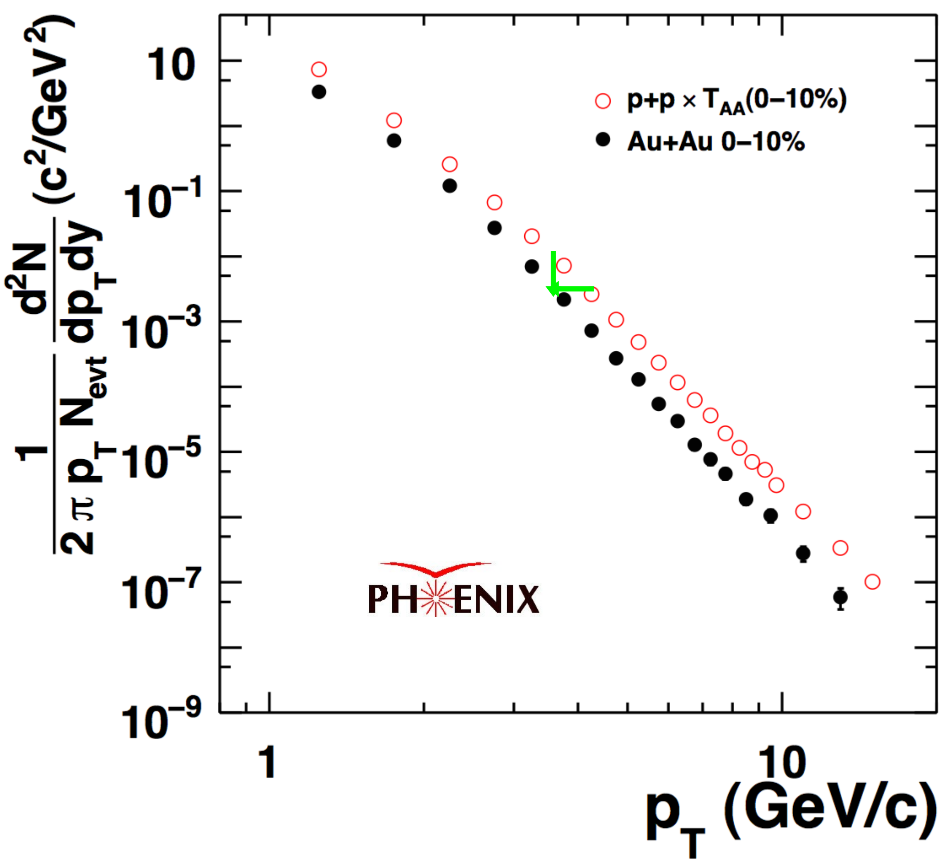
Aimed at graduate students and researchers in the field of high-energy nuclear physics, this book provides an overview of the basic concepts of large transverse momentum particle physics, with a focus on pQCD phenomena. It examines high-pT probes of relativistic heavy-ion collisions and will serve as a handbook for those working on RHIC and LHC data analyses. Starting with an introduction and review of the field, the authors look at basic observables and experimental techniques, concentrating on relativistic particle kinematics, before moving onto a discussion about the origins of high-pT physics. The main features of high-pT physics are placed within a historical context and the authors adopt an experimental outlook, highlighting the most important discoveries leading up to the foundation of modern QCD theory. Advanced methods are described in detail, making this book especially useful for newcomers to the field.

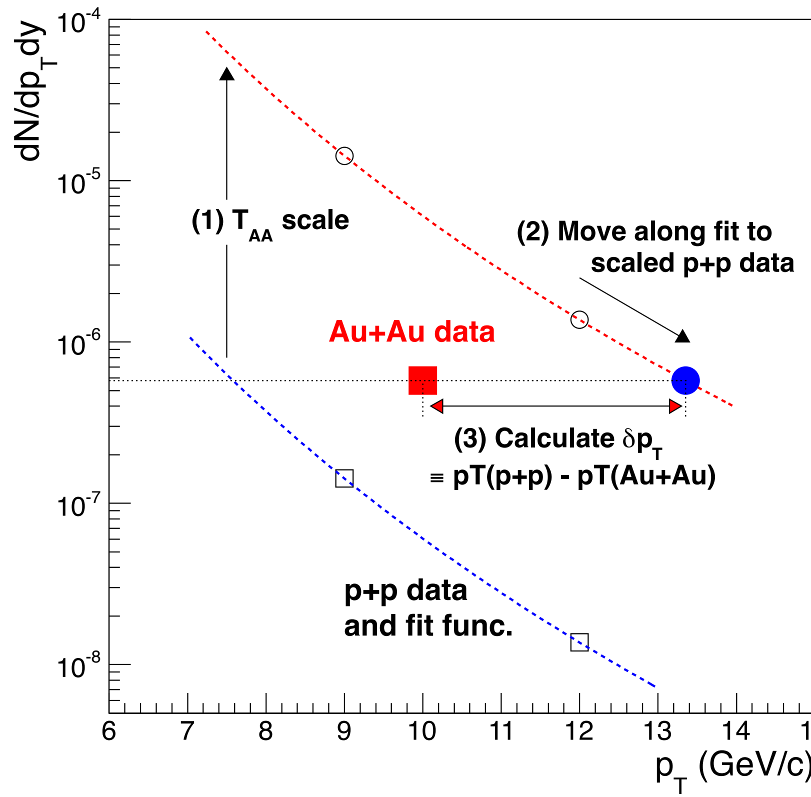
http://www.cambridge.org/knowledge/discountpromotion?code=E3RAK | 20% discount

This talk was original presented in 2013 so I go back a bit and start the new results where I left off in Utrecht 2011

RHIC π^0 pp vs AuAu

π^0 are suppressed in Au+Au eg 200 GeV





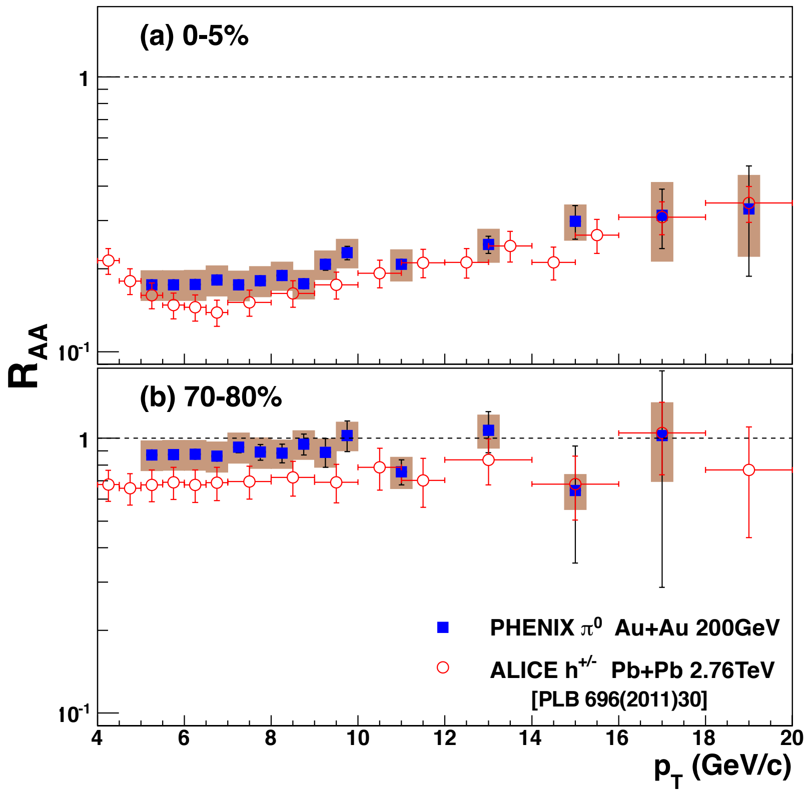
Nuclear Modification Factor

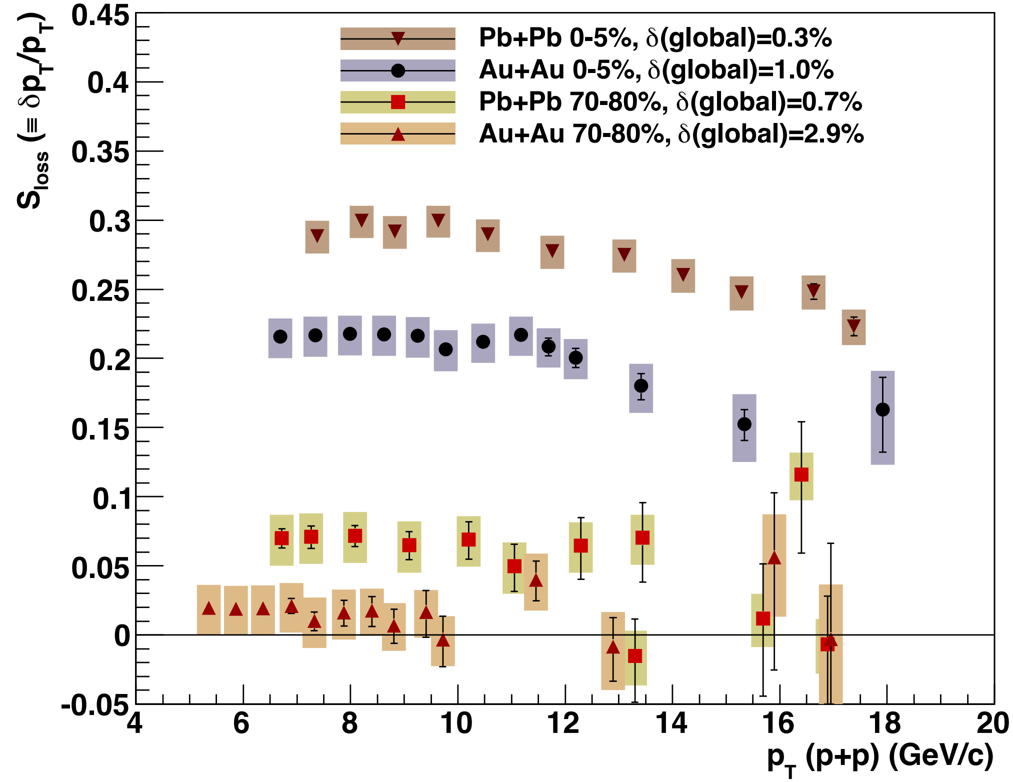
$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA}/dp_T dy N^{inel}_{AA}}{\langle T_{AA}\rangle d^2\sigma^{\pi}_{pp}/dp_T dy}$$

After a decade of the ratio R_{AA} we are now paying more attention to δp_T the shift in the p_T spectrum as an indicator of energy loss in the QGP, but first back to 2003 RHIC d+Au data

RHIC $\sqrt{s_{NN}}$=200 GeV cf. LHC $\sqrt{s_{NN}}$=2.76 TeV

PHENIX PRC **87** (2013) 034911





Agreement of ALICE $h^{\pm}$ R_{AA} with PHENIX π^0 in the overlap region $5<p_T<20$ GeV/c is incredible; BUT because invariant p_T spectrum at LHC is flatter than at RHIC, spectrum shift δp_T is 40% larger at LHC than at RHIC presumably due to the hotter and possibly denser medium.

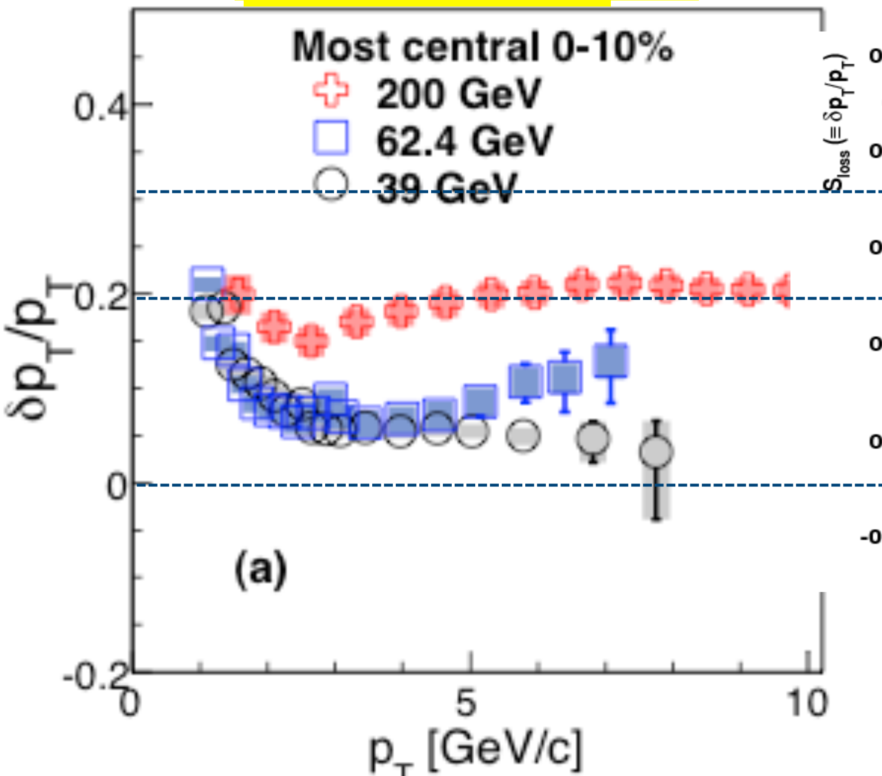
Energy dependence of $\delta p_T/p_T$

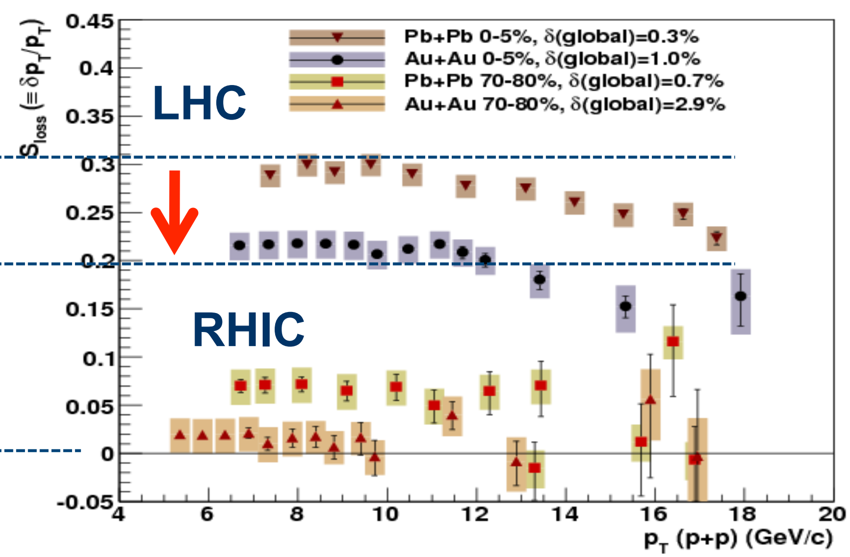
- $\delta p_T/p_T$ from 39GeV to 2.76TeV!

  steady decrease from 0.3 at LHC to 0.05 at 39 GeV

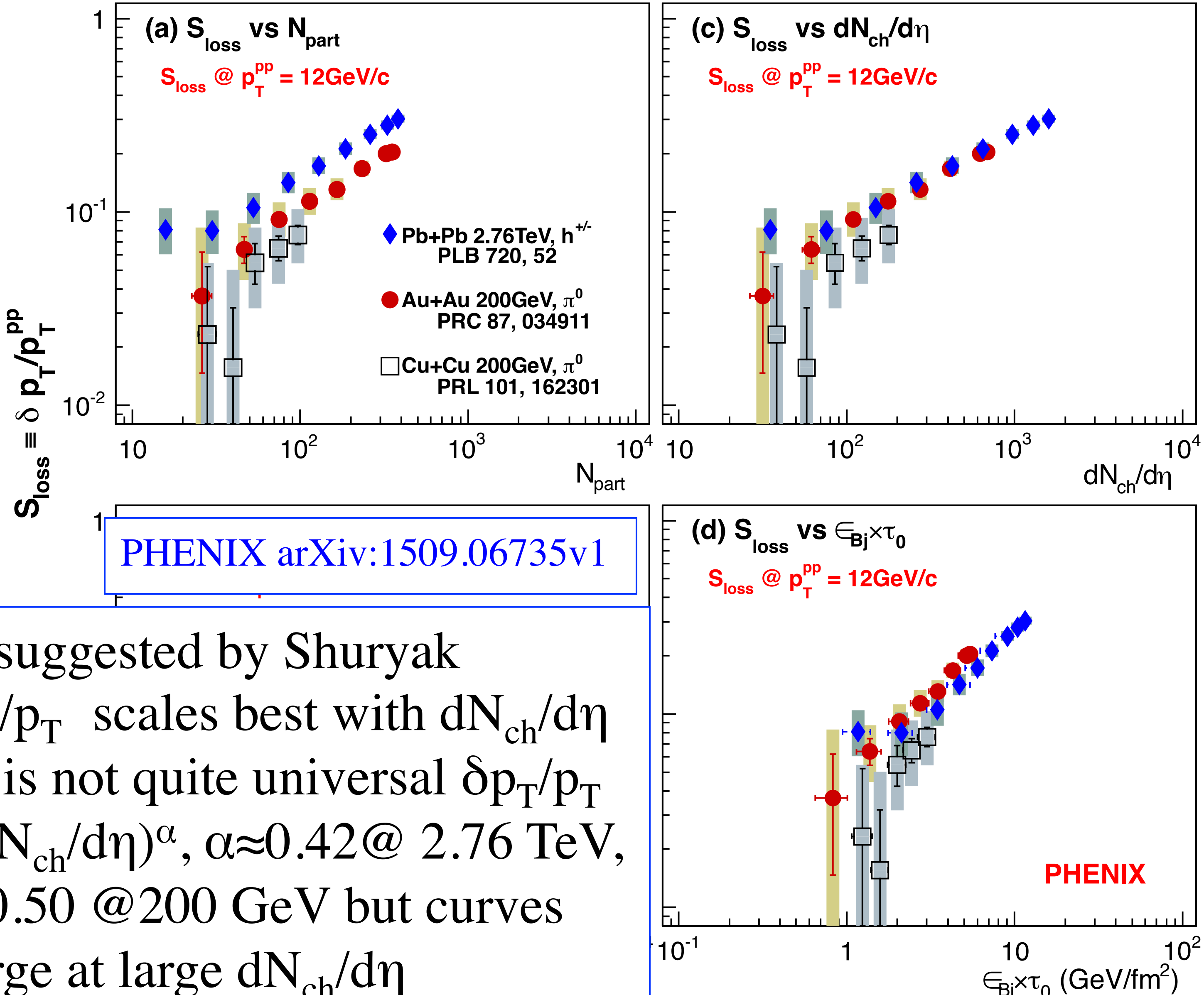
PRL 109 (2012) 152301

PRC 87 (2013) 034911





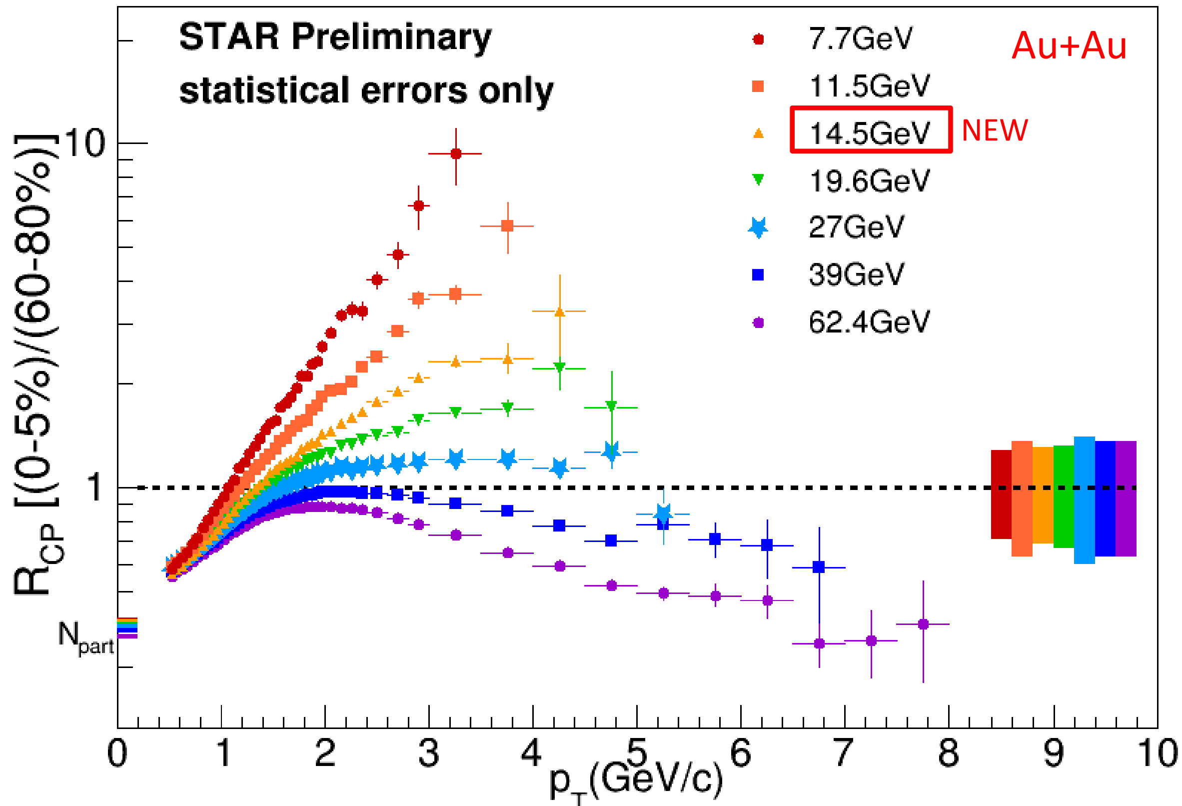
NEW-What determines energy loss $\delta p_T/p_T$?



PHENIX arXiv:1509.06735v1

As suggested by Shuryak $\delta p_T/p_T$ scales best with $dN_{ch}/d\eta$ but is not quite universal $\delta p_T/p_T \approx (dN_{ch}/d\eta)^{\alpha}$, $\alpha \approx 0.42$@ 2.76 TeV, $\alpha \approx 0.50$ @200 GeV but curves merge at large $dN_{ch}/d\eta$

BES I Charged Hadron R_{CP}



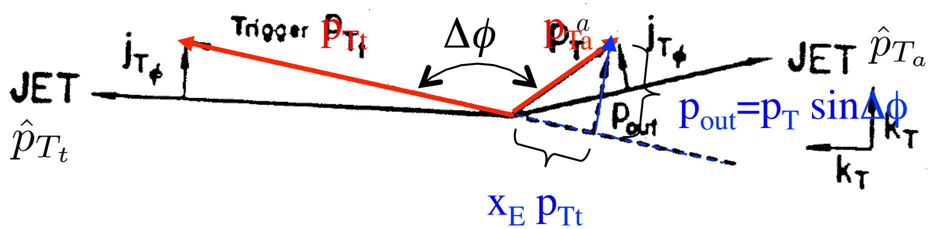
- Enhancement effects compete against suppression effects concealing the turn off of QGP formation at low $\sqrt{s_{NN}}$

MJT thinks that it actually does turn off at ≈ 30. How to find out ?

Two particle correlations: A very interesting new formula for the x_E distribution was derived by PHENIX in PRD74

High p_T LHC-2011

$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} \approx \langle m \rangle (n-1) \frac{1}{\hat{x}_h} \frac{1}{(1+\frac{x_E}{\hat{x}_h})^n}$$



Relates ratio of particle p_T

$$x_E = \frac{-p_{T_a}\cos\Delta\phi}{p_{T_t}} \simeq \frac{p_{T_a}}{p_{T_t}}$$

measured

Ratio of jet transverse momenta

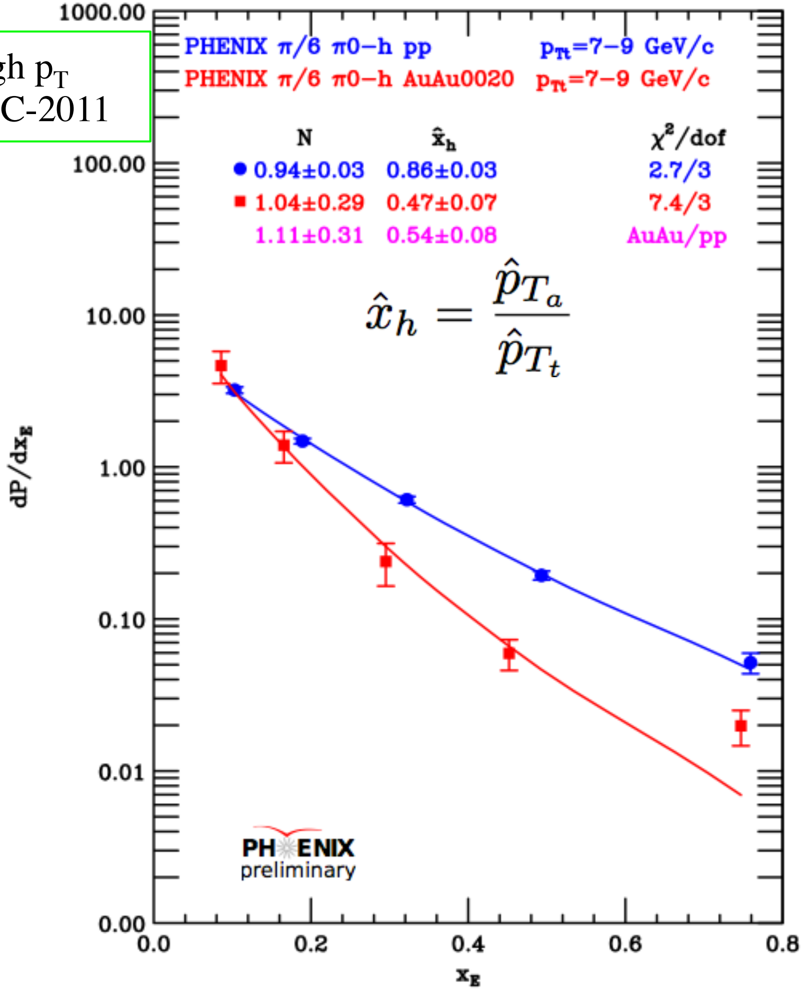
$$\hat{x}_h = \frac{\hat{p}_{T_a}}{\hat{p}_{T_t}}$$

Can be determined

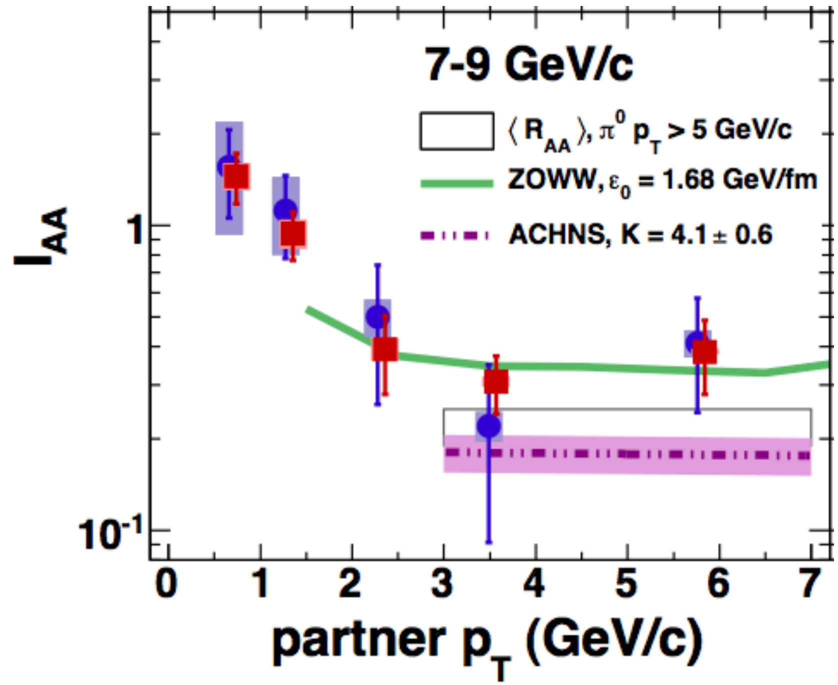
If formula works, we can also use it in Au+Au to determine the relative energy loss of the away jet to the trigger jet (surface biased by large *n*)

h-h or π^0-h correlations in Au+Au: Away-side yield vs $x_E \approx p_{Ta}/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss

High p_T
LHC-2011



Typically experiments just show I_{AA}, the ratio of AA and pp $x_E \approx z_T = p_{Ta}/p_{Tt}$ distributions. **Note all I_{AA} plots are flat for p_T>3 and rise for p_T<3 GeV/c**



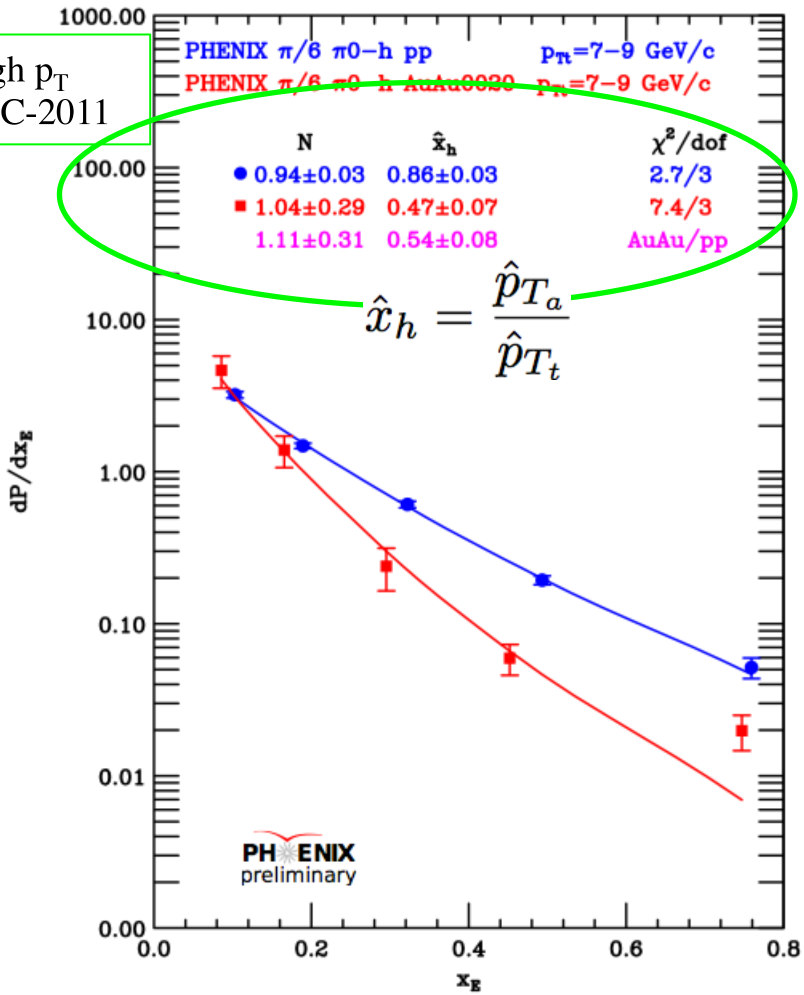
$I_{AA}=[dN^{AA}/dx_E]/ [dN^{pp}/dx_E]$

Steeper curve in Au+Au indicates that the away jet has lost energy relative to the trigger jet

PHENIX π^0-h correlations
PRL104(2010)252301

h-h or π^0-h correlations in Au+Au: Away-side yield vs $x_E \approx p_{Ta}/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss

High p_T
LHC-2011



Also, in p-p the jets do not exactly balance due to k_T, trigger bias, cuts, so take the measured away-jet imbalance relative to p-p as:

$$\boxed{1 - \hat{x}_h^{AA} / \hat{x}_h^{pp}}$$

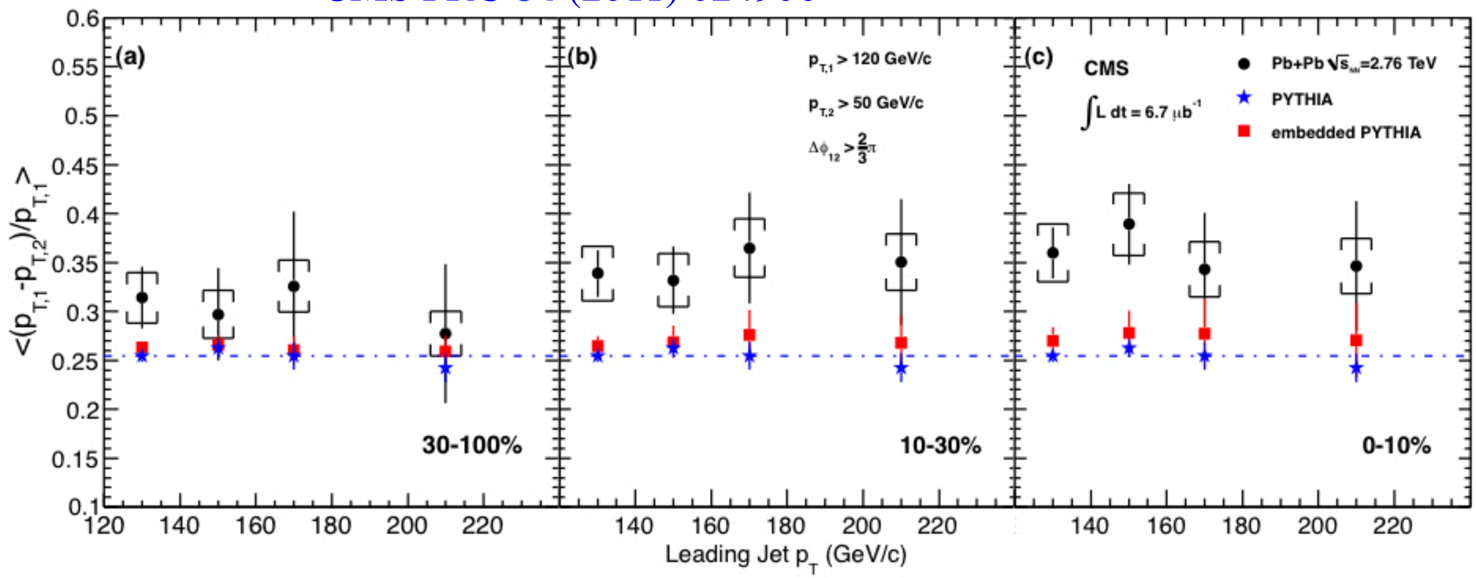
$1 - \hat{x}_h^{AA}/\hat{x}_h^{pp} = 1 - 0.47/0.86 = 0.47 \pm 0.07$
which is a quantitive measure that the away-jet has lost energy relative to the trigger jet in AuAu compared to pp collisions

Steeper curve in Au+Au indicates that the away jet has lost energy relative to the trigger jet

Comparison with CMS dijet imbalance

CMS PRC **84** (2011) 024906

High p_T
LHC-2011



Need to correct for the large non-zero effect in p-p collisions

$$(p_{T1}-p_{T2})/p_{T1} = 1-\hat{x}_h$$

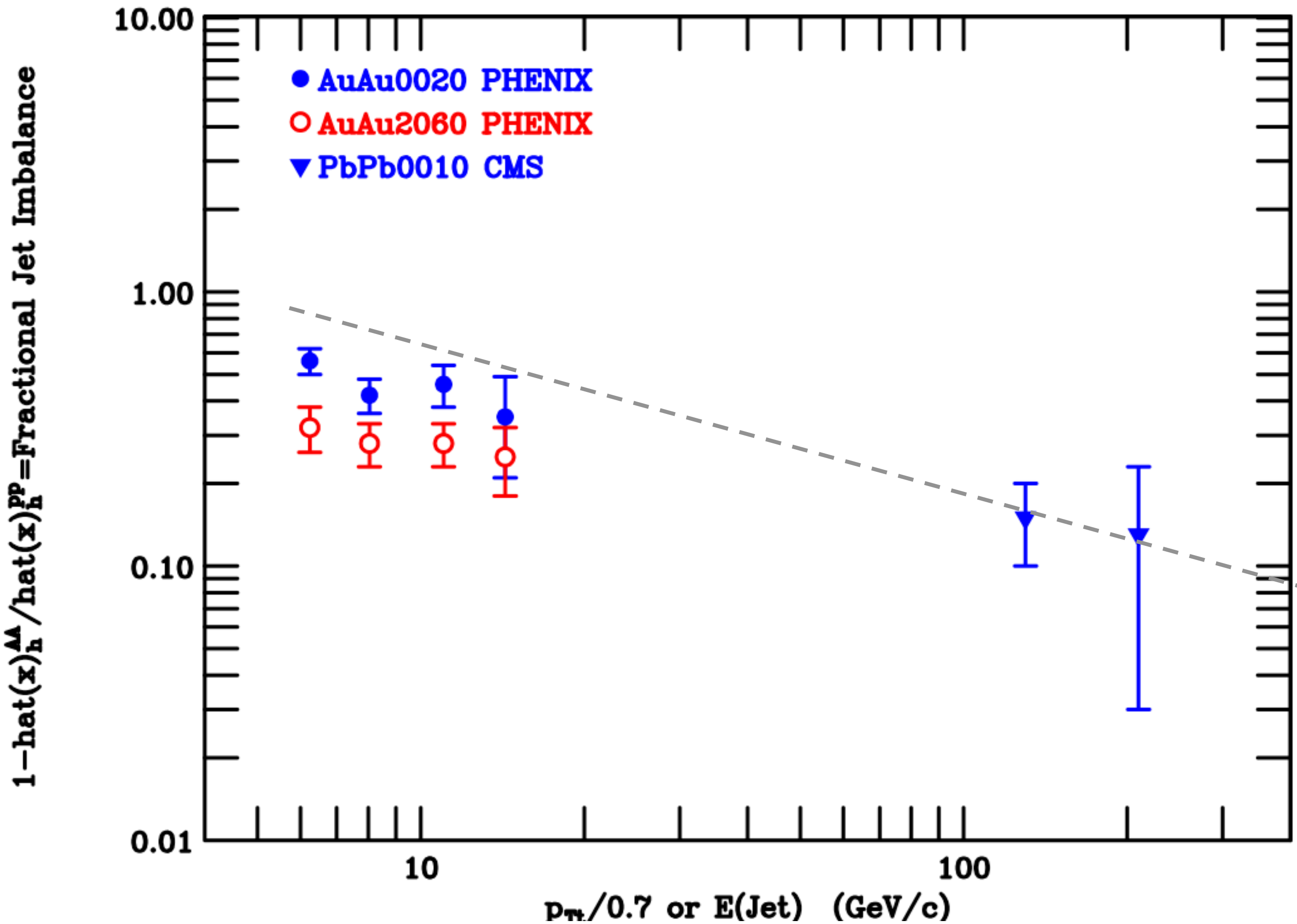
$$\hat{x}_h = 1-(p_{T1}-p_{T2})/p_{T1}$$

130: pp = 0.255, PbPb=0.36 $\Rightarrow$ $\hat{x}_h$: pp = 0.745, PbPb=0.64

$$1-\hat{x}_h^{AA}/\hat{x}_h^{pp} = 0.141 \Leftarrow \hat{x}_h^{AA}/\hat{x}_h^{pp} = 0.64/0.745 = 0.859$$

PHENIX 00-20, 20-60 cf CMS central

High p_T
LHC-2011



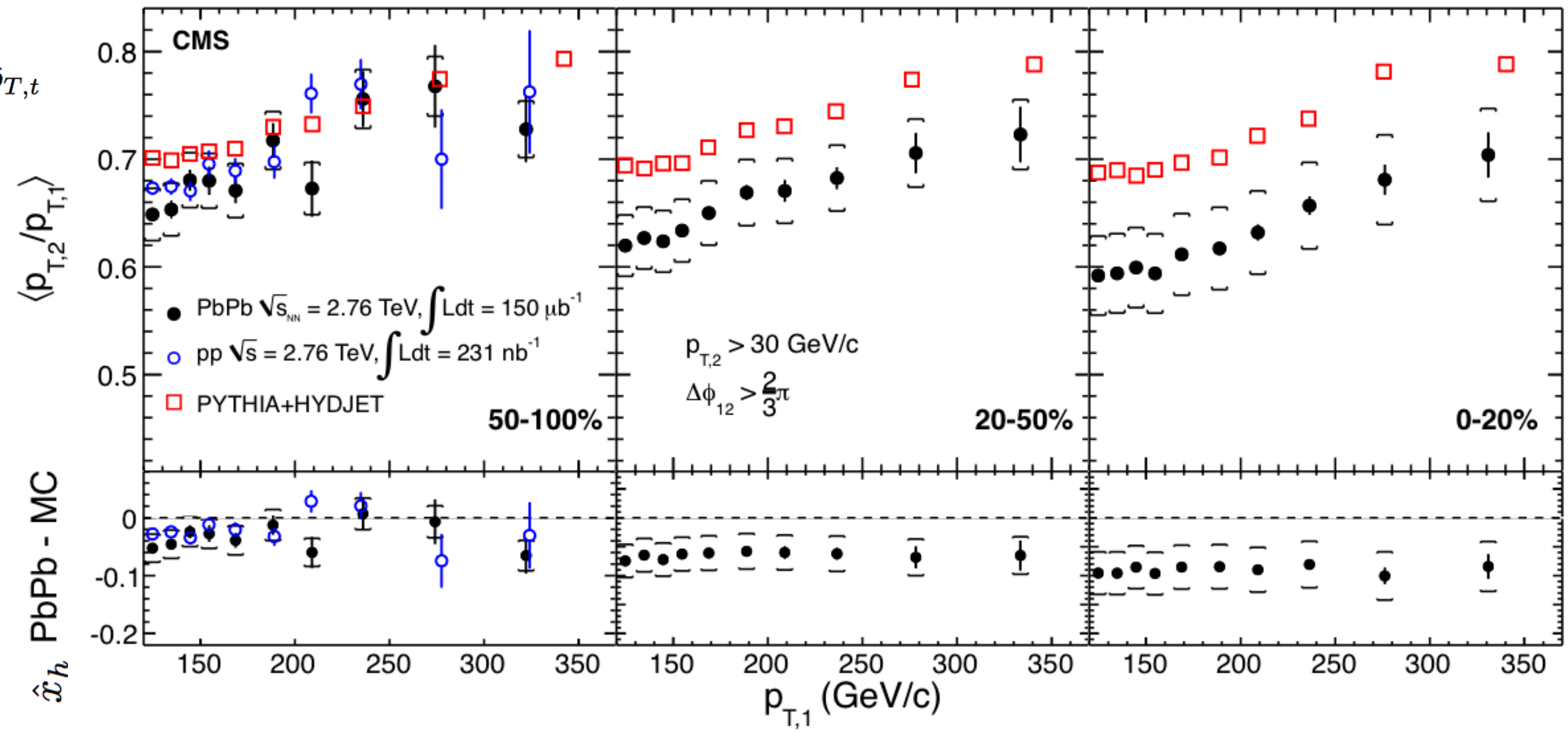
Dependence of Δ/E vs E at LHC ??

Big difference between RHIC and LHC in this analysis. What I wanted from the LHC was to check this analysis, and they did!

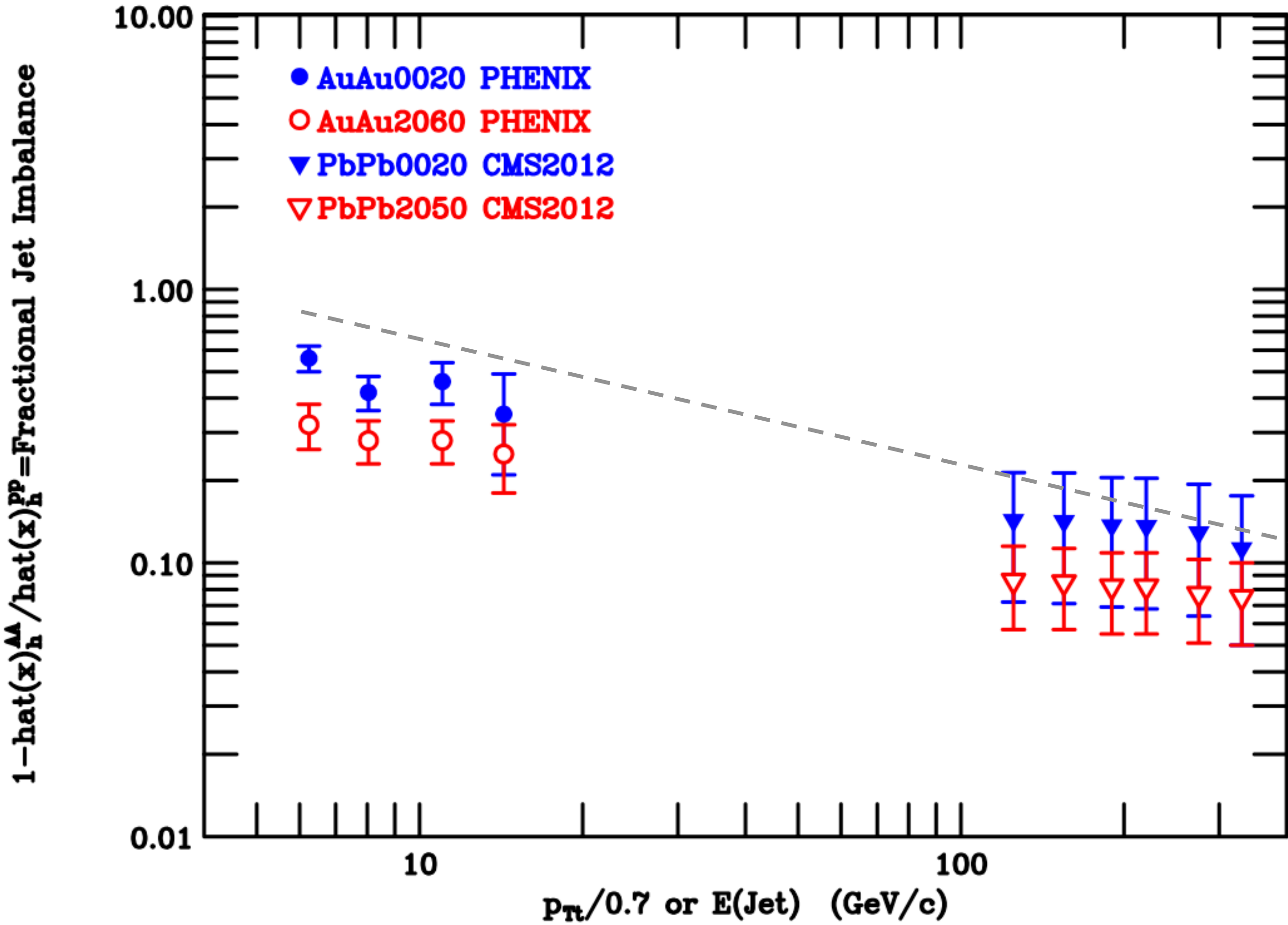
New CMS result confirms my idea

ratio of away jet to trigger jet i.e $\hat{x}_h = \hat{p}_{T,a}/\hat{p}_{T,t}$

CMS PLB **712** (2012) 176



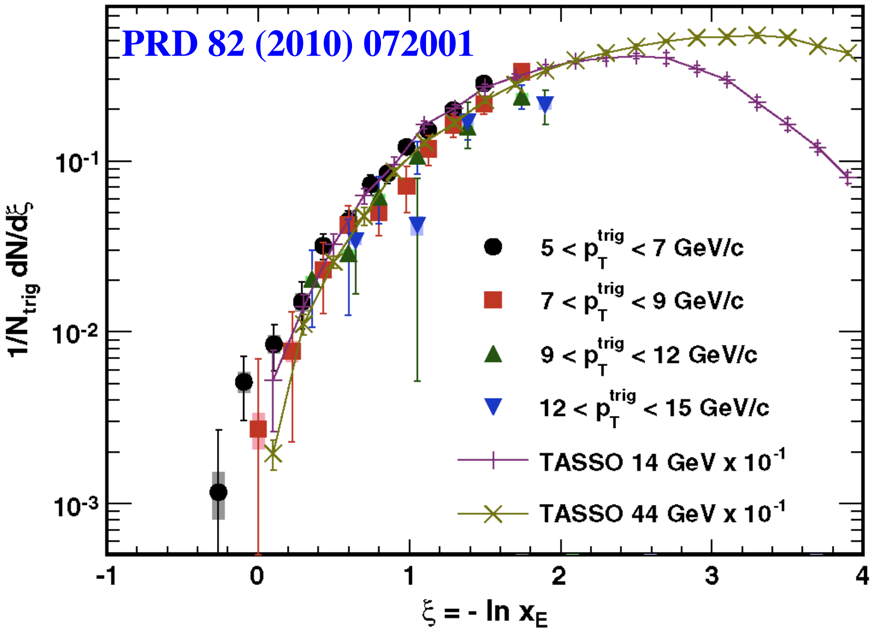
PHENIX cf. CMS corrected for pp



Dependence of Δ/E vs E at LHC ??

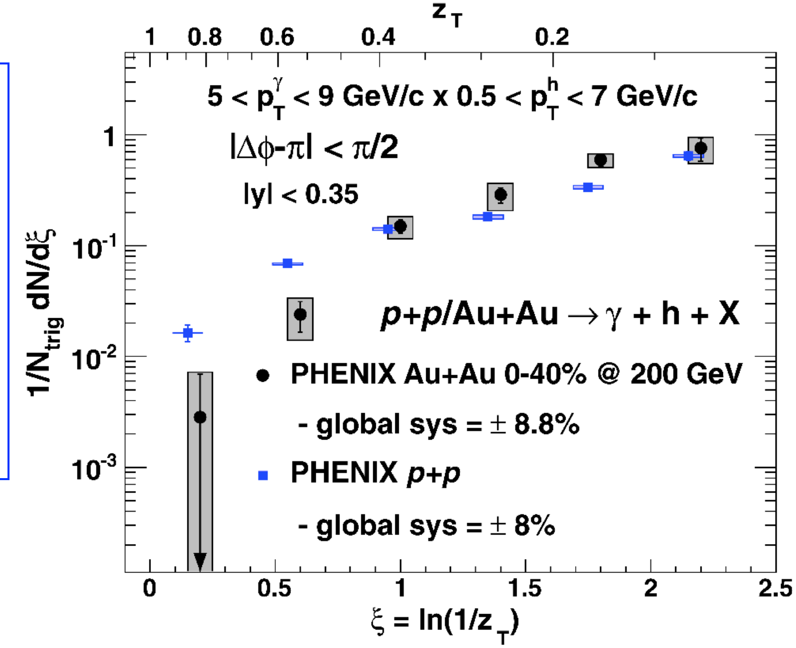
Emphasizes the need to understand the mechanism of energy loss by extending both the RHIC and LHC measurements to overlapping regions of p_T.

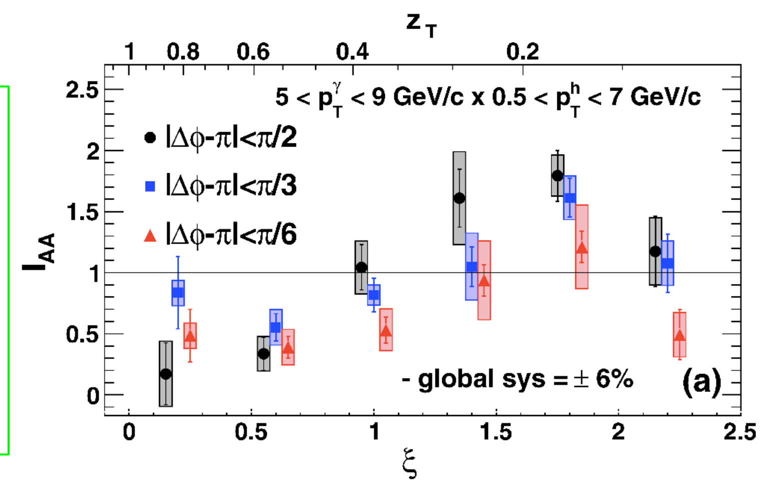
Direct-γ-h correlation measures (~u quark) fragmentation function in Au+Au



$\xi = \ln(1/z) = -\ln(p_{Th}/p_{T\gamma})$

PRL 111 (2013) 032301



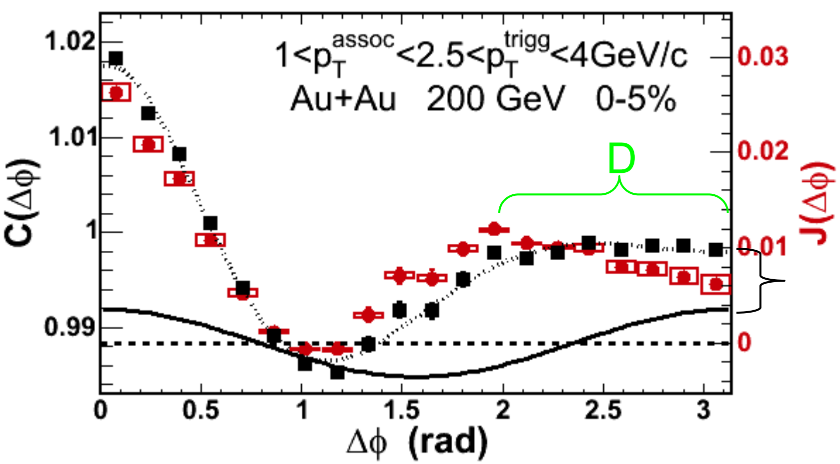


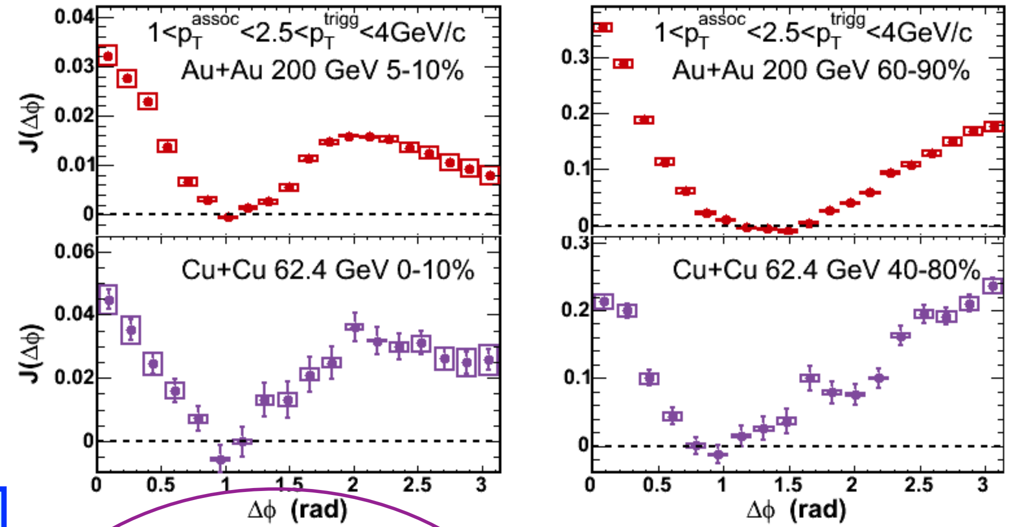
- $p+p$ consistent with e^+e^-
- Au+Au significant modification of frag. fn. Restricting the azimuthal range leaves the suppression at small $\xi<0.9$ relatively unchanged ≈ 0.5, but reduces the large $\xi>0.9$ ($p^h_T \leq 3$ GeV/c) enhancement similar to the effect observed by CMS with actual jets.

N.B. h-h correlations where both h are jet fragments does NOT measure the frag. Fn.

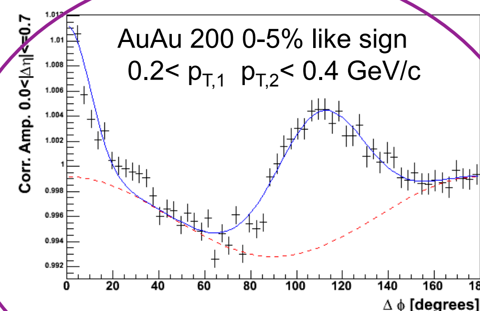
Di-Hadron, Di-Jet or recently Jet-Hadron Correlations in AA interactions suffer from a HUGE problem due to v_2,v_3,v_4 flow modulations of the background which obscure the hard-scattering away-side peak and had led to such RHIC “discoveries” as “Mach Cones”, The Ridge, “Head & Shoulders”. Uncertainties in determining the v_n modulated soft background (the bulk) still lead to large systematic uncertainties for the hard-scattering peaks.

Away side correlations in Au+Au much wider than in p-p

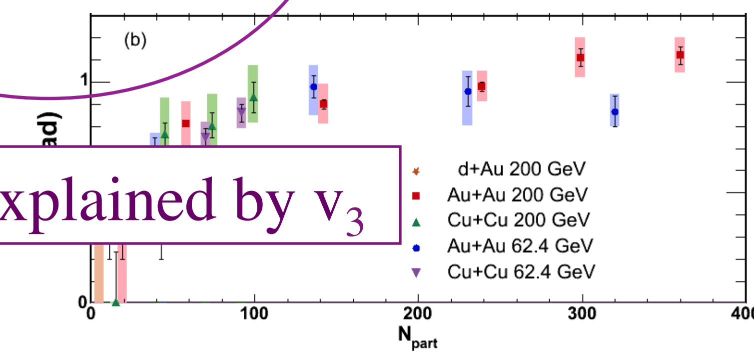




Away side distribution much wider in A+A than p-p in correlation fn. $C(\Delta\phi)$ Subtraction of v_2 (flow?) effect→ $J(\Delta\phi)$ causes a dip at 180° which gives 2 peaks at $\pi\pm D\sim1$ radian independent of system and centrality for $N_{part}>100$. This is also seen for (auto) correlations of low p_T particles. Is this the medium reaction to the passage of a color-charged parton? Why no dependence on centrality? Stay tuned, much more study needed.



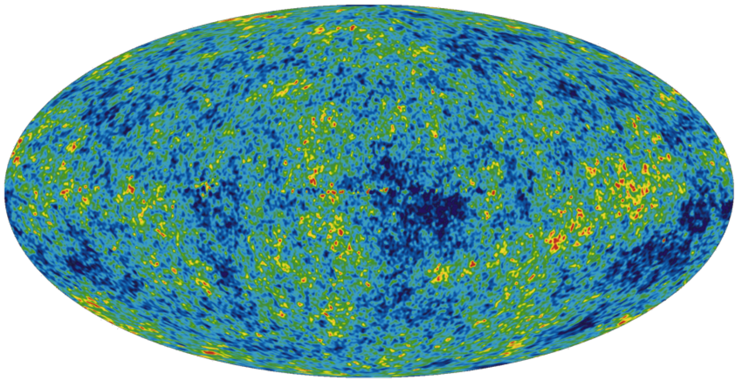
PHENIX AuAu
PRL **98** (2007) 232302



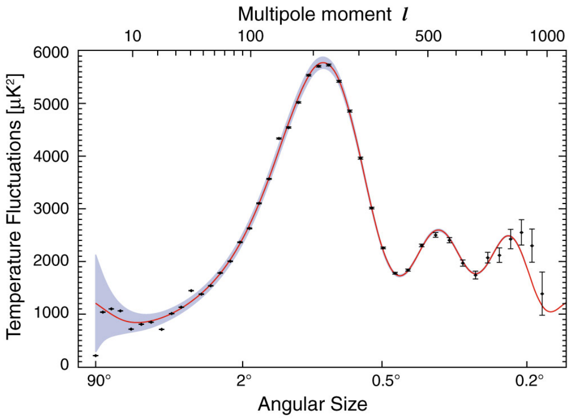
All Explained by v_3

The Ridge, Shoulder, "Mach Cone" i.e. previous slide, all explained by $v_2, v_3, . . .v_n$

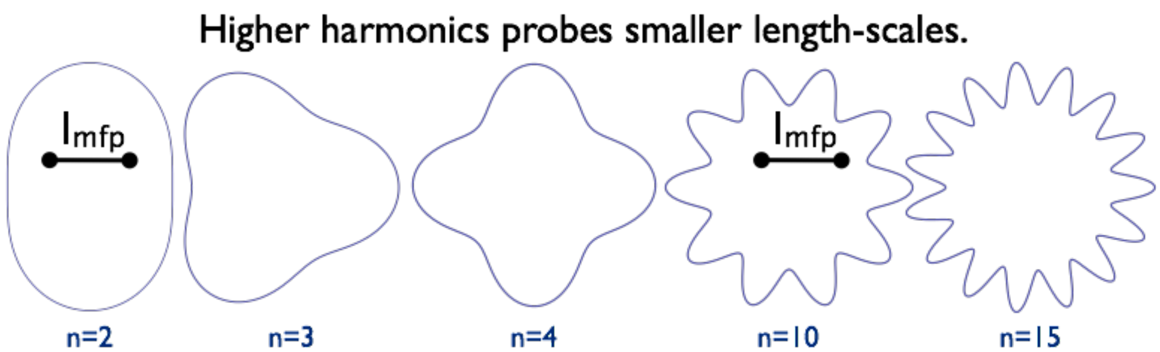
Paul Sorenson-From v_2 to v_n: and what we learn



WMAP, Astrophys.J.Suppl.170:288,2007



$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$



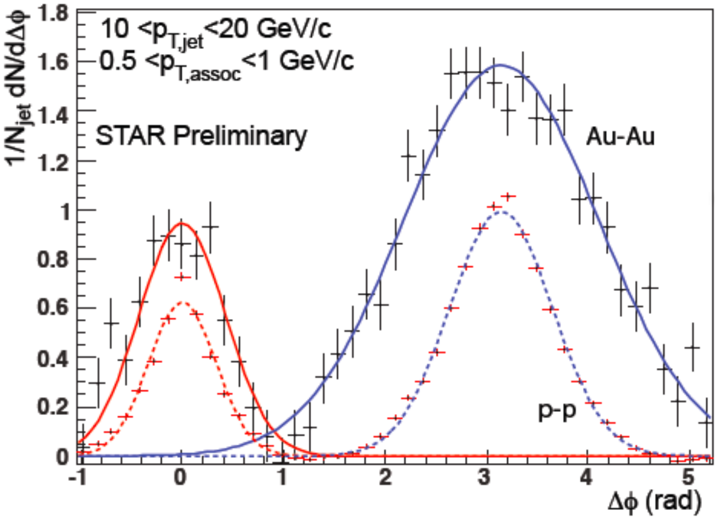
MJT-2013: easier to understand in terms of viscosity which is proportional to mean free path—the shorter the mfp, the lower the viscosity and more higher harmonics seen

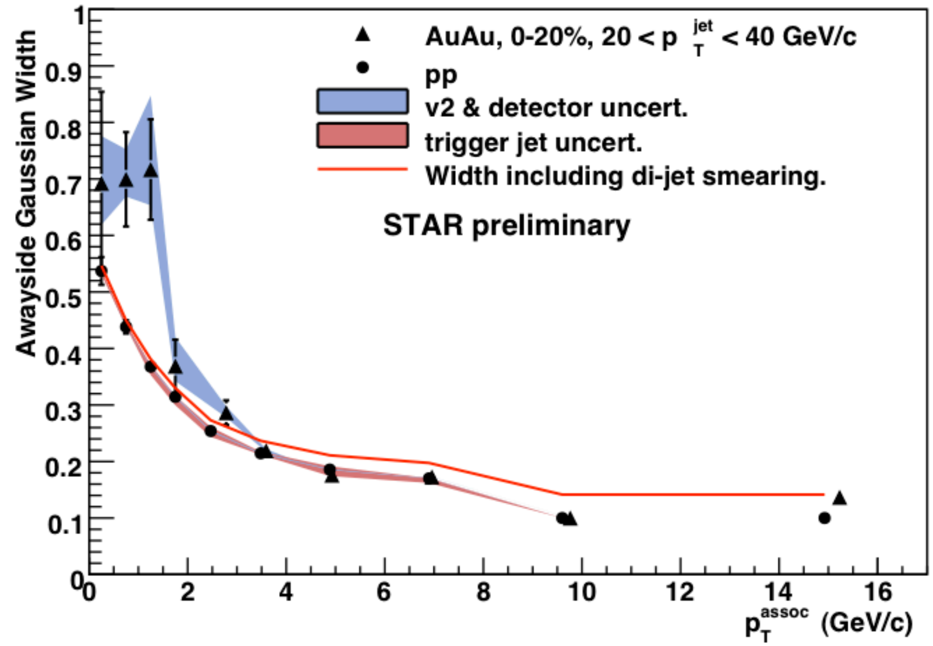
Analogous to the Power Spectrum extracted from the Cosmic Microwave Background

A.P. Mishra, R. K. Mohapatra, P. S. Saumia, A. M. Srivastava, Phys. Rev. C77: 064902, 2008
P. Sorensen, WWND, arXiv:0808.0503 (2008); J. Phys. G37: 094011, 2010

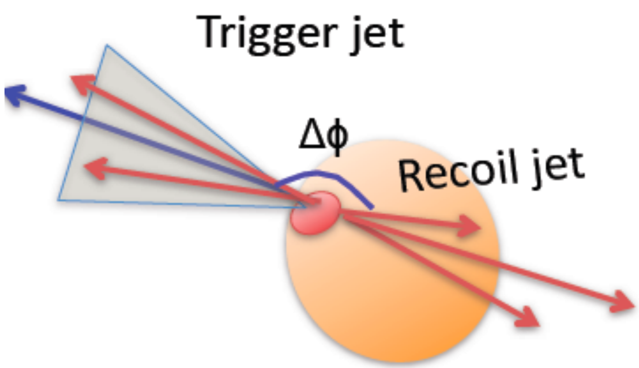
STAR Jet-hadron correlations-preliminary 2012

A.Ohlson, Hard Probes 2012





H. Caines , QM 2011

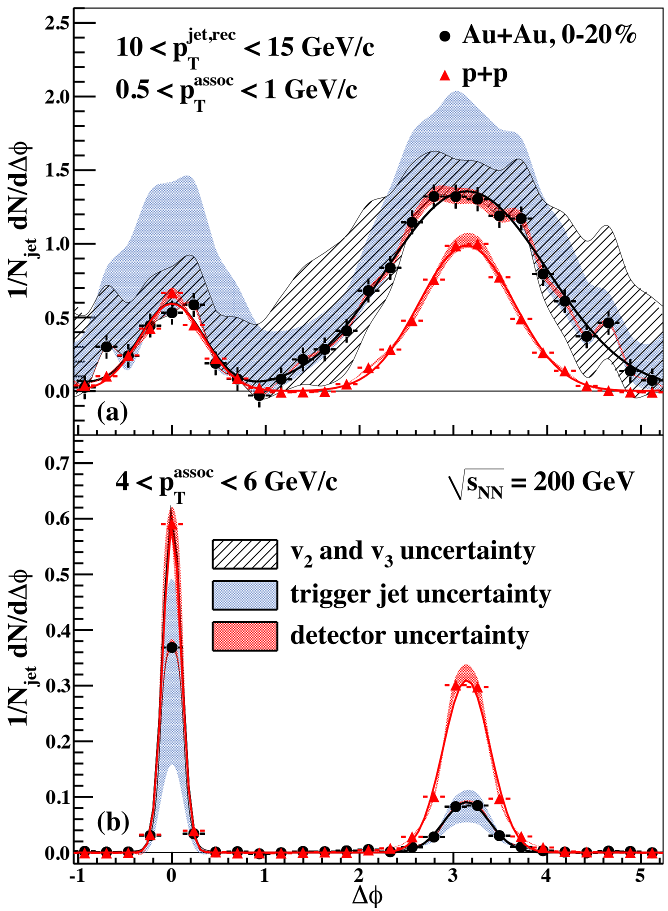


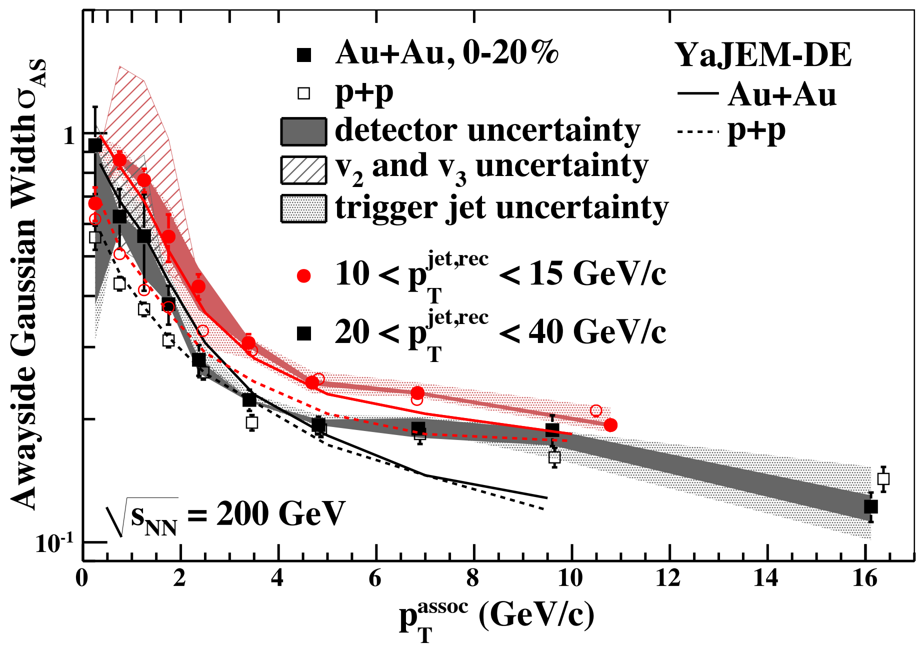
$\Delta\Phi = \Phi_{jet} - \Phi_{assoc.\text{-}hadron}$

Use Jet-hadron correlations to look for medium-induced-broadening of the away parton (Jet) w.respect to trigger Jet

Preliminary seems to look promising, but final data show no evidence:

STAR Jet-Hadron 2013 final—suggestive? (!)





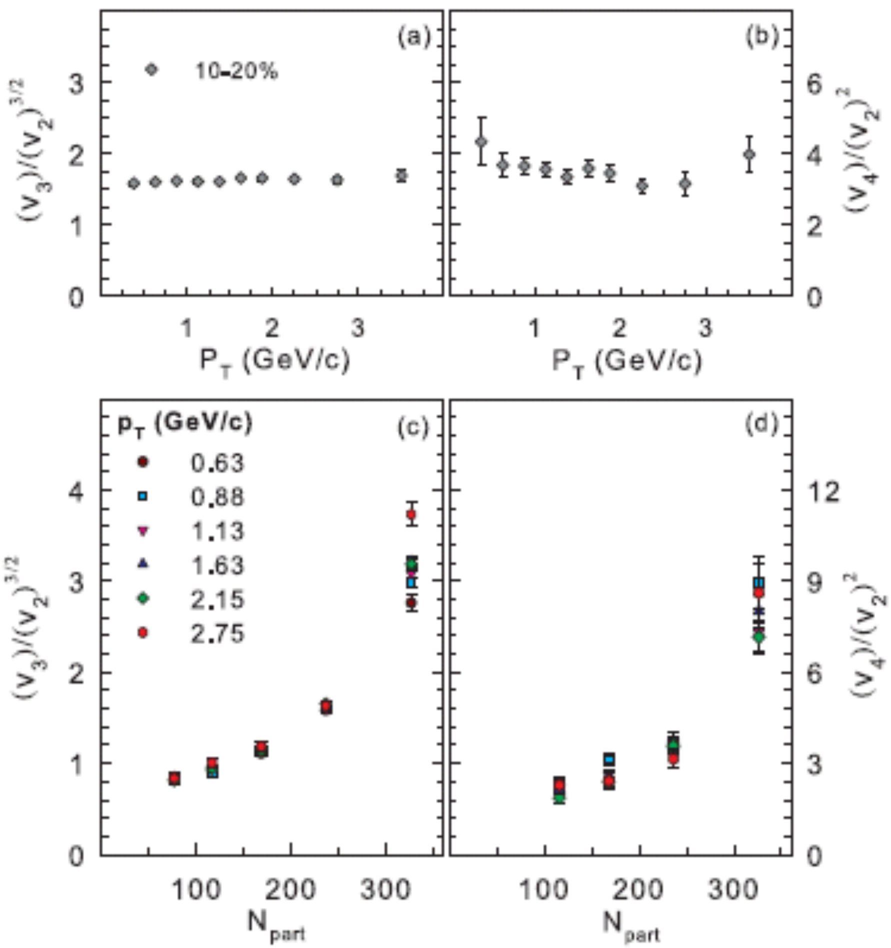
STAR PRL **112** (2014)122301, with systematic errors, is inconclusive due to v_2, v_3, ... uncertainties.

"While the widths of the awayside jet peaks are suggestive of medium-induced broadening, they are highly-dependent on the shape of the subtracted background,..."

My idea is to use acoustic scaling to constrain v_3,v_4... from v_2

Lacey:Acoustic Scaling from PHENIX v_2,v_3,v_4

In arXiv: 1105.3782v2 they claim that from hydrodynamics and kinetic theory, for a fixed initial collision geometry (centrality) one should get:



$$v_n / v_2^{n/2} = \text{constant, independent of } p_T$$

It works for PHENIX,v_2,v_3,v_4 data from PRL 107(2011) 252301. I checked it myself using Excel. Will allow us to measure hard-scattering correlations with good constraint on flow: know v_2 know everything.

I didn't do it yet because I was too busy working on Net-charge fluctuations. arXiv:1506.07834