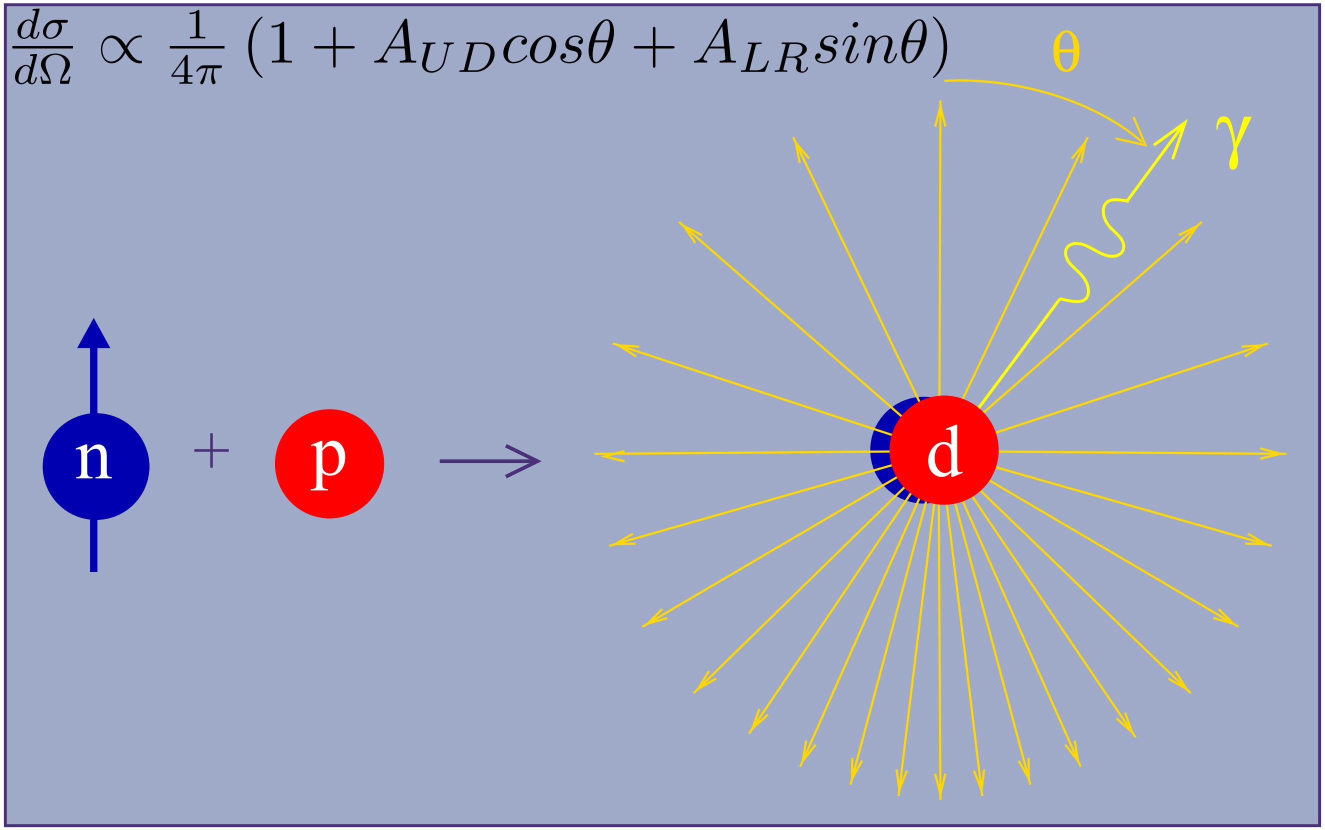
Status and Updates of the NPDGamma Experiment



Jason Fry, Indiana University
University of Virginia, Nuclear Physics Seminar
May 14th, 2015

The NPDGamma collaboration

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[15]High Energy Accelerator Research Organization (KEK), Japan
[16]Hamilton College
[17]Paul Scherrer Institute, Switzerland
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[21]Bhabha Atomic Research Center, India
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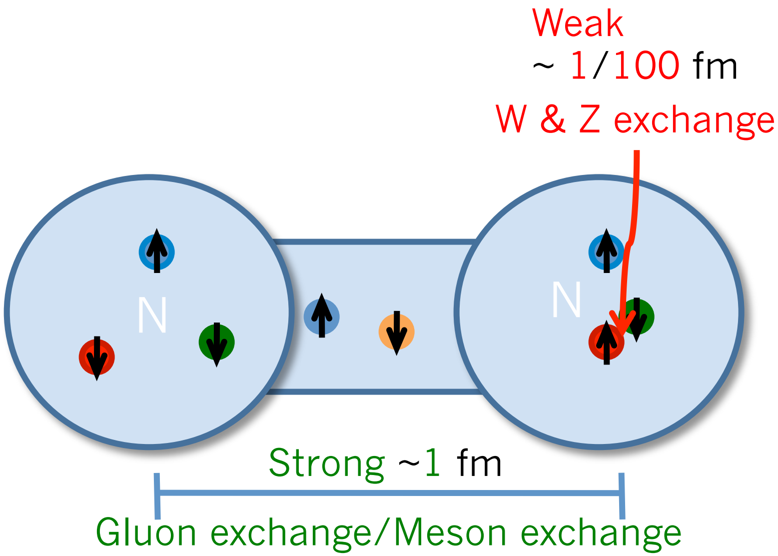
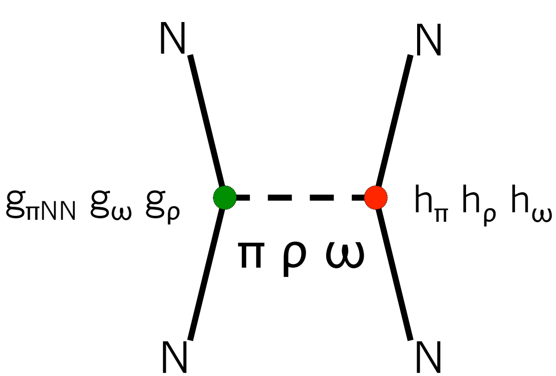
Hadronic Weak Interaction



Strong conserves Parity
Weak violates Parity
→ Use PV to isolate weak interactions



- Hadron Weak Interaction (HWI) among nucleons is not well constrained. Low energy, non-perturbative regime makes calculations and experiments difficult.
- The range for W and Z exchange between quarks (10^{-2}fm) is small compared to the nucleon size (1fm) → HWI is first order sensitive to short range quark-quark correlations in hadrons.
- Quark-quark weak interactions can give insight to non-perturbative ground state of QCD. New results are very exciting!
- Benchmark theory for HWI is the DDH meson exchange model. Couplings

$$h_\pi^1, h_\omega^{0,1}, h_\rho^{0,1,2}$$

← ΔI
← Meson exchange

- EFT and LQCD calculations in progress – will become the future of the theory

NPDGamma and HWI

- The parity-violating photon asymmetry in the reaction $\vec{n} + p \rightarrow d + \gamma$, A_γ is related to the couplings in the DDH model by

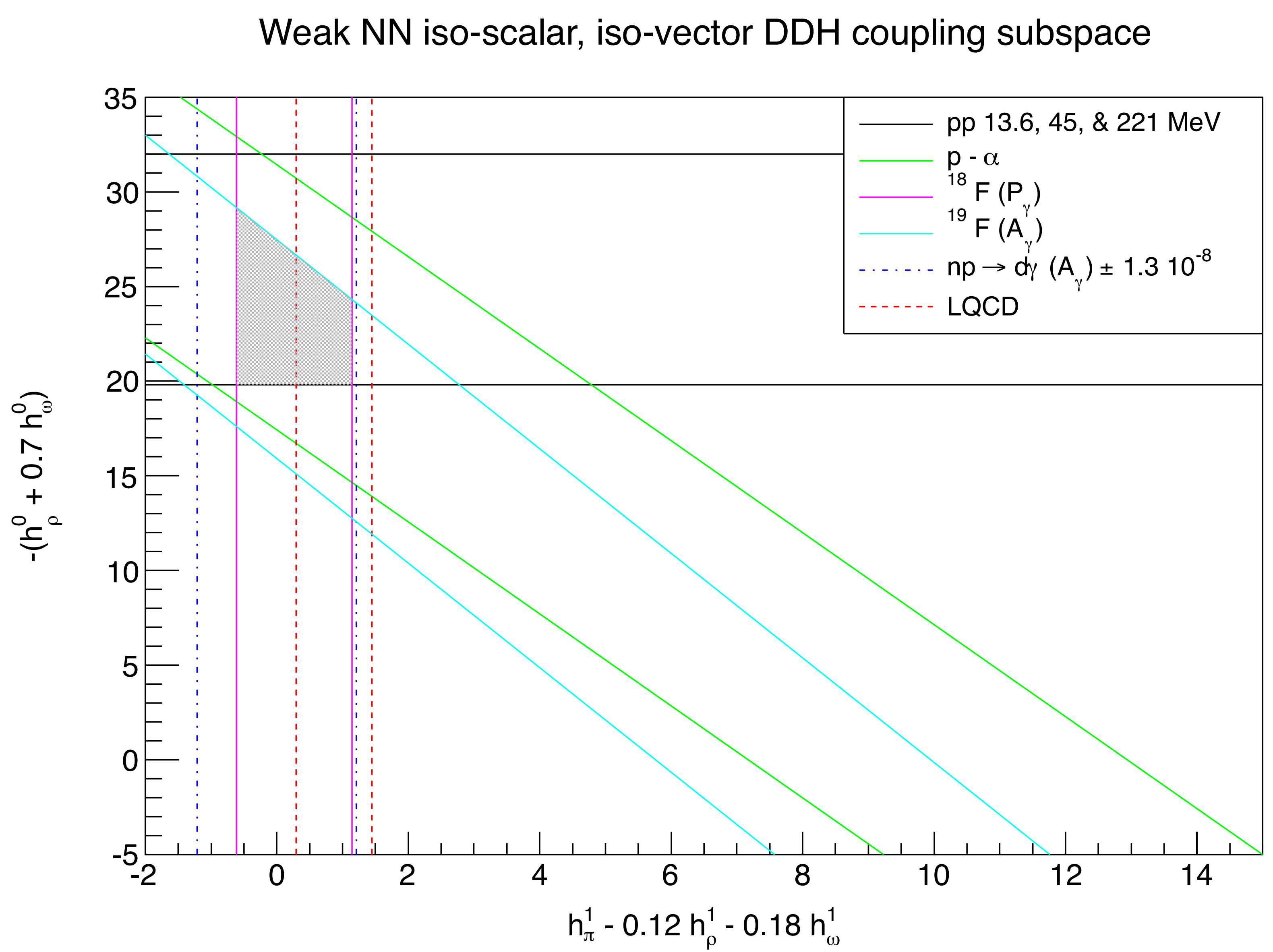
$$A_\gamma = -\underline{0.107 h_\pi^1} - 0.001 h_\rho^1 - 0.004 h_\omega^1$$

dominated by h_π^1 , h_ρ^1 and h_ω^1 small from K decay data

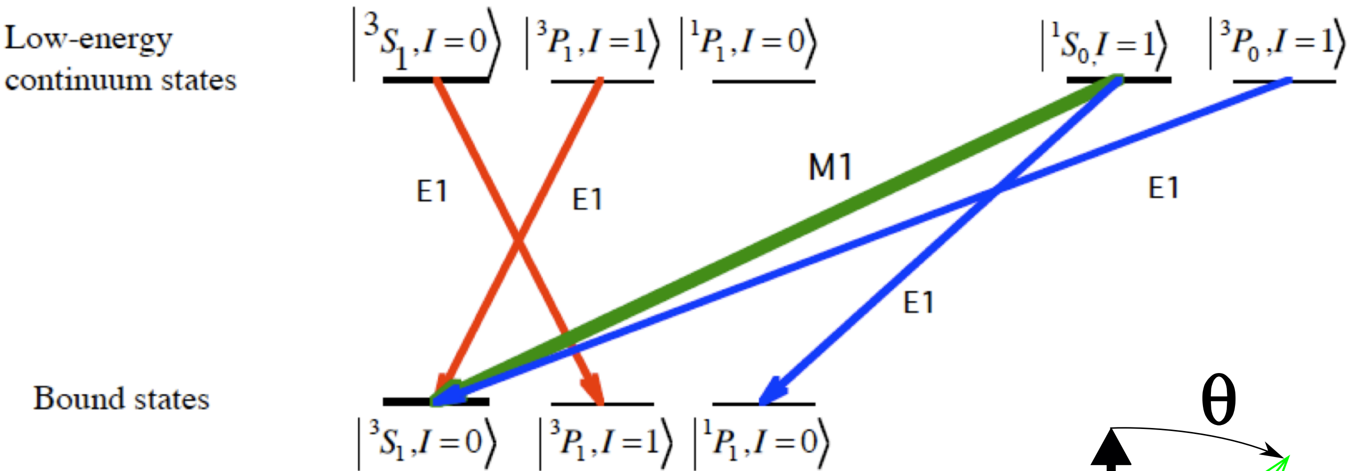
- NPDGamma seeks to measure h_π^1 to 10^{-7}, so A_γ must be measured to 10^{-8}. DDH best value of h_π^1 is $5\mathrm{x}10^{-7}$ → reasonable range is 0 → $11\mathrm{x}10^{-7}$. Theory is wide open.

- NPDGamma will perform the most precise few nucleon measurement of h_π^1: **sensitive to neutral weak currents**

NPDGamma and HWI

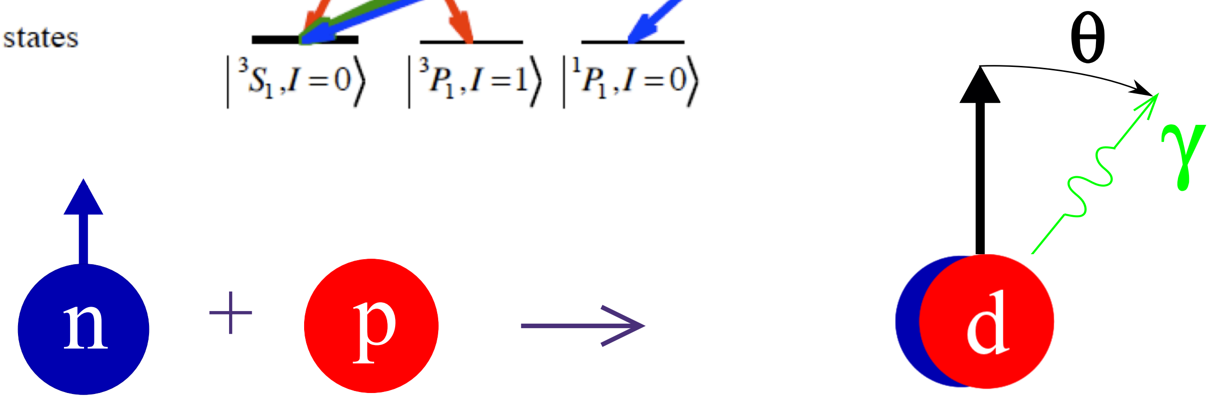


NPDGamma Reaction and PV



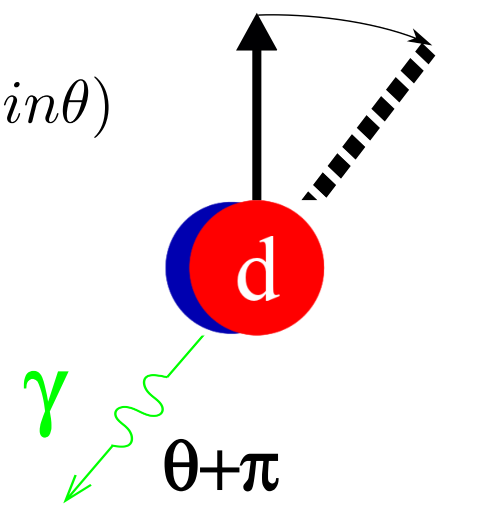
Electric and Magnetic dipole transitions from n-p radiative capture

Produces mixture of states with opposite parity



Flipping the neutron polarization is equivalent to a parity transformation

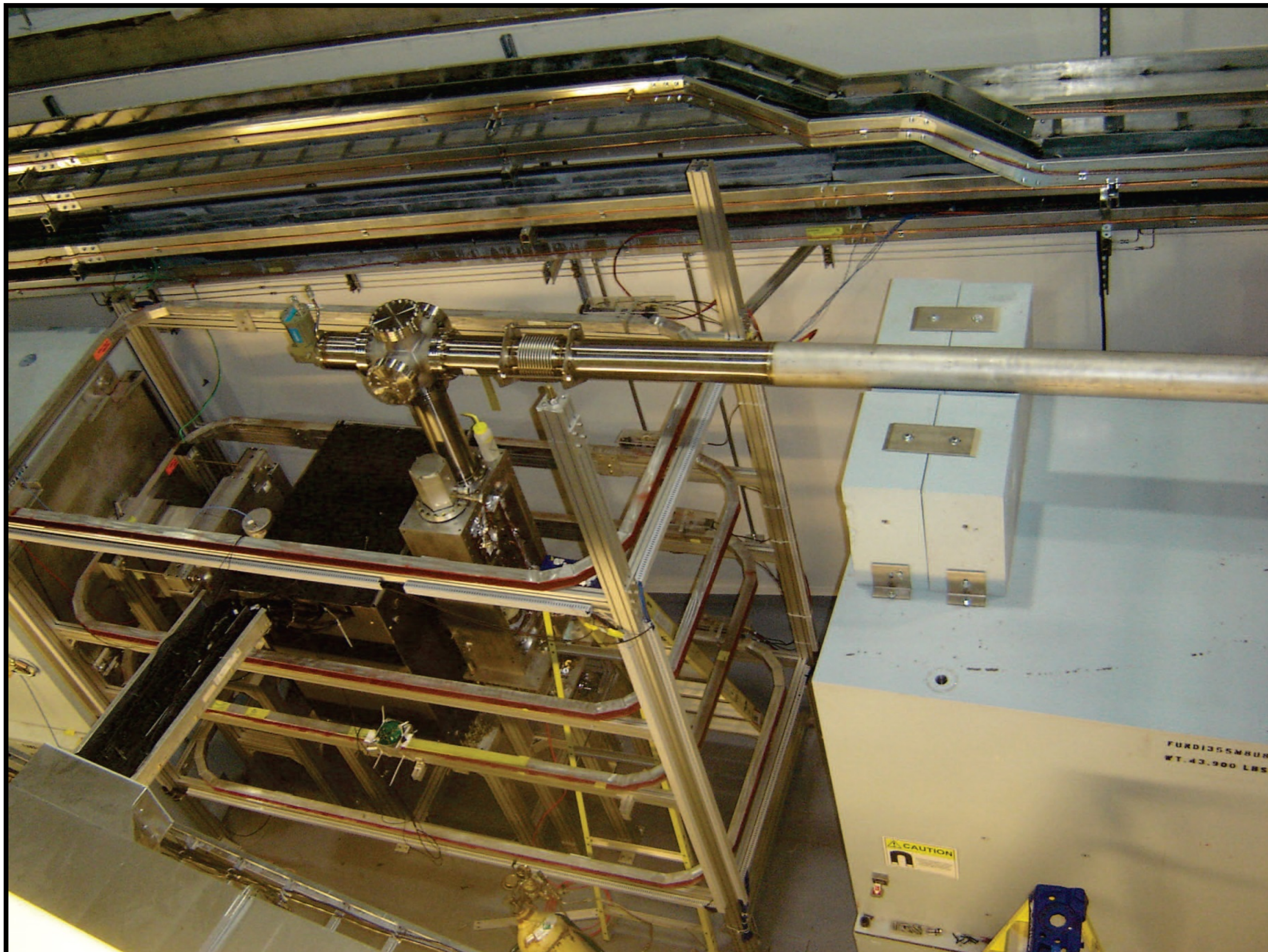
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_{UD} cos\theta + A_{LR} sin\theta\right)$$



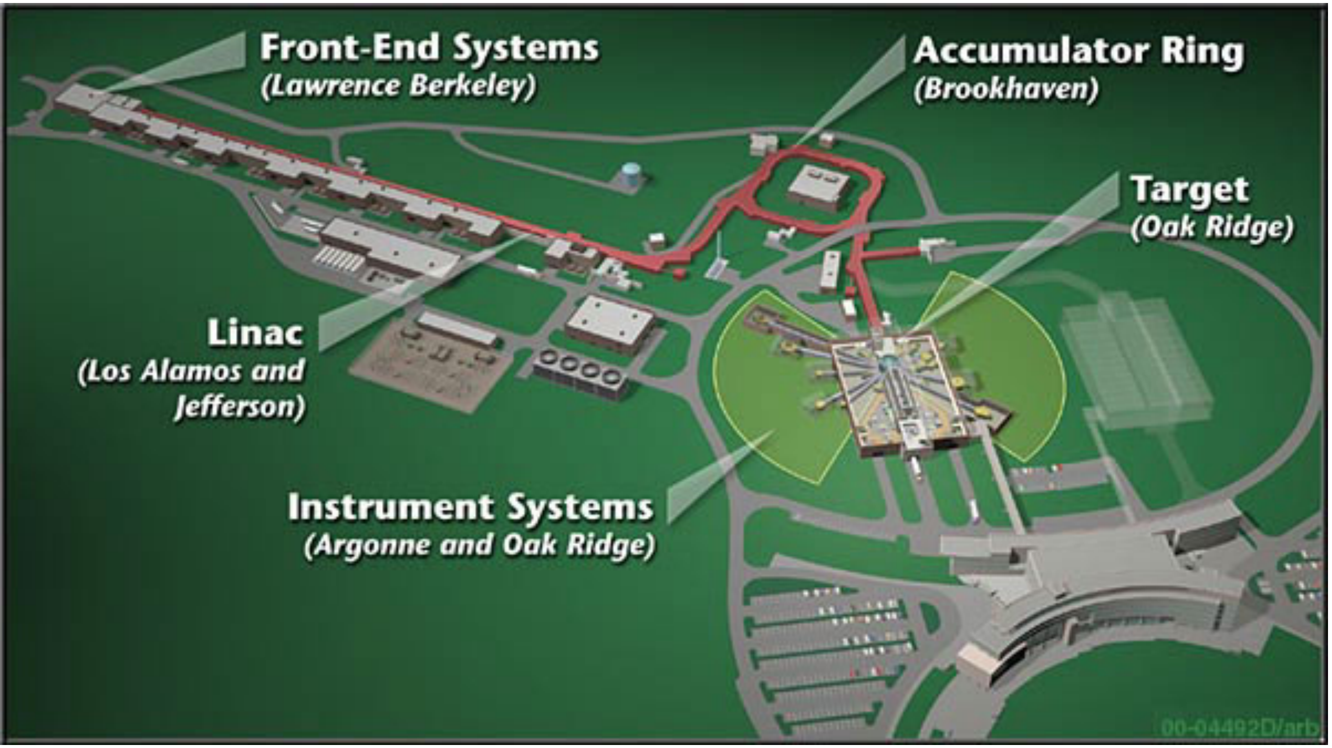
NPDG measures the asymmetry between the neutron polarization and the emitted photon's momentum

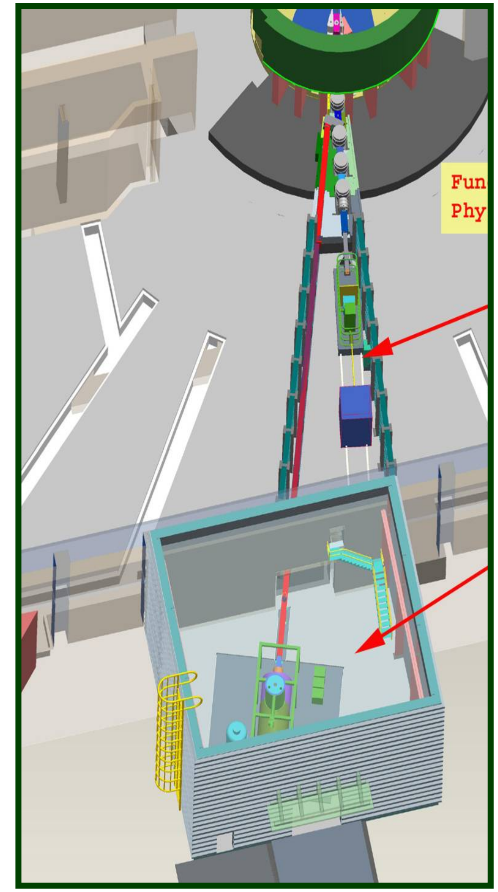
NPDG at SNS FNPB

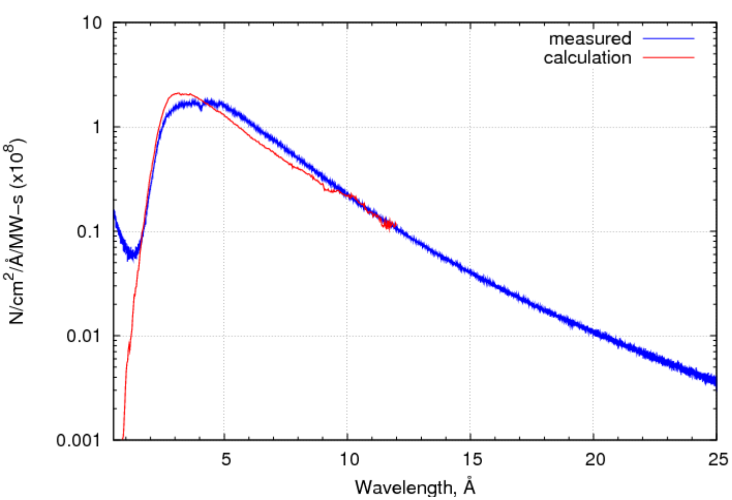
Reached 1.4MW at end of September, 2013 – Facility Goal



Neutrons at the SNS

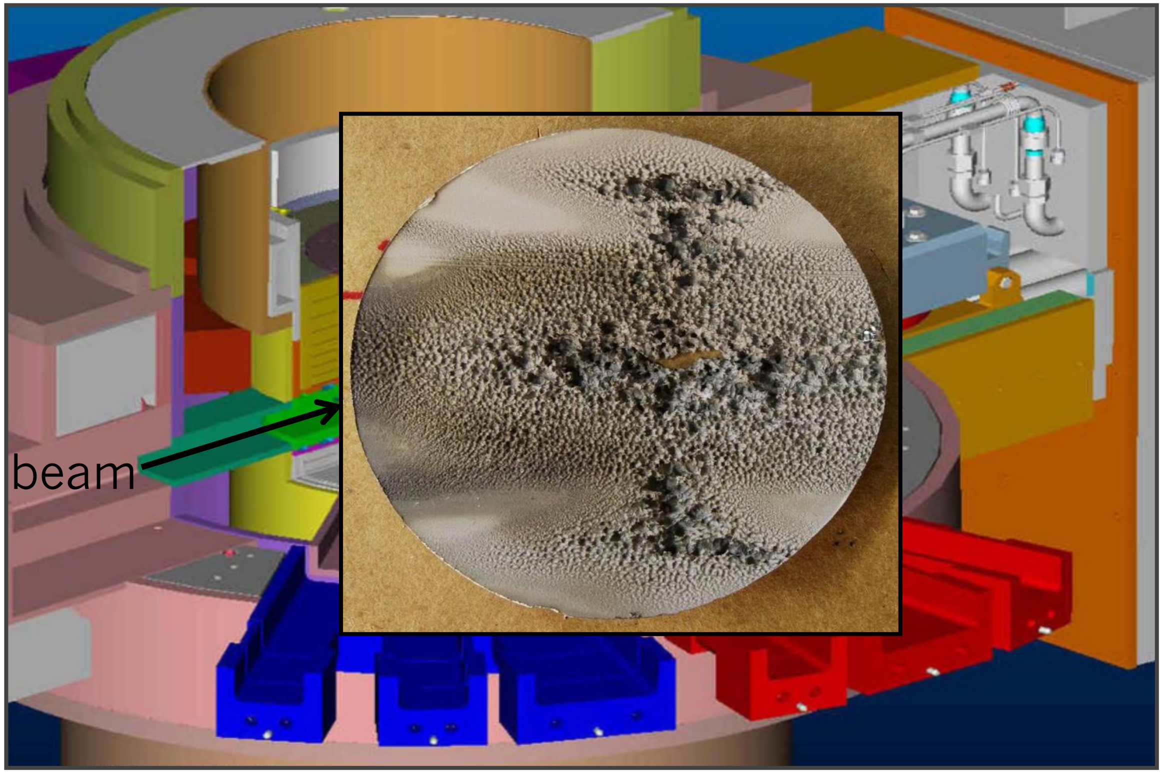


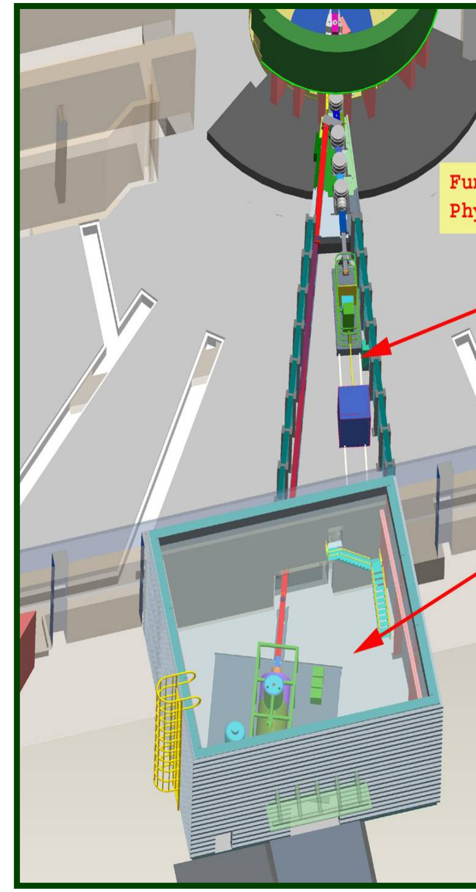


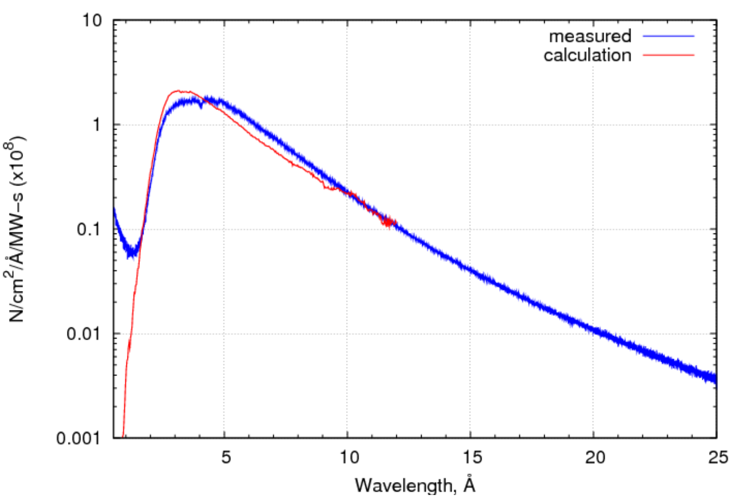


- Proton energy of 940MeV incident on a circulating target of mercury
- 60Hz rep rate with time-averaged proton power of 1.4MW
- Neutrons moderated by four H_2 moderators, H_2O moderators, and Be reflector

Neutrons at the SNS







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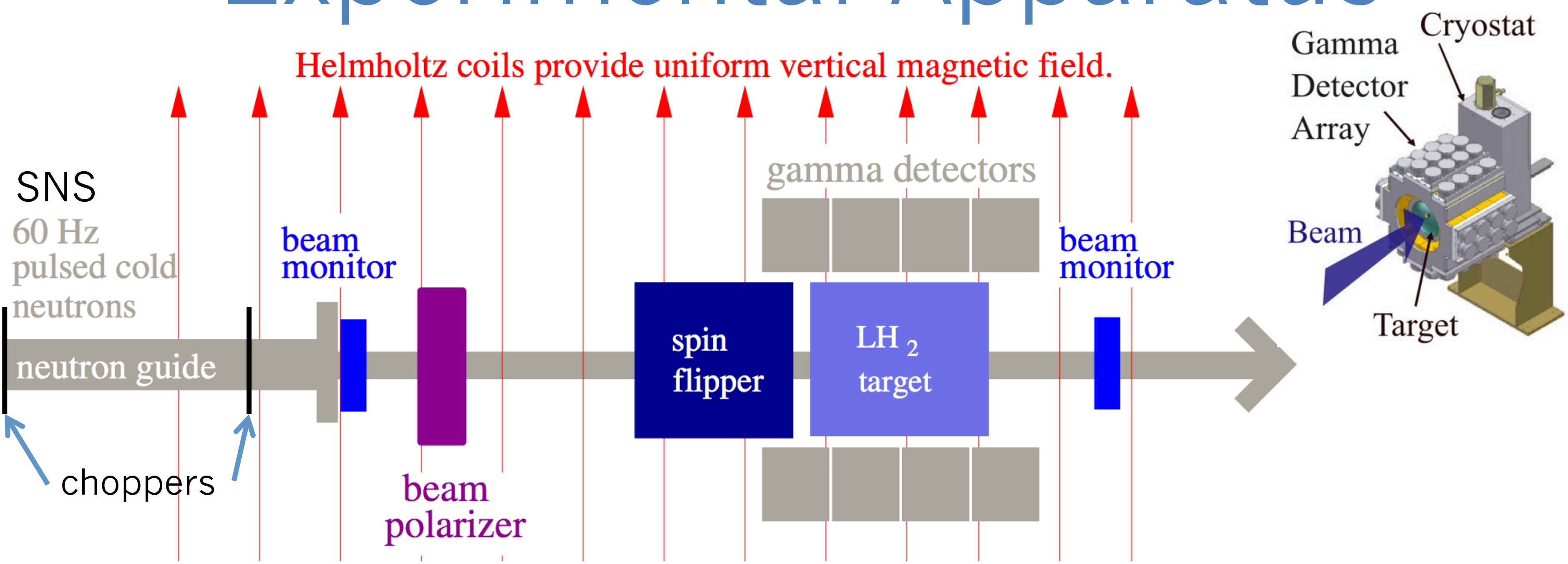

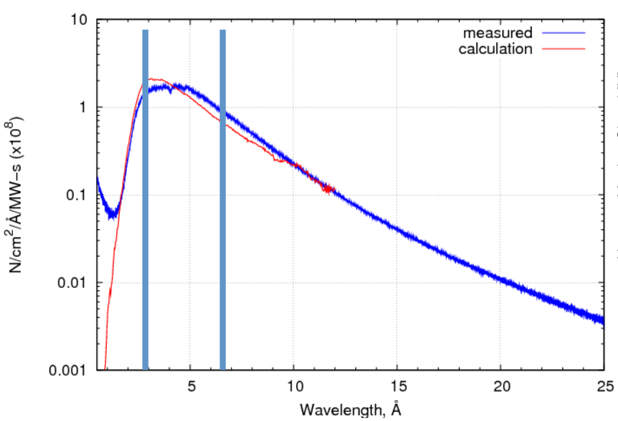

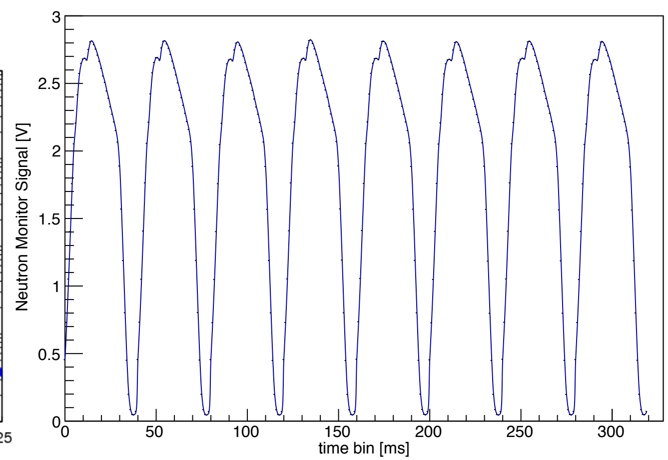

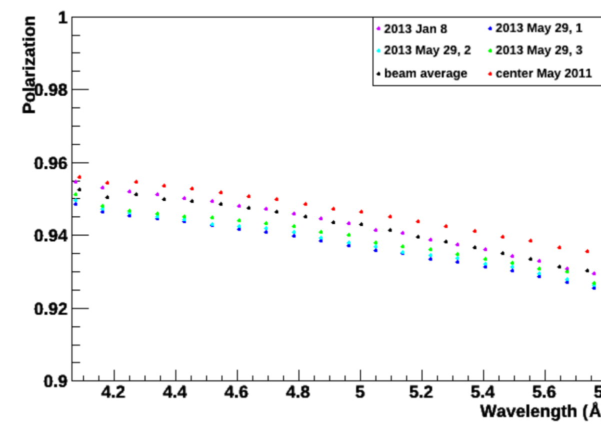

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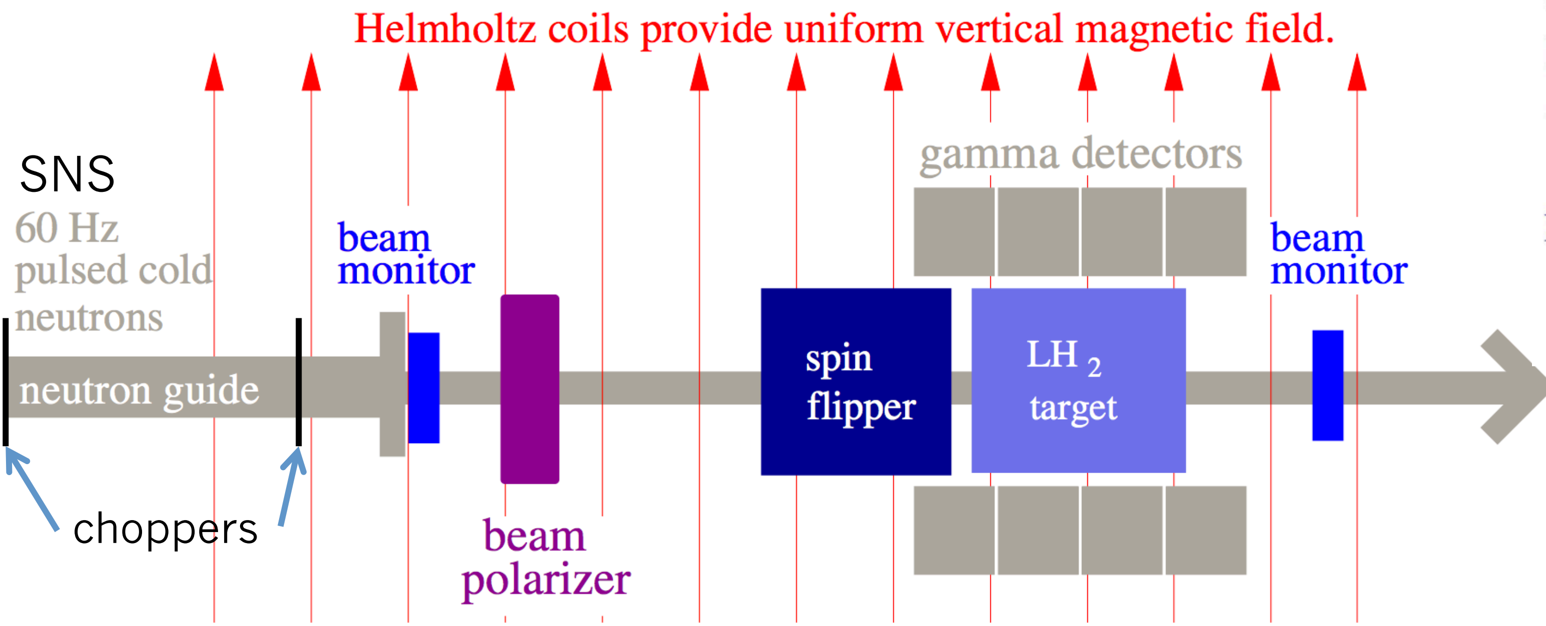
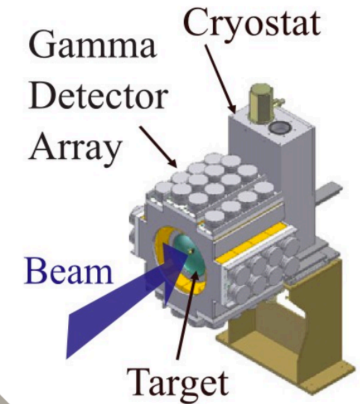
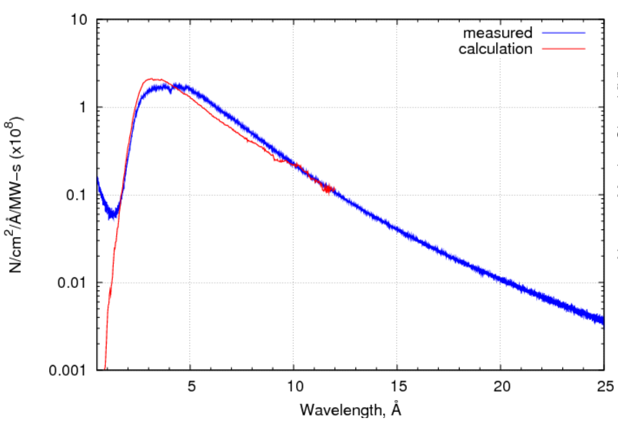
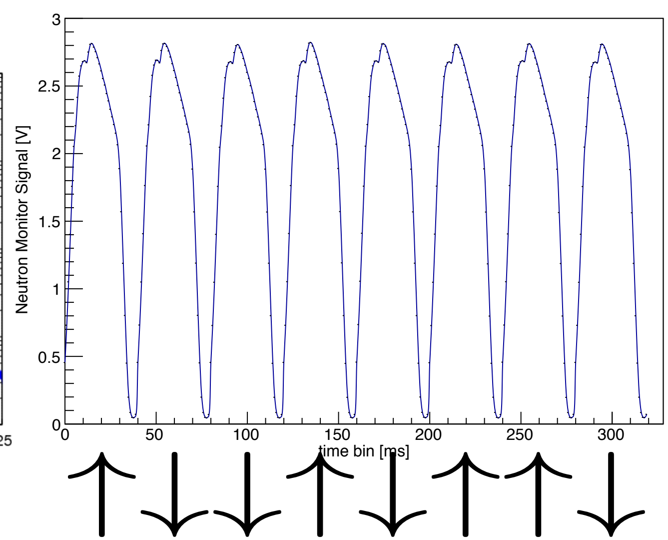


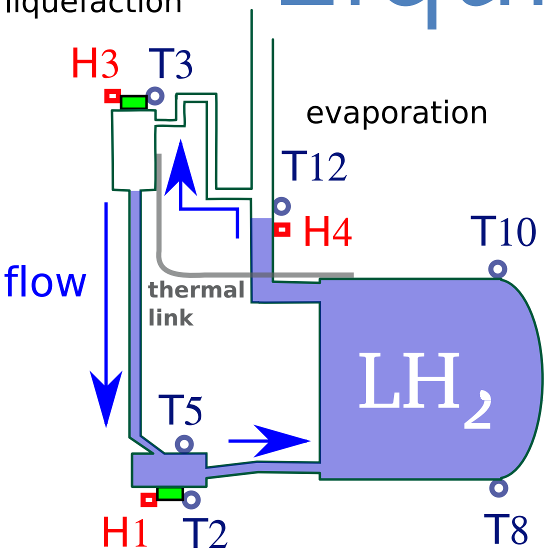


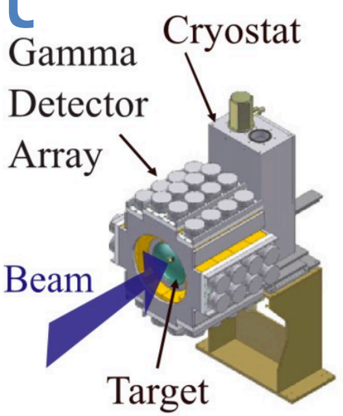


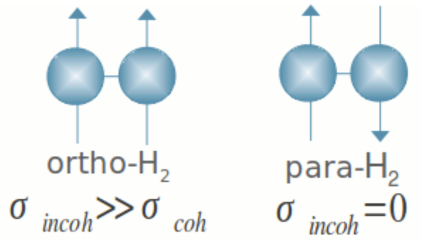


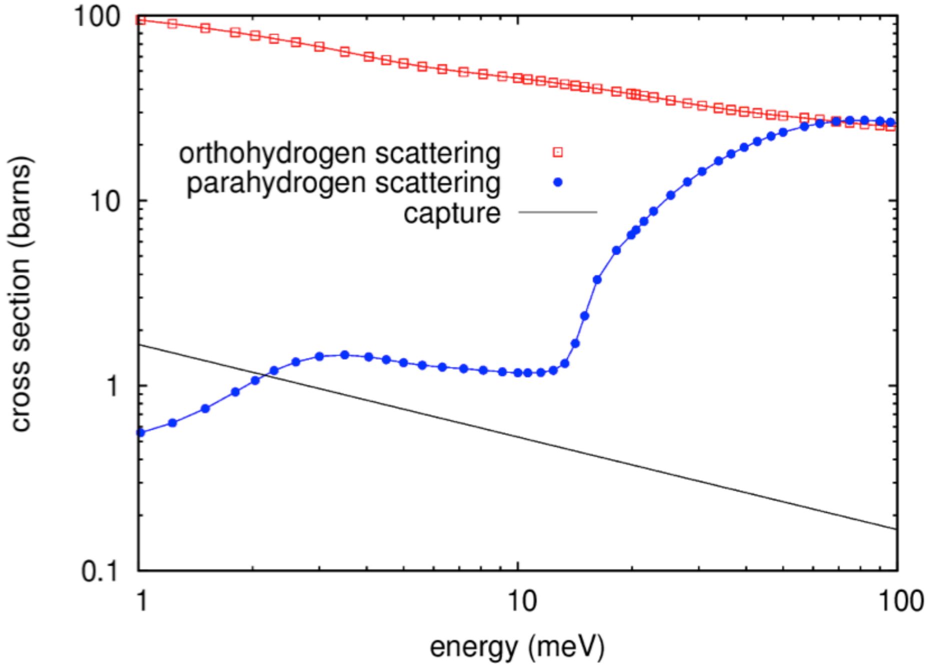
- Resonant Spin Rotator flips spins each pulse to cancel time dependent detector gain drifts
- Neutrons capture in LH_2 target, detected in a 3π CsI detector array (48)

Liquid para-H_2 Target



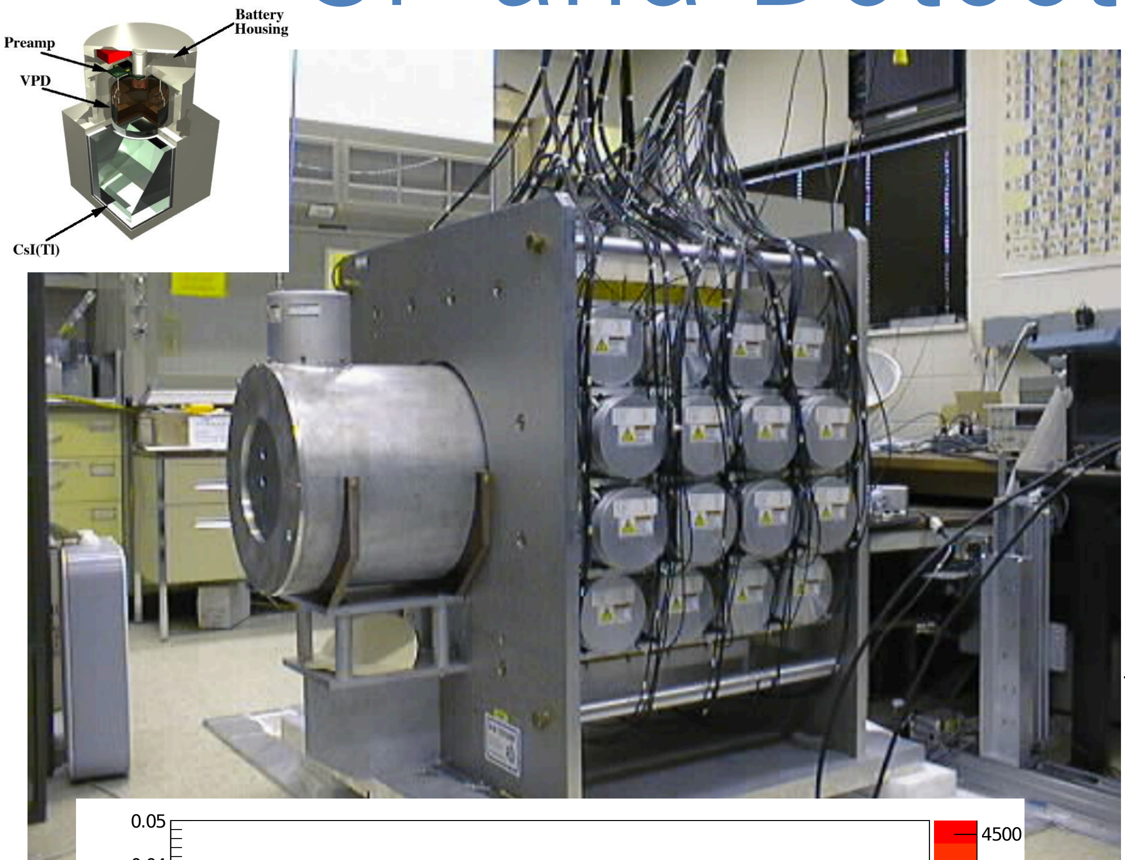


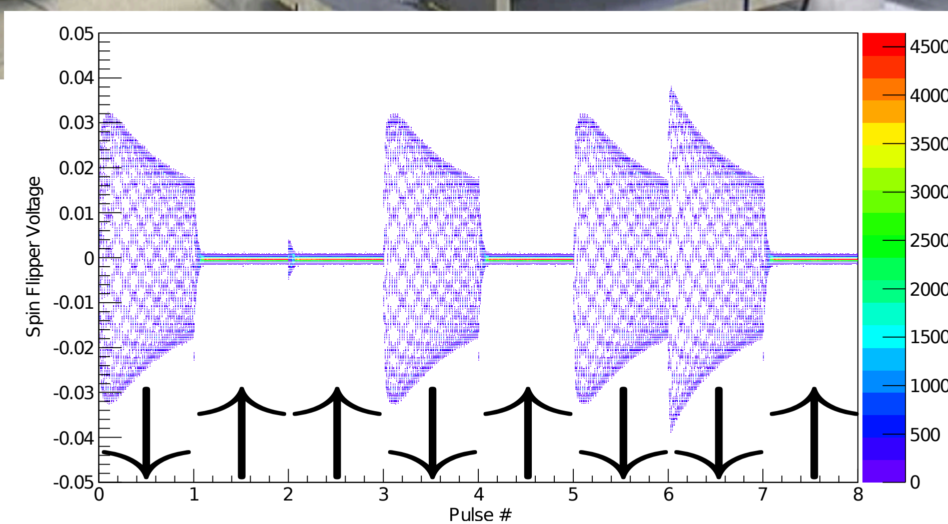




- Ortho significantly scatters and depolarizes a cold neutron beam
- Ortho thermodynamic equilibrium is low for liquid H temperatures
- Active circulation and catalyst to promote circulation from ortho to para
- Spin1 Ortho → Δ 15meV → Spin 0 para

SF and Detector Array

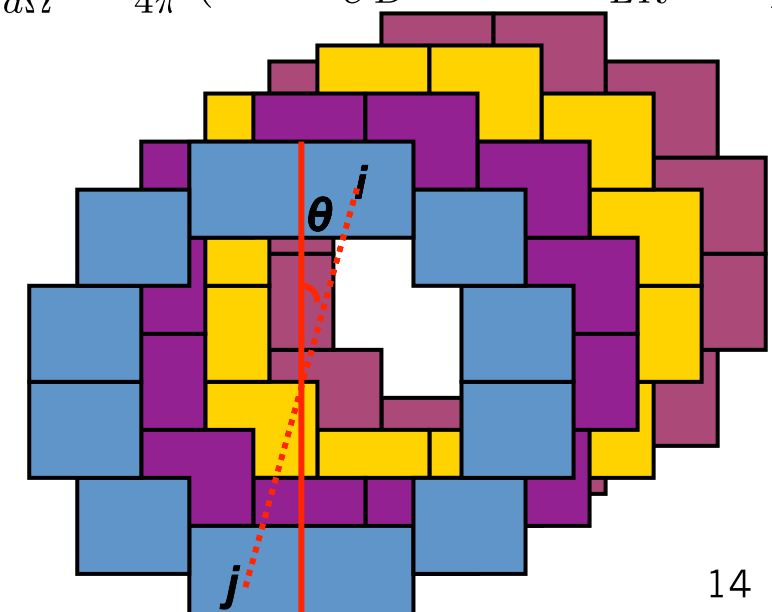




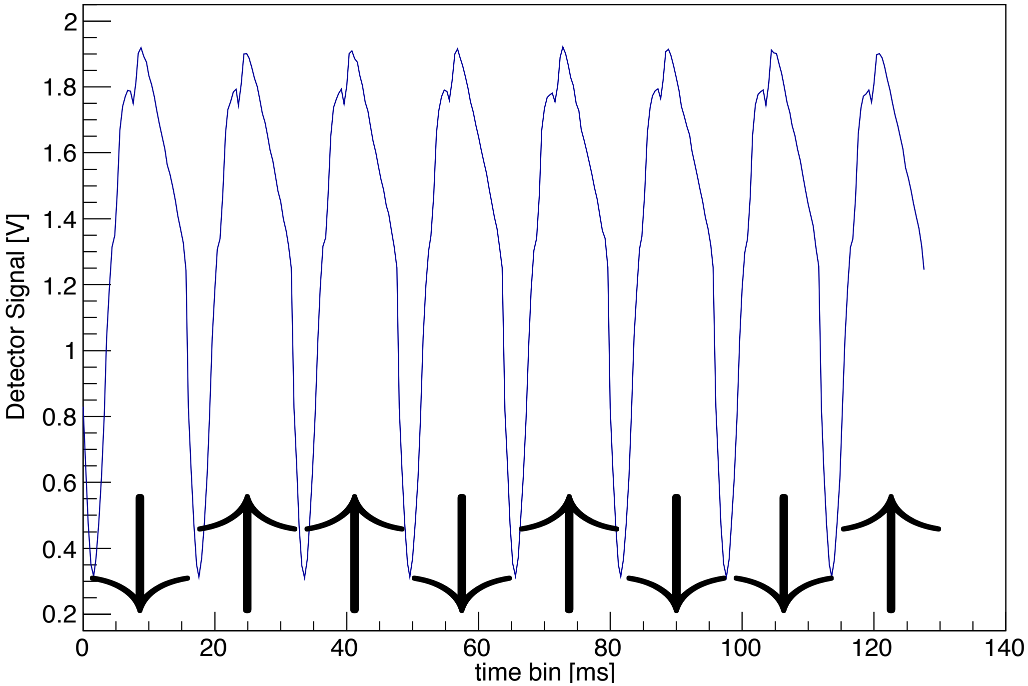
γ-Detector Array

- 4 rings of 12 CsI detectors → 48 total, form into 24 pairs
- 3π acceptance, current mode
- Rate: 100MHz

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_{UD}cos\theta + A_{LR}sin\theta\right)$$



Data Structure and Asymmetry



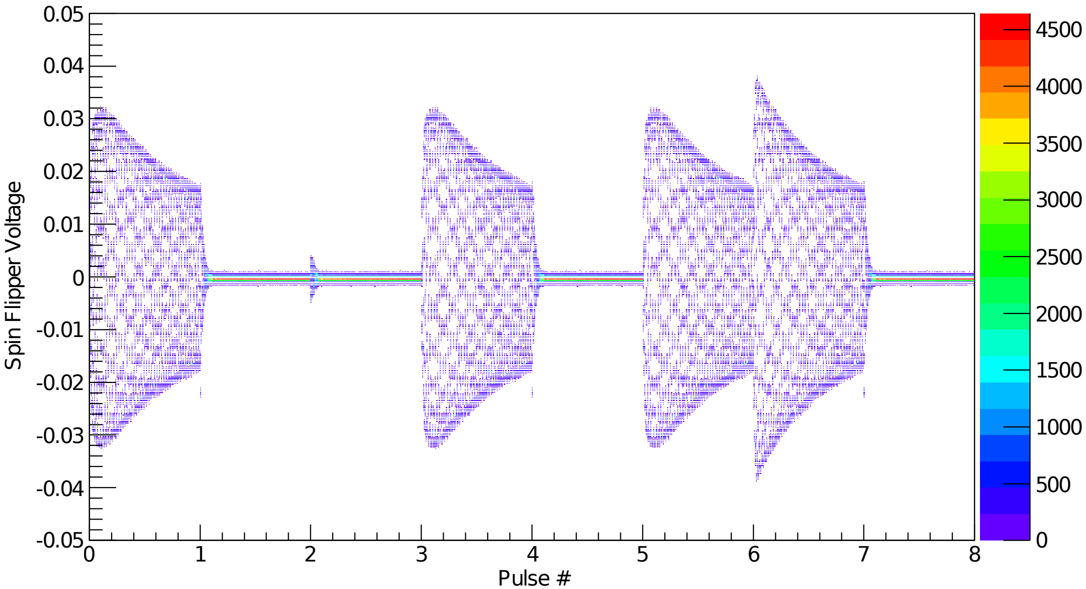
Asymmetry Extraction

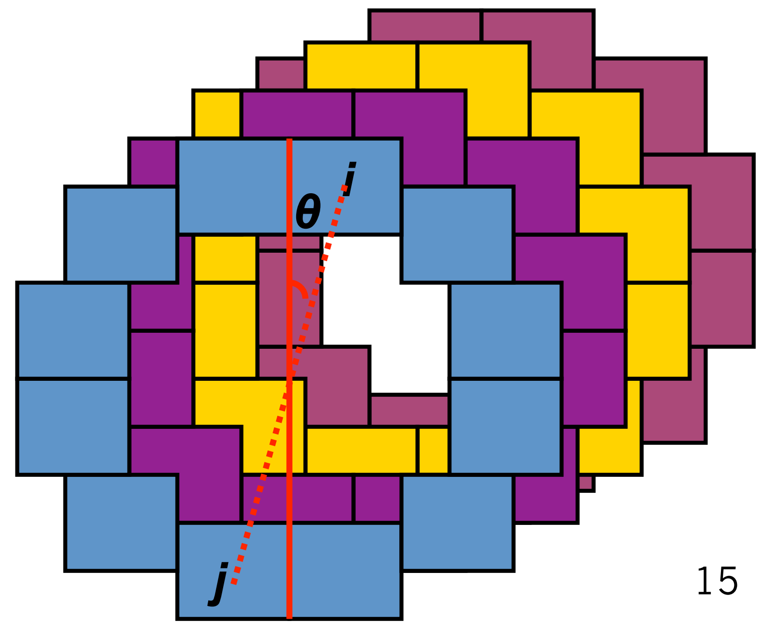
- Could extract asymmetry with just one detector, but since the asymmetry

$$\propto \frac{1}{4\pi}\left(1 + A_{UD}cos\theta + A_{LR}sin\theta\right)$$

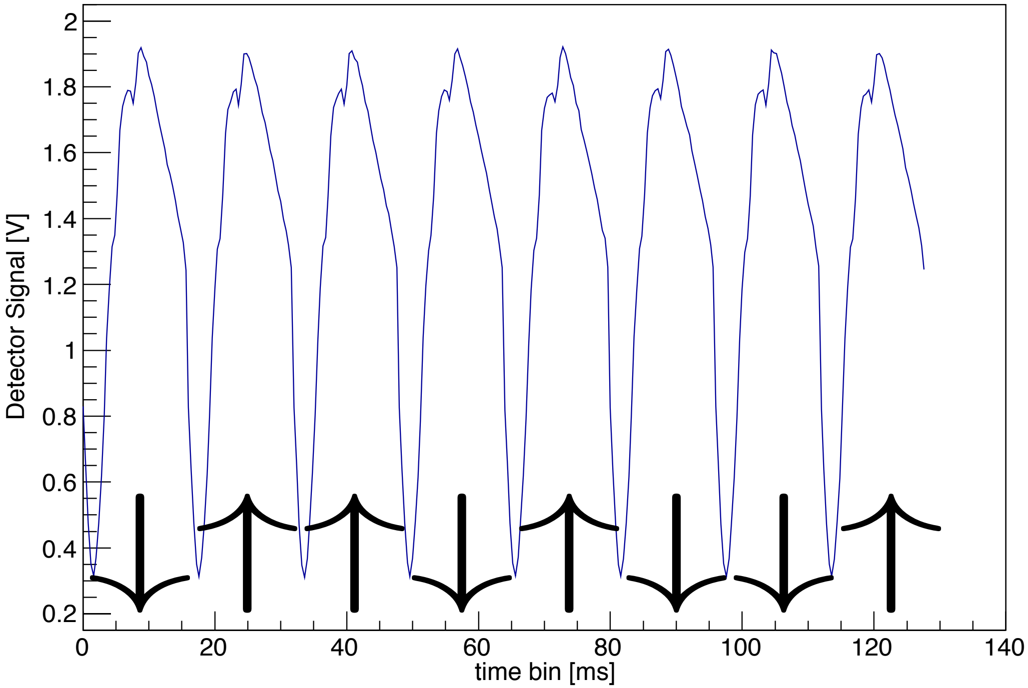
$$A_i^{raw} = \frac{\sqrt{\alpha}-1}{\sqrt{\alpha}+1}, \text{where } \alpha = \left[\frac{N_i^{\uparrow}}{N_i^{\downarrow}}\right]\left[\frac{N_j^{\uparrow}}{N_j^{\downarrow}}\right]$$

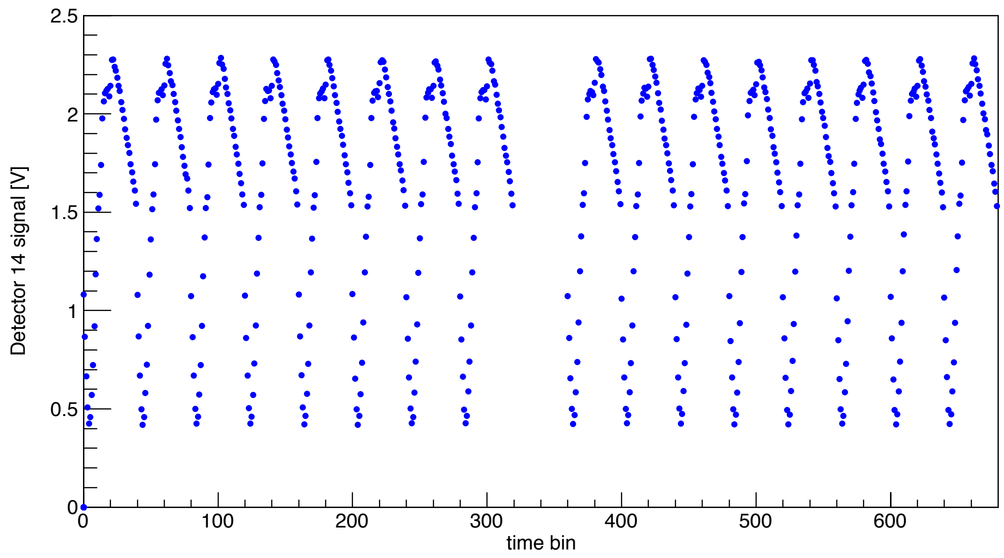
- Fit to all the detector signals via geometry of the detector array.





Data Structure and Asymmetry





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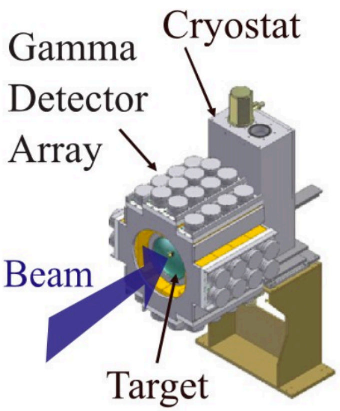
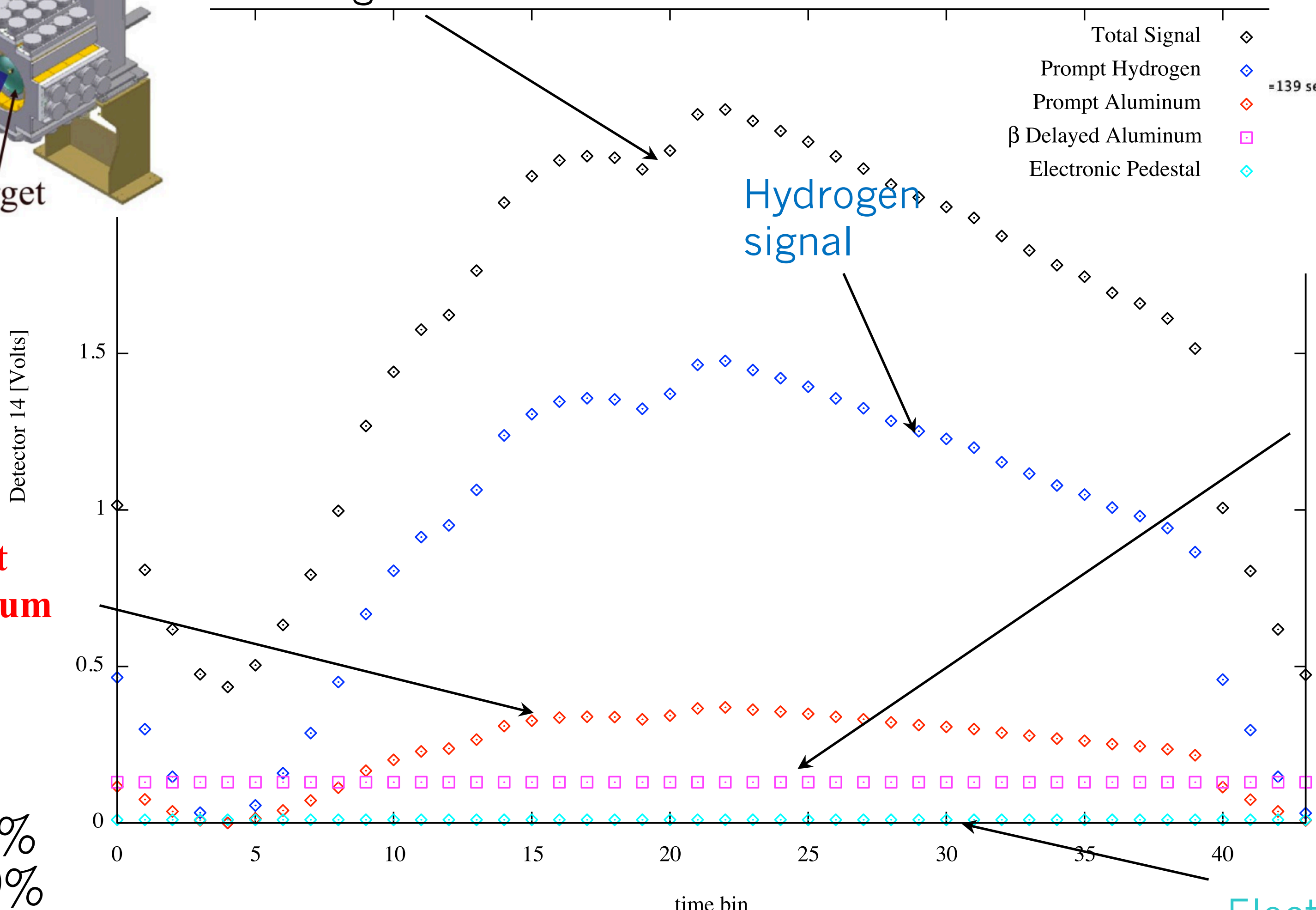
- Fit to all the detector signals via geometry of the detector array.

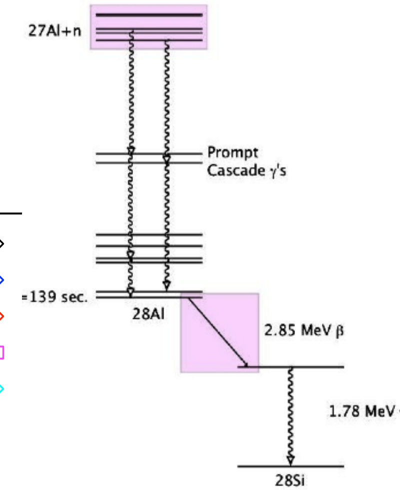
- Found transient asymmetry from contamination of the ring sum signals by the spin-reversal signal, move to a 16-step spin sequences

$$\uparrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\downarrow + \downarrow\uparrow\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow = 16 \text{ ss}$$

Fractions of the Signal







Total Signal

Hydrogen signal

Prompt aluminum signal

β-delayed aluminum signal

Electronic pedestal

H: 80%
Al: 20%
β -delayed: 5%

Phenomena to Overcome

Beam

- Dropped pulses
- Low powered pulses
- Pulse to pulse variation
- Chopper phases

Pedestals/corrections

- Constant pedestal
  - β -delayed Al
  - Essential for asymmetry
- Electronic pedestal

Eliminate data that have

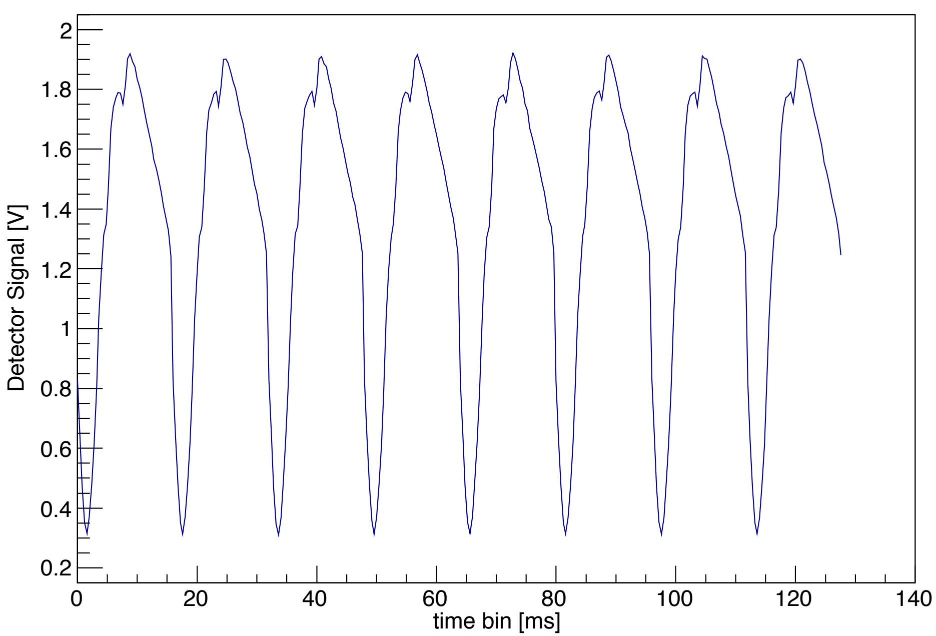
- False asymmetries, systematic error
- Polarization is unknown

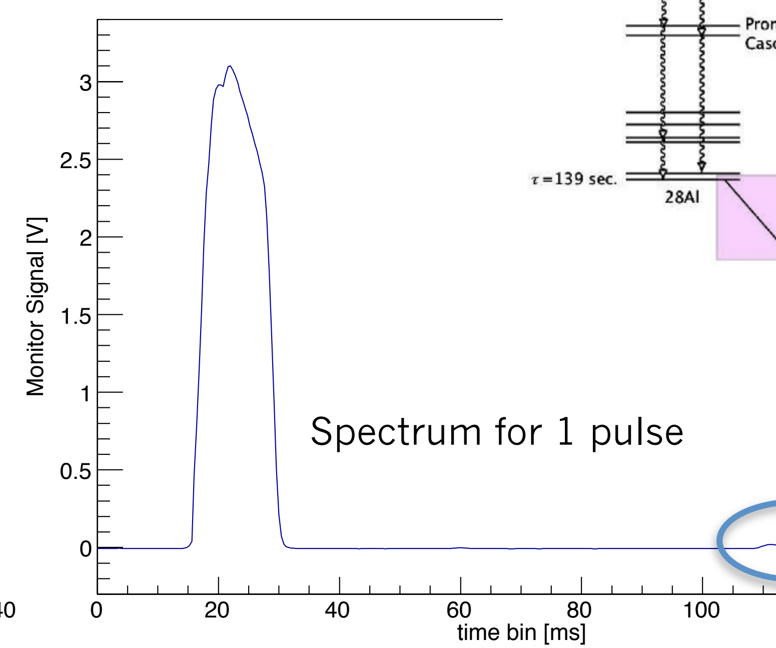
Measure the

- Prompt Al PV correction
- Fractions of prompt signals

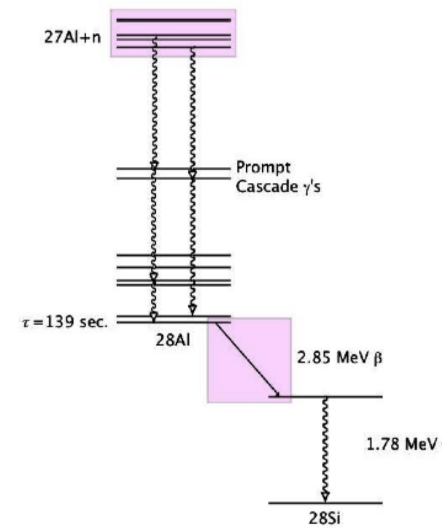
Analysis Goals of NPDG

- Eliminate systematics and false asymmetries
- Obtain the amplitude of each pulse (including read pulse) to keep track of dropped pulses, wrap-around neutrons
- Need to determine the dynamic β -delayed Al pedestal in the signal to properly calculate the asymmetry.
- No bias, simple algorithm, minimal assumptions



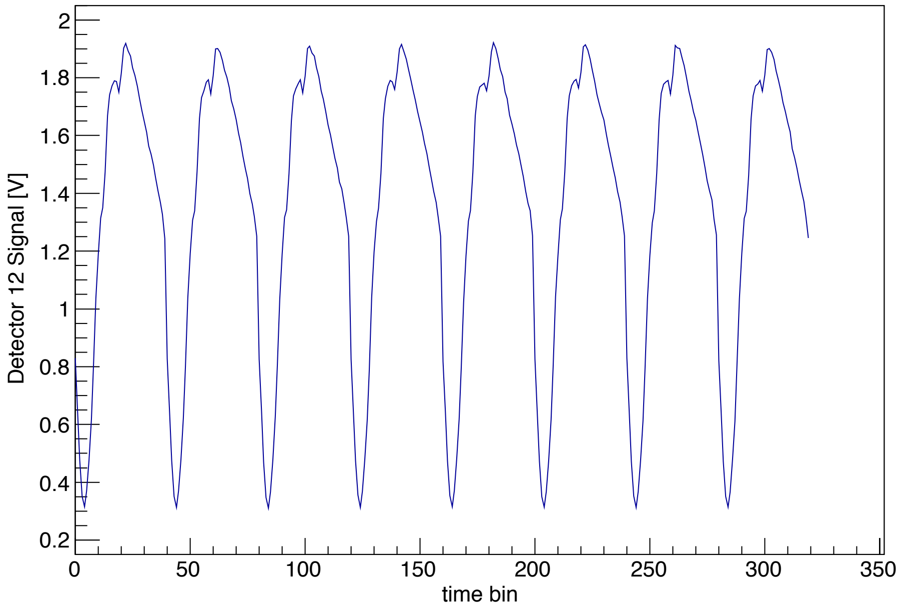


Spectrum for 1 pulse



Analysis Algorithm – "Perfect Pulse"

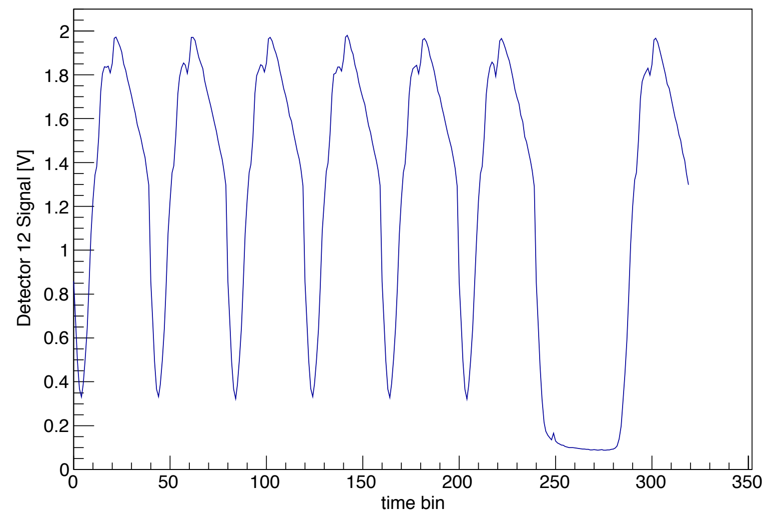
- Goal: Do a least squares fit with a "perfect pulse" to spin sequences yielding 9 amplitudes a_i and a pedestal for each spin sequence
  - The χ^2 value tests the quality of the fit
  - The a_i's (including read pulse) can be used to make high level cuts for subsequent analysis
  - Fitted pedestal will be subtracted from the asymmetry
- Use PP algorithm for diagnostics, not asymmetry calculations
- Use m1 monitor For spectra changes and chopper phases

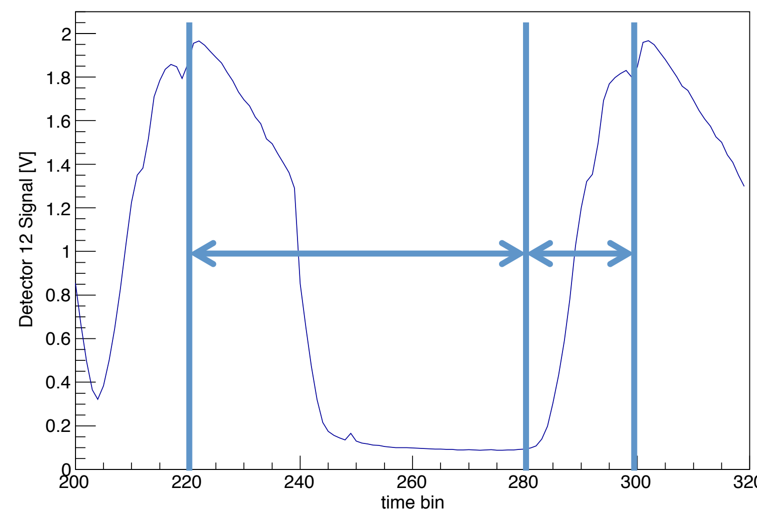


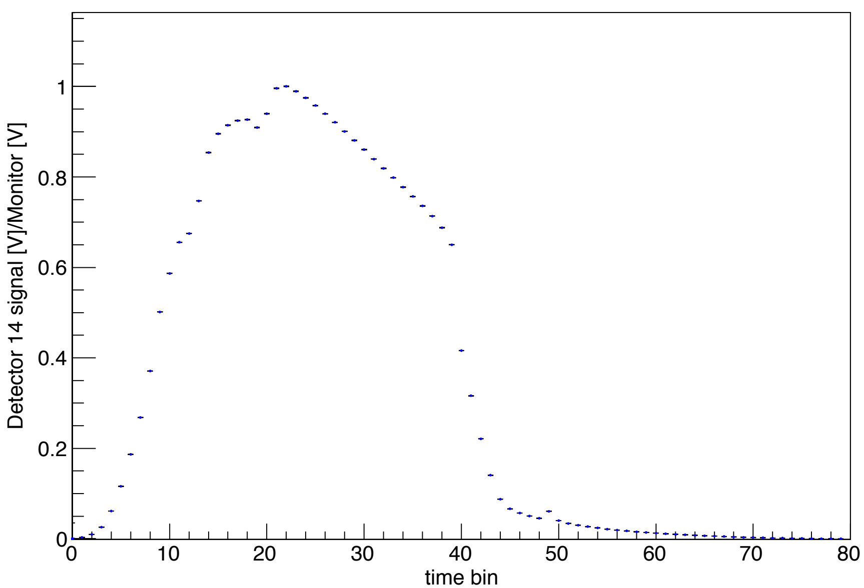
Constructing a Perfect Pulse

- Find a 16 step spin sequence that has a single dropped pulse. 1 in every 100 pulses intentionally dropped from the accelerator.

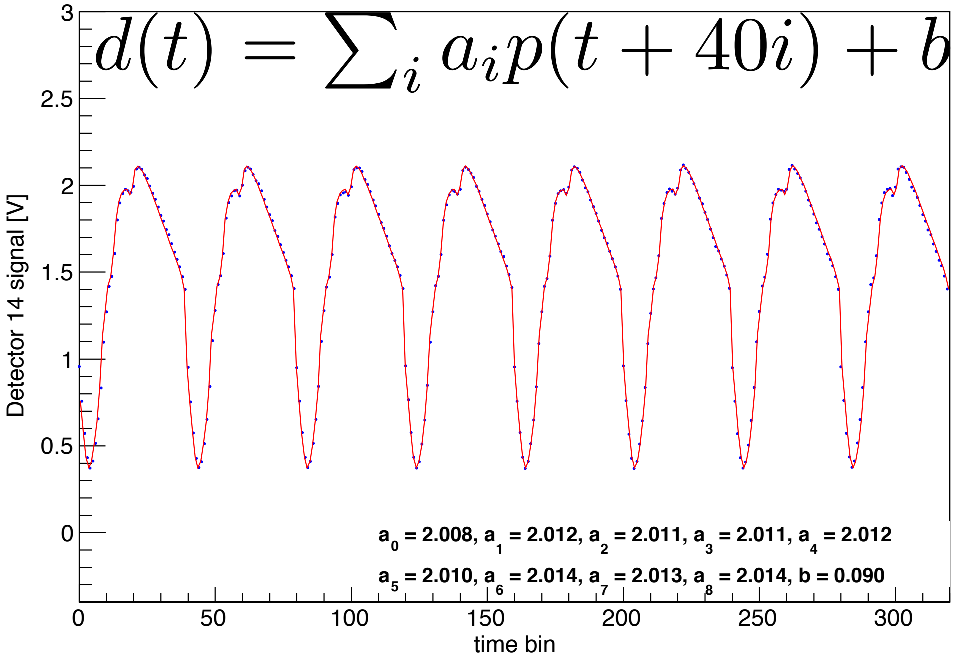
- Go over an entire run to get statistical significance for each bin, subtract the pedestal and normalize. Have what would be one stand alone pulse with wraparounds.

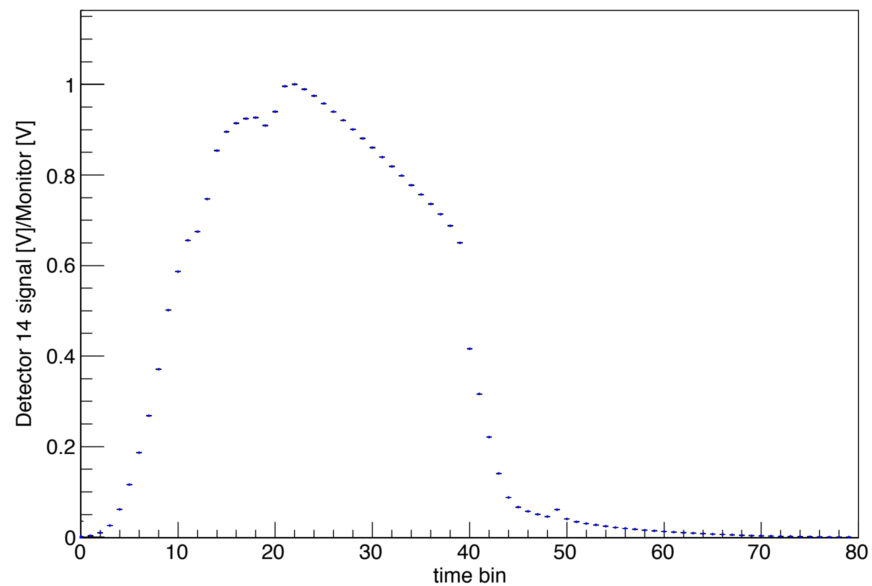






Fit to a Spin Sequence

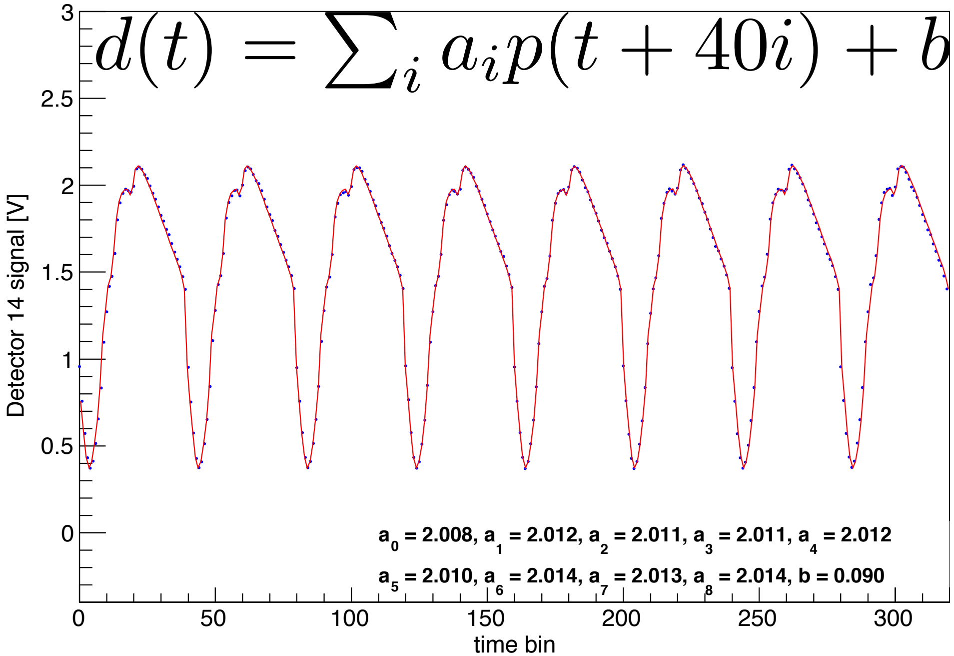


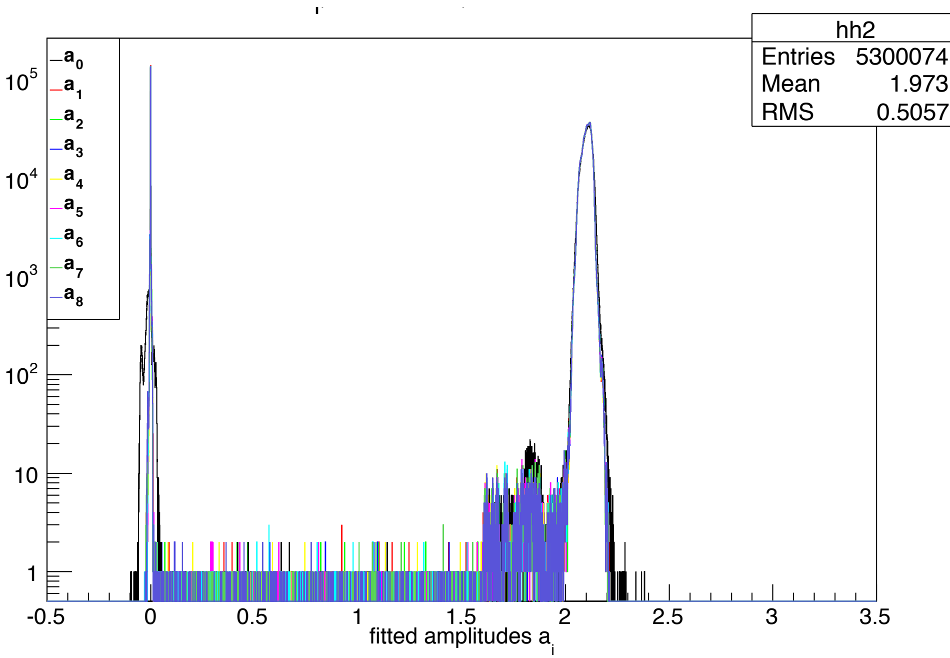


Fitted amplitudes provide information on:

- Dropped pulses
- Lower powered pulses
- Read pulse height
- Pulse height stability in a spin sequence
- Dynamic pedestal

Fit to a Spin Sequence





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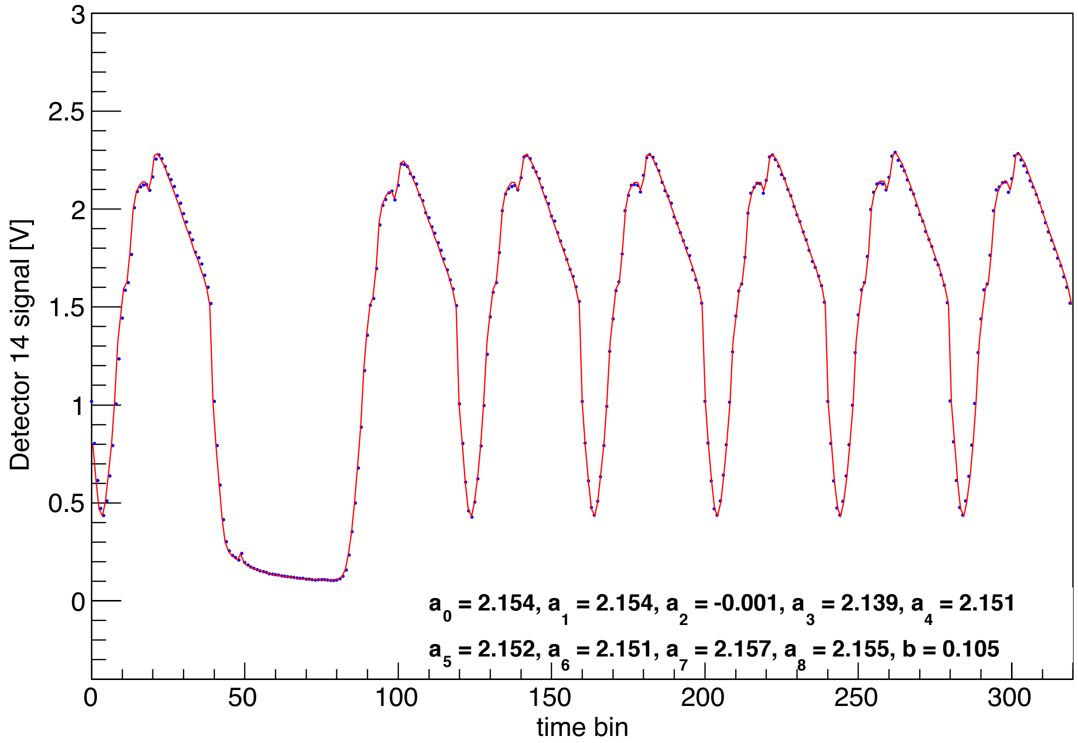

Fitted amplitudes provide information on:

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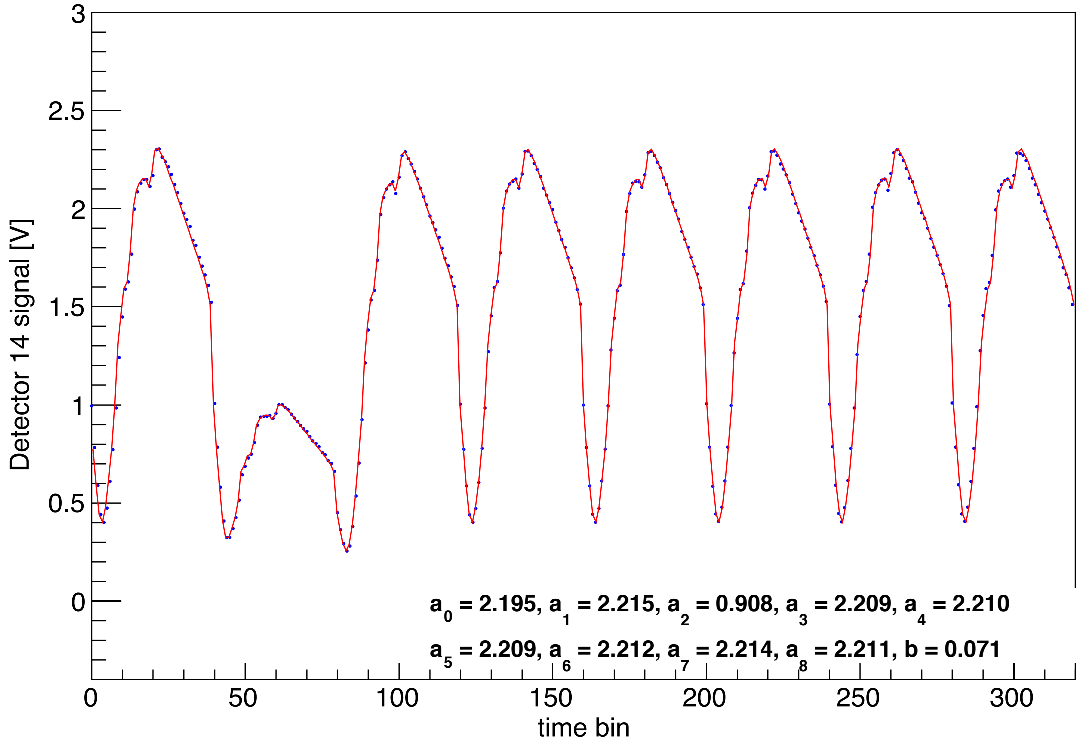
Fit to a Spin Sequence



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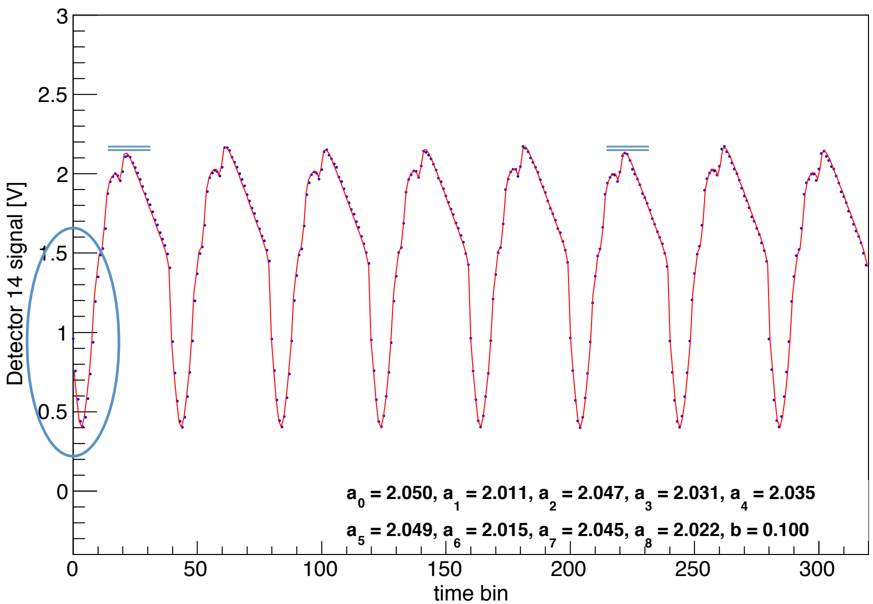
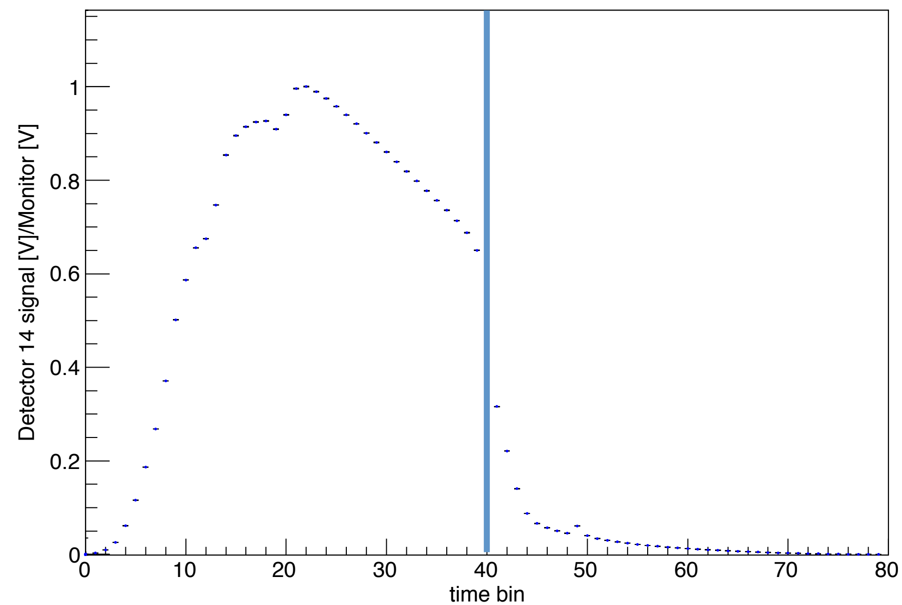
Fit to a Spin Sequence



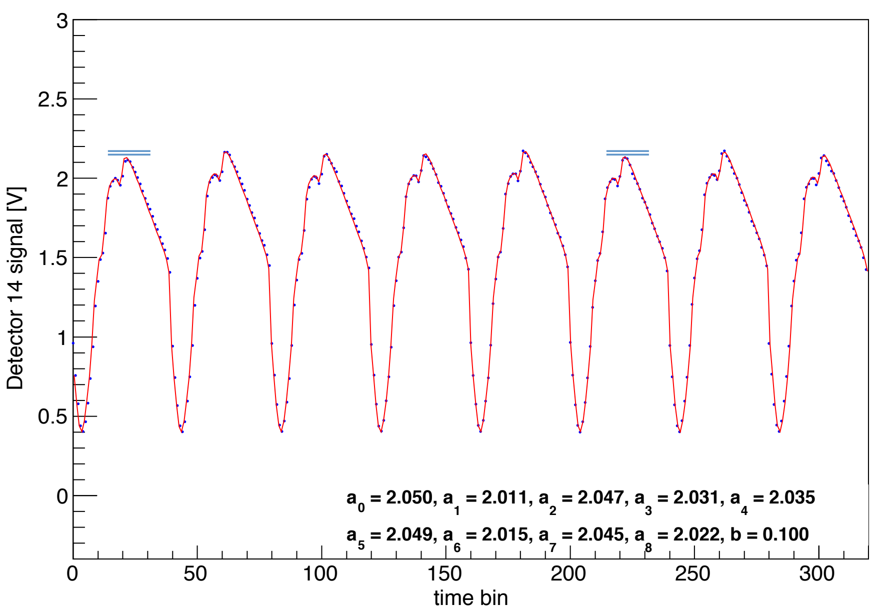


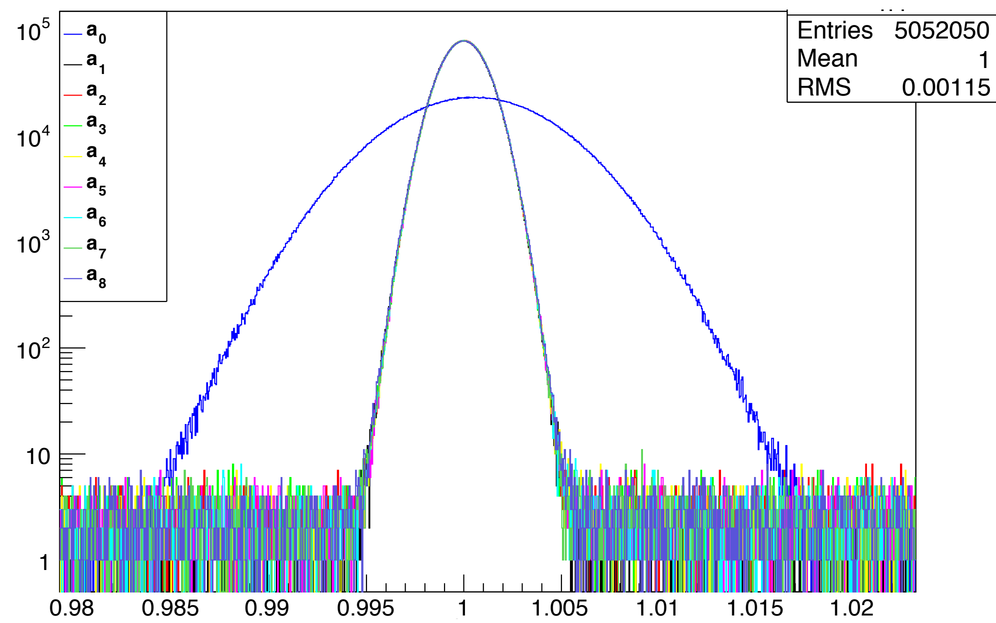
Fitted amplitudes provide information on:

- Dropped pulses
- Lower powered pulses
- **Read pulse height**
- Pulse height stability in a spin sequence
- Dynamic pedestal

Pulse fits contain the decay into the next pulse → can get the amplitude of the read pulse

Fit to a Spin Sequence



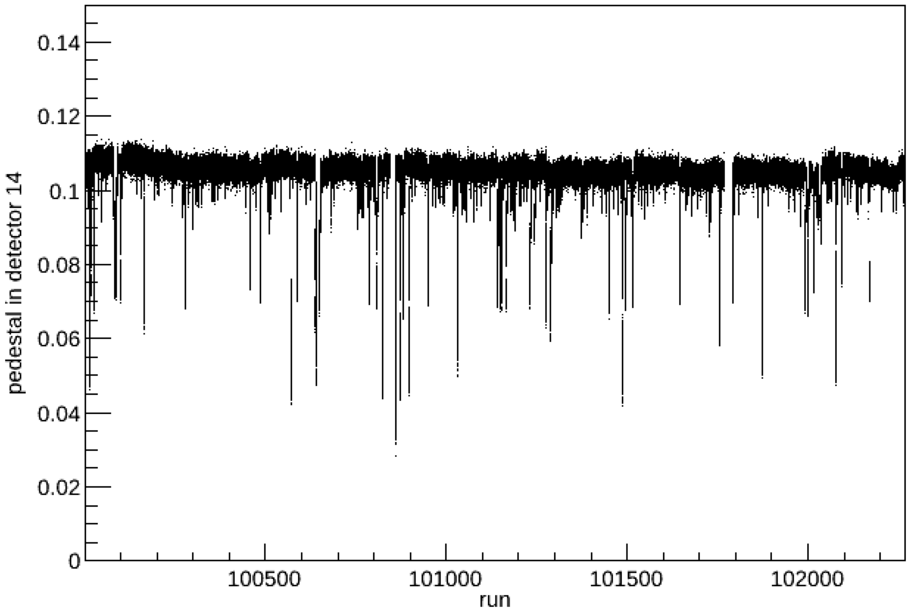


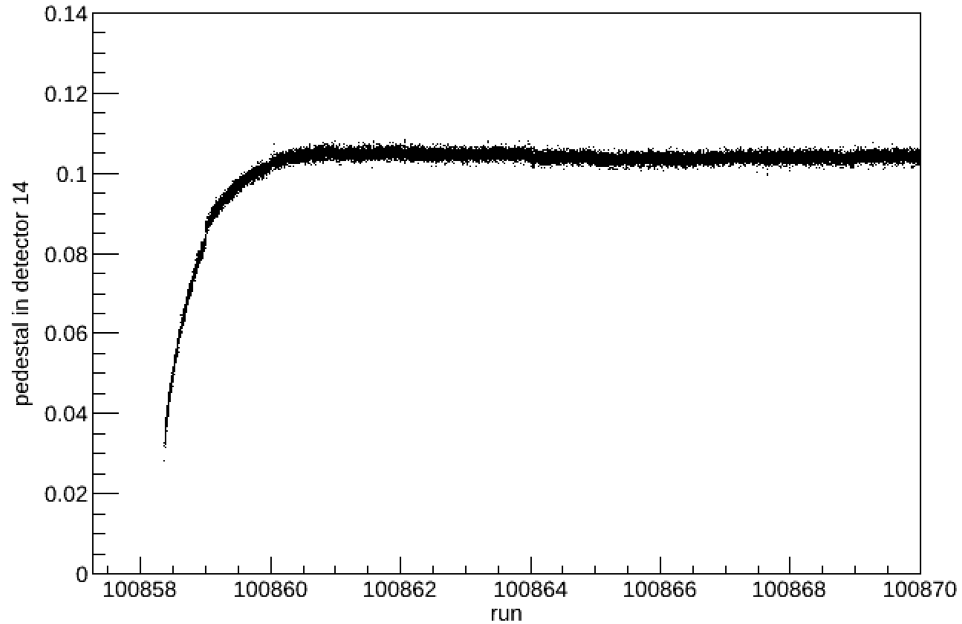
$$\alpha_i = \frac{a_i}{\frac{1}{7}\sum_{j\neq i} a_j}$$

Fitted amplitudes provide information on:

- Dropped pulses
- Lower powered pulses
- Read pulse height
- **Pulse height stability in a spin sequence**
- Dynamic pedestal

Fit to a Spin Sequence





2,200 runs = 10.7 beam days

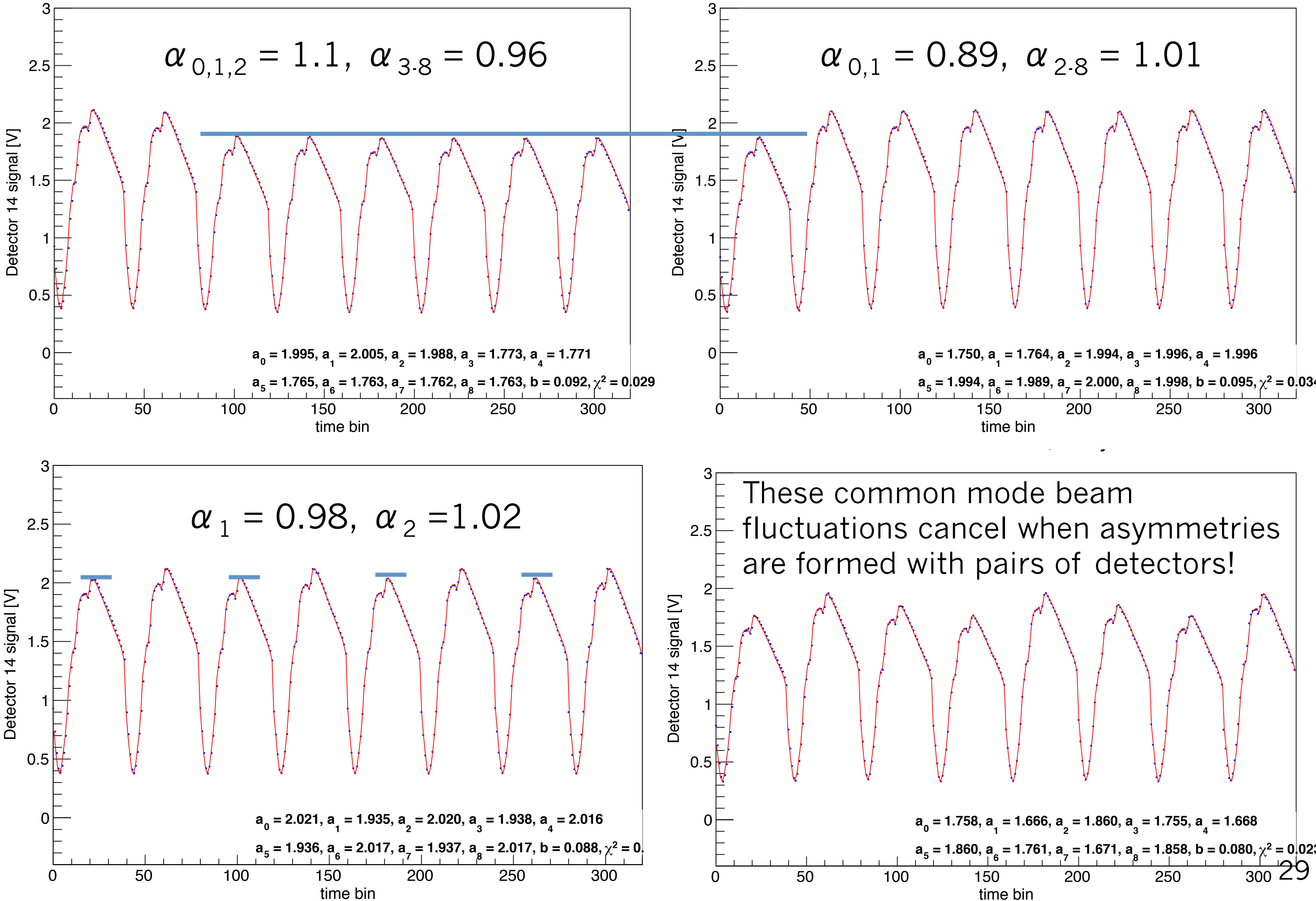
12 runs = 1.4 hours
198 sec Al β-decay buildup

Fitted amplitudes provide information on:

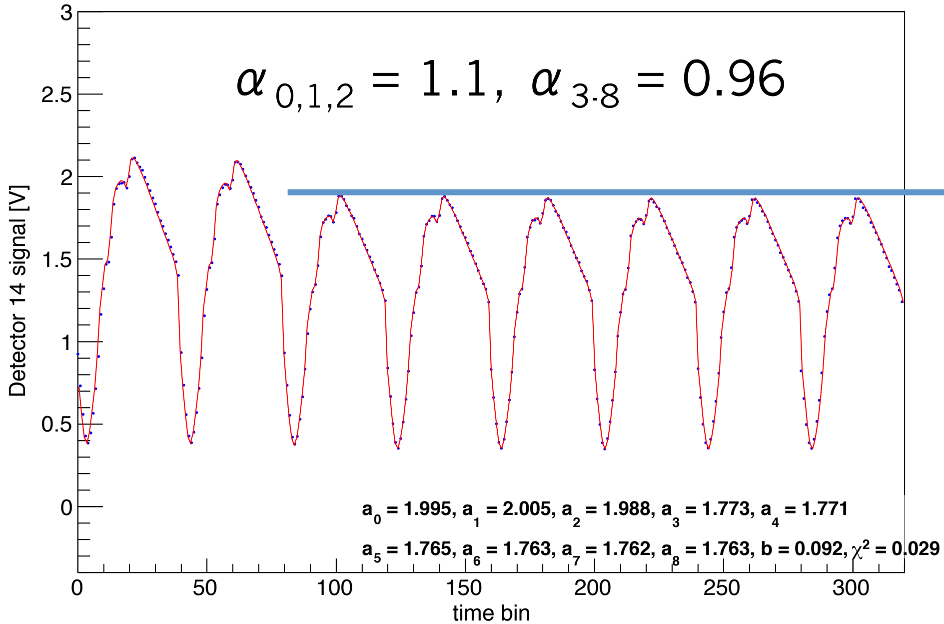
- Dropped pulses
- Lower powered pulses
- Pulse height stability in a spin sequence
- Read pulse height
- **Dynamic pedestal**

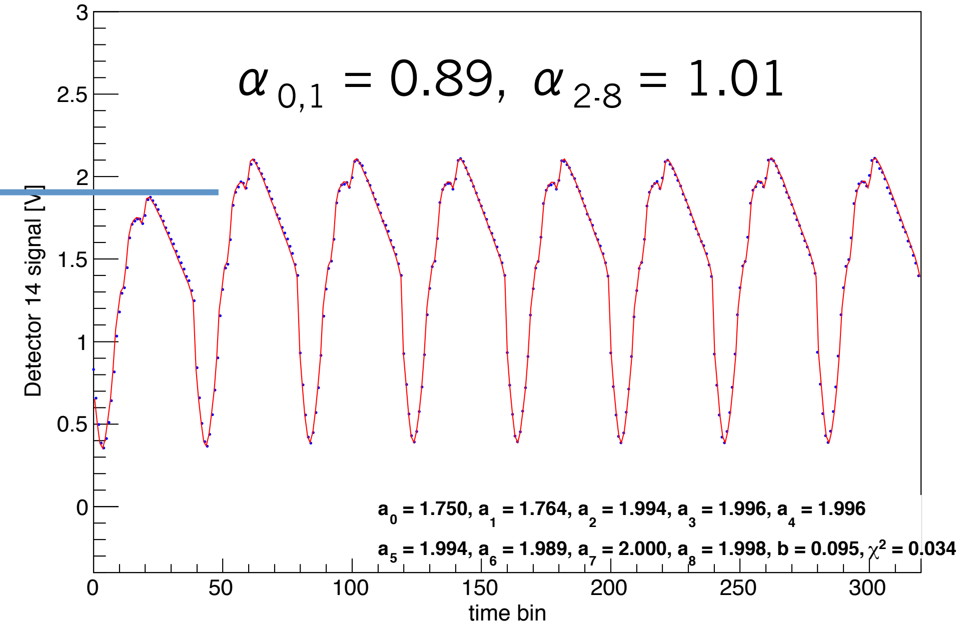
Aluminum β-delayed pedestal is ~5% of the signal. Need to properly subtract it for asymmetry calculation.

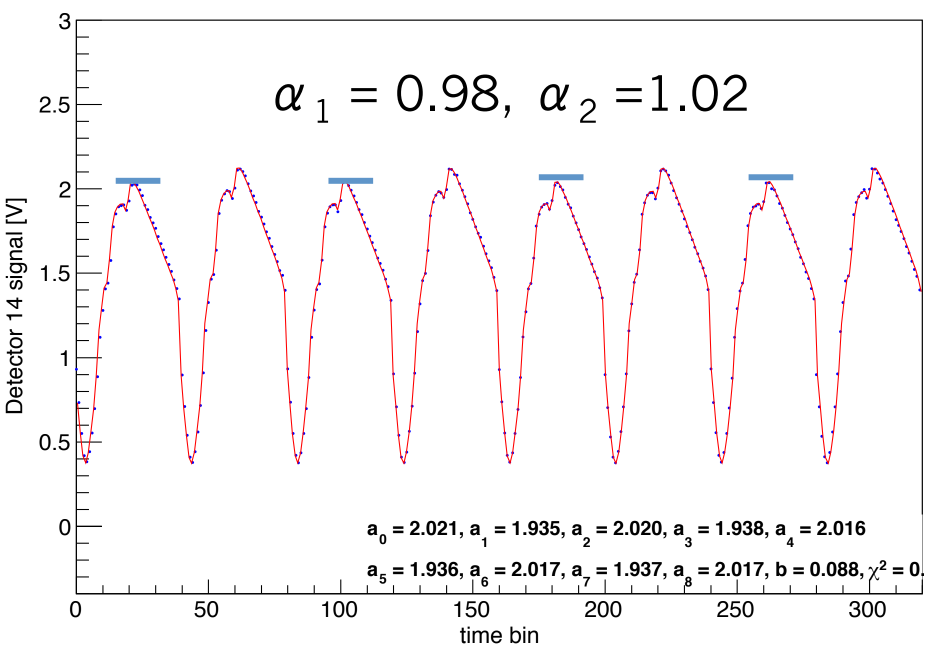
Example of Beam Fluctuations

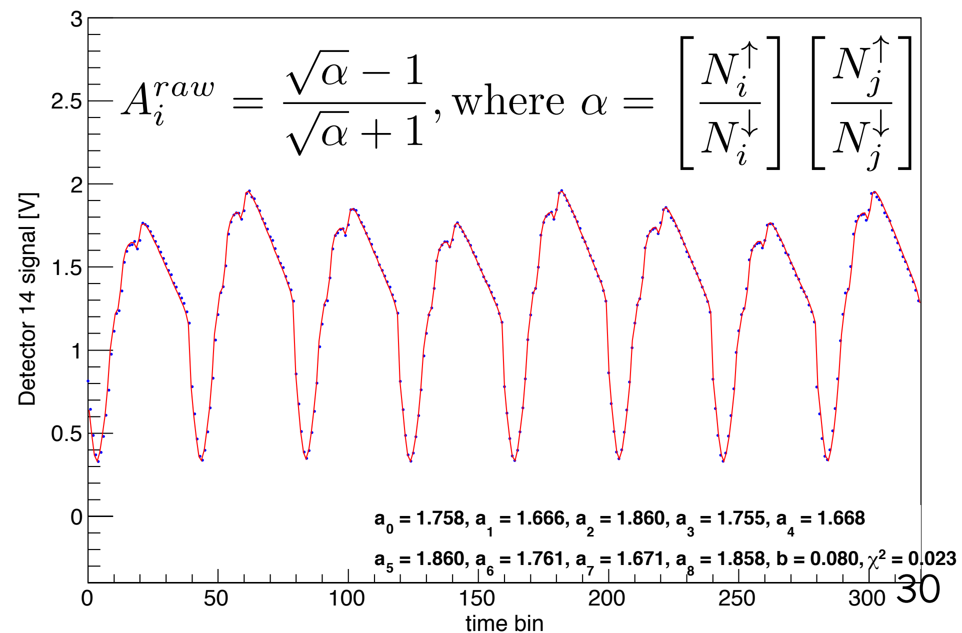


Example of Beam Fluctuations

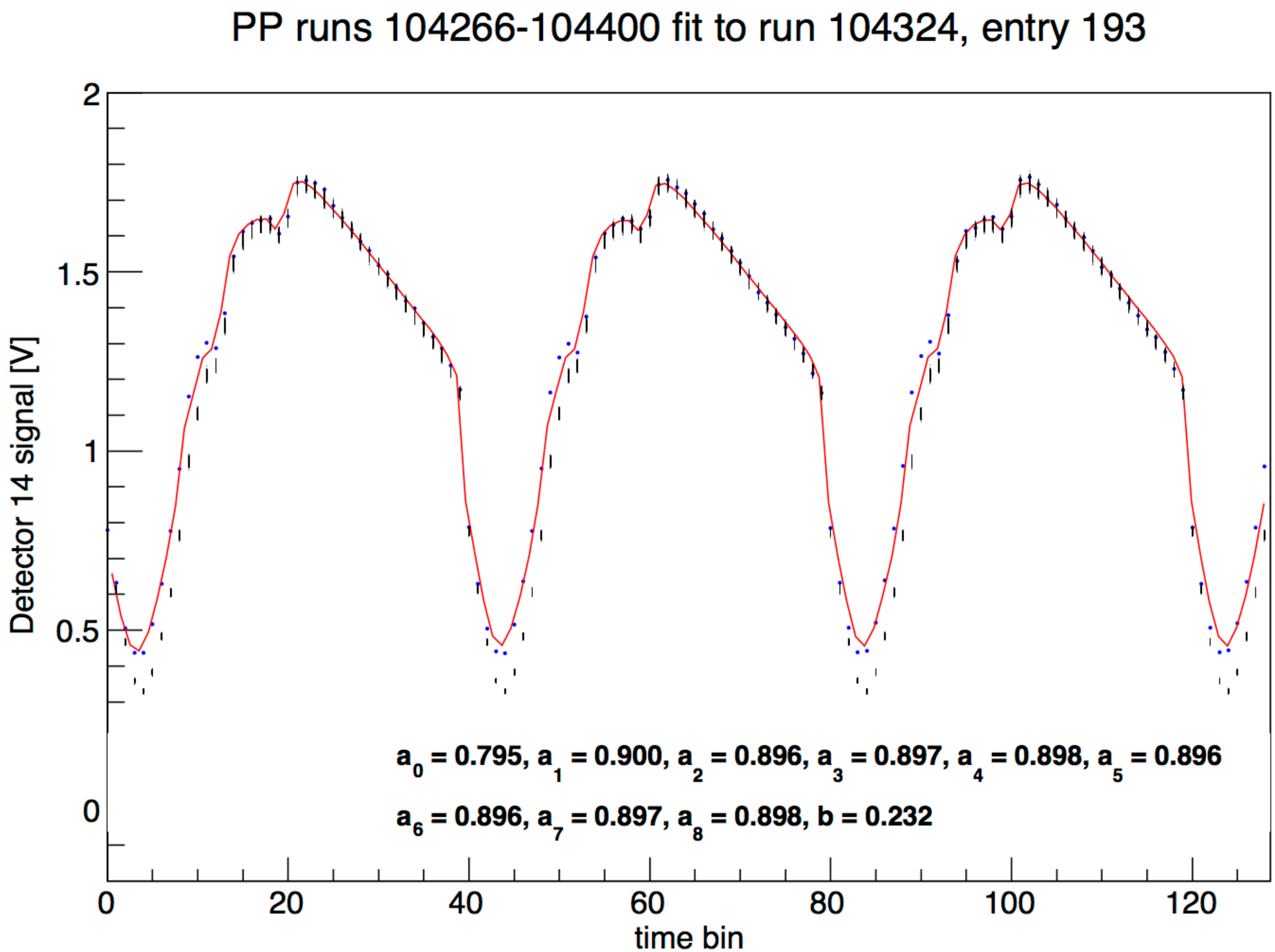




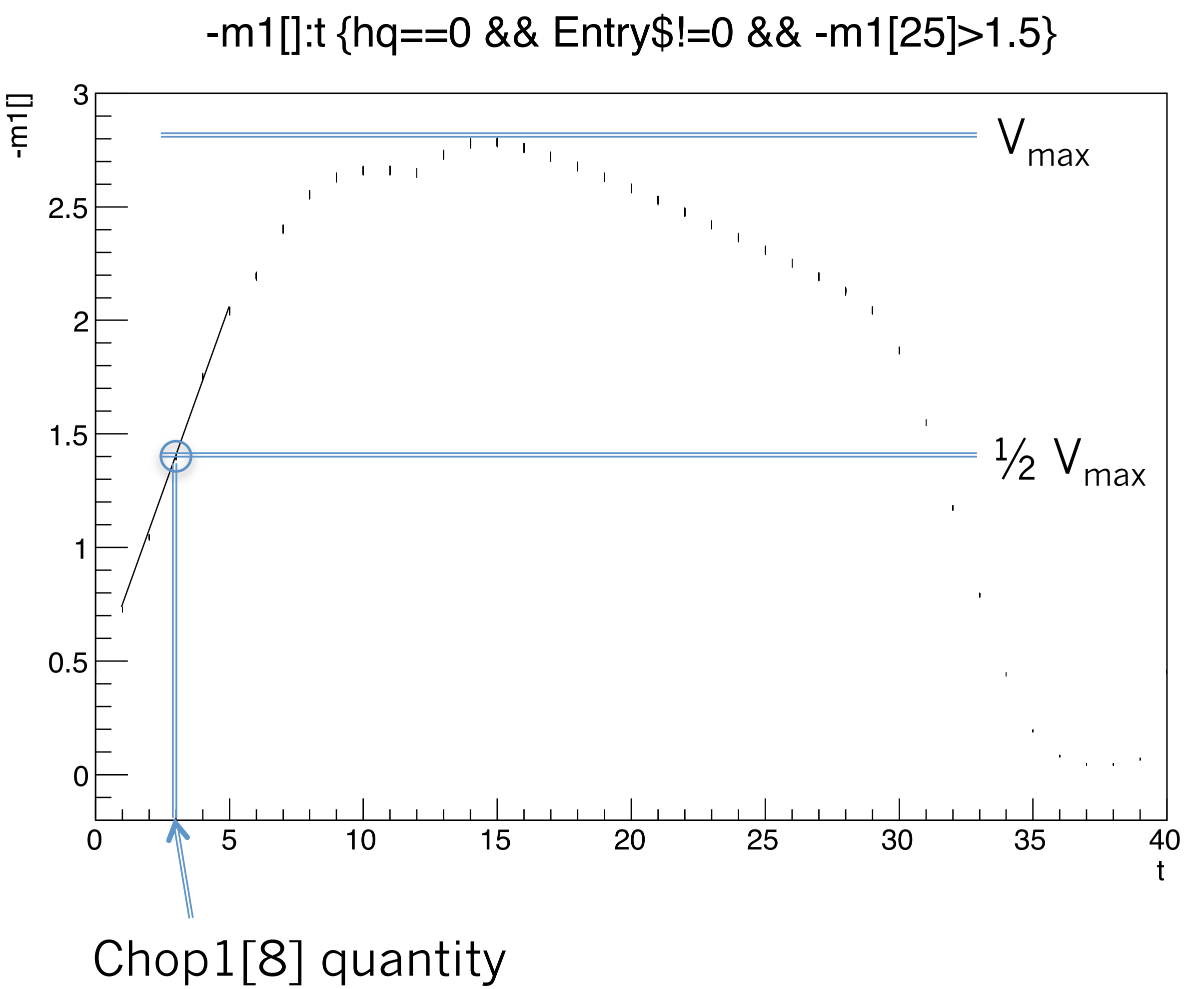




Chopper phases: Beam Monitor

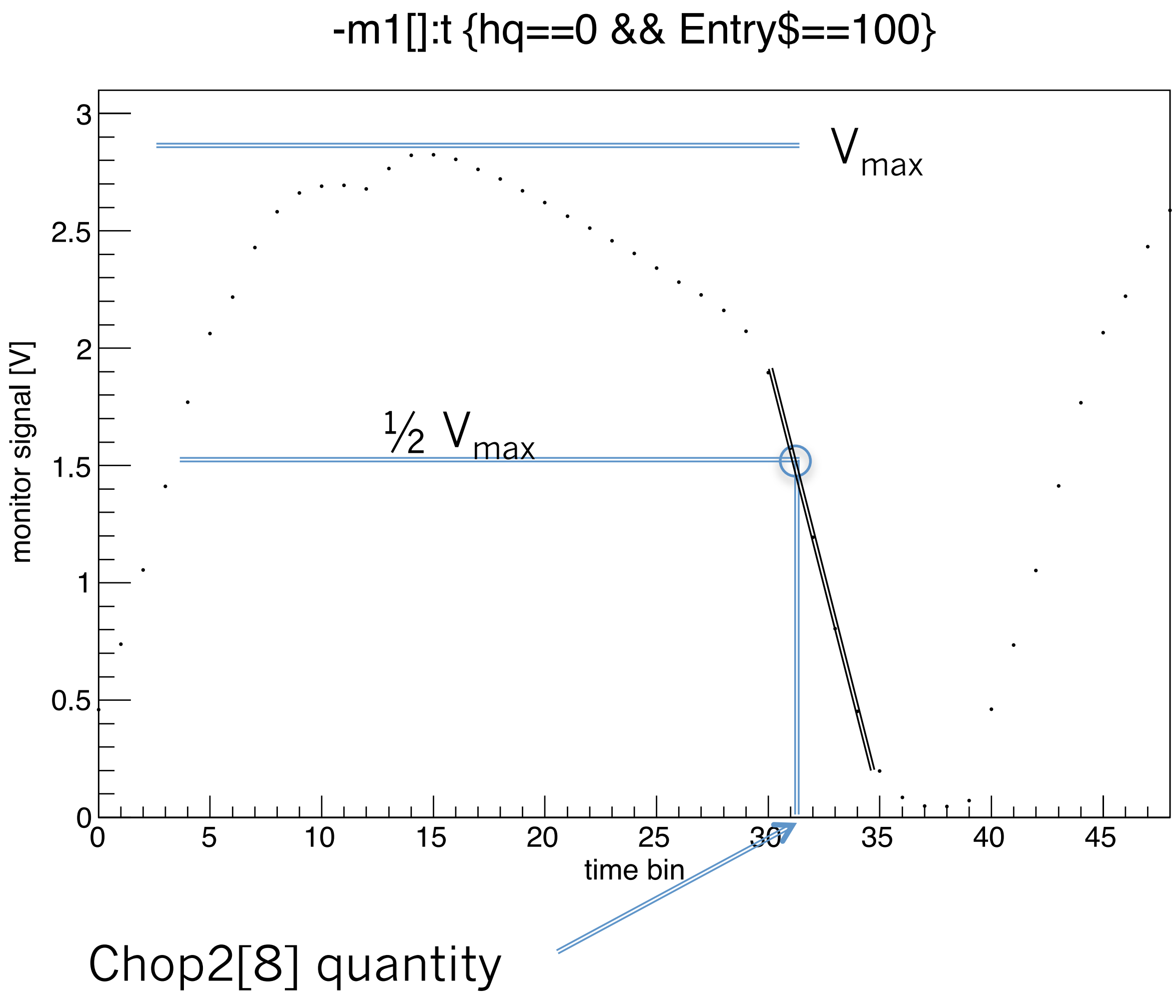


Chopper phases: Beam Monitor



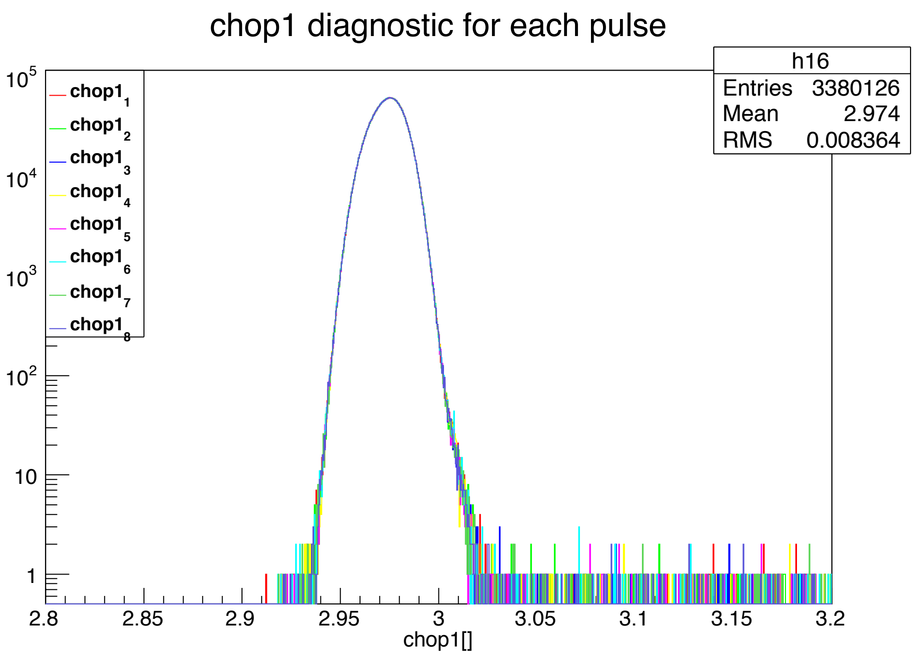
- Fit bins 1-5 to a line → good linear region and where chopper opens
- Find the time bin that is ½ of the peak in the spectrum → normalizes by the section not affected by the chopper opening
- Can be converted to a time in μs and compare with chopper phases

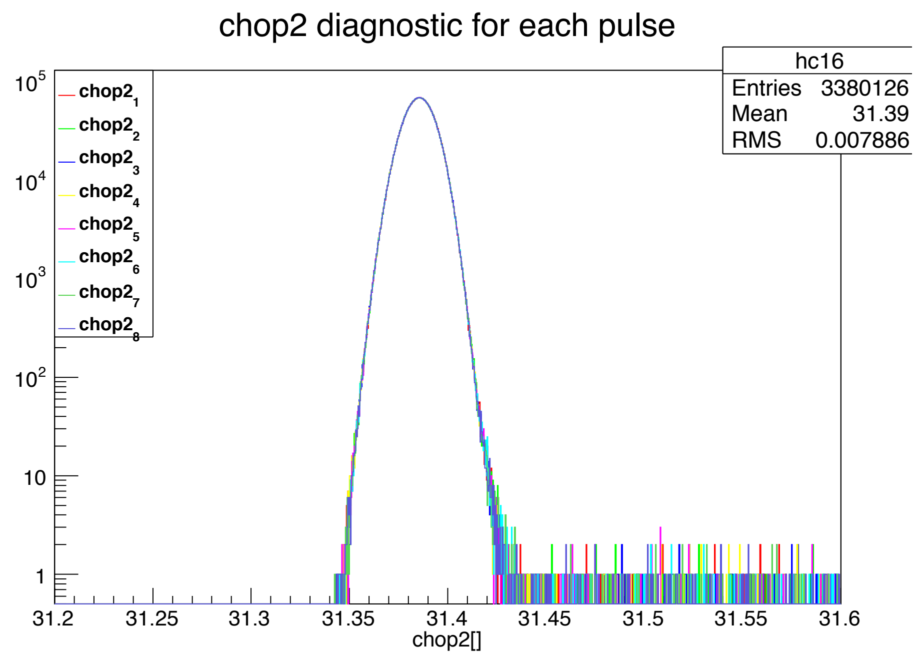
Chopper phases: Beam Monitor



- Fit bins 31-35 to a line → good linear region and where chopper opens
- Find the time bin that is ½ of the peak in the spectrum → normalizes by the section not affected by the chopper opening
- Can be converted to a time in μs and compare with chopper phases

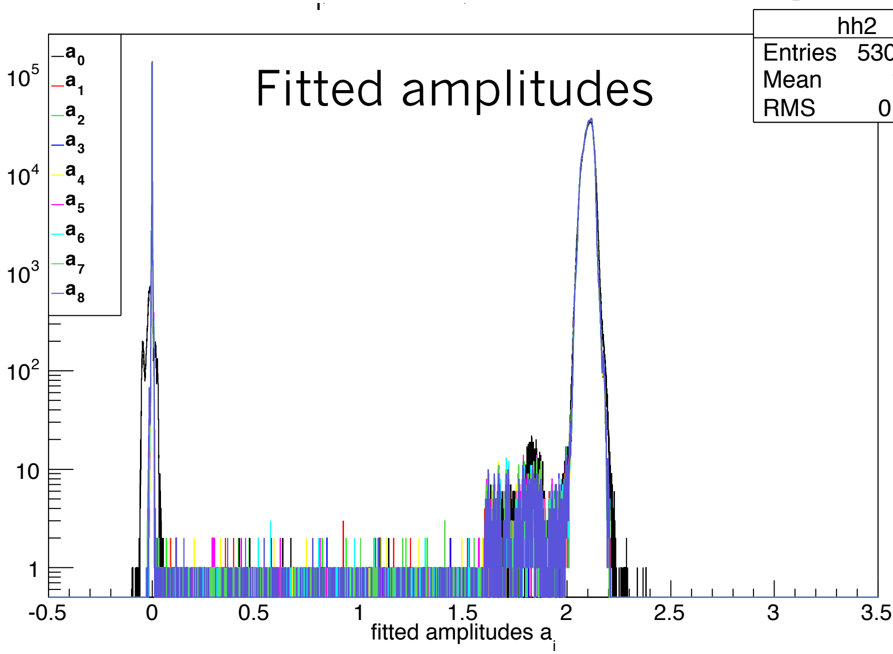
Typical chop1 & chop2

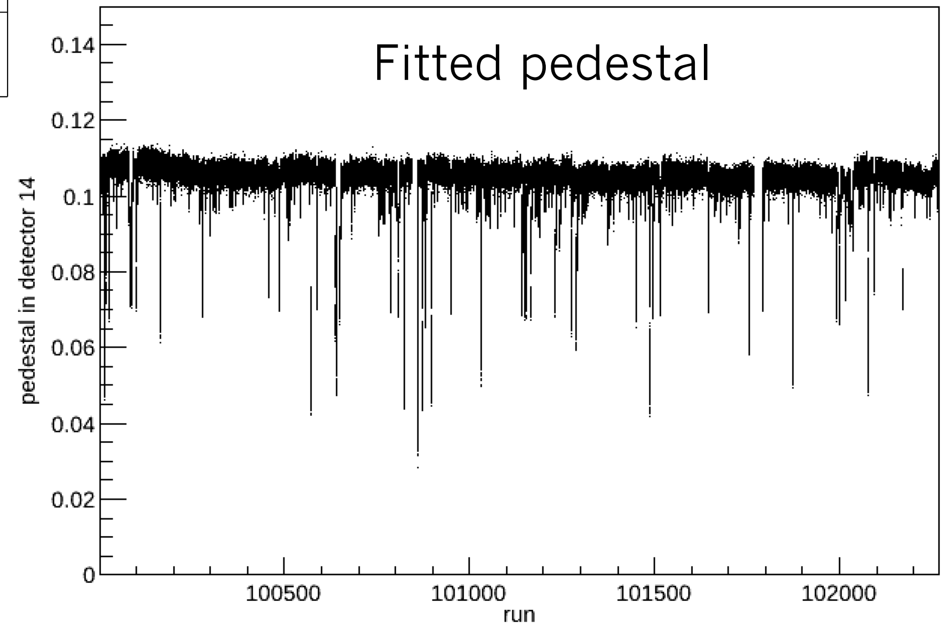


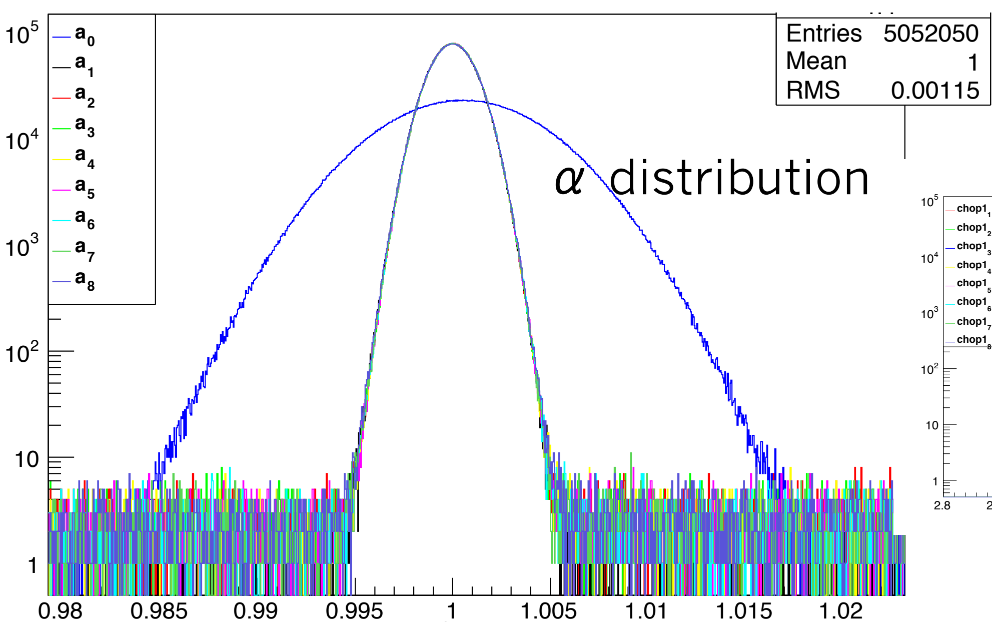


- RMS of 0.008 time bins = 3.2 μ s
  - During nominal operation, the chopper phases only change by up to 0.3 μ s, so these are large changes
- Dominated by counting statistics
- Since m1 is before the polarizer, can cut freely since this carries no polarization

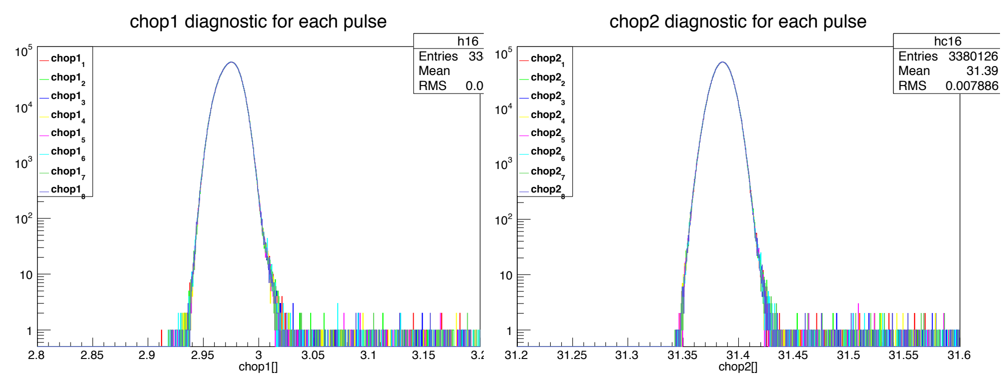
Summary of Algorithm







Chopper phase diagnostics



Cuts Applied

Three parallel analyses ongoing from IU, UT, ASU
Developed separate algorithms to overcome analysis criteria and goals

1) Minimum amplitude: A gross cut eliminating the dropped pulses which accounts for the majority of the cut data

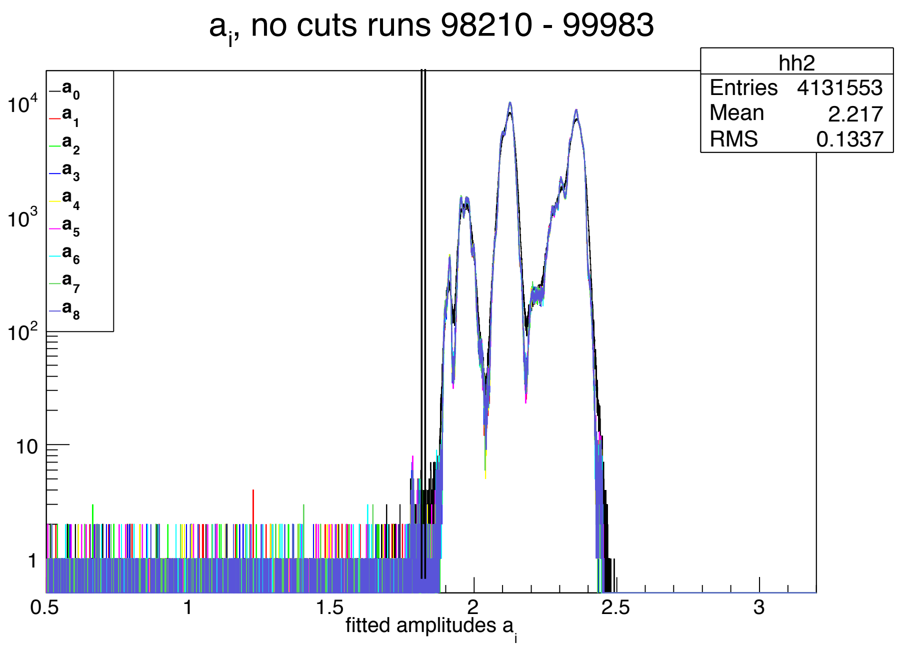
2) Chopper Phase: Eliminate chopper phase variations to keep data with known polarization and to get a proper β-delayed gamma from algorithm

3) Beam stability within a spin sequence: Eliminate pulse to pulse variations from the accelerator at the 1% level to keep data with the same statistical weight

4) Proper 16-ss: Eliminate transients, wraparounds, and bad SF spin sequences which may contain false asymmetries

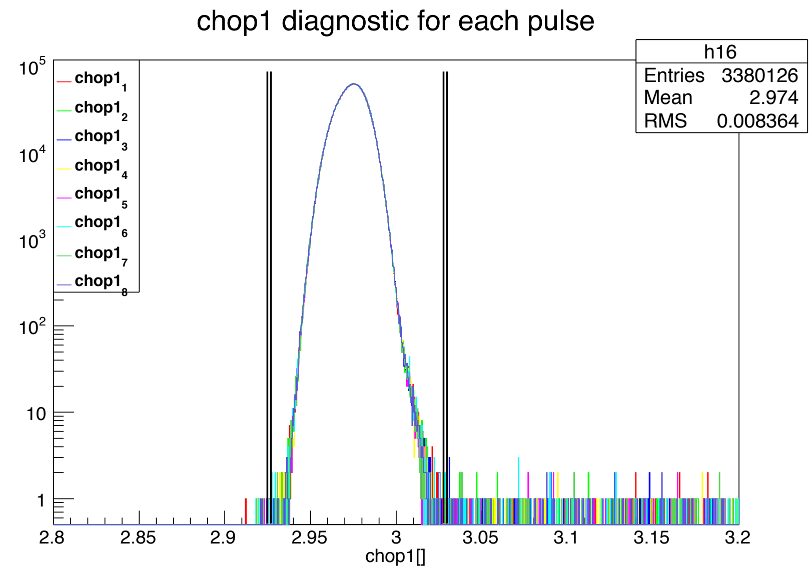
Cuts Applied

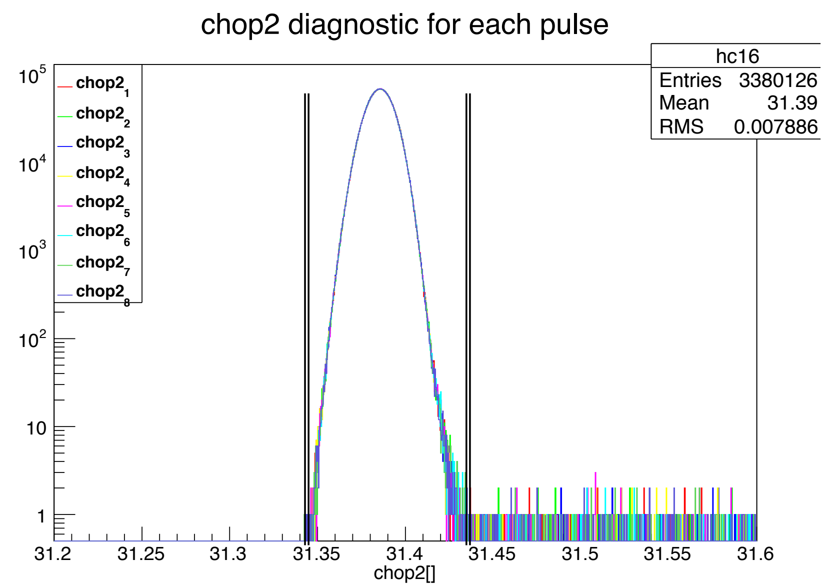
- Minimum Amplitude
- Chopper Phases
- α variation, 1%
- Good 16-step sequence



Cuts Applied

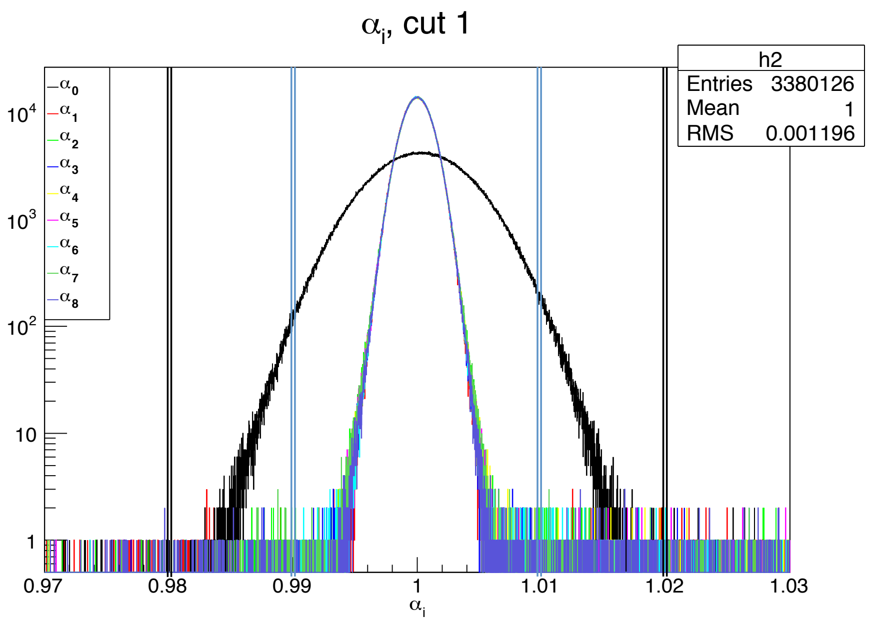
- Minimum Amplitude
- Chopper Phases
- α variation, 1%
- Good 16-step sequence





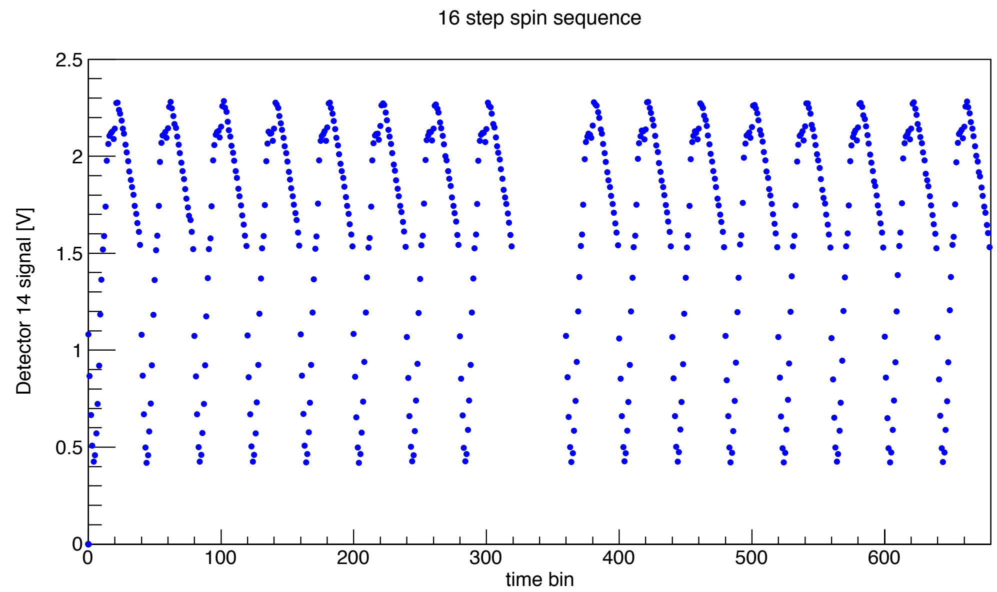
Cuts Applied

- Minimum Amplitude
- Chopper Phases
- α variation, 1%
- Good 16-step sequence

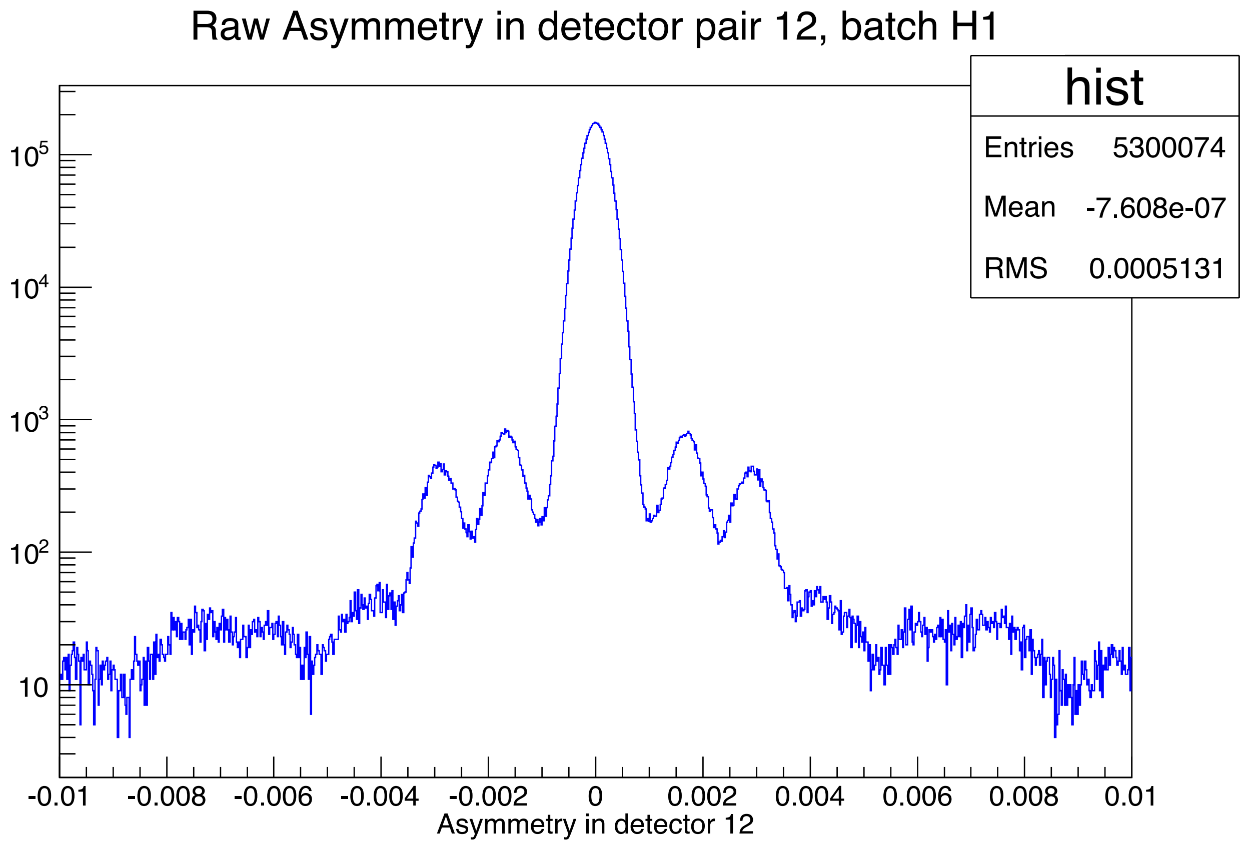


Cuts Applied

- Minimum Amplitude
- Chopper Phases
- α variation, 1%
- Good 16-step sequence



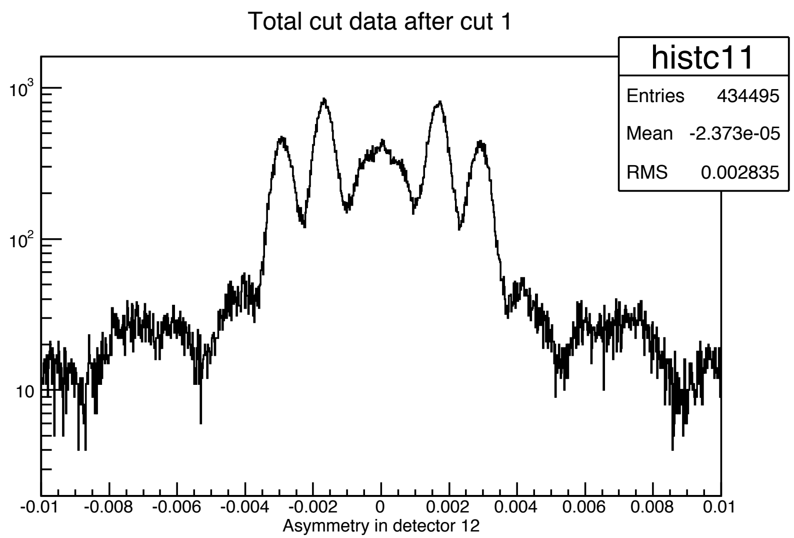
No Cuts: Asymmetry Pair 12

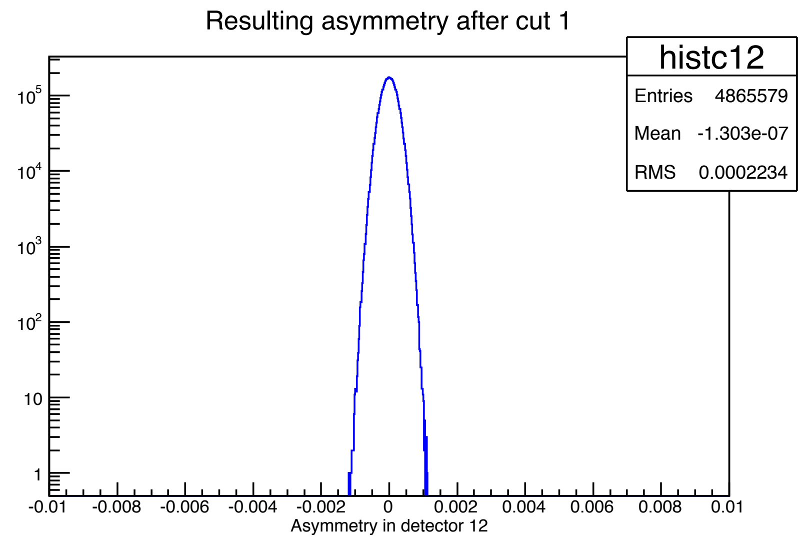


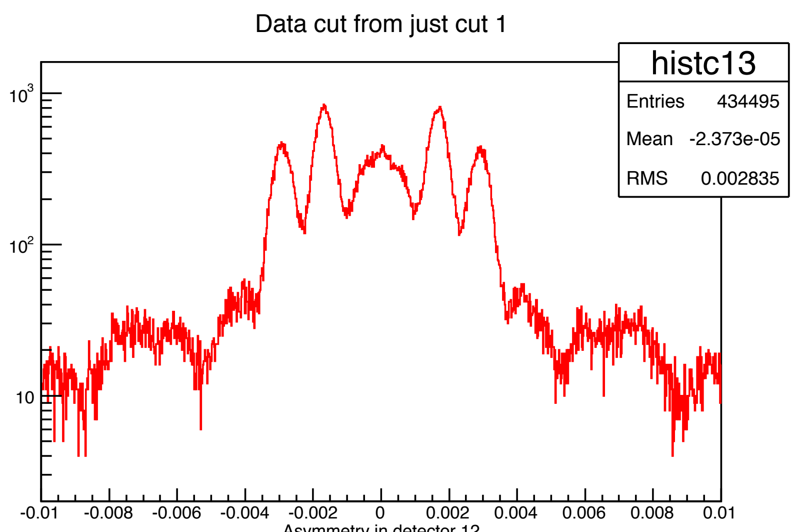
Batch H1

Cut 1: Minimum amplitude

A gross cut eliminating the dropped pulses which accounts for the majority of the cut data







Total cut data = -2.37e-05 ± 4.30e-06

Total cut data has 434495 8-ss

Resulting asymmetry = -1.30e-07 ± 1.01e-07

Resulting data has 4865579 8-ss

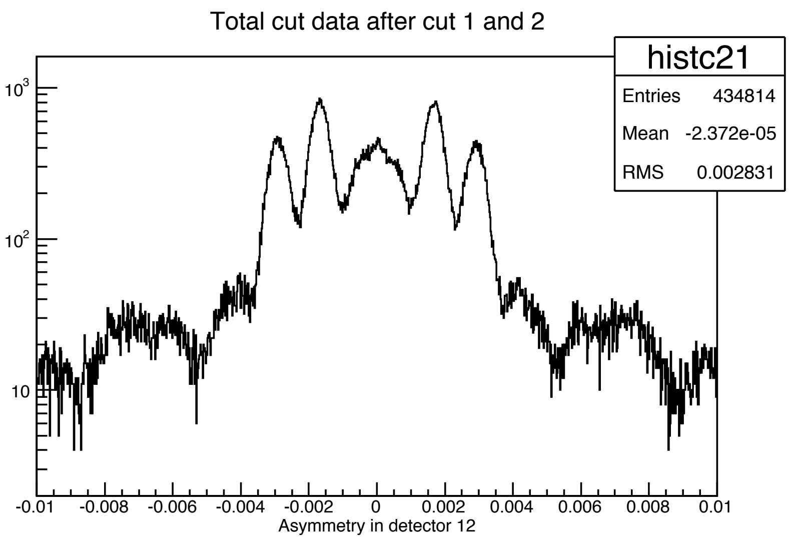
Data cut by this cut = -2.37e-05 ± 4.30e-06

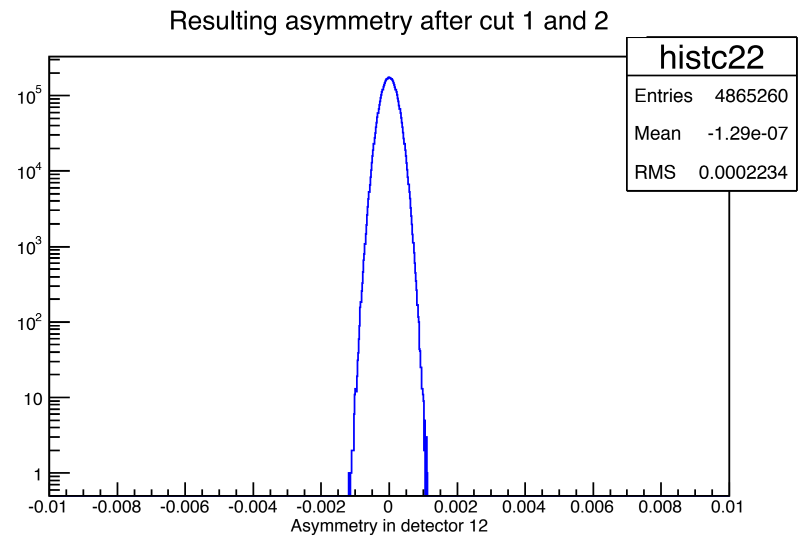
Data cut by this cut has 434495 8-ss

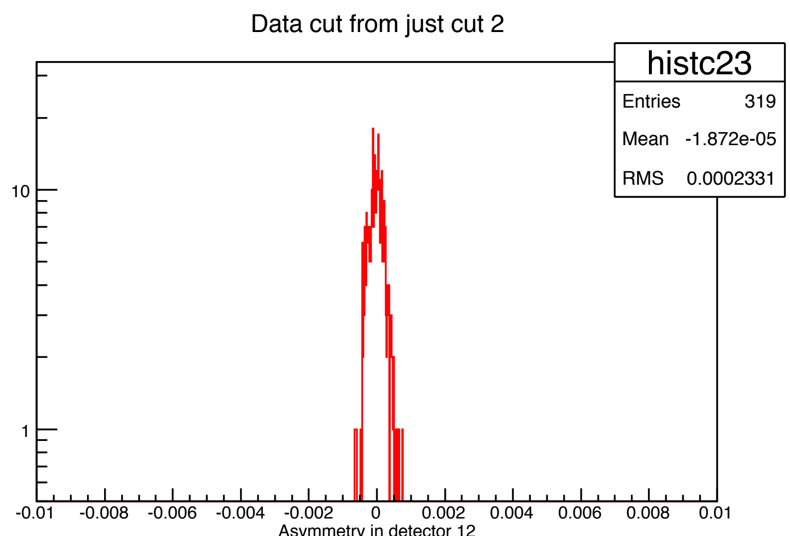
Batch H1 73% of all cut data cut here

Cut 2: Chopper Phases

Chopper Phase: Eliminate chopper phase variations to keep data with known polarization and pedestal from fits







Total cut data = -2.37e-05 ± 4.29e-06

Total cut data has 434814 8-ss

Resulting asymmetry = -1.29e-07 ± 1.01e-07

Resulting data has 4865260 8-ss

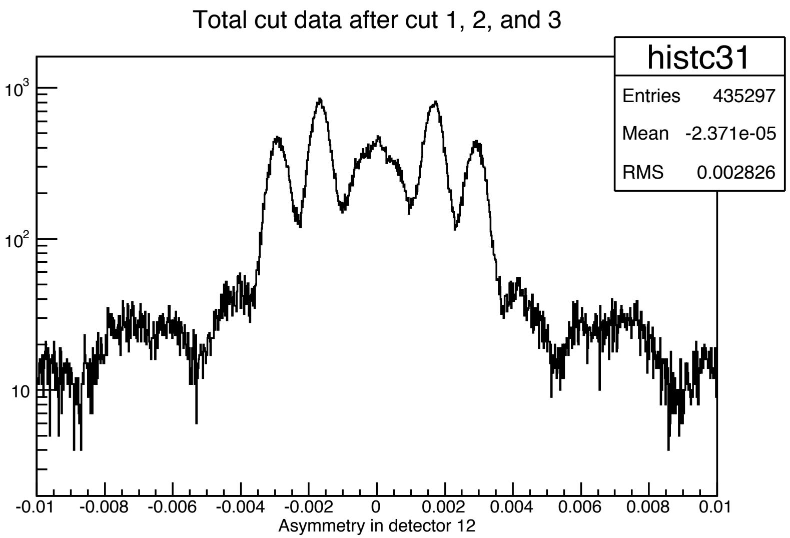
Data cut by this cut = -1.87e-05 ± 1.31e-05

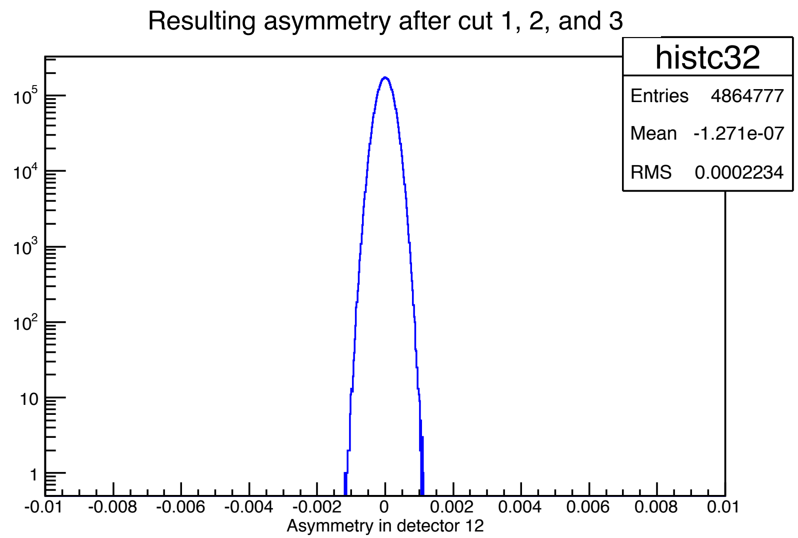
Data cut by this cut has 319 8-ss

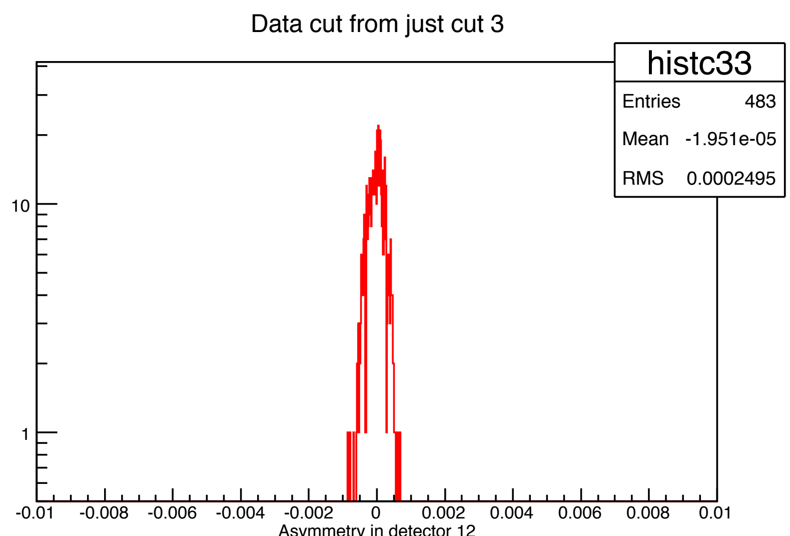
Batch H1

Cut 3: Pulse to Pulse Stability

Eliminate pulse to pulse variations at the 1% level to keep data with the same statistical weight







Total cut data = -2.37e-05 ± 4.28e-06

Total cut data has 435297 8-ss

Resulting asymmetry = -1.27e-07 ± 1.01e-07

Resulting data has 4864777 8-ss

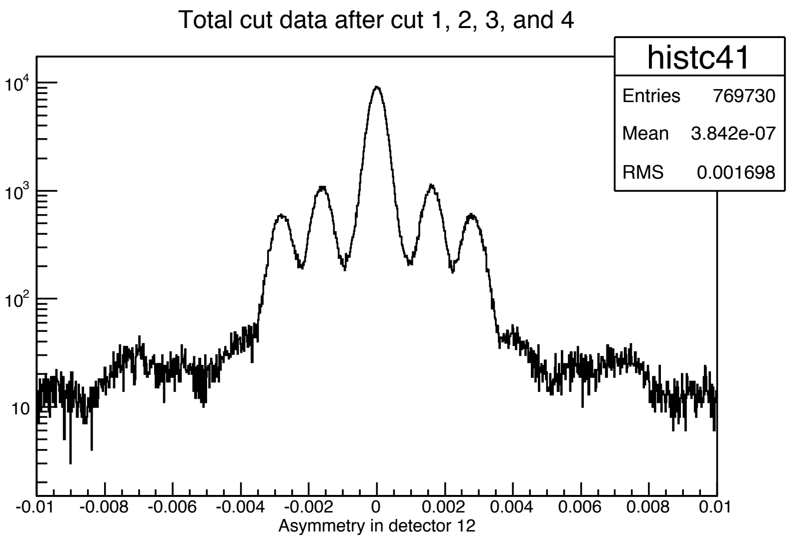
Data cut by this cut = -1.95e-05 ± 1.14e-05

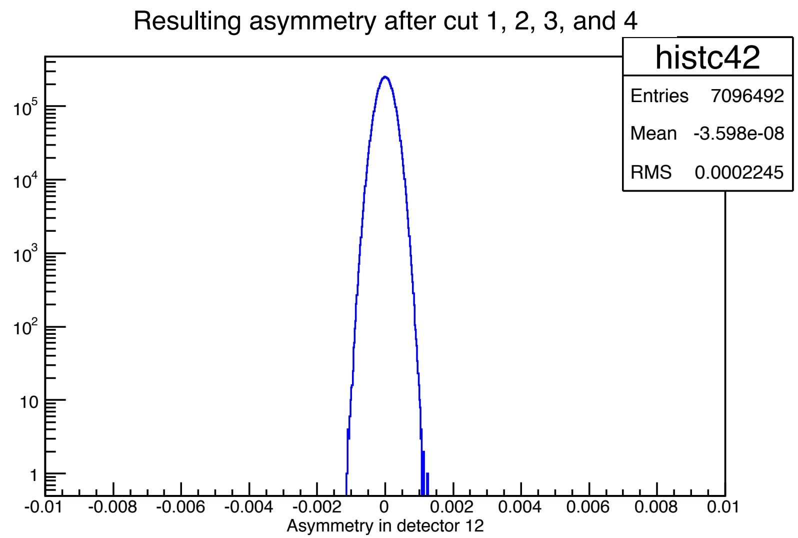
Data cut by this cut has 483 8-ss

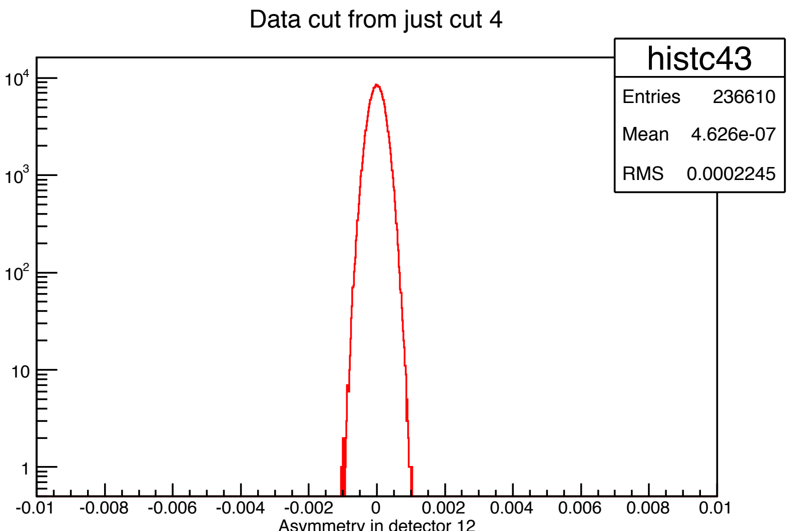
Batch H1

Cut 4: Good 16-ss

Eliminate transients, wraparounds, and bad SF spin sequences which may contain false asymmetries







Total cut data = 3.84e-07 ± 1.94e-06

Total cut data has 769730 8-ss

Resulting asymmetry = -3.60e-08 ± 8.43e-08

Resulting data has 7096492 8-ss

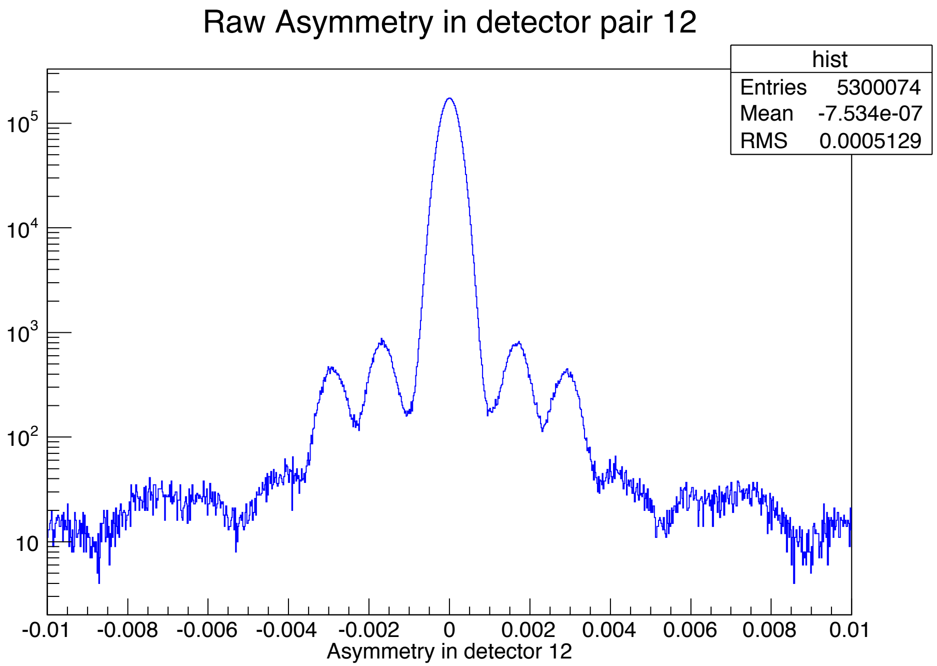
Data cut by this cut = 4.63e-07 ± 4.61e-07

Data cut by this cut has 236610 8-ss

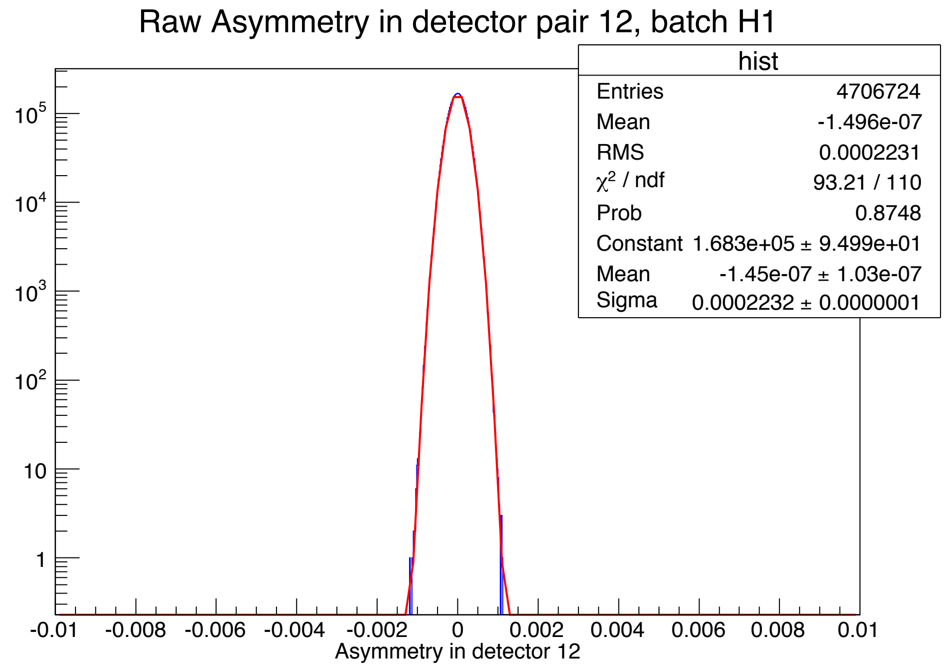
Batch H1 27% of all cut data cut here

Hydrogen Cuts and Asymmetry

No cuts



After cuts



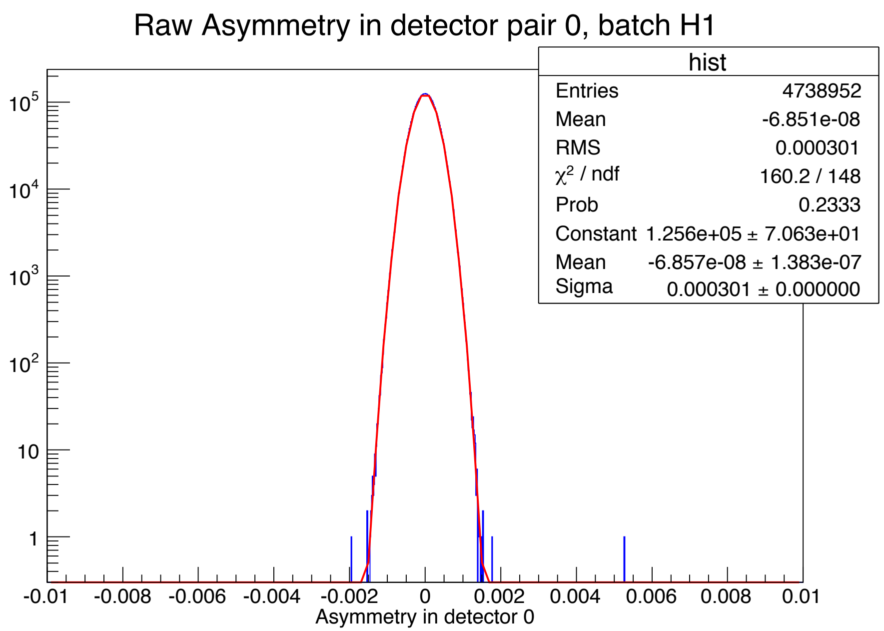
Analysis cuts are applied

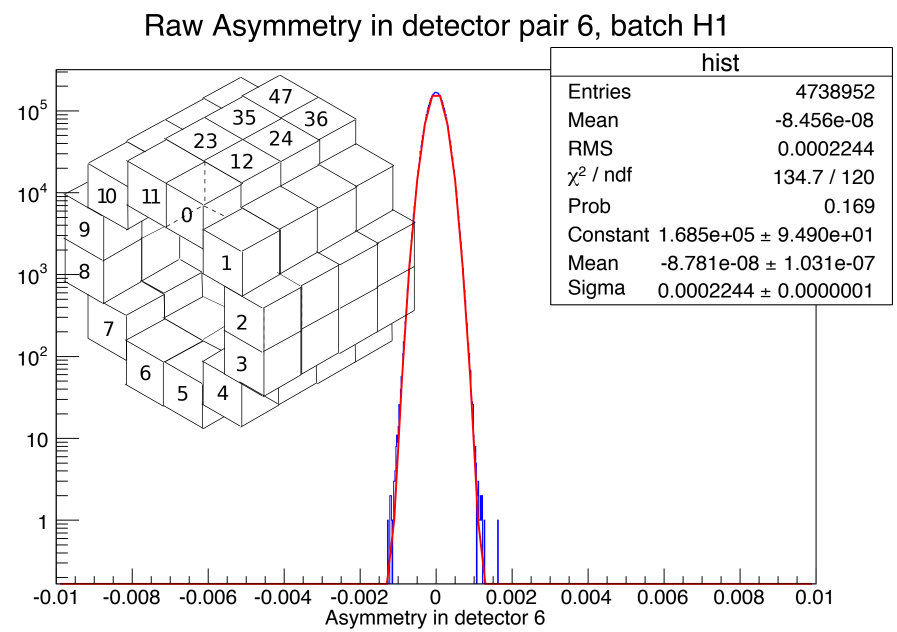
Cut about 15% of the data

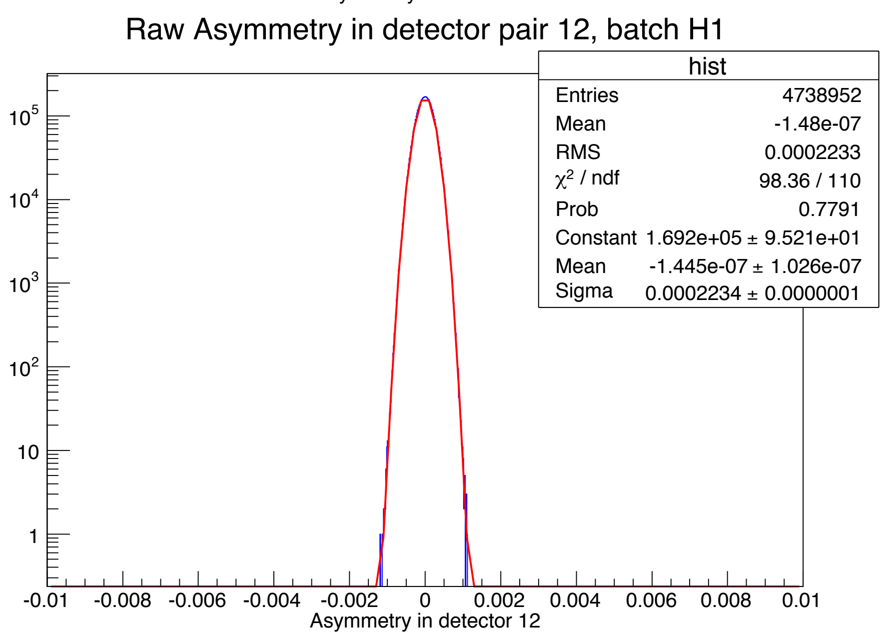
	H1	AVE:
1. Minimum amplitude	73%	74%
2. Chopper Phases	<1%	2%
3. Pulse height variation	<1%	3%
4. Proper 16-ss	27%	21%

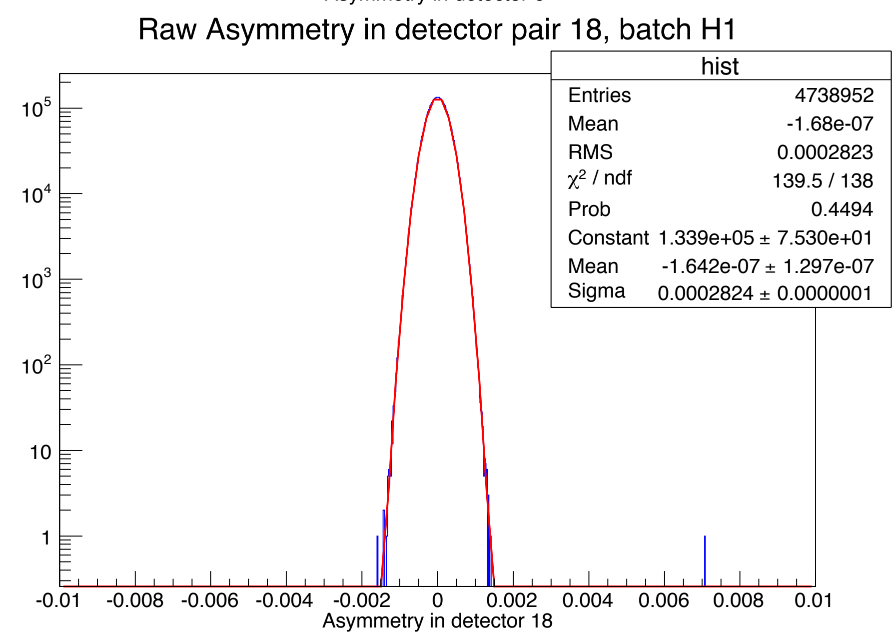
Cuts do not depend on polarization. Varying cuts do not change pair asymmetries

Hydrogen Cuts and Asymmetry

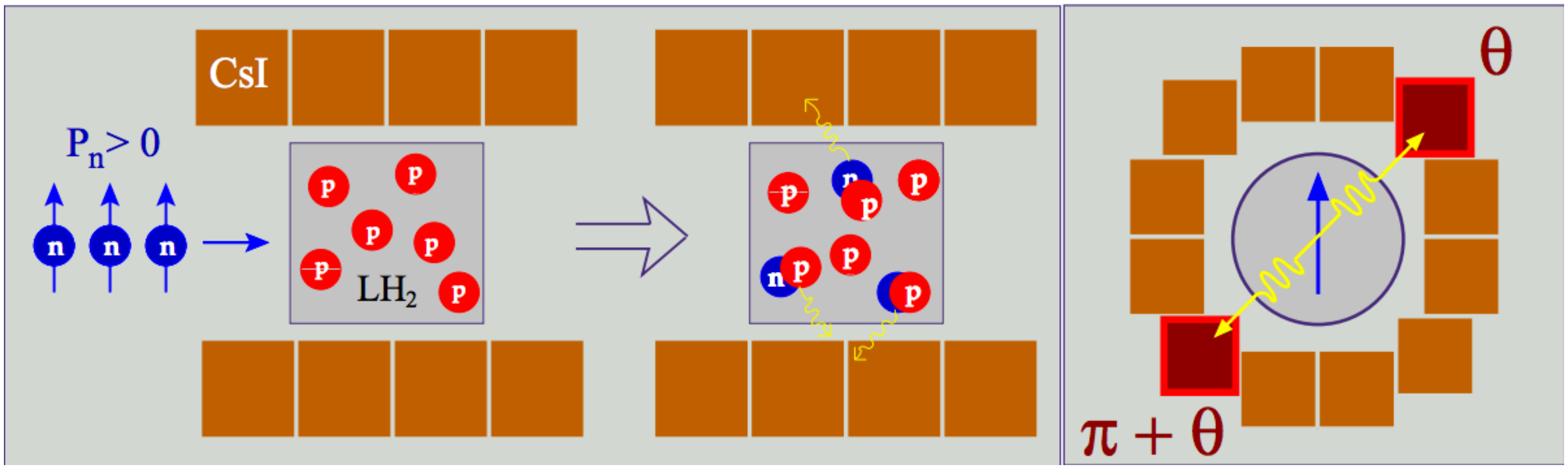








Asymmetry Definition

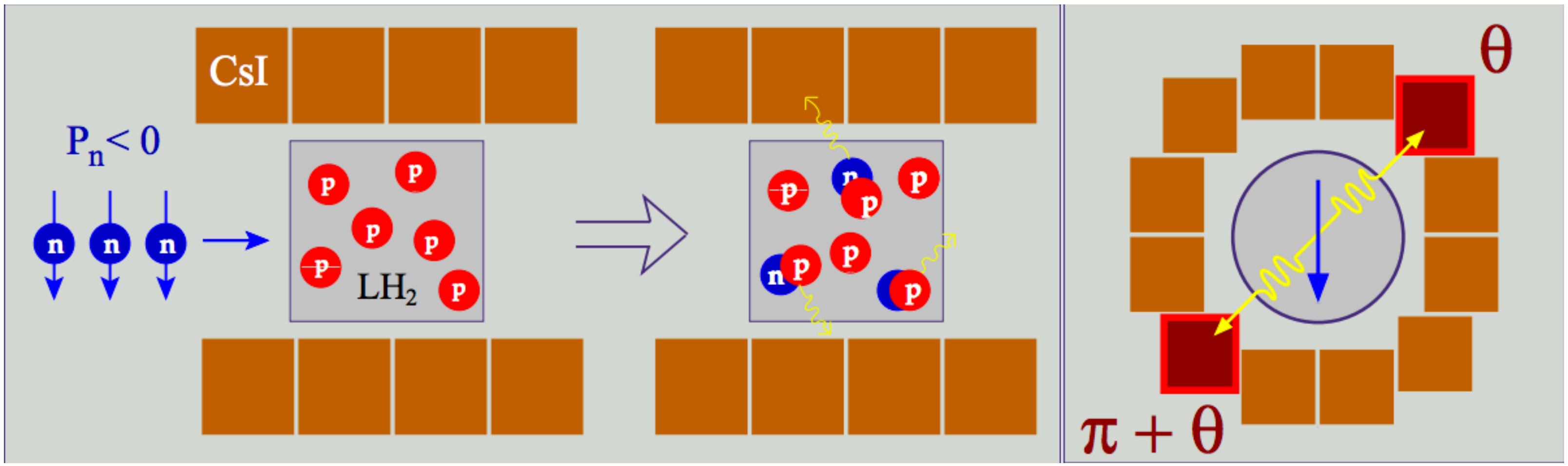


$$A_i^{raw} = \frac{\sqrt{\alpha} - 1}{\sqrt{\alpha} + 1}, \text{where } \alpha = \left[\frac{N_i^{\uparrow}}{N_i^{\downarrow}}\right]\left[\frac{N_j^{\uparrow}}{N_j^{\downarrow}}\right]$$

Any effect that manifests as a common mode beam fluctuation in the detectors are cancelled - whether they are slowly changing fluctuations or spontaneous lower powered pulses. Effects such as difference detector efficiencies and detector misalignments are suppressed in pairs.

Asymmetry Definition

$$A_{raw} = P_{tot}\left(A_{UD}cos\theta + A_{LR}sin\theta\right)$$ Ideal!



$$A_i^{raw} = P_{tot}\left(f_i^H(G_{UD,i}^H A_{UD}^H + G_{LR,i}^H A_{LR}^H) + f_i^{Al}(G_{UD,i}^{Al} A_{UD}^{Al} + G_{LR,i}^{Al} A_{LR}^{Al})\right)$$

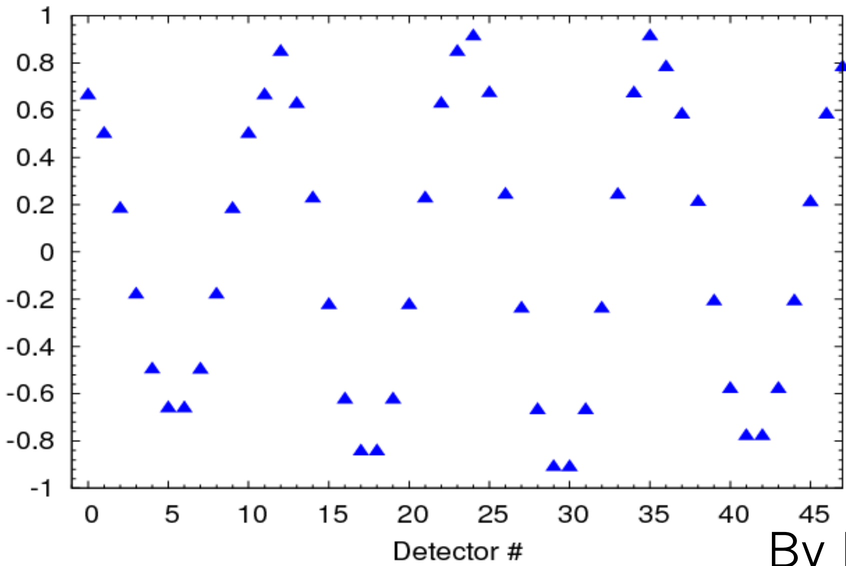
Apply polarization, spin flip efficiency, depolarization corrections (P_{tot}), subtract Aluminum UD and LR asymmetries with appropriate fractions. Al fraction is on average 22%.

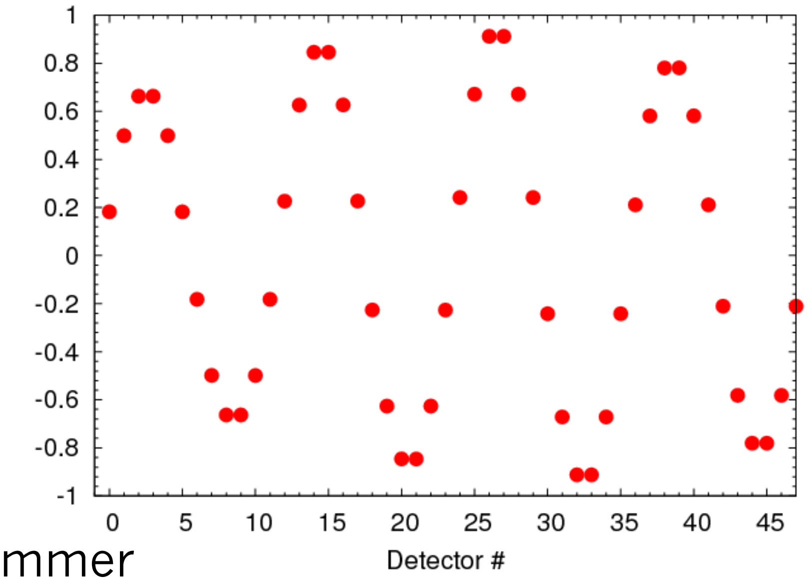
Have to **measure** PV Aluminum asymmetry and **calculate** geometric factors!

Geometry Factors

$$A_{raw} = P_{tot}\left(A_{UD}cos\theta + A_{LR}sin\theta\right)$$

Ideal!



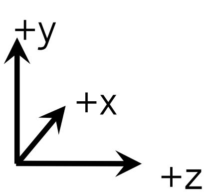


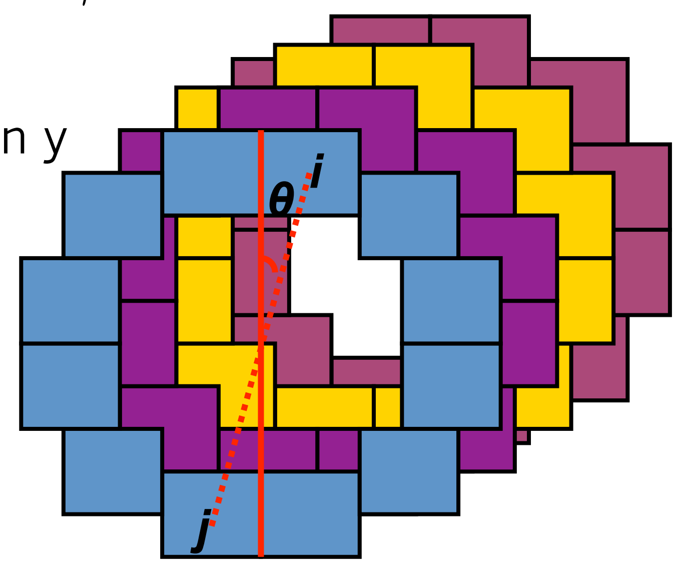
By K. Grammer

$$G^i_{UD} = < k_\gamma \cdot \hat{y} >$$

$$G^i_{LR} = < k_\gamma \cdot \hat{x} >$$

Neutrons polarized in y

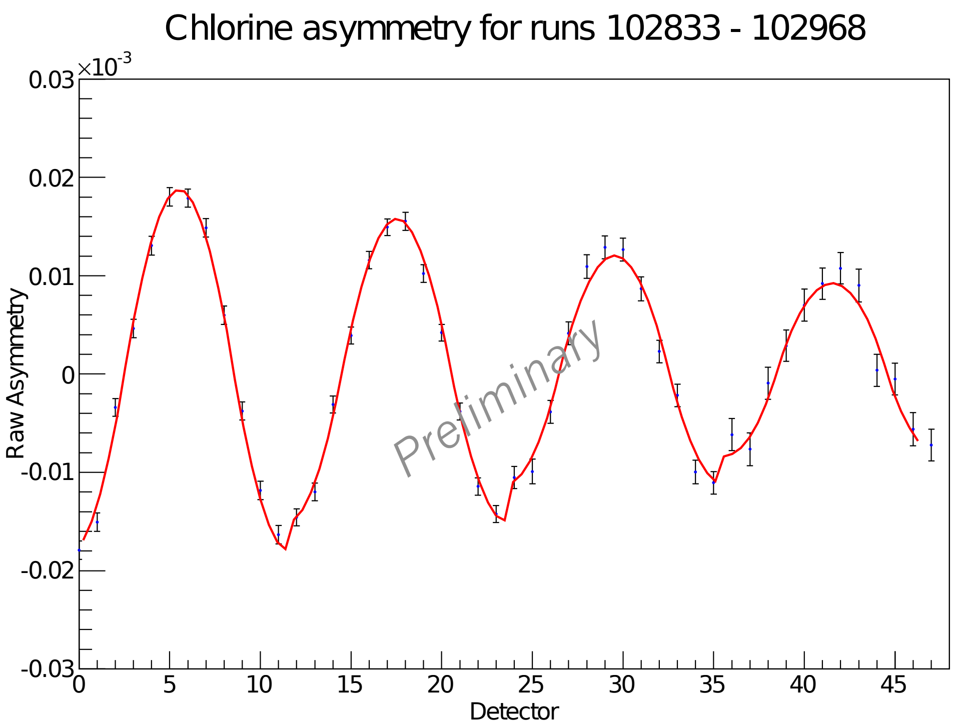




Used combination of MCNPX and Cs source

Correct for position and solid angle of detectors relative to target

Chlorine and Analysis Methods



$$A^i_{raw} = G^i_{UD} A_{UD} + G^i_{LR} A_{LR}$$

Chlorine has a known large PV gamma asymmetry – **check systematics and geometry factors**

Fit to the geometry factors to extract the PV A_{UD}

After background subtraction, beam polarization, target depolarization, and RFSF efficiency

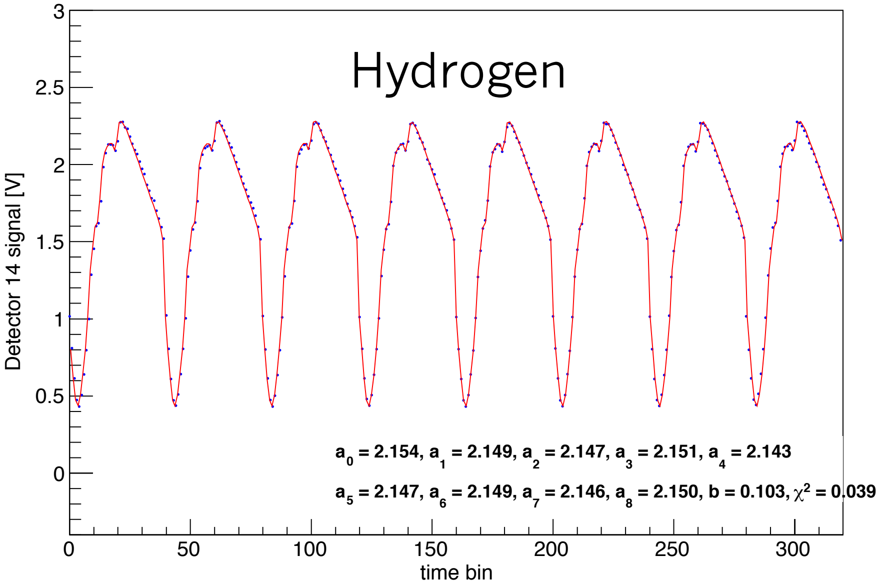
Preliminary result:

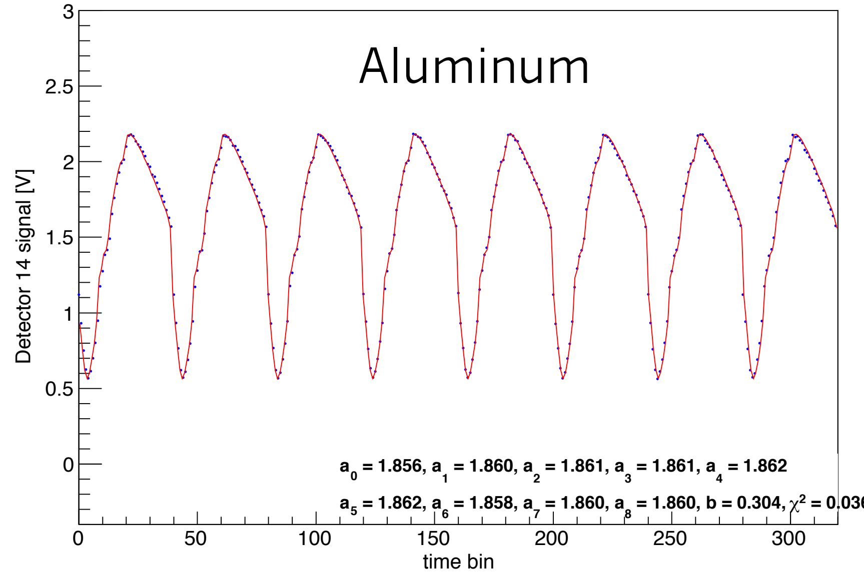
$$A_{UD} = 25.9 \pm 0.6 \times 10^{-6}$$

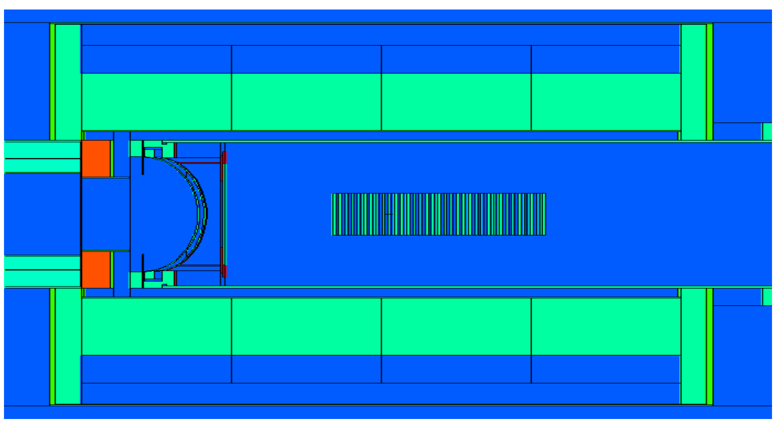
$$A_{LR} = 0.06 \pm 0.6 \times 10^{-6}$$

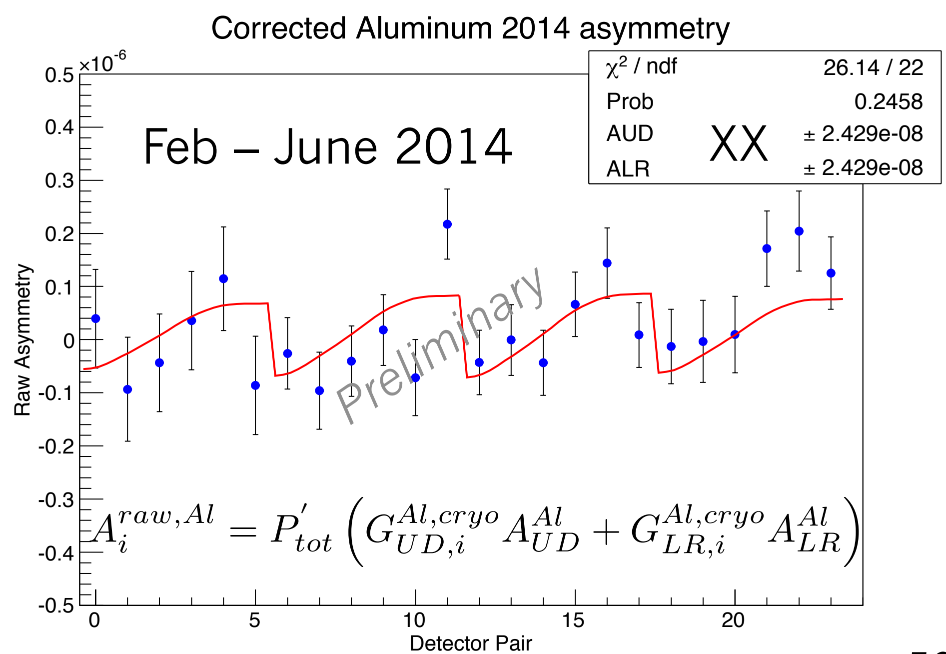
Most precise measurement to date. In agreement with other measurements

Aluminum Analysis









Aluminum target had to be installed inside the LH_2 cryostat to complete on time. Appropriate geometry factors were calculated for this configuration

Systematics

Other signals correlated with the polarization state or magnetic fields can create a false asymmetry and are cataloged below. Needs to be well below proposed statistical uncertainty of 1×10^{-8}. Instrumental asymmetries are on the order of 1×10^{-9}.

False Asymmetries	Correction	Uncertainty	Systematic Error
Additive Asymmetry (instrumental)			$< 1 \times 10^{-9}$
Multiplicative Asymmetry (instrumental)			$< 1 \times 10^{-9}$
Stern-Gerlach (steering of the beam)			$< 1 \times 10^{-10}$
γ - ray circular polarization			$< 1 \times 10^{-12}$
β - decay in flight			$< 1 \times 10^{-11}$
Capture on 6Li			$< 1 \times 10^{-11}$
Radiative β decay			$< 1 \times 10^{-12}$
β - delayed Al gammas (internal + external)			$< 1 \times 10^{-9}$
Total from False Asymmetries			$< 1 \times 10^{-9}$
Relative Uncertainties			
Geometry Factors		3%	
Polarization from Wrap-around Neutrons		0.1%	
Target Position		0.03%	
Multiplicative Correction			
Beam Polarization (2012-2013)	0.936	0.005	
Beam Polarization (2014)	0.936	0.005	
Beam Depolarization	0.9485	0.041	
RFSF Efficiency (2012-2013)	0.975	0.003	
RFSF Efficiency (2014)	0.966	0.009	
Total			$\sim 2 \times 10^{-9}$

Hydrogen Asymmetry

After subtracting Al and correcting for polarization, target depolarization, and SF efficiency, we have the preliminary intermediate result after 3000 runs or 15 beam days:

$$A_{UD} = -7.1 \pm 4.4 \times 10^{-8}$$

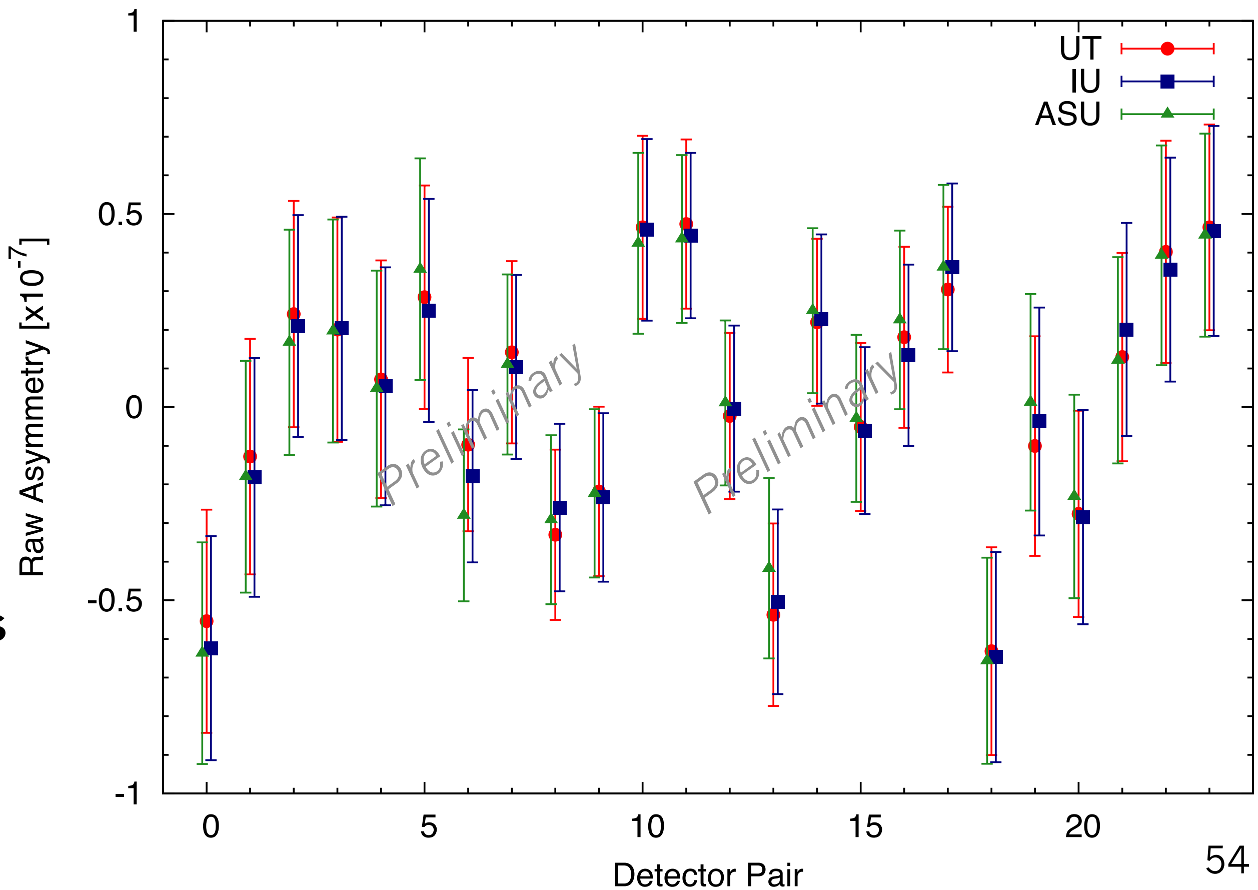
Hydrogen running has completed: have ~**250 beam days of Hydrogen runs** that have been analyzed

Cuts applied are independent of polarization

Result will be published soon.

"The preliminary result for the parity-violating asymmetry A_γ is that it is small with a statistical error of about 13 ppb"

Systematic error ~2x10^{-9}



Summary

- NPDGamma completed data taking at the end of June 2014
  - Statistical error is on par with counting statistics!
- All Hydrogen and Aluminum runs have been analyzed and behavior has been explored and explained
  - Cuts applied are independent of polarization and the asymmetry
- Plans for NPDGamma
  - Publish PV asymmetry in Al needed for proper asymmetry subtraction.
  - Publish PV in n-p very soon. Results will be presented at the April meeting.
- "The preliminary result for the parity-violating asymmetry A_γ is that it is small with a statistical error of about 13 ppb"

The NPDGamma collaboration

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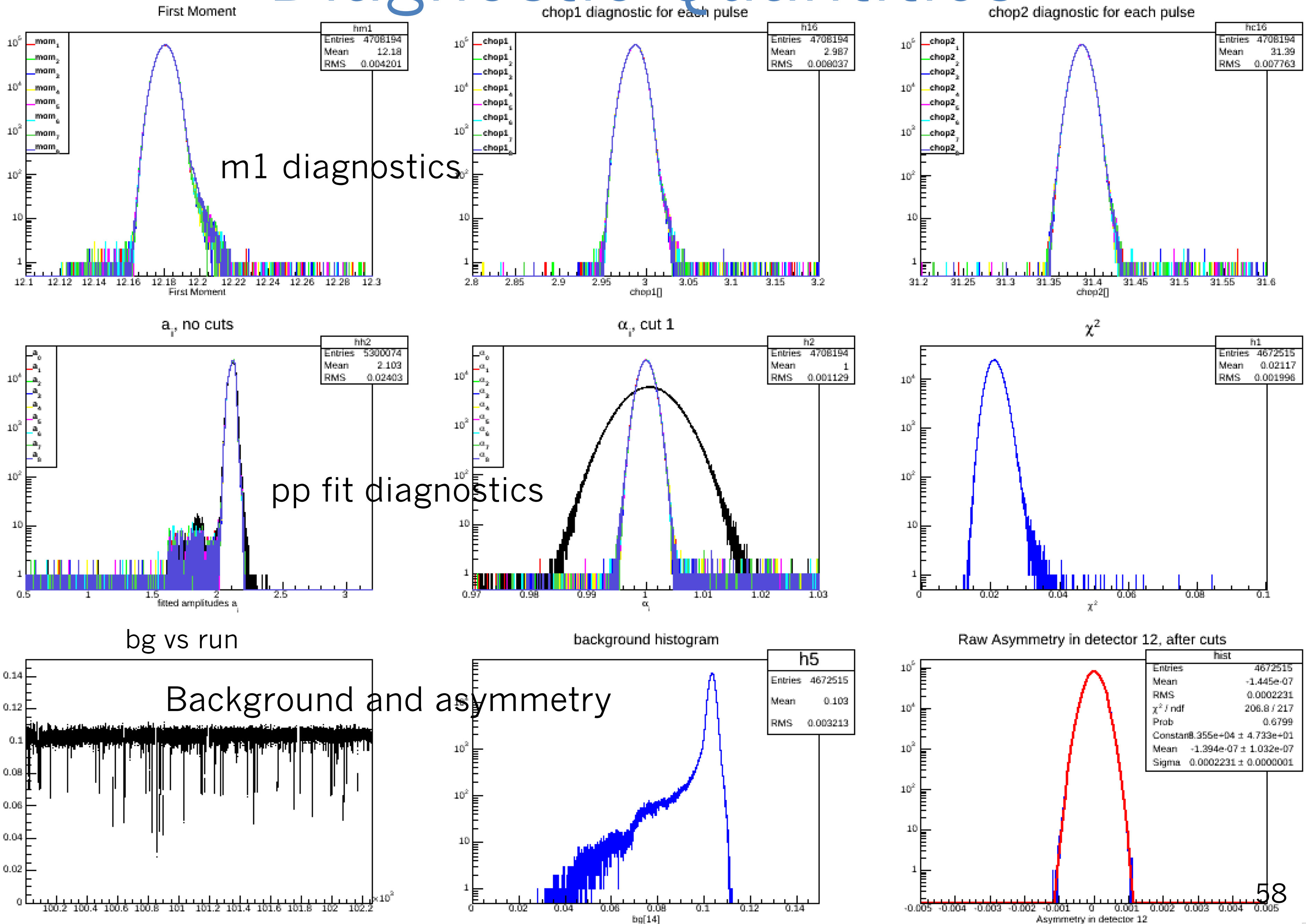
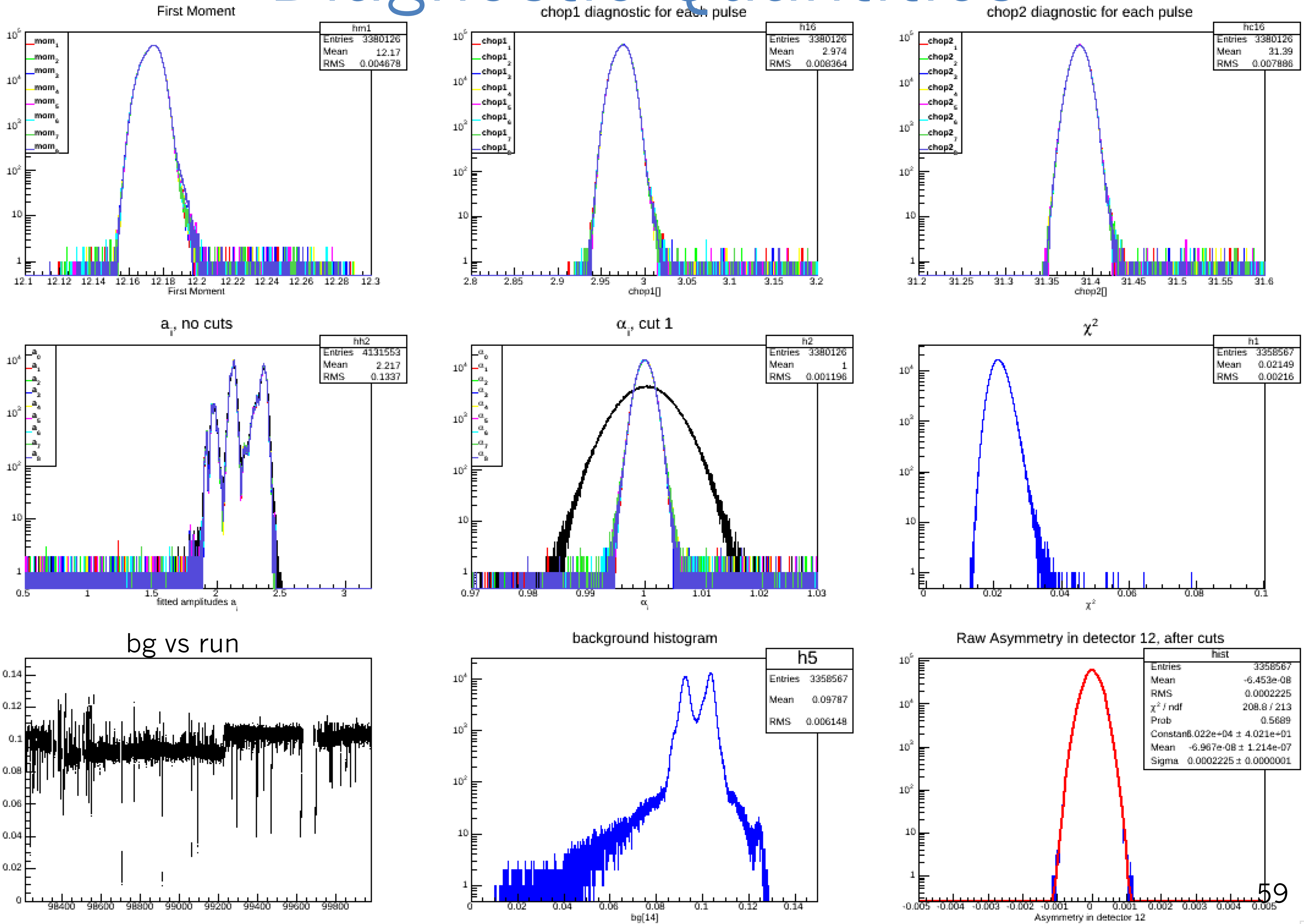
Extras

Diagnostic Quantities



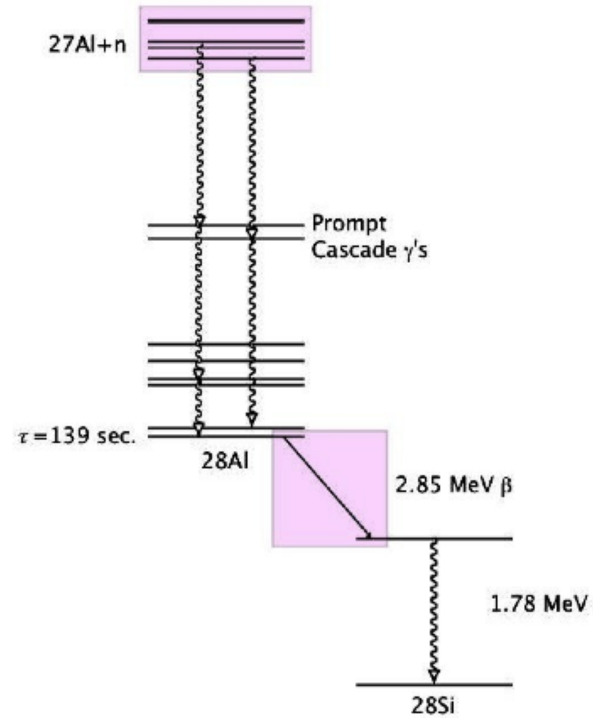
Diagnostic Quantities



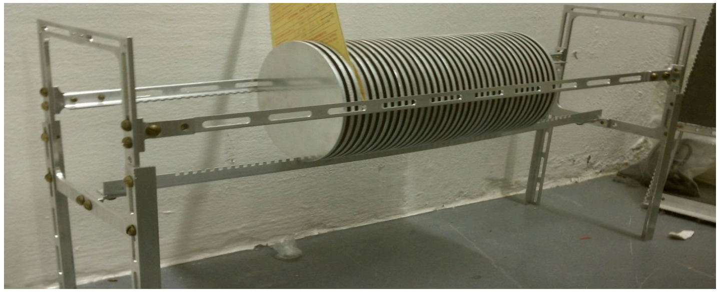
Systematics

Other signals correlated with the polarization state or magnetic fields can create a false asymmetry and are cataloged below. Needs to be well below proposed statistical uncertainty of 1×10^{-8}. Instrumental asymmetries are on the order of 1×10^{-9}.

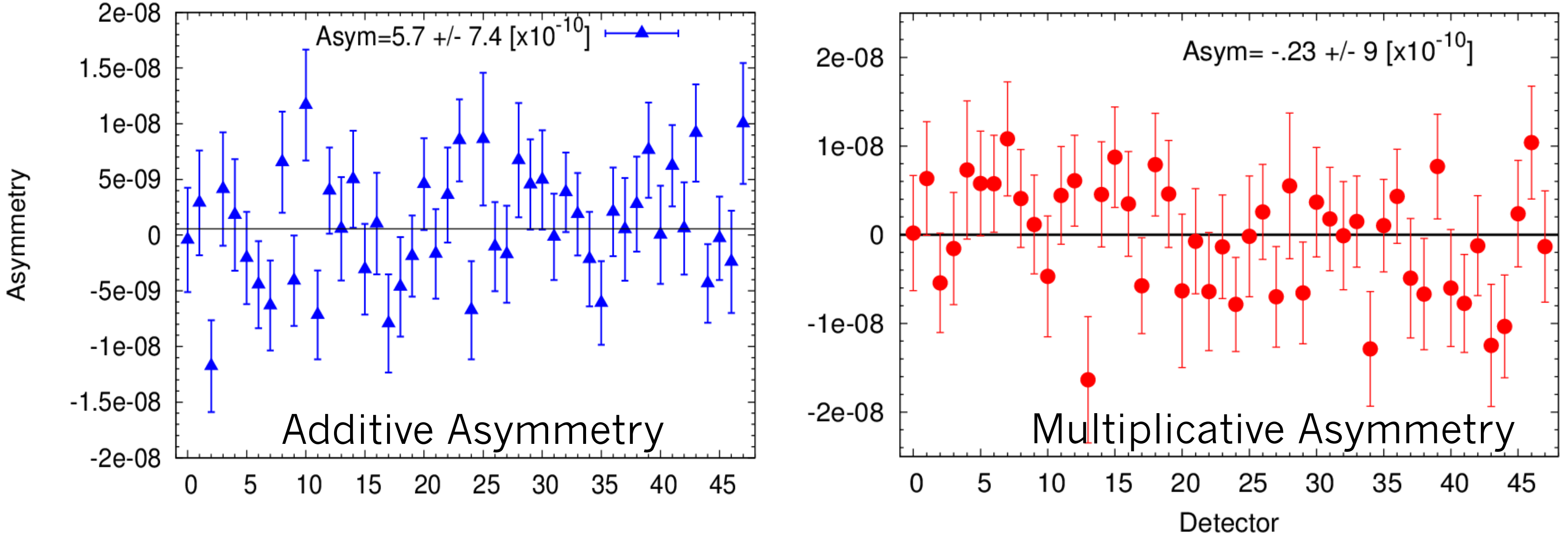
Systematic Effect	Size
Stern-Gerlach	1×10^{-10}
Circularly Polarized γ	1×10^{-12}
In flight β decay	1×10^{-11}
Capture on ^{6}Li	1×10^{-11}
Al Radiative β decay	1×10^{-9}
Al A_{UD} asymmetry	measure
Polarization	<1%
Target Depolarization	<0.5%
SF efficiency	<1%



Al asymmetry is measured, then subtracted
Preliminary Al measurement in 2012, more Al stats from Feb - June 2014

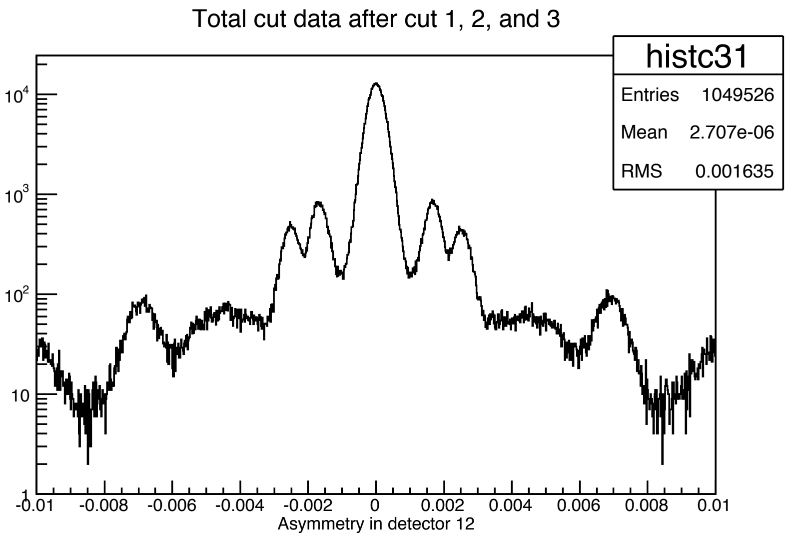


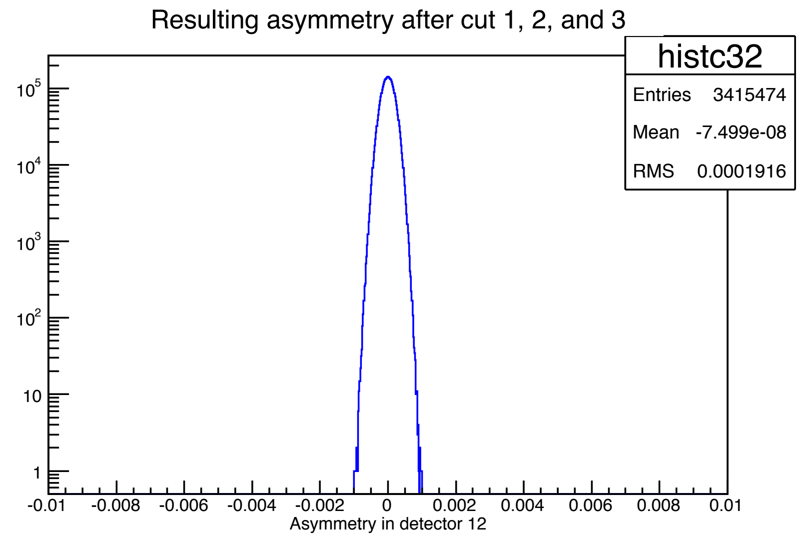
Instrumental Asymmetries

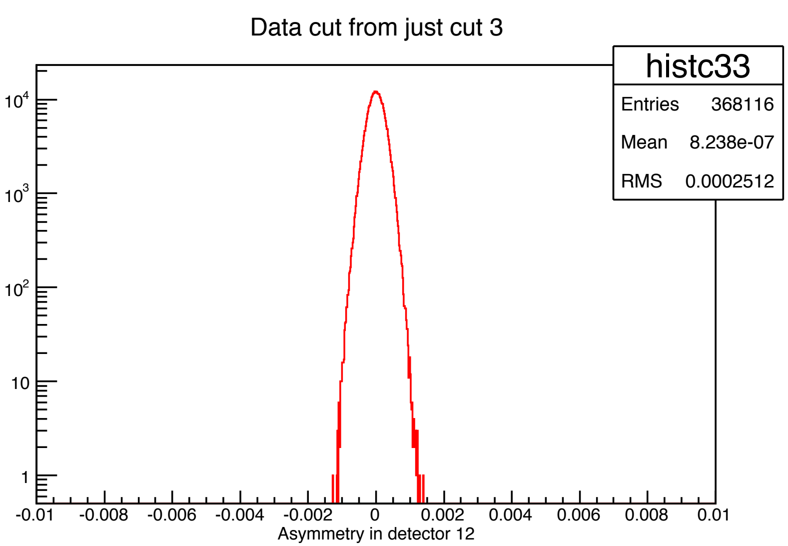


Instrumental effects are zero at the $1x10^{-9}$ level
using beam off and LED measurements

Cut 3: α Distribution







Total cut data = 2.71e-06 ± 1.60e-06

Total cut data has 1049526 8-ss

Resulting asymmetry = -7.50e-08 ± 1.04e-07

Resulting data has 3415474 8-ss

Data cut by this cut = 8.24e-07 ± 4.14e-07

Data cut by this cut has 368116 8-ss

Batch H16 31% of all cut data cut here