Advanced Modeling of Beam Physics and Performance Optimization for Nuclear Physics Colliders

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NP Accelerator R&D, PI Exchange Meeting
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Project members:

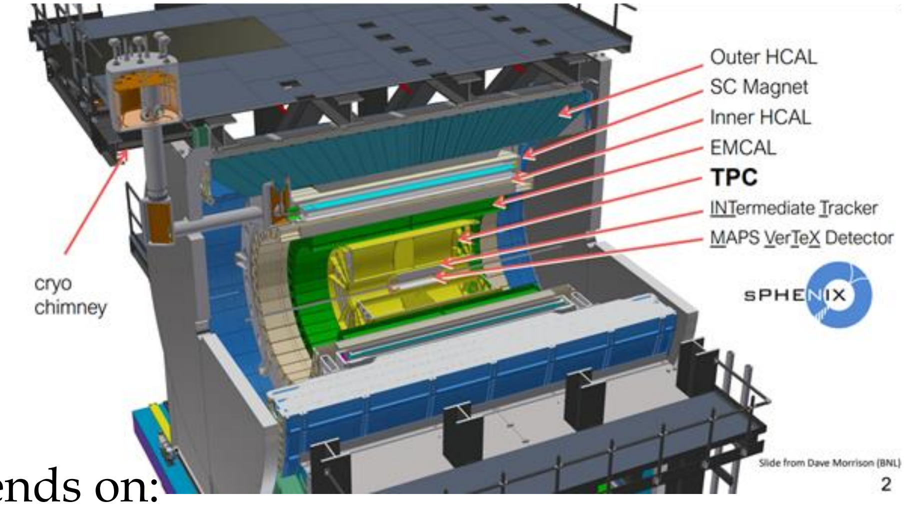
- BNL: Xiaofeng Gu
- LBNL: Ji Qiang, Xiaoye Li, Yang Liu, Yi-Kai Kan (postdoc, left 2024)
- MSU: Yue Hao, William Fung (graduate student)

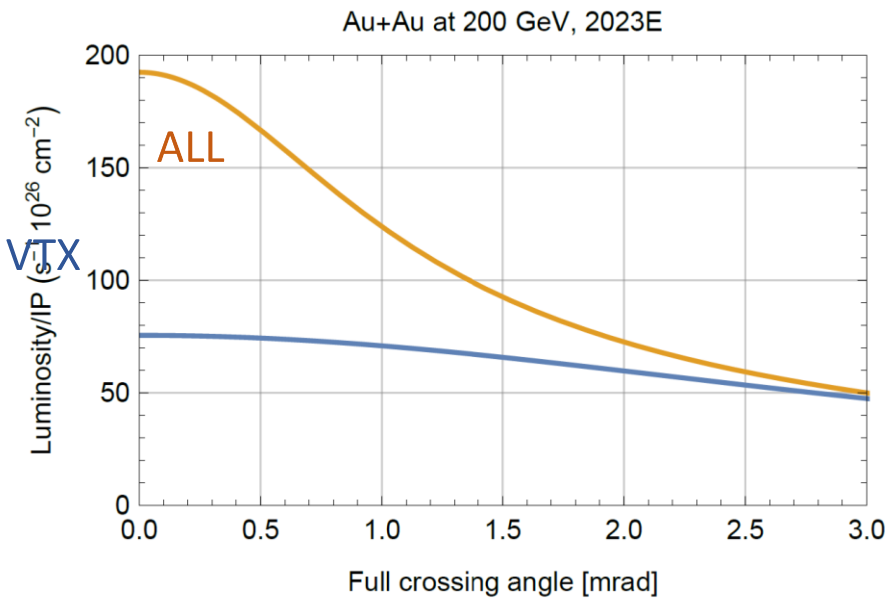
Outline

- Background of Proposed Research
- Method adopted
- Experimental Results
- Research Goal and Achievements
- Summary

Luminosity Optimization Needed at the New RHIC Detector

- New jet detector sPHENIX was commissioned in 2024.
- Physics study needs higher luminosity.
    - VTX (+/-10 cm)
    - Crossing angle (2mrad)
    - S/N - Background





Courtesy of W. Fischer

Luminosity depends on:

- Global Parameters:

1. Orbit (Dipole)
2. Tune (Quadrupole),
3. Chromaticity (Sextuple)
4. Octupole
5. RF cavity

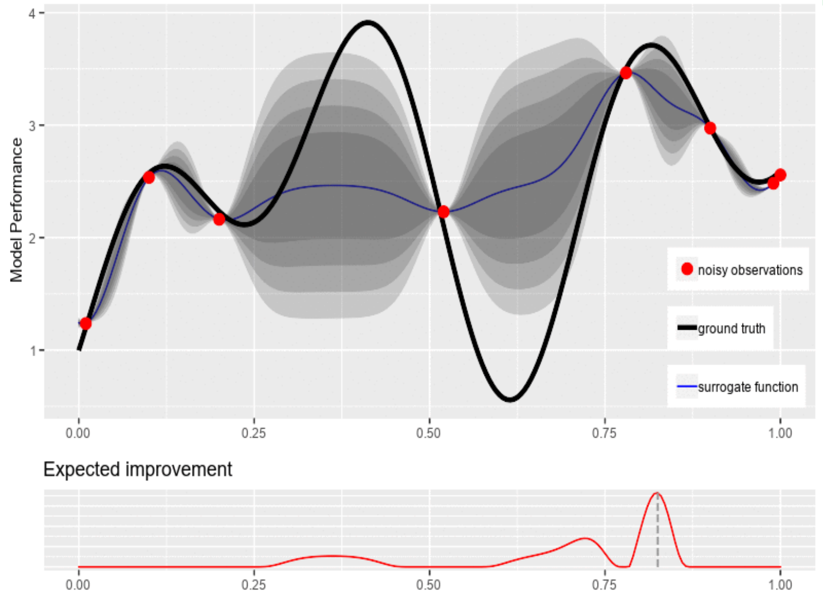
- Local (IR8) Parameters:

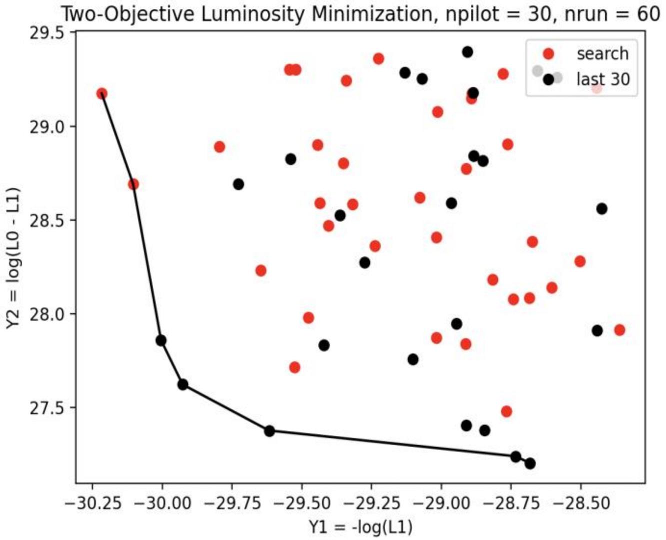
1. Beta*
2. S* (more sensitive than head on)
3. Short Bunch length via 56 MHz Cavity

Bayesian Optimization: A Model Based Black-Box Method

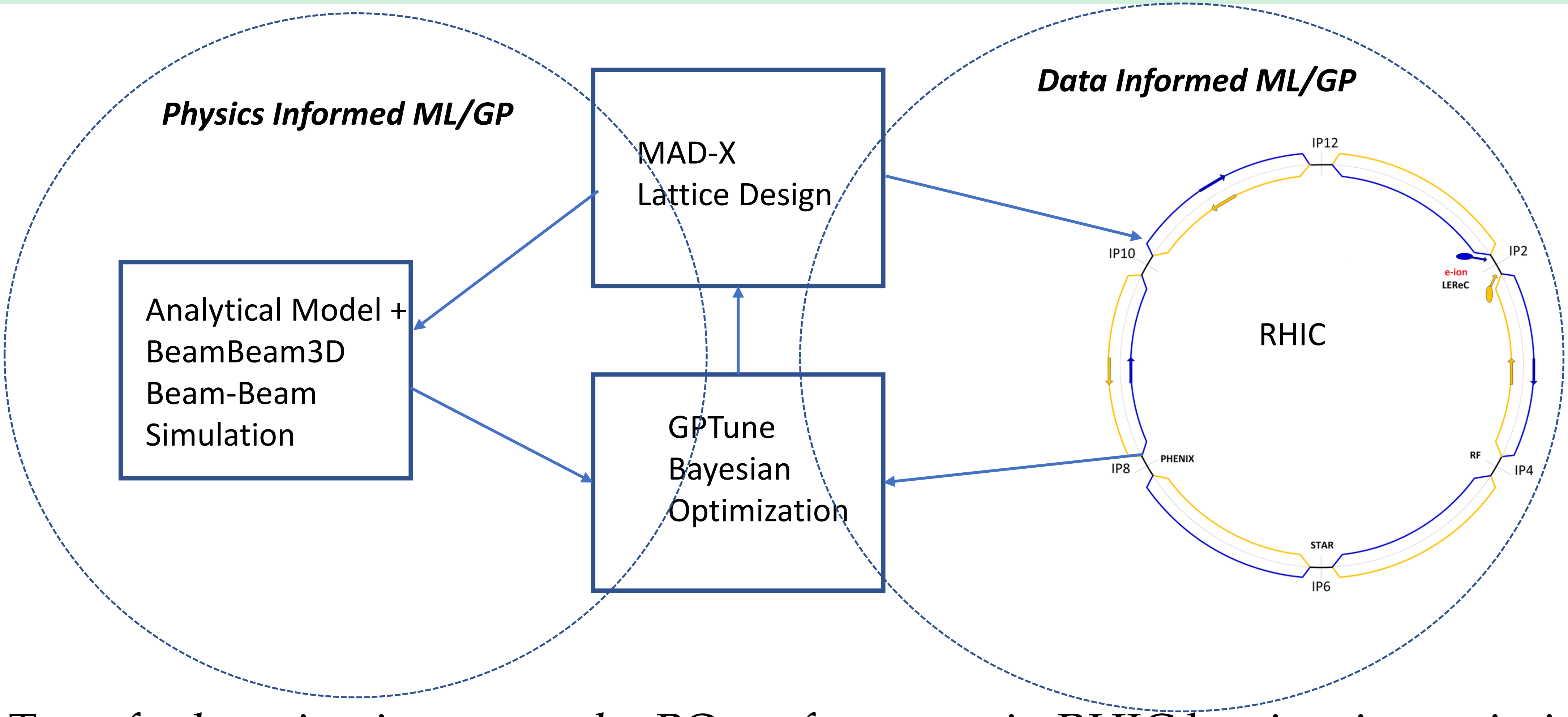
- GPTune: Gaussian Processes Tuning
  - **Bayesian Optimization**: Find an accurate model using the least amount of samples
  - Initial samples → search samples
    - **Acquisition function**: used for searching the next sample based on how uncertain we are

- 2D Simulation example with luminosity:
  - Objective 1: maximize luminosity inside
  - Objective 2: minimize luminosity outside
  - Parameters:
    - β^*_x, β^*_y: Focusing at IP
    - ϕ_c: Crossing angle
    - σ_z: longitudinal bunch length
  - Red: Initial random sample of parameters
  - Black: GPTune's search for more optimal parameters
  - **Pareto front**: optimal set solutions
    - Cannot improve one objective without sacrificing the other



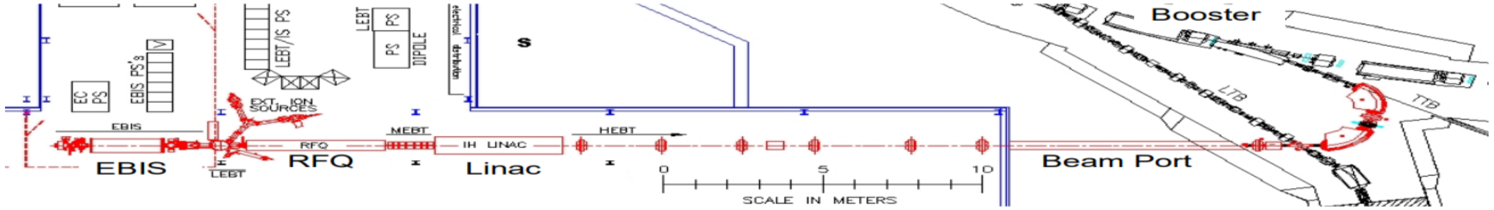


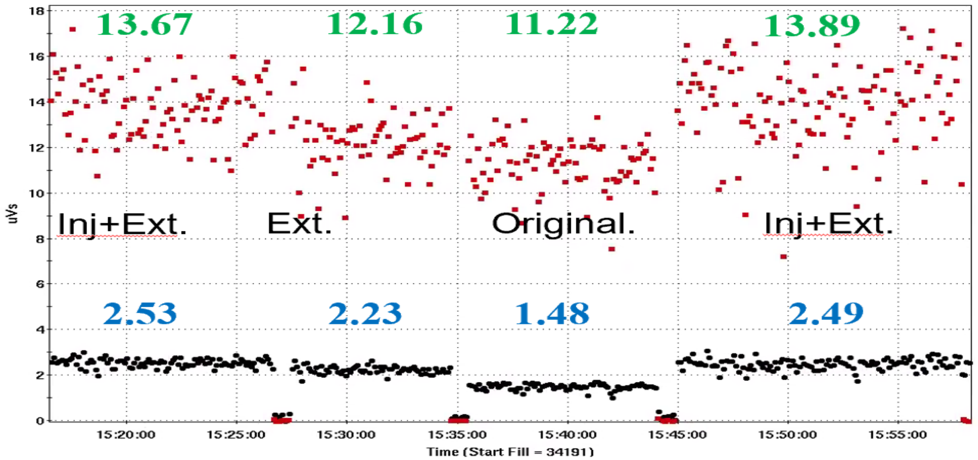
Advanced Modeling Framework for RHIC Lum. Optimization



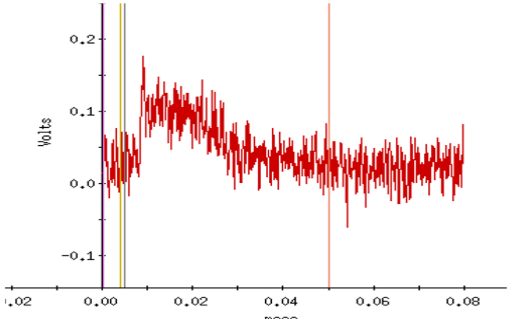
- Transfer learning improves the BO performance in RHIC luminosity optimization by the GP model trained by the physics simulation.

Online Bayesian Optimization Improves EBIS Performance





GPTune works with these noisy signals!



Intensity detector	Original	Ext. optimized with xf14	Gain	+ Inj. Optimized with FC96	Total Gain
xf14 (uVs)	1.48	2.23	42~50%	2.53/2.49	68~71%
fc96 (uVs)	11.22	12.61	8.4%	13.67/13.89	22-24%

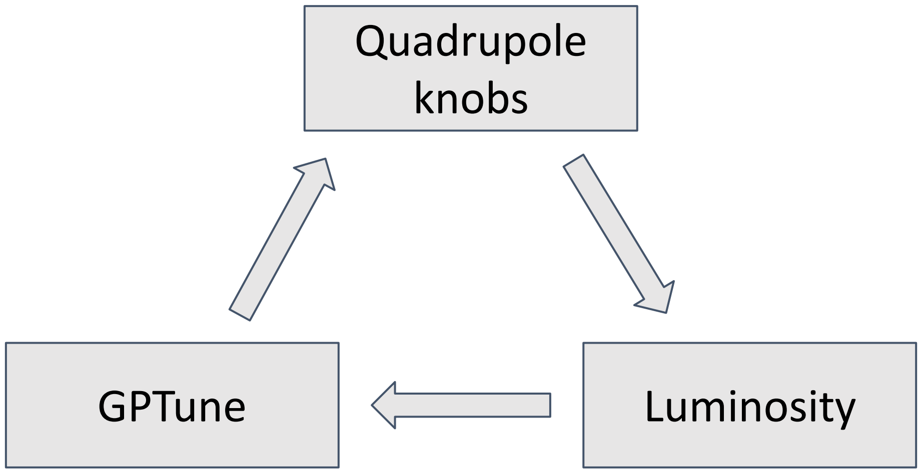
Online Optimization of Luminosity in RHIC

- Optimize the luminosity by correcting its loss of **geometric overlap due to beam optics mismatch**.
- There are 17 tuning quadrupoles at interaction region, most of them are independent and with tight tuning range.
- There are 4 targeting objectives (beta waists and its locations). In order not to disturb the optics function outside the interaction region and IBS rate in the entire ring, additional 9 constraints have to be satisfied.
- **It is not safe and inefficient to use optimizer (GPTune) directly on all 17 quadrupole knobs, instead, GPTune controls the change of s* and use model to calculate correct quadrupole settings. (Dimension Reduction)**

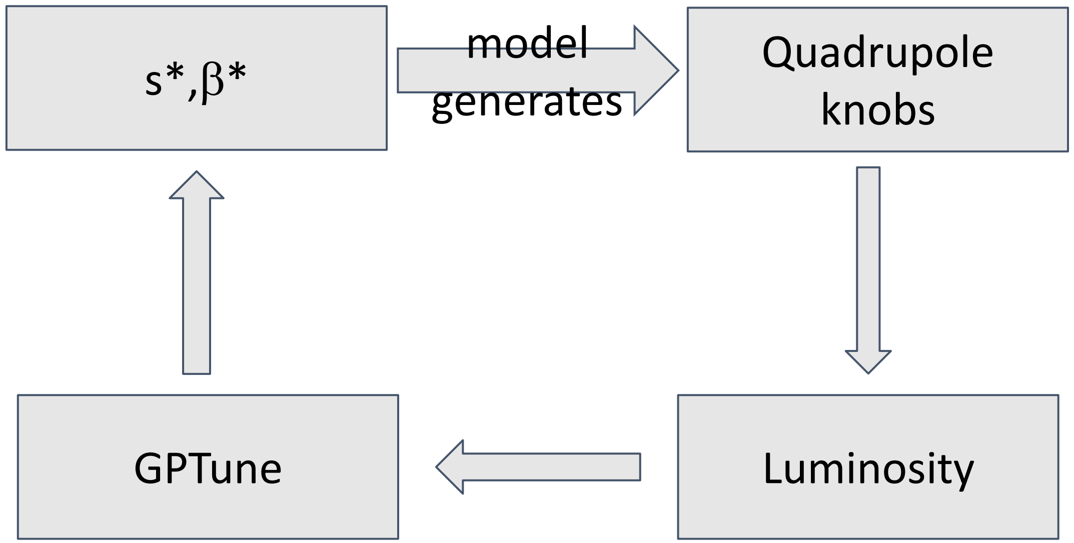
	@ IR boundary (6+0)			@IP (1+4)			Global (2+0)
Constraints	$\beta_{x/y}$	$\alpha_{x/y}$	η, η'			η	$\nu_{x/y}$
targets				$\beta^*_{x/y}$	$s^*_{x/y}$		

Online RHIC Optimization Diagram

Brute Force Method



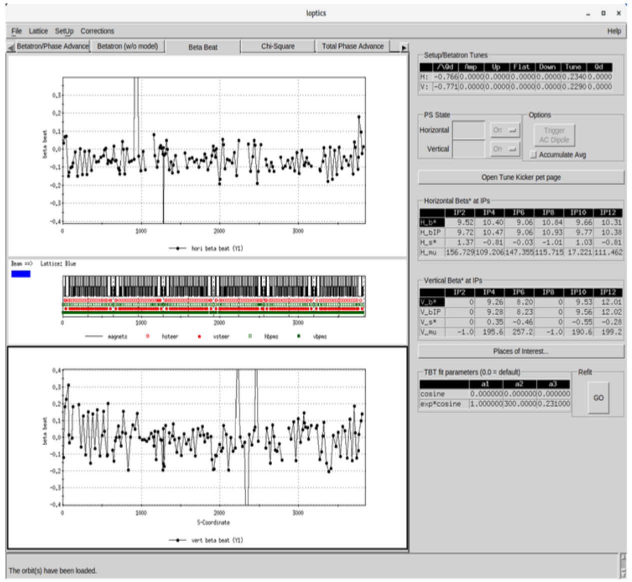
Model Based Method in this Project



Brute Force Method
Pros:
-- direct acting on the targeting objective (simple implementation)
Cons:
-- Not safe in experiment
-- Change global RHIC accelerator parameters
-- High dimension

Model Based Method
Pros:
-- lower dimension
-- Guaranteed safe outside IR region
Cons:
-- potential mismatch between model prediction and real settings

Experimental challenges



Base line measurement: s*x = -0.81m, s*y = 0.28m

Intend to move s*x -> 0.5 m: s*x = -1.30m, s*y = -0.48
Intend to move s*x -> -0.5m: s*x = -1.09m, s*y = -0.40

Intend back to base line1: s*x = -1.62m, s*y = -0.28m
Intend back to base line2: s*x = -0.89m, s*y = -0.20m

- Experimentally apply GPTune with transverse s* as the parameter using MAD-X matching
  - **Found out that the measured s* values differ from intended s* movement**
- Need to improve control and measurement of linear optics

Total integrated luminosity → ZDC rate (real time)
Current Vertex luminosity → minutes delays

→ Only use ZDC rate as optimization goal

56 MHz Cavity is not in operation → Bunch is long
→ The gain of luminosity is only a few percent

→ Need alternative way show the effectiveness

Improved Optics Tuning Method

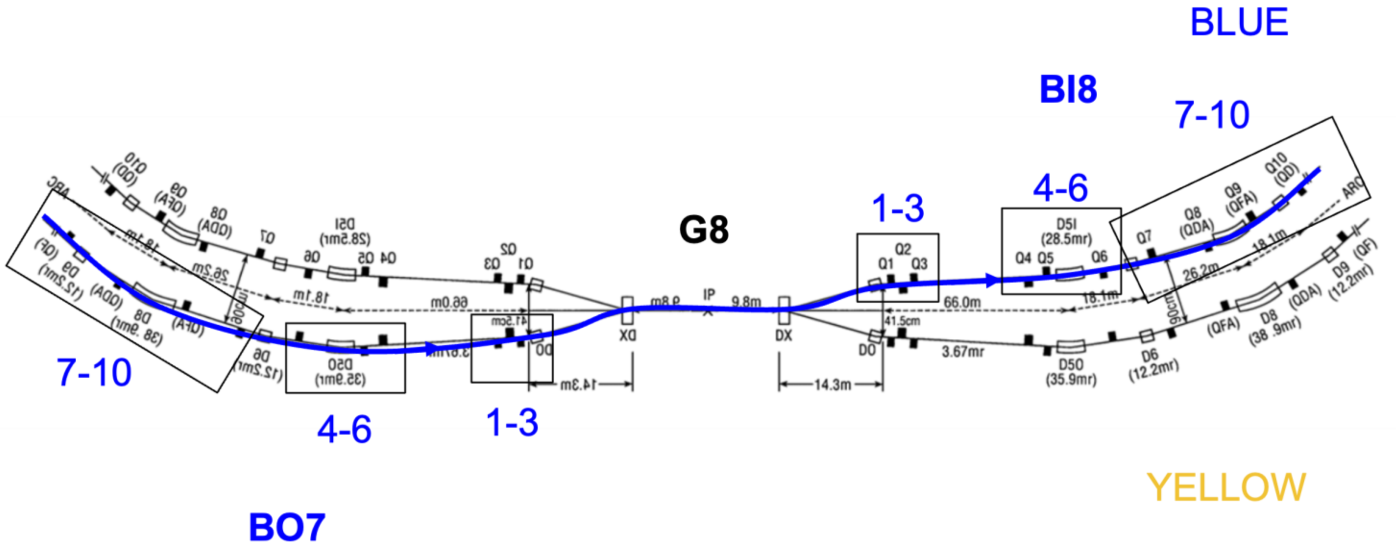
- **Optics response matrix (B)**: creates a linear relationship between the power supply and the optics
  - Invert to obtain required change in currents, 12 constrains; 17 vairables
  - Use null space to optimize specific constraints
    - Power supply limits
    - Beta function at Horizontal IR8 Collimator (for safety)
  - Translate current changes into magnet strength settings for the Control Room

Optics $\Delta O = B \Delta I$ Current

Response

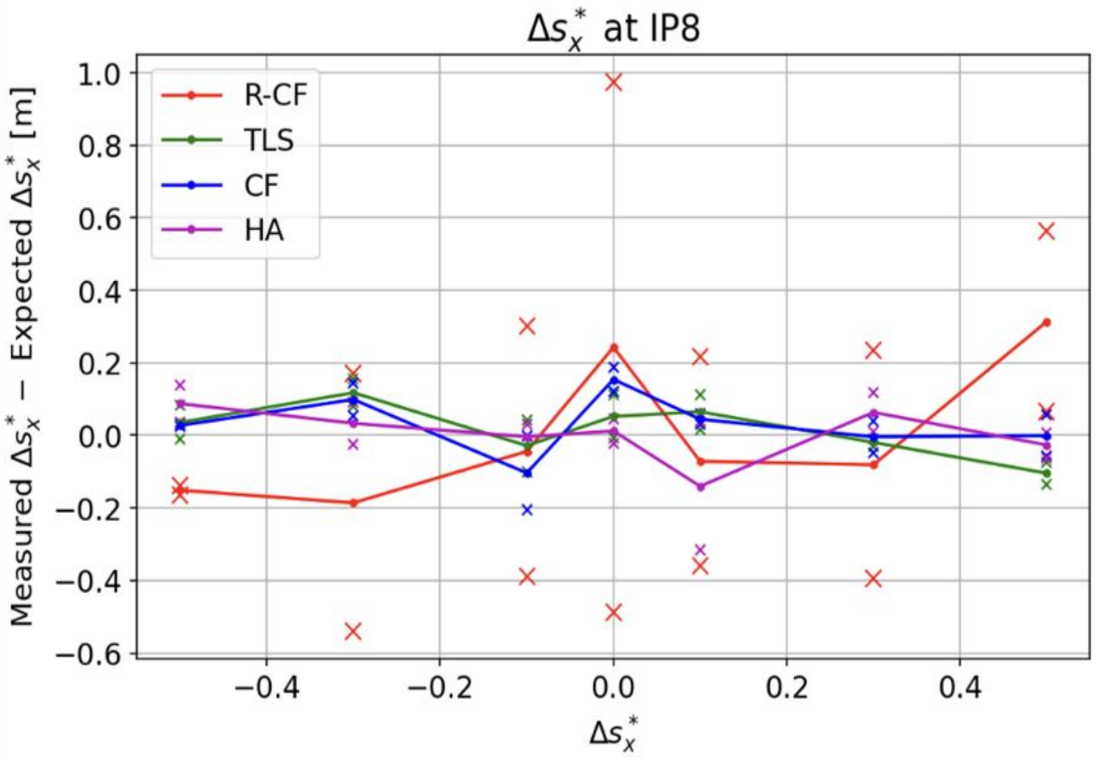
$$\Delta I = B^{-1}\Delta O - \mathrm{null}(B)C$$

- Adjust C to satisfy current limits.



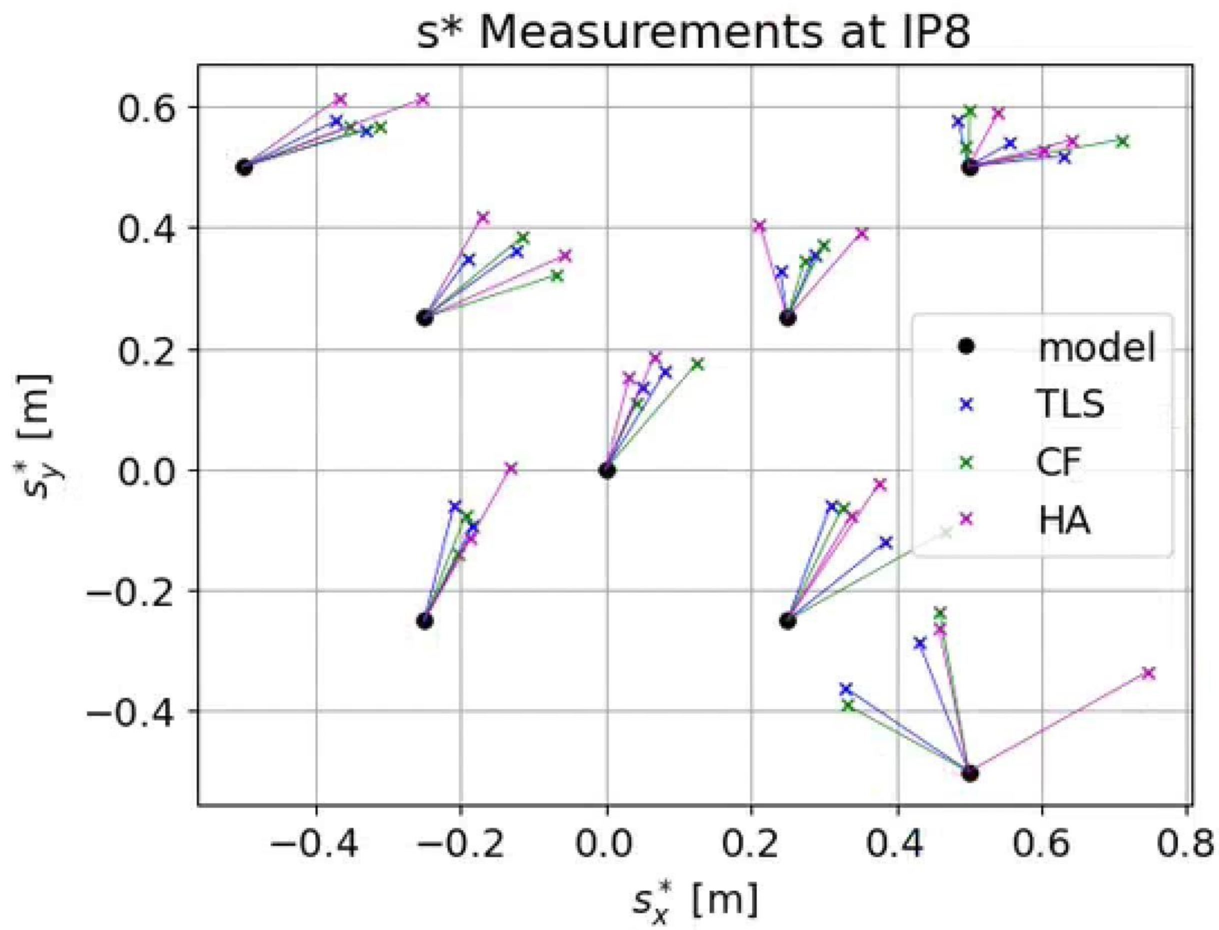
More reliable IR optics modification achieved

- Moved s^*_x from [-.5, .5] m using ORM, collect two TBT measurements
- Multiple data analysis method TLS, CF (curve-fitting method), HA (Harmonic Analysis, and R-CF (current RHIC loptics method)
- Measurement produces more accurate and consistent results than RHIC method when compared to the model. **<u>Beam loss not affect during tuning, READY FOR TEST</u>**

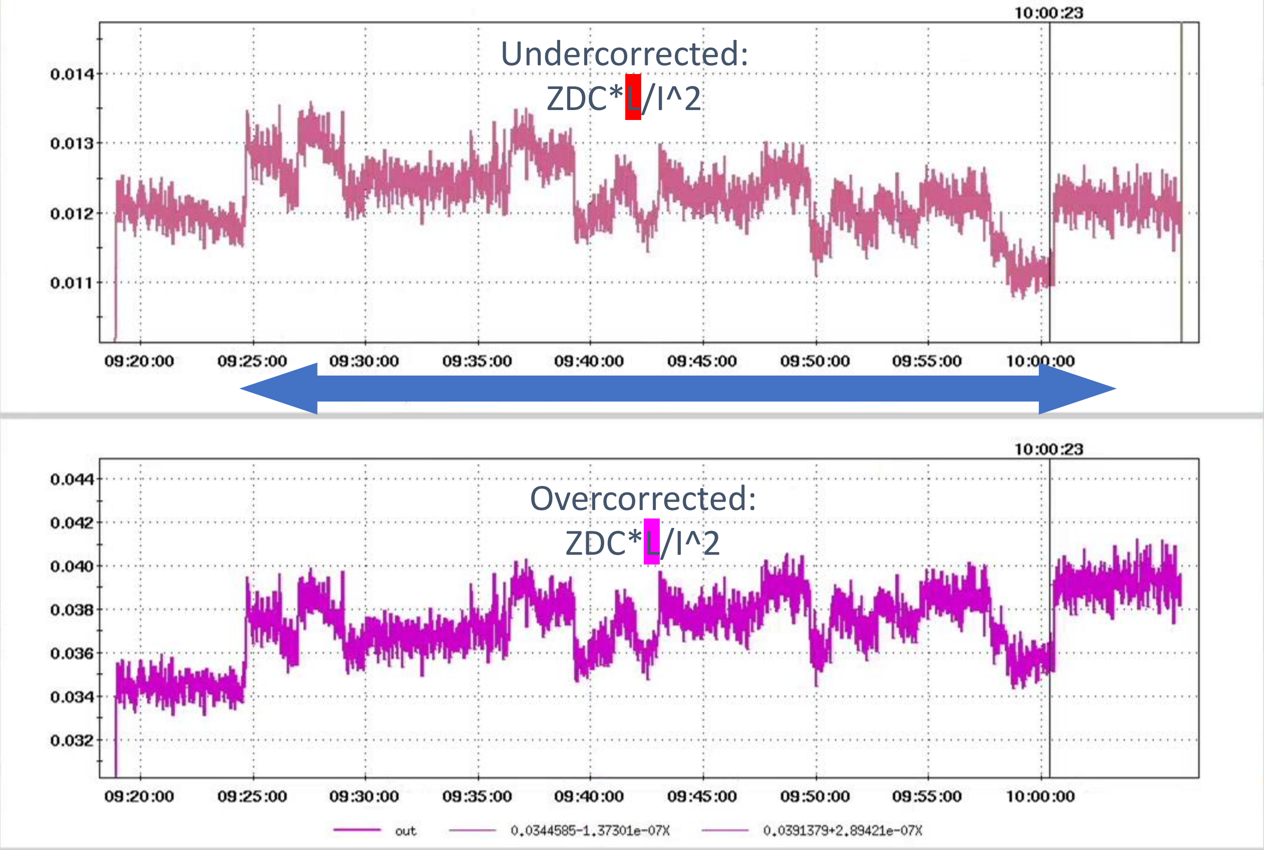


First Test 10/15, Run 25

Confirm the s* movements, show a systematic shift of 0.1m-0.2m (model vs. machine)

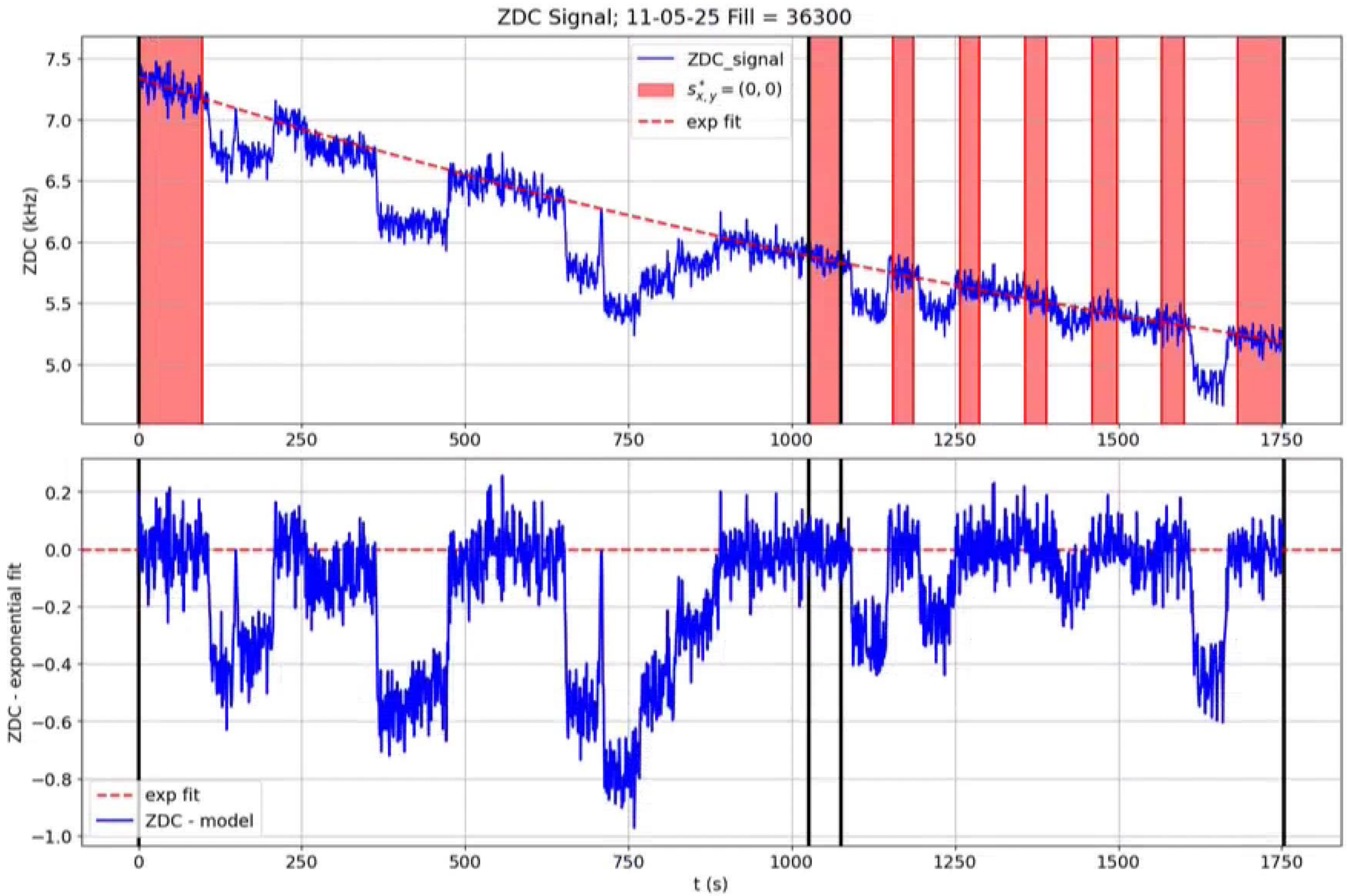


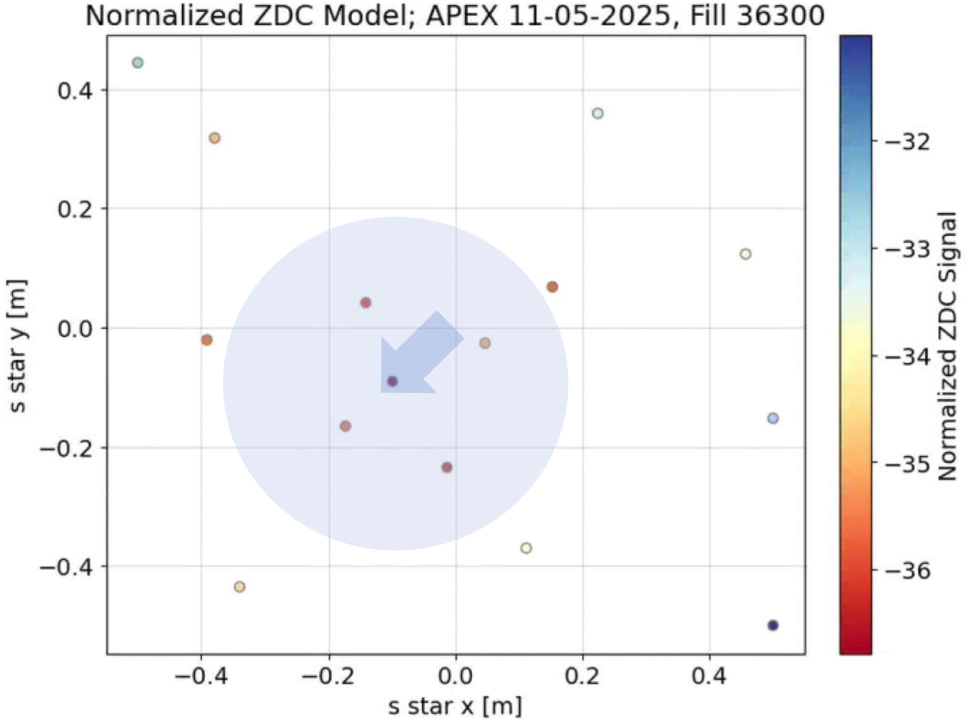
Time limited, we start optimization routine right after s* movement, (start from sub-optimum case)



Second Test 11/5 Run 25

We start from the optimum setting of s* (according to the model) and reset our change to revisit the 'base line'





Statistical trend on the shift of model s*. Agree with the measurement

Project Goals and Achievements

- Develop an advanced modeling framework based on first-principle physical simulations, lattice models and the state-of-the-art machine learning methods.
  - Achieved
- Apply this framework to the performance improvement of the RHIC experiments (sPHENIX).
  - Achieved within experimental limitations
- Train and educate early career researchers.
  - Achieved,
  - Yi-kai Kan (Postdoc in this projected, now active member of EIC)
  - Will Fung (Currently 3rd year graduate student, gain model/experiment experience, continue working at BNL on related topics)

Summary of expenditures by fiscal year (FY):

	FY22 ($k)	FY23 ($k)	Totals ($k)
a) Funds allocated	490	490	980
b) Actual costs to date	490	476	966

Summary

- Demonstrated **consistent control** in changing $\Delta s^*_{x/y}$ between [-.5, .5]m without beam quality degradation.
- Demonstrated **stable and Bayesian Optimization (BO)** using pseudo knobs, corresponds to the available optimization knobs and beam quality.
- **Successfully restore luminosity** from sub-optimal settings and found many 'equally good' settings which agrees with our optics measurement.
- Encouraging combination of **physics model and AI algorithm**
- **Gain confidence and ready in optimizing the vertex luminosity** when the corresponding lumi signal is ready for BO optimizer.
- The development is expected to be **crucial for EIC** operation due to 10x reduction in the vertical beta function of both beams.

Thank You!