1/2 + 1/2 + 1/2 = 1/10 (?)
Learning the nucleon spin algebra using RHIC

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&

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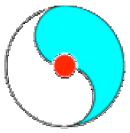
~~February 25~~, 2005

February 22, 2005



STONY BROOK
STATE UNIVERSITY OF NEW YORK

Some Spin Surprises!

- Stern & Gehrlach (1921) Space quantization associated with direction
- Goudschmidt & Ulhenbeck (1926): Atomic fine structure & electron spin magnetic moment
- Stern (1933) Proton anomalous magnetic moment 2.79 m_N
- Kusch(1947) Electron anomalous magnetic moment 1.00119m_0
- Prescott & Yale-SLAC Collaboration (1978) EW interference in polarized e-d DIS, parity non-conservation
- European Muon Collaboration (1988/9) Spin Crisis/Puzzle
- **Transverse single spin asymmetries:**
  - E704, AGS pp scattering, HERMES (1990s) RHIC Spin (2001)

    single spin neutron production(PHENIX)

    pion production (STAR) at 200 GeV Sqrt(S)

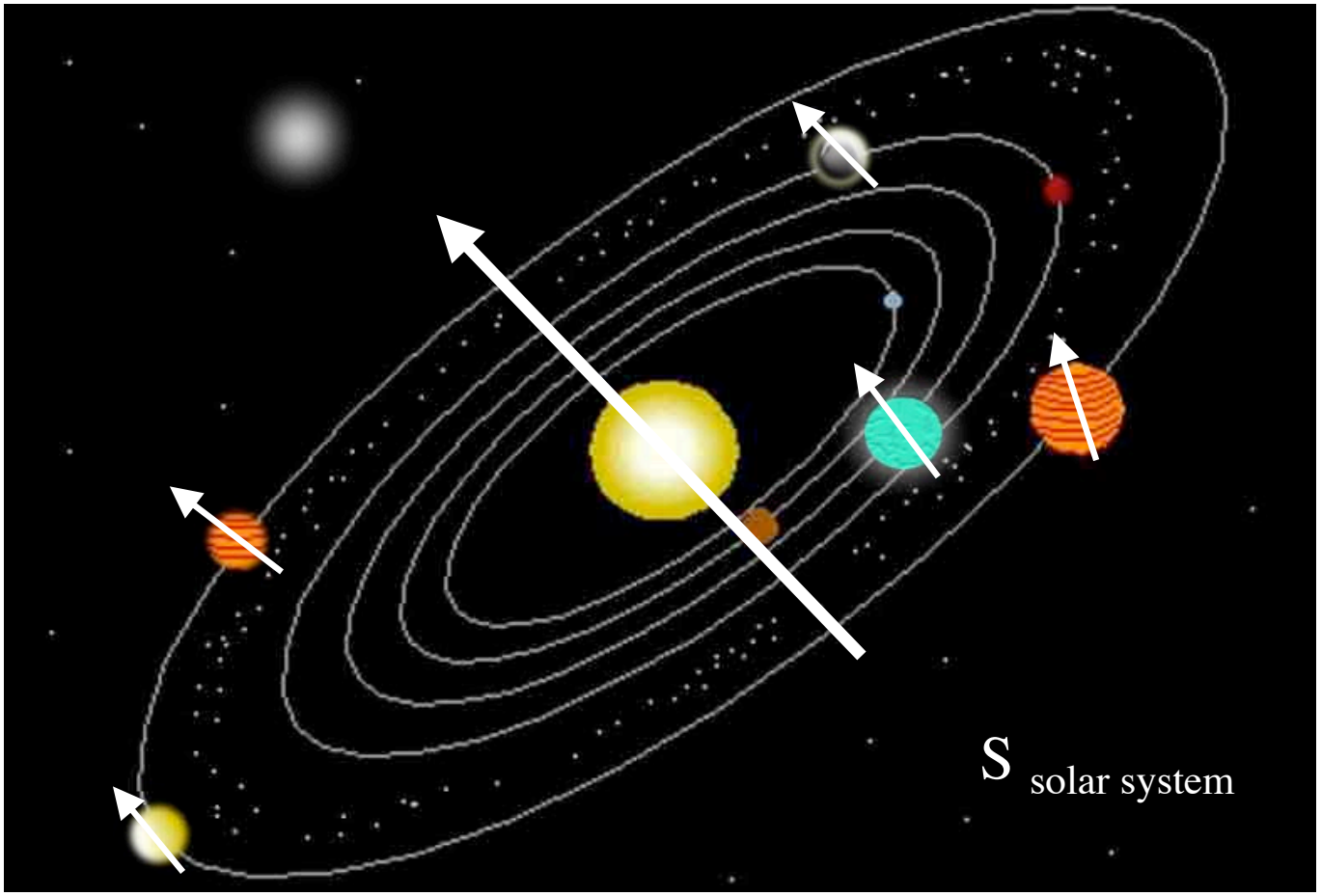
Outline

- What is "Nucleon Spin"?
  - Do we understand "spin"?
  - What is a nucleon? Do we understand its structure?
  - What about the nucleon *spin* structure?
- The Nucleon Spin Crisis (1980s)
- The Nucleon Spin Puzzle (1990s)
  - Precision fixed target experiments
- Present & Future Nucleon Spin Measurements
  - Relativistic Heavy Ion Collider at BNL: RHIC Spin
  - eRHIC for the future
- Search for nucleon spin, not just academic curiosity!

ROTATIONAL MOTION
Spin
Angular Momentum

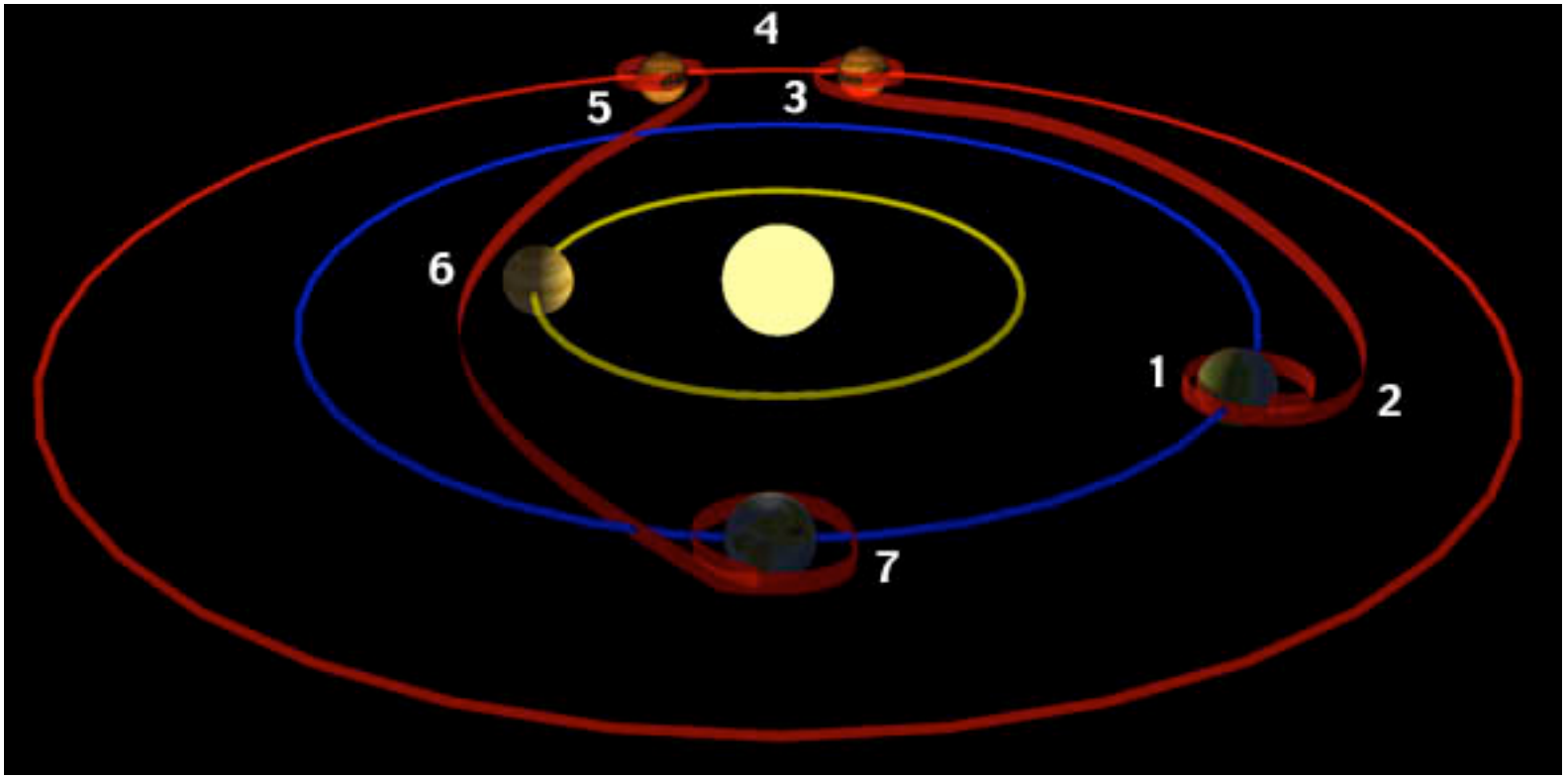
We think we understand them!
Classically and Quantum Mechanically

Revolution + Rotation = Total Spin



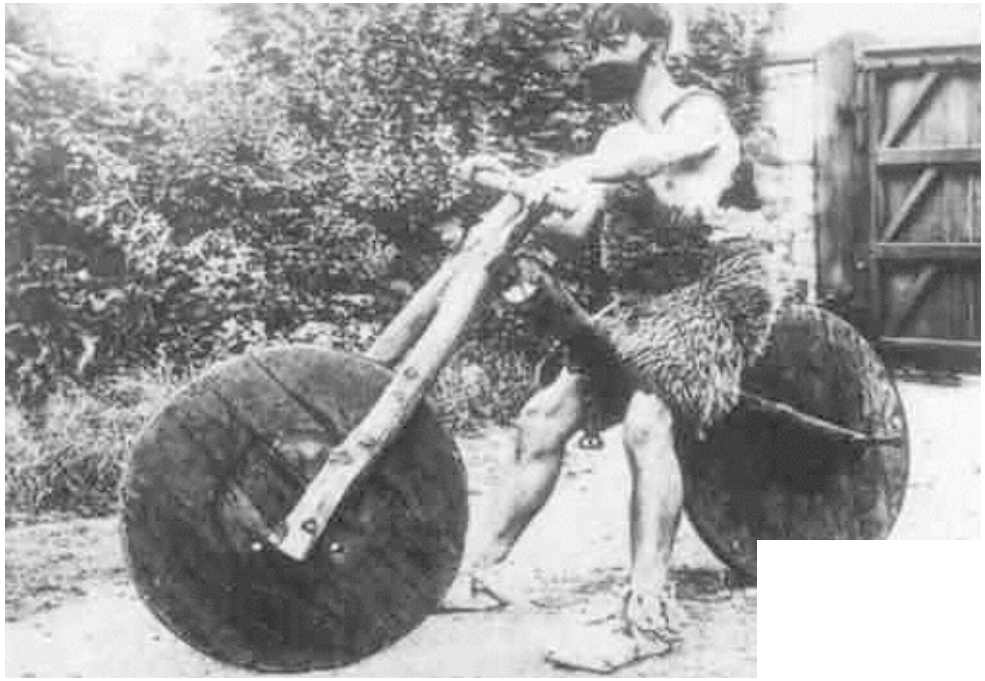
$$S_{\text{solar system}} = S_{\text{Sun}} + S_{\text{Mercury}} + S_{\text{Venus}} + S_{\text{Earth}} + \ldots\ldots$$

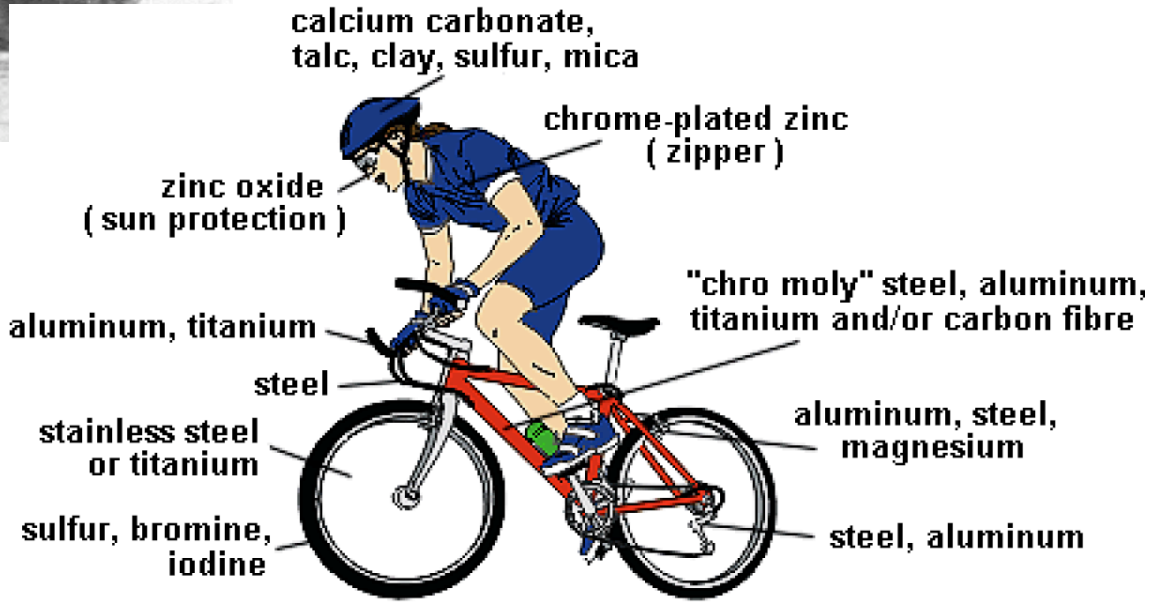
We understand Rotational Motion!



Precisely enough to plan Mars missions, for example, and time the departure and arrival of space crafts over such large distances!

We Use Rotational Motion!

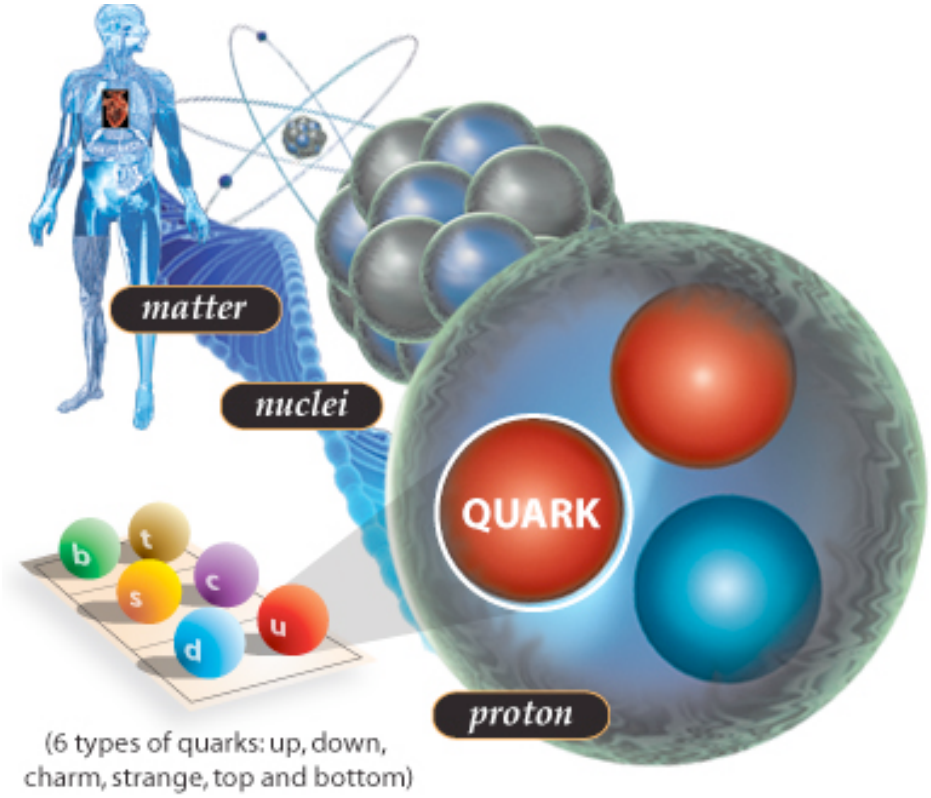




FUNDAMENTAL CONSTITUENTS OF MATTER

What's inside Protons?

- **QUARKS: Fundamental particle of matter (as far as we know today!):**



- Quarks have electric (+ and -) and "color charge" (R,B,G)

Building Blocks of Matter: no structure

- Quark Sector : "Three color charges: RED, BLUE, GREEN"

Charge	Spin	Flavor	Flavor	Flavor
+2/3 e	1/2	up	charmed	top
-1/3 e	1/2	down	strange	bottom

  - Proton Charge = up + up + down = (+2/3) + (+2/3) + (-1/3) = + 1
  - Neutron Charge = up + down + down = (+2/3) + (-1/3) + (-1/3) = 0

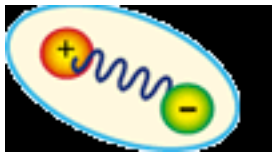
- Lepton Sector

Charge	Spin	Flavor	Flavor	Flavor
-1 e	1/2	electron	muon	tau-lepton
0 e	1/2	e-neutrino	mu-neutrino	tau-neutrino

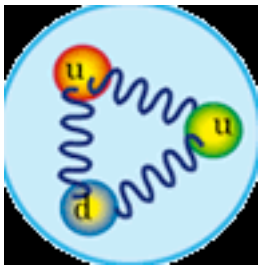
The six quarks!

Interactions

- **People communicate:**
  - Speak to each other: **exchange words, emails, phone calls…**
  - Under special circumstances: people have known to **exchanged looks** and communicated
- **Quarks communicate amongst themselves as well:**
  - Different charges **exchange** "Photons"



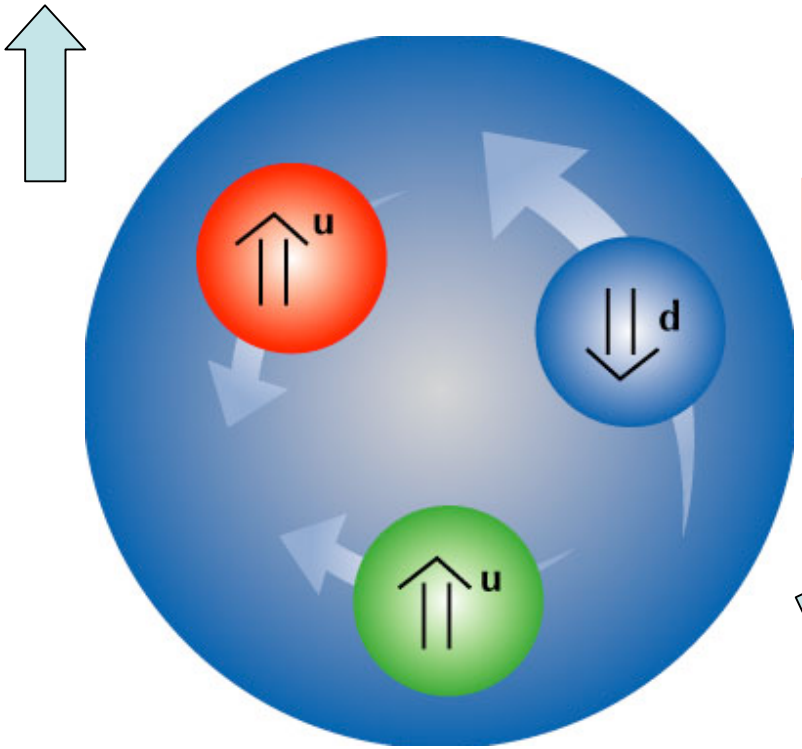
  - Quarks (have color) and **exchange** in addition "Gluons"



Think we understand nucleon structure!
What about nucleon spin?

What is Proton's Spin?

- **Protons and Neutrons are spin 1/2 particles**
  - Using this, build spins of atomic nuclei, medical uses MRIs etc.
- **Quarks that constitute them are also spin 1/2 particles**



And there are three of them in the nucleons:

Proton: u u d

Neutron: u d d

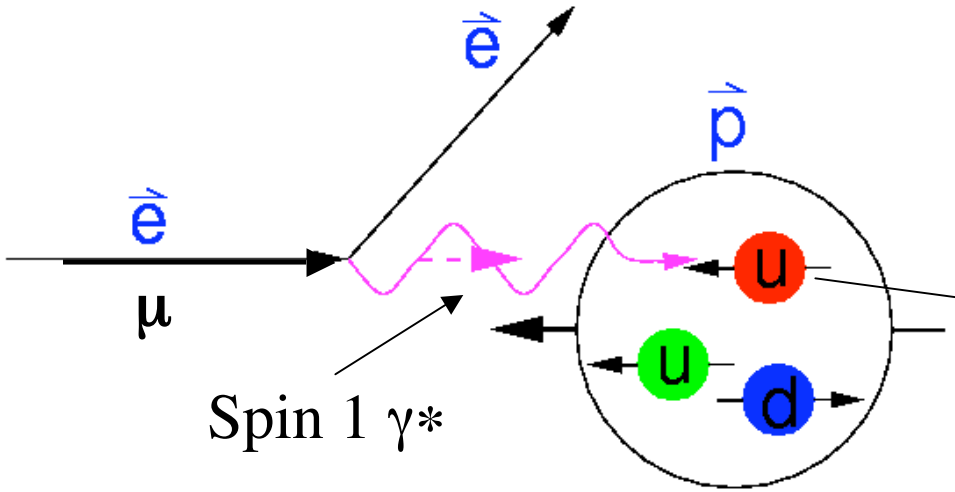
S_{proton} = Sum of all quark spins!

$$1/2 \overset{?}{=} 1/2 + 1/2 + 1/2$$

$$1/2 = 1/2 - 1/2 + 1/2$$

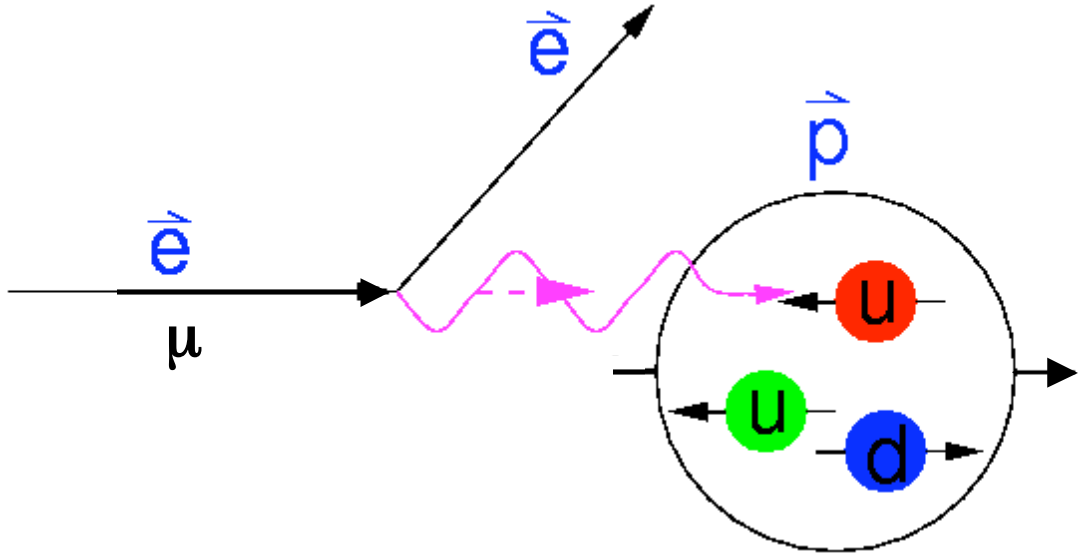
Scattering at High Energy

- **Deep Inelastic polarized electron or muon scattering**

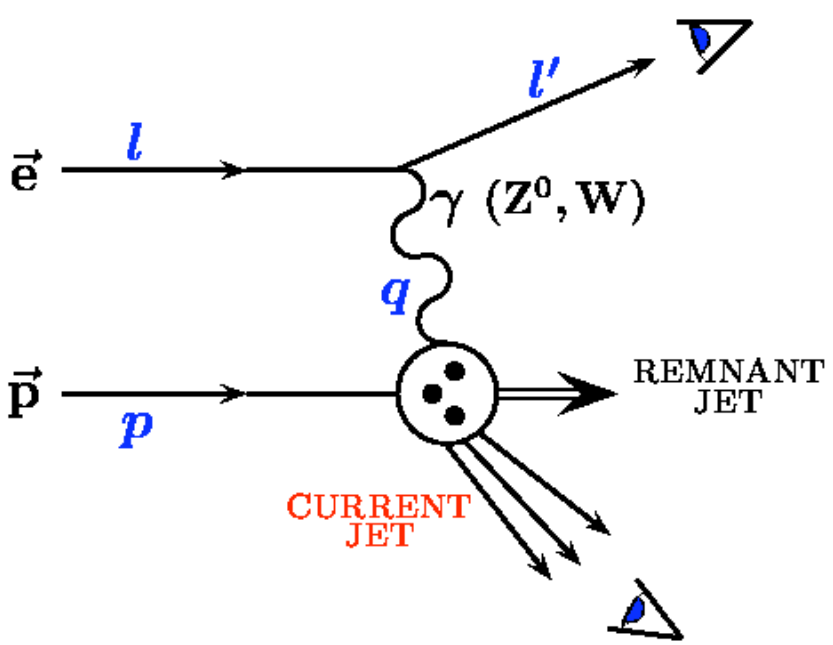


$$A_{\gamma^* p} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

$$\lambda = \frac{\text{Constant}}{p}$$



Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p\cdot q}$$

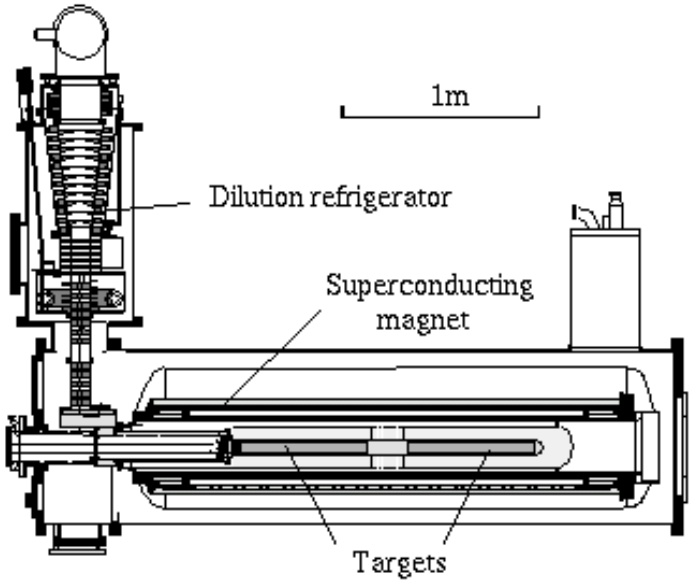
$$y = \frac{p\cdot q}{p\cdot l}$$

$$s = 4E_eE_p$$

$$W = (q+p)^2$$

- Observe scattered electron/muon & hadrons in current jets
- Observe spectator or remnant jet

European Muon Collaboration (EMC)
Spin Muon Collaboration (SMC)

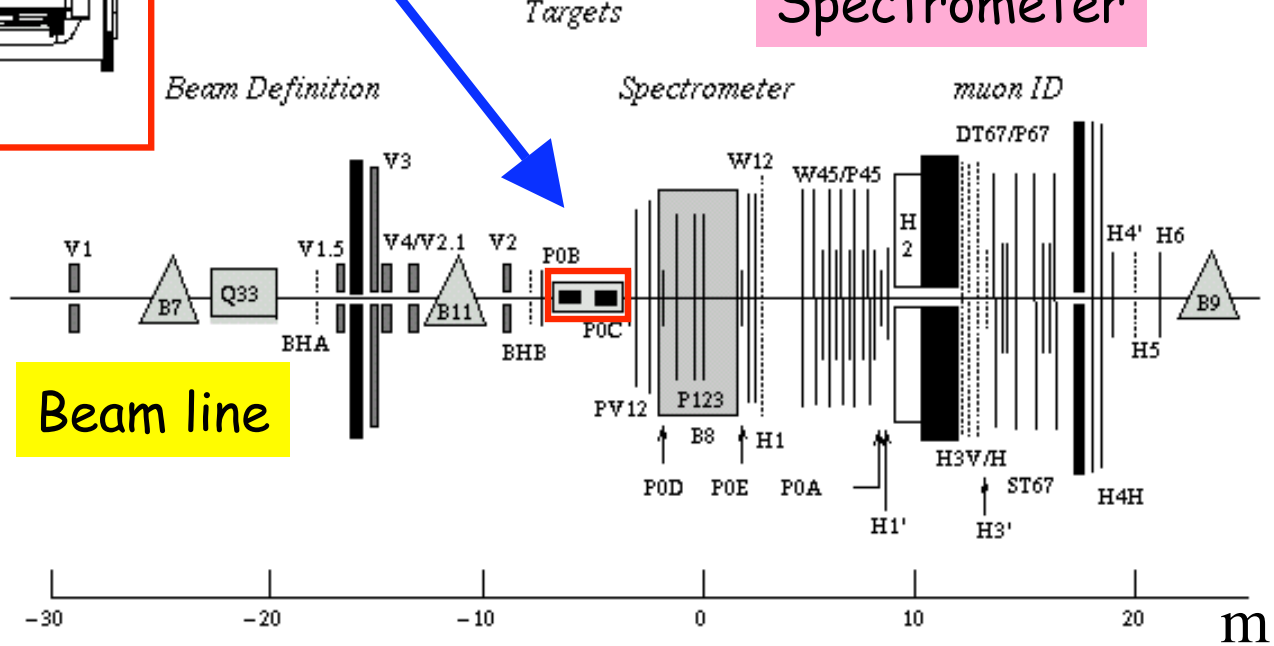


Polarized Target

CERN

Geneva, Switzerland

Spectrometer



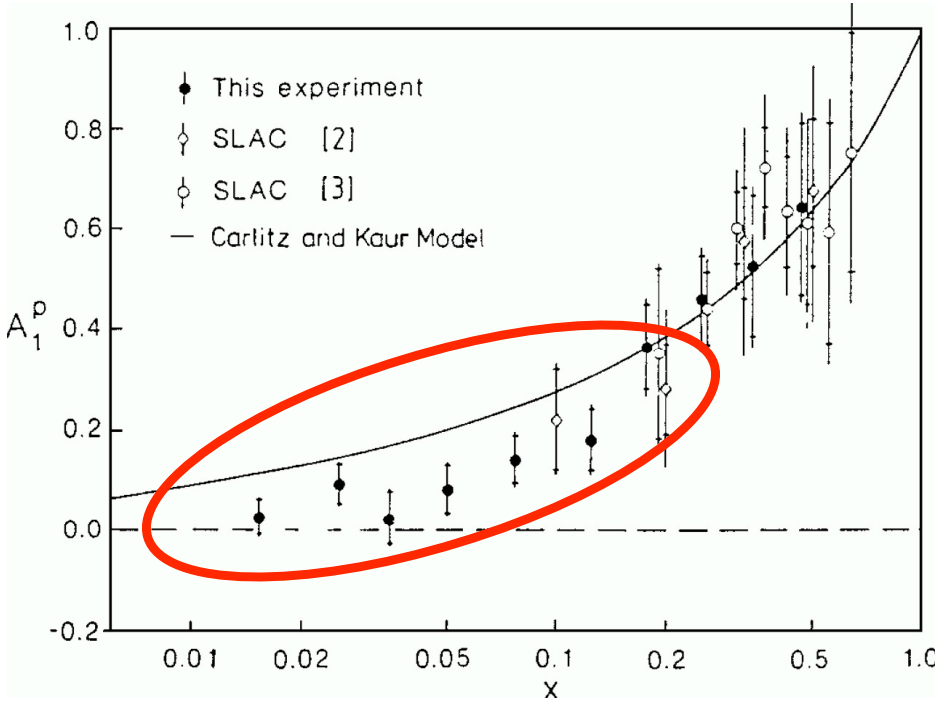
Beam line

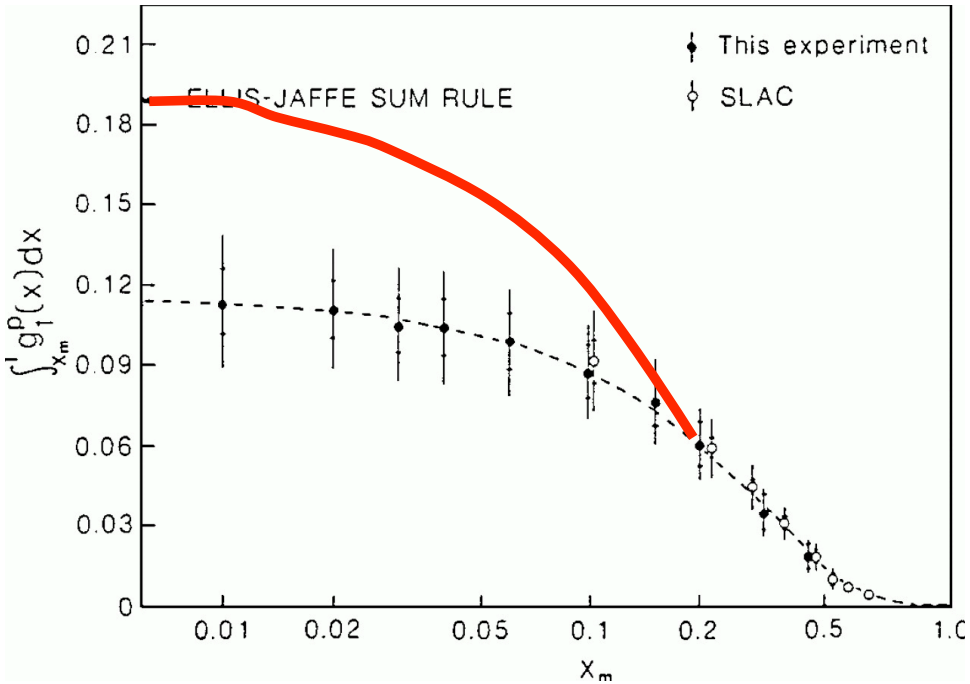
Geneva and EMC/SMC Exp. Hall!

Life was hard!

But the results made it worth it!

Proton Spin Crisis (1989)!





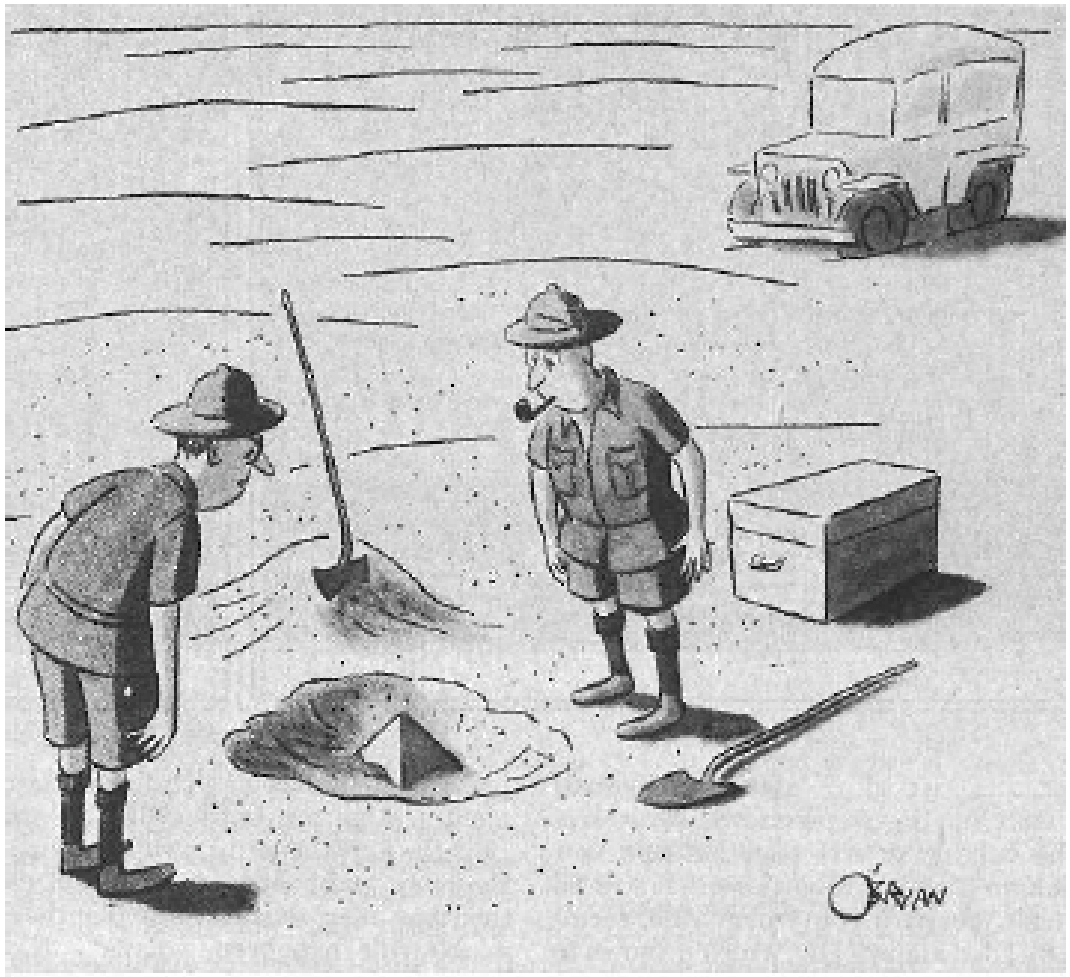
Quarks Don't Carry the Proton the Spin "1/2"

$\Delta\Sigma$ = (0.12) +/- (0.17) (EMC, 1989)

$\Delta\Sigma$ = 0.23 +/- 0.04 (SMC, 1998)

$\Delta\Sigma$ = 0.25 +/- 0.04 (SLAC, 1998)

How significant is this?



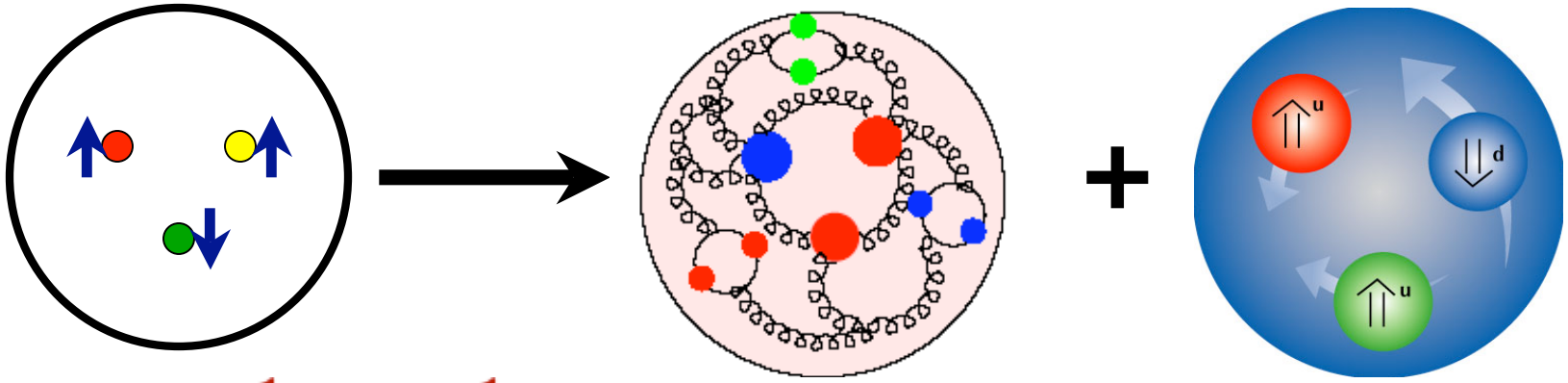
"This could be the discovery of the century. Depending, of course, on how far down it goes."

What's Wrong?….Think… Think…(1990s)

- Nucleon Spin is subtle: There aren't only quarks, there are gluons and further, quarks and gluons may be moving around in orbits adding to the TOTAL SPIN!

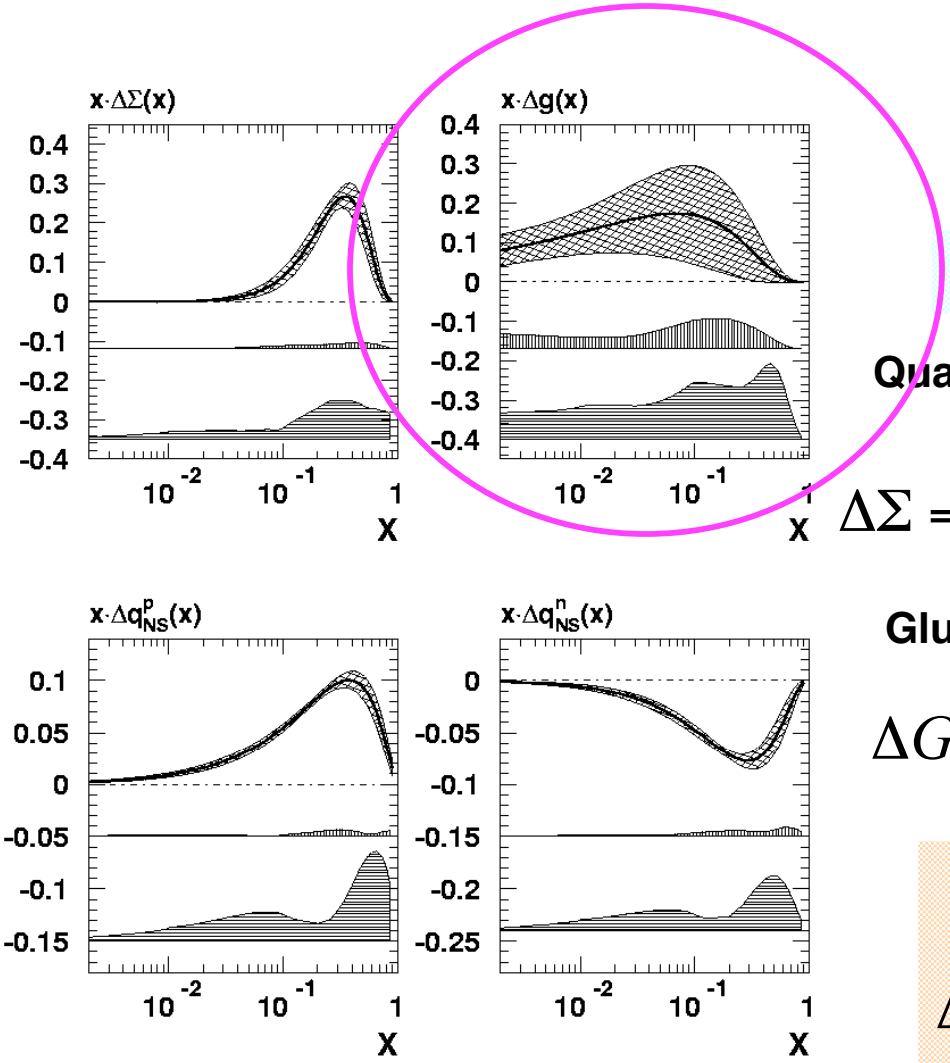
Quark Model

QCD + Orbital motion



$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{0.12} + \underbrace{\Delta G}_{\text{Significant(?)}} + \underbrace{I_{Q\&G}}_{???}$$

B. Adeva et al., SMC, PRD58, 112002(1998)



$$1/2=(1/2)\Delta\Sigma+\Delta G+L_q+L_g$$

Extensive uncertainty studies

Quark Spin Contribution:

$$\Delta\Sigma=\int_0^1\Delta\Sigma(x,Q^2=1\,\mathrm{GeV}^2)dx=0.23\pm0.07$$

Gluon Spin Contribution:

$$\Delta G=\int_0^1\Delta g(x,Q^2=1\,\mathrm{GeV}^2)dx=1.0^{+1.5}_{-1.0}$$

Proton Spin Puzzle remains unsolved!

$\Delta\Sigma$ constrained, need to measure ΔG

Similar results from other experiments and many theoretical groups….

Crisis --> Puzzle

How much spin does the gluon carry?

What role does the orbital motion of quarks and gluons play?

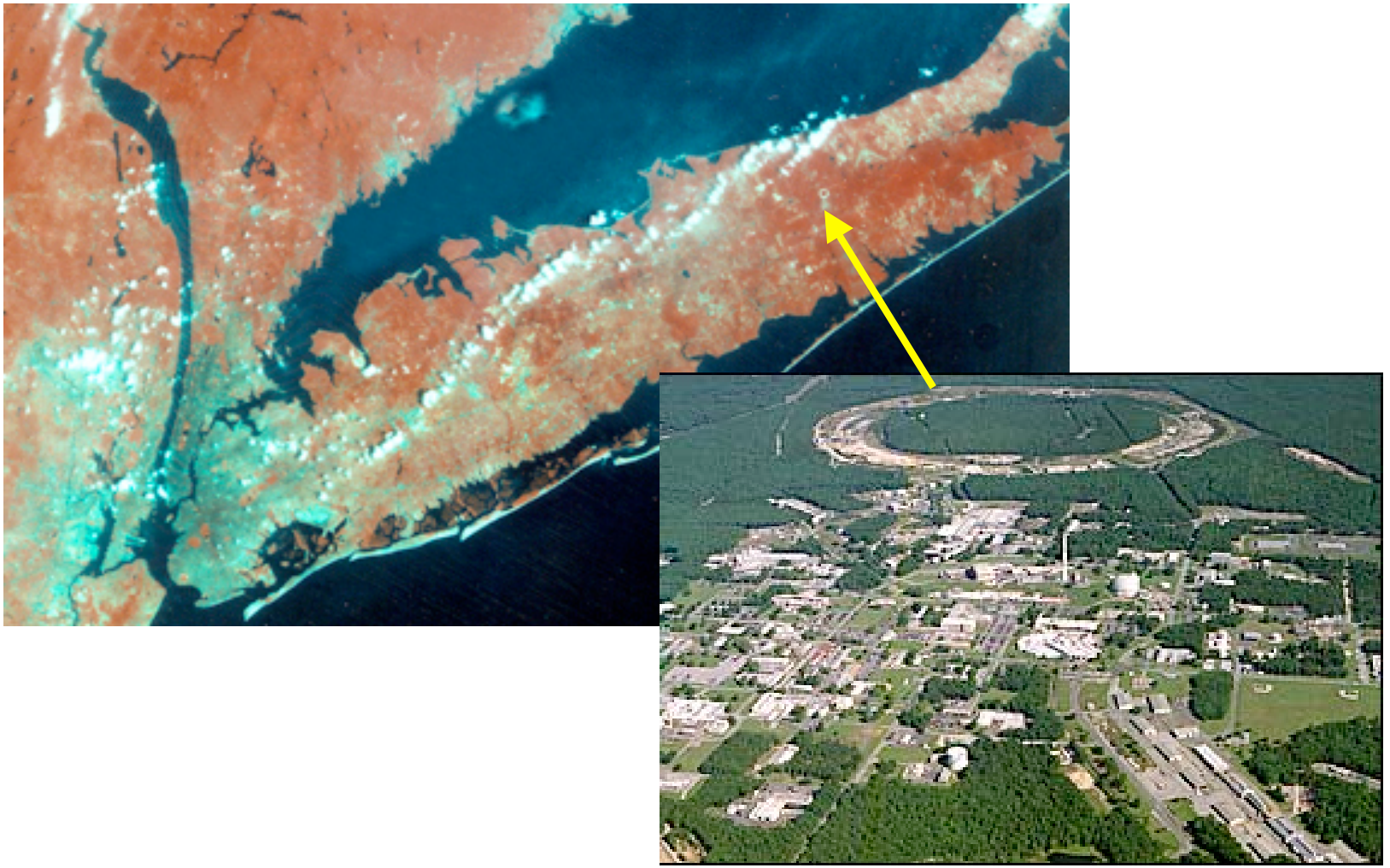
We will try to answer them at the

Relativistic Heavy Ion Collider (RHIC) at BNL

Why ΔG at RHIC?

- **RHIC is designed to store and collide polarized protons up to 250 GeV/c**
- **Remember "Interactions"?**
  - Photons interacted only with CHARGED particles (quarks)
  - Since gluons are UNCHARGED, photons do not see gluons
  - We need polarized **gluon-quark or gluon-gluon interactions** to study the gluon polarization, ΔG
  - RHIC provides abundant source of polarized protons and can collide them at high energies
- **Need appropriate detectors to look at such collisions… also exist!**

RHIC visible from Space



Relativistic Heavy Ion Collider

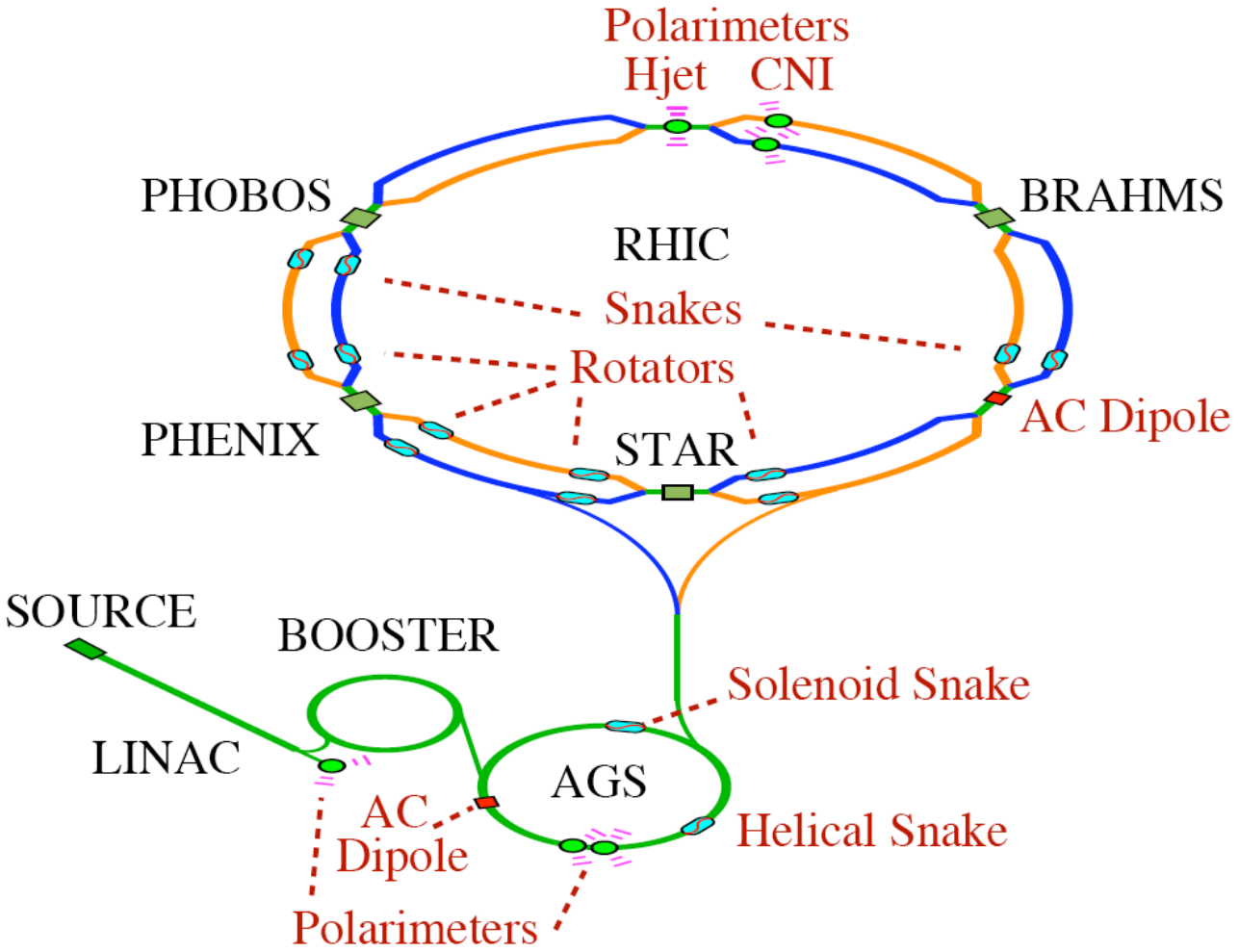
Design Parameters:

Performance	Au + Au	p+p
$\sqrt{s_{nn}}$	200 GeV	500 GeV
L [cm^{-2} s^{-1}]	2 x 10^{26}	2 x 10^{32}
Cross-section	7 barns	60 mbarn
Interaction rates	14 kHz	12 MHz

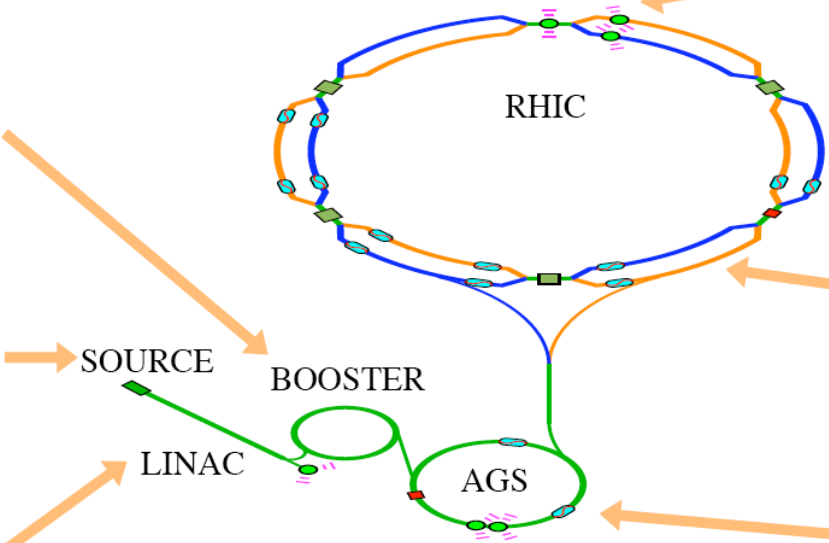
RHIC Capabilities

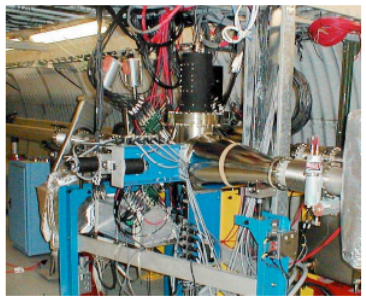
- ✓ Au + Au collisions at 200 GeV/u
- ✓ p + p collisions up to 500 GeV
- ✓ spin polarized protons (70%)
- ✓ lots of combinations in species and energy in between

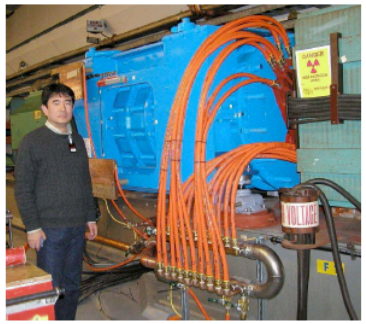
RHIC Schematic



In side RHIC Complex







LINAC: Linear Accelerator
AGS: Alternating Gradient Synchrotron
RHIC: Relativistic Heavy Ion Collider

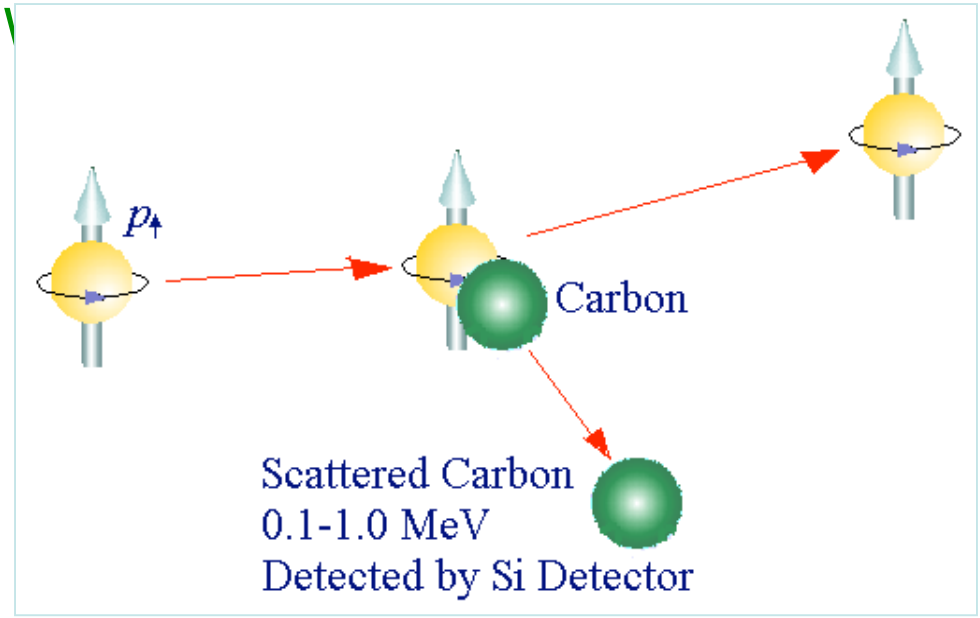
Proton beam polarimetry (I)

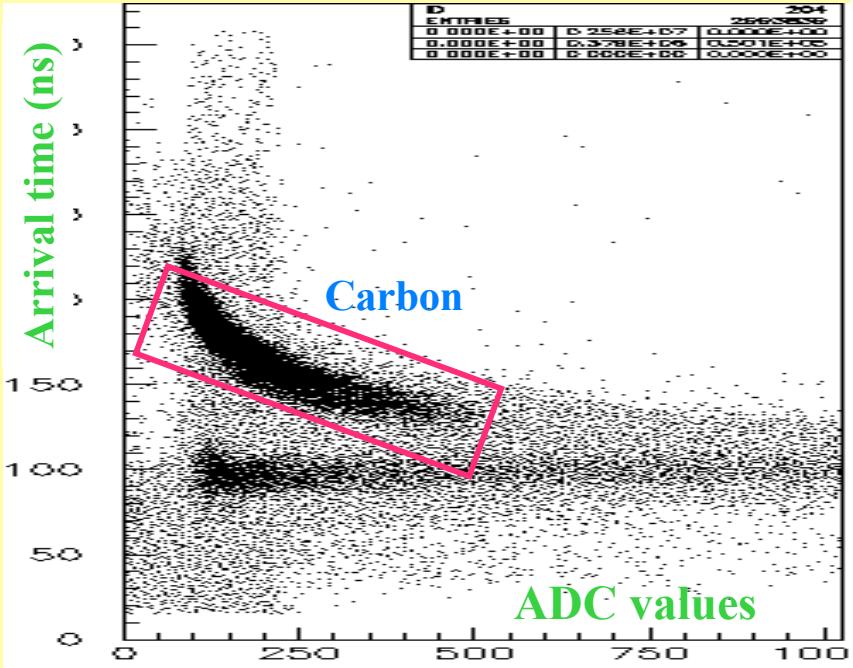
(AGS-E950 Experiment 1999/2000)

Carbon filament target (5μg/cm²) in the RHIC beam

Measure recoil carbon ions at q~90°

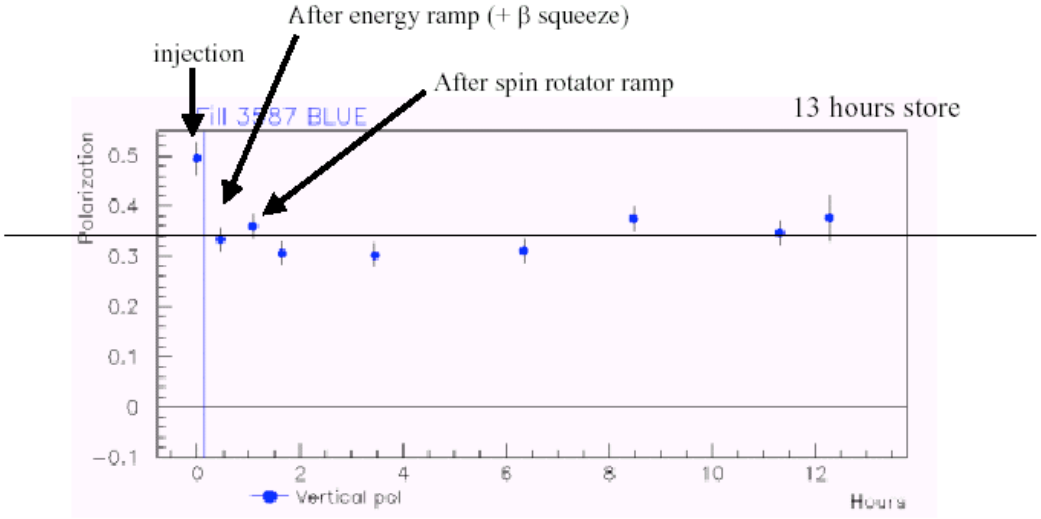
100 keV < E_{carbon} < 1 MeV





ANL, BNL, Kyoto, RIKEN/RBRC & **Yale** Collaboration

Polarization Run III & beyond



Presently: ~30% relative error
From unknown analyzing power:
Lack of experimental points in high Energy region.

Absolute pp gas jet polarimeter 2004
Will reduce this to ~5% (goal)

RUN	#proton/bunch [x10^9]	#bunch	Beta* (m)	Emittance ($\pi\mu$m)	Luminosity 10^{30} cm^{-2}s^{-1}	Pol. (%)
2001-2002	70	55	3	25	1.8	15-25
2002-2003	100	55	1	25	16	25-35
2005-	?	56	1	?	?	50

Siberian Snakes at RHIC

(Funded by RIKEN Institute in Japan)

Depolarizing Resonance:

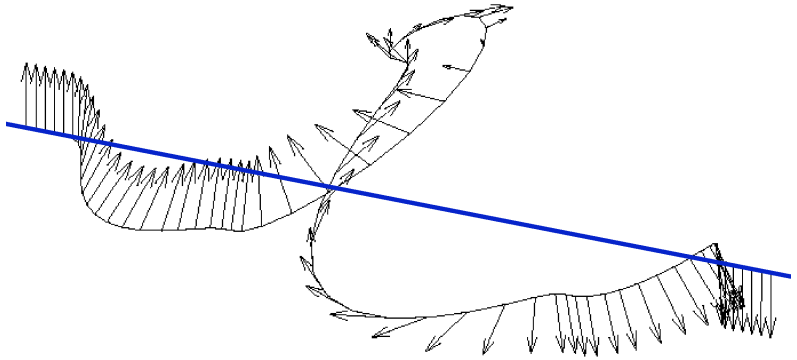
Spin tune = no. of spin kicks

Imperfection resonances:

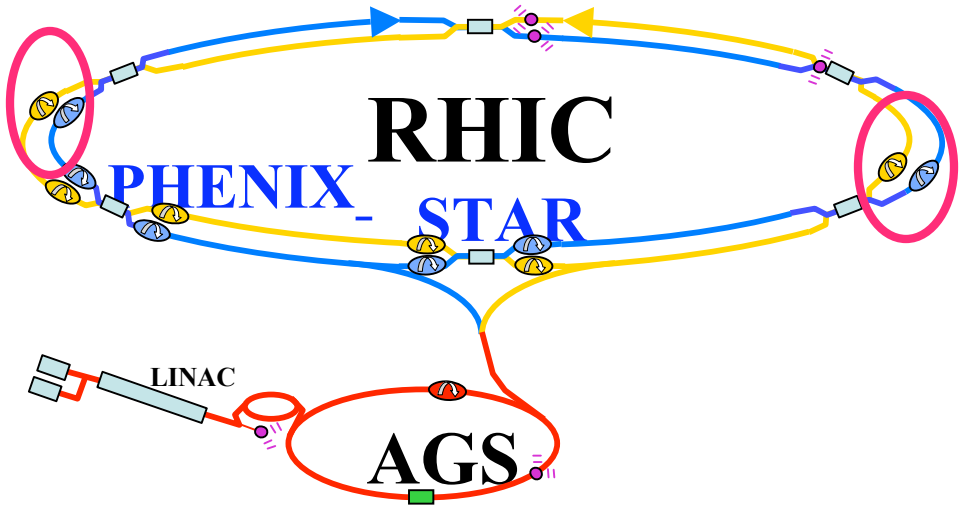
--magnet errors & misalignements

Intrinsic resonances:

--vertical focusing fields



Effect of depolarizing resonances averaged out by rotating spin by large angles on each turn



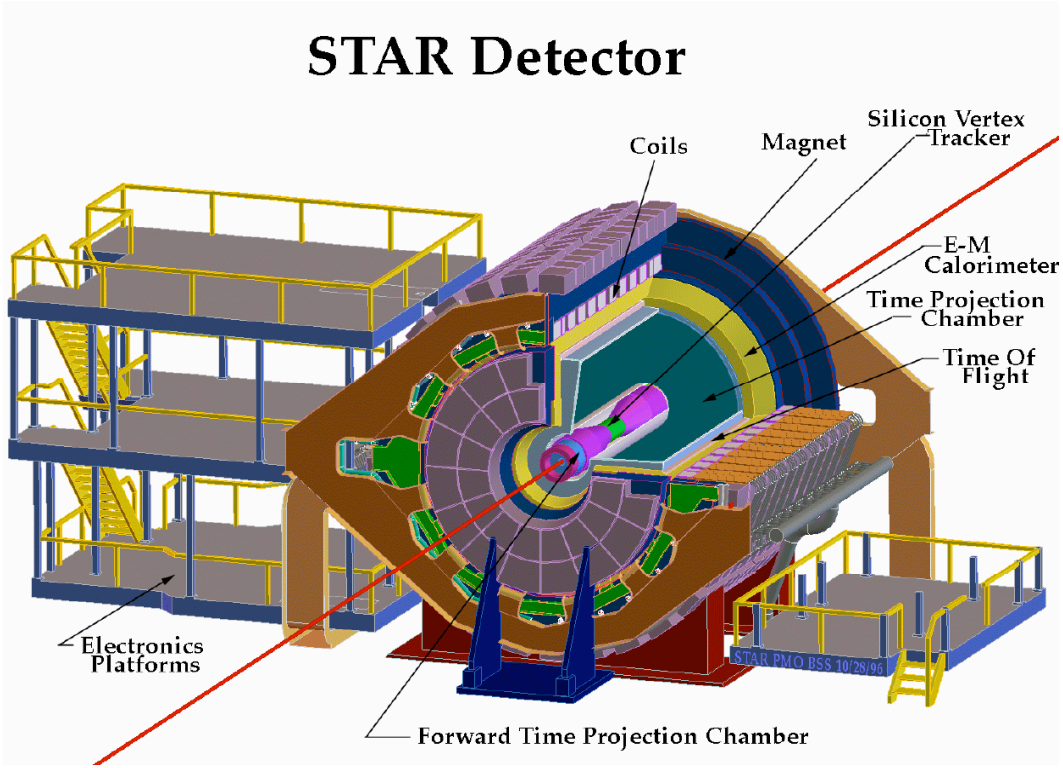
RIKEN/BNL

4 helical dipoles ➔ S. snake

2 snakes in each ring

-- axes orthogonal to each other

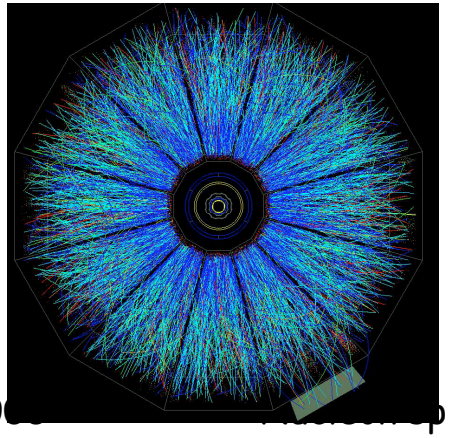
RHIC Detectors (I)

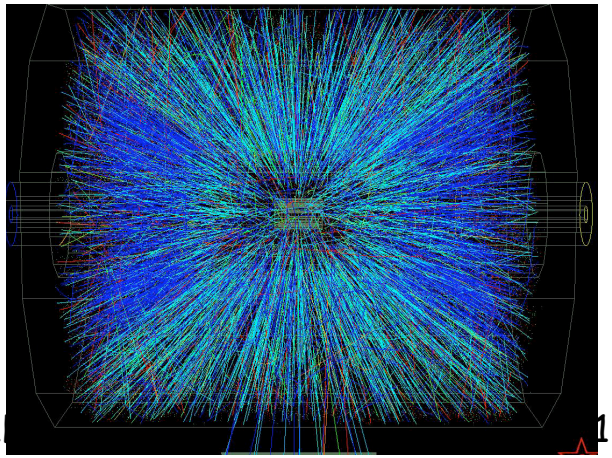


~1200 Tons

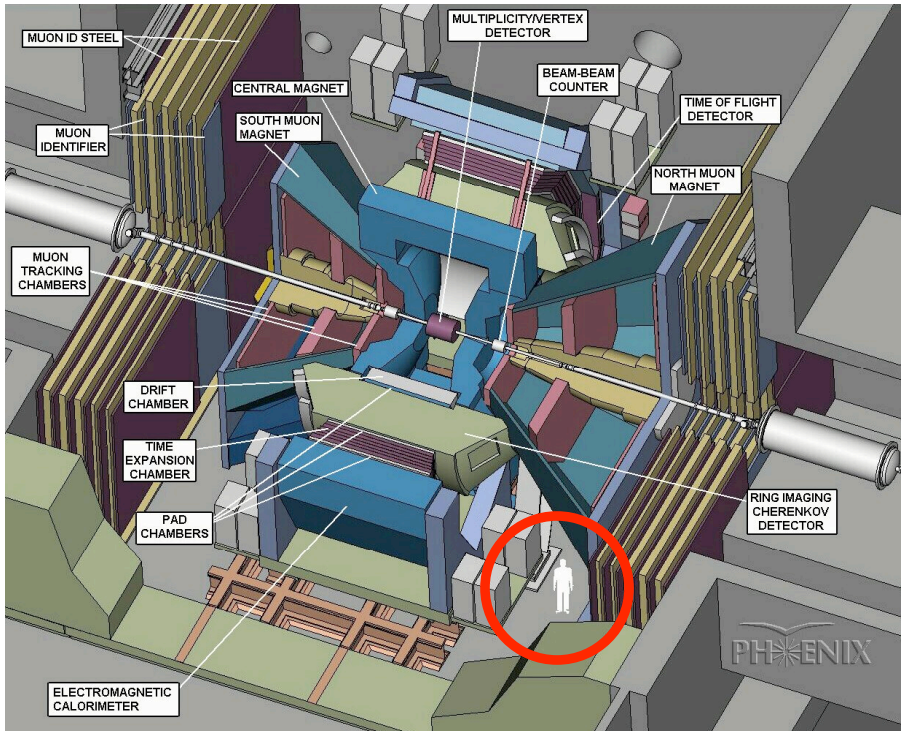
~350 people
~27 institutes
~10 countries

~$60 M





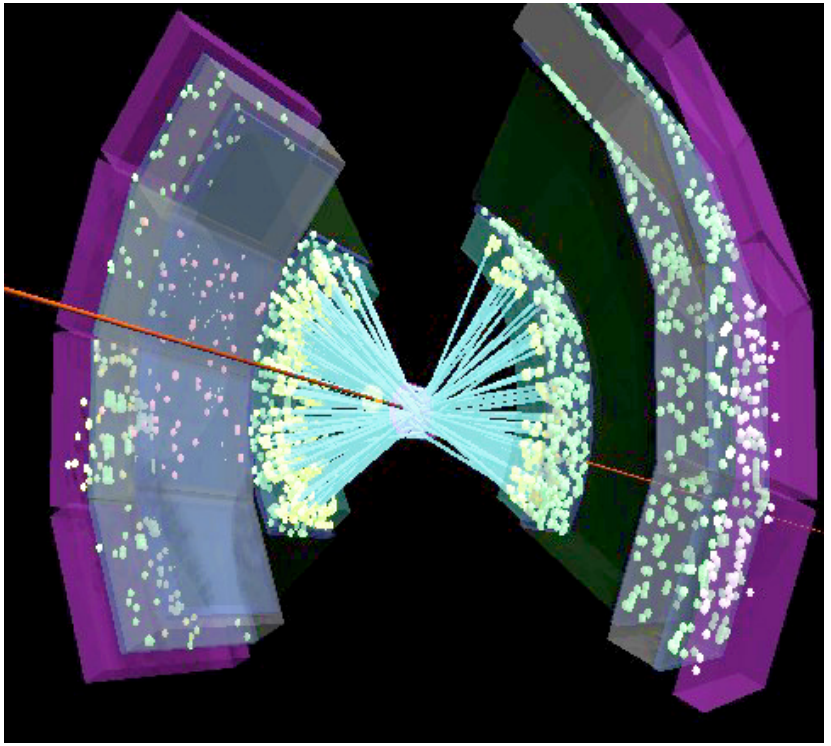
RHIC Detector (II)



~3000 Tons

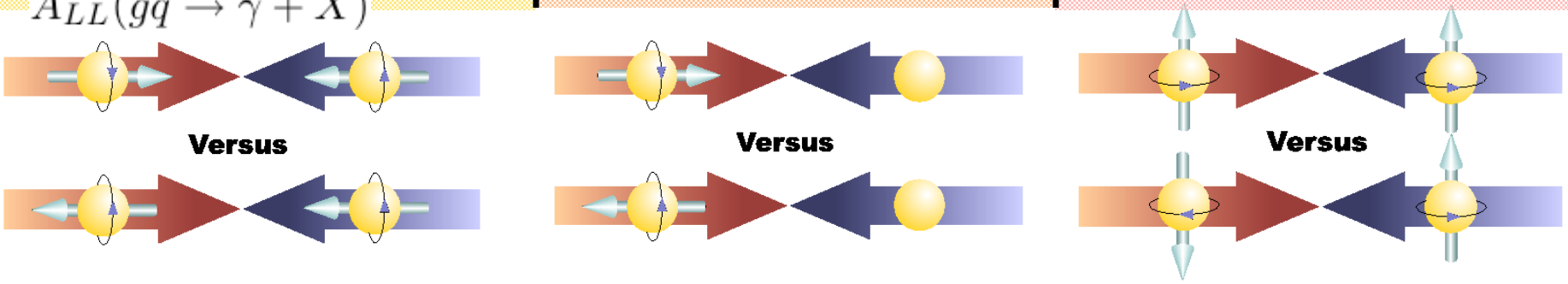
~450 people, ~57 institutions around the world, ~14 countries

~$100M

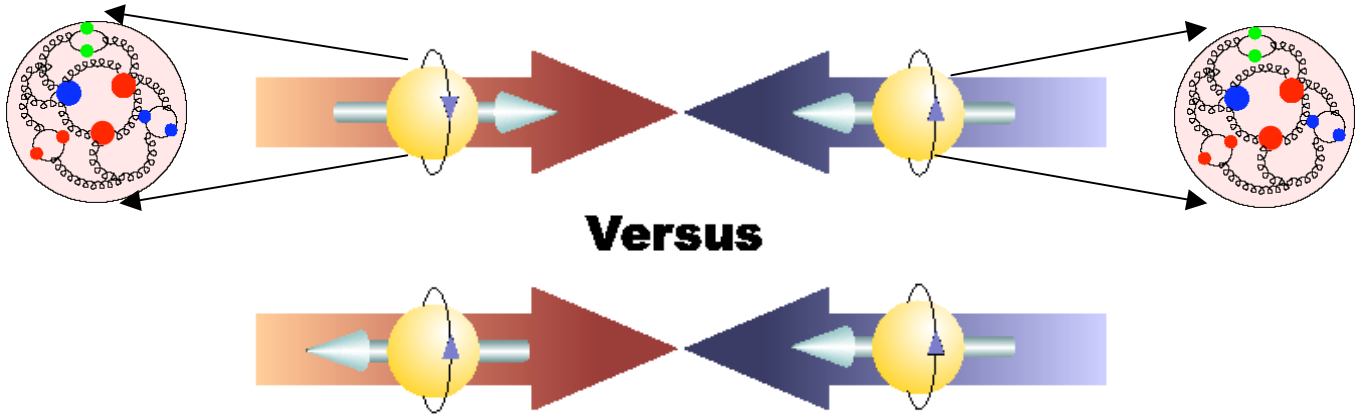


RHIC Spin Physics Program

Gluon Polarization	Flavor Decompsition	Transverse single/double spin physics
ΔG	$\frac{\Delta u}{u}, \frac{\Delta \overline{u}}{\overline{u}}, \frac{\Delta d}{d}, \frac{\Delta \overline{d}}{\overline{d}}$	
$\pi^{0,+,-}$ Production $A_{LL}(gg, gq \to \pi^{0,\pm} + X)$ Heavy Flavors $A_{LL}(gg \to c\overline{c}, b\overline{b} + X)$ Prompt Photon $A_{LL}(gq \to \gamma + X)$	W physics $A_L(u + \overline{d} \to W^+ \to l^+ + \nu_l)$ $A_L(\overline{u} + d \to W^- \to l^- + \overline{\nu_l})$ Longitudinal single spin physics	Transversity: Sivers vs. Collins effects & physics of higher twists; Pion interf. Fragmentation Transverse single spin physics Phenix-Local Polarimetry

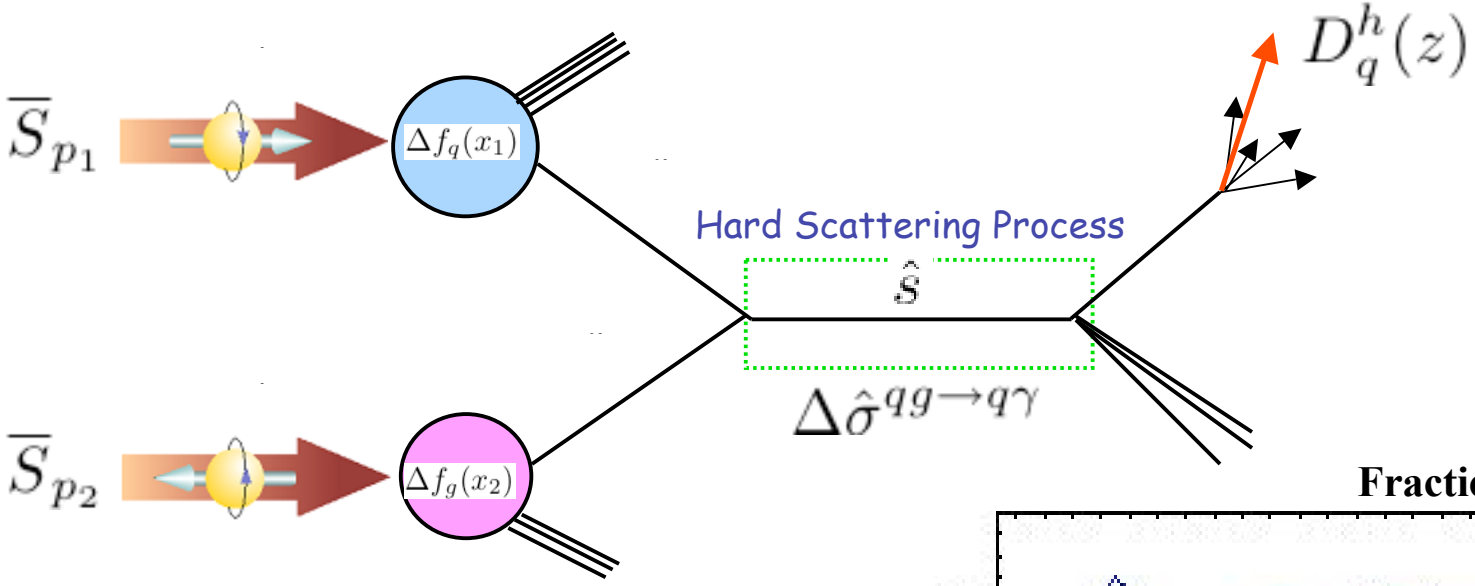


RHIC polarized gluon collisions



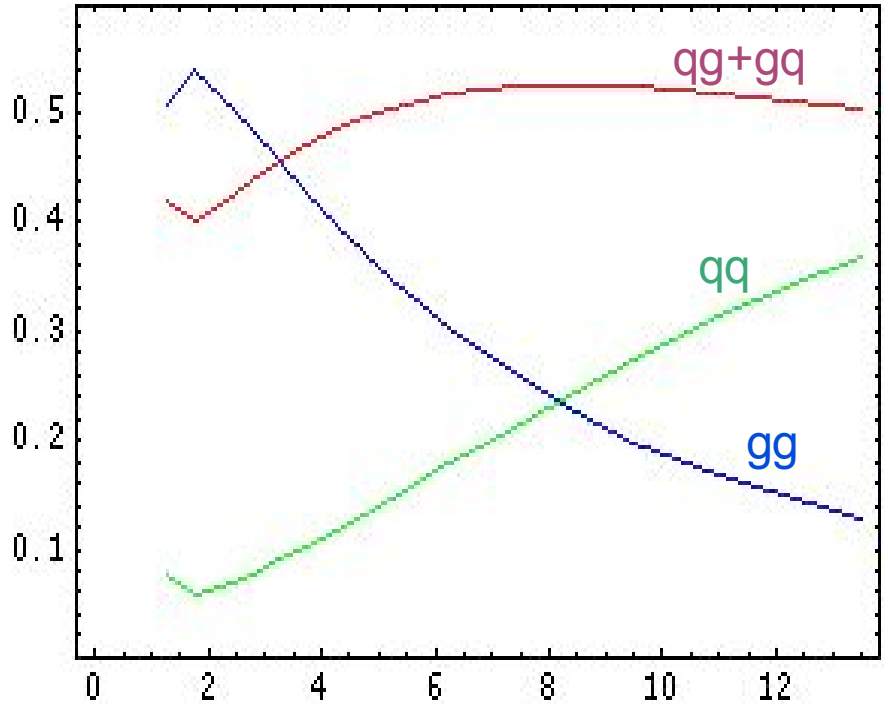
- **Detectors will record collisions between**
  - Polarized quarks and polarized gluons
  - We know the quark spin content (Spin Crisis value!) so we know how much of spin effect will be due to quarks:
    - **ANY "DEVIATION" WILL BE DUE TO GLUONS!**
- **All gluon spin related measurements are Double Spin Asymmetries: A_{LL}**
- **Definitive Results on gluon polarization expected in 2-4 years**

Double Spin: Leading hadrons



h = π^0

Fraction of π^0 produced



$gg \to gg$

$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$

$gq \to gq$

$\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$

$qq \to qq$

$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$

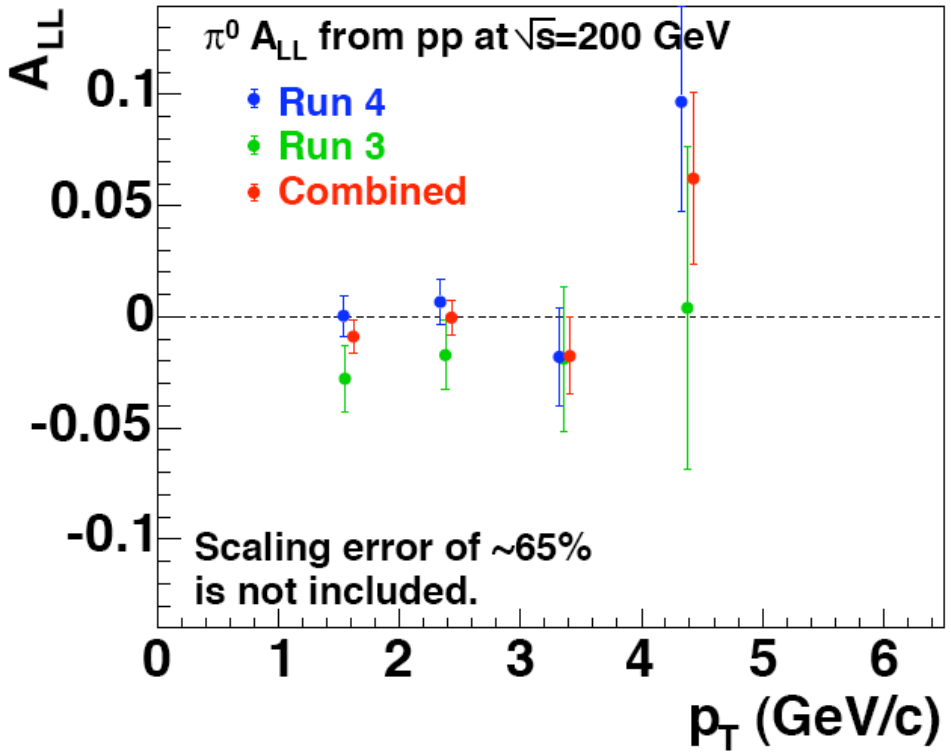
Gluon Spin Program has begun!

- Data taken in 4 weeks in Run 3 & 4 days of 2004
- Longitudinal polarization at PHENIX
  - *forward neutron production based local polarimetry*
  - *Relative luminosity variations less than 2.5 x 10^{-4}*

	Run Time	Int. Lum.	Pol.	P^4L
Run 3 (2003)	4 weeks	220 nb^{-1}	27%	1.17 nb^{-1}
Run 4 (2004)	4 days	75 nb^{-1}	40%	1.92 nb^{-1}

Double helicity asymmetry in inclusive mid-rapidity neutral pion production for polarized -pp collisions at Sqrt(s)=200 GeV hep-ex/0404027, Published OnLine: PRL 93, 202002 (2004)

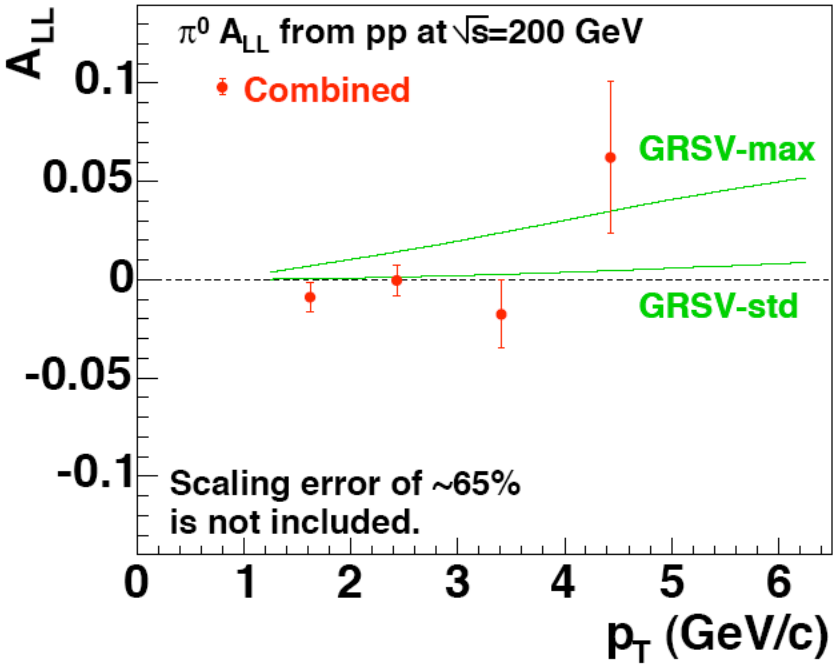
ALL(π^0) Results Run-3 & 4



- Data from Run-3 and Run-4 consistent:
  - $Ch^2/DF = 5.7/4$
- Figure of merit of Run3 and Run4 are: 1.17 and 1.92, respectively
  - Uncertainties in Run-4 smaller in spite of significantly fewer events

p_T (GeV/c)	$A_{LL}^{\pi^0}$ (Run 4) (%)	$A_{LL}^{\pi^0}$ (Run 3) (%)	$A_{LL}^{\pi^0}$ comb. (%)
1-2	0.0± 0.9	-2.7± 1.3	-0.9±0.7
2-3	0.7± 1.0	-1.3± 1.3	0.0±0.8
3-4	-1.8± 2.2	-1.7± 2.8	-1.8±1.7
4-5	9.7± 4.9	0.7± 6.2	6.2±3.8

Comparison with theory



- **GRSV-std: best fit to DIS data**

$$\int_0^1 \Delta G(x)dx \sim \ 0.7 \text{ at } \mathrm{Q}^2 \ 1 \ \mathrm{GeV}^2$$

- **GRVS-max**

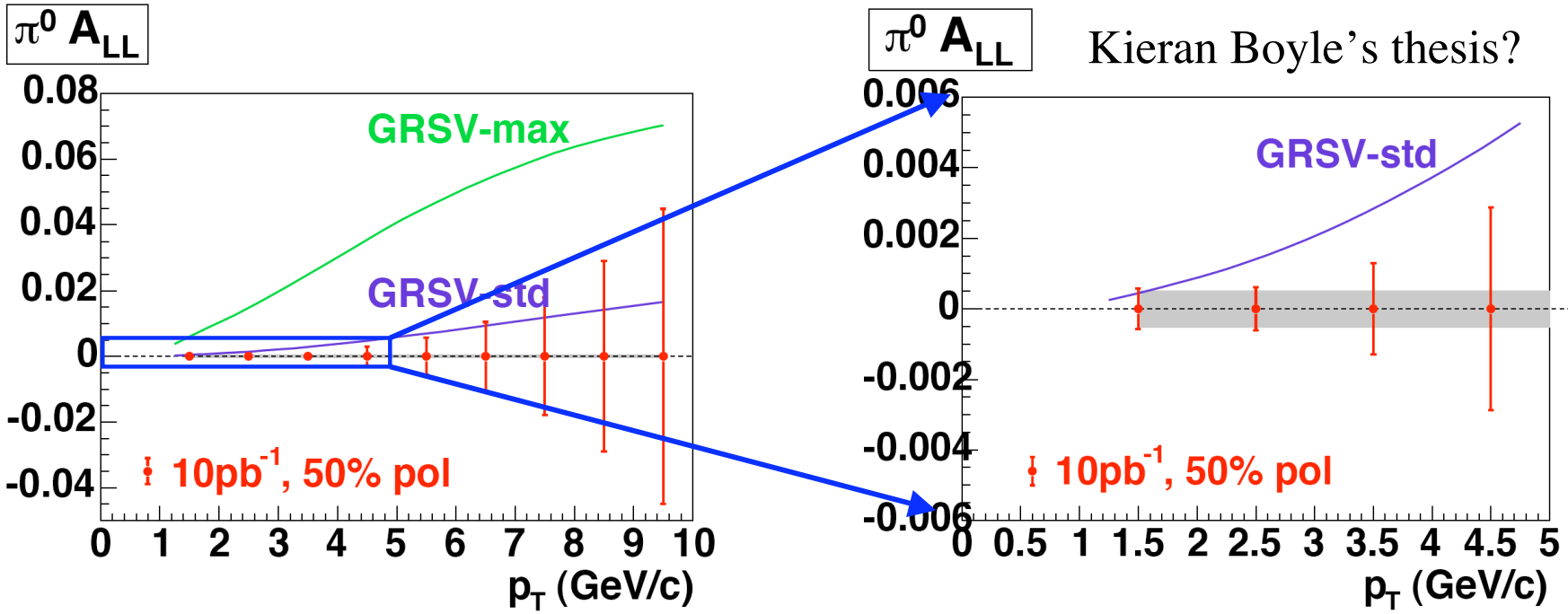
$$\Delta G(x) = G(x) \text{ at } \mathrm{Q}^2_{\mathrm{input}} = \ 0.40 \ \mathrm{GeV}^2$$

- **Data prefers the GRSV-std curve (and hence the gluon distribution and its first moment)**
  - B. DeJager et al. Phys. Rev. D67, 0504005 (2003)

	GRSV-std	GRSV-max
4 points (1-5 GeV/c)	21-24%	0.00-6%
3 points (2-5 GeV/c)	27-29%	0.01-13%

Run-5, Starting April'05

- Expect to get 32 total cryo-weeks
- 8-9 Physics Weeks
  - ~0.5 to 1.0 pb^{-1} per week to tape by PHENIX



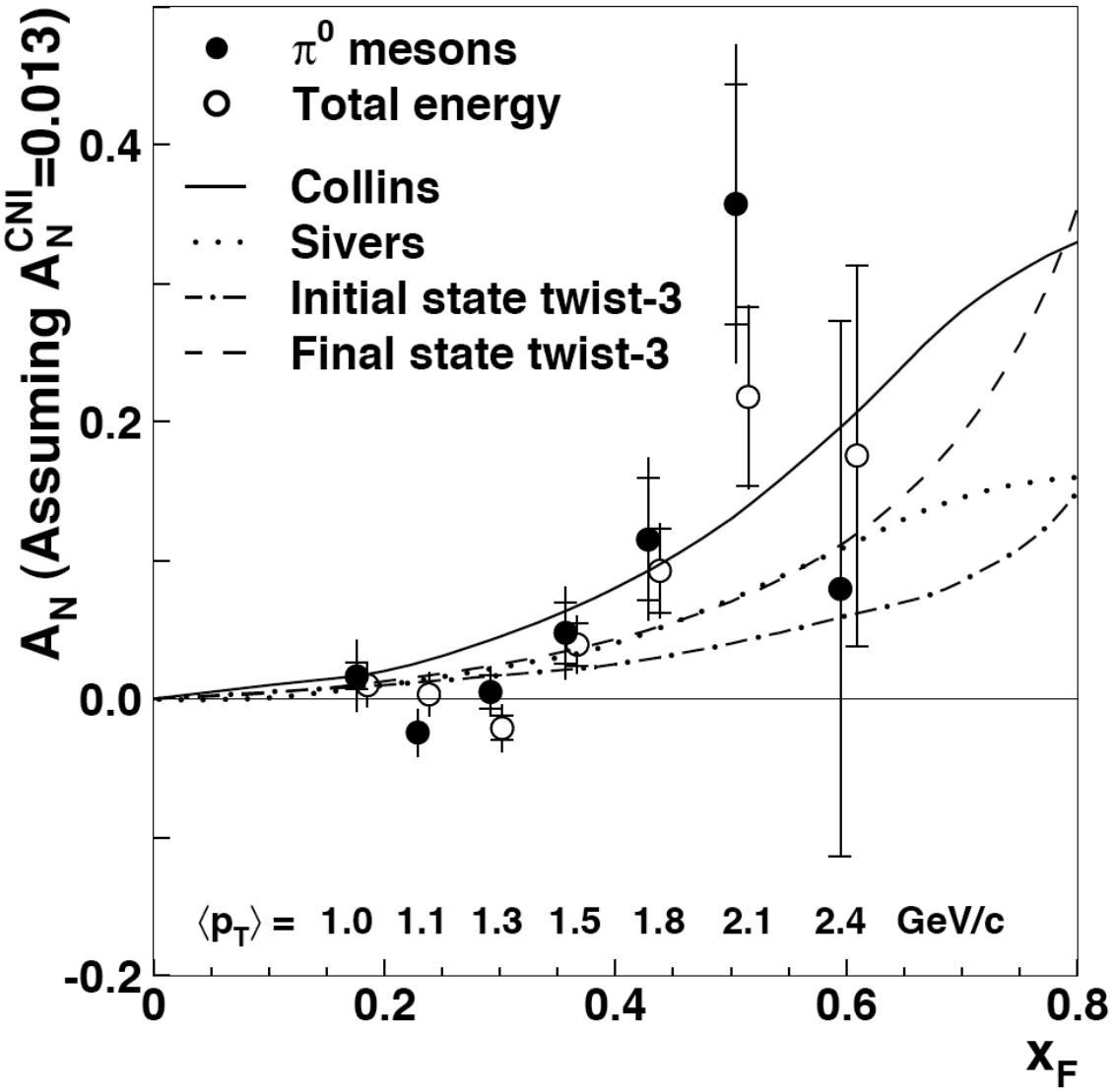
Gluon Spin…., Quark-Anti-Quark Spins and Transversity….

• Gluon spin measurement will continue in the next few years: Using DIFFERENT PROBES available at RHIC (pp ->($\pi^{0/+/-}$)X, γX, c-cbar, b-bbar) all independently checking each other, and slightly different kinematic region

• Followed up with measurements of transverse spin effects, any hints of non-zero transversity will be exciting in future quests of understanding nucleon spin

• Separation of quark-anti-quark components of the nucleon spin: needs RHIC running at 500 GeV CM of energy, trial runs next month!

A_N Results from PHENIX/STAR



A_N for both charged hadrons and neutral pions consistent with zero.

STAR sees a Single transverse asymmetry ~10% in very forward rapidity region, ~2 sigma significance:

What about the Orbital Motion?

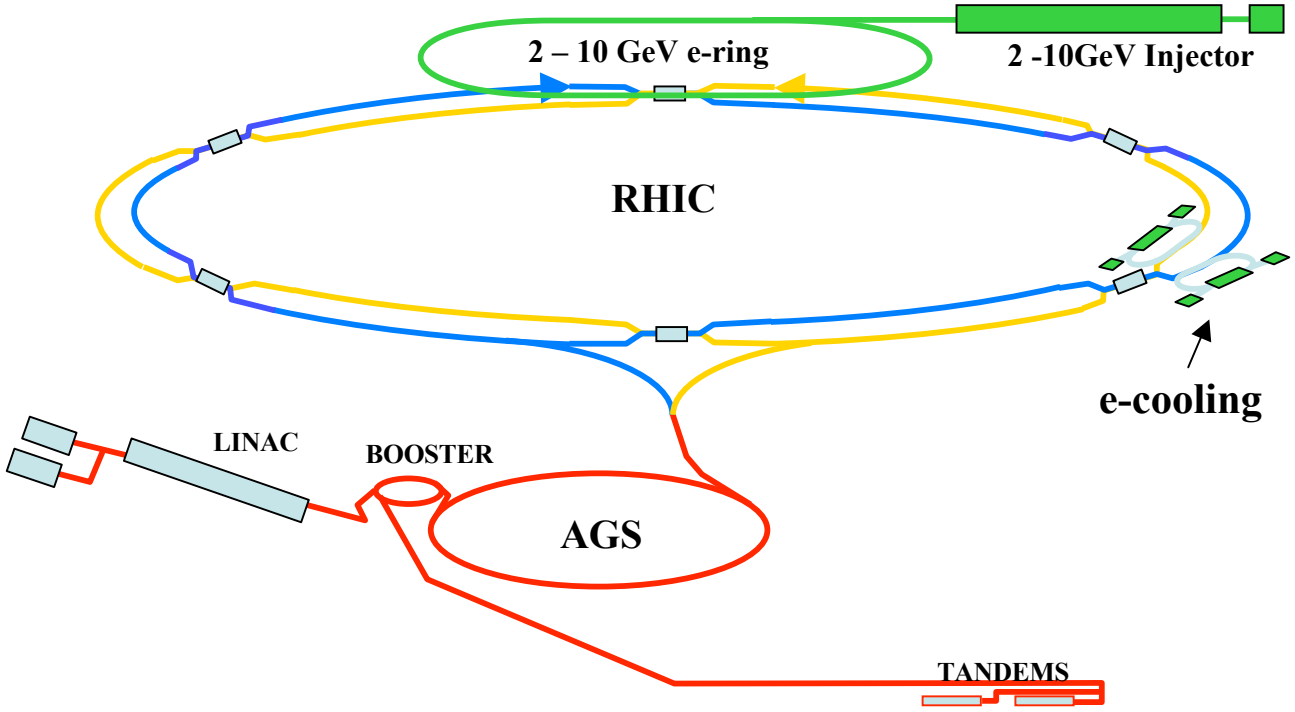
- **Measurement method still being developed….**
- **Present ideas and methods: electron-nucleon scattering!**
  - Typically three quarks carry equal "momentum" of the proton, but with small probability one of them, at certain time could carry a larger fraction, even a very significant fraction:
  - Catch the quark at that moment and measure e-u-quark scattering and e-d-quark scattering wih different spin orientations: see if they are along or against the nucleon spin
  - Predictions exist (transverse/azimuthal asymmetries) assuming NO orbital motion of quarks
- **Any** deviation from these predictions **would indicate evidence for orbital motion of quarks**

Investigating Orbital Motion

- **Very difficult topic to tackle**
  - Challenge to all of us
  - How to make clean measurements?
    - Not clear, still a developing field
- **How to distinguish between the orbital motion component of quarks, and gluons? Too hard a question for now**
  - Is this even a valid question?
  - Perhaps it depends on the specifics of experiment…
- **It is generally accepted that a Collider with high intensity and high energy lepton beam would be essential**
  - An exciting new spin physics program for precision measurements of nucleon structure can be carried out

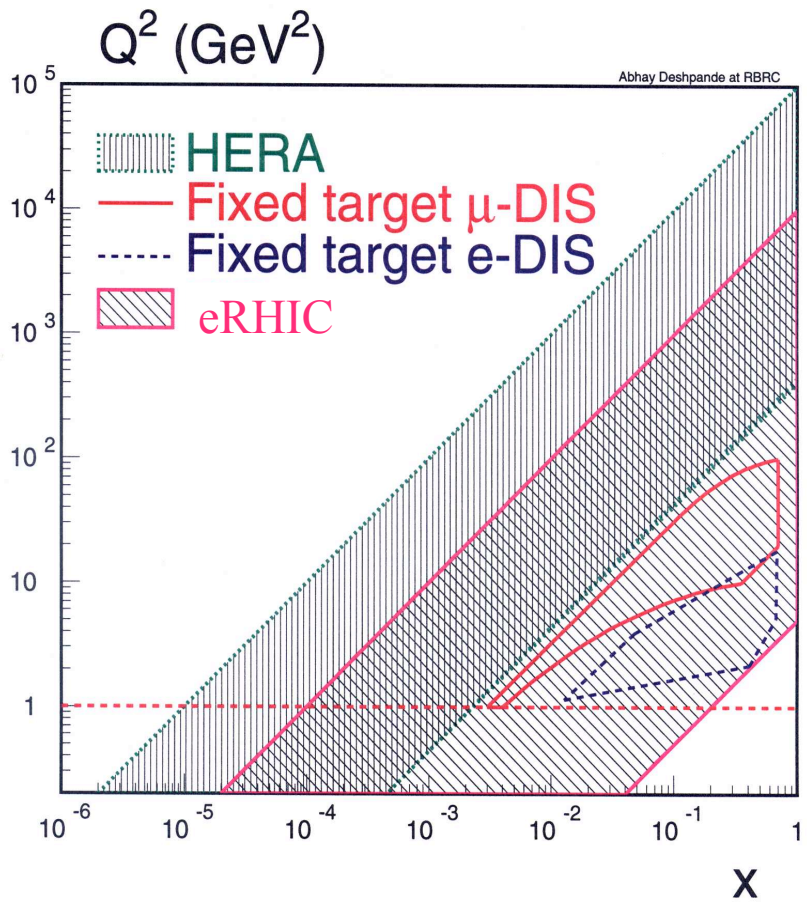
Future Collider at BNL: eRHIC

- A new 10 GeV polarized electron ring is proposed
- Will collide with the existing RHIC polarized proton ring
- Will also be able to explore heavy nuclei with the electrons collide with them



Operational
By ~2015(?)

eRHIC vs. other DIS Facilities (I)



New kinematic region

E_e = 5-10 GeV

E_p = ~30 – 250 GeV

Sqrt(s) = 20 – 100 GeV

Kinematic reach of eRHIC

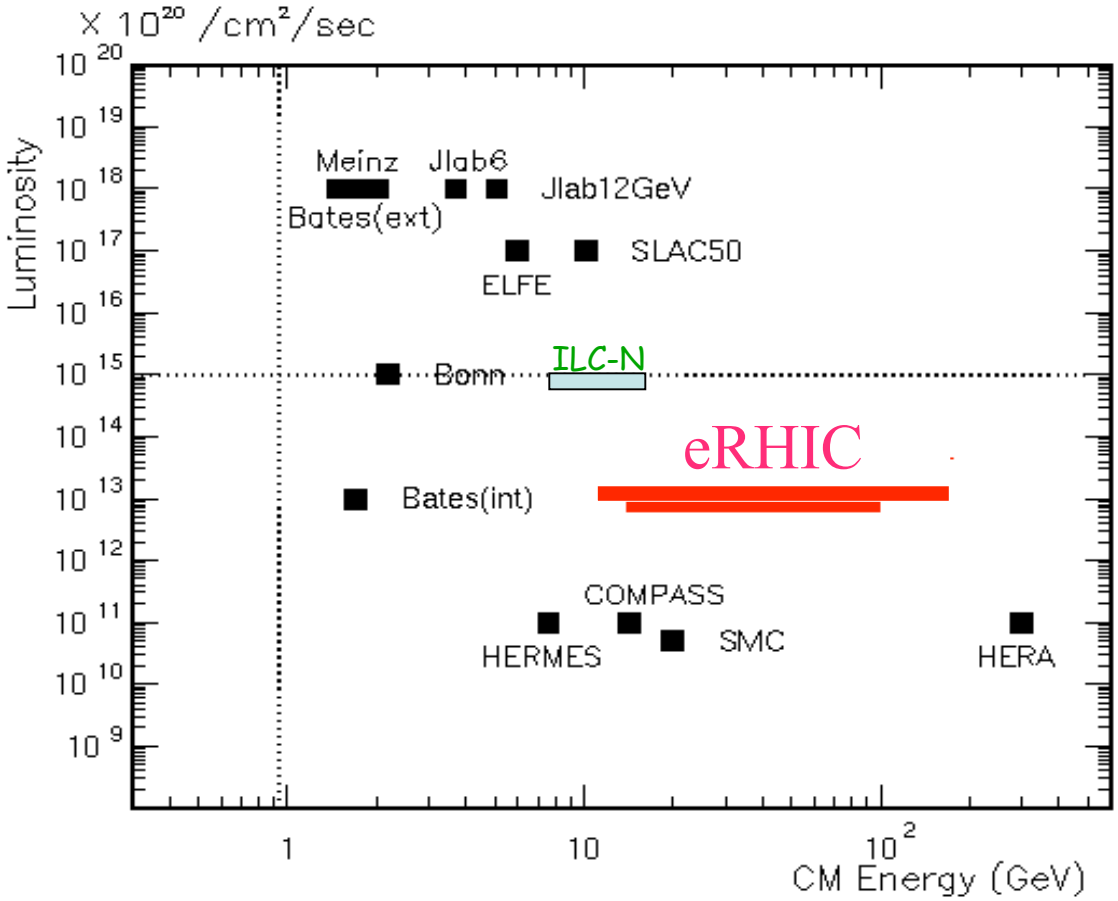
x = 10^{-4} → 0.6

Q^2 = 0 → 10^4 GeV

High Luminosity

L ~10^{33} cm^{-2} sec^{-1}(100 times HERA)

eRHIC vs. Other DIS Facilities (II)



Variable beam energy

Variable hadron species

Hadron beam polarization

Large luminosity

Scientific Frontiers Open to eRHIC

- Nucleon Structure: **polarized & unpolarized e-p/n scattering**

  -- Role of quarks and gluons in the nucleon: unpolarized quark & gluon distributions

  -- Spin structure: polarized quark & gluon distributions

  -- Correlation between partons ➔ hard exclusive processes leading to Generalized Parton Distributions (GPD's)

- Nuclear structure: **unpolarized e-A scattering**

  -- Role of quarks and gluons in nuclei

  -- e-p vs. e-A physics in comparison

- Hadronization in nucleons and nuclei & effect of nuclear media

  -- How do partons knocked out of nucleon in DIS evolve in to colorless hadrons?

- Partonic matter under extreme conditions

  -- e-A vs. e-p scattering; study as a function of A

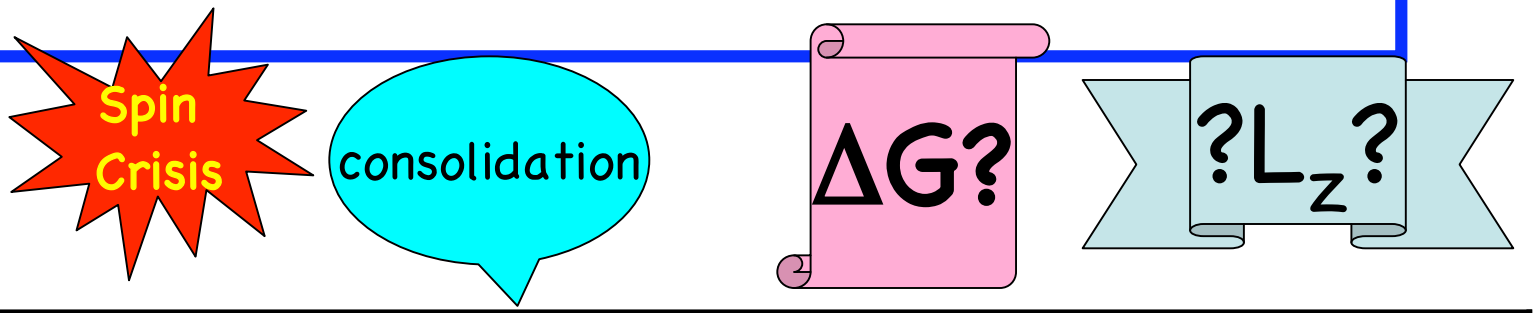
Polarized DIS at eRHIC

- Spin structure functions g_1 (p,n) at low x (10^{-4}), high precision
  -- g_1(p-n): Spin sum rule better than 1% accuracy
- Polarized gluon distribution function $\Delta G(x,Q^2)$
  -- at least three different experimental methods
- Polarized structure function of the photon from photo-production
- Electroweak structure function g_5 via $W^{+/-}$ production
- Precision measurement of a_S(Q2) from g_1 scaling violations
- Flavor separation of PDFs through semi-inclusive DIS
- Deeply Virtual Compton Scattering (DVCS) → Gerneralized Parton Distributions (GPDs)
- Transversity
- Drell-Hern-Gerasimov spin sum rule test at high n
- Target/Current fragmentation studies
- … etc….

Concluding Remarks

- **The Nucleon Spin is now a puzzle not a crisis**
  - With the development of QCD in the last few years and that expected in near future, we may be able to understand the Nucleon Spin Algebra better!
- **Expect first answers in the next few years from polarized RHIC**
  - Many other interesting investigations will occur simultaneously at RHIC in which we (Stony Brook) will be heavily involved and lead
- **Precision measurements will have to wait until the construction of eRHIC in the next decade**
- **Will it really solve the puzzle or create another crisis?**
  - Lets wait and see…

Future of "Nucleon Spin"



Year --> Experiments	Pre-1980s & 1980s…	1990s	2000s	2010s	2020s
Fixed target	Yale-Slac EMC-CERN, E704	SMC SLAC HERMES	HERMES, COMPASS	Jlab-12	TESLA-N (?)
Collider p-p			RHIC-Spin →		Pol. LHC (?)
Collider e-p				eRHIC(?) →	ELIC(?)

When I grow up.. Will I have a job?

Investigating Nucleon Spin:
Is this all just academic interest?

Nothing wrong with it, but…
this story has a different ending

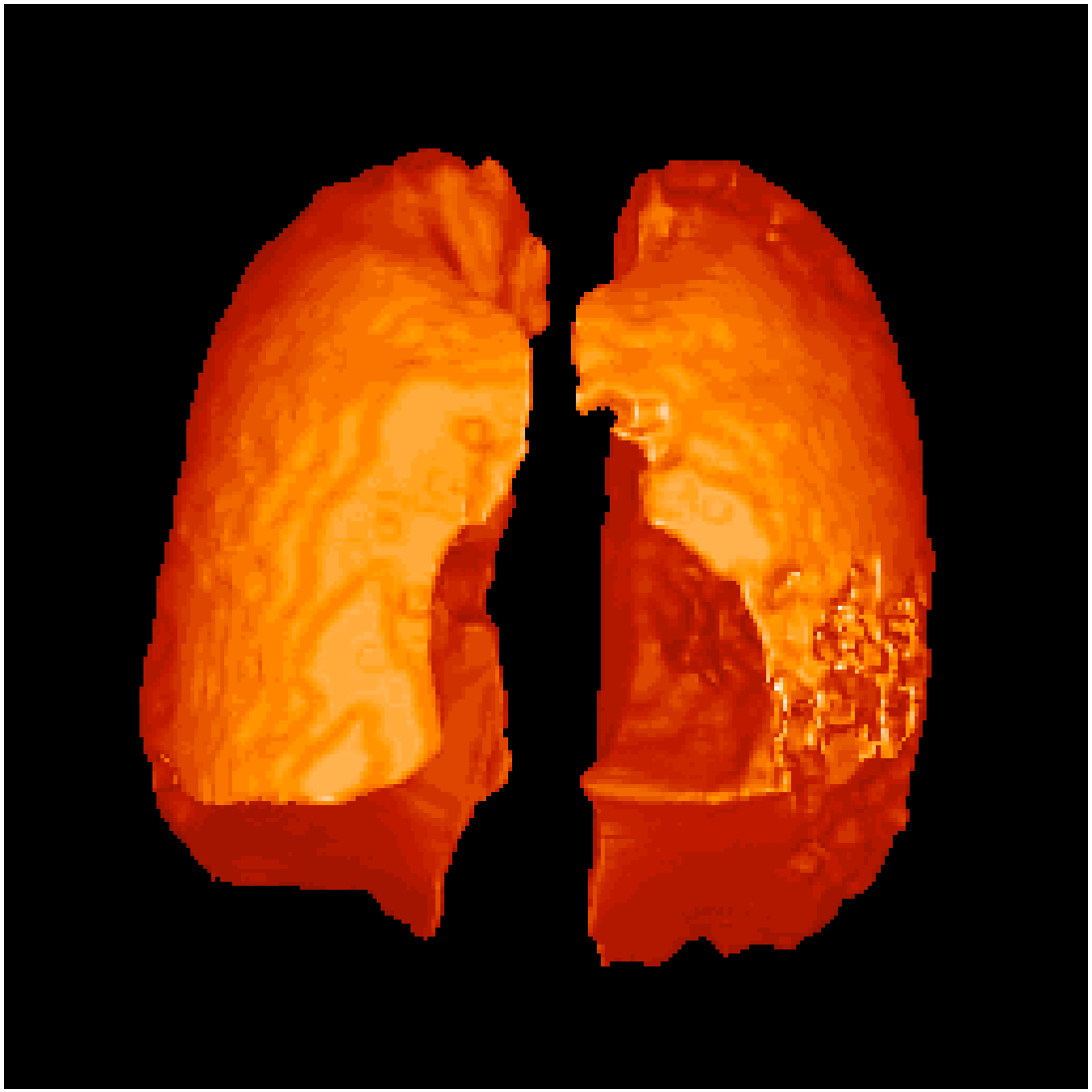
Answer is "NO"

Study of neutrons leads to…

- **What is a neutron rich element that can be (relatively) easily polarized?**
  - ^{3}He (Helium) nucleus: has 2 protons and 1 neutron
  - Two proton spins align opposite and we make measurements of the lone "neutron"
- **Helium is an inert gas, and for our experiments, polarized Helium needed to be produced in abundance (~1 ltr/day)**

- **Why not ask patients to inhale polarized ^{3}He? An MRI of the inhaled He would give us information on the medical conditions of the lungs!**
  - "Seeing" lungs is very very difficult, they are hollow and dry. Normal MRIs require water/hydrogen to create the signal

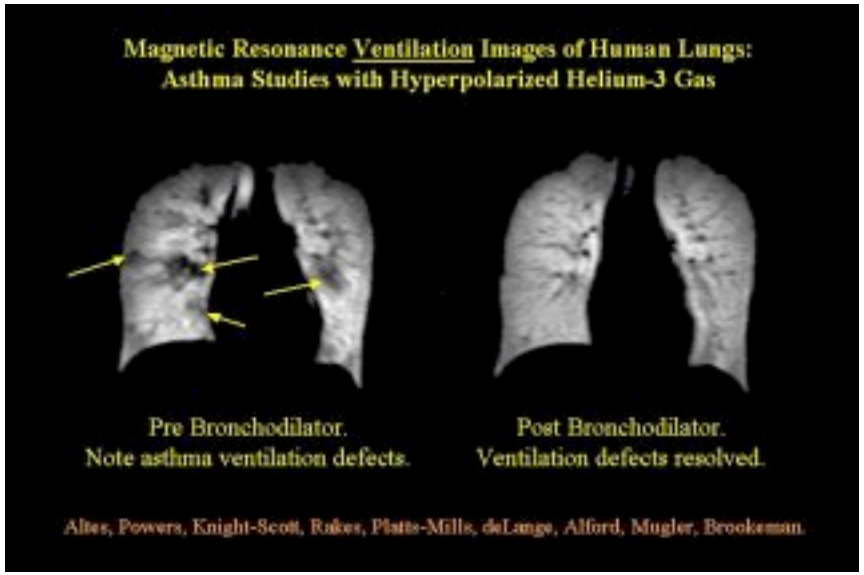
Human Lungs using ^{3}He MRI

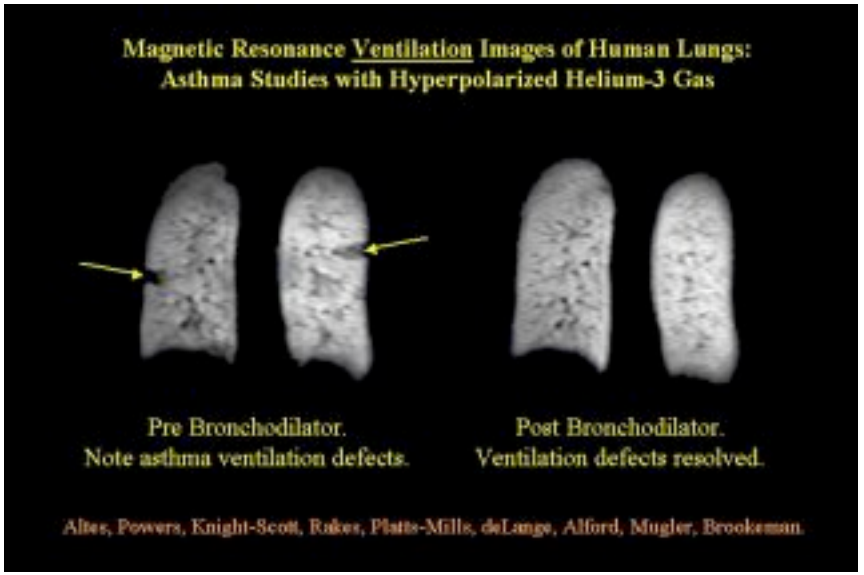


Resolution improved from 2 cm to ~0.1 cm

Princeton
Stony Brook
U. Of Virginia
Caltech

Detects Asthma before Symptoms!





U. Of Virginia

Presently an experimental technique but shows high potential.
Due to the relative difficulty with the supply of ^{3}He,
Xenon is being tried. Times scales: 3-7 yrs.