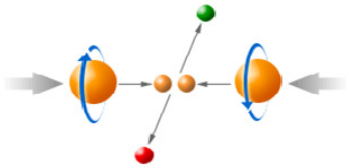
Acknowledgement

Thank to the ACFA/IPAC'10 Organizing Committee, and ACFA/IPAC'10 Accelerator Prize Committee for this prestigious prize

Also my deep appreciations to my mentors:

Prof. S. Y. Lee from Indiana University, Dr. T. Roser from BNL, Dr. M. Syphers from FNAL and Prof. Y. Pei from University of Science & Technology of China



Accelerating Polarized Protons to High Energy

Mei Bai

Collider Accelerator Department
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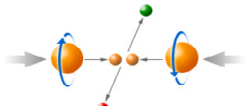


Outline

- **Challenges in accelerating polarized protons to high energy**
  - Depolarizing mechanism in synchrotron
  - Novel techniques in overcoming spin resonances
- **RHIC: the first polarized proton collider**
  - A long journey of $P^{\uparrow}$ development in the AGS
- **Why high energy polarized protons?**

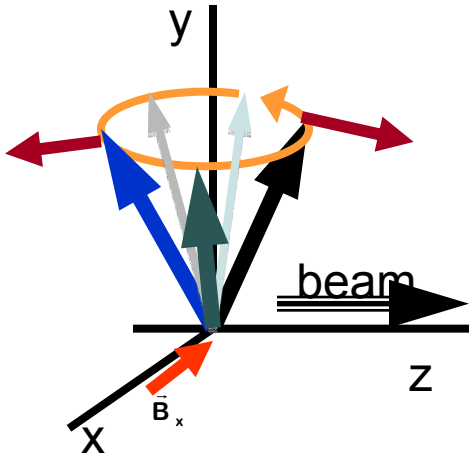
Spin motion in a circular accelerator

- Thomas BMT equation

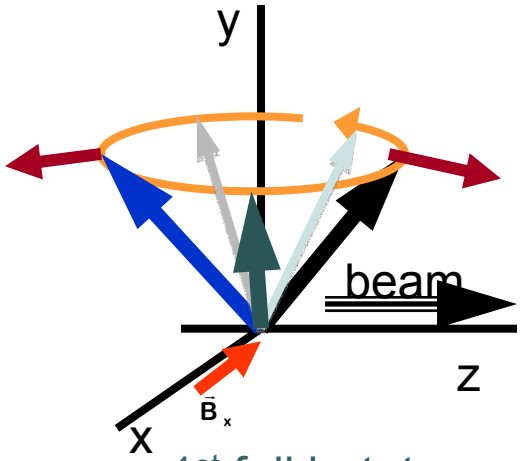
$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m}[G\gamma \vec{B}_y + G\gamma \vec{B}_x + (1+G)\vec{B}_s] \times \vec{S}$$

Spin tune $Q_s = G\gamma$

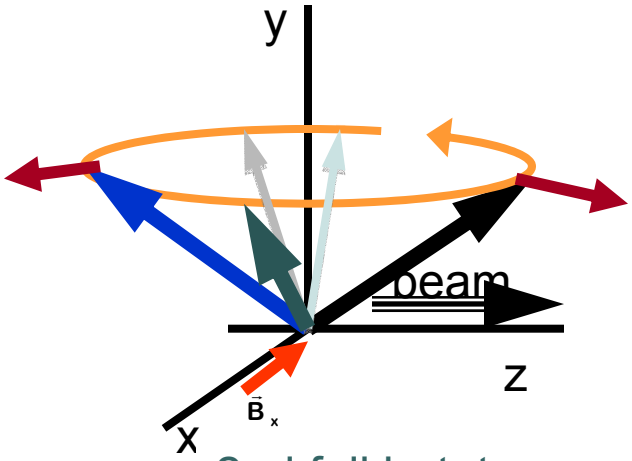
- Non-vertical field kicks the spin vector away from vertical,
  - depolarizing resonance



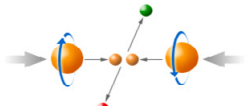
Initial



1st full betatron Oscillation period



2nd full betatron Oscillation period



Depolarizing spin resonances

Imperfection resonance

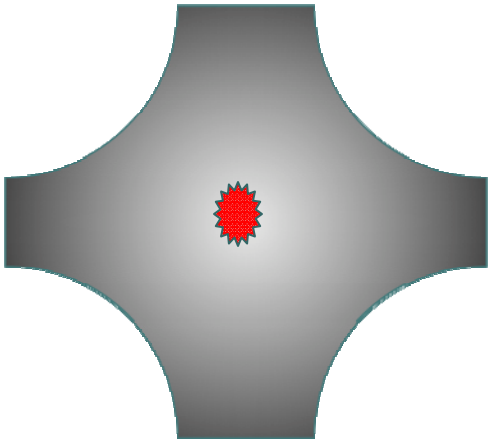
- dipole errors, steering correctors and mis-aligned quadrupoles
- location: $G\gamma = k$
- resonance strength: ~ size of the vertical closed orbit distortion
- correction:
  - harmonic orbit correction
  - partial snake

Intrinsic resonance

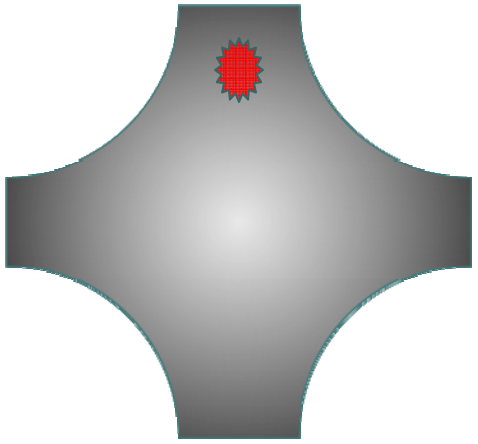
- focusing field due to vertical betatron oscillation
- location: $G\gamma = kP \pm Q_y$
- resonance strength: ~ size of the vertical betatron oscillation
- correction:
  - tune jump
  - RF dipole

Overcome Intrinsic Resonance w. RF Dipole

- Adiabatically induces a vertical coherent betatron oscillation
  - Drive all particles to large amplitude to enhance the resonance strength
    - full spin flip with normal resonance crossing rate
  - Easy to control and avoid emittance blowup
  - Employed for the AGS polarized proton operation from 1998-2005



w.o. coherent oscillation

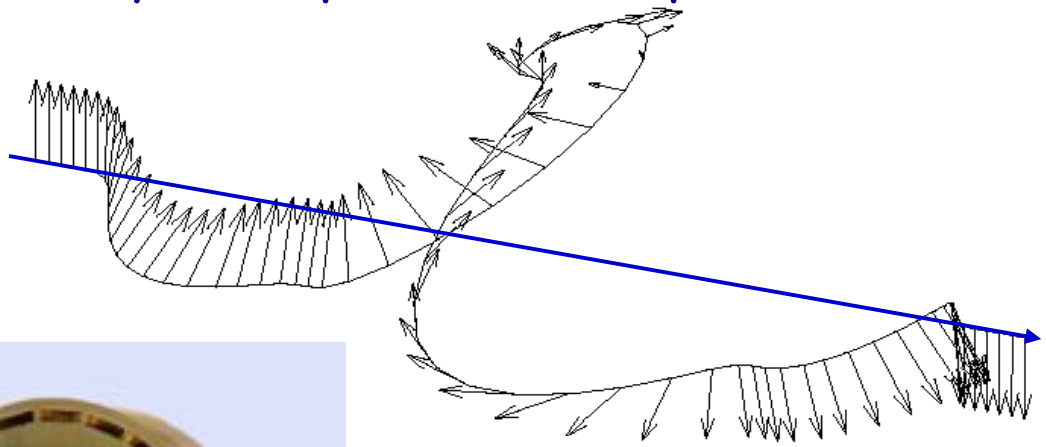


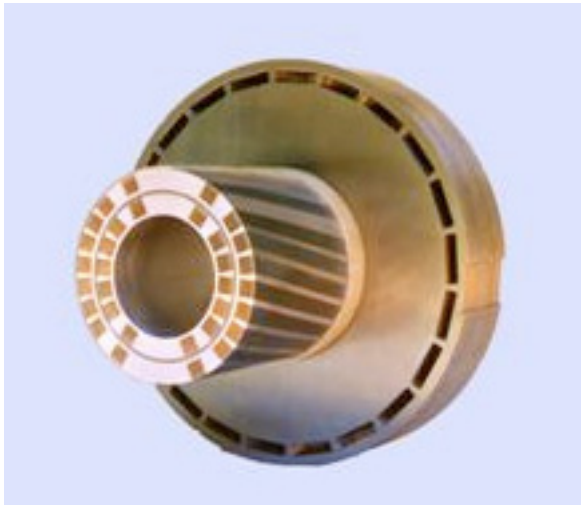
With coherent oscillation

- Can only be applied to strong intrinsic spin resonances

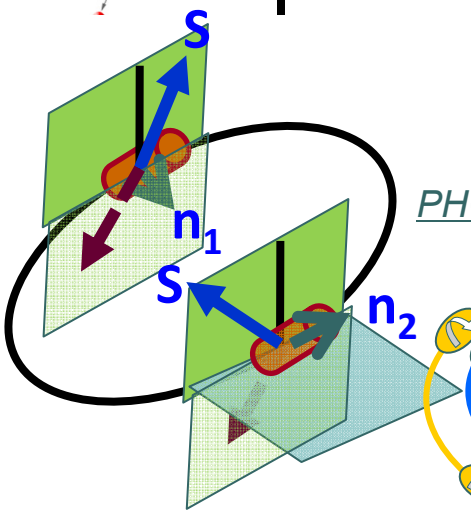
Full Siberian Snake

- A magnetic device to rotate spin vector by 180°
- Invented by Derbenev and Kondratanko in 1970s
- Keep the spin tune independent of energy

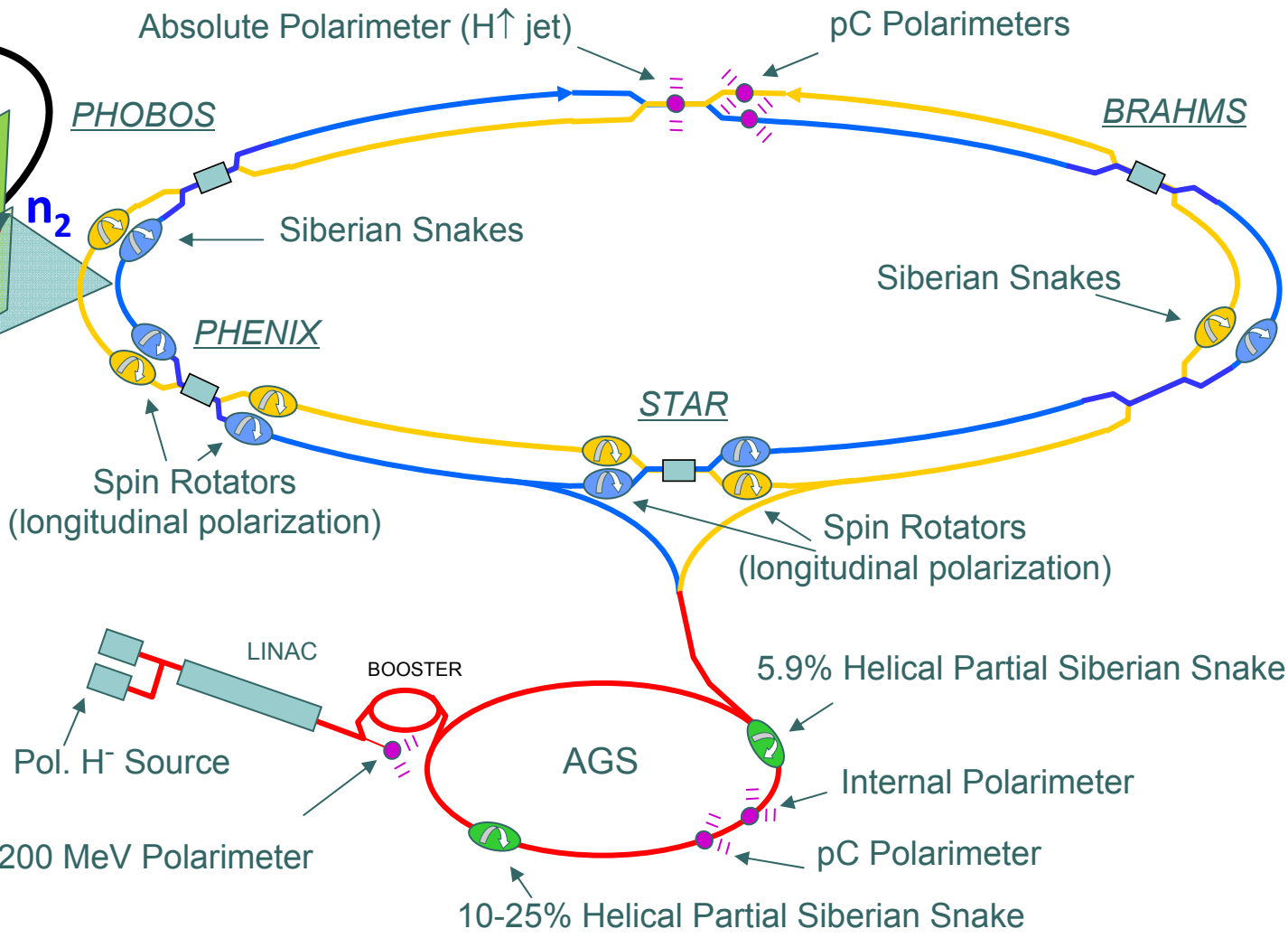




RHIC pp Configuration



$$Q_s = \frac{1}{2}$$



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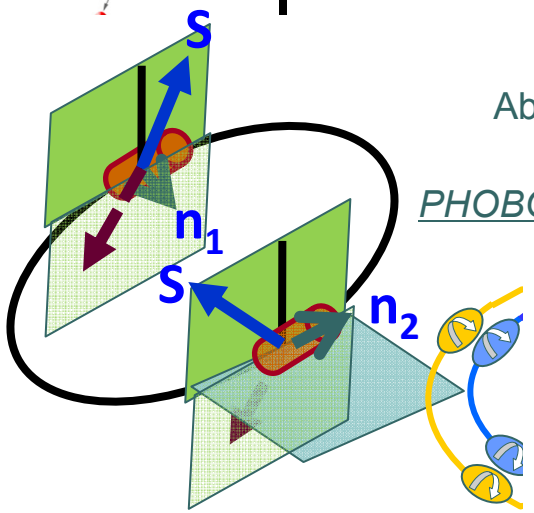
RHIC pp Configuration



Absolute Polarimeter (H↑ jet)

pC Polarimeters

PHOBOS

BRAHMS

~ 30 mins from source to top energy in RHIC

~ 30 years to reach RHIC injection energy !

$$Q_s = \frac{1}{2}$$

Spin Rotators
(longitudinal polarization)

Spin Rotators
(longitudinal polarization)

LINAC

BOOSTER

5.9% Helical Partial Siberian Snake

Pol. H^- Source

AGS

Internal Polarimeter

200 MeV Polarimeter

pC Polarimeter

10-25% Helical Partial Siberian Snake

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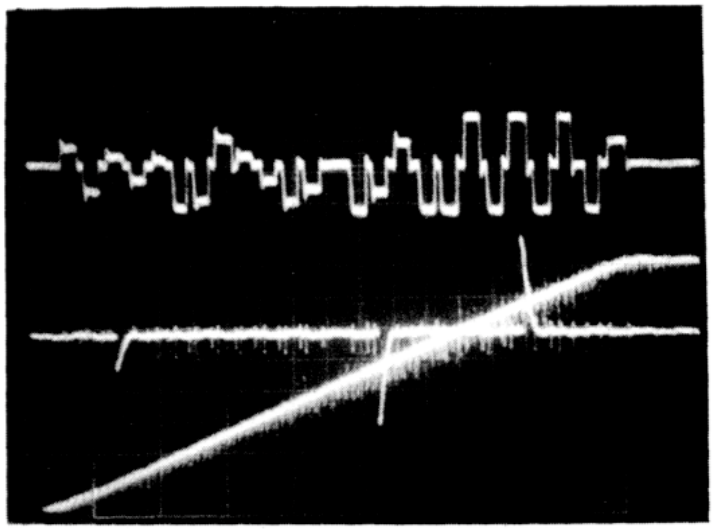
P⇧ development in the AGS

From T. Roser's presentation at A. Krisch Spin Physics Symposium, Nov, 2009

1980s

Alan Krisch and Larry Ratner in the AGS MCR.



Dipole corrector + Fast tune jump to overcome 45 resonance from injection to 22 GeV

~ 40% polarization at 22 GeV

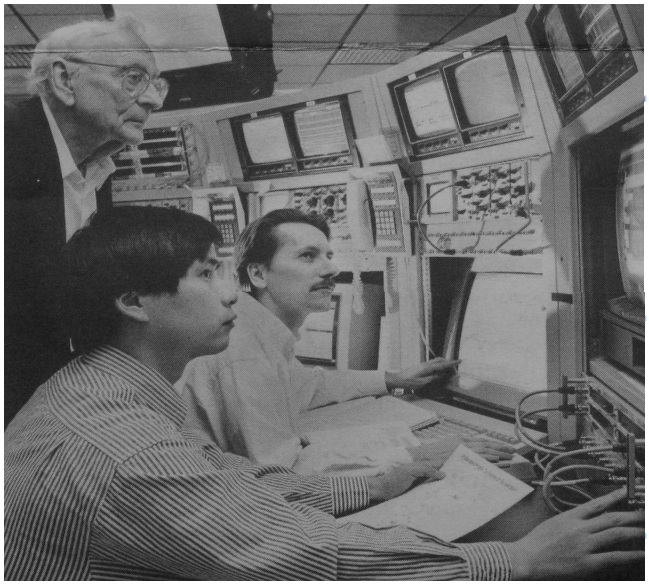
7 weeks dedicated time for setup

A. Krisch "Dr. Samios, Brookhaven's Director, visited me about once a week in the AGS control room to politely remind me that these studies were costing $1 Million a week."

P⇧ development in the AGS

From T. Roser's presentation at A. Krisch Spin Physics Symposium, Nov, 2009

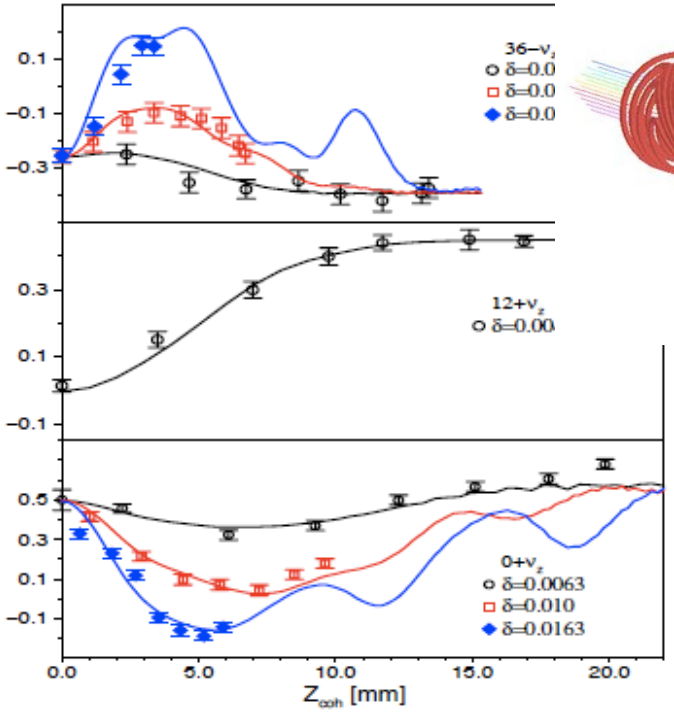
1990s



T. Roser, H.Huang and L. Ratner in the AGS MCR.

One 5% solenoid partial snake

1998 - 2005

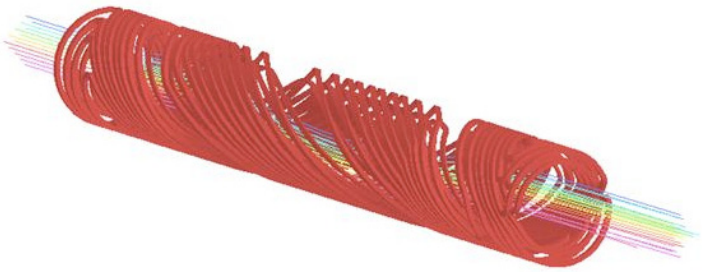


5% snake +RF dipole

~ 2 weeks setup parasitic to RHIC Ion program

50% at 24 GeV

2006 - now



6% warm helical snake +10% cold helical snake

~ 2 weeks setup parasitic to RHIC Ion program

60% at 24 GeV

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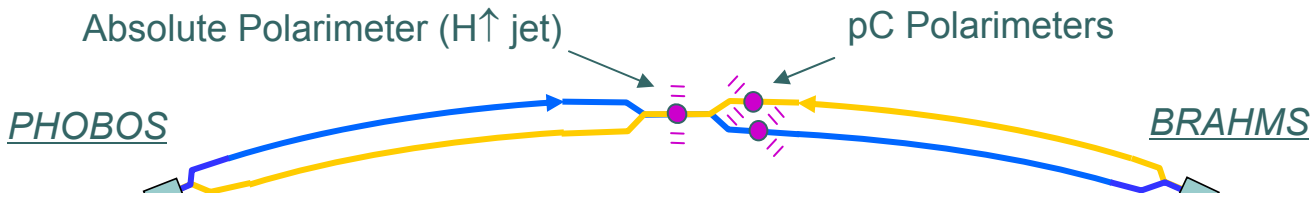
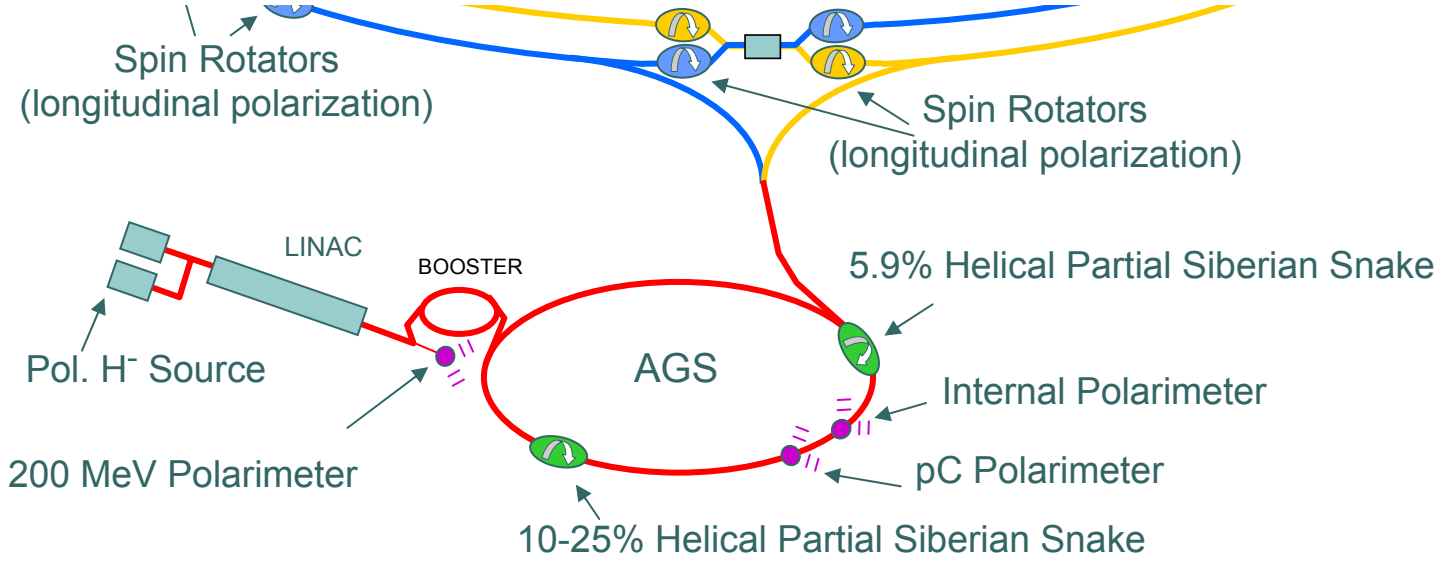
RHIC pp Configuration

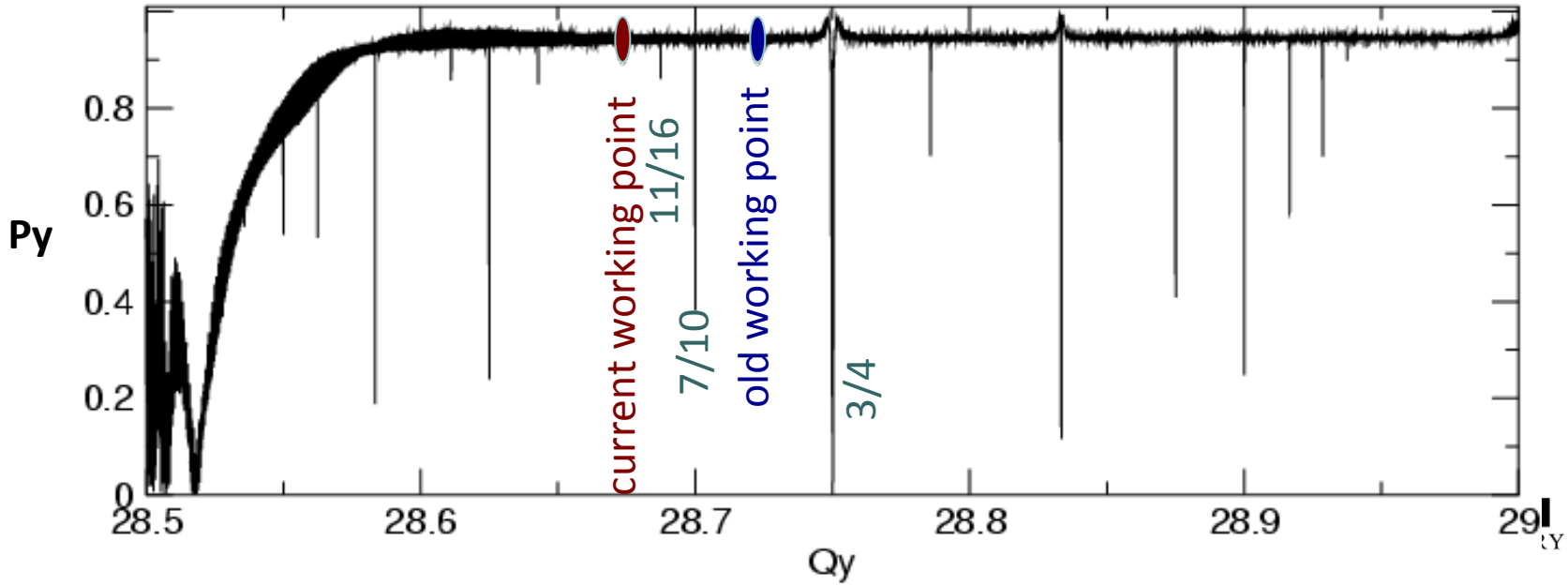


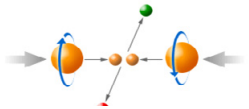
- **For protons, imperfection spin resonances are spaced by 523 MeV**
- **Between RHIC injection and 250 GeV, a total of 432 imperfection resonances**



Snake Depolarization Resonance

- Condition $mQ_y = Q_s + k$
- even order resonance
  - When m is an even number
  - Disappears in the two snake case like RHIC if the closed orbit is perfect
- odd order resonance
  - When m is an odd number
  - Driven by the intrinsic spin resonances





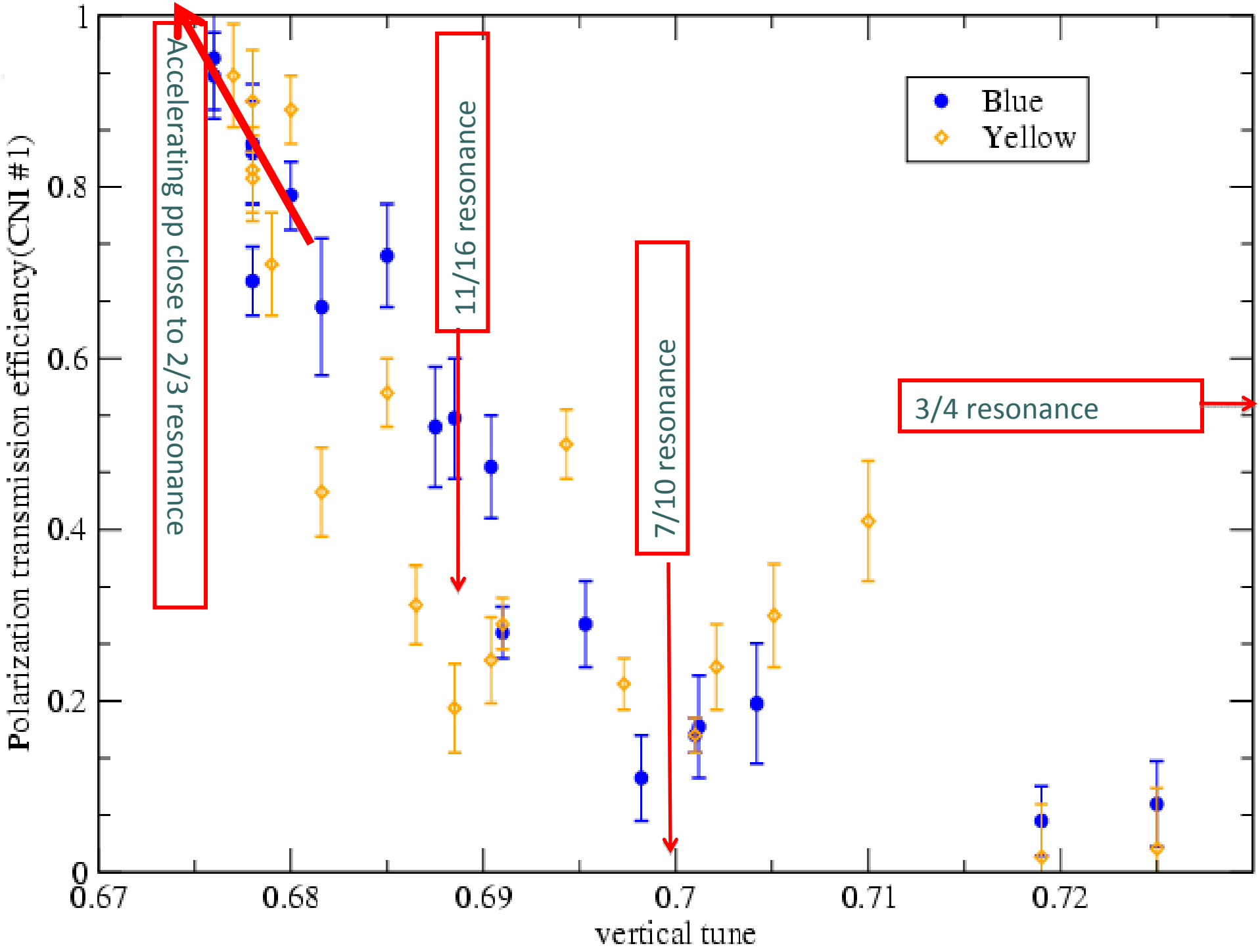
How to avoid a snake resonance?

- Keep spin tune as close to 0.5 as possible
  - Snake current setting
  - Minimize horizontal orbital angle between two snakes

$$\Delta Q_s = \frac{|\Delta\phi|}{\pi} + (1 + G\gamma)\frac{\Delta\theta}{\pi}$$

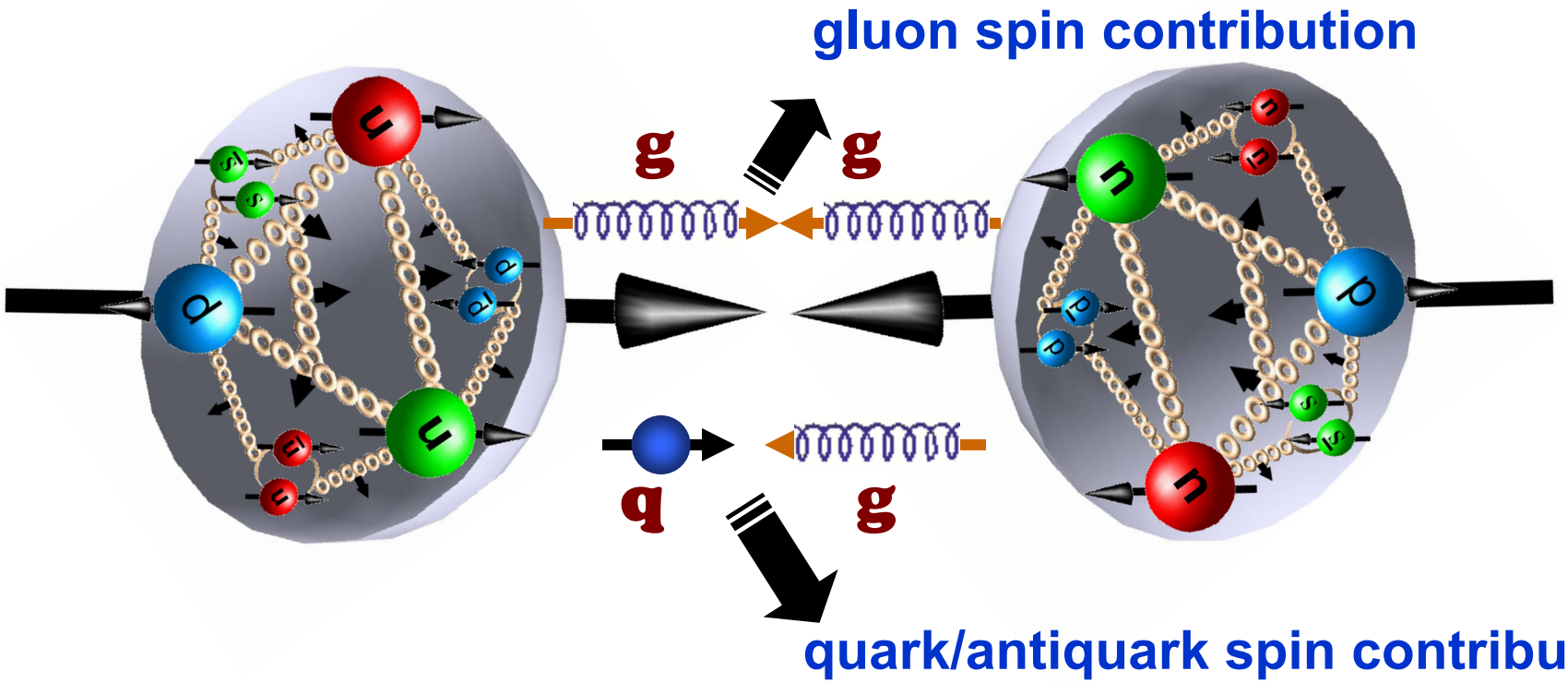
THPE054, V. Ptitsyn, M. Bai, T. Roser, *Spin Tune Dependence on Closed Orbit in RHIC*

- Precise control of the vertical closed orbit
- Precise optics control
  - Proper working point at a location with no or negligible snake resonances
  - Minimize the linear coupling to avoid the resonance due to horizontal betatron oscillation
  - Minimize spin tune spread


Polarization transmission efficiency(CNI #1)
vertical tune
Blue
Yellow
Accelerating pp close to 2/3 resonance
11/16 resonance
7/10 resonance
3/4 resonance
0
0.2
0.4
0.6
0.8
1
0.67
0.68
0.69
0.7
0.71
0.72

Why high energy polarized protons?

High energy proton proton collisions:
gluon gluon collision and gluon quark collision



$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

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An Incredible Team

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M. Okamura, F. Pilat, V. Ptitsyn
T. Roser, T. Satogata, V. Schoefer
D. N. Svirida, S. Tepikian
D. Trbojevic, N. Tsoupas,
J. Tuozzolo, A. Zelenski, K. Zeno
S.Y. Zhang and many others

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