PHENIX
for Beginners

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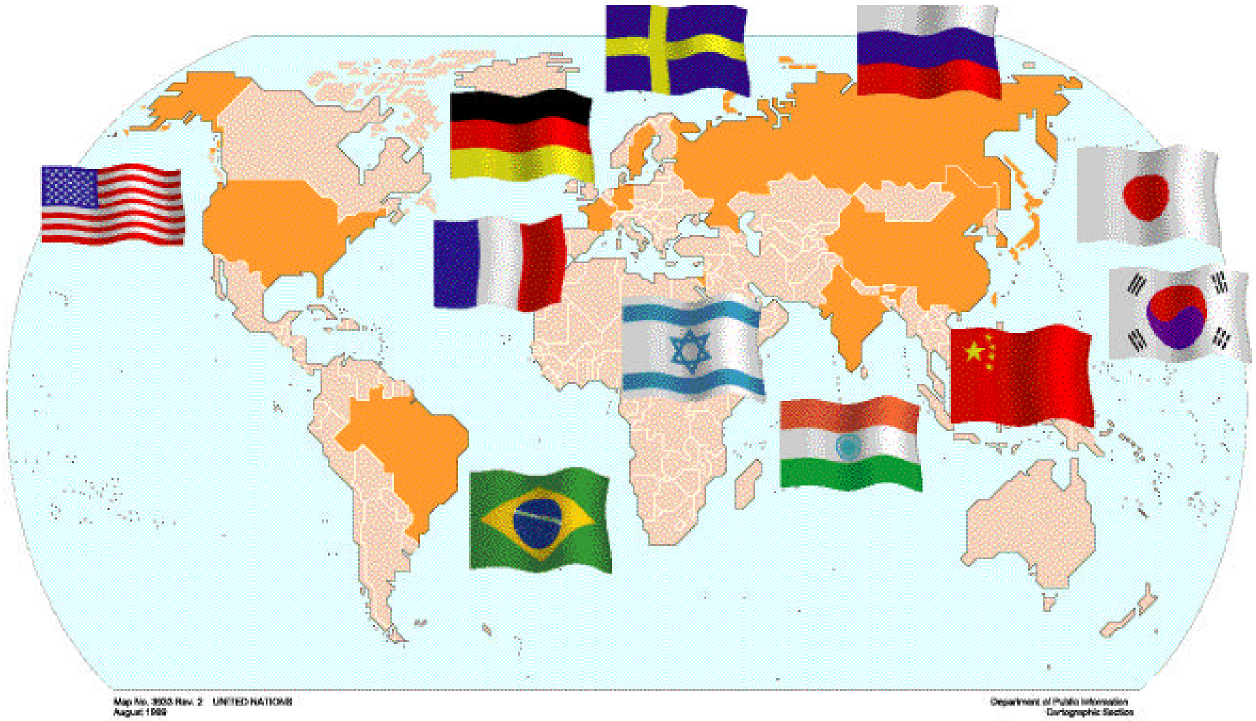
PHENIX



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Outline and Goals

- **What is the QGP phase transition?**
- **What is the best strategy for observing it?**
- **How has PHENIX implemented that strategy?**
  - **An introduction to PHENIX physics results**
  - **A (very) brief introduction to PHENIX detector technologies**
- **Goals:**
  - **Provide overview of the many observables already measured by PHENIX in RHIC Run-1**
  - **Understand the trade-offs made by experimenters in optimizing a detector**
  - **Understand vast potential of PHENIX in future RHIC runs**

Relevant Thermal Physics

Q. How to liberate quarks and gluons from ~1 fm confinement scale?

A. Create an energy density

$$\varepsilon > \sim (\hbar / 1\ \mathrm{fm})^4 \sim 0.2\ \mathrm{GeV/fm^3} \quad \sim \text{Normal nuclear density ??}$$

➡ **Need better control of dimensional analysis:**

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Energy density for "g" massless d.o.f

$$= \left\{ 2\cdot 8_g + \frac{7}{8}\cdot 2_s \cdot 2_a \cdot 2_f \cdot 3_c \right\} \frac{\pi^2}{30} T^4$$

8 gluons, 2 spins;
2 quark flavors, anti-quarks,
2 spins, 3 colors

$$= 37\cdot\frac{\pi^2}{30}T^4$$

37 (!)

$$\approx 12\cdot T^4 \approx 12\cdot\left(\frac{\hbar}{1\ fm}\right)^4 \approx 2.4\ \mathrm{GeV/fm^3}$$

"Reasonable" estimate

Rough Estimate

- ***Compare***

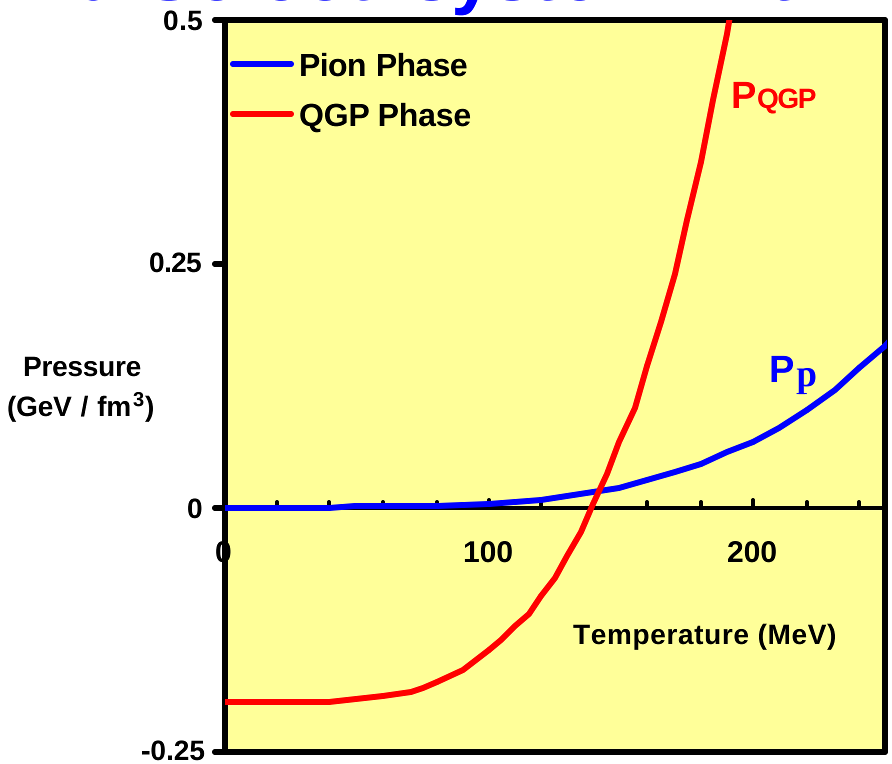
$$P_\pi = 3\frac{\pi^2}{90}T^4$$

Pressure of "pure" pion gas at temperature T

$$P_{QGP} = g\frac{\pi^2}{90}T^4 - B, \quad g = 37$$

Pressure in plasma phase with "Bag constant" B ~ 0.2 GeV / fm^3

- ***Select*** **system with higher pressure:**



➧ Phase transition at T ~ 140 MeV with latent heat ~0.8 GeV / fm^3

Compare to best estimates (Karsch, QM01) **from lattice calculations:**
T ~ 150-170 MeV
latent heat ~ 0.7±0.3 GeV / fm^3

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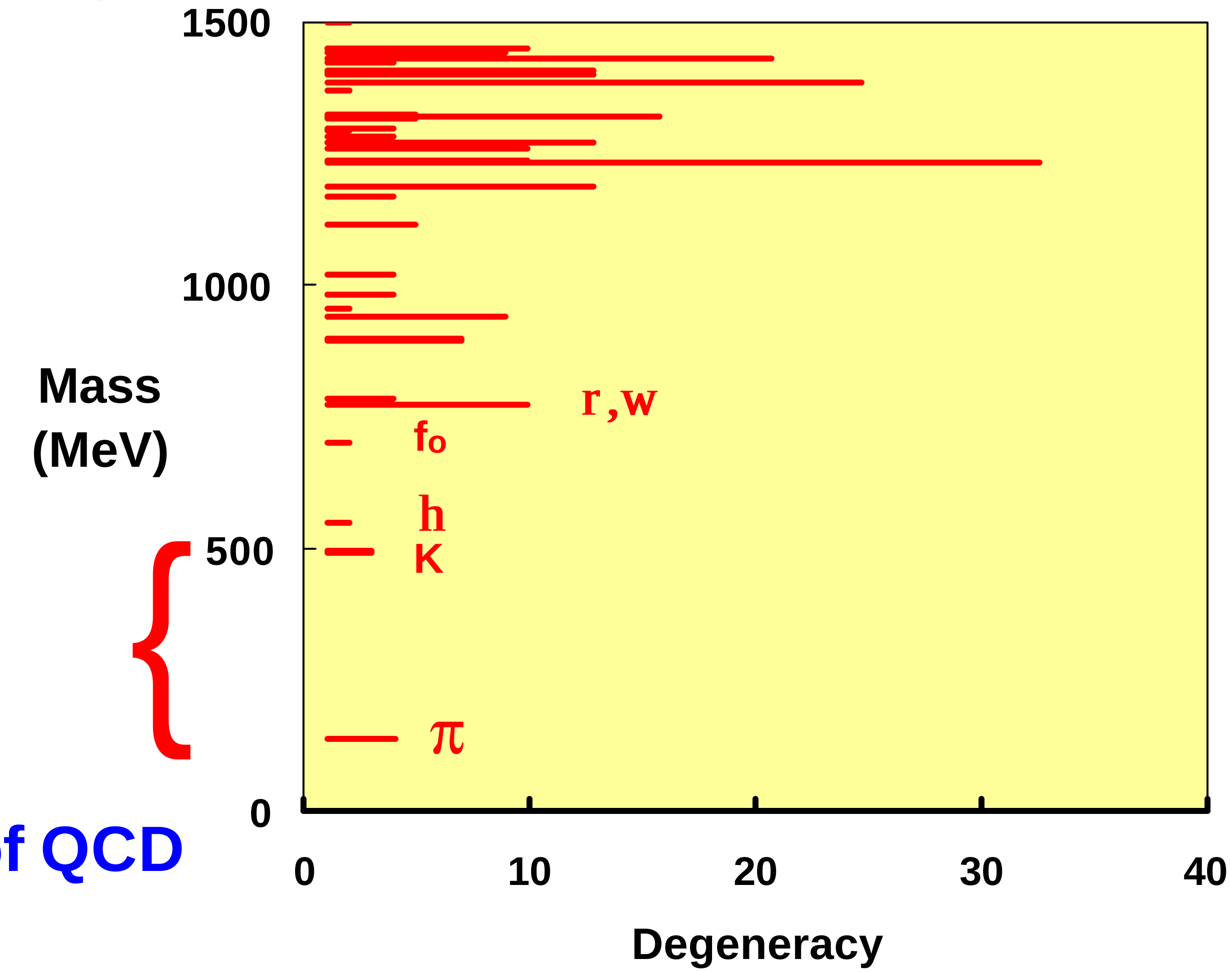
Aside 1

- Previous approach (using a “pure” pion gas) works because QCD is a theory with a mass gap

Hadron 'level' diagram



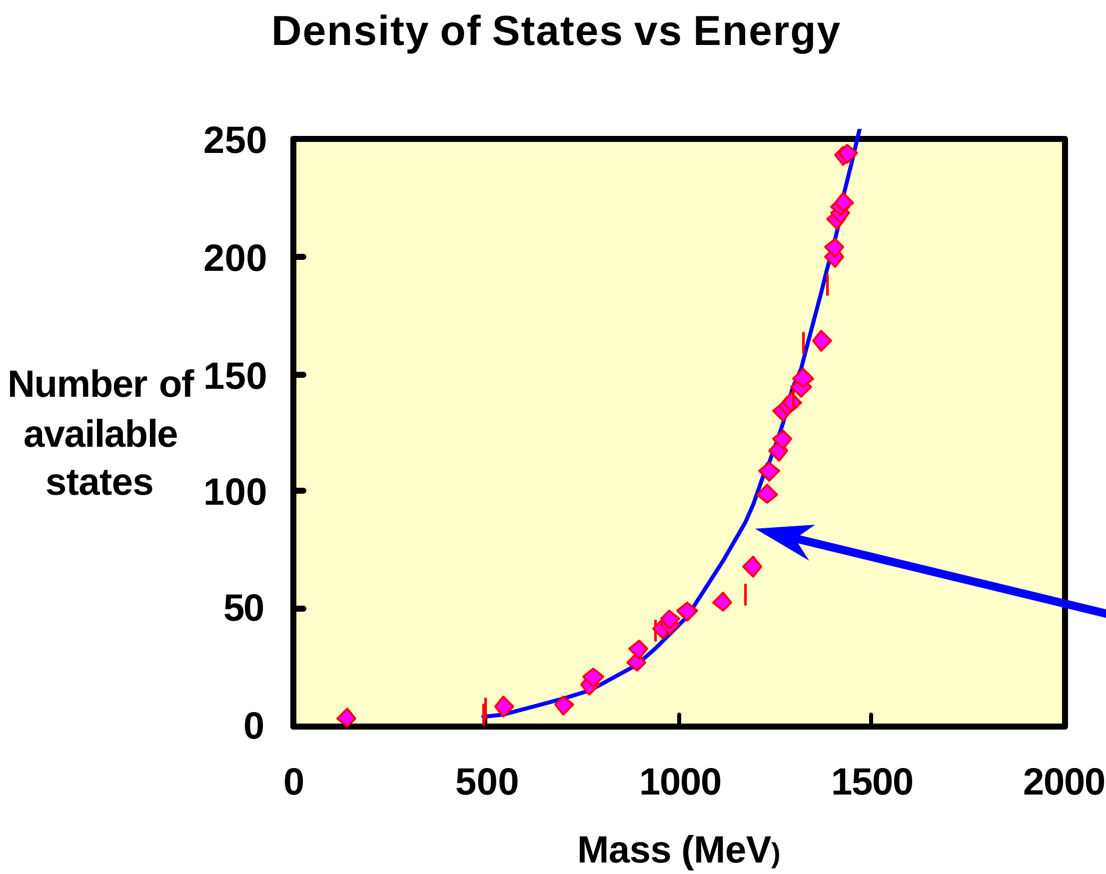
- This gap is a manifestation of the approximate $SU(2)_R \times SU(2)_L$ chiral symmetry of QCD with pions as the Nambu-Goldstone bosons

Aside 2

The frightening density of hadronic levels led to concepts of

- A "limiting temperature" T_H (Hagedorn, 1965)
- A phase transition(?) in hadronic matter

before **quarks were understood as underlying constituents**



$$\rho(m) \equiv \frac{dn}{dm} \sim m^a e^{m/T_H}$$

$$\Rightarrow \int_0^\infty \rho(m) e^{-m/T} dm$$

$$\sim \int_0^\infty m^a e^{m\left(\frac{1}{T_H}-\frac{1}{T}\right)} dm$$

requires $T < T_H$

Fit to this form with $T_H = 163$ MeV

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Making Something from Nothing

- **Explore non-perturbative "vacuum" that confines color flux by *melting it***

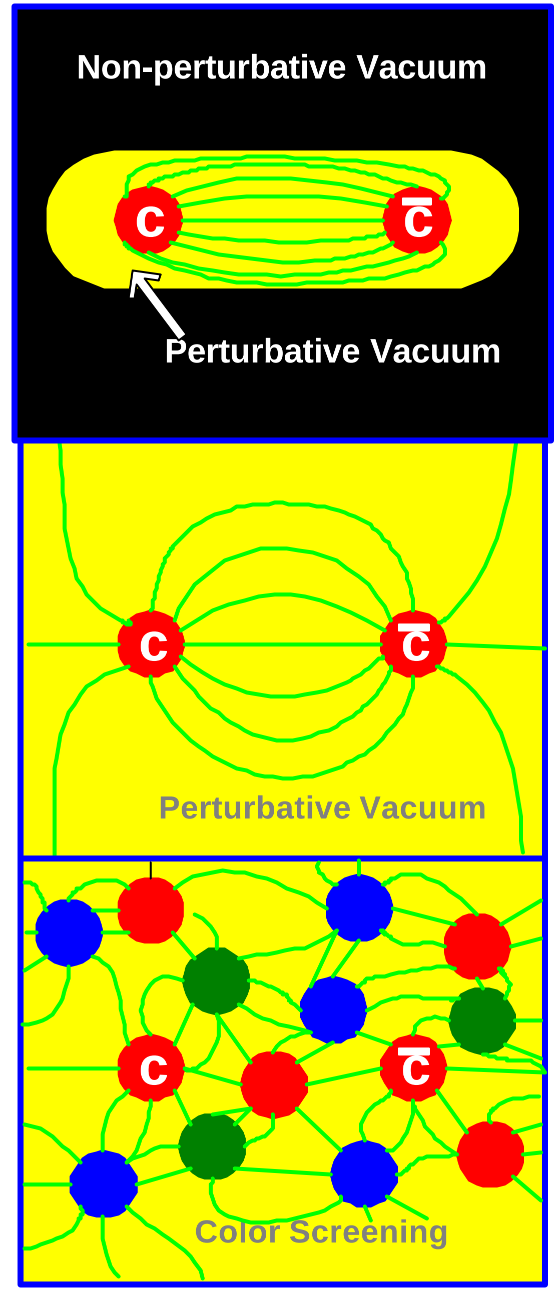
requires temperature $T \sim \hbar / (1\,\mathrm{fm}) \sim 200$ MeV

  - ➡ **Particle production**
  - ➡ **Our 'perturbative' region is filled with**
    - ◆ **gluons**
    - ◆ **quark-antiquark pairs**
  - ➡ **A Quark-Gluon Plasma (QGP)**

- **Experimental method:**

  Energetic collisions of heavy nuclei

- **Experimental measurements: Use probes that are**
  - ❑ **Auto-generated**
  - ❑ **Sensitive to all time/length scales**



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Design Guidelines for QGP Detection

Question: How to proceed with experimental design when

$$\sum_{\text{Theorists}} \overrightarrow{\text{(Theoretical Opinion)}} \approx 0$$

(Partial) answers:

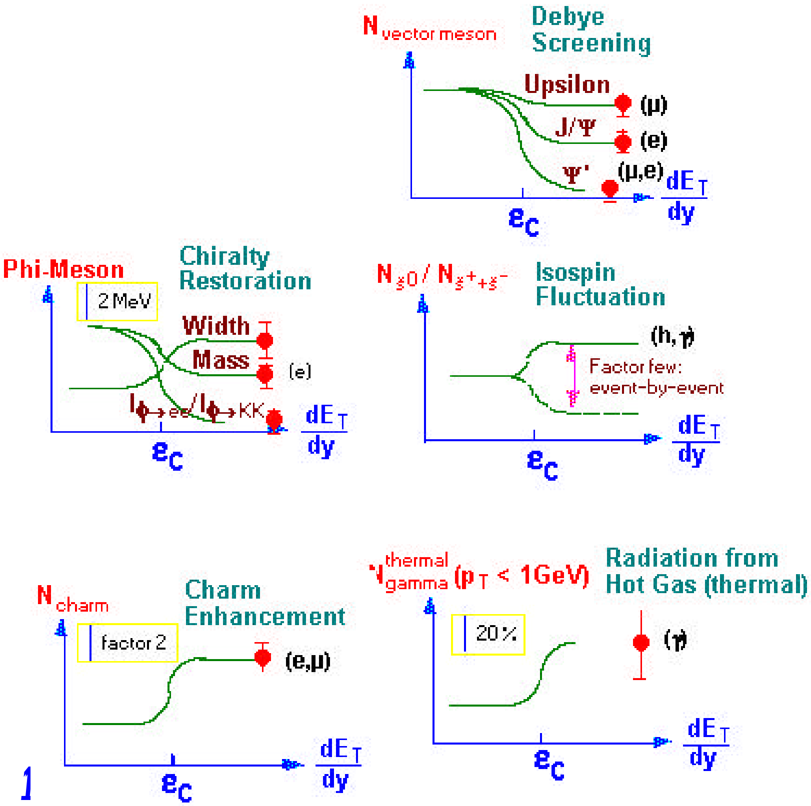
- **The QGP phase transition will not be "seen" at RHIC**
  - ❑ **Instead it will emerge as a consistent framework for describing the observed phenomena**
  - ➪ **Avoid single-signal detectors**

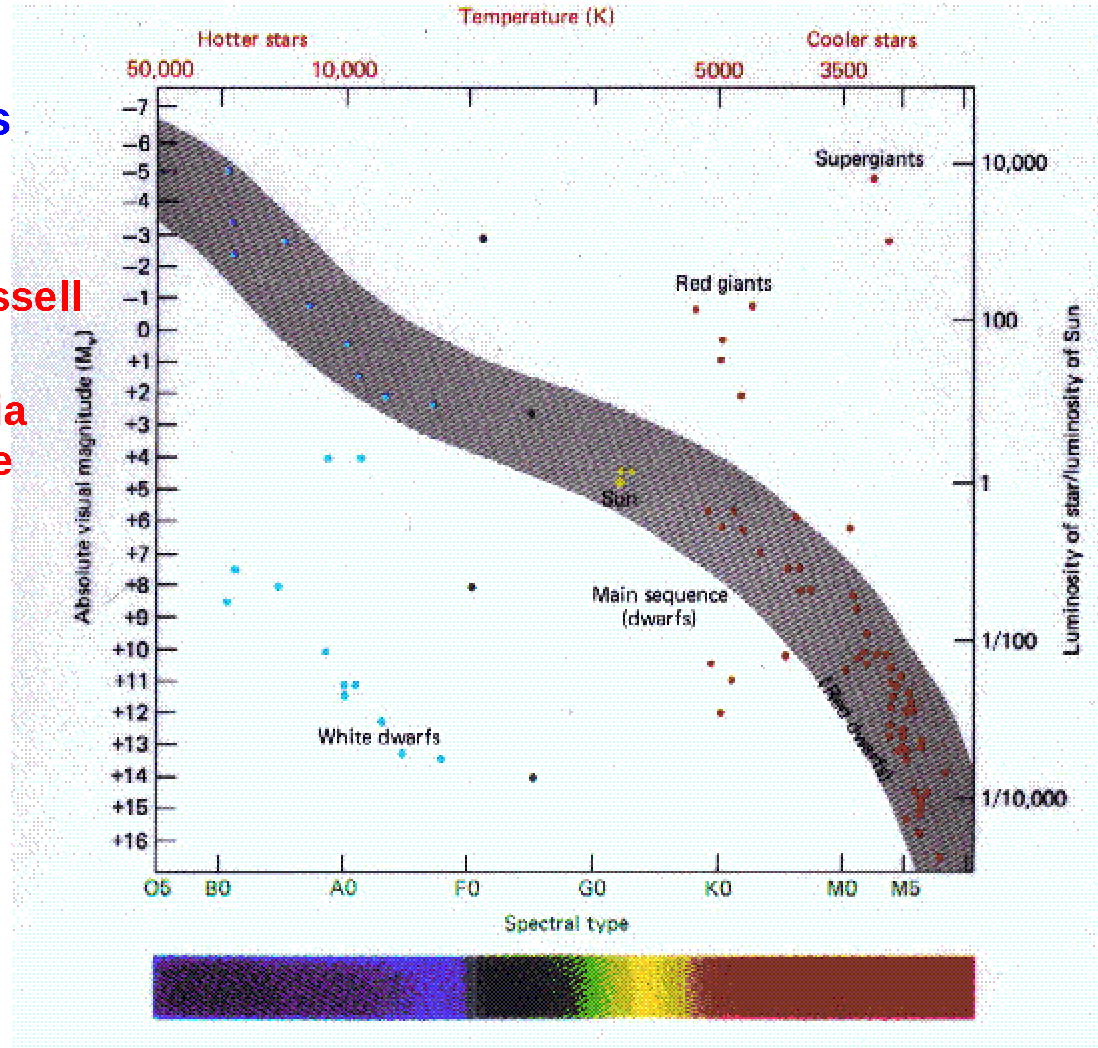
(Guidance written in 1991)

- **There are no* cross sections at RHIC**
  - * **Except**
    - * s_{GEOM} ~ **few barns**
    - * $s_{CENTRAL}$ ~ **(1-10)%** s_{GEOM}
    - * **but** s_{QGP} ~ $s_{CENTRAL}$ **??**
  - ➪ ***Preserve high-rate and triggering capabilities***
- **Expect the unexpected**
  - ❑ **High gluon density ➡ production of exotics?**
  - ❑ **Color topology ➡ high anti-baryon production?**
  - ❑ **New vacuum ➡ large isospin fluctuations?**
  - ➪ **Maintain flexibility as long as $'s allow**

Studying Complex Phenomena

- Ample historical evidence for categorizing complex physics through correlation of observables
  - For example, Hertzprung-Russell in astronomy
  - PHENIX will approach QGP via as many channels as possible





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PHENIX Approach to QGP Detection

1. Deconfinement

R(U) ~ 0.13 fm < R(J/Y) ~ 0.29 fm < R(Y ') ~ 0.56 fm

➪ Electrons, Muons

2. Chiral Symmetry Restoration

Mass, width, branching ratio of F to e^+e^-, K^+K^- with dM < 5 Mev:

➪ Electrons, Muons, Charged Hadrons

Baryon susceptibility, color fluctuations, anti-baryon production:

➪ Charged hadrons

DCC's, Isospin fluctuations:

➪ Photons, Charged Hadrons

3. Thermal Radiation of Hot Gas

Prompt g, Prompt g * to e^+e^-, m^+m^- :

➪ Photons, Electrons, Muons

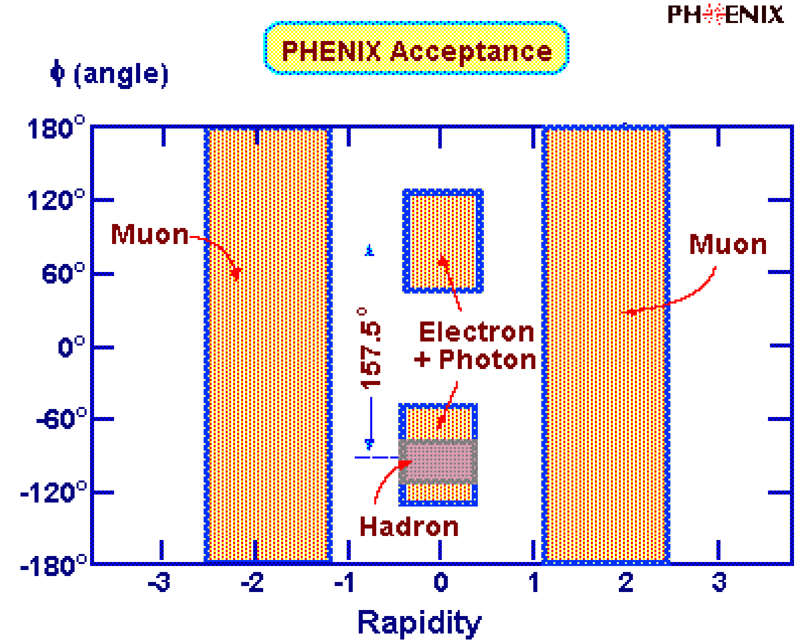
4. Strangeness and Charm Production

Production of K^+, K^- mesons:

➪ Hadrons

Production of F, J/Y, D mesons:

➪ Electrons, Muons



5. Jet Quenching

High pT jet via leading particle spectra:

➪ Hadrons, Photons

6. Space-Time Evolution

HBT Correlations of $p^\pm p^\pm$, $K^\pm K^\pm$:

➪ Hadrons

Summary: Electrons, Muons, Photons, Charged Hadrons

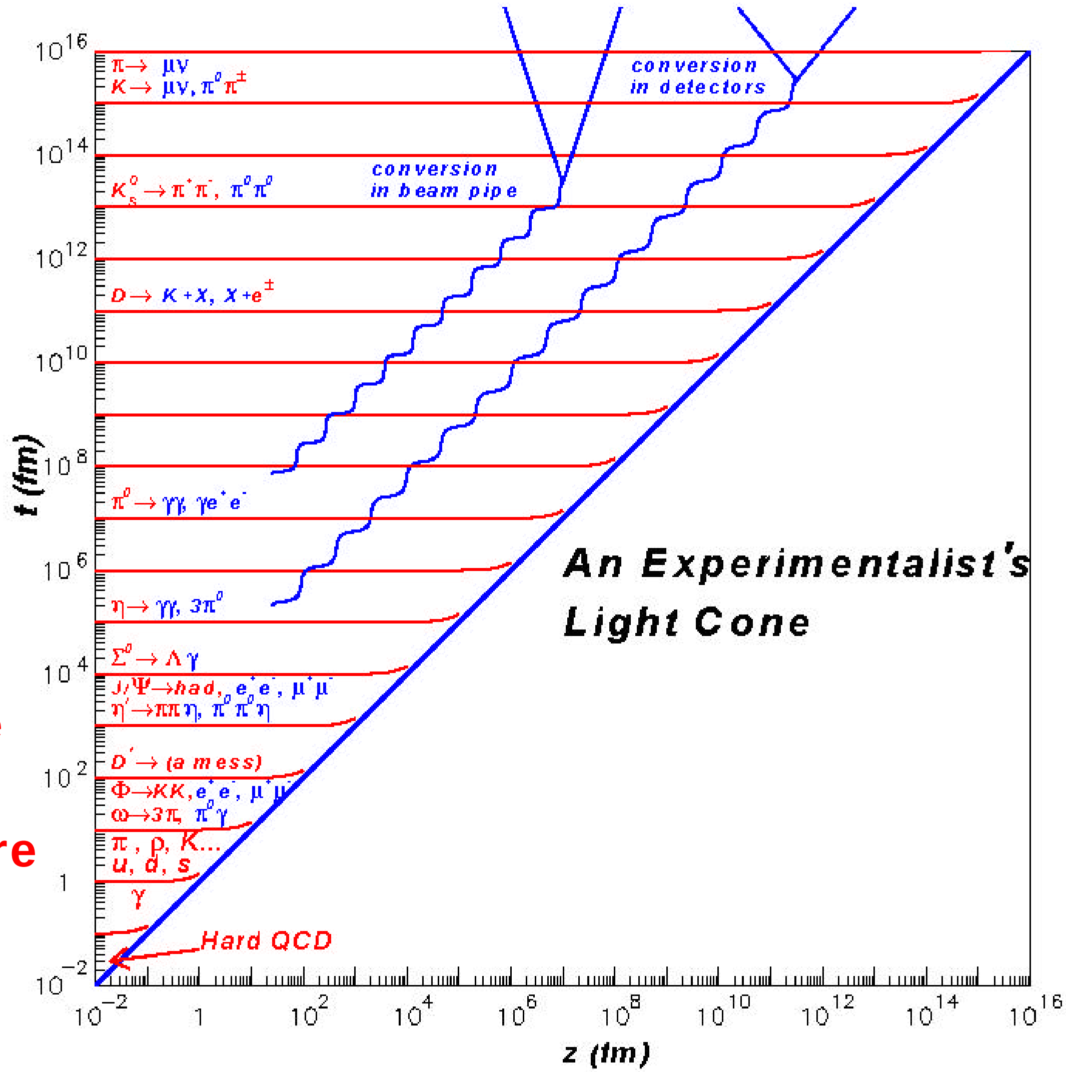
Measuring all Timescales

- **PHENIX can and will do this program**
  - Early timescales in collision typically probed by "hard processes".
  - "Hard"
    - ➡ high momentum transfer
    - ➡ rare
    - ➡ luminosity limited
- **Run-1 (Summer 2000):**
  - < ~1 mb^{-1} recorded
  - ~5M "minimum bias" events
- **Run-2 (2001-2)**
  - ~24 mb^{-1} recorded
  - ~200M events "sampled"

Timescale	Probe	Available Run-1?	Available Run-2?
Initial Collision	*Hard Scattering*		
	Single "jet" via leading particle	Yes	Yes
	photon + "jet"	No	Yes?
Deconfinement	*High-Mass Vector Mesons*		
	J/Y, Y' screening	No	Observation
	U (non)screening	No	No
Chiral Restoration	*Low-Mass Vector Mesons*		
	r, w, f mass, width	No	Yes?
	f branching ratios	No	Yes?
QGP Thermalization	*Photons*		
	p^0, h, h'	p^0 only	Yes
	continuum direct; very soft	No	Yes
QGP Thermalization	*Dileptons*		
	non-resonant: 1-3 GeV	No	Yes?
	soft continuum, <1 GeV	No	No
QGP Thermalization	*Heavy Quark Production*		
	open charm	No	No
	open charm via single lepton	Yes	Yes
Hadronization	*Hadrons*		
	HBT Interferometry, p/K	Yes	Yes
	strangeness production: K, f	Yes	Yes
	spectra of identified hadrons	Yes	Yes
Hydrodynamics	*Global Variables*		
	E_T, dN/dy	Yes	Yes

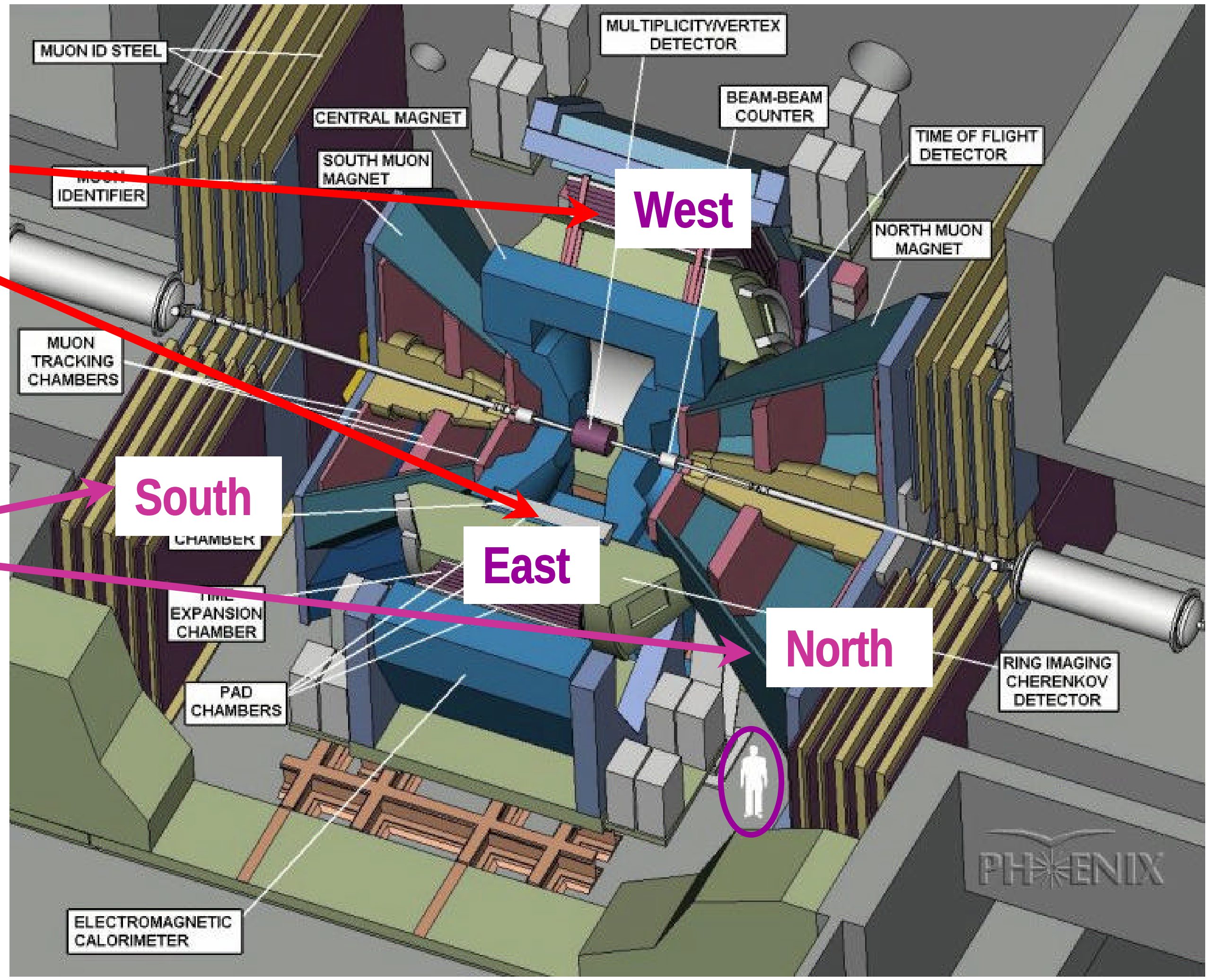
General Issues of Experimental Design

- One must deal with hadronic and electromagnetic interactions at ~all length scales
  - (I.e., not just the first 10 fm)
  - Convenient to represent on a “logarithmic light-cone”
- More importantly, PHENIX faced severe design contraints:
  - Central arms- minimize material in aperture
  - Muon arms- maximize absorber in aperture

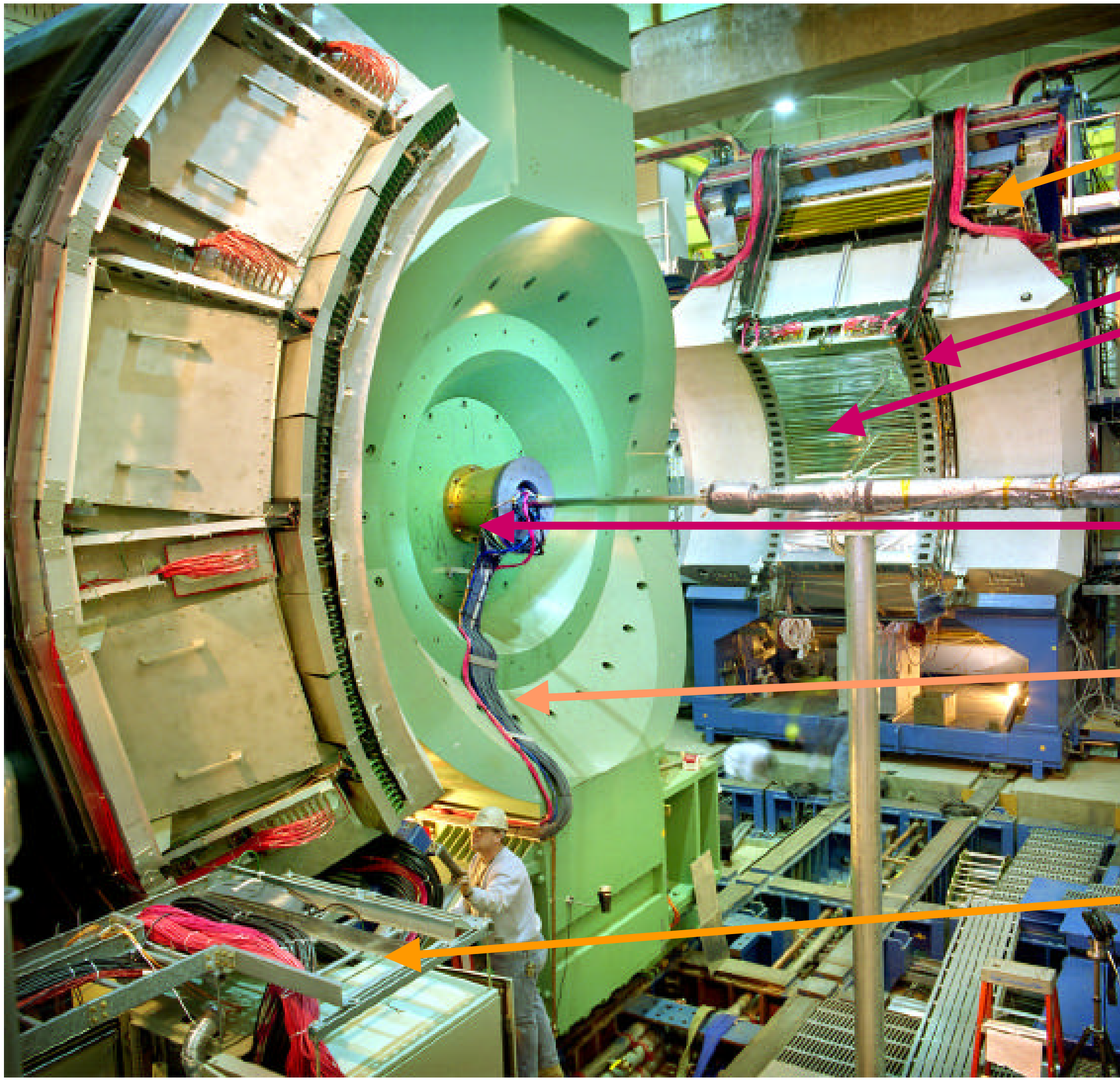


PHENIX at RHIC

- 2 central spectrometers
- 2 forward spectrometers
- 3 global detectors



PHENIX Central



East Carriage

Ring Imaging Cerenkov

Drift Chamber

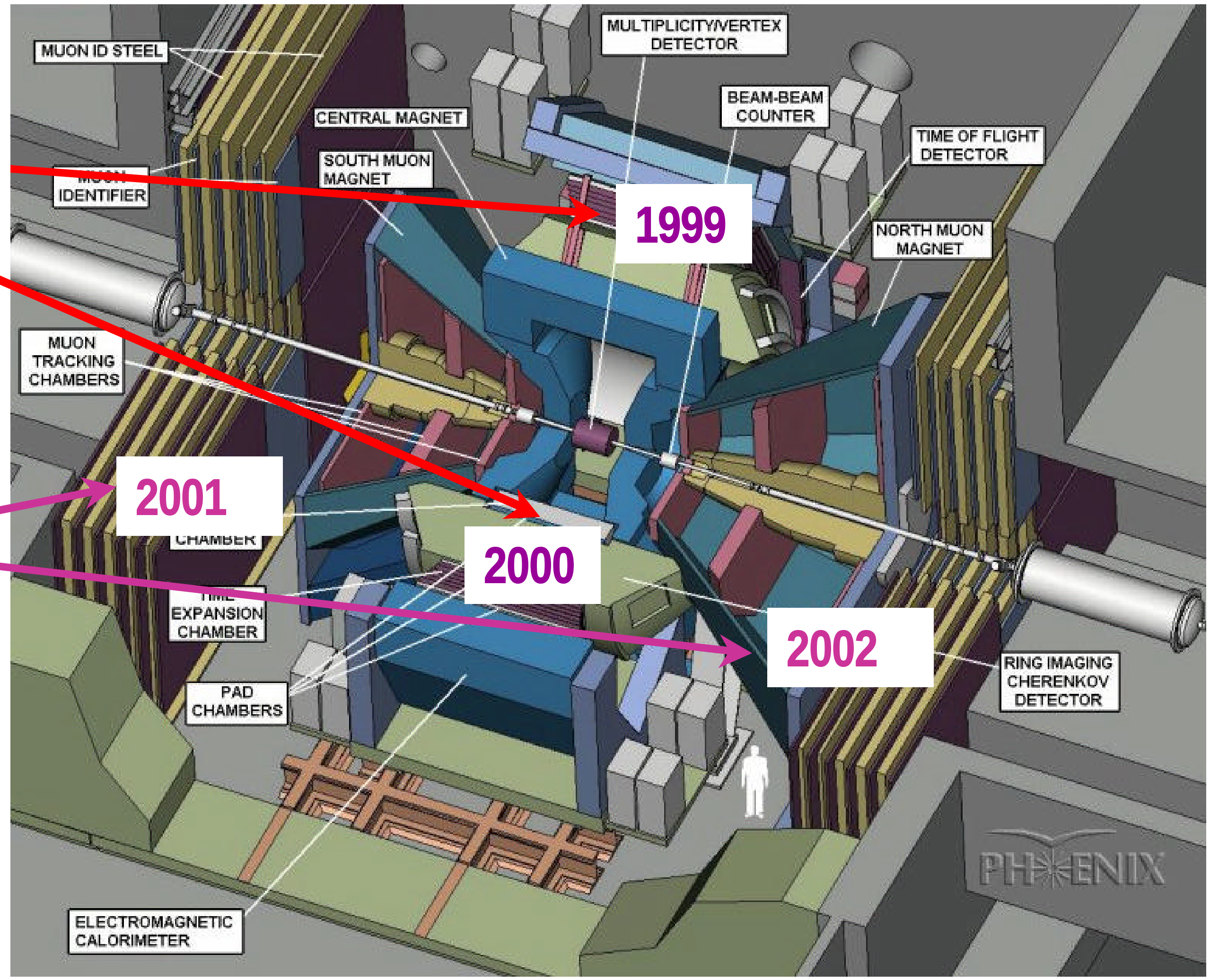
Beam-Beam Counter

Central Magnet

West Carriage

Schedule

- 2 central spectrometers
- 2 forward spectrometers
- 3 global detectors



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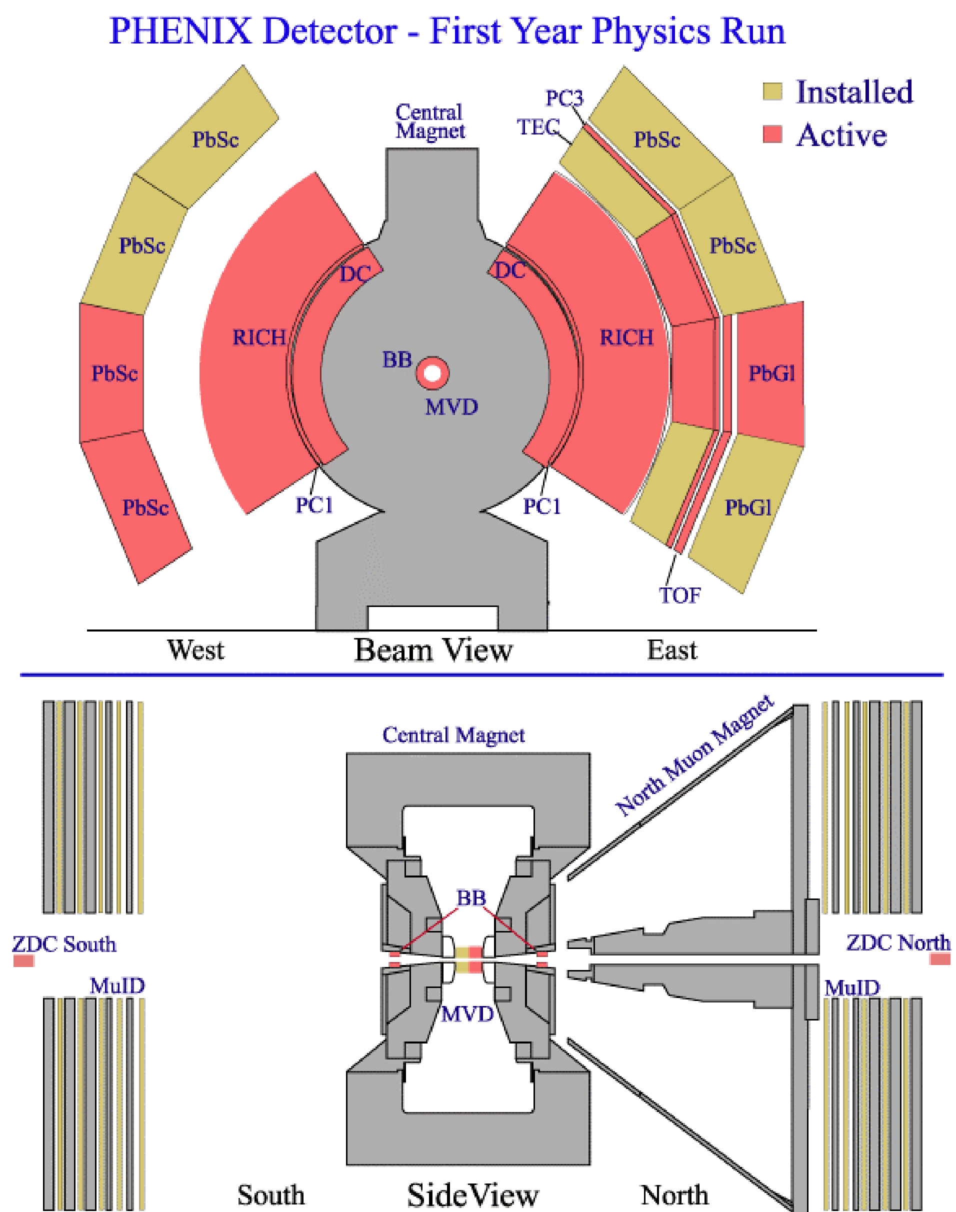
Run-1 Configuration

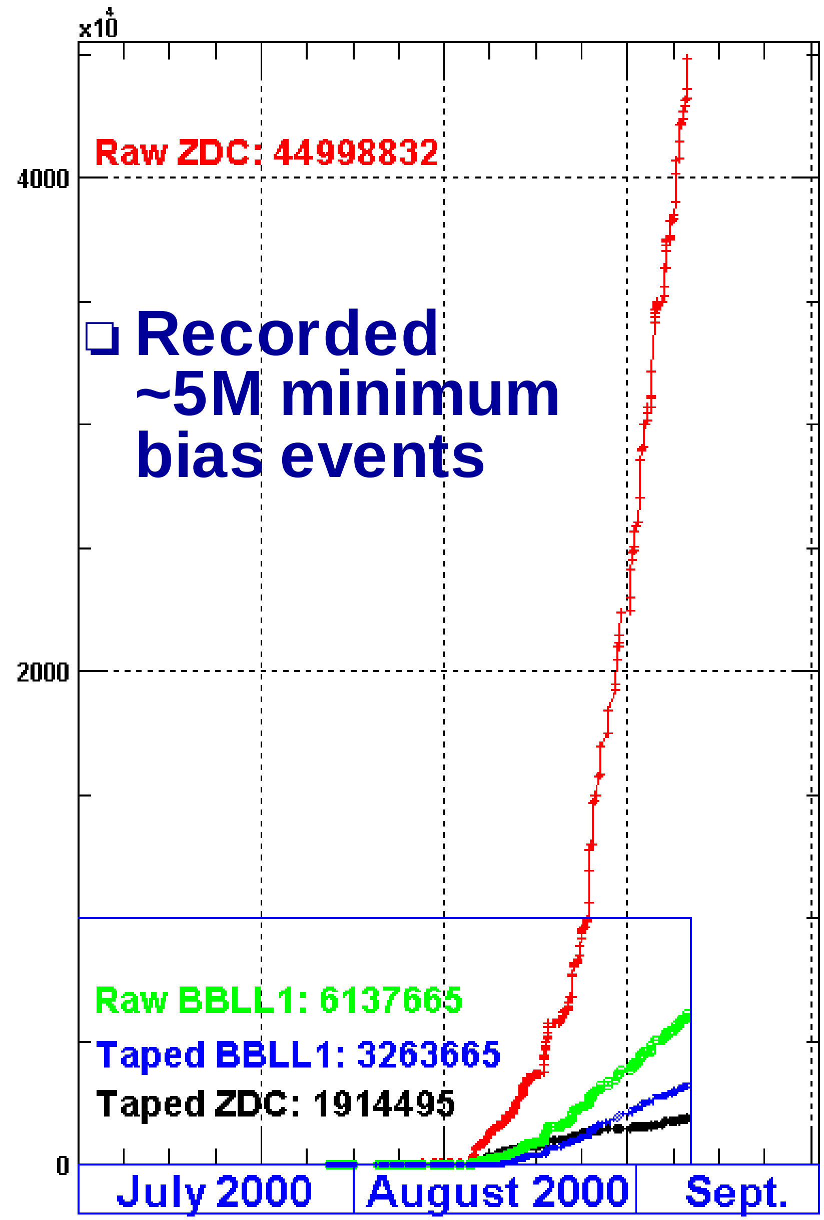
- Two central arms
  - Mechanically ~complete
  - Roughly half of aperture instrumented
- Global detectors
  - Zero-degree Calorimeters (ZDCs)
  - Beam-Beam Counters (BBCs)
  - Multiplicity and Vertex Detector (MVD, engineering run)



Run-1 Accomplishments

- First collisions:15-Jun-00
- Last collisions: 04-Sep-00
- During this period:
  - ❑ Commissioned
    - ◆ Zero-Degree Calorimeters
    - ◆ Beam-Beam Counters
    - ◆ Multiplicity and Vertex Counter
    - ◆ Drift Chambers
    - ◆ Pad Chambers
    - ◆ Ring Imaging Cerenkov Counter
    - ◆ Time Expansion Chamber
    - ◆ Time-of-Flight Counters
    - ◆ Electromagnetic Calorimeter
    - ◆ Muon Identifier
    - ◆ Minimum Bias Triggers
    - ◆ Data Acquisition System

❑ Recorded ~5M minimum bias events



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Topic 1

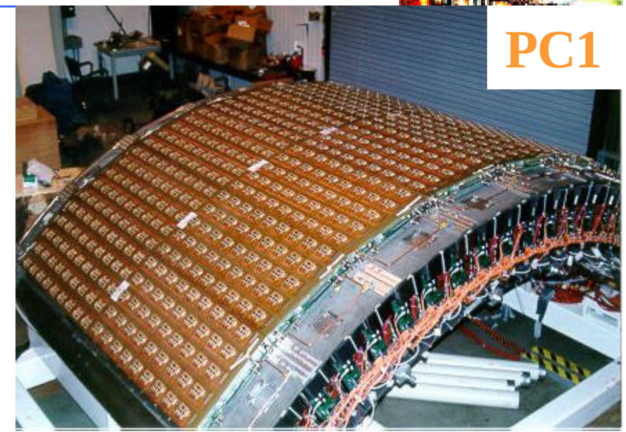
- **Charged particle multiplicity**
  - **How many particles are produced?**
  - **What to they tell us about underlying reaction mechanism?**

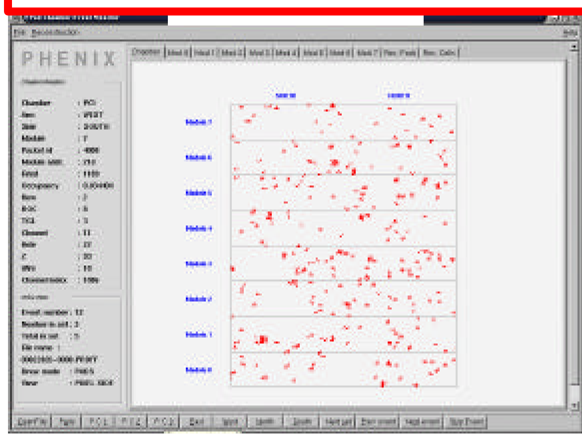
- **Answered in**

  "*Centrality Dependence of Charged Particle Multiplicity in Au-Au Collisions at sqrt(s) = 130 GeV*", K. Adcox et al, PRL 86 (2001) 3500, preprint nucl-ex/0012008.

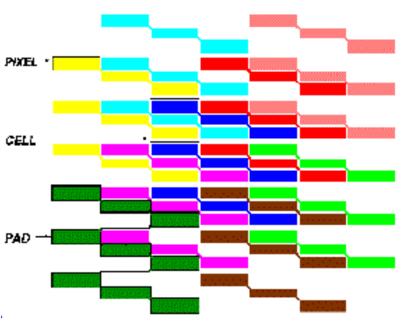
Tracking Detectors: Pad Chambers

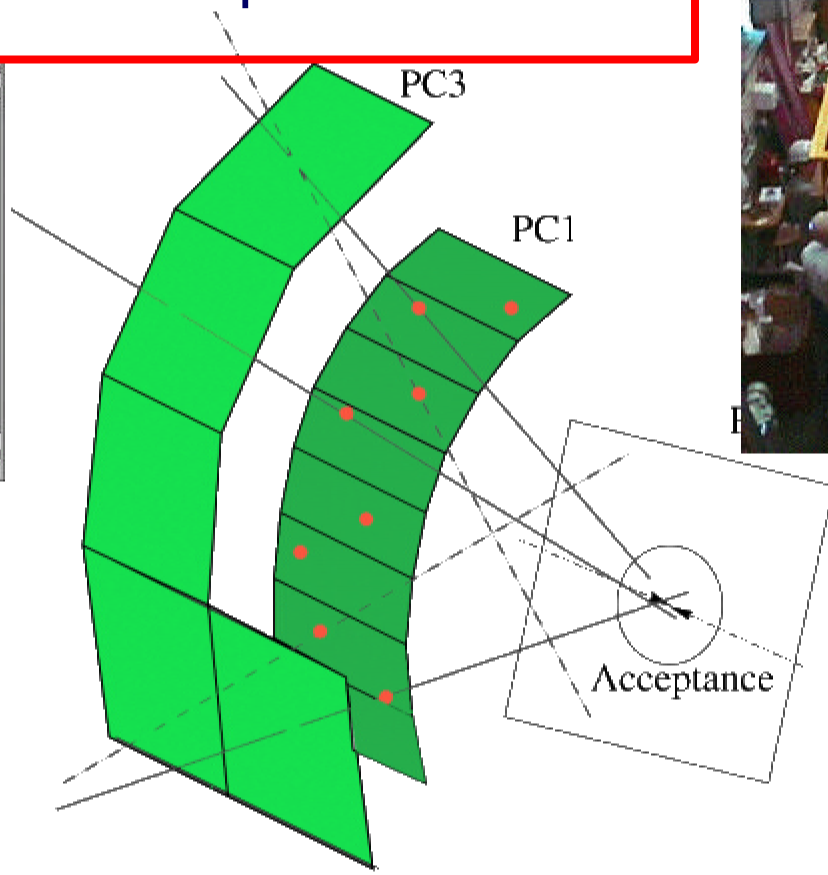
- Cathode wire chambers using fine granularity pixel pad readout
  - 2-D hit position, $\sigma_x = \sigma_y \sim O(\text{ mm})$
  - 173k channels total, ~ 100 m^2 detector coverage
- Low-mass , rigid honeycomb/circuit board construction
- All signal digitization takes place on-board in detector active region. Solves interconnect problem.

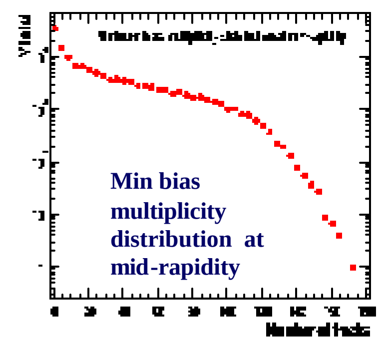




Pixel Pad Cathode Pattern







Pixel Pad Cathode Pattern

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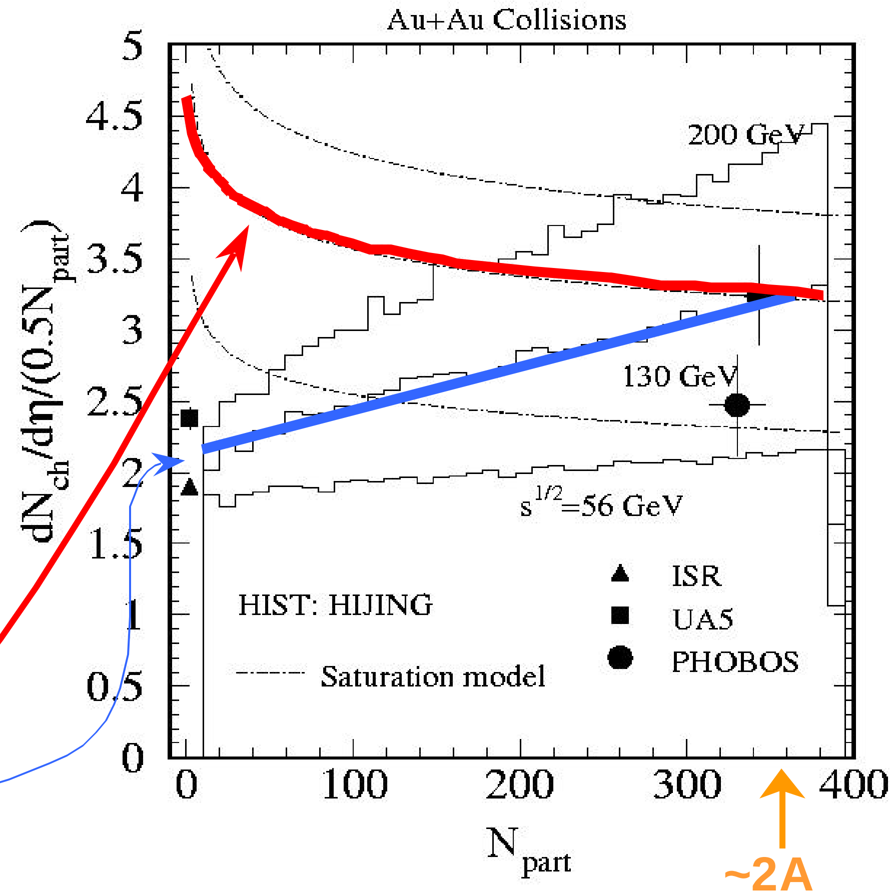
PHOBOS Result on dN_{ch}/dh

Q. How many charged particles per nucleon-nucleon collision?

A: Express using

- dN_{ch}/dh ~ "generic" dN_{ch}/dy
- N_{part}
  - ≡ Number of participating nucleons
  - = 2 for p-p collision
  - ~2A for central A-A collision
- Plot multiplicity *per N-N collision*
  (dN_{ch}/dh) / ($N_{part}/2$)



- **Does not (quite) distinguish between**
  - "Saturation" models, dominated by gg ® g
  - "Cascade" models, dominated by gg ® gg, gg ® ggq

(X.N. Wang and M. Gyulassy, nucl-th/0008014)

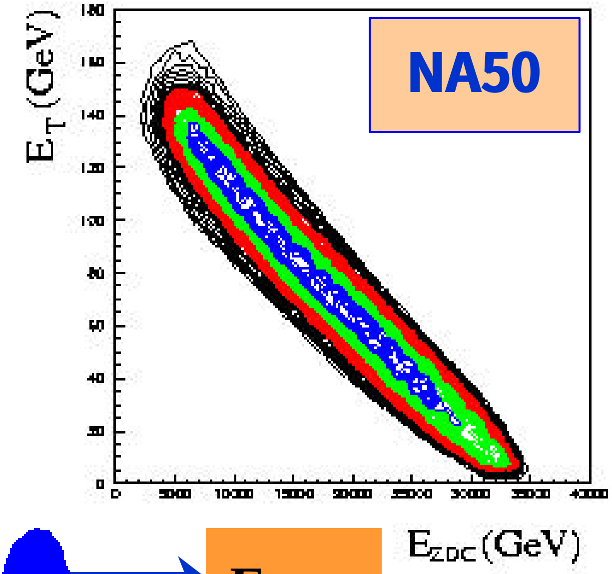
Determining N_{PART}

Best approach *(for fixed target!)*:

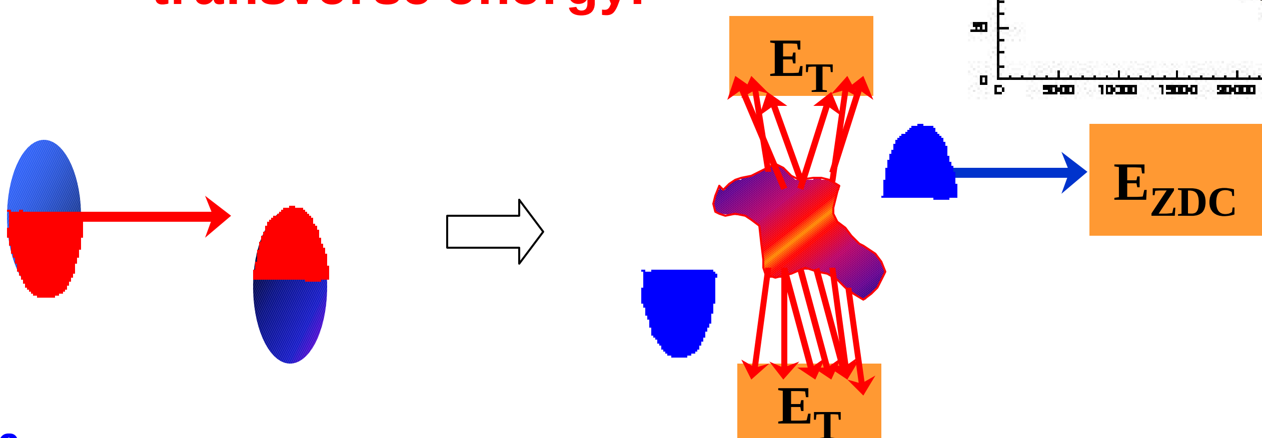
- Directly measure in a "zero degree calorimeter"

$$N_{PART} \approx 2 \times \left[A - \frac{E_{ZDC}}{E_{PerNucleon}} \right]$$

(for A+A collisions)



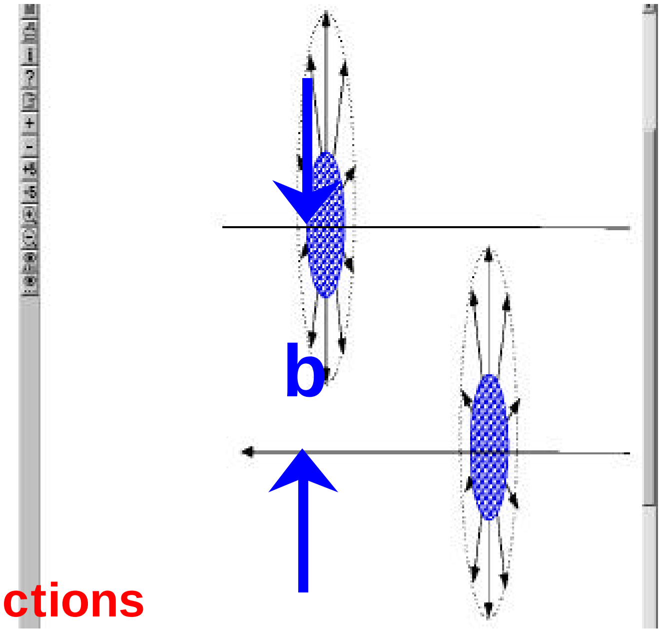
- Strongly (anti)-correlated with produced transverse energy:



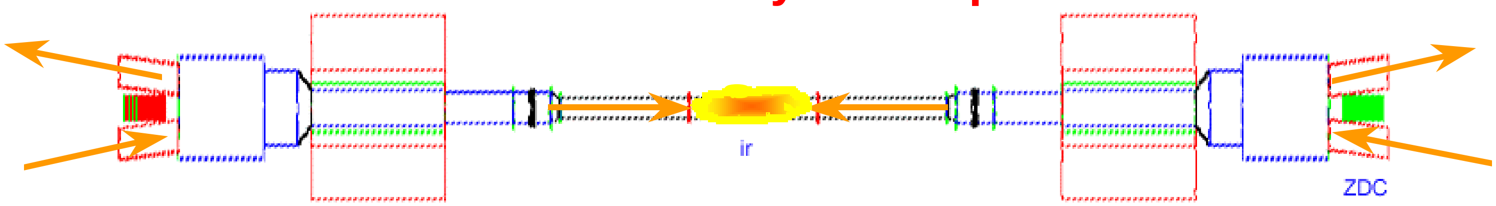
Fixing Initial Conditions

- Event characterization
  - Impact parameter b is *well-defined* in heavy ion collisions
  - Event multiplicity predominantly determined by *collision geometry*
  - Characterize this by global measures of multiplicity and/or transverse energy correlated with

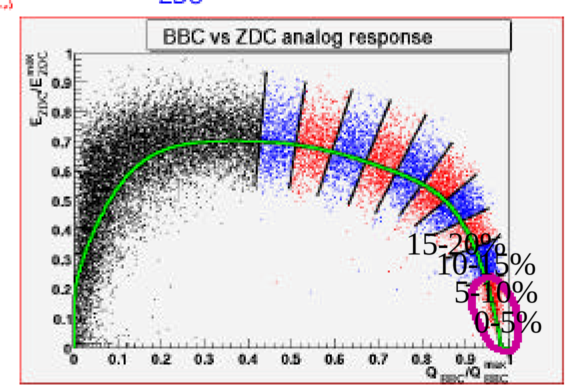
    ZDC   Zero Degree Calorimeter



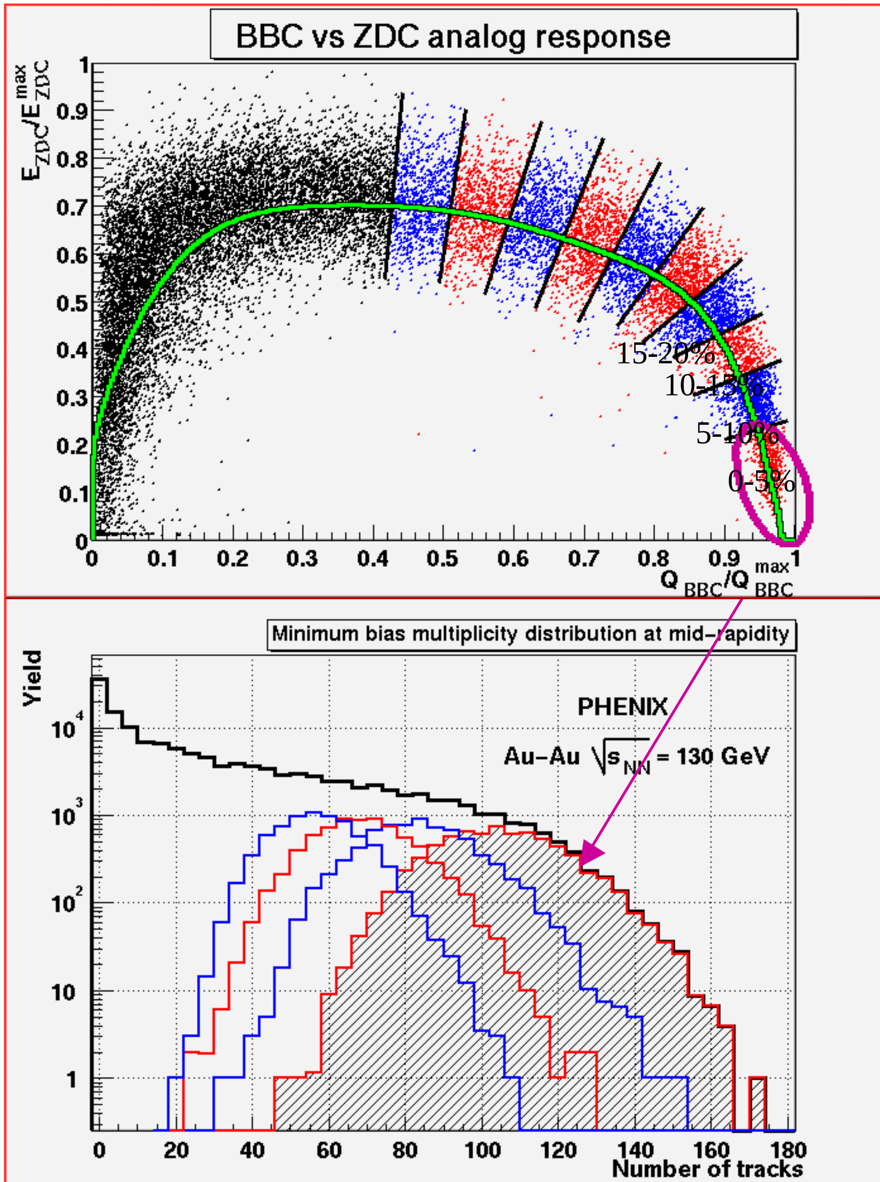
- Goals:
  - Uniform luminosity monitoring at all 4 intersections
  - Uniform event characterization by all 4 experiments



- Process:
  - Correlated Forward-Backward Dissociation
  - s_{tot} = 11.0 Barns (+/- few %)



Determining N(participants)



Use combination of

- **Zero Degree Calorimeters**
- **Beam-Beam Counters**

to define centrality classes

- **Glauber modeling**

to extract $N_{participants}$

determines Multiplicity vs. Centrality
i.e

$dN_{ch}/d\eta$ vs. $N_{participants}$

which is presented as
"specific particle production"

multiplicity *per N-N collision*

$(dN_{ch}/d\eta) \; / \; (N_{part}/2)$

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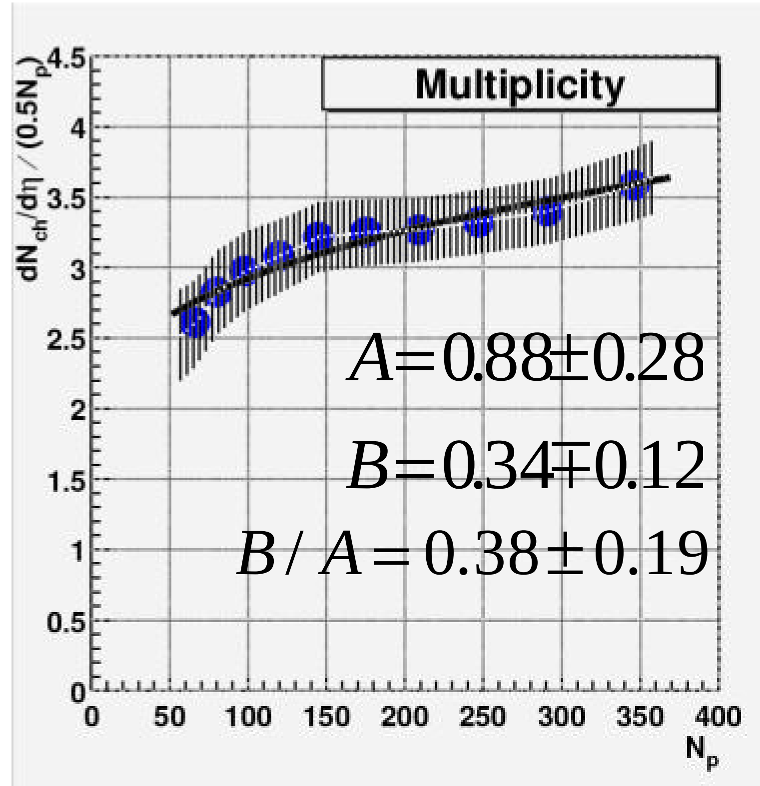
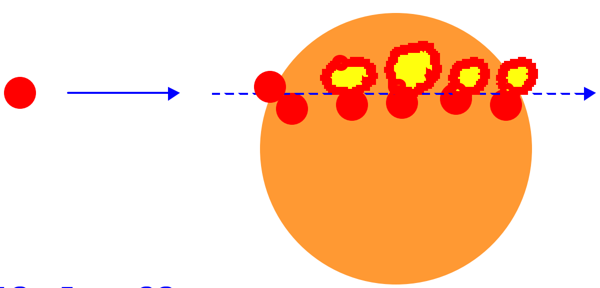
PHENIX Results

- **"Specific multiplicity" is not flat**
  - Yields grow significantly faster than $N_{participants}$
  - Evidence for term ~ $N_{collisions}$

$$dN_{ch}/d\eta\big|_{\eta=0} = A \times N_{part} + B \times N_{coll}$$

  - Qualitatively consistent with HIJING
  - Inconsistent with *some* saturation models
- **One interpretation:**
  - Evidence for both "soft " (~ $N_{participants}$) "hard" (~ $N_{collisions}$) processes





In this cartoon are there

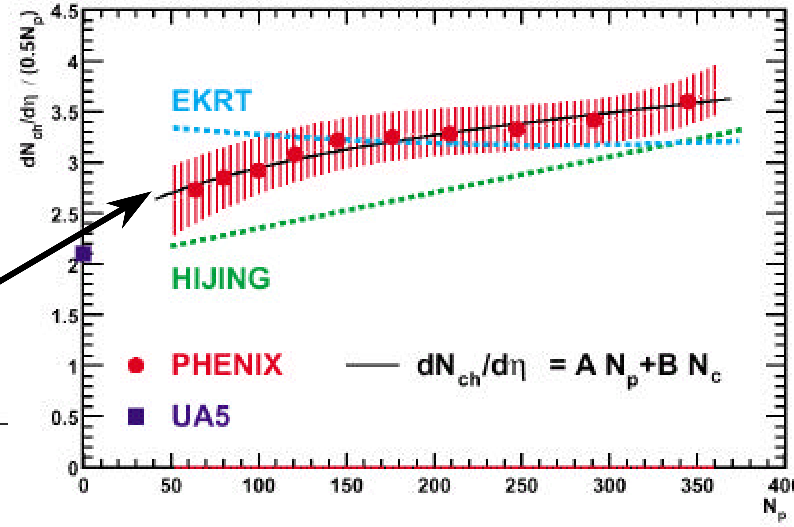
5 N-N collisions $\Rightarrow$ 5 x N_{pp}?

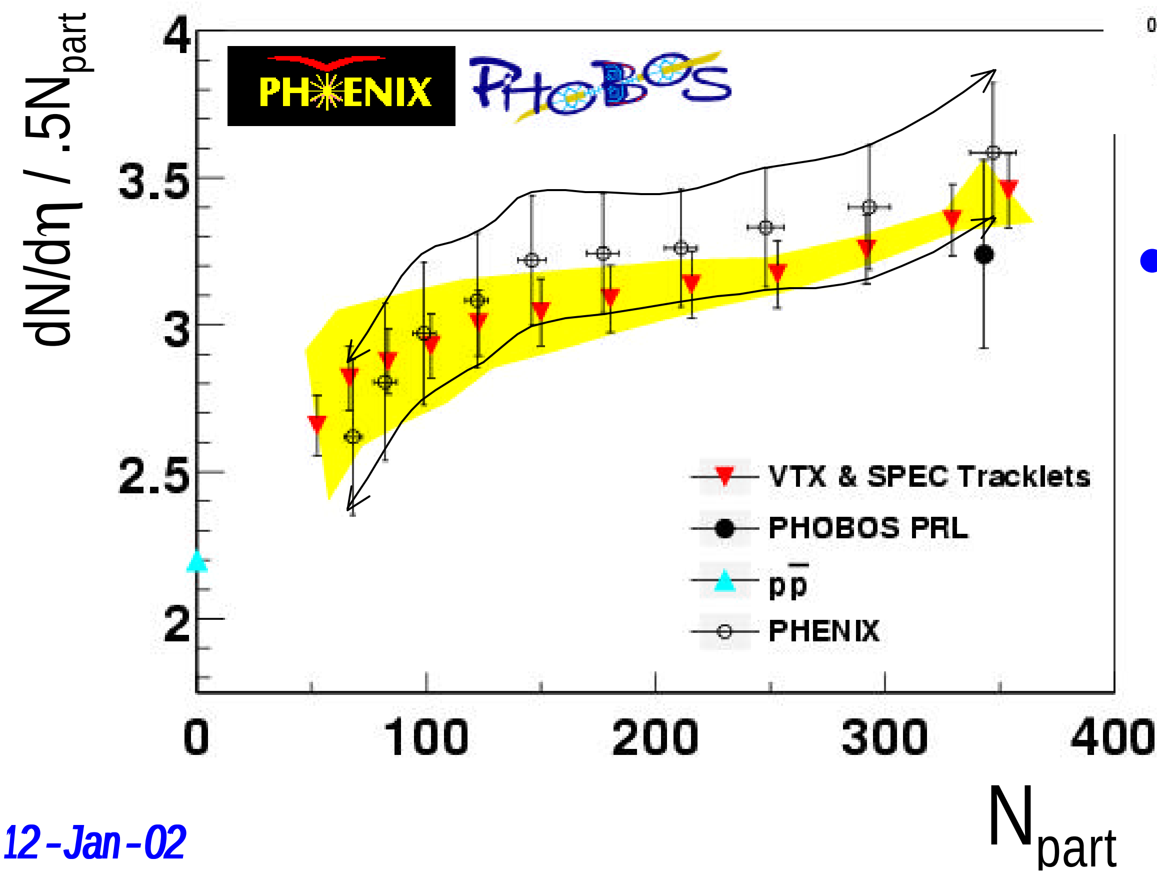
OR

6 participants $\Rightarrow$ 3 x N_{pp}?

PHENIX Consistency between Experiments

- **Trend**
  - **incompatible with final-state gluon saturation model**
  - **Good agreement with model based on *initial-state* saturation (Kharzeev and Nardi, nucl-th/0012025)**





- **Excellent agreement between (non-trivial) PHENIX and PHOBOS analyses of this systematic variation with nuclear overlap.**

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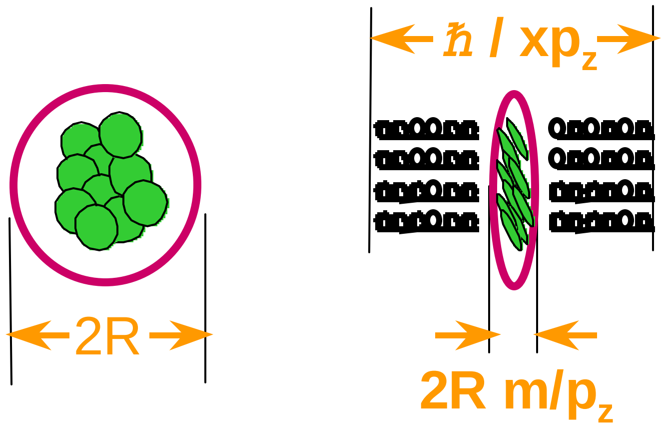
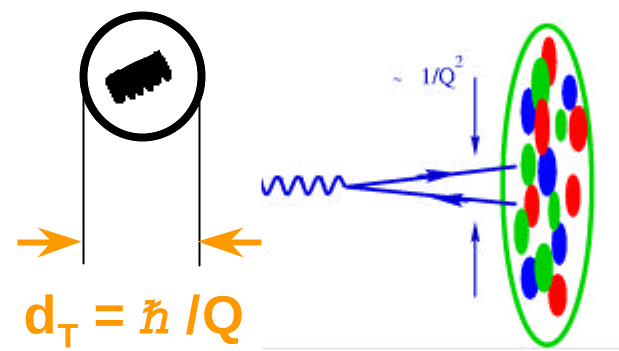
Gluon saturation at RHIC

When do the gluons overlap significantly?

[1] J.P Blaizot, A.H. Mueller, Nucl. Phys. B289, 847 (1987)





Longitudinal

So for $\hbar/mx \sim 2R$,

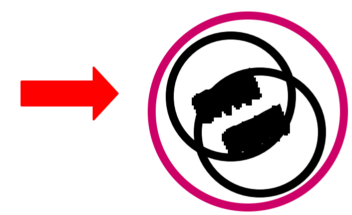
~ *all* constituents contribute

Parton density r ~ A $xG(x,Q^2)$ / pR^2

Transverse

Parton cross section

s ~ a$_S$ $\hbar^2 / Q^2$



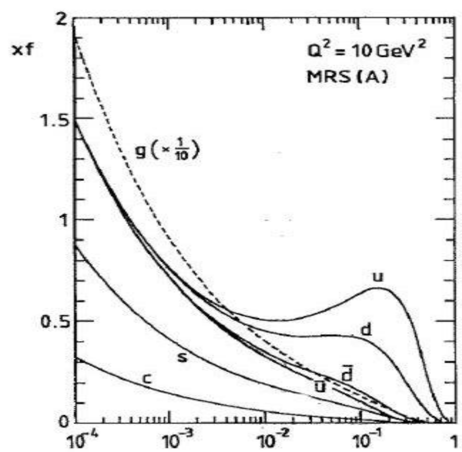
Saturation condition r s ~ 1

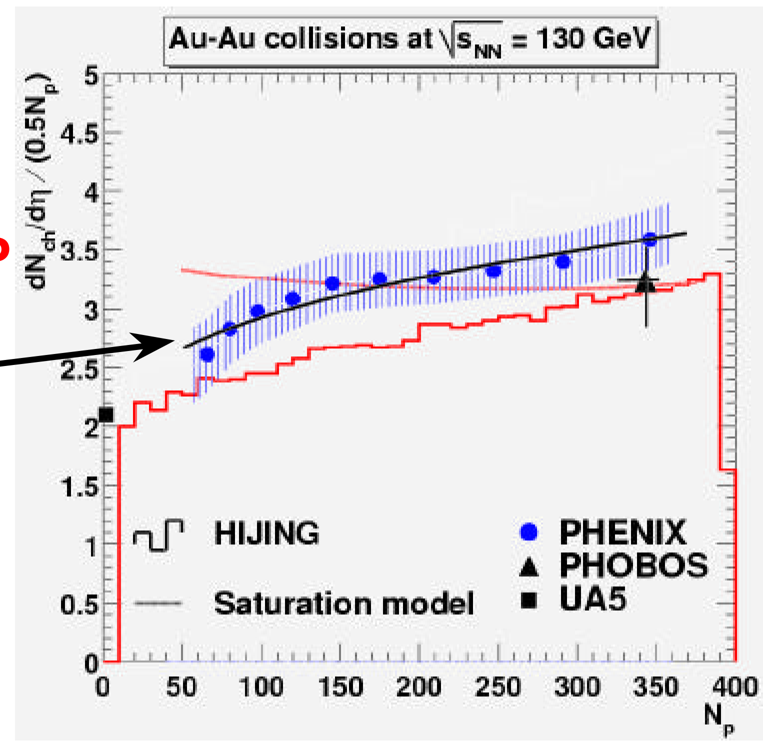
Q_S^2 ~ a$_S$ A $xG(x,Q^2)$ / pR^2 ~ $A^{1/3}$

D. Kharzeev, nucl-th/0107033

Initial State Partons?

- **Procedure:**
  - Determine scale Q_S^2 as function of nuclear overlap
    - $Q_S^2 \sim A^{1/3} \sim N_{part}^{1/3}$
  - Assume final-state multiplicities proportional to number of initial-state gluons in this saturated regime:
    - $dN/dh = c\ N_{part}\ xG(x, Q_S^2)$
  - Note that DGLAP requires evolution of $xG(x, Q_S^2)$:
    - $xG(x, Q_S^2) \sim \ln (Q_S^2 / L_{QCD}^2)$
- **Results:**
  - "Running" of the multiplicity yield directly from from $xG(x, Q^2)$ +DGLAP





Topic 2

- **Energy Density**
  - **What energy densities are achieved in central collisions at RHIC?**
  - **How does this compare to previous experiments?**

- **Answered in**

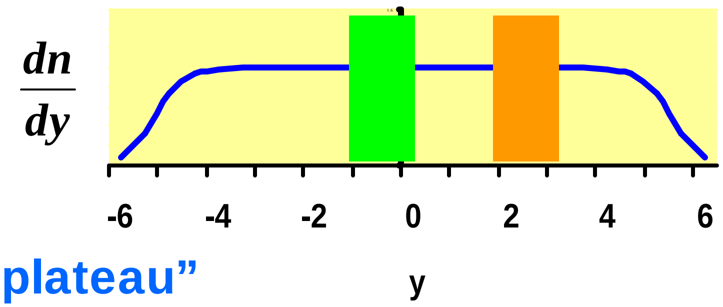
"Measurement of the Midrapidity Transverse Energy Distribution from sqrt(s) = 130 GeV Au-Au Collisions at RHIC",
K. Adcox et al., PRL 87 (2001) 052301,
preprint nucl-ex/0104015,
or from the PHENIX site: pdf, ps, ps.gz.

Dynamics 101

Q. How to estimate initial energy density?

A. From rapidity density

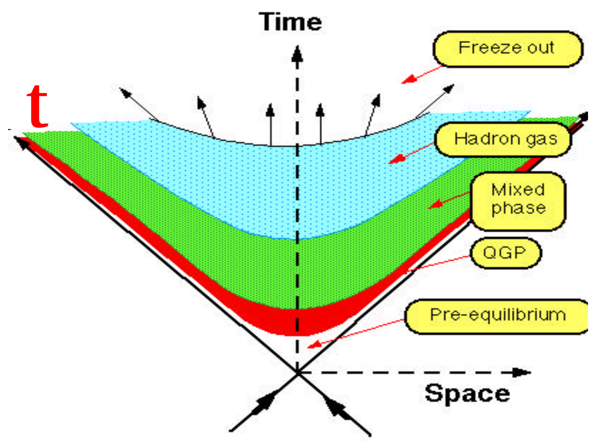
- "*Highly relativistic nucleus-nucleus collisions: The central rapidity region*", J.D. Bjorken, Phys. Rev. D27, 140 (1983).
- Assumes
  - ~ 1-d hydrodynamic expansion
  - Invariance in y along "central rapidity plateau" (I.e., flat rapidity distribution)
  - Then



$$\varepsilon = \frac{E}{V} \sim \frac{dE_T}{\pi R_T^2 \cdot dz} \sim \frac{dE_T}{\pi R_T^2 \cdot \tau dy} = \frac{1}{\pi R_T^2 \cdot \tau} \frac{dE_T}{dy}$$

since boost-invariance of matter

$\Rightarrow$ $dz = \tau\, dy$ where τ ~ 1 fm/c

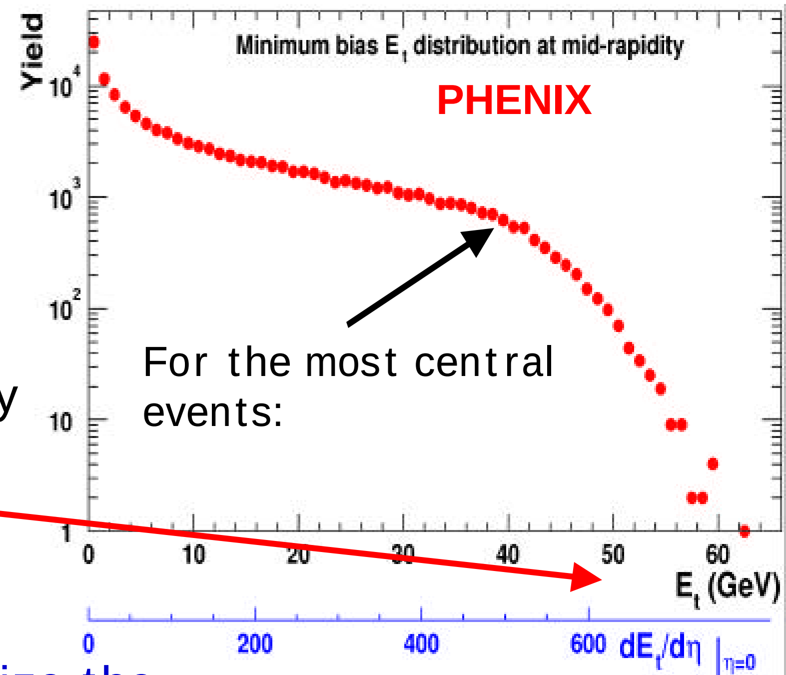


12-Jan-02

Determining Energy *Density*

- **What is the energy density achieved?**
- **How does it compare to the expected phase transition value ?**

EMCAL

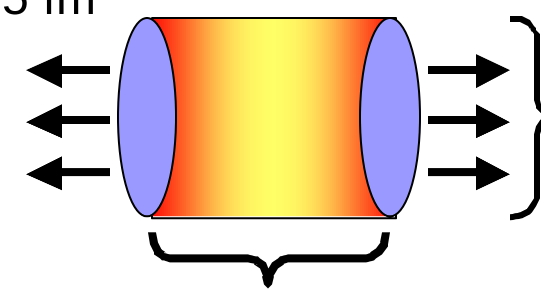


Bjorken formula for thermalized energy density

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

~6.5 fm

time to thermalize the system (τ_0 ~ 1 fm/c)



πR^2

$$dz = \tau_0 dy$$

$\epsilon_{Bjorken}$ ~ 4.6 GeV/fm^3

~30 times normal nuclear density

~<u>1.5 to 2 times higher</u> than any previous experiments

Topic 3

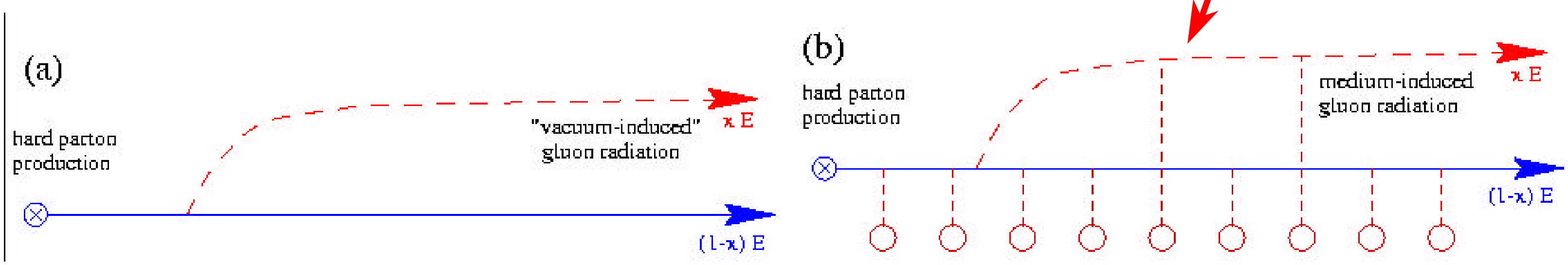
- **High Transverse Momenta Particle Production**
  - **What is the rate for producing high p_T particles?**
  - **How does it vary with centrality?**

- **Answered in**

  "Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at sqrt(s) = 130 GeV",
  K. Adcox et al., Phys. Rev. Lett. 88, 022301 (2001), preprint nucl-ex/0109003, or directly from Phenix

PHENIX Energy Loss of Fast Partons

- **Many approaches**
  - **1983: Bjorken**
    $$-\frac{dE}{dx} = \frac{3\sqrt{30}}{4}\alpha_S^2\sqrt{\varepsilon}\ln\left(\frac{4ET}{M^2}\right) \sim \alpha_S^2 T^2 \ln\left(\frac{4ET}{M^2}\right)$$
  - **1991: Thoma and Gyulassy (1991)**
    $$-\frac{dE}{dx} \approx \frac{4\pi}{3}C_F\alpha_S^2T^2\ln\left(\frac{E}{m_D}\right)$$
  - **1993: Brodsky and Hoyer (1993)**
    $$-\frac{dE}{dx} \approx \frac{\langle \Delta k_T^2\rangle}{2}$$
  - **1997: BDMPS- depends on path length(!)**
    $$-\frac{dE}{dx} \approx \alpha_S\frac{C_R}{8}\frac{m_D^2}{\lambda_g}L\ln\left(\frac{L}{\lambda_g}\right)$$
  - **1998: BDMS**
    $$-\frac{dE}{dx} \approx \alpha_s\frac{N_C}{4}\frac{\langle \Delta k_T^2\rangle}{2}$$
- **Numerical values range from**
  - **~ 0.1 GeV / fm (Bjorken, elastic scattering of partons)**
  - **~several GeV / fm (BDMPS, non-linear interactions of gluons)**



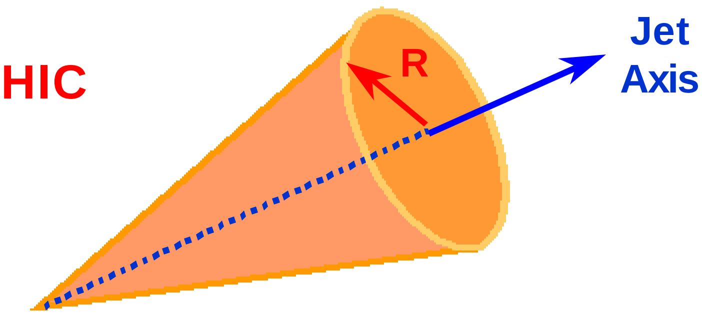
W.A. Zajc

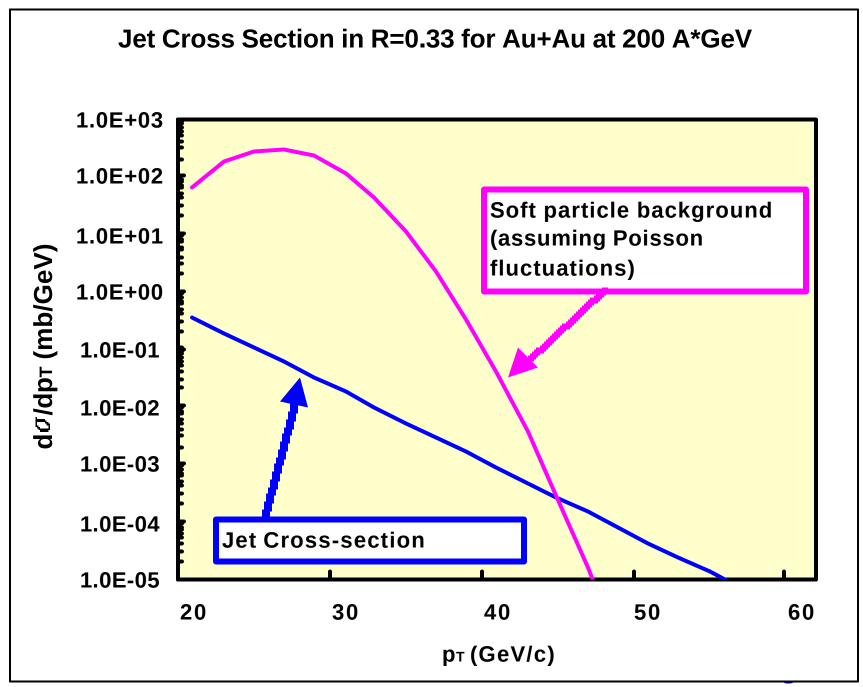
Jet Physics at RHIC

- **Tremendous interest in hard scattering (and subsequent energy loss in QGP) at RHIC**
  - Predictions that dE/dx ~ (amount of matter to be traversed)
  - Directly due to non-Abelian nature of medium
- **But:**
  - "Traditional" jet methodology fails at RHIC
  - Dominated by the soft background:
    - For a typical jet cone R = 0.33
      ($R^2 = \Delta\Phi^2 + \Delta\eta^2$)
      have

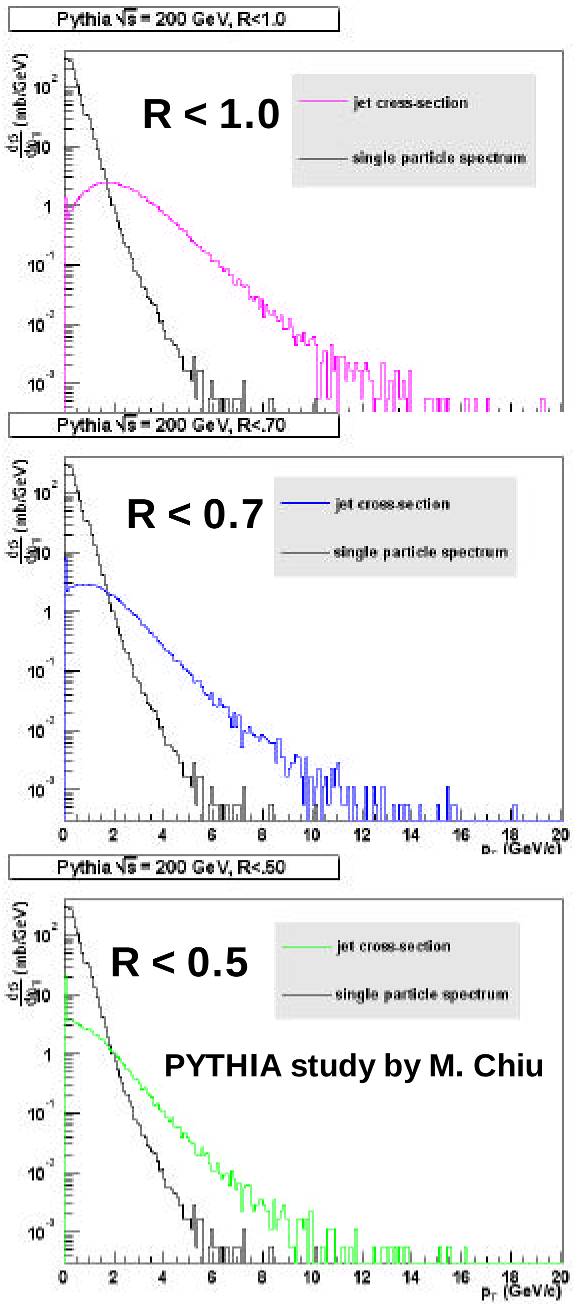
      $\langle n_{SOFT} \rangle \sim 64$

      $\langle E_T \rangle \sim 25$ GeV
    - *Fluctuations* in this soft background swamp any jet signal for $p_T < \sim 40$ GeV:





Shrinking the Cone



- **Why not let R → 0 ?**
  - **Good:**
    Reduces fluctuations of "underlying event"
  - **"Bad" :**
    Doesn't contain all the energy of the jet
- **But:**
  - **For "quenching", maximal effect expected on the "leading particle"**
    (that is, "lost" energy probably stays in the cone, which *confuses* picture)
  - **High p_T single particles have a simple relation to parent parton dynamics**

$$\frac{d\sigma(jet)}{dp_T} \sim \frac{A}{p_T{}^n} \quad , \frac{d\sigma(particle)}{dp_T} = \int dP_T \frac{d\sigma(jet)}{dP_T} \int D(z)\delta(p_T - zP_T)$$

$$D(z) \sim (1-z)^m / z \;\Rightarrow\; \frac{d\sigma(particle)}{dp_T} = (\text{constant})\frac{d\sigma(jet)}{dp_T} \approx \frac{1}{100}\frac{d\sigma(jet)}{dp_T}$$

***Hadron Interactions*, Collins and Martin**

W.A. Zajc

Magnetic Measurements

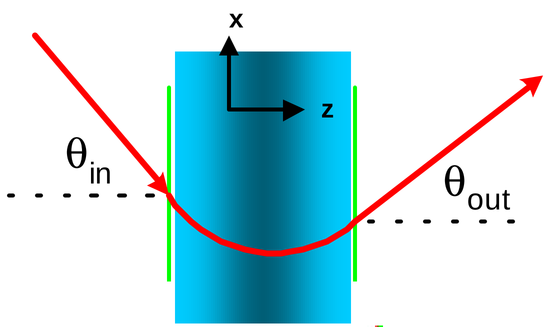
- **As you like it:**

$$\frac{dp^{\mu}}{d\tau} = \frac{e}{c} u_{\nu} F^{\mu\nu} \quad \Rightarrow \quad \frac{d\vec{p}}{dt} = \frac{e}{c}\vec{v} \times \vec{B} \quad \Rightarrow \quad \frac{d}{ds}\left(\frac{d\vec{r}}{ds}\right) = \frac{e}{c}\frac{d\vec{r}}{ds} \times \frac{\vec{B}}{|\vec{p}|}$$

- **More usefully:**

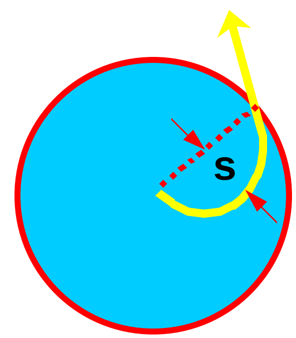
$$|\vec{p}_{\perp}| = \frac{e}{c} B \cdot R, \quad \frac{e}{c} = \frac{0.3\ GeV/c}{Tesla\text{ - }meter}$$

➡ **1 meter of 1 Tesla field deflects 1 GeV/c by ~17°**

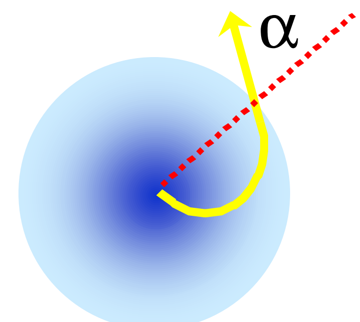


BRAHMS

PHOBOS



STAR



PHENIX

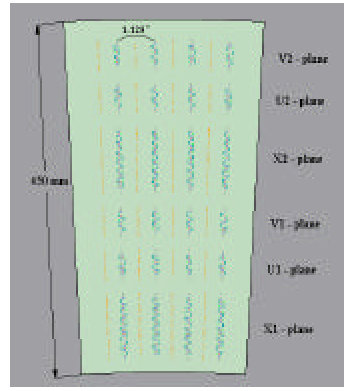
Real world: $$\frac{dp}{p} = (\sim 1\%) \oplus (\sim 1\%) \cdot p \ \ [\mathrm{GeV/c}]$$

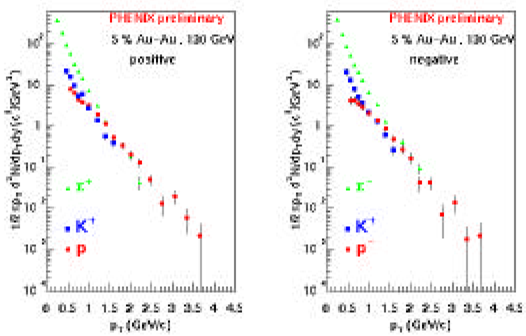
~stuff in aperture

~spatial accuracy

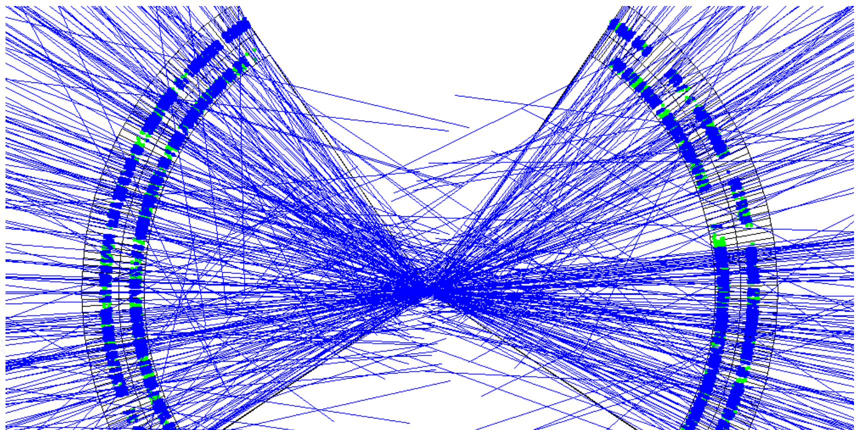
Drift Chamber

- Jet -chamber anode/cathode structure modified for HI high multiplicity
- Joint Russia/US design & construction
- All Titanium frame
- σ_x = 120 μm , two-track sep = 2mm

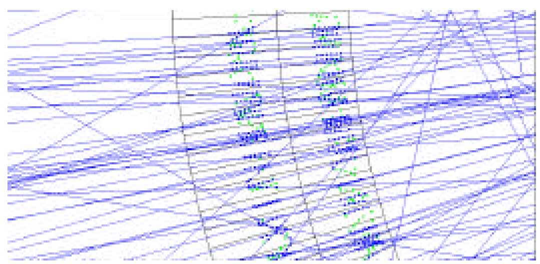




Identified particle spectra using tracking system and TOF



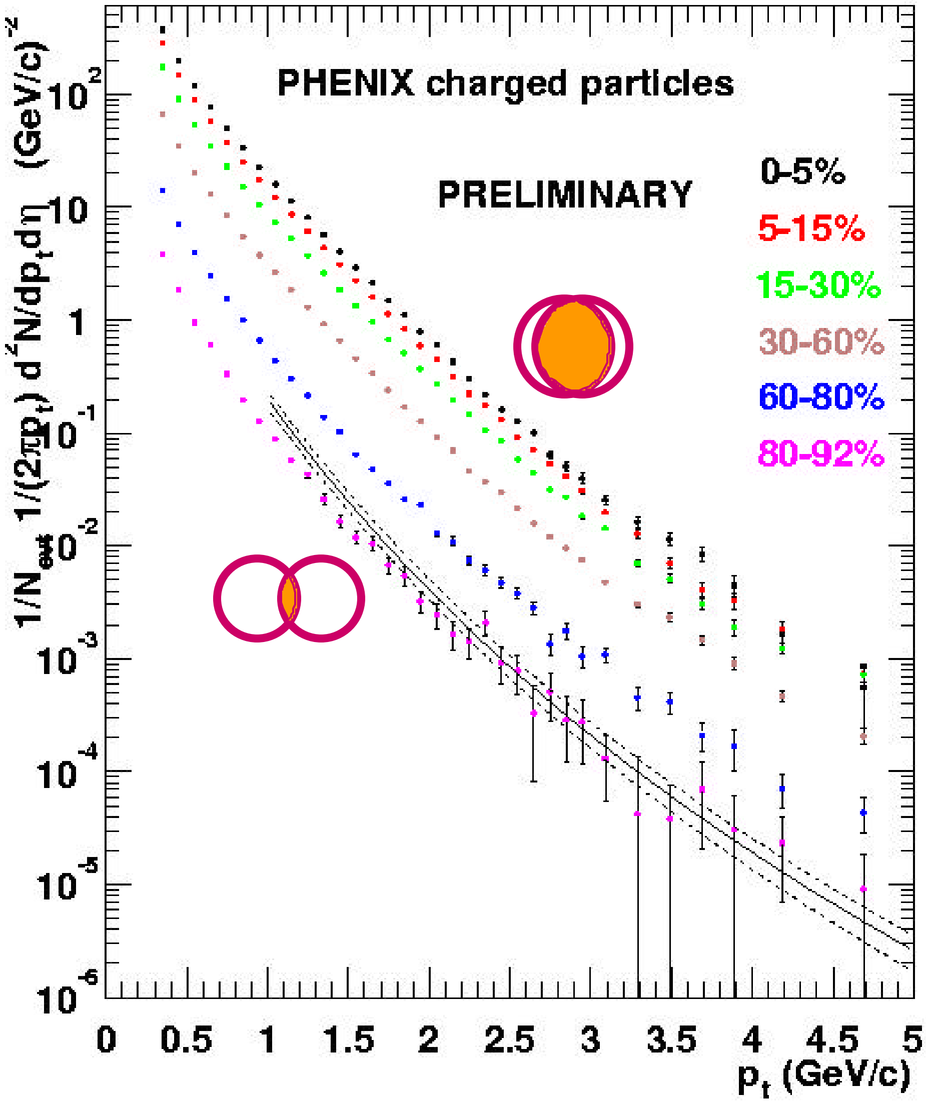
Tracks in DC from Central Au-Au collision

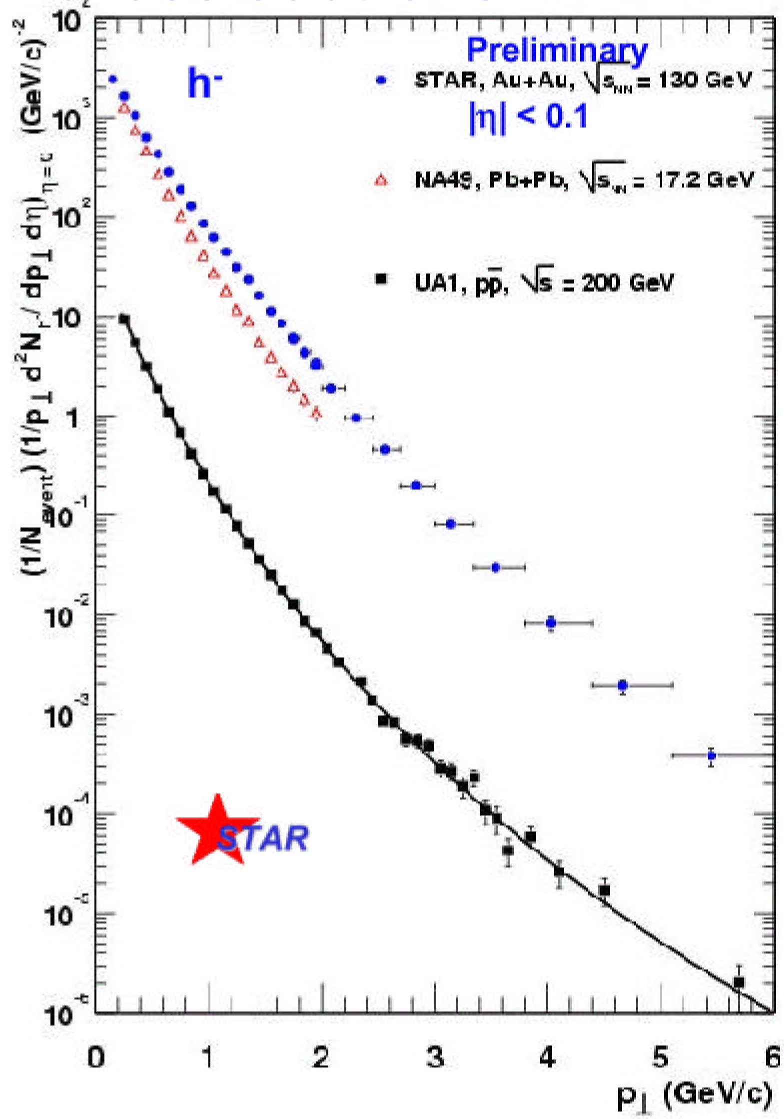


DC wires with kapton wire dividers

Rare processes at RHIC

Both PHENIX and STAR have measured charged particle spectra out to “small” cross sections

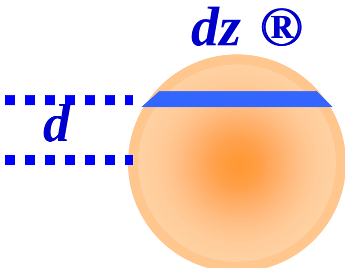




PHENIX

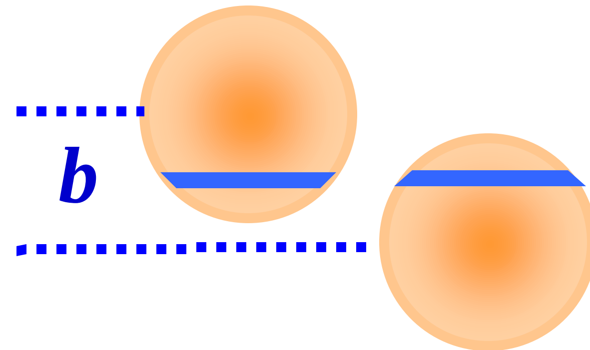
Expectations

- Particle production via *rare processes* should scale with N_{coll}, the number of underlying binary nucleon-nucleon collisions



$$T_A(d) = \int_0^\infty \rho(d,z)\,dz$$

Thickness Function



$$T_{AB}(b) = \int_0^\infty T_A\left(\vec{s} + \frac{\vec{b}}{2}\right) T_B\left(\vec{s} - \frac{\vec{b}}{2}\right) d\vec{s}$$

Overlap Function

If Nucleus "A" has A constituents and Nucleus "B" has B constituents which interact with cross section σ_{INT} the TOTAL cross section σ_{AB} is then

$$\sigma_{AB} = \int_0^\infty d^2b \left[1 - e^{-\sigma_{INT} T_{AB}(b)}\right]$$

$$\rightarrow \approx A \cdot B \times \sigma_{INT} \text{ for "small" } \sigma_{INT}$$

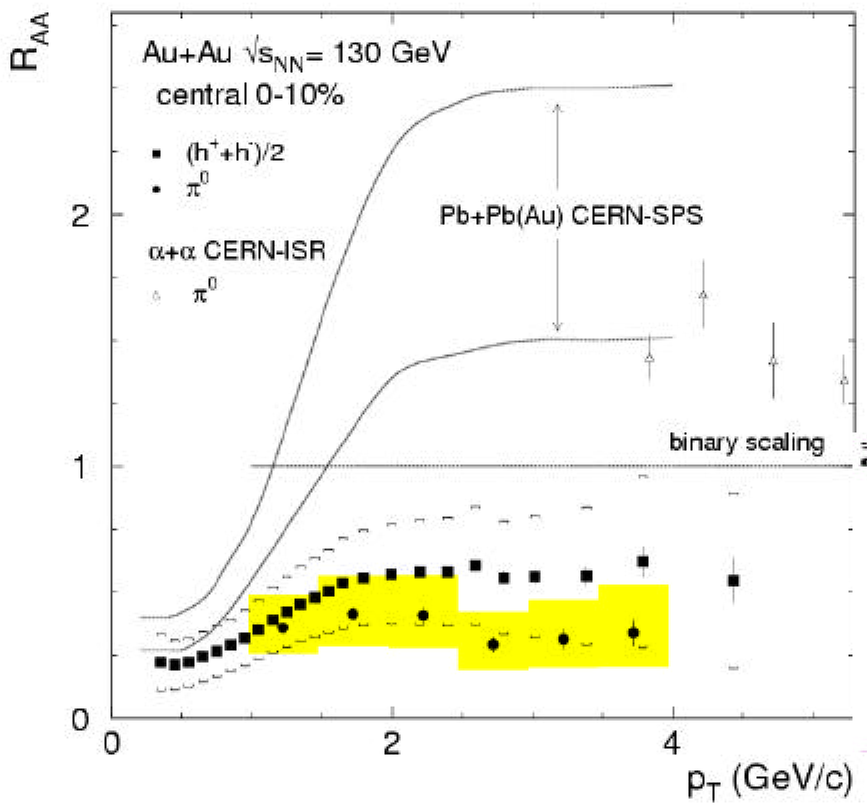
⇒ Assuming no "collective" effects

- Test this on production at high transverse momentum

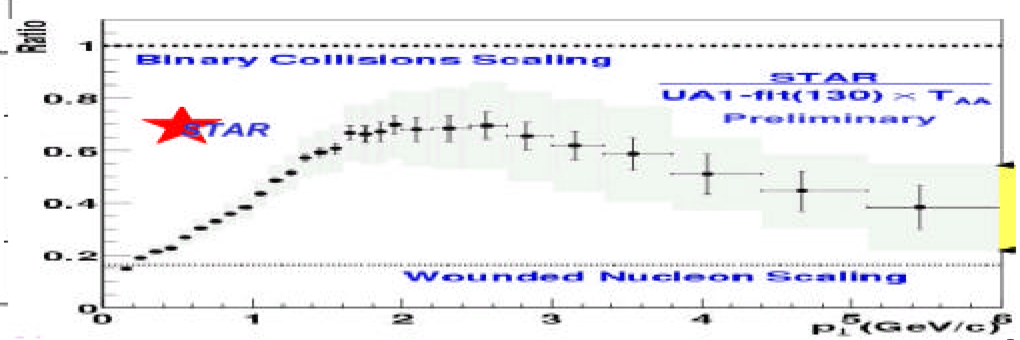
W.A. Zajc

A*B scaling at RHIC?

- **NO!**
- **Both STAR and PHENIX data see deficit of particles at high transverse momenta, *relative to expected A*B scaling:***



Deficit opposite sign of enhancements previously seen in nuclear collisions (Cronin effect)



W.A. Zajc

p^0 Reconstruction

- A good example of a "combinatoric" background
- Reconstruction is *not* done particle-by-particle
- Recall: p^0 ® gg and there are ~200 p^0 s per unit rapidity
  - So:

$p^0{}_1$ ® g_{1A} + g_{1B}
$p^0{}_2$ ® g_{2A} + g_{2B}
$p^0{}_3$ ® g_{3A} + g_{3B}

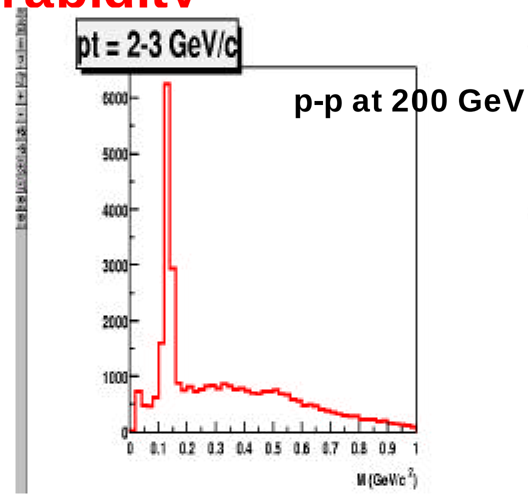
$p^0{}_N$ ® g_{NA} + g_{NB}

PHENIX

π^0 reconstruction

$p_T > 2$ GeV/c

Asymmetry < 0.8



  - Unfortunately, nature doesn't use subscripts on photons

➡ N correct combinations: (g_{1A} g_{1B}), (g_{2A} g_{2B}), … (g_{NA} g_{NB}),

➡ N(N-1)/2 – N *incorrect* combinations (g_{1A} g_{2A}), (g_{1A} g_{2B}), …

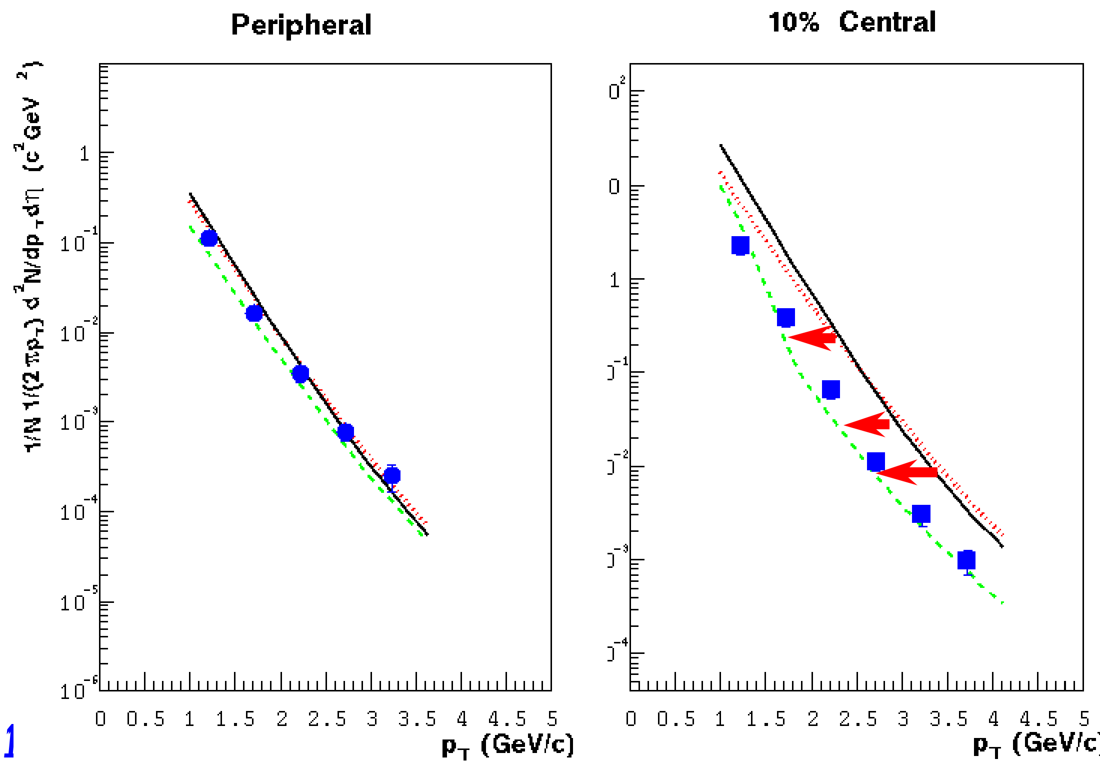
✖ Incorrect combinations ~ N^2 (!)

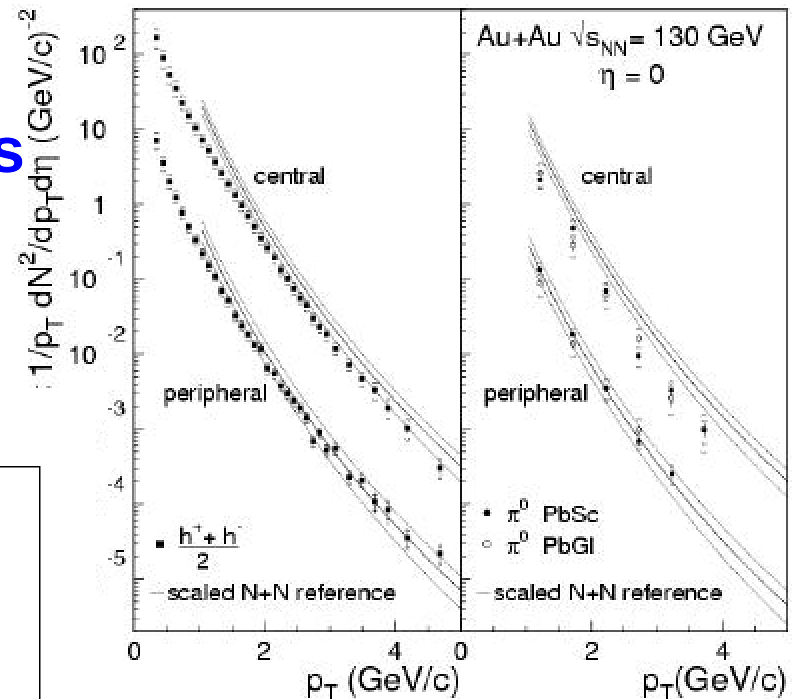
✔ Solution: Restrict N by p_T cuts
use high granularity, high resolution detector

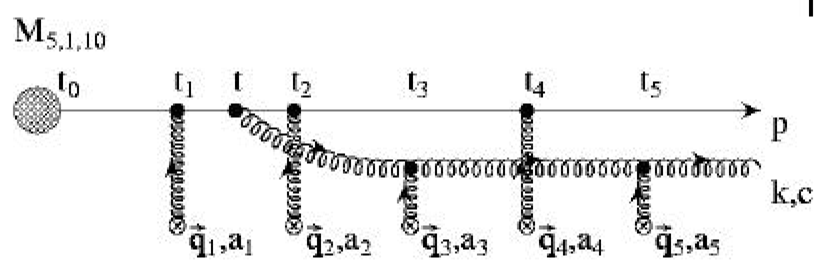
Additional Evidence

- PHENIX sees a *larger* effect in the p^0 spectrum:

- Consistent with crude estimates of additional energy loss in a *deconfined medium*



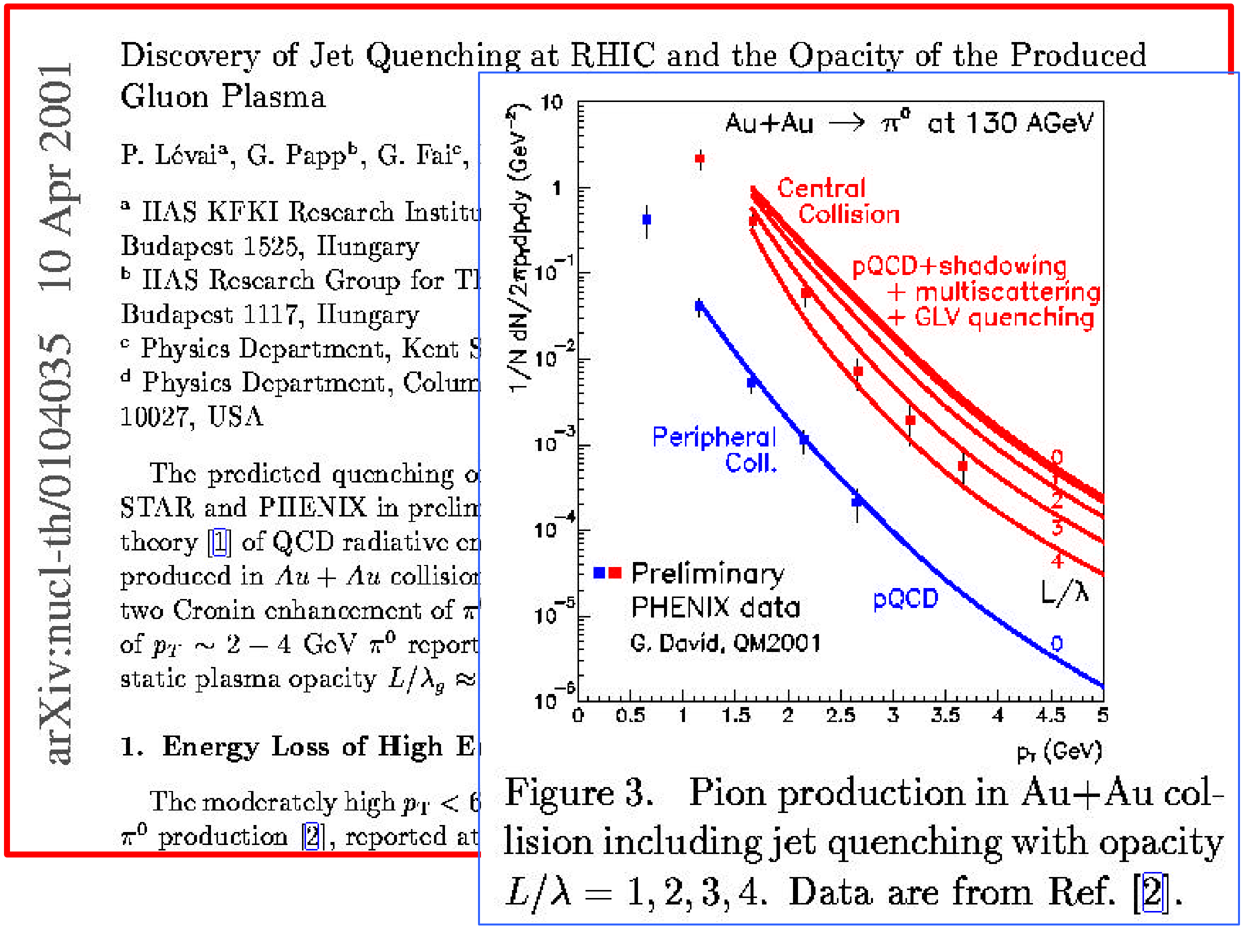




W.A. Zajc

Discovery of “Jet Quenching”?

- **Some would (have) claimed just that**
- **To be done before this can be experimentally established:**
  - ❐ **Improve p_T range (Run-2)**
  - ❐ **Measure p-p spectrum (Run-2)**


arXiv:nucl-th/0104035 10 Apr 2001

Discovery of Jet Quenching at RHIC and the Opacity of the Produced Gluon Plasma

P. Lévai[a], G. Papp[b], G. Fai[c], ...

[a] IIAS KFKI Research Institu... Budapest 1525, Hungary
[b] IIAS Research Group for T... Budapest 1117, Hungary
[c] Physics Department, Kent S...
[d] Physics Department, Colum... 10027, USA

The predicted quenching o... STAR and PHENIX in prelim... theory [1] of QCD radiative en... produced in $Au + Au$ collision... two Cronin enhancement of π... of $p_T \sim 2 - 4$ GeV π^0 report... static plasma opacity $L/\lambda_g \approx$ ...

1. Energy Loss of High E...

The moderately high $p_T <$ 6... π^0 production [2], reported at...

Figure 3. Pion production in Au+Au collision including jet quenching with opacity $L/\lambda = 1, 2, 3, 4$. Data are from Ref. [2].

☛ ***Study in “cold nuclear matter” with p-A collisions ~~(Run-2?)~~***

❐ **Vary system size ~~(Run-2??)~~**

Topic 4

- **Particle Composition**
  - **What are the relative yields of pions, kaons and protons?**
  - **How do their yields depend on transverse momentum?**
  - **How do their yields depend on centrality?**

- **Answered in**

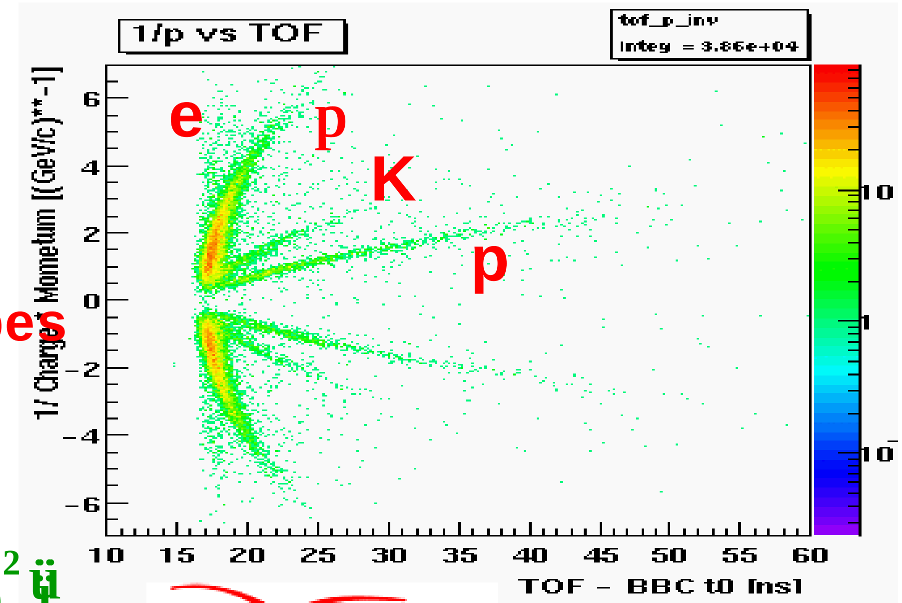
  ***"Centrality dependence of pi+-, K+-, p and pbar production from sqrt(s)=130 GeV Au + Au collisions at RHIC"*,**
  K. Adcox et al., Submitted to PRL,
  preprint nucl-ex/0112006,

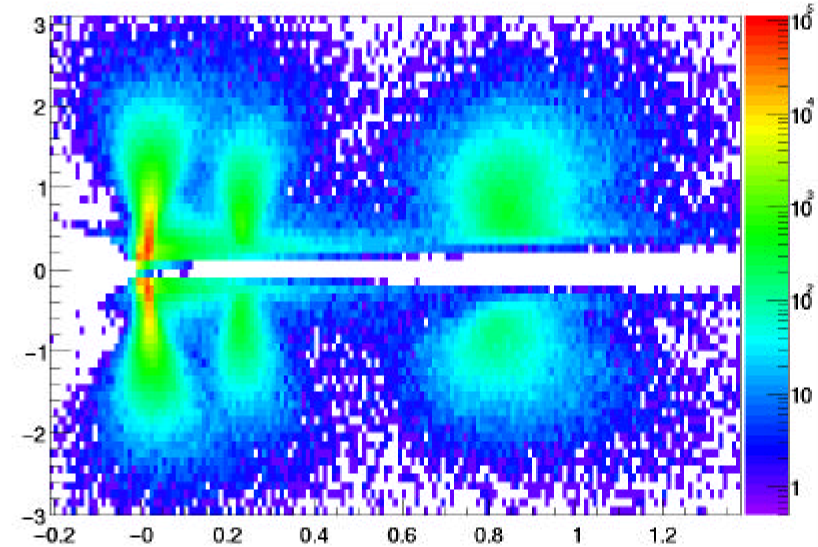
Particle Identification by TOF

- **The most direct way**
  - Measure β by distance/time
  - Typically done via scintillators read-out with photomultiplier tubes
  - Time resolutions ~ 100 ps
  - Exercise: Show

$$\left(\frac{dm}{m}\right)^2 = \left(\frac{dp}{p}\right)^2 + \gamma^4\left\{\left(\frac{dt}{t}\right)^2 + \left(\frac{ds}{s}\right)^2\right\}$$

- **Performance:**
  - dt ~ 100 ps on 5 m flight path
  - ➡ P/K separation to ~ 2 GeV/c
  - ➡ K/p separation to at least 4 GeV/c

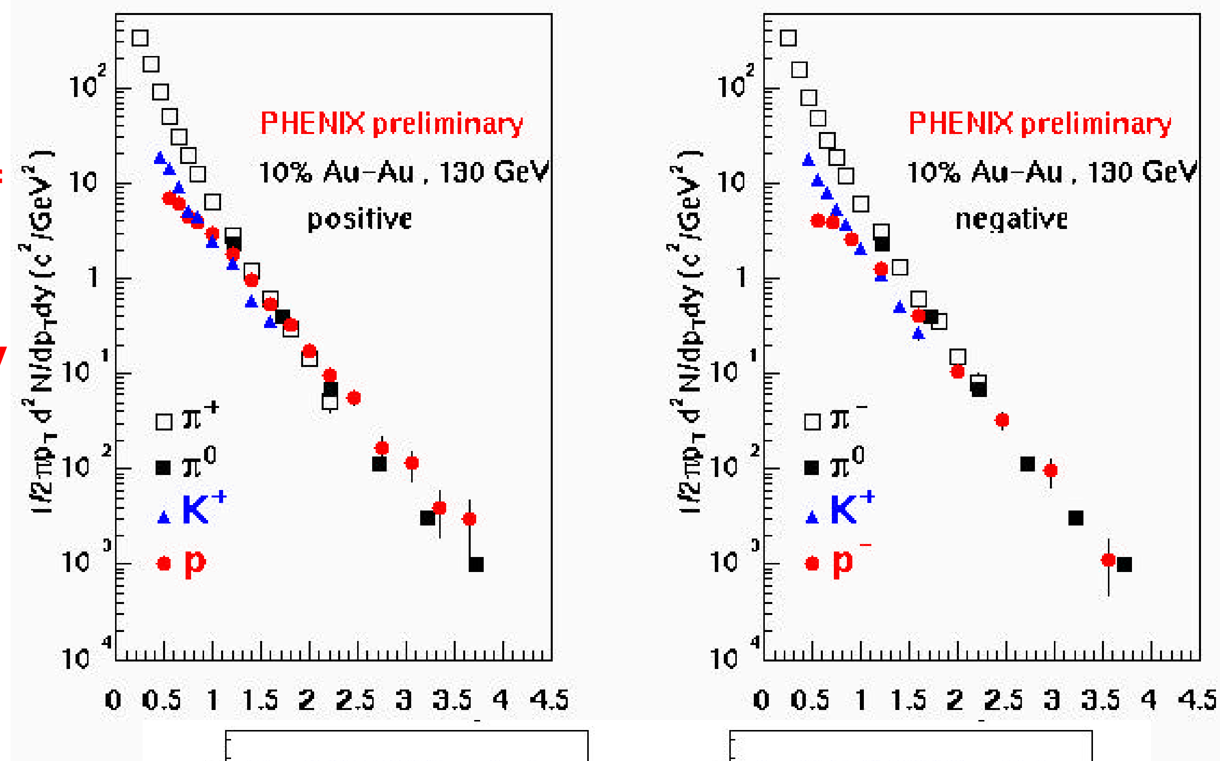


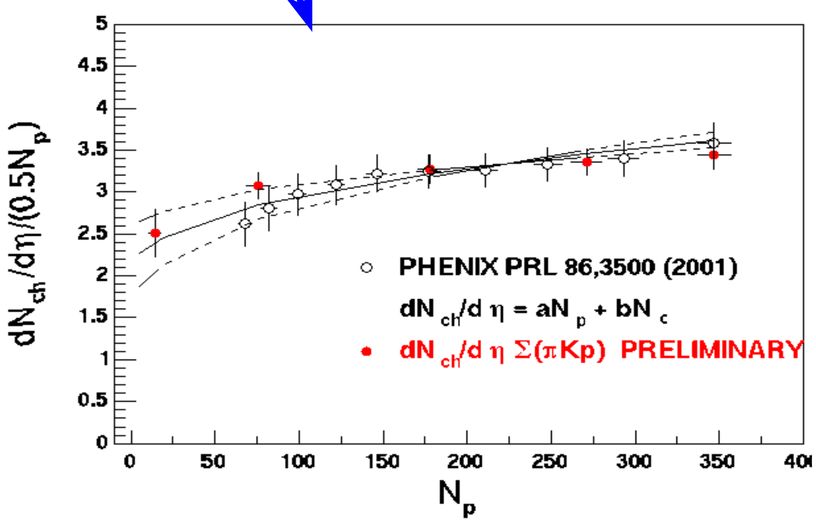


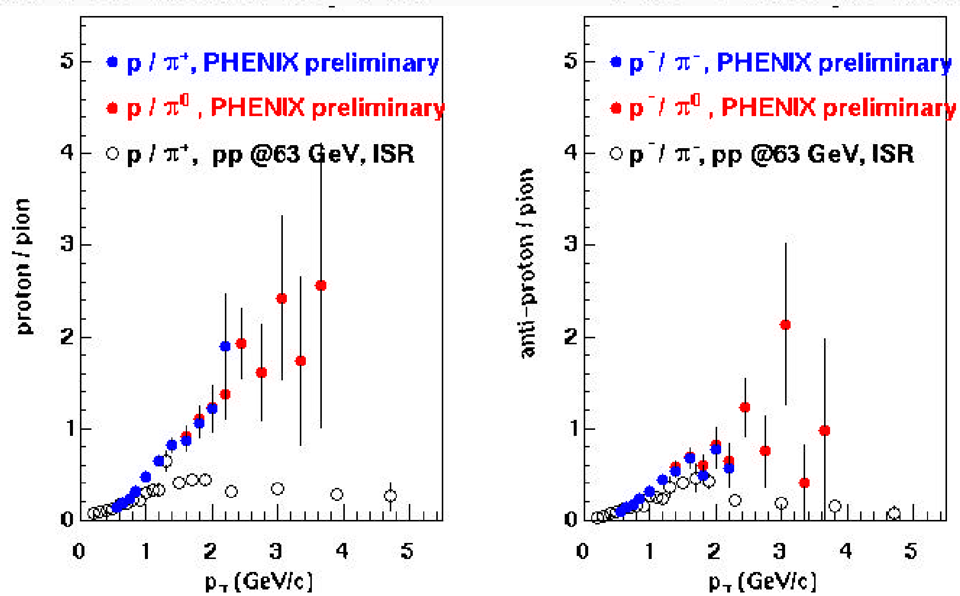
Putting it all together

- **Charged pions match nicely with p^0's**
  - Supports conclusion of preferential suppression of pions
  - "High" p_T dominated by protons and kaons??

- **Summed hadrons consistent with our first result on multiplicity**



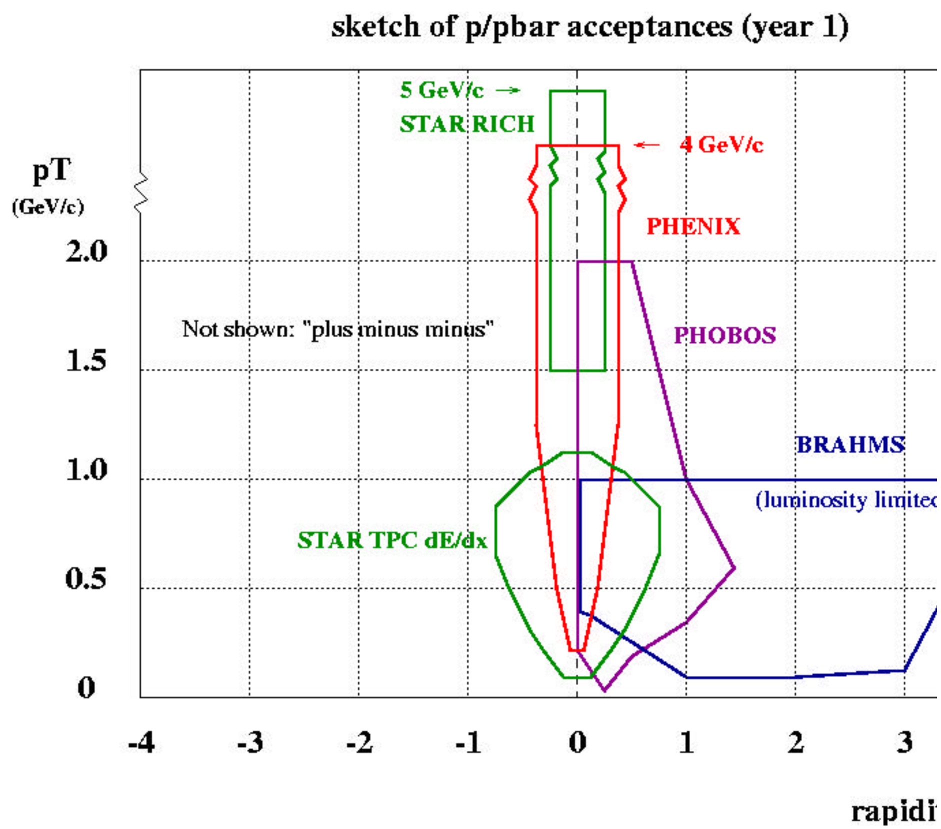


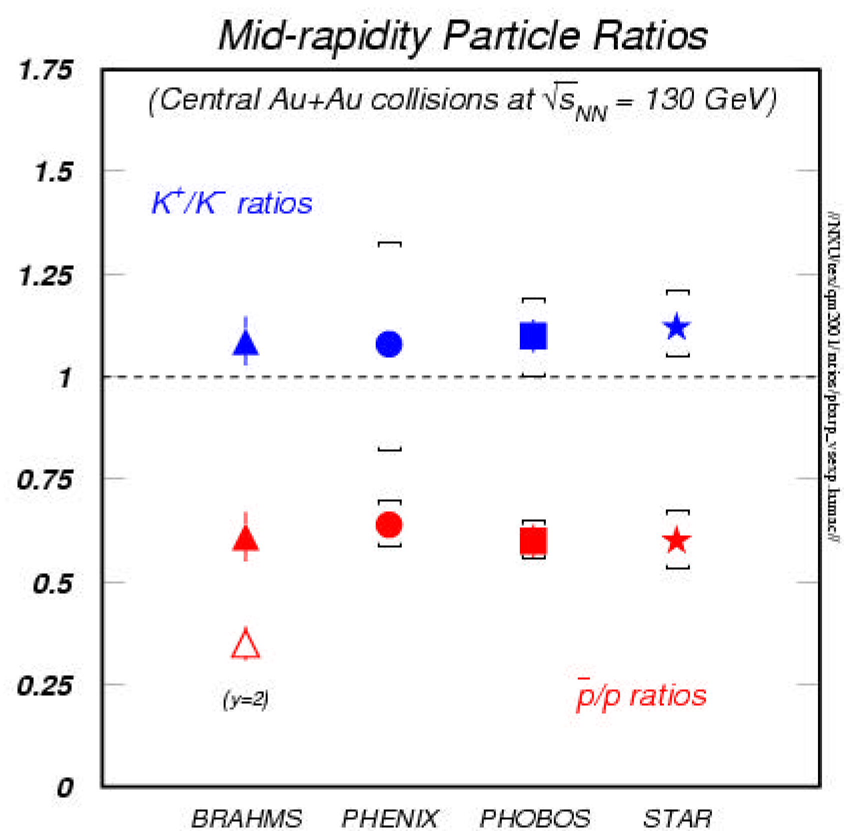


jc

Agreement between Experiments

- Overlaps in detector capabilities a feature of RHIC program
- Excellent agreement in common observables provides confidence

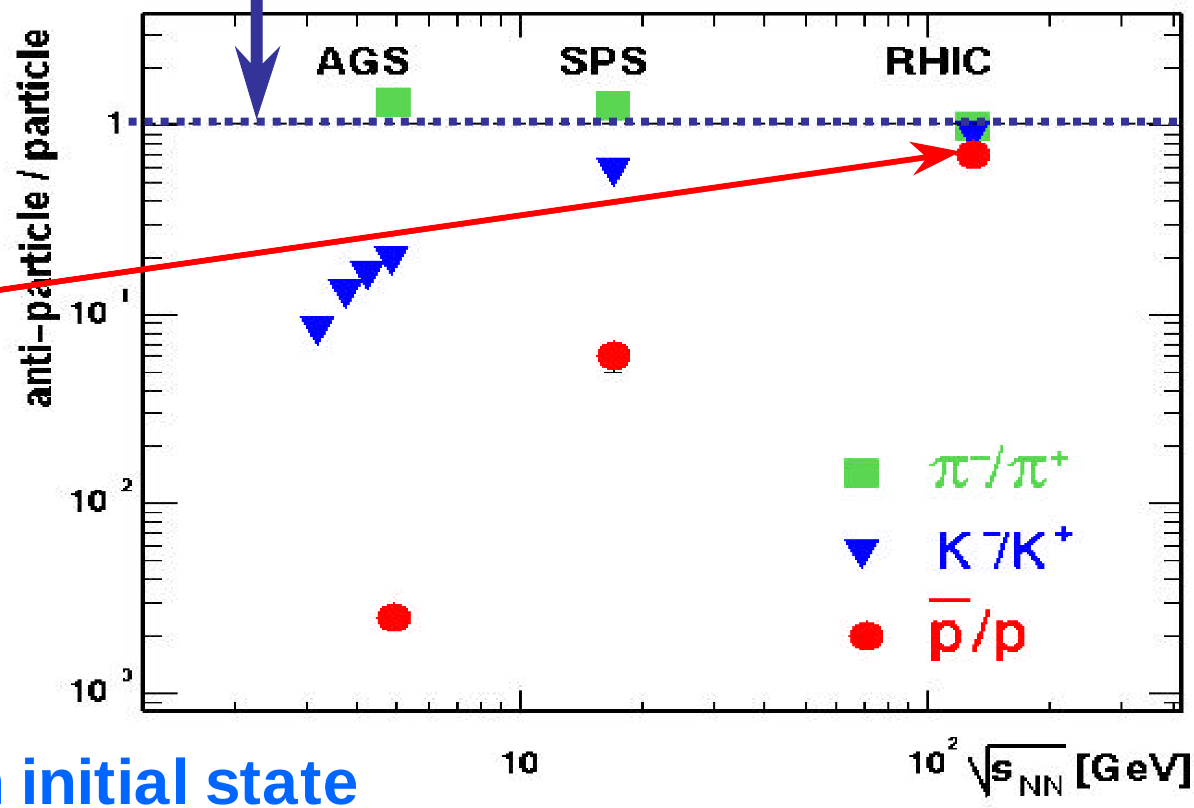




PHENIX Approaching the Early Universe

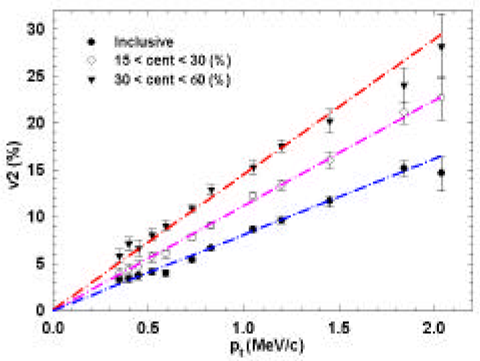
- **Early Universe:**
  - **Anti-proton/proton = 0.999999999**

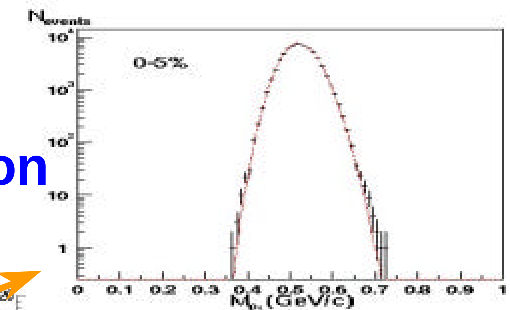
- **We've created "pure" matter approaching this value**
- **For the first time in heavy ion collisions, more baryons are pair-produced than brought in from initial state**

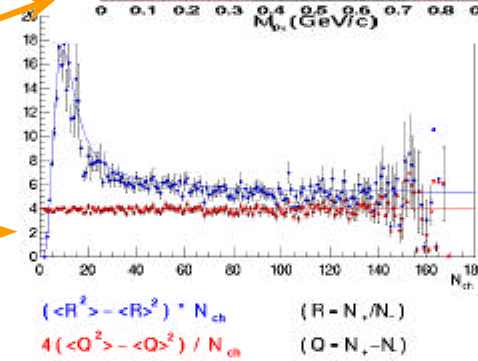


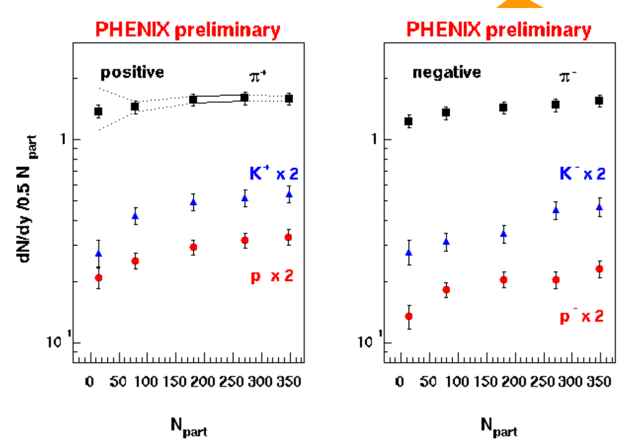
Topics not covered

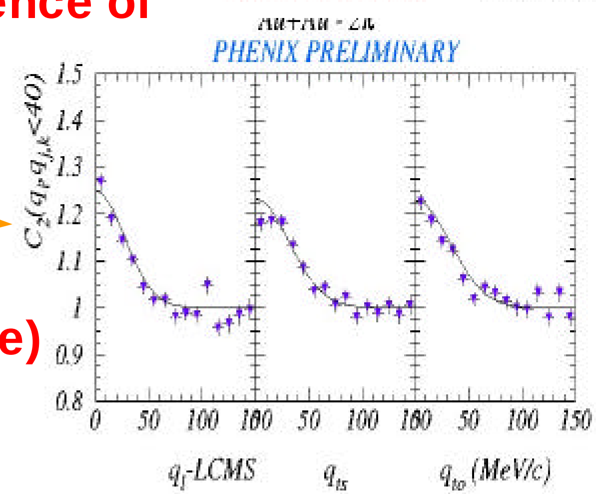
- This is a *sample* of the many physics topics addressed by PHENIX in Run-1.
- Additional results available on
  - Flow
  - Fluctuations in
    - <pT>
    - Charge
  - Centrality dependence of particle yields
  - HBT
  - Charm (next lecture)











PHENIX

Summary of Results

- ✓✓✓✓ **How many particles are produced?**
  - **More than ever produced previously**
- ✓✓✓✓ **Have we made contact with the early universe?**
  - **Closer than all previous heavy ion experiments**
- ✓✓✓ **Have we made sufficiently high energy densities for the phase transition?**
  - **Yes**
- ✓✓✓ **Is there evidence that the dense matter behaves collectively?**
  - **Yes**
- ✓✓ **Are there results consistent with the formation of a new state of matter?**
  - **Perhaps ??????!?**

(1 ✓ = 1 experiment)