Experimental study of the strong interaction with the spectrometer CLAS and ALERT at JLab

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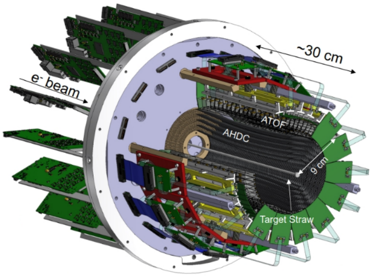
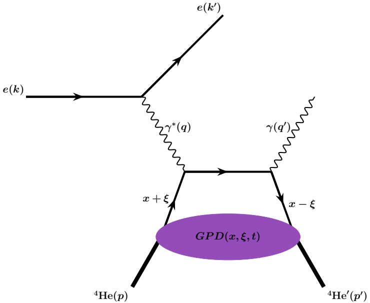
ALERT experiment

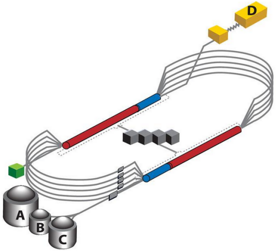
- ALERT is a detector. It stands for A Low Energy Recoil Tagger
  - a hyperbolic drift chamber (AHDC) $\rightarrow$ IJClab, France
  - $+$ a time-of-flight (ATOF) $\rightarrow$ Argonne Laboratory, US
- It is also an experiment with a wide program in nuclear physics
  - e.g. Deeply Virtual Compton Scattering (DVCS) on ^{4}He
- The experiment took place at JLab from April 2025 to September 2025



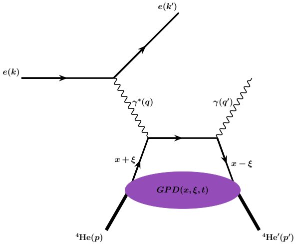


Run period at JLab

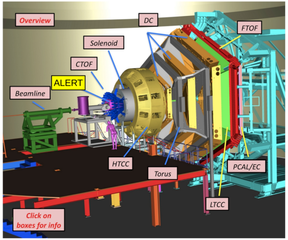
- The experimental setup was the following:
  - The electron beam is delivered by CEBAF
  - The target is located at the center of ALERT
  - The low recoil fragments are detected by ALERT
  - The scattered electrons and produced photons are detected by CLAS12



(a) CEBAF, can deliver spin polarized electron beam with energy up to 11 GeV



(b) example of physics process : nuclear DVCS on ^{4}He

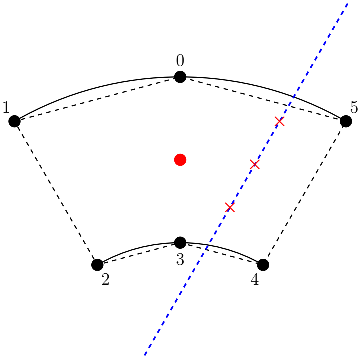


(c) CLAS12, good e^- and γ identification over a large kinematics coverage

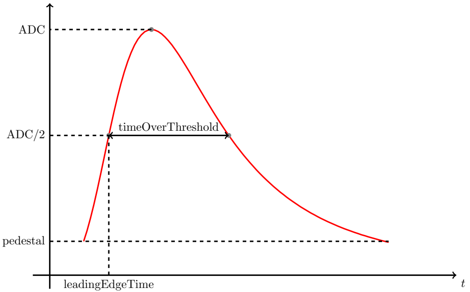
Run period at JLab

- We took data on several nuclear targets (H2, D2, He4) and with different beam energies (2 GeV, 6 GeV, 10.6 GeV)
- I was at JLab during a good part the run period (until July 2025)
    - Target expert (target change every one or two weeks, target purge every day)
    - ALERT expert (monitor the quality of the data taking, on-call person)
- The data taking was a success, we achieved our goal in terms of accumulated charge
- Now, all efforts are dedicated the finalization of the reconstruction software

- Generate the characteristic signal of the AHDC from the Geant4 digitization
  - collection of hits $\{(E_s, x_s, y_s, z_s, p_{x_s}, \ldots)\}_s \longrightarrow$ signal over the time

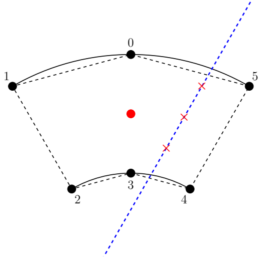


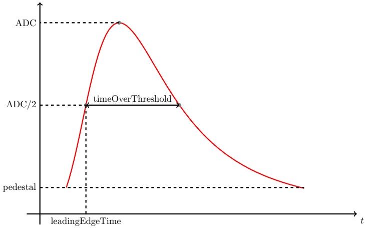
(a) AHDC detection cell



(b) Shape of the AHDC signal

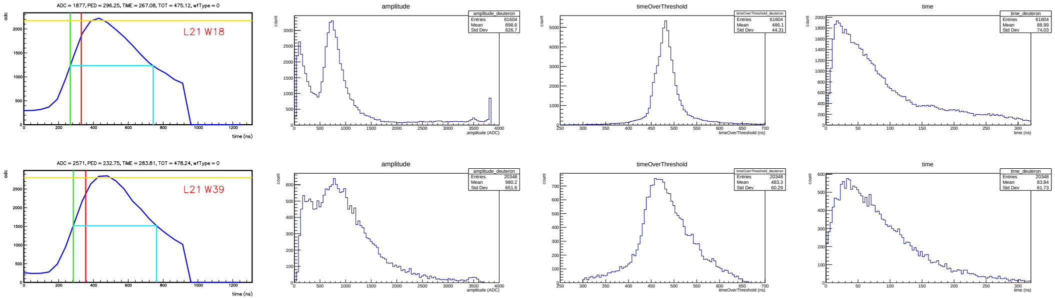
- We have identified few control parameters that have to be calibrated in order to match real data
  - (inverse of) time2distance
  - reference time (t_0)
  - signal width parameter (for a Landau distribution, it is linked to the timeOverThreshold)
  - proportionality factor (conversion of MeV to ADC)
  - noise level



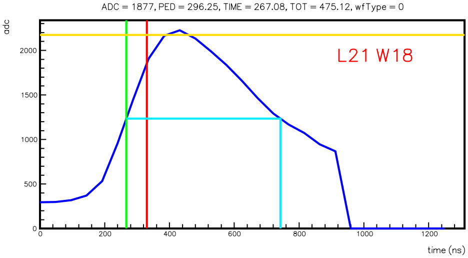


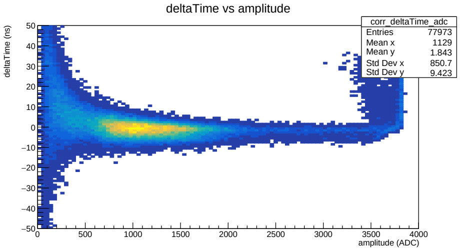
Simulation (results)

- The distributions look very similar (the peaks are located at the same place)
- Simulation (top) versus real data (bottom) for elastics deuterons (run 22712)
- We have overestimated the noise in simulation, but we didn't manage to spread the distribution as in real data
- Taking into account the calibration of the amplitude and of the timeOverThreshold in the future could improve the result for real data



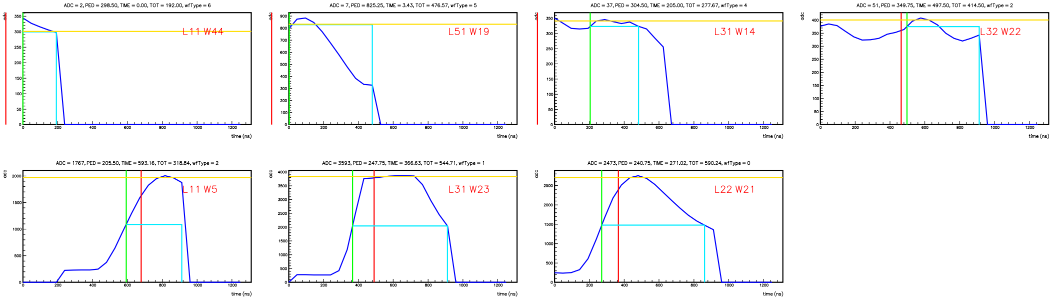
- The decoding consists of the extraction of the **leadingEdgeTime**, **timeOverThreshold**, **pedestal** and **amplitude** from a given AHDC pulse
- Even in simulation, the quality of the decoding varies with the amplitude of the signal (deltaTime = true - reconstructed)
- Proton signals have very low amplitudes (200 ADC), how can we trust the decoding?





Waveform classification

- We have identified seven different patterns for the AHDC signals
  - 6 $\rightarrow$ too short (nsamples $\leq$ 10)
  - 5 $\rightarrow$ decreasing baseline
  - 4 $\rightarrow$ bad ToT (ToT $<$ 300)
  - 3 $\rightarrow$ pileup (not done yet)
  - 2 $\rightarrow$ bad trailingEdgeTime
  - 1 $\rightarrow$ saturating
  - 0 $\rightarrow$ good



Hit selection

- Criteria: wfType $\leq$ 2 and quality cuts
- Run 23003, beam current 200 nA

	ALL	rawCuts 13.0.1	wfTye <= 1 coat 13.3.0	wfTye <= 2 coat dev	wfTye <= 2 & cuts coat 13.4.0	wfType <= 2 & cuts (strong) coat dev
		time >= 200 time <= 500			time >= 0 time <= 340 *t0 substractred	time >= 0 time <= 340 *t0 substractred
		tot >= 350 tot <= 650			tot >= 300 tot <= 750	tot >= 340 tot <= 620
		ped >= 180 ped <= 360			ped >= 120 ped <= 350	ped >= 120 ped <= 350
					samples > 10	samples > 14
Occupancy on the 1st layer	40 %	6 %	4 %	15 %	8 %	5.5 %
nb elastics nb protons nb deuterons	–	9472 2485 3662	5725 921 3020	-	17882 4394 6757	12650 2343 5502

before

(hidden ADC cut)

*after

Kalman Filter (principle)

- Give an estimation of the true state $\boldsymbol{x}_k$ knowing a series of measurements $\boldsymbol{z}_1 ... \boldsymbol{z}_k$

$$\hat{\boldsymbol{x}}_{k|k} = \mathbb{E}[\boldsymbol{x}_k | \boldsymbol{z}_1 ... \boldsymbol{z}_k]$$

- Conditions:
  - a discrete evolution model

$$\boldsymbol{x_k} = f(\boldsymbol{x}_{k-1}, u_{k-1}, w_{k-1})$$

  - an expression of the measurement as function of the state

$$\boldsymbol{z_k} = h(\boldsymbol{x}_k, v_{k-1})$$

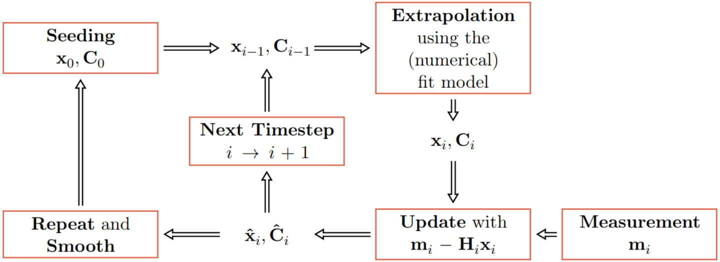
- w_k, v_k are respectively the process noise and the measurement noise; u_k is an optional control input

Kalman Filter (algorithm)

- The Kalman Filter is recursive
- During each update, the Kalman filter minimize the error covariance matrix

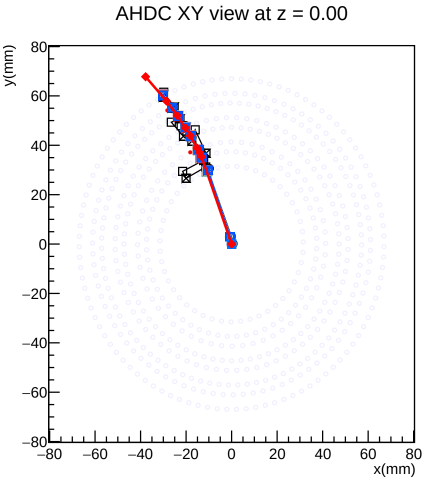
$$\boldsymbol{P}_{k|k} = \mathbb{E}[(\boldsymbol{x}_k - \hat{\boldsymbol{x}}_{k|k})(\boldsymbol{x}_k - \hat{\boldsymbol{x}}_{k|k})^T]$$

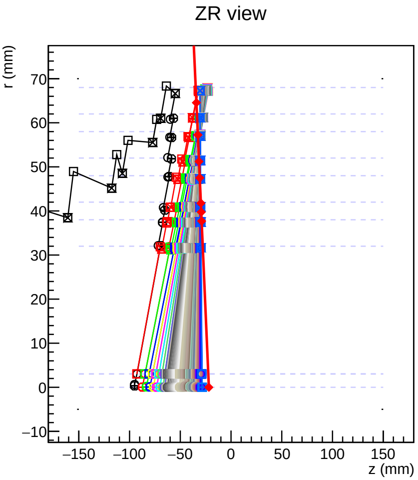
- Figure to be updated to match the notations



Kalman Filter (visualisation)

- This simulation. The system evolves from left to right. Niter = 60 (this example).



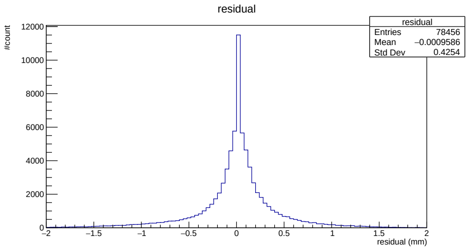


Kalman Filter (AHDC case)

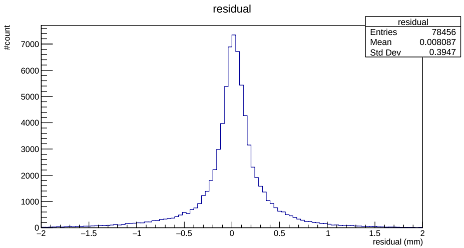
- For the AHDC, the state vector is $\boldsymbol{x} = (x, y, z, p_x, p_y, p_z)^T$
- The measurements are
  - the distances provided by the hits belonging to a given track, here $z = d$ is 1×1 matrix
  - the position with respect to the beamline, here $\boldsymbol{z} = (r, \phi, z)^T$ is a 3×1 matrix
- The evolution model is the one of a particle moving in an electromagnetic field

- The first implementation of the algorithm has been done by Mathieu Ouillon and Éric Fuchey
- My contributions: cleaning, reorganization, new features

1. **Use all hits** (before the code didn't manage more than one hit on the same layer)
   - the effect is more visible in simulation
   - a good part of the peak at 0 in figure (a) is due all the hits that are not used
   - looking at (b), almost 6.8 % of the information was missing



(a) before

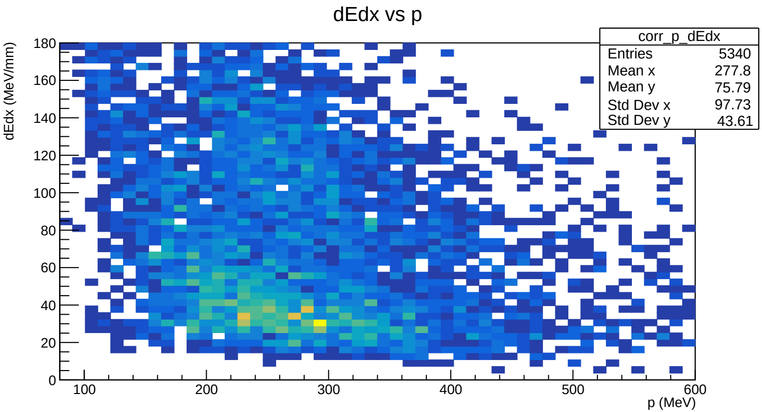


(b) after

Kalman Filter (new features)

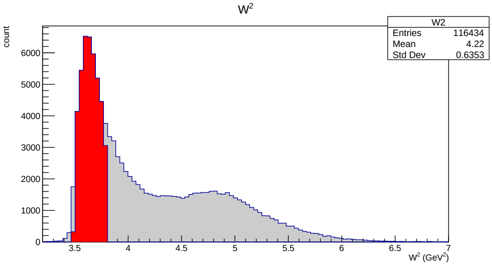
2. **Implement the electron vertex**
   - read electron vertex from CLAS12 reconstruction
   - set it to the track with a finite resolution
   - this resolution will depend on the momentum p_e and the θ_e angle of the electron (a fine-tuning will be done later)
   - handle a possible misalignment between the center of CLAS and ALERT
3. **Make the distance resolution dependent on the time and on the amplitude**
   - a fine-tuning will be done later
4. (Ongoing work) **Make the Kalman Filter reusable**
   - e.g. **KF 1** $\rightarrow$ clean bad hits $\rightarrow$ **KF 2**
5. (Next step) Add the ATOF hit in the Kalman Filter

- Run 22712 on D2 target, 2.23951 GeV beam energy
- Elastic cuts: $3.5\ \text{GeV}^2 < W^2 < 3.8\ \text{GeV}^2$ and $\Delta\phi < 20^\circ$
- Deposited energy dEdx versus momentum p of the track (after the Kalman filter)

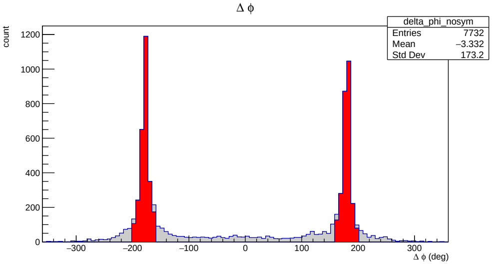


Conclusion

- A lot of software development
- ...
- (After the presentation), points non abordés : time2distance, geometry modification, Nombre d'itérations et computing time du Kalman réduit en améliorant le Propagator...



(a) Missing mass



(b) Delta Phi

Calibration (time2distance)

- Haha