Future upgrade plans at BNL
RHIC II and eRHIC

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Outline

- BNL - The QCD Lab
- Past Performance - RHIC program
- Near-term RHIC program and RHIC II
- eRHIC - A future electron-ion collider at RHIC
- Summary

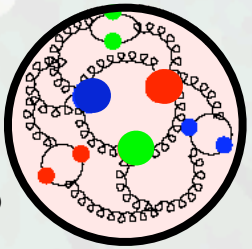
BNL - The QCD Laboratory

- Fundamental questions in QCD physics

$$\mathcal{L}_{QCD} = \bar{\psi}\left[i\gamma^\mu\partial_\mu - m\right]\psi - g_s\bar{\psi}\gamma^\mu G^a_\mu\frac{\lambda_a}{2}\psi - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^a_{bc} G^b_\mu G^c_\nu$$

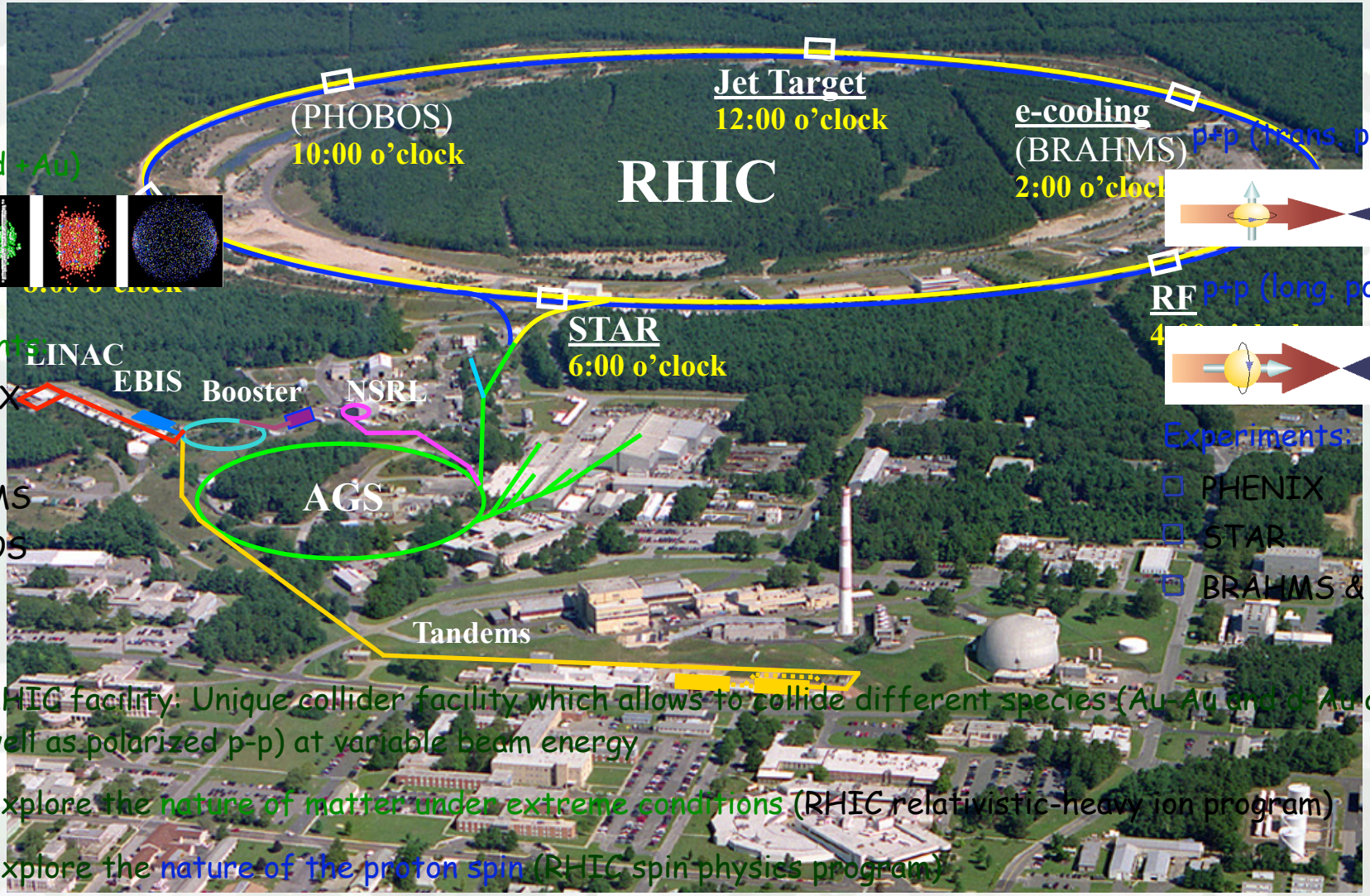
- Interactions arise from fundamental symmetry principles: $SU(3)_c$
- Visible phenomena (e.g. proton) emerge through complex structure of the vacuum (e.g formation of Hadrons from quarks/gluons)



- Fundamental questions:
  - How does ordinary matter get its mass, spin and other intrinsic and dynamical properties?
  - How does QCD matter behave at the extraordinary temperatures attained during the first microseconds following the big bang?
  - What is the structure of the QCD vacuum, and how is it affected by high temperature and density?
  - What are the universal properties of all strongly interacting systems in the limit of high gluon density?

BNL - The QCD Laboratory

- Overview - RHIC facility



Au + Au (d + Au)

Experiments:

- PHENIX
- STAR
- BRAHMS
- PHOBOS

p+p (trans. polarized)

p+p (long. polarized)

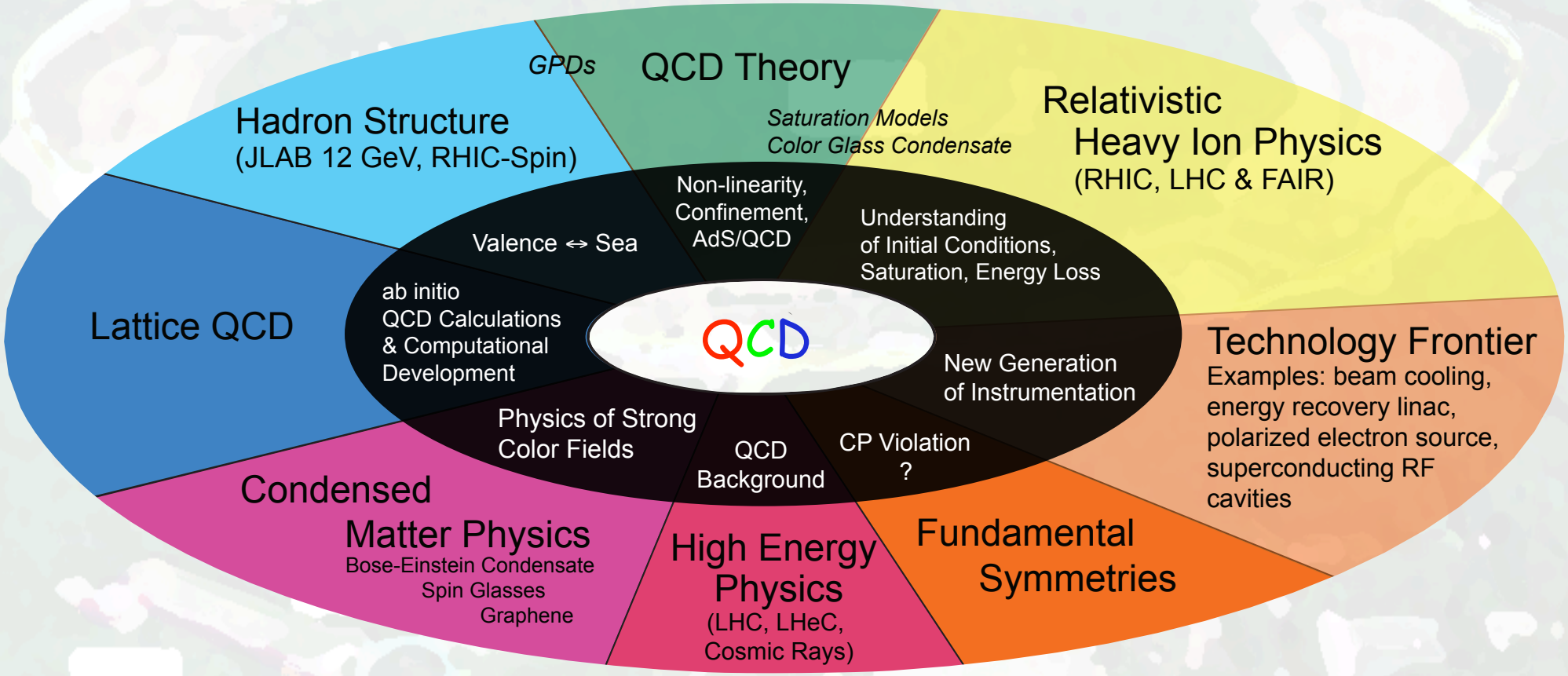
Experiments:

- PHENIX
- STAR
- BRAHMS & PP2PP

- RHIC facility: Unique collider facility which allows to collide different species (Au-Au and d-Au as well as polarized p-p) at variable beam energy
- Explore the nature of matter under extreme conditions (RHIC relativistic-heavy ion program)
- Explore the nature of the proton spin (RHIC spin physics program)

BNL - The QCD Laboratory

- Connections QCD physics and beyond



Introduction

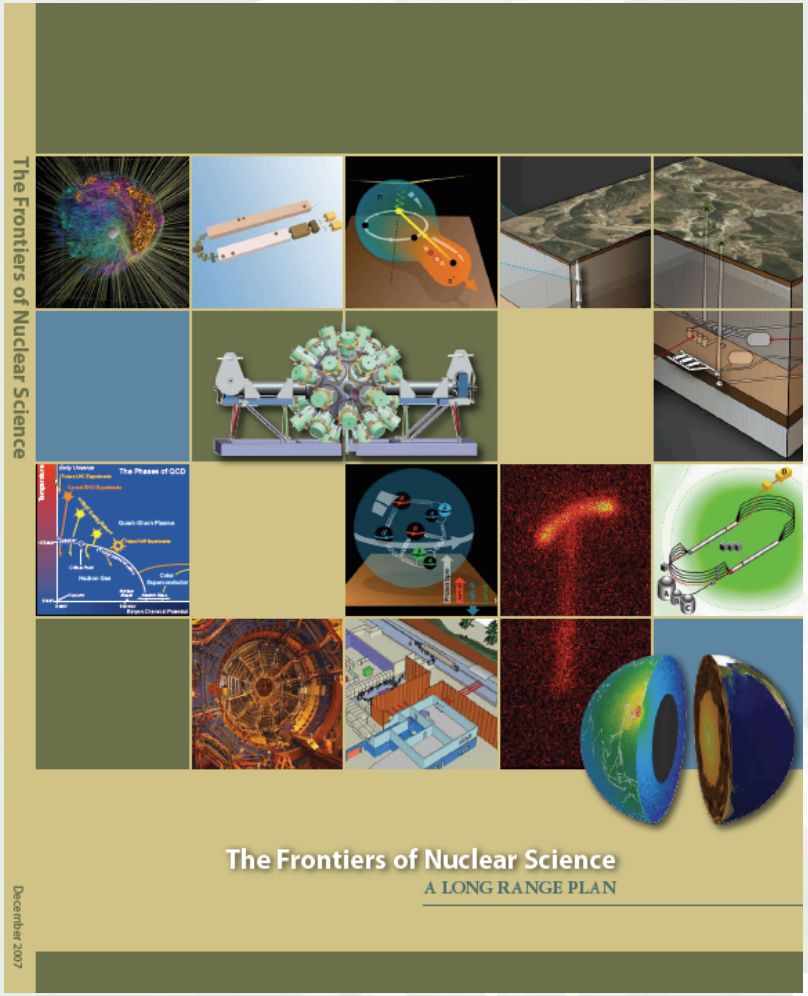
- Vision of the BNL QCD Laboratory
  - Goal: Evolve RHIC facility to address key questions on QCD
  - Four key elements of the BNL management plan:
    - Near-term upgrades to RHIC
      - Detector upgrades
      - EBIS (Electron-Beam Ion Source)
      - Enhanced luminosity and polarization
    - RHIC-II
      - Luminosity upgrade
        - Goal: Establish transverse stochastic cooling
        - Electron cooling might be necessary for eRHIC
    - eRHIC (EIC @ BNL)
    - Theory and computational QCD

Prominently featured in 2007 Long-Range planing process of the Nuclear Science Advisory Committee (NSAC)

RHIC plays a key role in the US Nuclear Science Mission

BNL - The QCD Laboratory

NSAC recommendations 2007 - QCD physics at RHIC



NSAC Recommendation (2007): RHIC II

The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density - a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

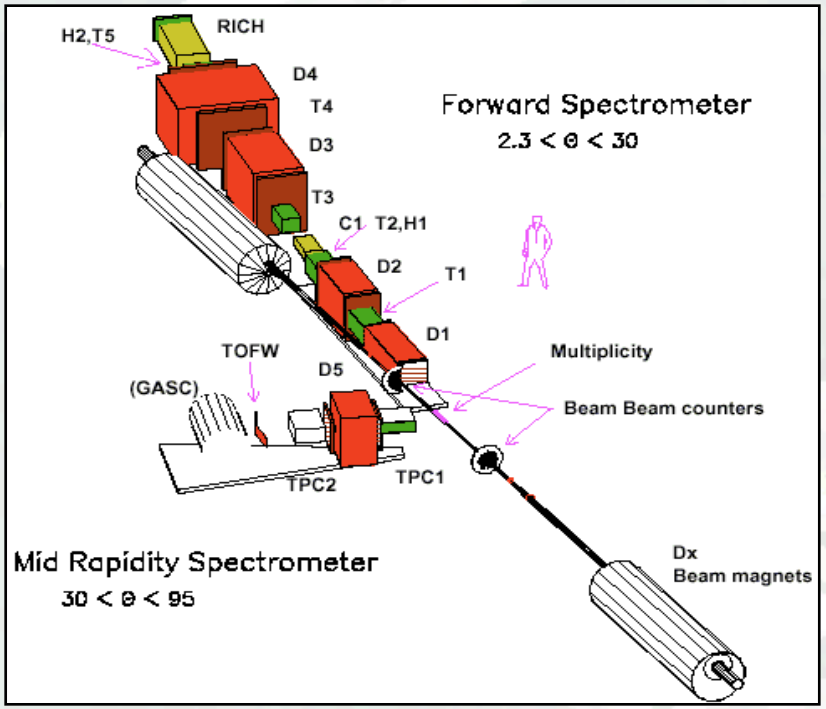
NSAC Recommendation (2007): EIC

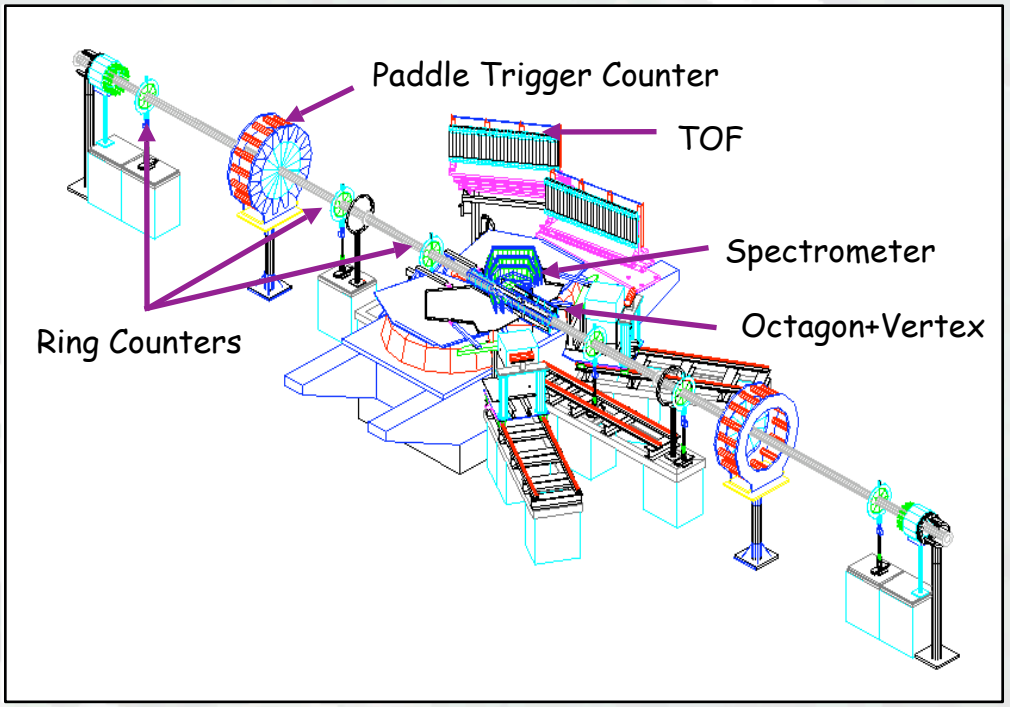
We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.

http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

Past Performance - RHIC program

- Detector systems - BRAHMS / PHOBOS





- Two spectrometers - fixed target geometry
- Magnets, tracking chambers, TOF, RICH

- Two arm spectrometer magnet
- Si μ-Strips, Si multiplicity rings, TOF

Past Performance - RHIC program

Detector systems - PHENIX

π^0/ γ / η detection

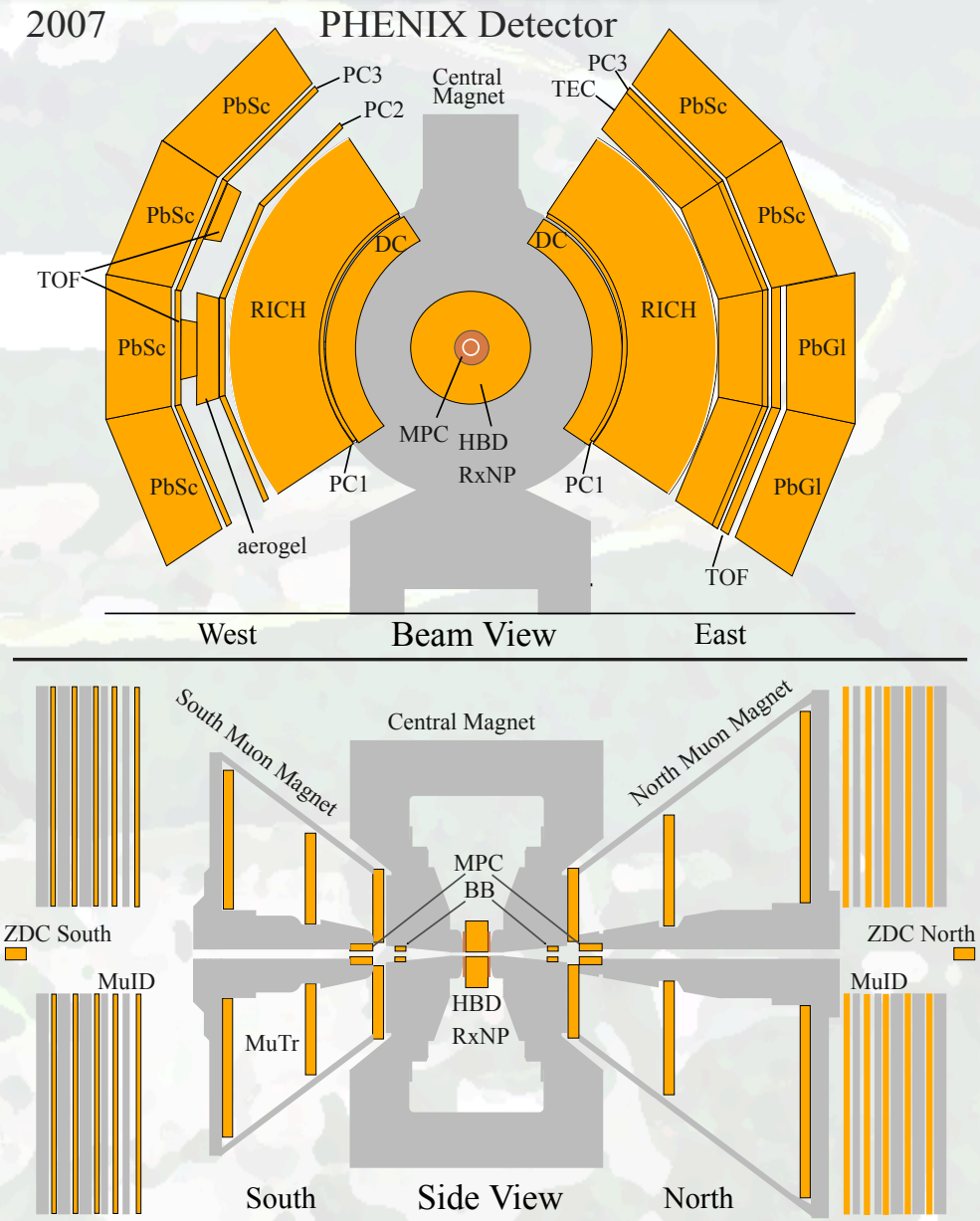
- Electromagnetic Calorimeter (PbSc/PbGl):
  - High p_T photon trigger to collect π^0's, η's, γ's
  - Acceptance: $|\eta|<0.35$, $\phi = 2 \times \pi/2$
  - High granularity (~10*10mrad^2)

π^+/ π^-

- Drift Chamber (DC) for Charged Tracks
- Ring Imaging Cherenkov Detector (RICH)

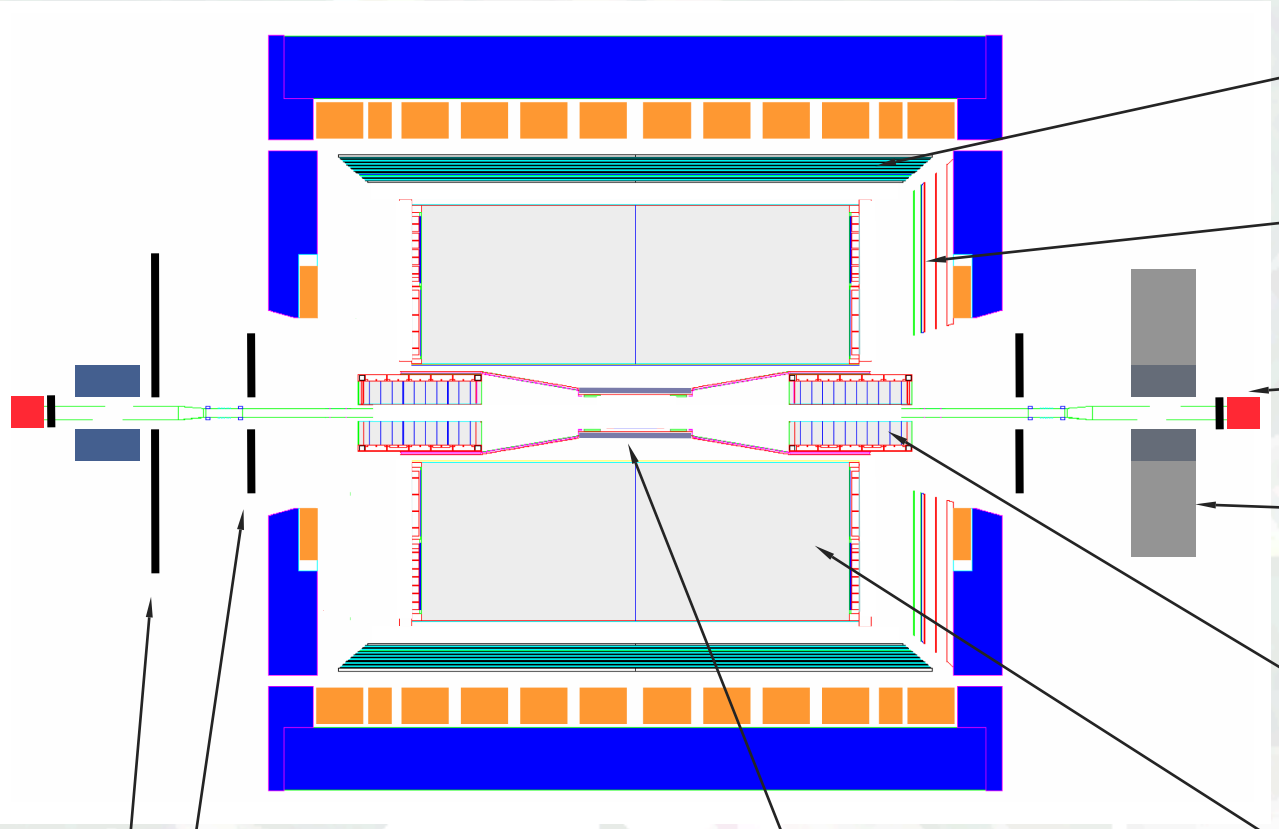
Relative Luminosity

- Beam Beam Counter (BBC)
  - Acceptance: $3.0<\eta<3.9$
- Zero Degree Calorimeter (ZDC / SMD)
  - Acceptance: ±2 mrad



Past Performance - RHIC program

Detector systems - STAR



BEMC (Barrel Electromagnetic Calorimeter: $-1 < \eta < 1$)

EEMC (Electromagnetic Endcap Calorimeter: $1.09 < \eta < 2$)

ZDC (Zero-Degree Calorimeter)

FMS (Forward Meson Spectrometer: $2.5 < \eta < 4$)

FTPC (Forward Time Projection Chamber)

TPC (Time Projection Chamber)

BBC (Beam-Beam Counter)

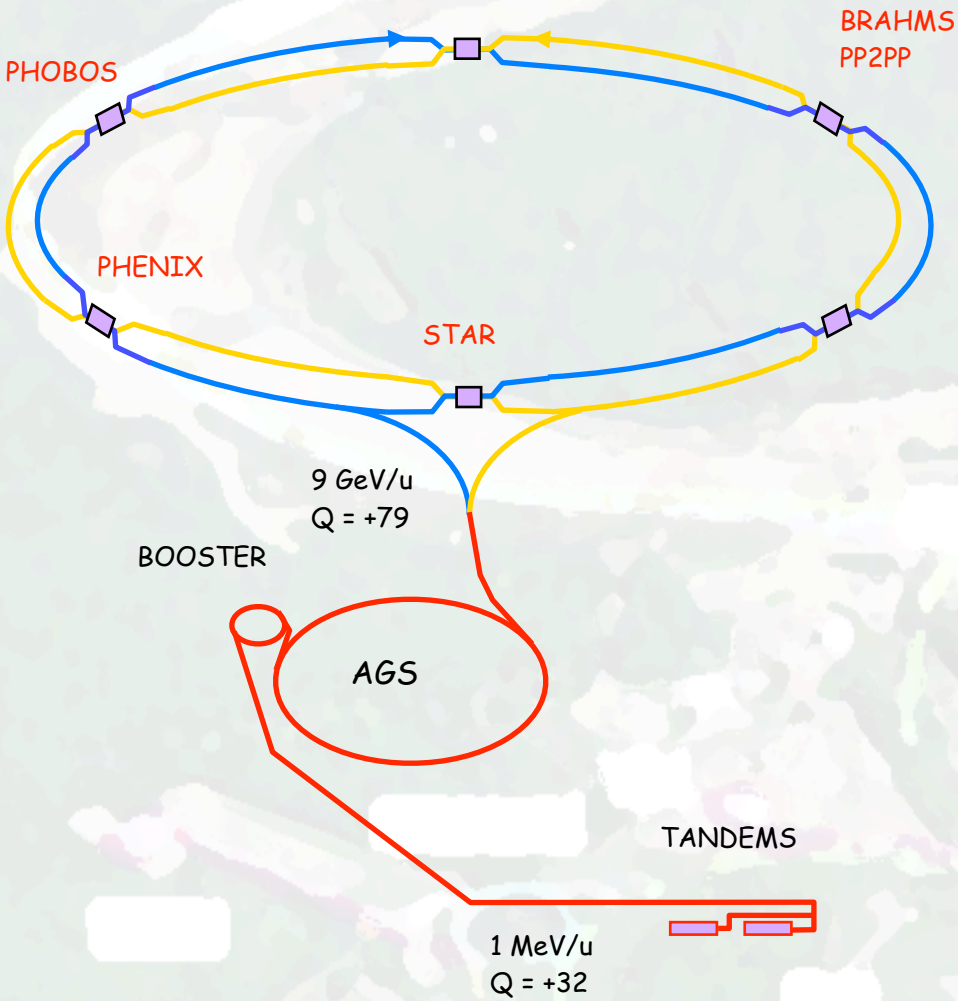
PMD (Photon Multiplicity Detector)

SVT (Silicon-Vertex Detector - removed)

SSD (Silicon-Strip Detector)

Past Performance - RHIC program

RHIC collider aspects: A-A - Layout



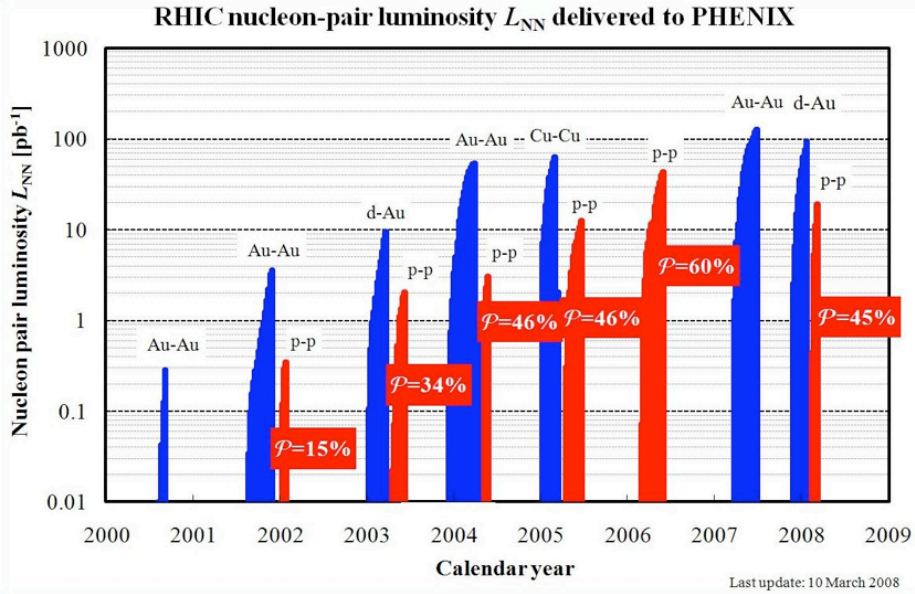
- RHIC: Two concentric superconducting magnet rings, 3.8km circumference
- 120 bunches/ring with 106ns bunch crossing time
- Start of construction: January 1991
- First collisions of Au-Au ions: June 2000
- First collision of trans. polarized protons: December 2001
- First collisions of long. polarized protons: May 2003

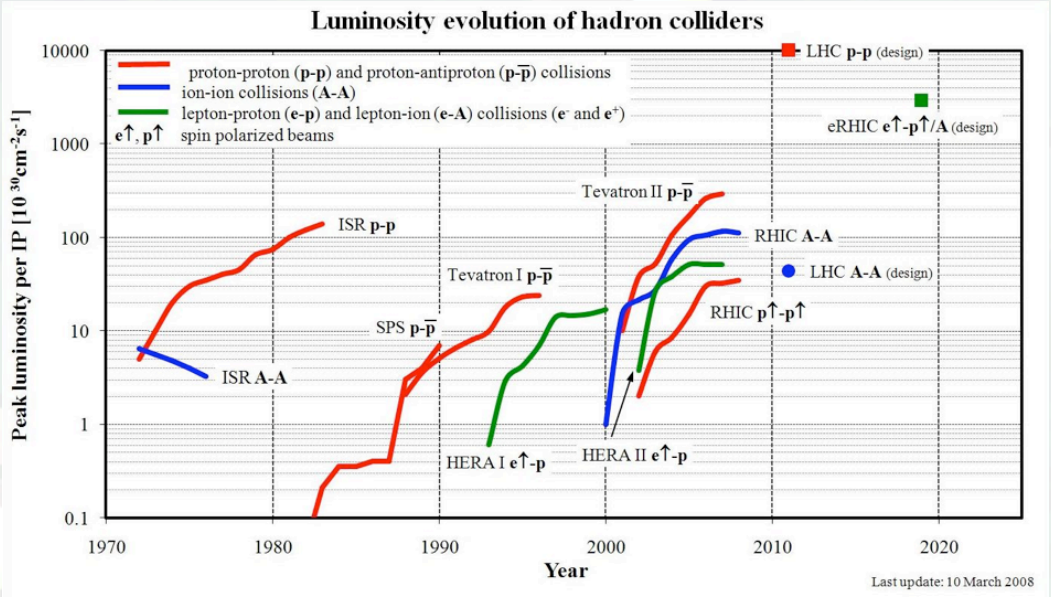
Operated modes (beam energies):

Au-Au	2.5, 4.6, 10, 28, 31, 65, 100 GeV/n
d-Au	100 GeV/n
Cu-Cu	11, 31, 100 GeV/n
p↑-p↑	11, 31, 100, 205, 250 GeV

Past Performance - RHIC program

- RHIC collider aspects: A-A - Performance





Nucleon-Nucleon Luminosities (100 GeV, nucl.-pair):

Au-Au 120×10^{30} cm^{-2} s^{-1}

p↑-p↑ 35×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar) 29×10^{30} cm^{-2} s^{-1}

LHC (p – p, design) 140×10^{30} cm^{-2} s^{-1}

Past Performance - RHIC program

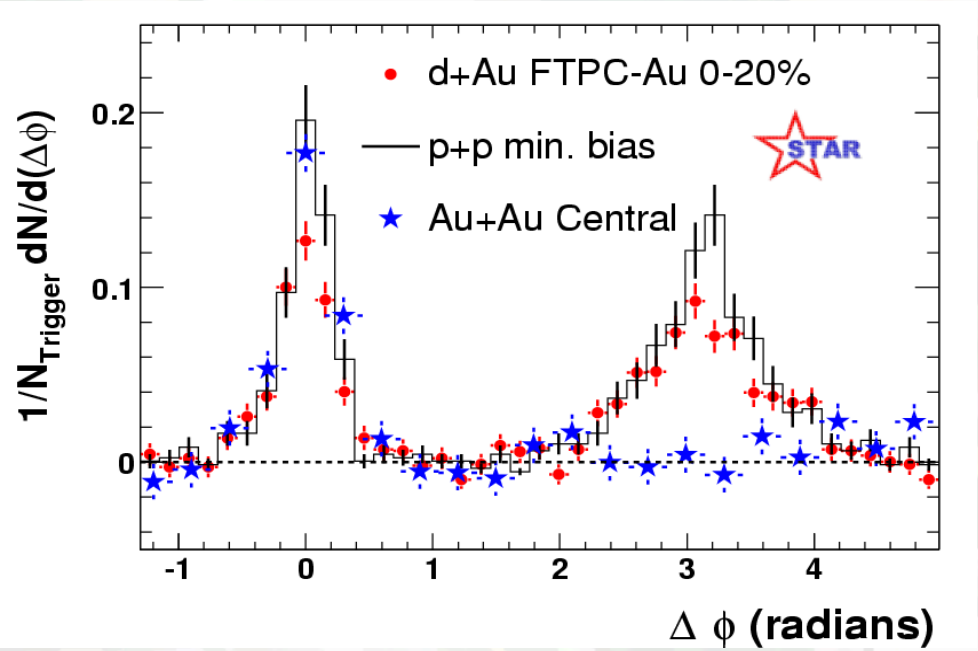
- RHIC collider aspects: A-A - Performance

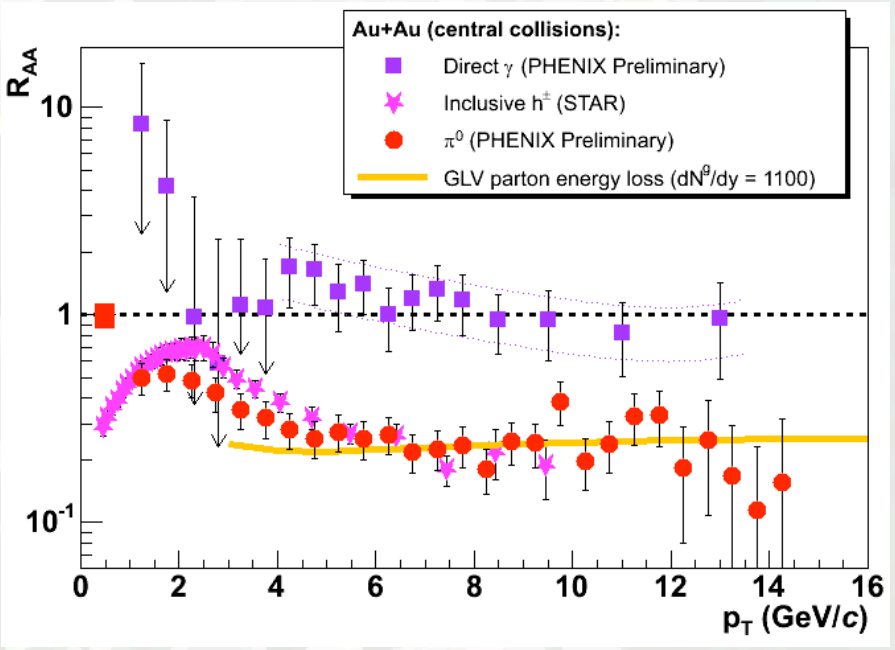
Mode	No of bunches	Ions/bunch [10^9]	β^* [m]	Beam pol.	$L_{store\ ave}$ [$cm^{-2}s^{-1}$]	$A_1A_2L_{store\ ave}$ [$cm^{-2}s^{-1}$]	$A_1A_2L_{peak}$ [$cm^{-2}s^{-1}$]
Design values (1999)							
Au – Au	56	1.0	2		2×10^{26}	8×10^{30}	
p – p	56	100	2		4×10^{30}	4×10^{30}	
Achieved values							
Au – Au	103	1.1	0.8		12×10^{26}	46×10^{30}	120×10^{30}
Cu – Cu	37	4.5	0.9		80×10^{26}	32×10^{30}	79×10^{30}
d – Au	95	100/1.0	0.85		13×10^{28}	51×10^{30}	99×10^{30}
p↑ – p↑	111	135	1	60%	20×10^{30}	20×10^{30}	35×10^{30}
Enhance design values (2009)							
Au – Au	111	1.1	0.9		8×10^{26} ✓	31×10^{30} ✓	
p↑ – p↑	111	200	0.9	70%	60×10^{30}	60×10^{30}	

Past Performance - RHIC program

Physics highlights - A-A program

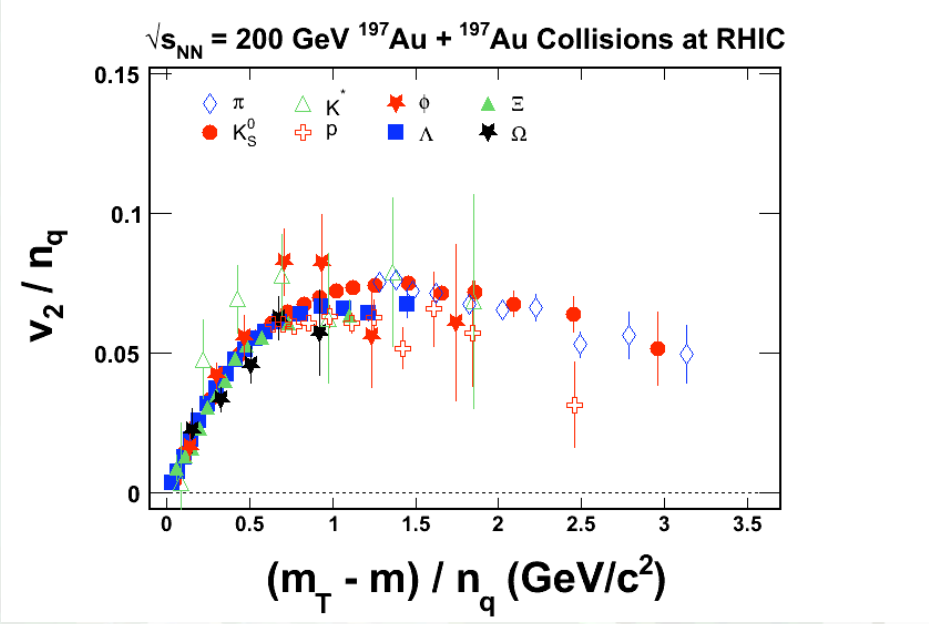
- It is the hottest and densest matter ever created in the Laboratory:
  T ~ 200 MeV - 400 MeV, ε ~ 30 - 60 x ε_0
- It is highly opaque to quarks and gluons, but transparent to photons
- This feature is a final-state effect!

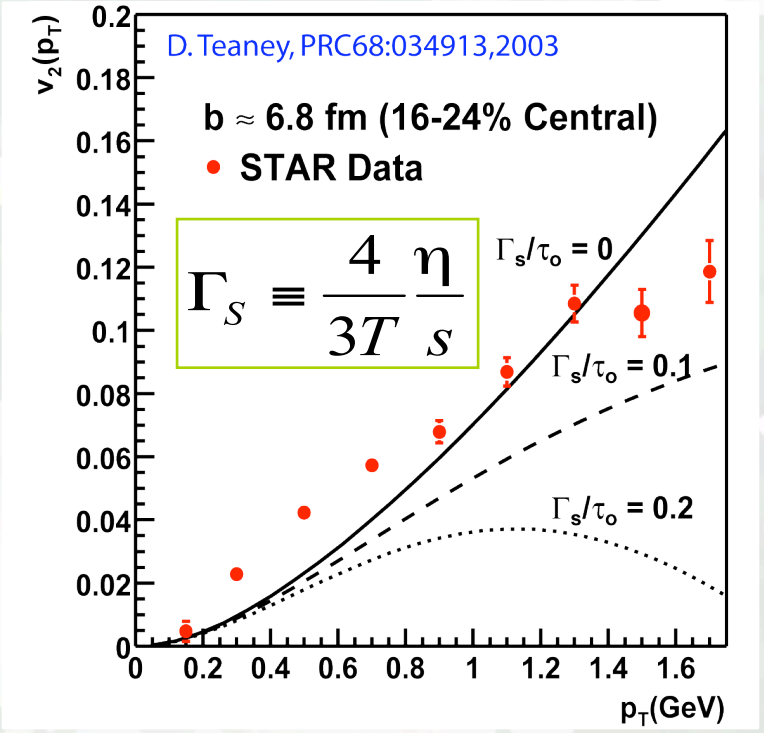




Past Performance - RHIC program

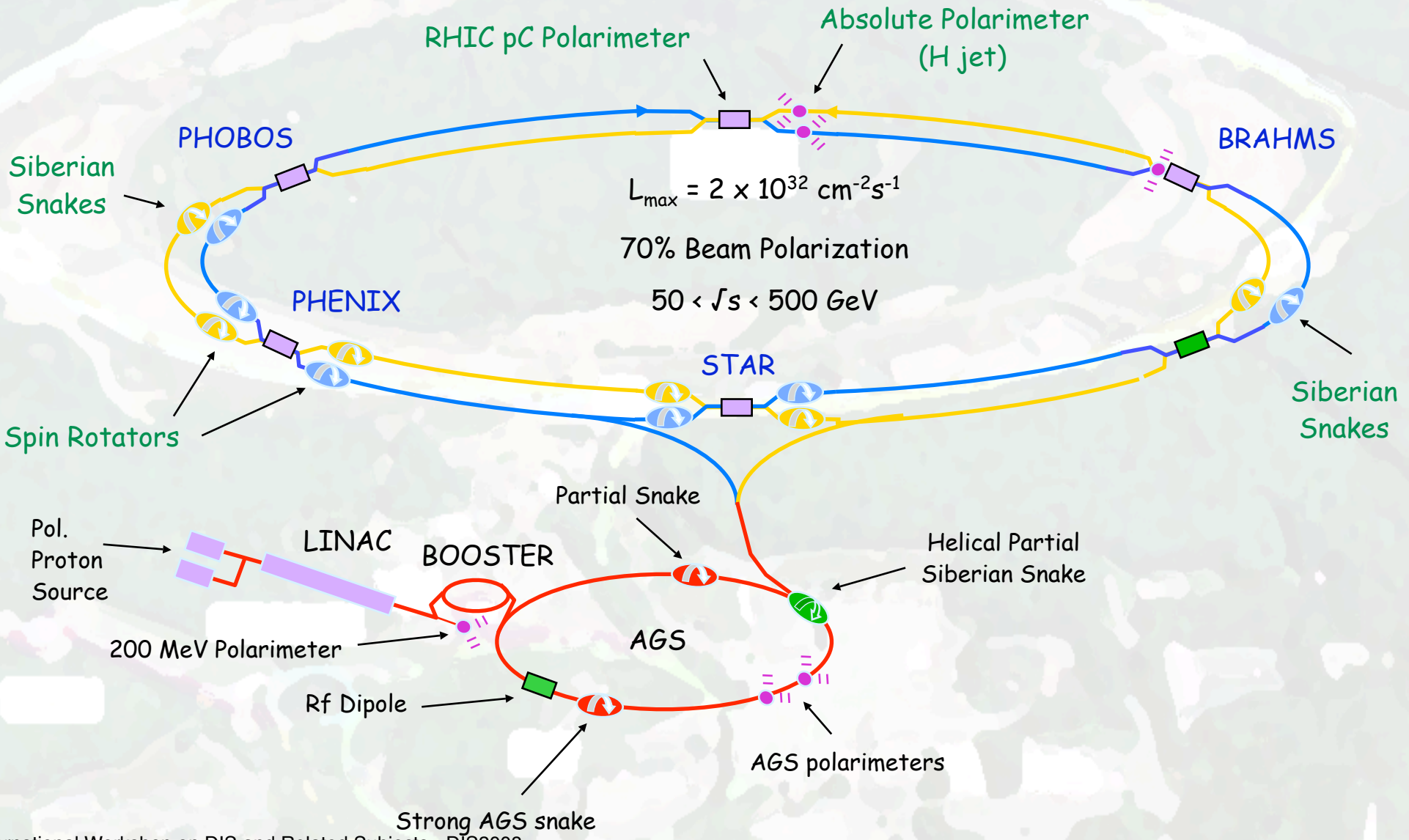
- Physics highlights - A-A program
  - The matter appears to flow as a relativistic liquid, with the lowest viscosity ever observed
  - ⇨ "The Perfect Liquid"
  - Yield and flow properties of baryons and mesons suggest partonic degrees of freedom before hadron formation
  - Very fast equilibration: $\tau < 1$ fm/c





Past Performance - RHIC program

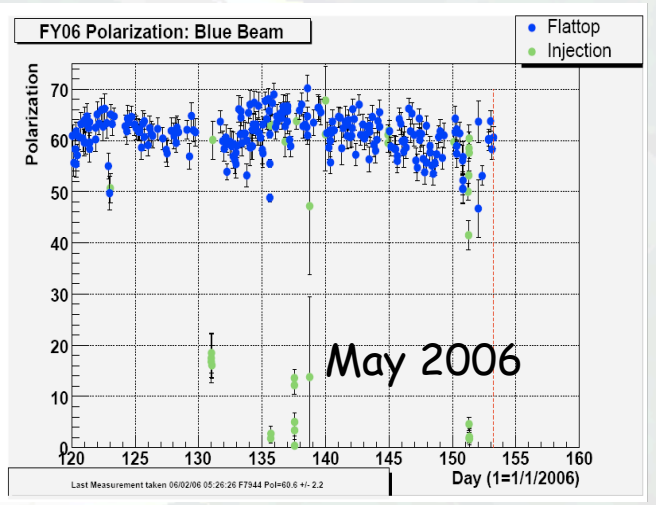
- RHIC collider aspects: p-p - Layout

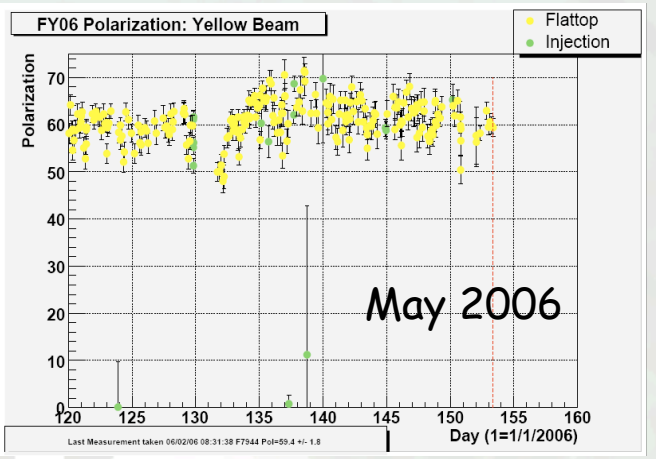


Past Performance - RHIC program

- RHIC collider aspects: p-p - Performance

RHIC RUN	s [GeV]	$L_{recorded}$ [pb^{-1}] (transverse)	$L_{recorded}$ [pb^{-1}] (longitudinal)	Polarization[%]
RUN 2	200	0.15	0.3	15
RUN 3	200	0.25	0.3	30
RUN 4	200	0	0.4	40-45
RUN 5	200	0.4	3.1	45-50
RUN 6	200	3.4/6.8	8.5	60



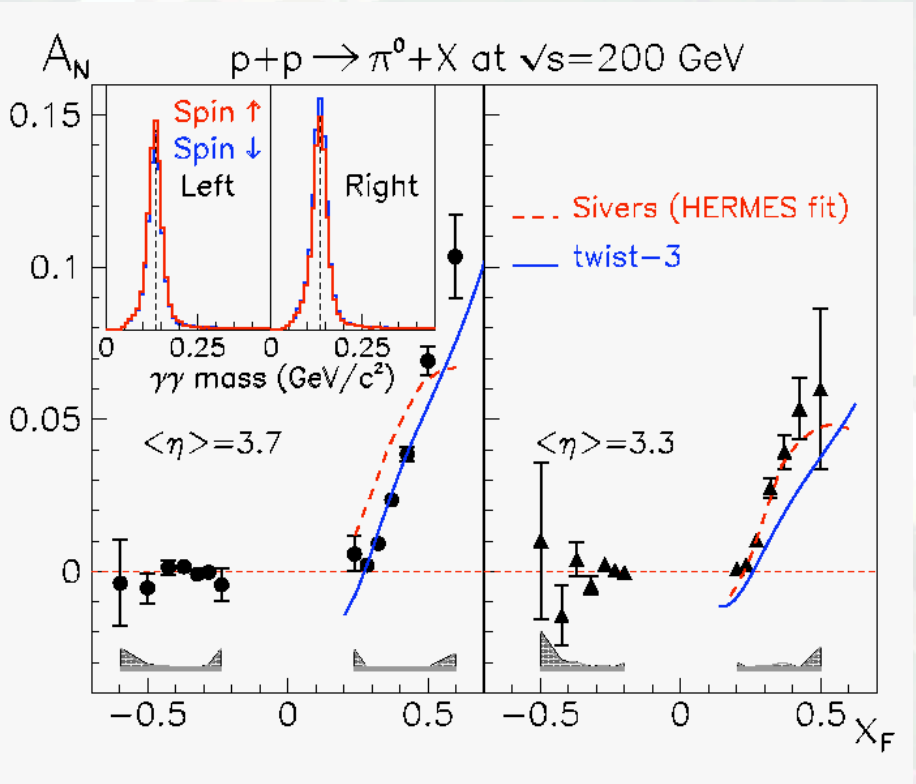


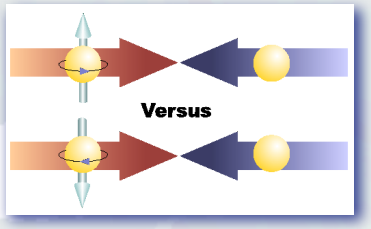
- All RHIC polarized pp accelerator components are in place!
- 2006 performance (√=200GeV): ~60% polarization (70% design) and ~1pb^{-1}/day (~3pb^{-1}/day design) delivered luminosity

Past Performance - RHIC program

Physics highlights - p-p program : Transverse Spin program

Submitted to PRL, hep-ex/0801.2990





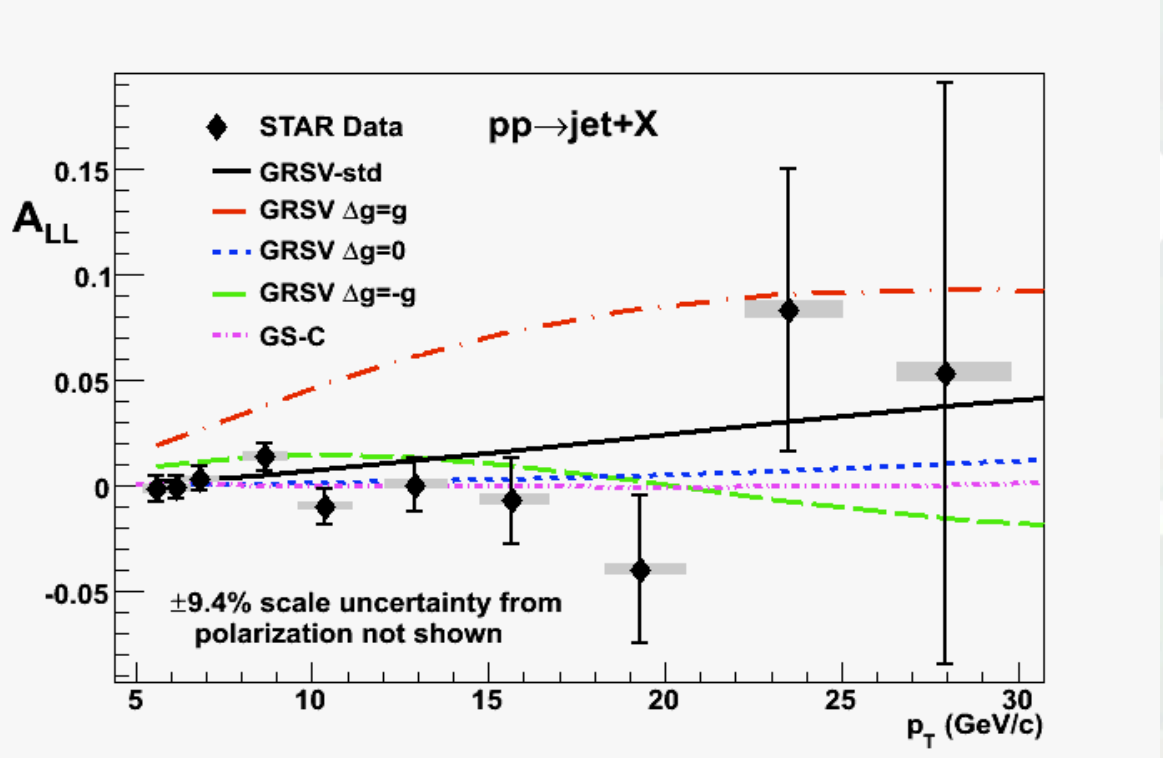
$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

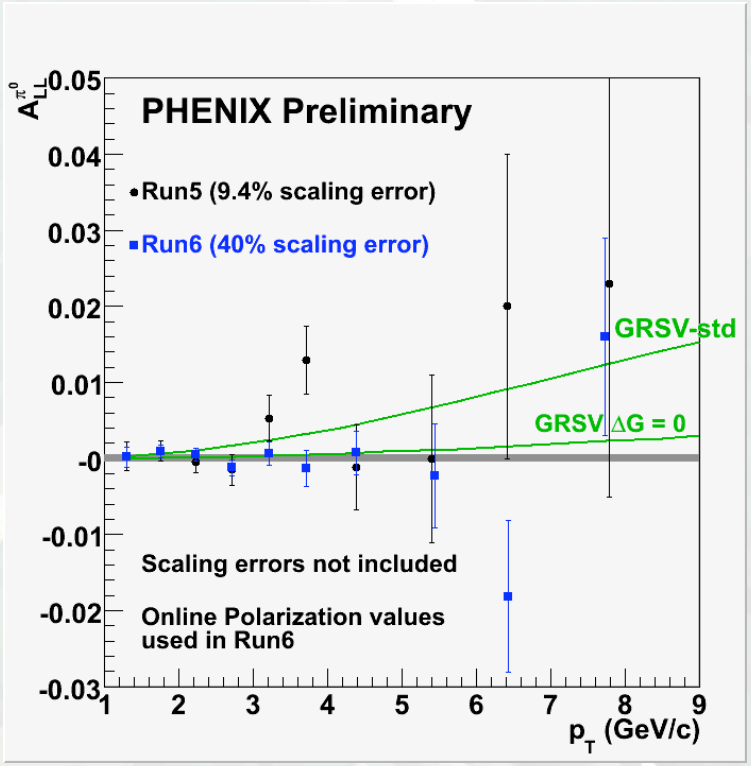
- A_N : First asymmetry measurement at RHIC
- A_N calculations (Sivers / Twist-3) in comparison to precise x_F dependence of measured A_N

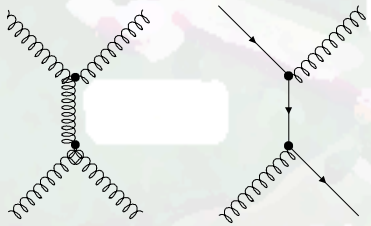
- Basic, naive QCD calculations (leading-twist, zero quark masses) predict: A_N=0 ($A_N \sim m_q/\sqrt{s}$)
- Study transverse spin effects:
  - Qiu and Sterman (Initial-state twist-3)/Koike (final-state twist-3)
  - Sivers: $k_\perp$ in initial state (Correlation of quark $k_\perp$ and transverse proton spin): ⇒ Orbital momentum
  - Collins: $k_\perp$ in final state (Correlation of transverse quark spin and $k_\perp$ of hadron): ⇒ Transversity

Past Performance - RHIC program

- Physics highlights - p-p program : Longitudinal Spin program





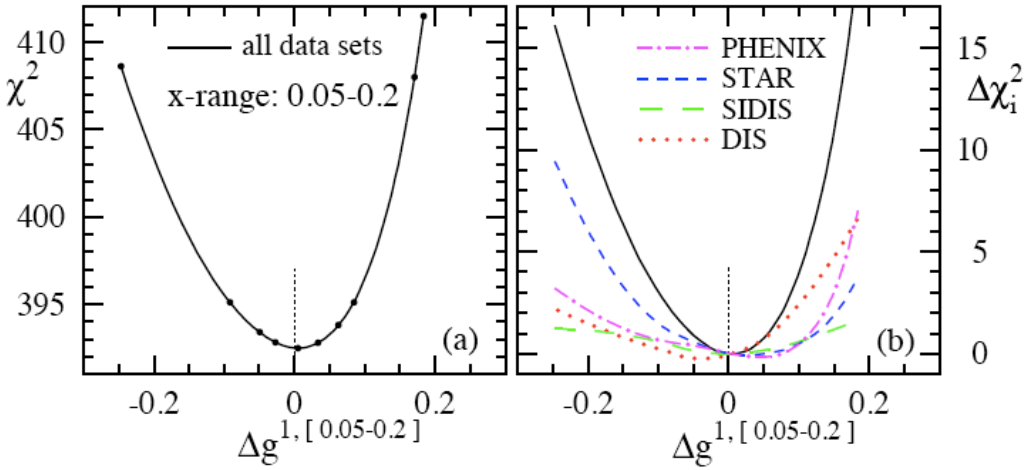


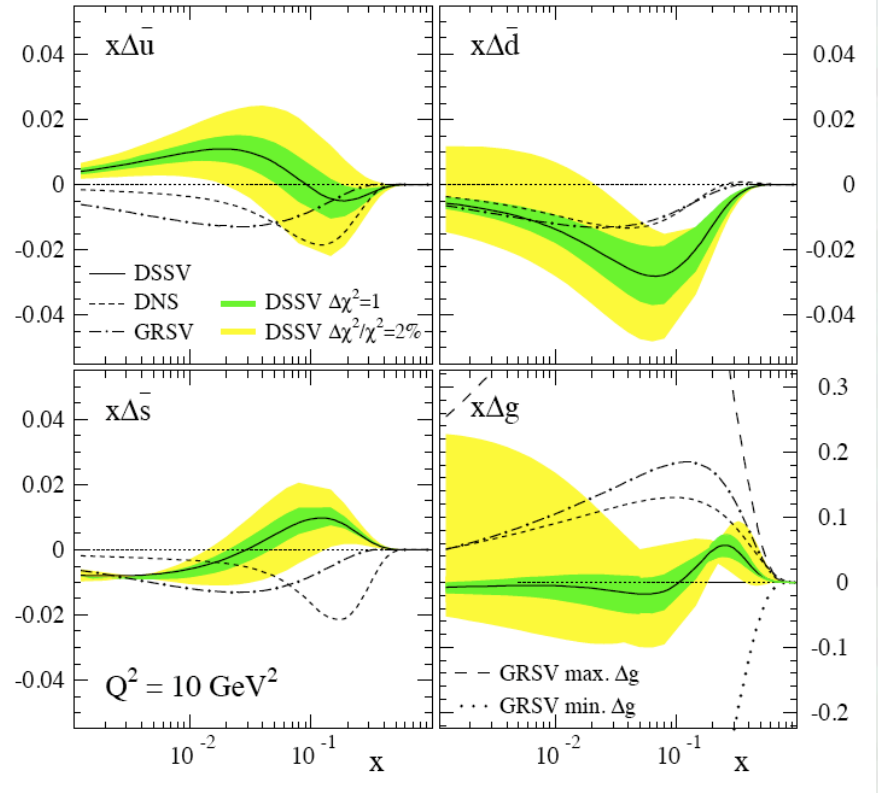
$$\text{jets} + X$$

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \propto \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

Past Performance - RHIC program

- Physics highlights - p-p program : Longitudinal Spin program





- Evidence for a small gluon polarization over a limited region of momentum fraction

- Strong constraint on the size of Δg from RHIC data for $0.05<x<0.2$

- Important: Mapping x-dependence and extension of x-coverage needed!

Near-term RHIC program and RHIC II

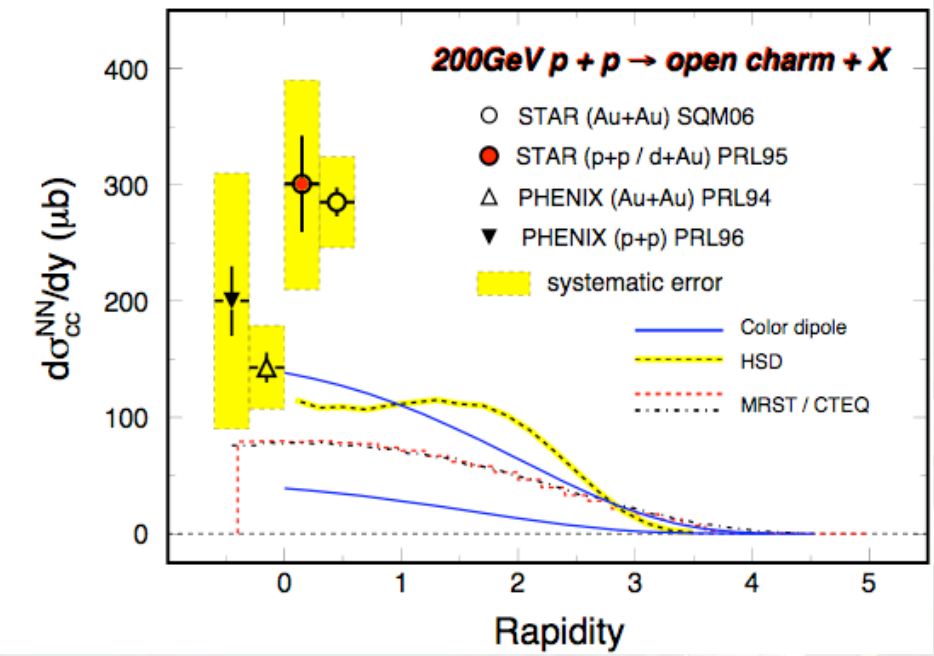
- Open questions: A-A program
  - What are the quantitative properties of the medium produced at RHIC?
  - What is the Equation of State, what is the energy density and the initial temperature?
    - Gamma-Jet correlations as a detailed probe for jet quenching
    - Heavy quark jets (less energy loss of heavy quarks via gluons)
    - photons, dileptons as thermometers
  - What is the viscosity of the medium?
    - Flow of heavy quarks
  - How does it reach thermal equilibrium so fast?
    - Heavy quark dynamics
  - Is there direct evidence for deconfinement?
    - Study of charmonium and bottomium states: Melting in the medium

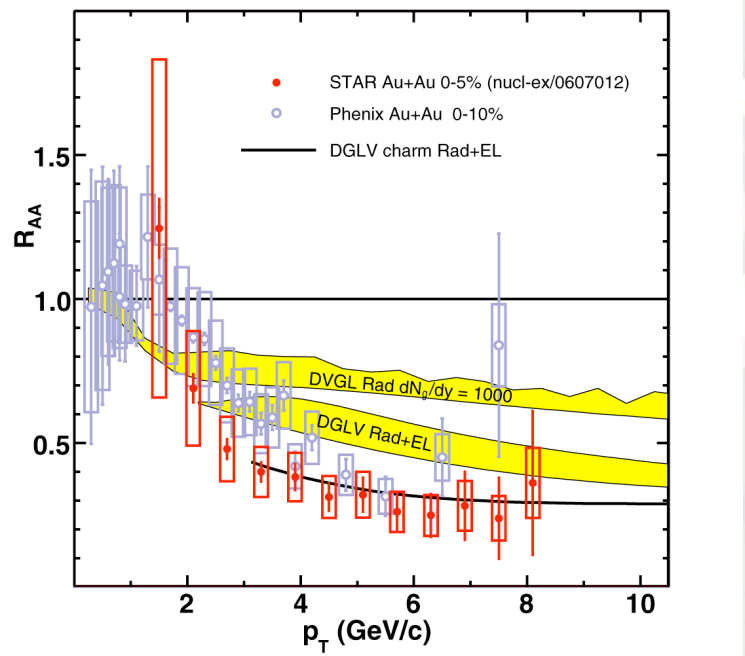
Near-term RHIC program and RHIC II

- Open questions: A-A program
  - Is there a Critical Point in the QCD phase diagram? Can we directly observe a phase transition?
    - Energy scan, study of fluctuations
  - What is the initial state in heavy ion collisions? Where is the gluon saturation scale?
    - Forward physics in d+Au collisions
  - How does the medium hadronize?
    - Study the interplay of recombination and fragmentation via identified particle spectra up to intermediate pt, resonances

Near-term RHIC program and RHIC II

- Physics highlights: *A-A* program





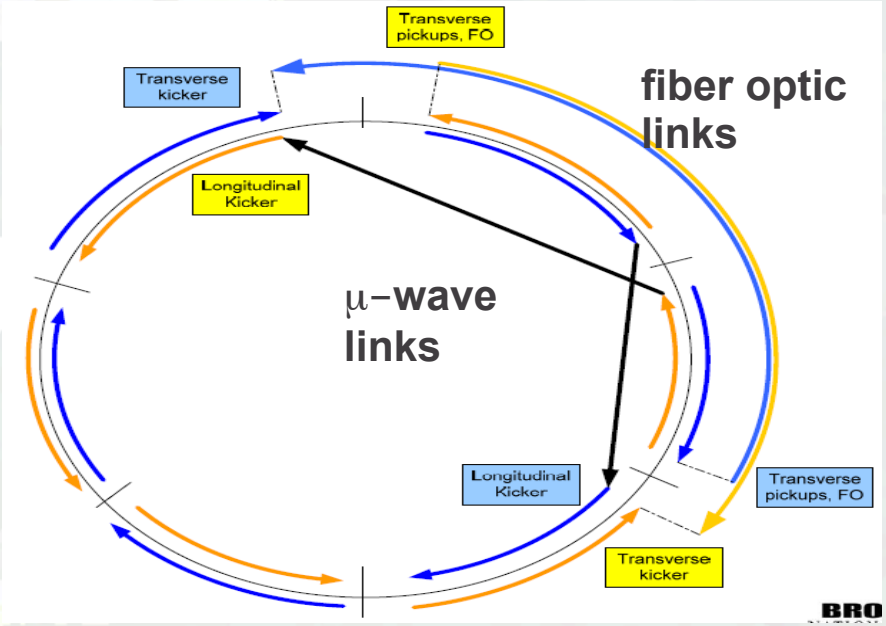
- Large systematic uncertainties in the measured charm cross-section from non-photonic electrons
- Theory below STAR measurements by ~2 and STAR ~2·PHENIX
- Expectation: Smaller energy loss for heavy quarks
- However: Non-photonic electron measurements indicate unexpectedly large energy loss!
- Direct reconstruction of charm hadrons critical ⇒ PHENIX / STAR Vertex Detector Upgrade

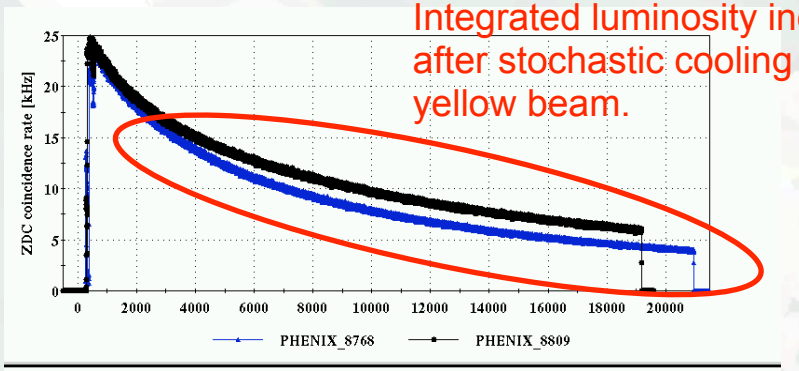
Near-term RHIC program and RHIC II

- Physics highlights: p-p program
  - What is the momentum dependence of the gluon polarization? What is the contribution to the proton spin in the RHIC accessible kinematic region?
    - Correlation measurements: Di-Jet production / Photon-Jet production
    - Extend kinematic coverage: Forward acceptance (asymmetric collisions / 500GeV operation)
  - What is the polarization of anti-u and anti-q quarks?
    - W production at RHIC (500GeV operation)
  - What is the mechanism for transverse single-spin asymmetries?
    - Study correlation Sivers / Collins

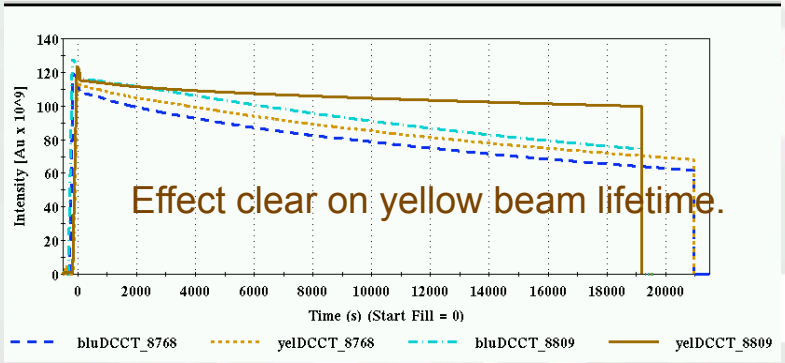
Near-term RHIC program and RHIC II

- Collider upgrades: Cooling
- Stochastic Cooling can help reduce beam emittance
- less effective than e^- cooling, but cheaper and earlier implementation
- First test with longitudinal cooling in yellow ring





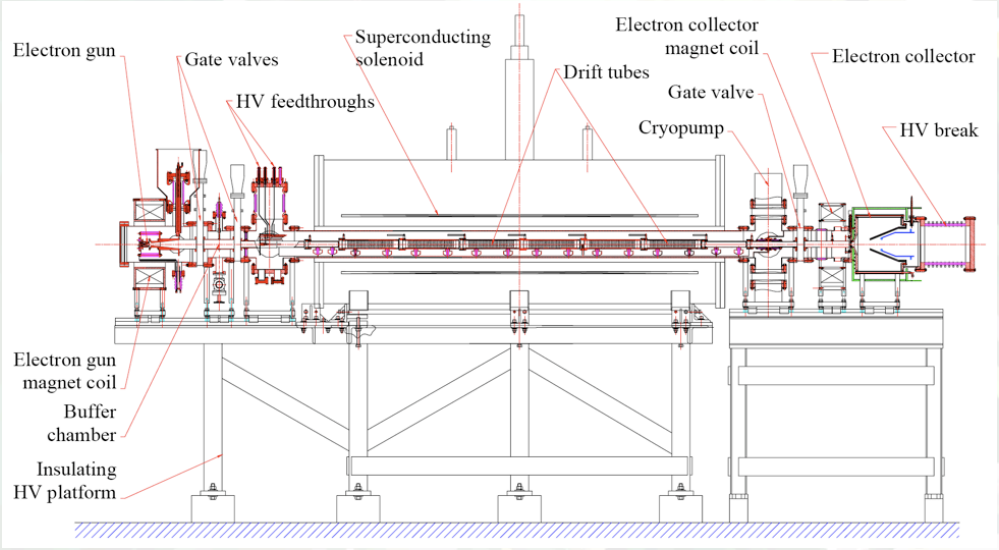
Integrated luminosity increased 10-20% after stochastic cooling introduced for yellow beam.

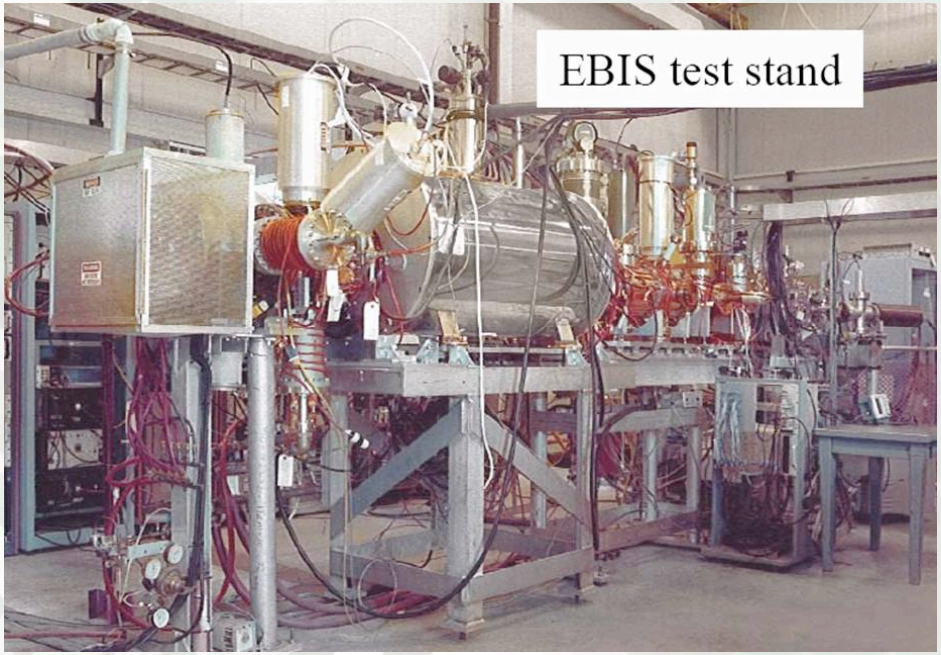


Effect clear on yellow beam lifetime.

Near-term RHIC program and RHIC II

- Collider upgrades: EBIS source
  - New high brightness, high charge-state pulsed ion source
  - Replaces 35 year old Tandem Van de Graafs
  - Improved reliability, lower operations costs
  - Enables new beams: noble gas ions, Uranium, polarized ^{3}He
  - Construction schedule: FY2006 -10





Near-term RHIC program and RHIC II

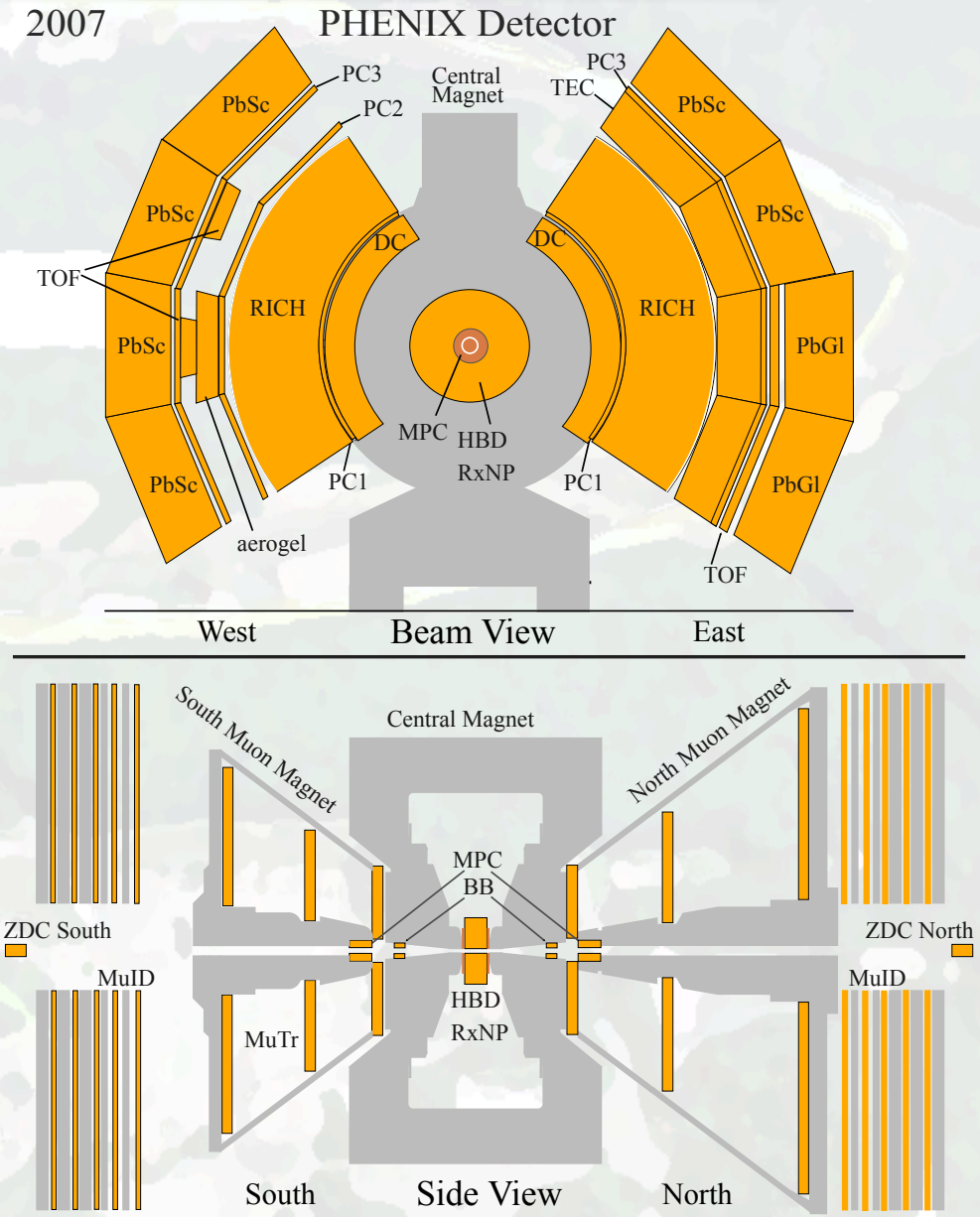
- Detector upgrades - PHENIX

Forward Muon Trigger Detector
Si Vertex Tracking Detector- Barrel
(Pixel + Strips)
Si Vertex Endcap (mini-strips)

Aerogel Cerenkov Counter
Multi-Gap Resistive Plate Chamber
ToF
Hadron Blind Detector

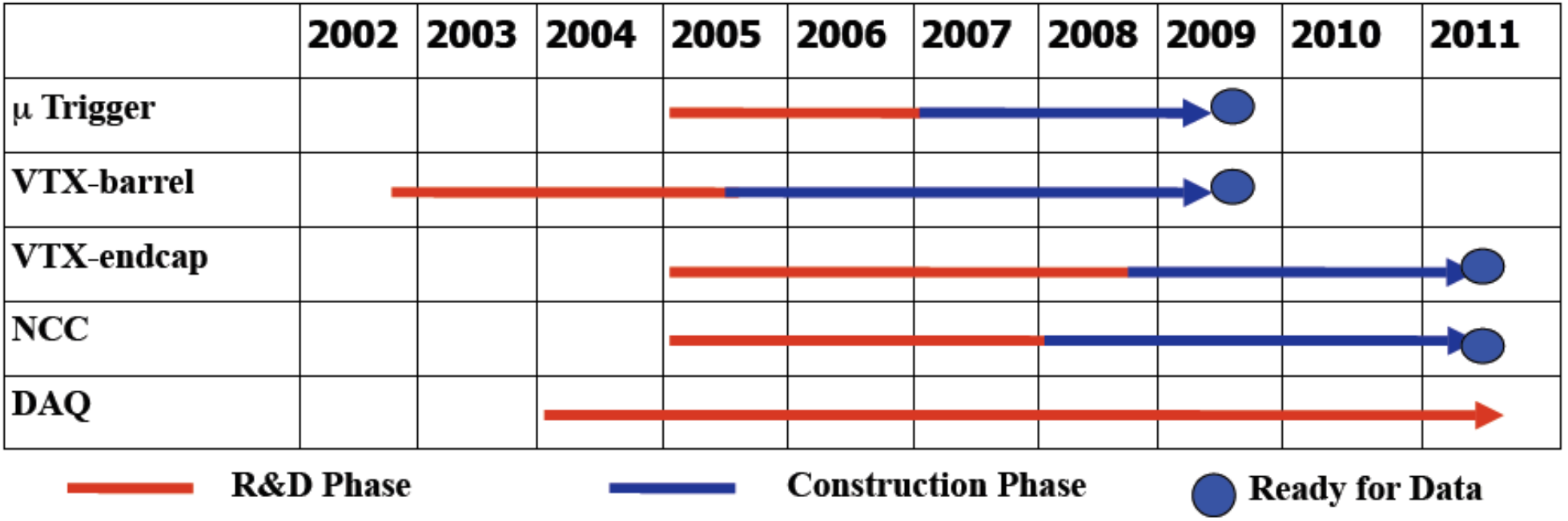
Nose Cone Calorimeter
Muon Piston Calorimeter

Reaction Plane Detector



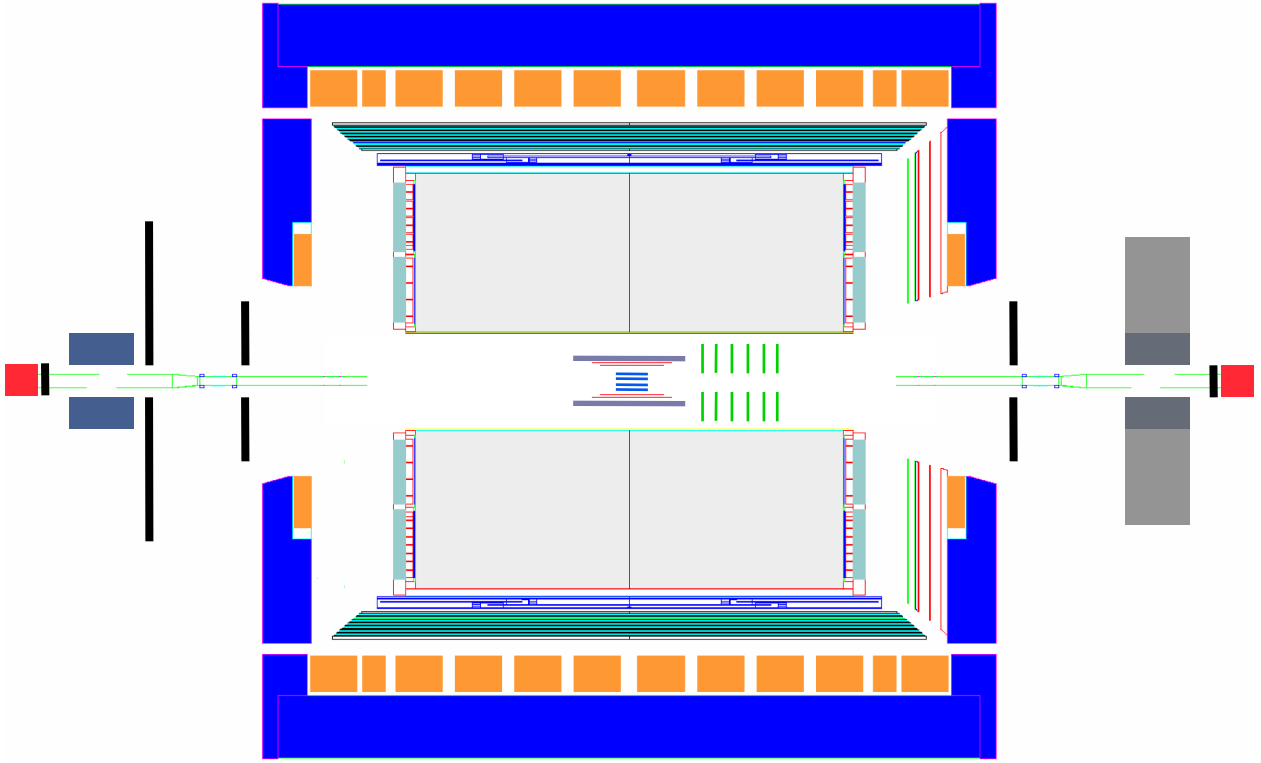
Near-term RHIC program and RHIC II

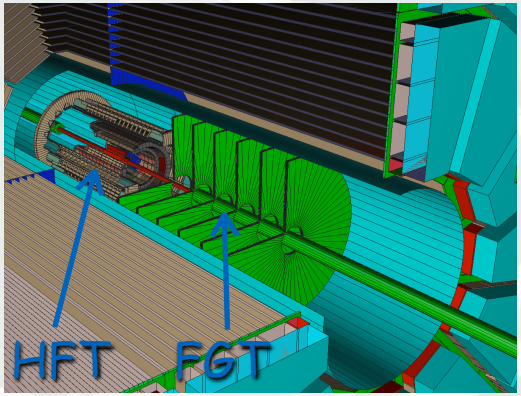
- PHENIX upgrade plan



Near-term RHIC program and RHIC II

- Detector upgrades - STAR





- DAQ upgrade
- TOF upgrade
- FMS upgrade (Completed!)

- Precision vertexing for charm and bottom reconstruction
- HFT: Silicon pixel (PIXEL) and silicon strip (Intermediate Silicon Tracker - IST)
- Forward GEM Tracker (FGT)

Near-term RHIC program and RHIC II

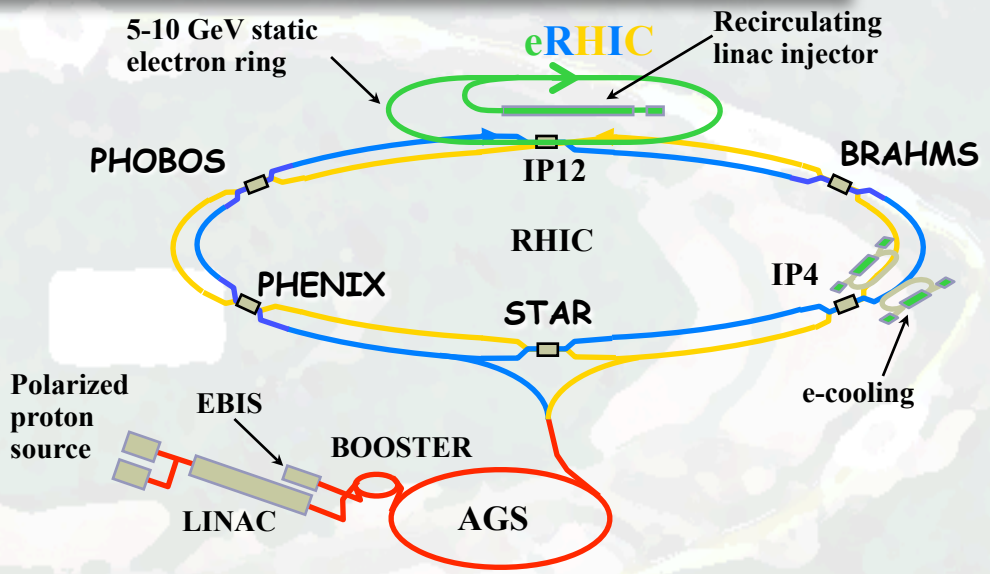
- STAR upgrade plan

eRHIC - A future electron-ion collider at BNL

eRHIC - Ring-Ring option

Electron storage ring design

- Intersection with RHIC blue beam
- RHIC Yellow beam: 3m excursion around IR region
- Injection system: Polarized electron source and recirculating linac
- Storage energy: 5-10GeV (electrons)
- Self-polarization of positrons in storage ring (20min. at 10GeV) injected at 10GeV
- Spin rotator setup in e-ring and blue RHIC ring around eRHIC IR region



Required modifications at RHIC:

- Electron cooling system: Achieve and maintain small beam emittances
- Increase of total current: Increasing the number of bunches from 120 (present design) to ultimately 360 bunches
- Additional spin rotator magnets in ep interaction region

eRHIC - A future electron-ion collider at BNL

eRHIC - Linac-Ring option

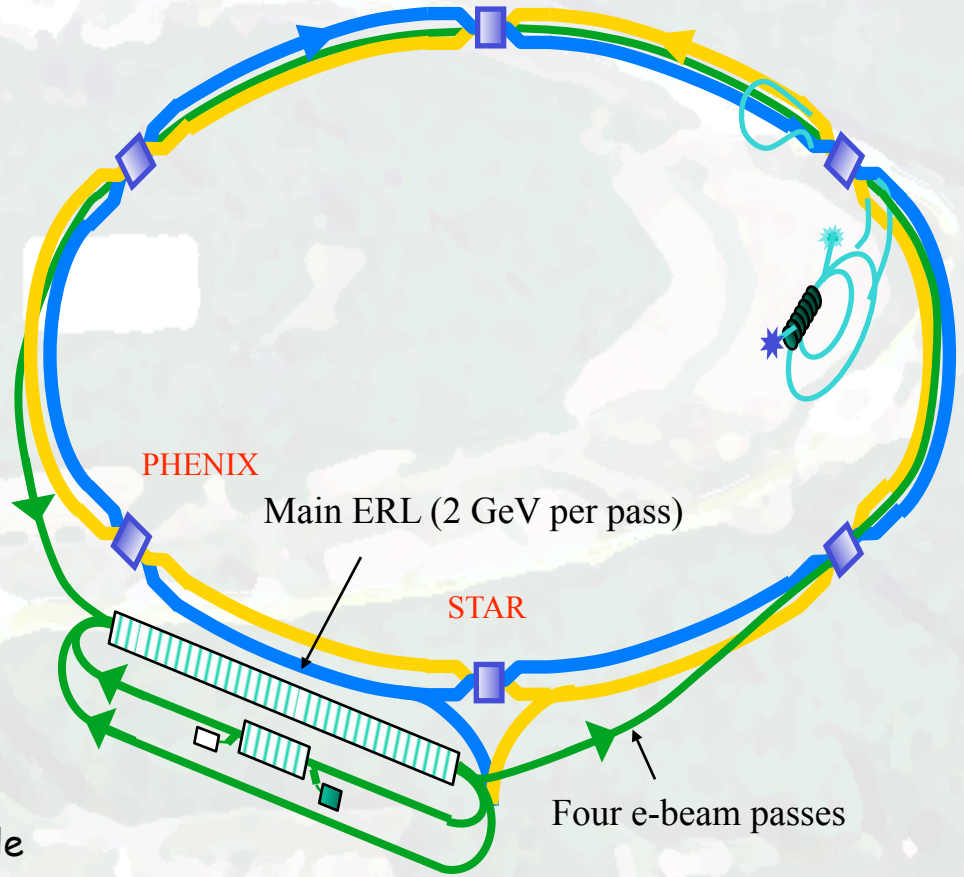
Energy Recovery Linac to RHIC

$E_e = 10\ (20)$ GeV

$E_A = 100$ GeV (up to U)

$\sqrt{s_{eN}} = 63\ (90)$ GeV

L_{eAu} (peak)/n ~ $2.9 \cdot 10^{33}$ cm^{-2} s^{-1}

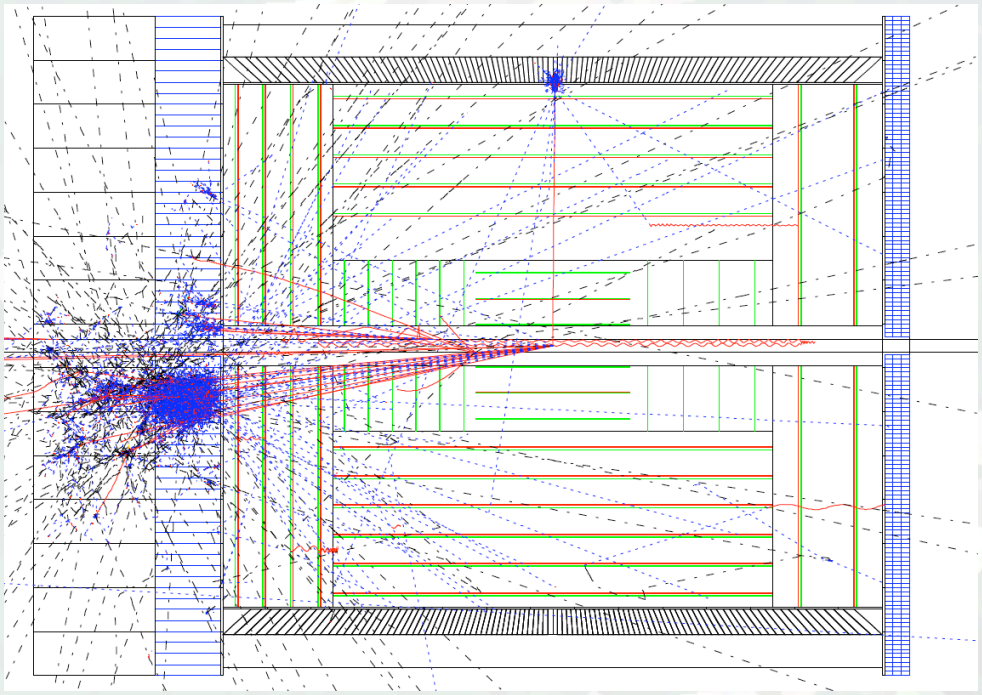


- Features:
  - High degree of polarization at any energy (>80%)
  - Machine elements free region approx. ±5m
  - Simpler IR region design: Round beams possible
  - Upgrade to higher energies beyond 10GeV possible
  - Multiple interaction regions
  - No positrons

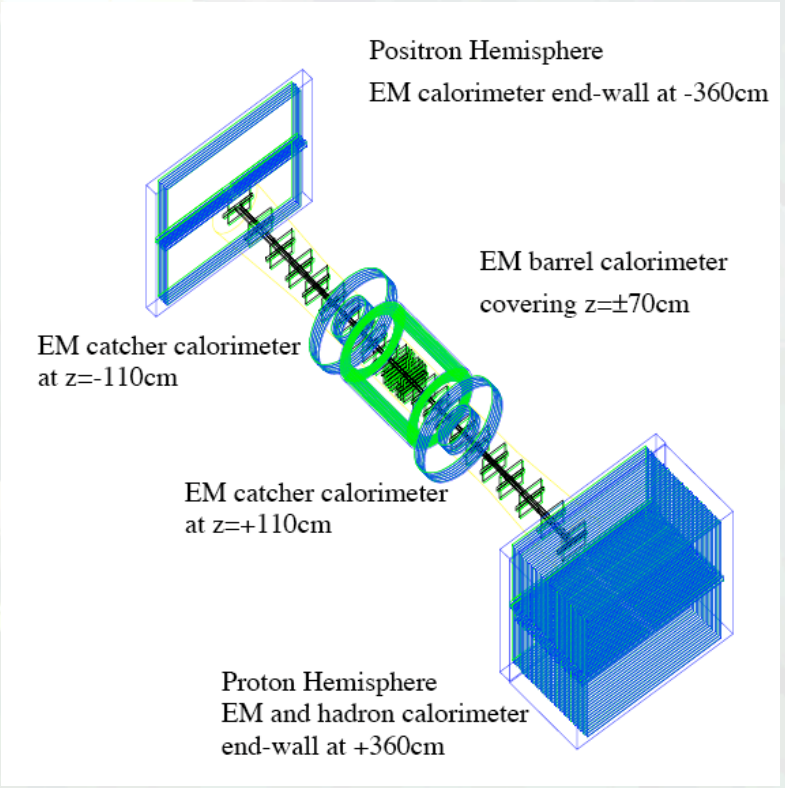
- R&D issues:
  - High current polarized electron source
  - Energy recovery technology for high energy and high current beams

eRHIC - A future electron-ion collider at BNL

Detector concepts



J. Pasukonis, B. Surrow, physics/0608290

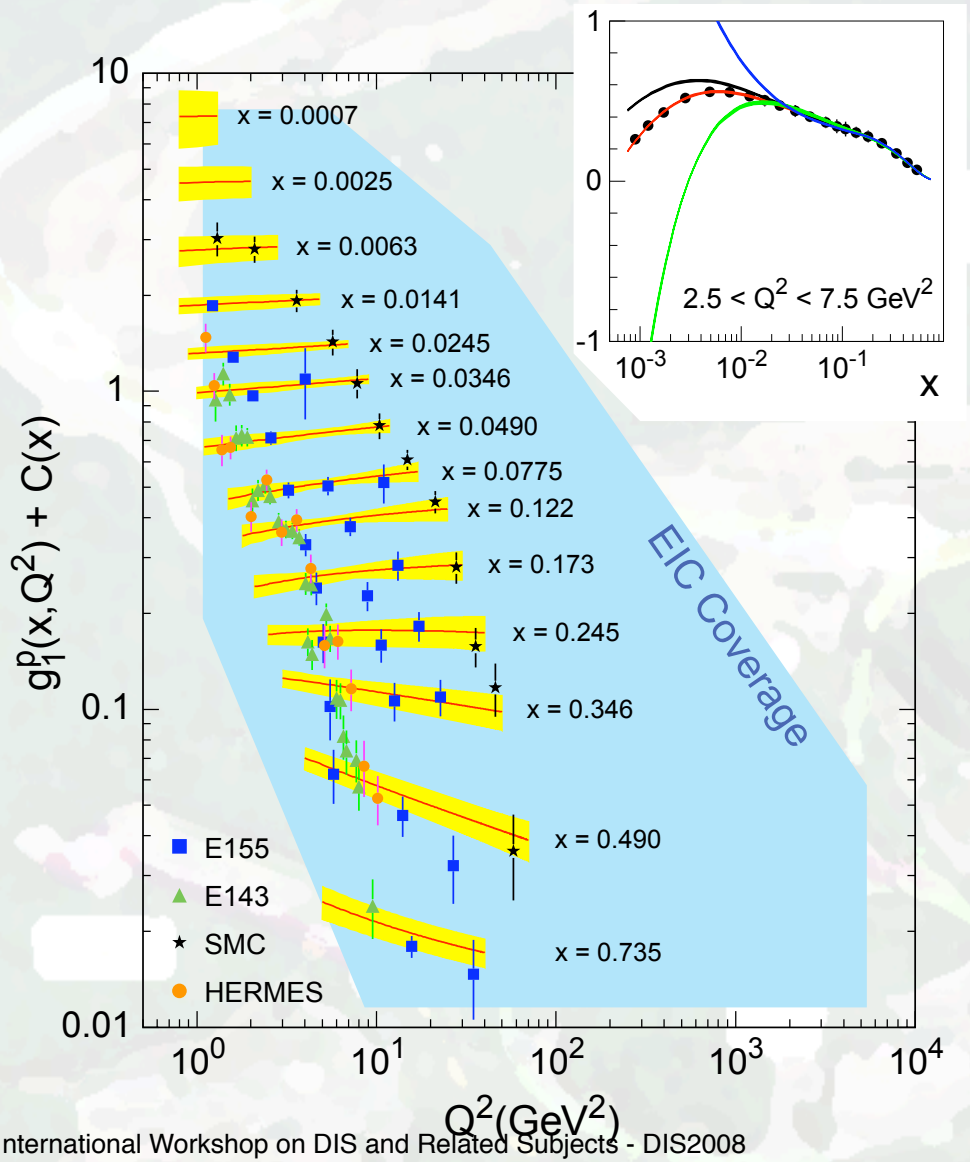


I. Abt, A. Caldwell, X. Liu,
J. Sutiak, hep-ex 0407053

- Rear/forward acceptance and thus on low-x / high-x physics
- Compact design
- Need detector system which allows both: Critical part - Magnetic field layout

eRHIC - A future electron-ion collider at BNL

- Polarized ep program - Projections

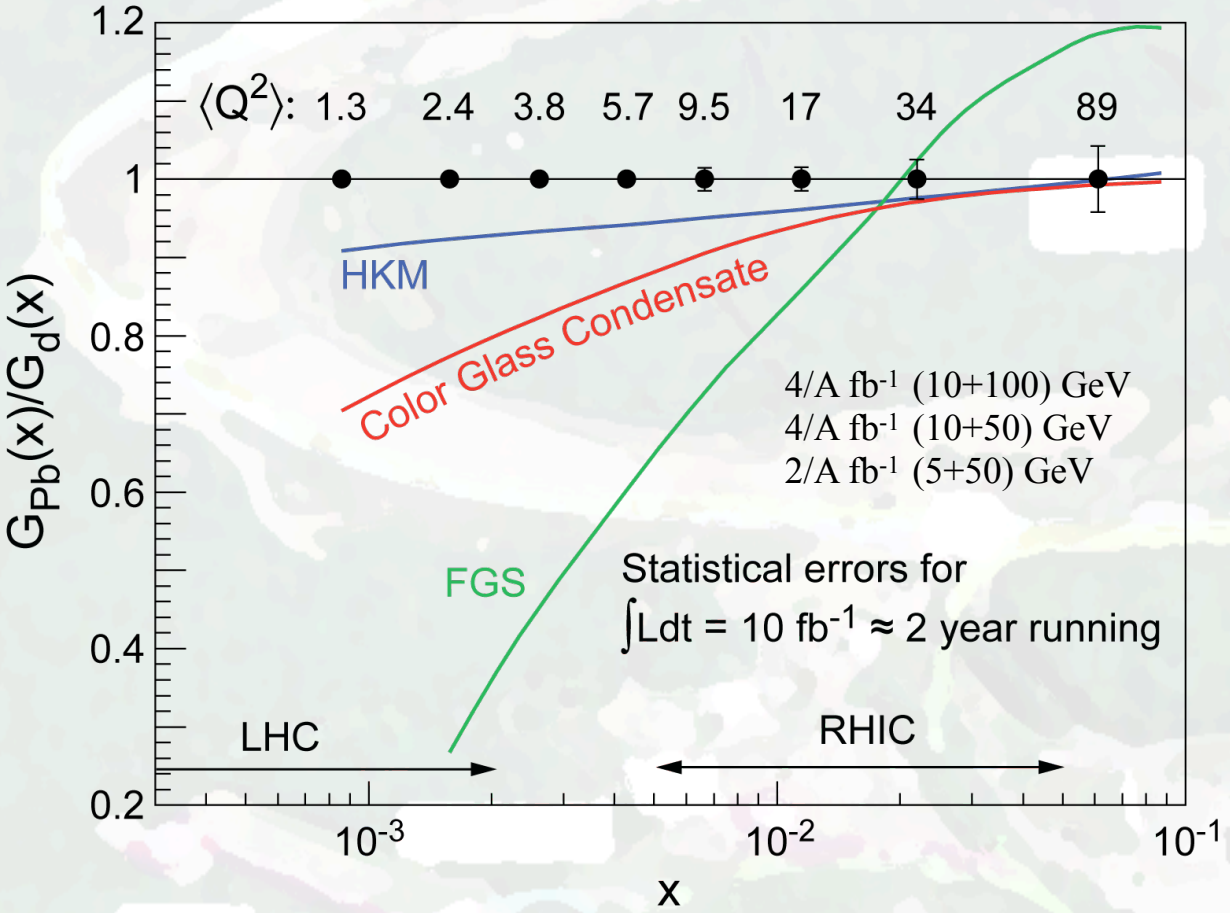


- E_e = 7GeV and E_p = 150GeV
- Luminosity: 5fb^{-1}

EIC allows a precision measurement of g^1_p at lower x values compared to previous experiments

eRHIC - A future electron-ion collider at BNL

eA program - Projections



- EIC will reach the unmeasured low-x region (<0.01) with high precision for Q^2>1GeV^2
- Constrain gluon modification due to nuclear effects in comparison to large range of models

EIC will measure modification of gluon distribution with high precision!

$$\left(\frac{d^2\sigma}{dydQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right) \qquad F_L = \frac{Q^2}{4\pi^2\alpha}\sigma_L^{\gamma^* p} \propto xg$$

eRHIC - A future electron-ion collider at BNL

- Schedule
  - NSAC Long Range Plan 2007
  - Recommendation: $6M/year for 5 years for machine and detector R&D
  - Goal for Next Long Range Plan 2012
  - EIC Roadmap (Technology Driven)
    - Finalize Detector Requirements from Physics 2008
    - Revised/Initial Cost Estimates for eRHIC/ELIC 2008
    - Investigate Potential Cost Reductions 2009
    - Establish process for EIC design decision 2010
    - Conceptual detector designs 2010
    - R&D to guide EIC design decision 2011
    - EIC design decision 2011
    - MOU's with foreign countries? 2012

Goal I: High-level recommendation at next LRP

Goal II: CD-0 Mission Need before next LRP

Goal III: Decision on EIC design before next LRP

Summary and Outlook

- Future Opportunities: RHIC

  - Unique opportunities to explore matter under extreme conditions at RHIC: Perfect Liquid
    - Flexible collider operation (Different beam species and energies)
    - Detector upgrades crucial
    - Key step: Heavy flavor detection capabilities
  - Unique opportunity to explore spin structure and dynamics of the proton at RHIC
    - Gluon polarization
    - W production
    - Transverse spin dynamics

Summary and Outlook

- Future Opportunities: EIC

- EIC: First polarized ep collider - Precision measurement of polarized gluon distribution at low-x and quark flavor structure

- EIC will allow to study the physics of strong color fields beyond ongoing low-x RHIC efforts

- Required: EIC at high luminosity and optimized detector

- EIC will allow to bridge several QCD communities (Hadron structure and Relativistic Heavy-Ion) - Future of JLab and BNL!

- Unique opportunity in precision QCD physics complementary to other next generation facilities in Europe (LHC/LHeC at CERN, FAIR at GSI) and Asia (J-PARC)

RHIC II / EIC related talks

- RHIC II
  - F. Simon: The future relativistic heavy-ion program at RHIC
  - J. Balewski: The future polarized p-p program at RHIC
- EIC (eRHIC / ELIC)
  - J. Bluemlein: Polarized pdf's at a future EIC Facility
  - A. Sandacz: The GPD program at a future EIC Facility
  - M. Lamont: The eA program at a future EIC Facility