First Results from RHIC

"A Look at Jet Quenching?"

Richard Seto

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Caltech, Feb 26, 2001

Outline

Note – MANY topics skipped – HBT, particle yields, fluctuations…

- Introduction
- The machine and detectors
- Centrality measurements
- Global Measurements
  - Energy density
  - Thermalization and flow
- The ideas
  - Jet quenching, what do we expect?
  - The baseline
- The data
  - High pt spectra– evidence of deconfinement?
- The future

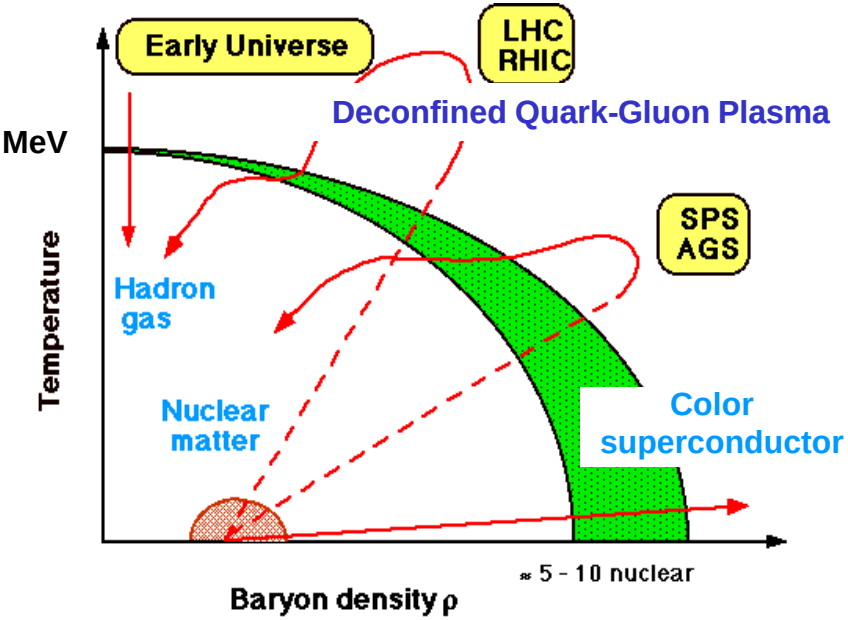
- Caveats
  - In the interest of clarity I have attempted to tell a story –but please remember
  - The data
    - still preliminary
    - generally the systematic errors are estimated to be 30%.
  - The ideas (theory):
    - In the energy regime we are exploring pQCD becomes a reliable tool –
    - but there are ancillary issues such as the time evolution of the system which are uncertain
  - In the Long Range Plan we are still using words like “preliminary” and “consistent with”

Why do this stuff?

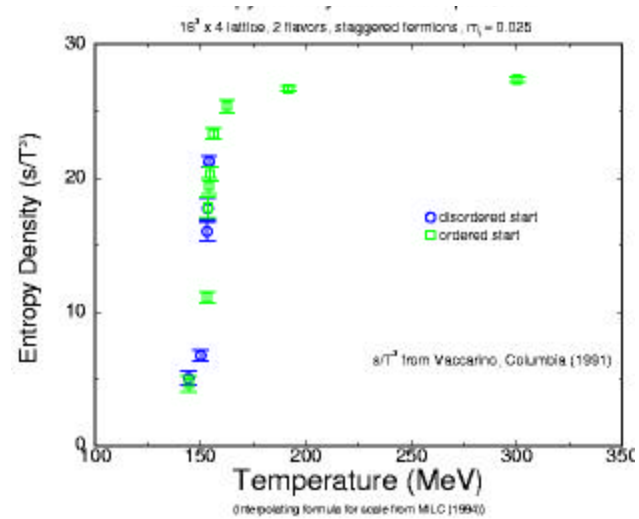
- Why Relativistic Heavy Ion Collisions?
  - To study a hadronic matter at high energy density
    - Early universe
    - Center of stars
  - To study the deconfined state of QCD
    - Where is the phase transition?
    - What order is it?
    - Are there critical phenomenon, e.g dis-oriented chiral condensates?
  - *To Study the Vacuum* - chiral symmetry restoration
    - Origin of (hadronic) mass
- To understand the spin of the proton (polarized pp)

The QCD phase diagram

- Two sets of conditions
  - High Temperature (RHIC, $T_C \sim 170$ MeV
  - High Baryon Density ρ_B
- TWO different phase transitions!
  - The deconfinement transition - particles are roam freely over large volume
  - The chiral transition - masses change
  - ~ same energy density
- Lattice QCD Calculations give T_C~150-200 MeV; $e_{critical}$ **~ 1-2 GeV/fm³**

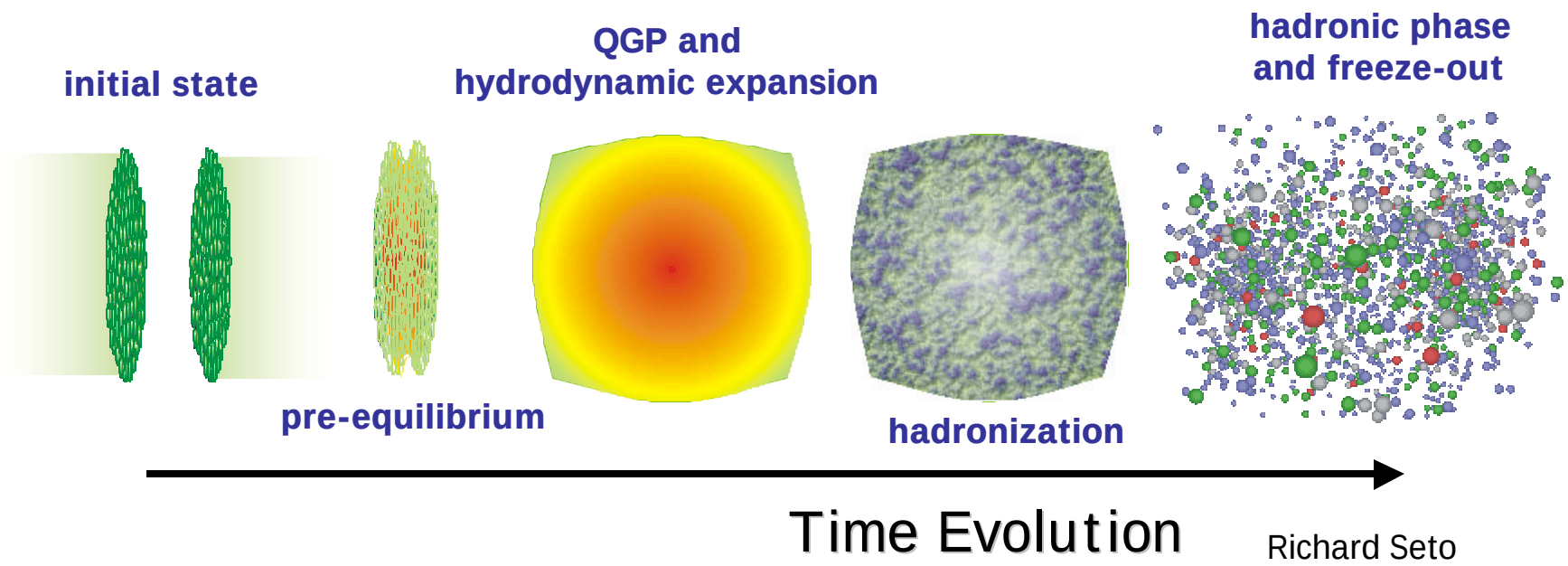


Entropy Density versus Temperature



How do we hope to see this phase transition?

- Relativistic Heavy Ion Collisions
  - It would nice if we created a bottle of compressed quark and gluon gas gas – but it isn't
  - Better analogy – early universe, exploding star
  - Time evolution
    - Lorenz contracted pancakes
    - Pre-equilibrium < τ~1fm/c ??
    - QGP and hydrodynamic expansion τ~ few fm/c ??
    - Hadronization and freezout τ~ 5-20 fm/c??



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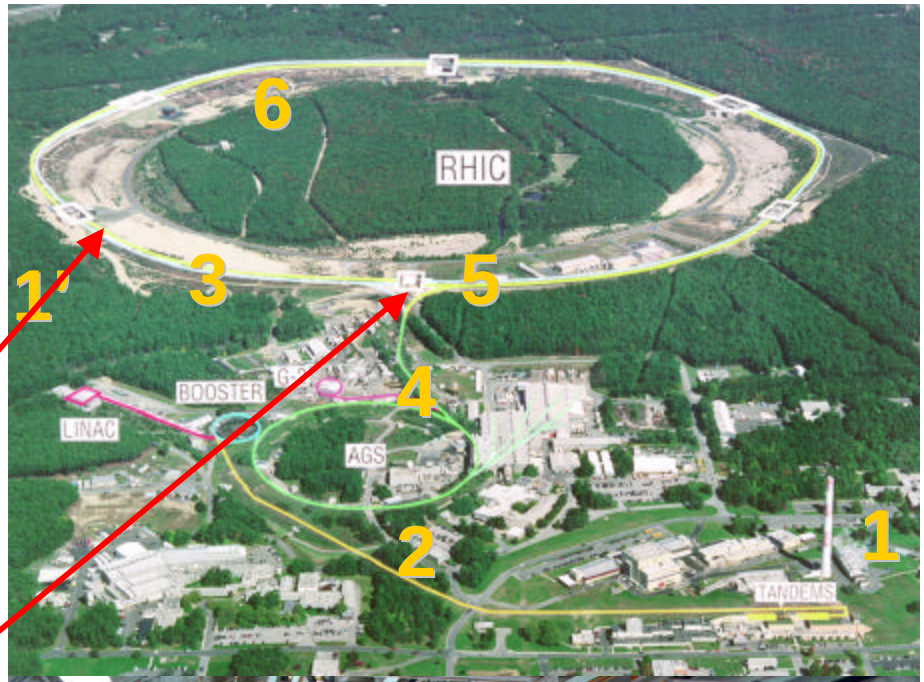
RHIC The Relativistic Heavy Ion Collider

- Located at Brookhaven National Laboratory, Long Island
- Schedule:
  - Commissioning: June-July, 1999
  - First physics run: ~May-00 through Sep-00
- Two independent rings - 4km circumference
- Capable of colliding pp, pA, AA (Au-Au)
- Energy:
  - 500 GeV for p-p (polarized)
    L ~2 x 10^{32} cm^{-2} s^{-1}
  - 200 GeV for Au-Au
    L ~2 x 10^{26} cm^{-2} s^{-1}
- Two Big Detectors
  - PHENIX, STAR
- Two Small Detectors
  - PHOBOS, BRAHMS



Sociology ~$50-100M – 400 collaborators

PHENIX

11 Countries
51 Institutions
~450 Collaborators

University of São Paulo, São Paulo, Brazil
Academia Sinica, Taipei 11529, China
China Institute of Atomic Energy (CIAE), Beijing, P. R. China
Laboratoire de Physique Corpusculaire (LPC), Universite de Clermont-Ferrand, 63170 Aubiere, Clermont-Ferrand, France
Dapnia, CEA Saclay, Bat. 703, F-91191, Gif-sur-Yvette, France
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
LPNHE-Palaiseau, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
SUBATECH, Ecole des Mines at Nantes, F-44307 Nantes, France
University of Muenster, Muenster, Germany
Banaras Hindu University,Banaras, India
Bhabha Atomic Research Centre (BARC),Bombay, India
Weizmann Institute, Rehovot, Israel
Center for Nuclear Study (CNS-Tokyo), University of Tokyo, Tanashi, Tokyo 188, Japan
Hiroshima University, Higashi-Hiroshima 739, Japan
KEK, Institute for High Energy Physics,Tsukuba, Japan
Kyoto University, Kyoto, Japan
Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki, Japan
RIKEN, Institute for Physical and Chemical Research, Hirosawa, Wako, Japan
University of Tokyo, Bunkyo-ku, Tokyo 113, Japan
Tokyo Institute of Technology, Ohokayama, Meguro, Tokyo, Japan
University of Tsukuba, Tsukuba, Japan
Waseda University, Tokyo, Japan
Cyclotron Application Laboratory, KAERI, Seoul, South Korea
Kangnung National University, Kangnung 210-702, South Korea
Korea University, Seoul, 136-701, Korea
Myong Ji University, Yongin City 449-728, Korea
System Electronics Laboratory, Seoul National University, Seoul, South Korea
Yonsei University, Seoul 120-749, KOREA
Institute of High Energy Physics (IHEP-Protvino or Serpukhov), Protovino, Russia
Joint Institute for Nuclear Research (JINR-Dubna), Dubna, Russia
Kurchatov Institute, Moscow, Russia
PNPI: St. Petersburg Nuclear Physics Institute, Gatchina, Leningrad, Russia
Lund University, Lund, Sweden
Abilene Christian University, Abilene, Texas, USA
Brookhaven National Laboratory (BNL), Upton, NY 11973
University of California - Riverside (UCR), Riverside, CA 92521, USA
Columbia University, Nevis Laboratories, Irvington, NY 10533, USA
Florida State University (FSU), Tallahassee, FL 32306, USA
Georgia State University (GSU), Atlanta, GA, 30303, USA
Iowa State University (ISU) and Ames Laboratory, Ames, IA 50011, USA
LANL: Los Alamos National Laboratory, Los Alamos, NM 87545, USA
LLNL: Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
University of New Mexico, Albuquerque, New Mexico, USA
New Mexico State University, Las Cruces, New Mexico, USA
Department of Chemistry, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA

The STAR Collaboration

7 Countries
36 Institutions
415 Collaborators

Brazil: Sao Paolo
England: Birmingham
Germany: Frankfurt, MPI - Munich
China: IHEP - Beijing, IPP - Wuhan
France: IReS - Strasbourg, SUBATECH-Nantes
Poland: Warsaw University, Warsaw U. of Technology
Russia: MEPHI - Moscow, JINR - Dubna, IHEP - Protvino

U.S.: Argonne, Berkeley, Brookhaven National Laboratories
UC Berkeley, UC Davis, UCLA, Creighton, Carnegie-Mellon, Indiana, Kent State, MSU, CCNY,

Smaller experiments

~ $5M

~50 Collaborators

BRAHMS Collaboration

Brookhaven National Laboratory, USA
Fysisk Institutt, University of Oslo Norway
IReS, Université Louis Pasteur, Strasbourg, France
Jagellonian University, Cracow, Poland
Johns Hopkins University, Baltimore, USA
New York University, USA
Niels Bohr Institute, University of Copenhagen, Denmark
Texas A&M University, College Station, USA
University of Bucharest, Romania
University of Kansas, USA
University of Bergen, Norway

I.G. Bearden[1], D. Beavis[1], Y. Blyakhman[4], J. Brzychczyk[8], B. Budick[6], H. Bøggild[3], C. Chasman[1], P. Christiansen[3], J. Cibor[8], R. Debbe[1], J. J. Gaardhøje[3], K. Grotowski[8], J. Jordre[13], F. Jundt[2], K. Hagel[11], O. Hansen[3], H. Heiselberg, A. Holm[3], C. Holm[3], A.K. Holme[3], H. Ito[9], E. Jacobsen[3], A. Jipa[5], C.E. Jørgensen[3], E.J. Kim[7], T. Kneisel, T. Kozik[8], T.M. Larsen, J. H. Lee[1], Y. K. Lee[4], O. Leviniotes[2], Z. Majka[8], A. Makeev[11], B. McBreen[1], M. Murray[11], J. Natowitz[11], B.S. Nielsen[3], K. Olchanski[1], D. Ouerdane[3], R. Planeta, F. Rami[2], D. Roemer[10], B. Sanzet[1], S. Sandoval[6], R.A. Schmitz[1], I.S. Sigurd[3], Z. Sorin, P. Staszel[8], T.S. Tveter[3], F. Videbæk[1], R. Wada[11] and A. Wieloch

The PHOBOS Collaboration

ARGONNE NATIONAL LABORATORY
Birger Back, Nigel George, Alan Wuosmaa
BROOKHAVEN NATIONAL LABORATORY
Mark Baker, Donald Barton, Alan Carroll, Stephen Gushue, George Heintzelman, Robert Pak, Louis Remsberg, Peter Steinberg, Andrei Sukhanov
INSTITUTE OF NUCLEAR PHYSICS, KRAKOW
Andrzej Budzanowski, Roman Holynski, Jerzy Michalowski, Andrzej Olszewski, Pawel Sawicki, Marek Stodulski, Adam Trzupek, Barbara Wosiek, Krzysztof Woźniak
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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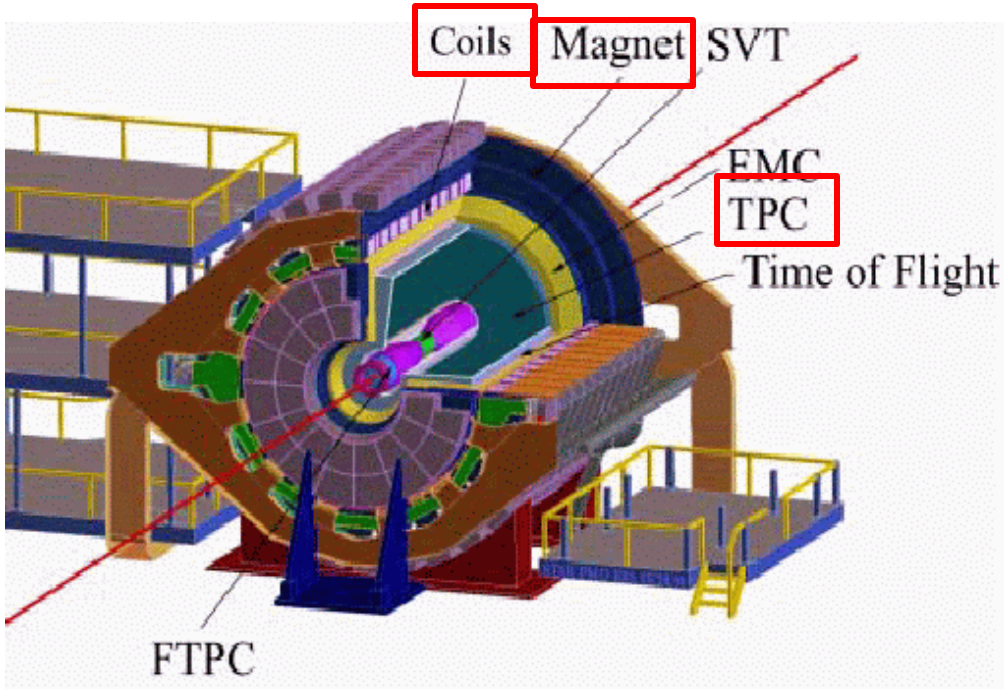
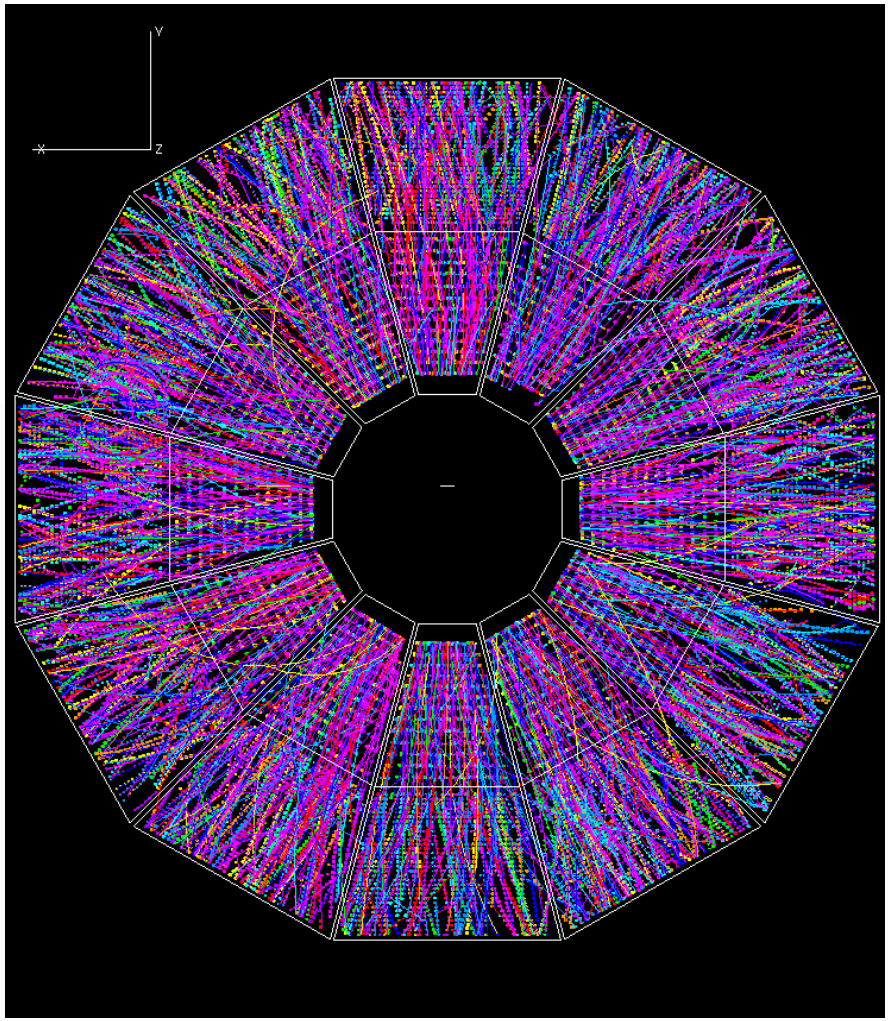
Willie Lin, JaeLuen Tang
UNIVERSITY OF ROCHESTER
Josh Hamblen, Erik Johnson, Nazim Khan, Steven Manly, Inkyu Park, Wojtek Skulski, Ray Tang, Frank Wolfs
UNIVERSITY OF ILLINOIS AT CHICAGO
Russell Betts, Clive Halliwell, David Hofman, Burt Holzman, Wojtek Kucewicz, Don McLeod, Rachid Nouicer, Michael Reuter
UNIVERSITY OF MARYLAND
Richard Bindel, Edmundo Garcia-Solis, Alice Mignerey
* spokesperson

A STAR – a large acceptance TPC

- Large acceptance TPC
- Solenoidal Field
- $-1 < \eta < 1$
- Vertex Detection - SVT
- Primarily Hadrons - year 1
  - Multi-strange baryons
- EMCAL - 2nd year - photons/electrons



STAR Central Event – year 1



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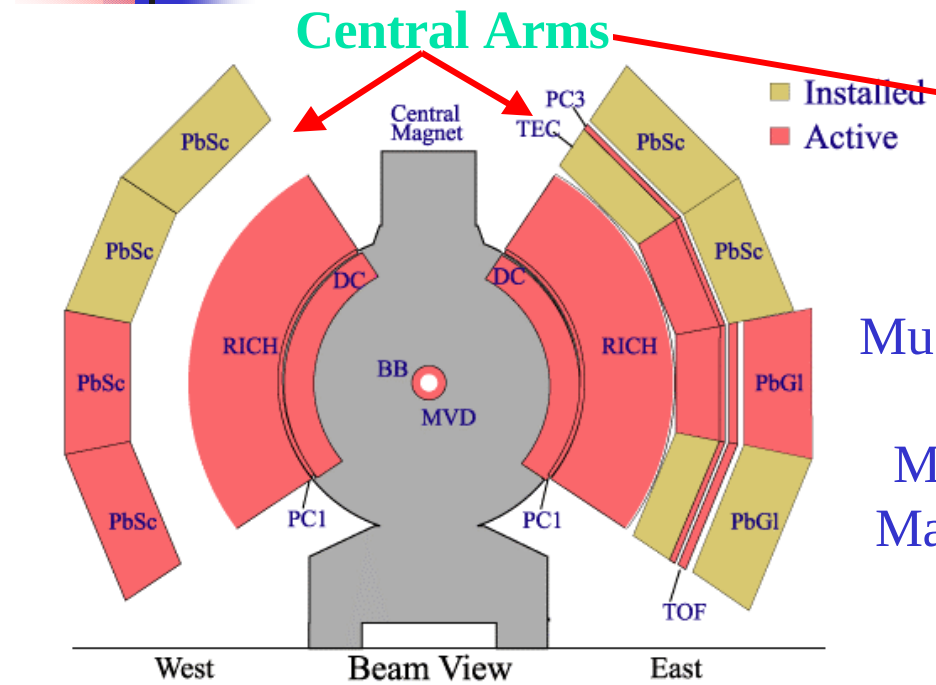
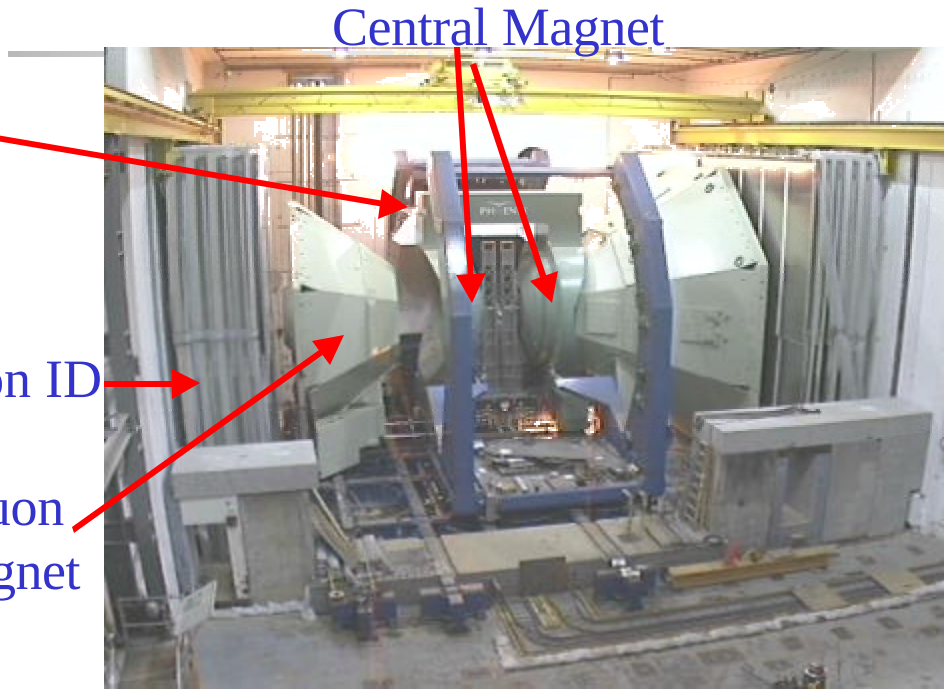
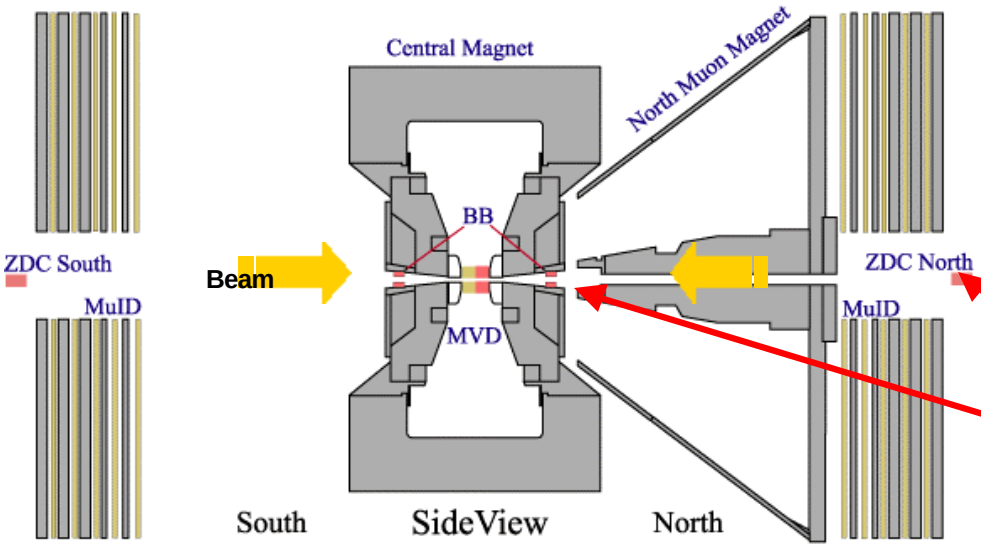
PHENIX: electrons,muons, photons, hadrons







- 2 Arm central spectrometers + 2 muon endcaps
  - -0.35< η <0.35 (e,γ, hadrons)
  - 1.2<| η |<2.5 (muons-2nd year)
  - Tracking : DC, PC, TEC
  - Particle ID : RICH, TEC , EMCal, TOF
- Global Detectors (centrality)
  - Zero Degree Calorimeters (ZDC)
  - Beam-Beam Counter (BBC)

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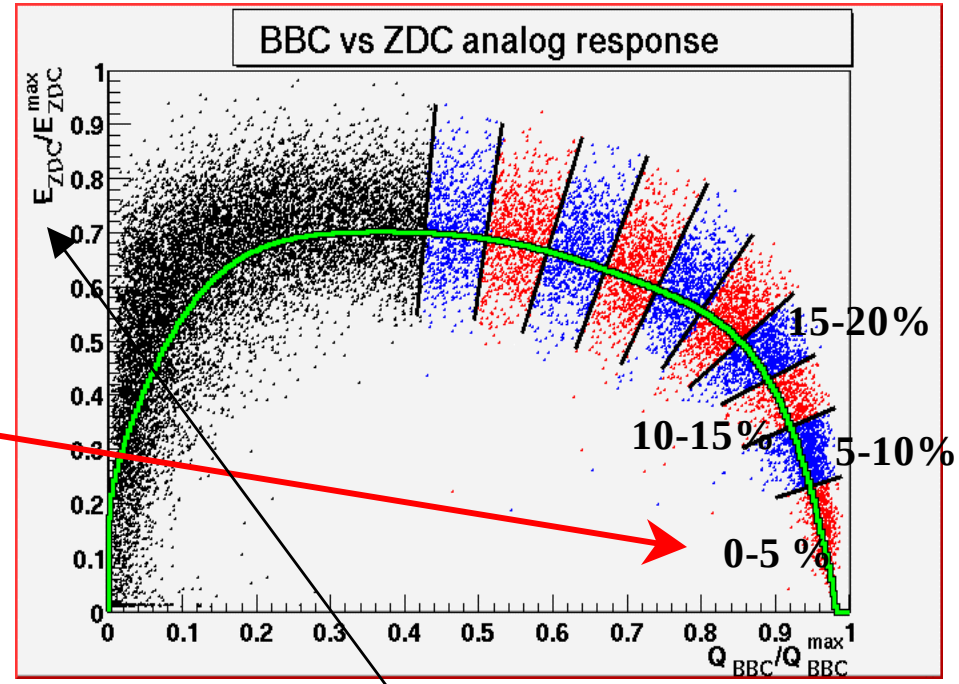
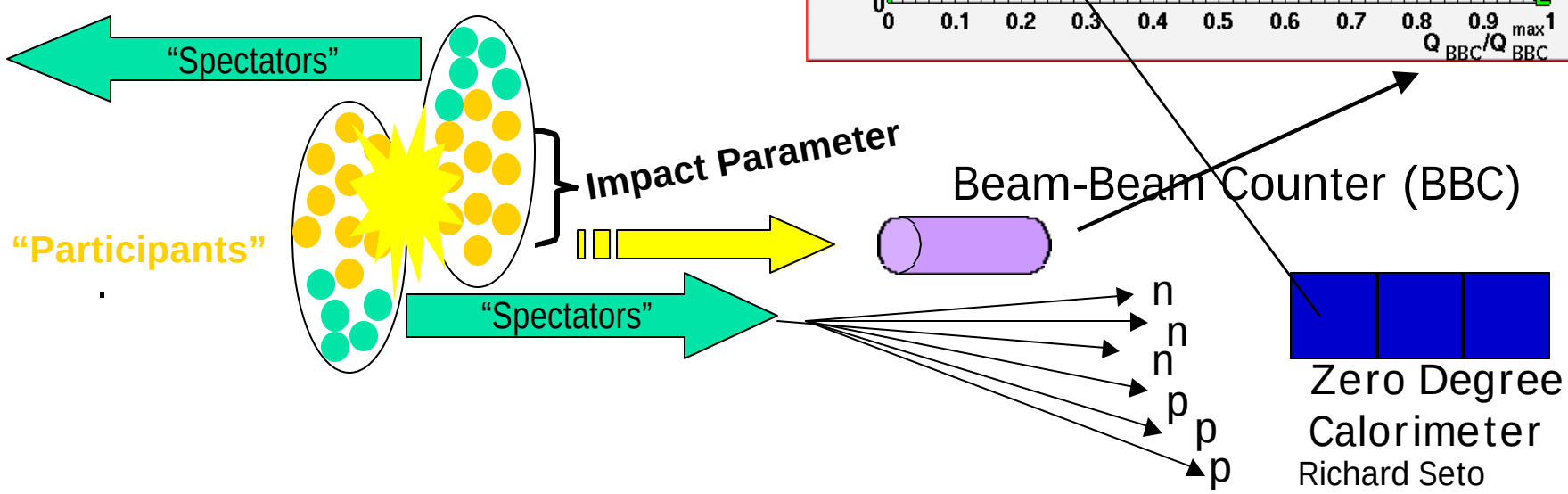
We need to worry about Geometry
Measuring Centrality (impact parameter)

- Zero Degree Calorimeters (ZDC)
  - Sensitive to spectator neutrons
  - common to all four RHIC experiments
- Using a combination of the ZDC's and BBC's we can define Centrality Classes





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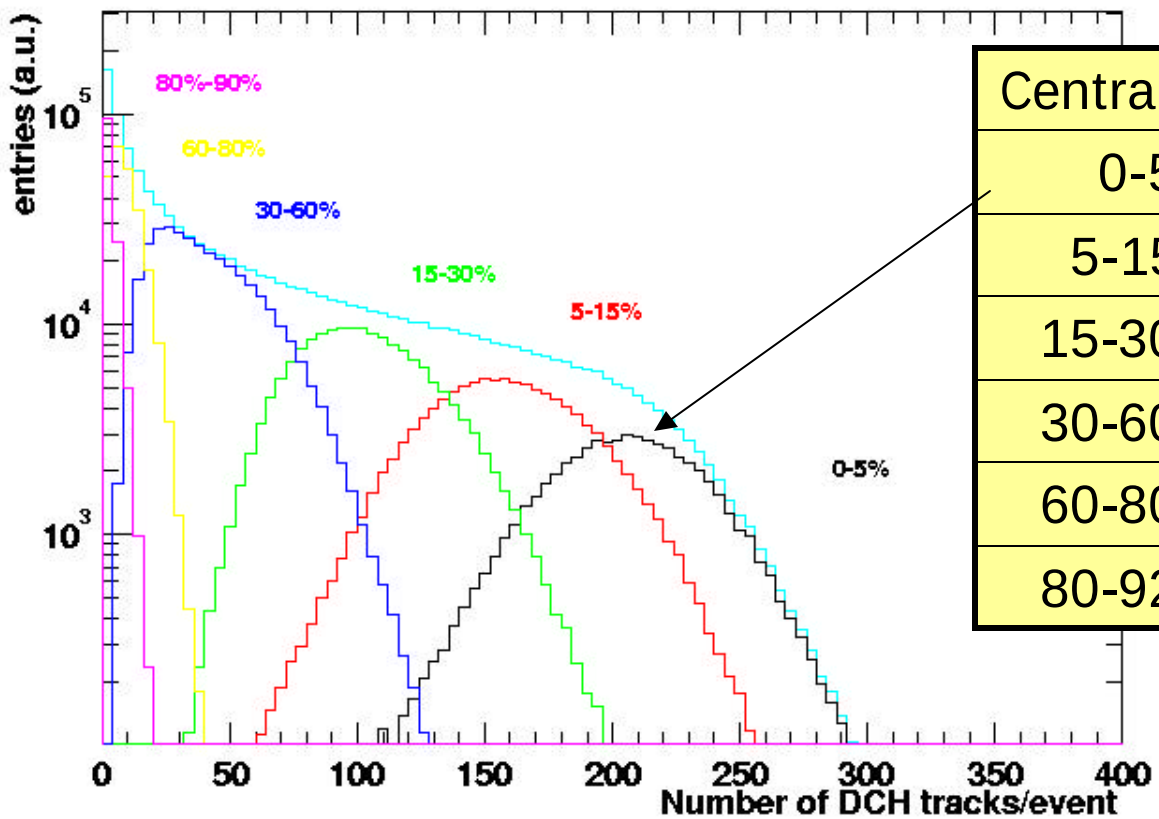
Conversion from Centrality to N_{binary} collisions and $N_{participants}$

- Many models of particle production identify two components.
  - Soft interactions where production scales with $N_{participants}$
  - Hard interactions where production scales with N_{binary}

$$dN_{ch}/d\eta\Big|_{\eta=0} = Soft \times N_{part} + Hard \times N_{bin}$$

A simple Glauber model gives N_{binary} and $N_{participants}$



Centrality	Collisions	Participants
0-5%	945 ± **15%**	347 ± **15%**
5-15%	673 ± **15%**	271 ± **15%**
15-30%	383 ± **15%**	178 ± **15%**
30-60%	123 ± **15%**	76 ± **15%**
60-80%	19 ± **60%**	19 ± **60%**
80-92%	3.7 ± **60%**	5 ± **60%**

Introduces systematic error
Large for peripheral events

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Initial Conditions

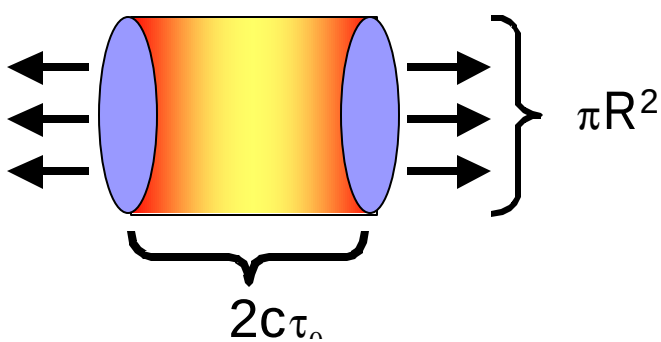
- What is the energy density achieved?
- How does it compare to the expect phase transition value from lattice QCD?
- Is this energy density thermalized?

Bjorken formula for thermalized energy density

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

Need to measure transverse energy (E_T)

Need to estimate the time to thermalize the system (τ_0 ~ 0.5 fm/c)



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Transverse Energy

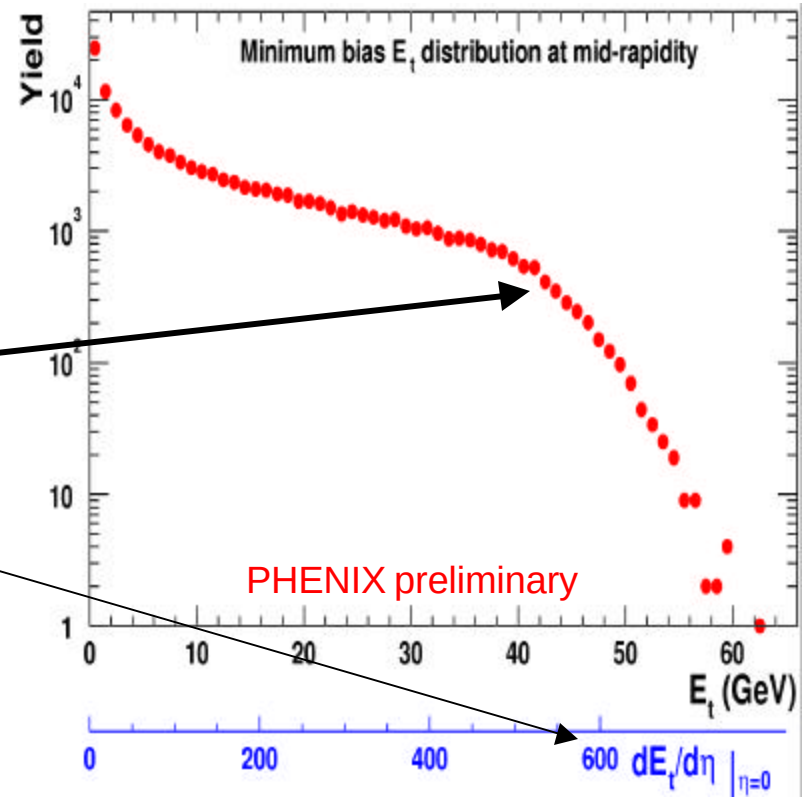
PHENIX Electromagnetic calorimeter measures transverse energy.

For the most central events:

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

~6.5 fm

$\varepsilon_{Bjorken}$ ~ 5.0 GeV/fm^3



Lattice phase transition:

$\varepsilon_{critical}$ ~ 1-2 GeV/fm^3

Energy deposition is certainly adequate, but does it create a thermalized new phase of matter?

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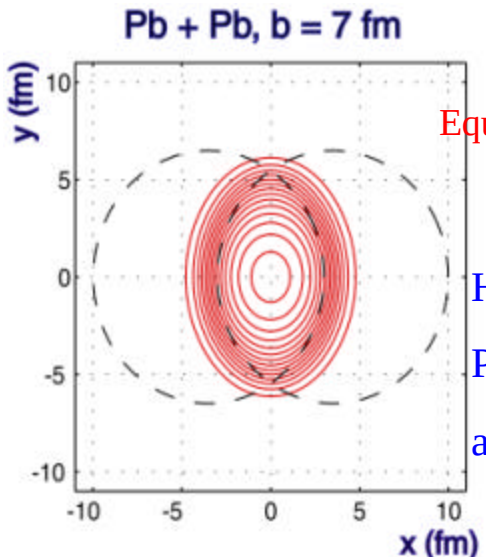
Is the system thermal? Look at “elliptic flow”

- Why flow!?!?
  - Imagine trying to study the phase transition of water by throwing two bags filled with ice cubes at each other and observing it from a distance
- Flow
  - Pressure build up (energy density profile)
  - Explosion with azimuthal asymmetry
    - Zero for central collisions
- Hydrodynamics
  - Assumes continuum matter with local equilibrium
    - Locally equilibrated or “thermalized”

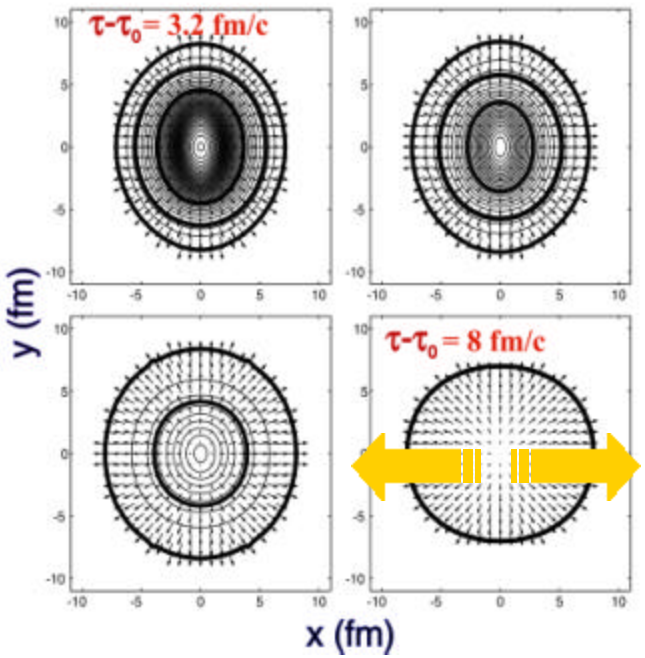


Equal energy density lines

Hydrodynamic Calculation

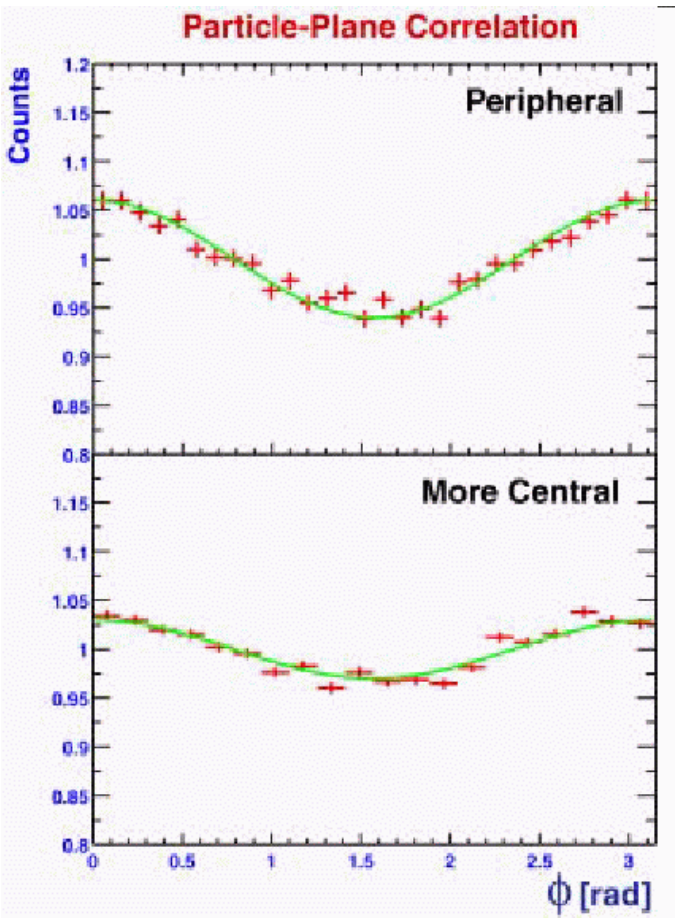
P. Kolb, J. Sollfrank,

and U. Heinz



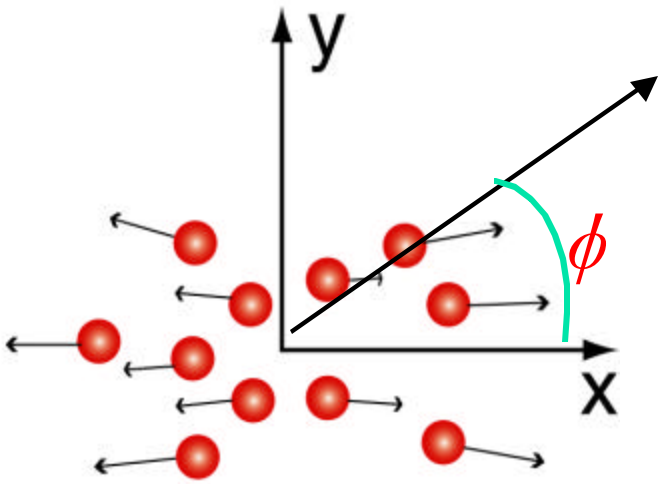
“elliptic flow”

Definitions - v_2, a measure of elliptic flow



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

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



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

Measure asymmetry in Momentum space

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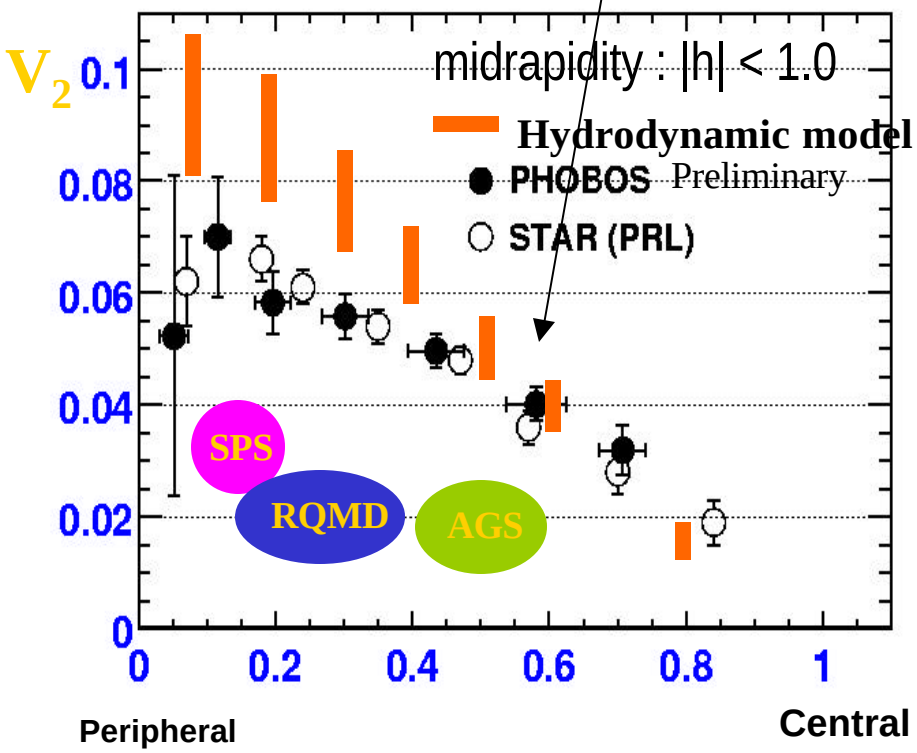
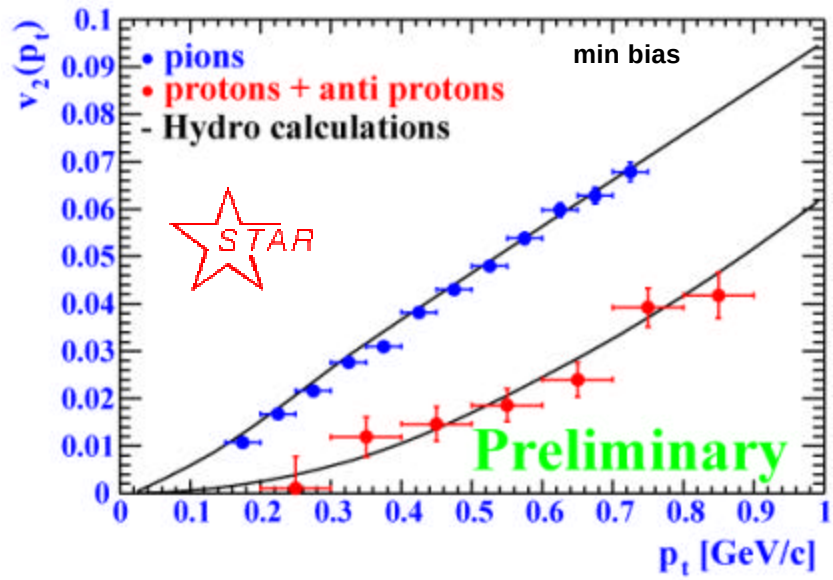
Centrality, PT Dependence of v_2

- Strong flow signal
- Non-equilibrium Cascade models e.g. RQMD: v_2 ~0.02
- Consistent with Hydrodynamics to mid-central





OK, looks like we might have a system of high energy density that is consistent with being reasonably thermalized

Now What?

Answer – Probe the system, Let's see what kind of muck we made!

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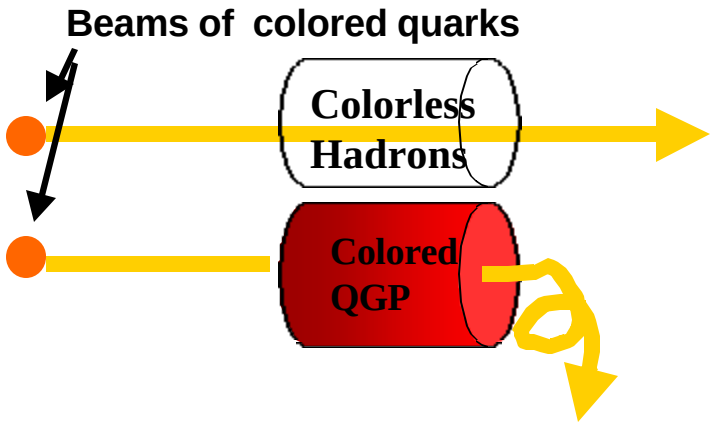
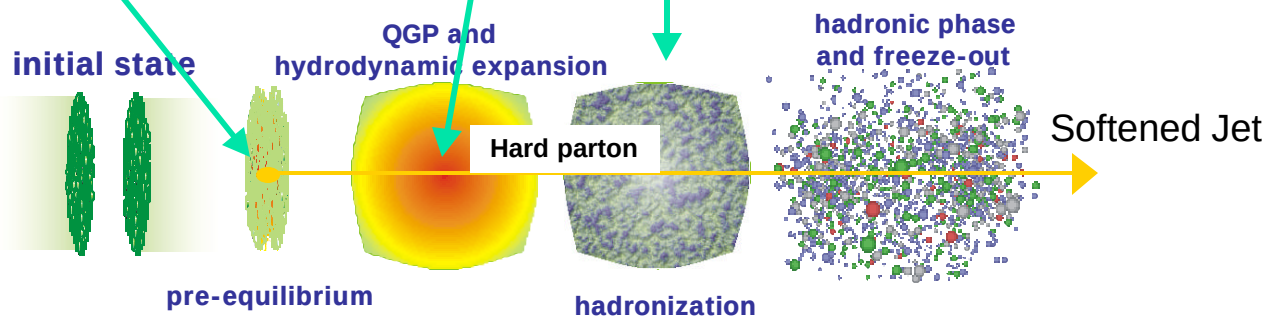
Hard Probes In Heavy Ion Collisions, aka Jet quenching

- The experiment we would like to do – Deep Inelastic Scattering of the QGP



- "hard" probes
  - **Formed in initial collision with high Q^2**
    - **penetrate hot and dense matter**
    - **sensitive to state of hot and dense matter**
      - dE/dx **by strong interaction**
      - Þ jet quenching



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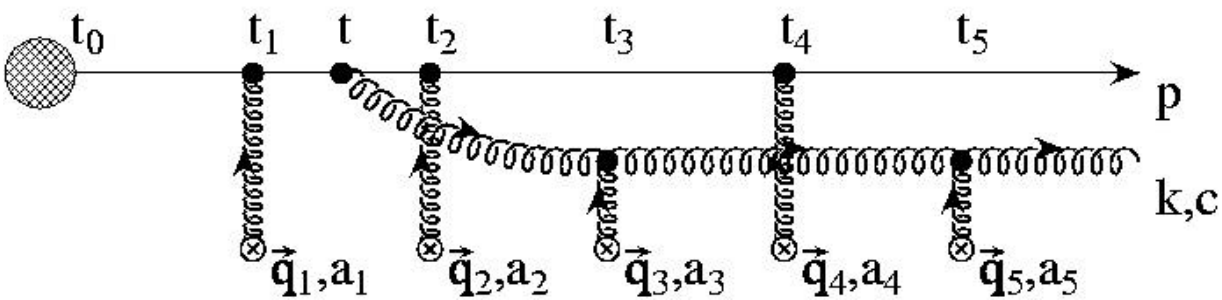
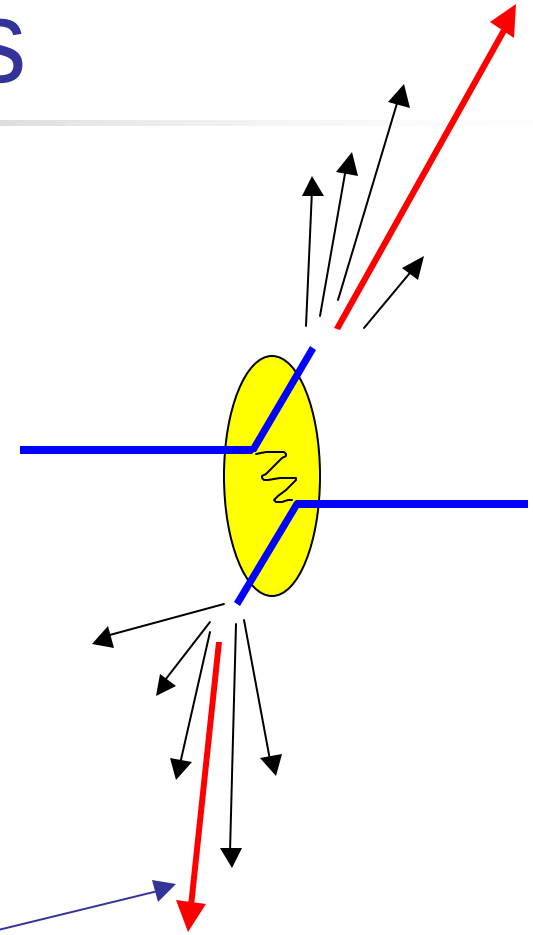
Parton Energy Loss

- Partons are expected to lose energy via gluon radiation in traversing a quark-gluon plasma





- Two forms of energy loss considered
  - dE/dx ~ constant, static plasma
  - dE/dx ~ L
    - This latter one is from QCD calculations (interference)
    - Both Static and expanding plasma considered

Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

The leading particle energy is lowered (jet quenching).
Hadrons above P_t > 1 GeV are expected to be from jet fragmentation.
Thus, we should look for *a suppression of high P_t hadron production.*

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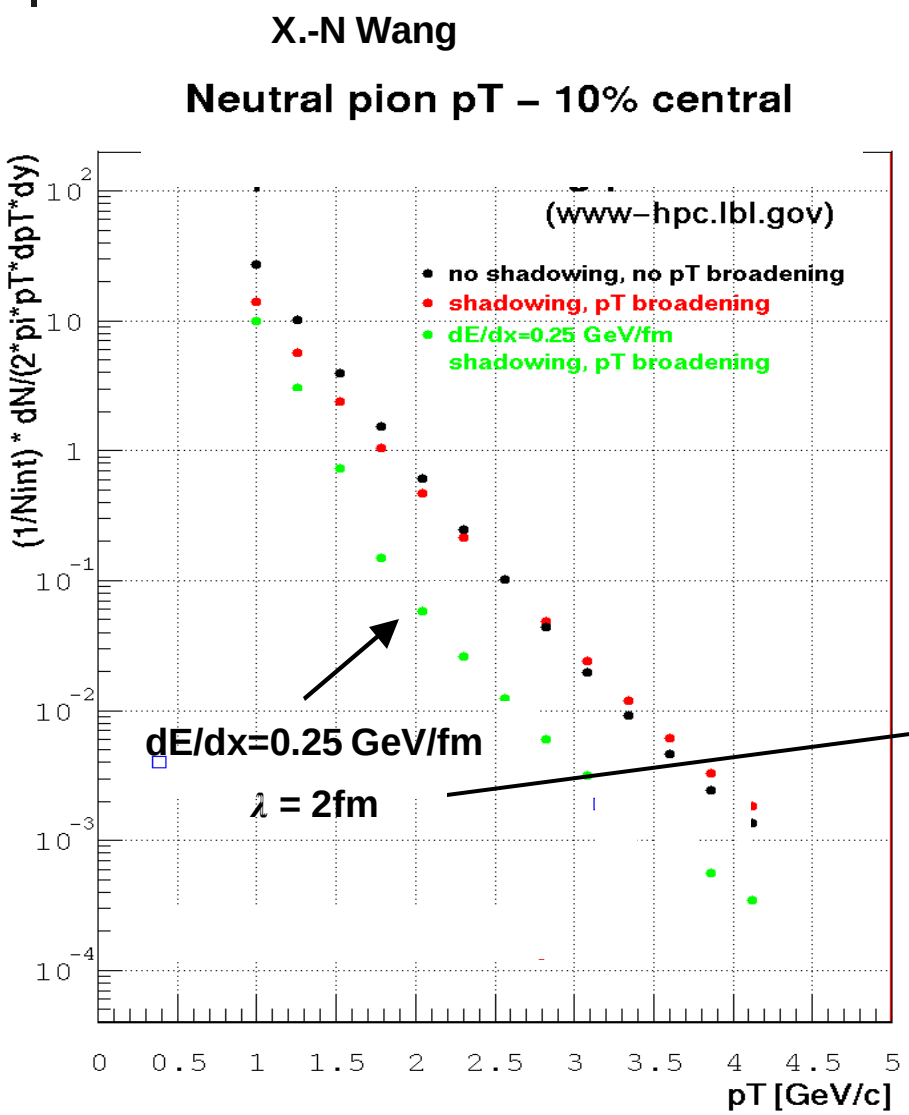
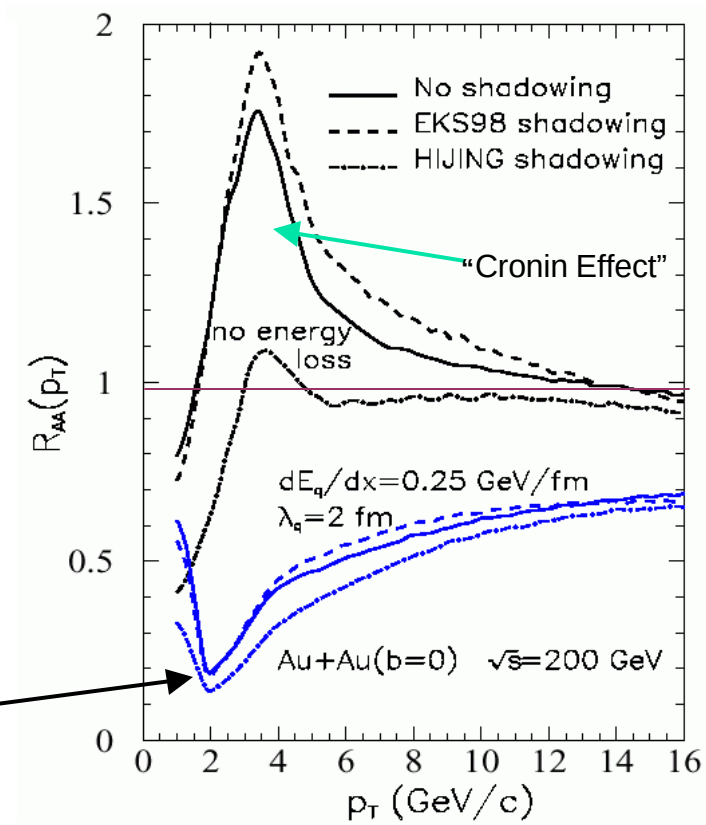
Some expectations – (predictions!)





Normalize to pp cross section

Define:

$$R_{AA} = \frac{1}{< N_{bin} >} \frac{AA}{pp}$$

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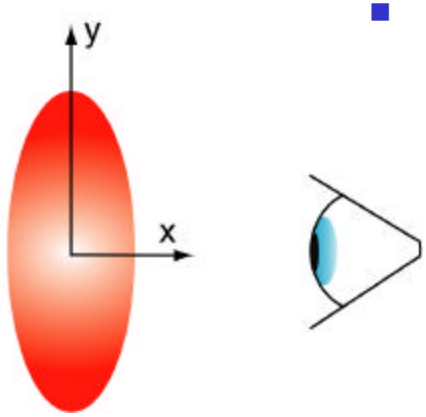
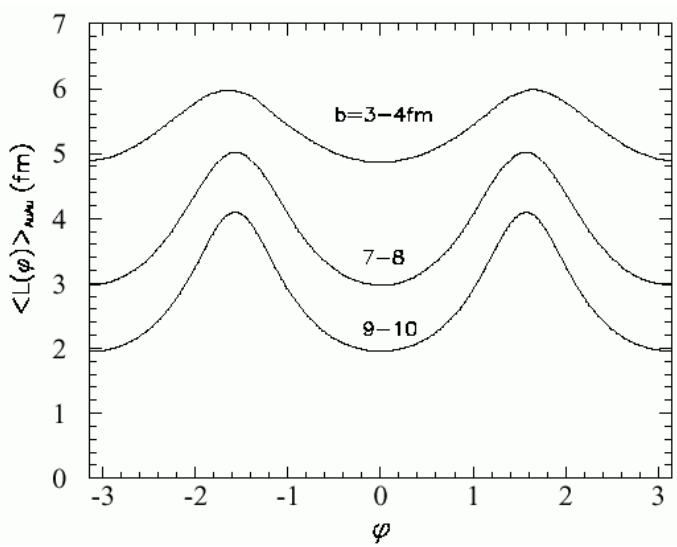
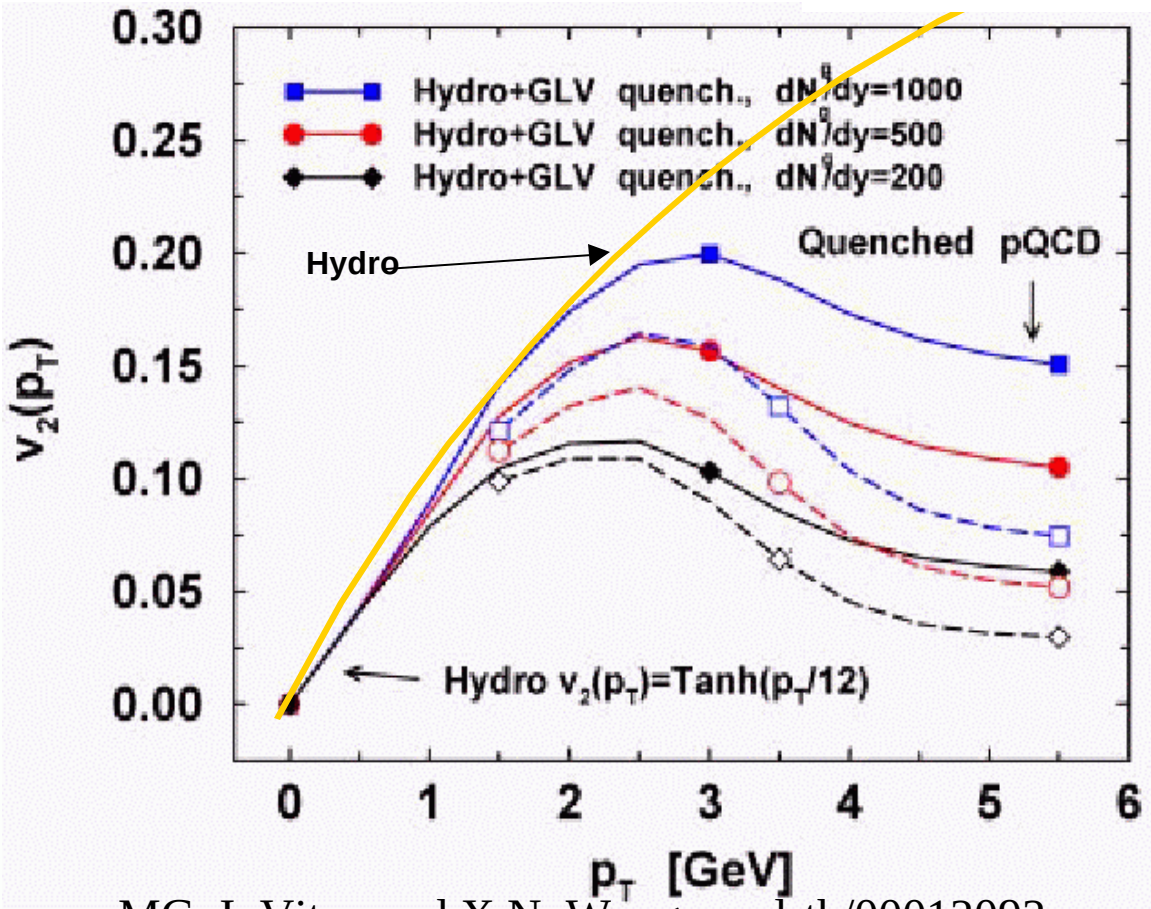
$v_2(p_t)$ for high p_t particles
Hydro + quench model

- Gyullasy, Vitev, Wang combine a hydrodynamic model with a jet quenching scenario.
- dE/dx ~ L





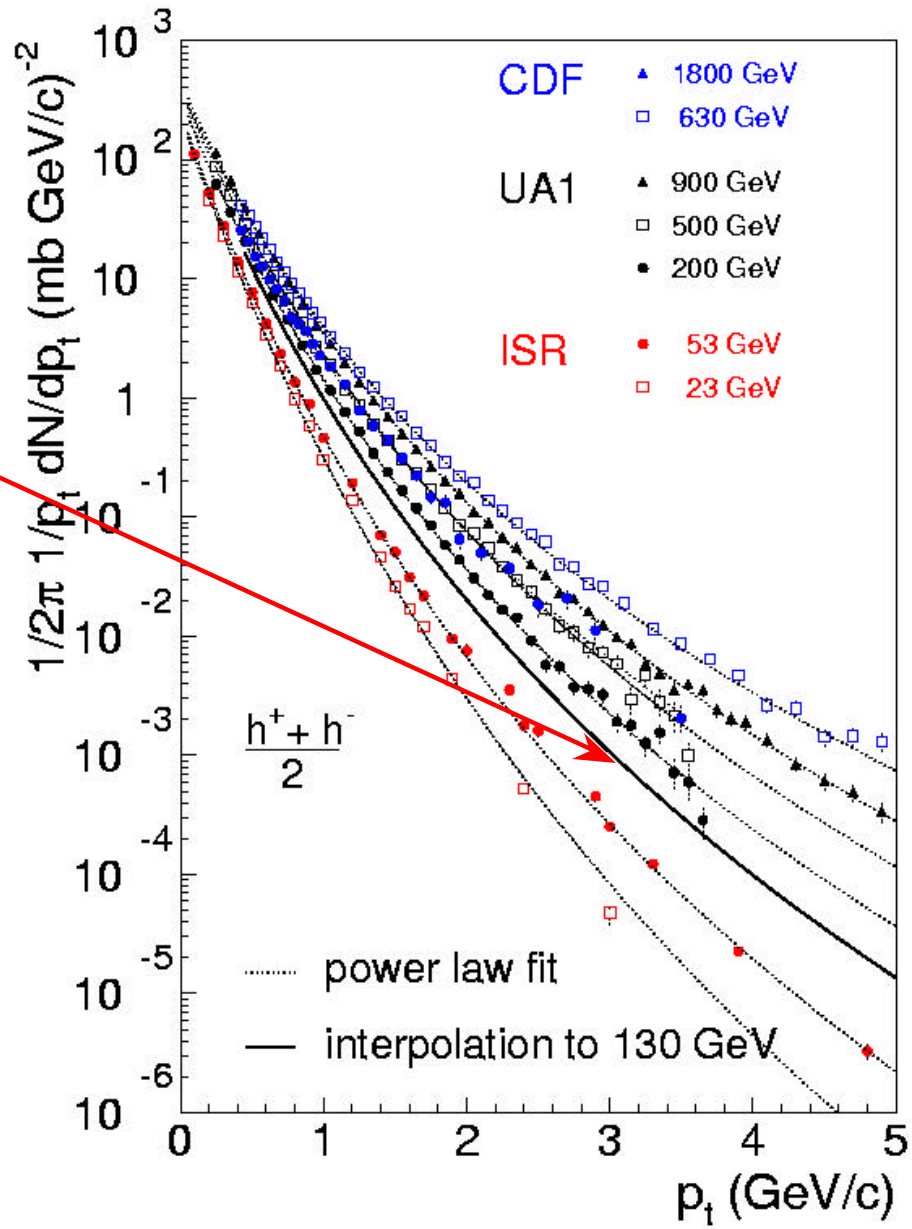


MG, I. Vitev and X.N. Wang, nucl-th/00012092

Setting the baseline

- To find jet suppression – compare to what?
  - Pp collisions scaled to √s = 130 GeV
    - Good fit to a power law
  - Peripheral collisions – an approximation to pp, or pA

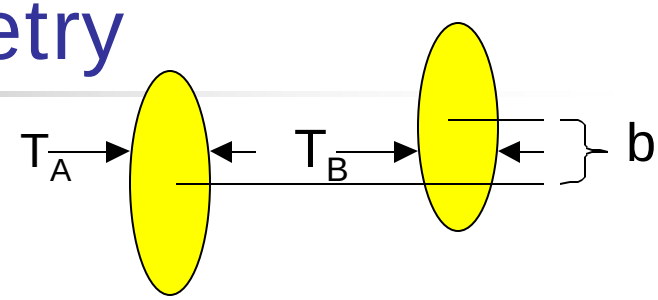
    and
- pQCD Models – Hijing, VNI, etc. + jet dE/dx
  - Needed to make quantitative statements about energy loss
  - Some are extensions of standard Monte-Carlo's



Models – scaling pp to AA

- How do we scale from pp to AA?
  - Nuclear Geometry
    - Scale Hard processes with N_{binary}
    - Scale soft processes with $N_{participants}$
  - pp effects
    - Intrinsic k_T
  - pp to pA effects
    - “Cronin effect”, initial state quark scattering
    - Nuclear shadowing
- I will explain each of these briefly

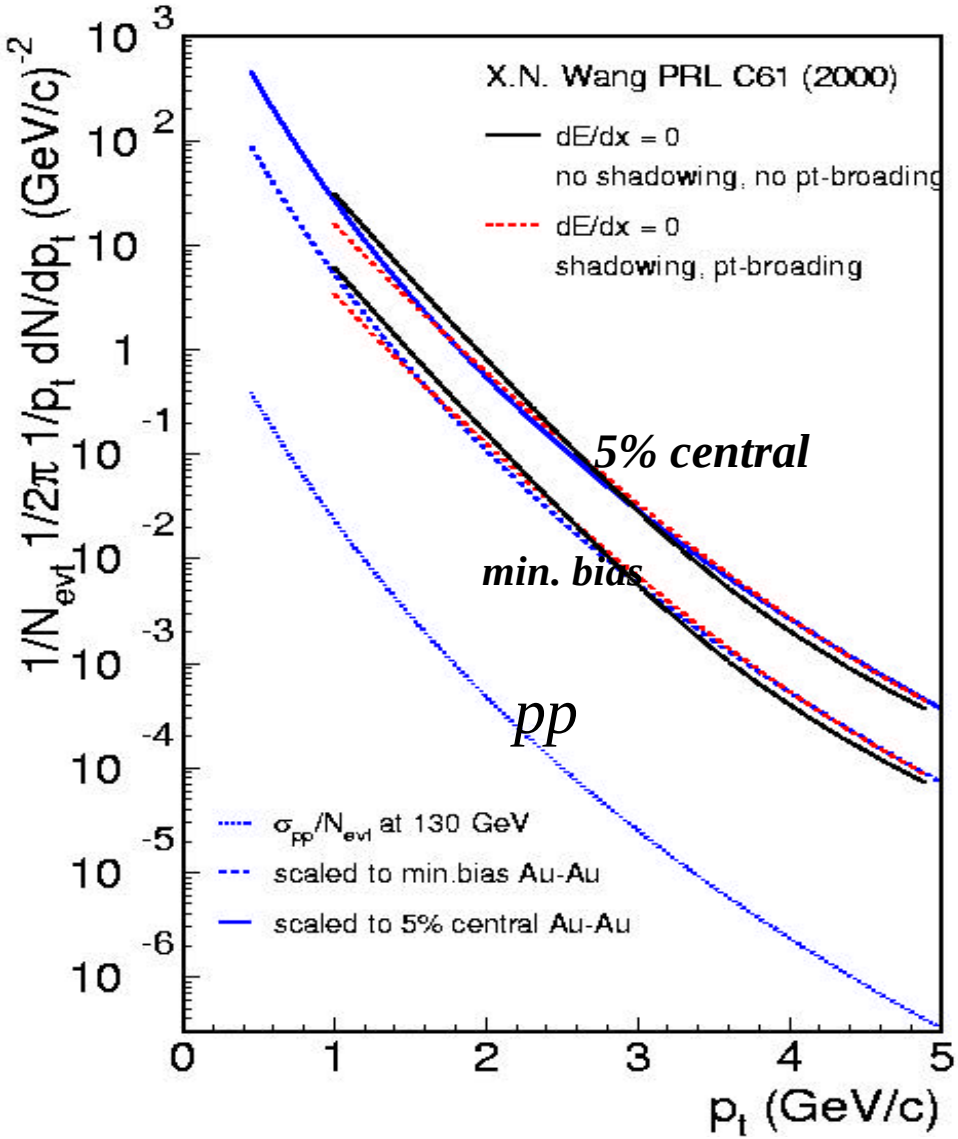
pp to AA: Nuclear Geometry



$$T_A(b) = \int dz\, \rho_A(z,b)$$

Glauber Eikonal Geometry

$$T_{AB}(b) = \int d^2s\, T_A(s+\tfrac{b}{2})T_B(s-\tfrac{b}{2})$$



- Hard processes scale with binary collisions
  - scaling to Au-Au (b_c) :

$$\sigma_{AA}(b < b_c) = \sigma_{pp} \int_0^{b_c} d^2b\, T_{AA}(b)$$

  - scaling to central collisions:

$$\sigma_{AA} = A^2 \sigma_{pp}$$

$$T_{AA}(b \ll R) \approx \frac{A^2}{\pi R^2} \approx \frac{A^{4/3}}{\sigma_{pp}}$$

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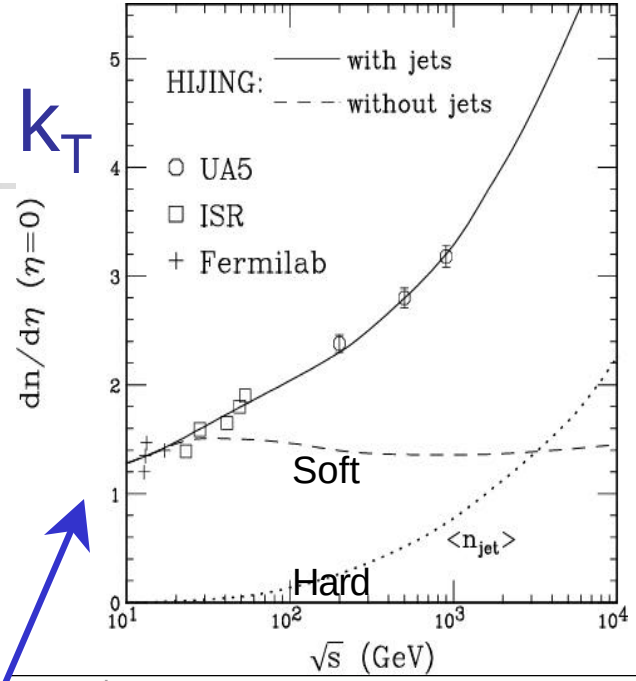
Models pp, $\bar{p}p$ – intrinsic k_T

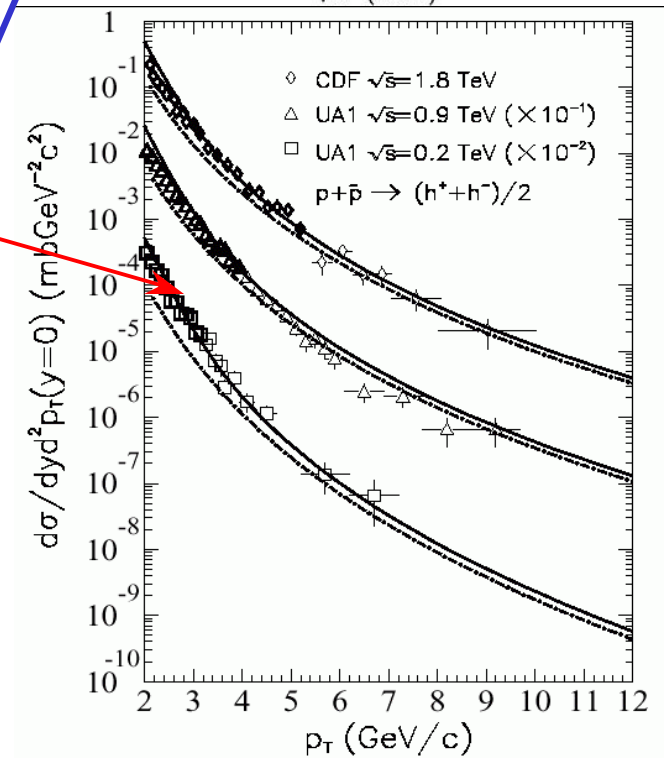
- Scaling
  - Soft interactions - production scales with $N_{participants}$
    - Strings : $p < p_0 \sim$ 1-2 GeV
  - Hard interactions - production scales with N_{binary}
    - pQCD : $p > p_0$
    - Initial k_T included

$$\sigma_{jet} = \int_{p_T > p_0} dp_T^2 dy_1 dy_2 \frac{1}{2} \sum_{a,b} x_1 f_a(x_1) x_2 f_b(x_2) \frac{d\sigma_{ab}}{d\hat{t}}$$

$$dN_{ch}/d\eta \Big|_{\eta=0} = Soft \times N_{part} + Hard \times N_{bin}$$

$$\sigma_{qq}(s) = \sigma_{jet}(s) + \sigma_{soft}(s)$$



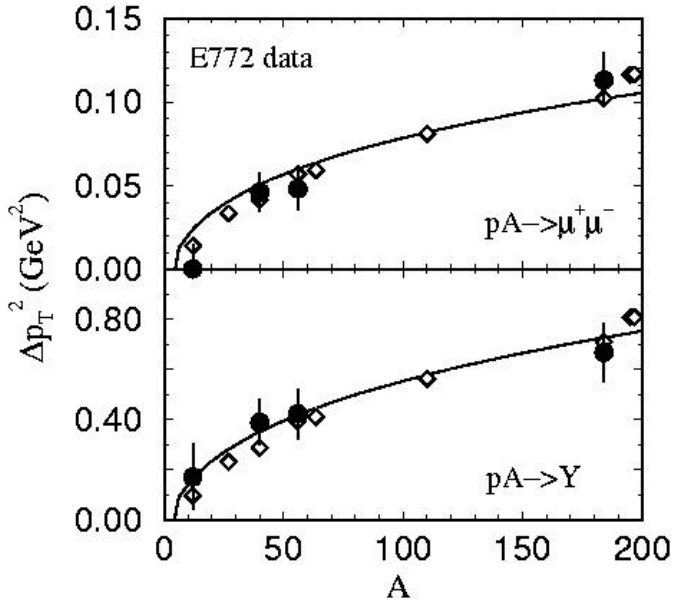


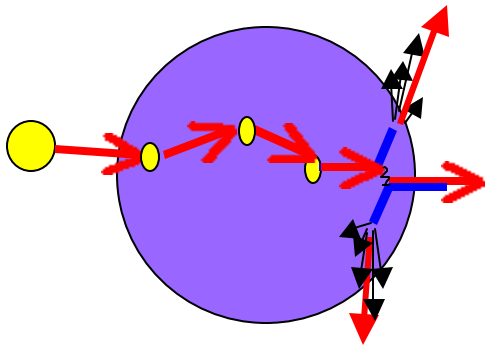
pp to pA: the Cronin Effect

- Prior parton scattering broadens the transverse momentum spectrum ("Cronin effect"). This has the opposite effect of "Jet Quenching."
  - i.e. it enhances high p_t

$$\langle p_t^2 \rangle_A = \langle p_t^2 \rangle_{pp} + (A-1)\ \Delta p_t^2$$

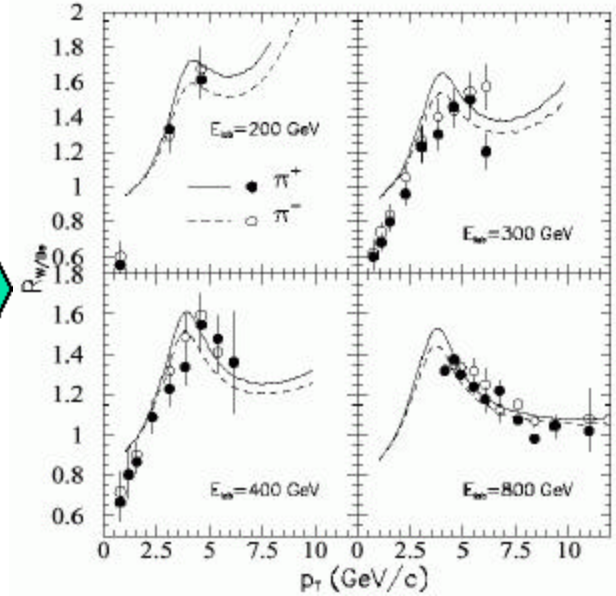
  - Not expected to be a large effect at RHIC energies. Big effect at CERN-SPS energies.





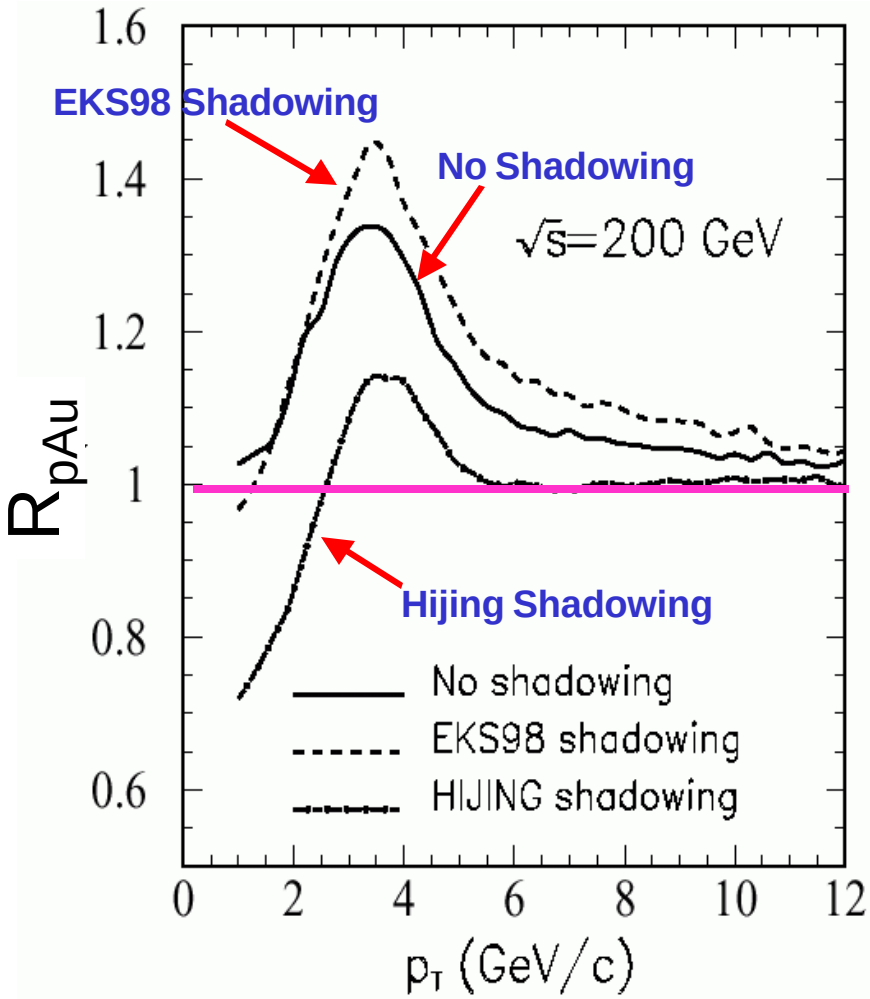
Hijing MC

$$R_{W/Be} = \frac{1}{A_W}\frac{pW}{pBe}$$

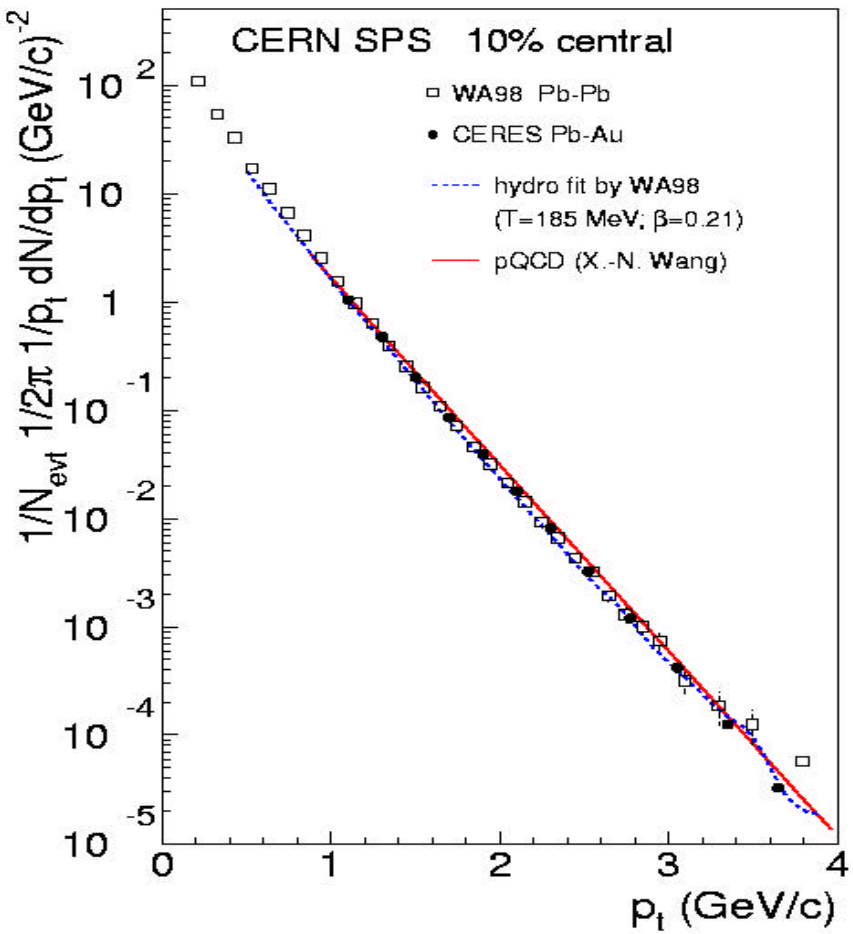


pp to pA: Nuclear shadowing

- Nucleon structure functions are known to be modified in nuclei. Fewer partons than otherwise expected will lead to fewer high P_t particles.
- Gluon shadowing
  - is not measured,
  - large role at RHIC
- Measure pA at RHIC!
  - For now depend on peripheral events



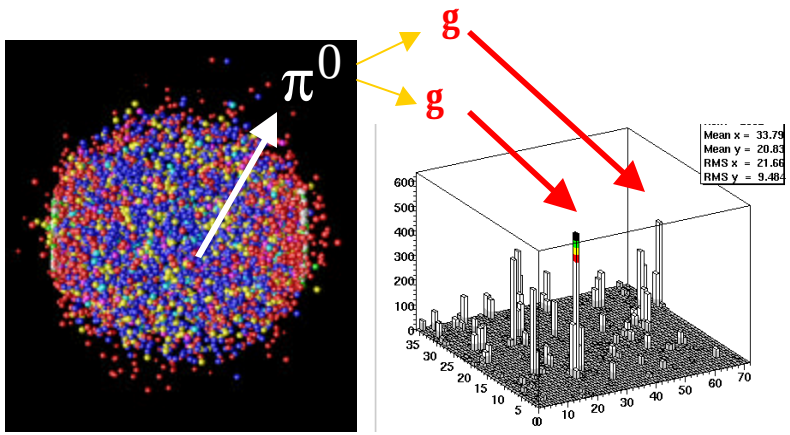
Results from the SPS

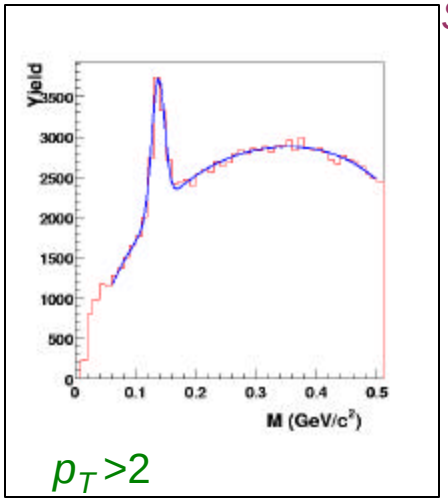


- data well described by pQCD
  - scaling
  - (intrinsic + initial) $k_T(A,Q)$ broadening

    I.e. Intrinsic k_T +Cronin effect

PHENIX Data: π^0 spectra





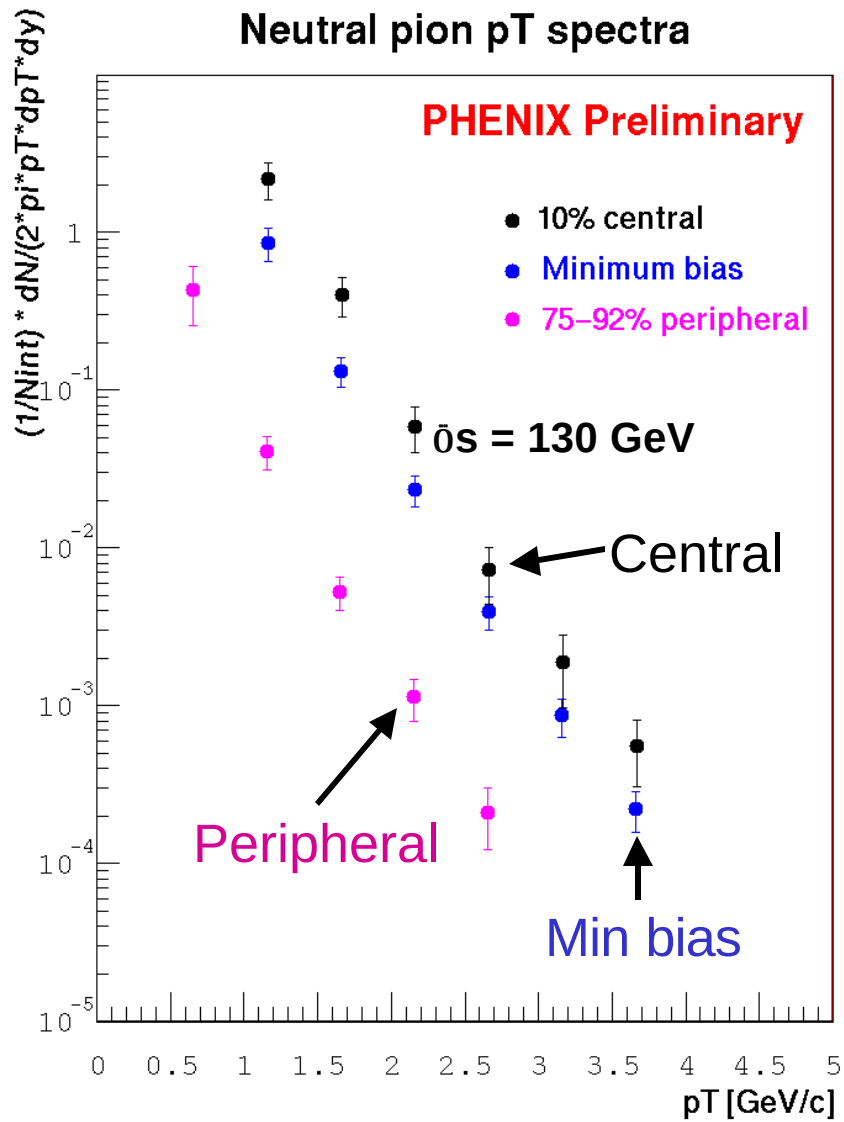
p_T>2 GeV,asym<0.8

Systematic errors included

Main sources:

- *peak extraction*
- *PID loss*
- *efficiency calculations*
- *non-vertex pions*
- *pT scale*

Centrality	~N_{bin}	~N_{part}
10%	800	300
M.B.	125	75
75-92%	10	10



~1M Min Bias AuAU events

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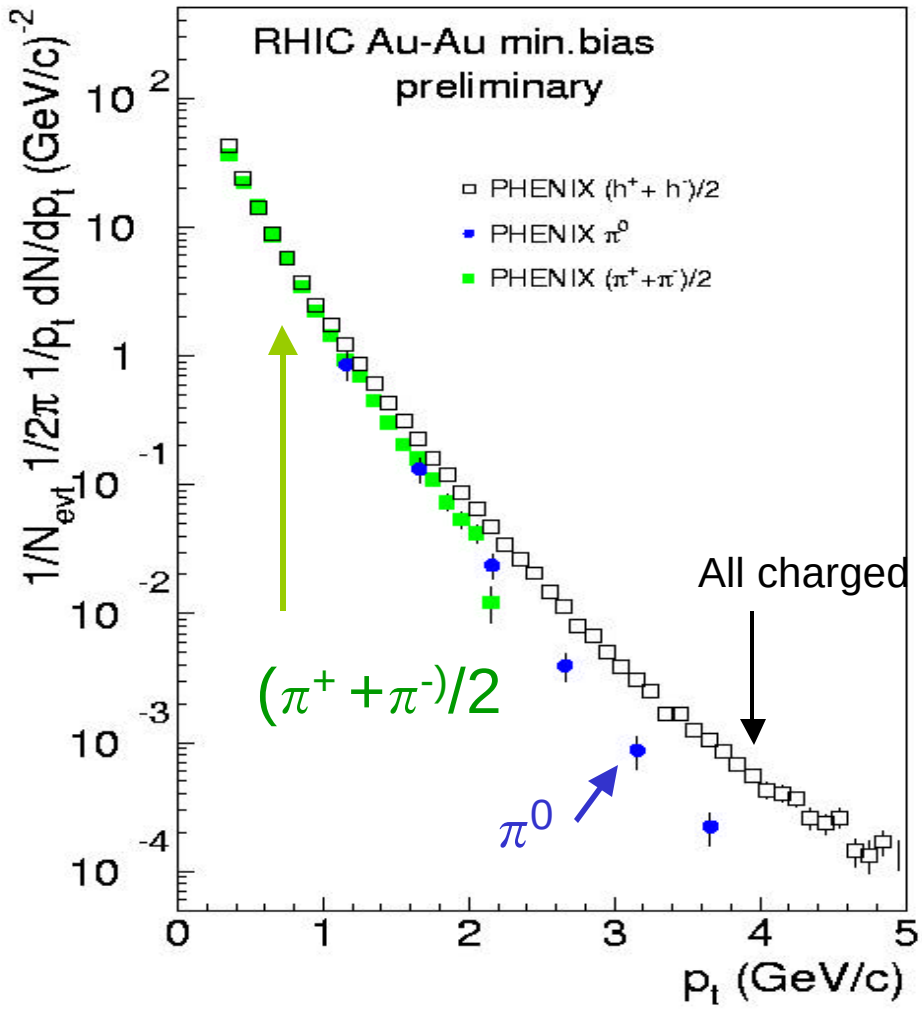
Comparison to charged spectra

- $\pi 0$ spectra matches identified charged pion spectra – different systematics!



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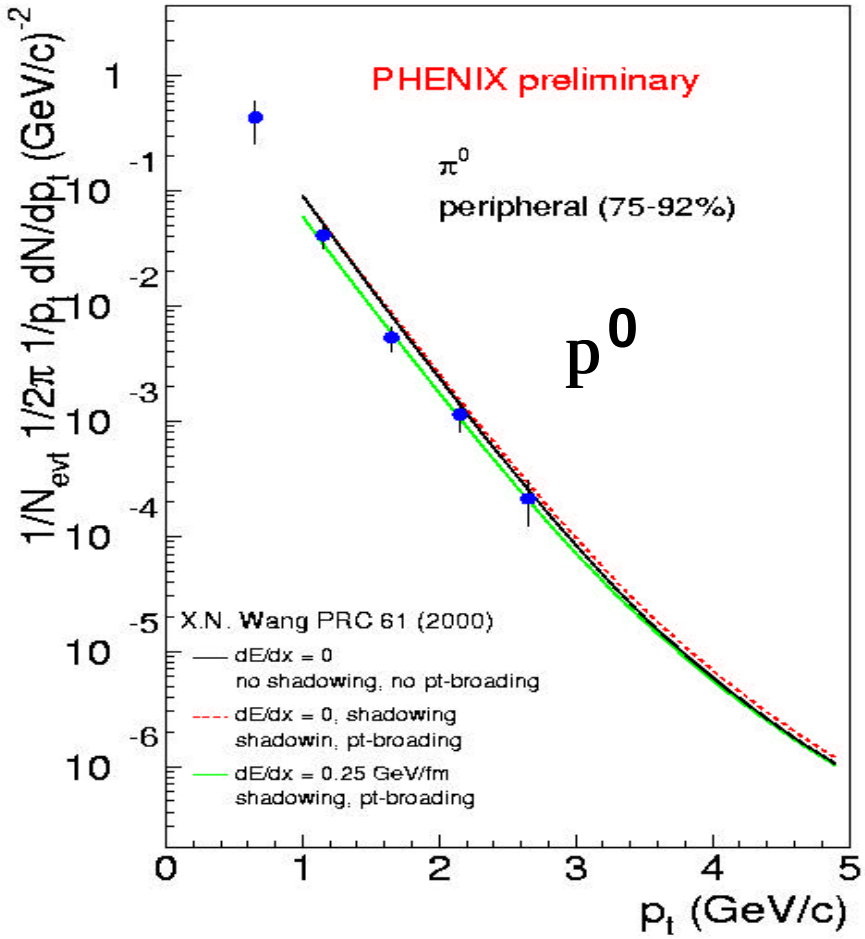
Comparison with QCD calculations:Peripheral Events



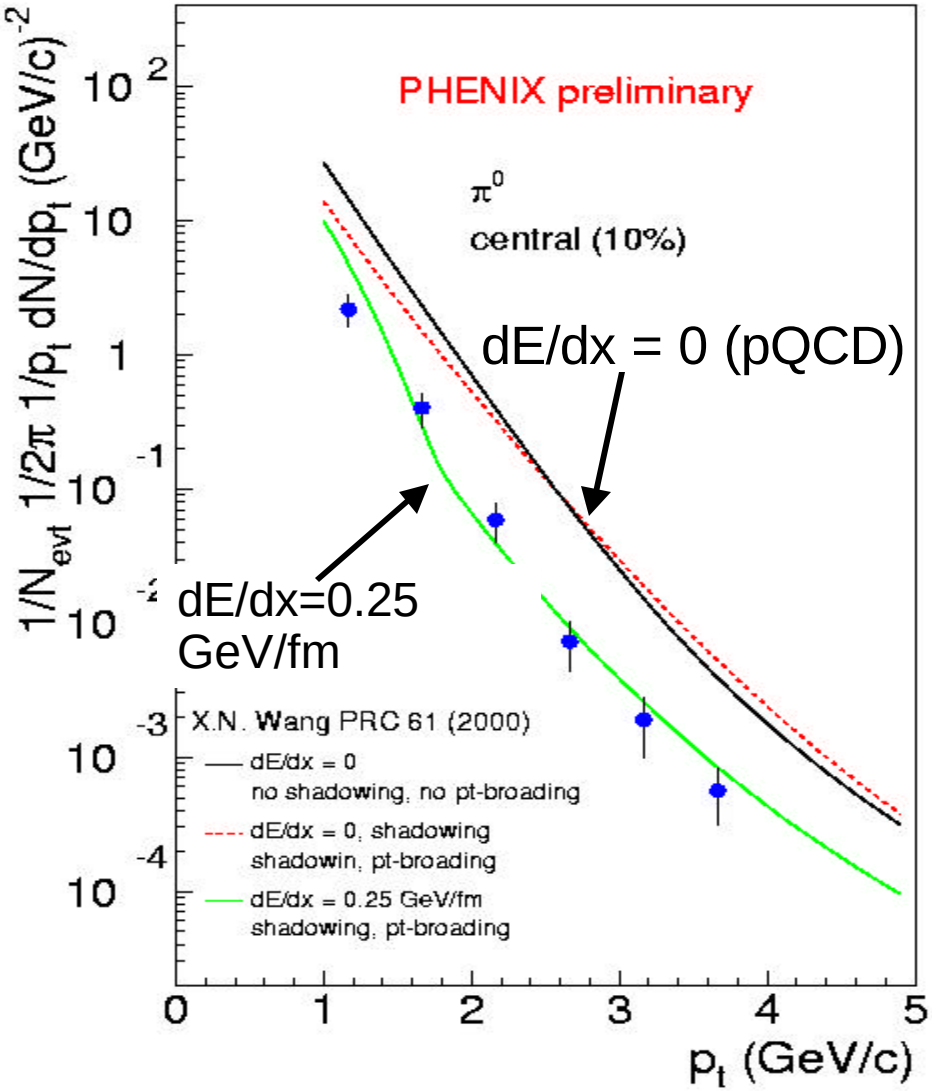
- good agreement with pQCD calculation in Peripheral Collisions
  - Includes Intrinsic k_T, Cronin, shadowing
- Baseline is OK

Richard Seto

Central Events – Jet quenching?

- p-QCD over estimates the cross-section
  - for π^0 at least $\times$***5***
- shadowing and p_t-broadening seem insufficient
- calculation including constant energy loss
  - consistent with π^0

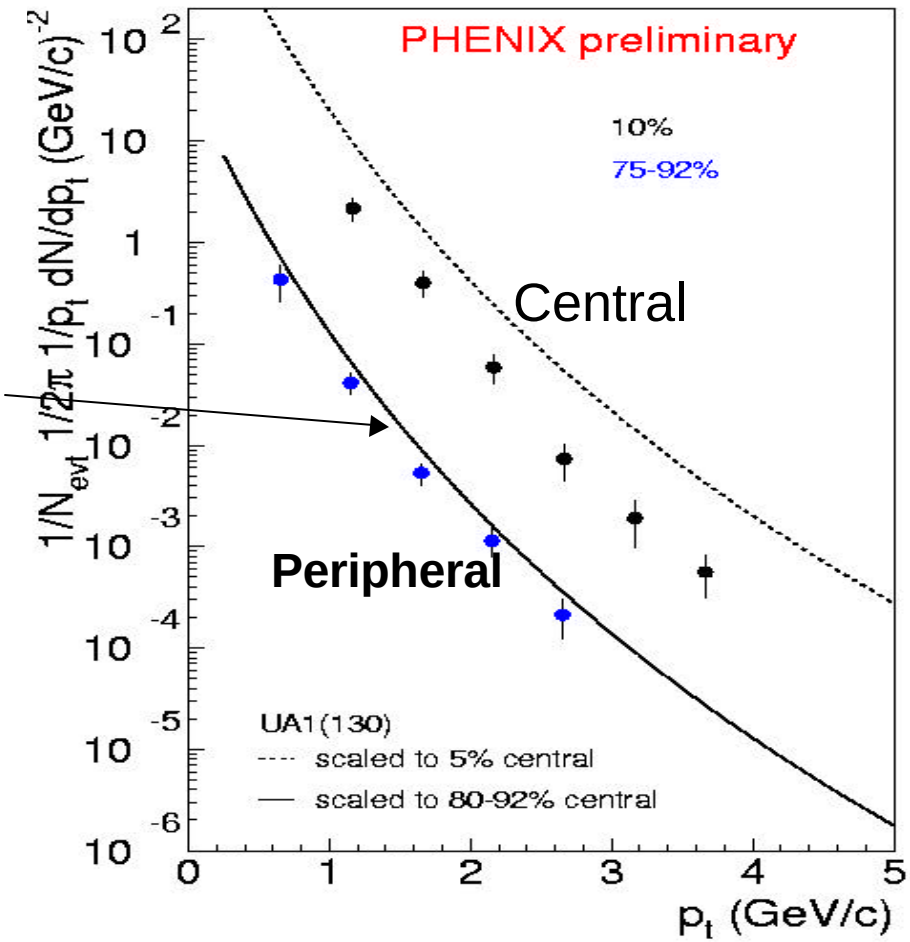
Evidence of Jet Quenching!?



Some sanity checks - 1

G.David, PHENIX

- Just compared to scaled σ_{pp}(UA1 fit 130)
- Still suppression x5
- Cronin and Shadowing effects not included



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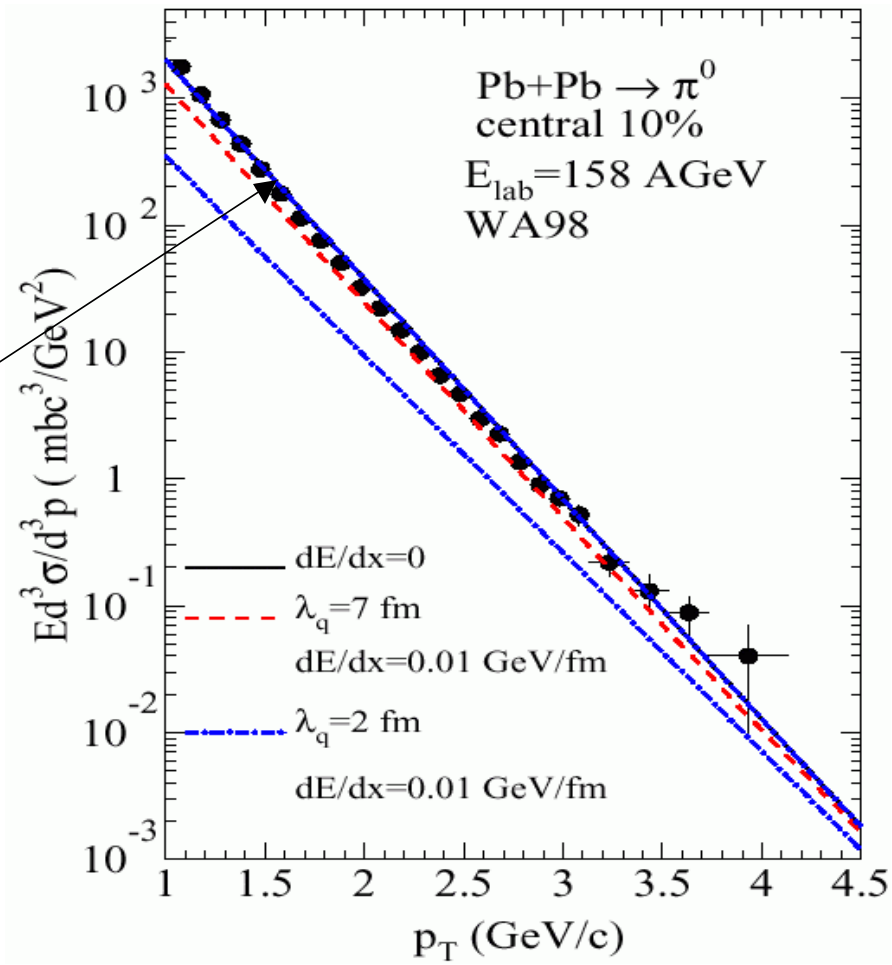
Some sanity checks - 2

- Maybe scaling is wrong?
- Check with central collisions at the SPS (where we don't see quenching)
- No quench hypothesis fits well to central events



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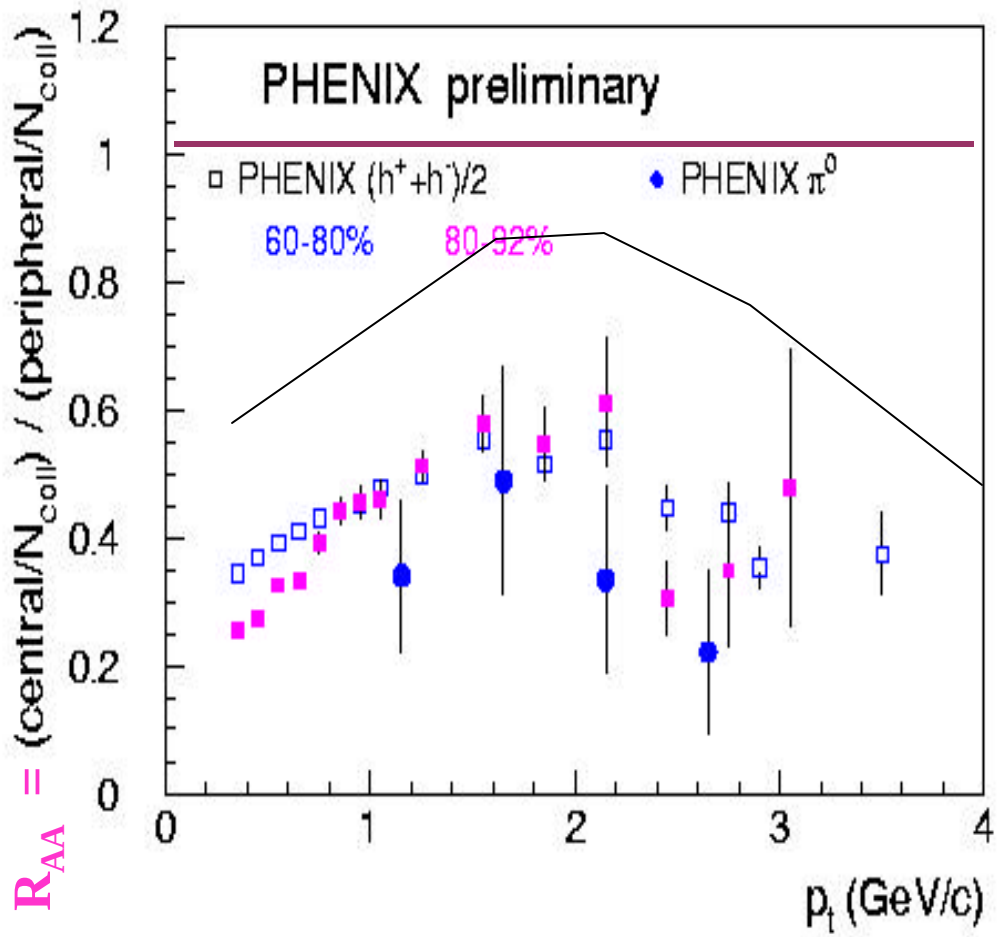
Sanity check – 3 Ratio Central/Peripheral

- normalize central to peripheral divided by N_{Binary}
- different systematic errors:
  - many experimental errors cancel
  - systematic uncertainty ~60% on N_{coll}

within systematic errors:

$R_{AA} < 1$



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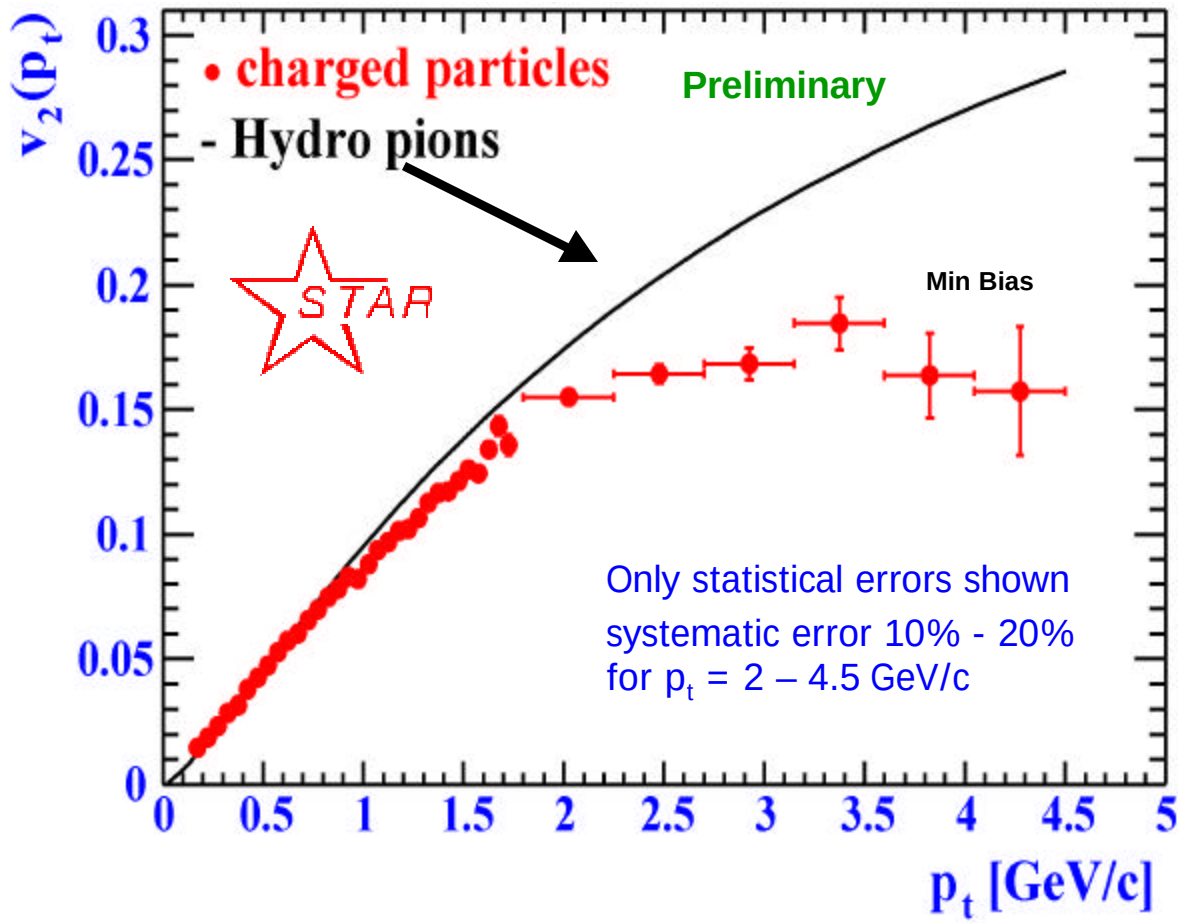
Charged particle anisotropy
p_t < 4.5 GeV/c vs Hydrodynamics

- Hydrodynamics seems to over predict v_2 for pT>2 GeV
- pT particles come from hard scattering
  - Not in equilibrium
  - hydrodynamics shouldn't work
- Jet quenching for non-Central events?
- Caveat – comparing to all charged



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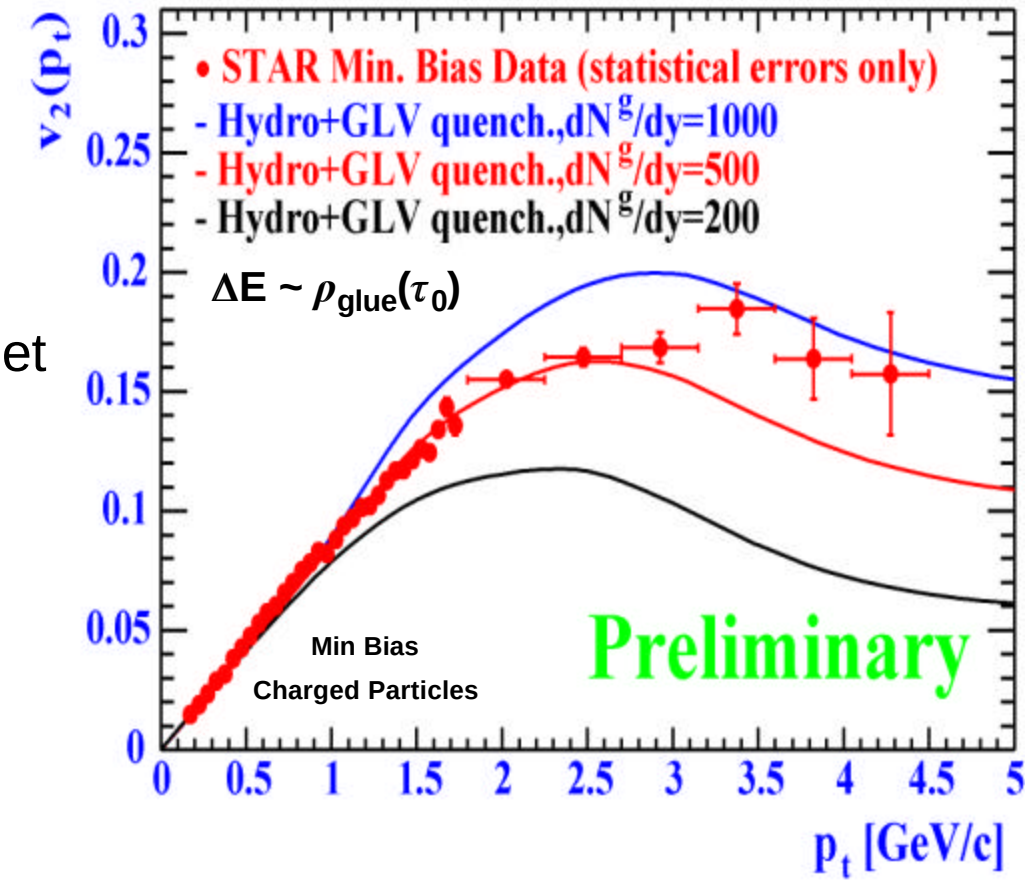
Preliminary STAR Charged particle anisotropy

- Differential $v_2(p_T)$:
  - Hydro up to ~1.5 GeV
  - Flow signal consistent with Jet Quenching!



systm. error 10% - 20% for p_t = 2 - 4.5 GeV/c

Flow signal consistent with Jet Quenching!

Kolb et al (Hydro) + MG, P. Levai, I.Vitev (dE_{QCD}/dx) PRL85(00)5535

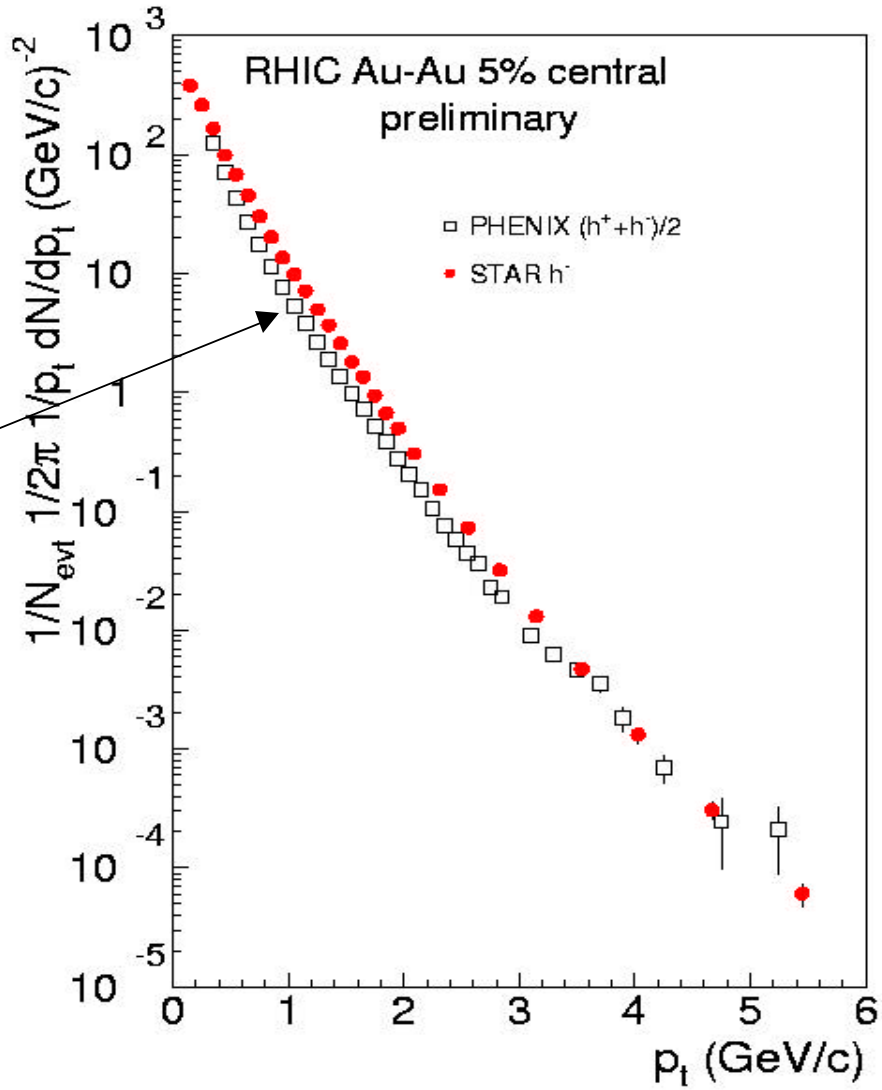
MG, I.Vitev and X.N. Wang, nucl-th/00012092, PRL in press

Richard Seto

Some Dirty Laundry

J.C. Dunlop, STAR
F. Messer, PHENIX

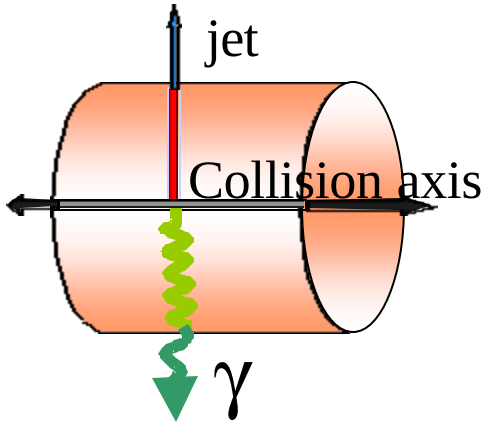
- Comparison of charged particle spectra from
  - PHENIX $(h^+ + h^-)/2$
  - STAR h^-
  - 30% discrepancy
  - Careful comparisons between experiments with the same cuts have yet to be made



Jets : the future

- Next run (starting in May 2001) ~ 100x statistics
  - p^0 to Pt ~ 10 GeV !
    - Greater sensitivity to exact energy loss
      - How big?
      - Proportional to mean free path?
  - Back to back high pt particles
  - pA running??? Critical !
  - Possibly high pt K-
    - Has no valence quarks ~ $\bar{u}$ s should be sensitive to gluon jets
      - Gluons should have more higher dE/dx than quarks

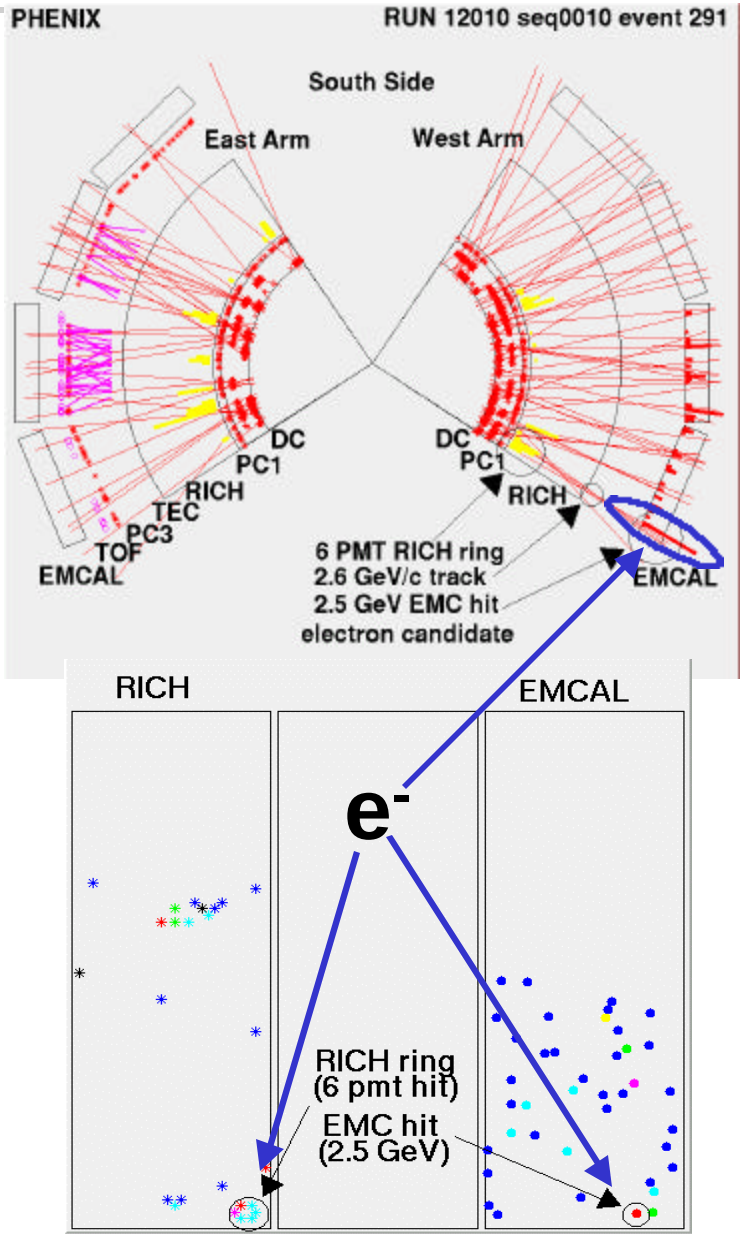
- Later as Luminosity increases
  - Direct γ-tagged events: $E_g \sim E_{jet}$



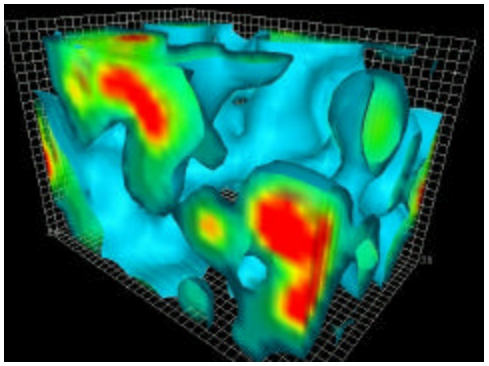
PHENIX: Shape of Things to Come – electrons, muons

- Completion of Central Arms
  - Significantly increased aperture
  - ➔ *Electrons!*
    - Tough in Heavy Ion Collisions
      - Low energy ~ < 3 GeV
    - All subsystems in concert
    - Redundancy of PID
- Addition of new capabilities
  - South Muon Arm
  - ➔ *Di-muon physics*

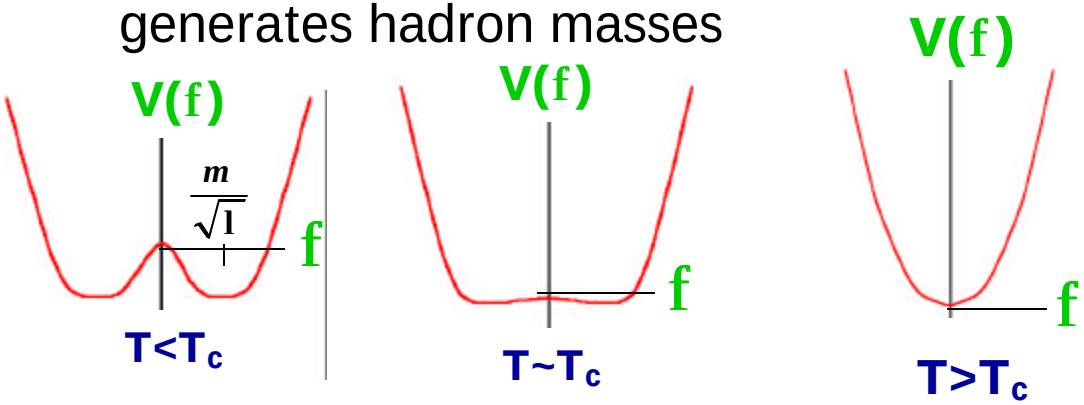
➡ The ~5M events recorded in Run-1 represent ~1 day of data-taking for RHIC+PHENIX in Run-2



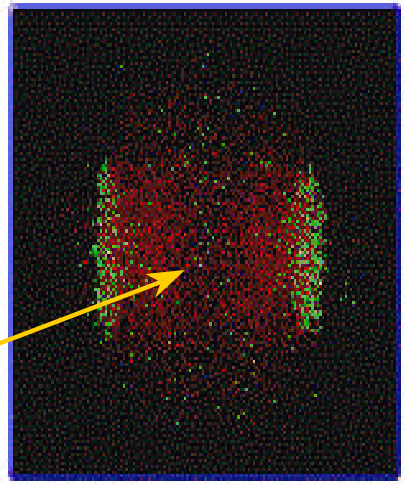
What about the chiral phase transition or Where does mass (hadronic) come from?



- Space filled with a chiral condensate $\bar{\psi}\psi$
  - Similar to the higgs field for E-W theory
  - $\bar{\psi}\psi$ - goo of quarks and gluons
  - Couples to quarks and gluons
  - Spontaneous symmetry breaking (I.e. chiral) of the quark condensate at low Temperature generates hadron masses



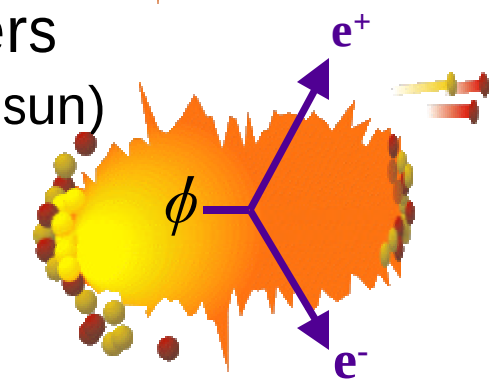
  - As $T \rightarrow T_C$, mass $\rightarrow 0$
  - How do we heat up the vacuum?
  - RHI collision leaves a region of excited $\bar{q}q$, g – ie hot vacuum

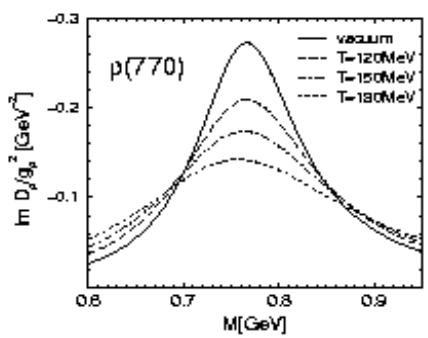


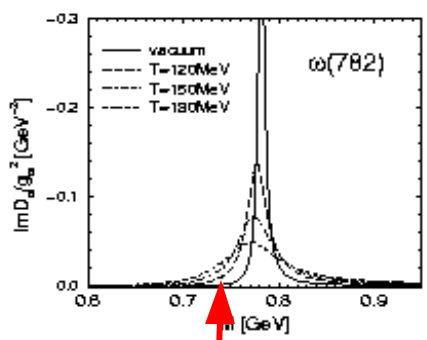
Looking for Chiral symmetry restoration
Vector Meson mass shifts in the dilepton channel

- "Light" Vector mesons are ideal probes (ρ,ω,ϕ)
  - Like putting a scale to measure mass inside the fireball
  - Short lifetime ~ few fm/c
  - ➜ Decay inside hot fireball

- Electrons (and muons) are ideal messengers
  - Don't interact strongly (e.g. neutrinos from the sun)







- In Medium ρ,ω
  - R. Rapp (Nucl. Phys A661(1999) 238c
  - ◆ shows low mass tail -
    - With its good mass resolution PHENIX should be able to see this

Richard Seto

Other topics

- Phenix will add
  - Complete central arms – Electron physics!
  - Muon arms – J/ψ, heavy quark physics
- STAR will add
  - Silicon Vertex Tracker
    - Measurement of Ξ Ω
  - large acceptance EMCAL over the next several year
    - Will get into the electron and photon game
- Other Physics Topics – all detectors
  - J/ψ suppression
  - Search for chiral symmetry restoration, mass shifts of the light vector mesons
  - Heavy quarks
  - pA physics
  - Of course spin physics

Conclusions

- Energy density ~ 1.5 x value at CERN SPS
- Observation of significant elliptic flow indicating thermalization
- Systematic study of p_T spectra for π^0's versus centrality show
  - Good agreement for peripheral collisions with predictions from hard scattering
  - Clear deficit in more central collisions
    - Data-to-data comparisons
    - Data-to-model comparisons

high-p_t data are consistent with "jet quenching" predictions !

- *Ideally positioned to dramatically extend these results in the future and hopefully answer:*
  - What is the nature of the deconfinement transition?
  - Where is the chiral phase transition? – are they related? – how?
  - Order of transitions?
  - What is the energy loss as particles travel through the qgp?
  - Any critical phenomena associated with the phase transitions?