Beam Energy Scan @ RHIC/STAR

George S.F. Stephans

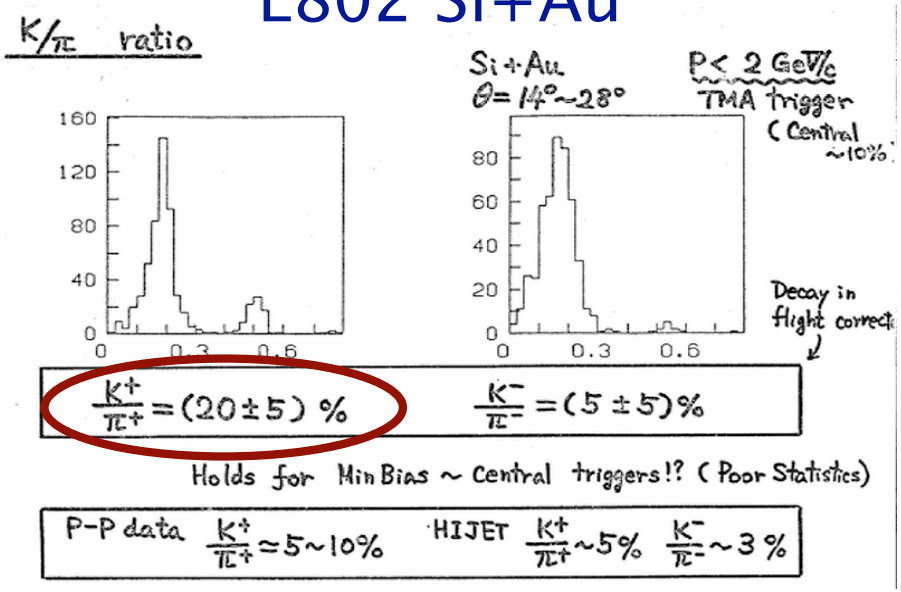
Massachusetts Institute of Technology

For the STAR collaboration

Many discoveries in relativistic HI physics @ BNL

The first one: strangeness enhancement in HI collisions

E802 Si+Au



Yasuo Miake QM87
Nordkirchen Germany

Almost 21 years ago!

Idea to run lower energy at RHIC is newer

~~Fixed Target~~ @ RHIC

Lower Energies

- Using ~~internal targets~~, a whole new energy regime is opened up. Enormous potential exists to expand RHIC's coverage of strongly- interacting matter under extreme conditions.
- Good reason to believe the QCD phase diagram has interesting features in this region
- Good reason to think that high(est??) baryon densities are created around these energies

G.S.F.Stephans BNL Nuclear Physics Town Meeting 14-Oct-2003

14-Oct-2003

Low Energy Collider Mode??

- In principle, RHIC can circulate and collide beams at energies below injection
  - Would use existing experiments most efficiently

Note that I was skeptical … but I was wrong!

Why a beam energy scan is possible

- Accelerator physicists who view “machine development” as an exciting challenge, not as an expletive.
  - Also, an extensive record of accomplishment at successfully achieving new running conditions.
- Lab and facility management eager to push the limits of the physics capabilities of RHIC into the future.

Motivation - I

- RHIC has made major discoveries in our understanding of QCD matter under extreme conditions.
  - Results are well covered by the talks at this meeting.
- But… More detailed understanding and further major discovery potential remains both at high and low energy.
- I will focus on the beam energy scan whose goal is to explore a broad region of the QCD phase diagram.
  - Evolution with beam energy of the unusual medium properties found at RHIC is not known in detail.
  - New surprises may await in the unexplored region.

Motivation - II

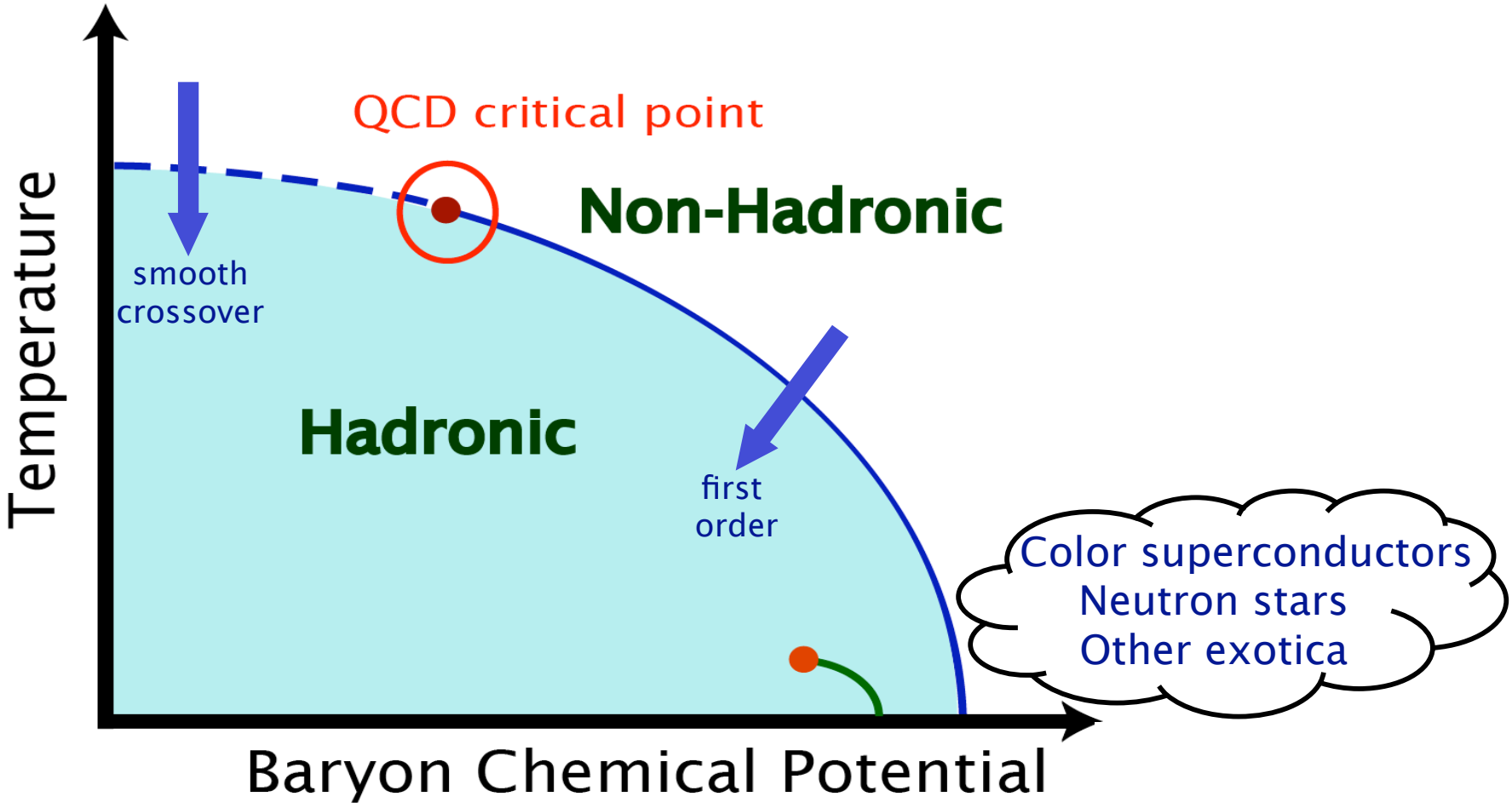
- Colliding heavy ions at energies below the full RHIC value will produce systems with slightly lower freezeout temperatures and significantly higher baryon densities.
- This study will address two fundamental questions:
  - How do the unusual medium properties found at the highest RHIC energies evolve as the energy is lowered.
    - In what way do the partonic properties change or "turn off"?
  - Does the character of the phase transition change?
    - The discovery of a 1st degree transition and/or its associated critical point is the most exciting possibility.
    - However, we have been surprised before by relativistic heavy ion collision data. Perhaps something entirely unexpected will appear.

Critical Point & 1st Order Transition

- Theory at the "edges" is believed to be well understood:
  - Lattice QCD finds a rapid, but smooth, crossover at large T and $\mu_B \approx 0$.
  - Various models find a strong 1st order transition at $T \approx 0$ and large μ_B.
    - Recent suggestion of another critical point at $T \rightarrow 0$ and very large μ_B.
- Either the theory is badly broken or there must be a critical point.
- Theory problem: Including $\mu_B > 0$ "breaks" existing numerical techniques at a very basic level (the notorious "sign problem")
  - Quantitative predictions of the critical point location require new approaches, not just extensions of existing calculations.

Given the very significant theoretical difficulties, using data first to constrain the phase transition may be the quickest way to establish the broader characteristics of the QCD phase diagram.

My Cartoon of the Phase Diagram



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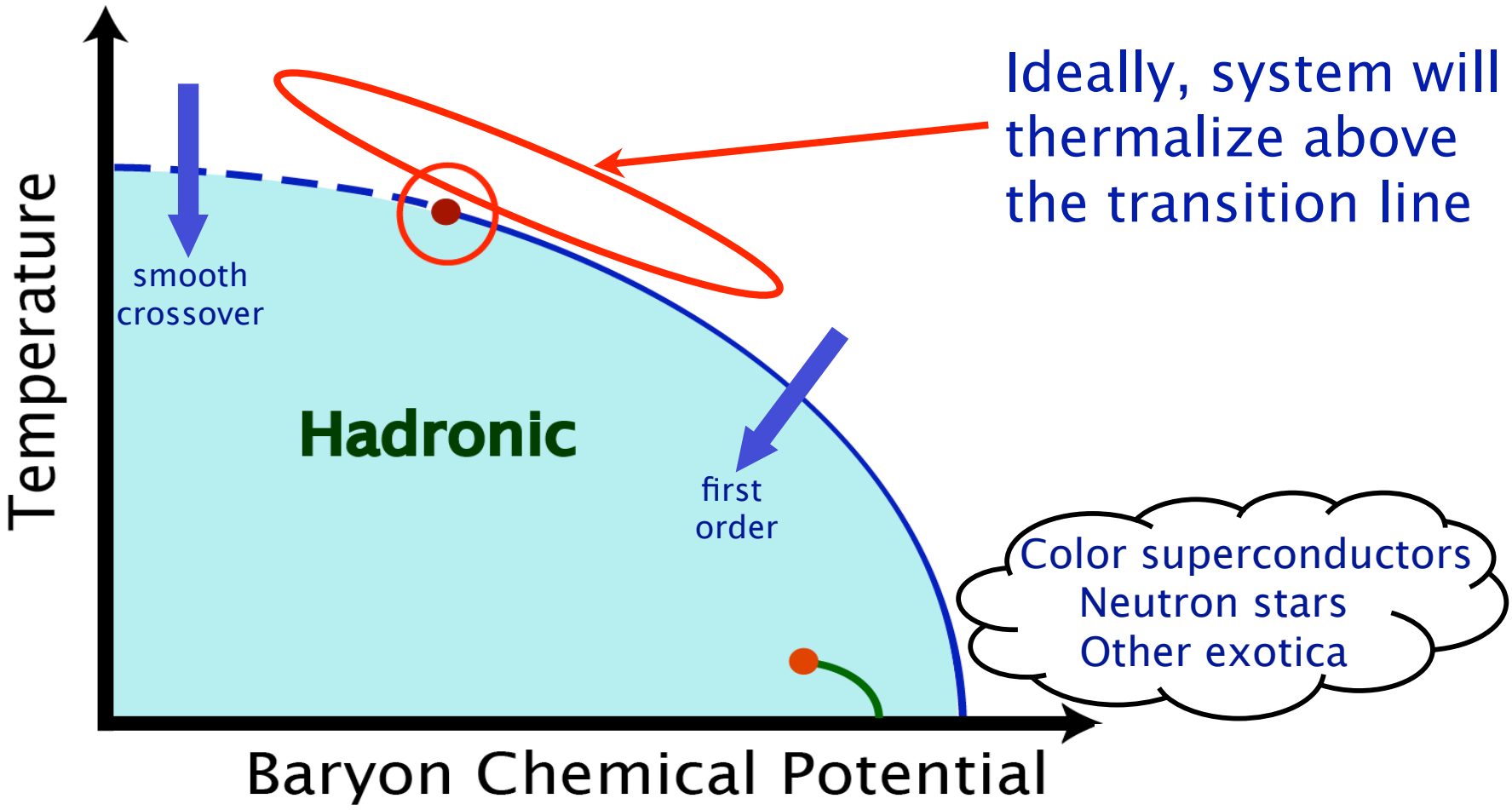


If there, a critical point doesn't hide…

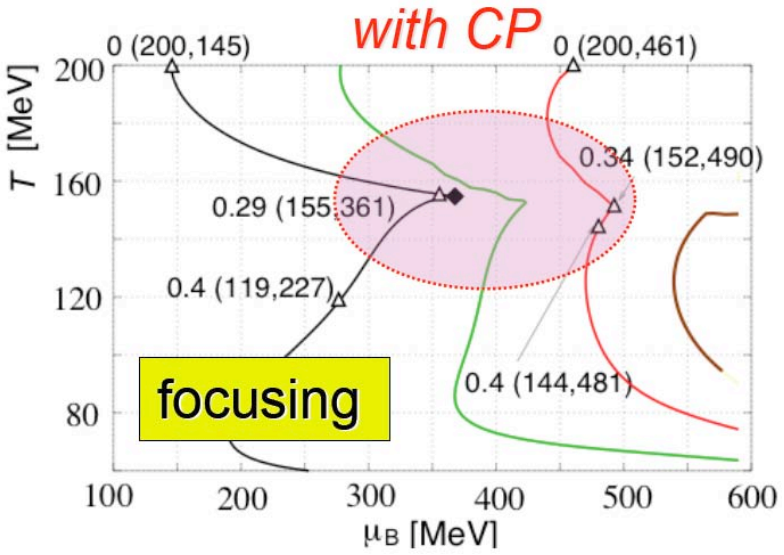


Image courtesy of C.Nonaka

Hydro predicts that the evolution of the system is attracted to the critical point (an effect observed already for liquid-gas nuclear transition)

Also, finding evidence for a 1st order phase transition at any energy would immediately narrow the location of the critical point.

Ongoing Theoretical Work - I

This question is getting a lot of attention

Ongoing Theoretical Work - II

And will continue to be further refined…

INSTITUTE FOR NUCLEAR THEORY

UNIVERSITY OF WASHINGTON

The QCD Critical Point (INT-08-2b)

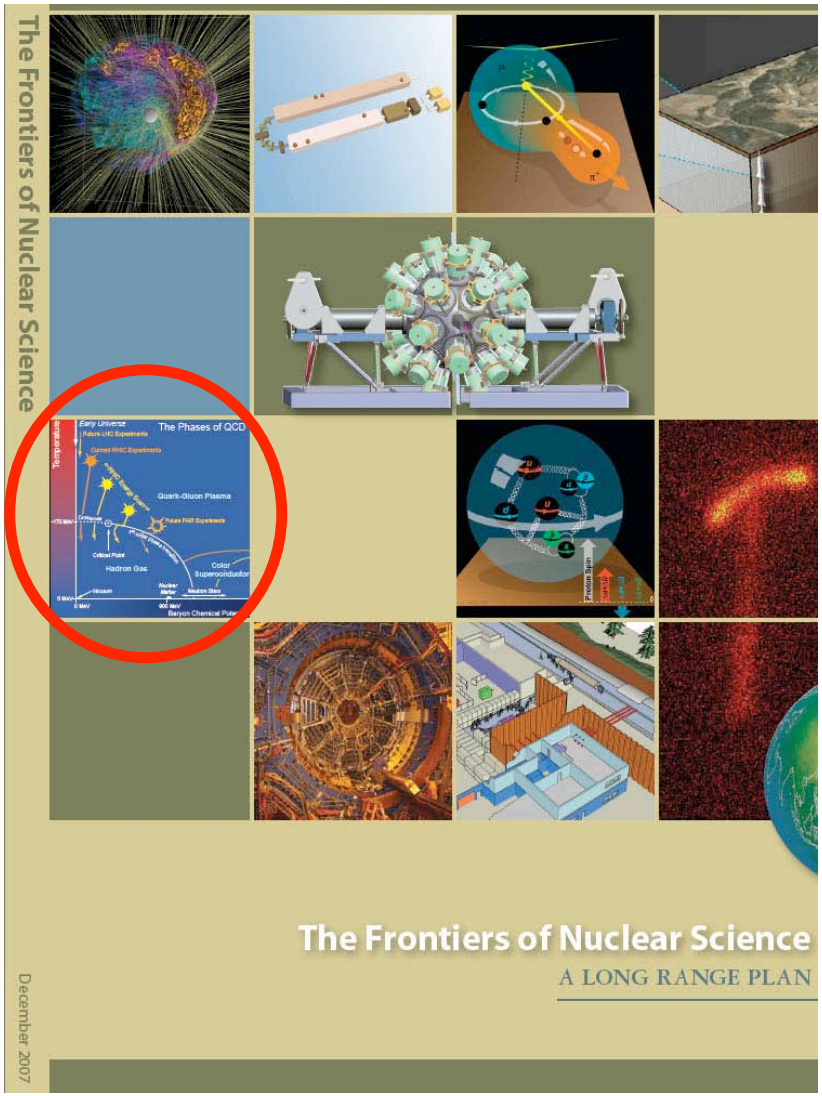
July 28 - August 22, 2008

The phase diagram of QCD is a subject of active theoretical and experimental research. The focus of this program is on properties of the phase diagram which can be studied by the upcoming heavy-ion collision experiments at RHIC/BNL…

Ongoing Theoretical Work - II

And will continue to be further refined…

Guidance from the NSAC Long Range Plan

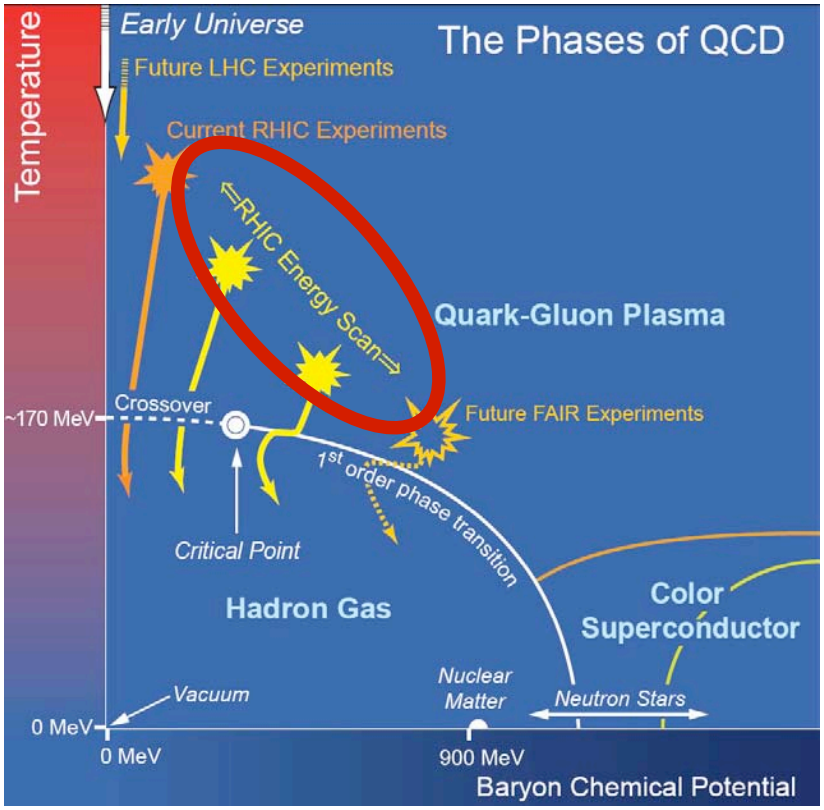


Search for the Critical Point:
"A Landmark Study"

The large range of temperatures and chemical potentials … along with … advantages provided by a collider coupled with advanced detectors, give RHIC scientists an excellent opportunity for discovery of the critical point and the associated phase boundaries.

Guidance from the NSAC Long Range Plan

Figure from cover and concluding quote from pg. 46



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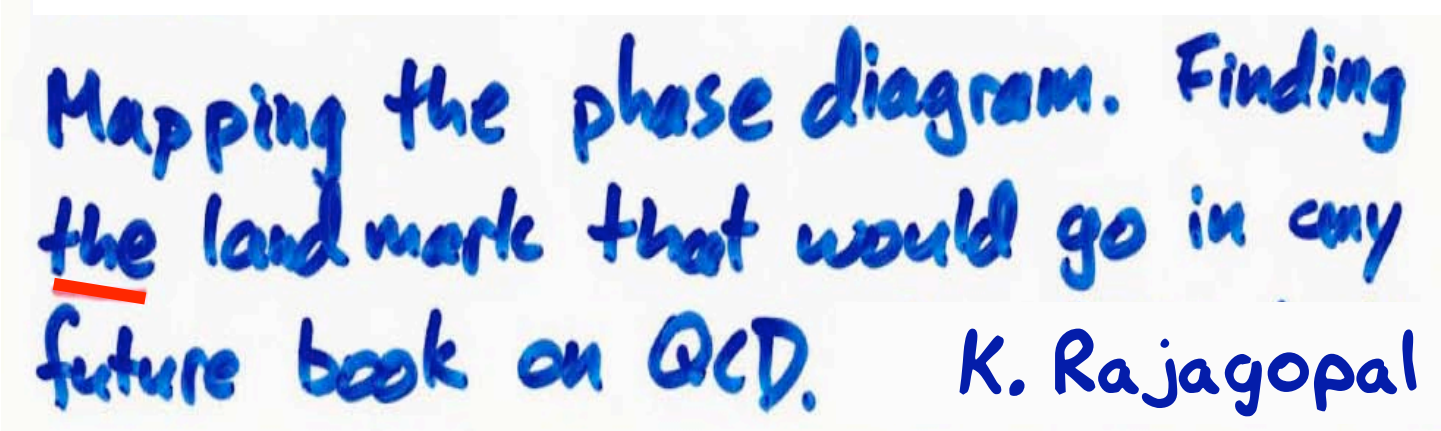
Motivation: Concluding Thoughts



My favorite quote from a theorist

In order to explore this exciting physics, STAR & RHIC represents the best option, beyond a shadow of a doubt, of all the existing or planned experimental programs.

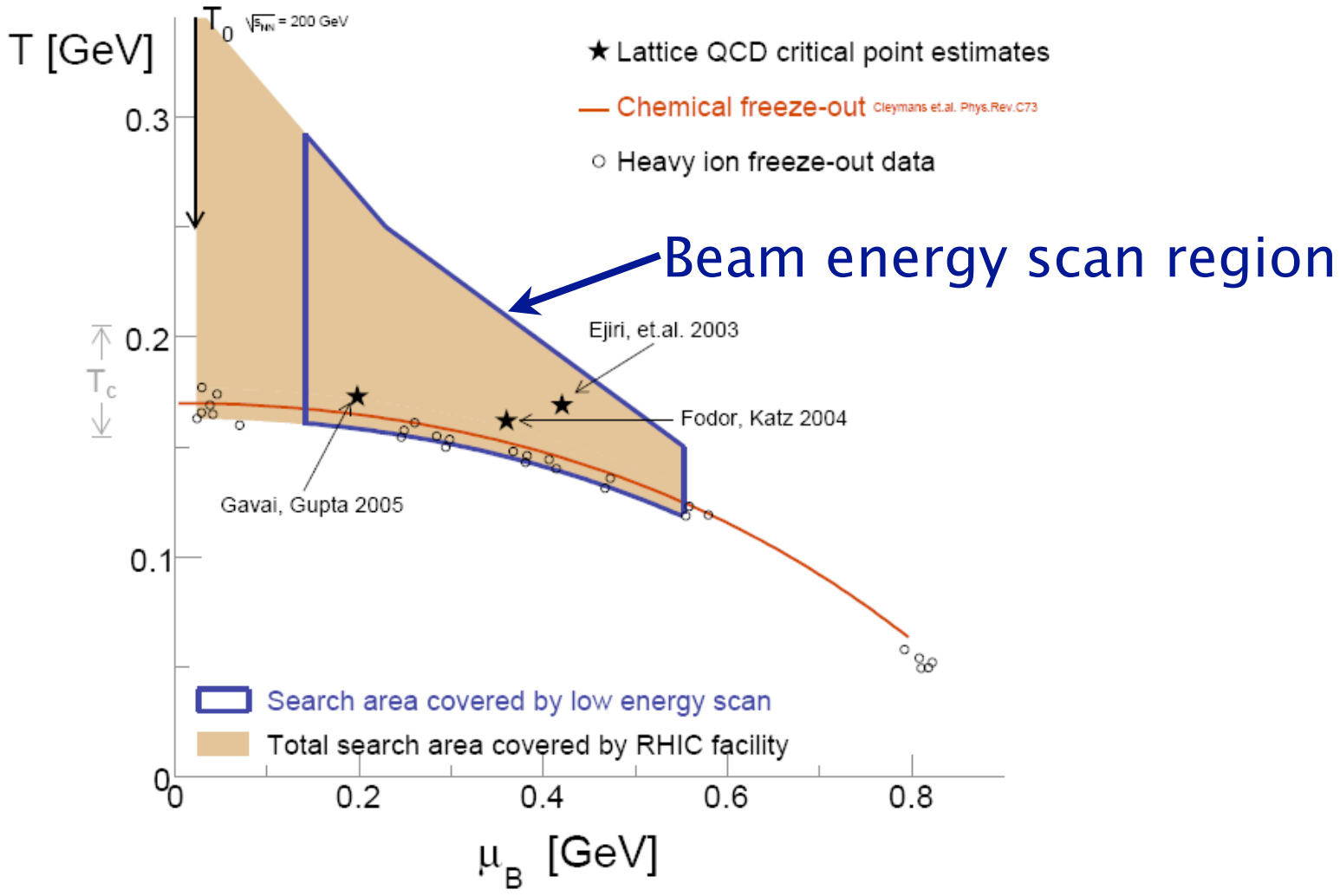
What should be measured?

- Lots of ideas, mostly qualitative or semi-quantitative
  - Largely related to bulk properties so very large data samples are not critical to the program
  - Fluctuations & correlations of many varieties
  - Energy dependence of flow characteristics, both v_1 and v_2, and especially pions compared to protons
  - "Lumpy" ("clumpy"?) final states
- Imminent data will "encourage" theorists to be more specific.
- Excellent overlap with STAR detector capabilities and existing, well understood, STAR analysis techniques.

Going out on a limb (personal opinion) …

- STAR & RHIC excel at the currently proposed signals.
- STAR & RHIC will excel at future proposed signals.
- RHIC lower energy data will help guide our interpretation and understanding to the same extent as RHIC higher energy data have done.

Potential RHIC Phase Space Coverage



Luminosity is the key issue

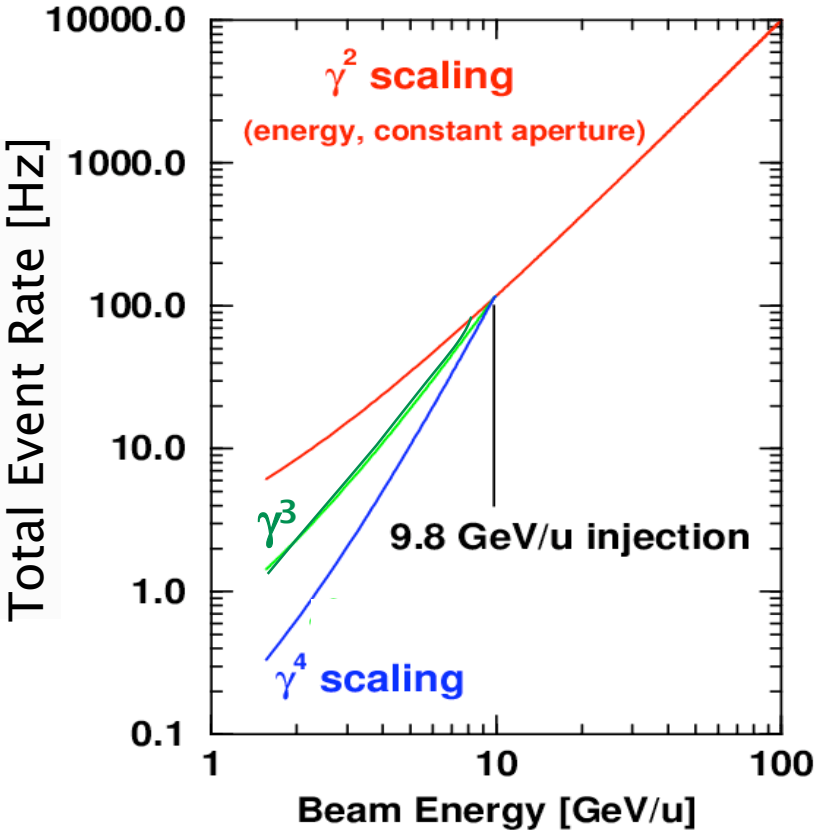


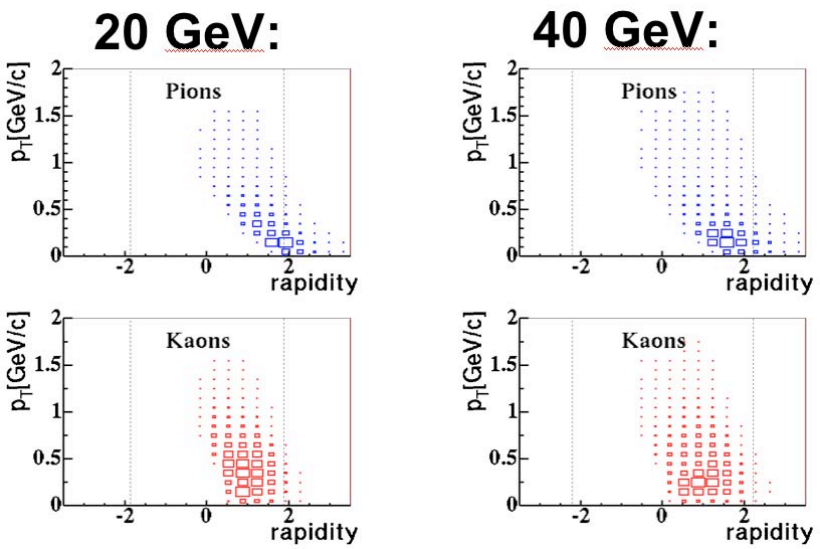
Image courtesy of T.Satogata

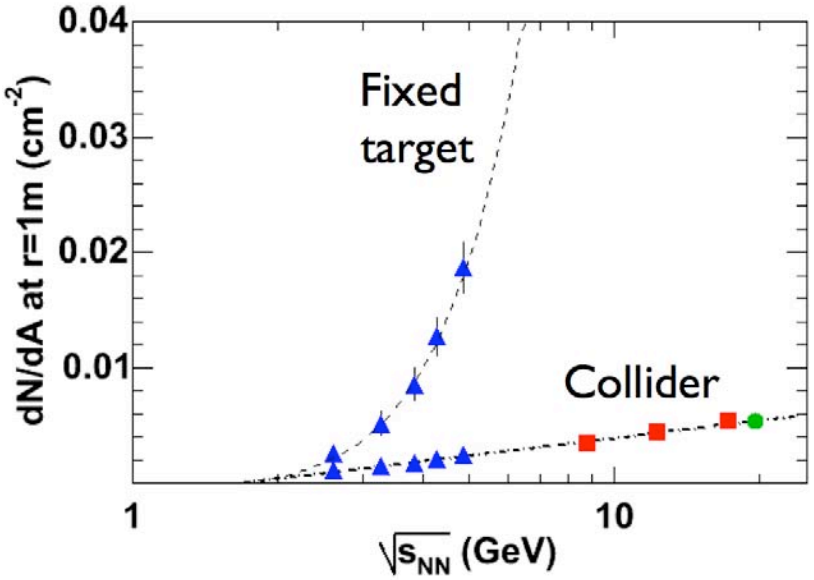
No apparent show-stoppers down to the lowest energies

Electron cooling in RHIC could improve luminosity substantially

Why is a collider the best choice?

NA49 acceptance





Big advantage that acceptance for collider detectors is totally independent of beam energy

Big advantage that occupancy for collider detectors is much less dependent on beam energy

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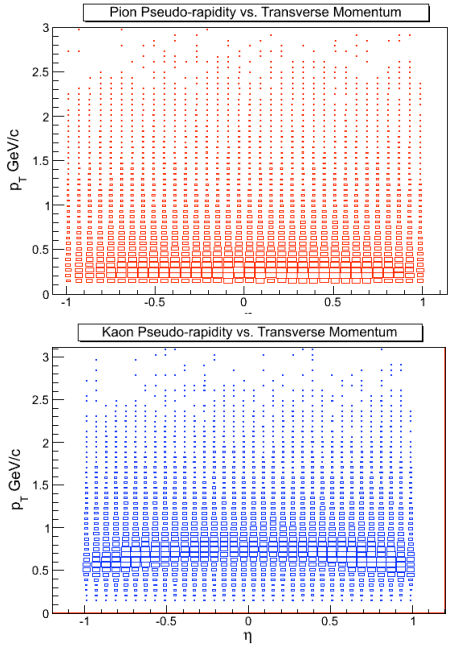
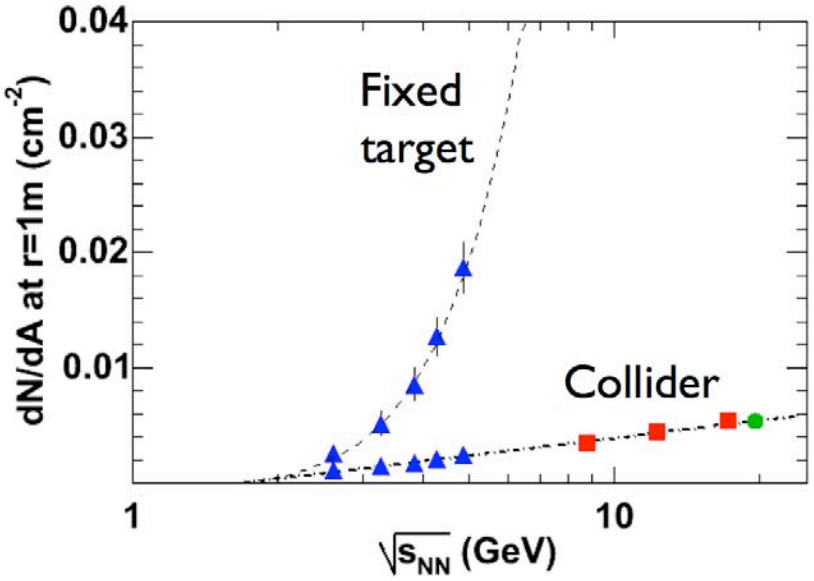
STAR acceptance



Pion

Kaon



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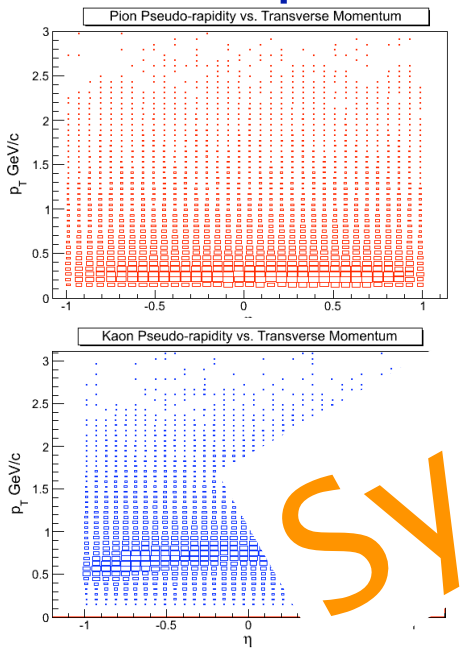
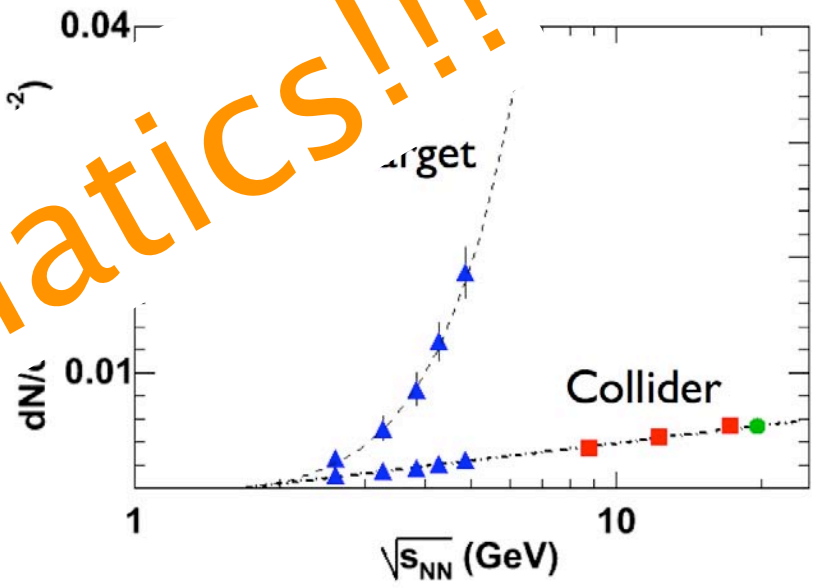


Pion

Systematics!!!



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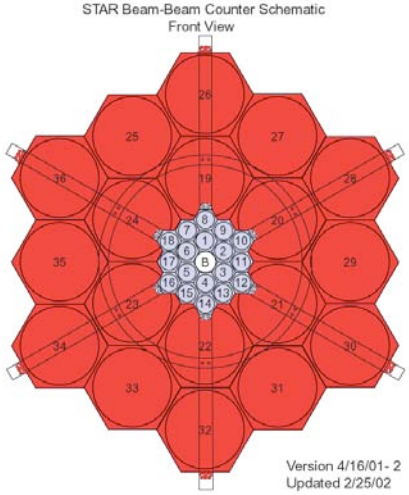
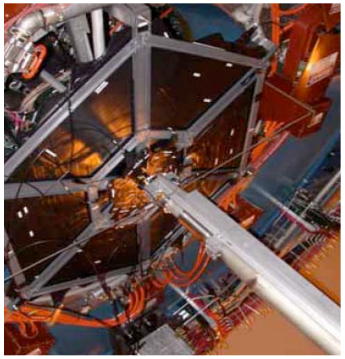
Triggering is not a problem

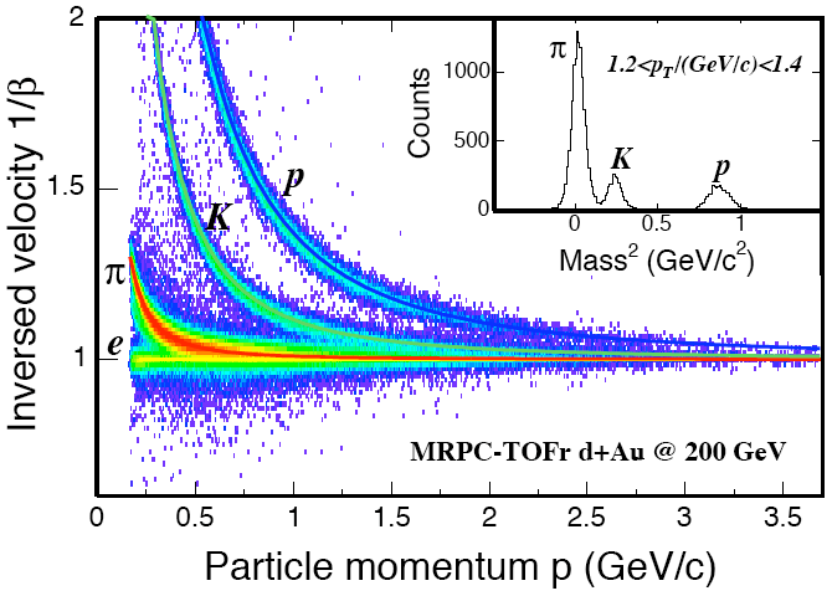




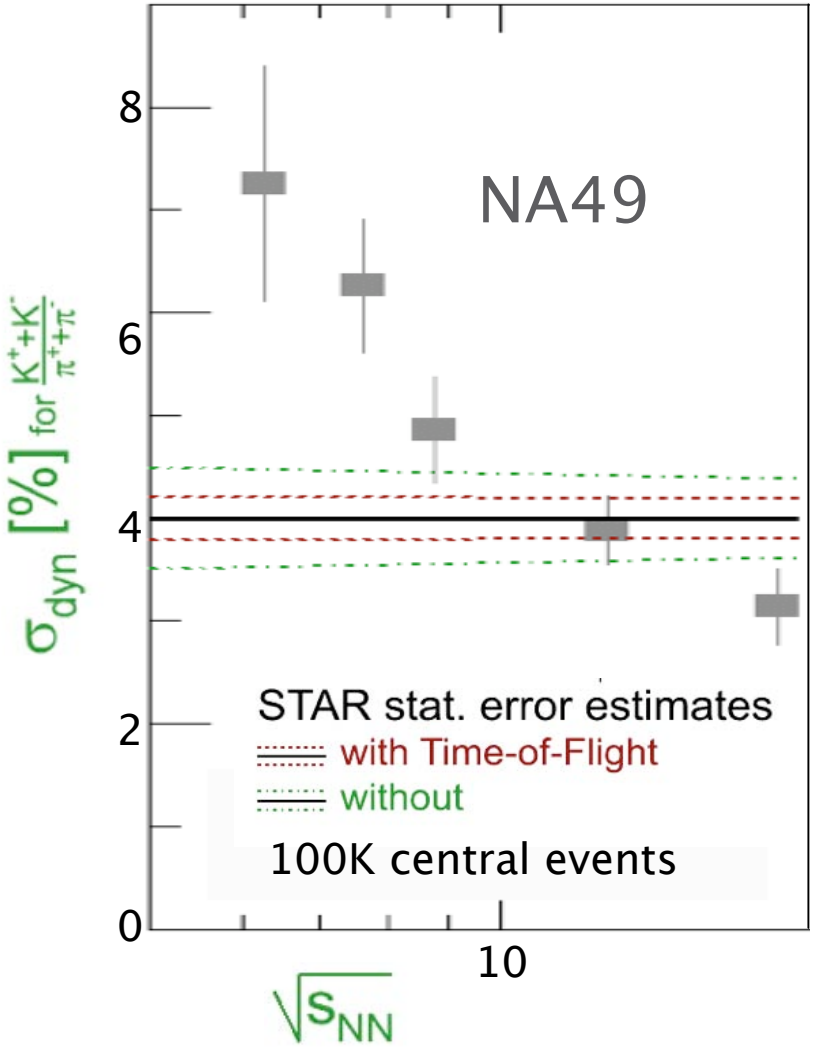
Number of particles within BBC coverage

Centrality (b in *fm*)	AuAu $E_{c.m.}$= 5 GeV		AuAu $E_{c.m.}$= 8.75 GeV	
	BBC Inner 3.3<η<5.0	BBC Outer 2.1<η<3.3	BBC Inner 3.3<η<5.0	BBC Outer 2.1<η<3.3
b<3	5	27	12	54
3<b<6	11	30	21	57
6<b<9	22	35	39	40
b>9	44	30	66	8

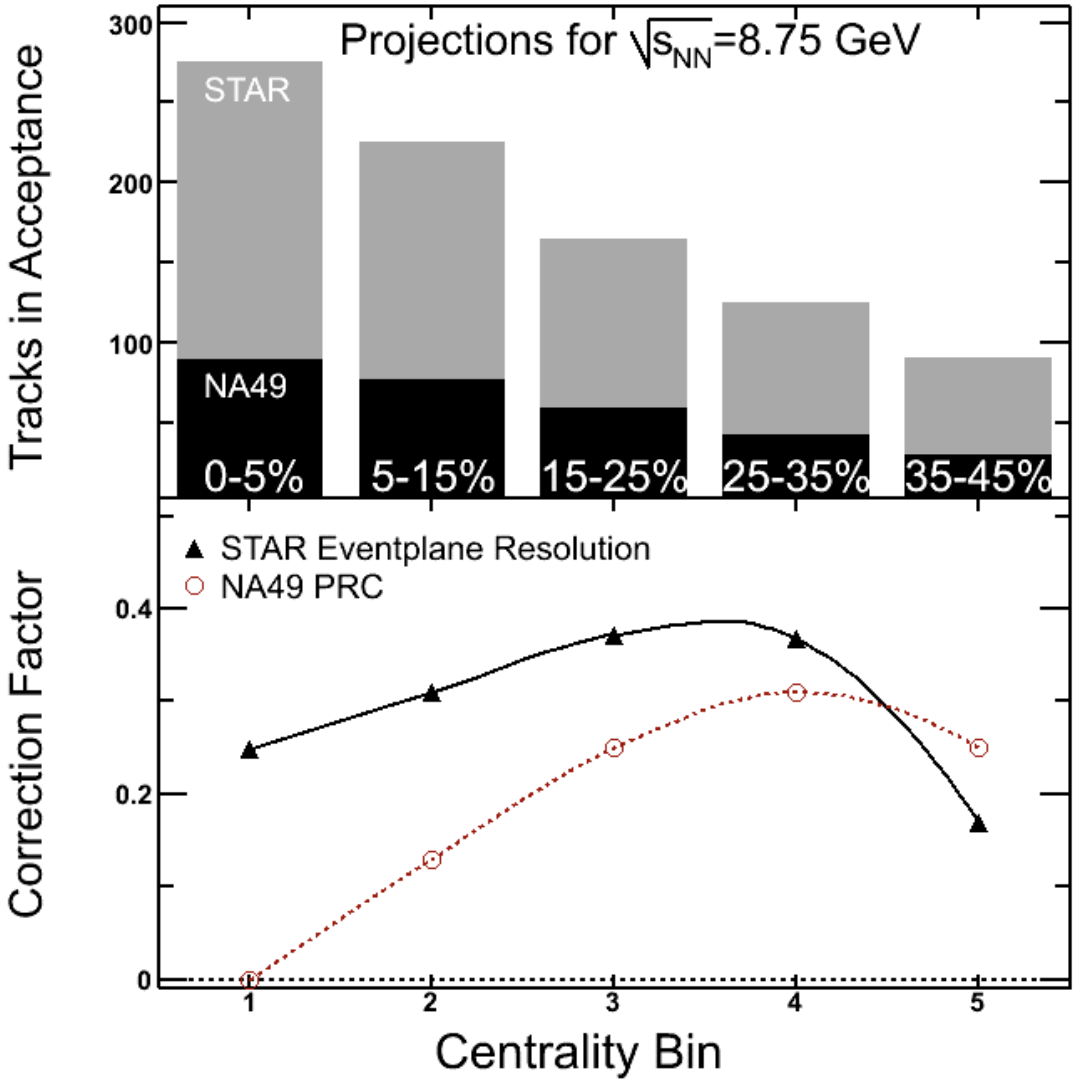
Excellent Particle Identification with TOF



TOF to be complete before Run10



Event Plane Resolution for Elliptic Flow



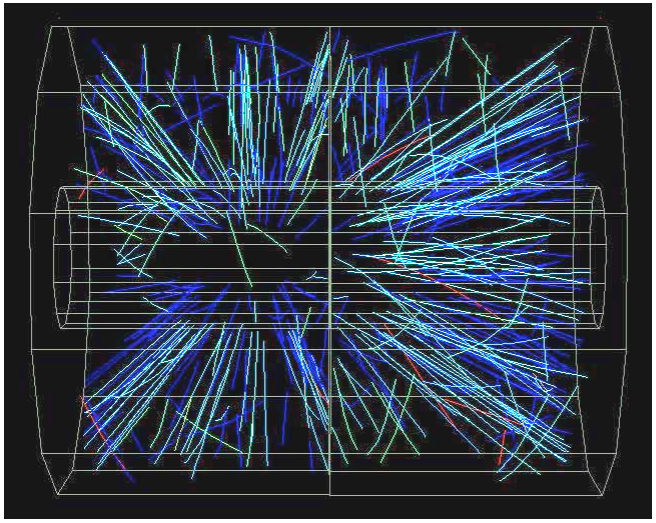
Early Low Energy Beam Tests

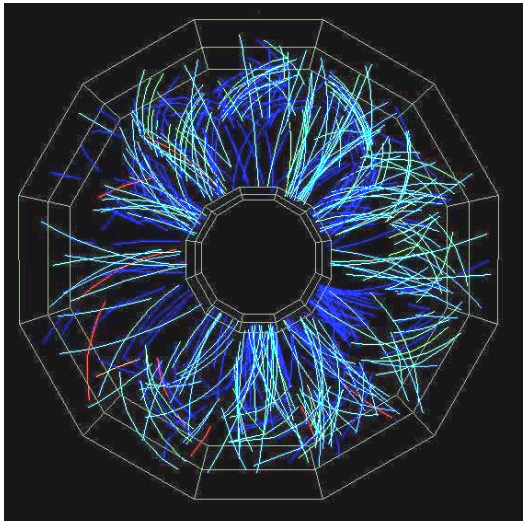
- 2006:One day of machine studies with protons
  - Proton+proton @ center of mass energy of 22 GeV
    - Magnet settings appropriate for Au+Au @ nucleon-nucleon center of mass of ~9 GeV, equivalent to fixed target with ~40 AGeV beam.
  - Results were very encouraging!
- 2007: Injecting and colliding Au+Au @ $\sqrt{s_{NN}} = 9.2$ GeV
  - Running below design injection energy for the first time
  - Same magnetic rigidity as 2006 low energy proton test
  - Overall, the run was a major success!
    - For the first time at RHIC, the RF frequency limits no longer could accommodate 360 RF buckets.

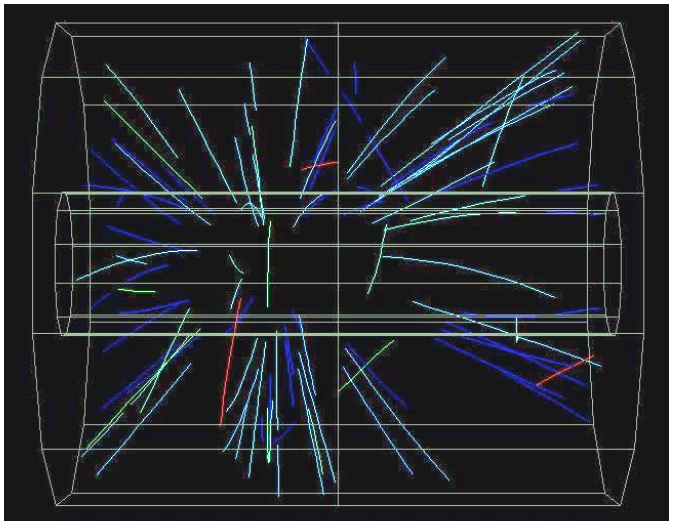
2008 Low Energy Beam Test

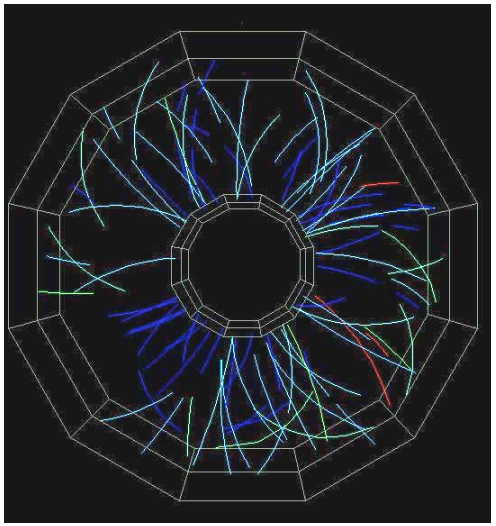
- Injecting and colliding Au+Au @ $\sqrt{s_{NN}}$ = 9.2 GeV
  - Setup and experimental DAQ problems with new harmonic number h=366 solved.
  - Stable running with collisions at STAR ⇒ Data!!
    - Couldn't cog simultaneously at PHENIX and STAR⇒limited data :-(
    - This problem will be fixed in the future by choosing a slightly different energy
- Short test at Injecting Au+Au @ $\sqrt{s_{NN}}$ = 5 GeV
  - Interrupted by power supply problems but did allow study of some beam characteristics.
  - Additional important work needs to be done in Run 9.

Experimental Au+Au Data @ $\sqrt{s_{NN}}$ = 9 GeV!!



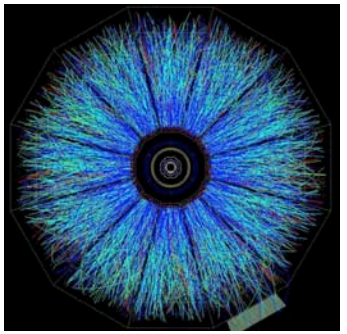




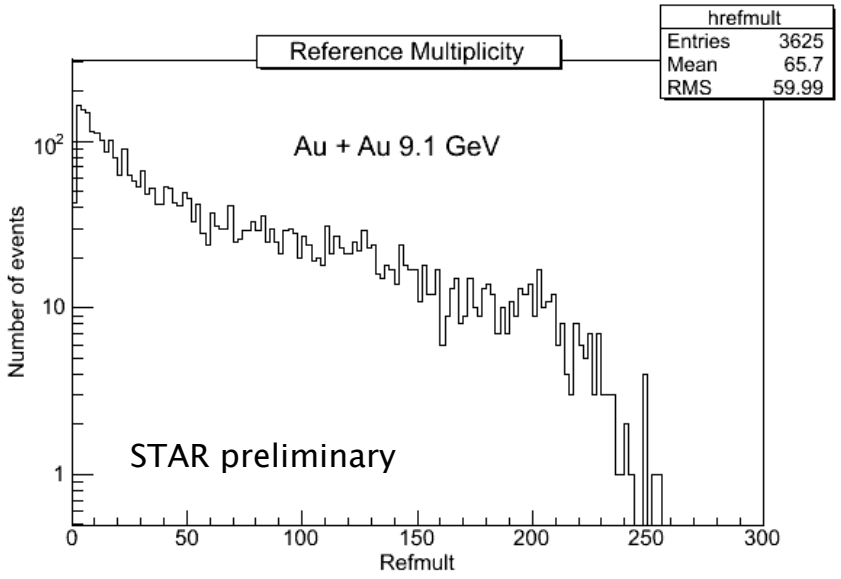


Unambiguous 2008 results

$\sqrt{s_{NN}}$ = 200 GeV



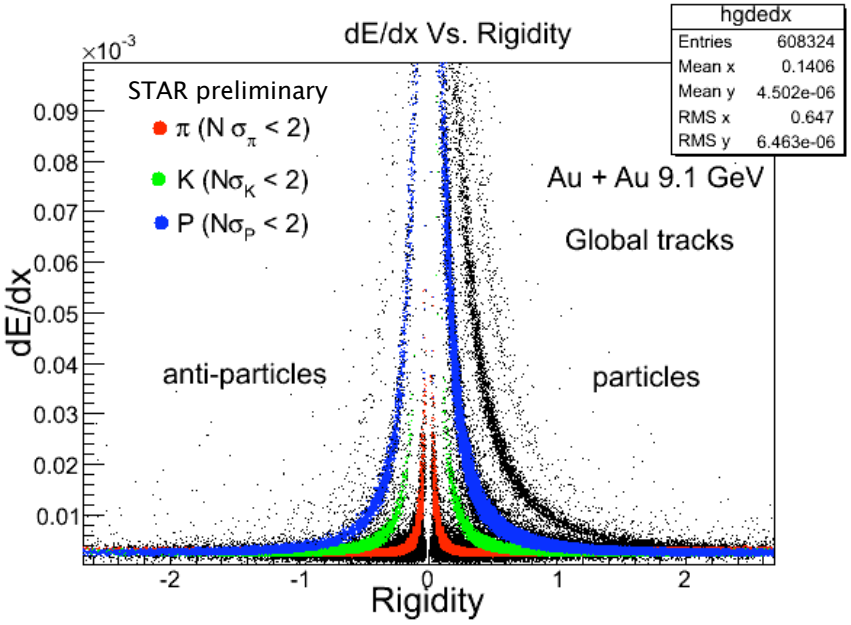
Au+Au @ $\sqrt{s_{NN}}$=9 GeV: Preliminary Analysis



Raw multiplicity

Note: Plots should be taken only as illustrative of data quality and analysis capability

PID (dE/dx only)



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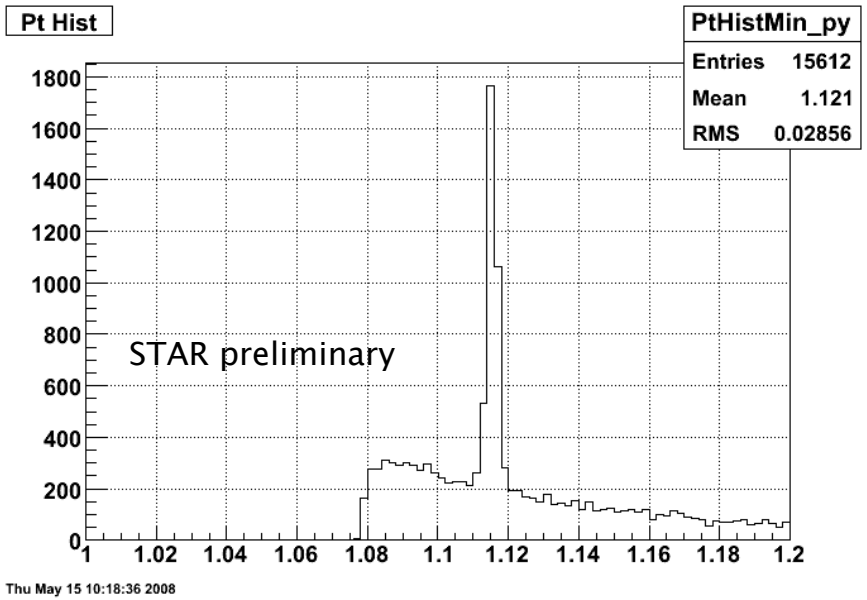
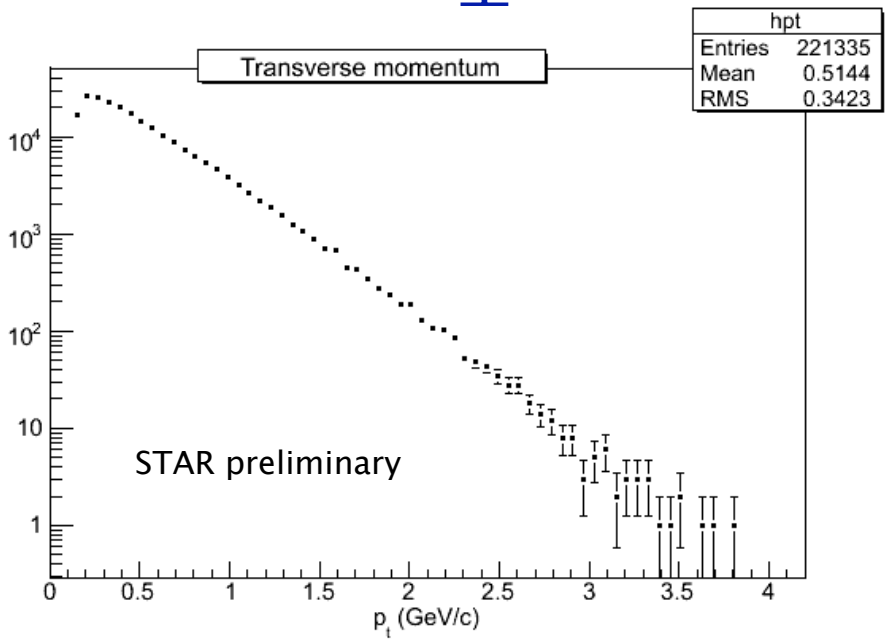


Λ invariant mass

Note: Plots should be taken only as illustrative of data quality and analysis capability

Uncorrected $p_\perp$ spectra



Current Status

STAR & RHIC have clearly proven that they are ready today for a robust beam energy scan program.

- Luminosity upgrades in RHIC will improve the rate.
  - Projections are for increase by a factor of at least 6 at 9 GeV.
    - Increase would be ×15 or more with electron cooling in RHIC.
- STAR TOF will dramatically improve the PID capability.
  - This is critical for many of the most interesting proposed measurements.
  - Plans call for TOF completion before Run 10.

STAR Beam Scan Proposal - 2010

- First scan aiming to cover wider range
- $\sqrt{s_{NN}}$ from ~6 to ~40 GeV
  - Lower energies will focus on phase transition properties, higher ones will focus on disappearance of the partonic medium.
  - Also beam development at 5 GeV, expanding on work in Run 9.
- Lower energies will be similar to SPS values but should allow collisions at two experiments where possible.
  - Energy choices will be modified if theoretical guidance appears.

Note that STAR may lose some FTPC functionality after Run 10.

STAR Beam Scan Proposal - 2010

- Goal is to look for clear signals of interesting physics or at least identify the most interesting regions.
- Most exciting discovery potential is finding a 1st order phase transition and/or a critical point.
- Guaranteed results:
  - Narrow down the region where exotic medium effects disappear.
  - Significant extension and improvement over existing SPS data.
    - Also, major advantages over future SPS data.

STAR Beam Scan Proposal - 2012

- Second scan aiming to focus on specific ranges
  - Energies and physics topics will be chosen to explore in more depth the most interesting regions found in the first scan.
  - Luminosity upgrades will be useful at the lowest energies *unless* first scan indicates those regions are not interesting.
- Guaranteed results: To be predicted once data from the first scan is analyzed.

Some Closing Thoughts

- Lower energy collisions at RHIC will greatly broaden the experimental exploration of the QCD phase diagram.
- Evolution (disappearance) of partonic effects will be studied.
- QCD theory is suggestive that a critical point should exist.
  - Opportunity to settle the question with data instead of theory?
  - Colliding beam setup will produce data with dramatically different (and much better) systematic errors than fixed target.
- All machine & experimental tests to date are very encouraging
- STAR is well designed to maximally exploit this physics.
- Yet another case of major future discovery potential for RHIC.
  - We are eagerly awaiting opening this new and exciting window!

Mapping the phase diagram. Finding the landmark that would go in any future book on QCD. K. Rajagopal

In order to explore this exciting physics, STAR & PHENIX & RHIC represents the best option, beyond a shadow of a doubt, of all the existing or planned experimental programs.