First Results from PHENIX at the Relativistic Heavy Ion Collider

"A Look at Jet Quenching?"

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For the **PHENIX Collaboration**

Frontiers in Contemporary Physics
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P ioneering
H igh
E nergy
N uclear
I nteraction
e **X** periment

Outline

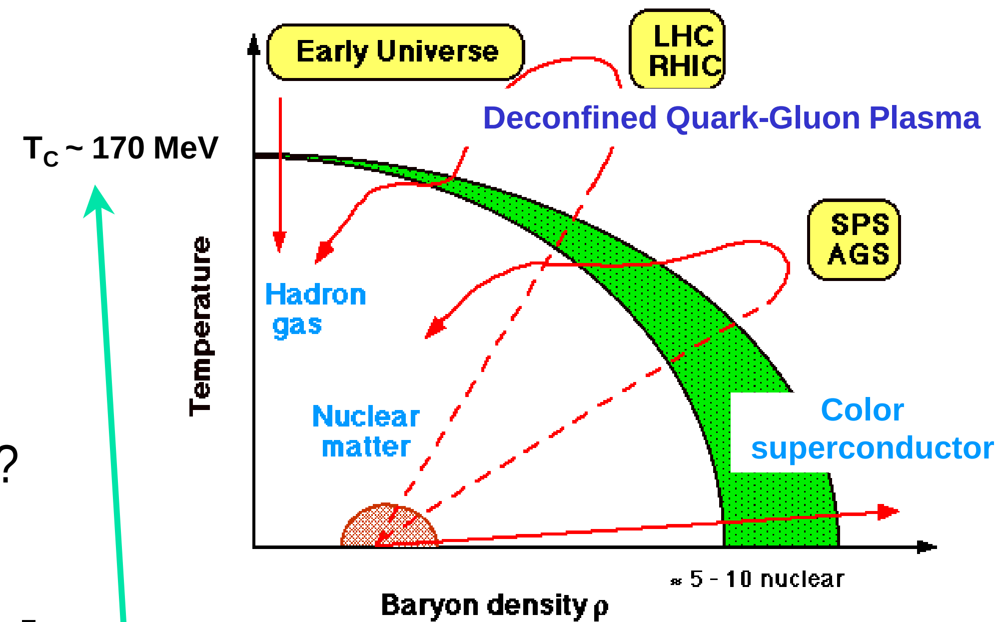
Note – MANY topics skipped – HBT, flow, fluctuations…

- Introduction
- PHENIX
- Nuclear Geometry
  - Centrality measurements
- Global Measurements
- Hadron Spectra
- Jet Quenching
  - The ideas
  - 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

Why Relativistic Heavy Ion Collisions?

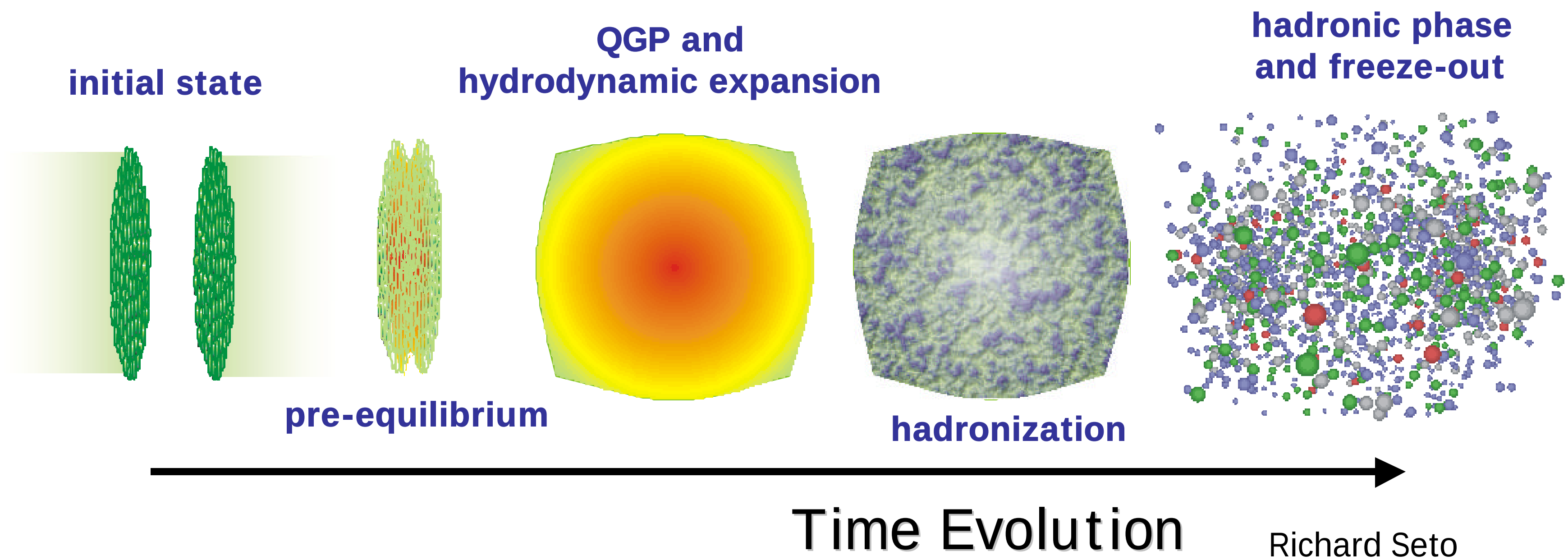
- To study matter at high density
  - Early Universe
  - Center of stars
- To study the phases of QCD
  - Where are the transitions?
  - What order is it?
  - Are there critical phenomena?
- TWO different phase transitions!
  - The deconfinement transition - particles are roam freely over large volume
  - The chiral transition - masses change
  - ~ same energy density



- Lattice QCD Calculations give T_C~150-200 MeV; $e_{critical}$ ~ **1-2 GeV/fm³**

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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How do get information out of this collision?

Note – This list is NOT all inclusive!
HBT, flow, fluctuations…

- Global Quantities
  - Multiplicity
  - E_T

  } Collision Dynamics, Energy Density, Entropy
- Conserved quantum numbers
  - Baryon number
  - Strangeness

  } Baryon Density- Baryon Free region? Chemical Composition
- Hard probes
  - "Deep inelastic scattering"

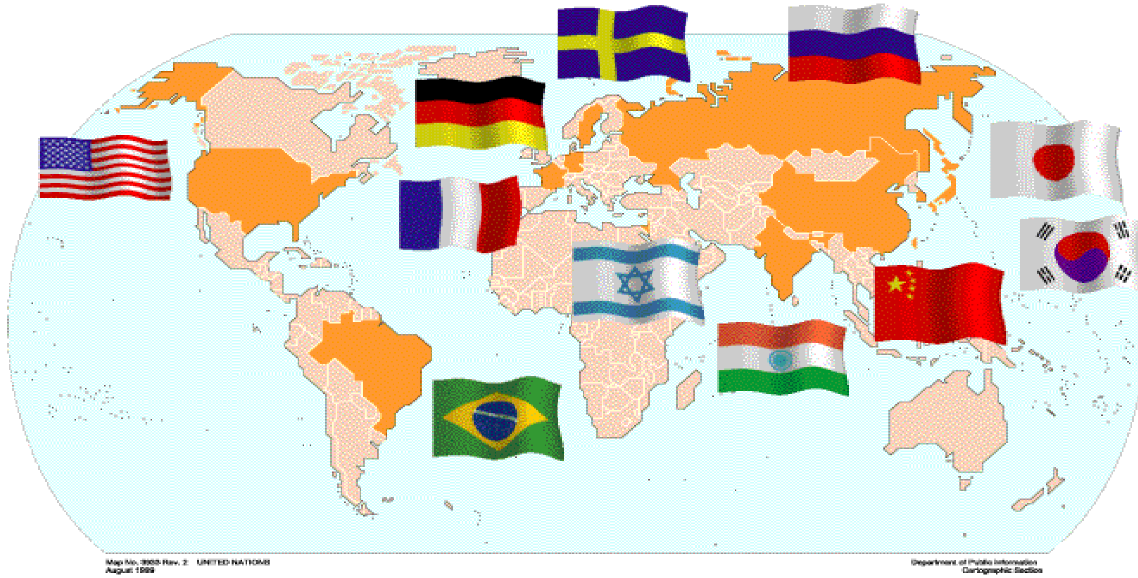
  } dE/dx of probes Deconfinement
- Leptonic probes
  - Electrons, muons, photons

  } Debye Screening Length Chiral symmetry restoration

PHENIX

The people:
~450 Collaborators
11 Countries
51 Institutions

The money:
~ $50-100M



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The data: Commissioning: June-July, 1999
First physics run:
~May-00 through Sep-00

- ~5M triggers, 1.5M "useful"
- $\sqrt{s}$ = 130 GeV
- (next year = 200 GeV)

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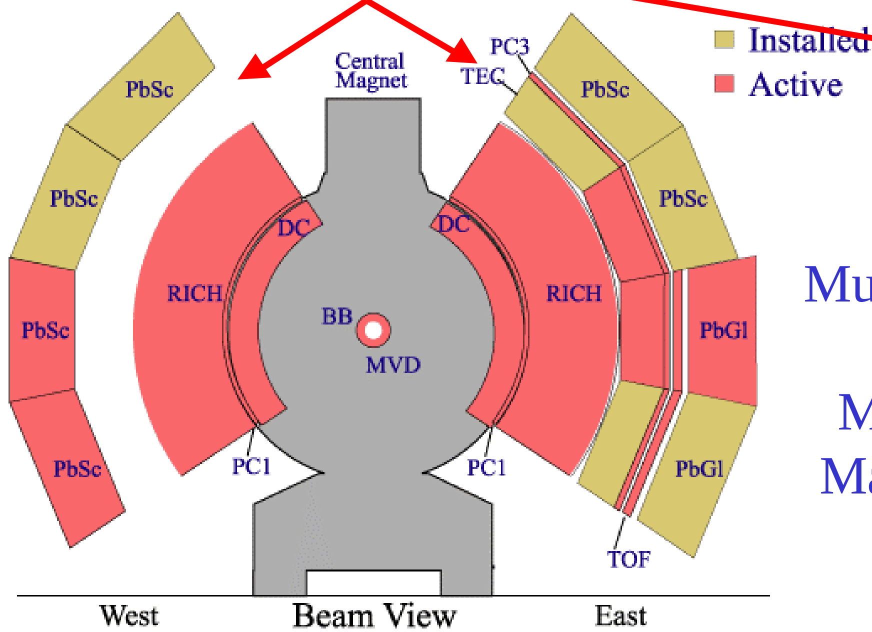
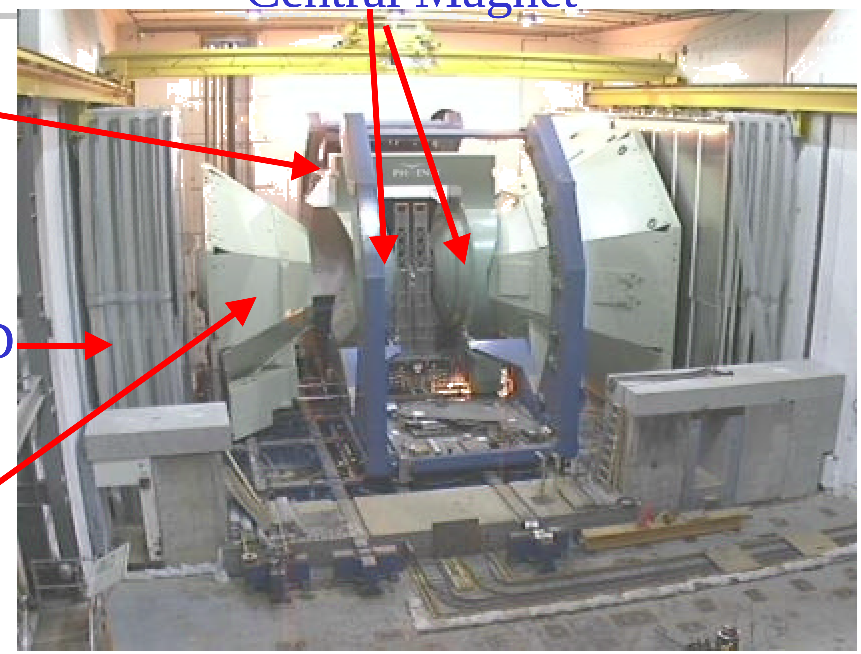
PHENIX: electrons,muons, photons, hadrons

Central Arms

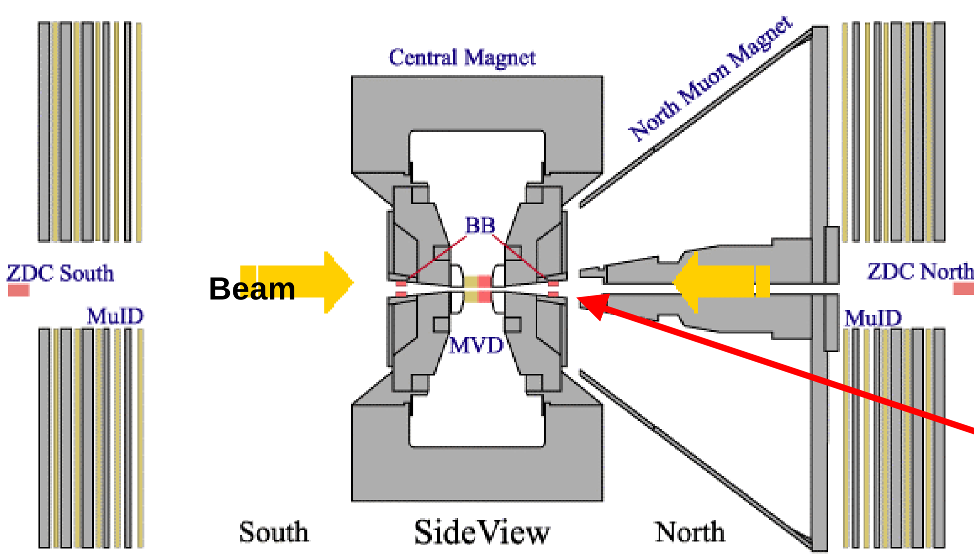


Central Magnet



Muon ID

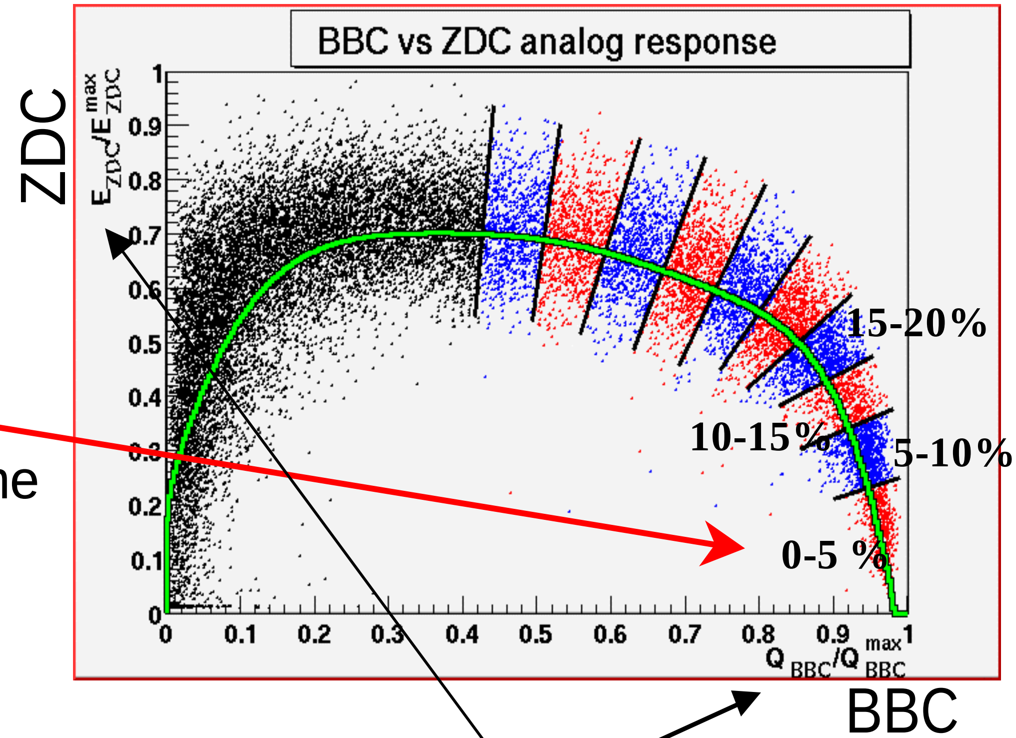
Muon Magnet

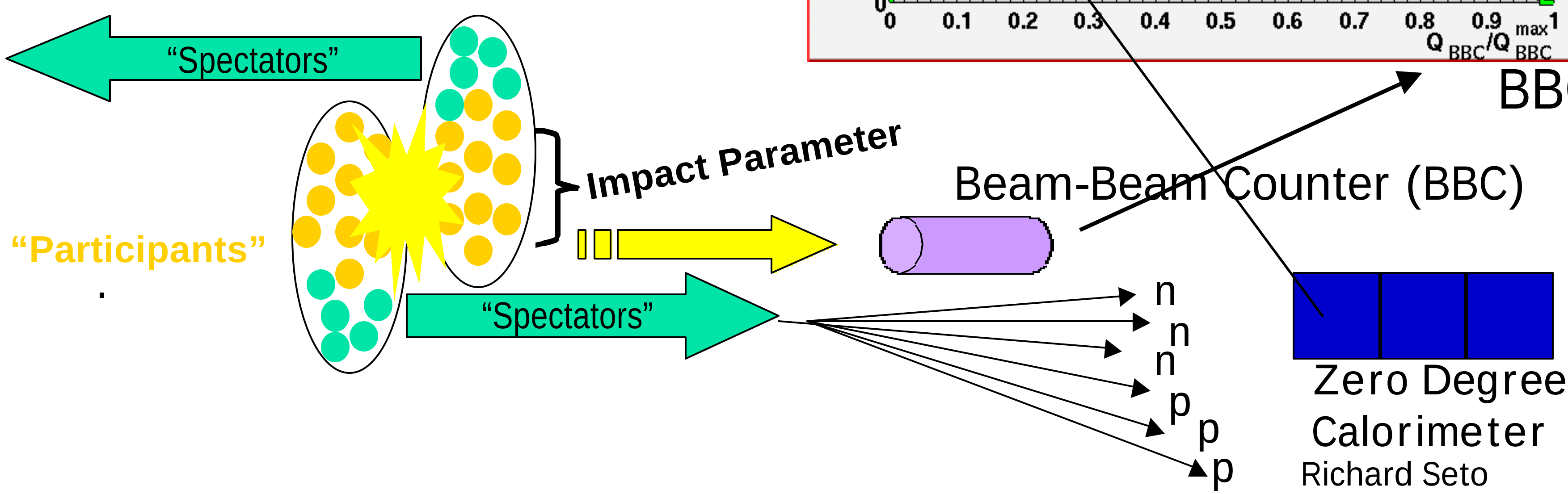


- 2 Arm central spectrometers + 2 muon endcaps
  - $-0.35 < \eta < 0.35$ (e,γ, hadrons)
  - $1.2 < |\eta| < 2.5$ (muons-2nd year)
  - Tracking : DC, PC, TEC
  - Particle ID : RICH, TEC , EMCal, TOF
- Global Detectors (centrality)
  - Zero Degree Calorimeters (ZDC)
  - Beam-Beam Counter (BBC)

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

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





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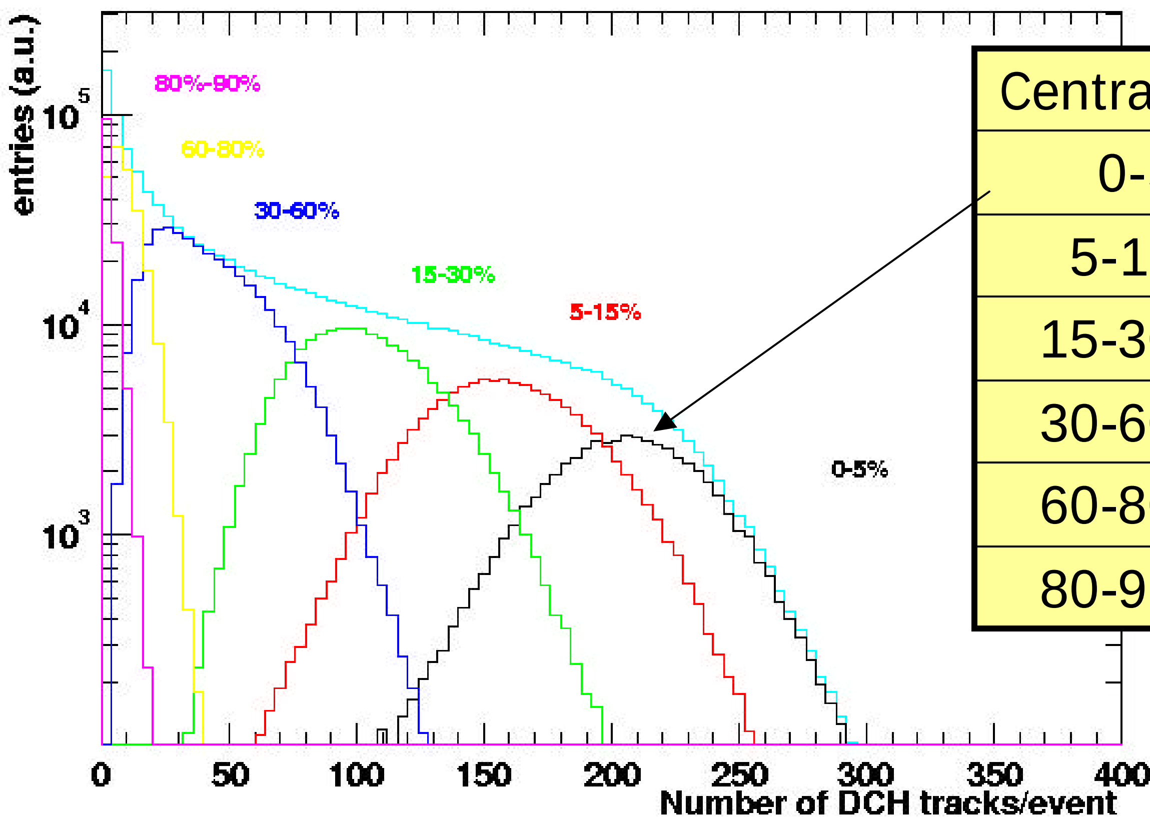
Conversion from Centrality to N_{binary} collisions and $N_{participants}$

- 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	Binary	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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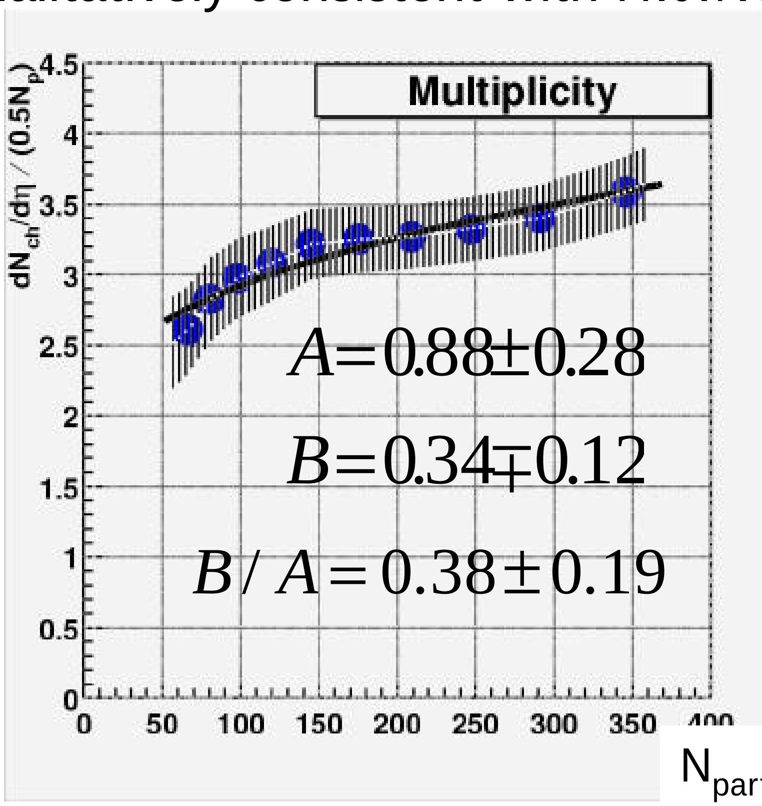
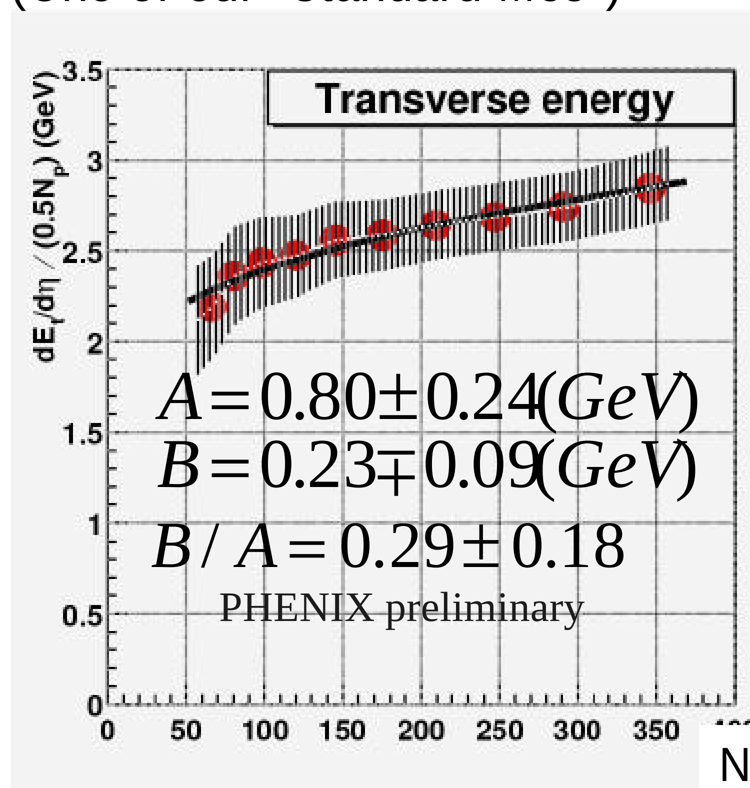
Multiplicity & E_T per participant

- Multiplicity–Pad chambers E_T–Electromagnetic Calorimeter
- Yields grow significantly faster than N_{part}
- Evidence for term ~ N_{binary} $$dX/dh\Big|_{h=0} = A \times N_{part} + B \times N_{bin}$$
  - Qualitatively consistent with HIJING (One of our “Standard MCs”)

Divide by N_{part}



N_{part}



N_{part}

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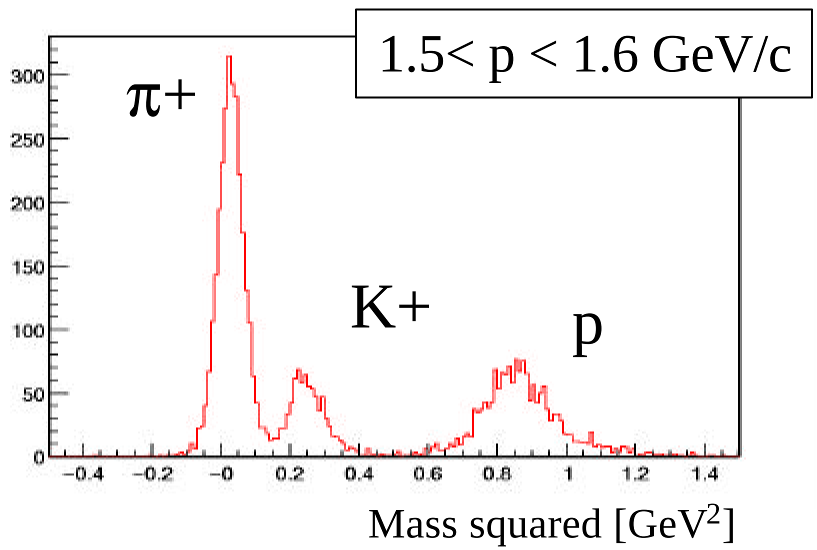
Hadrons: Identification

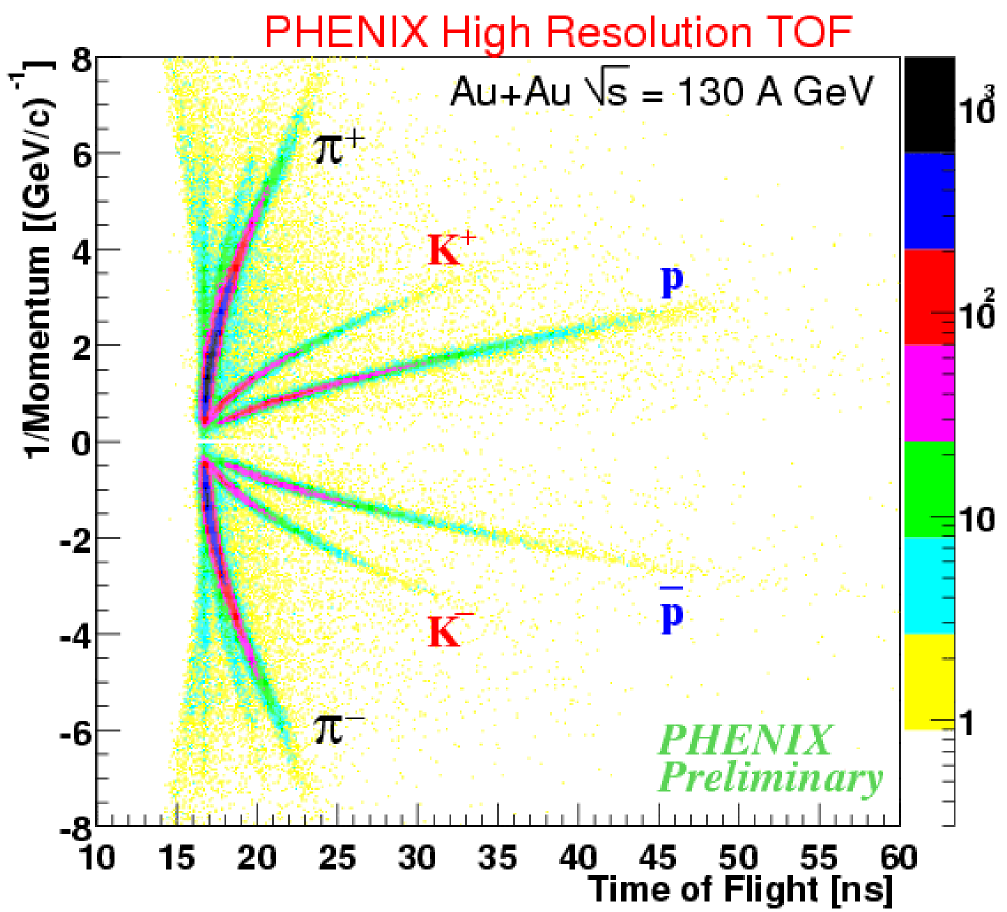
σ_{TOF} = 115 ps
π/K separation < 1.6 GeV/c
Proton separation < 3.5 GeV/c

Combined

- Tracking
- Beam-Beam Counter (t_0)
- Time-of-Flight array (tof)

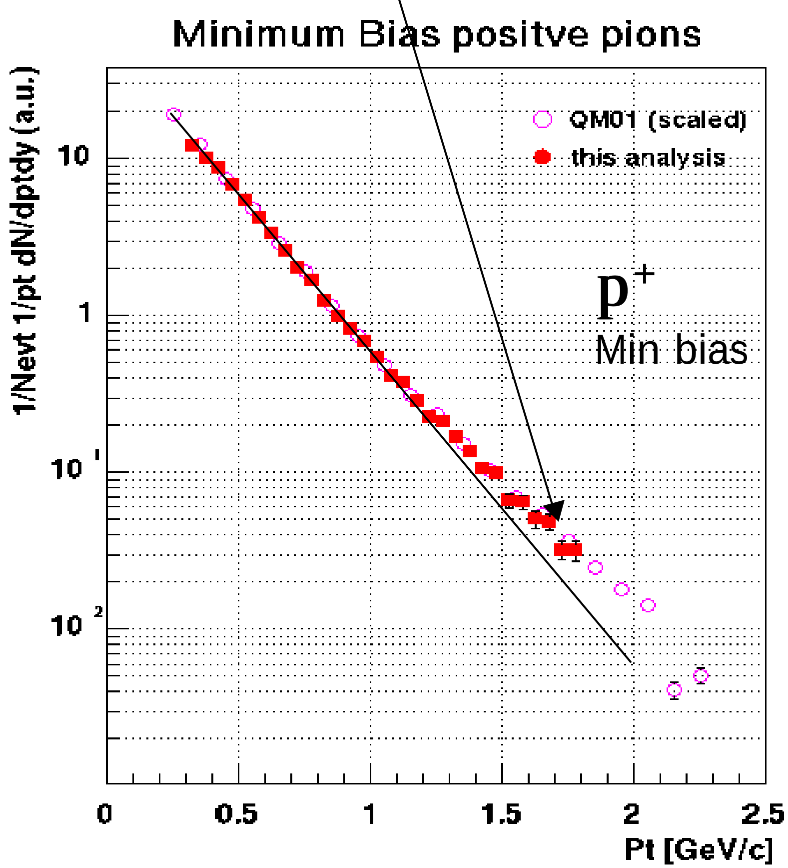
provides excellent hadron identification:





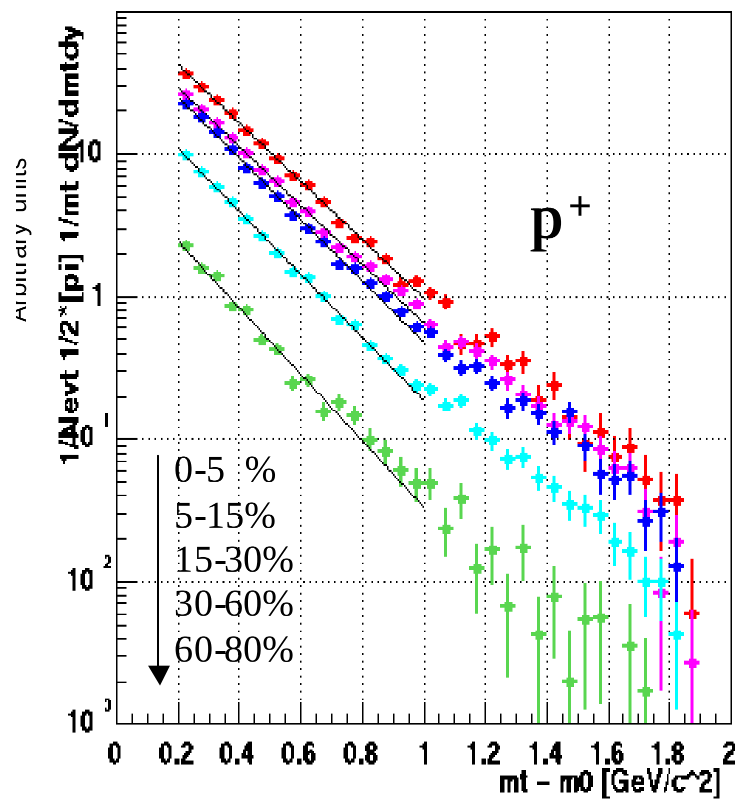
Pion spectra – Hard Scattering

- Power law tail in p_T indicating hard scattering



- More evident in non-central collisions

(mostly I just wanted to show you the quality of the spectra)

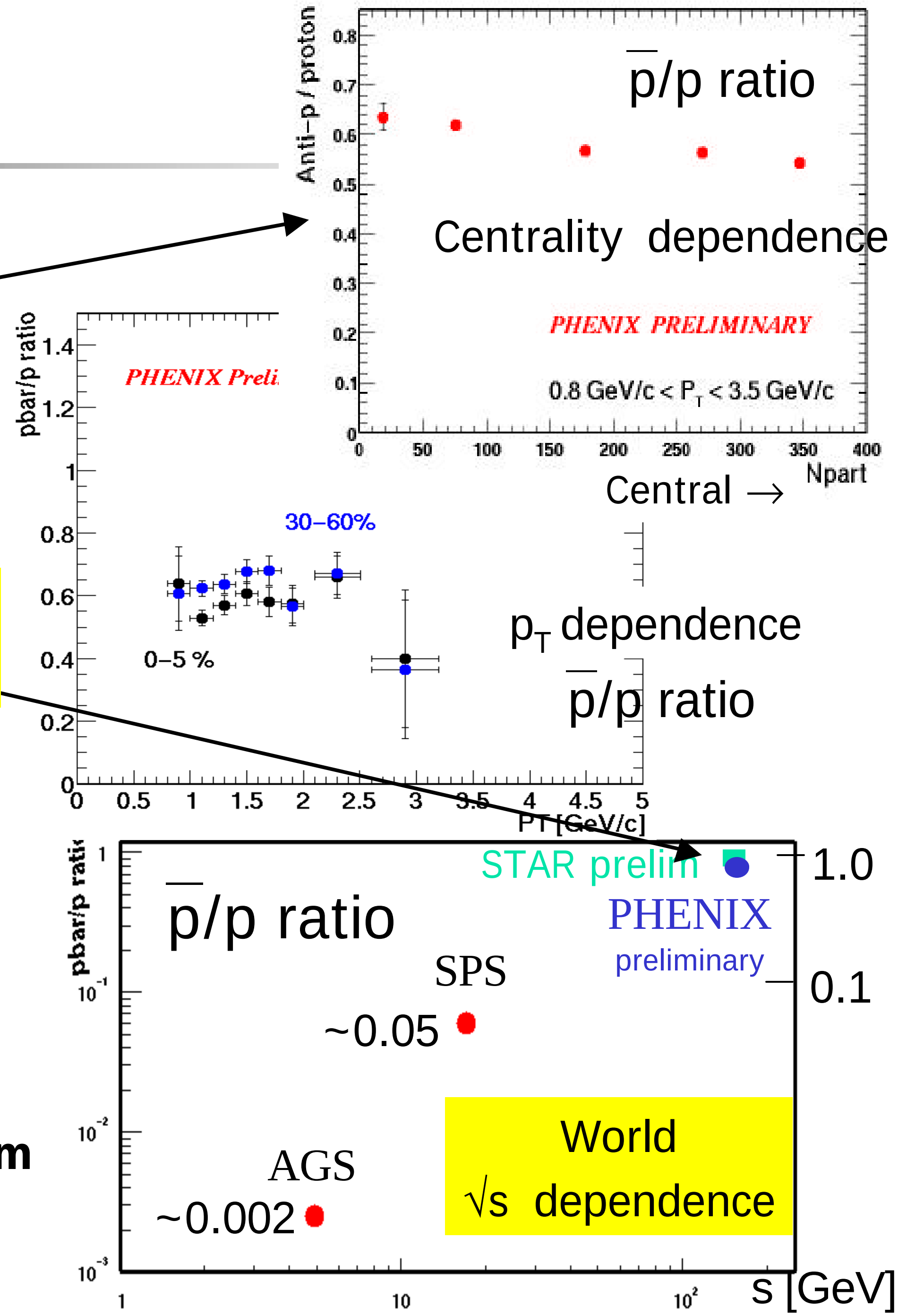


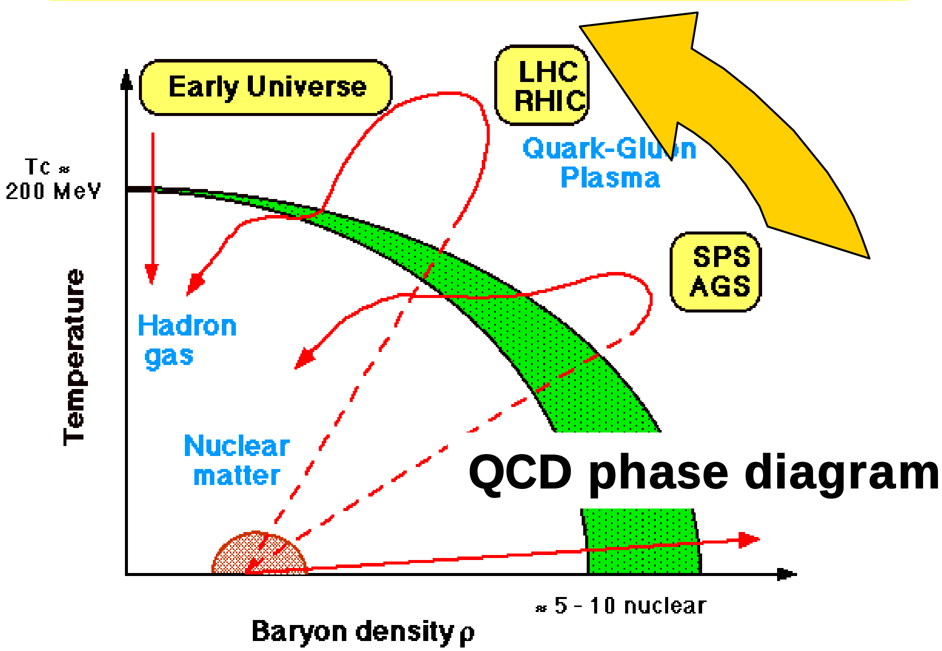
$\bar{p}/p$ ratio

- Little or no dependence on
  - Centrality (N_{part})
  - p_T
- $\bar{p}/p$= 0.54±0.01(stat.)±0.08(sys.)

  5% Central

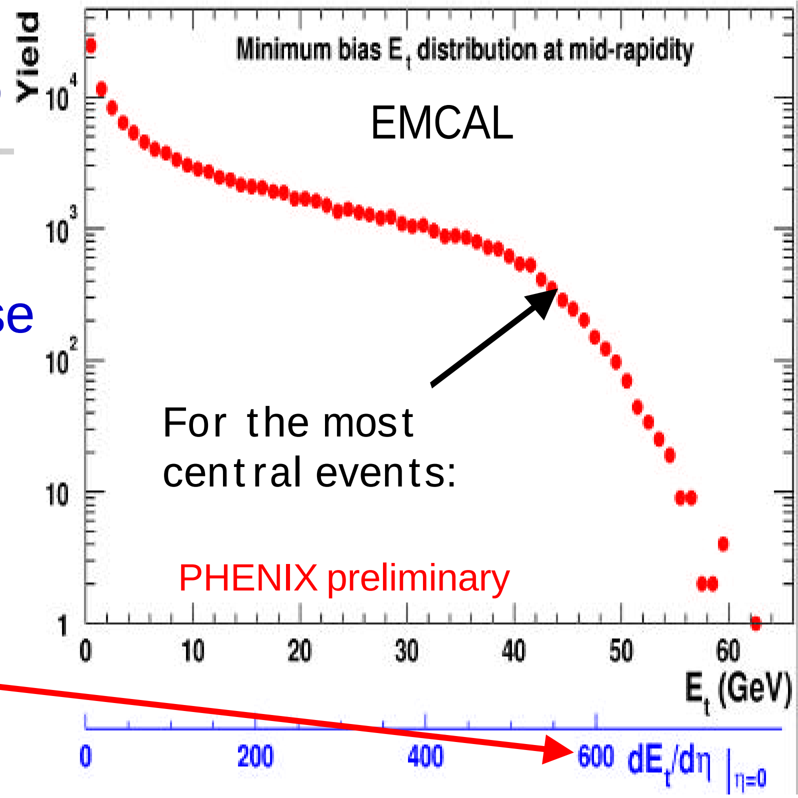
We are reaching a baryon free system – an excited QCD vacuum!





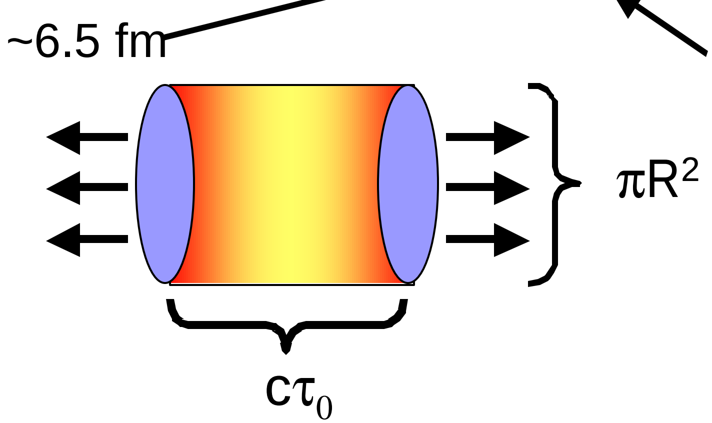
Initial Conditions

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



Bjorken formula for thermalized energy density

$$e_{Bjorken} = \frac{1}{p R^2}\frac{1}{t_0}\frac{dE_T}{dy}$$



time to thermalize the system (τ_0 ~ **1.0** – 0.3 fm/c)

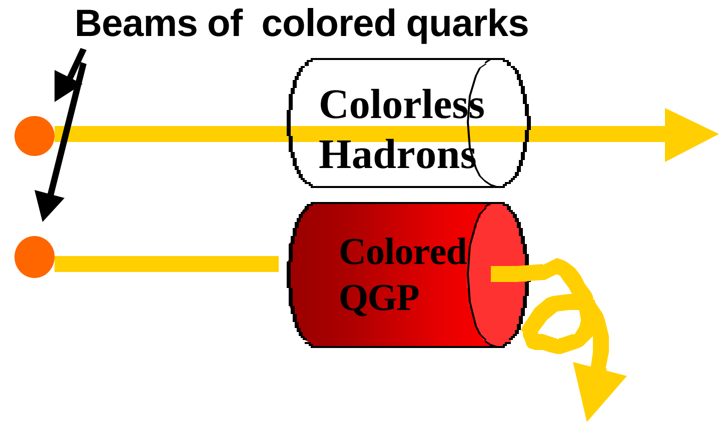
$\varepsilon_{Bjorken}$ ~ 5.0 GeV/fm^3 ~1.5xCERN

Lattice phase transition:

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

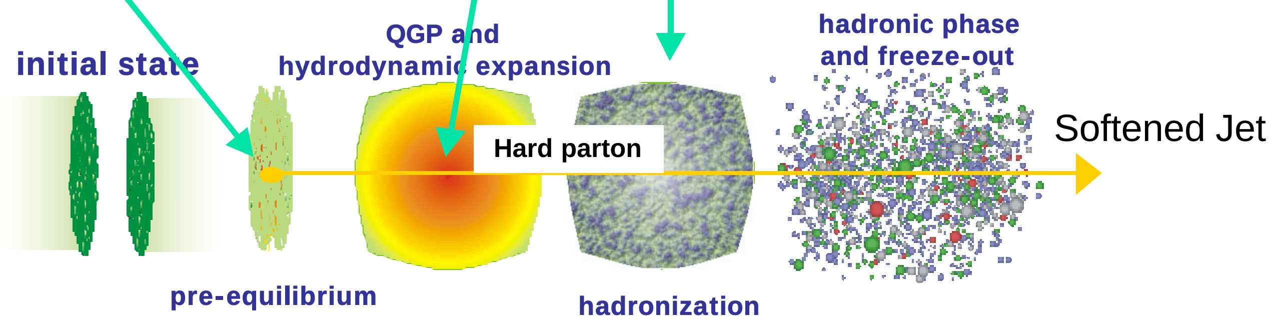
Energy deposition is certainly adequate, but does it create a new phase of matter, I.e. the QGP?

Hard Probes In Heavy Ion Collisions, aka Jet quenching



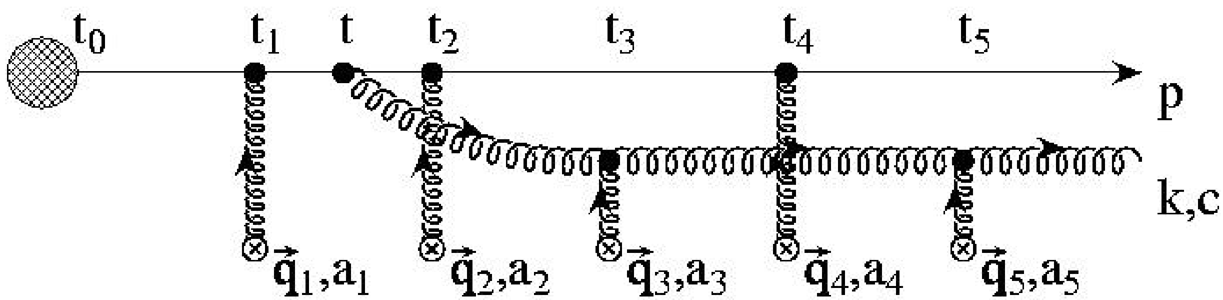
- The experiment we would like to do – Deep Inelastic Scattering of the QGP

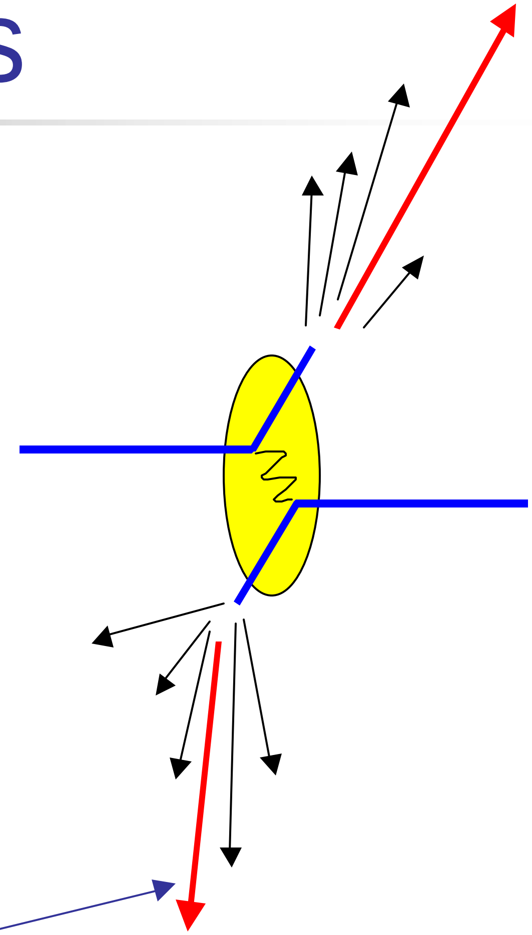
- “hard” probes
  - **Formed in initial collision with high Q^2**
    - **penetrate hot and dense matter**
    - **sensitive to state of hot and dense matter**
      - dE/dx **by strong interaction**
      - Þ   jet quenching



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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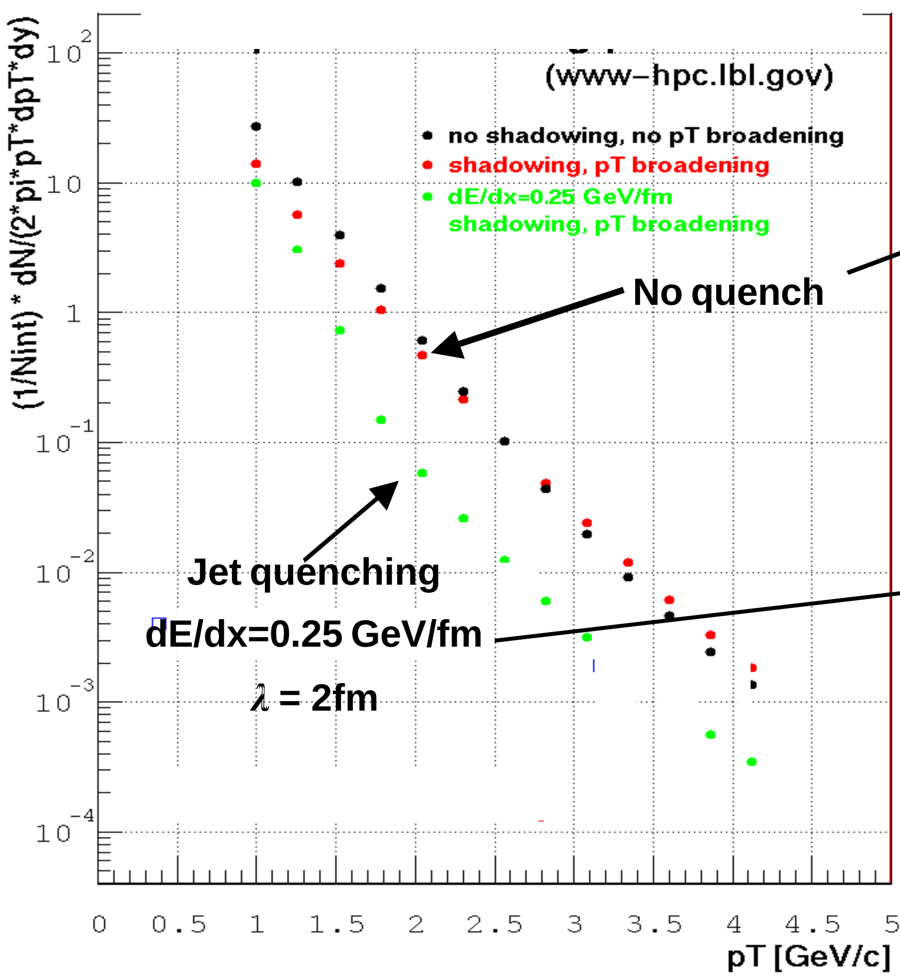
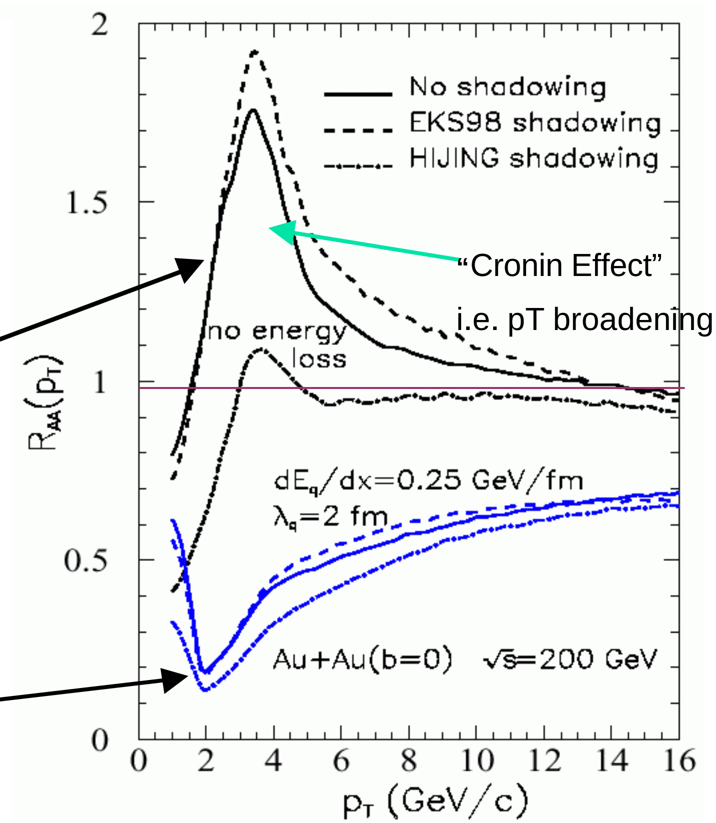
Some expectations – (predictions!)

Prediction: X.-N Wang

Neutral pion pT – 10% central





Normalize to pp cross section

Define:

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

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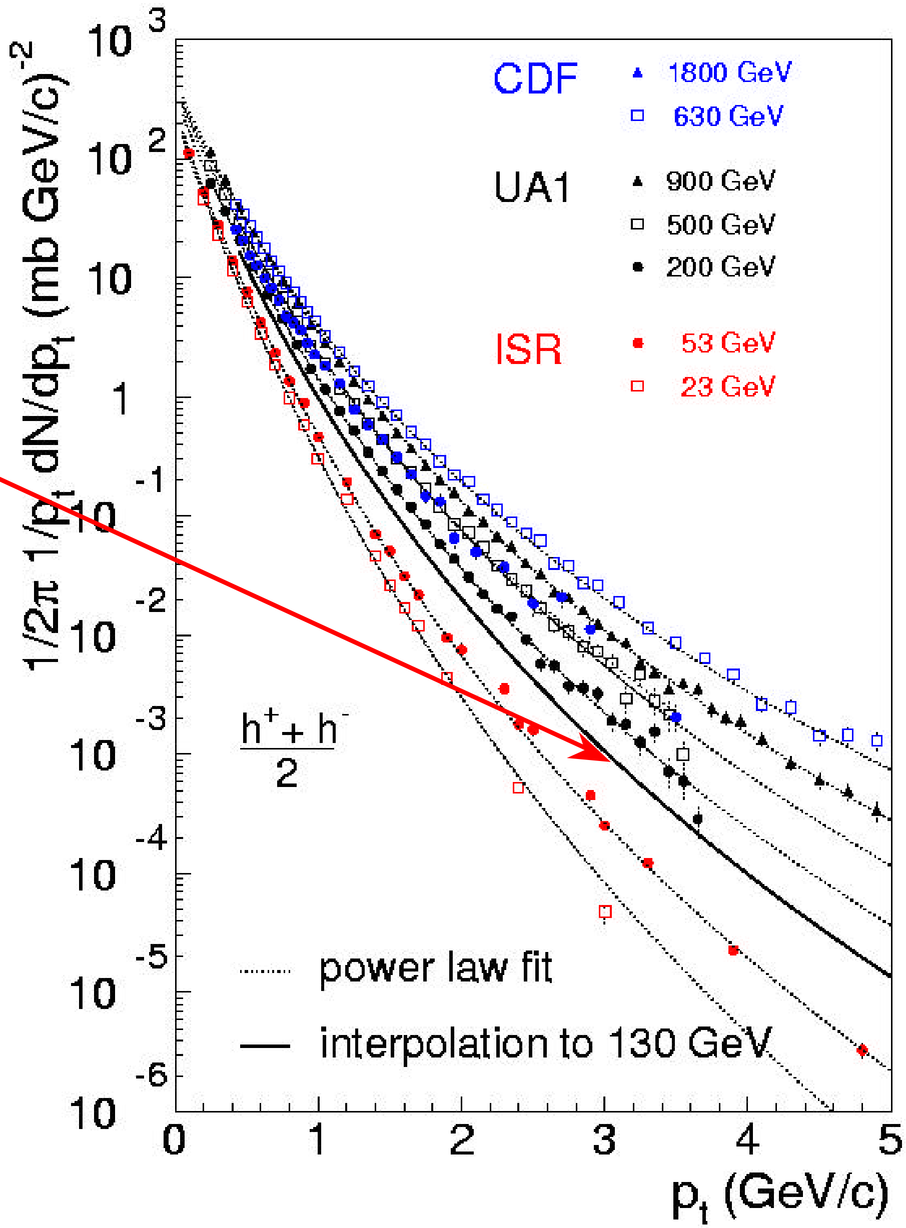
Setting the baseline

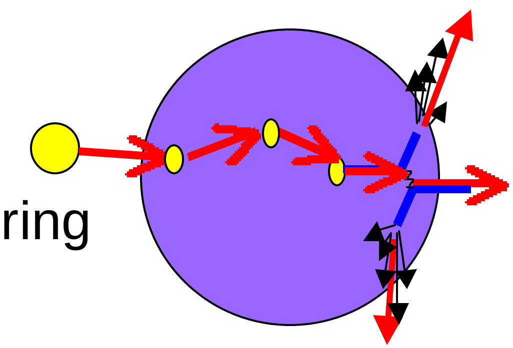
- To find jet suppression – compare to what?
  - Pp collisions scaled to √s = 130 GeV
    - Good fit to a power law
  - Peripheral collisions – an approximation to pp, or pA

    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



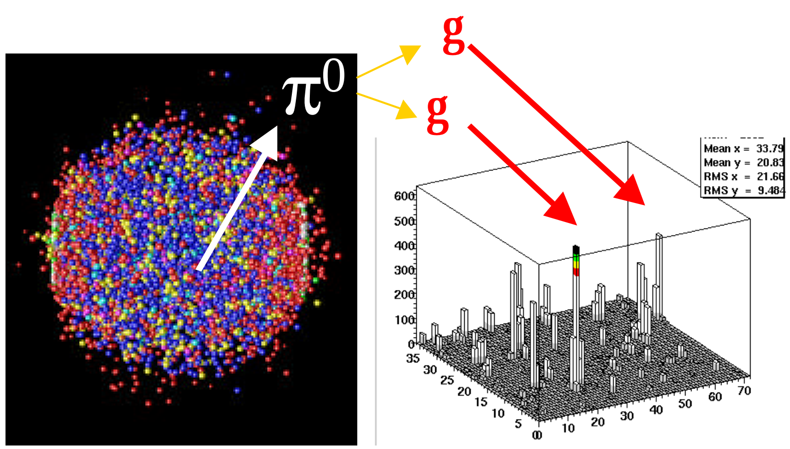
Models – scaling pp to AA

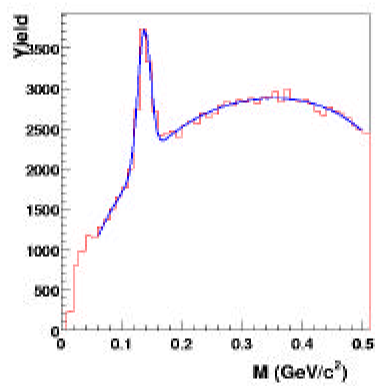
- How do we scale from pp to AA?
  - Nuclear Geometry
    - Scale Hard processes with N_{binary}
    - Scale soft processes with $N_{participants}$
      - Remember – N_{bin} and N_{part} taken from centrality measurement
  - pp effects
    - Intrinsic k_T
  - pp to pA effects
    - "Cronin effect", initial state quark scattering
      i.e. p_T broadening
      Enhances higher p_T
    - Nuclear shadowing
      - Gluon shadowing
        - is not measured
        - large role at RHIC



Measure pA at RHIC!

PHENIX Data: π^0 spectra





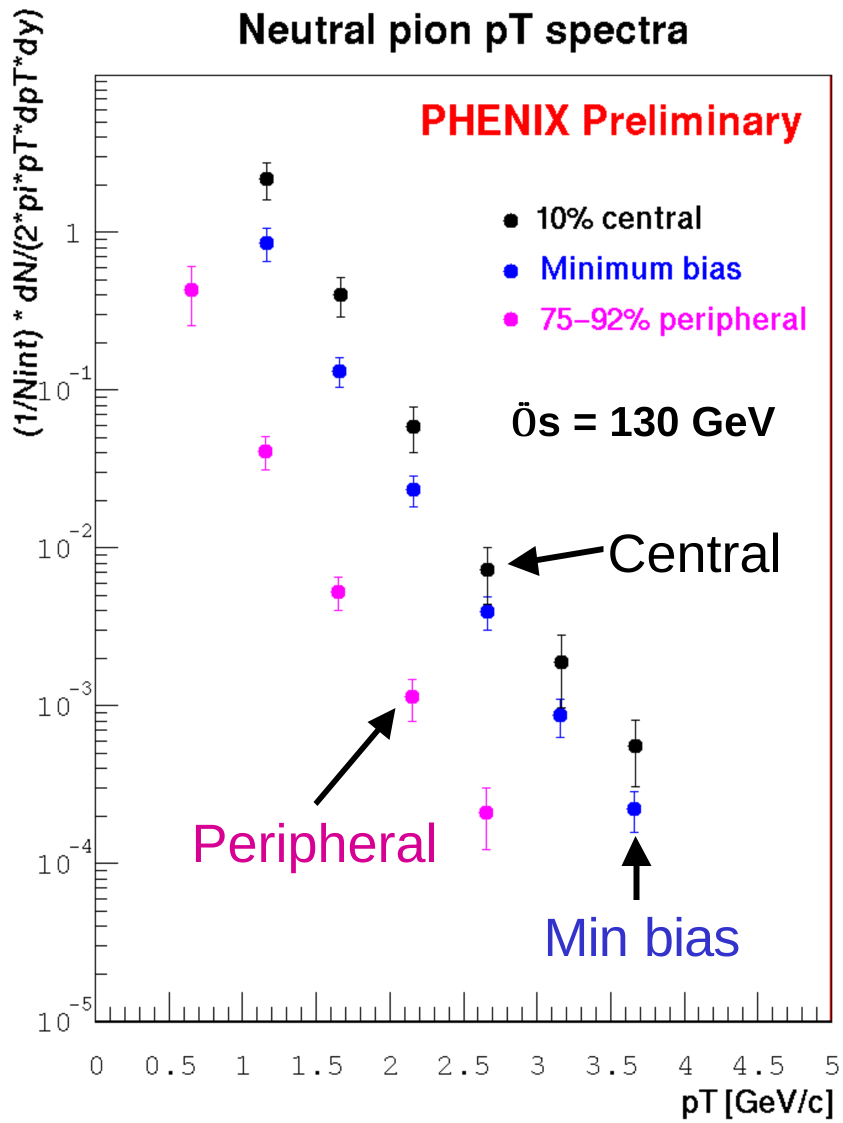
$p_T>2$ GeV,asym<0.8

Systematic errors included

Main sources:

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

Centrality	~N_{bin}	~N_{part}
10%	860	300
M.B.	125	75
75-92%	6	6



~1M Min Bias AuAU events

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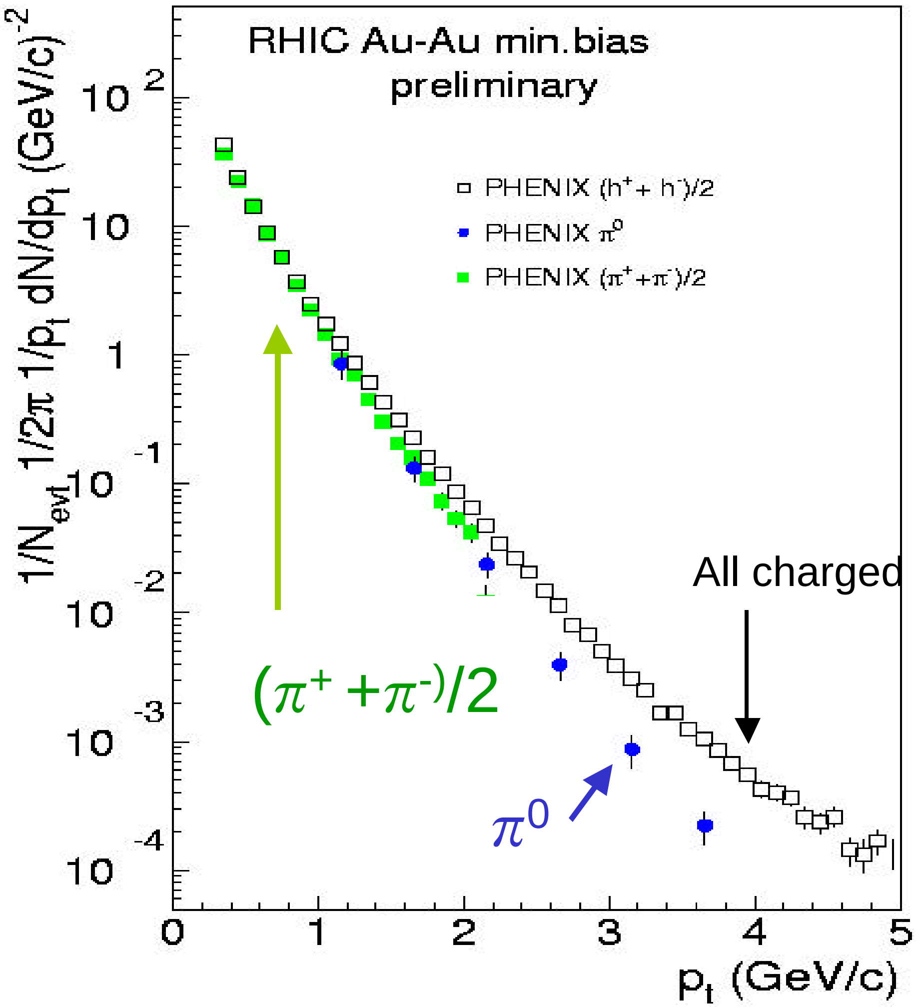
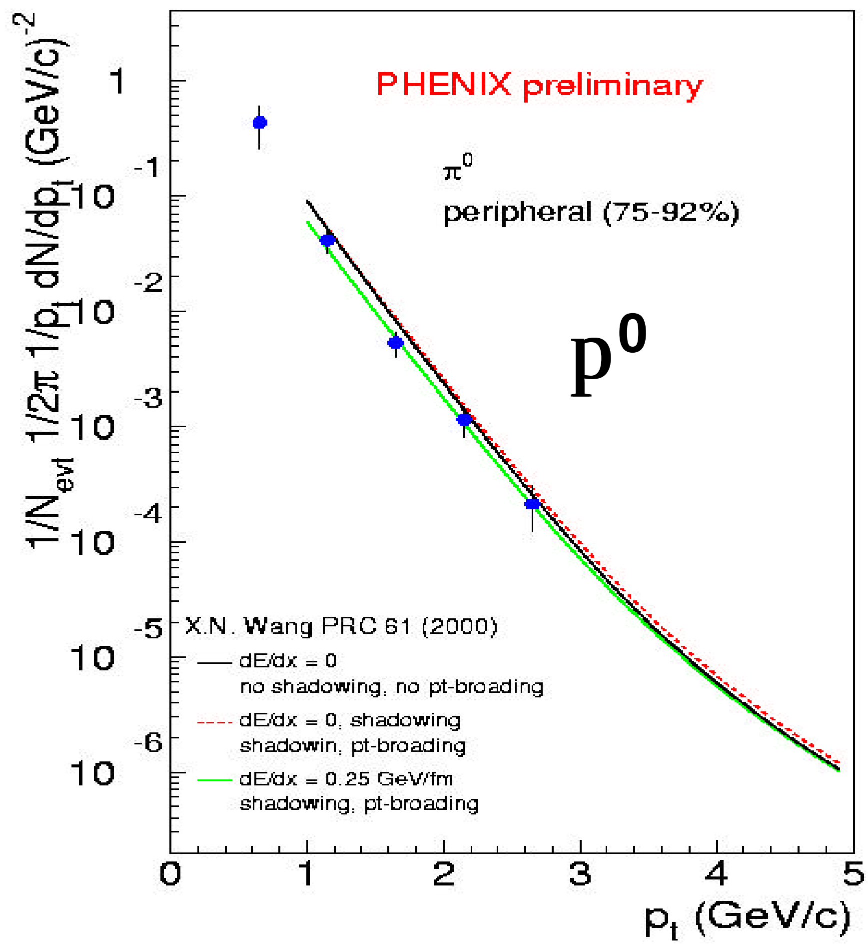
Comparison to charged spectra

- π0 spectra matches identified charged pion spectra – different systematics!



Comparison with QCD calculations:Peripheral Events

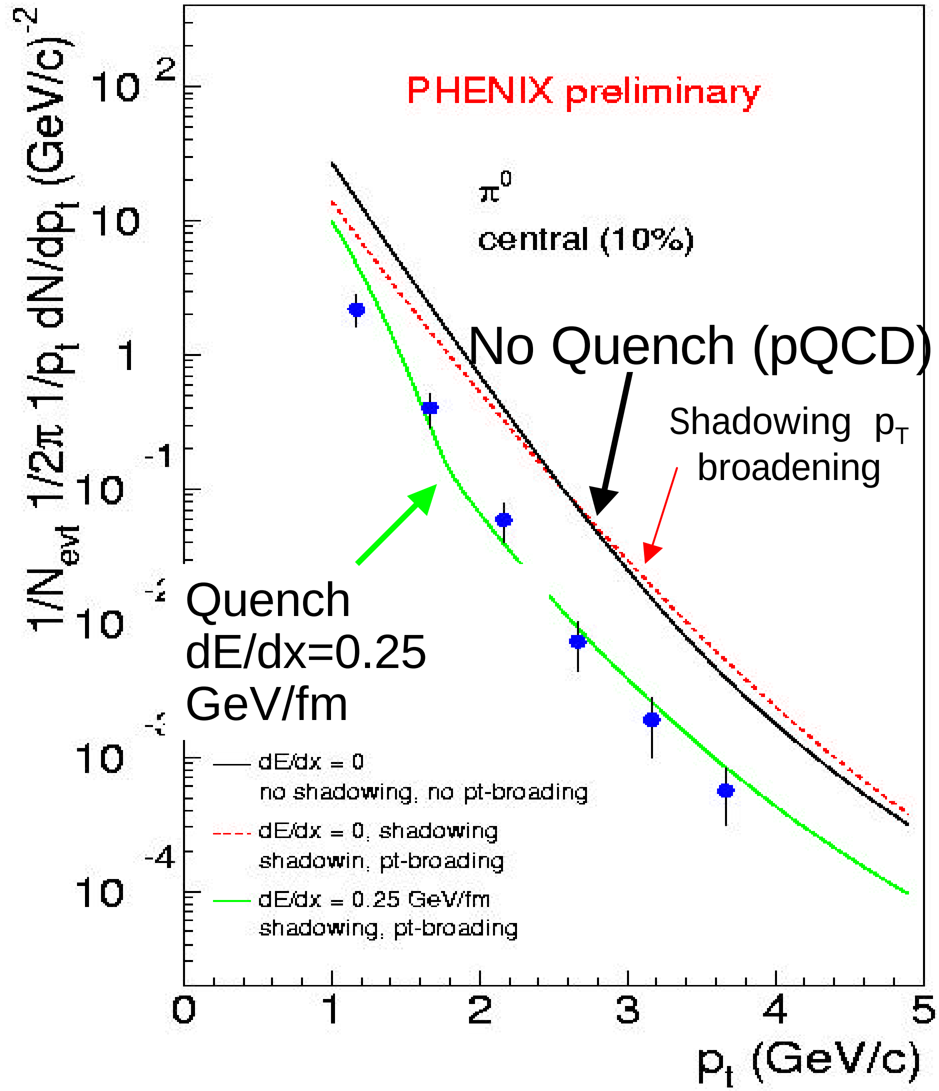


- good agreement with pQCD calculation in Peripheral Collisions
  - Includes Intrinsic k_T, Cronin, shadowing – – – –
- Baseline is OK

Central Events – Jet quenching?

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

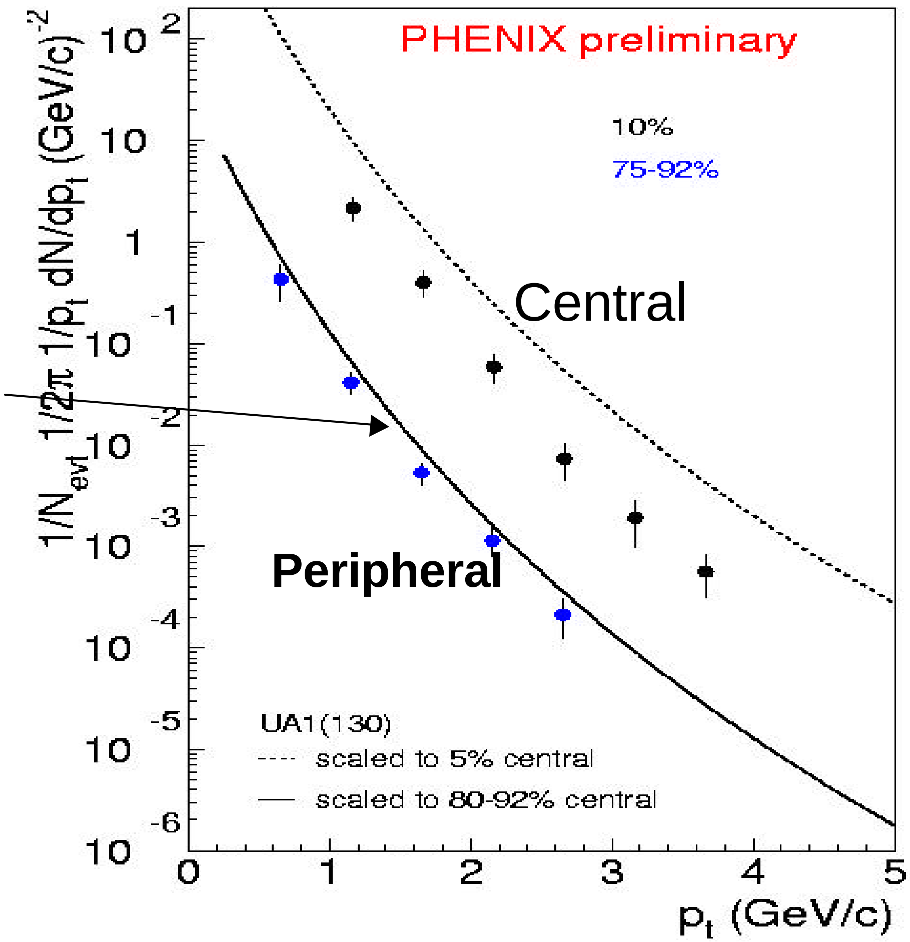
Evidence of Jet Quenching!?



Some sanity checks - 1

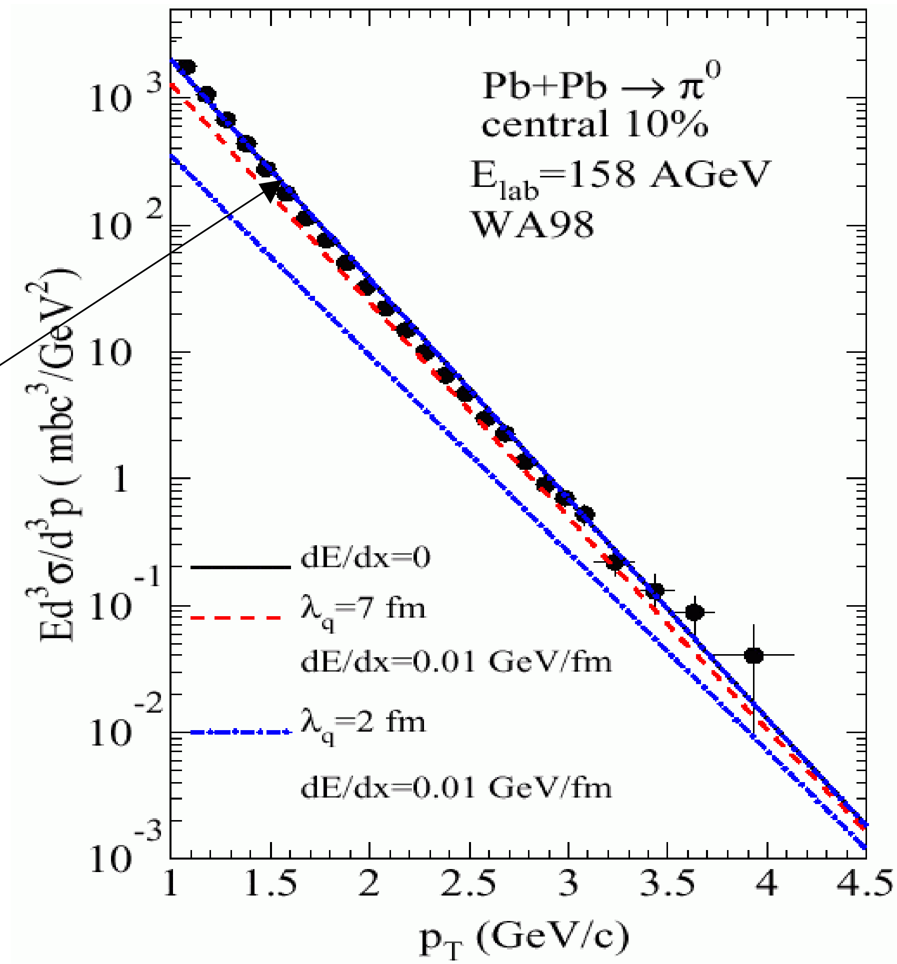
G.David, PHENIX

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



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

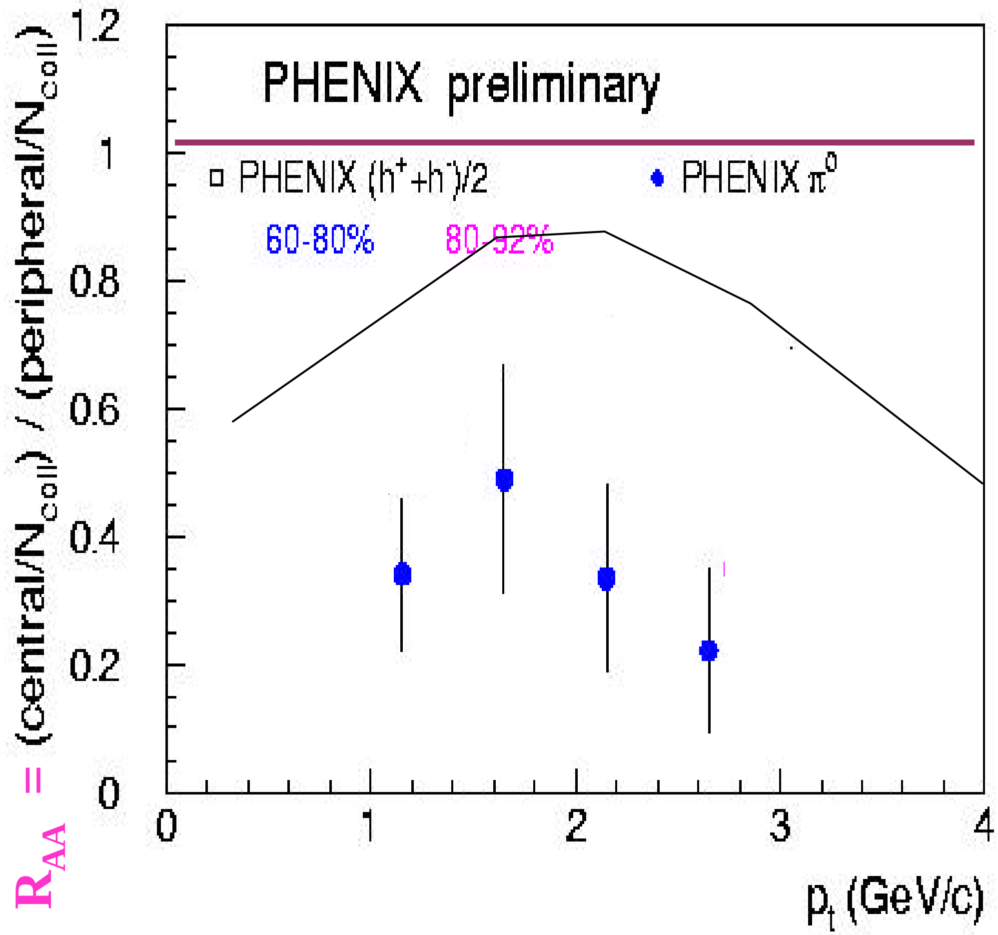


Sanity check – 3 Ratio Central/Peripheral

- 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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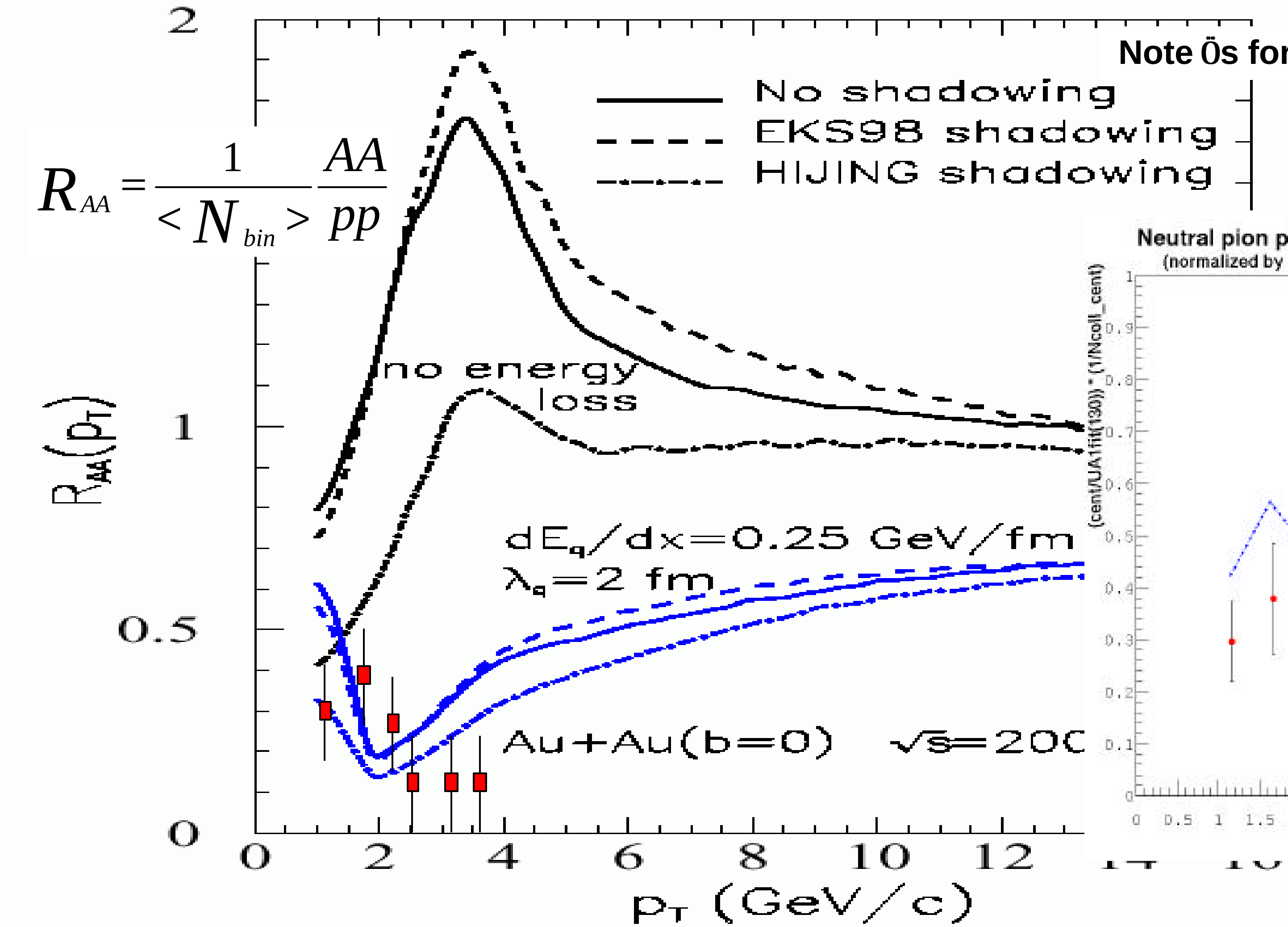
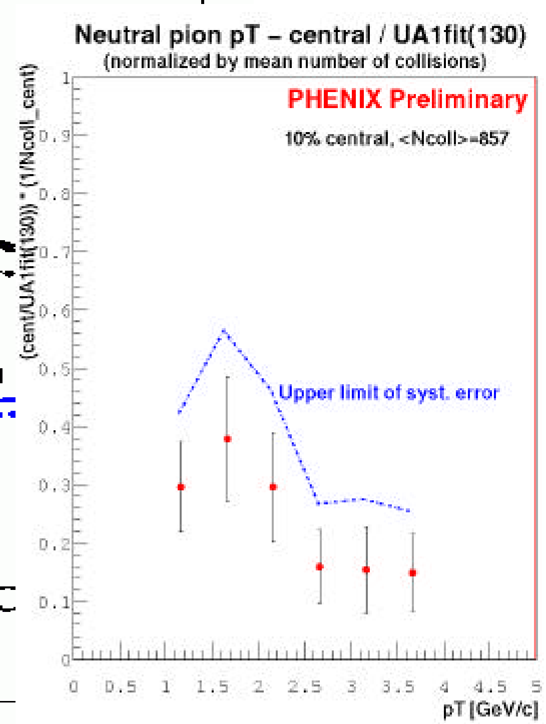
Divide by $<N_{binary}>\sigma_{pp}$(UA1 fit 130)

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

Note Ös for model is 200 GeV



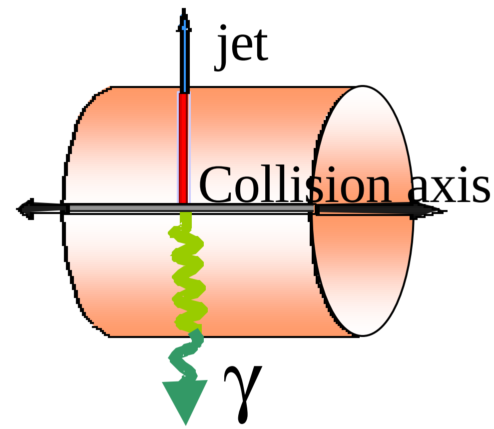


- With cautious optimism

Data seems consistent with jet quenching

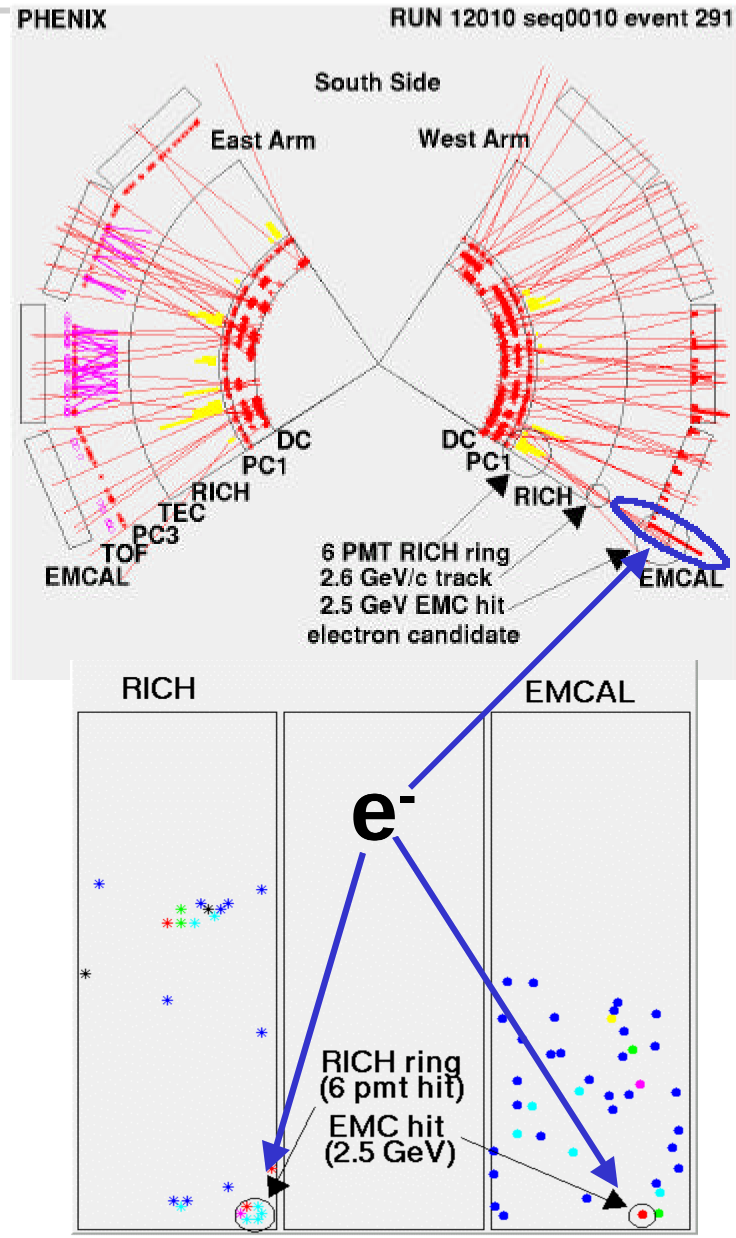
Jets : the future

- 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?
  - 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: $E_g \sim E_{jet}$



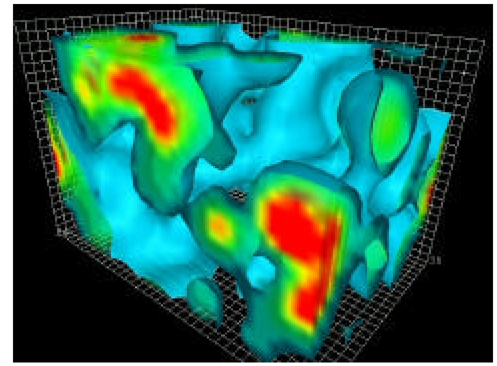
PHENIX: Shape of Things to Come – electrons, muons

- 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*

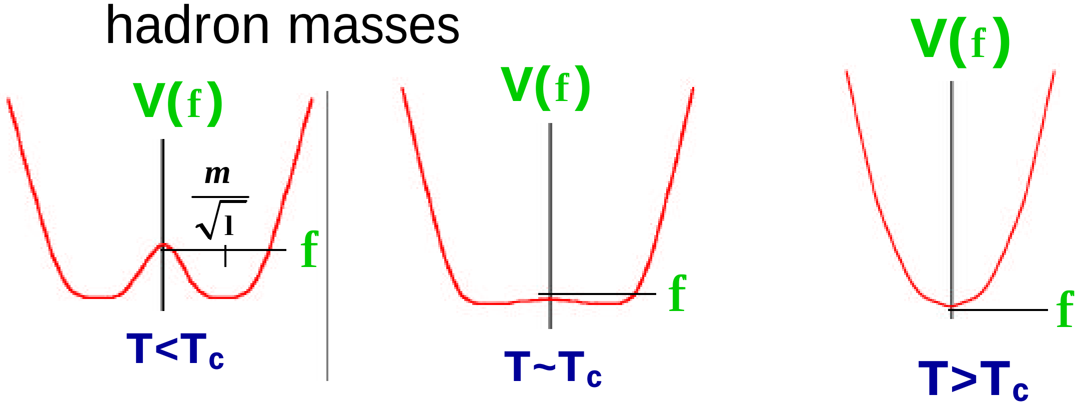


➜ The ~5M events recorded in Run-1 represent ~1 day of data-taking for RHIC+PHENIX in Run-2

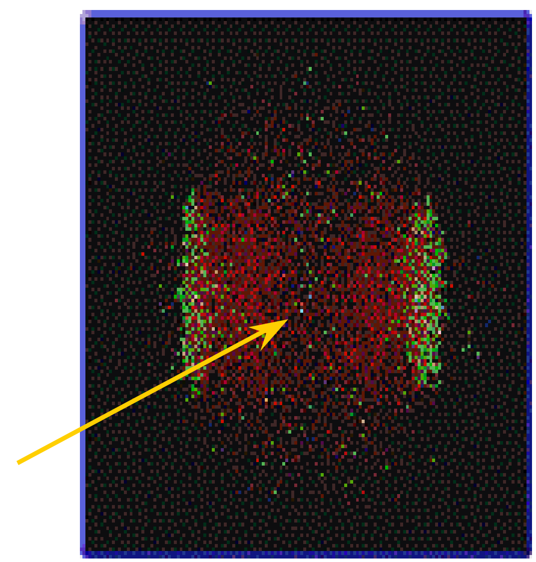
What about the chiral phase transition or Where does mass (hadronic) come from?



- Space filled with a chiral condensate $\phi = \bar{\psi}\psi$
  - 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

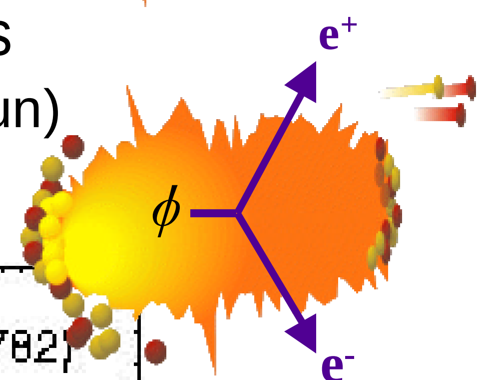


Richard Seto

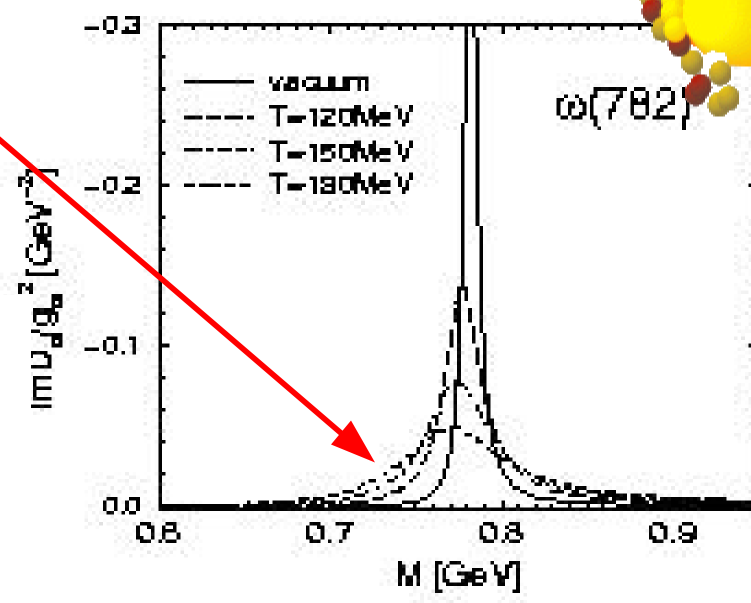
Looking for Chiral symmetry restoration Vector Meson mass shifts in the dilepton channel

- "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)



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



Other Physics topics

- J/ψ suppression – top priority next run
- Search for chiral symmetry restoration, mass shifts of the light vector mesons
- Heavy quarks
- Thermal di-leptons and photons
- pA physics
- Of course high pt particles

  And
- spin physics

Conclusions

- Energy density high ~ 1.5 x value at CERN SPS
- Observation of hard collisions in heavy ion collisions
- $\bar{p}/p$ ~ 0.54 ~ a baryon free system – an excited QCD vacuum!
- 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 transition from region of "no jet quenching" to the new regime?
  - What is the energy loss as particles travel through the qgp?
  - Where is the chiral phase transition? – are they related? – how?
  - Order of transitions?
  - Any critical phenomena associated with the phase transitions?