# UVA Spin Physics Group Update

## Status and Plans

**Dustin Keller 6/3/26**

# Contents

- General Group Status Update
- Recent developments and activities
- Activities related to Tensor Collab

# General Status

## Limited Funding

- The next SpinQuest production run is delayed to after the long-shutdown (2030). Commissioning was completed and some production data obtained which we are analyzing now and expect to release preliminary results coming up.
- Funding limitations and delays for group funding. Have been able to keep the group together but very limited funding for travel, parts, cooldowns, etc…
- UVA helium liquefier and closed loop DNP setup has been tested but need purifier for longterm running tests and commissioning. We are constructing our own purifier and planning cooldowns funded by outside collaborators.

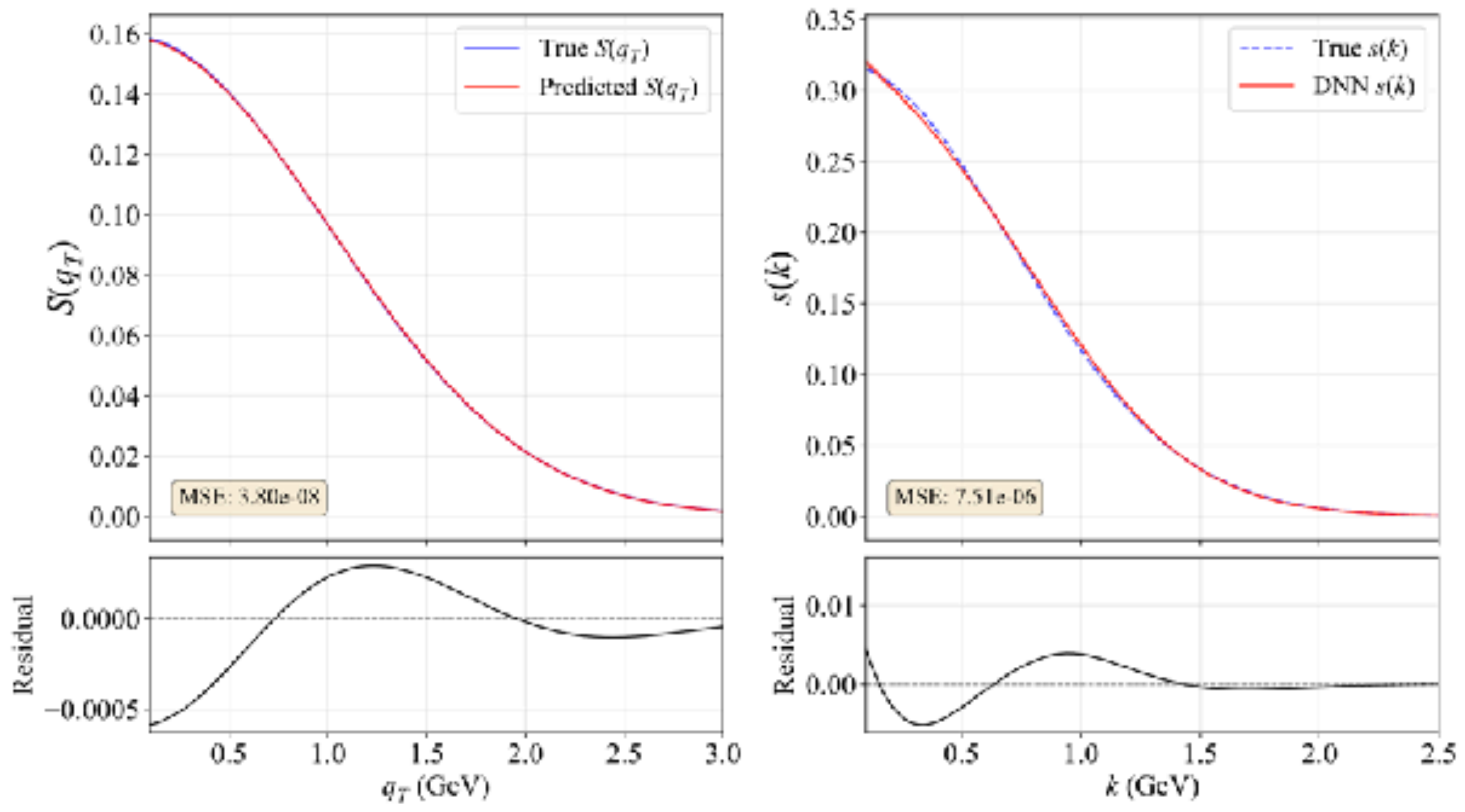
# Some High-level Group Activities

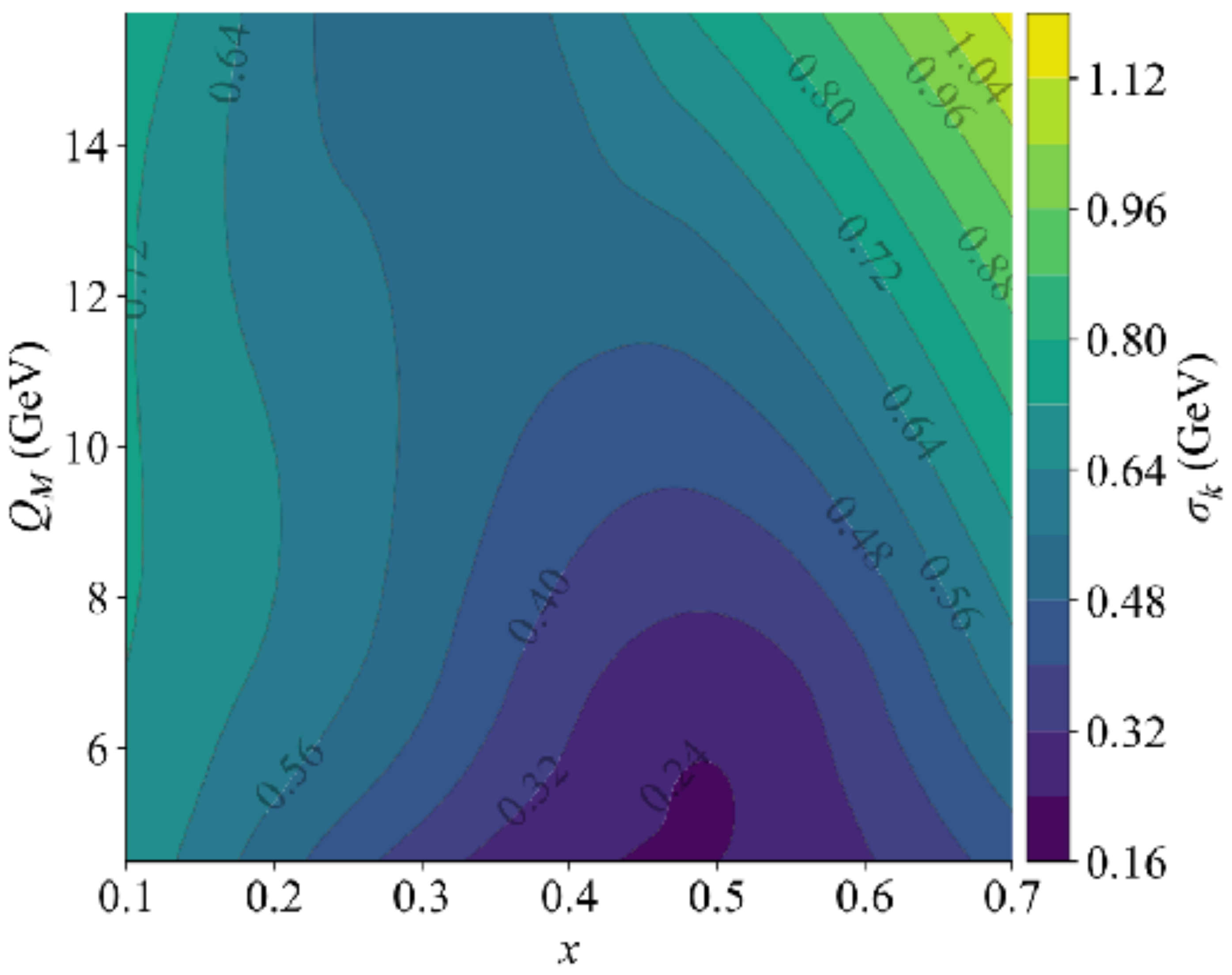
## And the projects lead (you will not hear about here)

- SeaQuest data analysis: (**Kenichi Nakano**) Flavor asymmetry of the proton light-quark sea, nuclear effects, angular distribution, J/ψ production,…
- SpinQuest data analysis: (**Forhad Hossain**) Extraction of signals for future Sivers analysis using iterative AI classifier based information extraction and normalizing flow.
- Phenomenological DNN driven TMD extraction: (**Ishara Fernando**) First DNN global extraction of a TMD (Sivers function), First DNN extraction of the unpolarized TMD directly in momentum space, First to solve the inverse problem directly for a specific TMD using a DNN (technique generalizes).

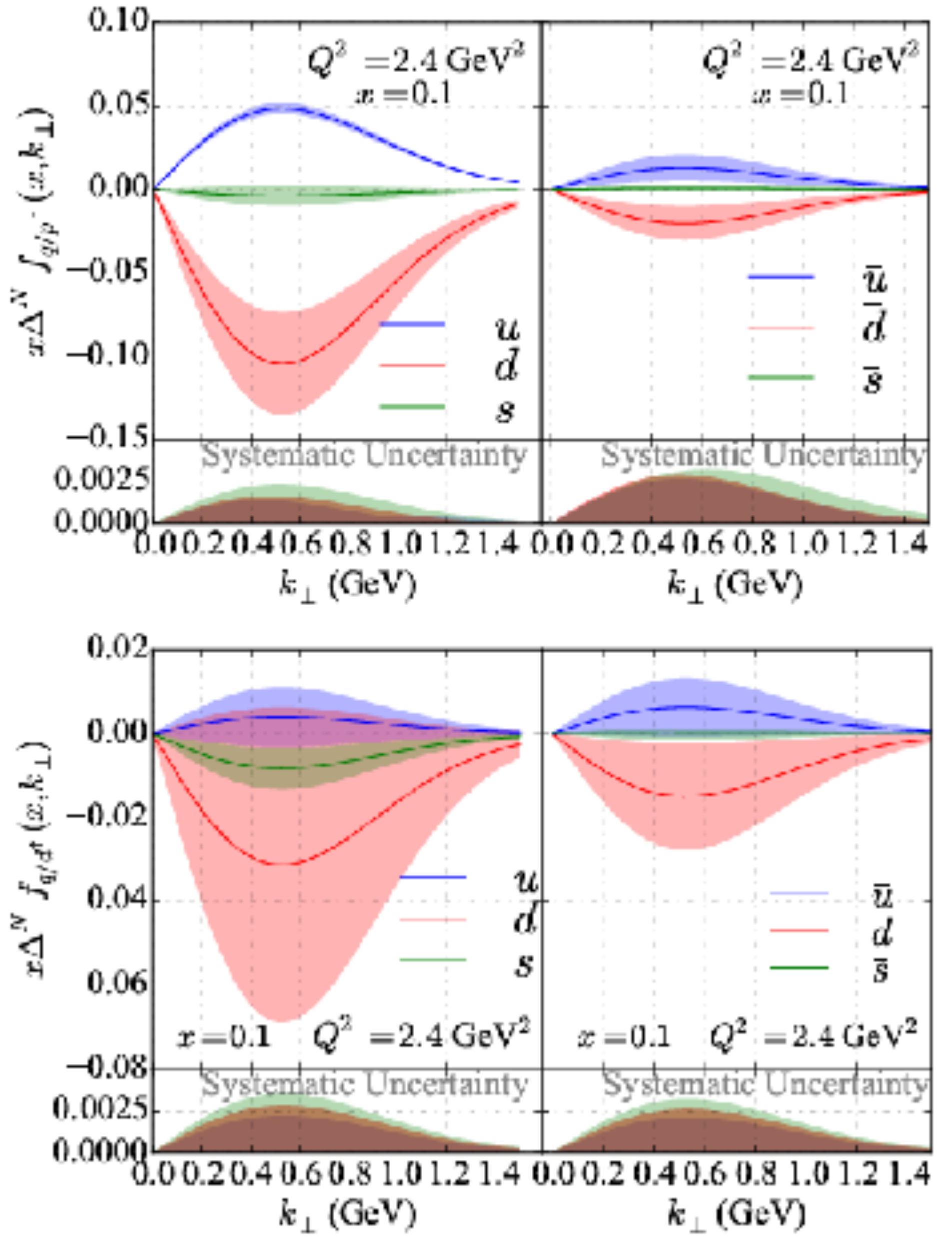
# Phenomenological DNN TMD/GPD Extraction

## *Ishara Fernando et al.*

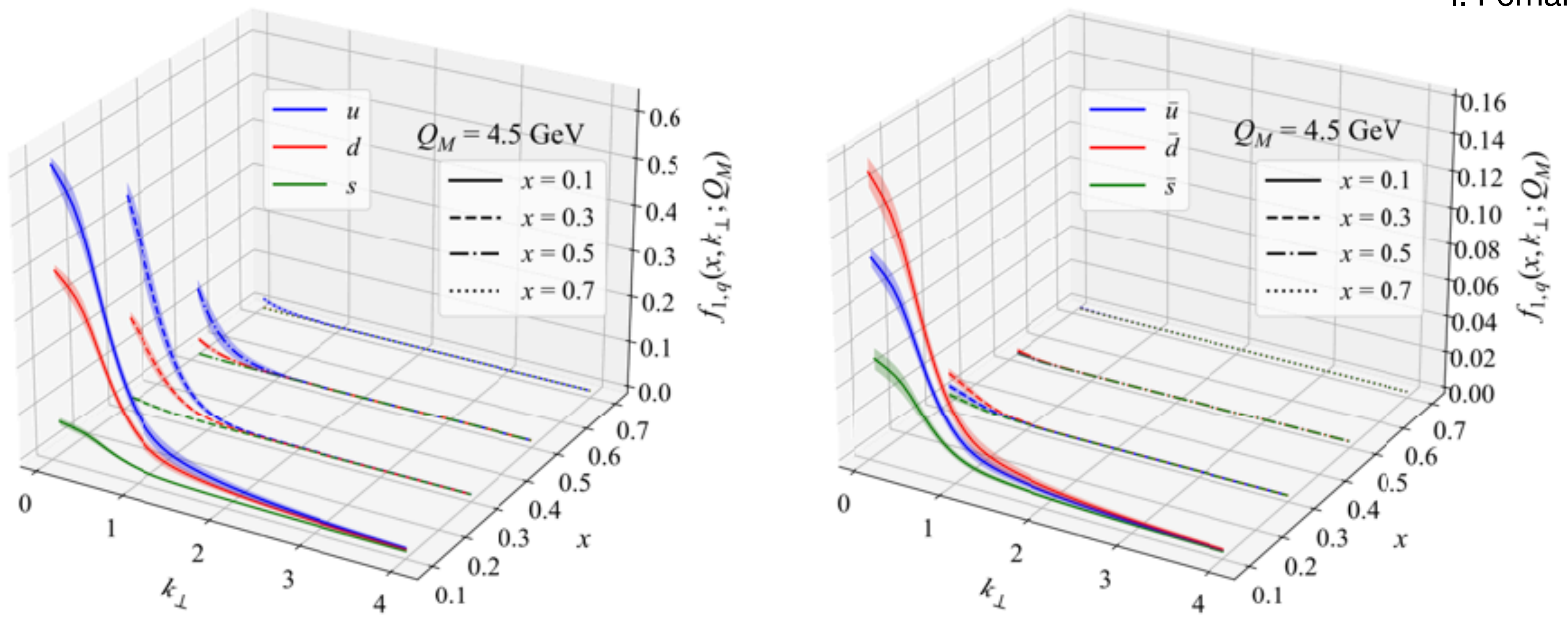


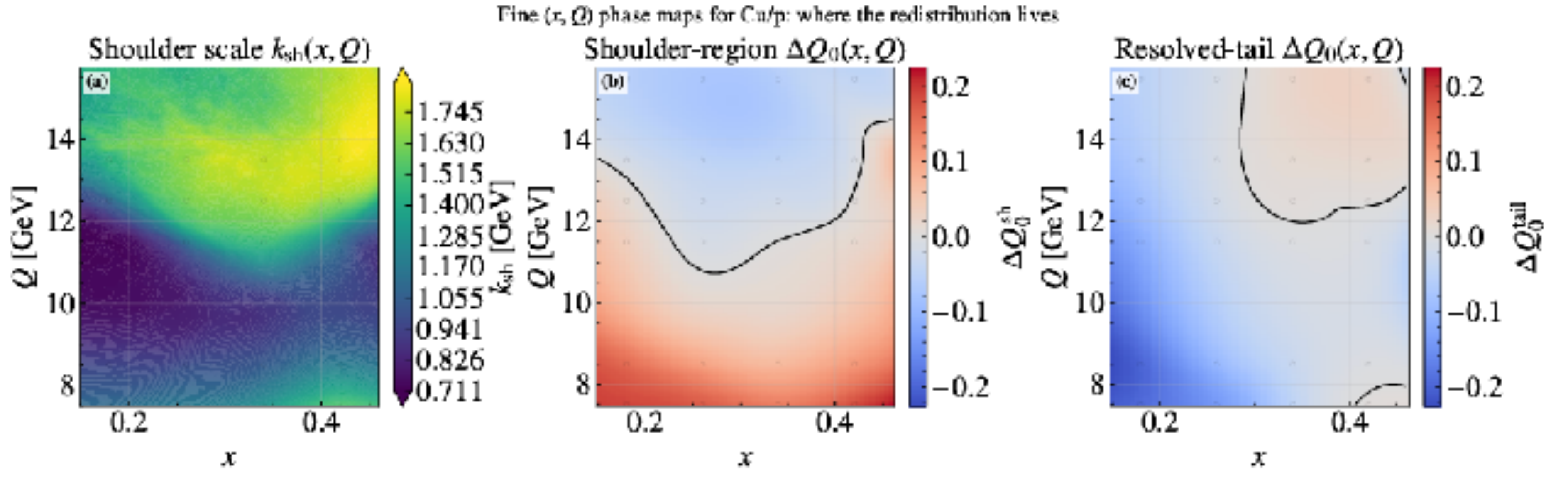


I. Fernando et al. Phys. Rev. D **113**, 096017



I. Fernando et al. Phys. Rev. D **108**, 054007





https://arxiv.org/pdf/2605.05425

https://arxiv.org/pdf/2604.10025

https://arxiv.org/pdf/2512.21761

# Some High-level Group Activities

## And the projects lead (you will not hear about here)

- Compton Form Factor (and GPD) Extraction : (**Dima Watkins**) AI drive extraction of from experimental data, Differentiable Principal-Value Inversion for Neural-Network Extraction of Generalized Parton Distributions.

- Sivers Extraction and DY based dilution factors : (**Nuwan Chaminda**) Use of SpinQuest data extraction information on the Sivers Function.

- Higher Rank Polarized Targets: Leading-twist quark and gluon TMDs and GPDs for polarized spin-3/2 targets as an exploratory first step.

# Some High-level Group Activities

## And the projects lead (you will hear about here)

- Fast NMR information extraction : (**Devin Seay**) Fast AI driven extraction providing quick (<100 ms) inference to interface with FPGA as digital receivers for direct digital synthesis, quadrature detection, filtering, and demodulation internally and configured as data acquisition for high-speed ADCs interfaced directly for capturing maximum information.

- Supervisory Agents for polarization and cryogenic controls : (**Jay Roberts**) DNP enhancement and control along with autonomous operations of complex cryogenics systems and layered with optional human in the loop monitoring and response system.

- Quantum properties of ammonia targets: (**Sujan Subedi**) Building a DFT-to-ESR workflow for polarized-target radicals: calculating g- and A-tensors for $\bullet NH_2$/$\bullet ND_2$, simulating ESR lines with EasySpin, benchmarking the $\bullet ND_2$ linewidth, testing additional radical candidates, and beginning phonon/INS/lattice-band calculations tied to spin-lattice $T_1$ relaxation; this now provides the framework to move beyond the known warm $\bullet ND_2$ center and test cold-irradiation candidates such as D•, N-related defects, mixed radicals, and trapped-charge centers against ESR linewidths, phonon coupling, and the observed higher $ND_3$ polarization.

- Past AFP results and new measurement techniques: (**Forhad Hossain**) Reporting past experimental results from UVA and the new lineshape fitting analysis of AFP manipulated signals.

- Exploring further tensor polarized experiments: (**Kenichi and Ishara**) Exploring DIS and SIDIS to look see about additional information that may be accessible with additions to the Hall C setup.

# Tensor Collab Related Activities

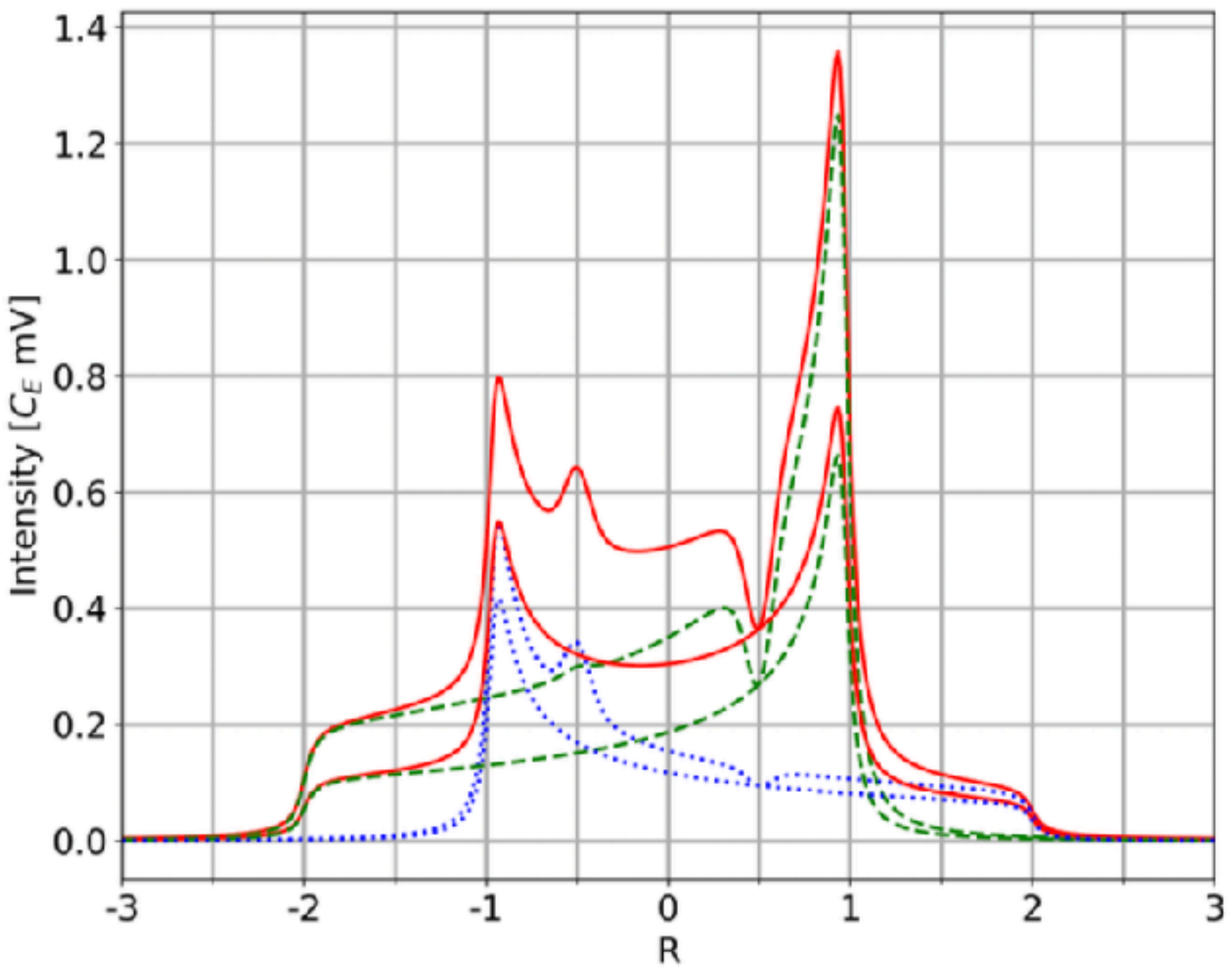
## With limited funds

- Setup purifier and get system fully function (top priority: shooting for July)
- Expand the fast AI measurement tools into fast NMR manipulation and measurement tools.
- Study theory and experimentally cold irradiated $ND_3$ to try to understand if further optimization could be possible.
- Microwave power and modulation schemes for $ND_3$ ramp up enhancement.
- AFP studies and coil passage optimization.
- Fine frequency control of ssRF.

# Simple Principles For Measurement

## Monitor and Modify in Realtime

- Quick and easy bin by bin measurements after RF pulses (assuming high power limit)
  - ***Differential binning:***
    - Breaks things up into NMR bins for fast and easy interpretation.
  - ***Rates response:***
    - For RF driven part, implies $A_{loss} = 2A_{gain}$ under high RF power limit.
  - ***Spin Temperature Consistency:***
    - Just for the hole, but assumes nothing much is changing in the other part of the line.



https://doi.org/10.1016/j.nima.2023.168177

***Polarization mechanism and diffusion model Independent***

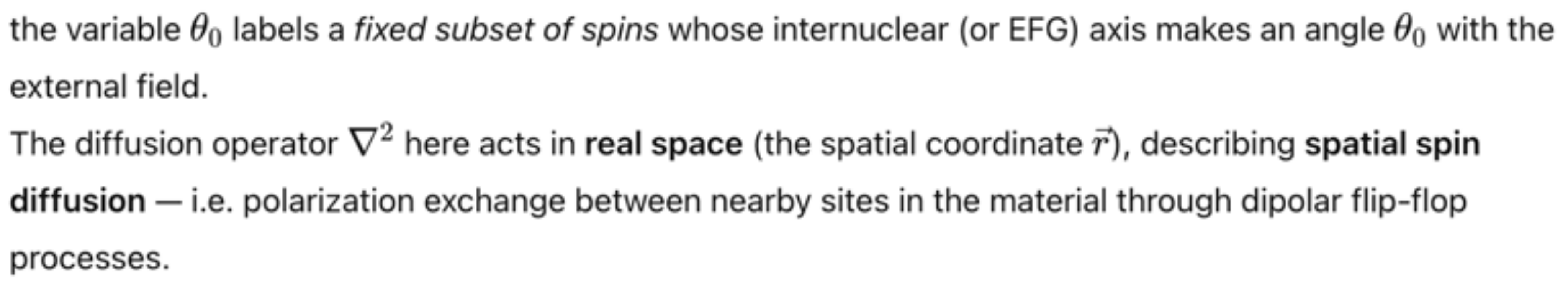
*But how do we know the error from the high power limit?*

# Characterize Spin Diffusion

## With and without DNP

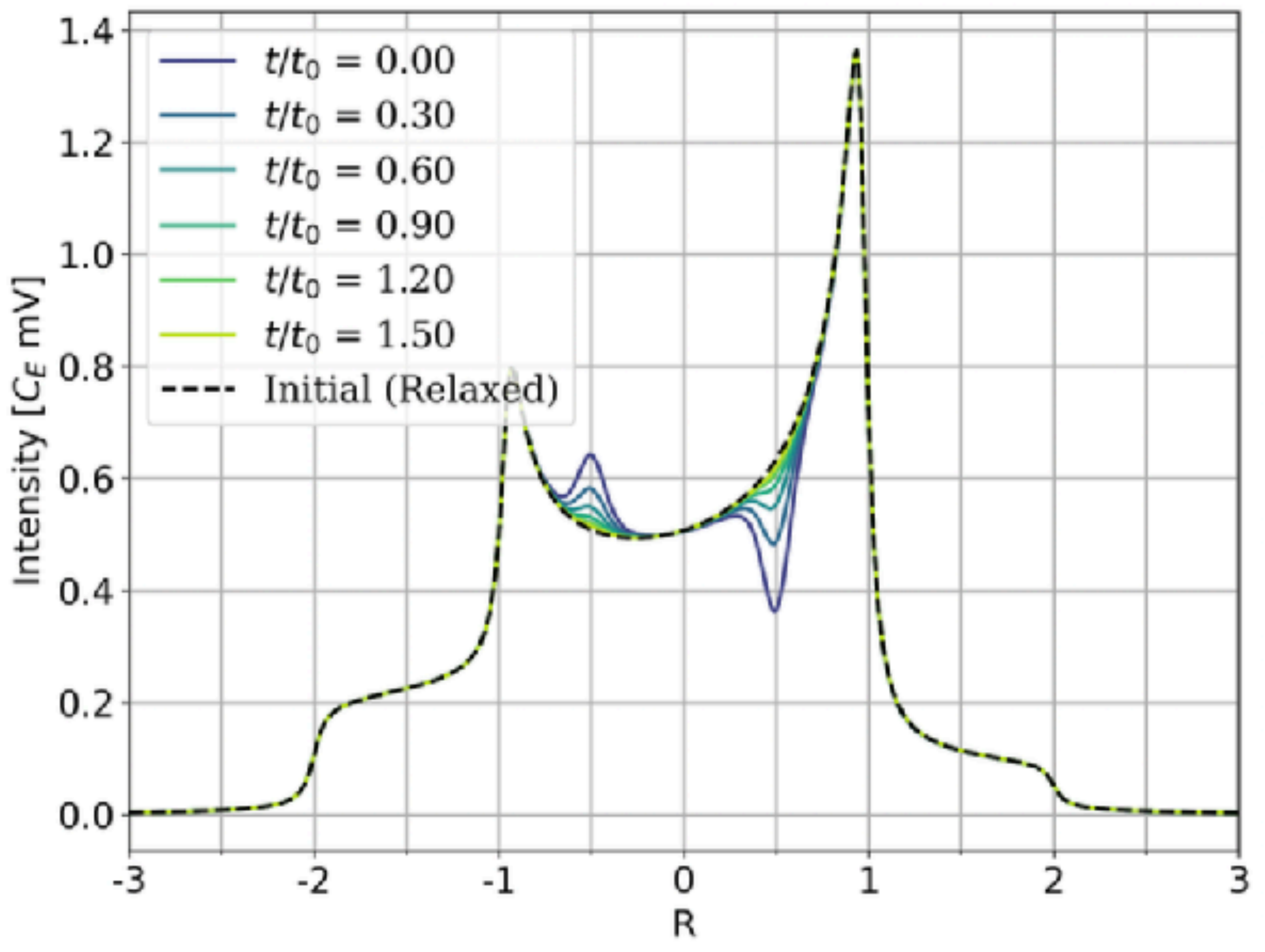
- Assume diffusion changes not only as a function of intensity but also the angle.
- Then map out from measurements at different intensity and angle to quantify.
- Stick it in the expression and test by predicting recovery under not measured scenarios.

$$\frac{dn_i(\theta_0,\vec{r})}{dt} \supset D[n_i(\theta_0,\vec{r})]\nabla^2 n_i(\theta_0,\vec{r})$$



the variable $\theta_0$ labels a *fixed subset of spins* whose internuclear (or EFG) axis makes an angle $\theta_0$ with the external field.
The diffusion operator $\nabla^2$ here acts in **real space** (the spatial coordinate $\vec{r}$), describing **spatial spin diffusion** — i.e. polarization exchange between nearby sites in the material through dipolar flip-flop processes.

https://doi.org/10.1140/epja/s10050-026-01790-y



**Continuum Laplace–Beltrami form**

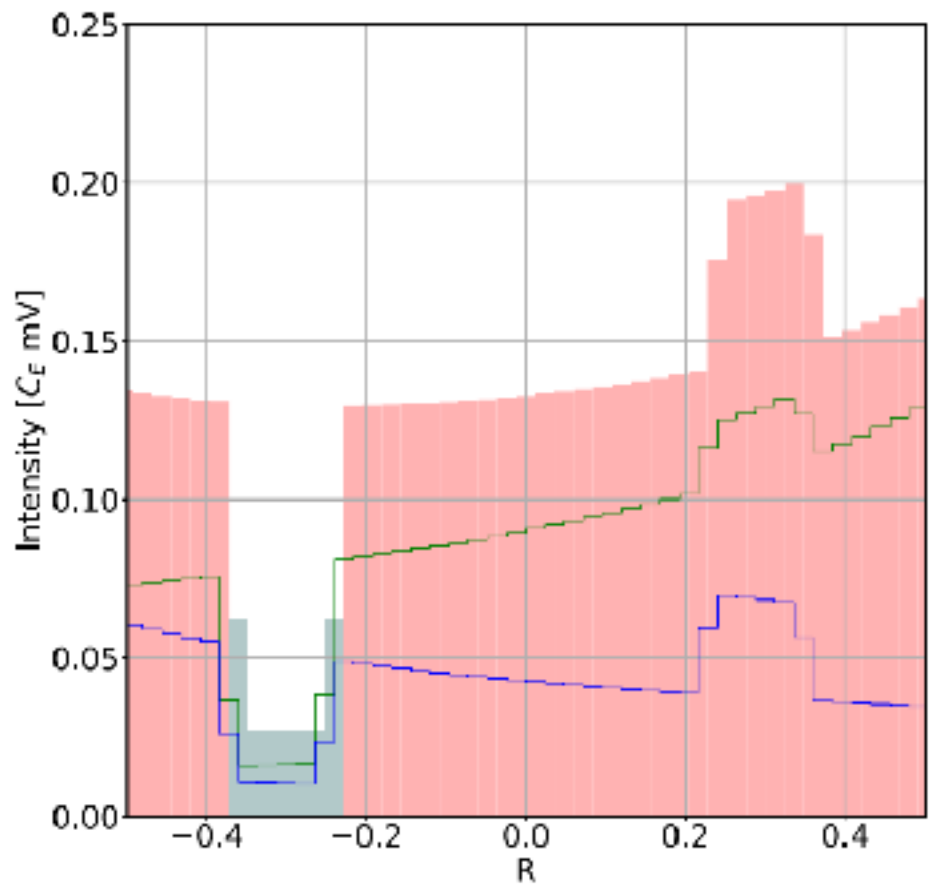
$$\left(\frac{\partial n_i}{\partial t}\right)_{\text{diff}} = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(D(\theta)\sin\theta\,\frac{\partial n_i}{\partial\theta}\right)$$

*$\theta$ is orientation of the coupled spin packets along the NMR line*

# Error from HP-limit

## Acquired bin by bin

| Target error | Required pulse duration at $f_b$ |
|---|---|
| 1% | $t_b \lesssim 0.01\,\tau_{\rm dyn}(f_b)$ |
| 5% | $t_b \lesssim 0.05\,\tau_{\rm dyn}(f_b)$ |
| 10% | $t_b \lesssim 0.10\,\tau_{\rm dyn}(f_b)$ |



$$\epsilon_{\rm sd/evol}(t_b, f_b) = \eta_Q(f_b)\left[1 - e^{-t_b/\tau_{\rm dyn}(f_b)}\right]$$

*error due to signal evolution*

$$\tau_{\rm dyn}(f_b) = \left[\frac{1}{\tau_{\rm diff}(f_b)} + \frac{1}{T_1(f_b)}\right]^{-1}$$

*dynamic time at frequency bin*

$$t_b \lesssim -\tau_{\rm dyn}(f_b)\ln\left[1 - \frac{\epsilon_{\rm tol}}{\eta_Q(f_b)}\right]$$

*High power limit time threshold*

$$\epsilon_{\rm sd/evol}(t_b, f_b) \approx \eta_Q(f_b)\frac{t_b}{\tau_{\rm dyn}(f_b)} \qquad t_b \ll \tau_{\rm dyn}(f_b)$$

*contribution from over-burn*

$$\epsilon_{\rm center}(t_b, f_b) = \frac{|a_c(t_b, f_b) - a_{\rm tar}(f_b)|}{a_{\rm tar}(f_b)}$$

*Total error at that bin*

$$\epsilon_{\rm total}(t_b, f_b) \approx \epsilon_{\rm center}(t_b, f_b) + \eta_Q(f_b)\left[1 - e^{-t_b/\tau_Q(f_b)}\right]$$

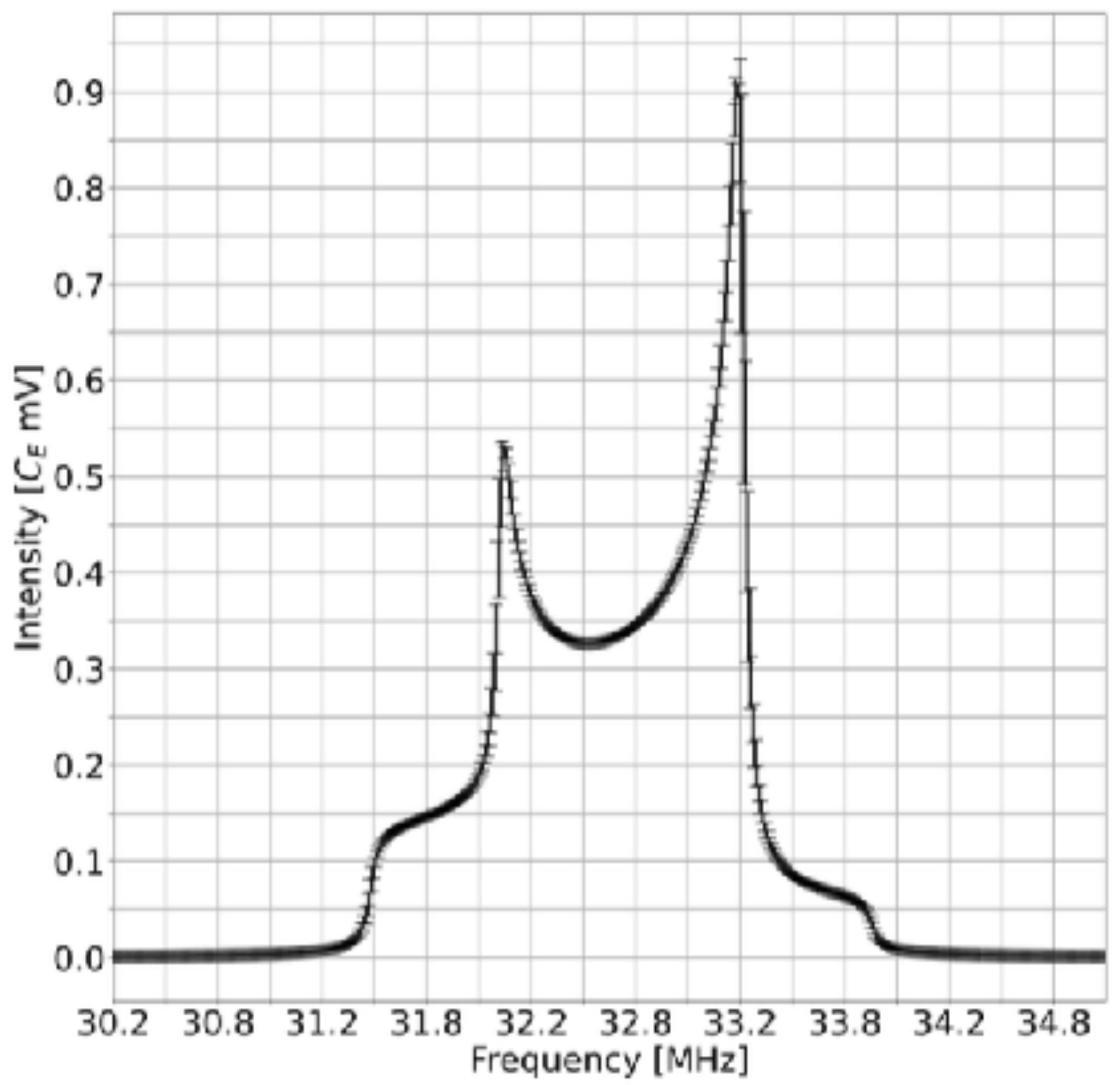
| Burn time | error | Practical interpretation |
|---|---|---|
| 0.05 s | 0.10% | Safely high-power / pulse-like |
| 0.10 s | 0.20% | Safely high-power / pulse-like |
| 0.20 s | 0.40% | Very small correction |
| 0.30 s | 0.60% | Still essentially negligible |
| 0.50 s | 1.00% | Chosen high-power cutoff |
| 0.75 s | 1.50% | Small but no longer zero |
| 1.00 s | 1.99% | Correction should be tracked |
| 1.50 s | 2.97% | Noticeable correction |
| 2.00 s | 3.94% | Not negligible; usable with correction |
| 3.00 s | 5.85% | Significant dynamic error |
| 5.00 s | 9.56% | Long-burn regime |
| 10.00 s | 18.21% | Strongly model-dependent |
| 20.00 s | 33.10% | Approaching driven-equilibrium behavior |

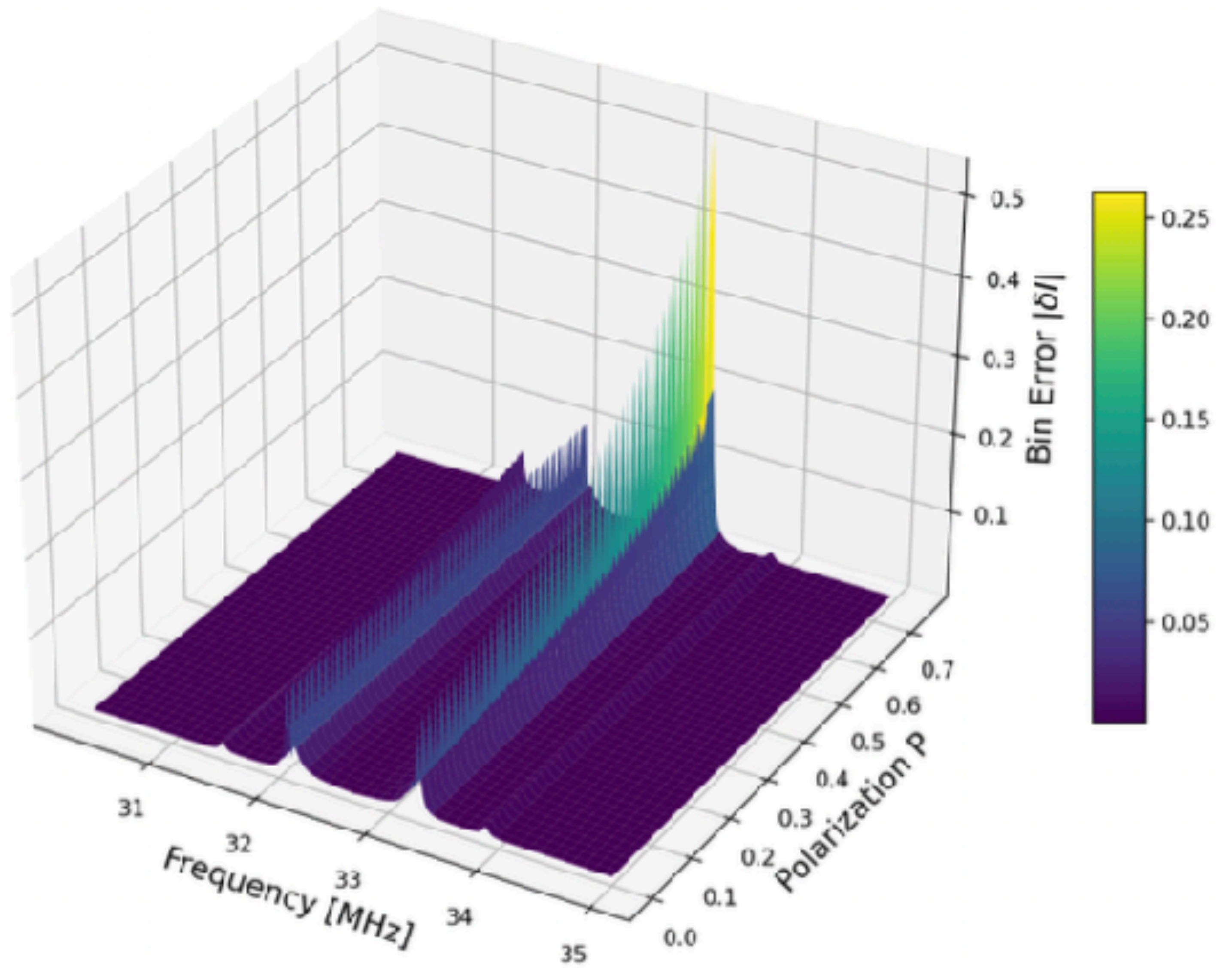
*Each error correlates to two bin*

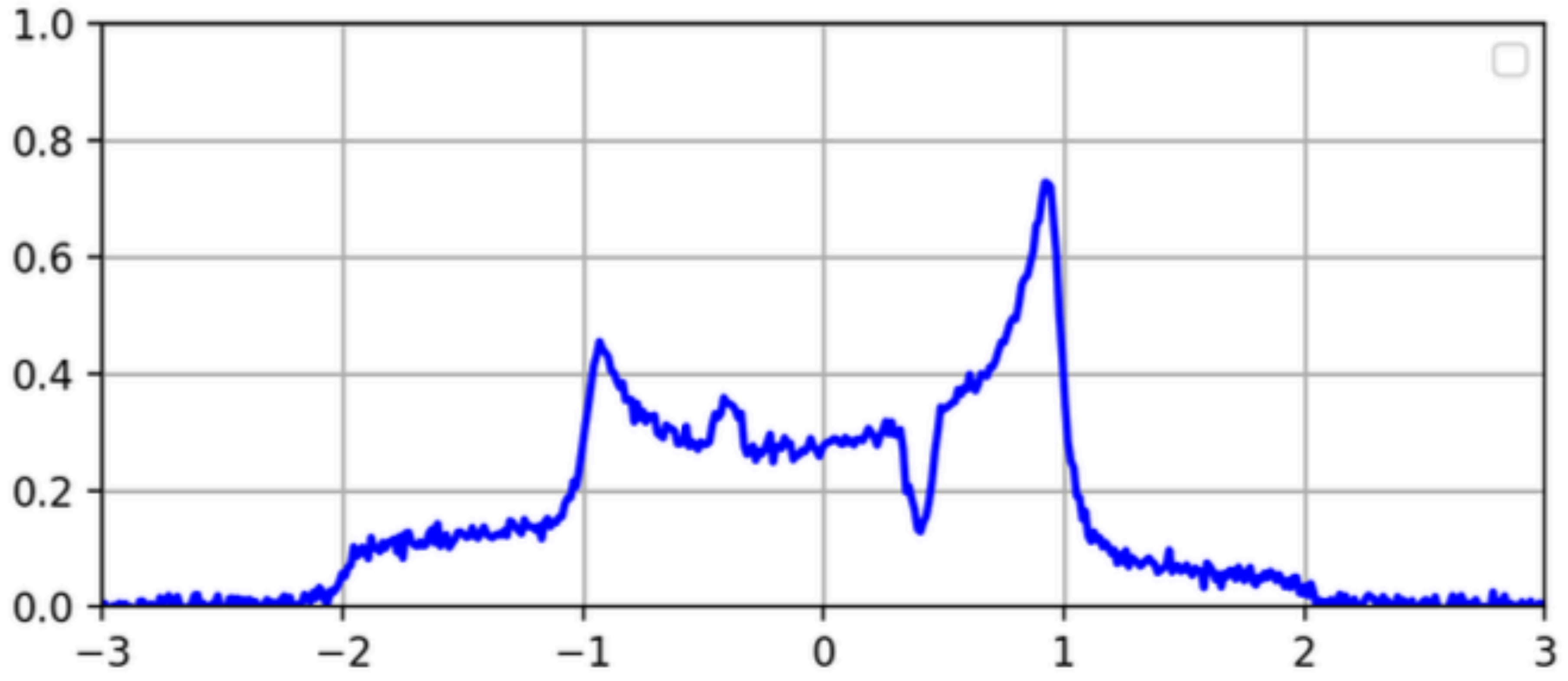
# How To Make Sense out of NMR data

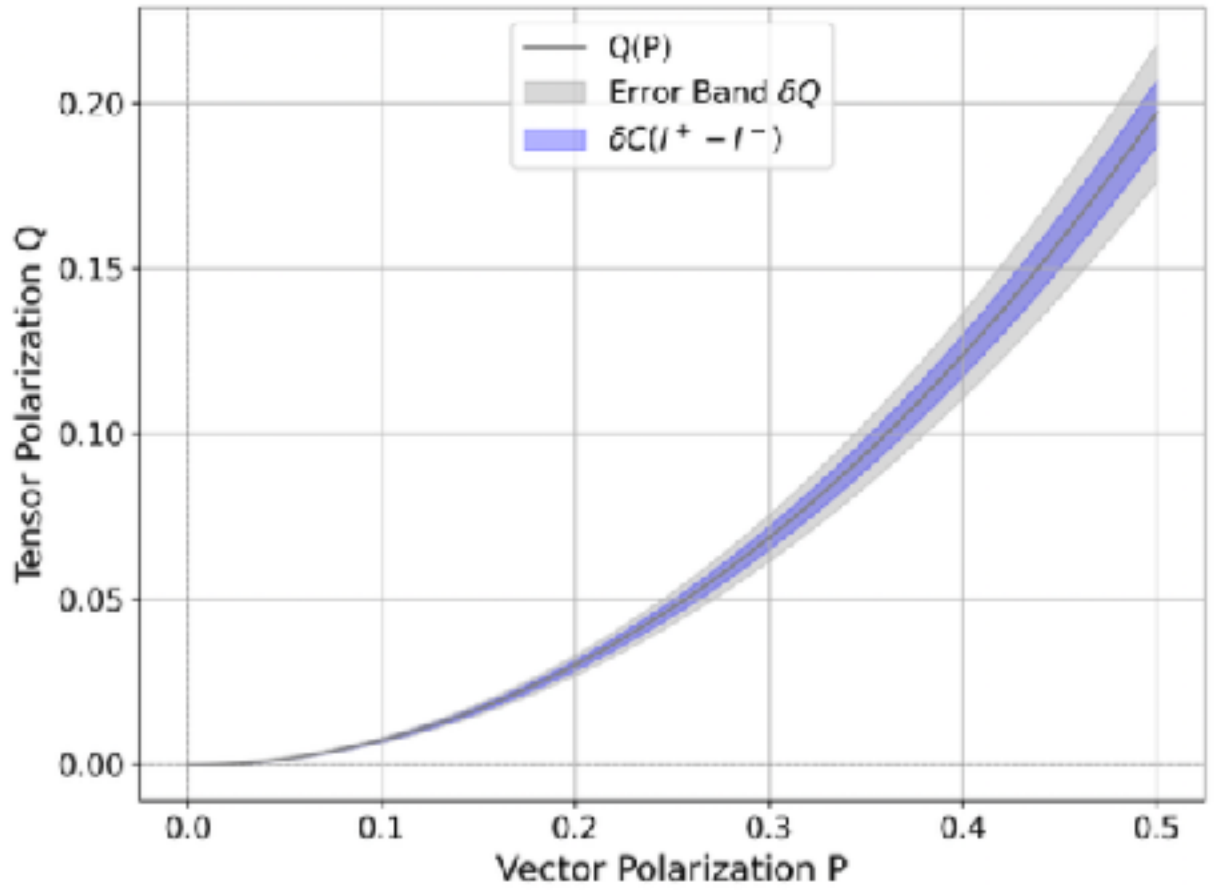
## Error specific to ss-RF

- Bin Error (from differential binning) - smaller bins…
- Changes in signal during NMR (sensitive to sweep rate)
- Averaging over sweeps is greater error than not
- Burning bin error (lineshape and evolution)





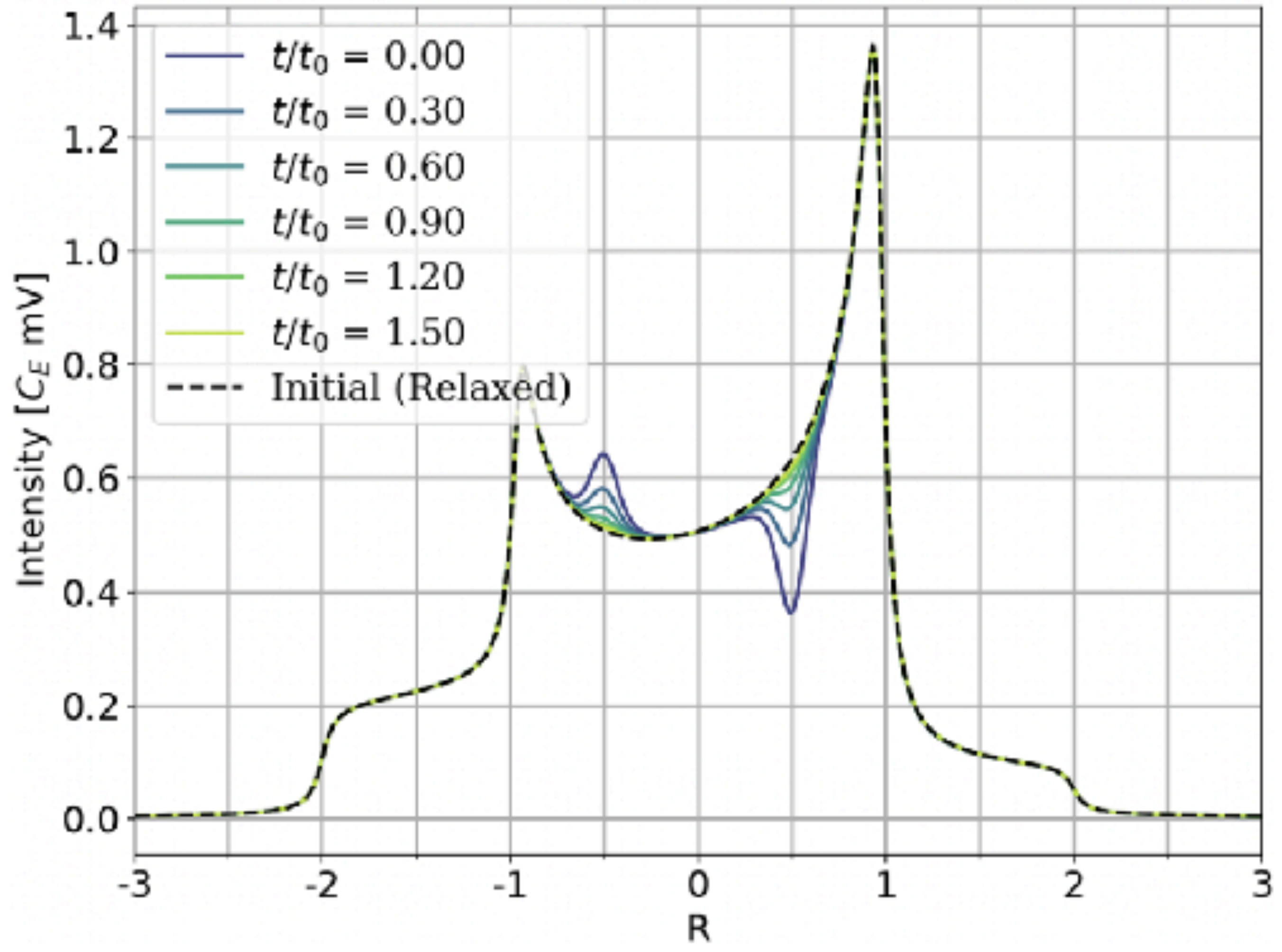


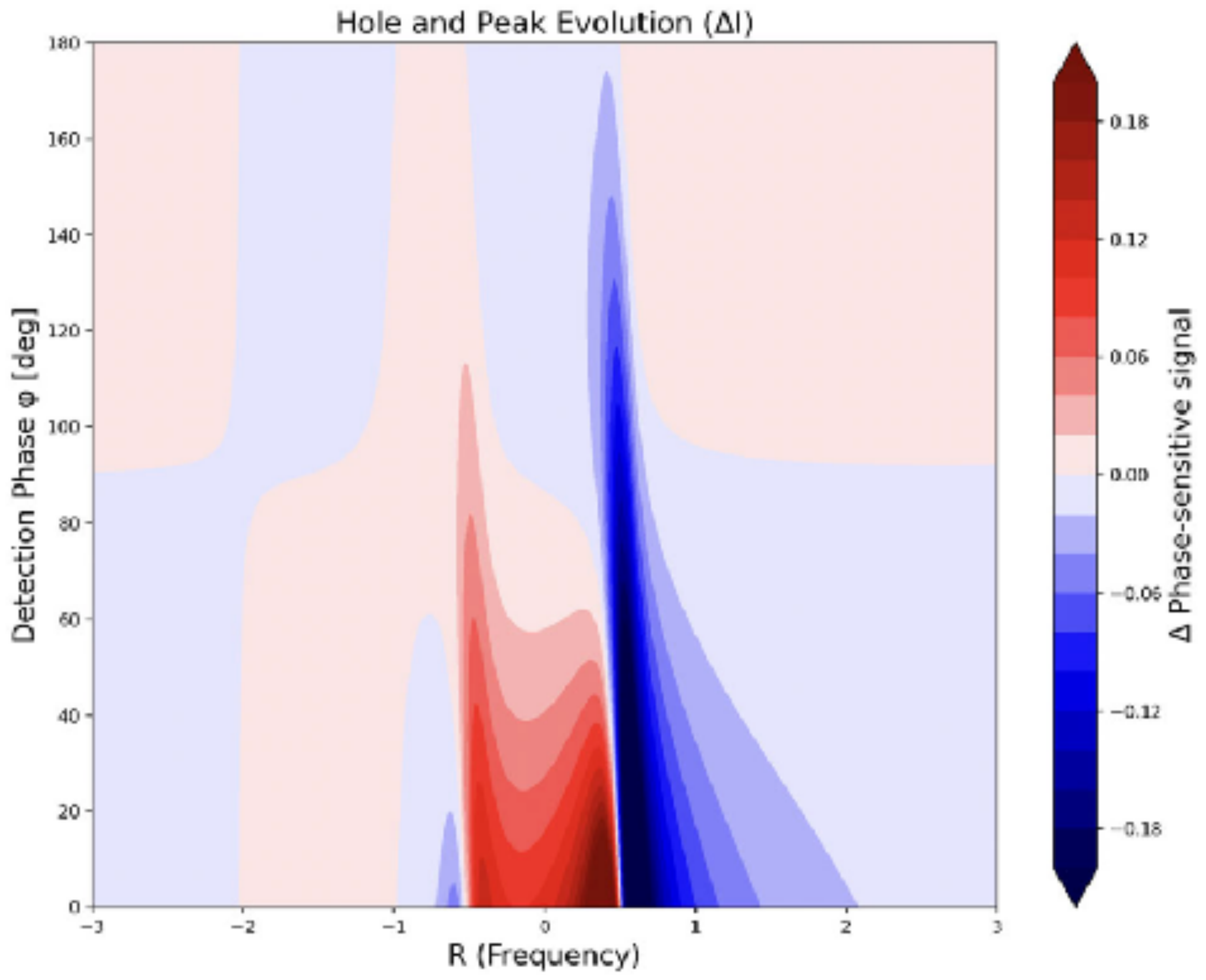


# Resolving Bin Errors

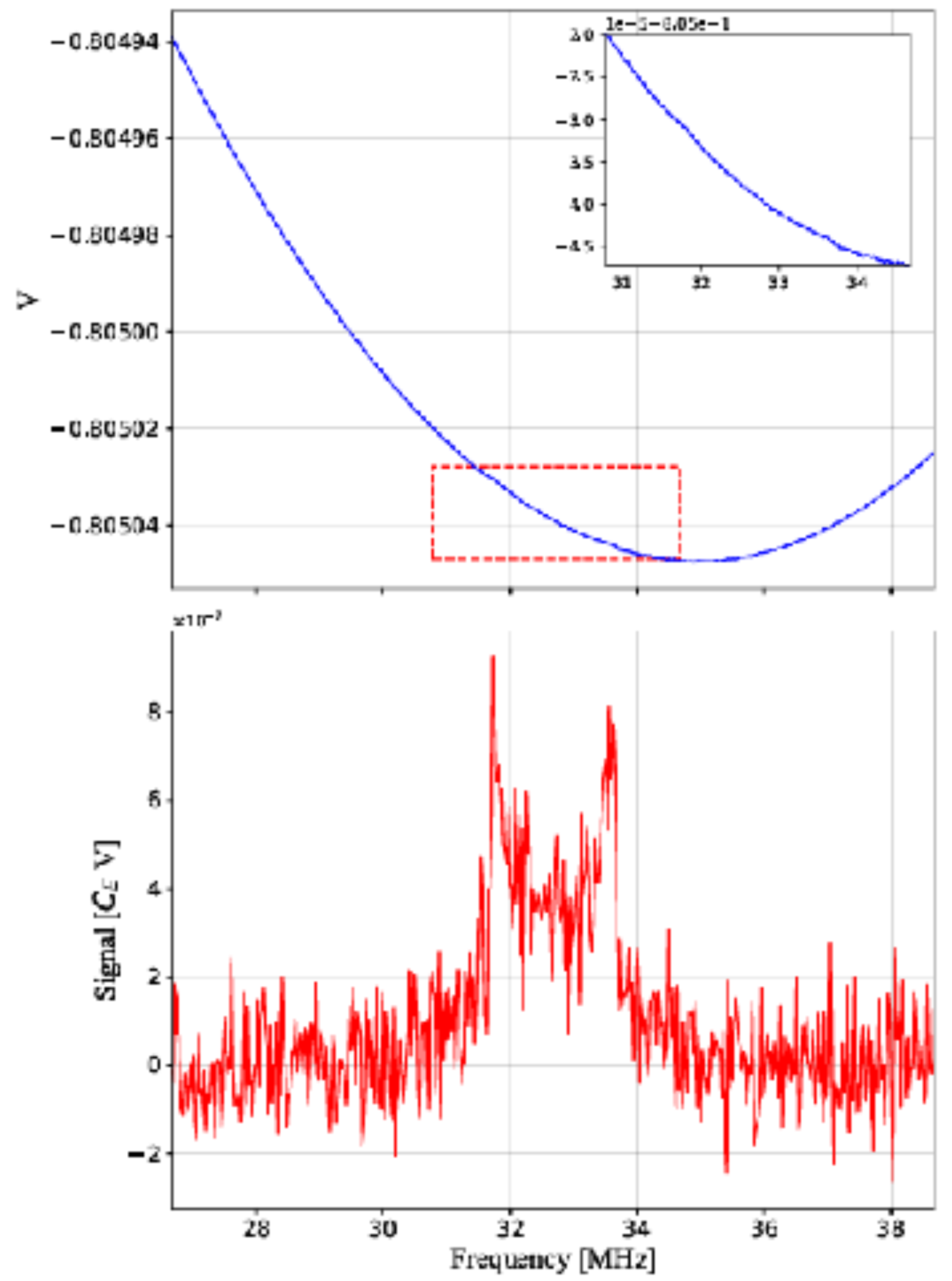
## With more…

- More information
  - More bins
  - Multiple phase measurements
  - More time steps





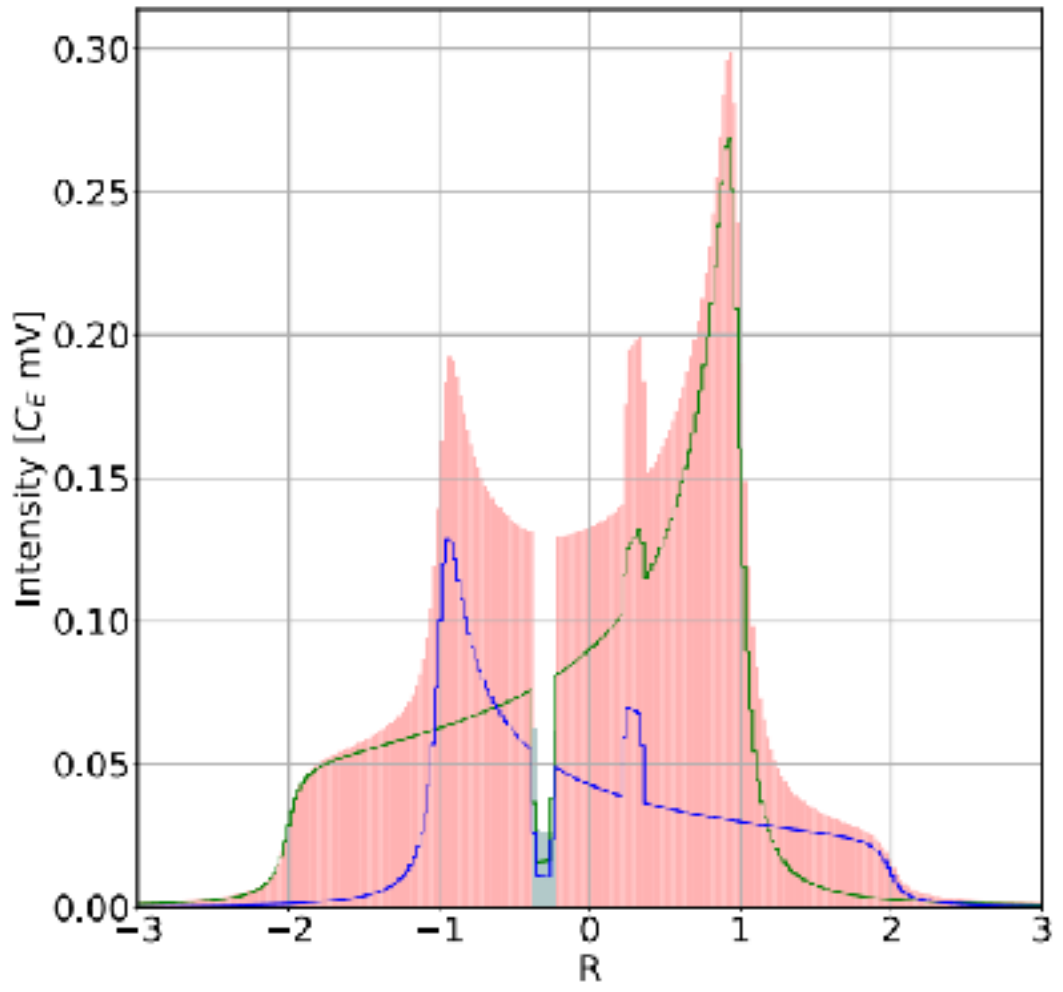
- Turn into time sequenced data
  - Many larger error time steps
  - Much more signal information
  - Much more evolution details
  - CNN…

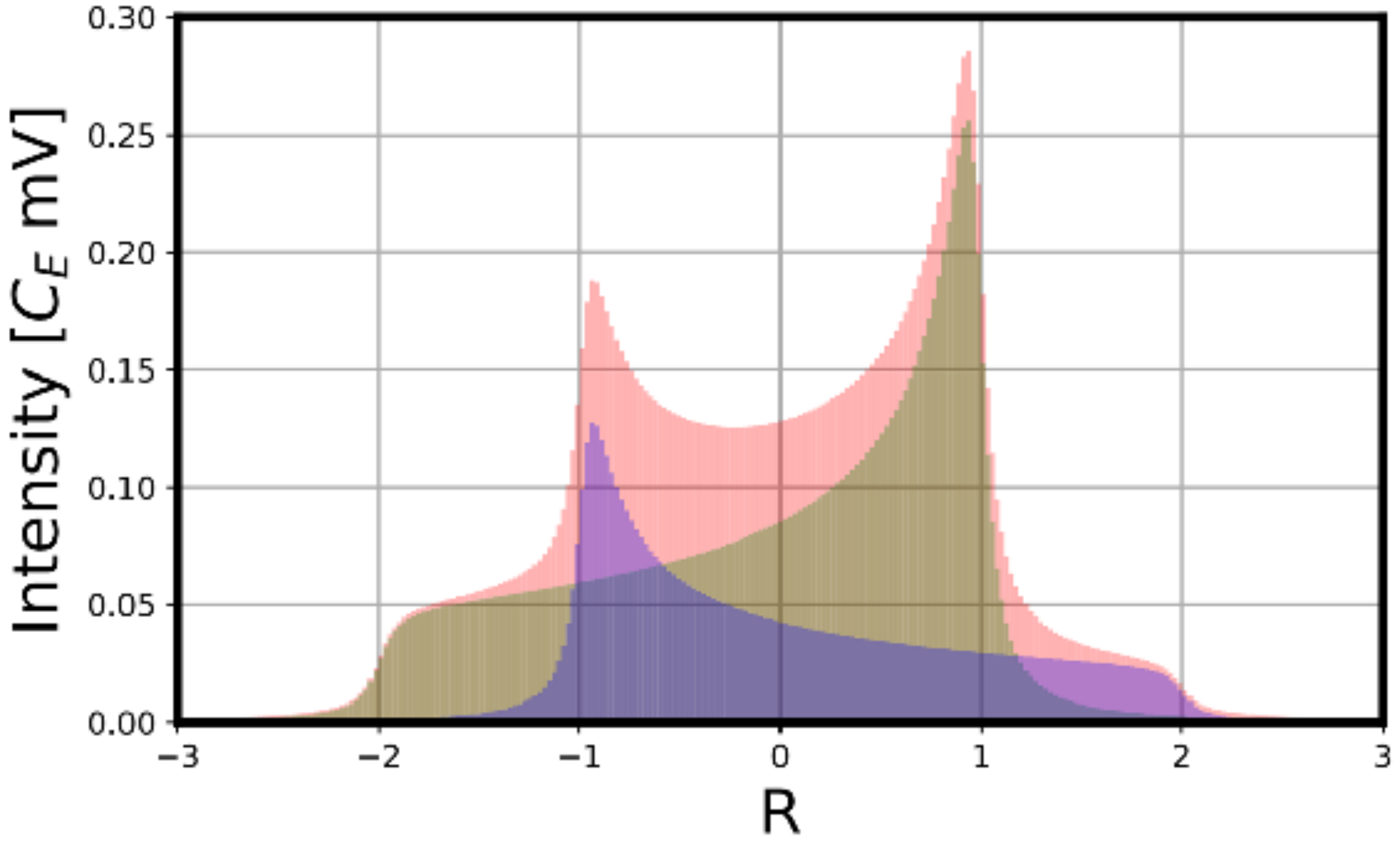


# Putting it all Together

## Without realtime evolution

- Differential binning with all the tricks in place
  - Calibrate to interpret differential areas.
  - Use STC-method for high precision measurements.
  - Assumes application of power sensitive pulses.
  - High power, short pulses, narrow width (for shaping).
  - So best measurement, immediately after pulse.

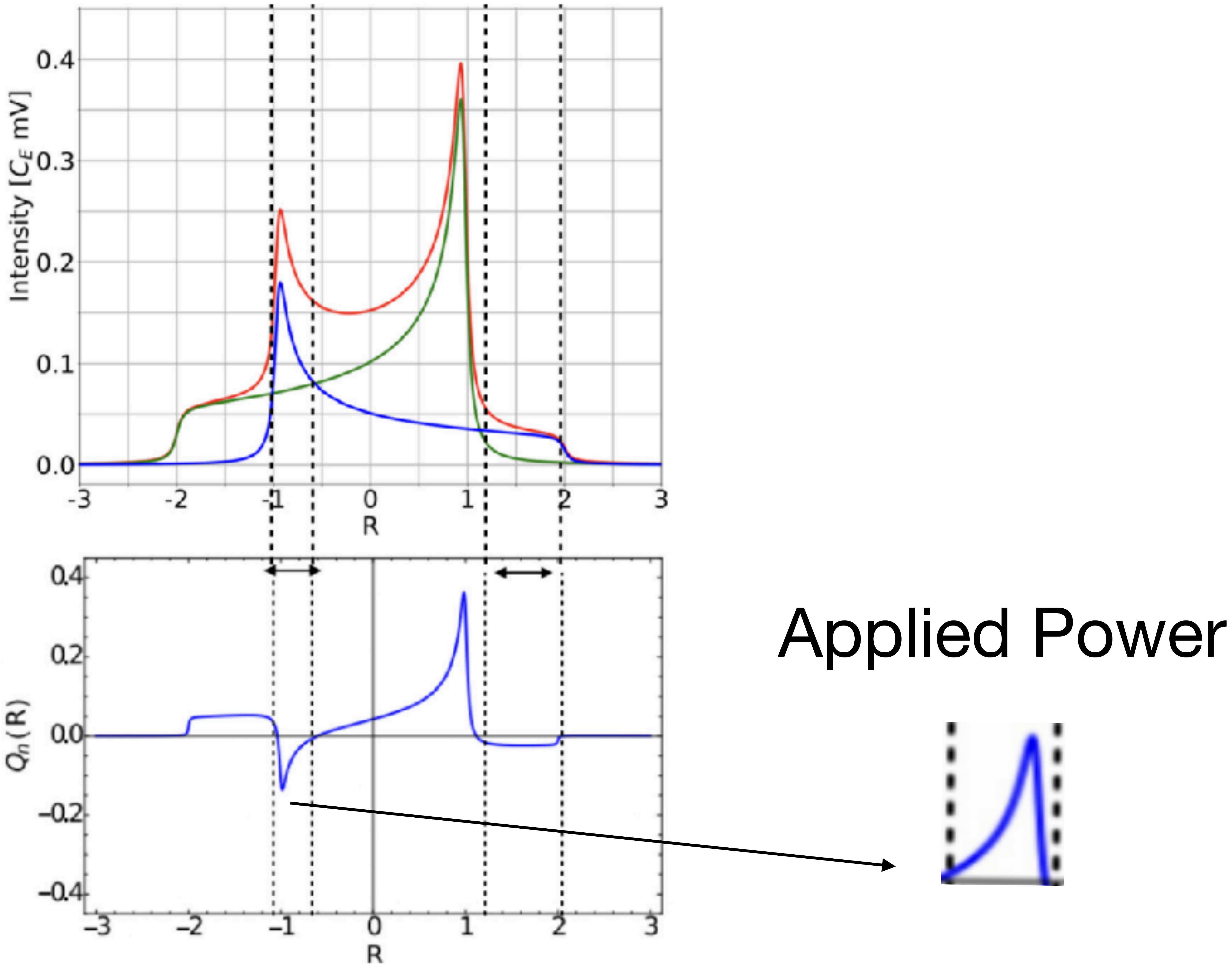




# Experimental Running

## Assuming low budget option (but many other possibilities)

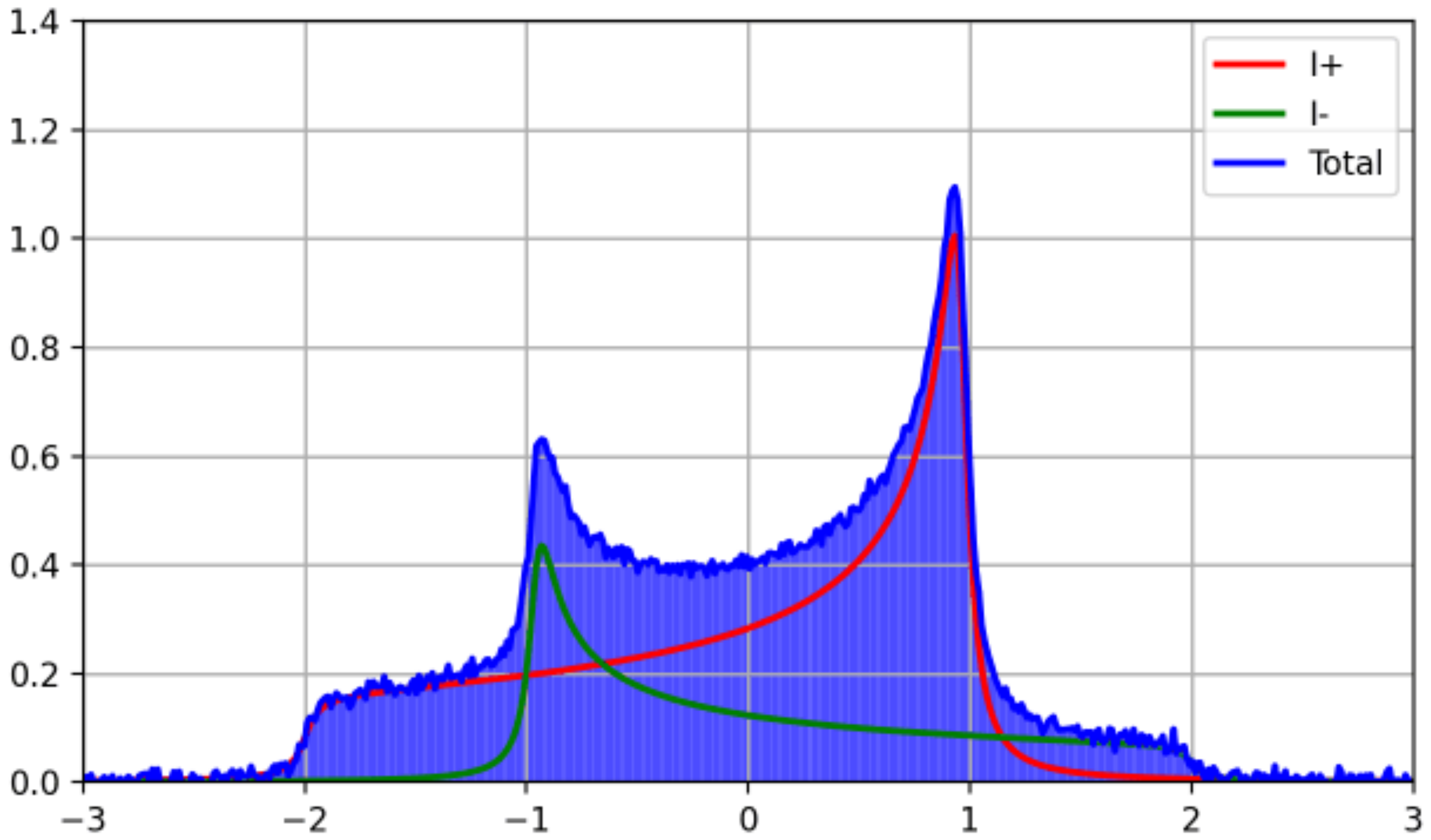
- Protect NMR.
- Apply ss-RF as a function of power profile defined by Q(R) in the sweep pulses in the high power limit using the AFP coil rather than specialized NMR.
- Have fast DAQ to do high averaging of many sweeps quickly.
- Update sequence per bin and power profile as system evolves under DNP and radiation damage.
- Whats needed: Optimized coil (for both AFP and ss-RF), amplifier, generator, maybe upgrade to NMR DAQ, automated software to adaptively control power profile and pulse sequences.

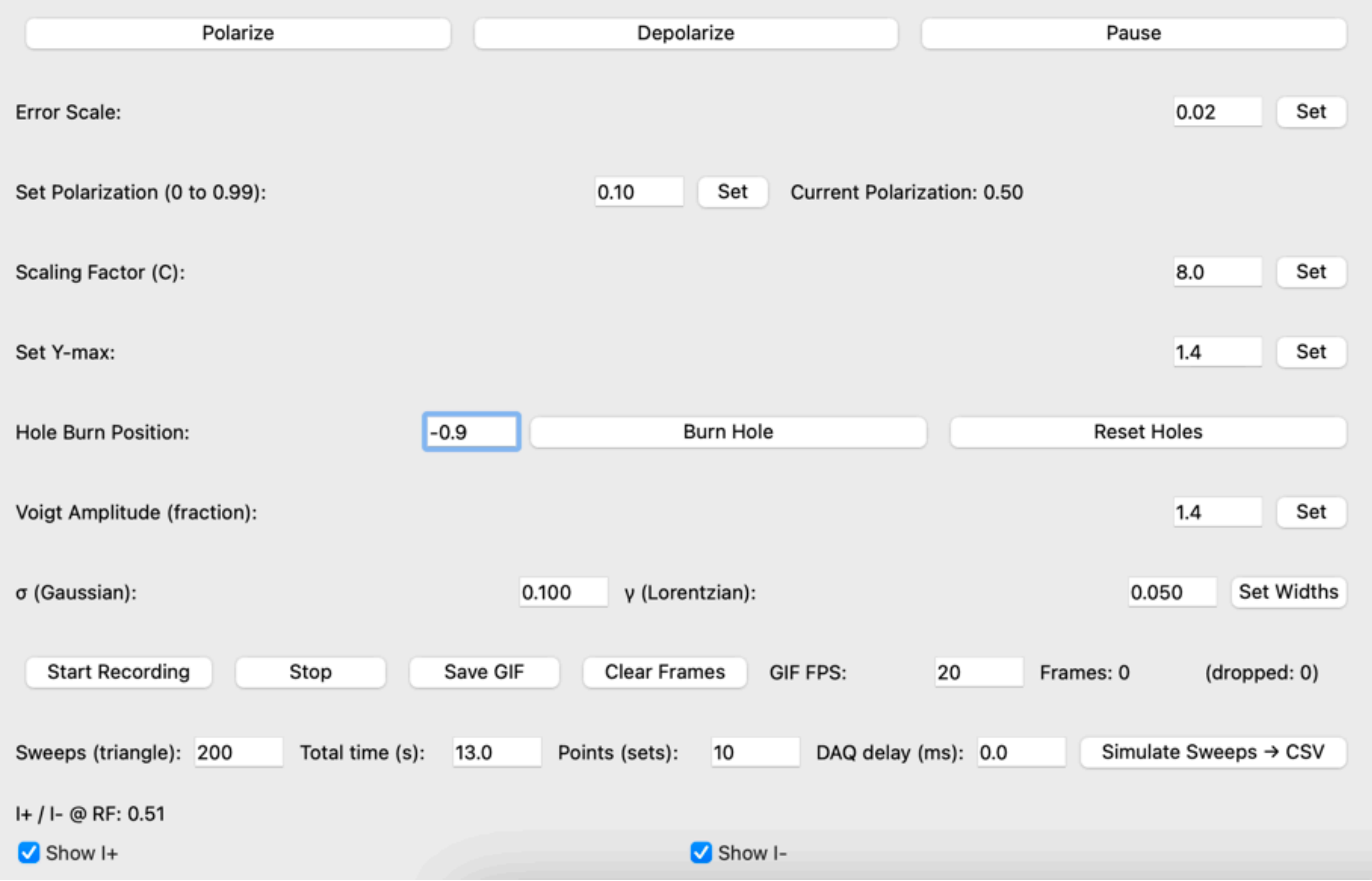


# Realtime Simulations

## With simulated sweep rate and DAQ time

- Needed to evaluate errors associated with loss of information during system evolution.





Error Scale: 0.02

Set Polarization (0 to 0.99): 0.10 Current Polarization: 0.50

Scaling Factor (C): 8.0

Set Y-max: 1.4

Hole Burn Position: -0.9

Voigt Amplitude (fraction): 1.4

σ (Gaussian): 0.100 γ (Lorentzian): 0.050

GIF FPS: 20 Frames: 0 (dropped: 0)

Sweeps (triangle): 200 Total time (s): 13.0 Points (sets): 10 DAQ delay (ms): 0.0

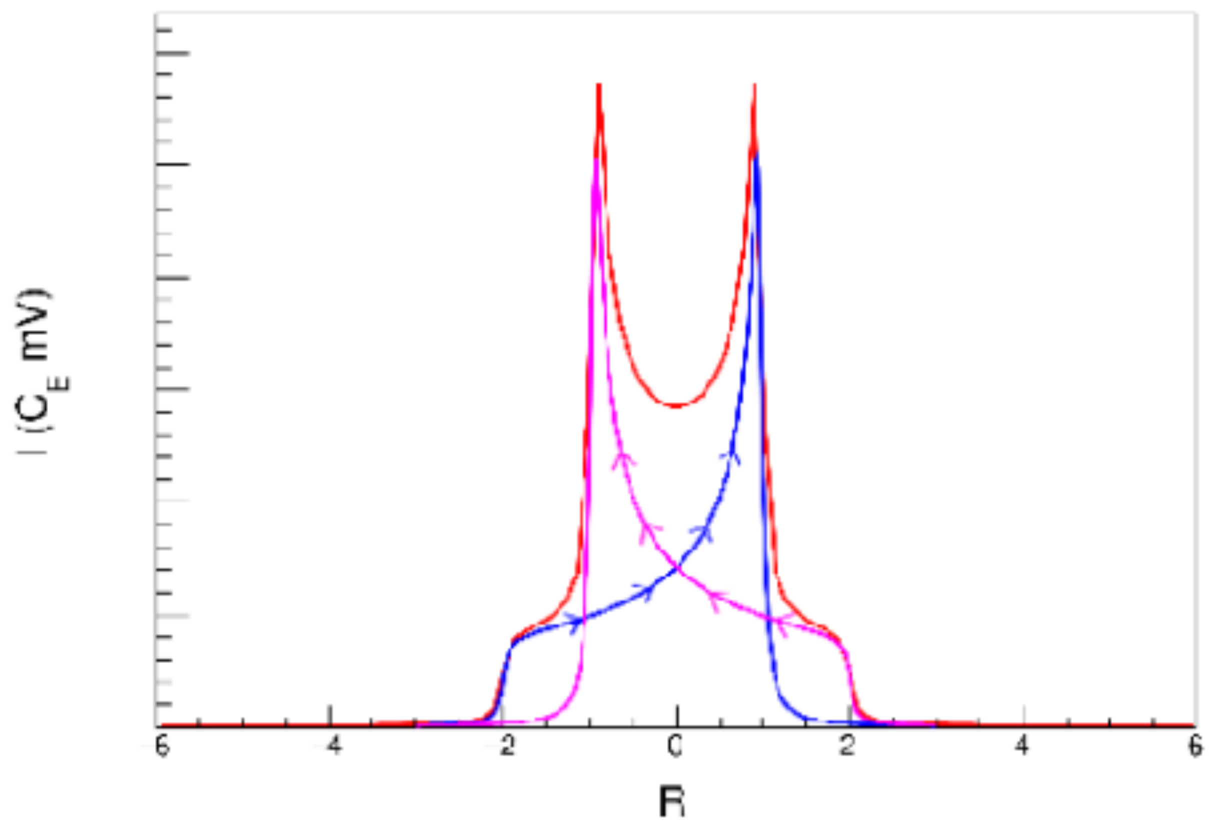
I+ / I- @ RF: 0.51

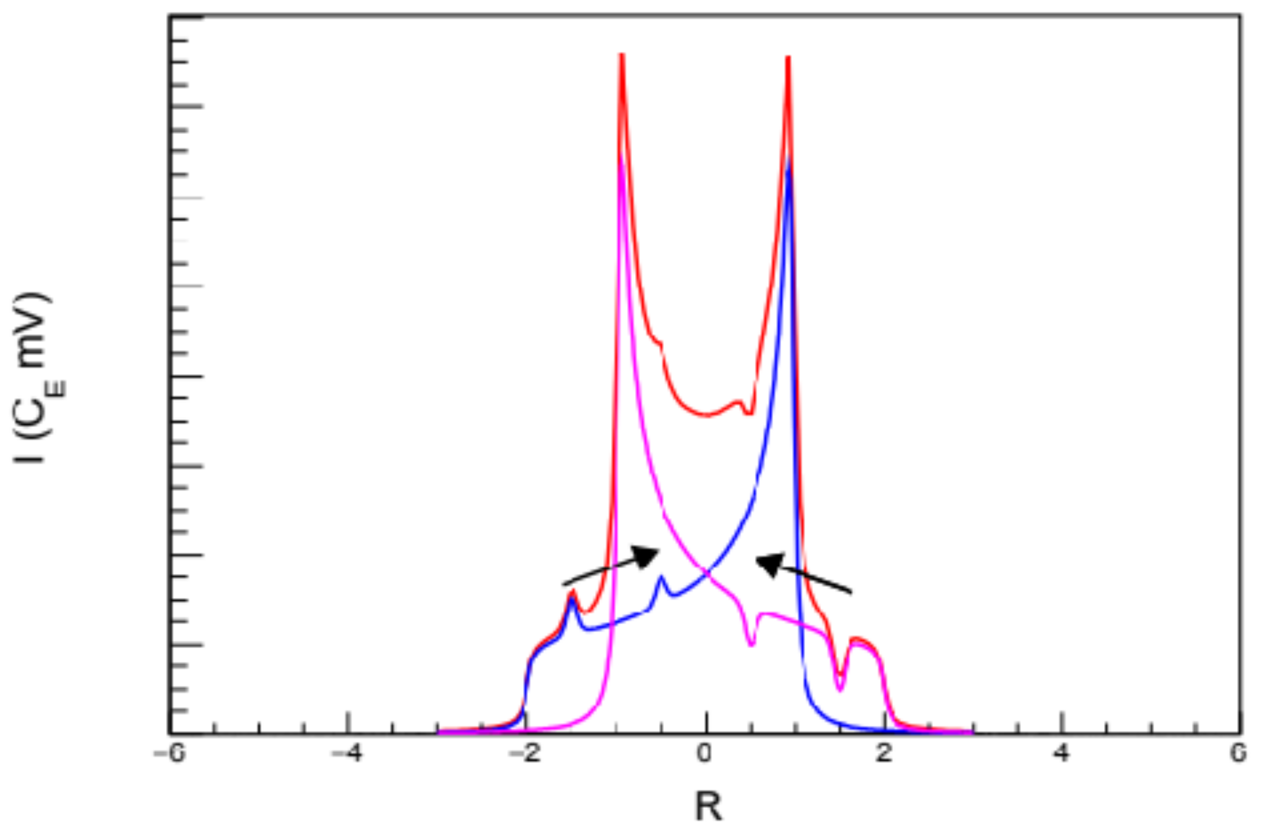
☑ Show I+ ☑ Show I-

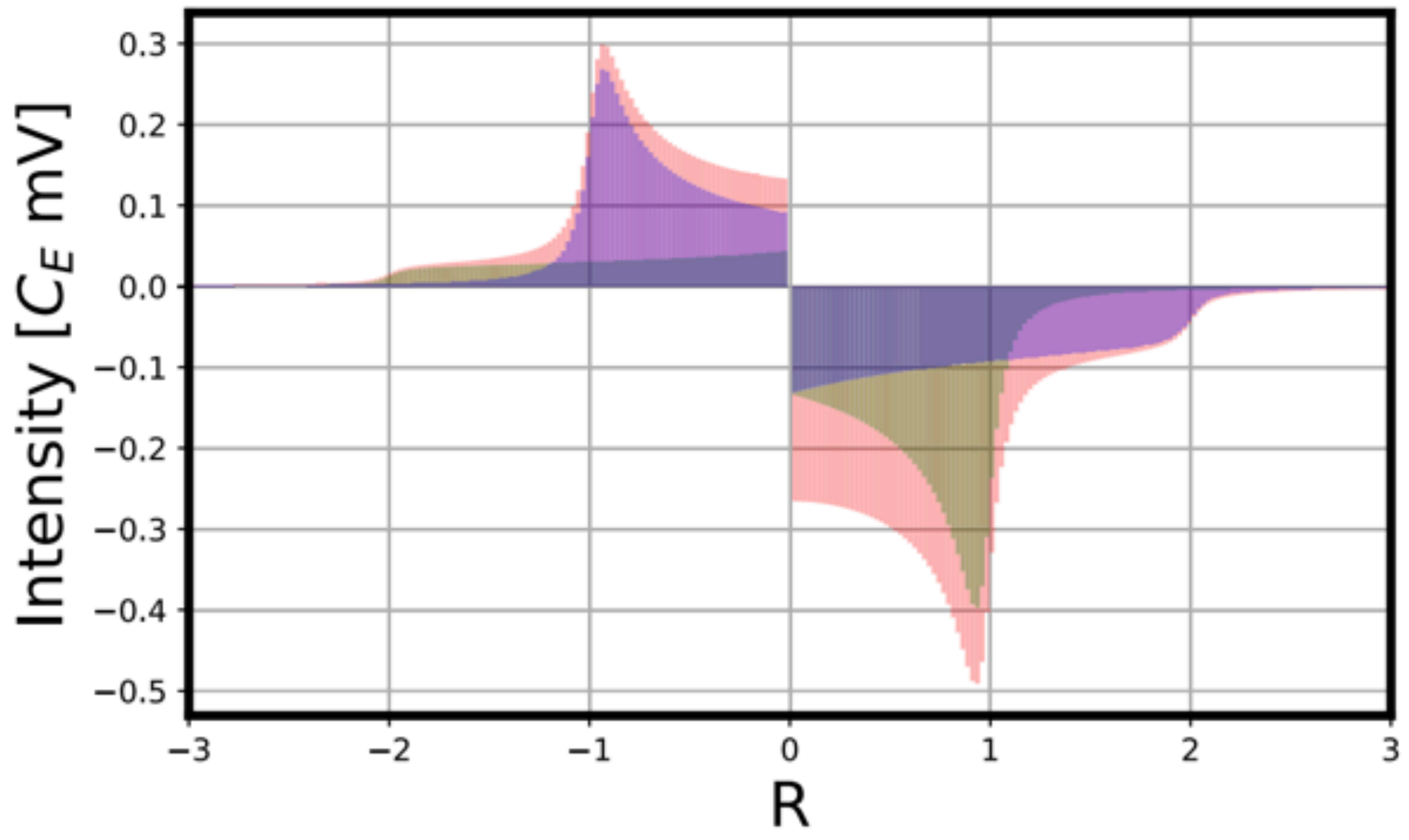
# Higher Tensor Polarization Benchmark

## Under certain conditions

- Both higher max and higher average Pzz are possible and I still think its wise to be putting effort into these other tricks…

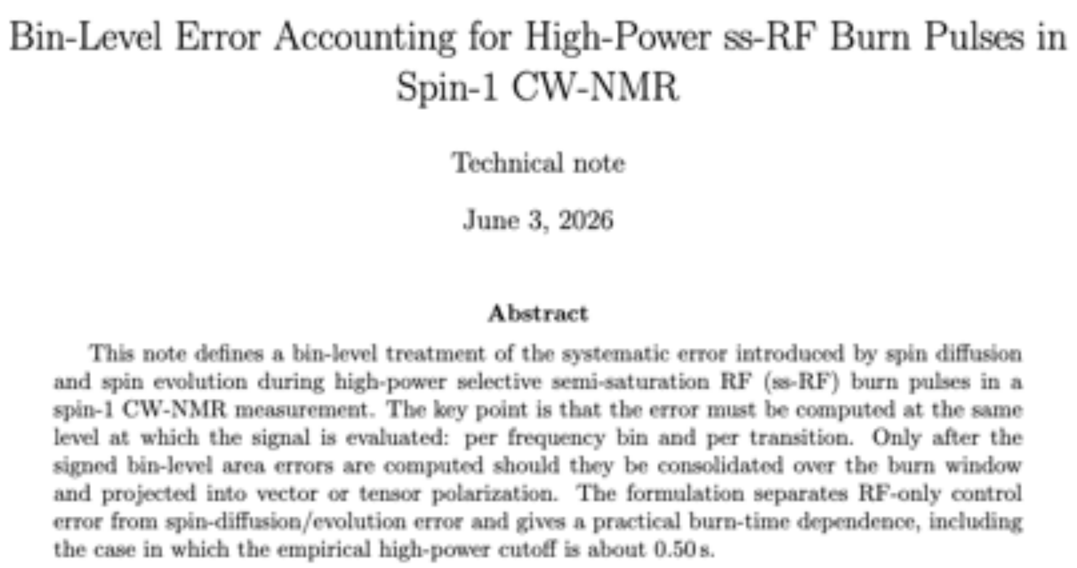






- Second Generation Tensor Polarized target : ~0.5 K (probably supercooled He-4) with higher magnetic holding field ~6.5T. Especially for longitudinal a greater holding field using a solenoid type is very practical. Run at lower current $I \lesssim 30\ \mathrm{nA}$
  - Significant expense and R&D…

# Summary



Bin-Level Error Accounting for High-Power ss-RF Burn Pulses in Spin-1 CW-NMR

Technical note

June 3, 2026

**Abstract**

This note defines a bin-level treatment of the systematic error introduced by spin diffusion and spin evolution during high-power selective semi-saturation RF (ss-RF) burn pulses in a spin-1 CW-NMR measurement. The key point is that the error must be computed at the same level at which the signal is evaluated: per frequency bin and per transition. Only after the signed bin-level area errors are computed should they be consolidated over the burn window and projected into vector or tensor polarization. The formulation separates RF-only control error from spin-diffusion/evolution error and gives a practical burn-time dependence, including the case in which the empirical high-power cutoff is about 0.50 s.

- We understand ND3 and the lineshape theory better than ever before.
- We understand how to Tensor Enhance better than every before.
- We understand how to configure run cycles for these types of experiments better than ever before.
- We understand how to measure the error from manipulated signals
- We understand how to mitigate the ss-RF specific errors
- What’s next?