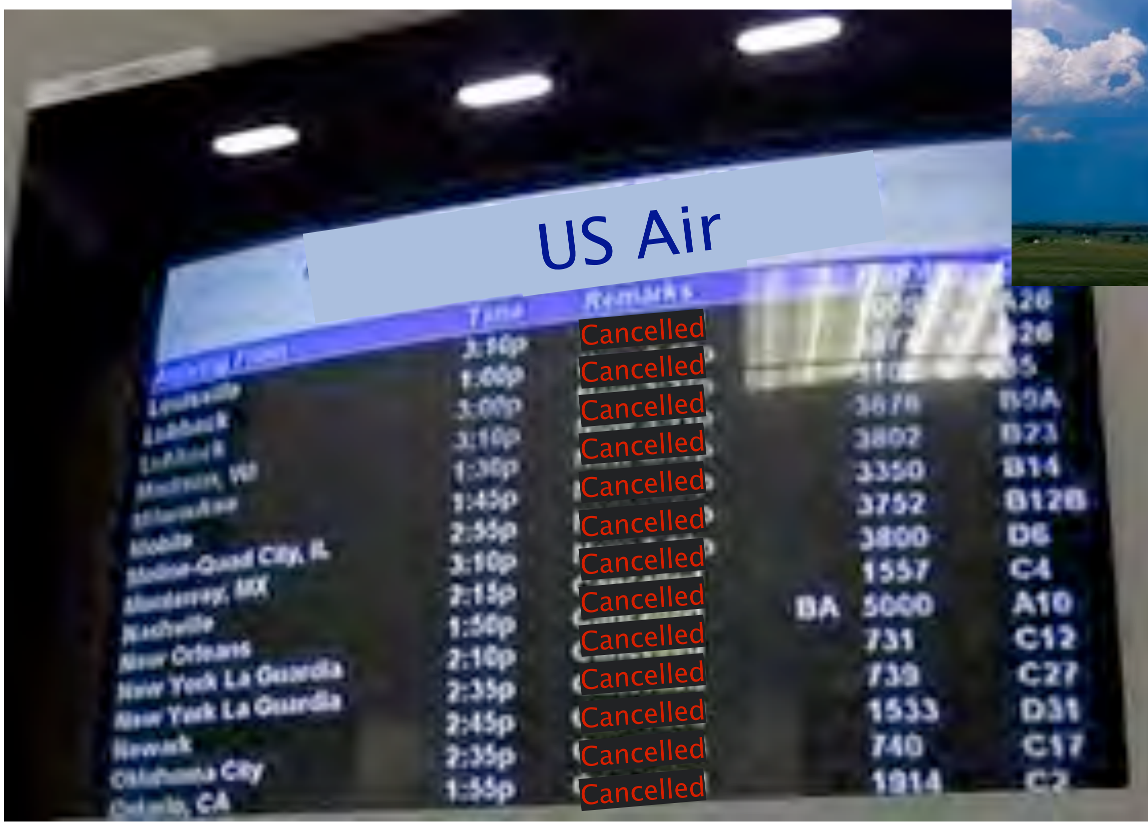
Experimental Exploration of the QCD Phase Diagram

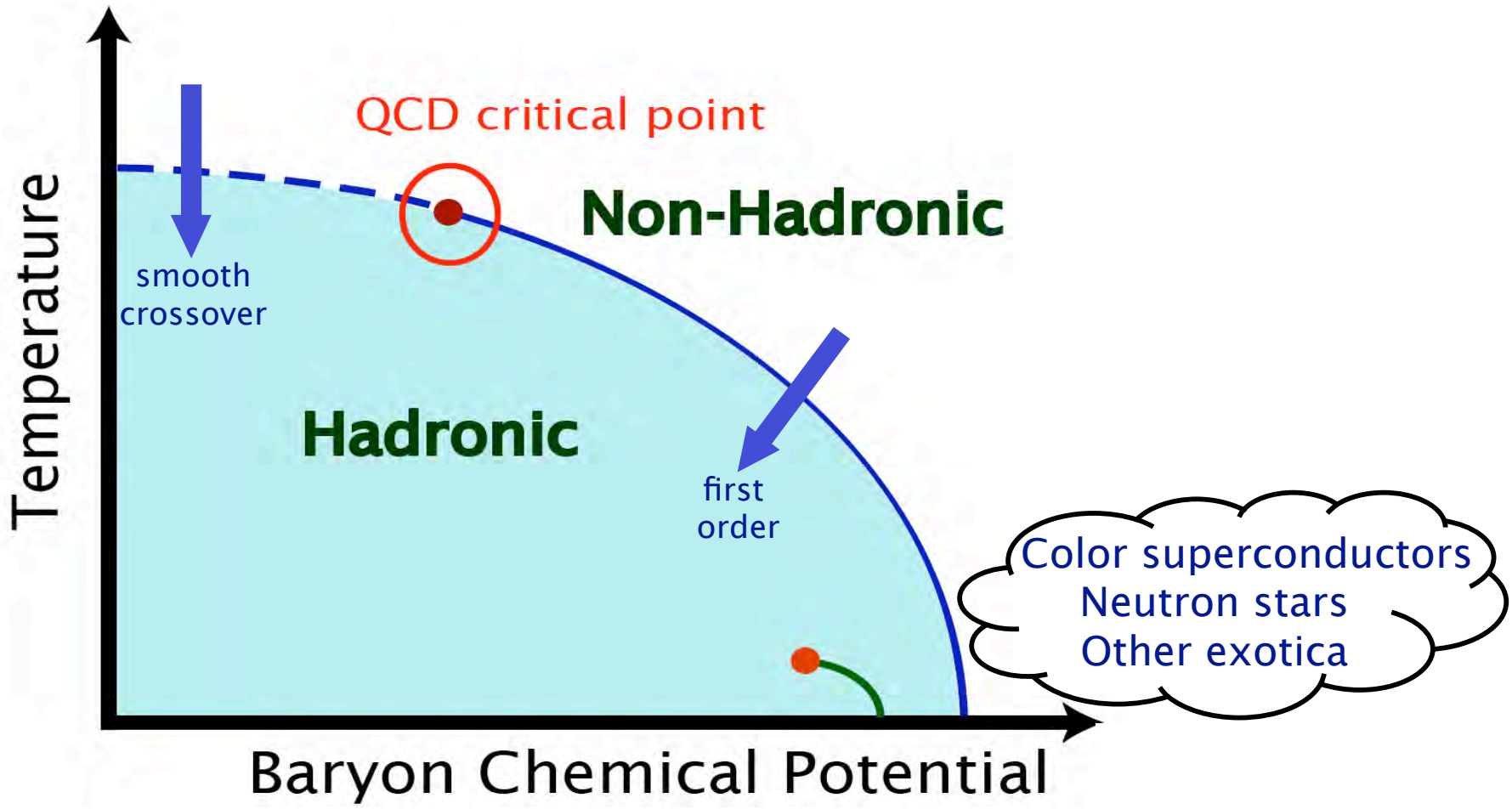
George S.F. Stephans

Massachusetts Institute of Technology

My apologies for disrupting the schedule

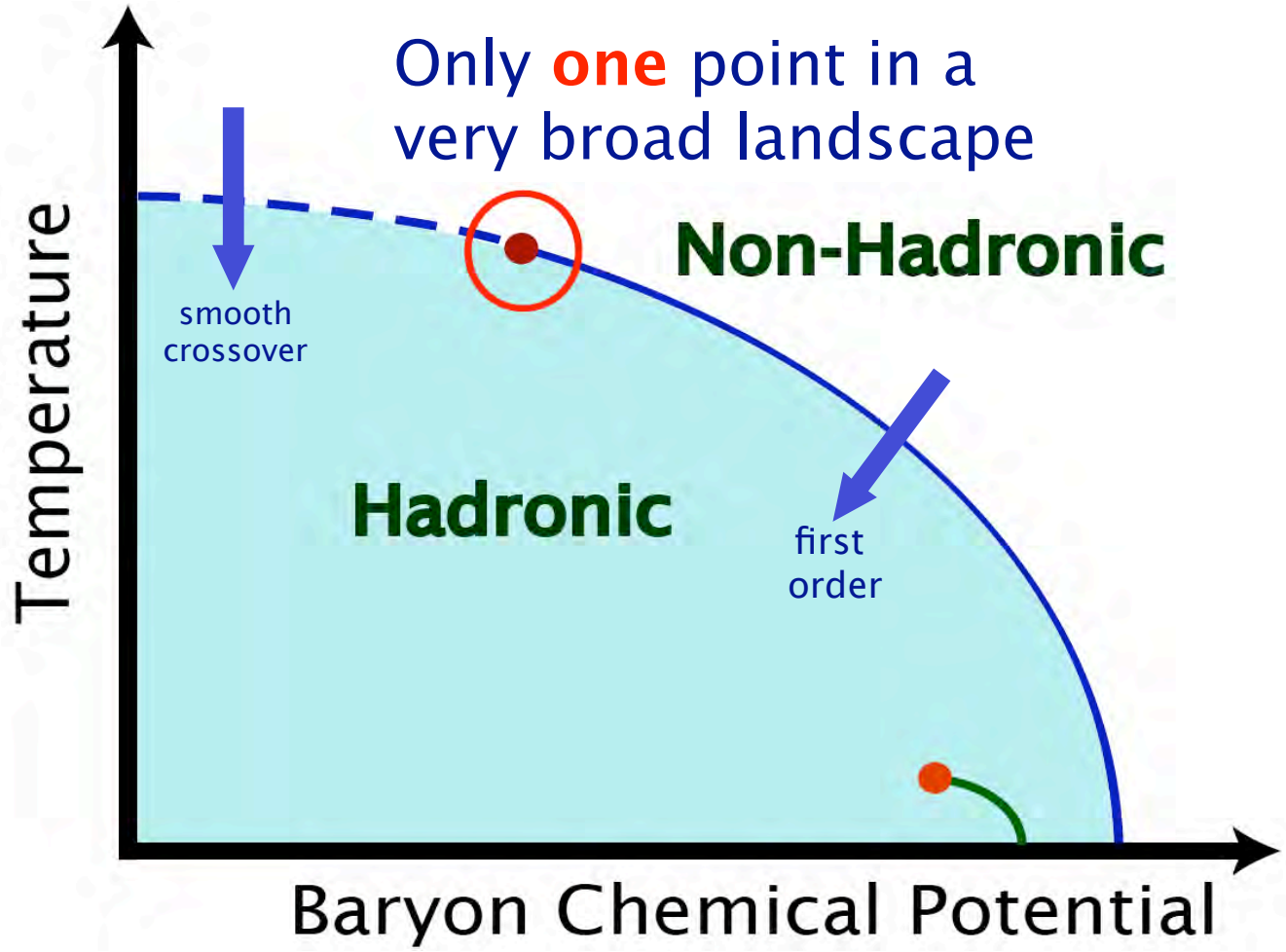


My Cartoon of the Phase Diagram

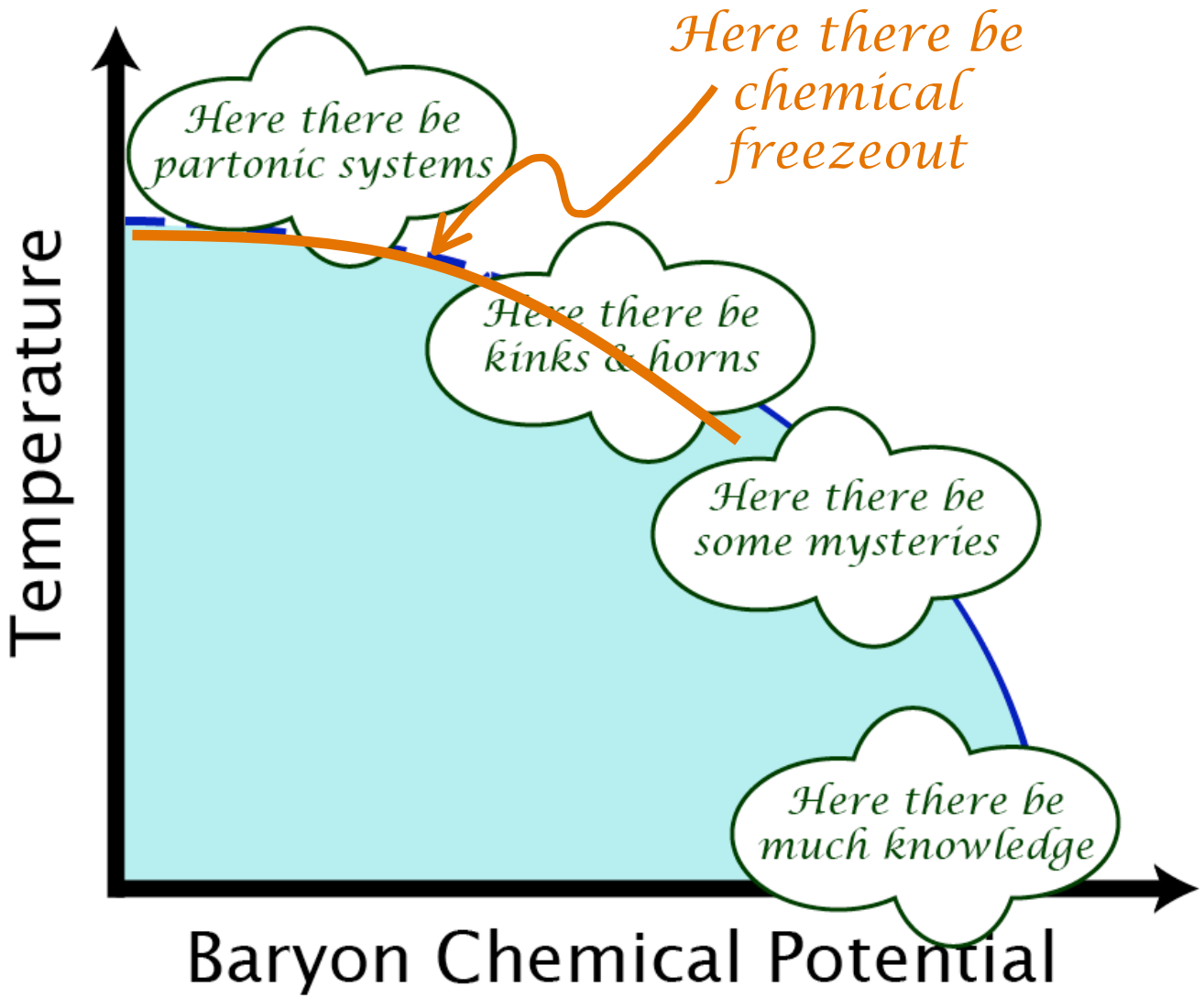


A Cautionary Comment

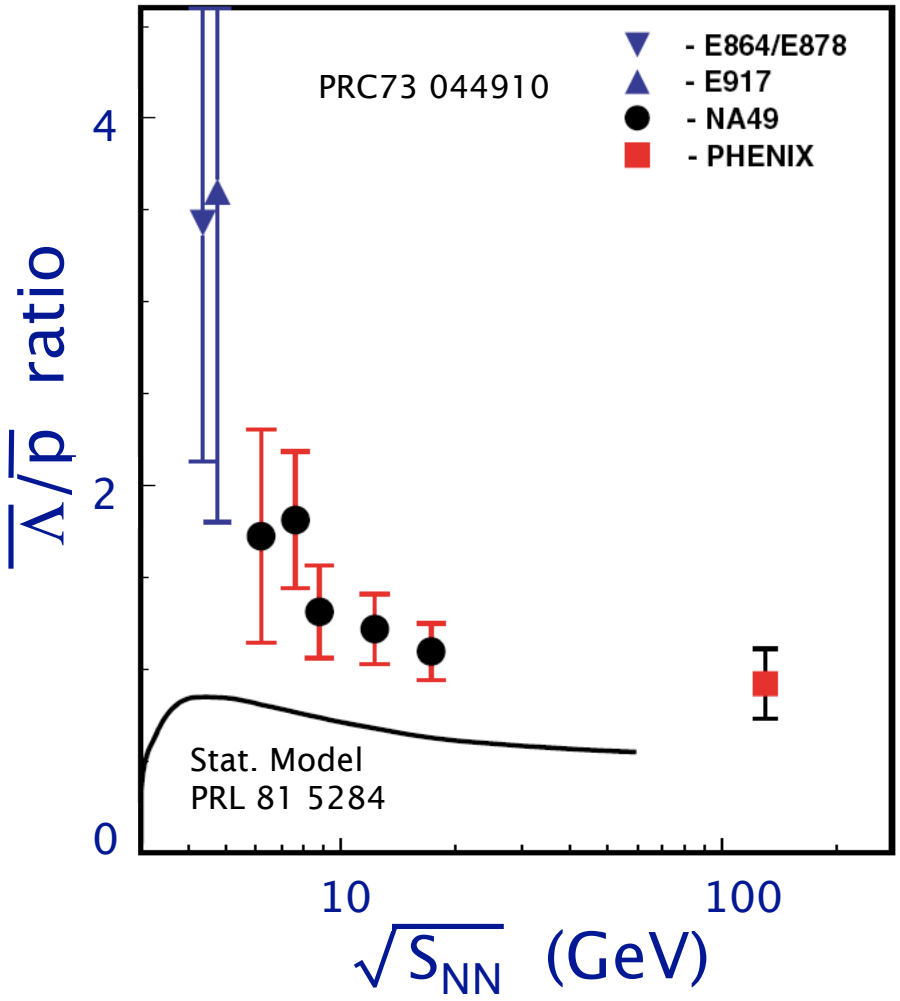
- The Critical Point in **not** the only thing to study!

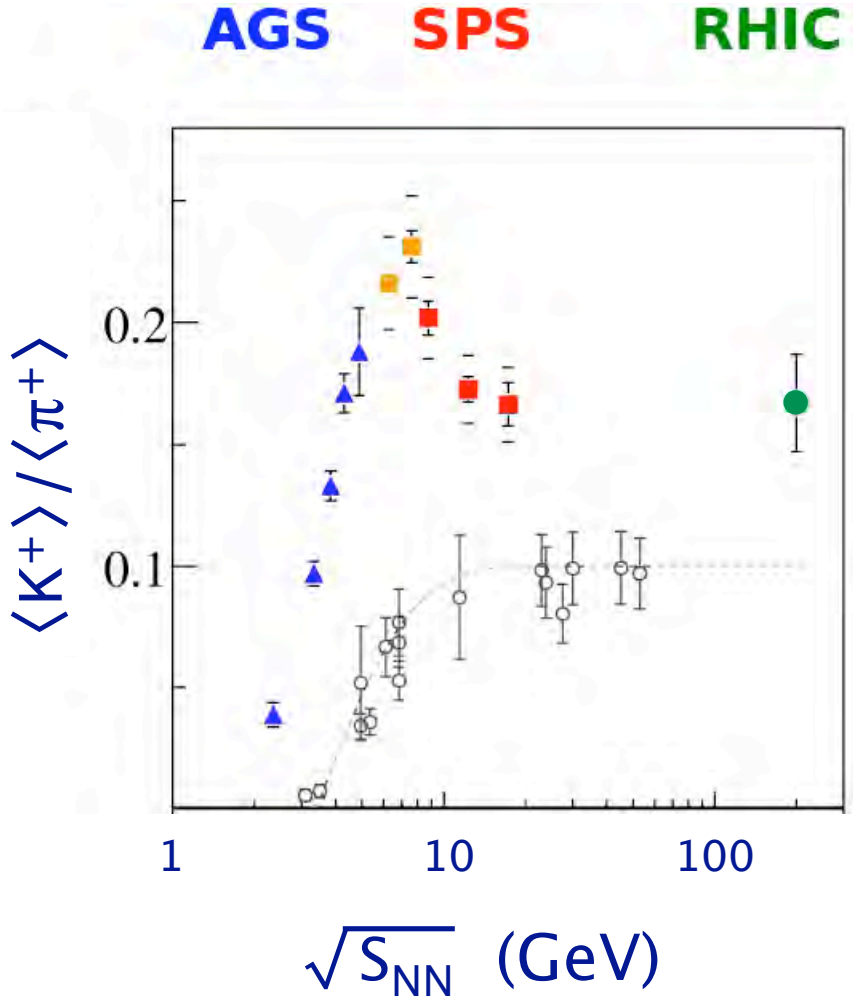


Data Leave Many Possibilities for Discovery



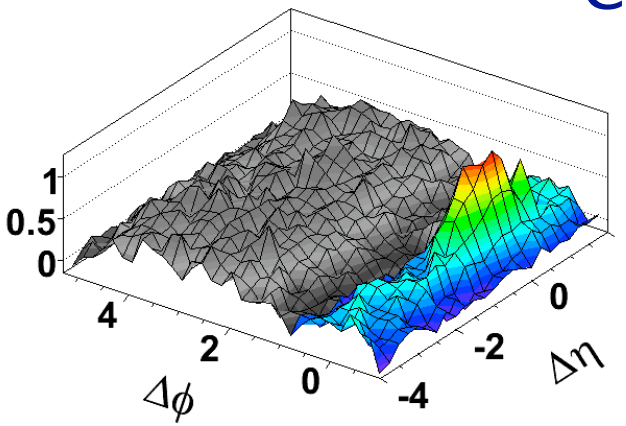
A Few Mid-Energy-Range Mysteries

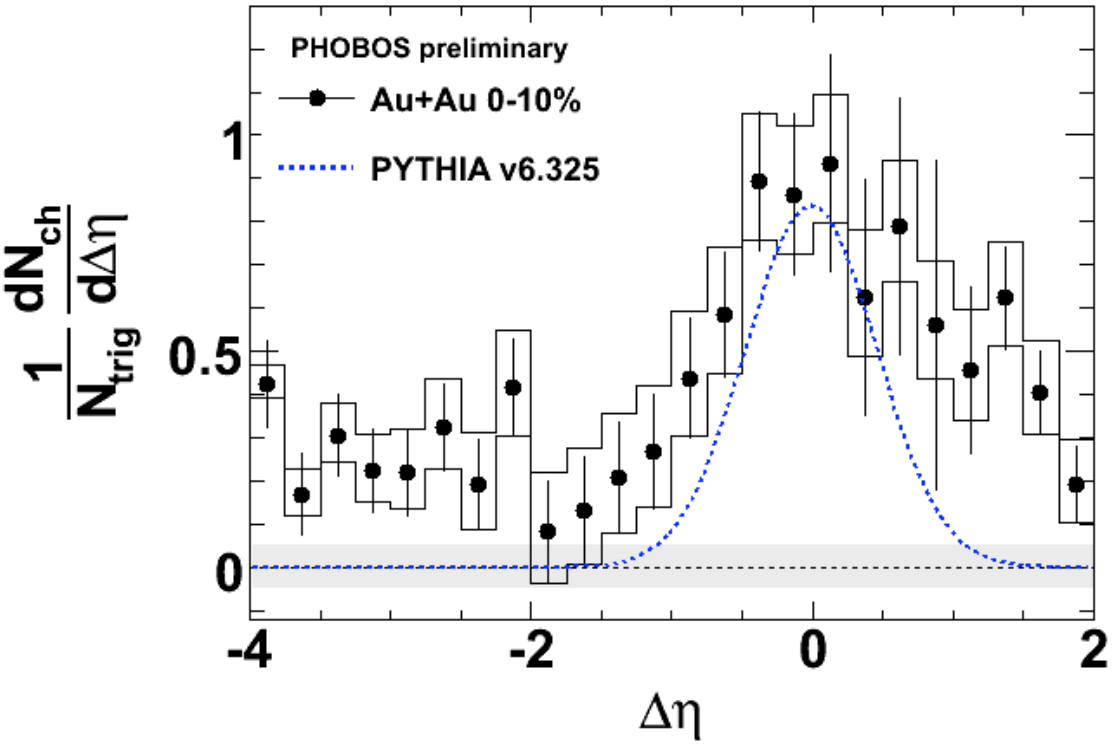




One (of many) Intriguing RHIC Results

Phobos 2-particle correlations with respect to a >2.5 GeV trigger track
Correlated yield on near-side ($|\Delta\phi| < 1$)





A Many-Featured Program

- This study will address many fundamental questions:
- More systematic data will shed light on mysteries in existing data.
- 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 were surprised before by relativistic heavy ion data. Something entirely unexpected may appear.

Connection between Theory & Experiment

- Gold Standard:
  - Well defined quantitative theoretical predictions that can be directly compared to experiment.
  - Not very realistic in the complicated QCD environment.

However…

- Theoretical speculations which are as specific as possible will help to guide experimental analyses.
- Consideration of realistic experimental capabilities will help to guide theoretical work into areas more likely to support a possible discovery.

I hope we can make a good start on these last two…

My Personal Biases - I

- No single observable will provide an unambiguous signature proving a discovery.

- Using a proposed effect to predict the signal in a single very-specific observable is of only limited utility.
  - What happens to the “rest of the event” due to that effect?
  - Given that the proposed effect is present, what other effects must follow as a direct consequence?
  - What other observables are ruled out if the effect is present?

My Personal Biases - II

- Either the theory, as I understand it, is badly broken or there must be a critical point.

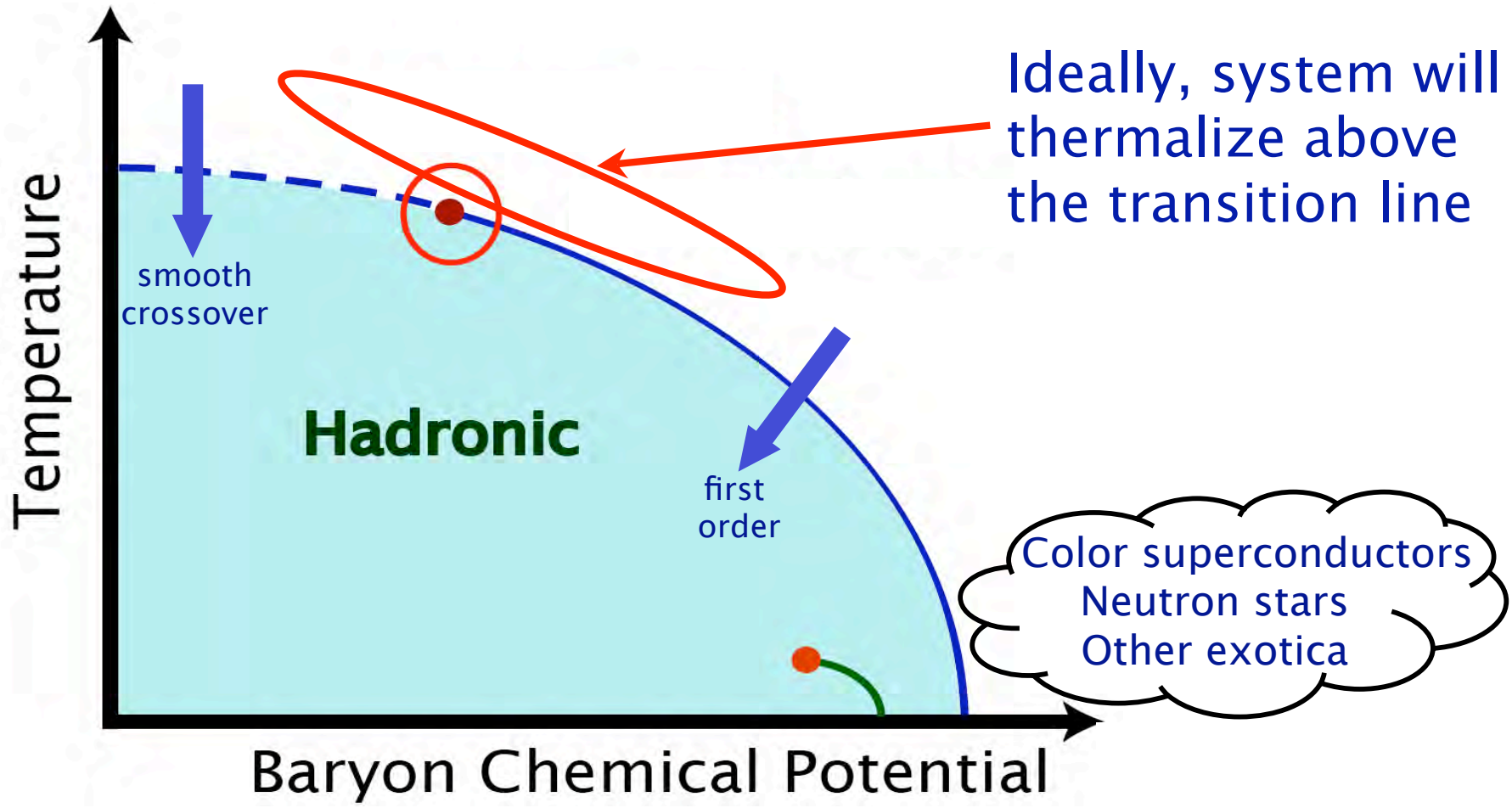
However…

- Given the significant theoretical difficulties, using an ongoing interplay between theory and data to constrain the phase transition may be the quickest way to study the broader characteristics of the QCD phase diagram

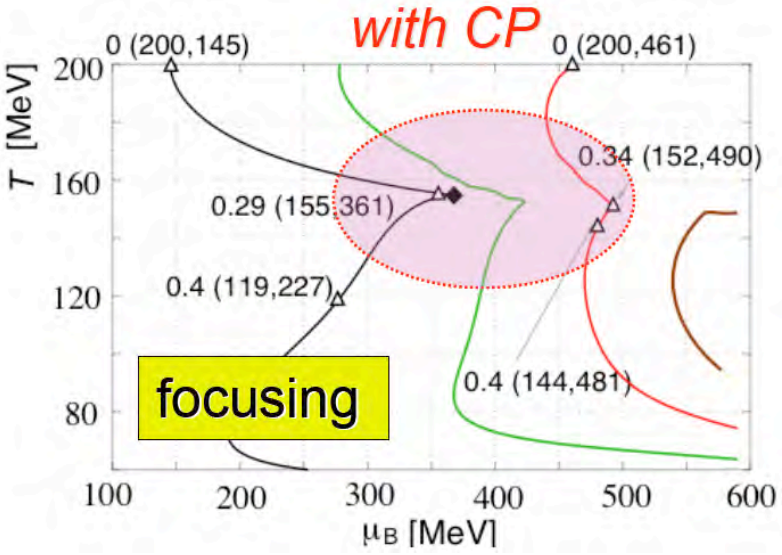
More General Theoretical Guidance

- Predictions of multiple global properties of an event with (or without) sufficient thermalization to allow study of phase properties.
- Models of "initial conditions" combining kinematic projections forward and hydro-type evolution backward.
- Guidance about how the thermal properties of the system do (or do not) span across rapidity.
  - How small a window does it make sense to look through?
- What does it mean for the properties of a system at chemical freeze-out to be (possibly) so close to those at the theorized phase transition?

My Cartoon of the Phase Diagram



Theoretical Guidance on Search Strategy



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.

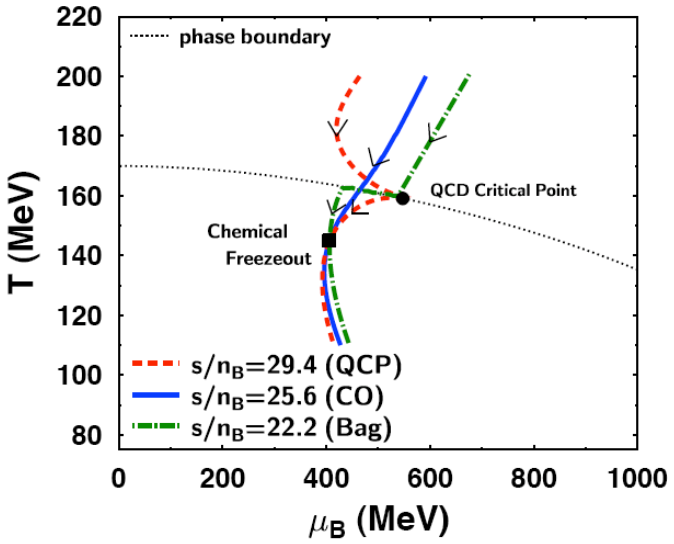


Image courtesy of M.Asakawa

Advertisement for Future Discussions

Critical Point and Onset of Deconfinement

5th International Workshop • June 15–19, 2009

Brookhaven National Laboratory, Long Island, New York, USA

World-Wide Experimental Efforts

- Low energy scan @ RHIC with STAR & PHENIX
- Energy & system scan @ SPS with NA61 (and others?)
- CBM @ FAIR (GSI)

Also…

- MPD @ NICA (JINR-Dubna, up to $\sqrt{s_{NN}} \approx 7$ GeV)
  - Possible collider complement to FAIR
- Existing low energy data (AGS, SPS, RHIC)
- Existing and/or future forward rapidity data @ RHIC

Current Experimental Plans - I

- Low energy scan @ RHIC with STAR & PHENIX
  - Au+Au @ $\sqrt{s_{NN}} \approx$ 5–50 GeV
    - Schedule specifics under negotiation between STAR, PHENIX, RHIC
  - Starts in 2010-2011
  - Pros:
    - Broadest energy coverage
    - Collider geometry results in minimal variation of detector environment with beam energy
  - Cons:
    - Low event rate, especially at the lower energies

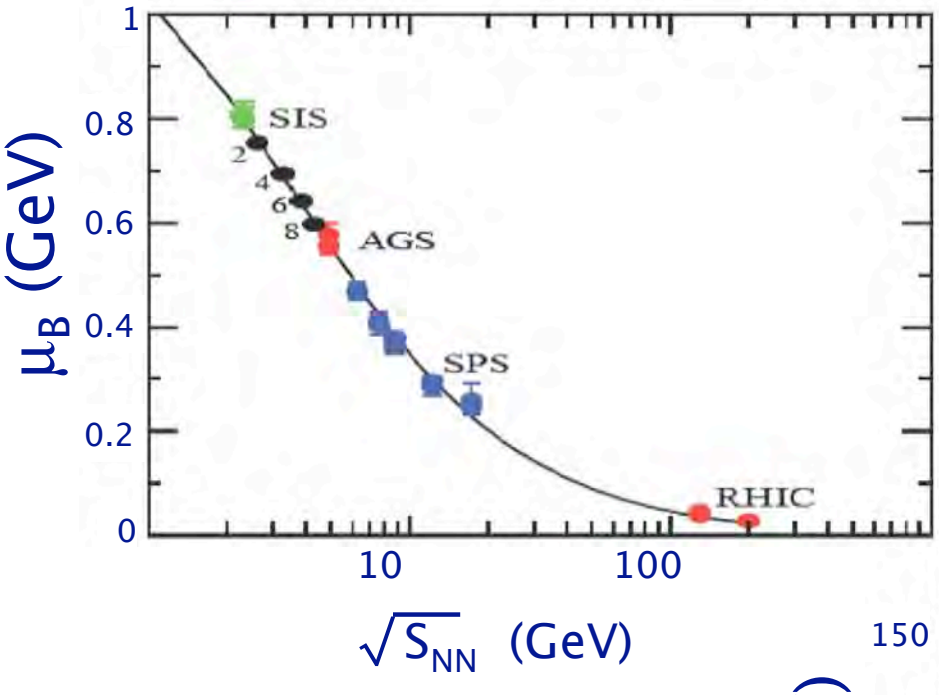
Current Experimental Plans - II

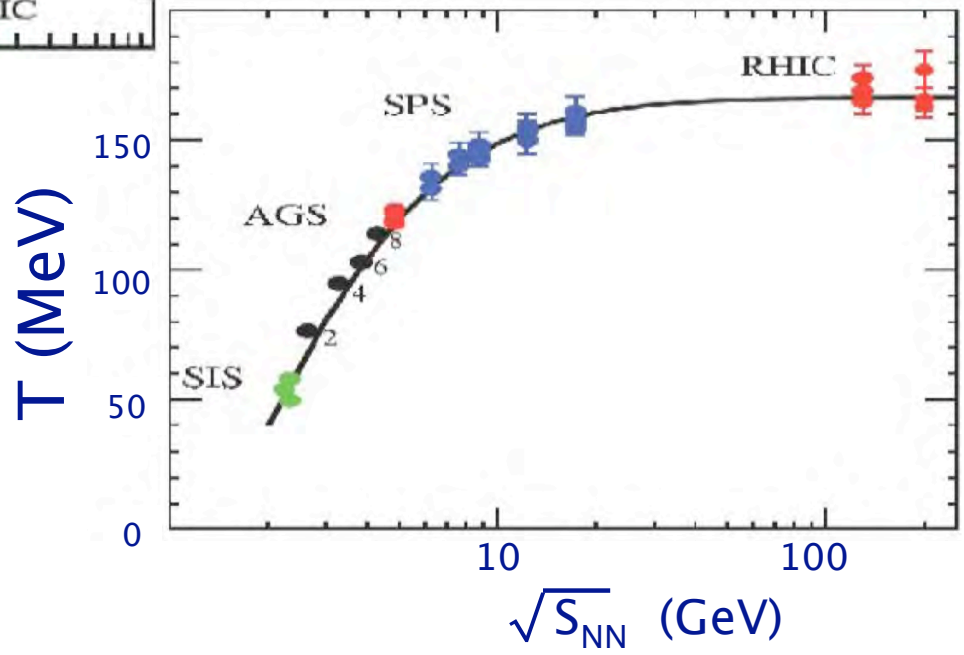
- Energy & system scan @ SPS with NA61
  - C+C, S+S, In+In @ $\sqrt{s_{NN}} \approx$ 5–17 GeV
  - Starts in 2011
  - Pros:
    - Higher rate possible with fixed target
    - Different systems believed to probe different phase space regions
  - Cons:
    - Detector environment is challenging and varies between energies

Current Experimental Plans - III

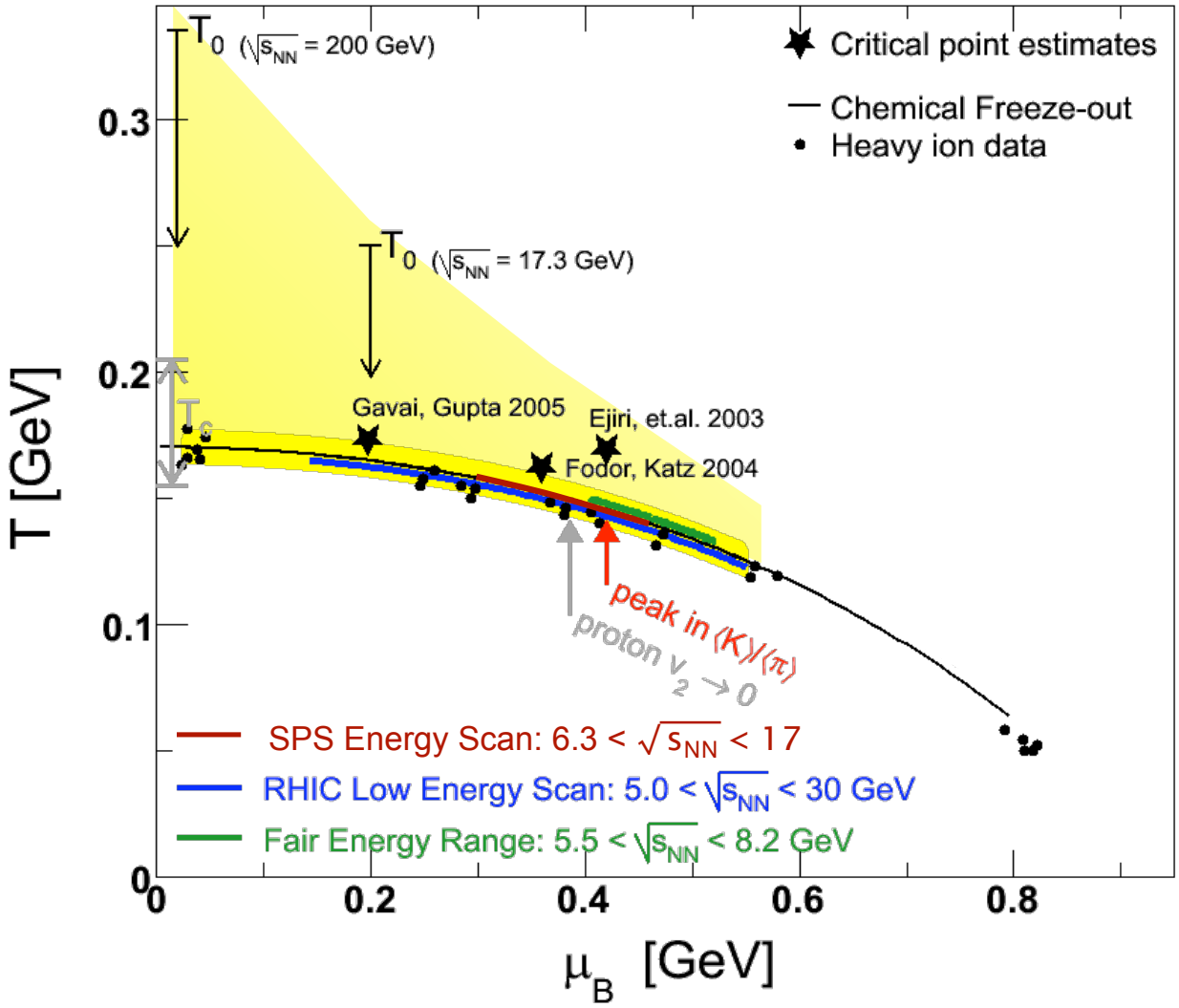
- CBM @ SPS FAIR
  - Multiple species @ $\sqrt{s_{NN}}$ up to ≈ 8–9 GeV
  - Starts in 2014–2015
  - Pros:
    - Very high rate
    - All new equipment, specifically built for these measurements
  - Cons:
    - Detector environment is challenging and varies between energies
    - Energy range is limited

Scanning Phase Space with Beam Energy

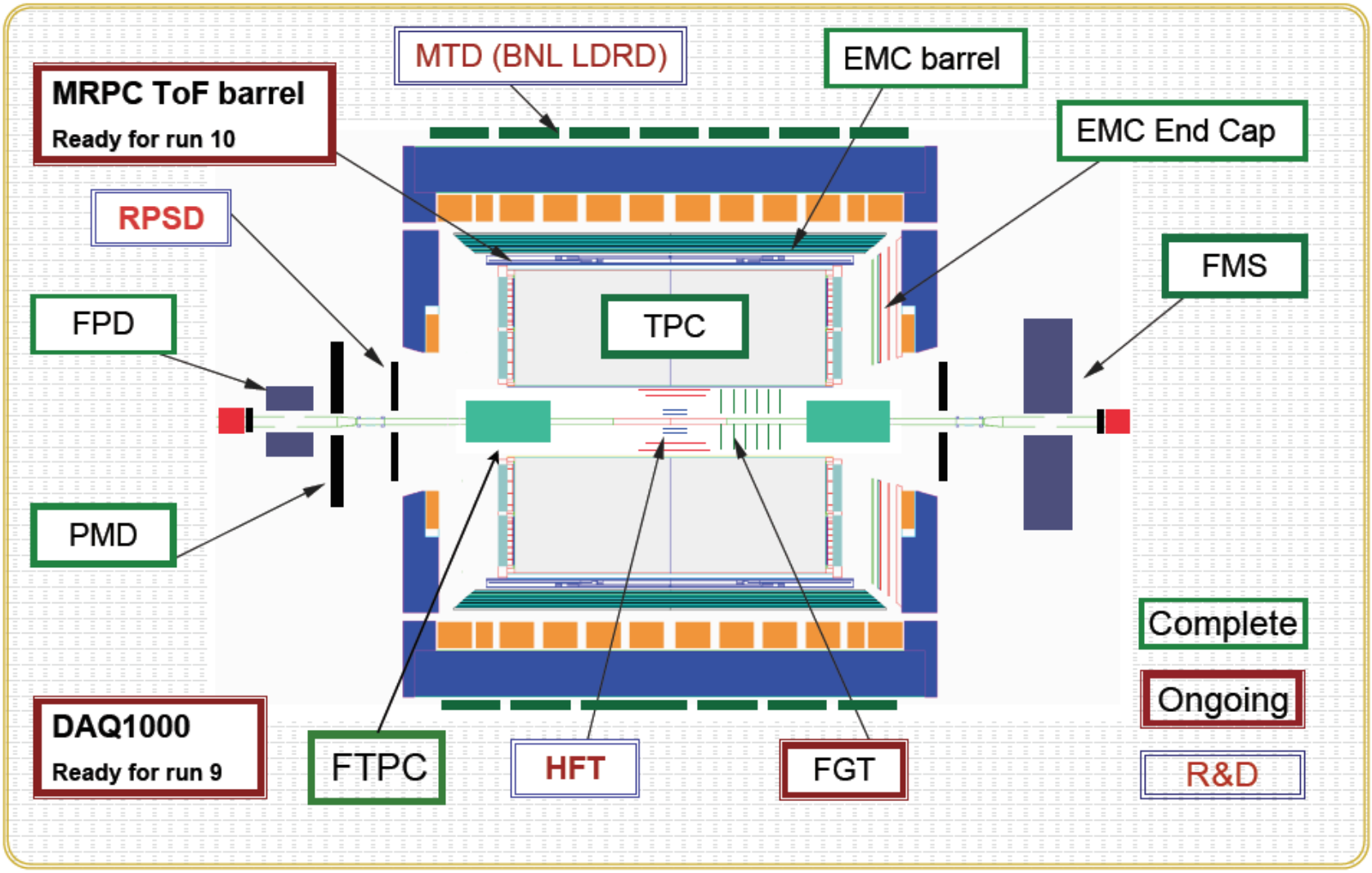




Experimental Phase Space Coverage



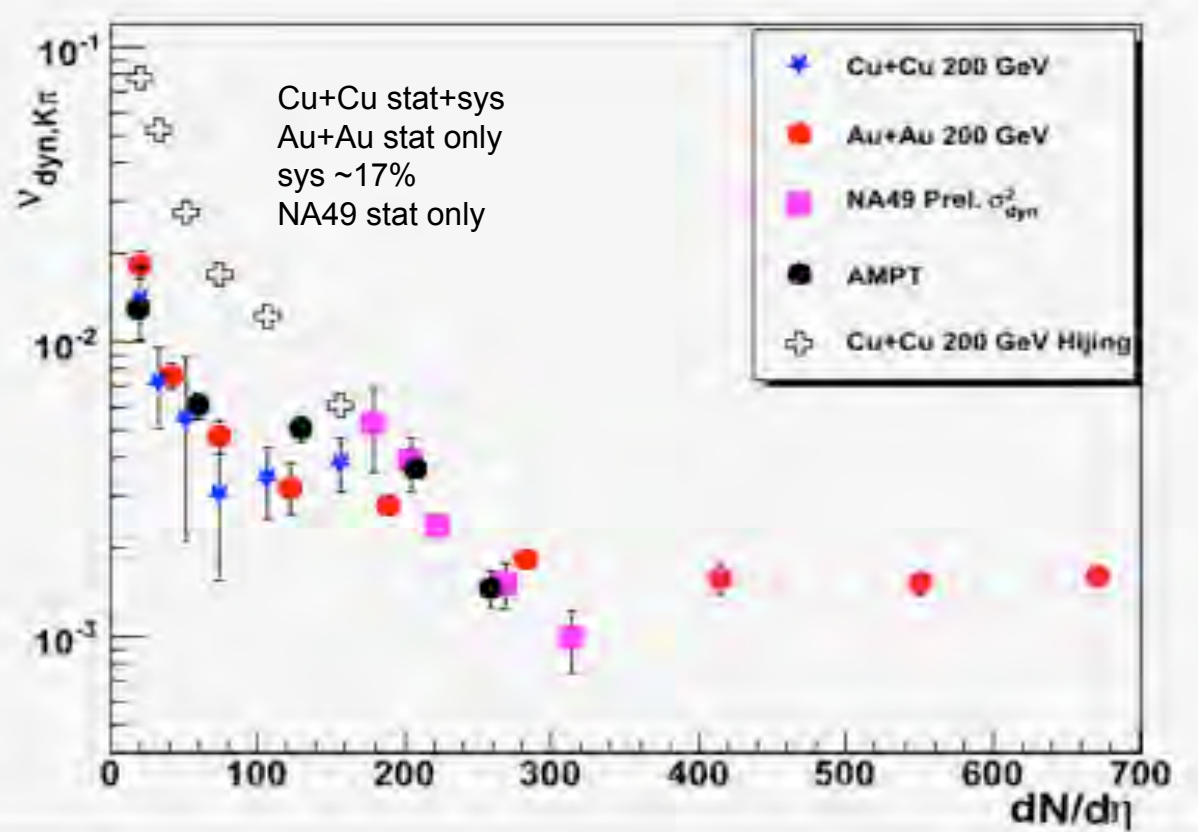
STAR@RHIC (~2010)



Compatibility of FTPCs and FGT/HFT being investigated

One Example of STAR Analysis

K/π fluctutaions

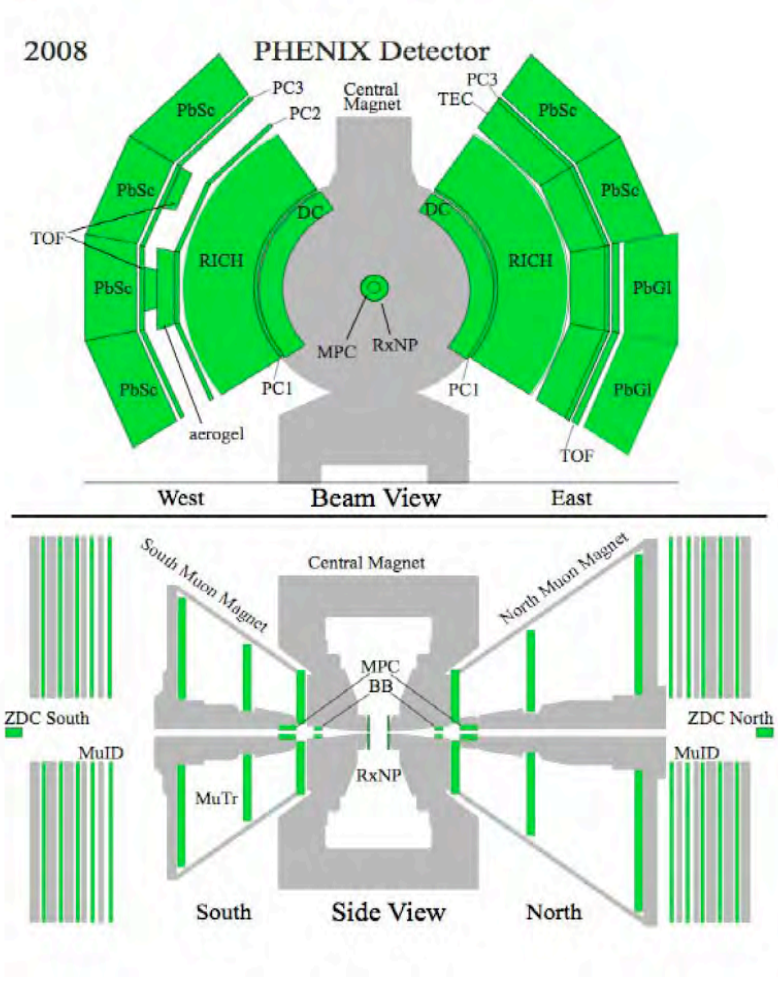


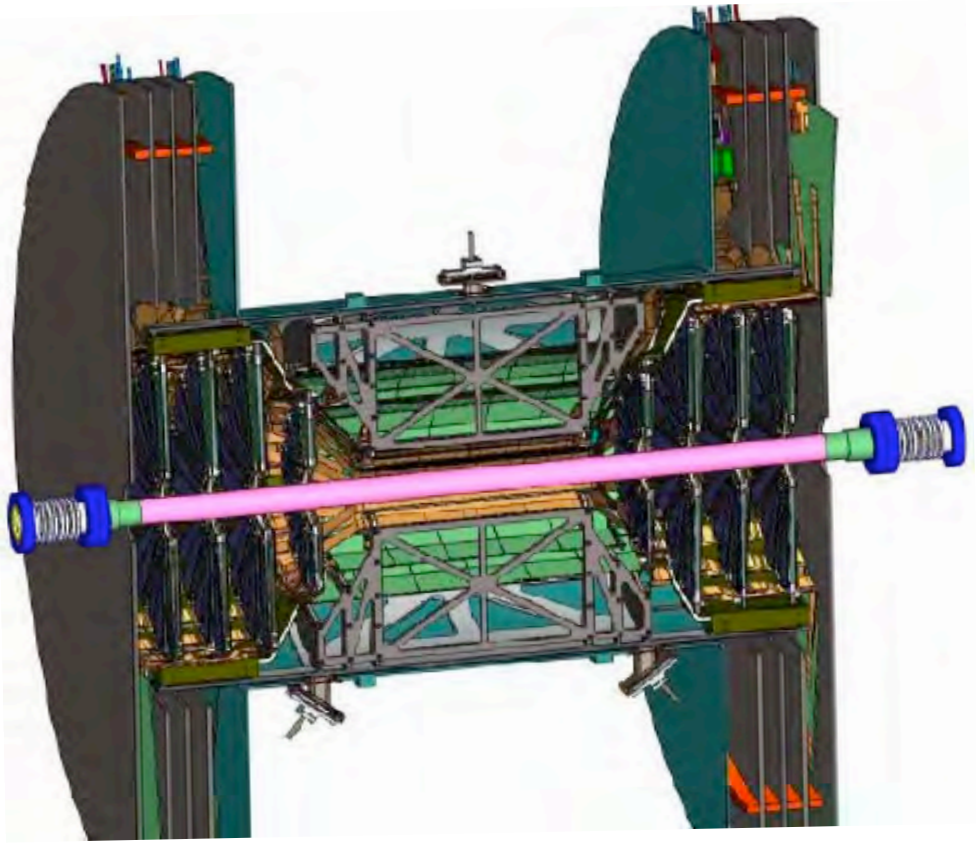
Fluctuations scale with dN/dη.

At lower dN/dη:
HIJING - too high
AMPT - much better

Z. Ahmed QM2008

PHENIX@RHIC





Images courtesy of M.Leitch

One Example of PHENIX Analysis

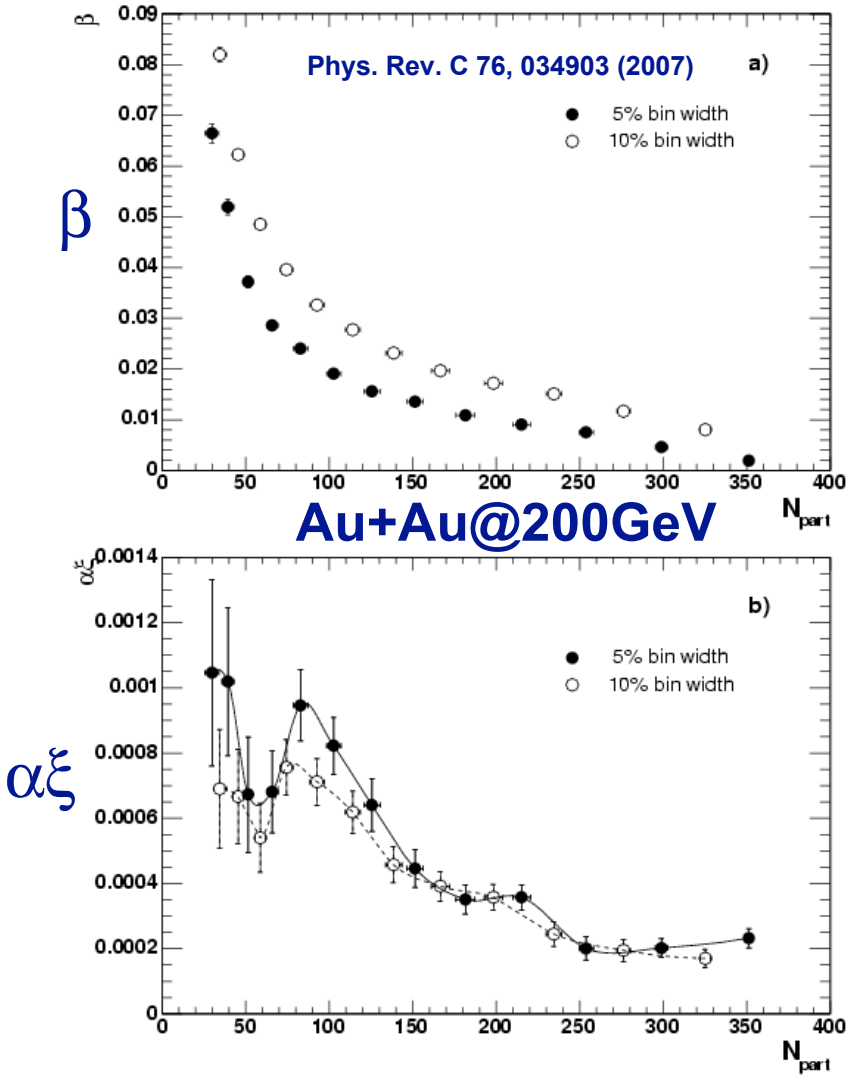
Parametrization of two particle correlation

$$C_2(\eta_1,\eta_2) \equiv \rho_2(\eta_1,\eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)$$

$$\frac{C_2(\eta_1,\eta_2)}{\overline{\rho}_1^2} = \alpha e^{-\delta\eta/\xi} + \beta$$

Approximated functional form with NBD *k*

$$k(\delta\eta) = \frac{1}{2\alpha\xi/\delta\eta + \beta} \quad (\xi << \delta\eta)$$



N_{part}

NA61 @ SPS

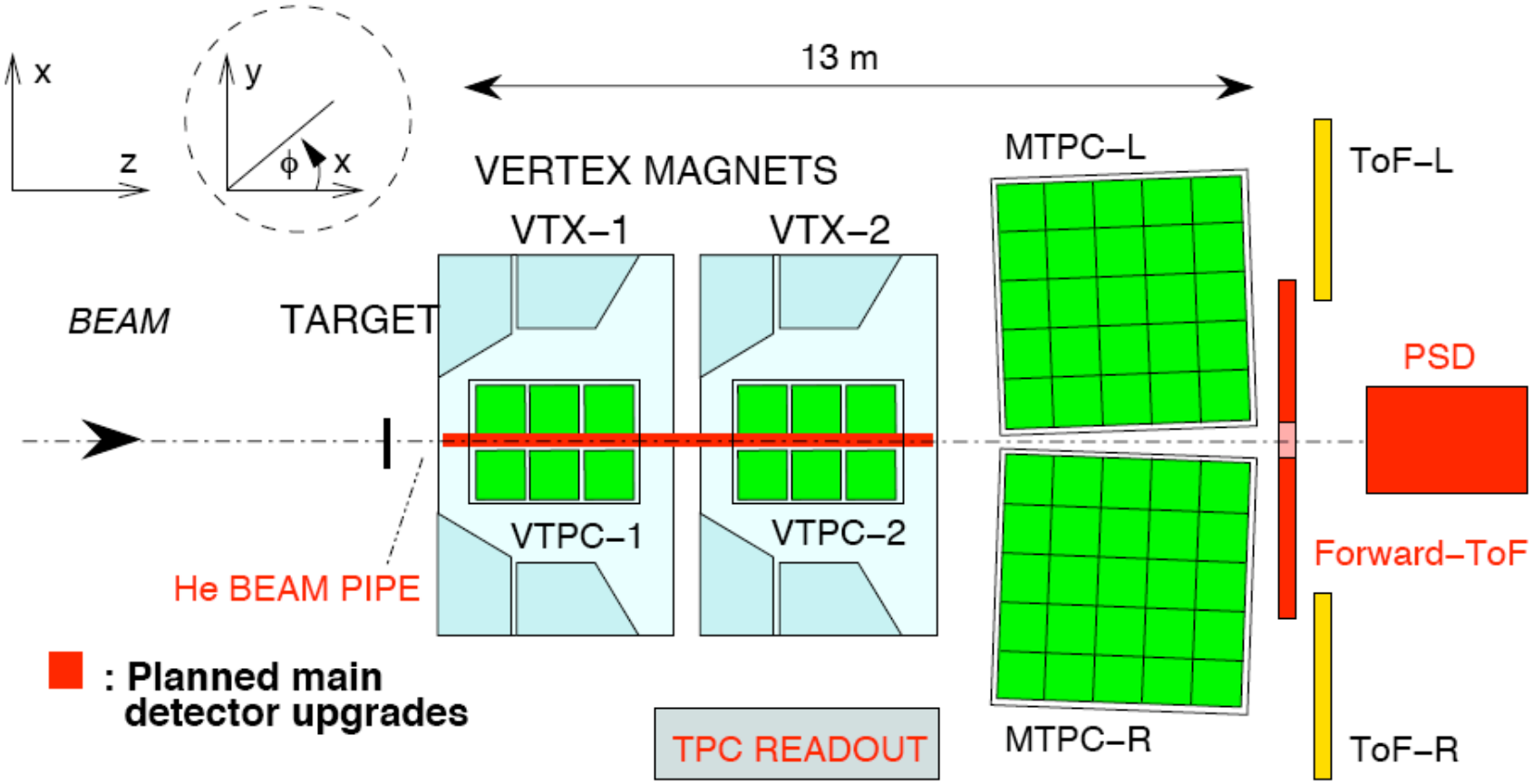
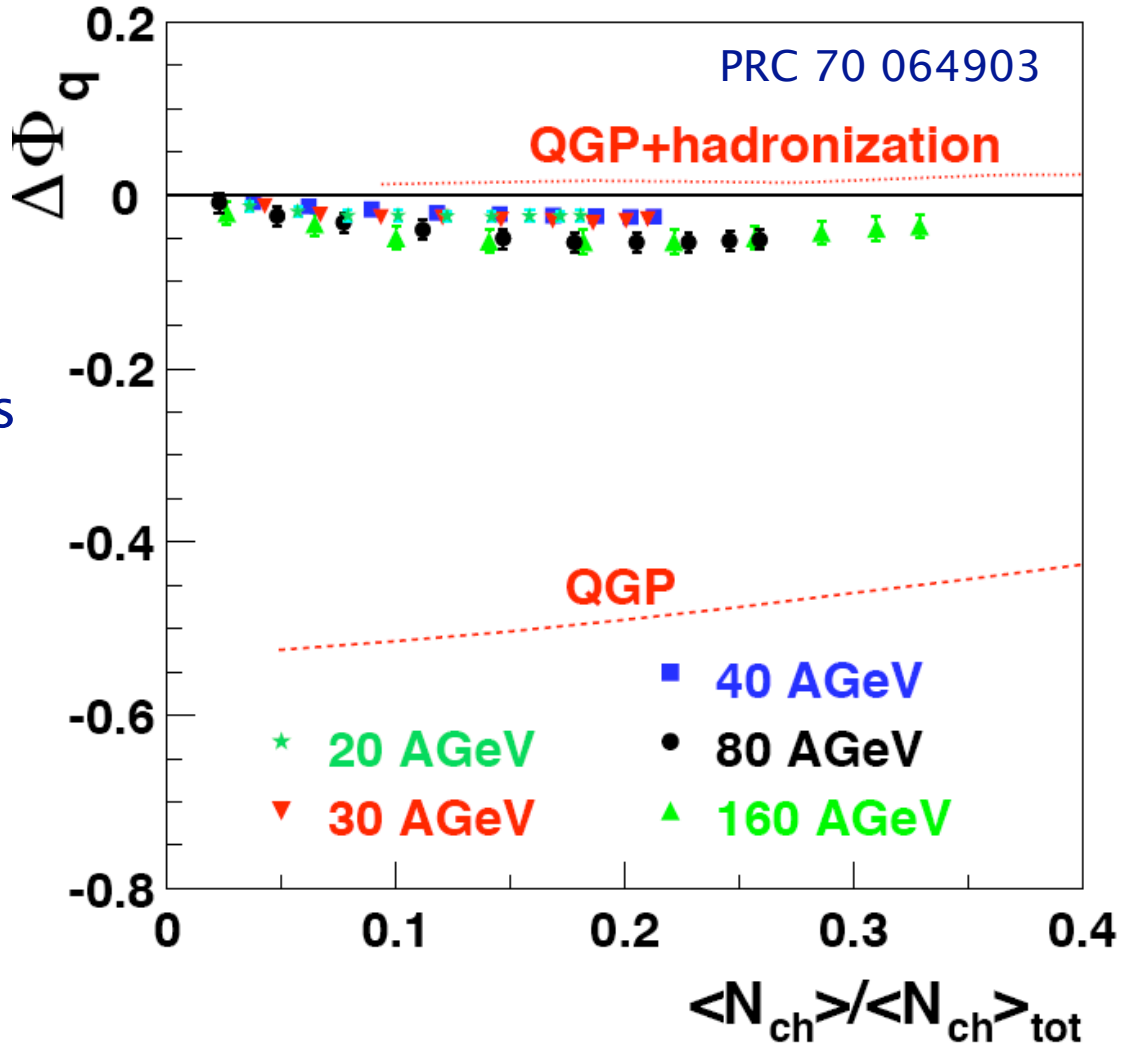


Image courtesy of T.Schuster

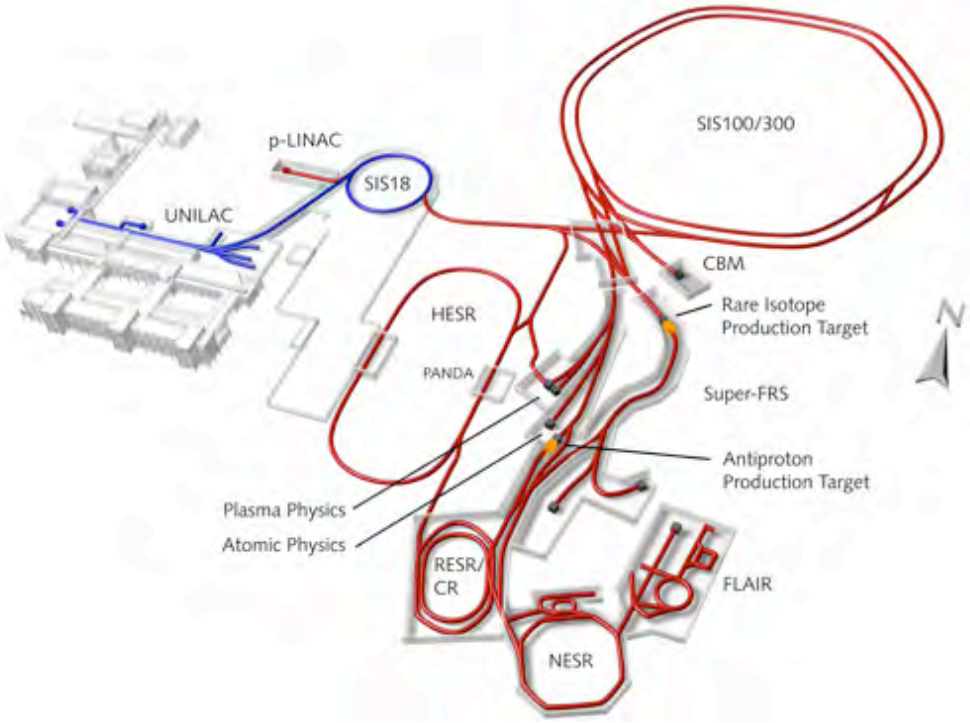
One Example of NA49 (NA61) Analysis

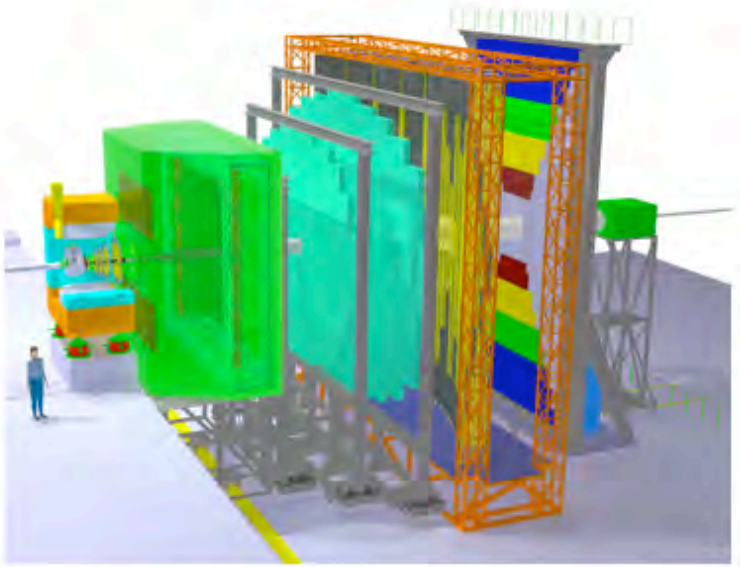
Energy dependence of net charge fluctuations versus centrality

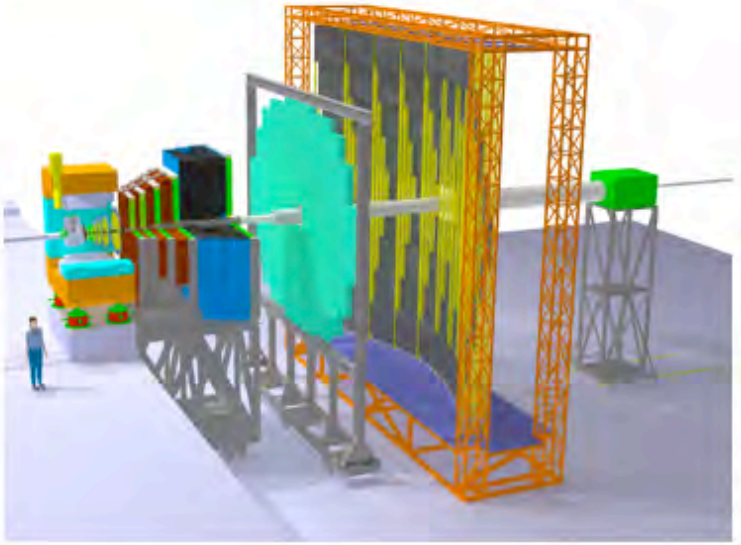


CBM @ FAIR

First beams planned for 2014 – 2015

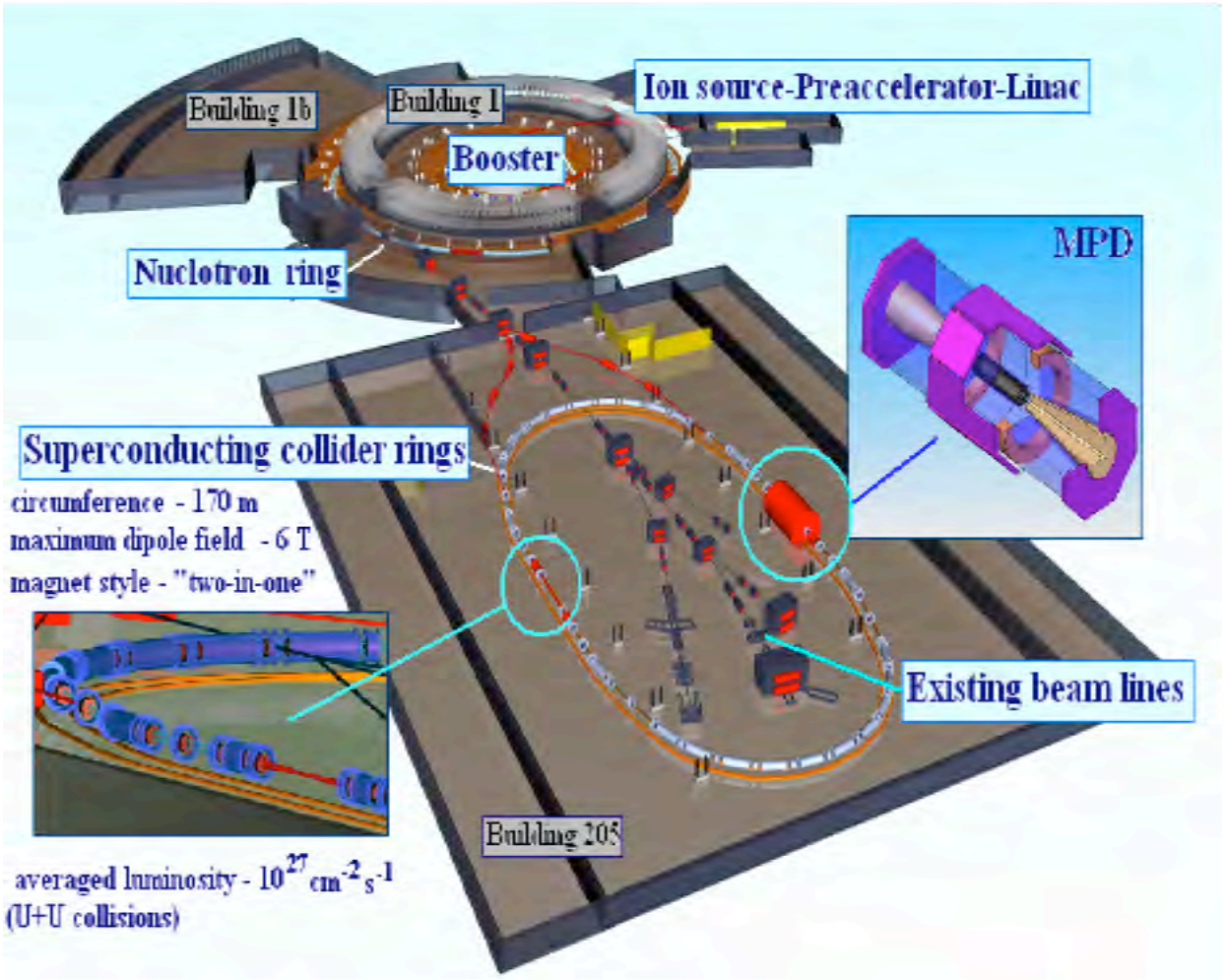






Images courtesy of P.Senger

NICA & MPD @ JINR (Dubna)

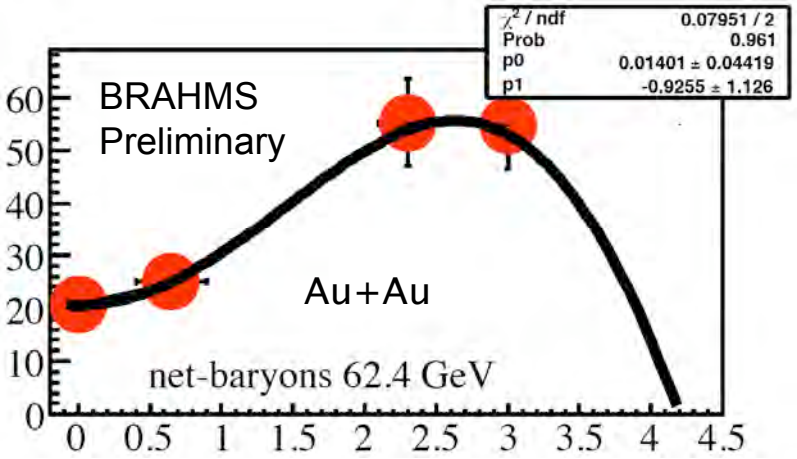


Colliding beams up to U+U @ $\sqrt{s_{NN}}$=7 GeV

Design ongoing

Images courtesy of V.Toneev

Scanning in Beam Energy and Rapidity



BRAHMS H.H. Dalsgaard QM2008

$\sqrt{s_{NN}}$ = 200 62 17

B/π

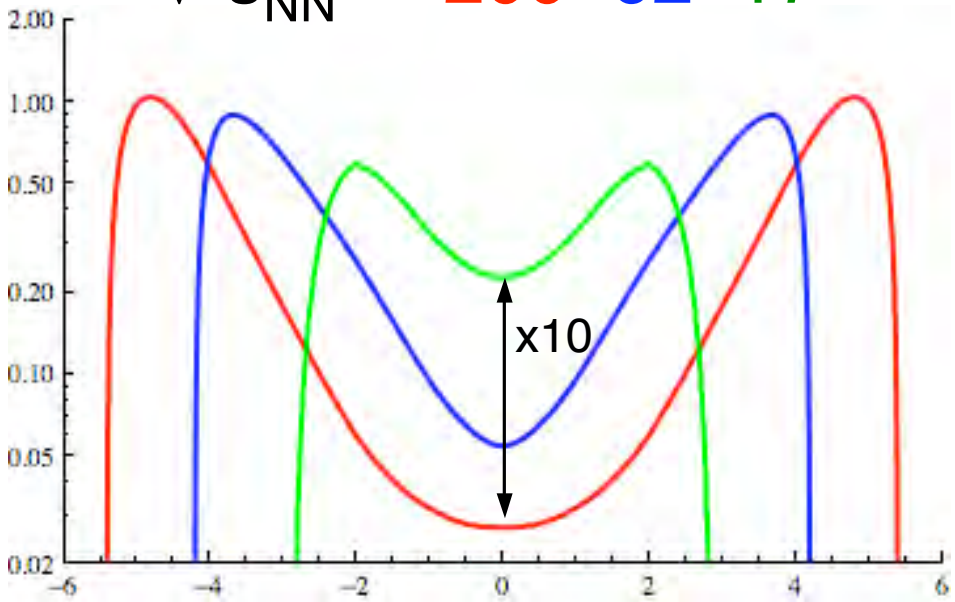


Image courtesy of P.Stankus

Experimental Overview Summary - I

- A broad suite of experiments with high quality detectors and a range of conditions.
  - High rate fixed target
  - Uniform acceptance collider geometry
  - Accelerators optimized for different energy ranges
- It would be wonderful if we are lucky and the critical point is at about 400–500 MeV!
- The upcoming years will see enormous progress

Experimental Overview Summary - II

- Important note #1: Scans at each facility are critical, especially for systematic comparisons. It will be very difficult to conclude anything using isolated data from RHIC @ $\sqrt{s_{NN}}$=20 GeV, SPS @ 15 GeV and FAIR @ 5 GeV

- Important note #2: All experimental efforts are at labs with many competing priorities. The significance of this physics needs to be stressed whenever possible.

What should be measured?

- I'm here to listen and learn but this is what I expect:
  - 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
- Excellent overlap with existing detector capabilities and existing, well understood, analysis techniques.
- Imminent data will encourage us to be more specific.

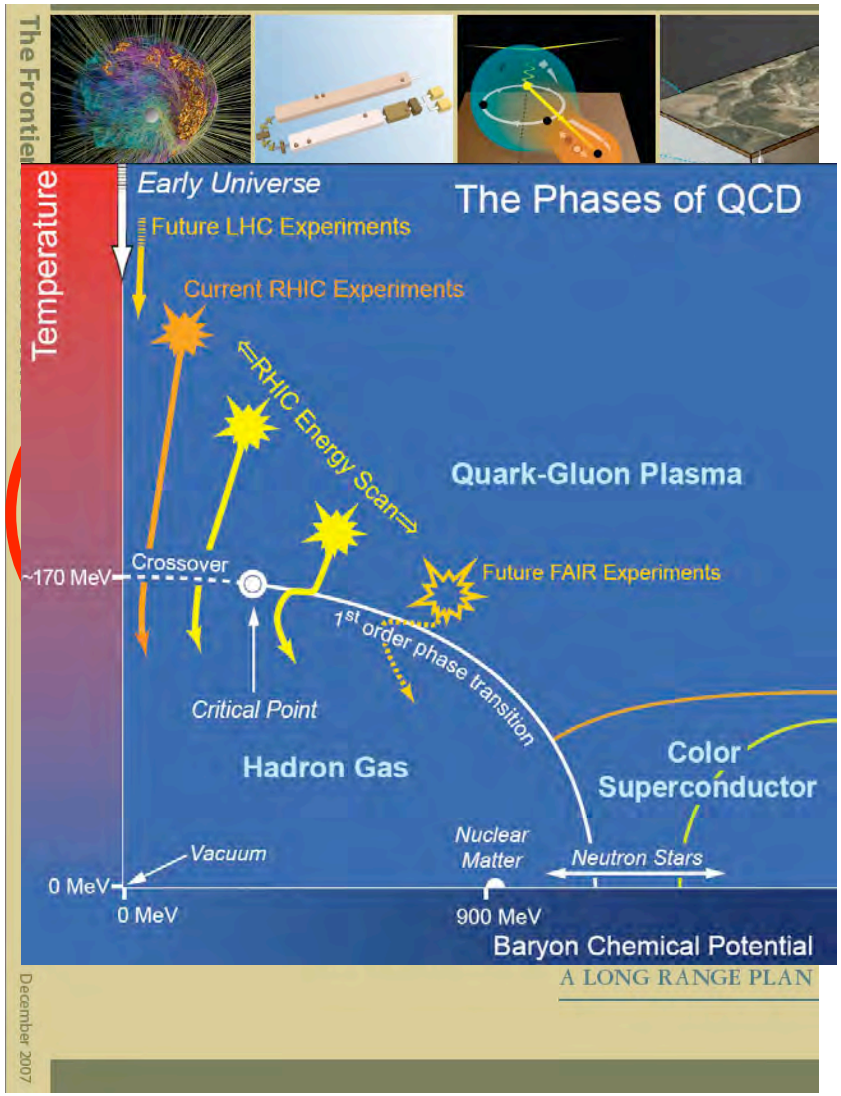
Going out on a limb …

- STAR, PHENIX, NA61, CBM (&MPD?) excel at the currently proposed signals.
- They will also will excel at future proposed signals.
- RHIC specific: Lower energy data will help guide our interpretation and understanding to the same extent as RHIC higher energy data have done.

Additional Details on the Status @ RHIC

By request…

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.

Low Energy @ RHIC: Luminosity is Key

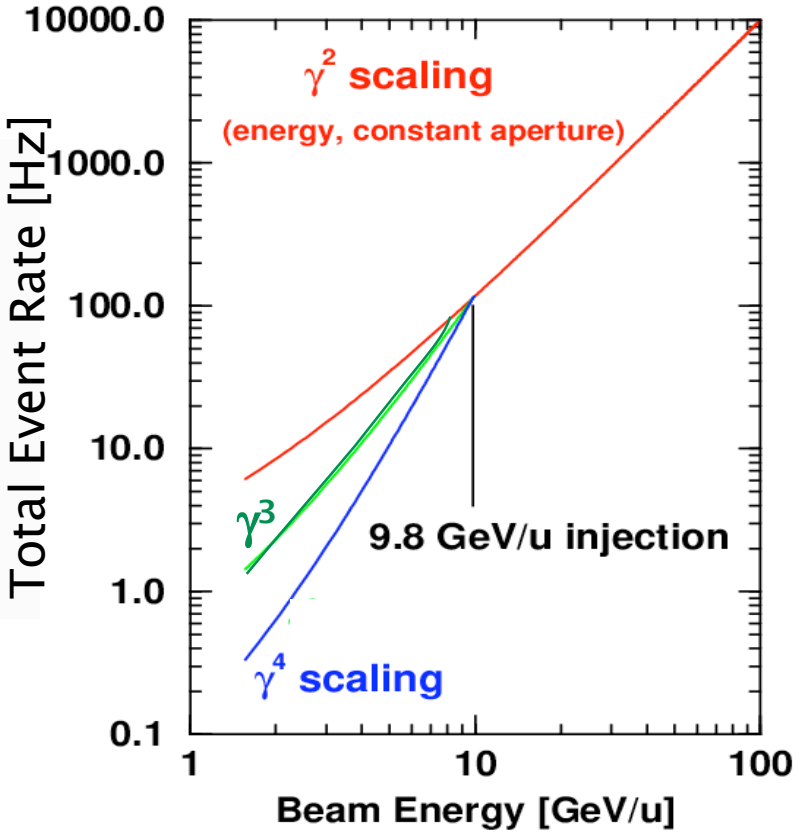


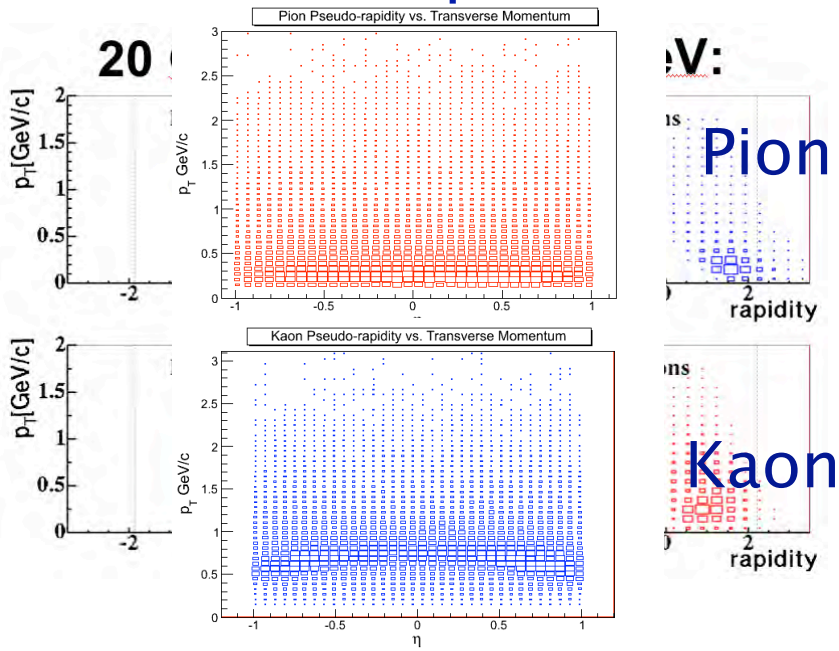
Image courtesy of T.Satogata

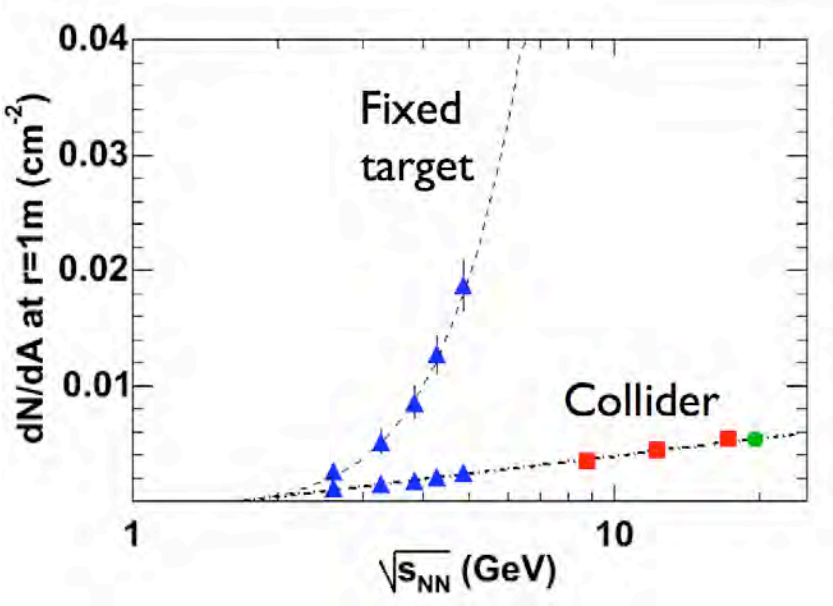
No apparent show-stoppers down to the lowest energies

Electron cooling in RHIC could improve luminosity substantially

Why is a collider a good choice?

STAR acceptance

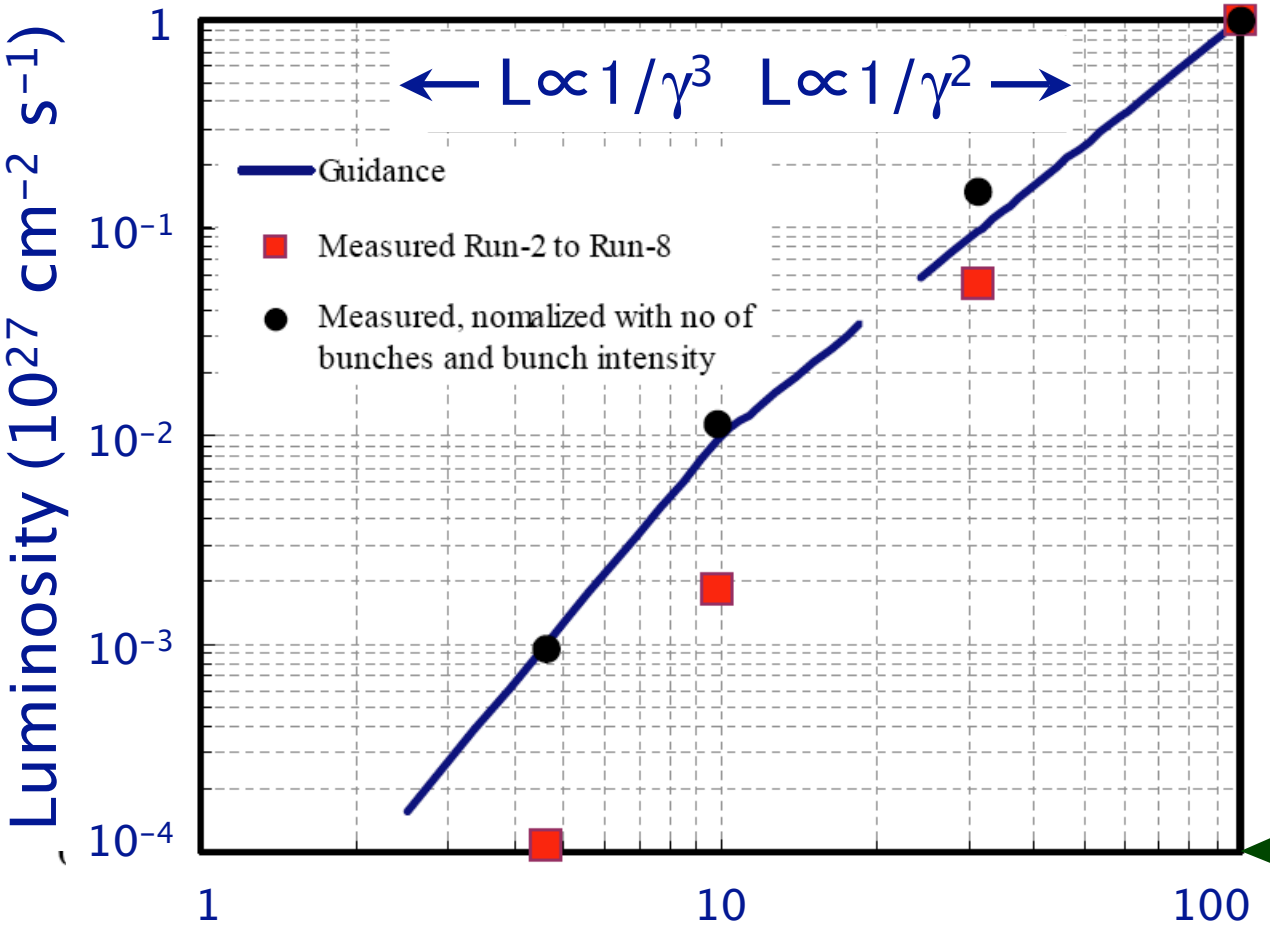




Big advantage that acceptance for collider detectors is totally independent of beam energy

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

Actual Luminosity Scaling With Energy



Current expectation is that $1/\gamma^3$ scaling would hold down to somewhere below ~9 GeV but not all the way to ~5 GeV.

← ~ 1 event/sec

Image courtesy of T. Roser

RHIC @ Low Energy: Luminosity Options

- Standard techniques:
  - Use all bunches (×2+), put more beam in each bunch (×3–6).
  - Spend more time on tuning for maximum performance (×1.5?).
- Top-off mode:
  - Replace 1–4 RHIC bunches every AGS cycle (×2–3).
- E-cooling in RHIC:
  - Use partly existing equipment built for full energy cooling R&D.
  - Expect ×3 (×6) improvement at $\sqrt{S_{NN}}$~5 (~12) GeV, more if not limited by space charge.
- Always new ideas…
  - Possibly using 56 RF cavity upgrade (2011, ×2+).

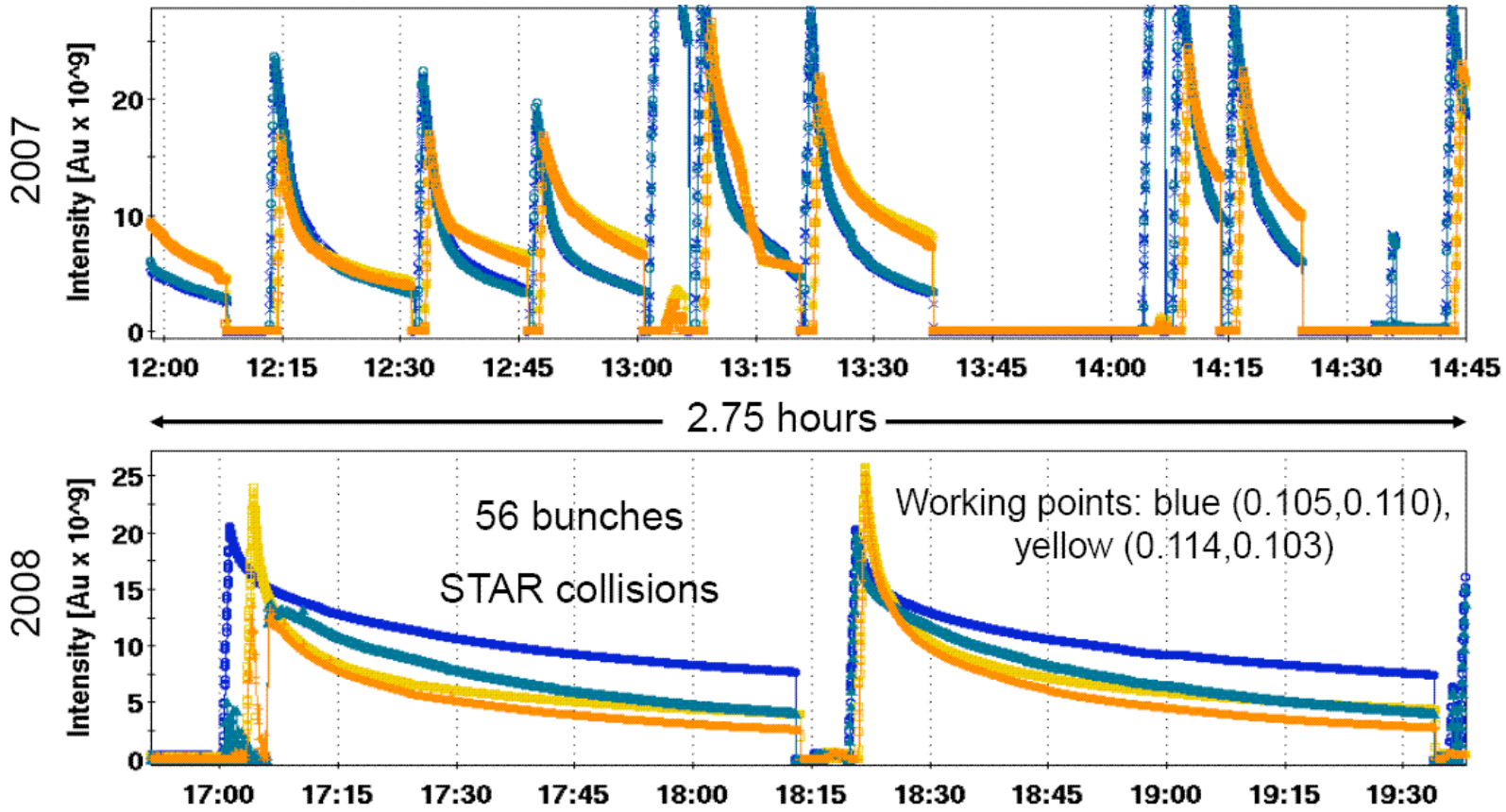
Early Low Energy Beam Tests @ RHIC

- 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 @ RHIC

- 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 (if the accelerator physicists don't fix it first…).
- 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.

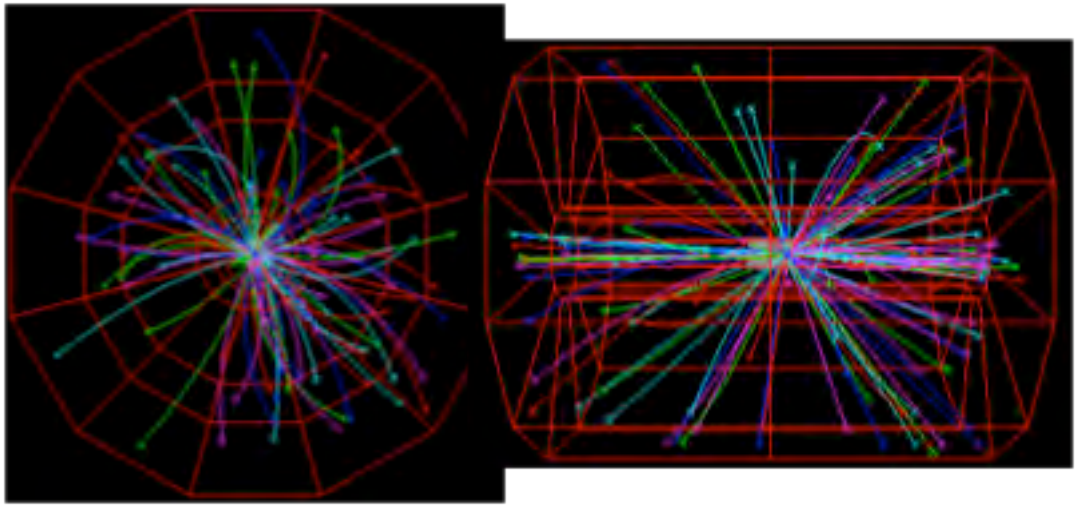
Au-Au operation in RHIC @ $\sqrt{s_{NN}}$=9 GeV

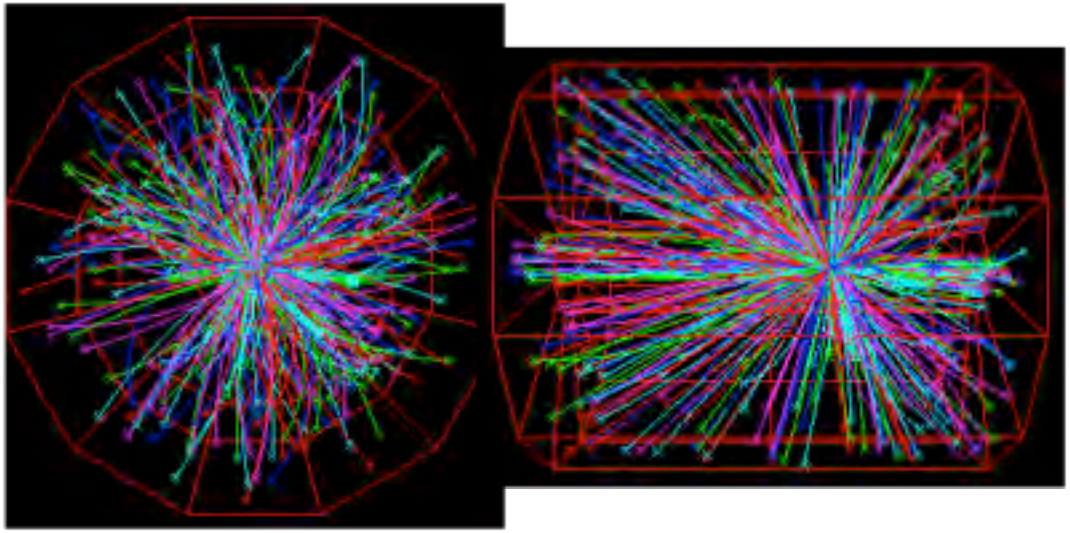


- 2008 blue beam lifetime: 3.5 minutes (fast), 50 minutes (slow)
- Sextupole reversal and elimination of octupoles clearly helped beam lifetime
- Injection efficiency and yellow beam lifetime can clearly benefit from further tuning

Image courtesy of T.Satogata

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

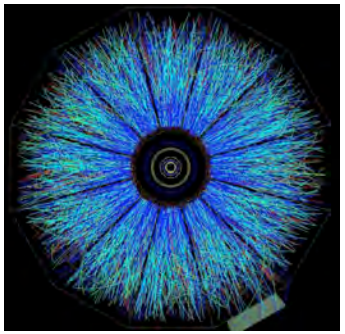




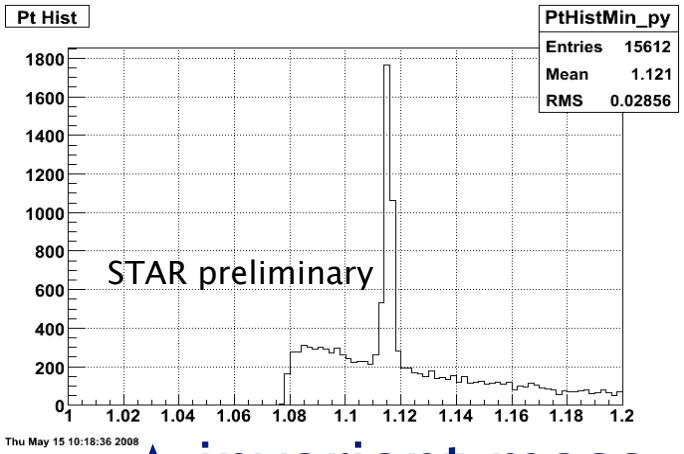
Unambiguous beam-beam collisions!

~3500 good events

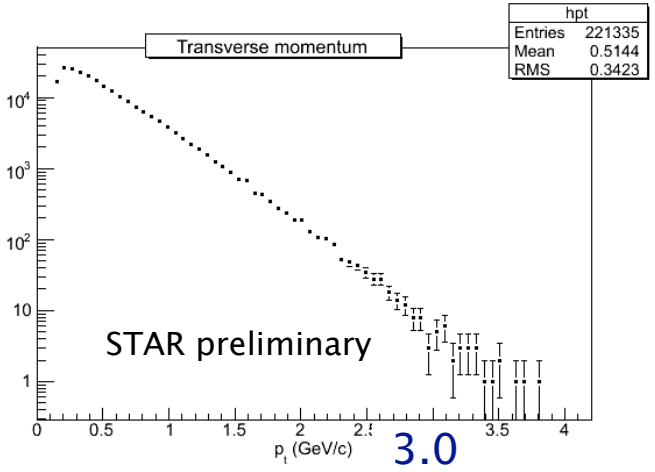
$\sqrt{s_{NN}}$ = 200 GeV



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

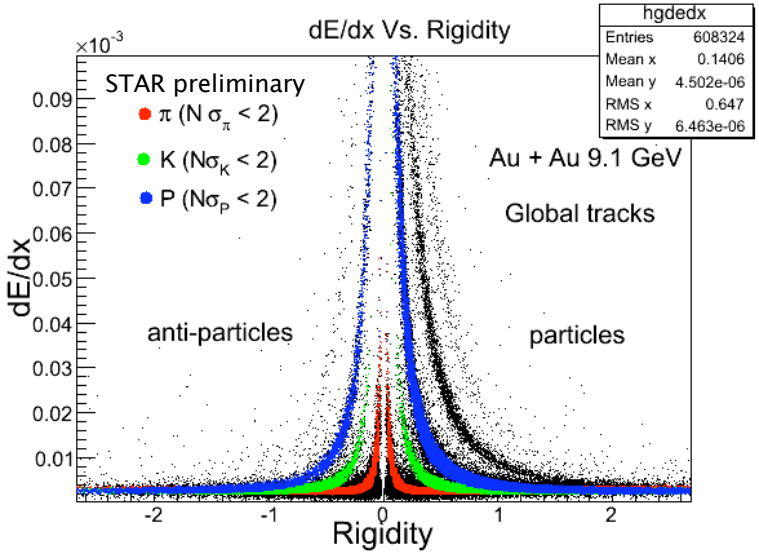


Λ invariant mass



Uncorrected $p_\perp$ spectra

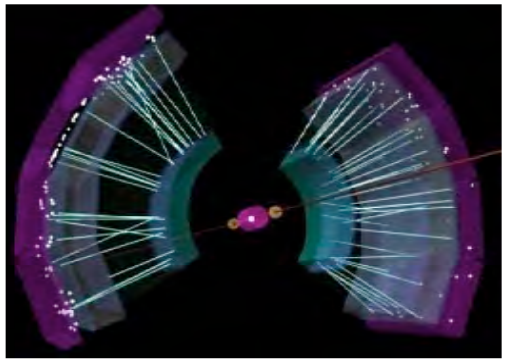
Note: Plots should be taken only as illustrative of data quality and analysis capability

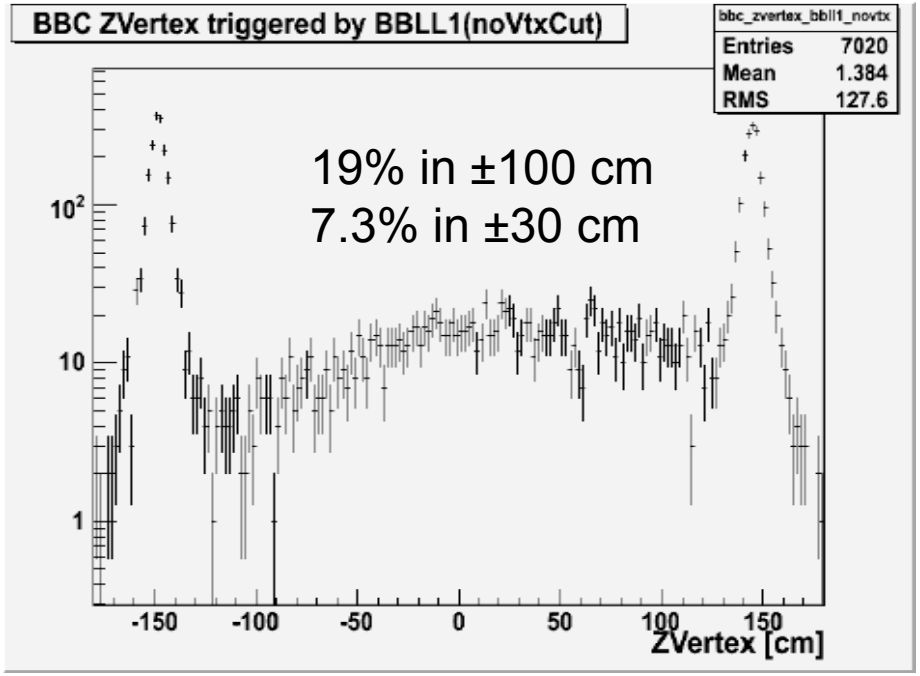


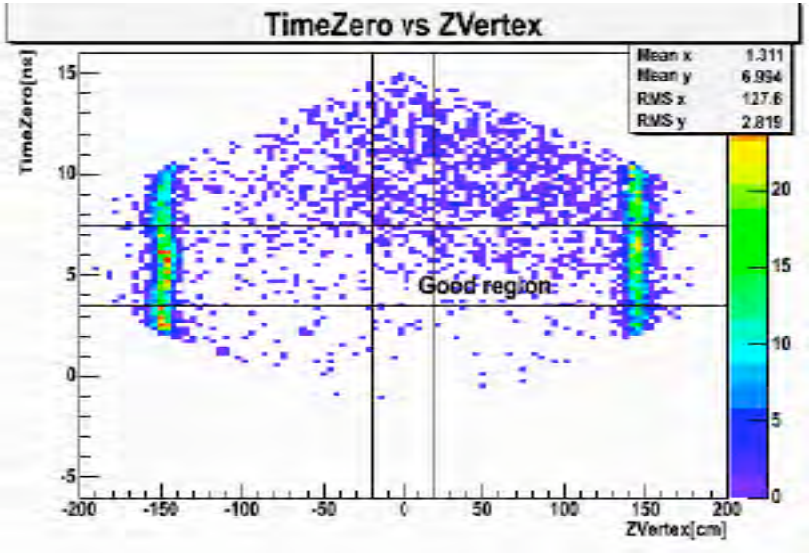
PID (dE/dx only)

3.0

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







Images courtesy of M.Leitch

Early Energy Scans

- Should aim to cover a wide range.
  - $\sqrt{s_{NN}}$ from ~6 to ~40 GeV possible at RHIC.
    - Lowest energies (down to ~5?) require further development.
  - Lower energies will focus on phase transition properties, higher ones will focus on disappearance of the partonic medium.
  - Energy choices will be modified if theoretical guidance appears.
- 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.

Early Energy Scans

- Guaranteed results:
  - Narrow down the region where exotic medium effects disappear.
  - Clarify and significantly expand our understanding of the existing mysteries in data from low to mid range energies.
  - If not a major discovery (likely but cannot guarantee :-), at the very least provide extensive guidance both to theory and to the planning of the next step in the experimental program.

Farther Future Scans

- Use the results of the first scans to focus on the most interesting specific energy ranges
  - RHIC specific: Luminosity upgrades at the lowest energies *unless* first scan indicates those regions are not useful.
- Guaranteed results: To be predicted once data from the first scan is analyzed.

Some Closing Thoughts

- On the verge of a vast expansion of the experimental exploration of the QCD phase diagram.
  - High quality detectors using a variety of techniques (such as fixed target versus colliding beams) to attack this problem from a variety of directions.
- Evolution (and eventual disappearance) of partonic effects will be studied.
- Mysteries in existing data will be solved.
- QCD theory is suggestive that a critical point exists.
  - As a challenge to theorists: Do we have an opportunity to settle the question with data first?