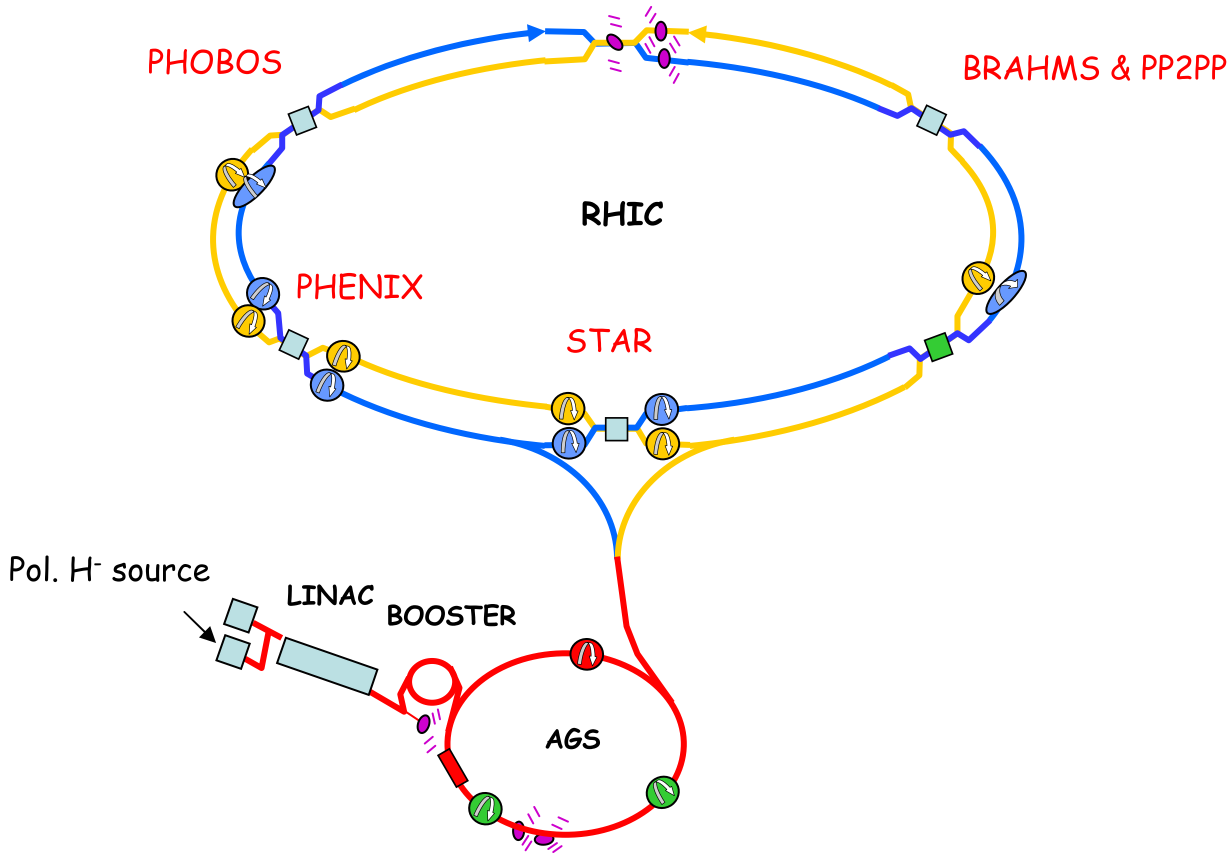
Experimental Results from RHIC and Plans for eRHIC

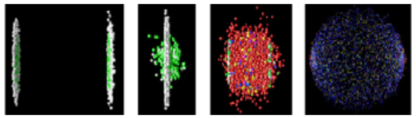


Richard Milner

DIS2004, April 17th 2004

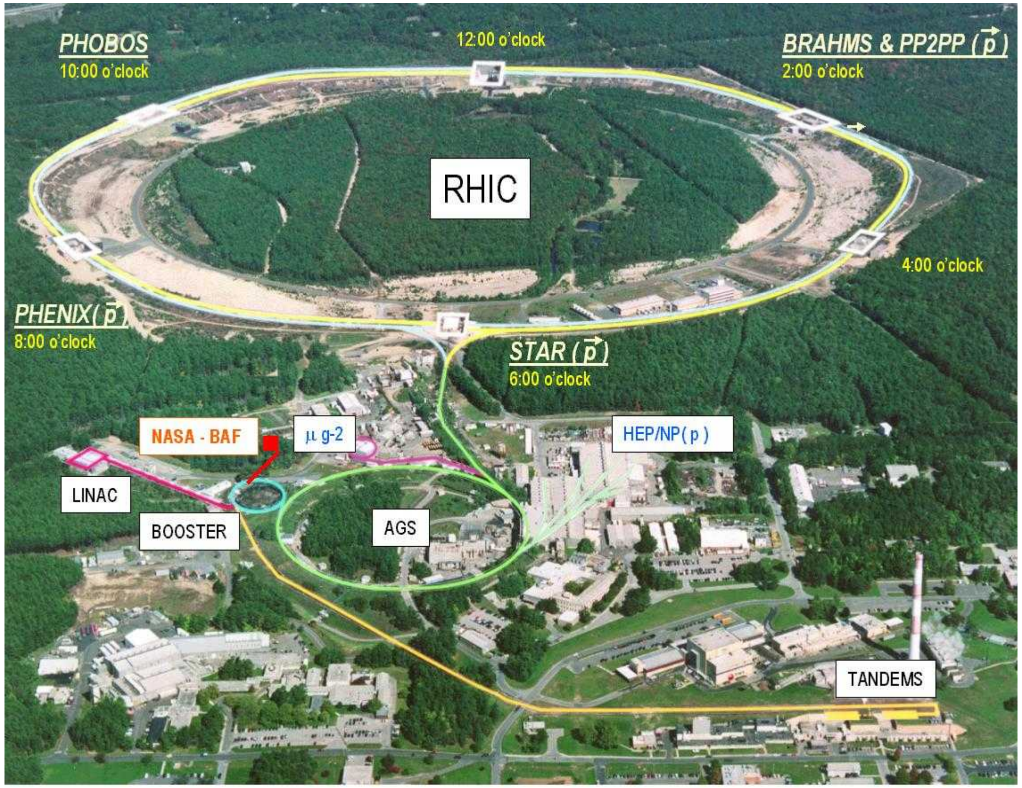
Relativistic Heavy Ion Collider

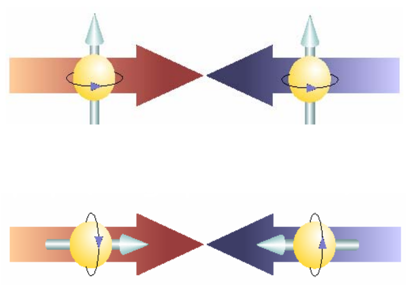
Au+Au (d+Au)



Experiments:

- ⇨ PHENIX
- ⇨ STAR
- ⇨ BRAHMS
- ⇨ PHOBOS



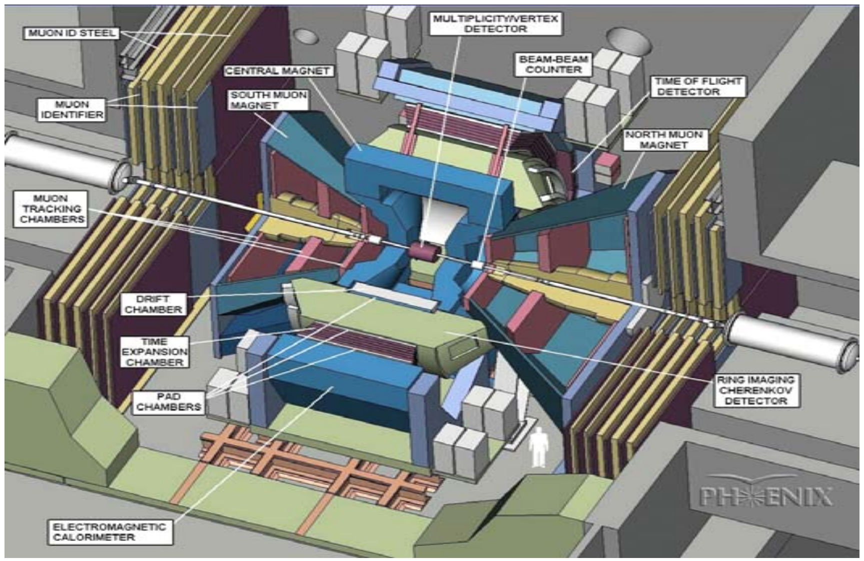


- ⇨ PHENIX
- ⇨ STAR
- ⇨ BRAHMS & PP2PP

- 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)

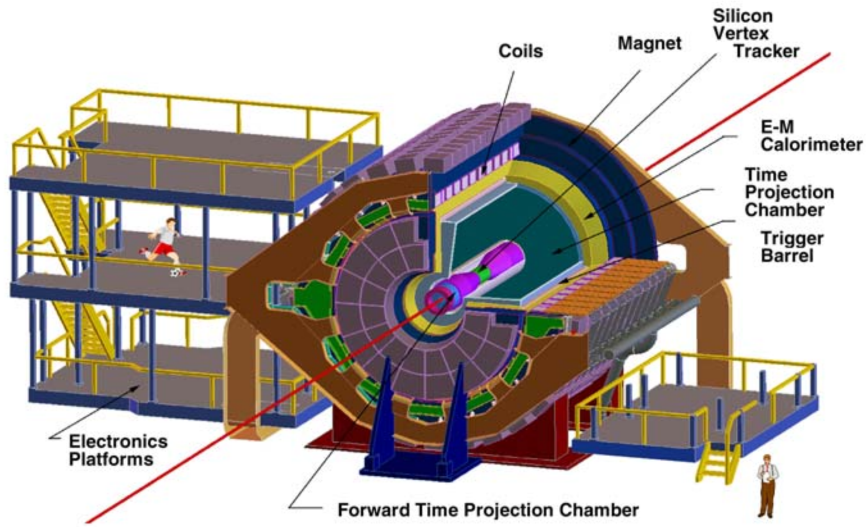
The RHIC experiments

- PHENIX (450 collaborators)



- Axial Field
- Two instrumented central and forward arms
- RICH, EM Calorimetry, TEC, Si, TOF, μ-ID

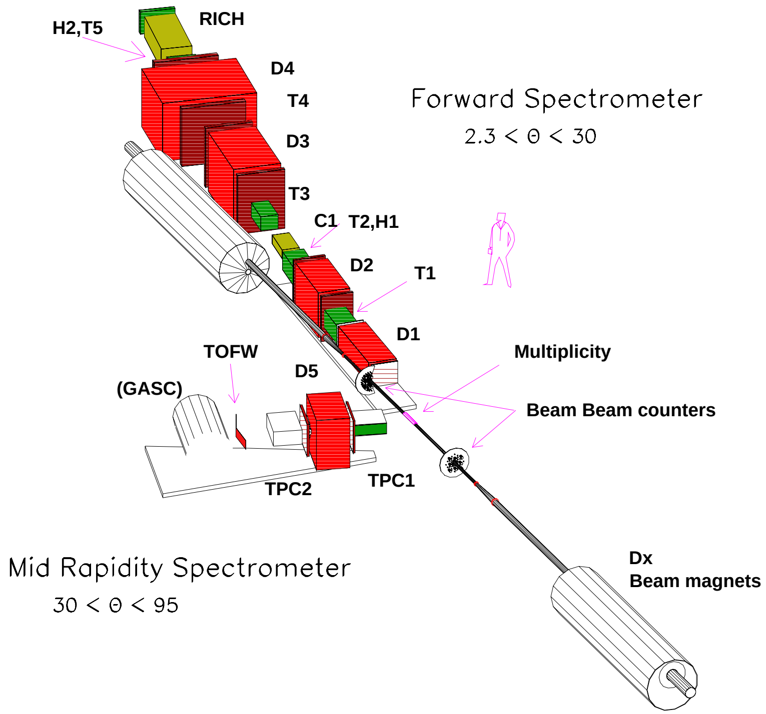
- STAR (420 collaborators)



- Solenoidal field
- Tracking: TPC's, Si-Vertex detector
- EM Calorimetry (barrel and forward)

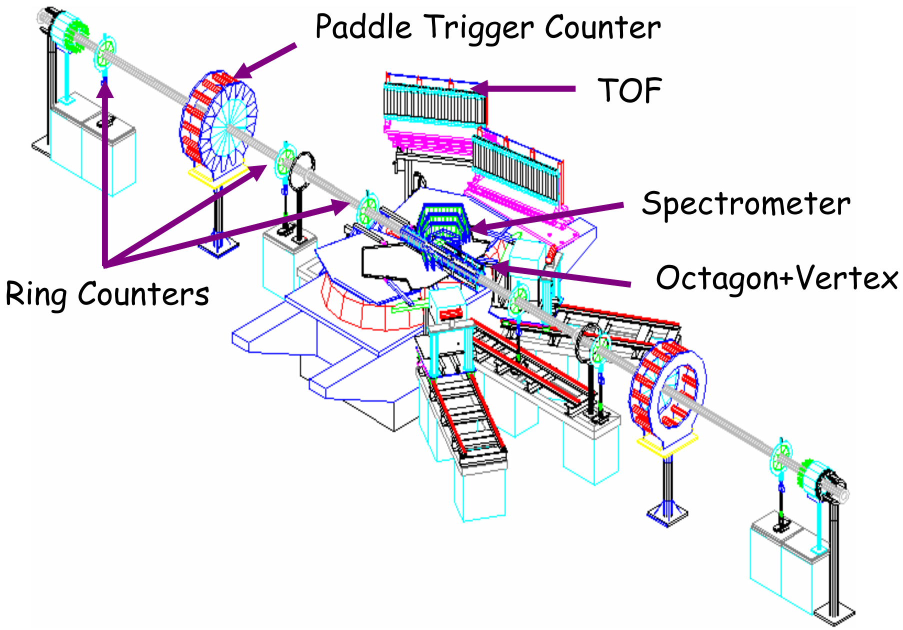
The RHIC experiments

- BRAHMS (40 collaborators)



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

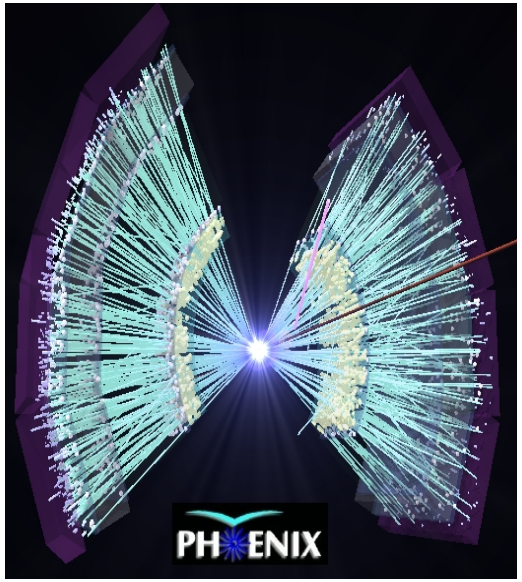
- PHOBOS (80 collaborators)



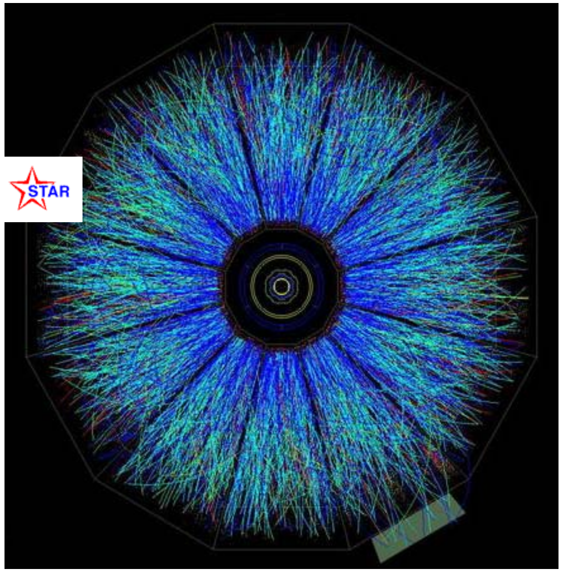
- "Table-top" two arm spectrometer magnet
- Si μ-Strips, Si multiplicity rings, TOF

RHIC experiment events

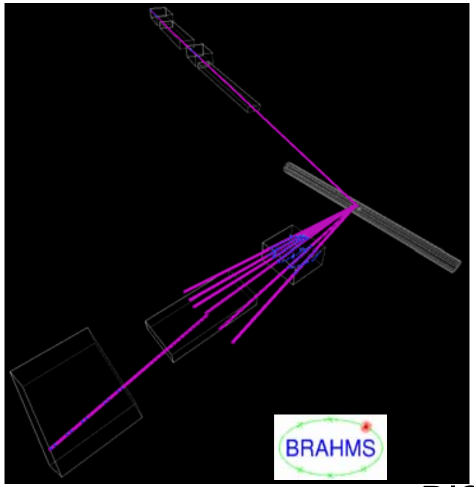
- PHENIX



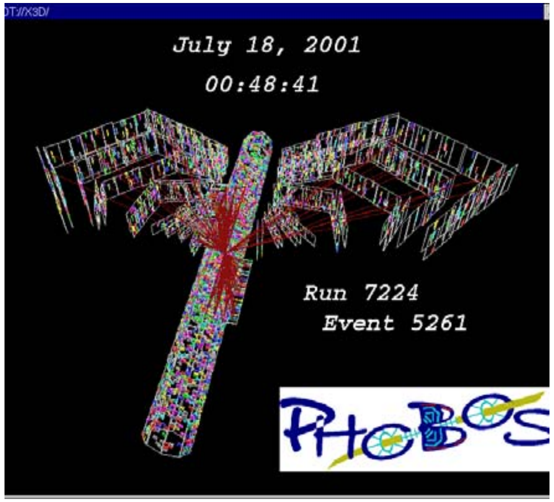
- STAR



- BRAHMS



- PHOBOS



Relativistic Heavy Ion Collider

Constructed in ~1990-2000 to search for the predicted quark-gluon plasma in heavy ion collisions and to probe nucleon spin structure in polarized proton collisions

			Int. Lumi/expt.
Run 1	Au-Au	66 GeV/nucleon	~5 μb^{-1}
Run 2	Au-Au	100 GeV/nucleon	~80 μb^{-1}
Run 3	d-Au	100 GeV/nucleon	~2500 μb^{-1}
Run 4	Au-Au	100 GeV/nucleon	~1000 μb^{-1}

Run duration ~ 10 weeks

What has been learned so far?

- Some see convincing evidence for the QGP, for example

  The QGP Discovered at RHIC – M. Gyulassy nucl-th/0403032

- RHIC experimenters say `it's too early for sure but observations to date are very promising'

- Here I will give an overview of the important results

Relativistic Heavy Ion Collision

- Two nuclei (collections of quark and gluon partons) collide producing an initial, intense heating of the collision volume to an energy density of ~ 10 GeV/fm^3
- A large fraction of the KE is converted into a high temperature system of quarks, antiquarks and gluons: QGP with critical temperature T_C~ 160 MeV that last for ~ 3 x 10^{-23} s
- QGP expands and cools: condenses into a system of mesons, baryons and antibaryons perhaps in thermal equilibrium
- As expansion continues, system reaches `freeze-out' density: hadrons no longer interact and stream into particle detectors

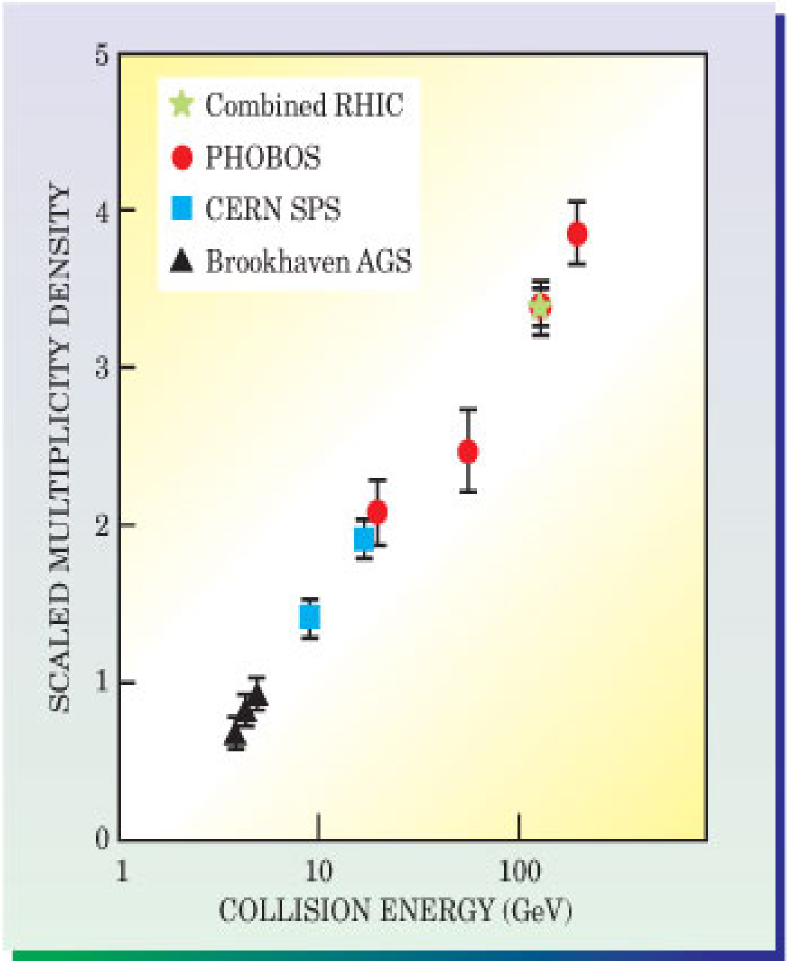
RHIC data

•detailed examination of distribution of produced particles in high multiplicity events determines the volume and energy of the collision region energy density > 10 GeV/fm^3 T ~ 200 MeV

•Temperature at freeze out can be inferred by measuring the relative abundance of the different meson and baryon species

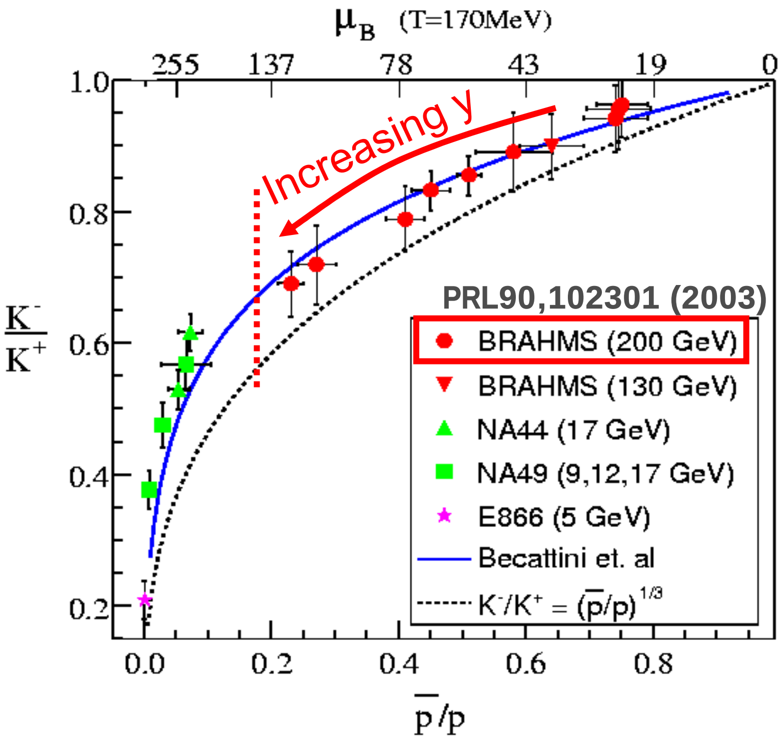
T~ 176 MeV

•Implies particles seen by detectors are produced at a freeze-out temperature close to the predicted T_C and that the initial temperature of the expanding fireball is much higher than T_C

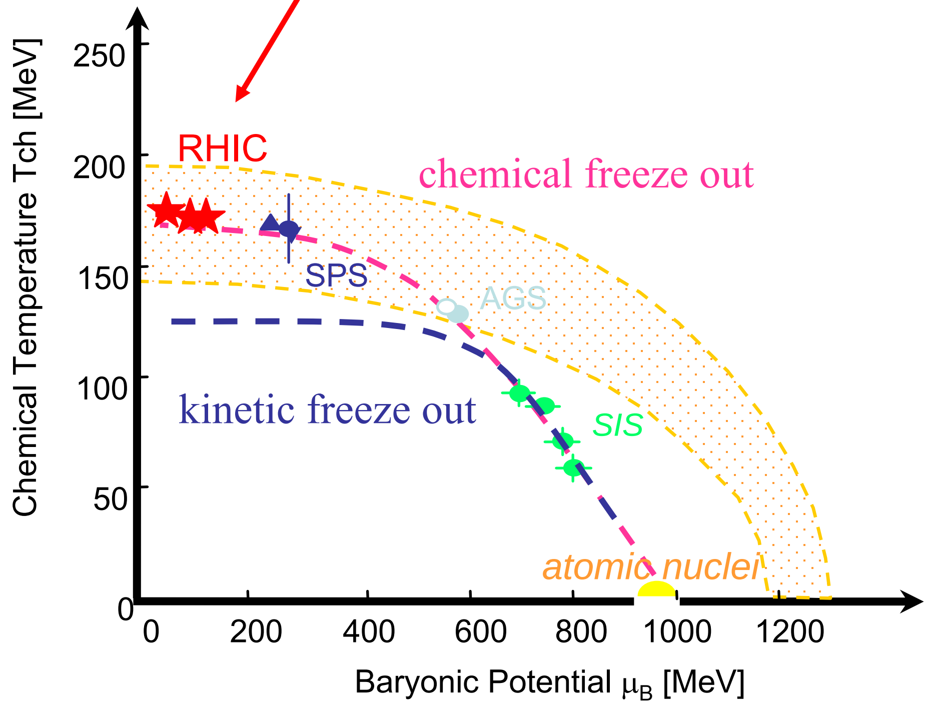


Hadron ratios and chemical freeze out

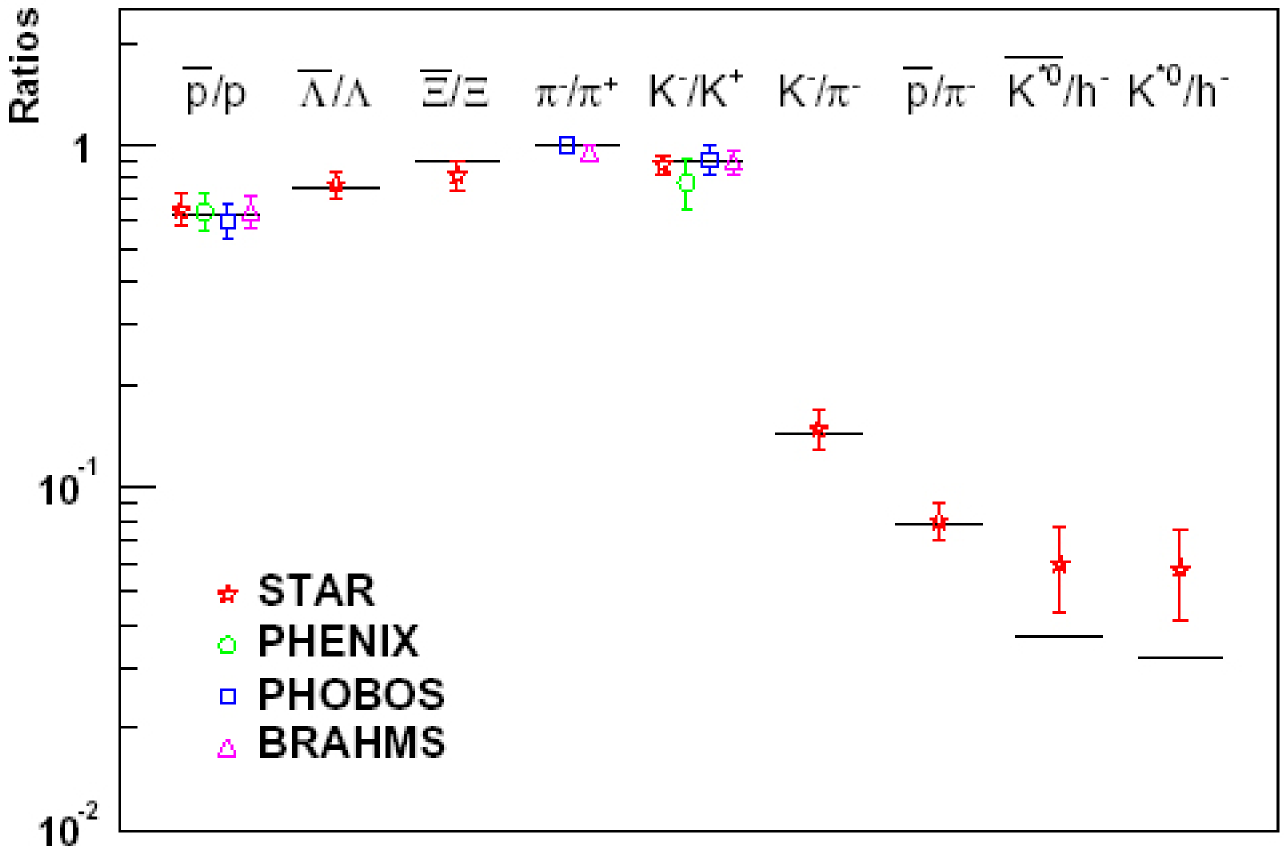
Hadron Gas Statistical model
(grand canonical ensemble)
reproduces (all) particle ratios
$\Rightarrow T_{ch}, \mu_B$



Freeze out at QCD phase boundary.

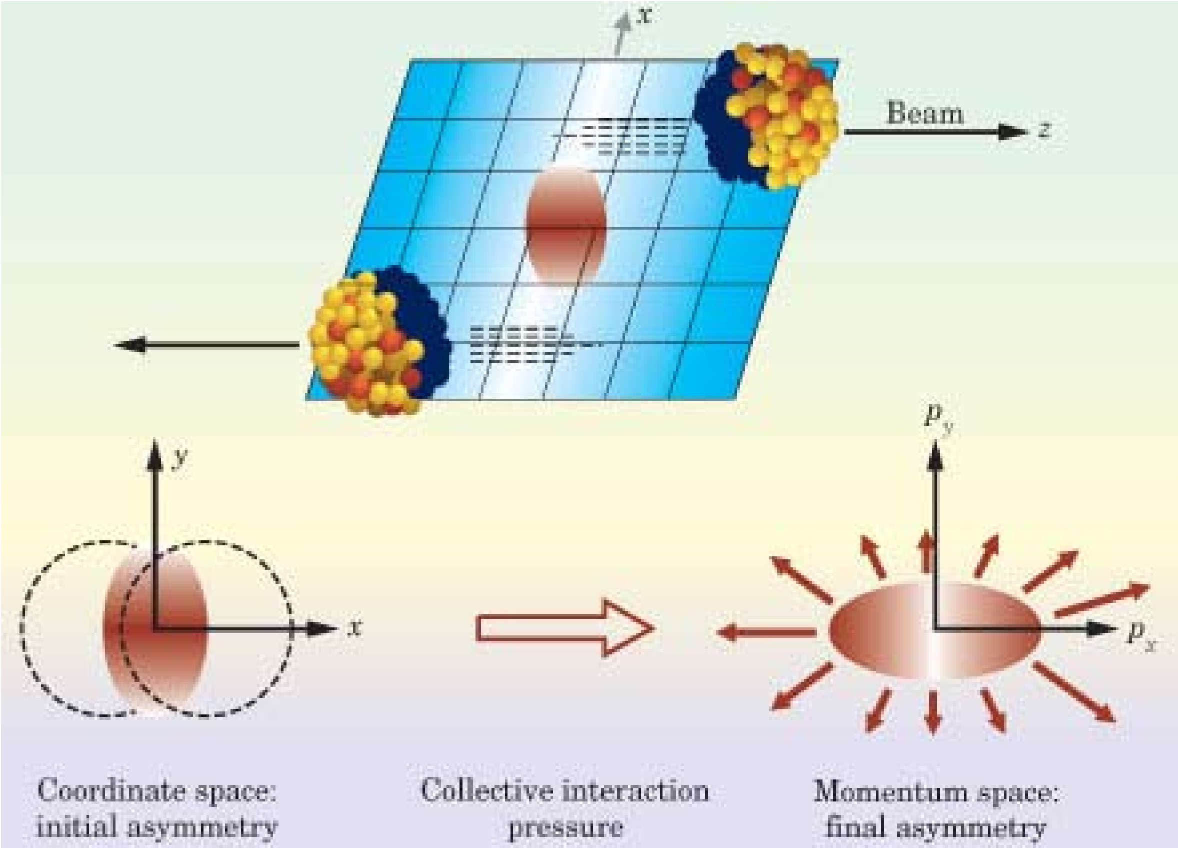


Comparisons between RHIC data and statistical model calculations with T =174 MeV and μ_B=46 MeV



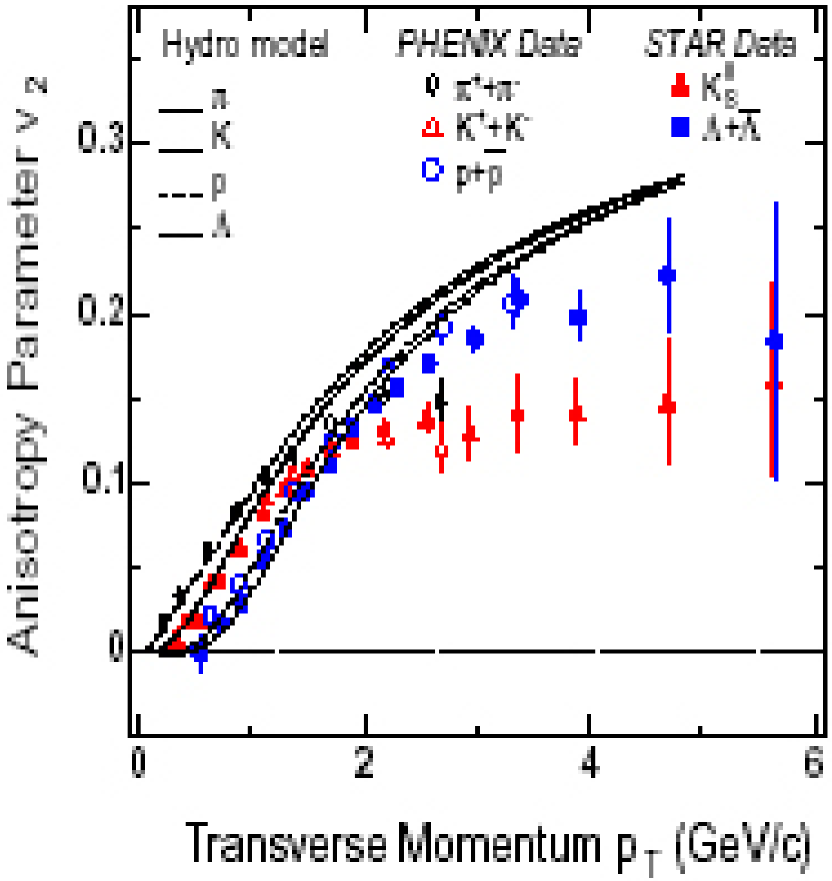
P. Braun-Munzinger *et al.*, hep-ph/0105229

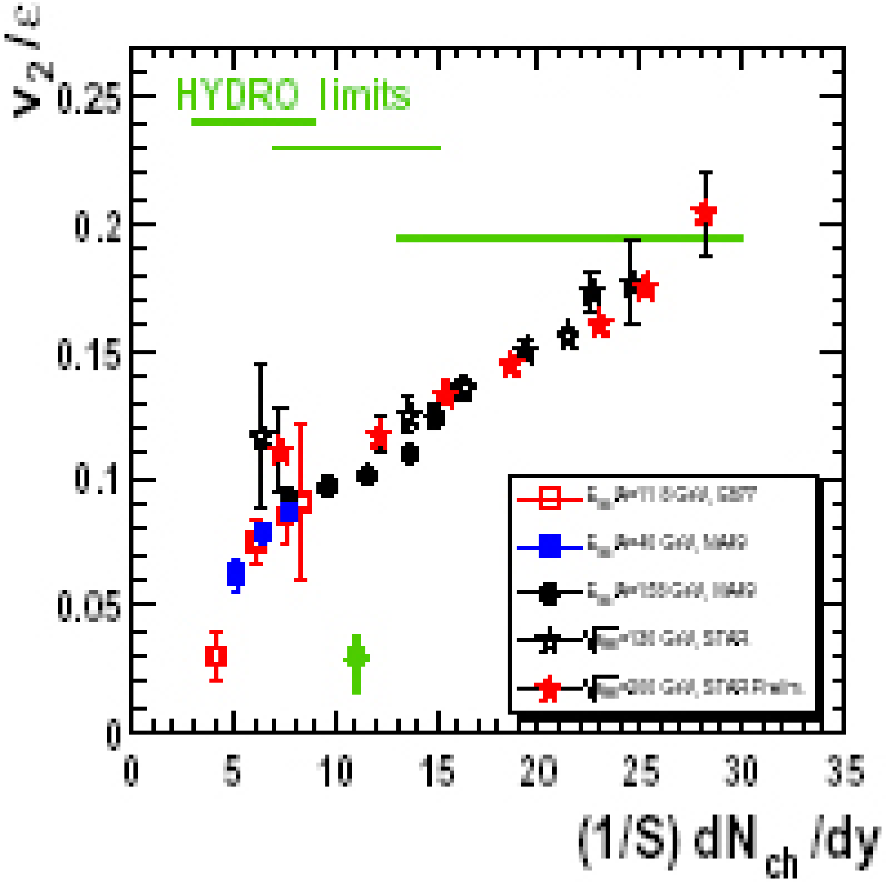
Large collective flow



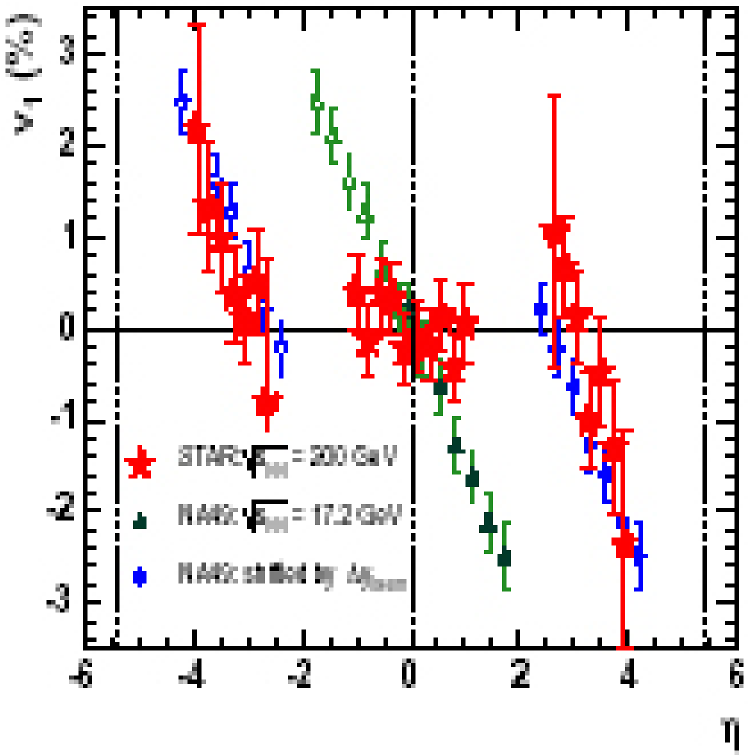
Elliptic flow at RHIC indicates almost maximal effect - close to what one expects for an expanding system in thermal and hydrodynamic equilibrium

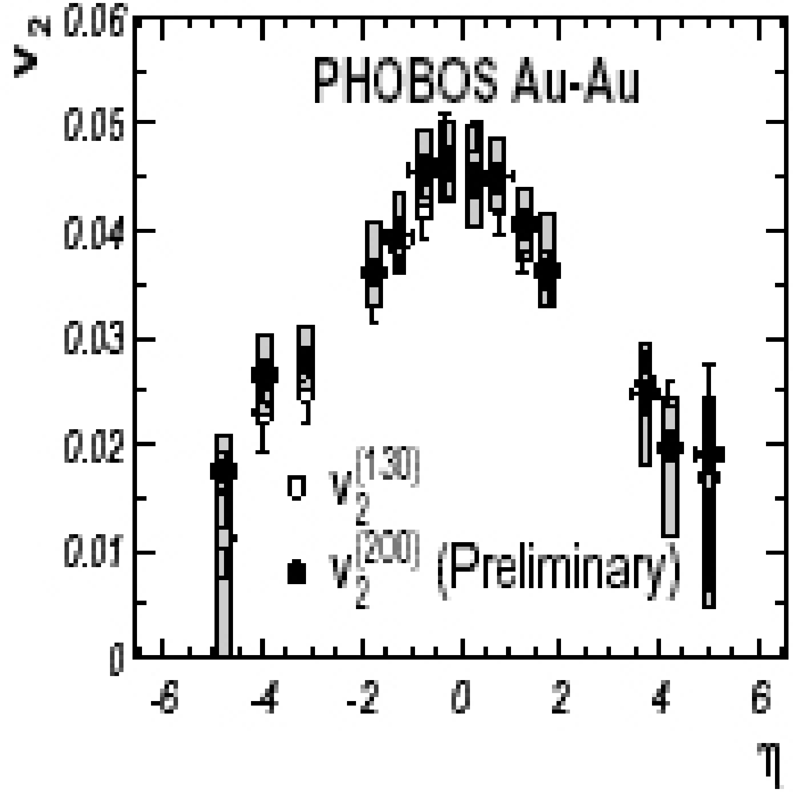
- Azimuthal elliptic flow $v_2(p_T)$ of π, K, p, Λ in Au+Au at 200 GeV
- Bulk collective flow is a barometric indicator of QGP production



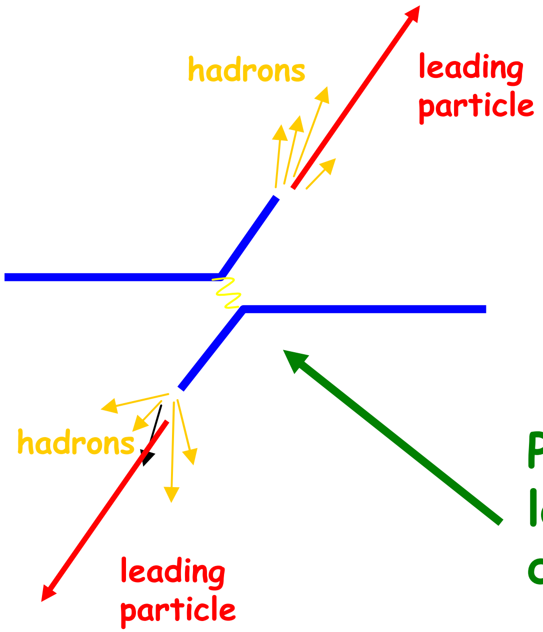


Long range nature of collective flow



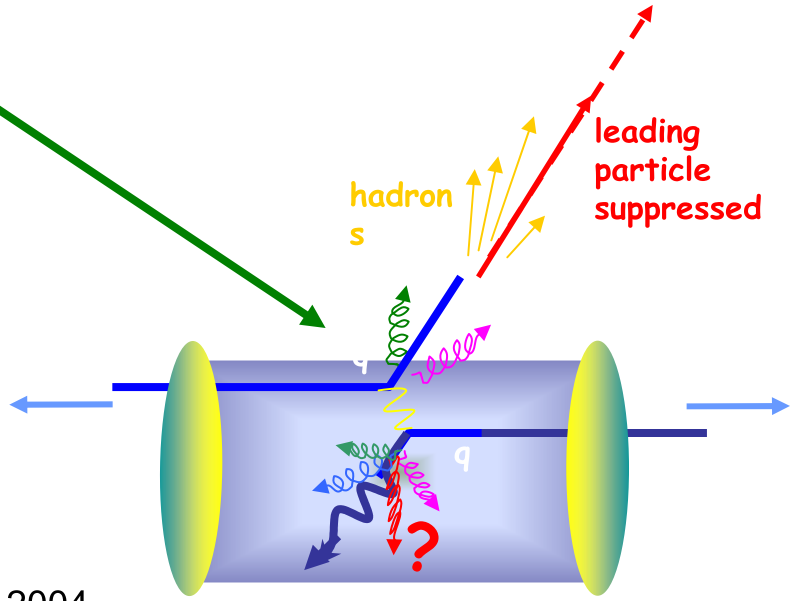


Partonic energy loss



Partonic Energy loss in high density matter

- Hard scattering in p-p collisions produces back-to-back jet topology
- Gyulassy and Wang: In the presence of a surrounding color-deconfined medium, partons lose energy through induced gluon radiation which is proportional to the gluon density
- Net result: Suppression of leading hadron yield ("Jet quenching")

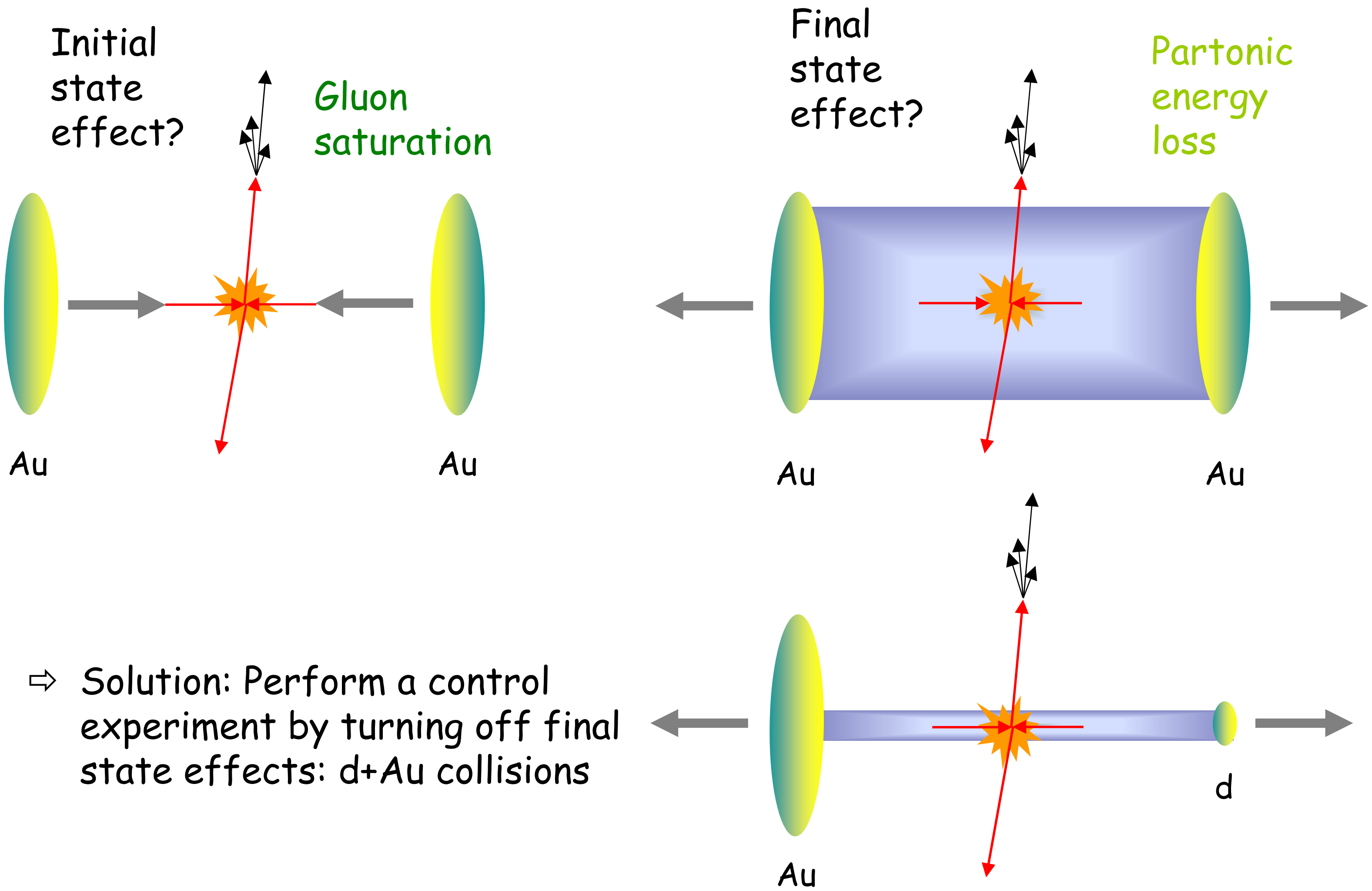


Quantify possible modification of the p_T distribution in Au-Au collisions compared to p-p by the :

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

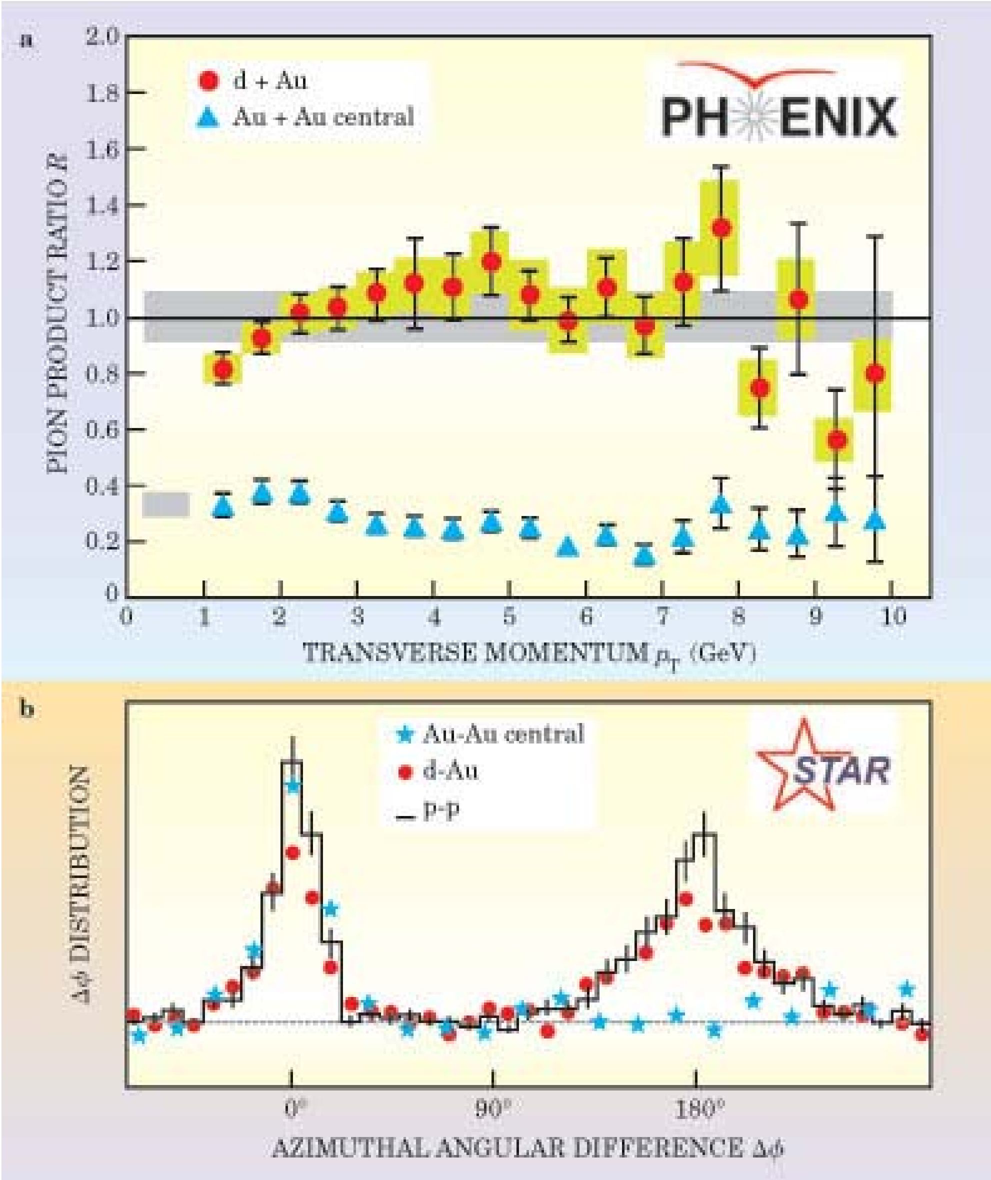
$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$ (Nuclear Geometry)

Is suppression an initial or final state effect?



- ⇨ Solution: Perform a control experiment by turning off final state effects: d+Au collisions

Jet Quenching observed at RHIC



Production rate of high p_T pions suppressed in Au-Au

Recoil peak in back-to-back jets at 180° is absent in Au-Au data

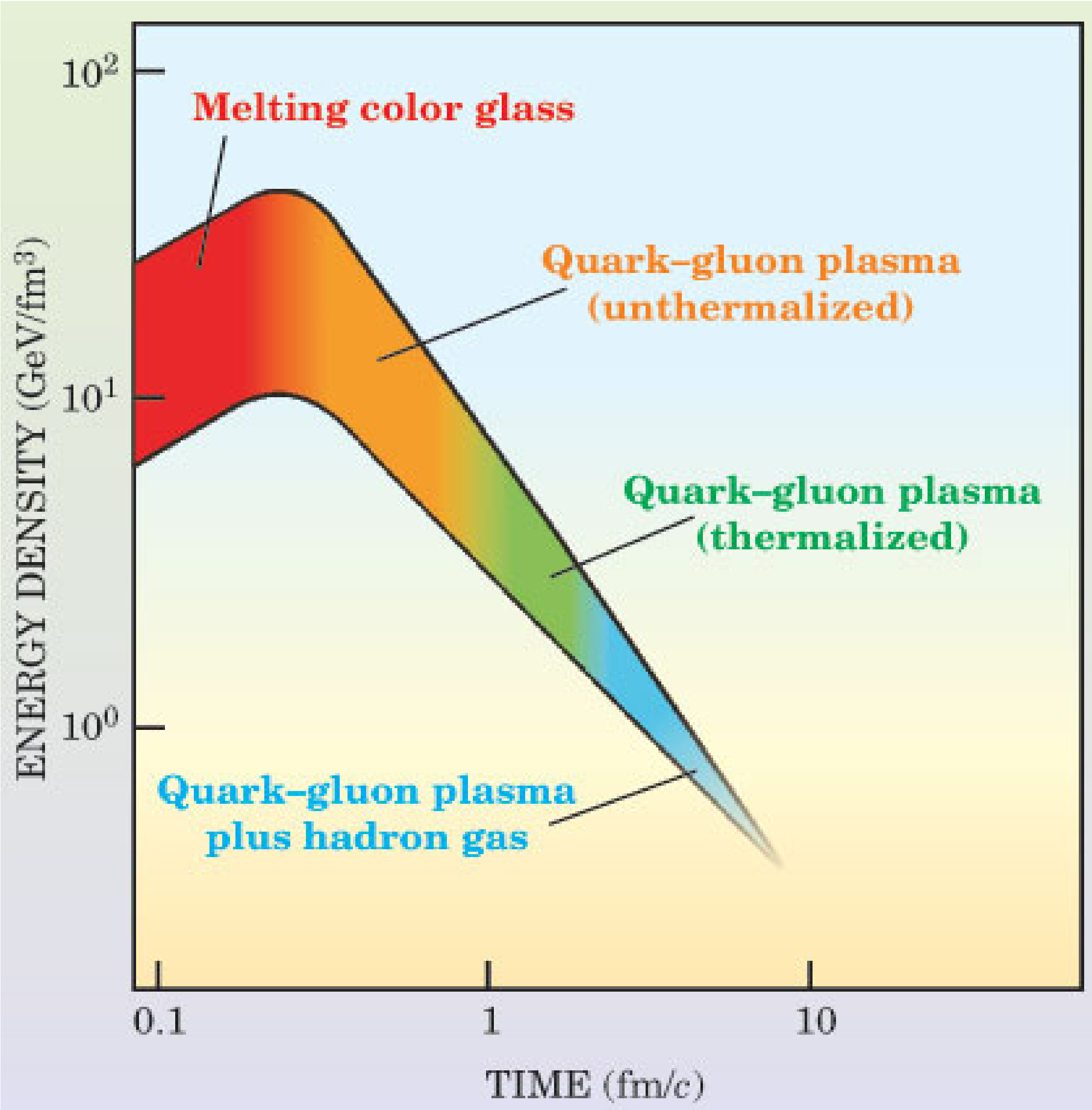
Dramatic experimental signature !

The Source Size Puzzle

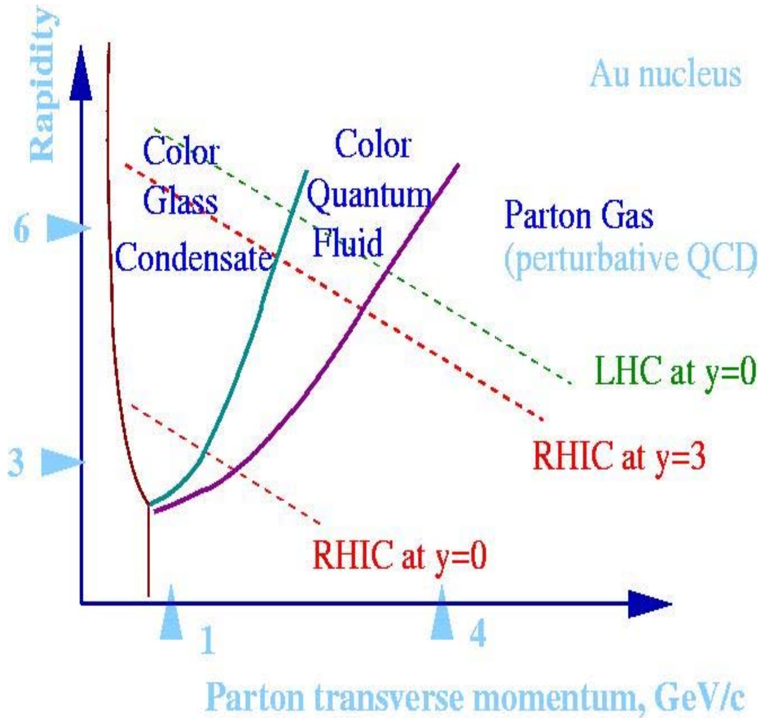
- Hanbury-Brown Twiss (HBT) interferometry of two-pion correlations provides a determination of the source size at freeze-out
- Long-lived systems, e.g. QGP, are expected to have larger source sizes at RHIC
- However, HBT studies from RHIC indicate a source size comparable to measurements at lower energies "HBT Puzzle"

One emerging picture

L. McLerran hep-ph/0402137

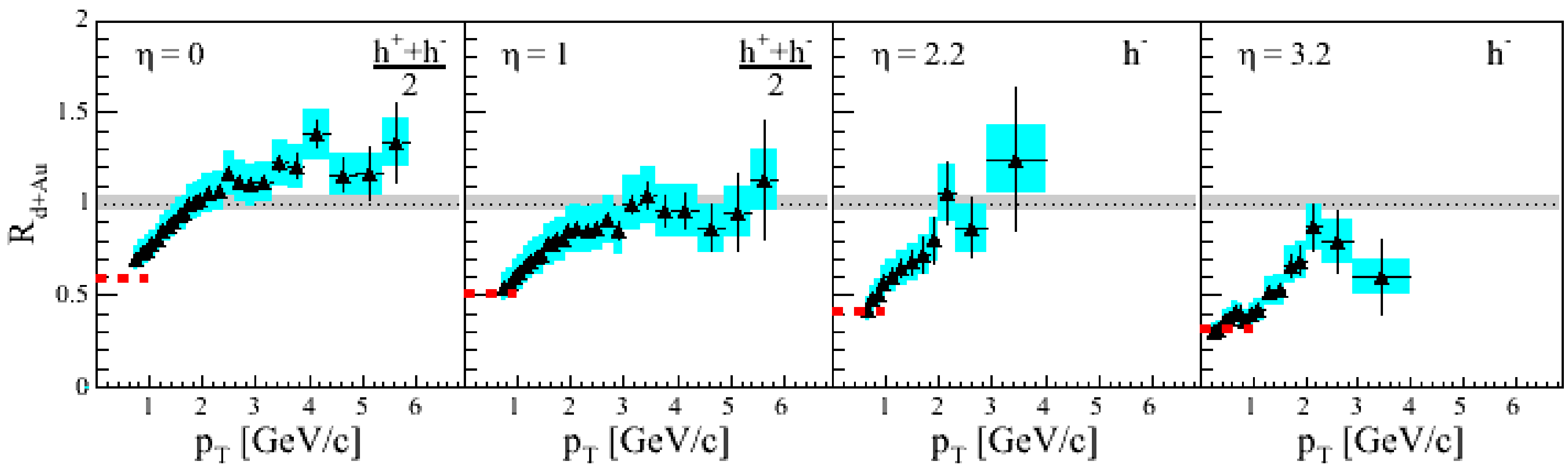


Nuclear Suppression vs. Rapidity

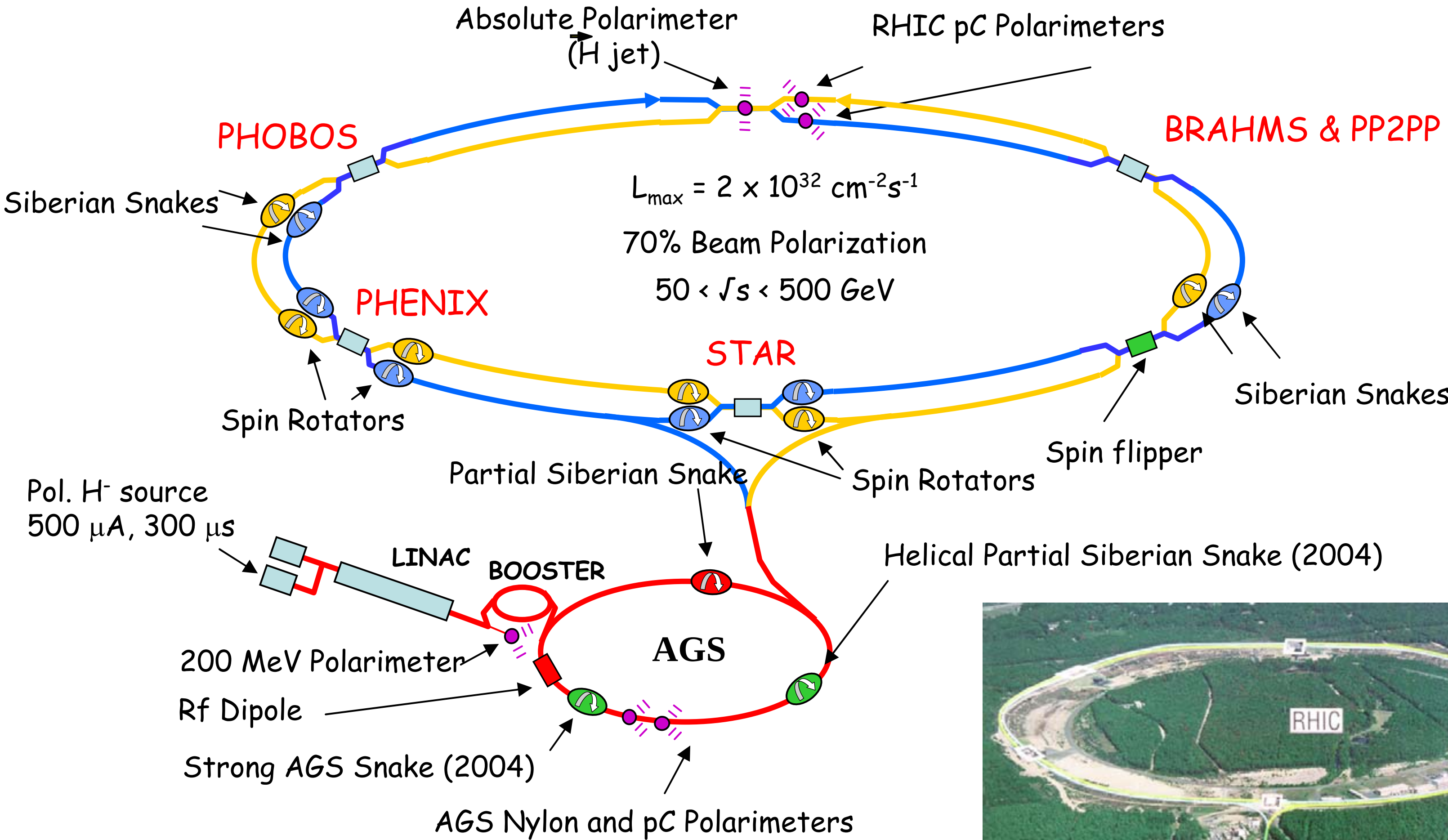


- Motivation for measurements at large rapidity in d-Au collisions comes from the investigation of *CGC* which predicts $\sigma(dA)/\sigma(pp)<1$

- Data probe gluon structure of gold nucleus in an x range from 10^{-2} to 4×10^{-4}



Polarized proton collider RHIC



RHIC-spin

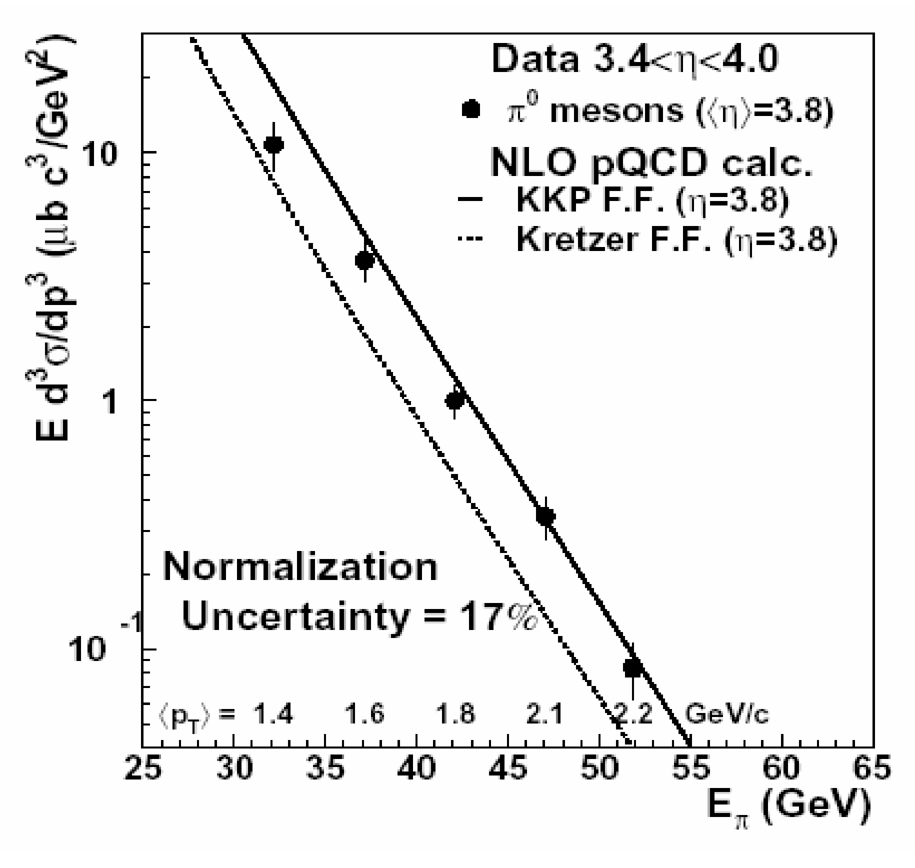
All polarized proton-proton running to date at 100 GeV on 100 GeV in runs of about 5 weeks duration

Int. Lumi/expt.

Run 2 p-p $p\sim20\%$ $\sim400\ nb^{-1}$
Run 3 p-p $p\sim30\%$ $\sim1000\ nb^{-1}$
$Lumi_{max}\sim 6 \times 10^{30}\ cm^{-2}\ s^{-1}$ vacuum, beam-beam limitations
Run 4 p-p commissioning run in progress
Already $p_{inj}\sim$ 50%!

- Before Run 5 a partial snake will be installed in the AGS
- Only after Run 5 are all elements for RHIC-spin in place

Forward π^0 production cross-section in comparison to NLO calculations

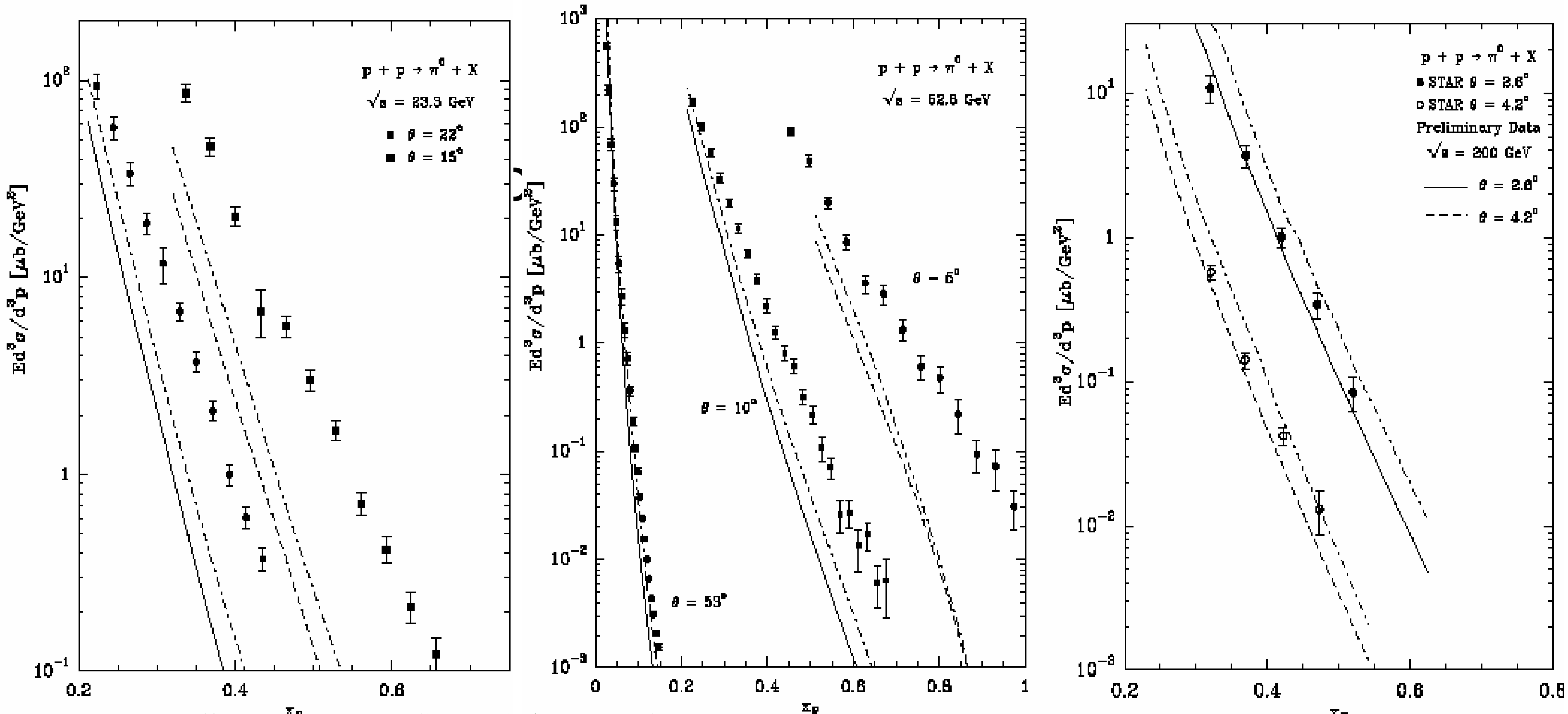


STAR collaboration, hep-ex/0310058, submitted to Phys. Rev. Lett.

- Measured forward π^0 production cross-section in comparison to NLO pQCD calculations
- NLO pQCD calculations:
  - CTEQ6M parton distribution function
  - Equal renormalization and factorization scale set to p_T
  - Two sets of fragmentation functions:
    - ⇨ Kniehl-Kramer-Pötter (KKP)
    - ⇨ Kretzer
- Measured results fall in-between two NLO pQCD which reflect uncertainties in the underlying fragmentation functions
- Data compares favorably to NLO pQCD at $\sqrt{s}$ = 200GeV in contrast to fixed-target or ISR energies

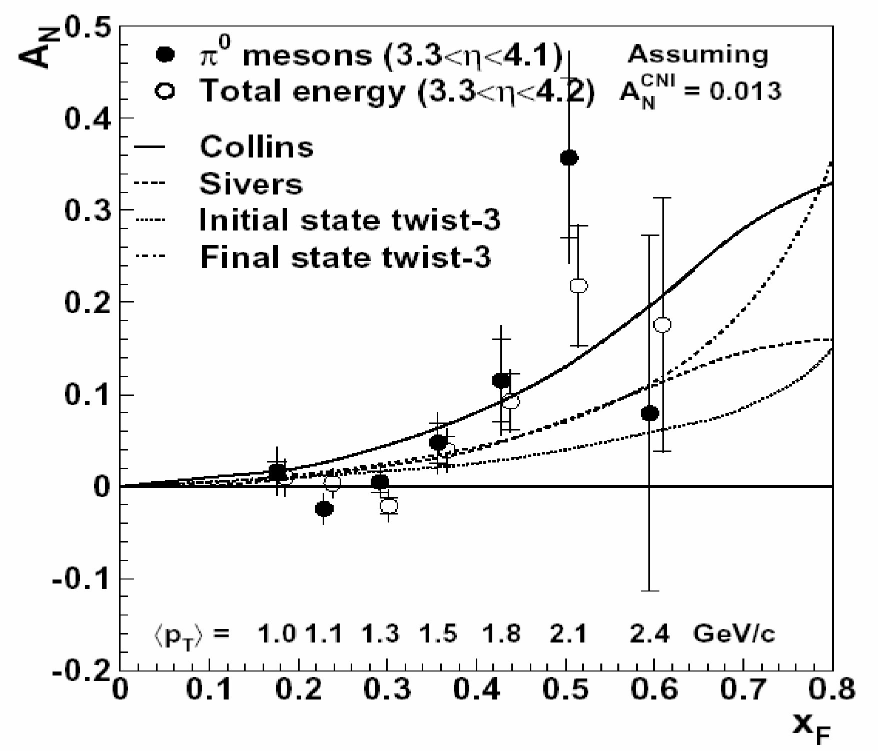
Energy dependence

√s=23.3GeV √s=52.8GeV √s=200GeV



- Bourelly and Soffer (hep-ph/0311110): Comparison of forward π^0 production to pQCD NLO calculations
- Comparison illustrates that agreement of measured cross-sections to pQCD NLO calculations for forward π^0 production improves with increasing center-of-mass energy, i.e. from fixed-target to RHIC

First measurement of A_N for forward π^0 production at RHIC



STAR collaboration, hep-ex/0310058

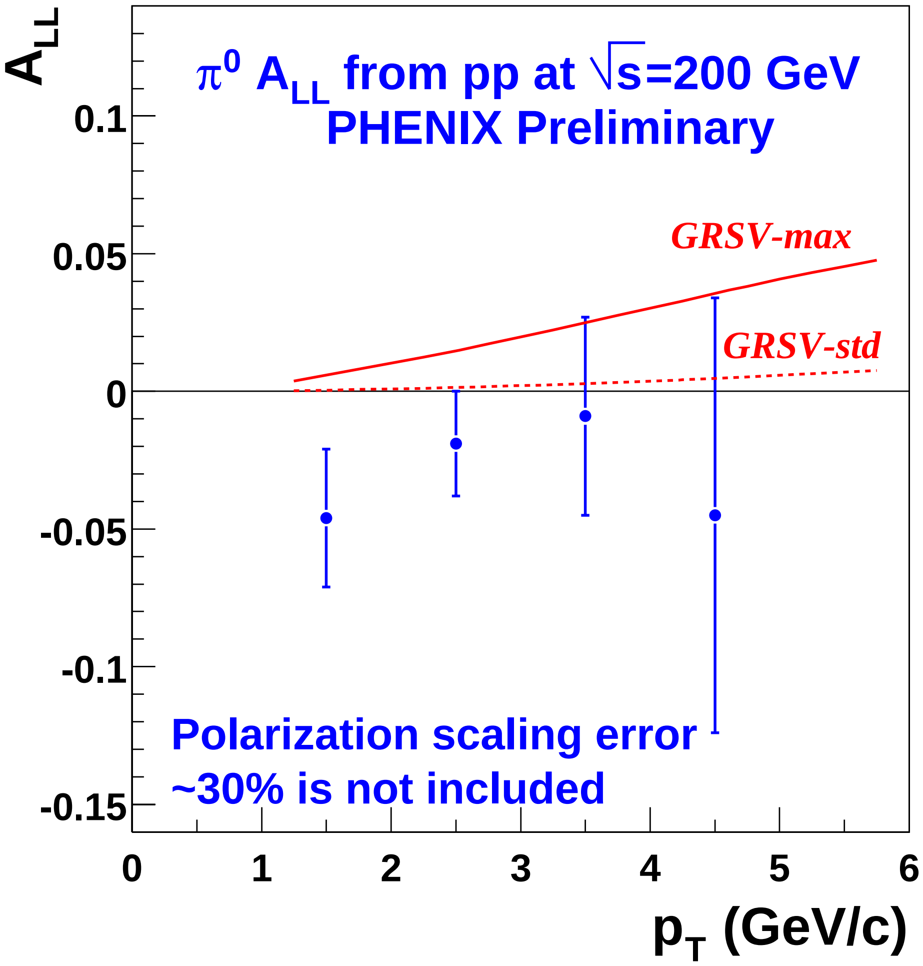
- A_N is found to increase with energy similar to E704 result ($\sqrt{s}$ = 20 GeV (10 X smaller than at RHIC), 0.5 < p_T < 2.0 GeV)
- This behavior is also seen by several models which predict non-zero A_N values
- Several approaches beyond the basic "naive QCD calculations" yield non-zero A_N values at RHIC energies:

⇨ Sivers: include intrinsic transverse component, $k_\perp$, in initial state (before scattering takes place)

⇨ Collins: include intrinsic transverse component, $k_\perp$, in final state (transversity) (after scattering took place)

⇨ Qiu and Sterman (Initial-state twist-3)/Koike (final-state twist-3): more "complicated QCD calculations" (higher-twist, multi-parton correlations)

First results on Gluon Polarization

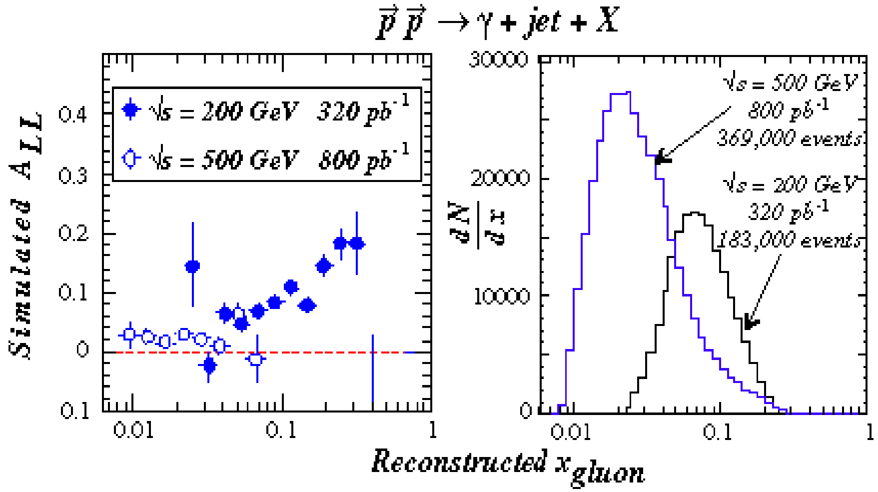


Luminosity: 0.215 pb^{-1}, Average polarization: 26%

- Polarization scaling error $\delta P/P$ ~30% is not included:
  - Enters A_{LL} in quadrature
  - Analyzing power A_N(100 GeV) = A_N(22GeV) is assumed
  - $\delta P/P$ ~ 30%: combined stat. and sys. error for A_N(22GeV) (AGS E950)
- Relative luminosity contribution to π^0 A_{LL} error is < 0.2%
- p_T smearing correction is not included

Future gluon polarization measurements at RHIC

- Simulated A_{LL} at two different RHIC center-of-mass energies::

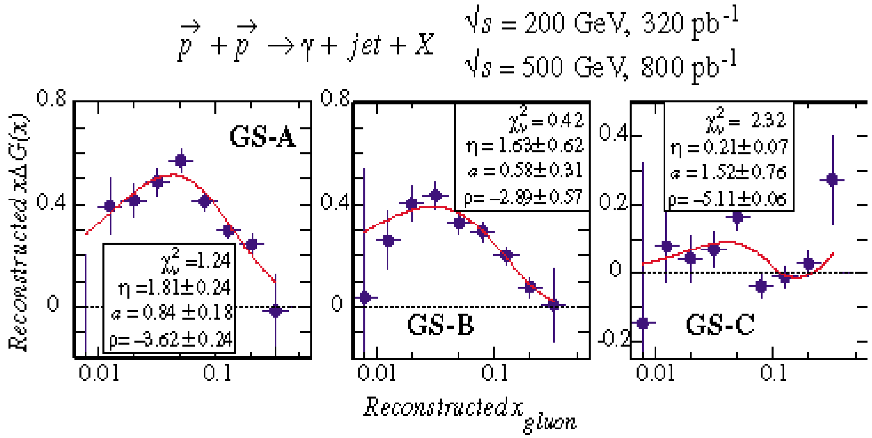


⇨ Multi year program at RHIC which

requires:

1. High luminosity
2. High polarization
3. √s = 200 / 500GeV

$$A_{LL} \cong \frac{\Delta G(x_g)}{G(x_g)} \cdot A_1^p(x_q) \cdot \hat{a}_{LL}^{(g+q\rightarrow\gamma+q)}(\cos\vartheta^*)$$



⇨ Combined data sample at 200 GeV and 500 GeV is essential to minimize extrapolation errors in determining ΔG:

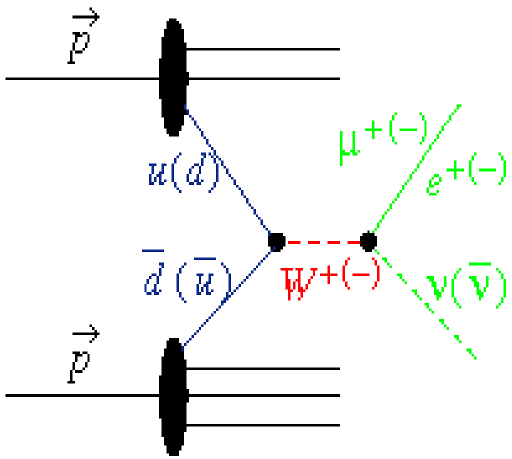
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)\,dx$$

Accuracy: 0.5

⇨ Ultimately: Global analysis of various ΔG!

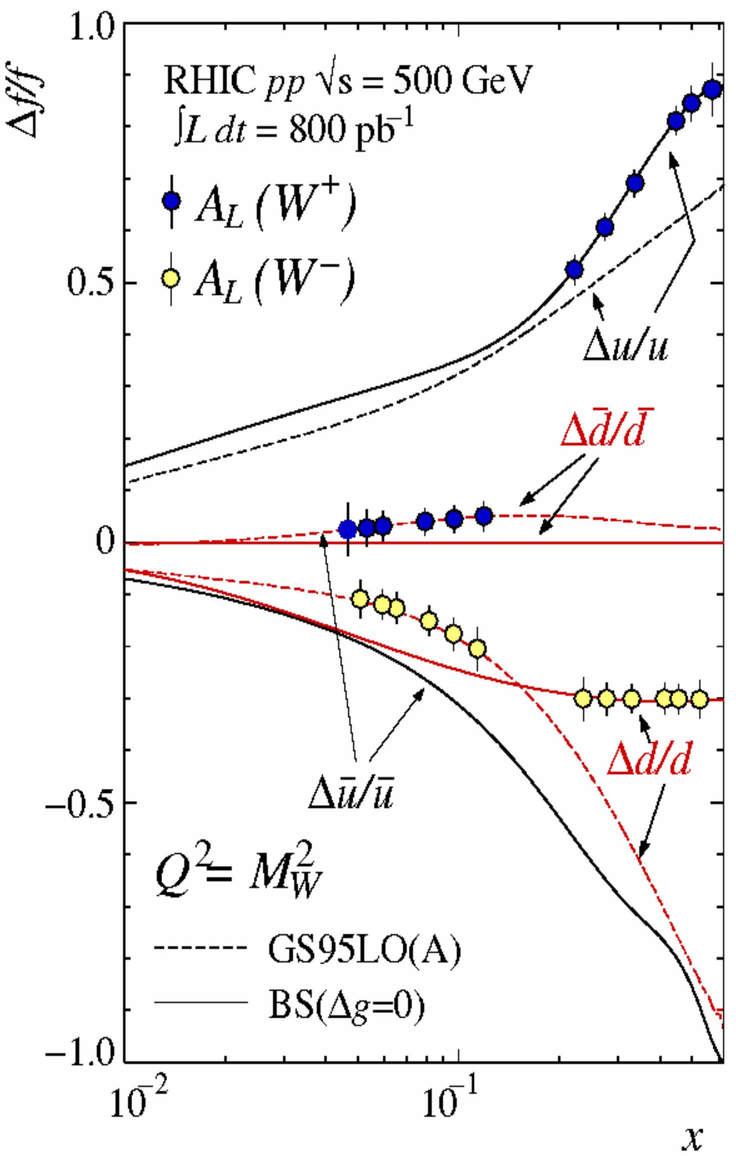
Flavor decomposition

- Explore spin structure of sea is crucial:
  - Is polarization of sea shared by quarks and anti-quarks?
  - Is there any flavor dependence?
- $W^{\pm}$ production in pp collisions probes flavor structure analogous to deep-inelastic scattering
- Polarized proton beams allow the measurement of (the expected large) parity violation in $W^{\pm}$ production
- Forward e/μ detection gives direct access to probe the underlying quark (anti-quark) polarization which is dominated at RHIC by u/d quarks



$W^{-} \rightarrow d + \bar{u}$

$W^{+} \rightarrow u + \bar{d}$



The Electron-Ion Collider (EIC)

- Substantial international interest in high luminosity ($\sim 10^{33} cm^{-2} s^{-1}$) polarized electron-ion collider over last several years
- Workshops

Seeheim, Germany	1997
IUCF, USA	1999
BNL, USA	1999
Yale, USA	2000
MIT, USA	2000

- Electron Ion collider (EIC) received very favorable review of science case in US Nuclear Physics Long Range Plan, with strong endorsement for R&D
- At BNL Workshop in March 2002, EIC Collaboration has formulated a plan to produce a conceptual design within three years using RHIC : eRHIC
- US NSAC in March 2003, declared eRHIC science `absolutely central' to Nuclear Physics

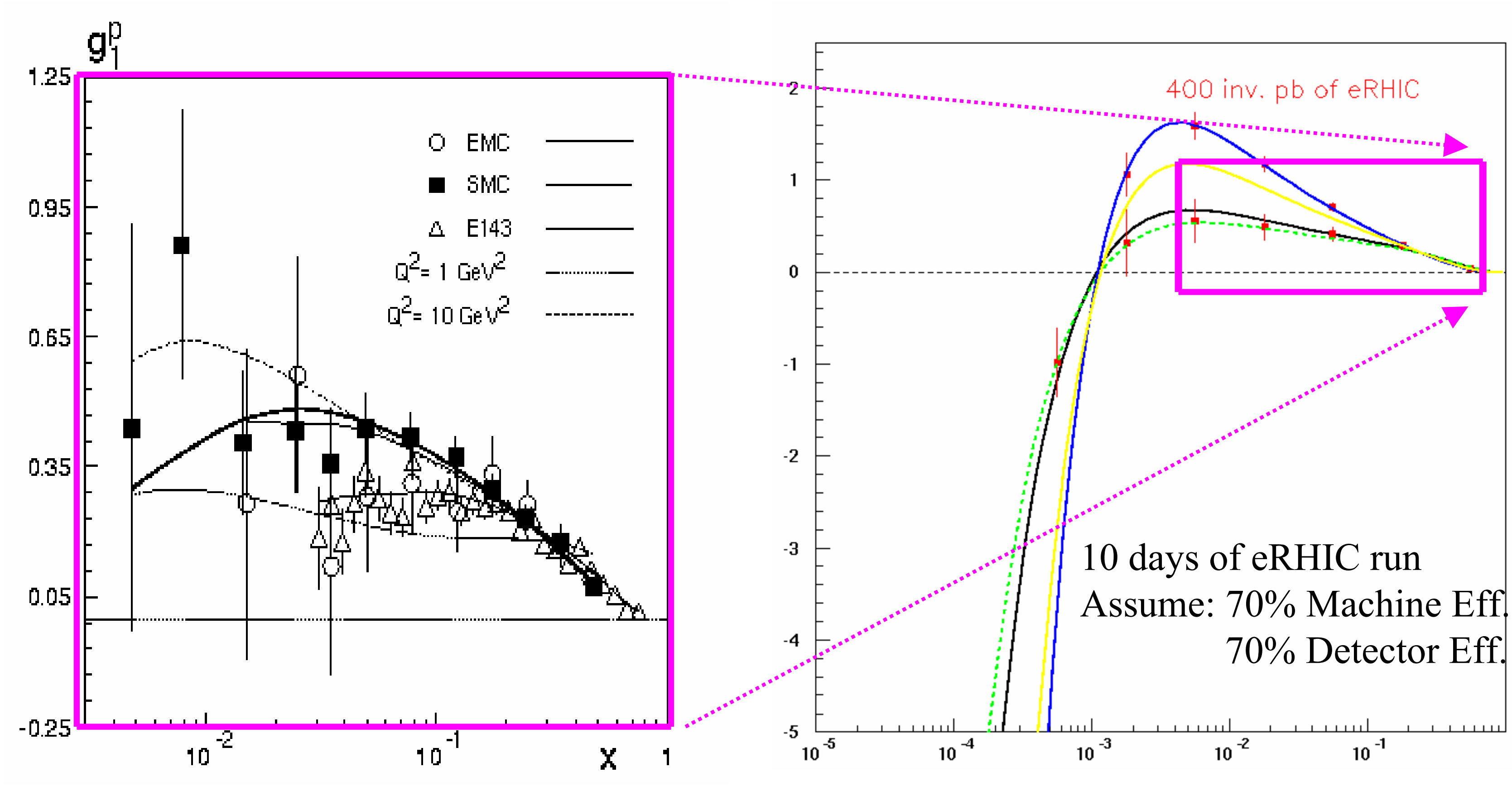
Scientific Highlights

- nucleon structure
  - sea quarks and glue
  - spin structure test of QCD
  - new parton distributions
- Meson structure
  - π, K are Goldstone Bosons of QCD
  - essential to nuclear binding
- hadronization
  - evolution of parton into hadron
  - process in nuclei of fundamental interest
- nuclei
  - role of partons hot QCD
  - initial conditions for relativistic heavy ion collisions
- matter under extreme conditions
  - saturation of parton distributions
  - new phenomena, e.g. colored glass condensate

Spin structure function g^p_1 at low x

$x = 10^{-3} \rightarrow 0.7$
$Q^2 = 0 \rightarrow 10^3$ GeV
Fixed target experiments
1989 – 1999 Data

$x = 10^{-4} \rightarrow 0.7$
$Q^2 = 0 \rightarrow 10^4$ GeV
eRHIC 250 x 10 GeV
Lumi=85 inv. pb/day



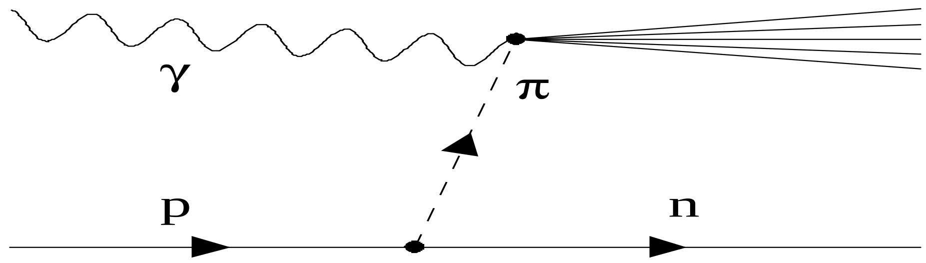
Structure of the Goldstone Bosons

Light mesons: pions and kaons

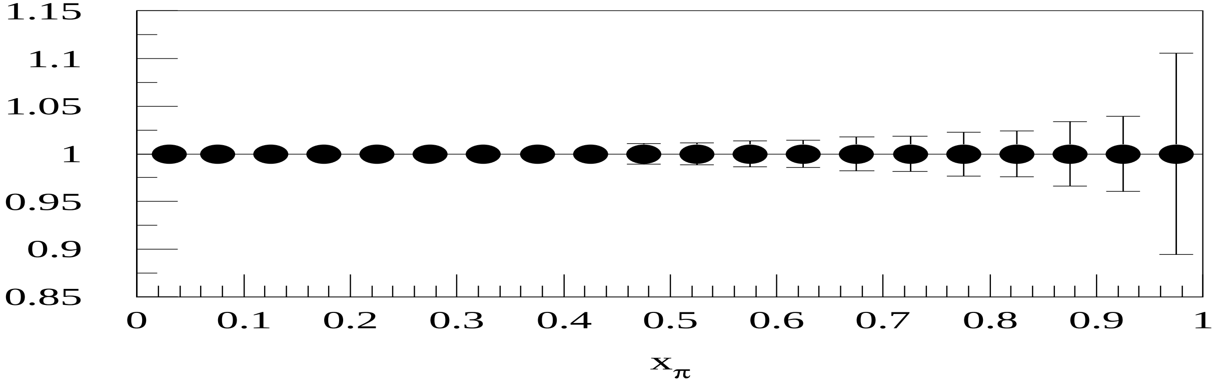
- important role in nuclear physics
- important component of nucleon structure
- approximate chiral symmetry
- Goldstone bosons of chiral models
- nuclear medium effects

- In collider kinematics the pion can be probed essentially on shell.
- with light nuclear projectiles, pions and kaons in medium can be studied.
- Partonic origin of nuclear binding

Pion Structure Function with eRHIC



Expected Errors for 1 day of eRHIC running



Quark momentum distribution of pion

Using Nuclei to Increase the Gluon Density

- Parton density at low x rises as $\frac{1}{x^{\delta}}$
- Unitarity $\Rightarrow$ saturation at some Q_s^2
- In a nucleus, there is a large enhancement of the parton densities / unit area compared to a nucleon

$$\frac{G_A / \pi R_A^2}{G_N / \pi r_N^2} \approx A^{1/3} \frac{G_A}{A G_N} \approx A^{1/3}$$

$$\approx 6 \quad \text{for} \quad A = 200$$

$$x_{ep}\left(Q_s^2\right) = \frac{X_{eA}\left(Q_s^2\right)}{\left(\frac{4}{3} A^{1/3}\right)^{1/\delta}}$$

Example

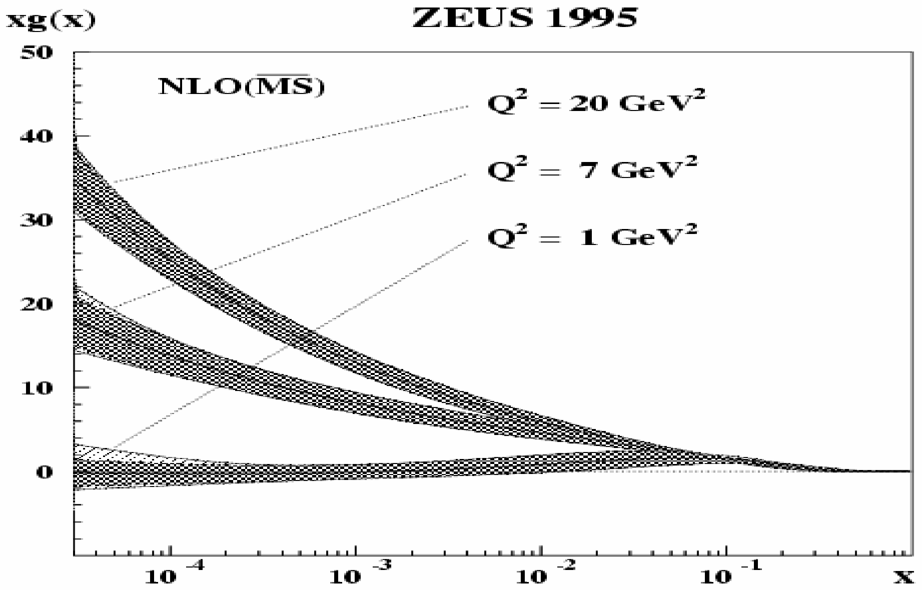
$Q^2 = 4\ (GeV/c)^2$

$\delta < 0.3$

$A = 200$

$X_{ep} = 10^{-7}$ for $X_{eA} = 10^{-4}$

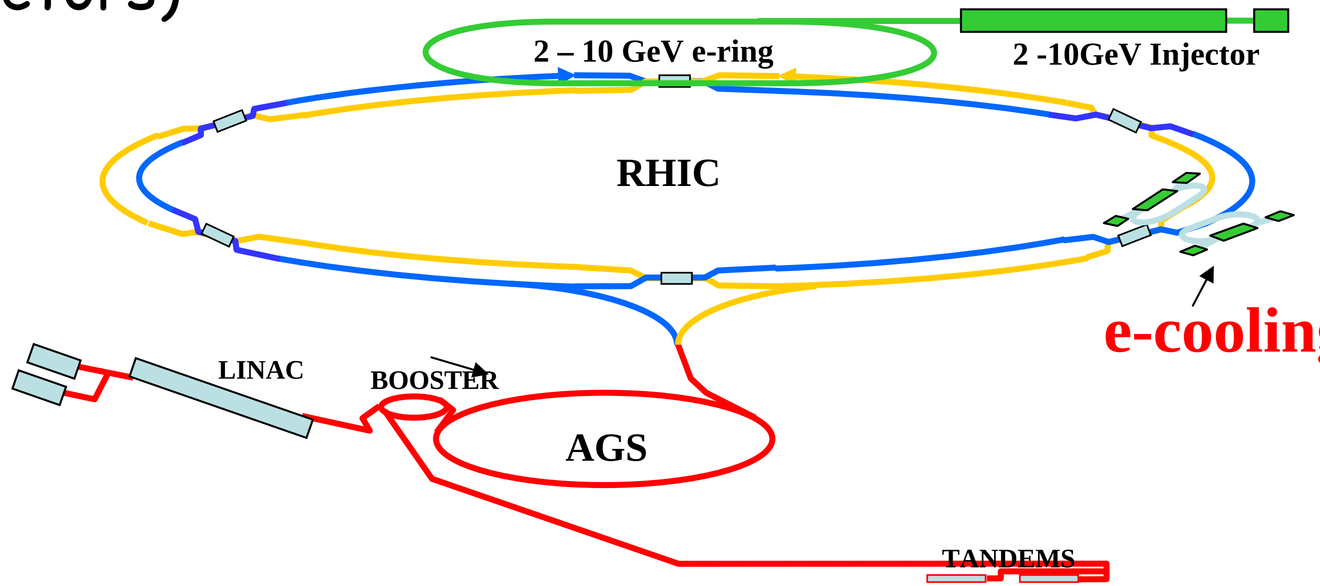
Gluon Momentum Distribution from DIS



eRHIC will probe gluons in nucleon and nuclei using a number of complementary techniques

eRHIC layout

- Collisions at 12 o'clock interaction region
- 10 GeV, 0.5 A e-ring with $\frac{1}{4}$ of RHIC circumference (similar to PEP II HER)
- Inject at full energy 2 – 10 GeV
- Existing RHIC interaction region allows for typical asymmetric detector (similar to HERA or PEP II detectors)

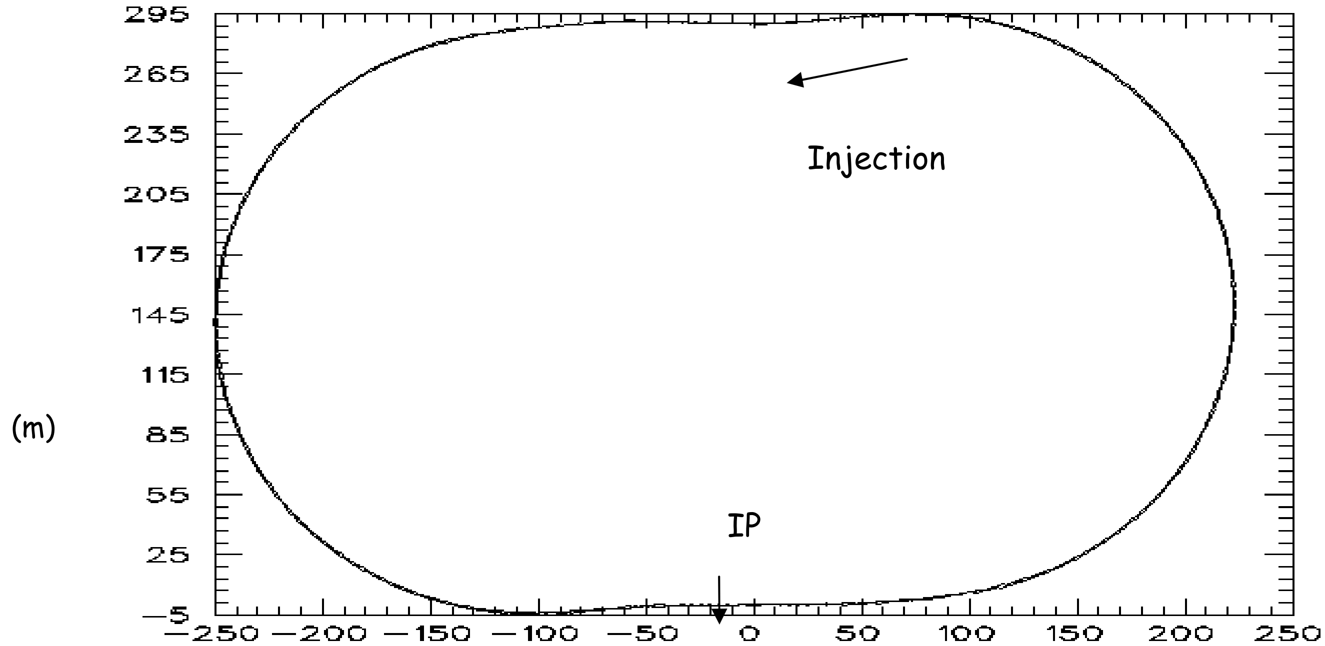


Status of eRHIC

- A Zero-order Design Report (ZDR) has been prepared by BNL and MIT-Bates. The Ion beam and Ring and the IR by BNL and the electron beam and ring by MIT-Bates.
- The present design includes a full energy linac injecting polarized electrons into the electron ring. Both room temperature and superconducting electron linacs are considered.
- The ZDR will be reviewed by an external expert accelerator physics committee in spring 2004.
- In addition, linac-ring design under considration
- eRHIC is included in Office of Science 20 year plan

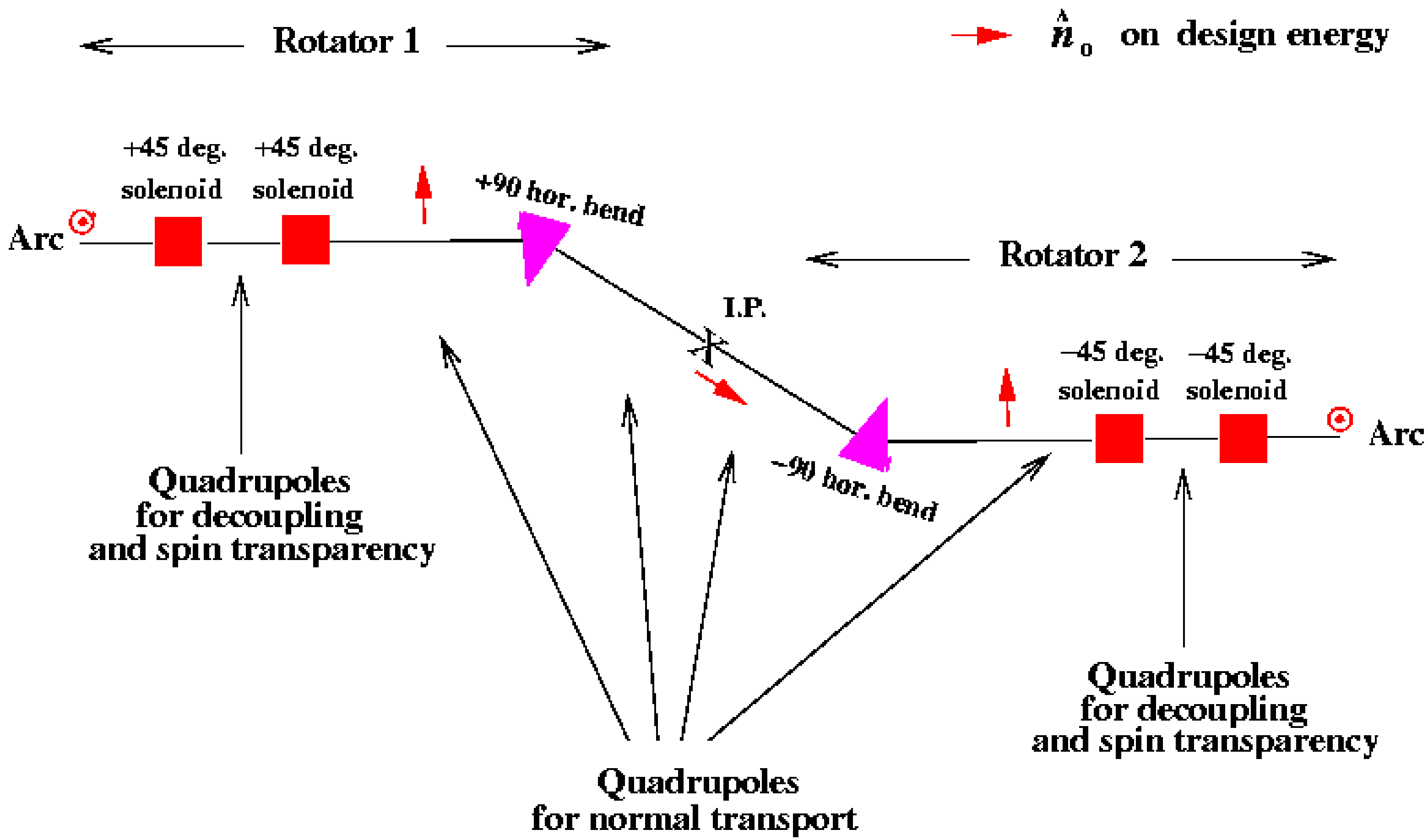
http://www.agsrhichome.bnl.gov/eRHIC/index.html

Electron/Positron Ring



- Race track shaped storage ring in one plane
- Vertical polarization in arcs – spin rotators for long. pol. (> 70%) at IP
- Polarized electron injection from 5-10 GeV
- Unpolarized positron injection from 5-10 GeV
- Self polarization of positrons at 10 GeV – τ_p = 20 minutes

Solenoidal Spin Rotator



No vertical bends

Pure long. poln. only at 8.5 GeV

eRHIC

e-/e+ Ring Parameters

10 GeV electrons – 250 GeV protons

- Luminosity assumes collisions at two other IPs
- Dedicated operations yields Luminosity ~ 10^{33} cm^{-2} s^{-1}

Ion beam Energy	**p 250 GeV**
Circumference(m)	1278
Electron Energy (GeV)	10
Bending radius(m)	81
Bunch spacing(m)	10,6
Number of bunches	120
Bunch population	1,00E+11
Beam current(A)	0,45
Energy loss/turn (MeV)	11,7
Accelarting voltage(MV)	25
Total rad. Power(MW)	5,27
Syn. Rad. Power/m (KW) in Arc	9,63
Self-pola. Time at 10GeV(minutes)	22,03
Emittance-x, no coupling (n m.rad)	56,6
Beta function at IP (cm) β_y^*/β_x^*	19.2/26.6
Emittance Ratio ($\varepsilon_y/\varepsilon_x$)	0,18
Beam size at IP(um) σ_x	104
Beam size at IP(um) σ_y	52
Momentum spread σ_E	9,61E-04
Bunch length (cm) σ_z	1,17
S.R. damping time(x) (mS)	7,3
Beta tune μ_x	26,105
Beta tune μ_y	22,145
Natural chromaticity $\xi x/\xi y$	-35.63/-33.84
Luminosity (10^33/cm^2/s)	0,44

Luminosity Considerations

$$L = \frac{\pi}{r_e r_i} F_c \gamma_e \gamma_i \xi_i \xi_e \sigma'_{i,x} \sigma'_{e,x} k_e \frac{(1+k)^2}{k^2}$$

Fc is the collision frequency

ξ the beam-beam tune shift

ke = εe,y/εe,x is the electron beam emittance ratio

k=σy/σx is the beam aspect ratio at IP.

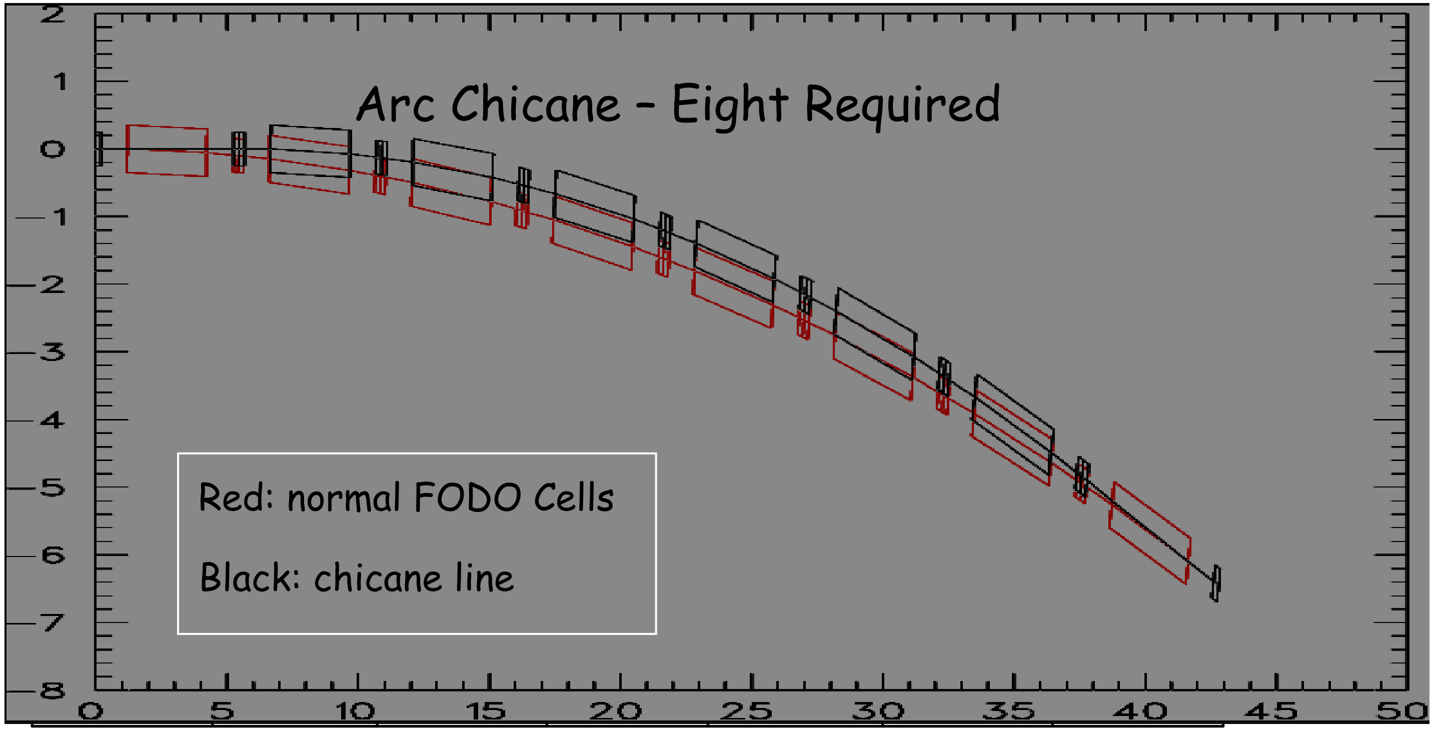
σ' is the beam angular amplitude at IP.

- Round Beams would be preferable for maximum luminosity.
  → Comparable balanced beam-beam tune shifts (x,y)
- But … virtually impossible through IP and problematic for polarization
- Flat Beams Adopted for the baseline ZDR

Variable Path Length for Lepton Ring

- The proton (heavy ion) velocity (energy) determines the collider frequency and consequently the electron path length. ΔL_{max} = 89 cm

- A minimum proton energy of 50 GeV (rather than 25 GeV) reduces ΔL_{max} to 22 cm

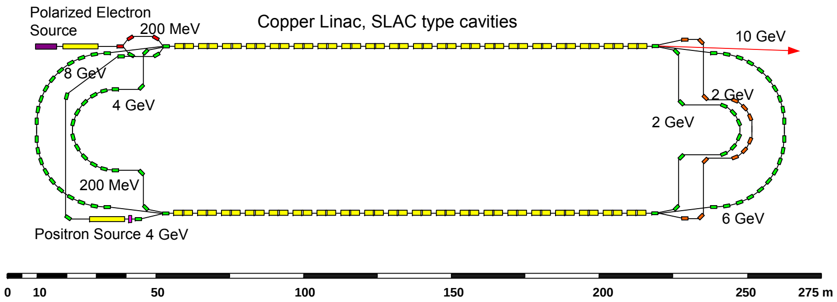


- A conceptual engineering design is underway

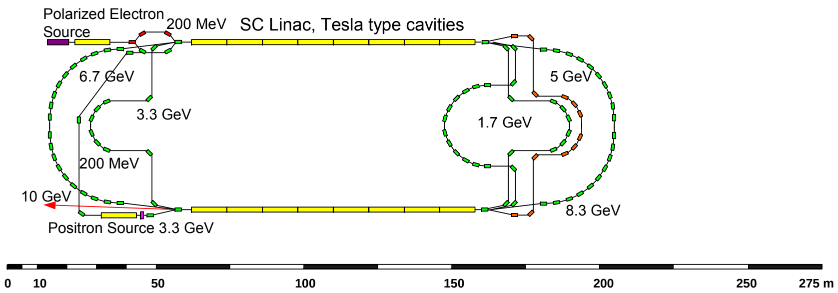
10 GeV Accelerator Options

-Several variants appear viable

-Injector is expensive, but will not limit eRHIC physics performance

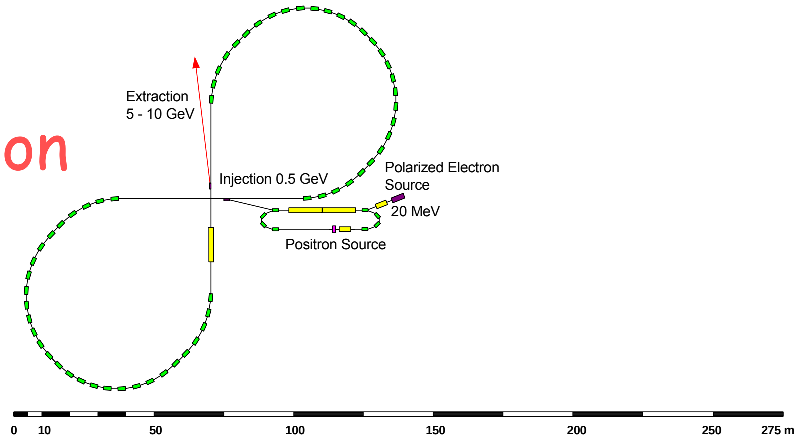


Recirculating NC linac



Recirculating SC linac

Figure 8 booster synchrotron



eRHIC Outlook

- Maintain and enhance community wide and international support
- Focus and sharpen scientific case
- Continue to develop machine designs and options
- Detectors under design
- Several meetings planned for later this year
  - eRHIC ZDR review ~ May 2004
  - workshops on GPDs, saturation ~ late summer
  - meeting to organize final preparation for LRP ~ early 2005

EIC Steering Committee

- A. Caldwell (MPI Munich)
- A. Deshpande (StonyBrook)
- R. Ent (JLab)
- G. Garvey (LANL)
- R. Holt (ANL)
- E. Hughes (Caltech)
- K.-C. Imai (Kyoto Univ.)
- R. Milner (MIT)
- P. Paul (BNL)
- J.-C. Peng (Illinois)
- S. Vigdor (Indiana Univ.)

http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/

Summary

- Exciting results from RHIC collider
- Hot, dense matter being formed and its characteristics being determined
- Polarized protons accelerated in RHIC with increasing polarization and collision luminosity
- Anticipate RHIC-spin design parameters being reached within several years
- eRHIC preliminary but realistic machine design with luminosity $\sim 10^{33}\ cm^{-2}\ s^{-1}$
- Anticipate serious consideration of eRHIC as a machine for construction within US in next several years
- Strongly urge participation of DIS community worldwide in eRHIC realization