Study of the Polarization Deterioration During Physics Stores in RHIC Polarized Proton Runs

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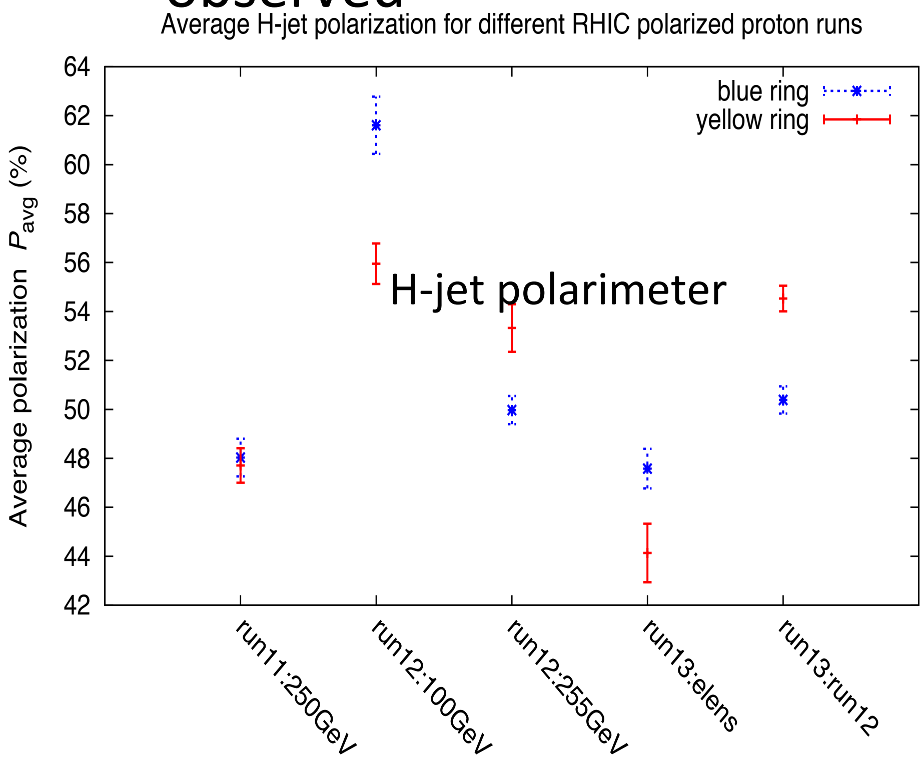
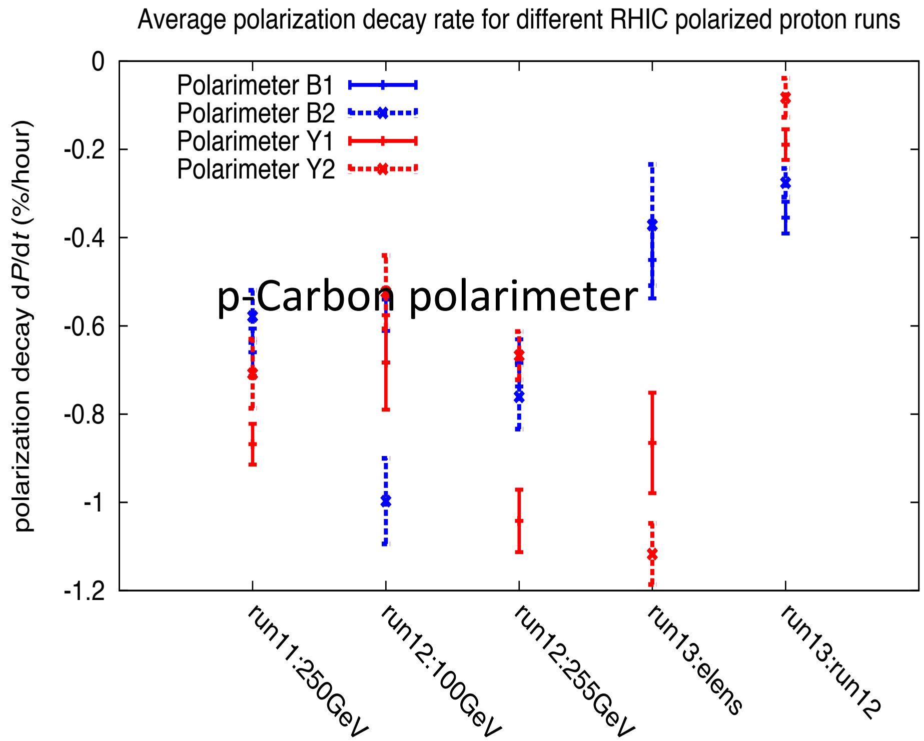
Outline

- Motivation
- Possible physical mechanisms
- RHIC data analysis
- Simulation progress
- Conclusion

Motivation

- Polarization deterioration was observed in RHIC during a typical polarized proton store for physics data taking[1]
- Significant improvement of polarization deterioration in the latest RHIC polarized proton operation in 2013 was also observed





[1] RHIC spin group website:http://www.phy.bnl.gov/cnipol/

Stable spin direction and polarization

- $\vec{n}(\vec{z},\theta)$ is the stable spin direction at phase space point $\vec{z}$ and azimuthal angle ϑ, and $\vec{n}(\vec{z},\theta+2\pi)=\vec{n}(\vec{z},\theta)$. It also satisfy Thomas BMT equation

$$\frac{d\vec{n}(\vec{z},\theta)}{d\theta} = \vec{\Omega}(\vec{z},\theta) \times \vec{n}(\vec{z},\theta)$$

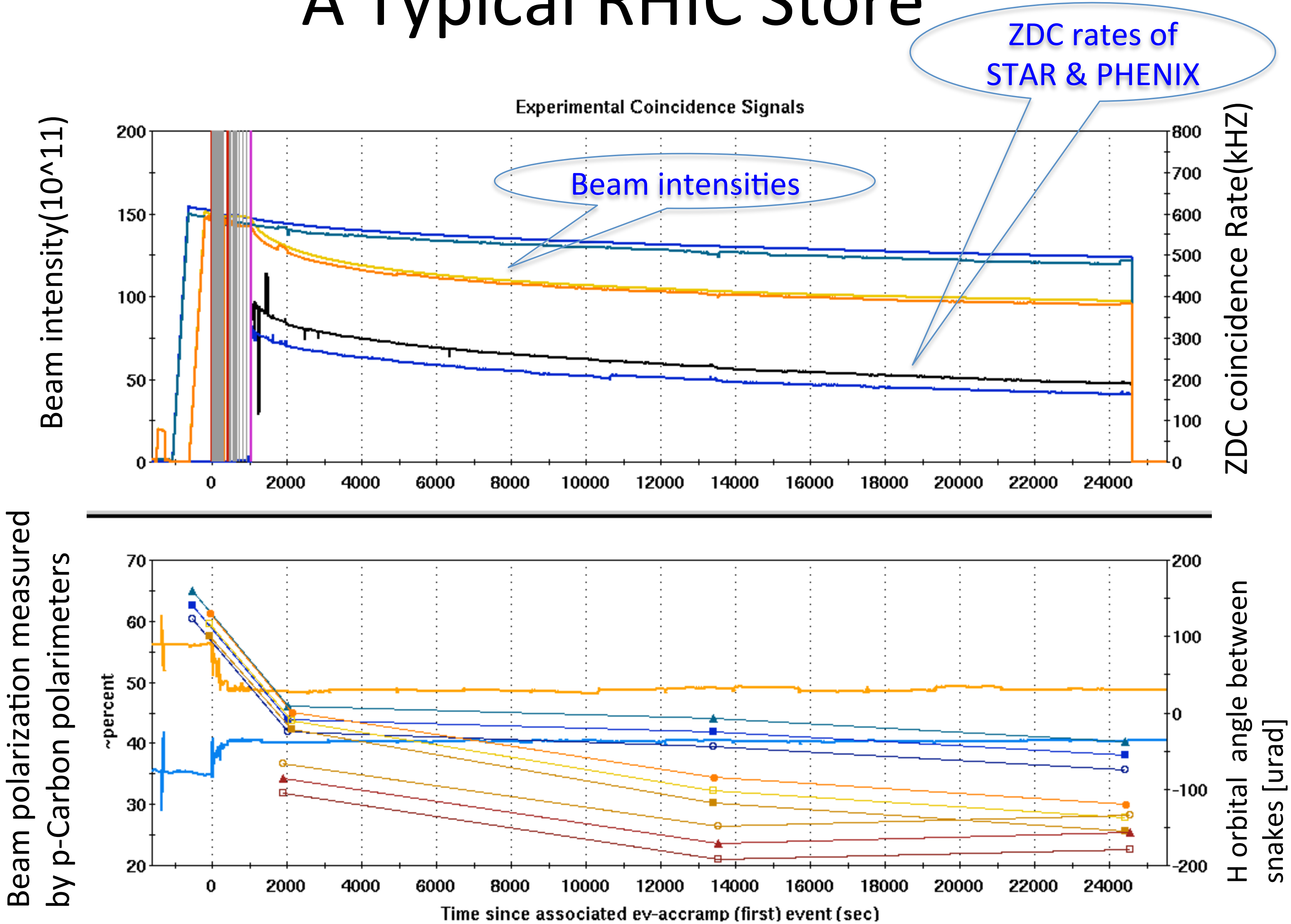
$$\vec{n}(\vec{z},\theta+2\pi) = \vec{n}(\vec{z},\theta)$$

- A polarimeter samples the particle spins in a beam for more than millions of turns. The measured beam polarization is then an average of the contribution from the beam particles, which is an average of the particle's turn-by-turn spin vectors over the duration of measurement. While each particle's turn-by-turn spin vectors average to its spin projection over the local $\vec{n}(\vec{z},\theta)$ in the long term. In the ideal case, if each particle spin is parallel to the local $\vec{n}(\vec{z},\theta)$, then the maximum achievable polarization is[1]

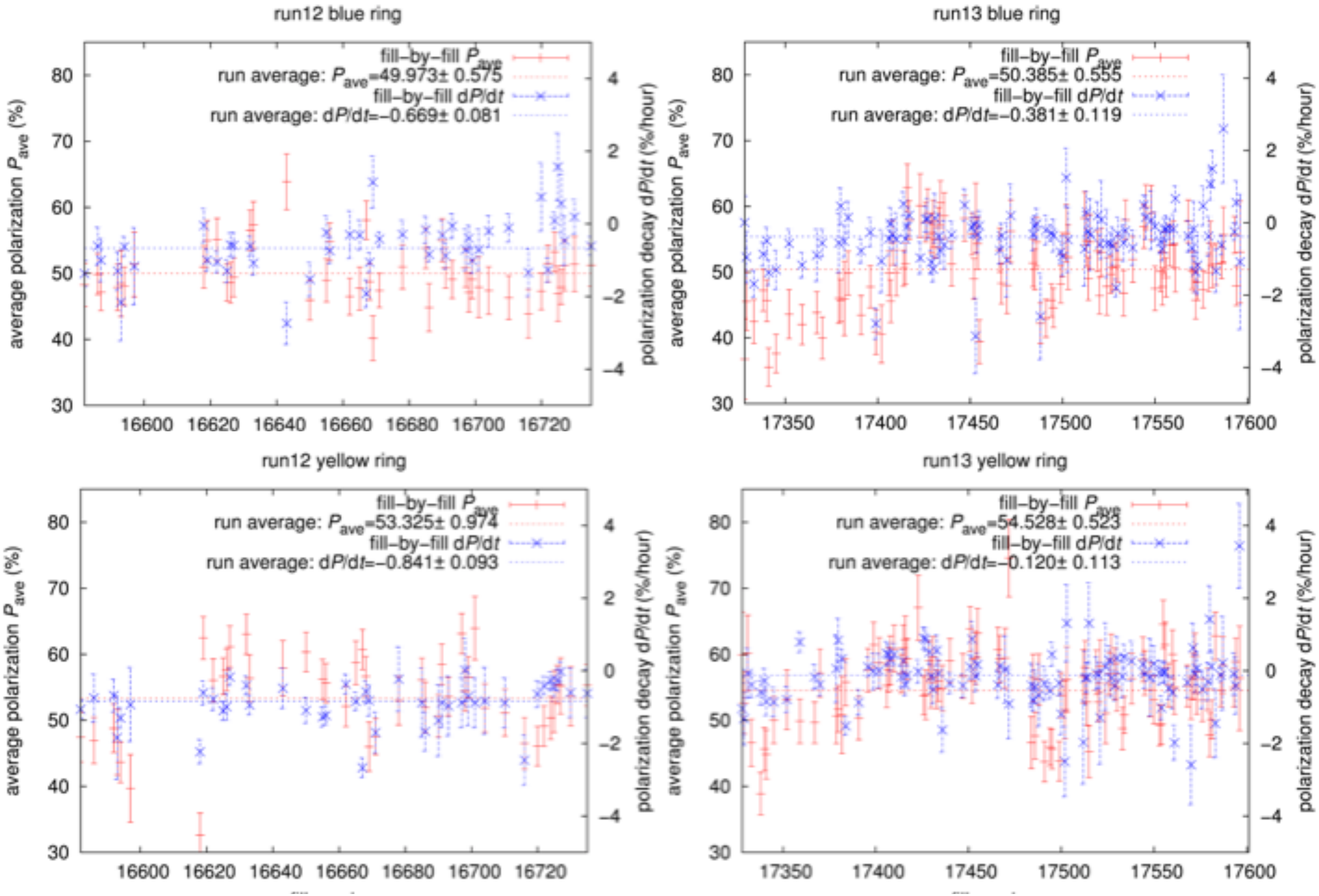
$$P_{\lim} = | < \vec{n}(\vec{z},\theta) >_{\vec{z}} |$$

[1] G. H. Hoffstaetter, High-energy polarized proton beams: A modern view, Springer Tracts Mod.Phys. 218, 2006

A Typical RHIC Store



Fill by fill average polarization and polarization decay rate



Possible Sources for Polarization Deterioration

- Depolarizing resonances in the presence of snakes

$$m \cdot \nu_y = \nu_s + k, \text{where } m, k \in \text{integer}$$

  - The major snake resonance for RHIC operation is 5-th order, $\nu_y = 0.7$
- Variation of the vicinity to the nearby resonance(s)
  - beam working point drift
  - beam-beam induced tune shift change
    - Beam-beam effect is expected to be weakened during collision
  - Spin tune change due to local orbit drift at snakes, as well as spin rotators around Ips
- spin tune spread induced by the difference between dispersion slope at the two snakes, as well as spin rotators

$$\Delta \nu_{spin} = G\gamma(\Delta p / p)\Delta D'$$

- Beam emittance growth due to beam-beam, high order orbital resonances, etc

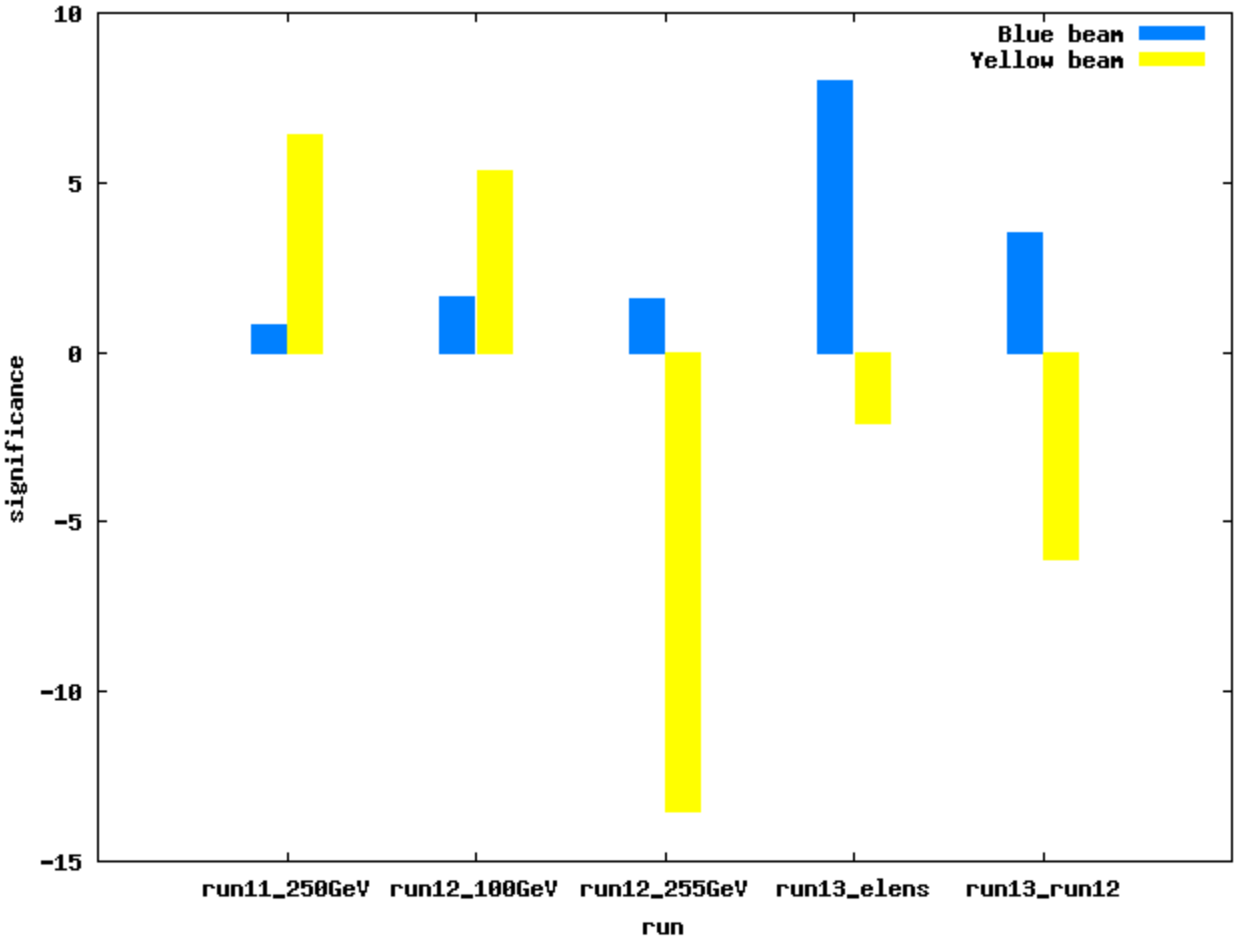
RHIC data analysis

- Comparison of Asymmetry for bunches with different number of collisions
  - In a typical RHIC fill, ~1/10 of RHIC bunches have 1 collision per revolution, while other have 2 for polarized proton runs
  - Data from pCarbon polarimeter were reanalyzed to compare the bunch-by-bunch asymmetry for bunches with single collision vs. the bunches with double collisions
  - To improve the statistics, statistically combined the asymmetry relative difference of bunches with similar conditions of all physics fills.

Define the relative difference of asymmetry as:

$$\delta = \frac{A_{\text{single}}}{A_{\text{double}}} - 1, \sigma_{\delta} = \frac{A_{\text{single}}}{A_{\text{double}}} \sqrt{\frac{\sigma^2_{A_{\text{single}}}}{A^2_{\text{single}}} + \frac{\sigma^2_{A_{\text{double}}}}{A^2_{\text{double}}}}$$

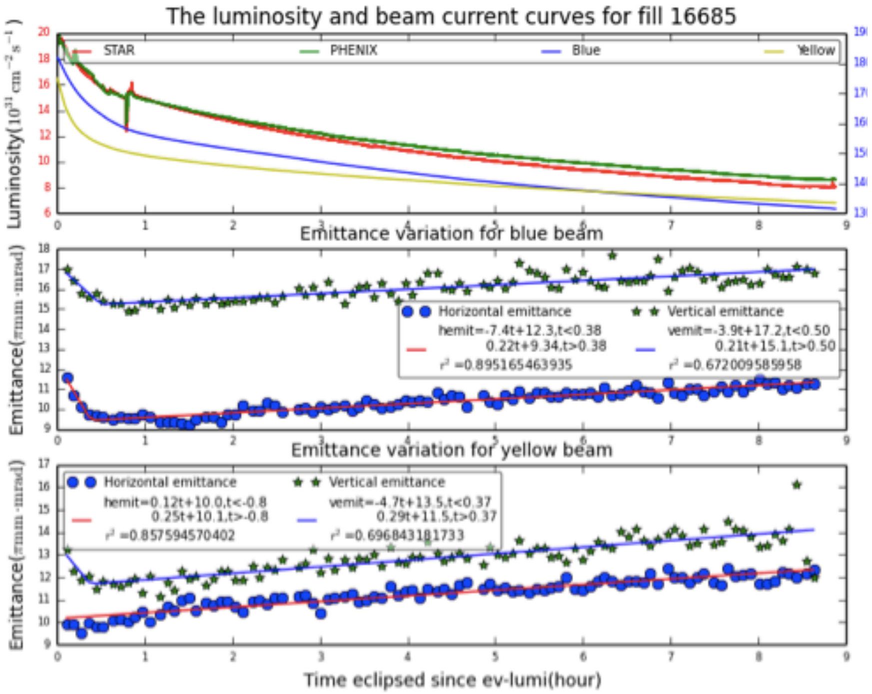
$$\text{Significance} = \frac{\delta}{\sigma_\delta}$$

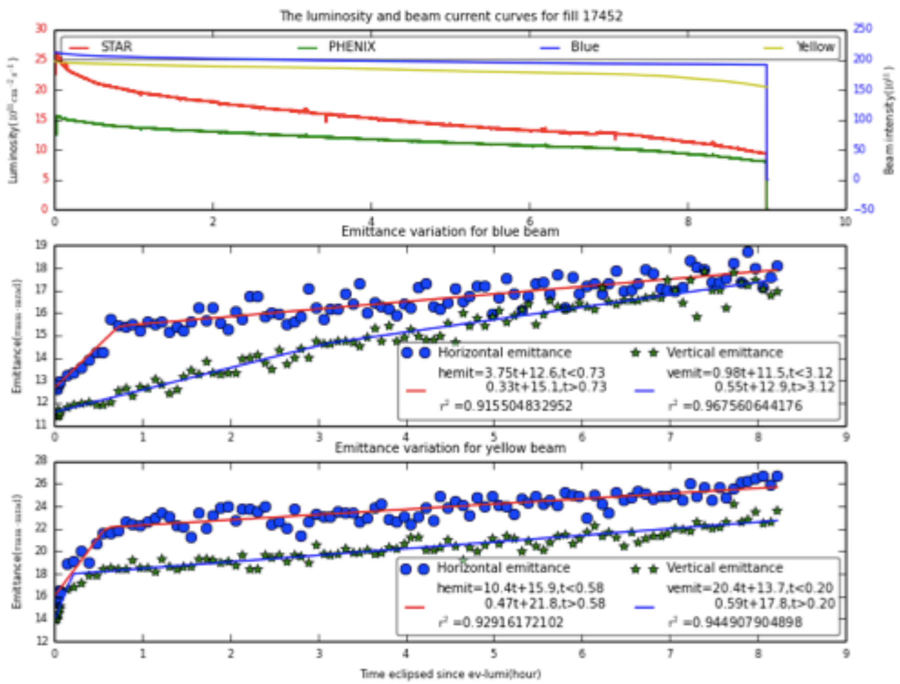


- There is no consistent conclusion among different runs and the two beam
- Current data strongly indicate that the direct beam-beam spin kick is not the dominating cause for the depolarization.

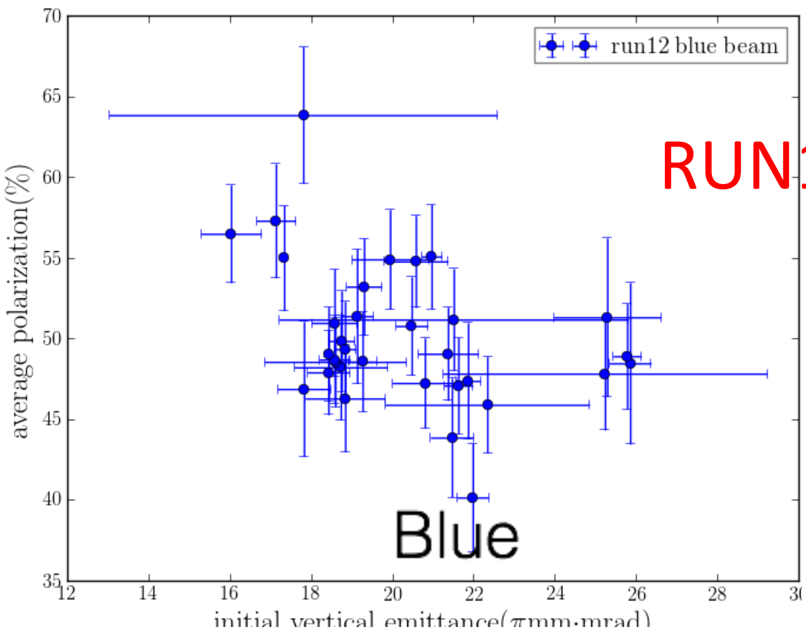
RHIC data analysis

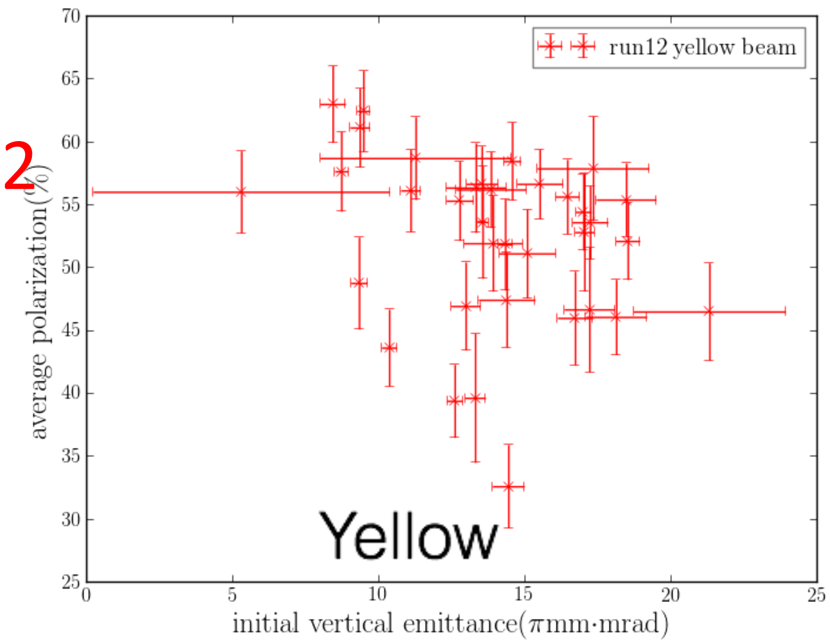
- Correlation of beam emittance vs. beam polarization
  - A piece-wise linear fit is applied to the beam emittance data for each fill measured by RHIC IPMs. The fill-by-fill fitted initial emittance, slopes are then correlated against the average polarization, as well as the polarization decay rate.
  - Comparison between run12 and run13 255GeV runs with the same lattice settings are made.



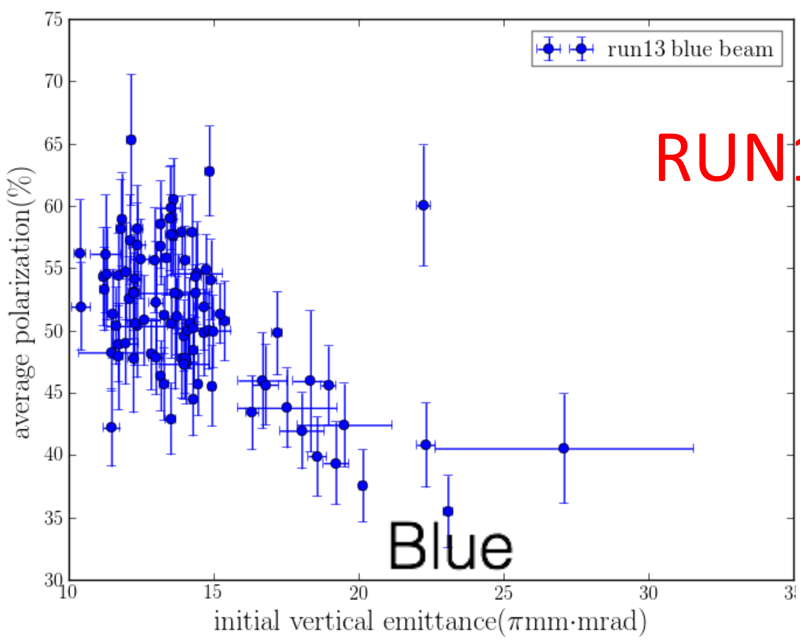


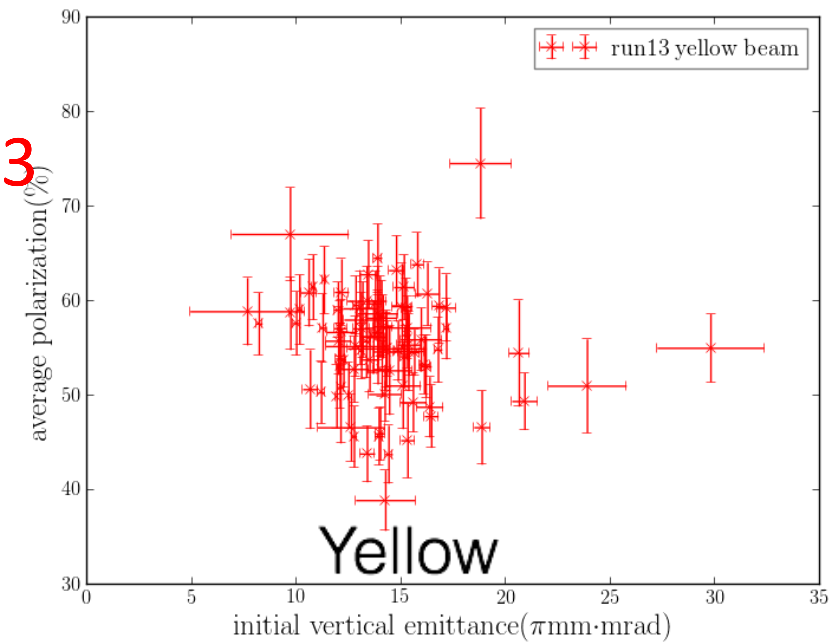
RUN12

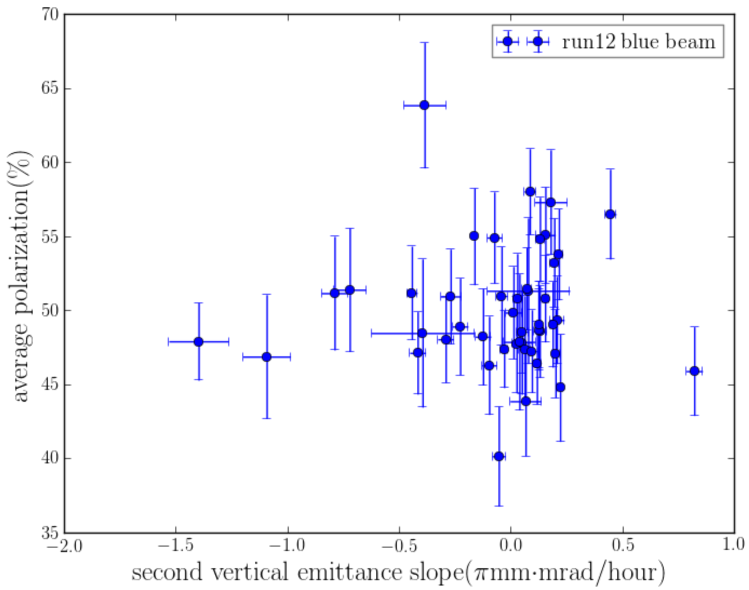

run12 blue beam
average polarization(%)
initial vertical emittance(πmm·mrad)
Blue


run12 yellow beam
average polarization(%)
initial vertical emittance(πmm·mrad)
Yellow

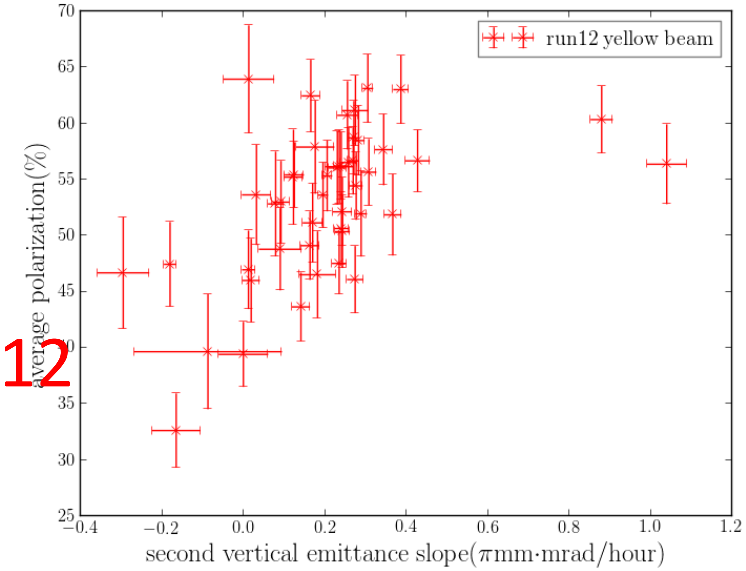
RUN13

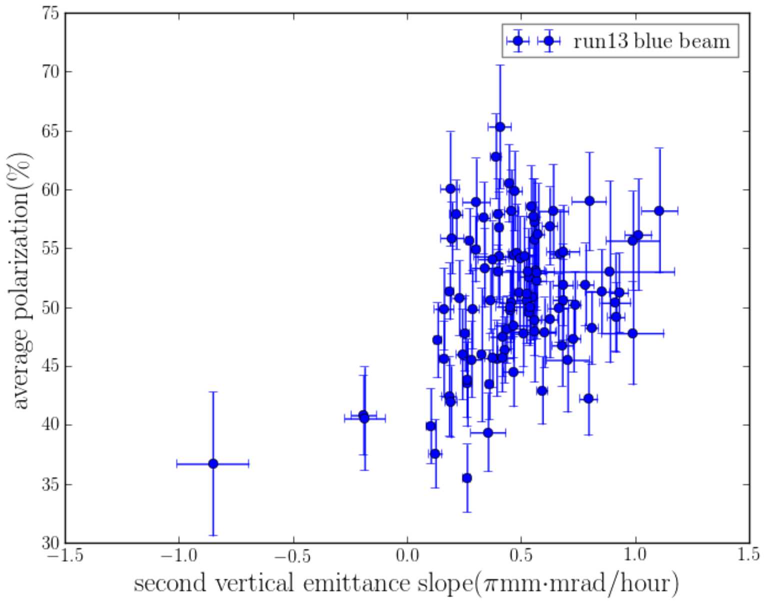

run13 blue beam
average polarization(%)
initial vertical emittance(πmm·mrad)
Blue


run13 yellow beam
average polarization(%)
initial vertical emittance(πmm·mrad)
Yellow

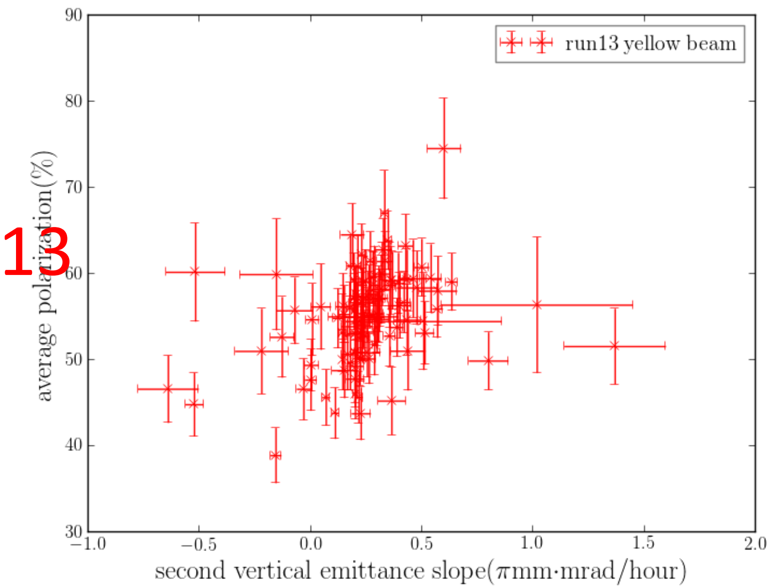

run12 blue beam
average polarization(%)
second vertical emittance slope(πmm·mrad/hour)

RUN12


run12 yellow beam
average polarization(%)
second vertical emittance slope(πmm·mrad/hour)


run13 blue beam
average polarization(%)
second vertical emittance slope(πmm·mrad/hour)

RUN13


run13 yellow beam
average polarization(%)
second vertical emittance slope(πmm·mrad/hour)

Spin tune shift in RHIC

- Source of spin tune shift from 0.5
  - Imperfection of helical dipole snakes
  - H orbital angle between the two snakes

$$\Delta\nu_{spin} = G\gamma\Delta\theta / \pi$$

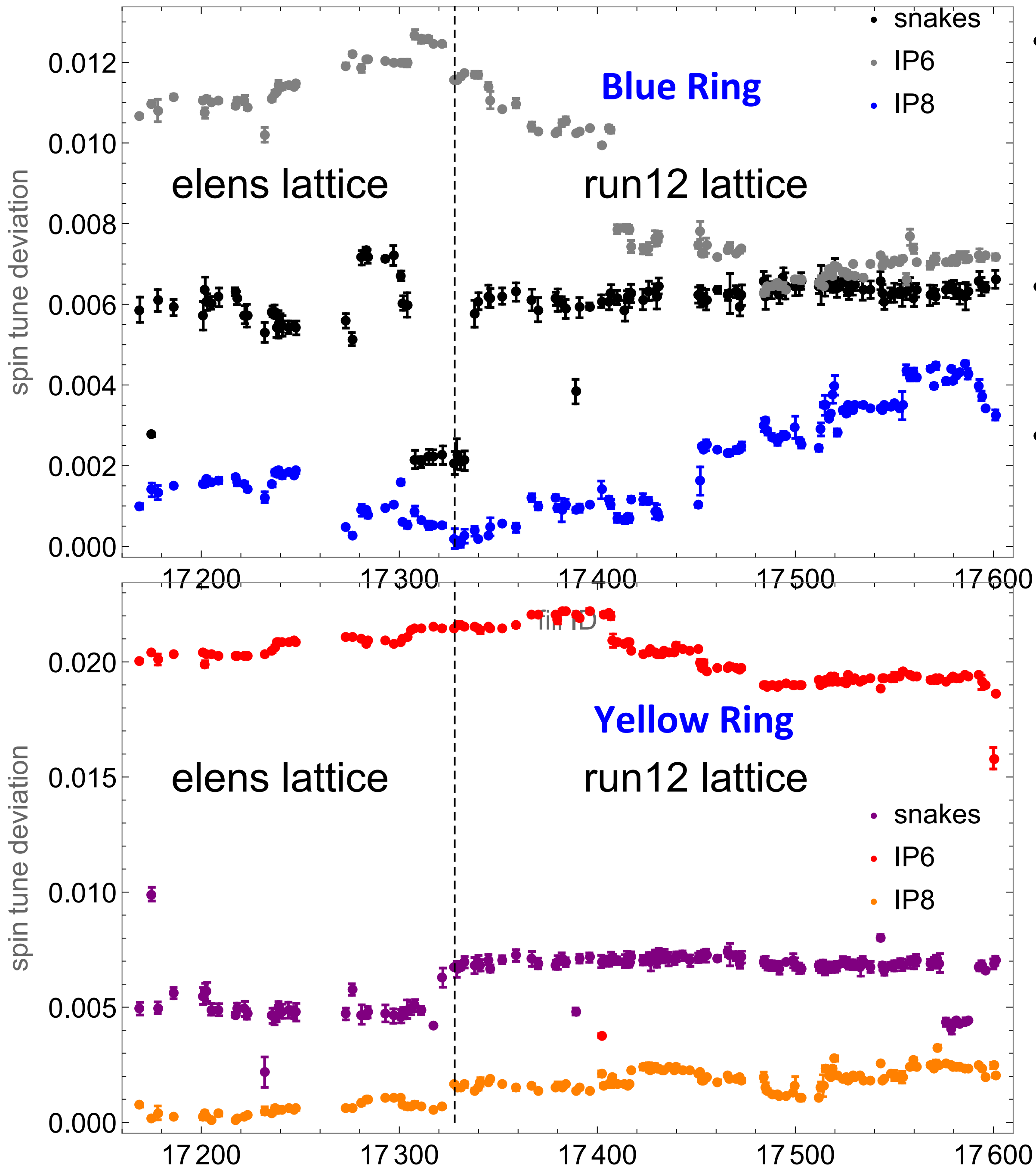
  - Local orbit at the spin rotators,

radial component of stable spin direction n_0 in the triplets

$$\Delta\nu_{spin} = G\gamma n_{x\_tr}\left(y'_{lrt} - y'_{rrt}\right) / 2\pi$$

Vertical closed orbit angles at the rotators

- For run13, longitudinal spin program, a 3mm orbit bump @IP6 introduces spin tune shift of ~0.013



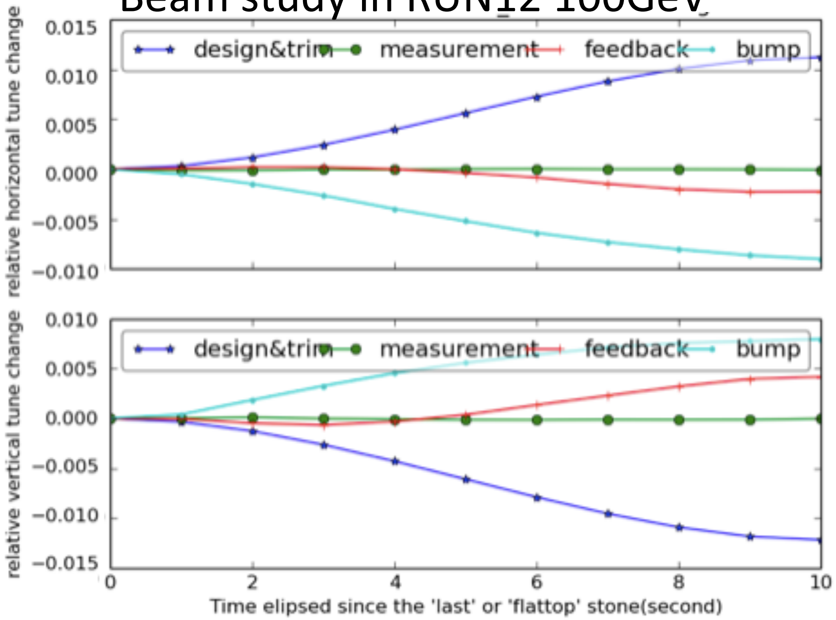
- Contribution to the spin tune deviation from the three sources are shown for RUN13. (Limited data for RUN12 due to missing data of some BPMs).
- ~0.005 max variation for each contribution

- Within the current RHIC polarization measured by H-Jet polarimeter statistics, no clear correlation between polarization decay rate verus spin tune deviation is seen

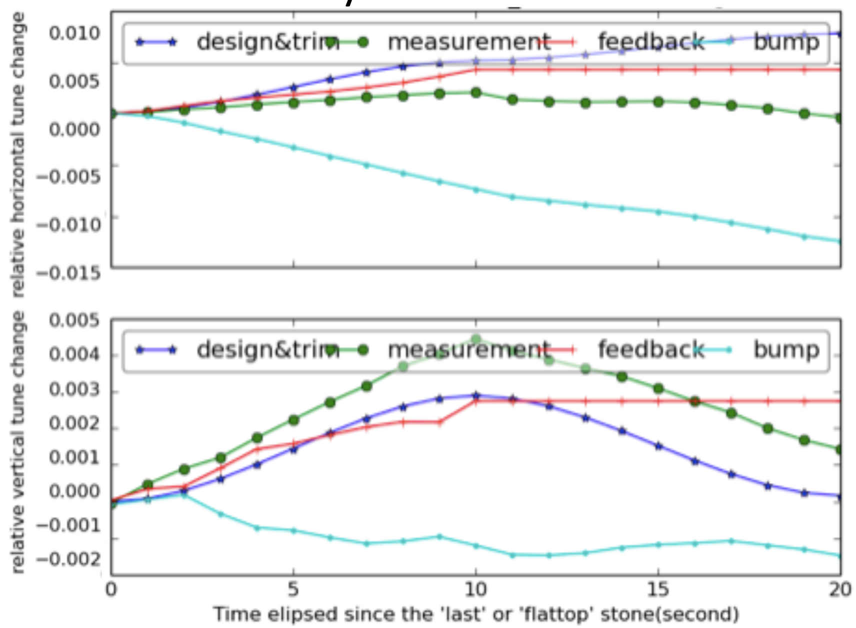
Correlation of polarization vs. working point

It is found that the working point at store in run13 255GeV is in general lower than that of run12 255GeV for vertical plane, because of different tune feedback settings towards end of rotator ramp & cogging into collision.

Beam study in RUN12 100GeV

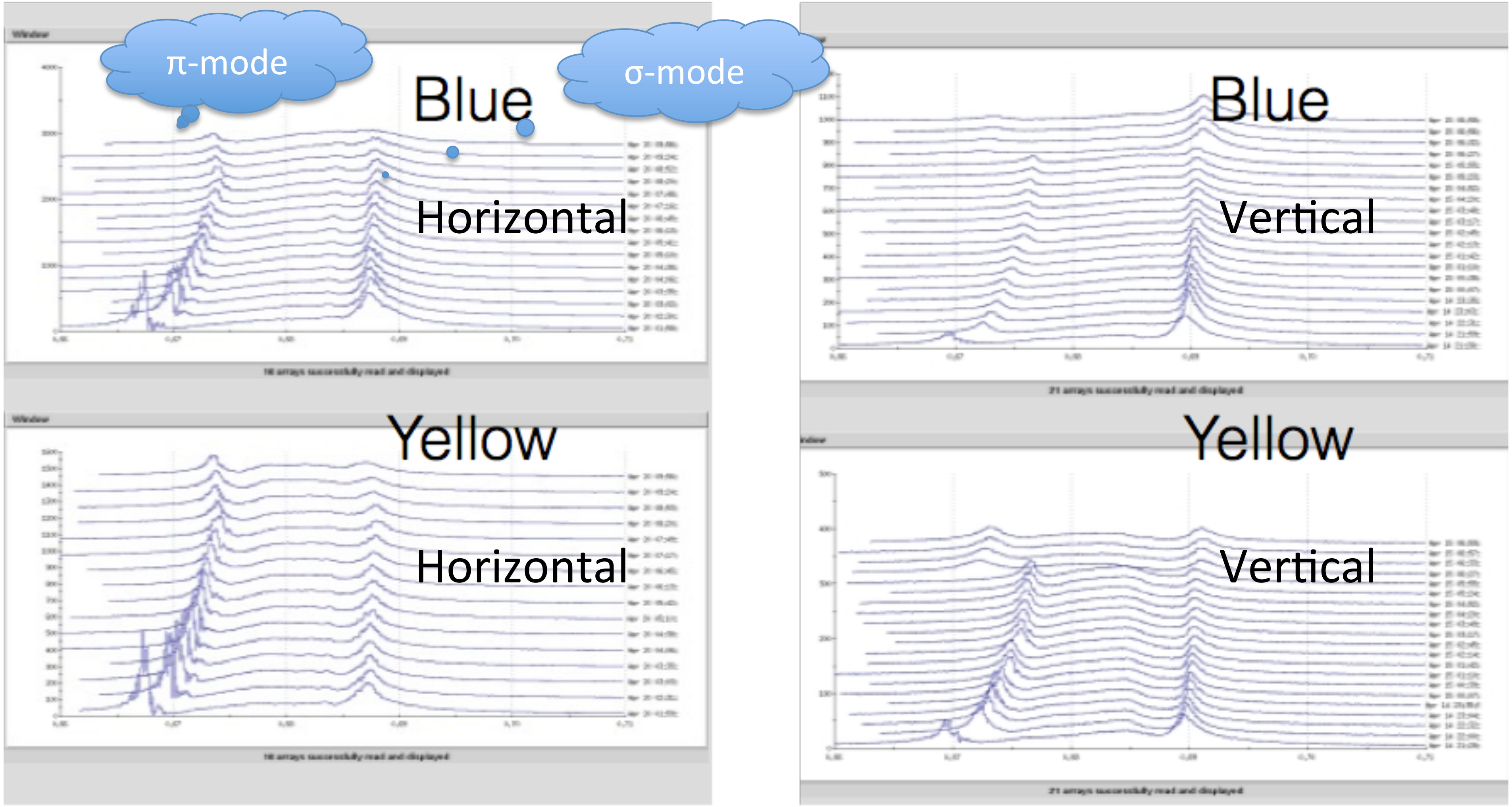


Beam study in RUN13 255GeV



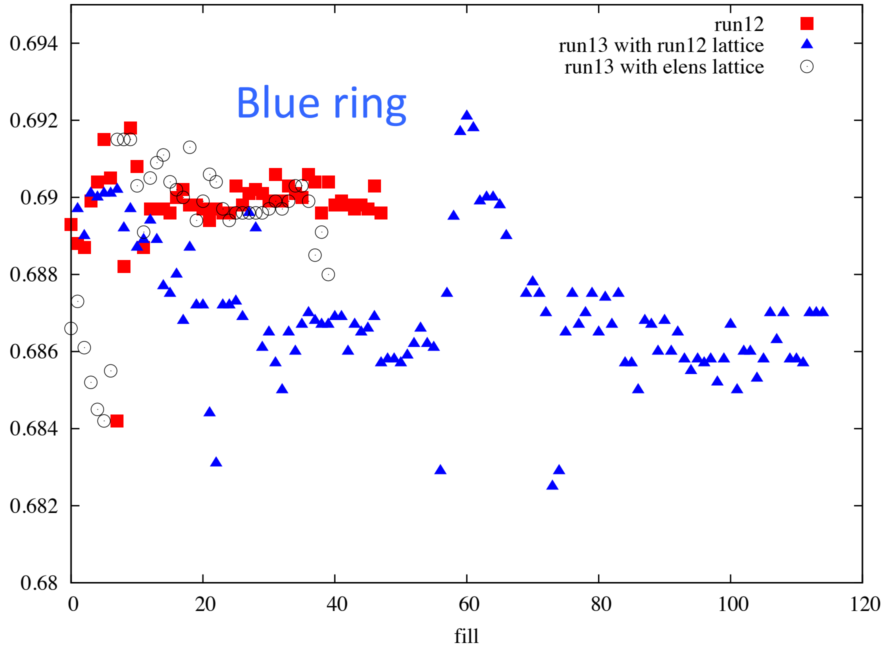
Beam Transfer Function (BTF) for typical fills

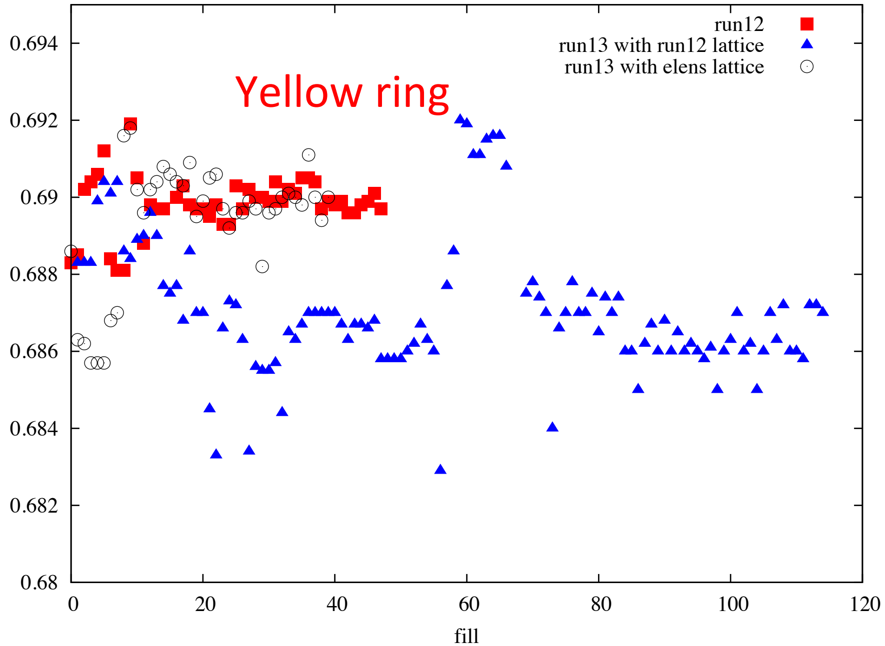
Fill 17406 run13 | Fill 16724 run12

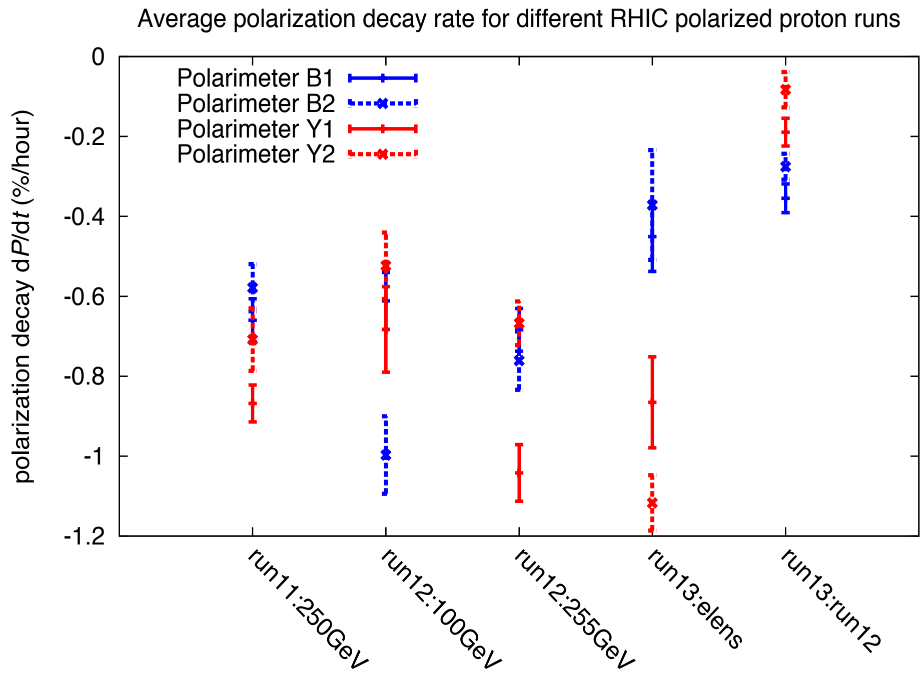


- It is difficult to directly measure un-colliding betatron tune while beams in collision
- In a collision of the same species and round beam, σ -mode of BTF is the best approximation of the un-colliding tune

The vertical sigma modes for different runs







- Vertical tunes for run12 is typically larger than those for run13.
- The larger vertical tune, the closer to 7/10 snake resonance, which could lead to larger polarization deterioration.

Simulation Goal and Progress

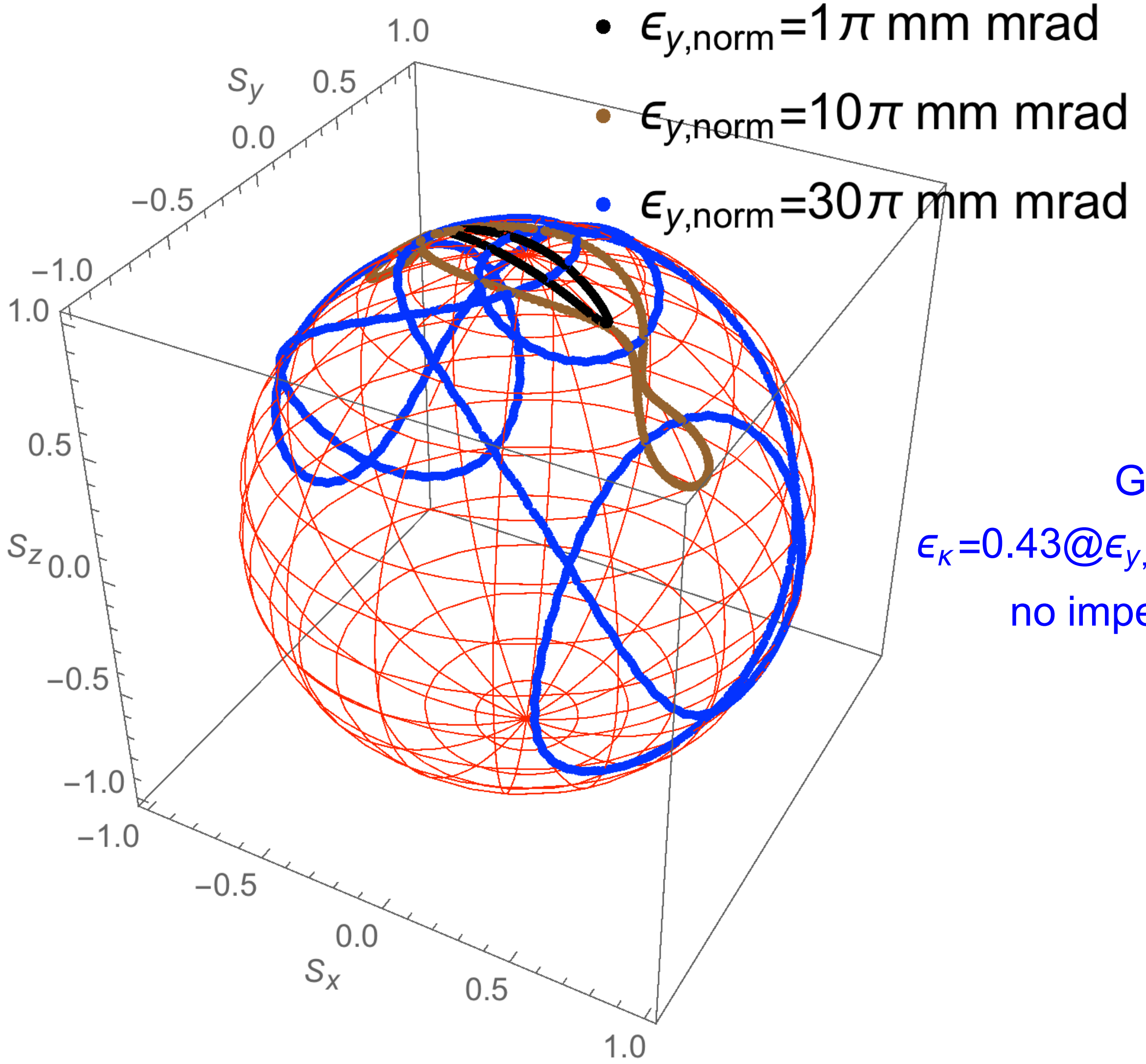
- Goal is to scan of P_{lim} as function of beam working point, beam-beam parameter, as well as betatron amplitude with RHIC model including
  - the orbital imperfection, betatron tune spread with synchrotron motion

- Compute $P_{\lim} = | < \vec{n}(\vec{z}, \theta) >_{\vec{z}} |$ by obtaining $\vec{n}$ via stroboscopic averaging[1] with PTC[2]
  - Up to 20,000 turns of tracking to obtain $\vec{n}$ at each initial coordinates.
  - Track the same initial coordinates with spin parallel to the computed $\vec{n}$ for 5000 turns, and compute P_{lim} with the turn-by-turn spin vectors for the same initial actions but different orbital phases

- Benchmarking with well-established model as well as RHIC polarized proton data

[1] K. Heinemann and G. H. Hoffstaetter, Phys. Rev. E 54:4240-4255 (1996).
[2] E. Forest, , F. Schmidt, and E. McIntosh. Introduction to the Polymorphic Tracking Code. Technical Report KEK-2002-3, KEK, Tsukuba, Japan, 2002. S. Mane, Technical Report No. KEK Report 2009-8, KEK (unpublished).

Computation of $\vec{n}$

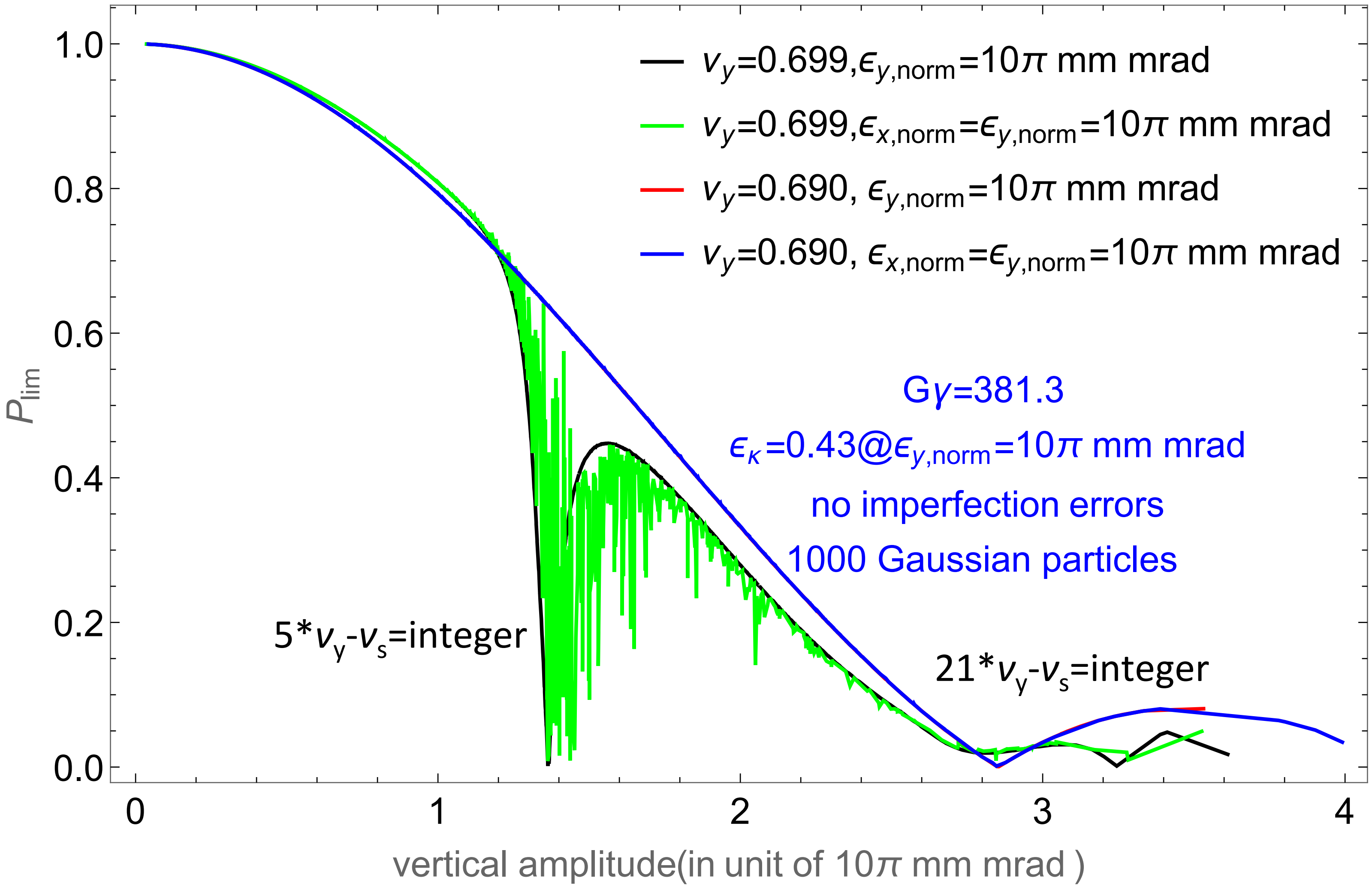


Gγ=381.3

ϵ_κ=0.43@$\epsilon_{y,norm}$=10π mm mrad

no imperfection errors

P_{lim} as a function of vertical betatron amplitude



Future plan of simulation

- Further benchmarking with synchrotron motion included
- Inclusion of orbital imperfection & snake imperfection
- Scan P_{lim} as a function of various beam parameters
  - Working point
  - Beam-beam parameter
  - Emittance
  - Spin tune shift from 1/2

Conclusion

- Due to the limit of RHIC polarimeter statistics, fill-by-fill correlation of beam polarization as well as polarization decay with beam data is too difficult to yield conclusive results

- Comparison of the average polarization decay rate for various RHIC polarized proton operation modes over the past a few years shows
  - Most of the operation modes have similar working point for collision
    - No strong correlation of polarization lifetime performance with collision energy
    - No strong correlation of polarization lifetime performance with beam-beam parameter

Run condition	Run11 250GeV	RUN 12 100GeV	RUN 12 255GeV	RUN13 255GeV
Peak luminosity($10^{32}cm^{-s}$)	1.45	0.46	1.65	2.45

  - During the second part of RHIC RUN 13, the collision working point was significantly below due to different practice of RHIC tune/coupling feedback operation.
    - significant improvement of polarization lifetime during this period was observed

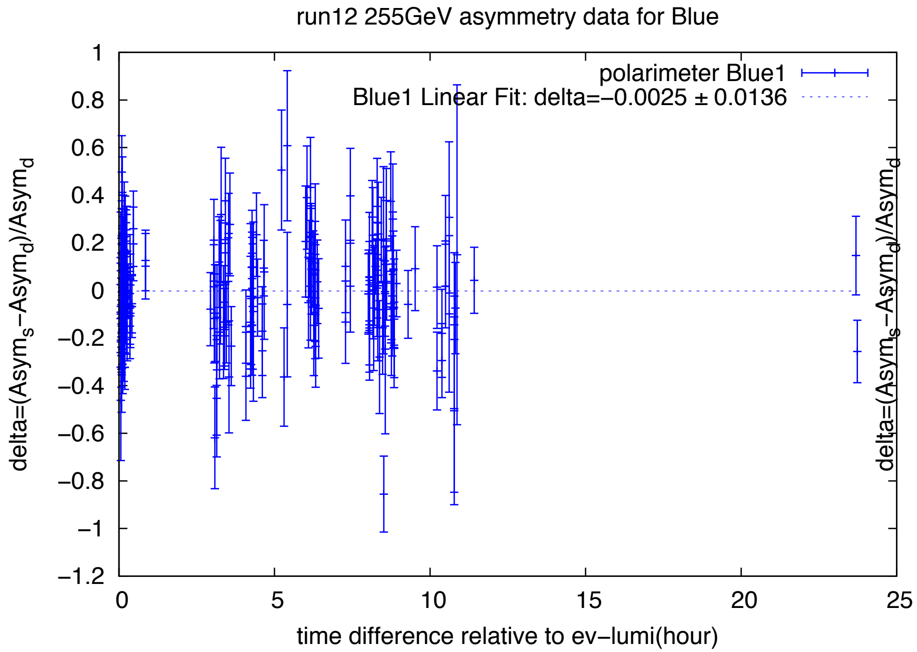
- Simulation study is in progress to study the P_{lim} as function of various beam parameters: working point, closed orbit distortion, imperfection of snakes

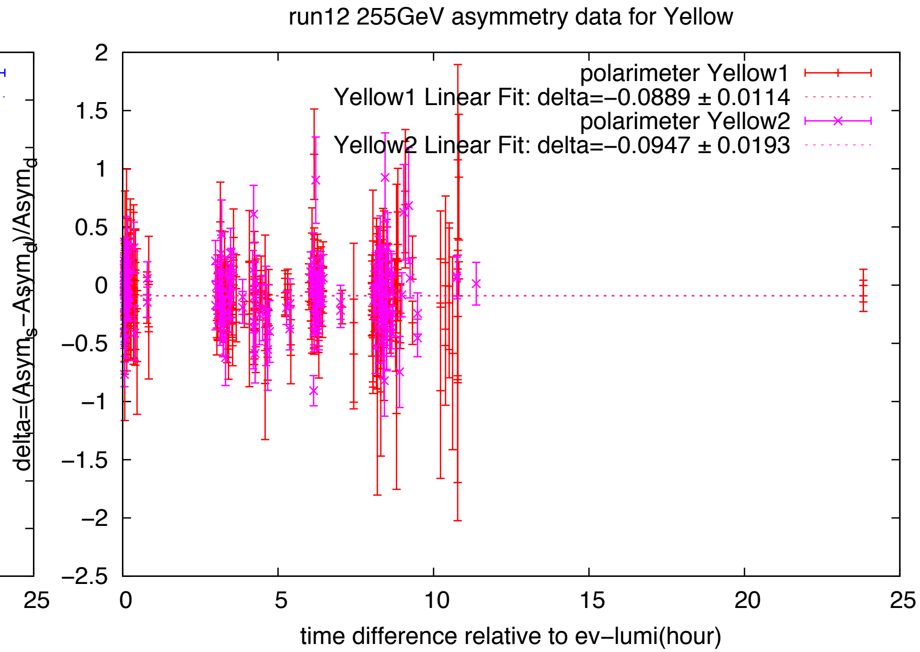
Acknowledgement

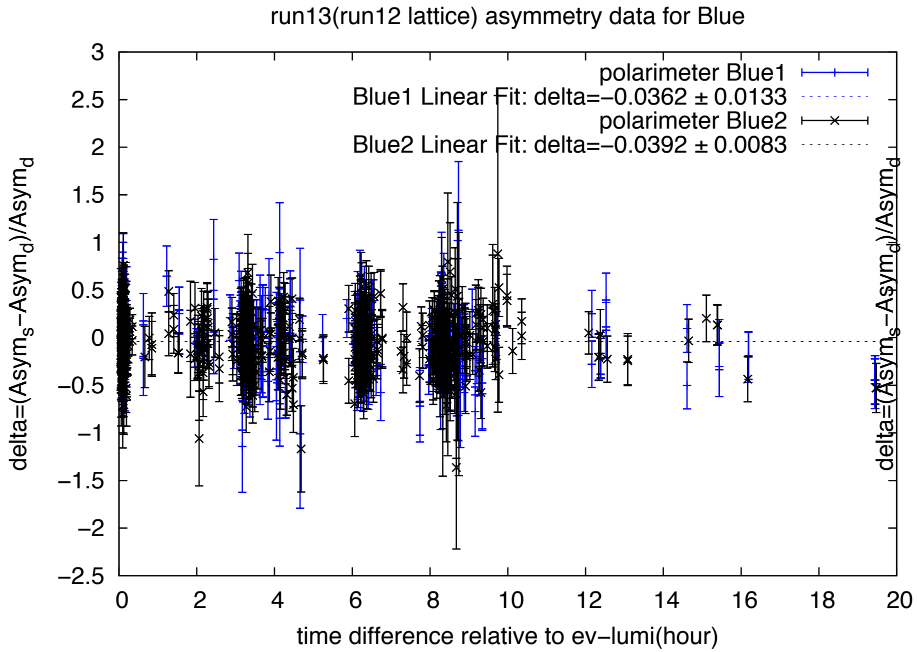
- This work is performed under the auspices of the US Department of Energy, RIKEN Japan, and Institute of High Energy Physics of China, CAS.
- The simulation used resources of NERSC, which is highly appreciated.
- I would like to express my high appreciations to Dr. D. Barber(DESY), Dr. D. Abell(TechX), Dr. E. Forest(KEK), Dr. F. Meot(BNL), Dr. Y. Luo(BNL), Dr. V. Ptitsyn(BNL), Dr. V. Ranjbar(BNL) and many others for their advices and many fruitful discussions.
- The authors also would like to thank the BNL Polarimeter group for their support.

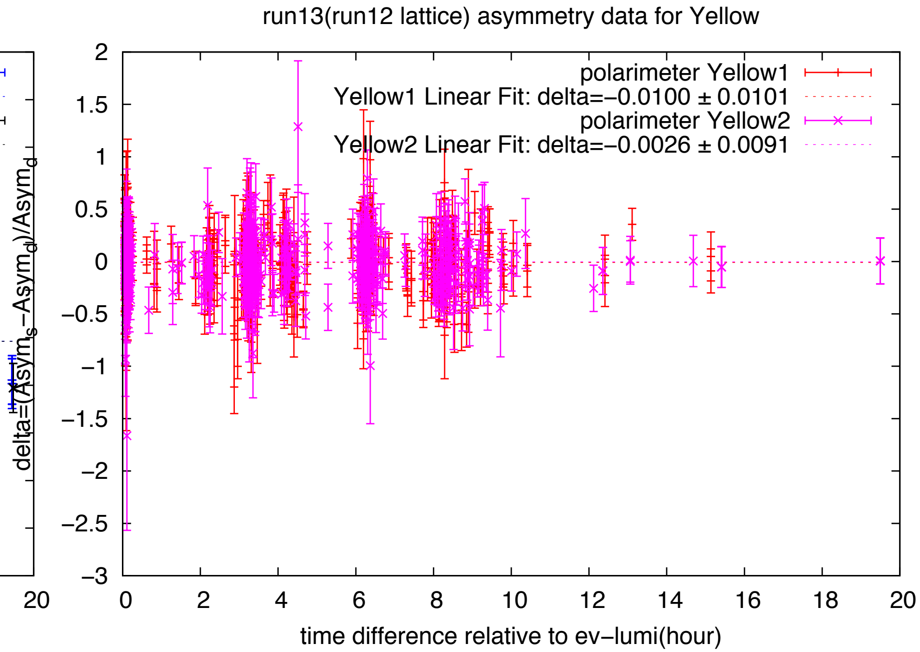
Thank you!

- Backup


run12 255GeV asymmetry data for Blue
polarimeter Blue1
Blue1 Linear Fit: delta=−0.0025 ± 0.0136
delta=(Asym_s−Asym_d)/Asym_d
time difference relative to ev−lumi(hour)

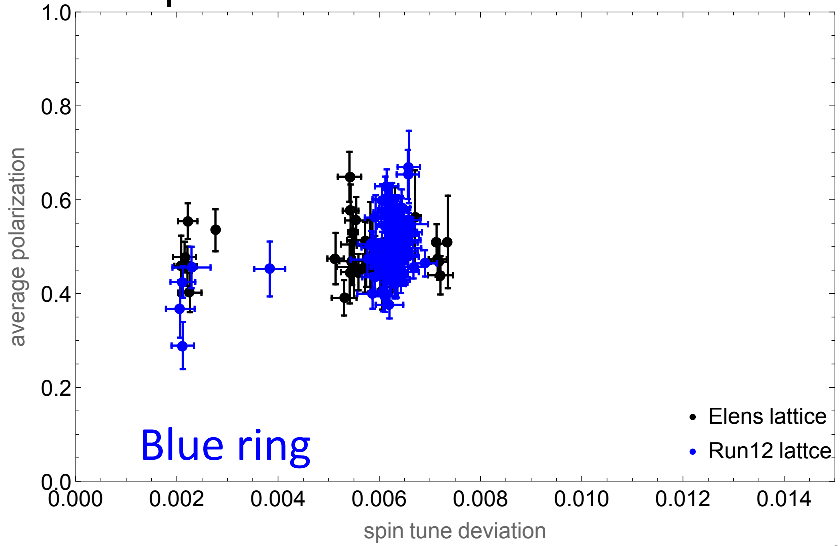

run12 255GeV asymmetry data for Yellow
polarimeter Yellow1
Yellow1 Linear Fit: delta=−0.0889 ± 0.0114
polarimeter Yellow2
Yellow2 Linear Fit: delta=−0.0947 ± 0.0193
delta=(Asym_s−Asym_d)/Asym_d
time difference relative to ev−lumi(hour)

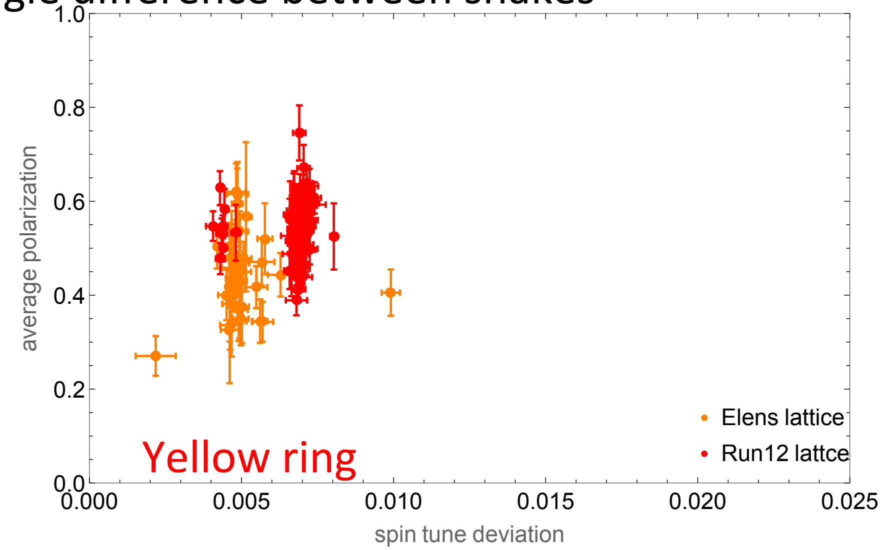

run13(run12 lattice) asymmetry data for Blue
polarimeter Blue1
Blue1 Linear Fit: delta=−0.0362 ± 0.0133
polarimeter Blue2
Blue2 Linear Fit: delta=−0.0392 ± 0.0083
delta=(Asym_s−Asym_d)/Asym_d
time difference relative to ev−lumi(hour)


run13(run12 lattice) asymmetry data for Yellow
polarimeter Yellow1
Yellow1 Linear Fit: delta=−0.0100 ± 0.0101
polarimeter Yellow2
Yellow2 Linear Fit: delta=−0.0026 ± 0.0091
delta=(Asym_s−Asym_d)/Asym_d
time difference relative to ev−lumi(hour)

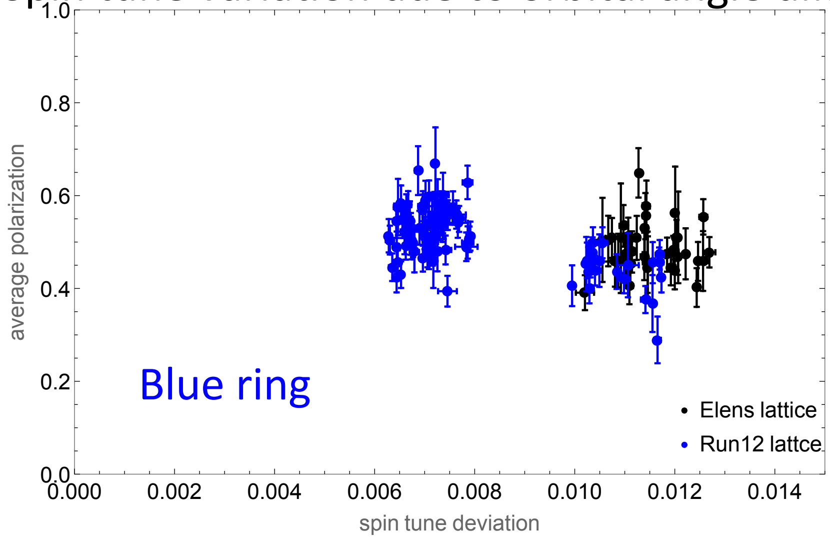
Correlation of average polarization versus spin tune deviation due to orbit imperfection

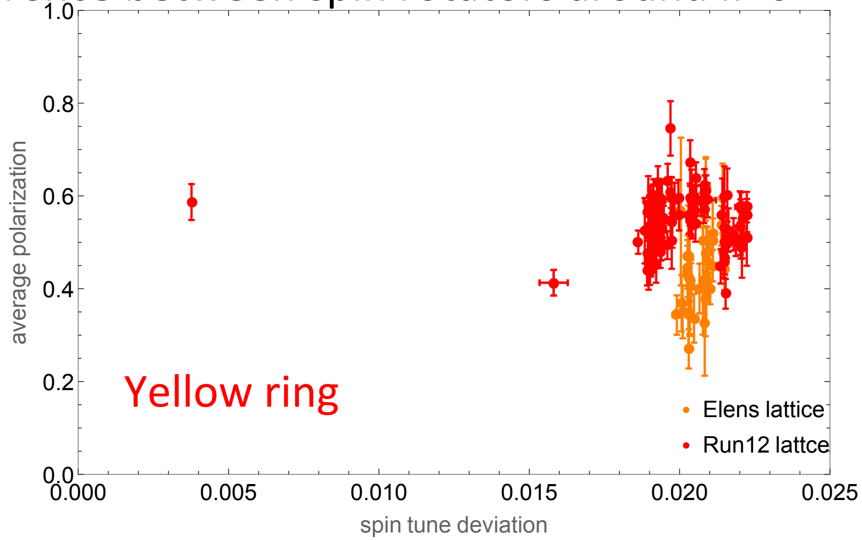
Spin tune variation due to orbital angle difference between snakes



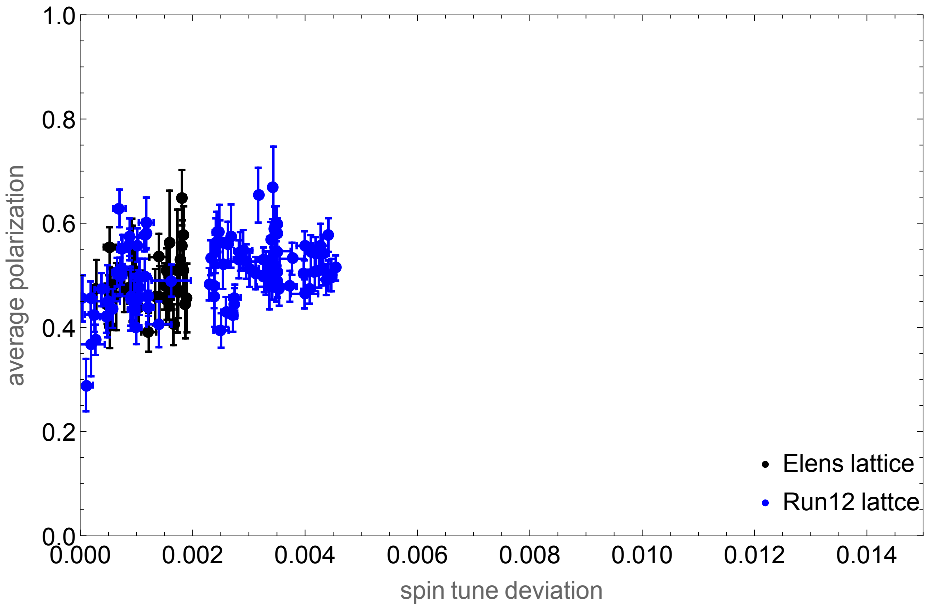


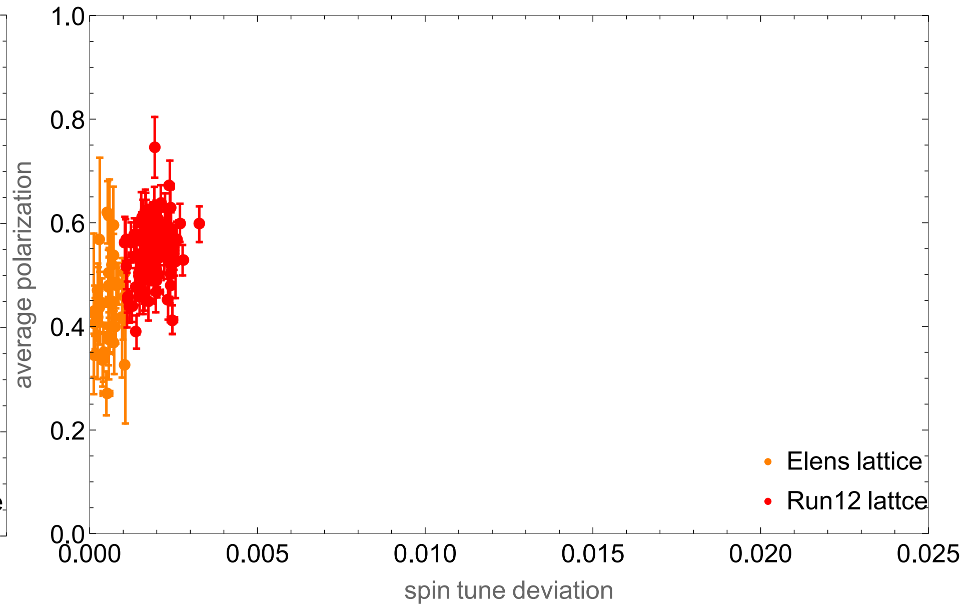
Spin tune variation due to orbital angle difference between spin rotators around IP 6





Spin tune variation due to orbital angle difference between spin rotators around IP 8





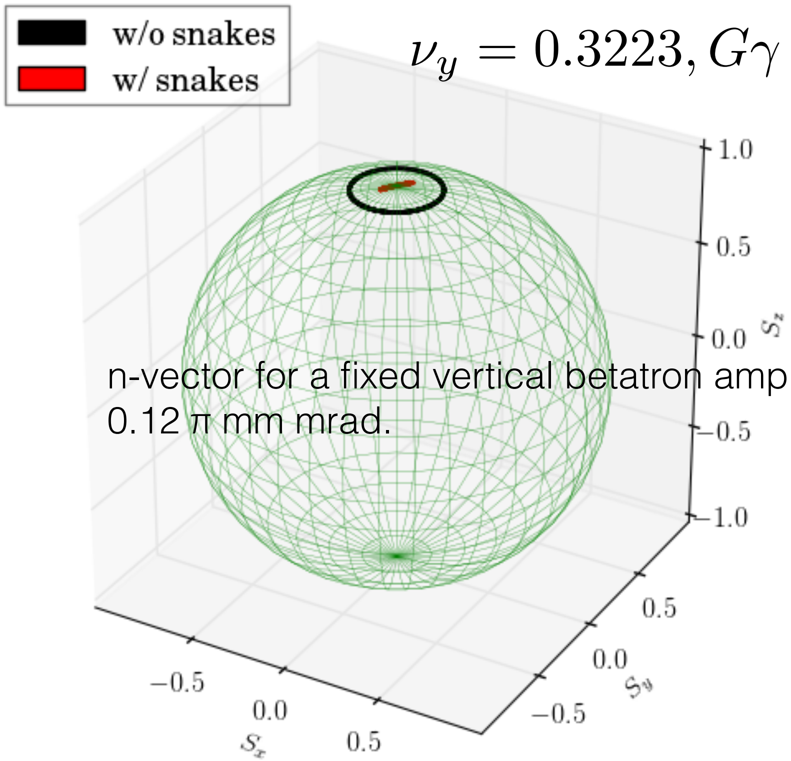
Simulation benchmark(2)

- FODO lattice, without snakes, close to a single isolated resonance,

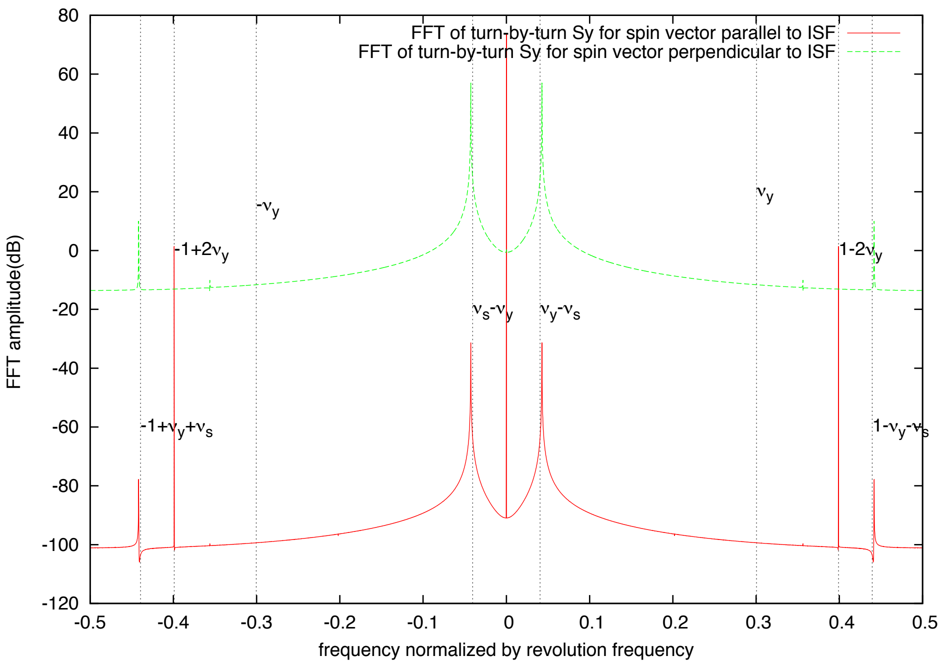
here only vertical motion is included, no coupling nor synchrotron motion.

- For a fixed vertical betatron amplitude, if launch a particle at $(\vec{z}, \theta)$ with spin parallel to $\vec{n}(\vec{z}, \theta)$, then the Fourier spectrum of the turn-by-turn spin vector doesn't contain peaks corresponding to spin tune[1].

$$\nu_y = 0.3223, G\gamma = 461.29, \epsilon_\kappa = 0.0137$$



n-vector for a fixed vertical betatron amplitude
0.12 π mm mrad.



[1] D.P. Barber, J. A. Ellison and K. Heinemann, PRST-AB 7, 124002 (2004).

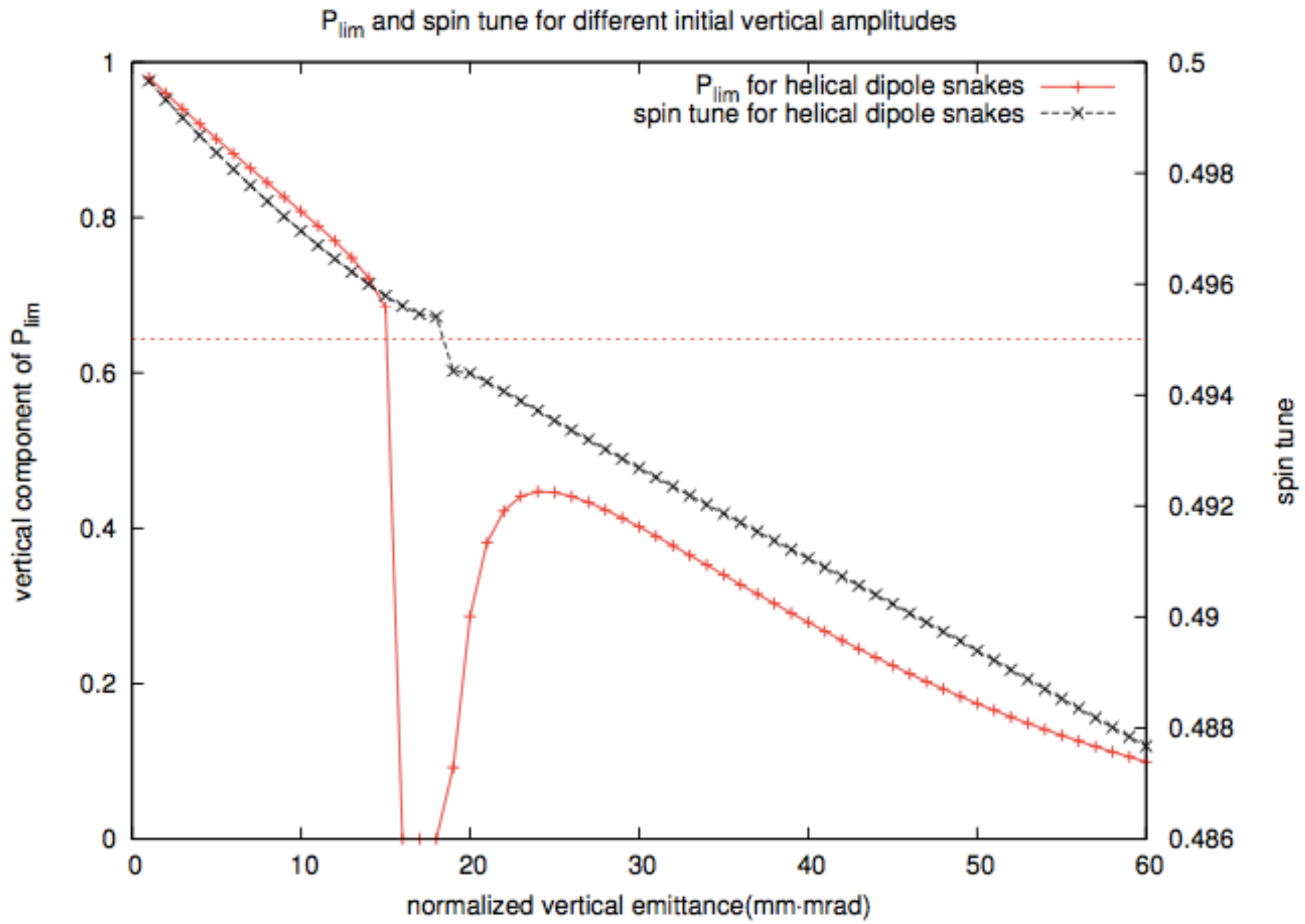


FIG. 22. The spin tune and $P_{\rm lim}$ for different vertical amplitudes, the RHIC lattice is set so that $G\gamma = 381.31$, where the instrinsic resonance strength is around 0.4 for a normalized emittance 10πmm $\cdot$ mrad and the vertical tune for these amplitudes is 0.699, the location of spin resonance $5\nu_y - \nu_s =$ integer is also indicated in the plot.