PHENIX of the Future

Ed O'Brien

2007 RHIC/AGS Users Meeting

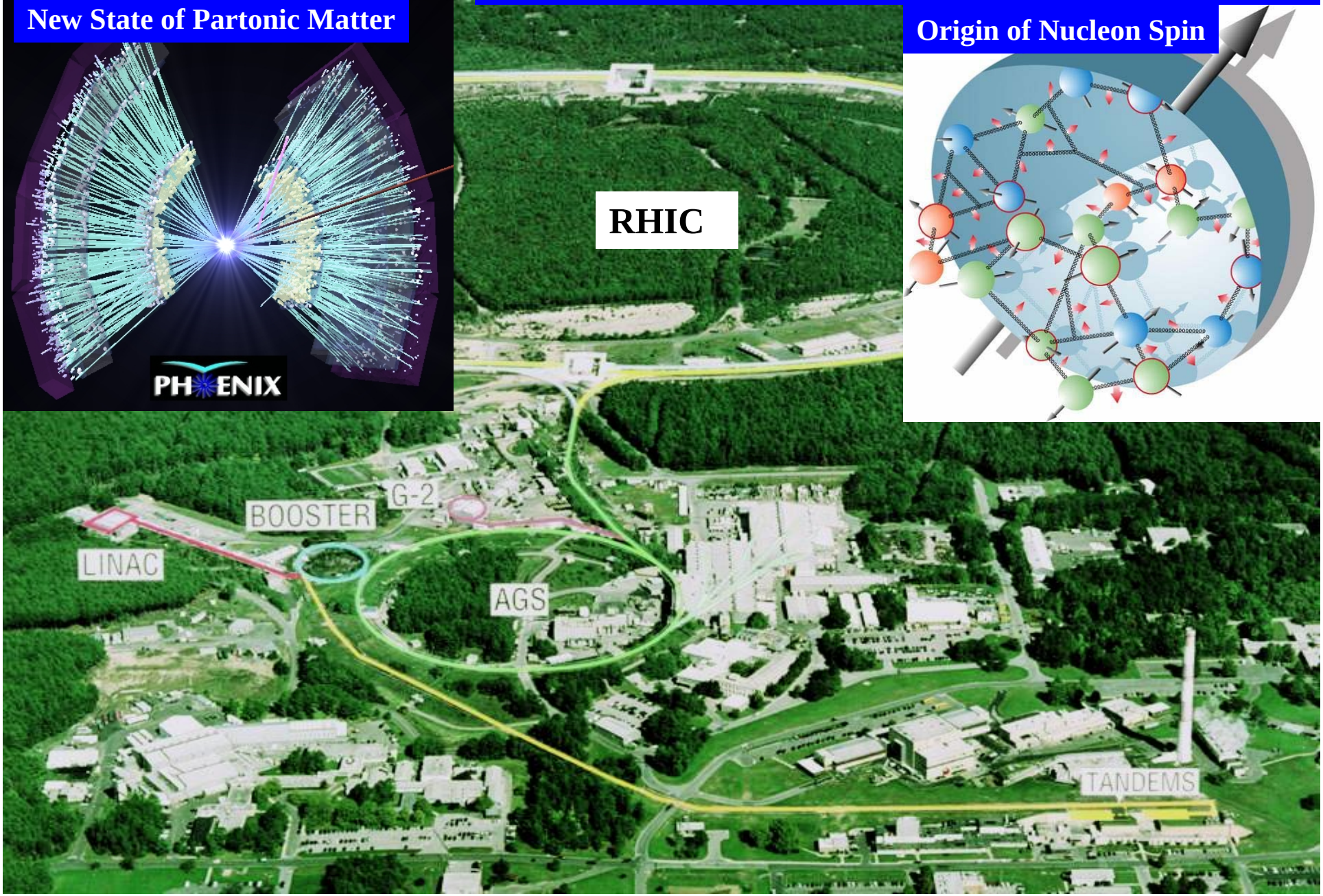
June 22, 2007

Brookhaven National Lab

The RHIC Physics Program

New State of Partonic Matter

Origin of Nucleon Spin



The PHENIX Detector (2007 Run)

- Detector Redundancy
- Fine Granularity, Mass Resolution
- High Data Rate
- Good Particle ID
- Limited Acceptance

Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)

Particle ID:

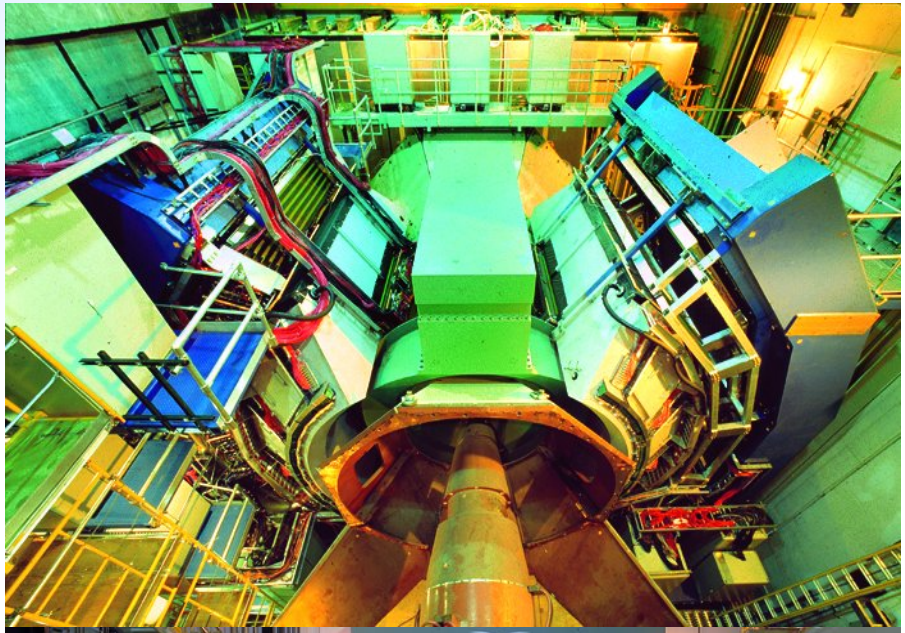
- Time of Flight (East and West)
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Hadron Blind Detector

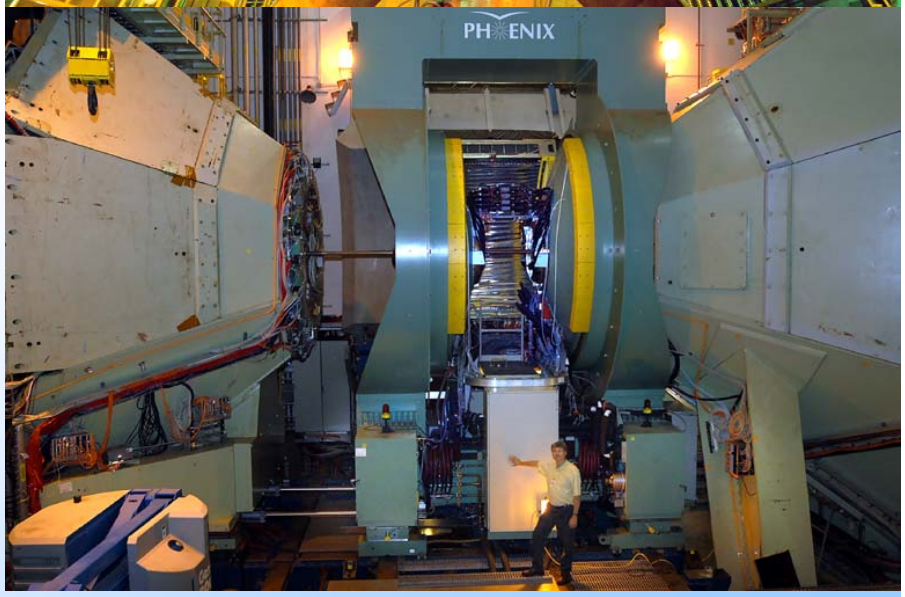
Calorimetry:

- Pb Scintillator
- Pb Glass
- Muon Piston Calorimeter

Event Characterization:

- Reaction Plane Detector
- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter





The RHIC Run History

The RHIC machine performance has been very impressive:

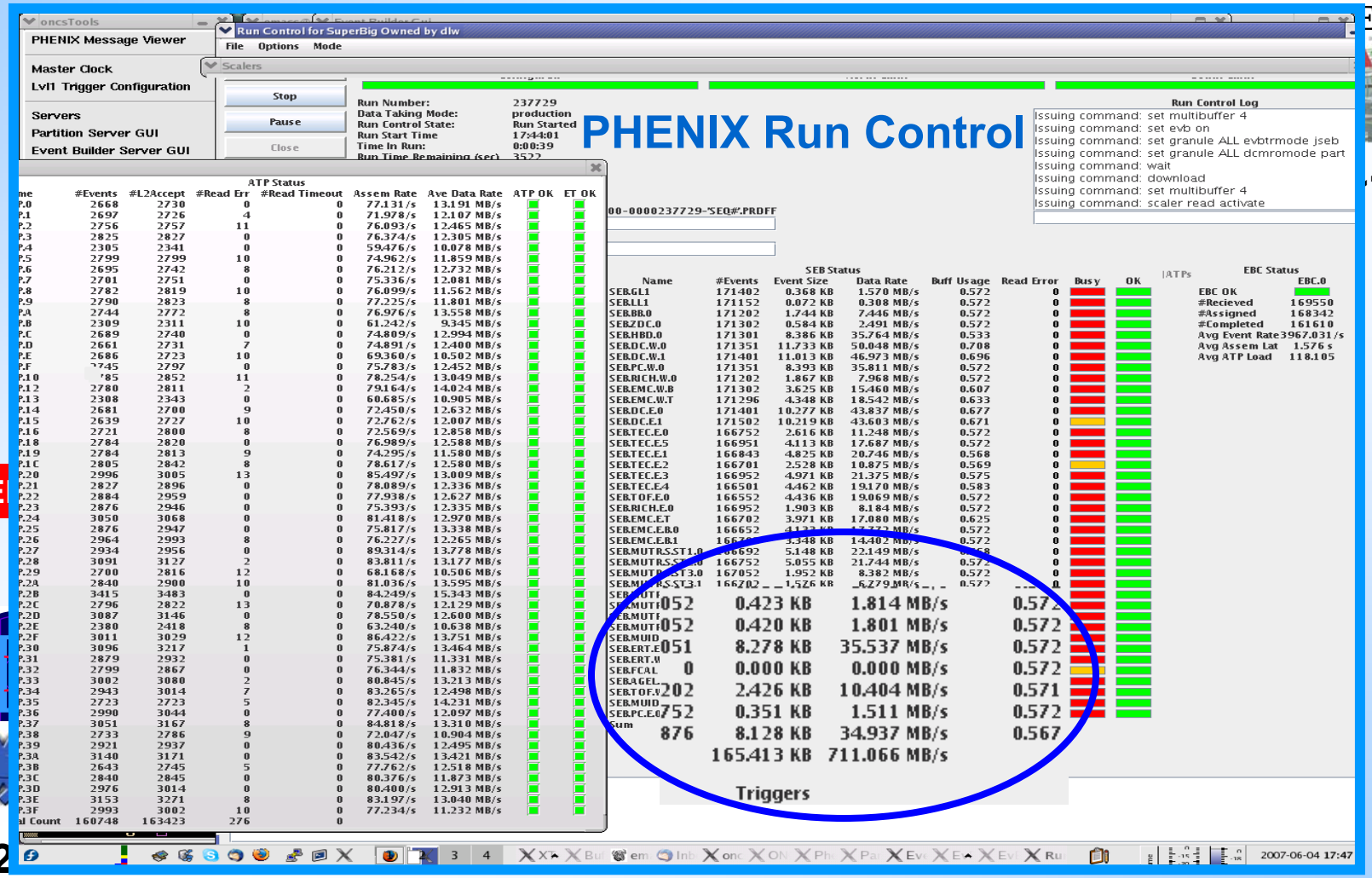
- Collided 4 different species in 7 years
  - AuAu, dAu, pp, CuCu
- 6 energies run
  - 9.2 GeV, 19 GeV, 22.5 GeV, 62.4 GeV, 130 GeV, 200 GeV

Most machine design luminosity specs have been surpassed !

PHENIX	Year	Species	$s^{1/2}$ [GeV]	∫Ldt	N_{tot} (sampled)	Data Size
Run1	2000	Au-Au	130	1 μb^{-1}	10 M	3 TB
Run2	2001/02	Au-Au	200	24 μb^{-1}	170 M	10 TB
		Au-Au	19	------	<1 M	
		p-p	200	0.15 pb^{-1}	3.7 G	20 TB
Run3	2002/03	d-Au	200	2.74 nb^{-1}	5.5 G	46 TB
		p-p	200	0.35 pb^{-1}	6.6 G	35 TB
Run4	2003/04	Au-Au	200	241 μb^{-1}	1.5 G	270 TB
		Au-Au	62.4	9 μb^{-1}	58 M	10 TB
Run5	2005	Cu-Cu	200	3 nb^{-1}	8.6 G	173 TB
		Cu-Cu	62.4	0.19 nb^{-1}	0.4 G	48 TB
		Cu-Cu	22.4	2.7 μb^{-1}	9 M	1 TB
		p-p	200	3.8 pb^{-1}	85 G	262 TB
Run-6	2006	p-p	200	10.7 pb^{-1}	233 G	310 TB
		p-p	62.4	0.1 pb-1	10 G	25 TB
Run-7	2007	Au-Au	200	725 μb^{-1}	4.6 G	570 TB

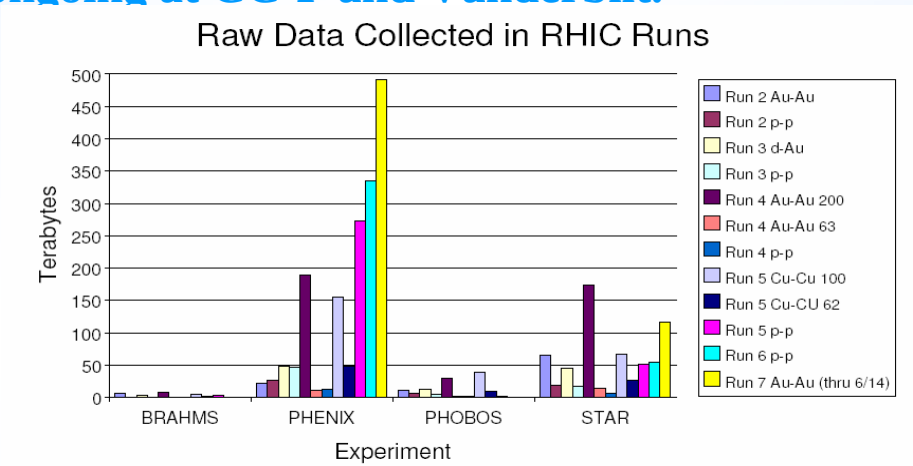
Transferred 0.6 PB of data to Japan via the GRID for Analysis in 2005/06

Comparable Data Archiving Rates



Processing of PHENIX Data

- **Data Production takes place at 5-6 sites**
  - **RHIC Computing Facility, CC-J (RIKEN), CC-F(Ecole Polytechnique), PHENIX Counting House, ORNL, Vanderbilt**
  - **We have made substantial use of the GRID (> 600 TB transferred to Japan)**
- **With the exception of some specialized jobs, data production from earlier runs is complete**
- **We anticipate MB data production for Run-7 will start in the early summer at RCF.**
  - **Preliminary data production for Run-7 is ongoing at CC-F and Vanderbilt.**



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Computing News and Features

PHENIX experiment uses Grid to transfer 270 TB of data to Japan

During the polarized proton-proton run that ended in June at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, Grid tools were used by the PHENIX experiment to send recently acquired data to a regional computing centre for the experiment in Japan. Brookhaven National Laboratory, on Long Island, New York, is home to the RHIC/ATLAS Computing Facility (RCF/ACF), which is the main computing centre for experiments at RHIC and a Tier-1 computing centre for ATLAS. The PHENIX regional computing centre in Japan (CCJ) is at the RIKEN research centre on its Wako campus close to Tokyo.

Going into the polarized proton-proton run, PHENIX faced the challenge that the RCF would be busy reconstructing and analysing gold-gold and copper-copper data recorded in 2004 and 2005. The enormous polarized proton-proton data set was transferred to Japan to make use of the substantial computing resources at CCJ, which is comparable to the PHENIX portion of the RCF.

Data transfer

The PHENIX data acquisition can sustain a peak data rate of up to 600 MB/s, and runs at a typical rate of 250 MB/s while beam is stored in RHIC. The data were buffered at the experimental site before being transferred and archived in the RCF tape library. A 35 TB disk-storage system (about 60 h at typical data rates) allowed PHENIX to archive and transfer data at a lower steady rate, taking advantage of various breaks in the flood of data. A transfer rate of 60 MB/s sustained steadily around the clock was able to keep up with the incoming data stream.

Initially, PHENIX had planned to transfer the polarized proton-proton data by physically transporting tape cartridges to CCJ. During the early part of the run, however, it was found that network transfer rates of 700-750 Mbits/s could be achieved. A dedicated network path was established from the PHENIX counting house to the BNL perimeter network, and the tape option became a fall-back solution. In the end, not a single tape was shipped.

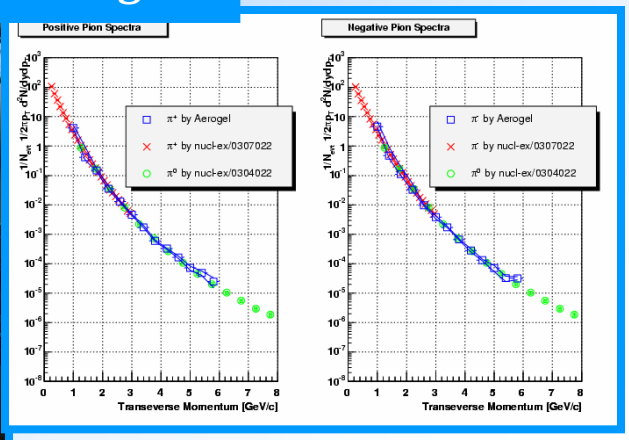
The principal tool used for the transfer was GridFtp, which proved to be very stable. Brookhaven has a high-speed connection (OC48) to ESNET, which is connected to a transpacific line (10 Gbit/s) served by SINET in Japan. Apart from two half-day outages of ESNET, the transfers continued around the clock for the entire 11 week run.

Approximately 270 TB of data (representing 6.8 billion polarized proton-proton collisions) were transferred to CCJ. After a few days of fine-tuning the transfer parameters, the transfers became part of the regular data-handling operation of the PHENIX shift crews, requiring experts to intervene only occasionally.

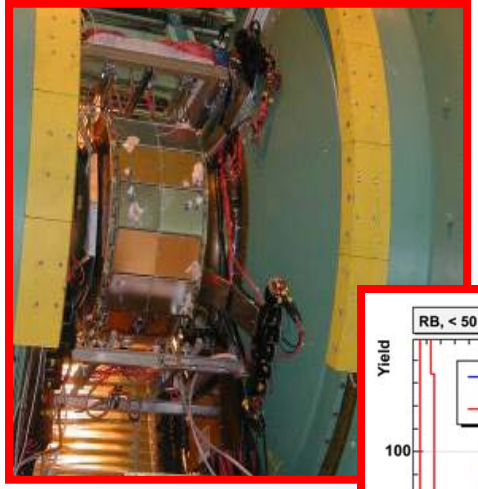
This seems to be the first time that a data transfer of such magnitude was sustained over many weeks in actual production, and was handled as part of routine operation by non-experts. The successful completion of this large-scale transfer project demonstrates both the maturity of today's Grid tools and the real feasibility of integrating remote resources into the data-handling and processing chain of large experiments.

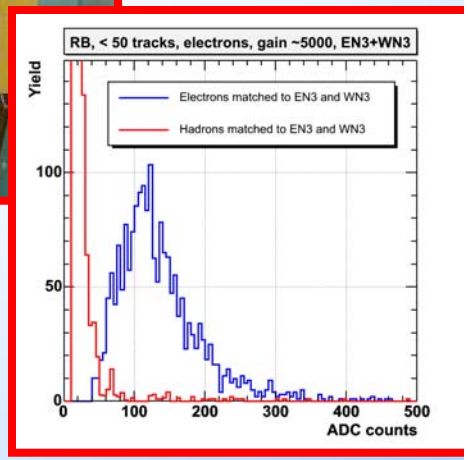
Examples of Recent Progress

Aerogel

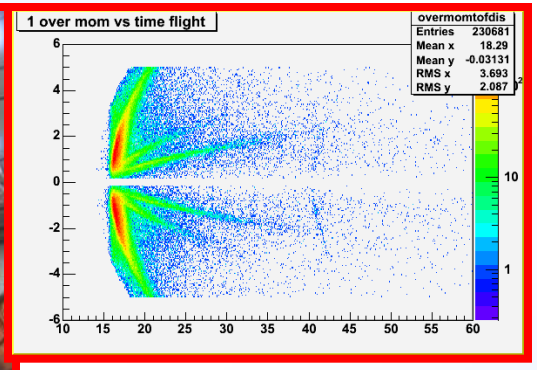


Hadron Blind Detector

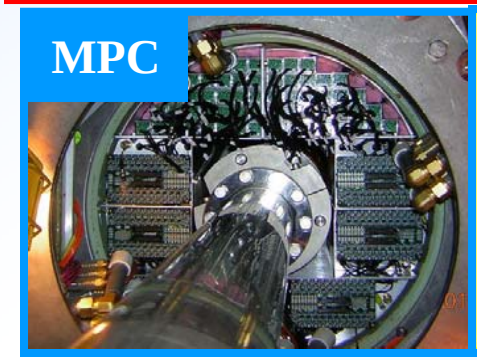


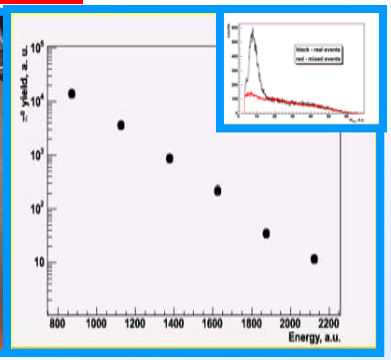


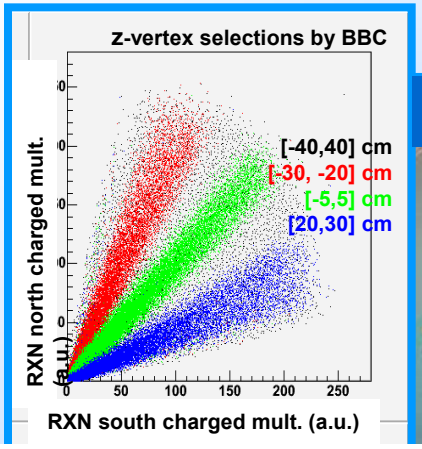
Time of Flight-West



MPC



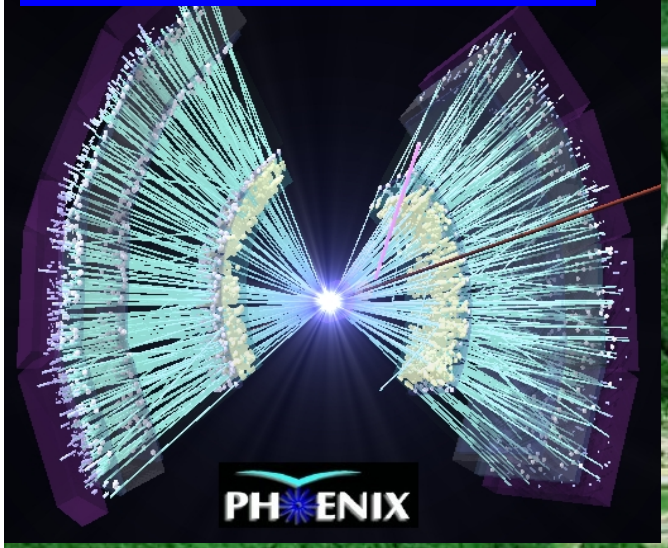




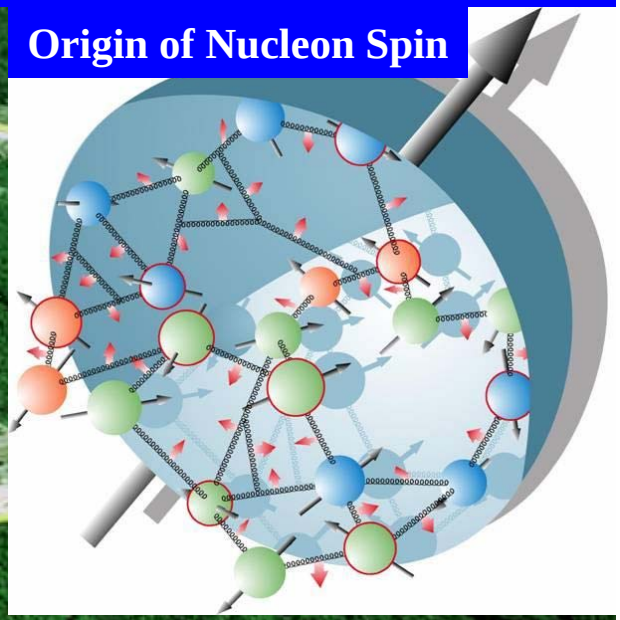
Reaction Plane Detector

The RHIC Physics Program

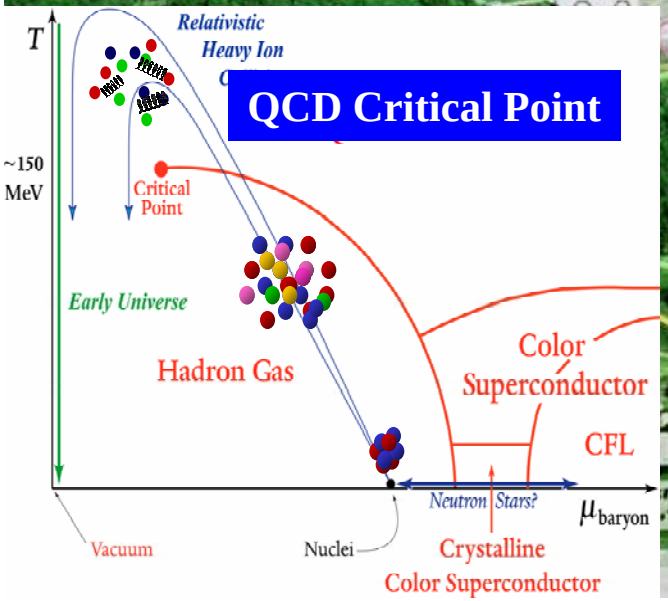
New State of Partonic Matter



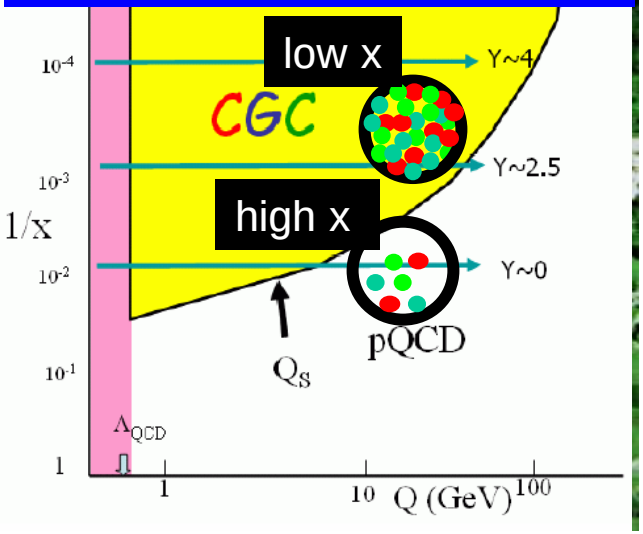
Origin of Nucleon Spin



QCD Critical Point



Gluon Saturation & Color Glass



The Upgraded PHENIX Detector

Charged Particle Tracking:

- Drift Chamber
- Pad Chamber
- Time Expansion Chamber/TRD
- Cathode Strip Chambers(Mu Tracking)
- Forward Muon Trigger Detector (MuTrig)
- Si Vertex Tracking Detector- Barrel (VTX)
- Si Vertex Endcap (FVTX)

Particle ID:

- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Resistive Plate Chamber Time of Flight
- Hadron Blind Detector

Calorimetry:

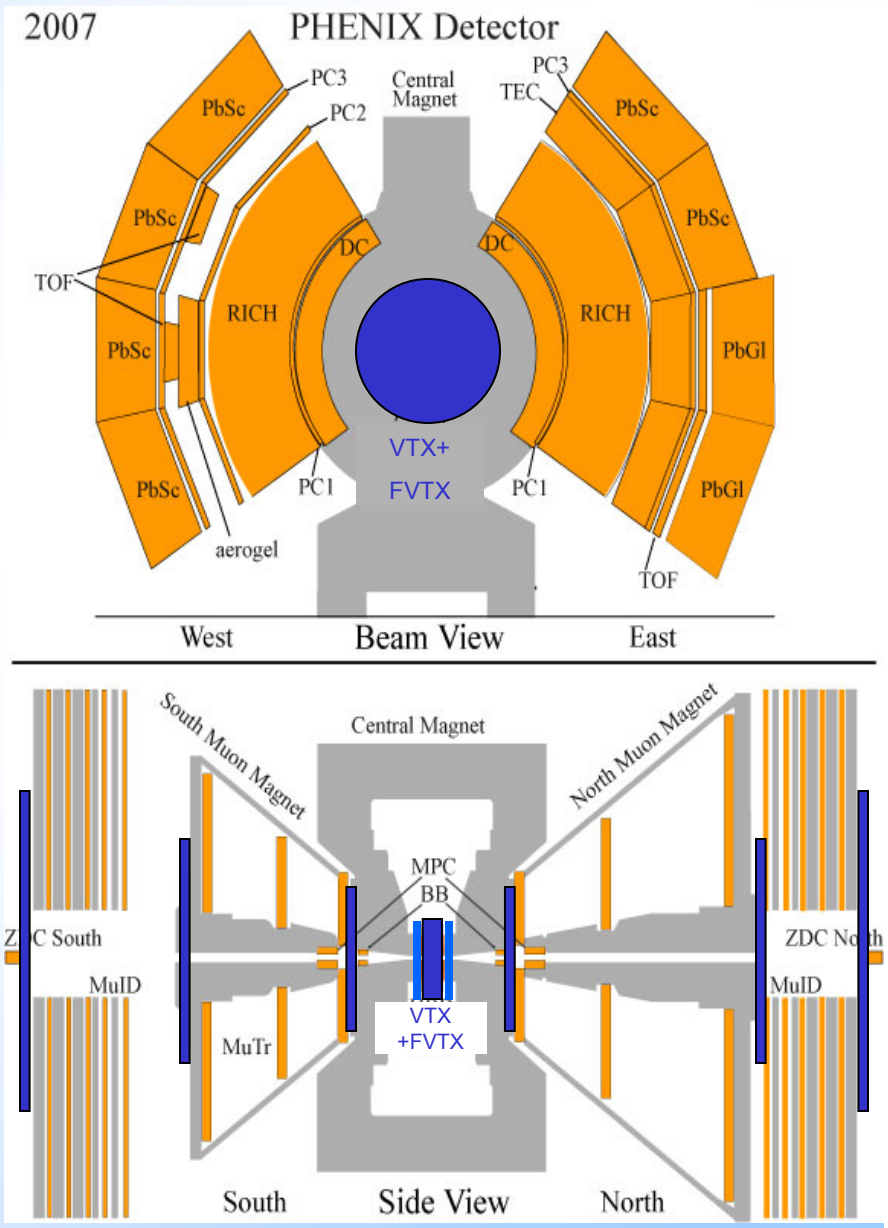
- Pb Scintillator
- Pb Glass
- Nose Cone Calorimeter (NCC)
- Muon Piston Calorimeter

Event Characterization:

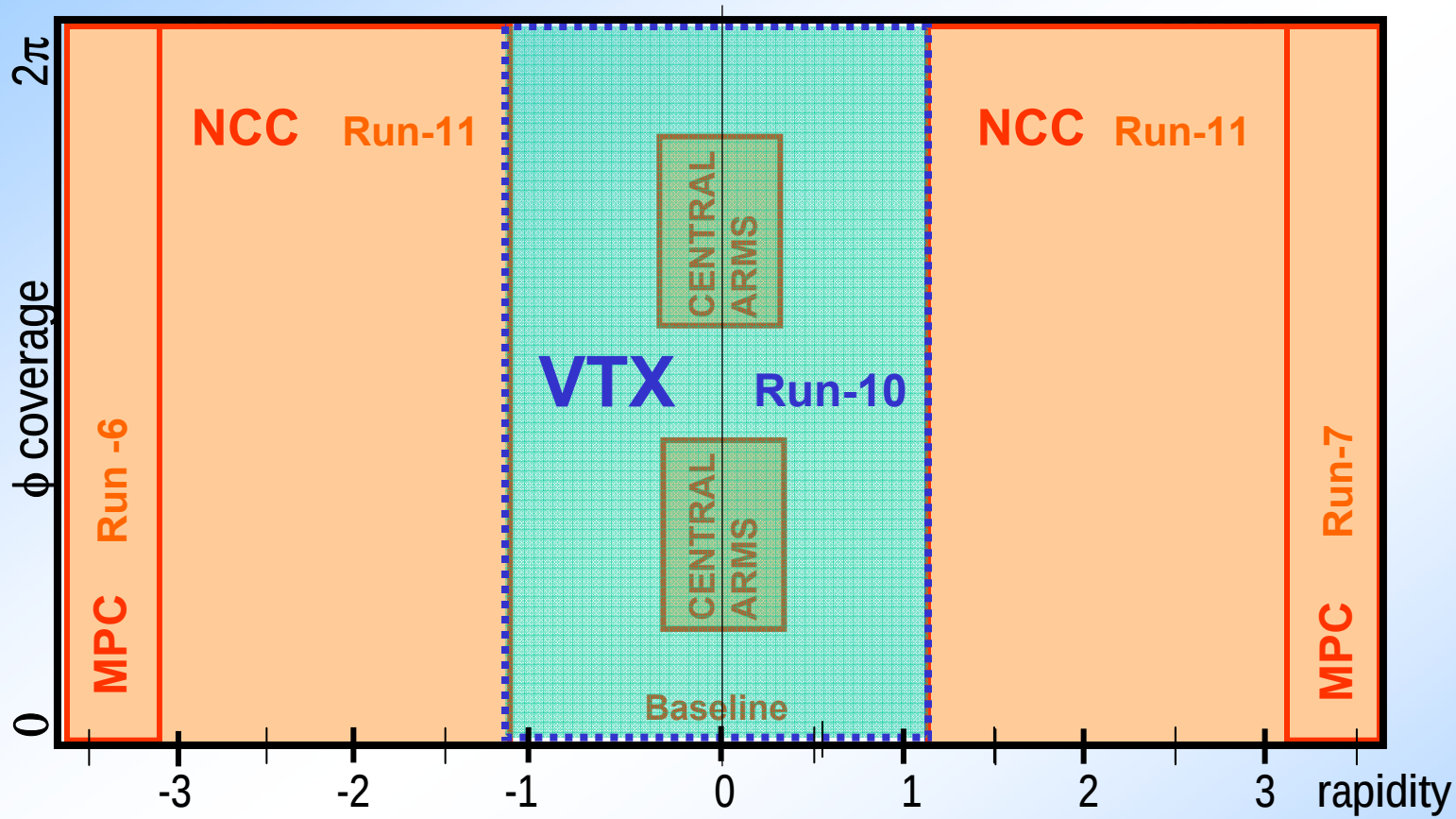
- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter
- Reaction Plane Detector

Data Acquisition:

- DAQ Upgrade



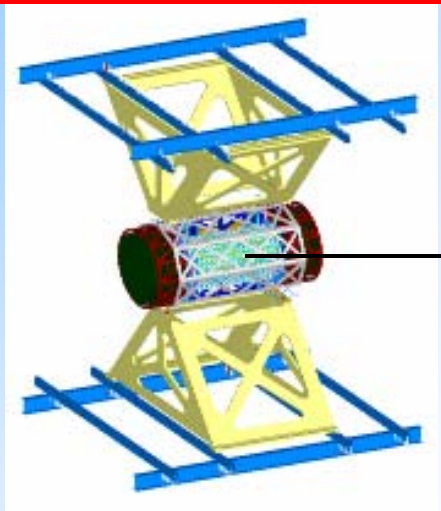
Future PHENIX Acceptance for Hard Probes

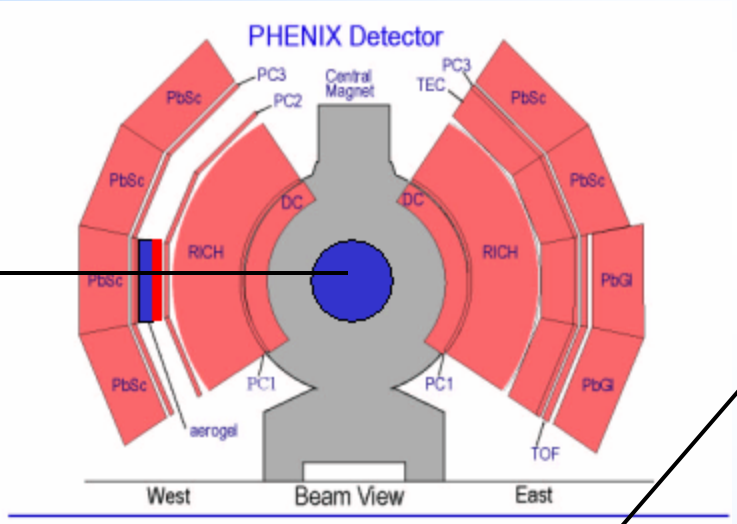


a) Heavy flavor with precision vertex tracking with silicon detectors
b) Direct γ and π^0 with combination of all electromagnetic calorimeters
c) Combine a) & b) for jet tomography with γ-jet

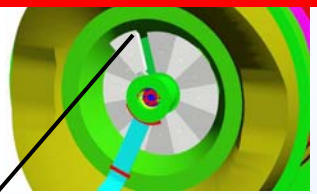
Future Upgrades

Silicon VTX and FVTX

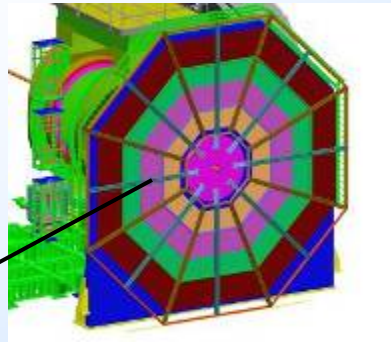


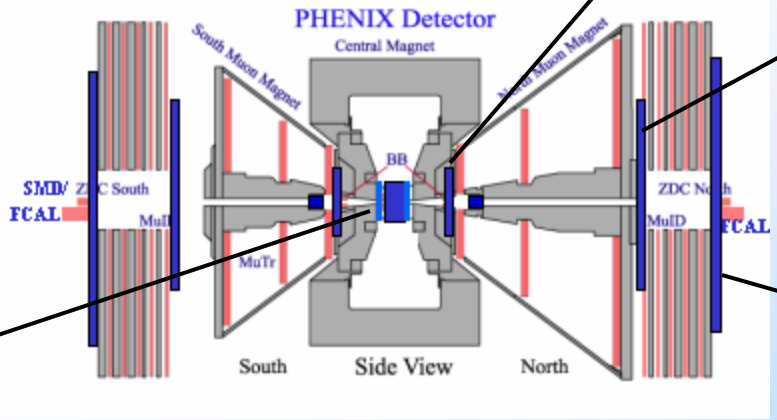


MuTrig Station 1

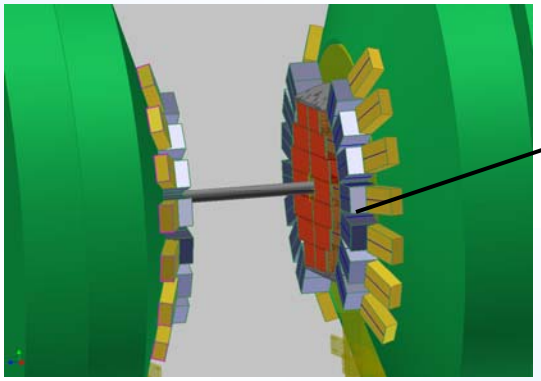


MuTrig Station 2

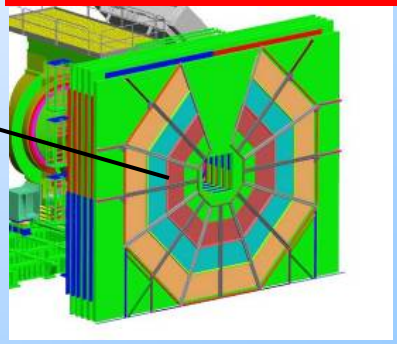




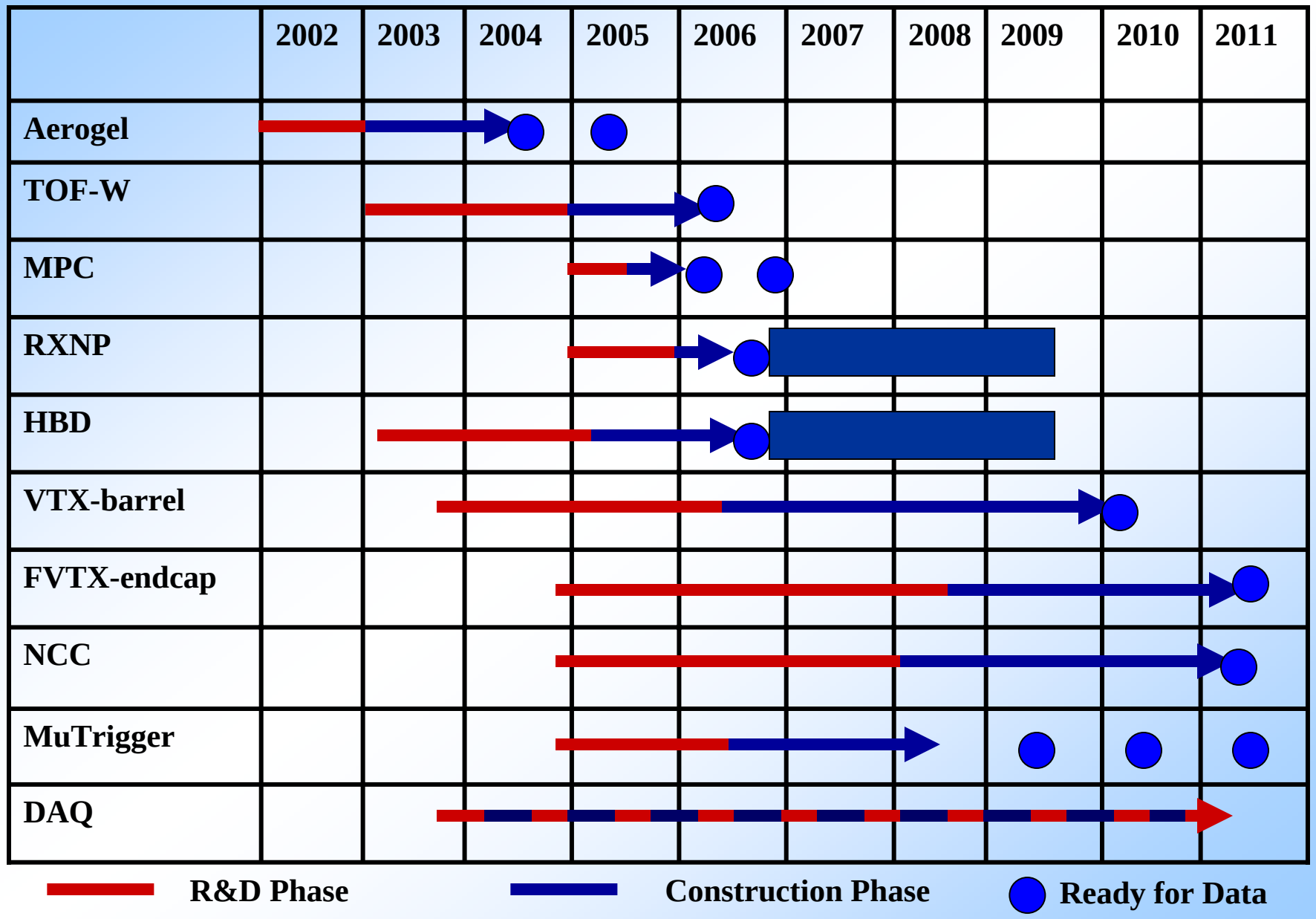
Nose Cone Calorimeter



MuTrig Station 3



Upgrade Schedule Scenario



R&D Phase Construction Phase Ready for Data

RHIC Physics Program

Heavy Ion Physics:

- **QCD Phase Transition: new state of partonic matter (sQuark Gluon Plasma)**
  - Global ($dN/d\eta$, HBT, E_T, fluctuations)
  - Particle Spectra and ratios
  - Photons and Thermal Radiation (including e^+e^- continuum)
  - Azimuthal Anisotropy (v2)
  - J/Ψ Production/ Absorption
  - Energy Loss, R_{AA}
  - Jet Modifications
  - Heavy Quark/Open Charm

Polarized Protons:

- **Nucleon Spin**
  - Gluon spin: ΔG
  - W-parity sea quark spin: Δubar, Δdbar
  - Nucleon transverse spin distr., transversity

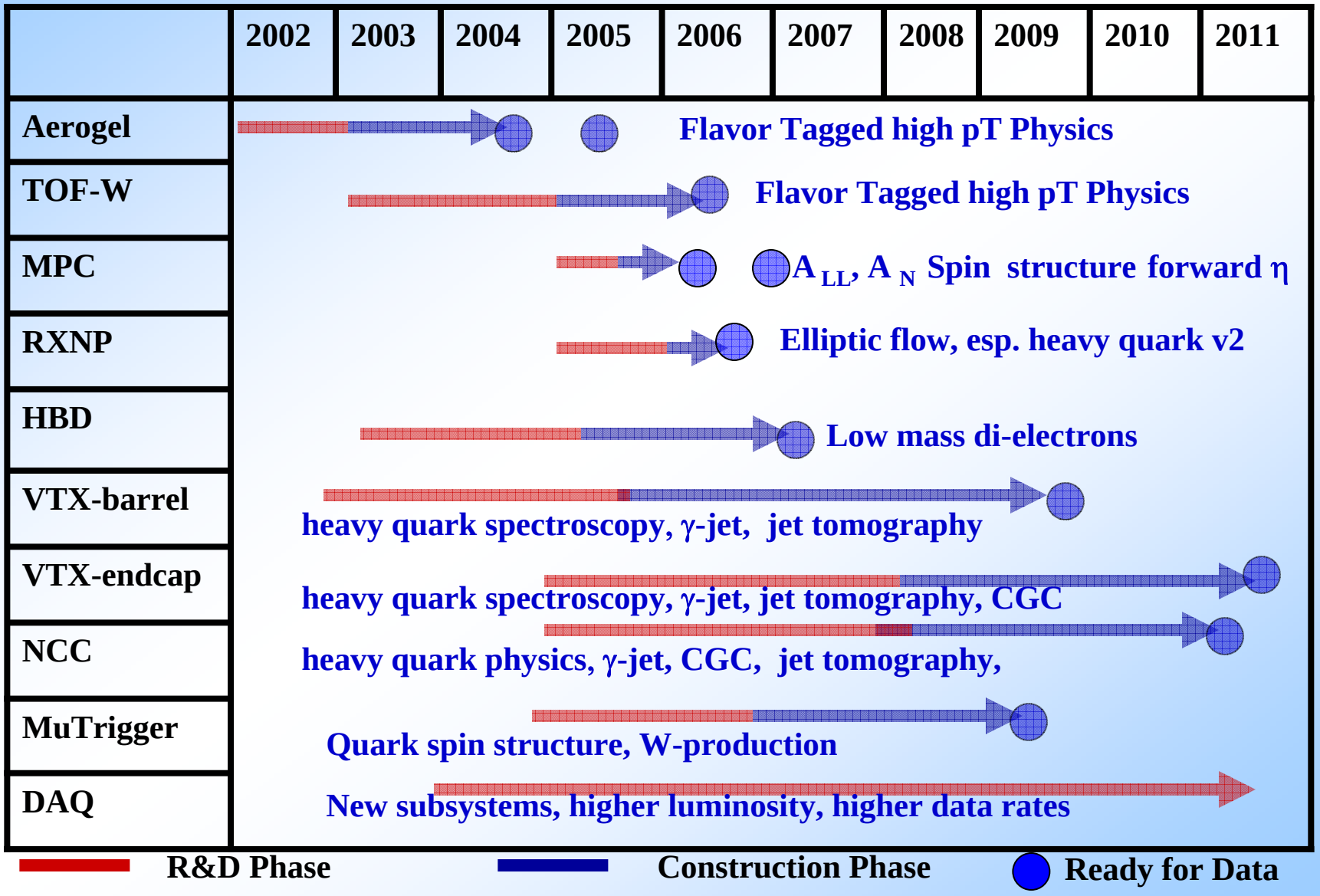
Proton-Nucleus:

- **Structure function physics**
  - Gluon saturation
  - Shadowing, anti-shadowing…
  - Color Glass Condensate
  - Cold nuclear physics (Cronin effect)

Search for the QCD Critical Point:

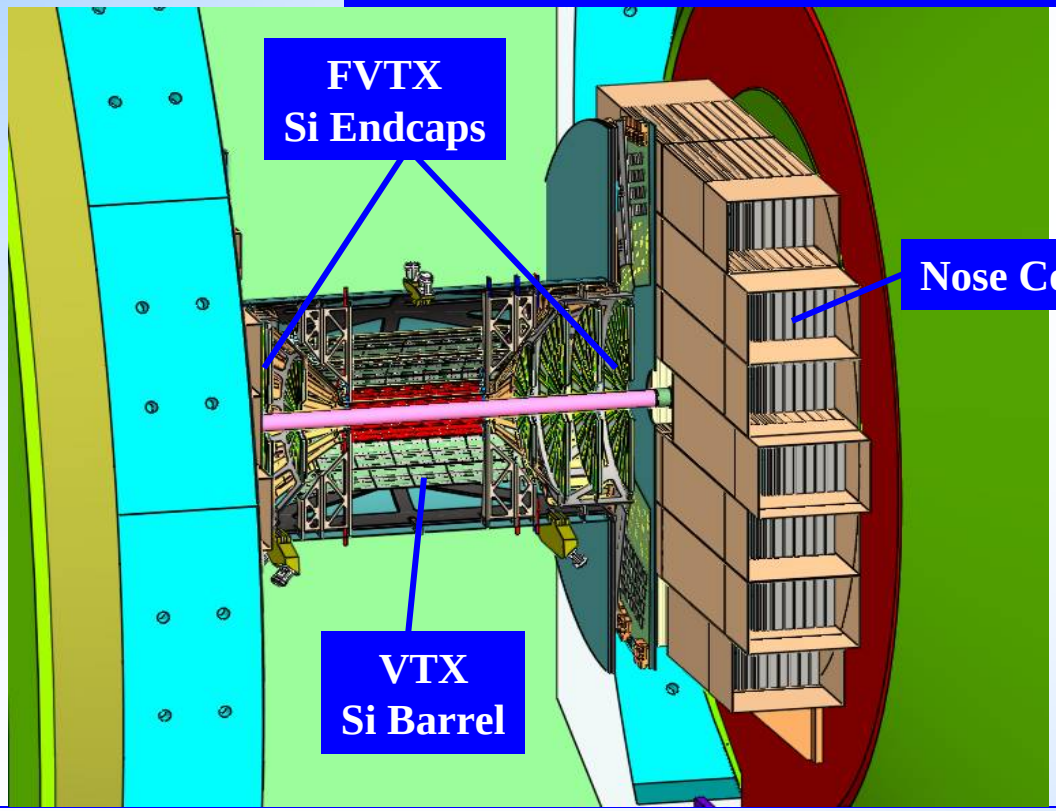
- **Is there a QCD Critical Point and if so where is it (T, μ_B) ?**
  - Global (Correlation functions, Fluctuations $\langle n \rangle$, $\langle p_T \rangle$)
  - Particle spectra and ratios
  - e^+e^- continuum
  - Azimuthal Anisotropy (v2), v2 scaling with quark number
  - Energy Loss, R_{AA}
  - Jet Modification, shape of away-side peak

Upgrade Physics



R&D Phase Construction Phase Ready for Data

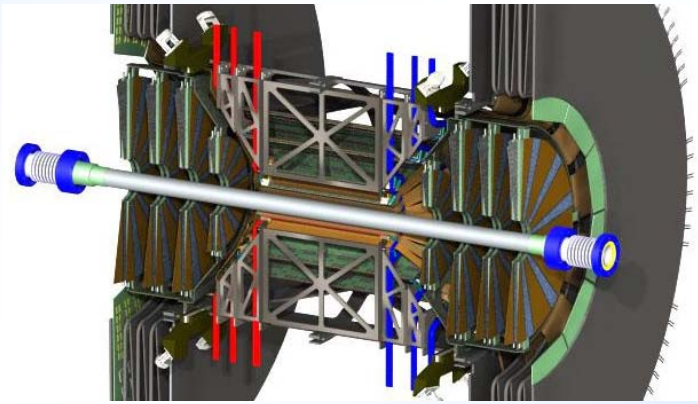
PHENIX Upgrades



The VTX, FVTX and NCC both individually and in combination make the following measurements possible:

- **Heavy quark behavior (c, b quark characteristics in dense medium)**
- **Charmonium spectroscopy (J/ψ, ψ' , χ_c and Υ)**
- **Gluon spin structure ($\Delta G/G$) through g-jet correlations**
- **Transversity**
- **A-, p_T-, x-dependence of the parton structure of nuclei**
- **Gluon saturation and the color glass condensate at low x**

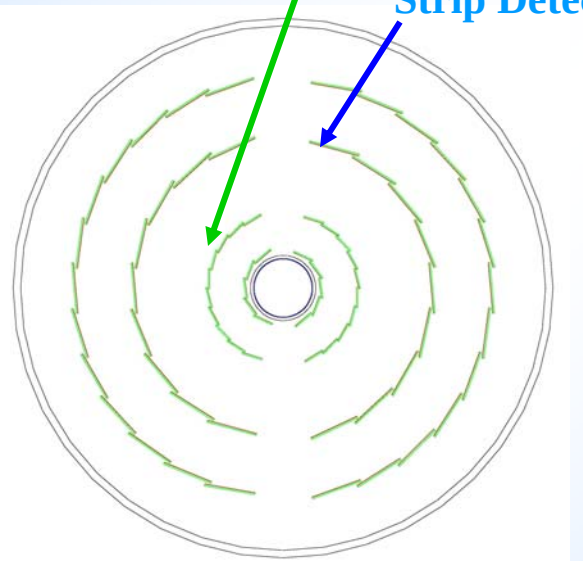
Barrel VTX Detector

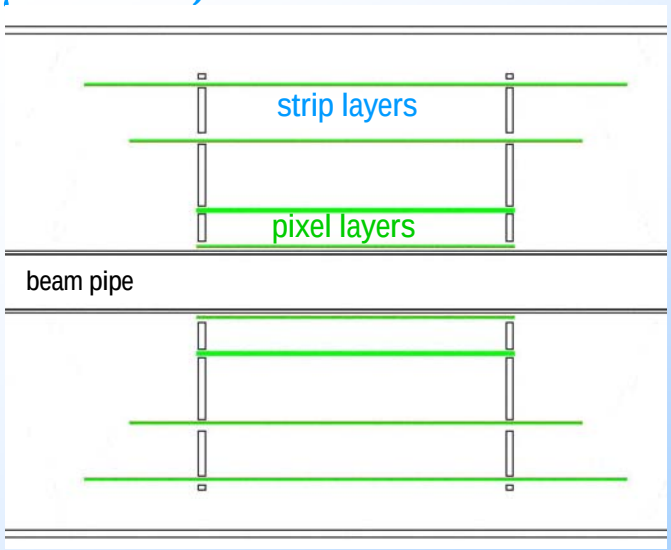


- **Specifications:**
  - Large acceptance ($\Delta\phi \sim 2\pi$ and $|\eta| < 1.2$)
  - Displaced vertex measurement $\sigma < 40\ \mu m$
  - Charged particle tracking $\sigma_p/p \sim 5\%$ p at high pT
  - Detector must work for both HI and pp collisions.
- **Technology Choice**
  - Hybrid pixel detectors developed at CERN for ALICE
  - Strip detectors, sensors developed at BNL with FNAL's SVX4 readout chip

Hybrid Pixel Detectors (50 μm x 425 μm) at R ~ 2.5 & 5 cm

Strip Detectors (80 μm x 3 cm) at R ~ 10 & 14 cm

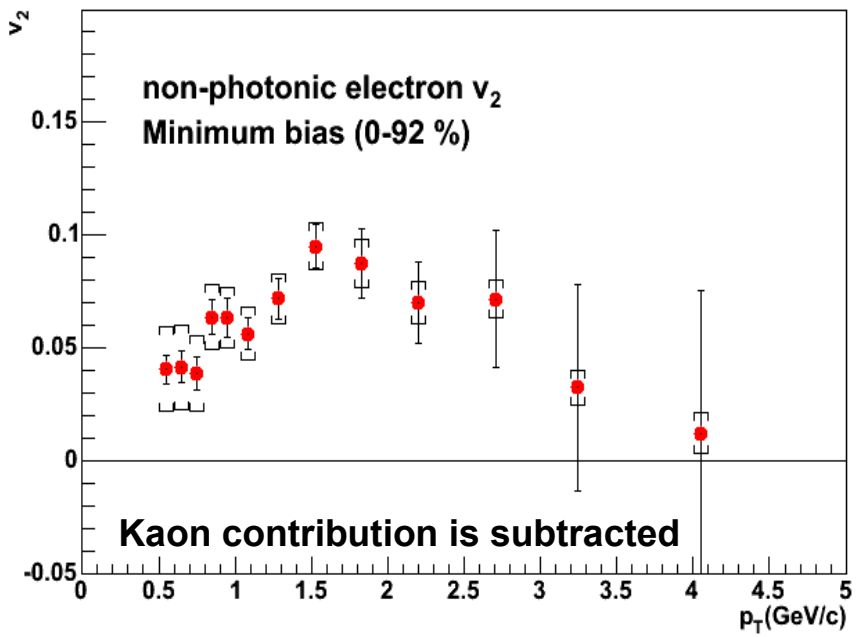




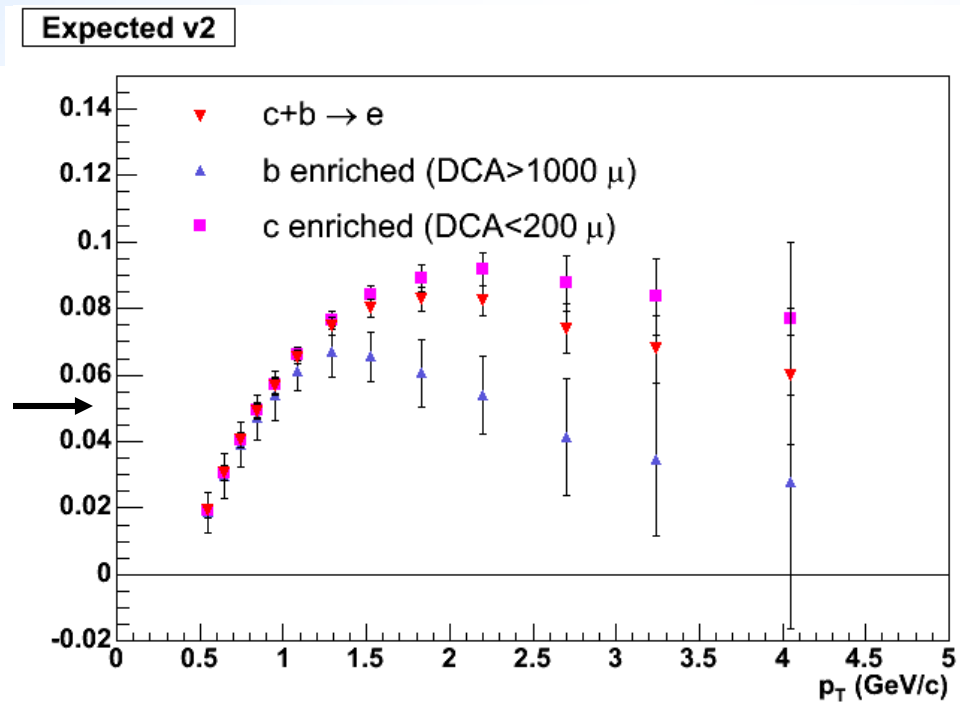
$|\eta| < 1.2$
$\phi \sim 2\pi$
$z \sim \pm 10$ cm

VTX Separation of c, b v2

PHENIX RUN4 preliminary



Expected with VTX @ RHIC (1 RUN)

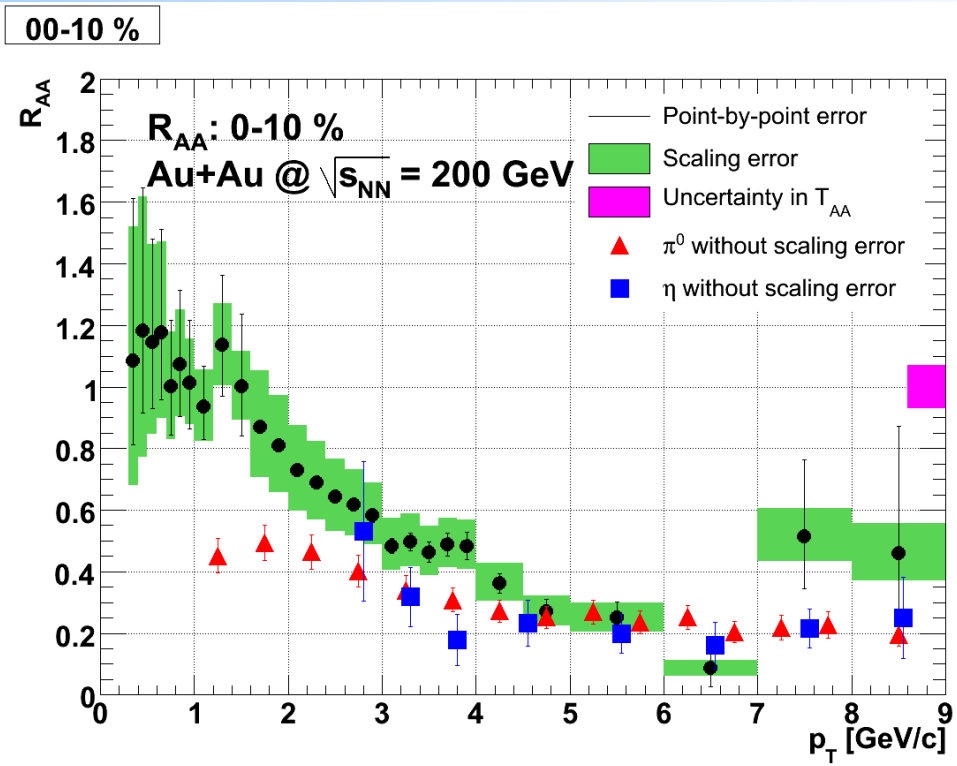


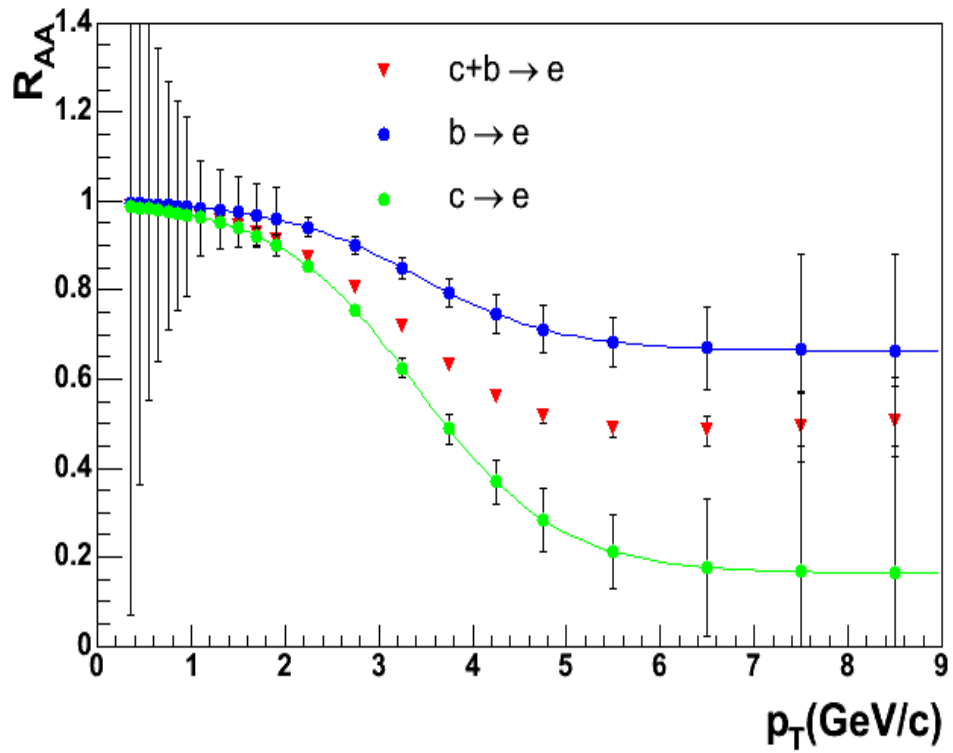
- **v2 of single electron is measured by PHENIX in RUN4**
- **The measured v2 is mixture of b→e and c→e**
- **With VTX, we can separate b→e and c→e component**

VTX Measurement of R_{AA} for c and b

PHENIX RUN4 preliminary

Expected with VTX for first Au+Au run

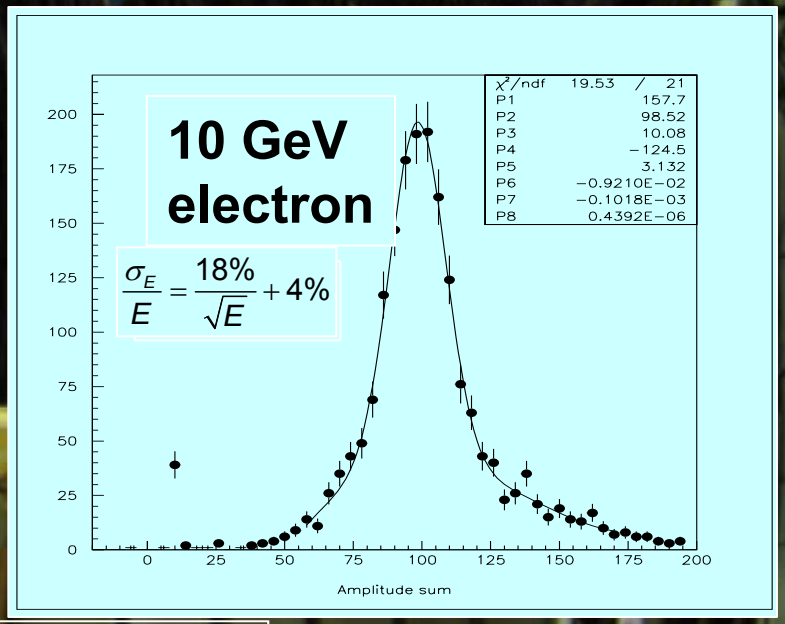


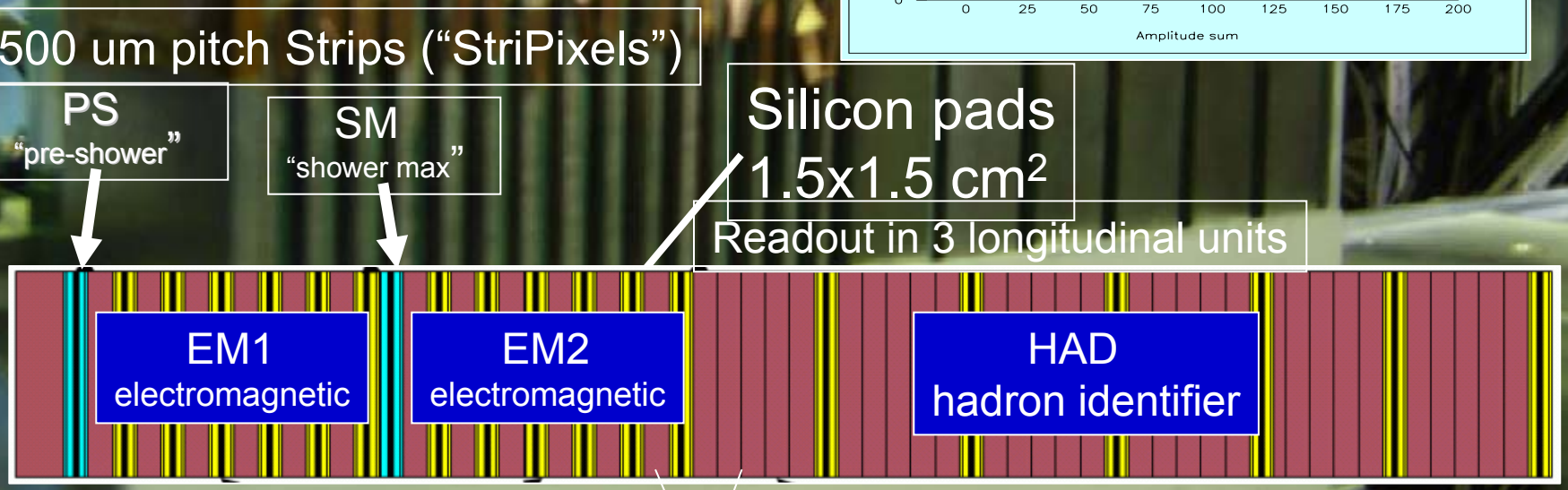


Nose Cone Calorimeter

Tungsten-Silicon Calorimeter

- **Combination EM and Hadronic section**
- **Includes both preshower and shower max sections to optimize π^0 identification**
- **Smallest practical Moliere radius needed due to location 40 cm from PHENIX IP**
- **Covers 2π in azimuth and $1.0 < \eta < 3.0$**





Depth: $42X_0$ ($1.6\ \lambda_{ABS}$)

$R_{Moliere}$ **~1.8 cm**

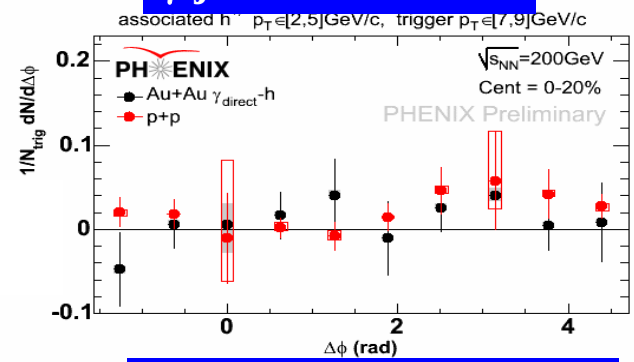
Tungsten 3 mm (EM) & 15mm (HAD)

Nose Cone Calorimeter

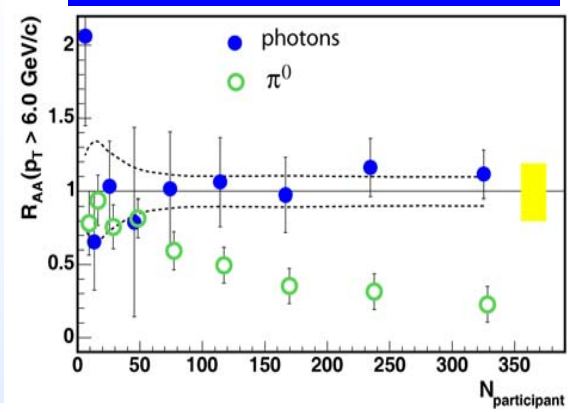
Physics Program of NCC includes:

- Factor of 5 increase in coverage for γ-jet measurements
- Energy loss at forward rapidiites
- Charm through electron channel at forwai rapidities
- Suppression effects of χ_c in HI collisions
- Nuclear modification factor (CGC effects) in dAu using π^0, η
- Transverse Spin Physics

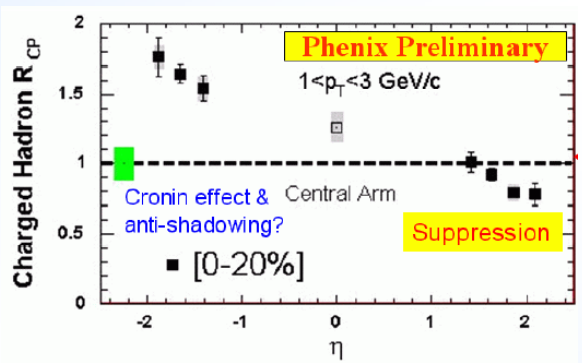
γ-jet measurements



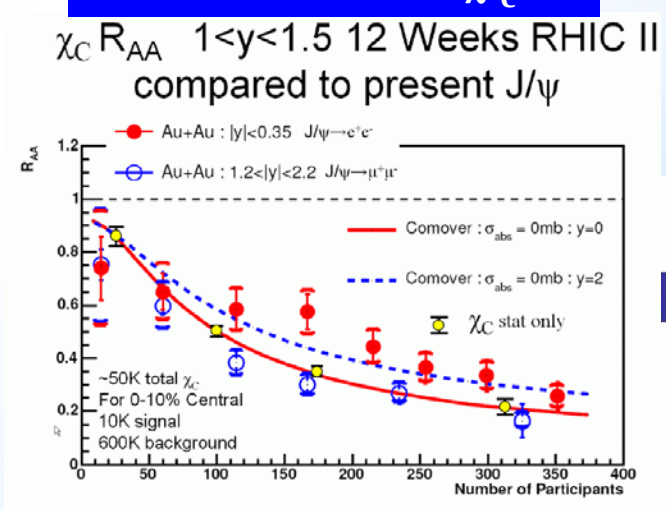
Energy loss at forward η

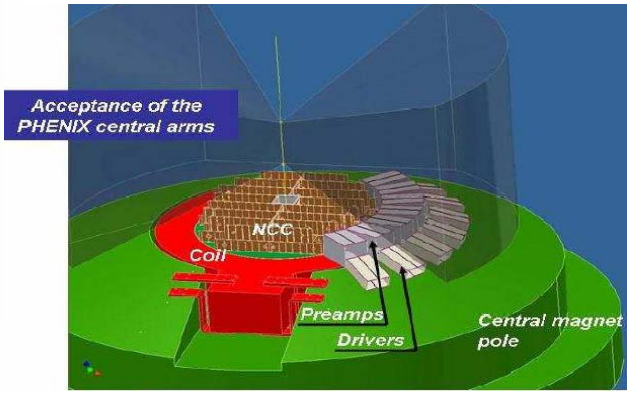


Gluon Saturation/CGC



Measurement of the χ_c

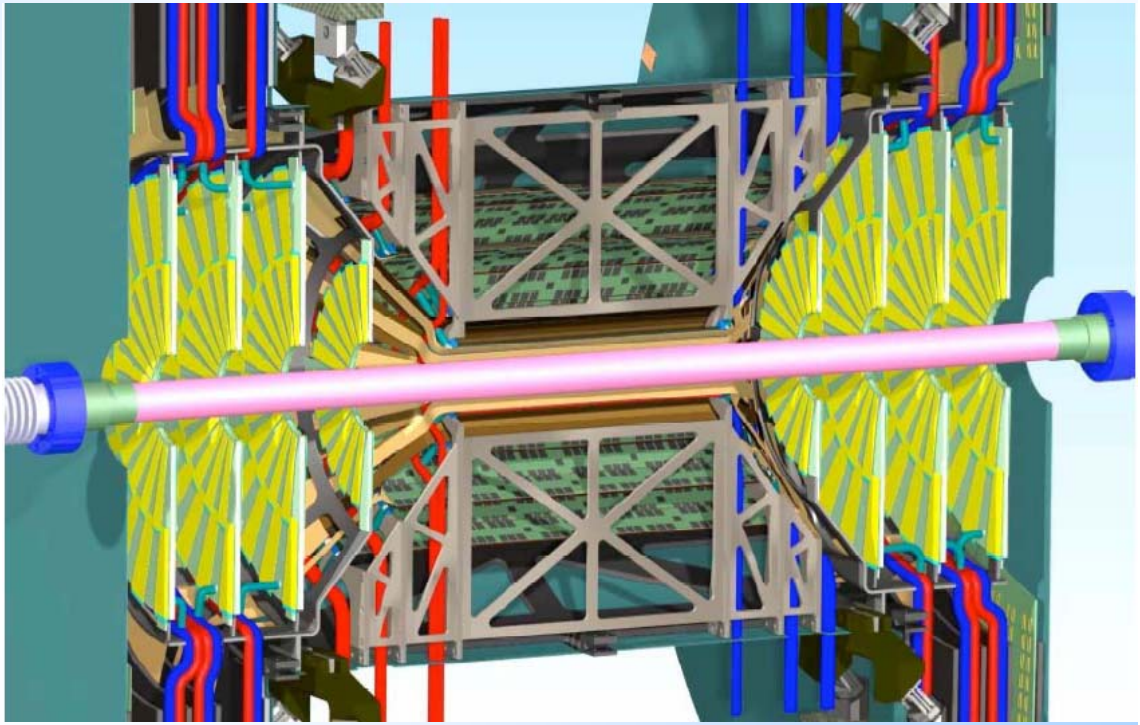




Forward Silicon Vertex Detector - FVTX

FVTX Specifications:

- **2 endcaps**
- **4 pixelpad layers/endcap**
- **~550k channels/endcap**
- **Electronics a mod of BTeV readout chip**
- **Fully integrated mech design w/ VTX**
- **2π coverage in azimuth and $1.2 < |\eta| < 2.4$**
- **Better than 100 μm displaced vertex resolution**

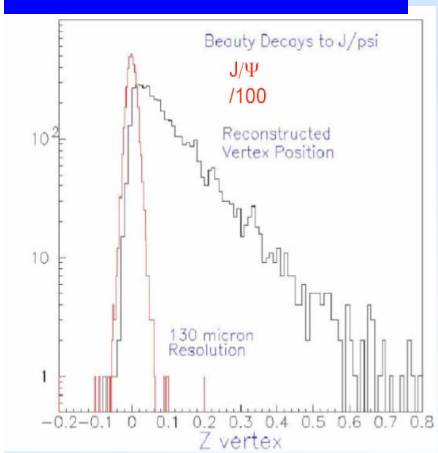


Forward Silicon Vertex Detector - FVTX

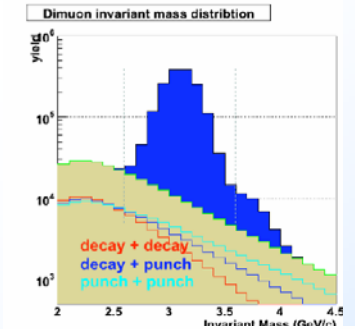
Physics Program of FVTX includes

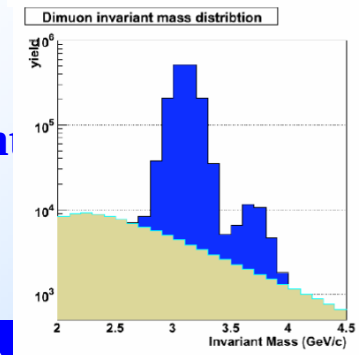
- Resolving J/ψ and ψ' in Muon arms
- Resolving ϒ at y=0 using Muon arms
- Direct measure of B meson through displaced J/ψ
- Drell-Yan Measurements in dAu at both forward and midrapidities
- c, b ID for both HI physics & ΔG spin measurement
- Nuclear modification factor (CGC effects) in dAu using hadrons, c, b, and J/ψ

Direct measure of B

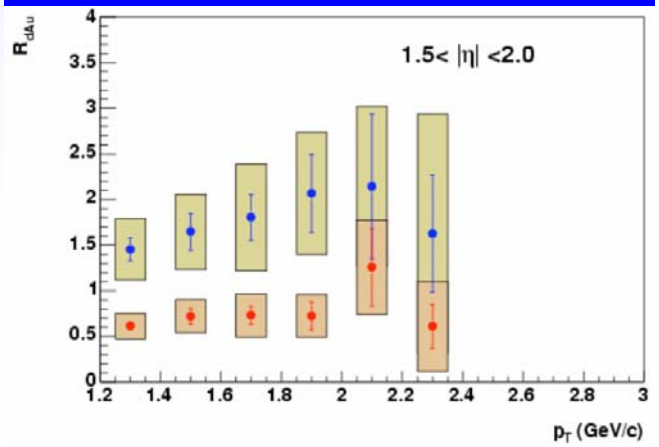


J/ψ, ψ' separation

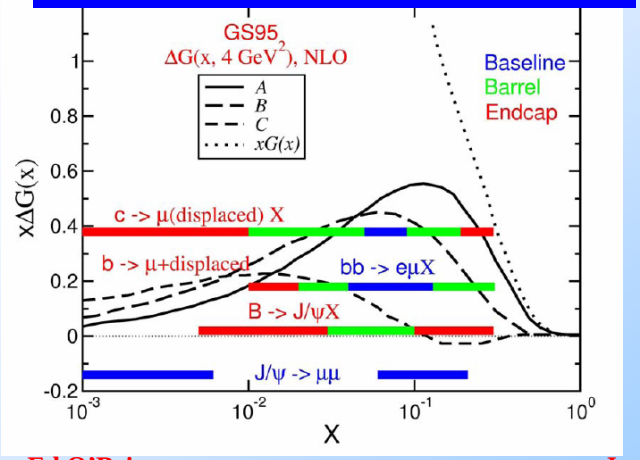




Hadron suppression at forward η



Large expansion of x coverage

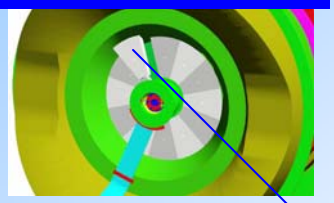


Muon Trigger

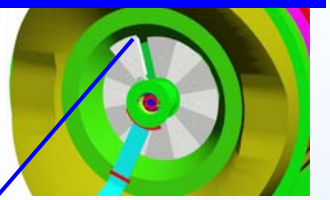
The Muon Trigger Upgrade consists of:

- **6 Stations of Resistive Plate Chambers**
  - **3 North, 3 South**
- **Addition of LVL1 electronics to MuTracker**
  - **St2, St3 North and St2, St3 South**
- **Increases LVL1 rejection by 2 orders of magnitude**

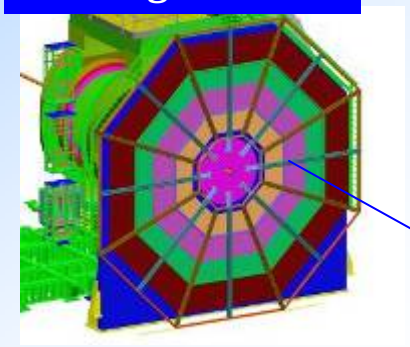
MuTrig Station 1



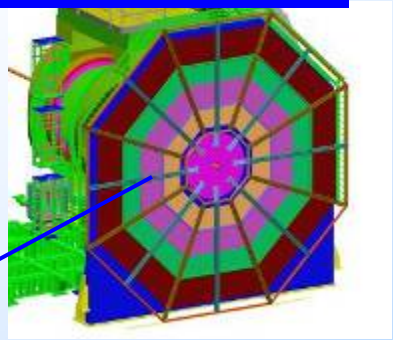
MuTrig Station 1

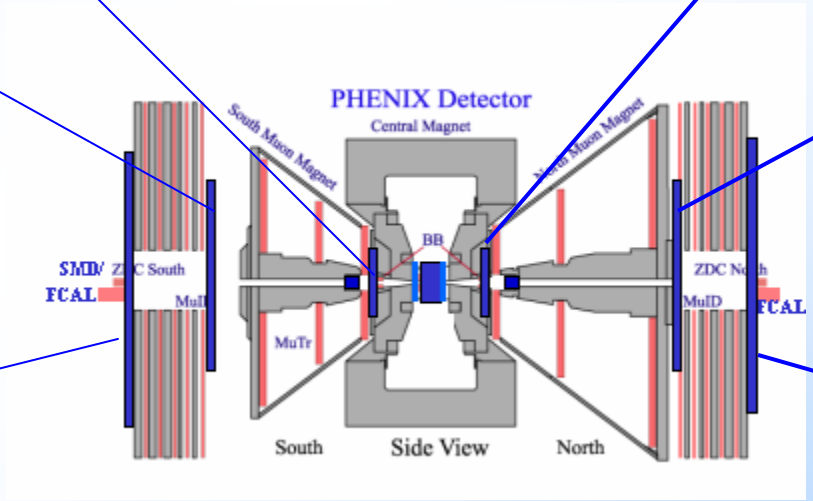


MuTrig Station 2

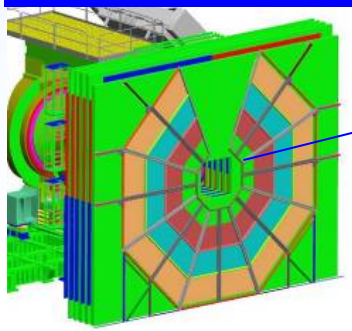


MuTrig Station 2

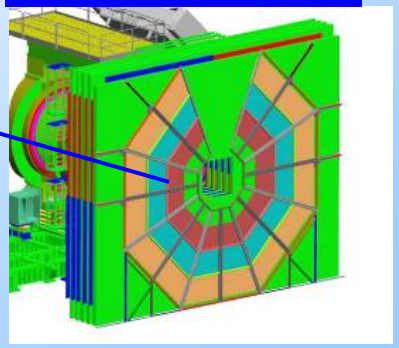




MuTrig Station 3



MuTrig Station 3

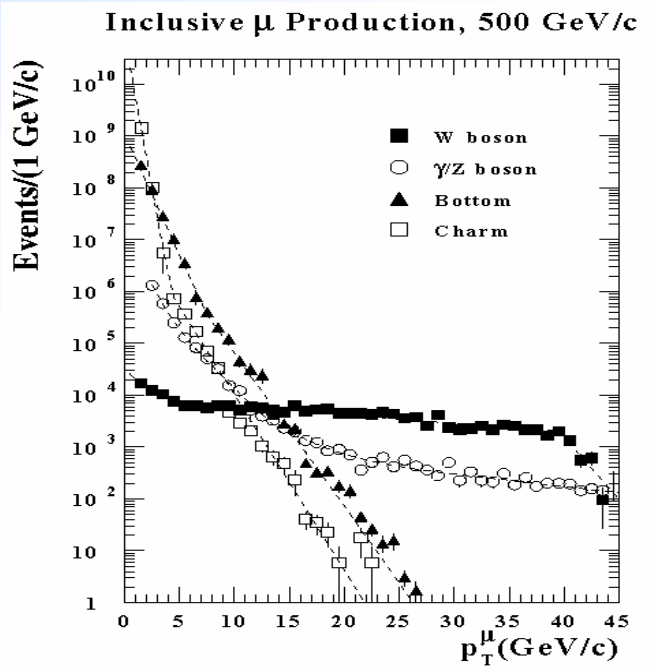


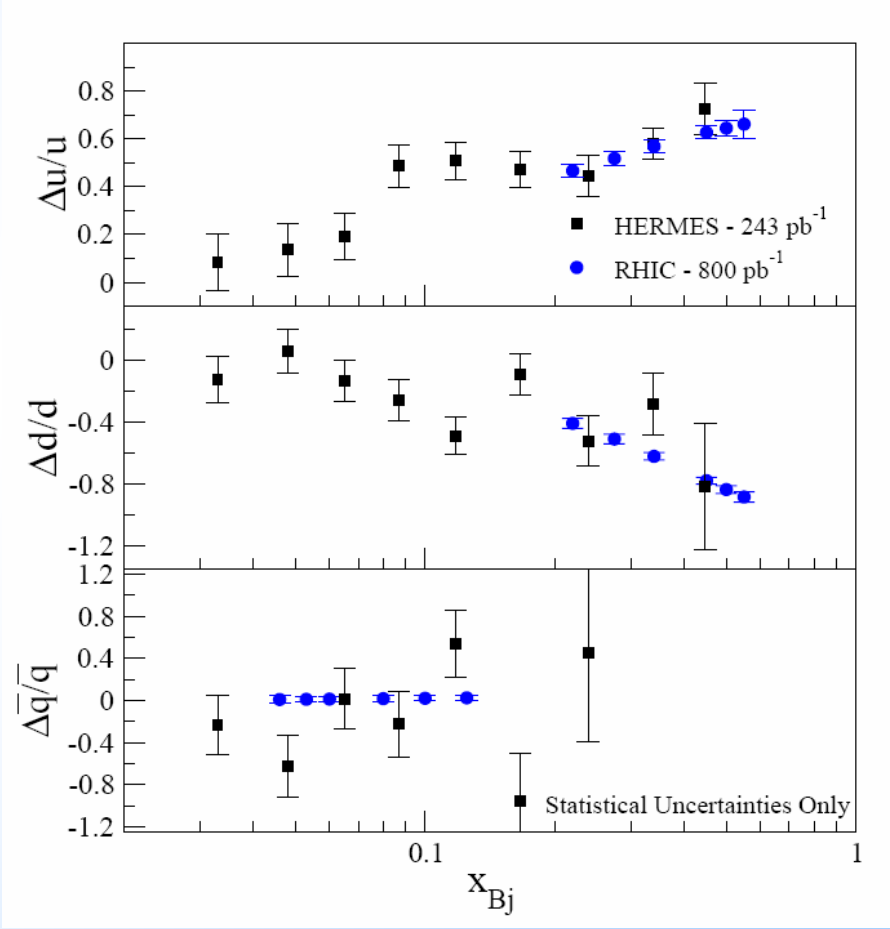
Muon Trigger

Measuring sea quark contributions to proton spin via W production at RHIC

Ws in polarized p-p:

- limited x-coverage
- high Q^2 → theoretically clean
- no Form Factor-info needed





RHIC Physics Program

Heavy Ion Physics:

- **QCD Phase Transition: new state of partonic matter (sQuark Gluon Plasma)**
  - Global ($dN/d\eta$, HBT, E_T, fluctuations)
  - Particle Spectra and ratios
  - Photons and Thermal Radiation (including e^+e^- continuum)
  - Azimuthal Anisotropy (v2)
  - J/Ψ Production/ Absorption
  - Energy Loss, R_{AA}
  - Jet Modifications
  - Heavy Quark/Open Charm

Polarized Protons:

- **Nucleon Spin**
  - Gluon spin: ΔG
  - W-parity sea quark spin: Δubar, Δdbar
  - Nucleon transverse spin distr., transversity

Proton-Nucleus:

- **Structure function physics**
  - Gluon saturation
  - Shadowing, anti-shadowing…
  - Color Glass Condensate
  - Cold nuclear physics (Cronin effect)

Search for the QCD Critical Point:

- **Is there a QCD Critical Point and if so where is it (T, μ_B) ?**
  - Global (Correlation functions, Fluctuations $\langle n \rangle$, $\langle p_T \rangle$)
  - Particle spectra and ratios
  - e^+e^- continuum
  - Azimuthal Anisotropy (v2), v2 scaling with quark number
  - Energy Loss, R_{AA}
  - Jet Modification, shape of away-side peak

RHIC Physics Program

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  - W-parity sea quark spin: Δubar, Δdbar
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Topics addressed by PHENIX Upgrades

Proton-Nucleus:

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  - Color Glass Condensate
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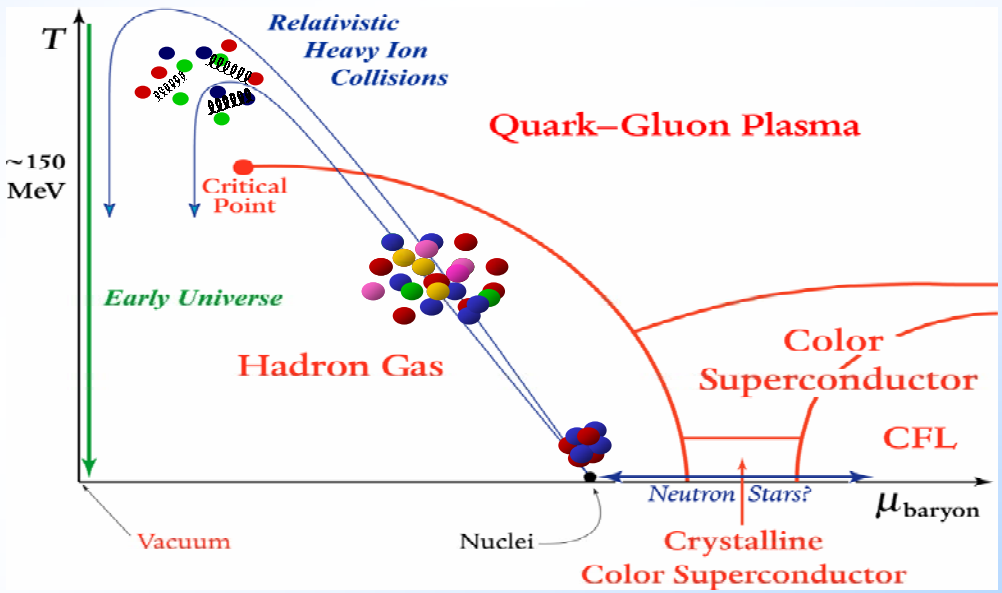
Nucleon Spin Structure: Physics Impact of VTX, FVTX, NCC & Muon Trigger Upgrades

	Physics Goals	Present vs with upgrades
$\Delta G(x)$	determine first moment of the spin dependent gluon distribution, $\int_0^1 \Delta G(x)dx$.	Inclusive hadrons + photons heavy flavor, photons, photon-jet ➔ increase x-range ➔ parton kinematics
$\Delta q(x)$ $\Delta \bar{q}(x)$	flavor seperation of quark and anti-quark spin distri-butions	not possible without upgrades
δq	measurement of trans-versity quark distributions.	A_N for inclusive hadronen A_T in Interference-Fragmentation A_T Collins FF in jets
Sivers Effect	Measurement of the Sivers distributions	A_N for back-to-back hadronen $A_{N,T}$ jets, Ds, DY

Physics studies with Low Energy RHIC Running

Is there a QCD Critical Point and if so where is it (T, m_B) ?
Vary energy and possibly beam species and measure:

- Global (Correlation functions, Fluctuations <n>, <p_T>)
- Particle spectra and ratios
- e^+e^- continuum
- Azimuthal Anisotropy (v2), v2 scaling with quark number
- Energy Loss, R_{AA}
- Jet Modification, shape of away-side peak



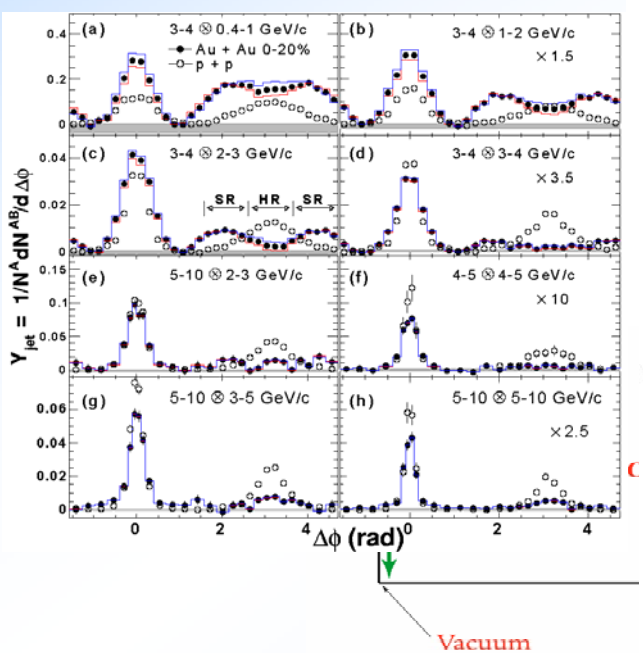
Physics studies with Low Energy RHIC Running

Is there a QCD Critical Point and if so where is it (T, m_B) ?

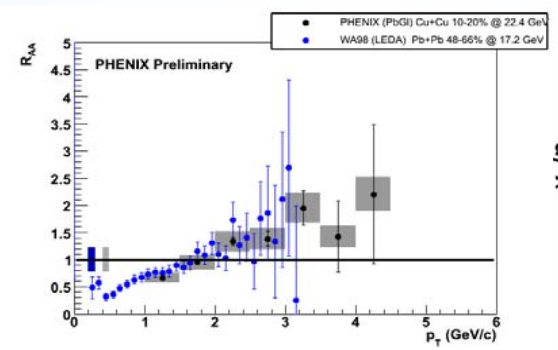
Vary energy and possibly beam species and measure:

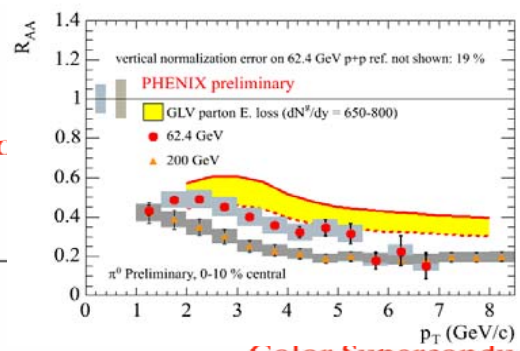
- **Azimuthal Anisotropy (v2), v2 scaling with quark number**
- **Energy Loss, R_{AA}**
- **Jet Modification, shape of away-side peak**

Jet modification/Wake front

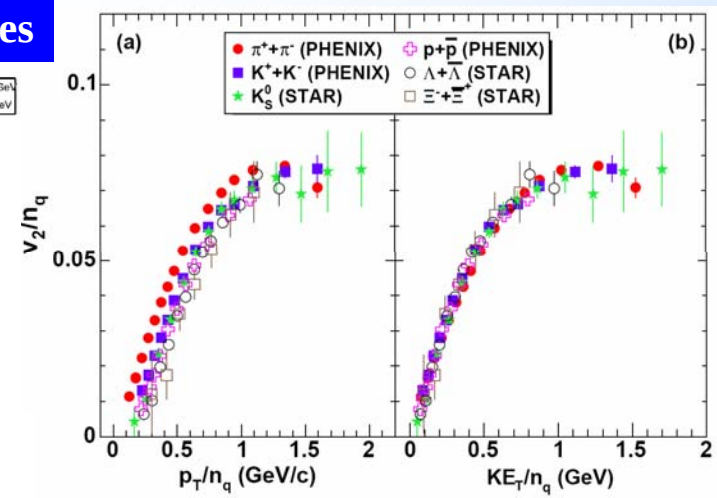


R_{AA} vs s ½ and beam species





Scaling of v2 by #quarks



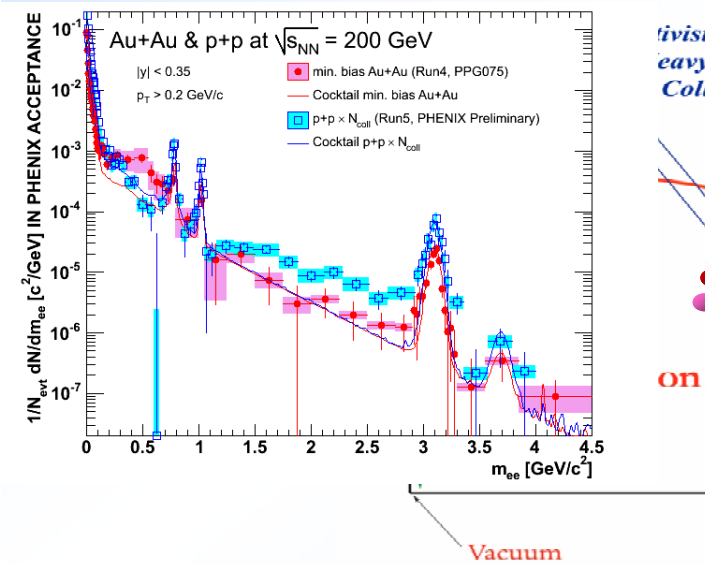
Color Superconductor

Physics studies with Low Energy RHIC Running

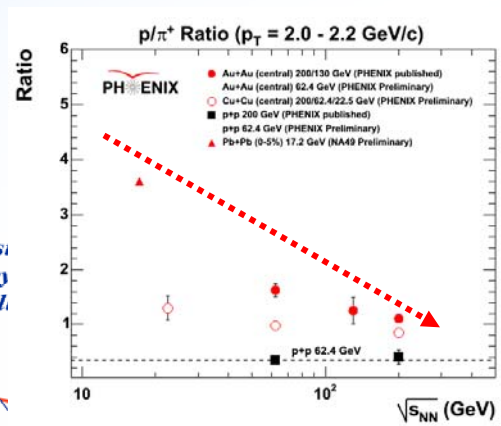
Is there a QCD Critical Point and if so where is it (T, m_B) ?
Vary energy and possibly beam species and measure:

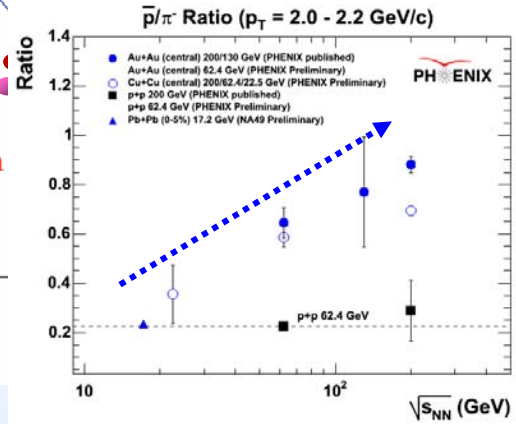
- **Global (Correlation functions, Fluctuations <n>, <p_T>)**
- **Particle spectra and ratios**
- **e^+e^- continuum**

e^+e^- continuum

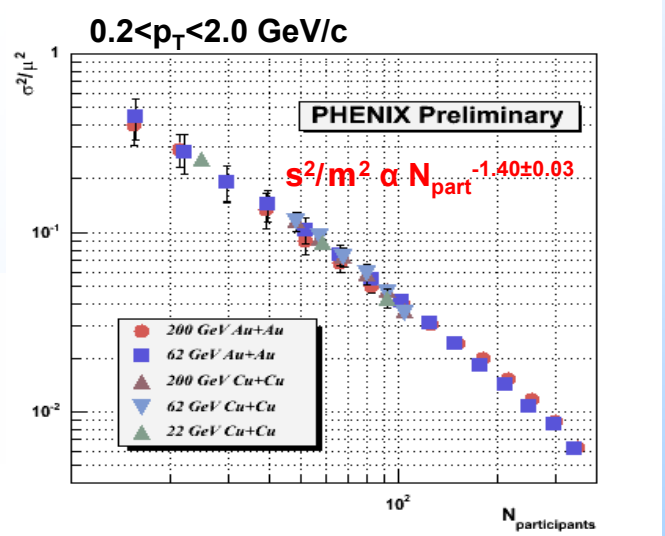


p/π ratio vs s $^{1/2}$





Multiplicity Fluctuation: Universal Scaling



Low Energy Running

Hypothetical Run Strategy

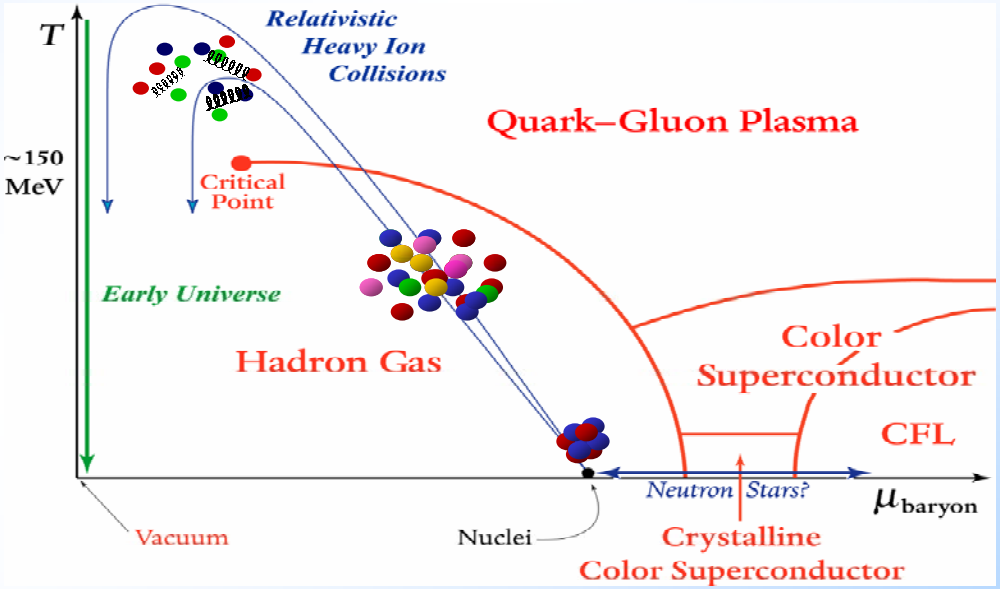
- ~few M events/energy point
- 4-5 points $s^{1/2}$ ranging from $s^{1/2}$ =5 GeV to 30 GeV

Run once in next 2-3 years with current detector including HBD

Run a second time with enhanced luminosity and Central region upgrade

- VTX+FVTX+NCC

A small diamond would really help here

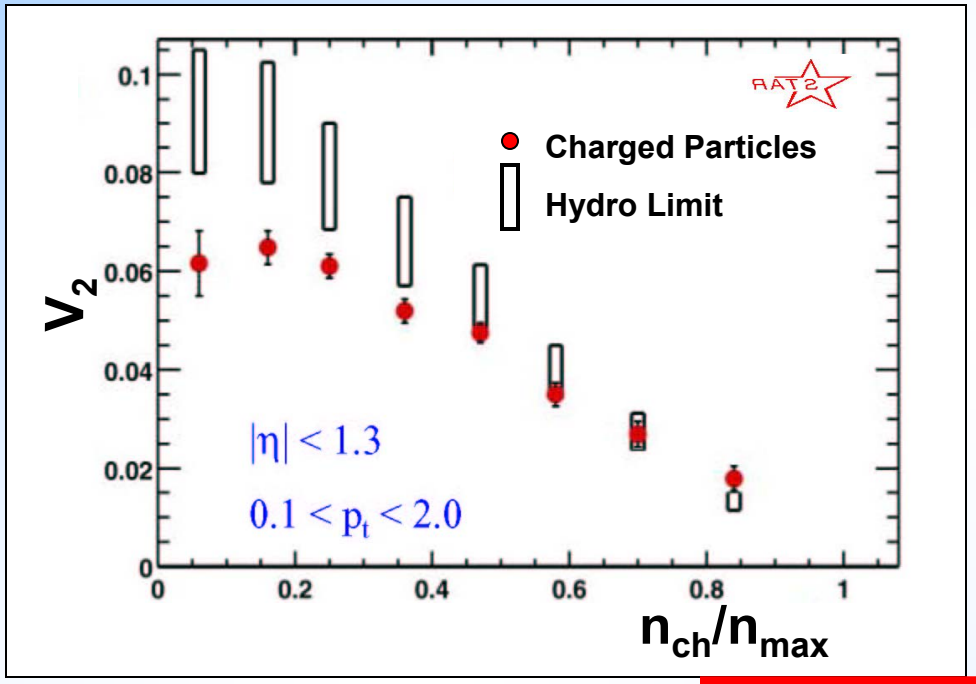


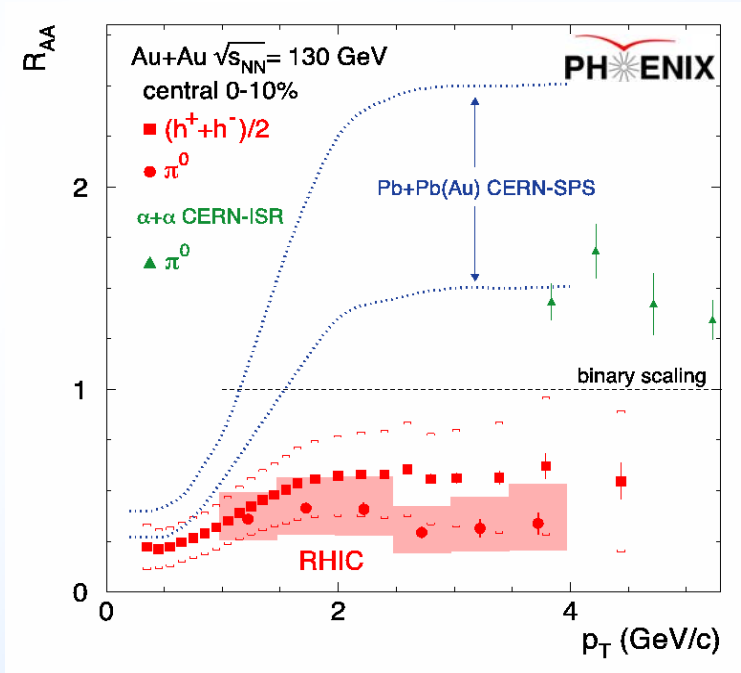
Physics of the Perfect Fluid

Two of the most important discoveries at RHIC came in the first year

Azimuthal anisotropy observed For charged particles vs centrality STAR: PRL 86, (2001) 402

Jet Quenching observed in charged hadrons and π^o vs centrality PHENIX: PRL 88,(2002) 022301





$$Au + Au\sqrt{s_{NN}} = 130\,\text{GeV}$$

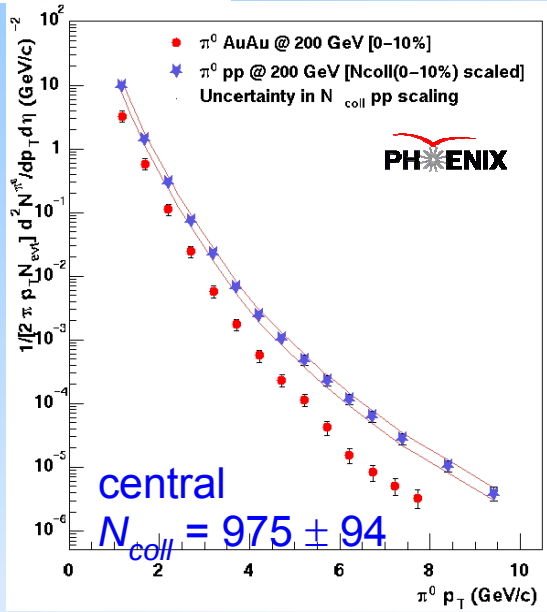
$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi) + \ldots$

Azimuthal asymmetry of charged particles observed as a function of p_T and Centrality

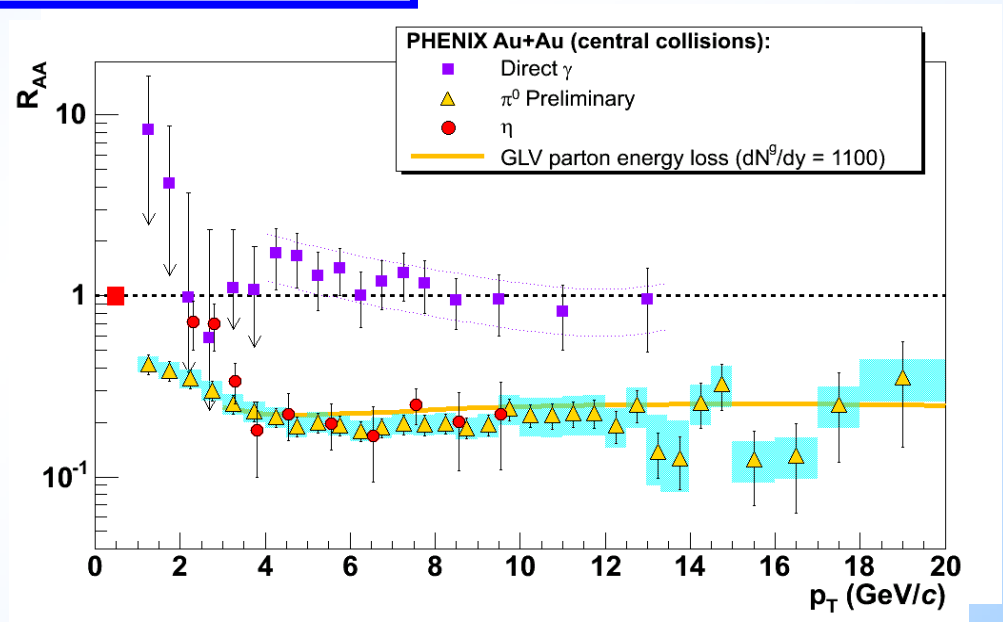
Hadron production in Central collisions was nearly a factor of 5 less than what was observed in peripheral collisions.

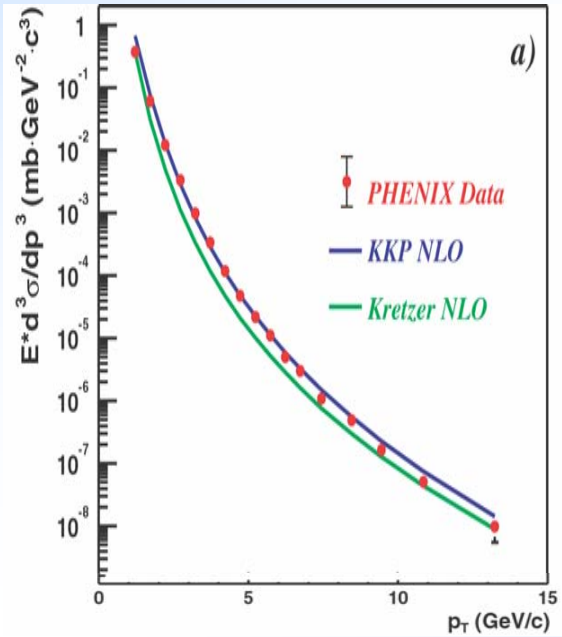
Physics of the Perfect Fluid

The Matter Created is Very Opaque. π^0 is Suppressed out to 20 GeV/c



$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$





Hadron are suppressed
Direct photons are NOT

ε > 15 GeV/fm^3; dN_g/dy > 1100

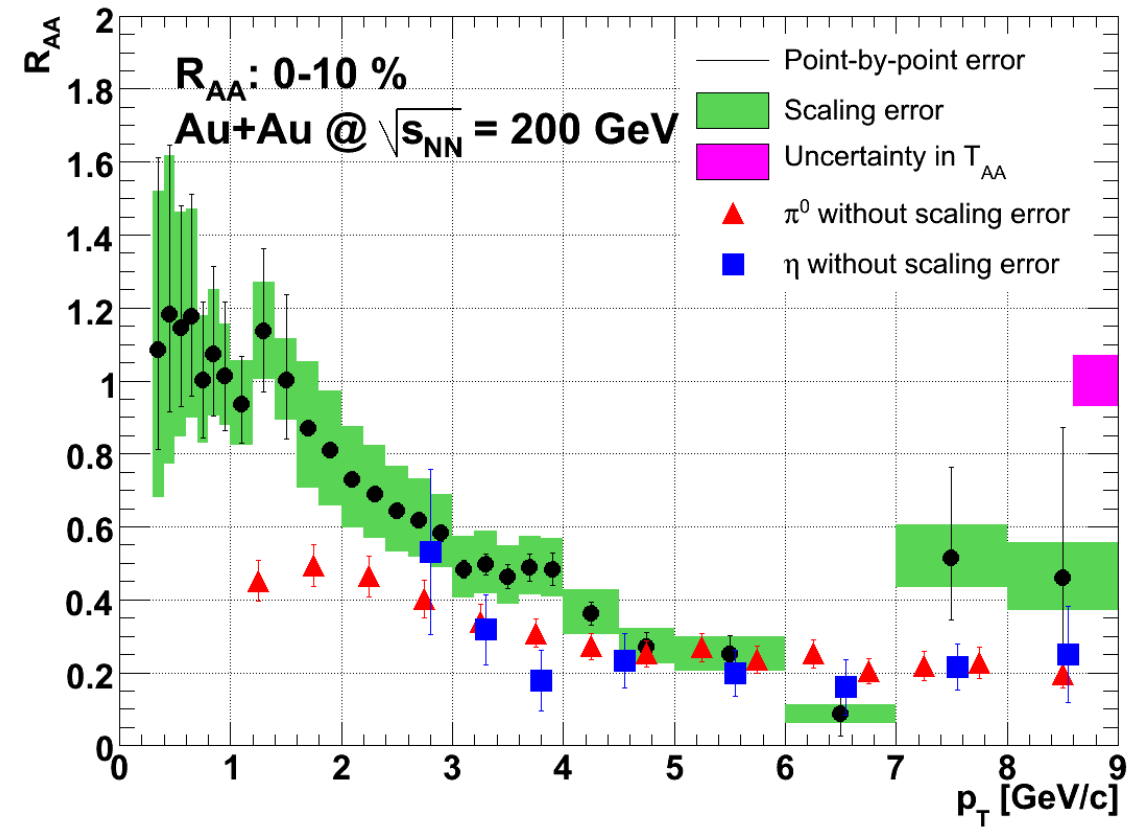
Physics of the Perfect Fluid: Energy Loss

The energy loss mechanism is far from understood

Suppression level for non-photonic electrons (presumably leptons from c,b decays) is the almost same as π^0 and η in high p_T region

00-10 %

R_{AA} for non-photonic electrons

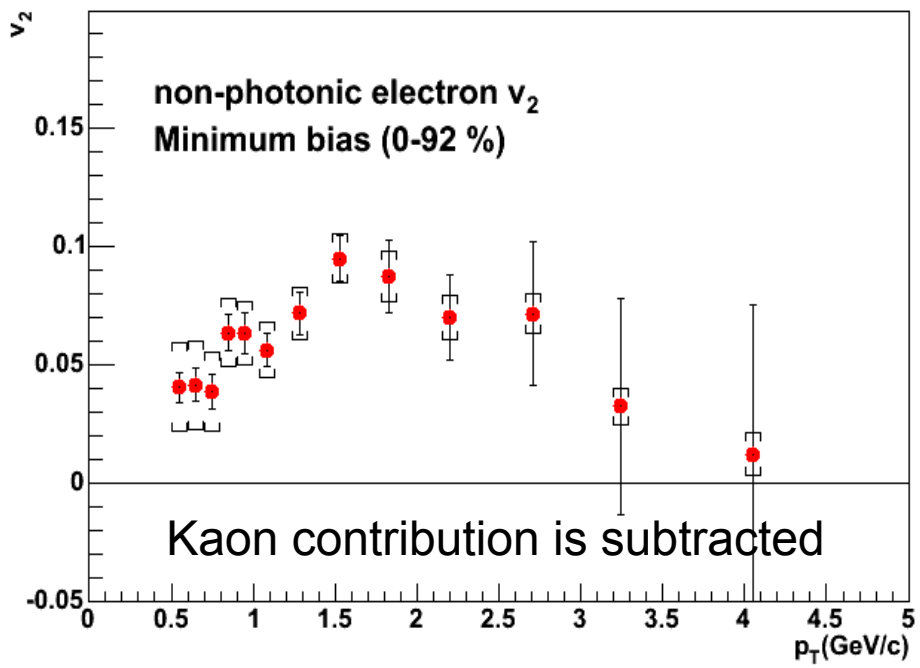


$$R_{\mathrm{AuAu}}(p_{\mathrm{T}}) = \frac{dN^{e}_{\mathrm{AuAu}}/dp_{\mathrm{T}}}{N_{\mathrm{col}} \cdot dN^{e}_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

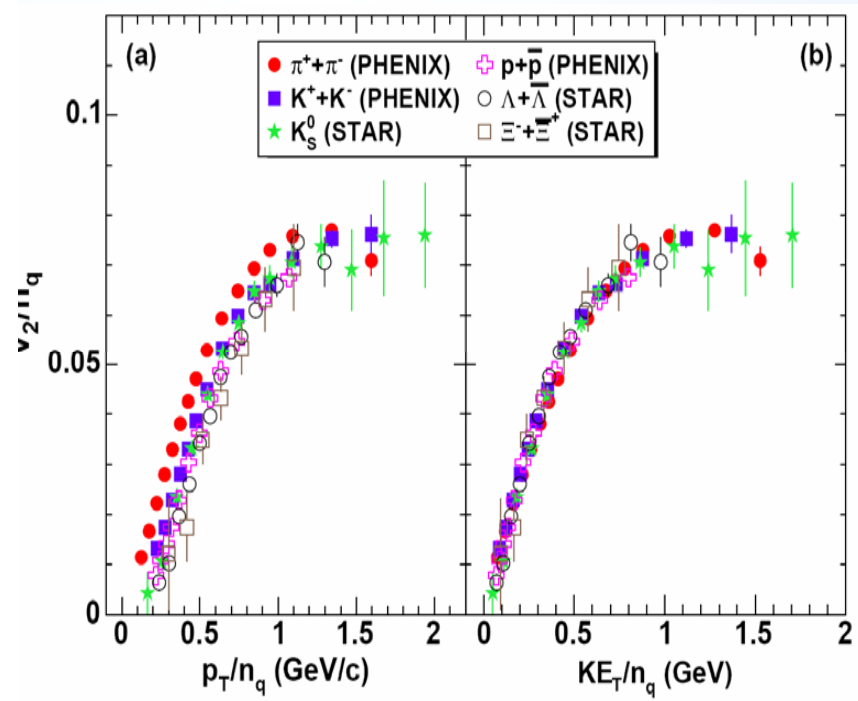
Physics of the Perfect Fluid
Elliptic Flow: v_2

Non-zero elliptic flow for heavy-flavor electron → indicates non-zero D v_2

v2 for non-photonic electrons (heavy quark decays)



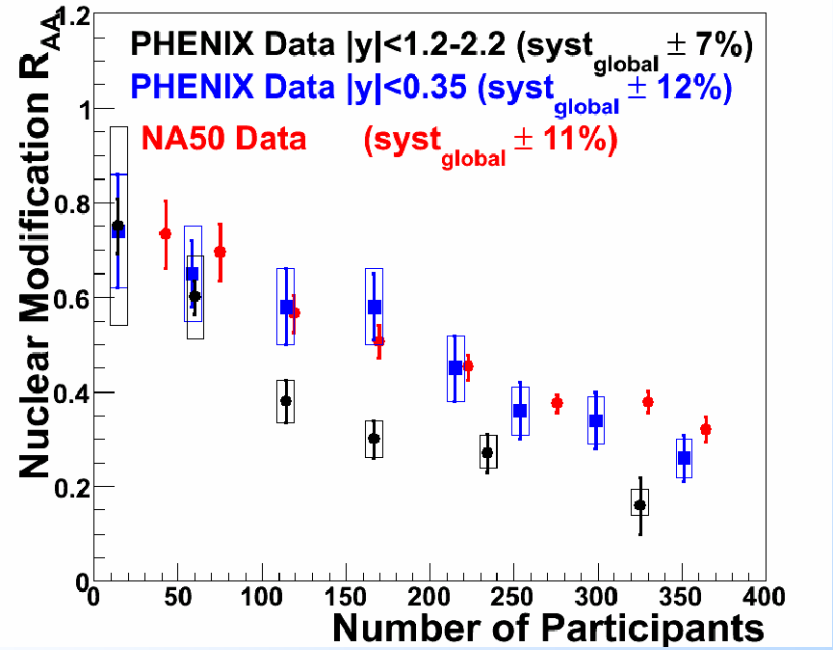
Scaling of v2 by #quarks



If partonic thermalization is driving the flow of the light quarks, then does v2 of non-photonic electrons mean both the c and b quarks are thermalized too? Do the c and b quarks flow differently?

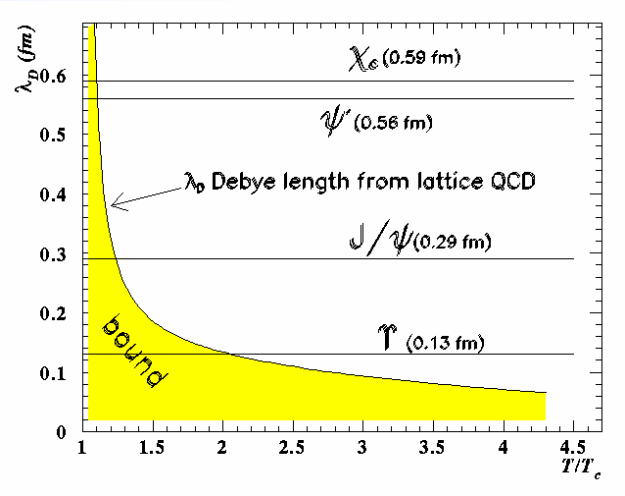
Physics of the Perfect Fluid: J/ψ Suppression Mechanisms

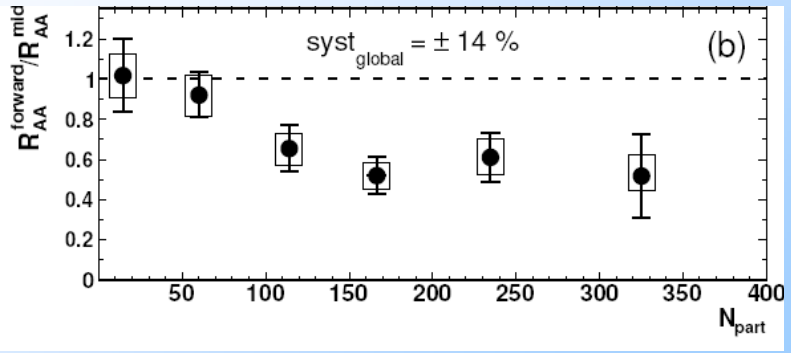
Less suppression at central rapidity than at forward rapidities
Same suppression levels at RHIC as seen at NA-50



It is hard for existing suppression mechanisms to explain this data.

More data needed for J/ψ, ψ', χ_c and ϒ

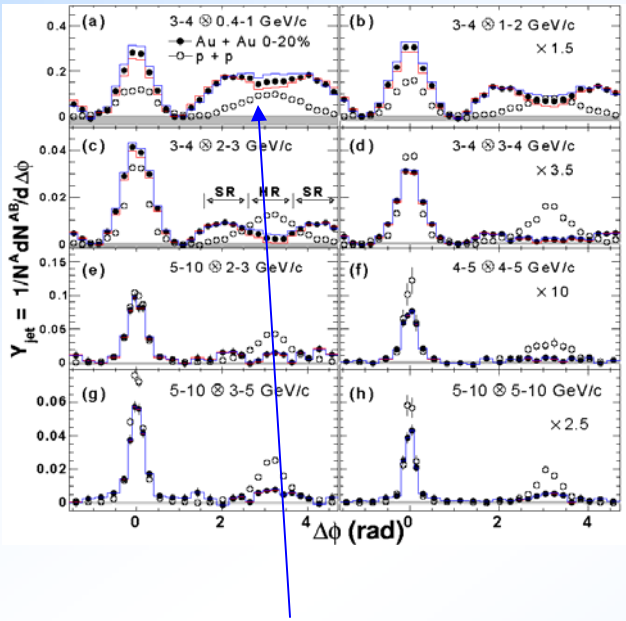




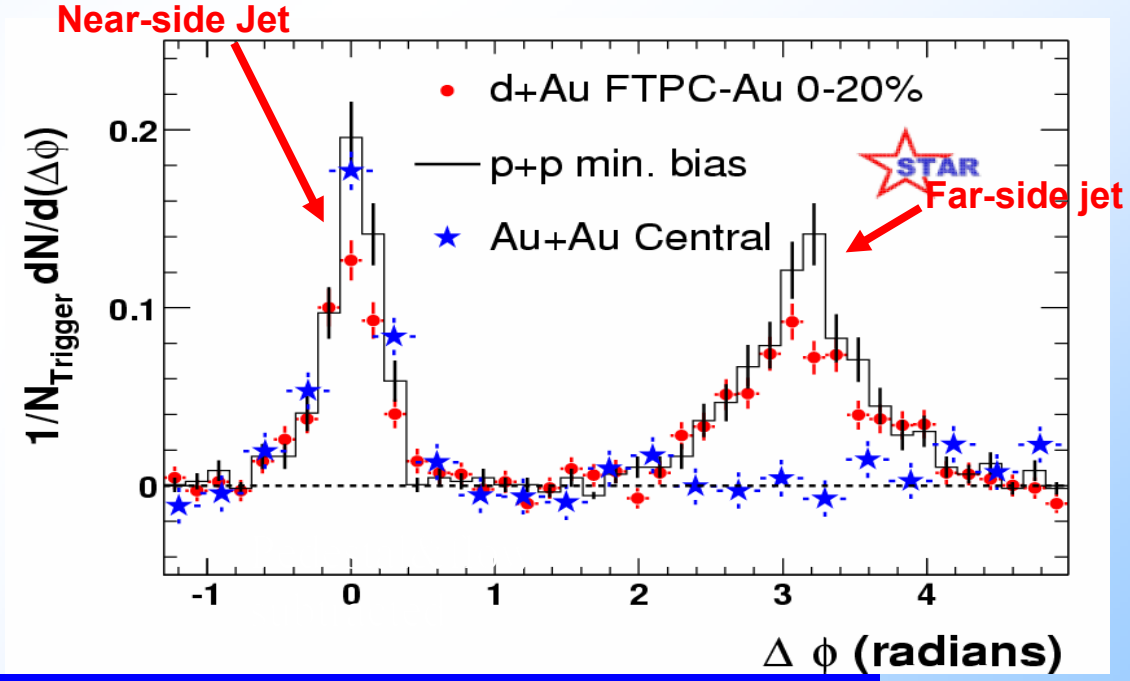
Physics of the Perfect Fluid: Jet Modification

The physical processes governing Jet Modification at RHIC are not understood, separating medium effects from geometric and surface effects are difficult and require both sophisticated detectors and analysis tools

Jet modification



Disappearance of away-side jet in central AuAu collisions



Are we observing a wake front traveling through the partonic fluid?

Physics of the Perfect Fluid

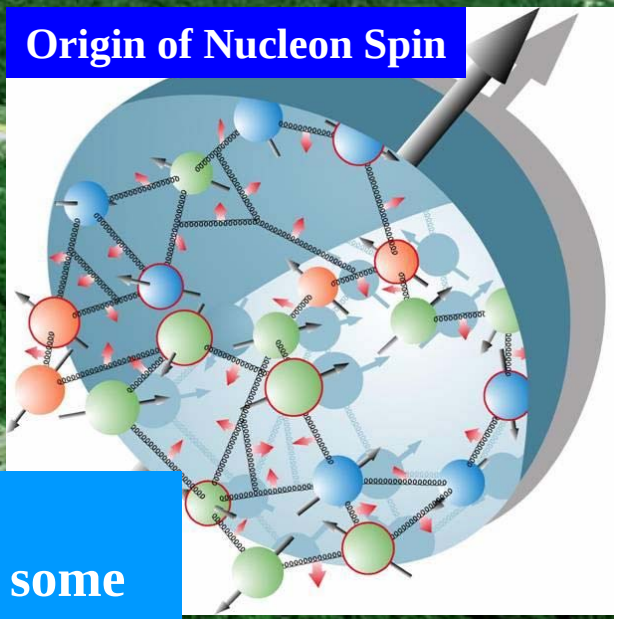
RHIC has produced billions of events, from which we have created thousands of plots, publishing over a hundred papers in seven years of operation.

No models come close to explaining the many characteristics of the partonic matter we have created at RHIC

Conclusion - 1

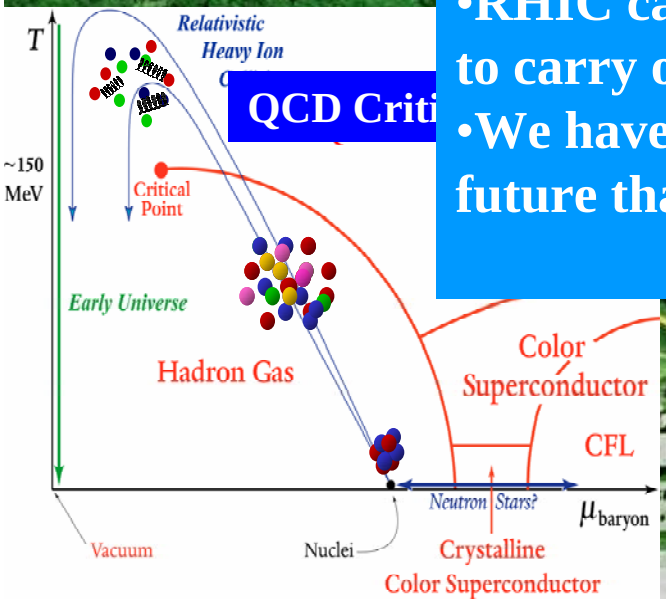
New State of Partonic Matter

Origin of Nucleon Spin

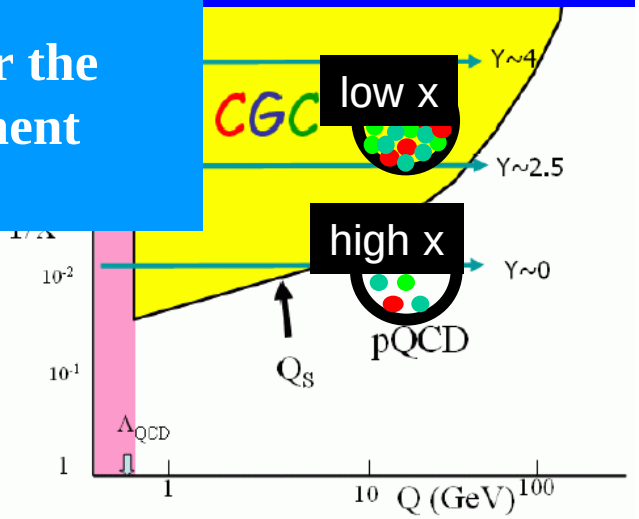


- We have a four component physics program which uses RHIC to explore some of the most important questions in QCD
- RHIC capabilities make it uniquely suited to carry out this program
- We have a detailed upgrade plan for the future that we are starting to implement

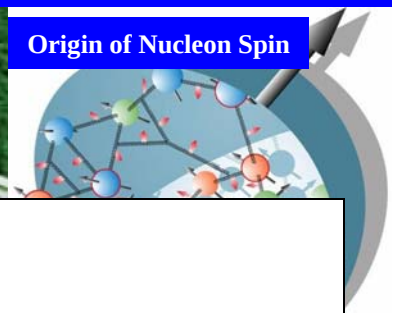
QCD Criti



turation & Color Glass



Conclusion - 2

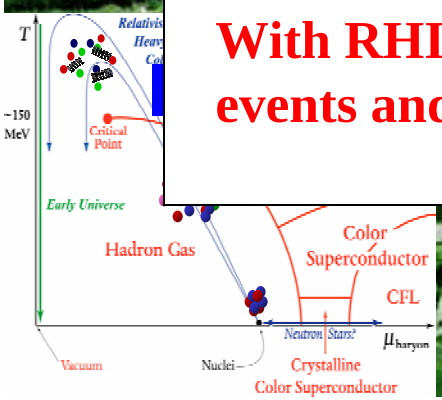
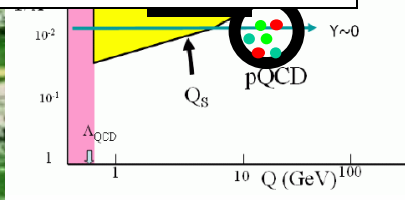


RHIC II is:

- **10X Luminosity Upgrade**
- **Order of Magnitude increase in Detector Acceptance or DAQ Rate**
- **Order of Magnitude S/B improvement for many physics signals**

Potentially a 3 order of magnitude improvement in physics performance

When RHIC started running in 2000 many were looking to create a QGP that would display many interesting QCD characteristics.

Instead we have created partonic matter (The Perfect Fluid) that may be as fundamental to QCD as the proton.

With RHIC II we will create more of that matter, capture more of the events and study it more precisely.