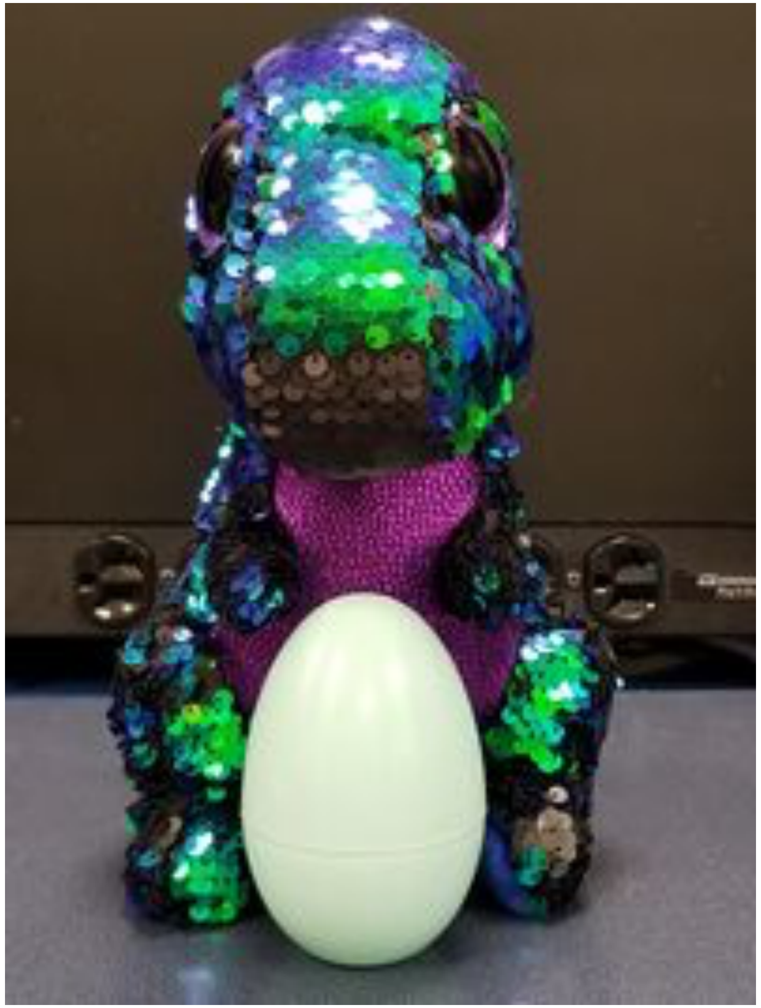
Outlook for CREX



Don Jones *for the CREX collaboration*

January 2021

Hall A Collaboration Meeting

Temple University

Jefferson Lab

CREX Overview

- Sister experiment to PREX-2 measuring the neutron skin of Ca-48 (doubly magic and well understood and precisely measured atom)
- Finished taking data Sept 2020
- Measured parity-violating (PV) asymmetry to get at neutron distribution
  - Weak charge of neutron ~1, and proton ~0.07 so weak charge distribution close to neutron distribution
- In Born approximation, PV asymmetry proportional to weak form factor (charge form factor accurately known)

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \sim \left\{ 1 - \boxed{\frac{Q^2}{6}\left[\langle r_n^2 \rangle - \langle r_p^2 \rangle\right]} \right\} \ll 1$$

- Coulomb corrections significant but precisely calculated
- Measurement at single low Q^2 allows one to infer $F_W(Q^2)$ and from that the weak radius

CREX Parameters	Values
Avg Scattering Angle (Lab)	4.6 degrees
Q^2	$0.03\ (\mathrm{GeV/c})^2$
Beam current	150 μA
Beam energy	2.178 GeV
Longitudinal polarization	>85%
Helicity flip rate	120 Hz

Motivation for CREX

Ca-48 nucleus is doubly magic and so within reach of *ab initio* (based on NN and 3N) calculations

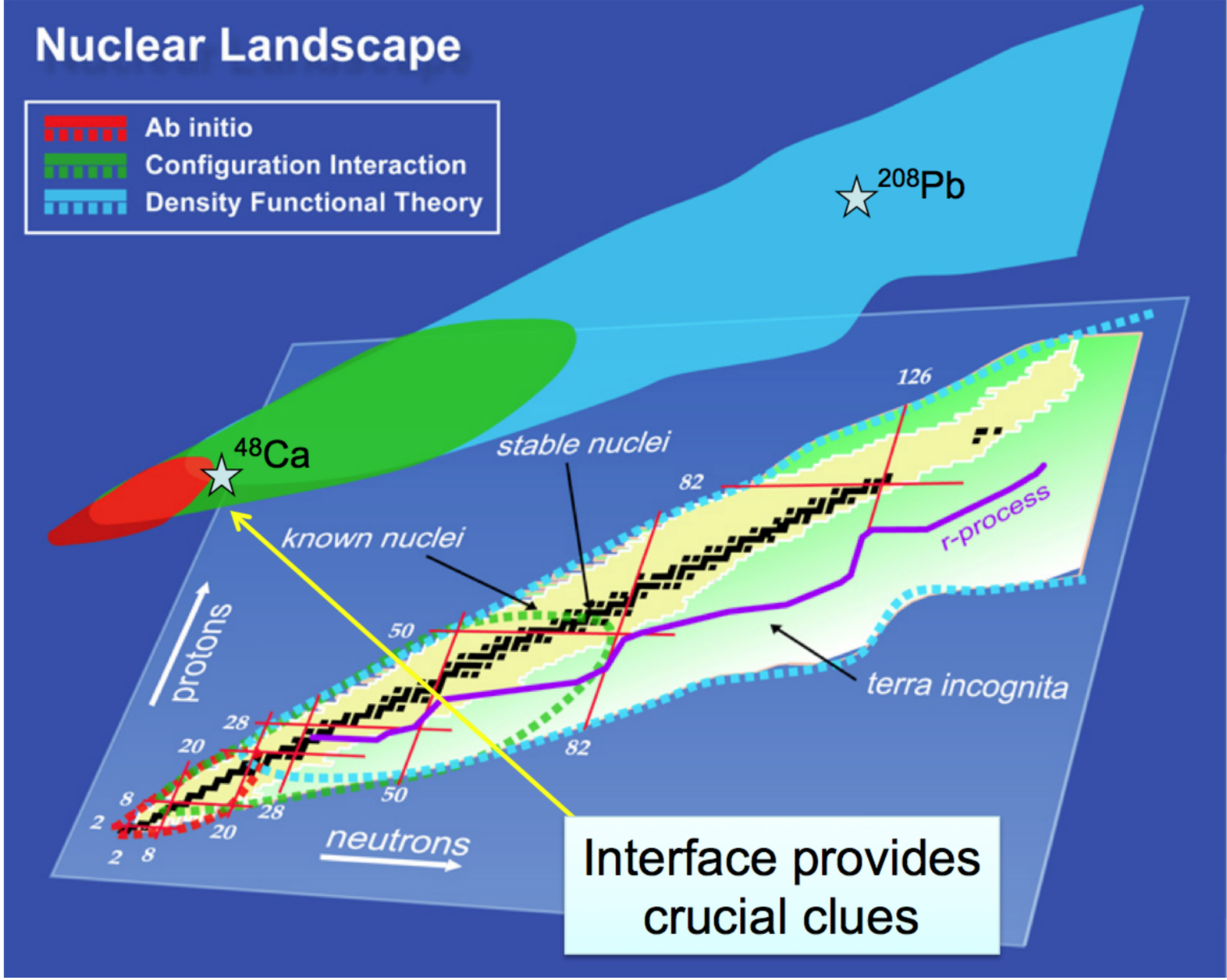
Pb-208 well modelled with density functional theory (DFT) approach

These are the only two stable doubly magic elements suitable for a target

Provides critical bridge between DFT and ab initio calculations

Provides benchmark for calibrating hadronic measurements at RIB facilities

Ca-48 more sensitive to surface effects and spin-orbit correction



Motivation for CREX

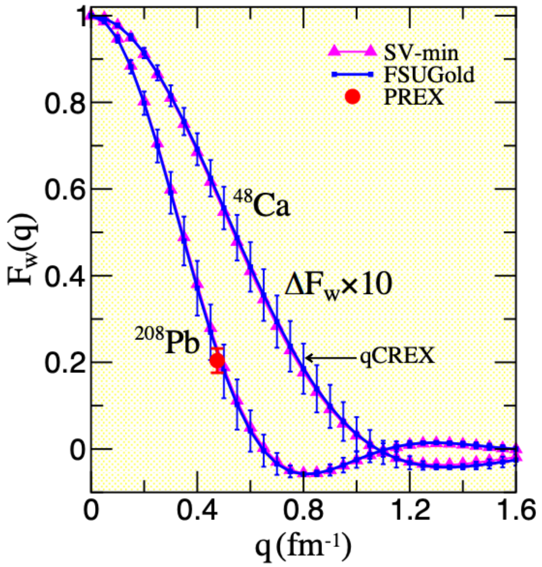
DFT accurately calibrated to observables of stable nuclei like charge radius and binding energy

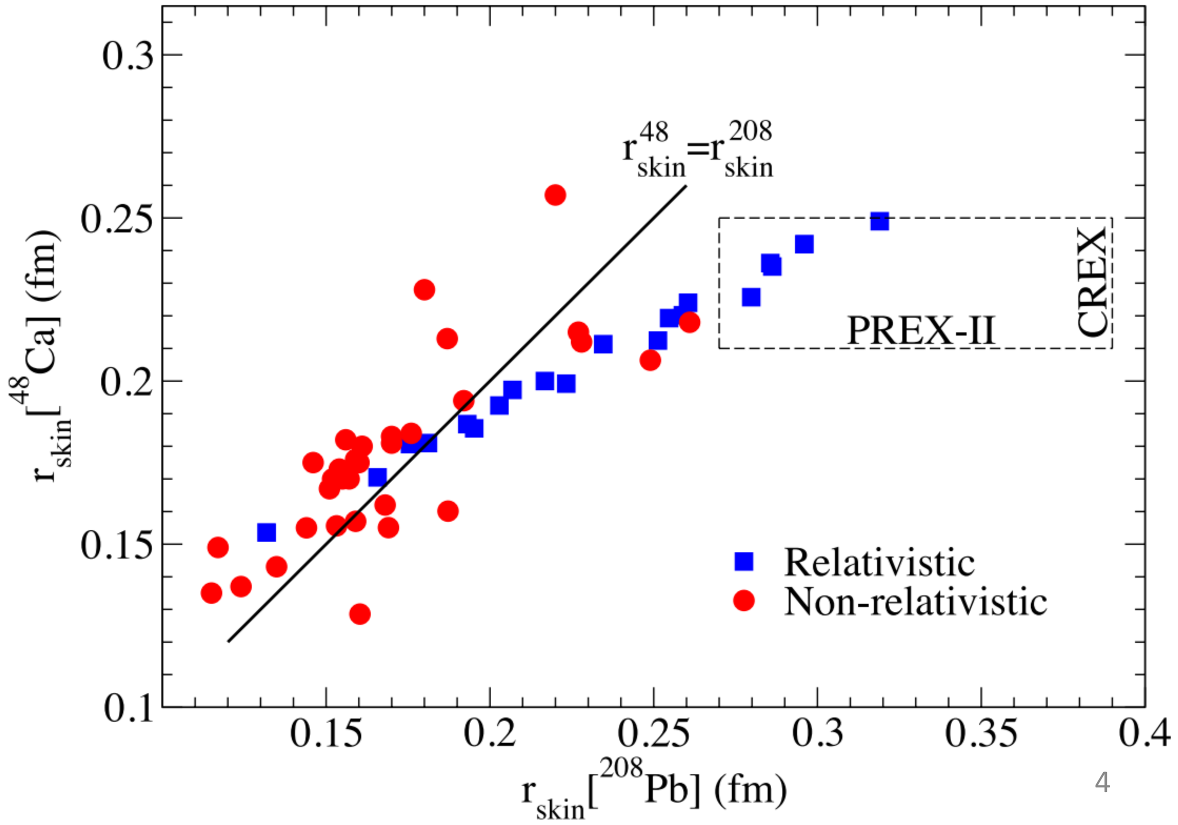
- constrained dependence on isoscalar density
  $\rho_0(r) = \rho_p(r) + \rho_n(r)$
- largely unconstrained isovector density
  $\rho_1(r) = \rho_n(r) - \rho_p(r)$

So while DFT models all accurately predict charge radius throughout the nuclear chart, they disagree on the neutron skin thickness

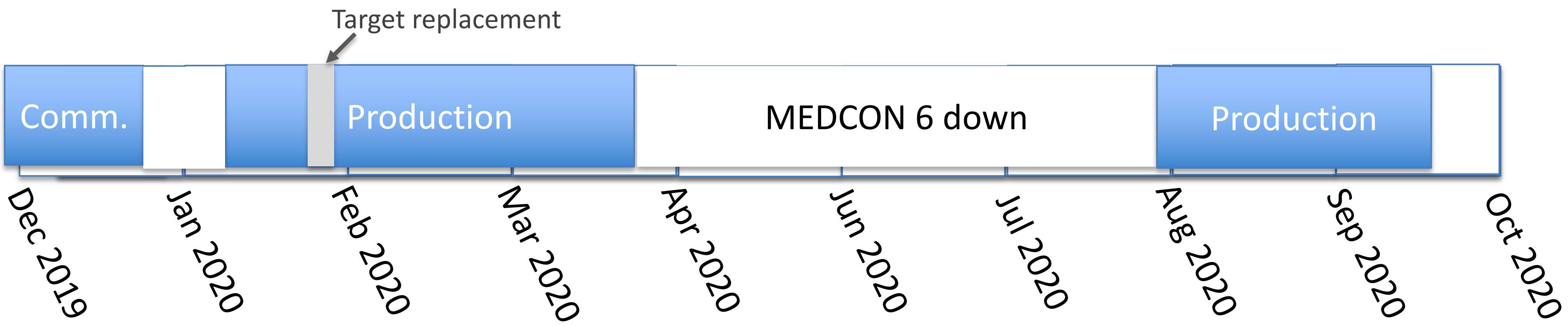
- Can't even agree on whether Ca-48 or Pb-208 has thicker skin

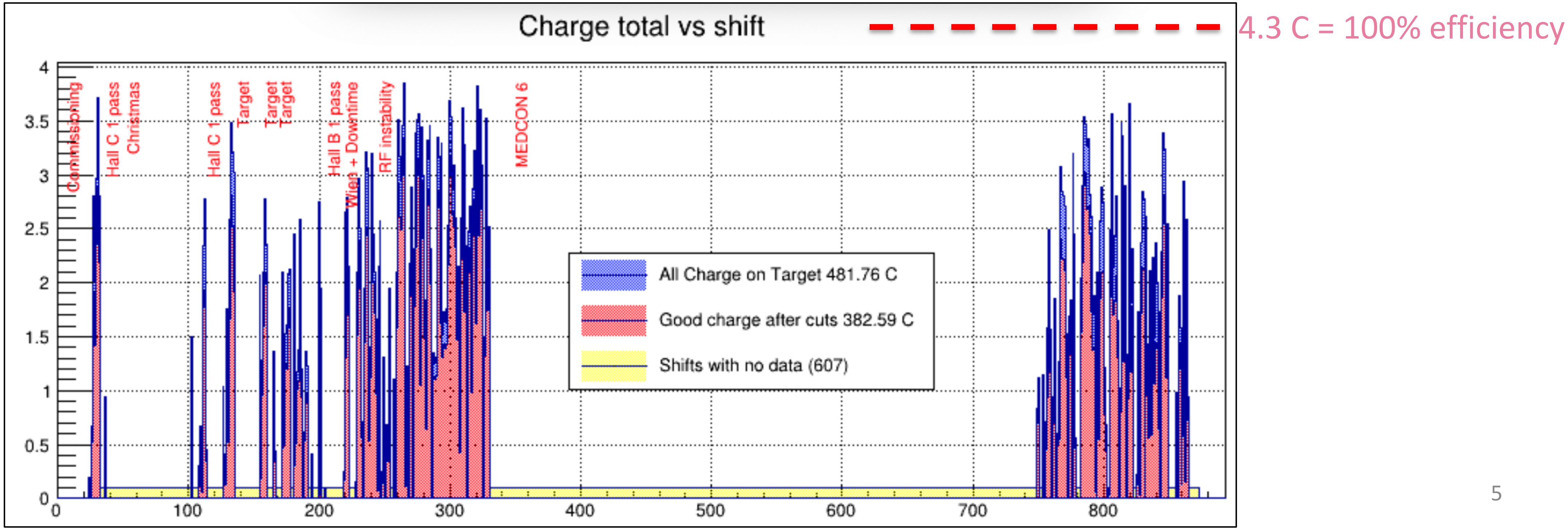
Given the size of the PREX-2 error bar, CREX will be useful constraining isovector sector of energy density functionals (EDFs)





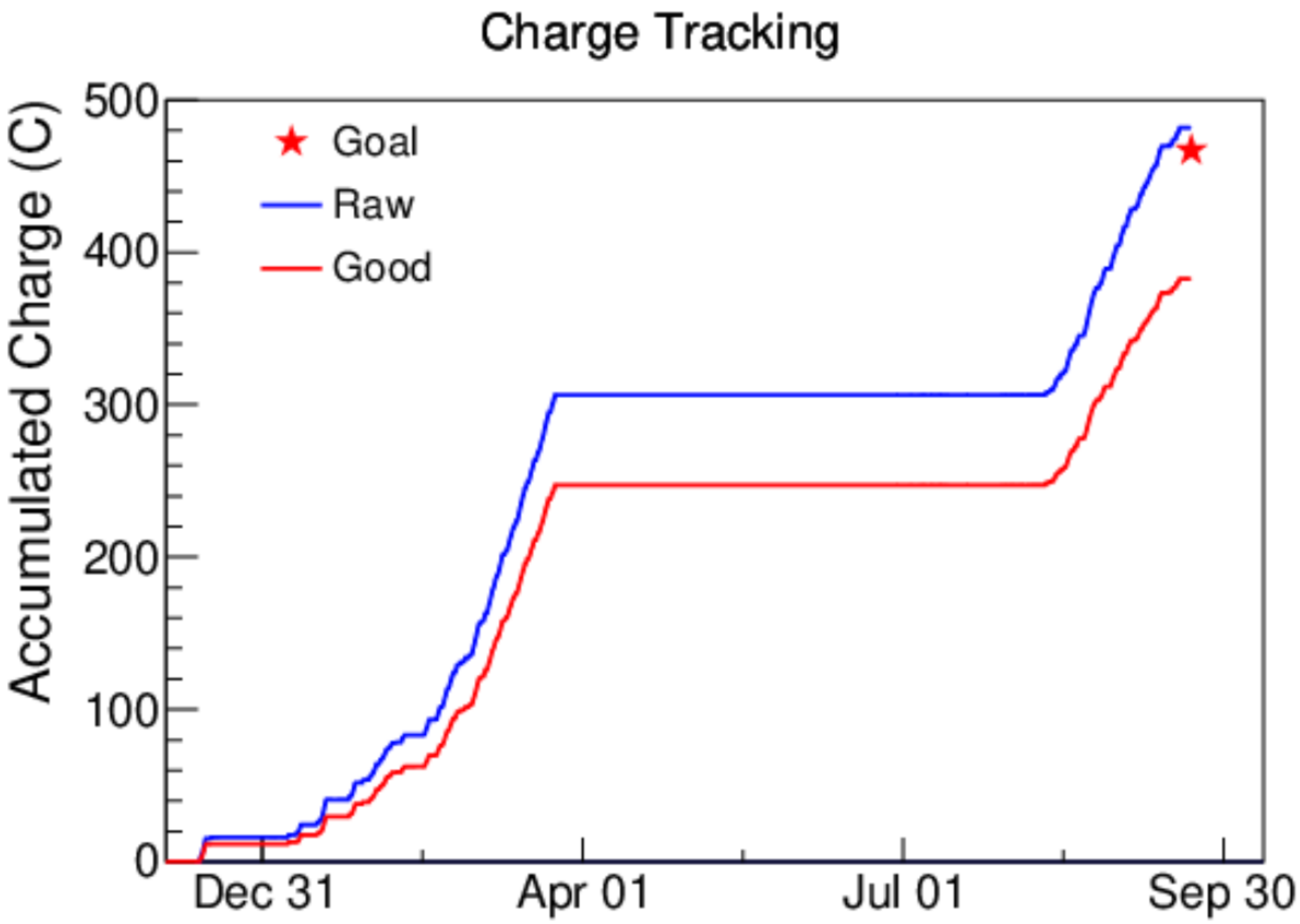
CREX timeline





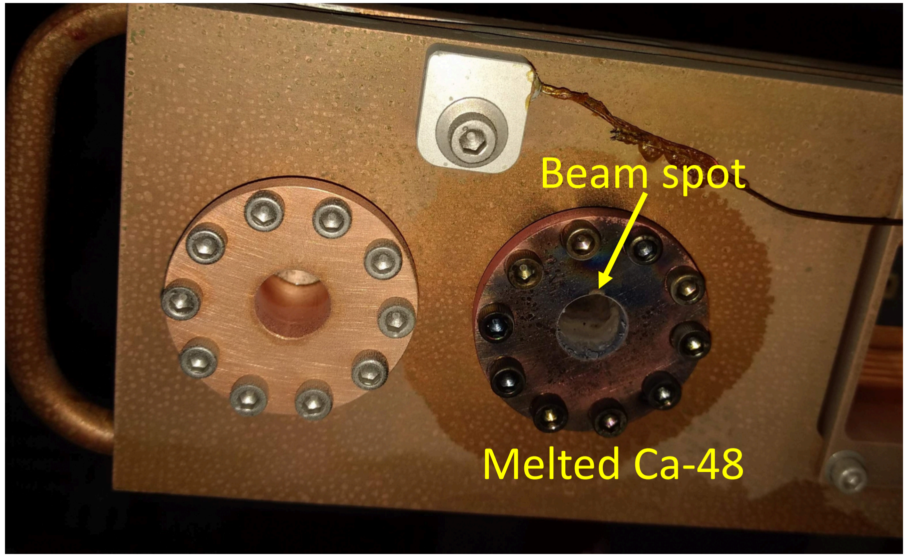
CREX accumulated charge

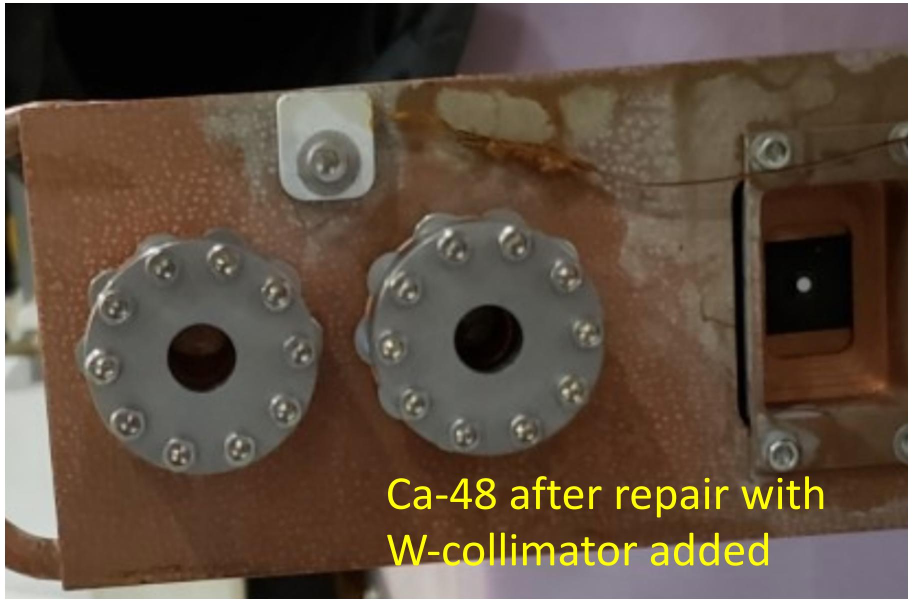
- Ran 1-Pass (2.2 GeV) @150 μA when possible collecting a total of 481 C during production running
- 382 C passed all cuts
- Goal 470 C after cuts so
- ~80% of goal or 1.12 x proposed statistical error



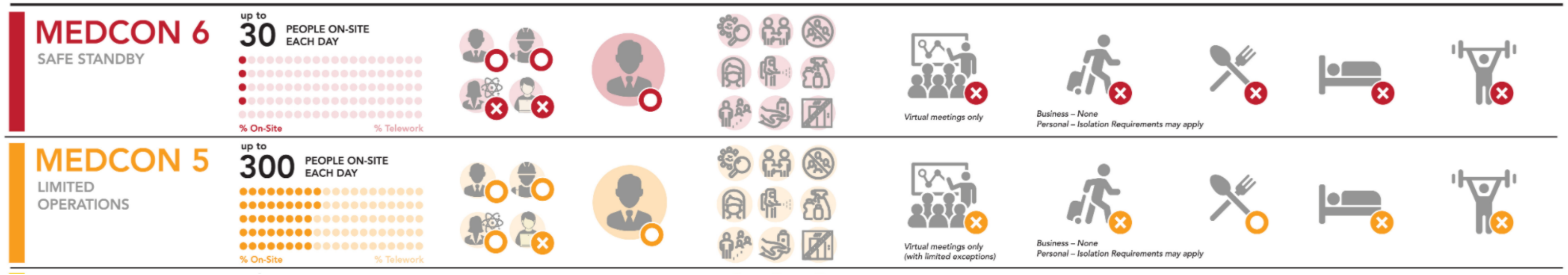
Significant challenges: target melt incident

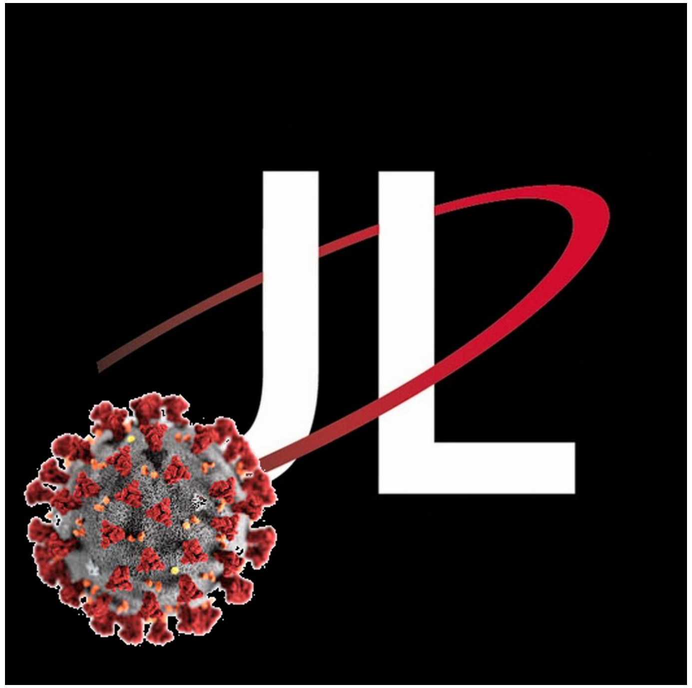
- Target was expensive high-purity Ca-48 puck made by ORNL (5.7mm thick and 12.7mm diameter)
- Close to midnight Jan 18, 2020 there was an excursion on the electron beam of several mm from its lock position and the beam clipped the edge of the thick copper holder
- Within a few seconds the copper got so hot it melted the Ca-48 target (Ca-48 melts at 1115K)
- Within 1 week the target group led by D. Meekins + a special task force from Radcon had reassembled a new target of nearly identical size by sandwiching several thinner targets together.
- Lab took this very seriously, developed a number of safety measures to ensure a repeat would not occur
  - Phased ramping, new alarms, tighter thresholds for ion chambers, added tungsten collimator layer





Significant challenges: COVID 19 + MEDCON





Jefferson Lab moved to MEDCON 5 on Mar 17, 2020 restricting the number of folks onsite in the Counting House and in meetings.

Significant changes to the way we were used to operating including only 2 shifters allowed, social distancing, communications remote and no more wandering over to MCC to see how things were progressing or to make requests

MEDCON 6 came on March 23, cutting short our data taking

Approved to restart taking data under MEDCON 5 in late July

- Only a few students, post-docs+researchers still stationed at the lab or given special permissions to travel, in addition to lab staff left to fill the shifts and run the onsite program.
- Continued taking data with this increasingly weary skeleton crew for almost 2 months.

From measured asymmetry to Apv

$$A_{meas} = \frac{D_R/I_R - D_L/I_L}{D_R/I_R + D_L/I_L}$$

$D_{R(L)}$ are integrated detector responses, $I_{R(L)}$ are the beam current monitor response for right(left) helicity

$$A_{corr} = A_{meas} - \boxed{\sum_{i=1}^{N} B_i \, \Delta x_i} - \boxed{A_T}$$

False asymmetries from helicity-correlated beam properties removed by

1. Beam Modulation: deliberate non-helicity-correlated modulation of beam parameters and measuring the detector response.
2. Regression: detector responses measured using natural beam fluctuations

Parity-conserving asymmetry from residual transverse polarization on the electron beam

$$A_{sig} = \frac{A_{corr} - A_{bkg} f_{bkg}}{f_{sig}}$$

Background fraction from ^{40}Ca impurity in target
Events from excited states of ^{48}Ca.
Inelastic events re-scattered into detector acceptance

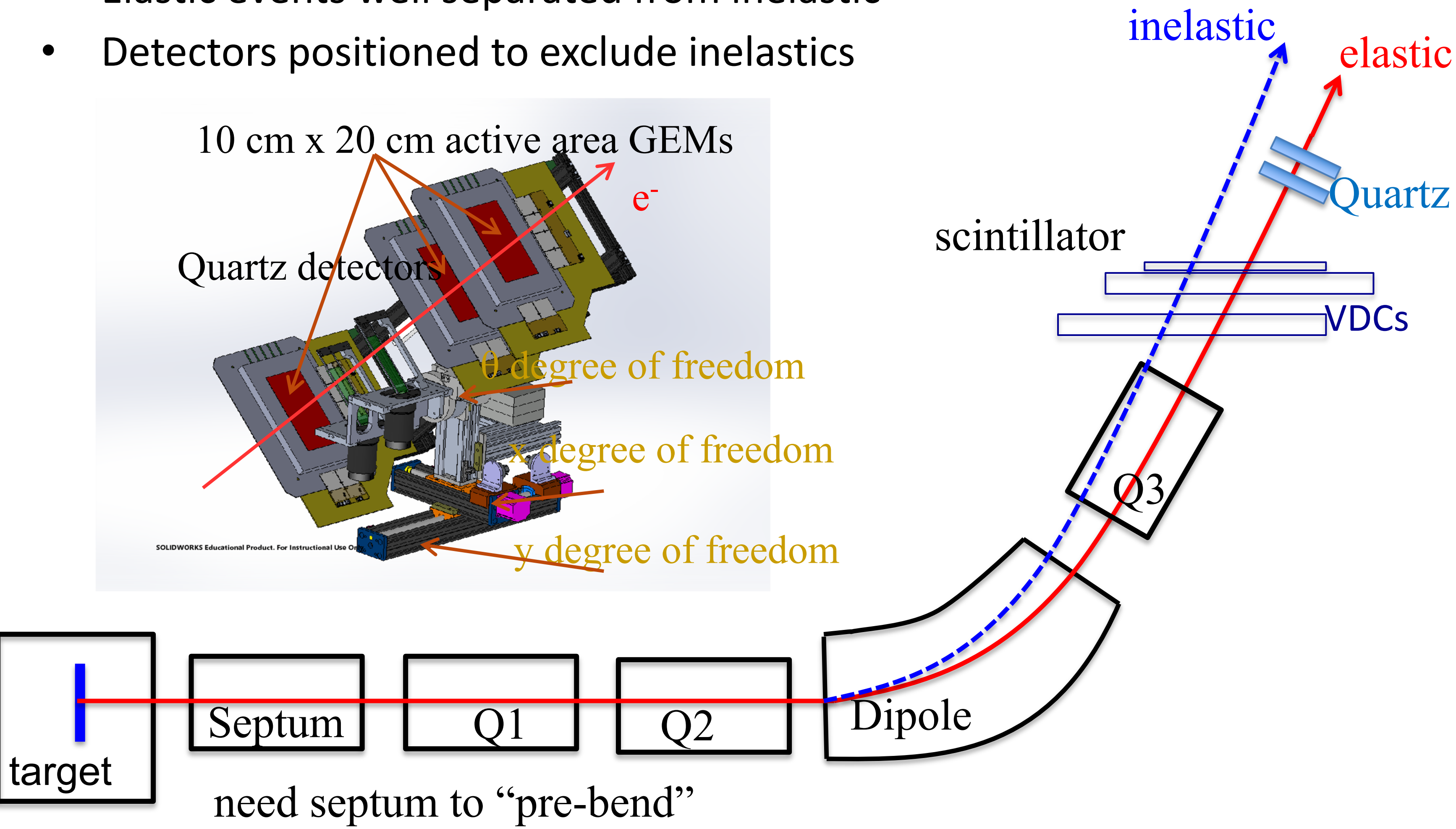
$$A_{PV} = \frac{A_{sig}}{\boxed{P_{beam}}}$$

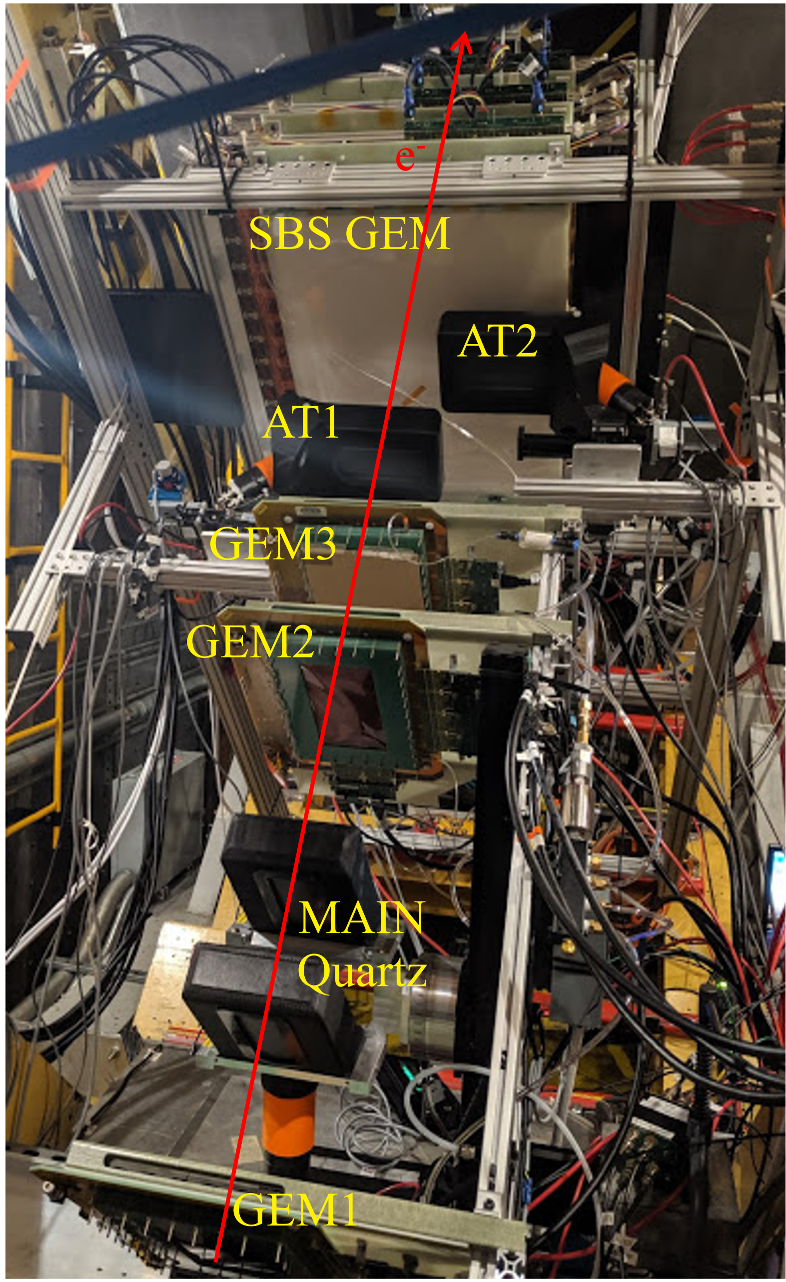
Longitudinal beam polarization

Interpreting Apv as a neutron radius also requires accurate knowledge of Q^2

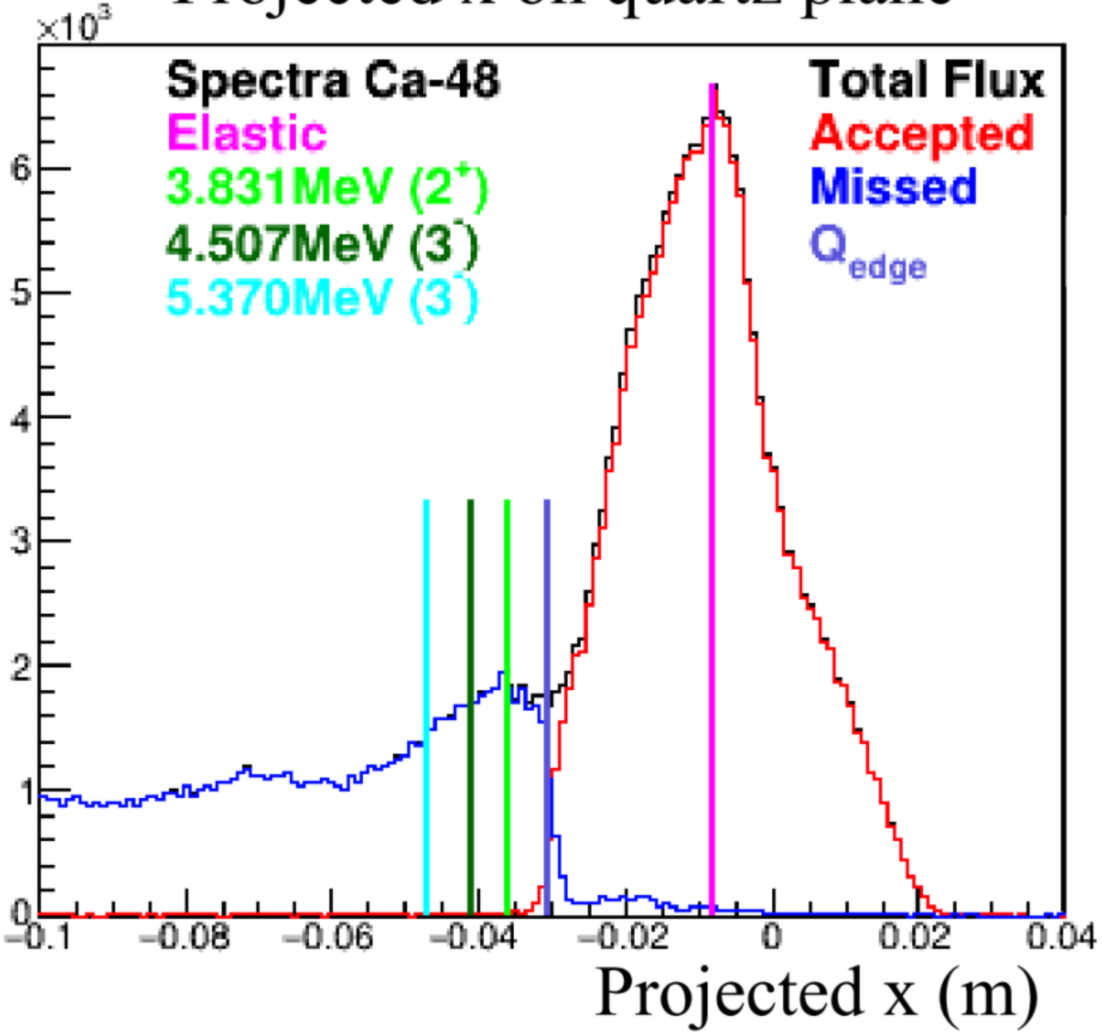
Spectrometer + detector package

- Hall A HRS package focusses elastic events on detector (dispersion ~14m at detector)
- Elastic events well separated from inelastic
- Detectors positioned to exclude inelastics



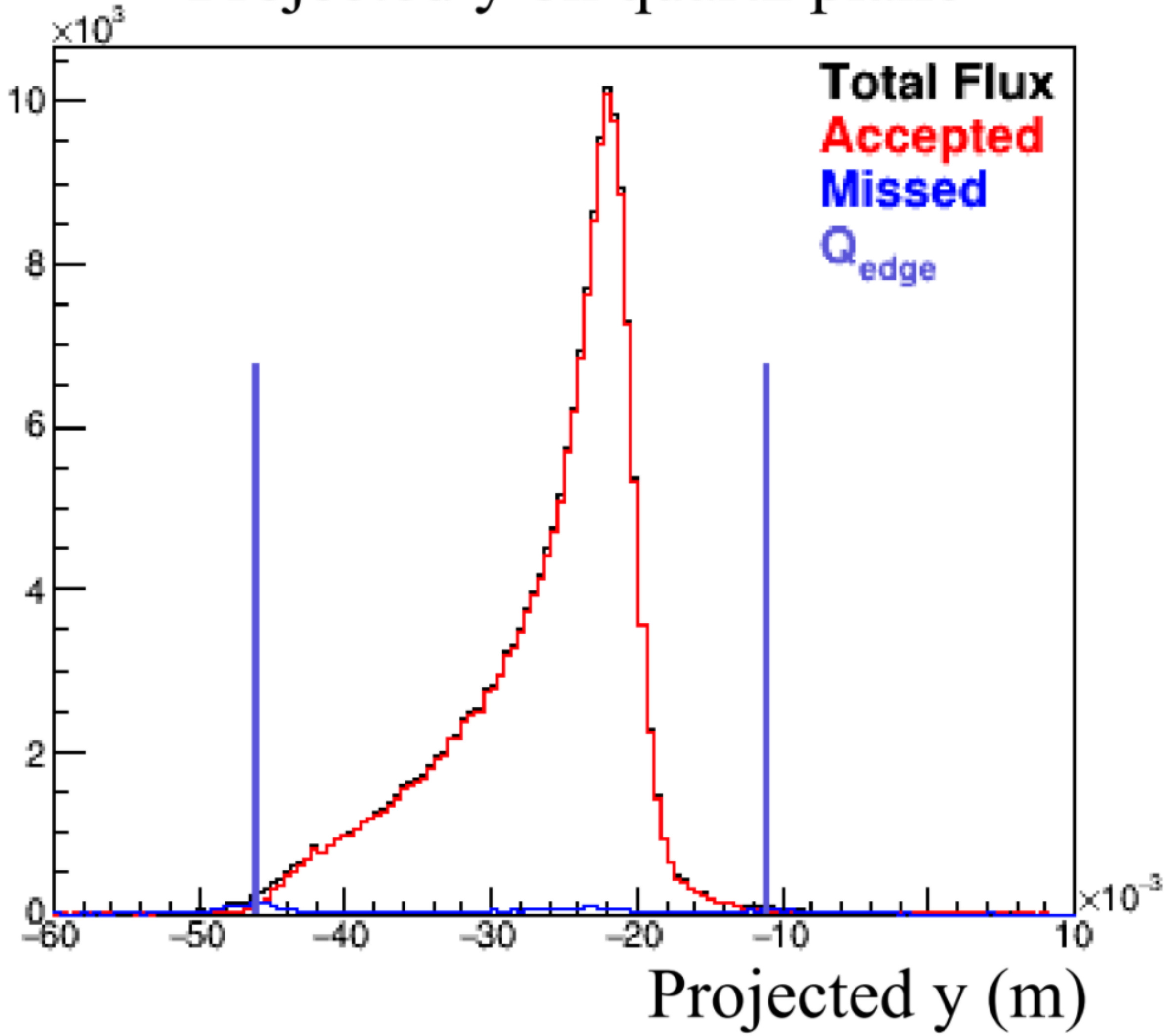


Projected x on quartz plane



- Well excluded excited states from acceptance
- Inelastic contamination should be small
- We are working on estimating contamination from each low lying excited state, should be done in about a month

Projected y on quartz plane

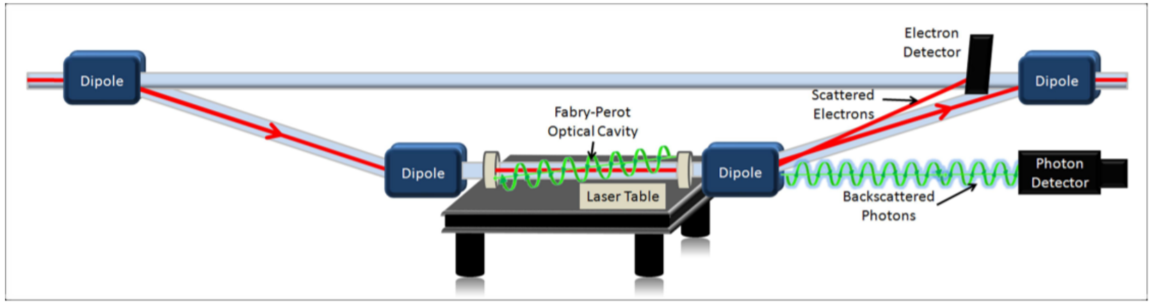


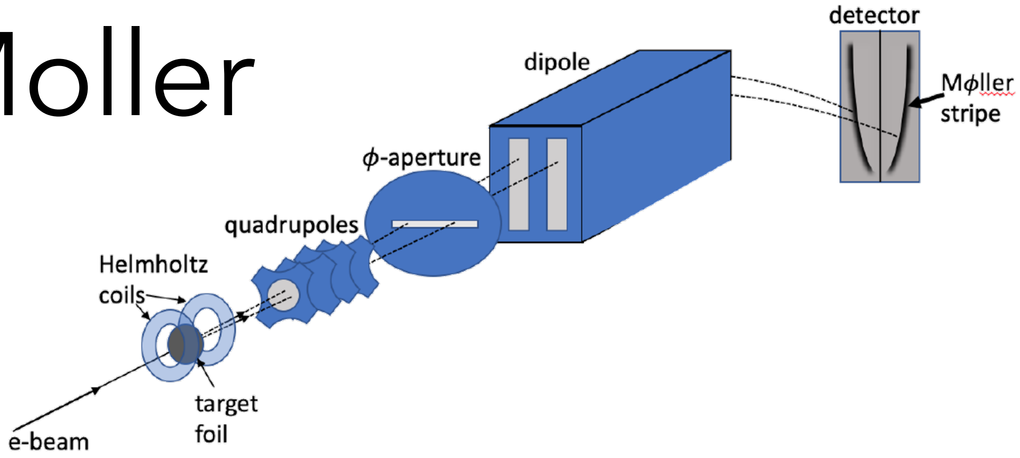
- Readjusted alignment when there was considerable shift in beam energy
- Nearly full acceptance of 3.5 cm quartz width

Transverse asymmetry

- Beam horizontal spin launch angle adjusted at the injector for fully longitudinal polarization in the hall after precession in the arcs and asymmetry suppressed by cancellation in acceptance.
- Vertical transverse polarization expected to be small and cancels in left/right arm measurements
- Dedicated measurements taken at fully transverse beam polarization
- Transverse asymmetries are interesting in their own right but required for correcting for the small fraction of events in our data from transverse polarized scattering

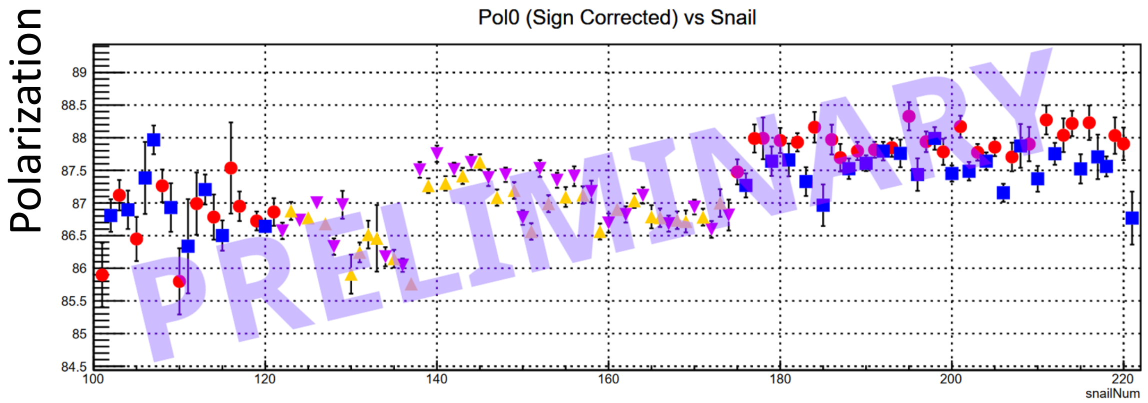
Polarimetry: Compton + Moller

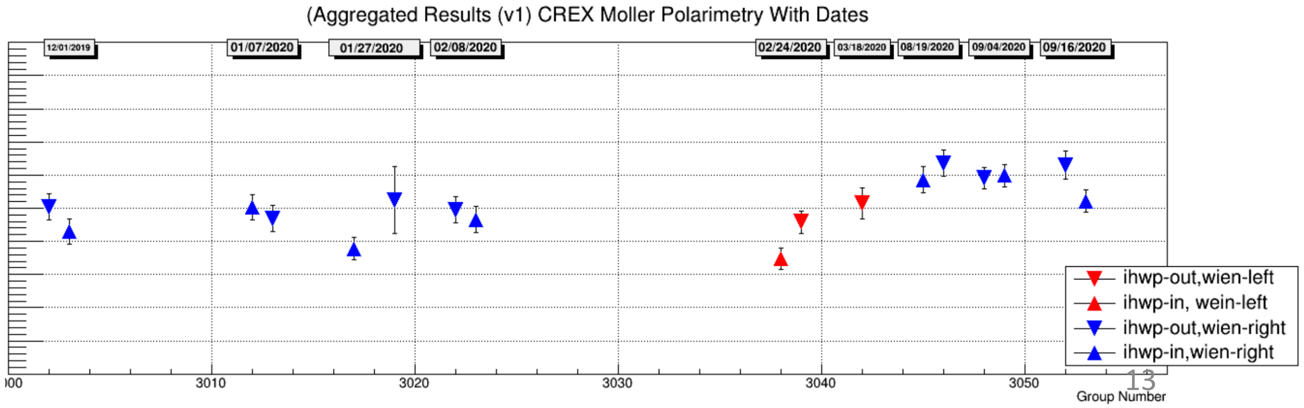




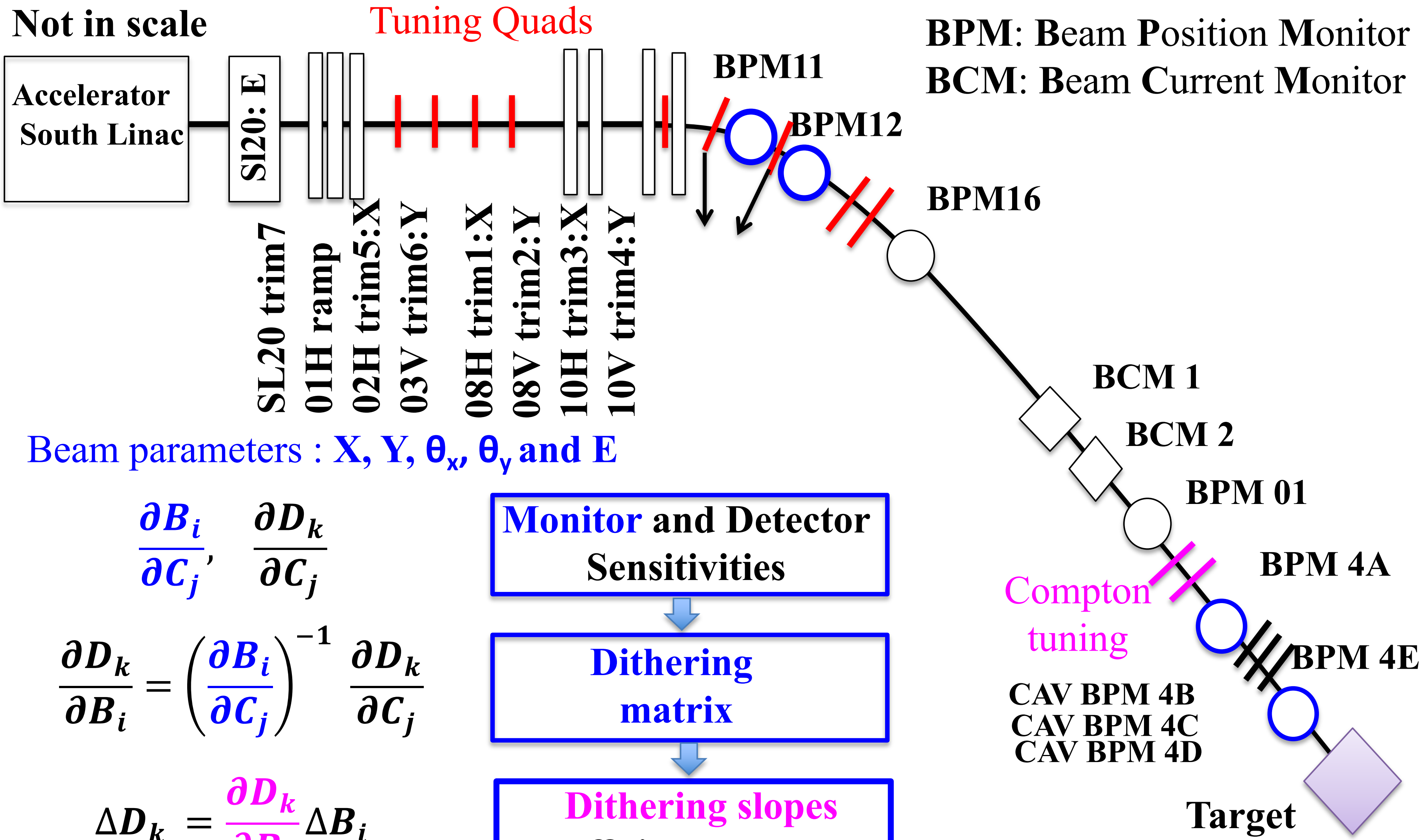
- Non-invasive green laser target amplified in cavity to 2-3kW
- $e\gamma$ scattering asymmetry proportional to electron polarization
- Can detect both electron and photon
- Photon detector PbWO4 crystal array attached to single PMT and read out in integrating mode provides primary measurement for CREX
- Ongoing analysis of systematics and corrections

- Thin Fe foil polarized along beam direction
- ee scattering asymmetry proportional to beam polarization
- Difficult beam conditions + two target magnet quenches + nicely working Compton + need for CREX statistics = fewer Moller measurements (about every two weeks)
- See Eric King's talk for details





Beam Modulation



Beam parameters : **X, Y, θ_x, θ_y and E**

$$\frac{\partial B_i}{\partial C_j}, \quad \frac{\partial D_k}{\partial C_j}$$

$$\frac{\partial D_k}{\partial B_i} = \left(\frac{\partial B_i}{\partial C_j}\right)^{-1} \frac{\partial D_k}{\partial C_j}$$

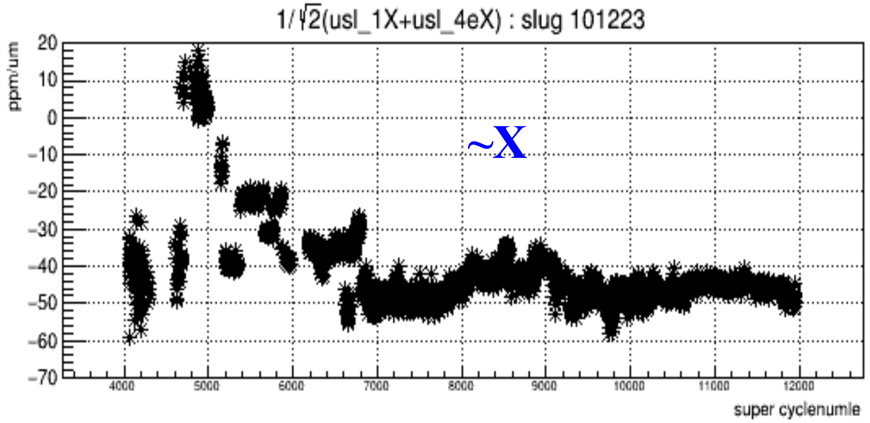
$$\Delta D_k = \frac{\partial D_k}{\partial B_i} \Delta B_i$$

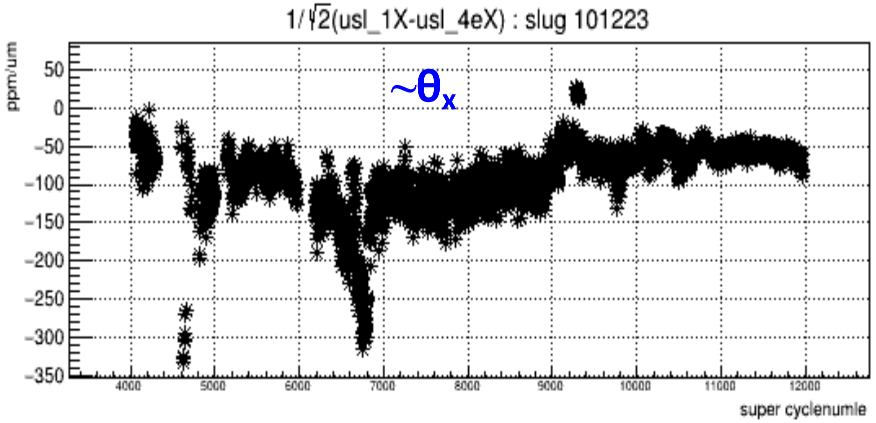
Monitor and Detector Sensitivities

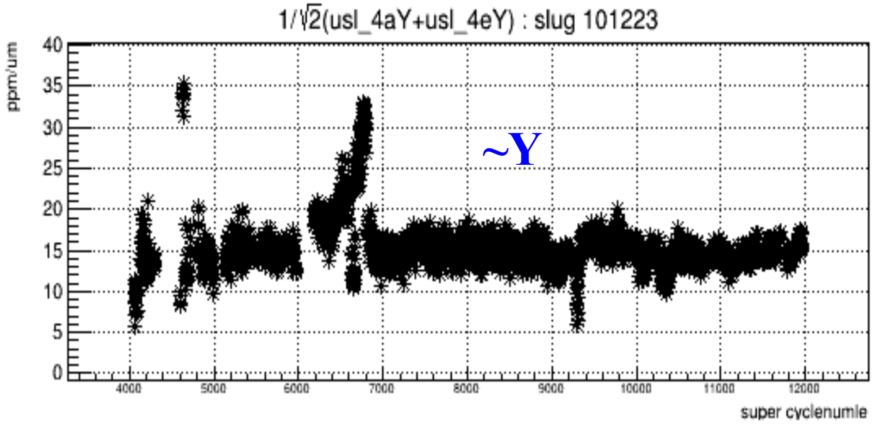
Dithering matrix

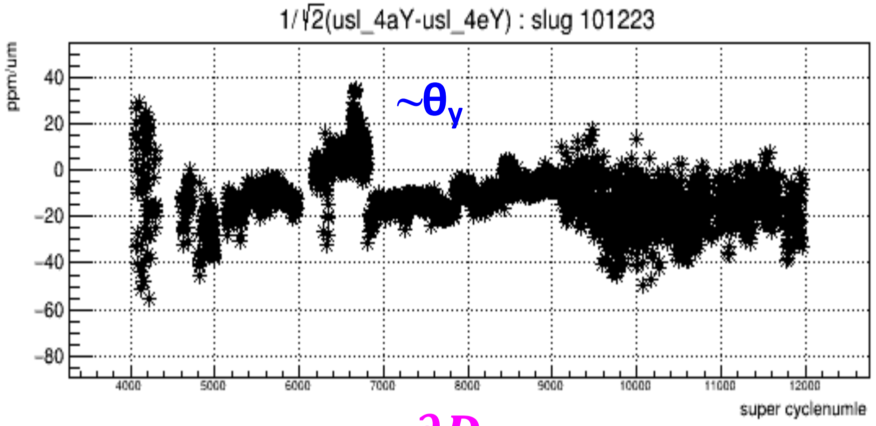
Dithering slopes sufficient accuracy

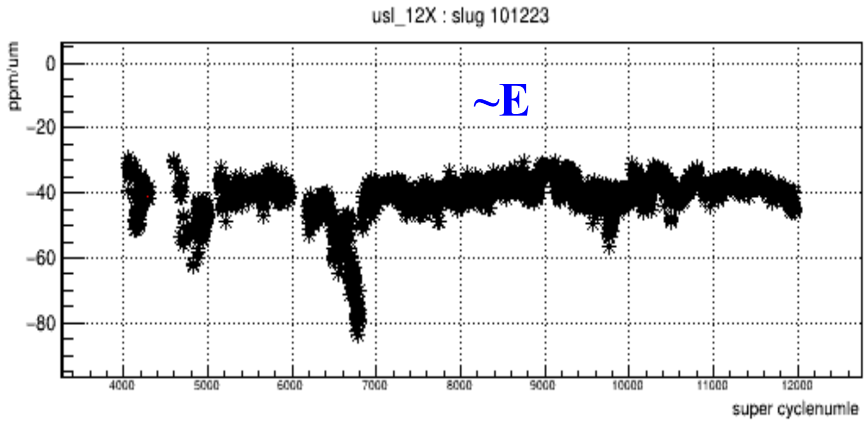
CREX beam modulation data











Dithering slope $\frac{\partial D_{usl}}{\partial B_i}$

- Fairly stable (except changing the beam tune and quads)
- Set up modulation system to keep slope error small

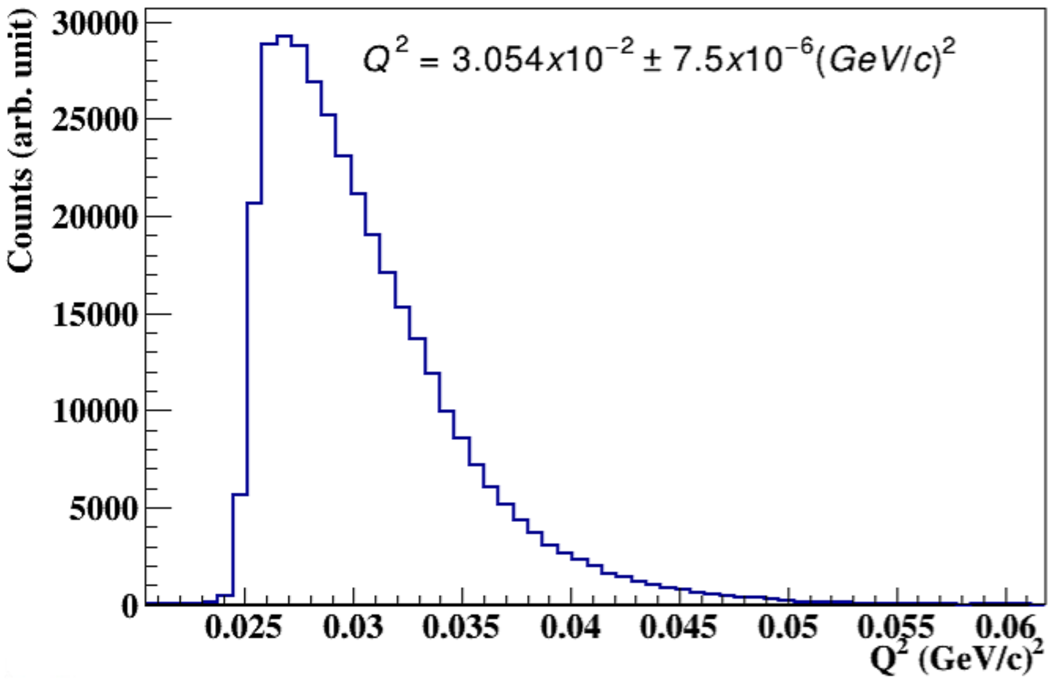
Q^2 measurements

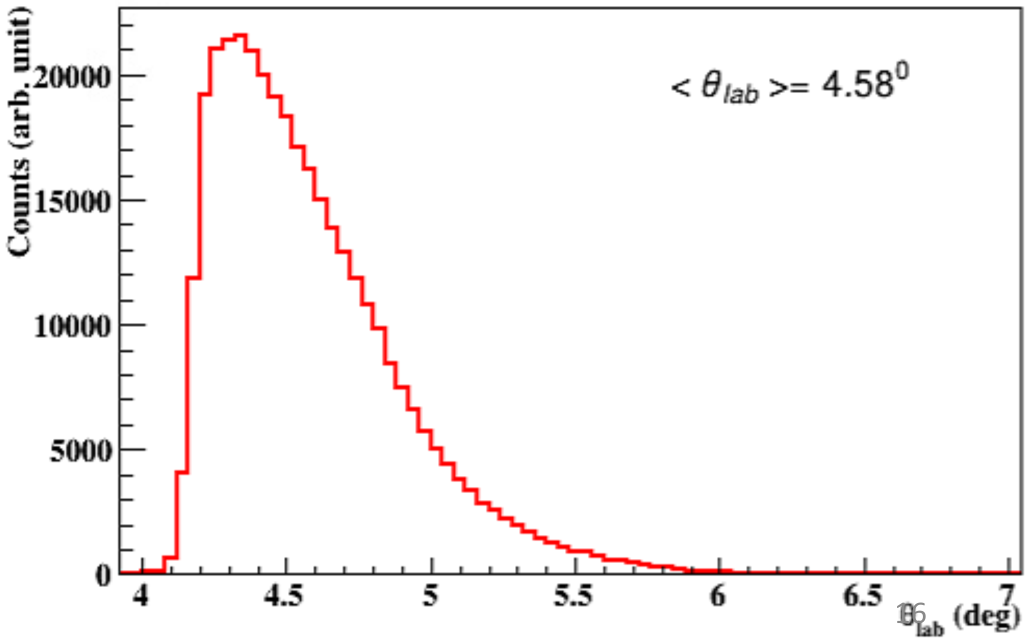
$$\boxed{\begin{aligned} &Q^2 = 2EE'(1-\cos\theta) \\ &E, E' \equiv incident\ and\ scattered\ energy \\ &\theta \equiv scattering\ angle \end{aligned}}$$

- CREX took dedicated low current tracking runs using GEMs to measure position distributions at the detector
- Optics model used to convert GEM tracks to and θ and Q^2 (see Siyu Jian's talk on GEMs)
- Average Q^2 and $\boldsymbol{\theta}$ over the experimental acceptance shown in plots

$Q^2 = 3.054(0.00075)\text{x}10^{-2}\ (\text{GeV/c})^2$
Similar Q^2 values are observed for both arms

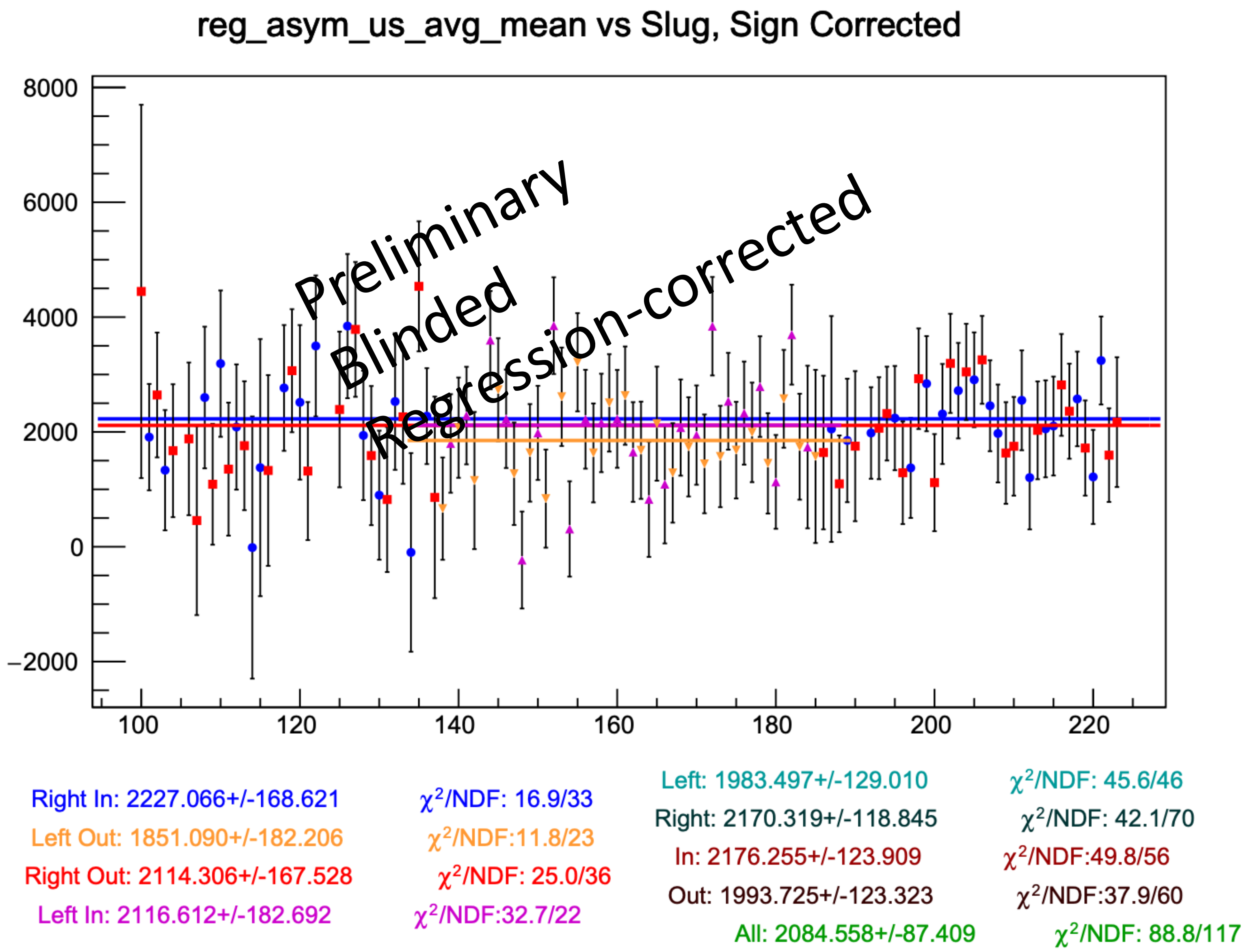
Q^2 measurements are performed periodically over the run and found to be stable during online analysis



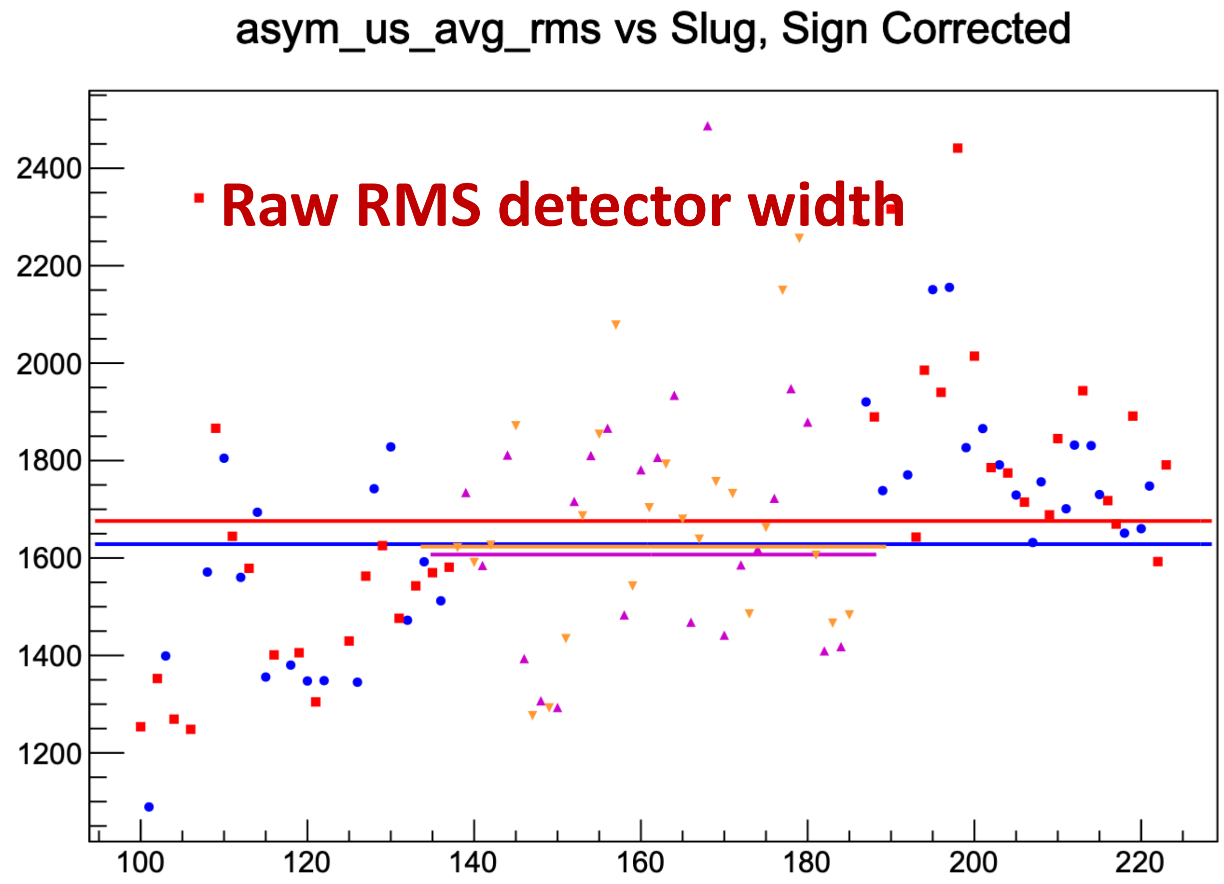


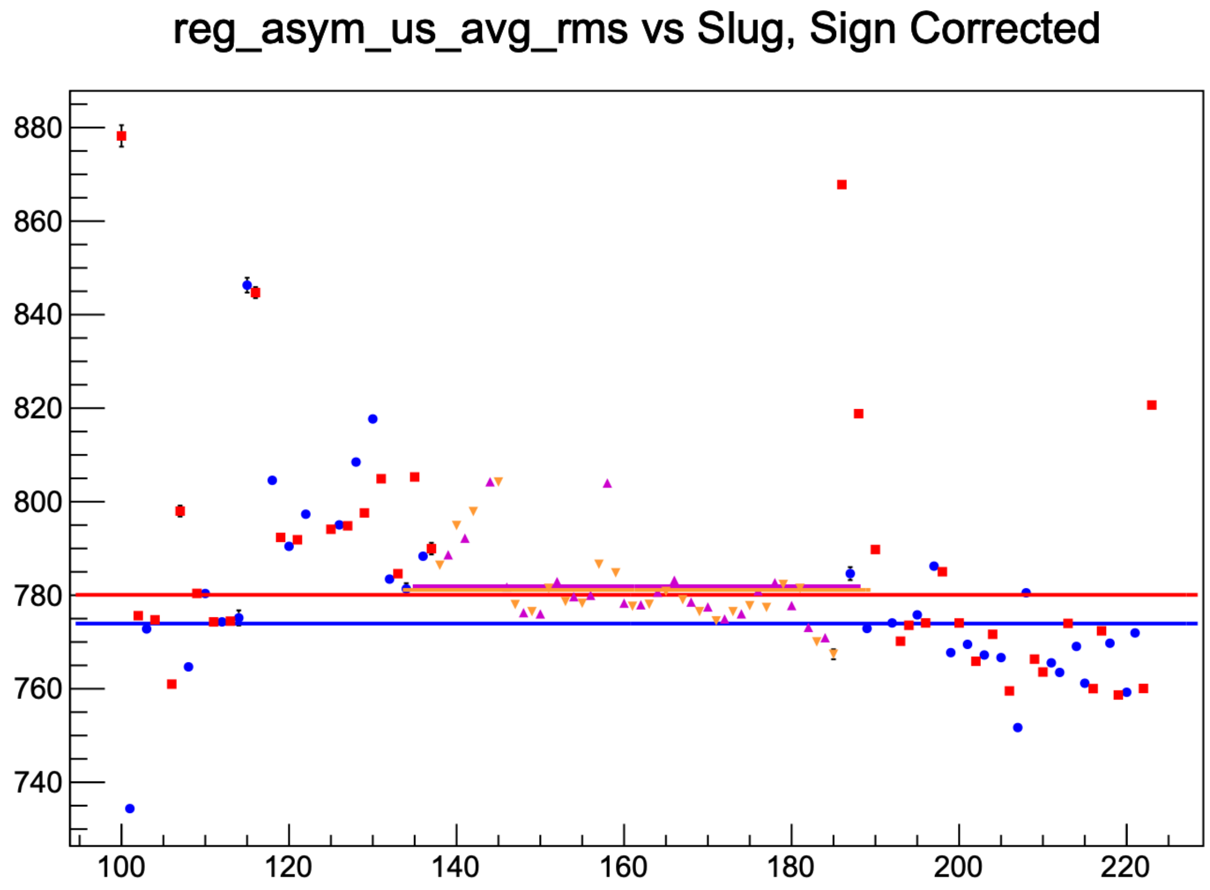
Preliminary results

- Blinded results (+/-900 ppb blinding box)
- Analysis is ramping up after the push for releasing PREX-2 results
- Many of the tools developed for PREX-2 can be used for CREX
- Expect analysis to mature over next few months



Preliminary results: regression reduces width by >2x

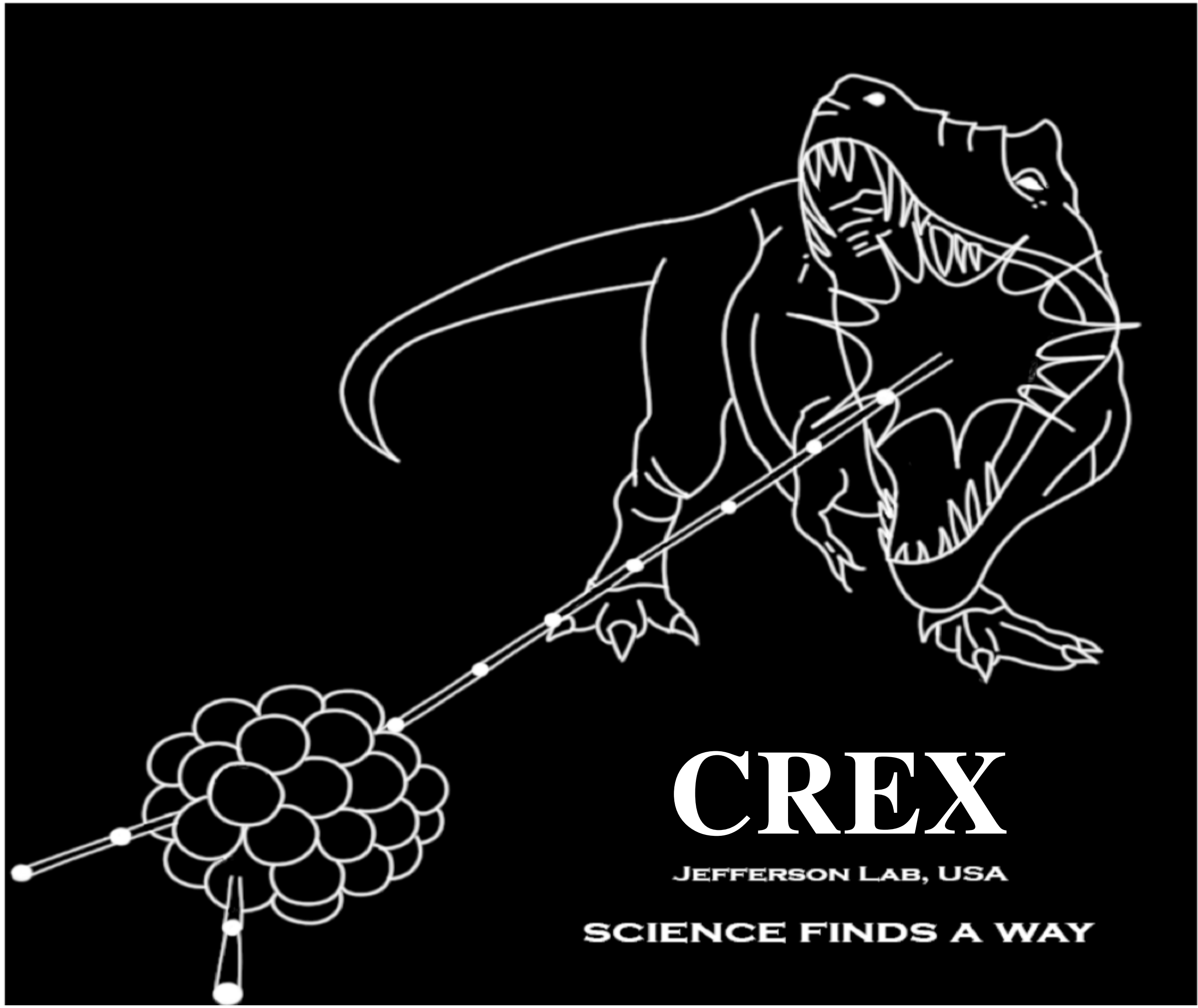




Summary

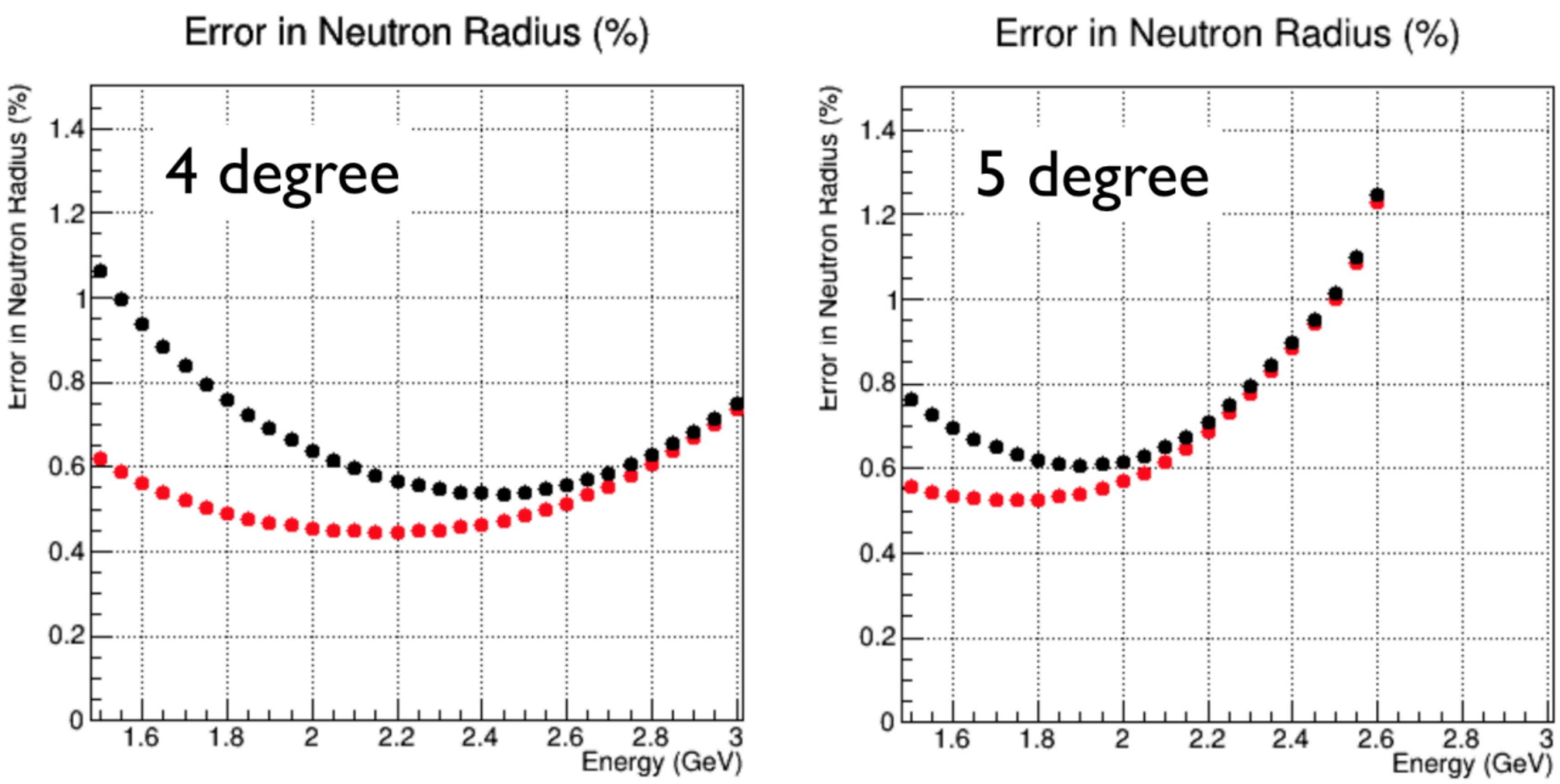
- CREX adds complementary information to PREX helpful in calibrating nuclear models and narrowing down the phase space of the EOS of neutron rich matter
- CREX completed data taking last September successfully navigating through a melted target and COVID-19 difficulties
- Data analysis is ongoing
- Expect results later this year

Thank you



Backups

CREX FOM (error on neutron radius) depends on cross section, asymmetry, acceptance, Q^2, angle (or beam energy), sensitivity to neutron radius and systematic error



The advantages of 5 degree over 4 degree design are the simpler design from single target location, the septum will be safely inside its proven operation range, and reduced production of radiation during the CREX run

Figure 1: The CREX Figure of Merit as a function of beam energy, averaged over the acceptance. Left is for the 4° configuration, right is for 5°. The black points include the effect of an assumed 1.2% systematic uncertainty.

Achievable results from CREX proposal @ 5 deg

angle	energy	rate [MHz]	A_{PV} [ppm]	$\delta A/A$ (stat) [%]	$\delta R/R$ (total) [%]
5°	1.8 GeV	130	2.16	2.0	0.62
5°	**1.9 GeV**	**79**	**2.28**	**2.4**	**0.61**
5°	2.0 GeV	48	2.37	3.0	0.62
5°	2.1 GeV	28	2.44	3.8	0.65
5°	2.2 GeV	16	2.49	4.9	0.71

PREX-2: 3% stat, 0.06 fm

CREX: 4% stat, 0.024 fm

PREX-I

E=1.1 GeV, 5°

A=0.6 ppm

Charge Normalization	0.2%
Beam Asymmetries	1.1%
Detector Non-linearity	1.2%
Transverse Asym	0.2%
Polarization	1.3%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q^2	0.5%
Total Systematic	**2.1%**
Total Statistical	**9%**

Achieved, published

statistics limited result,
systematics well under control

PREX-II

E=1.1 GeV, 5°

A=0.6 ppm

70 μA, 25+10 days

Charge Normalization	0.1%
Beam Asymmetries*	1.1%
Detector Non-linearity*	1.0%
Transverse Asym	0.2%
Polarization*	1.1%
Target Backing	0.4%
Inelastic Contribution	<0.1%
Effective Q^2	0.4%
Total Systematic	**2%**
Total Statistical	**3%**

*Experience suggests that leading systematic errors can be improved beyond proposal

CREX

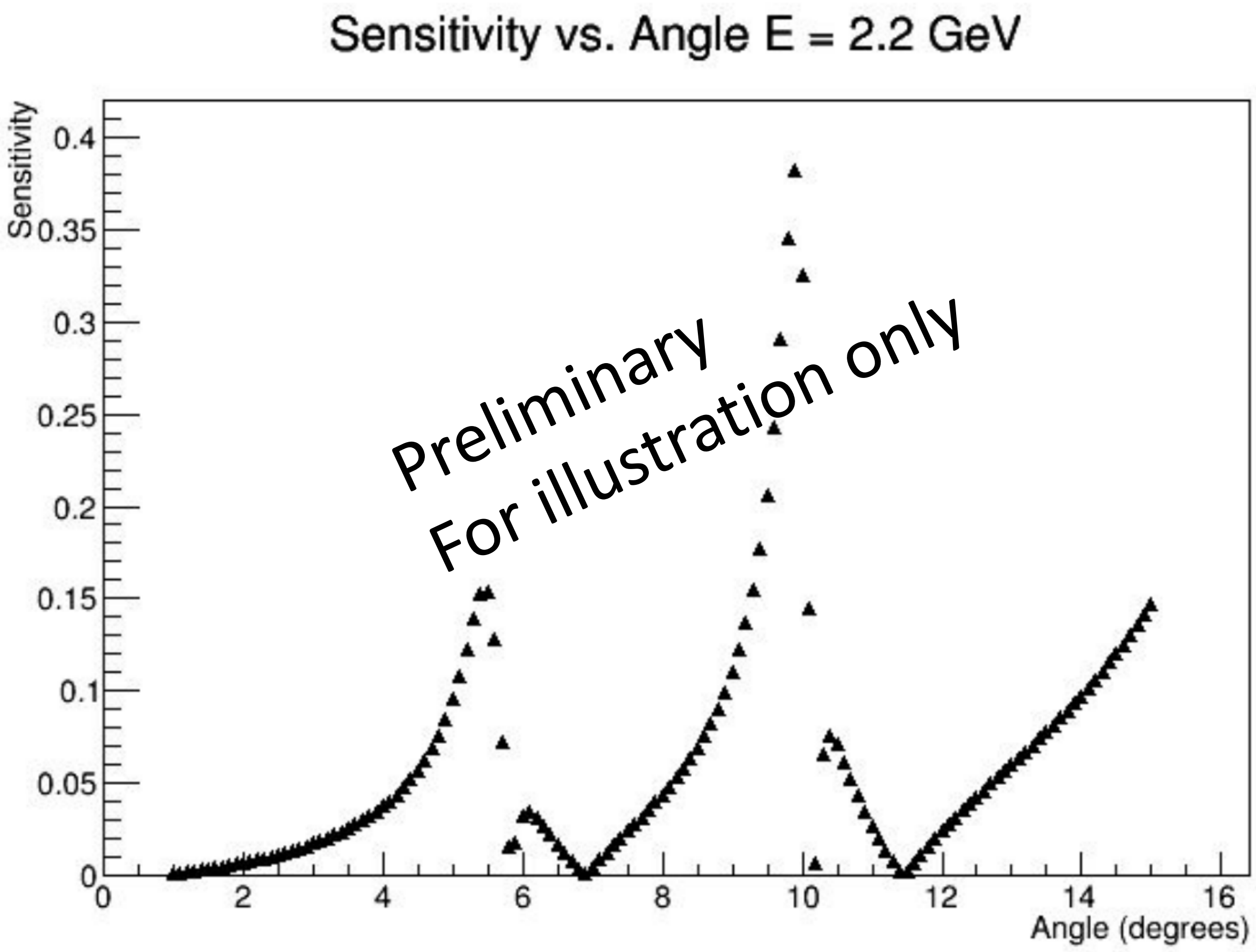
E=2.2 GeV, 5°

A = 2.3 ppm

150 μA, 35 + 10 days

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse Asym	0.1%
Polarization	0.8%
Target Contamination	0.2%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total Systematic	**1.2%**
Total Statistical	**4%**

Sensitivity 2.2 GeV



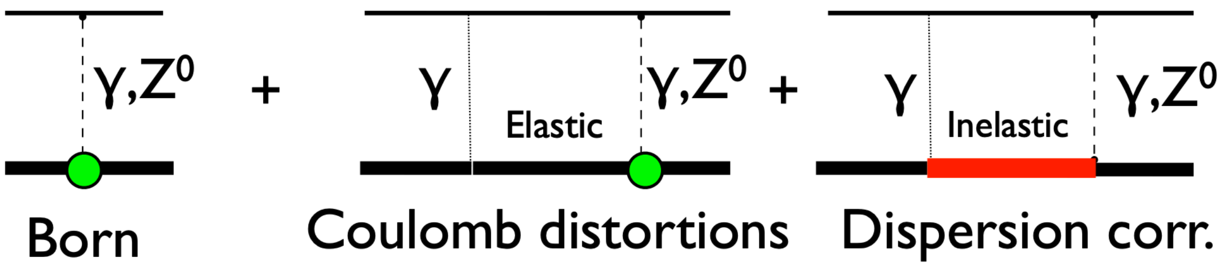
$$S(\theta) = | A_0(\theta) - A_1(\theta) | / A_0(\theta)$$

$A_0(\theta)$ - unstretched

$A_1(\theta)$ - stretched

Sensitivity - fractional change of asymmetry for a 1% change in radius

CREX corrections



- Coulomb corrections large and required for interpretation of parity-violating asymmetry
- Coulomb distortion corrections which are order $Z\alpha$ can be distinguished from dispersion corrections which are order α by comparing PREX/CREX with low Z data