# PIONEER Data Acquisition Development

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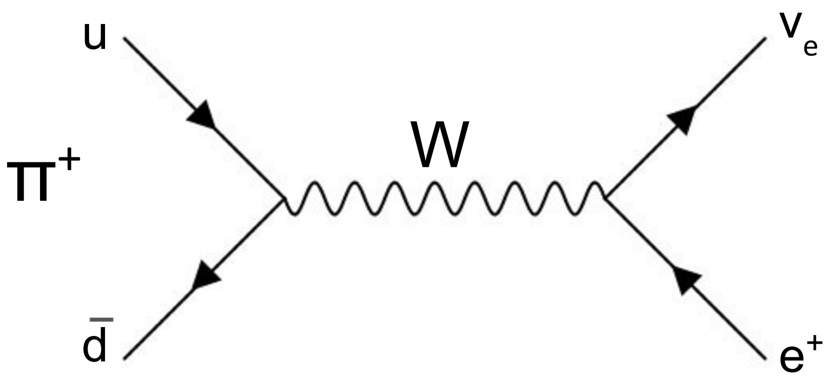
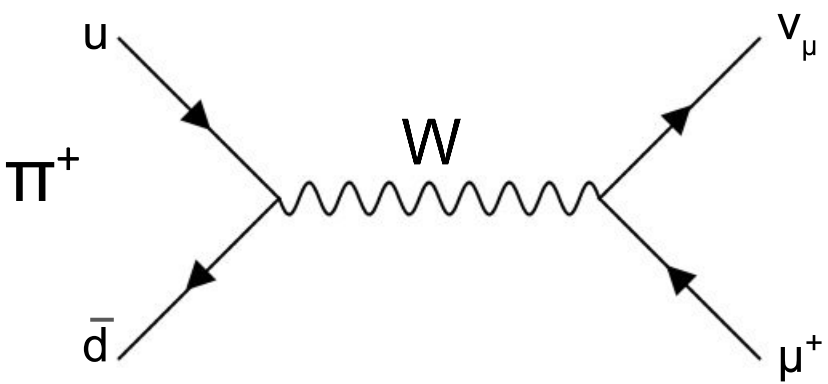
# Outline

I. [3-14] Physics Background/PIONEER goals
   A. $\pi \rightarrow e\nu$, $\pi \rightarrow \mu\nu$
   B. Lepton Universality
   C. Branching Ratio $R_{e/\mu}$
   D. Detector Design
II. [15-21] Frontend Development
   A. Proposed DAQ framework
   B. Midas Framework
   C. Wavedream UKY teststand
   D. g-2 Cornell teststand → more versatile frontend
III. [22-30] Fitting and Compression
   A. Algorithm
   B. Bottleneck
   C. Benchmarking
IV. [32-34] Future Endeavors
   A. FPGAs
   B. November PSI beam time

# $\pi \rightarrow e\nu_e$ and $\pi \rightarrow \mu\nu_\mu$

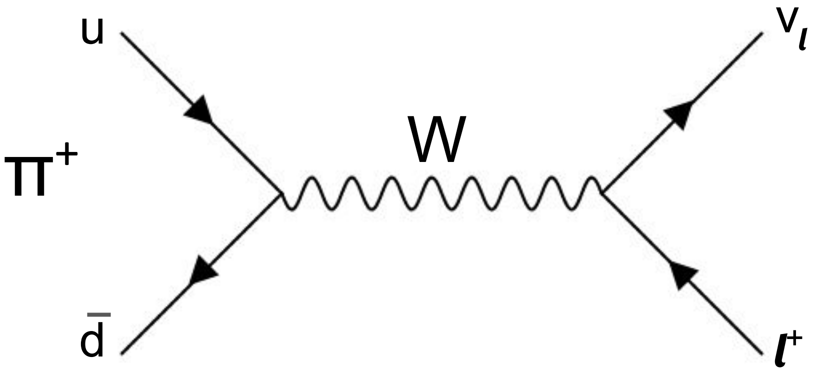


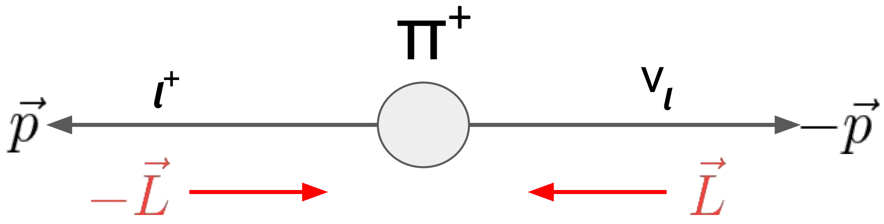




- Corresponding diagrams for $\pi^-$
- Tau decay forbidden
  - tau too massive ~ 1000 MeV/$c^2$
  - Pion ~ 100 MeV/$c^2$
- Muon decay more likely
  - branching fraction of 0.999877

# Helicity Suppression (Why is Muon Decay Most Likely?)

- Naively, $\Gamma \propto p'$ → electron decay more likely
- Weak force only affects left-handed (LH) chiral particle states and right-handed (RH) chiral anti-particle states
- Neutrinos are all LH chirality
- $m_\nu << E$ means LH neutrino chirality→ LH (negative) neutrino helicity
- Conservation of momentum → anti-lepton is LH (negative) helicity



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# Helicity Suppression (Why is Muon Decay Most Likely?)

- We can write the LH (negative) helicity anti-particle state in the chiral basis:

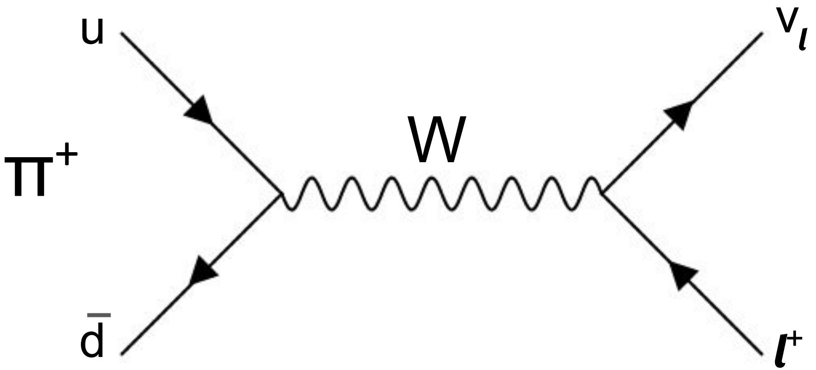
$$v_{\downarrow} = \frac{A}{2}\left[\left(1-\frac{p}{E+m}\right)v_R - \left(1+\frac{p}{E+m}\right)v_L\right]$$

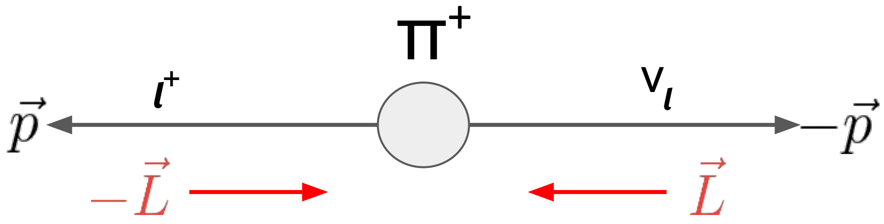
- We ignore the LH term (weak force only acts on the RH term), anti-particle's matrix element contribution:

$$\mathcal{M} \sim \frac{1}{2}\left(1-\frac{p_l}{E_l+m_l}\right) \xrightarrow[m_\nu \to 0]{} \frac{m_l}{m_\pi + m_l}$$

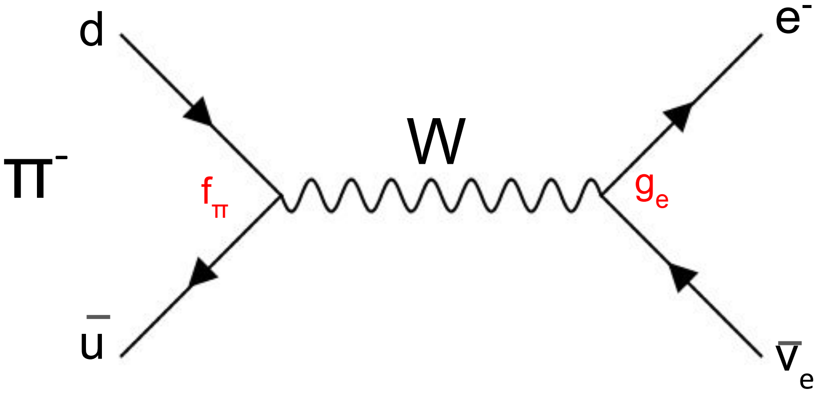
- This effect ends up making the matrix element smaller → decay rate smaller

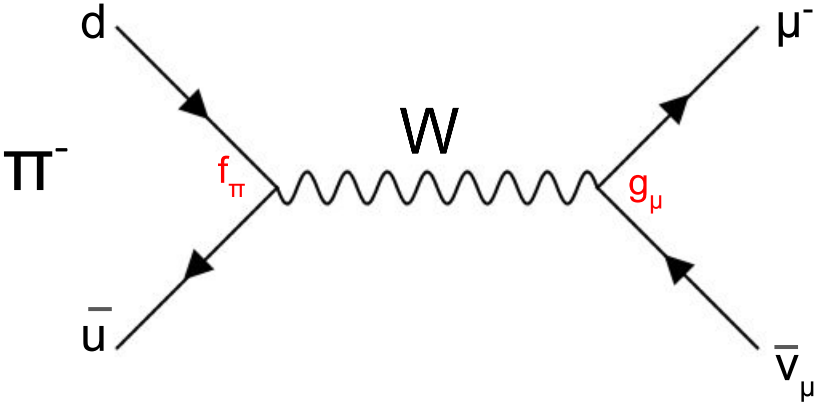
$$\Gamma \propto |\mathcal{M}|^2$$



# Lepton Universality




- States coupling strengths (vertices) $g_e = g_\mu = g_\tau$
- Using the Feynman rules for the weak interaction, we can approximate the matrix element

$$\mathcal{M}_{fi} = \underbrace{\left[\frac{g_W}{\sqrt{2}}\frac{1}{2}f_\pi p_\pi^\alpha\right]}_{\text{Pion vertex}} \cdot \underbrace{\left[\frac{g_{\alpha\beta}}{m_W^2}\right]}_{\text{W-boson propagator}} \cdot \underbrace{\left[\frac{g_W}{\sqrt{2}}g_l\bar{u}(p_l)\gamma^\beta\frac{1}{2}(1-\gamma^5)v(p_\nu)\right]}_{\text{Lepton vertex}}$$

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# Lepton Universality

- After some "massaging" we can find the matrix element to be

$$\mathcal{M}_{fi} = \left(\frac{g_W}{2m_W}\right)^2 f_\pi g_l \cdot \sqrt{m_\pi^2 - m_l^2}$$

- Pion spin zero → no spin averaging needed, i.e.:

$$\langle|\mathcal{M}_{fi}|^2\rangle = |\mathcal{M}_{fi}|^2 = \left(\frac{g_W}{2m_W}\right)^4 f_\pi^2 g_l^2 \cdot (m_\pi^2 - m_l^2)$$

- We can use the general formula for 2-body decay to to find the decay rate

$$\Gamma = \frac{p\langle|\mathcal{M}_{fi}|^2\rangle}{8\pi m_\pi^2} = \frac{f_\pi^2}{16\pi^2 m_\pi^3}\left(\frac{g_W}{2m_W}\right)^4 \left[m_l g_l (m_\pi^2 - m_l^2)\right]^2$$

- Finally, we compute the branching ratio

$$\frac{\Gamma(\pi^- \to e^-\bar{\nu}_e)}{\Gamma(\pi^- \to \mu^-\bar{\nu}_\mu)} = \left(\frac{g_e}{g_\mu}\right)^2 \left[\frac{m_e(m_\pi^2 - m_e^2)}{m_\mu(m_\pi^2 - m_\mu^2)}\right]^2$$

# Lepton Universality

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} = \left(\frac{g_e}{g_\mu}\right)^2 \left[\frac{m_e(m_\pi^2 - m_e^2)}{m_\mu(m_\pi^2 - m_\mu^2)}\right]^2$$

- Lepton universality assumes $g_e = g_\mu$, so the first factor disappears
- Improving the branching ratio measurement and comparing to the theoretical value acts as a test of lepton universality
- Another test would consider pure leptonic decays, but such decays involving taus are too rare for high precision measurements

# Branching Ratio $R_{e/\mu}$

- We can measure the branching ratio by measuring # of decays e and μ decays

$$R_{e/\mu} \equiv \frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)}$$

- Theoretical prediction is simple in first (and second) order
  - No $f_\pi$ or CKM element $V_{ud}$

$$R^0_{e/\mu} = \left(\frac{g_e}{g_\mu}\right)^2 \left[\frac{m_e(m_\pi^2 - m_e^2)}{m_\mu(m_\pi^2 - m_\mu^2)}\right]^2$$

= 1 [in theory]

- 3rd order correction and beyond the pion structure becomes relevant

$$R^{(\text{theory})}_{e/\mu} = R^0_{e/\mu}\left(1 - \frac{3\alpha}{\pi}\ln\left(\frac{m_\mu}{m_e}\right) + \dots\right)$$

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# Current state of $R_{e/\mu}$

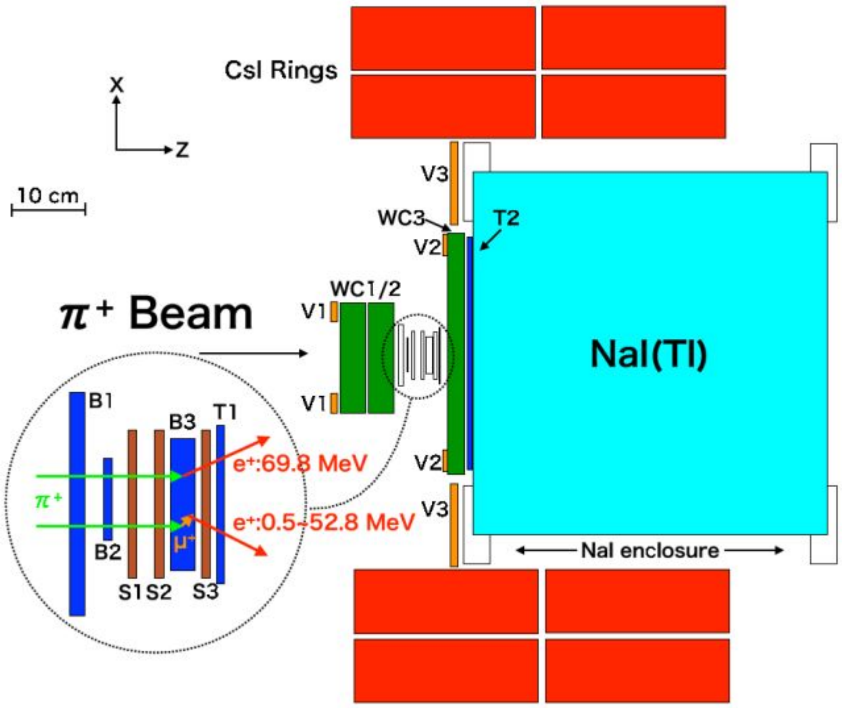
$$R_{e/\mu}^{exp} = 1.2327(23) \times 10^{-4} \text{ (PIENU collab)}$$

$$R^{theo} = 1.23524(15) \times 10^{-4}$$

- Consistent with each other
- Expect factor of ~10 precision improvement on experimental value from PIONEER
    - “Catches up” with theoretical uncertainty

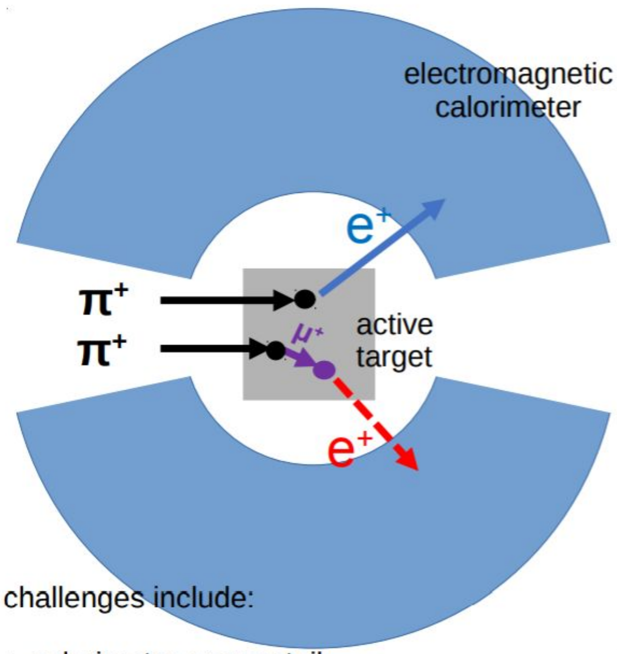
# Past Experimental Approach (PIENU)

- NaI has a long primary decay time
  - ~ 250 ns
- Event pileup forces the experiment to run at a low rate
  - ~70 kHz
- “inactive target”, muons aren’t tracked
- CsI Rings for shower leakage detection



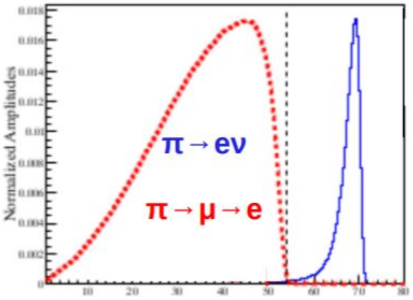
# PIONEER Experimental Proposal

- LXe (or LYSO) has smaller decay time
  - ~ 25 ns
- Allows experiment to run at much higher rate
  - ~300kHz (phase 1)
  - ~2000kHz (phase 2 and 3)
- “active target”, muons and pions are “tracked”

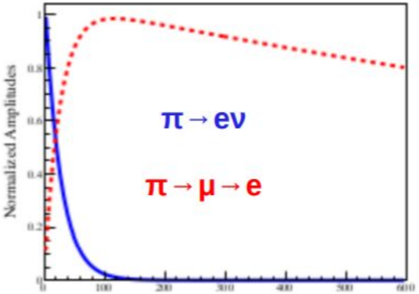



challenges include:

- calorimeter energy tail
- in-flight pion decay
- beam, positron pileup

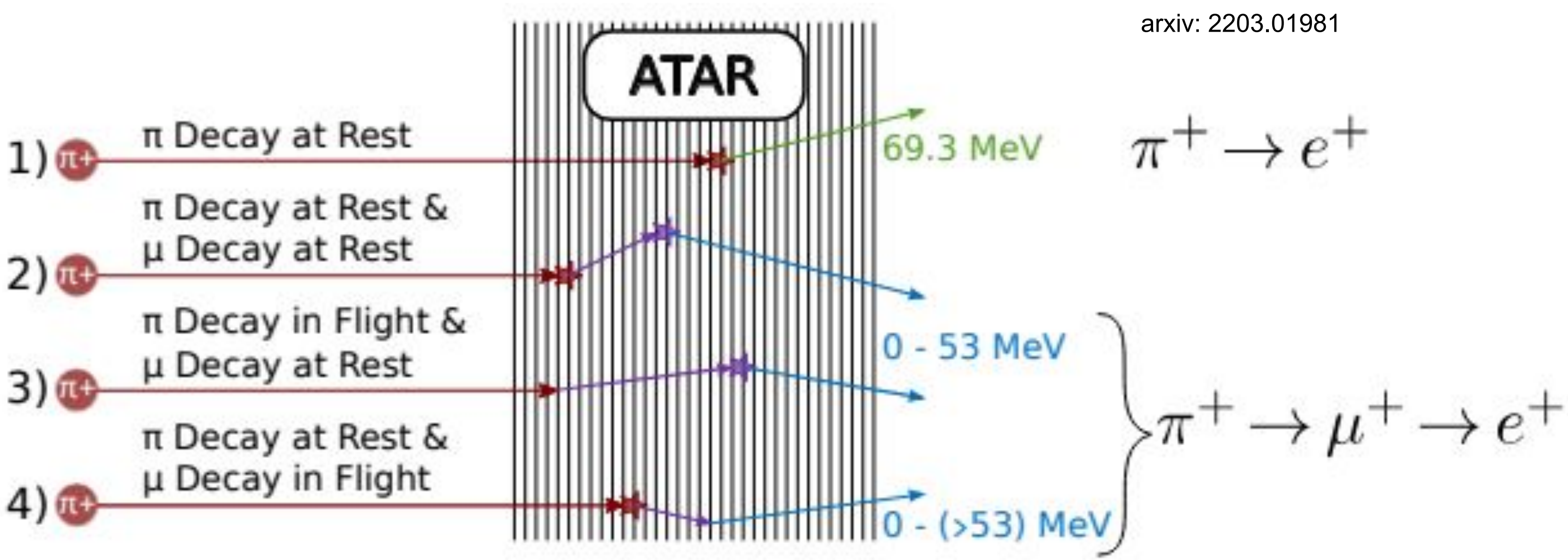



positron energy distribution




positron time distribution

# Active Target (ATAR) Purpose




arxiv: 2203.01981

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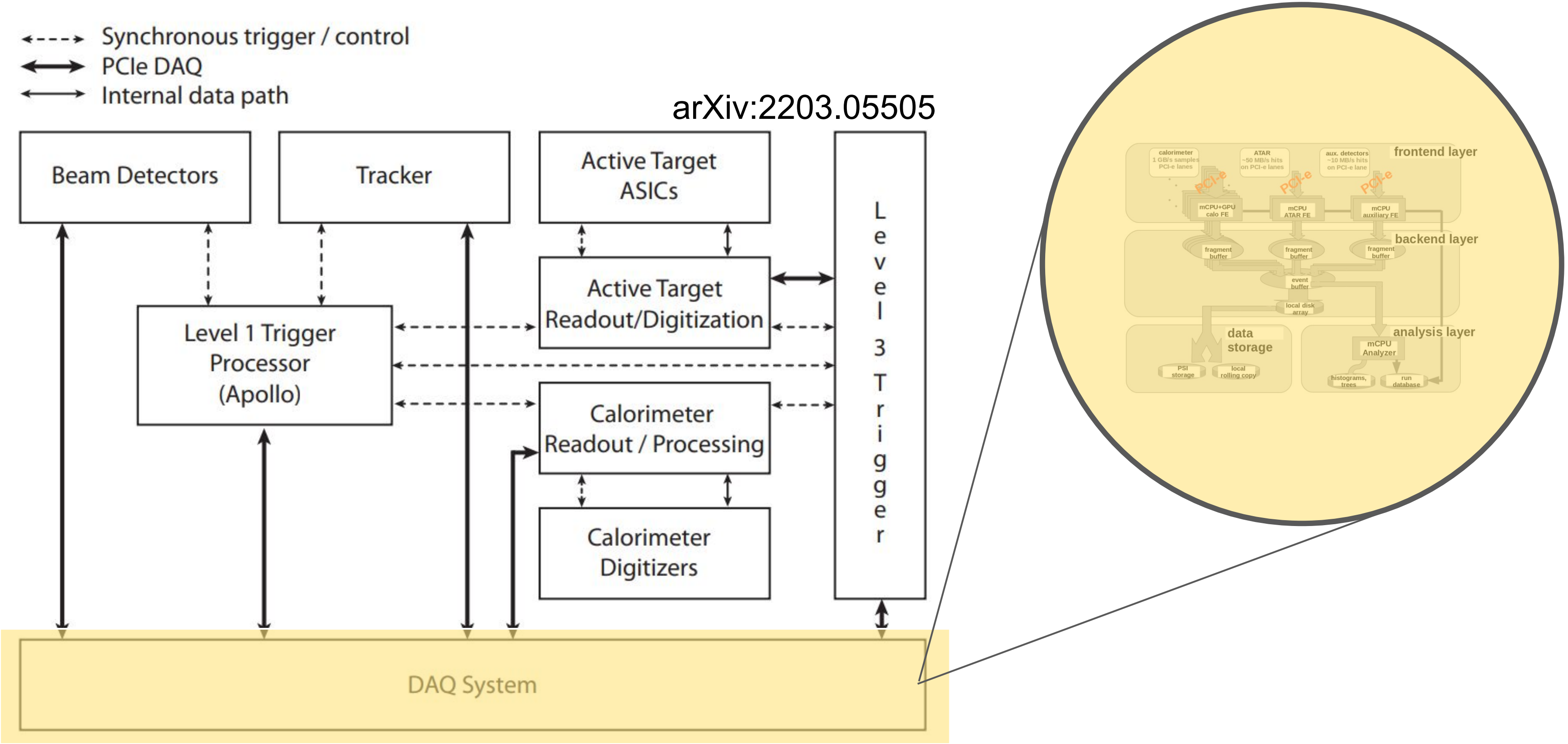
# How PIONEER Will Improve the $R_{e/\mu}$ Measurement

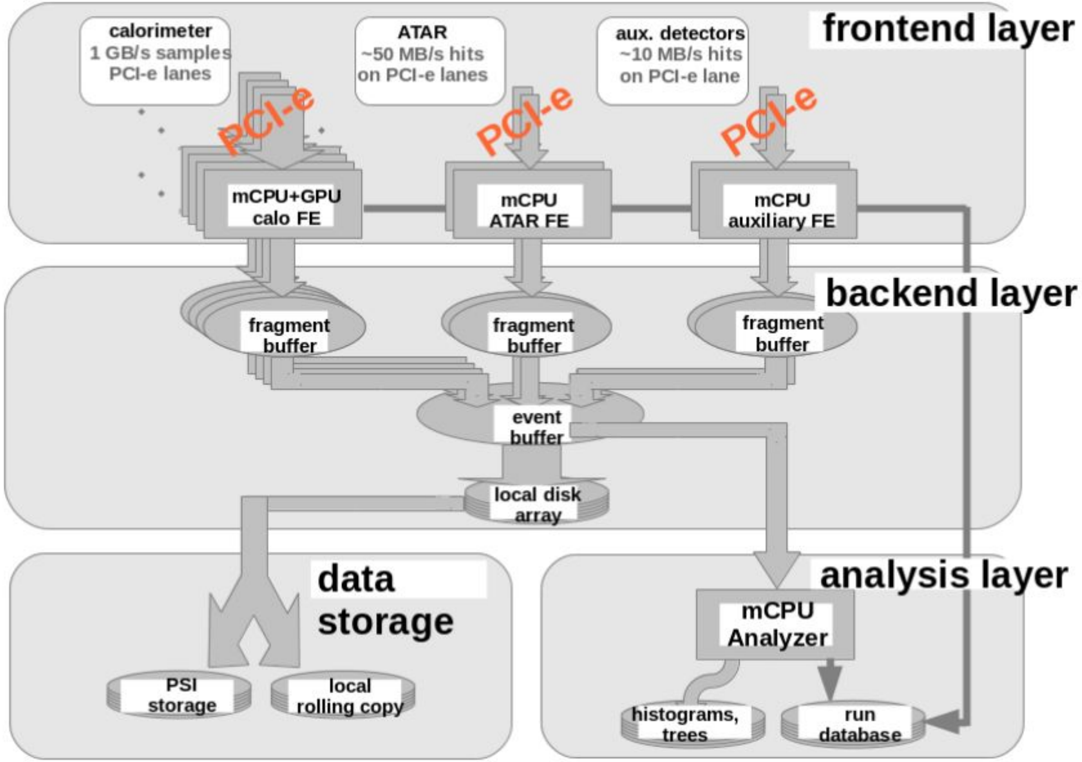
- 4D space-time active pion stopping target (ATAR)
  - Reduce $e^+$ energy tail, identify beam pileup, identify $\pi \rightarrow \mu\nu_\mu$ decays
- Large acceptance, deep radiation length calorimeter
  - LXE or LYSO for high resolution, fast response, small tail
- Fast electronics, high-speed acquisition
  - Giga sample/second digitizers, new gen PCIe readout
- PSI high intensity pion beams
  - 2 mA proton beam, large acceptance beamline

# Proposed Data Acquisition (DAQ) Framework



# Proposed Data Acquisition (DAQ) Framework

arXiv:2203.05505



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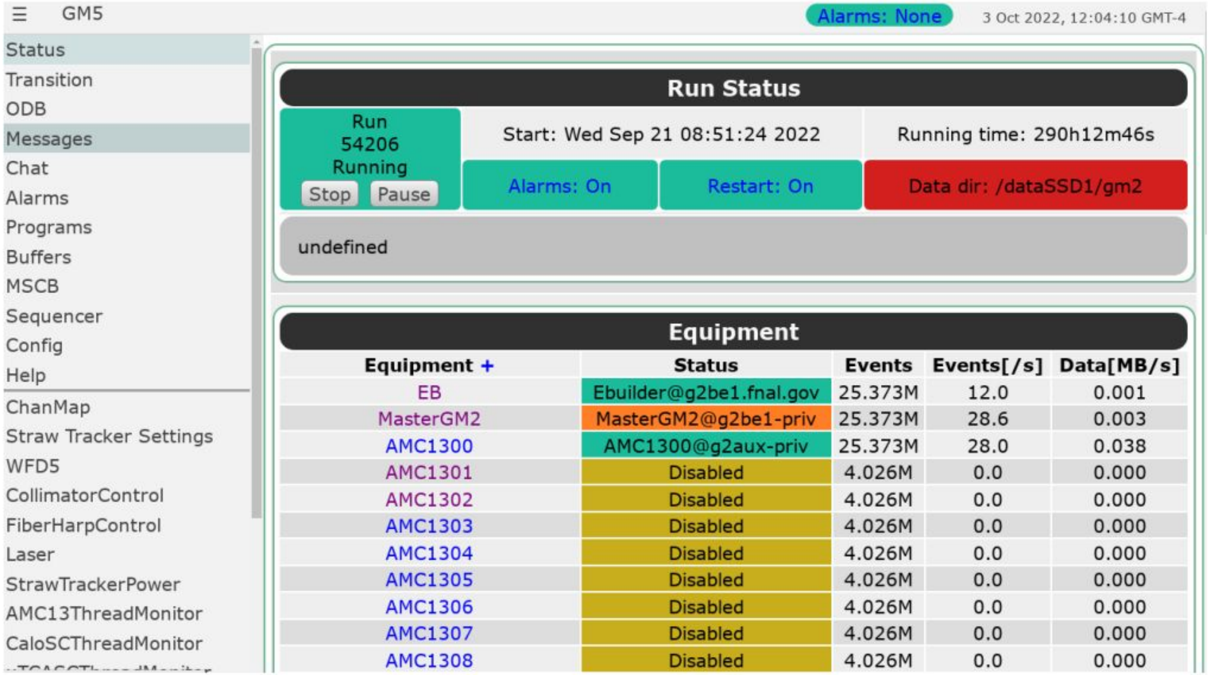
# Midas Framework

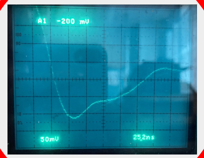
- Package of modules for
  - run control,
  - expt. configuration
  - data readout
  - event building
  - data storage
  - slow control
  - alarm systems
  - etc.



# WaveDREAM Teststand

CAEN Digital Detection Emulator

- Creates fake analog signals
- Configurable rate

BNC-SMA

WaveDREAM board

- Configurable triggers on signals
- Digitizes data

10GbE

- Host midas server
- Stores data

ZIP

Frontend (FE) computer

- Executes frontend code
- Packages Data
- Uses GPU and CPU for real time data compression

1GbE

Backend (BE) computer

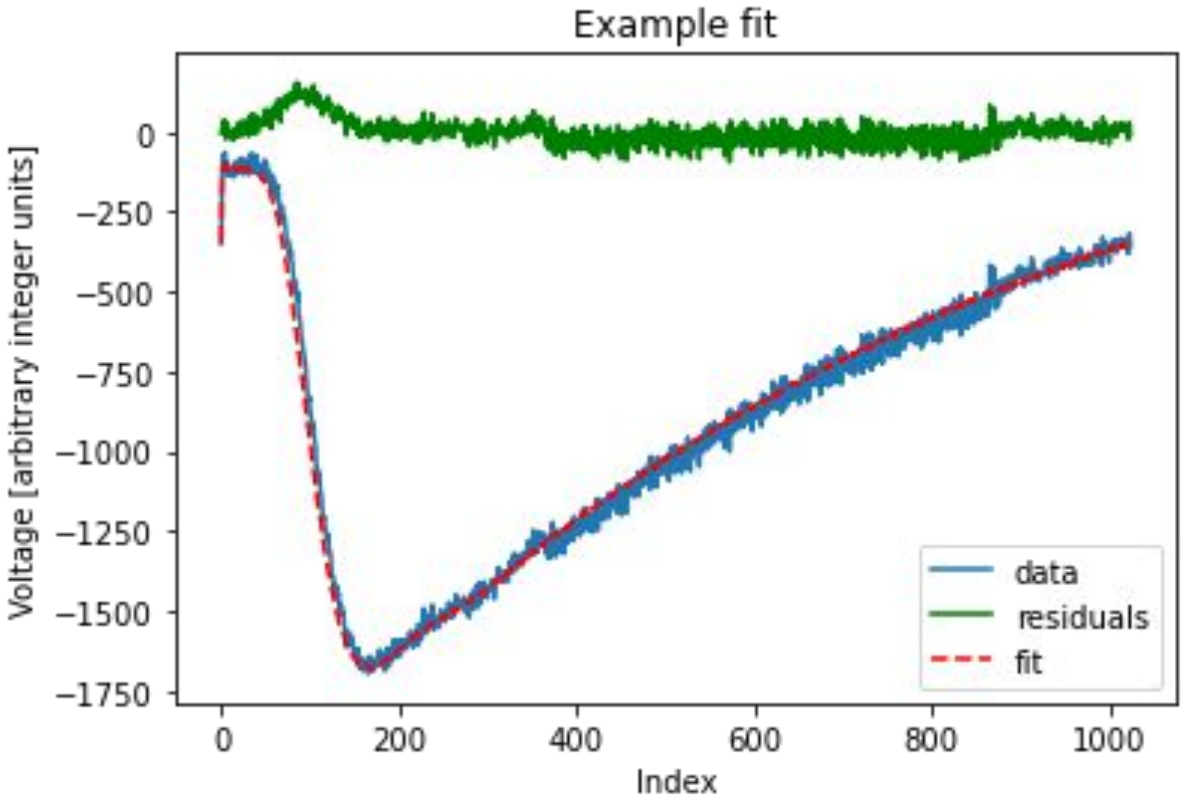
1GbE

- Allows for remote connection

UKY Network

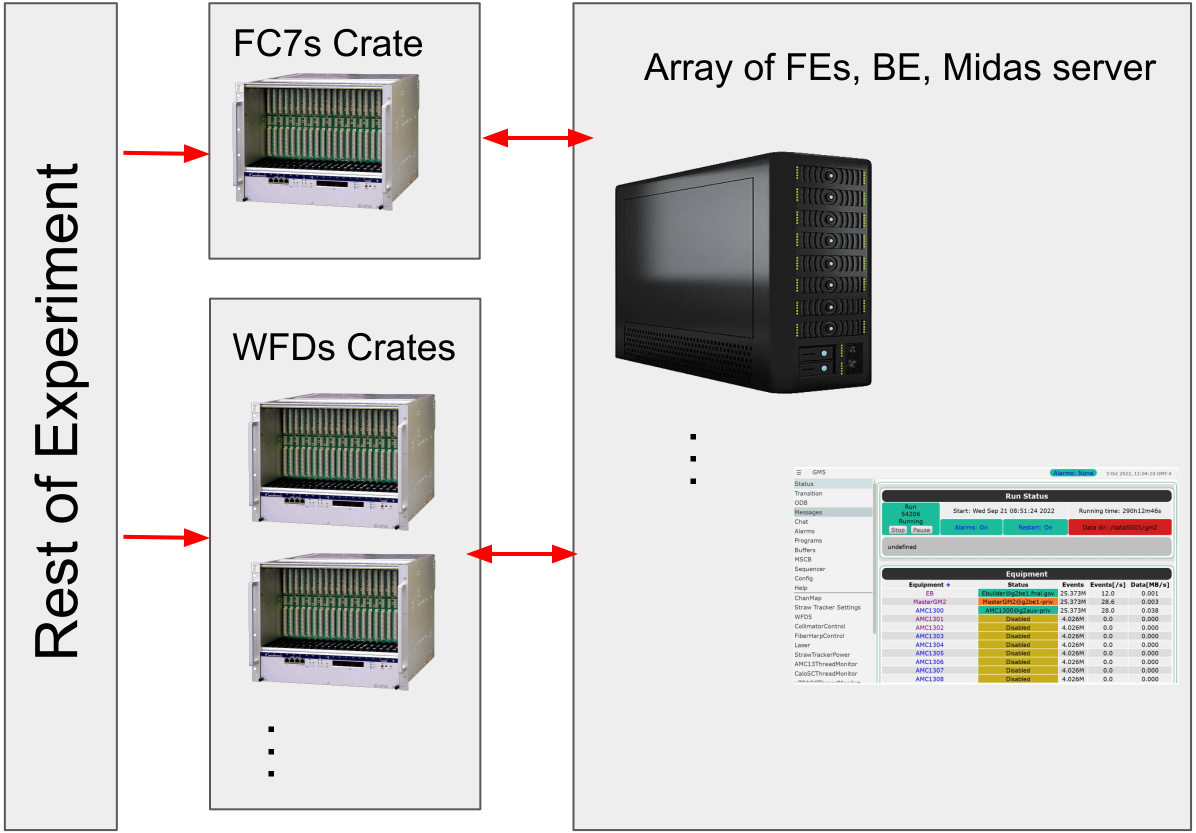
# Example Signal

- CAEN module produces and sends “fake” double exponential signal
- WaveDREAM triggers on low voltage signal, sends time window of data
- FE receives data, packages, and compresses it, sends to be stored
- BE stores data, can be remotely accessed



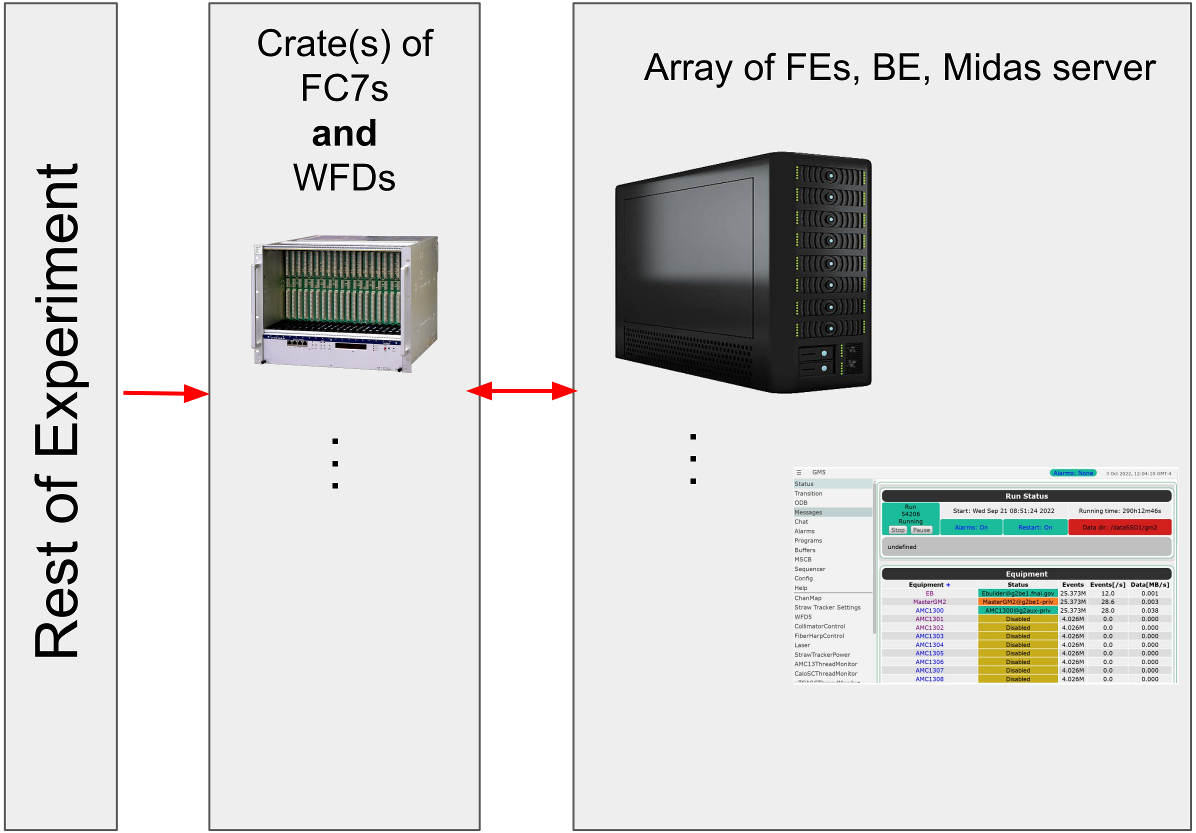
# g-2 DAQ set-up

- FE expects a crate of just FC7s (hard-coded in)
  - Send timing information, triggers, etc, to FEs
- Can have as many WFD crates as we want
  - Digitize data to be processed by FE code



# g-2 DAQ Modified for November Beam Time

- FE code modified to allow crates with FC7s **and** WFDs
- More versatile
  - Allows for one crate setups
- Useful for:
  - Beamtime test DAQ
  - Stony Brook DAQ
  - Washington DAQ



# Data Rates

arXiv:2203.01981

| triggers | prescale | range TR(ns) | rate (kHz) | CALO ΔT(ns) | CALO chan | CALO MB/s | ATAR digitizer ΔT(ns) | ATAR digitizer chan | ATAR digitizer MB/s | ATAR high thres chan | ATAR high thres MB/s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PI | 1000 | -300,700 | 0.3 | 200 | 1000 | 120 | 30 | 66 | 2.4 | 20 | 0.012 |
| CaloH | 1 | -300,700 | 0.1 | 200 | 1000 | 40 | 30 | 66 | 0.8 | 20 | 0.004 |
| TRACK | 50 | -300,700 | 3.4 | 200 | 1000 | 1360 | 30 | 66 | 27 | 20 | 0.014 |
| PROMPT | 1 | 2,32 | 5 | 200 | 1000 | 2000 | 30 | 66 | 40 | 20 | 0.2 |

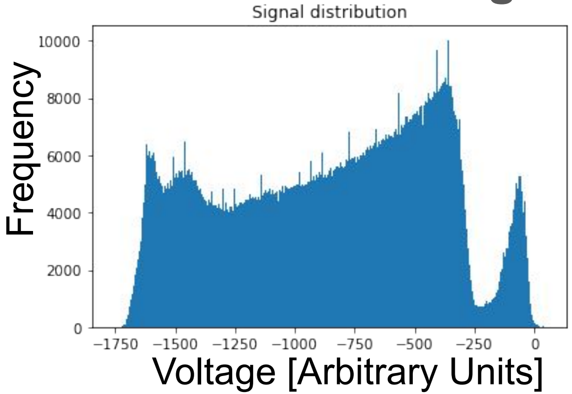
- PIONEER expects data rate of ~**3.5GB/s**

- This is ~**100,000 TB/year**

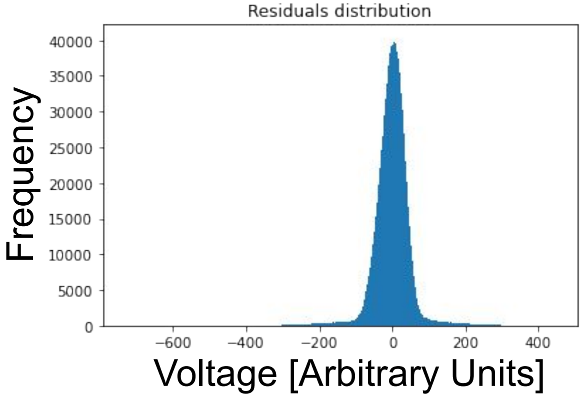
# Signal Conditioning

- Want a narrow distribution for compression. Let $r_i$ be the numbers we compress
- Methods tried:
  - No conditioning
  - Delta encoding:
    $r_i = y_{i+1} - y_i$
  - Twice Delta Encoding:
    $r_i = y_{i+2} - 2y_{i+1} + y_i$
  - Double Exponential Fit:
    $r_i = y_i - (A \cdot \exp(at_i) + B \cdot \exp(bt_i))$
  - **Shape Fit**:
    $\mathbf{r_i = y_i - (A \cdot T(t_i - t_0) + B)}$

## No Conditioning




## Shape Fit



# Shape Fitting Algorithm

1. Construct a discrete template from sample pulses
2. Interpolate template to form a continuous Template, *T(t)*
3. "Stretch" and "shift" template to match signal:

$$X[i] = a(t_0)T(t[i] - t_0) + b(t_0)$$

   [Note: a and b can be calculated explicitly given $t_0$]

4. Compute $\chi^2$ (assuming equal uncertainty on each channel i)

$$\chi^2 \propto \sum_i \{X[i] - a(t_0)T(t[i] - t_0) + b(t_0)\}^2$$

5. Use Euler's method to minimize $\chi^2$

# Lossless Compression Algorithm

- Rice-Golomb Encoding
  - Let x be number to encode
    y = “s”+“q”+”r”
    - q = x/M (unary)
    - r = x%M (binary)
    - s = sign(x)
  - Any distribution
  - Close to optimal for valid choice of M
  - One extra bit to encode negative sign
  - Self-delimiting
  - If quotient too large, we “give up” and write x in binary with a “give up” signal in front

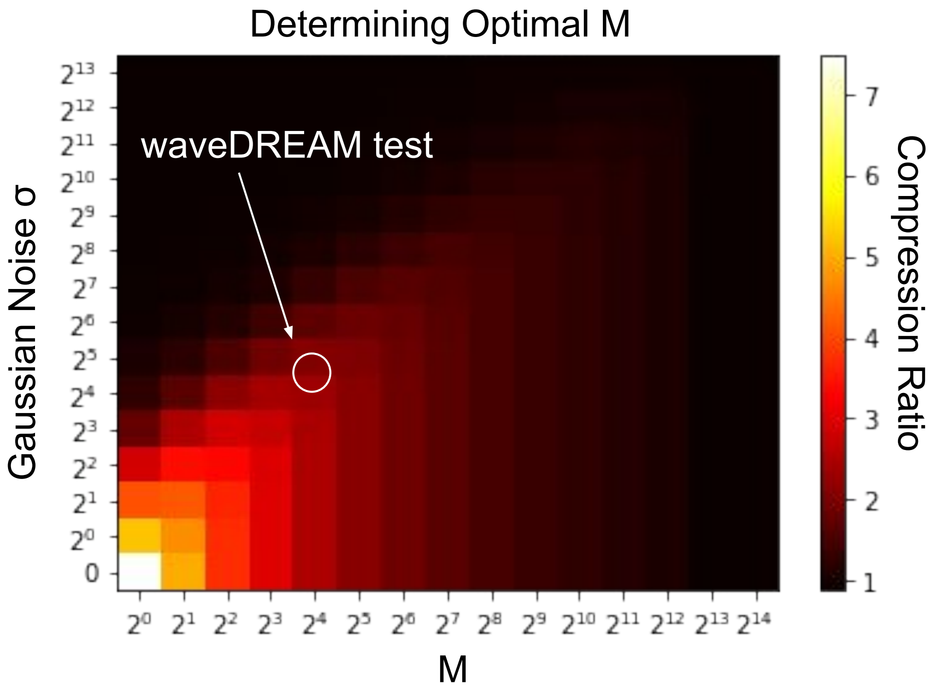
## Rice-Golomb Encoding (M=2)

| Value | Encoding |
|---|---|
| -1 | 011 |
| 0 | 000 |
| 1 | 001 |
| 2 | 1000 |

Red = sign bit
Blue = quotient bit(s) (Unary)
Yellow = remainder bit (binary)

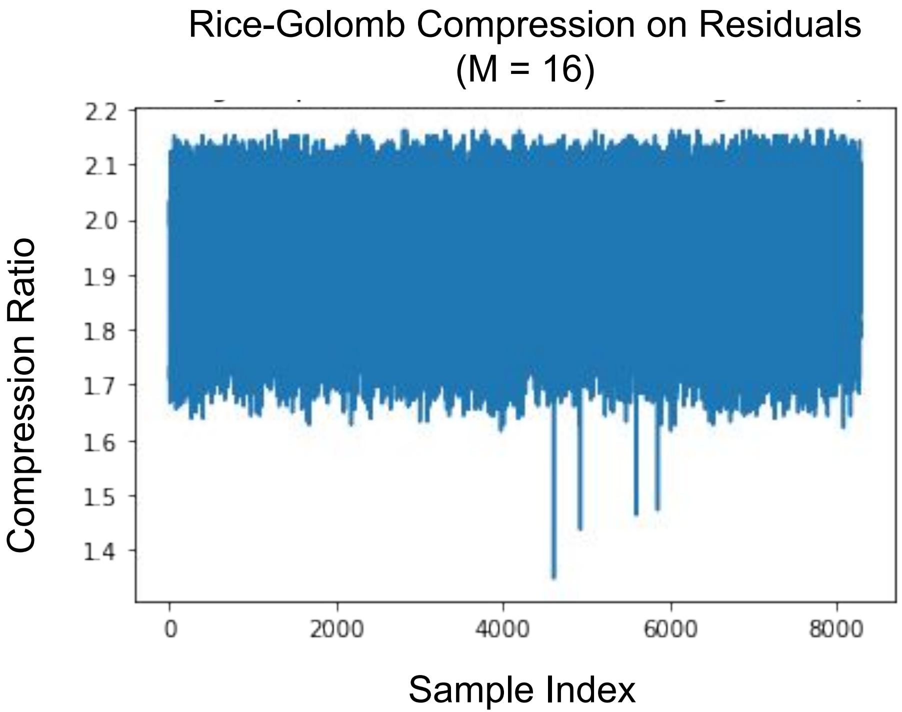
# How to choose Rice-Golomb parameter M

- Generated fake Gaussian data (centered at zero) with variance $\sigma^2$
- For random variable X, M ≈ median(|X|)/2 is a good choice
  - This is the close to the diagonal on the plot
- σ ≈ 32 for residuals of shape on wavedream data → M = 16 is a good choice



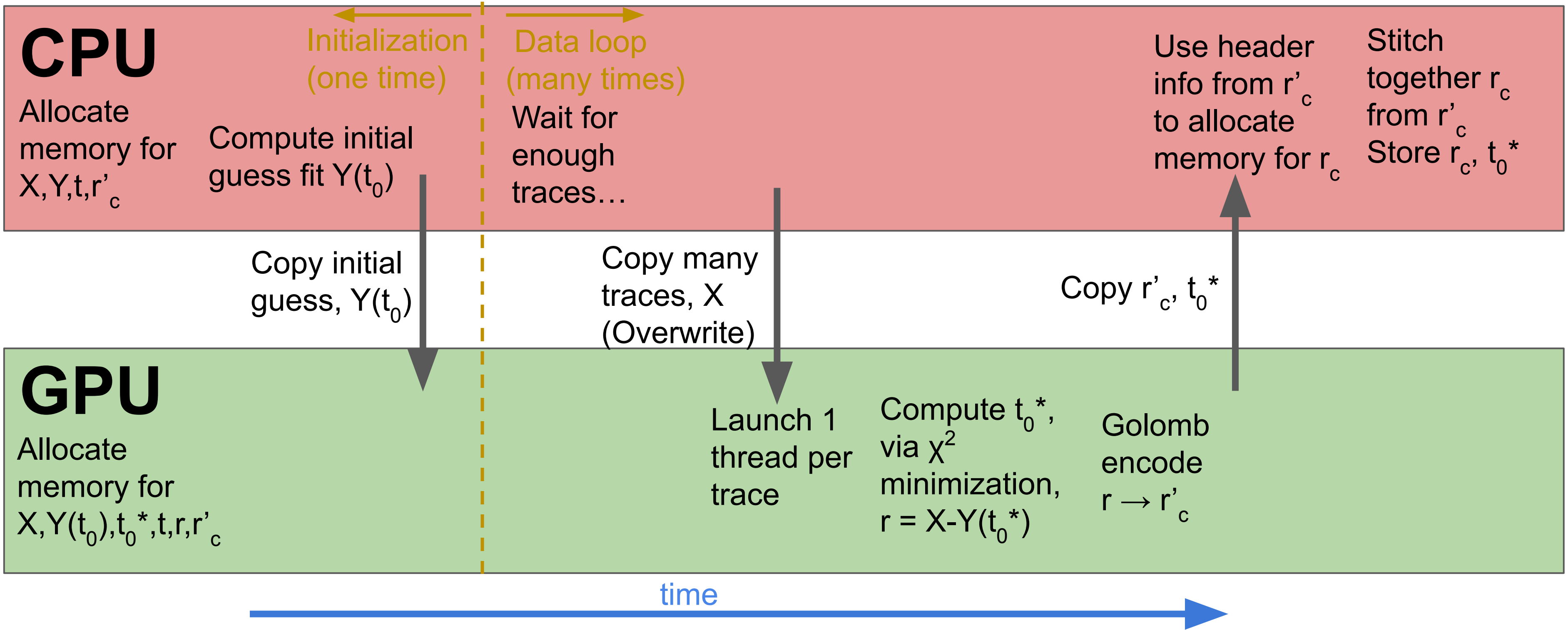
# Compression Ratio from Rice-Golomb Encoding

- Lossless compression factor of ~2
- In agreement with plot from simulated data on last slide
- Best compression ratio we achieved



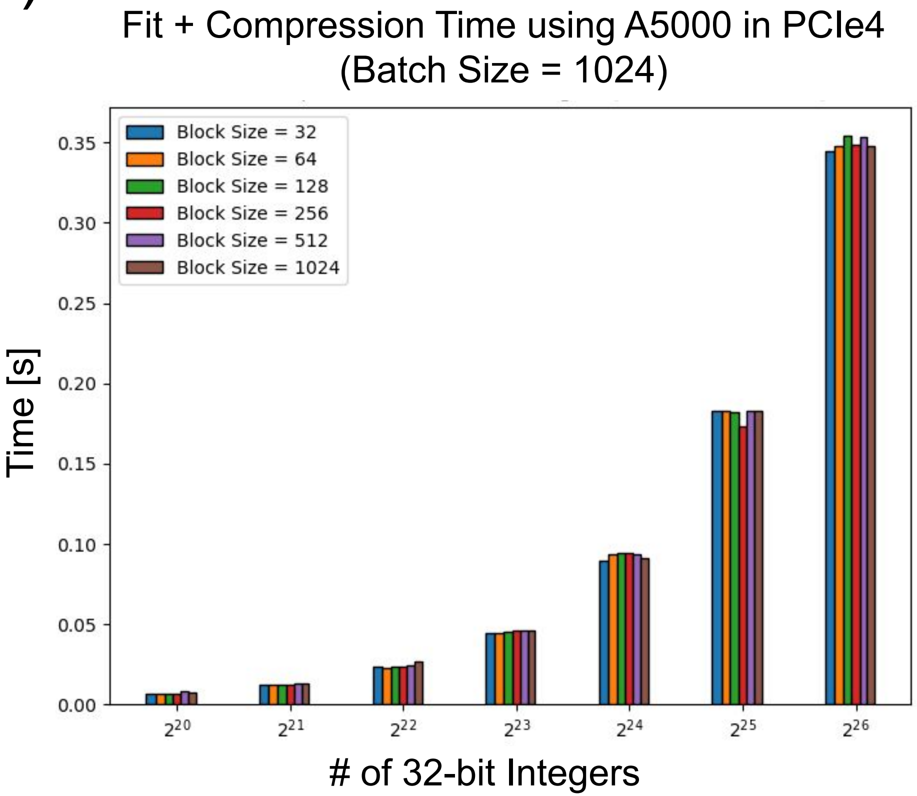
# Real Time Compression Algorithm

- We choose to let the FE's GPU and CPU handle compression for flexibility



# GPU Benchmarking (Timings)

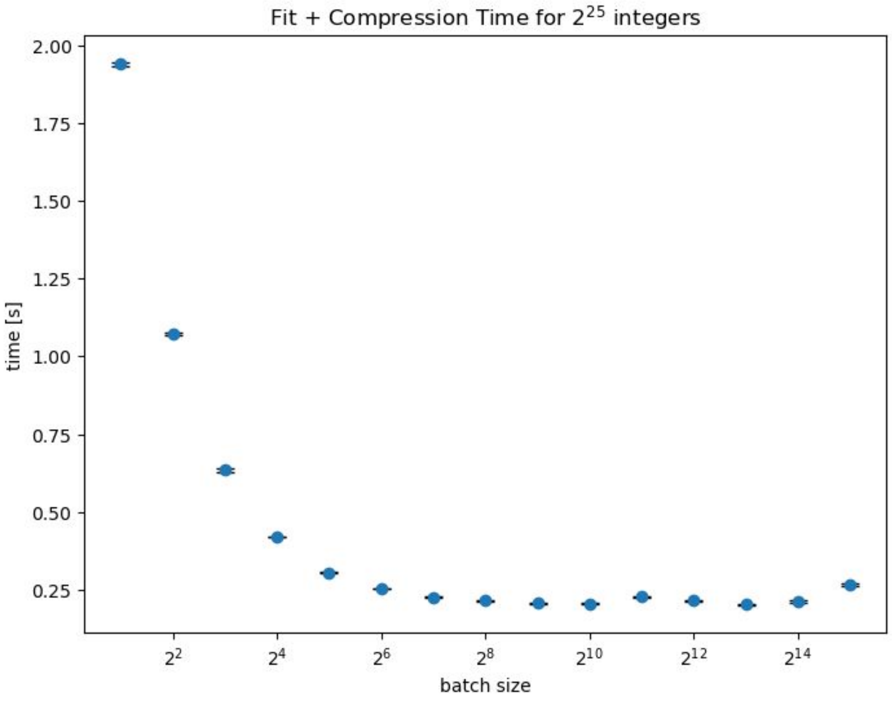
- Block Size:
  - A GPU parameter, number of threads per multiprocessor
- Can compress $2^{26}$ integers (32-bit) in roughly ⅓ of a second. → ~ **0.8 GB/s** compression rate



# GPU Benchmarking (Timings)

- Batch Size:
  - How many integers are compressed by a single GPU thread

- Data must be sent to GPU in batches (not a continuous flow) to take full advantage of parallel computation



# Handling the data rate

- Again, data rate ~3.5GB/s

- We expect to achieve this using the following method(s)
  - Multiple GPUs/CPUs
  - Newer PCIe versions available by start of experiment

| triggers | prescale | range TR(ns) | rate (kHz) | CALO $\Delta T$(ns) | CALO chan | CALO MB/s | ATAR digitizer $\Delta T$(ns) | ATAR digitizer chan | ATAR digitizer MB/s | ATAR high thres chan | ATAR high thres MB/s |
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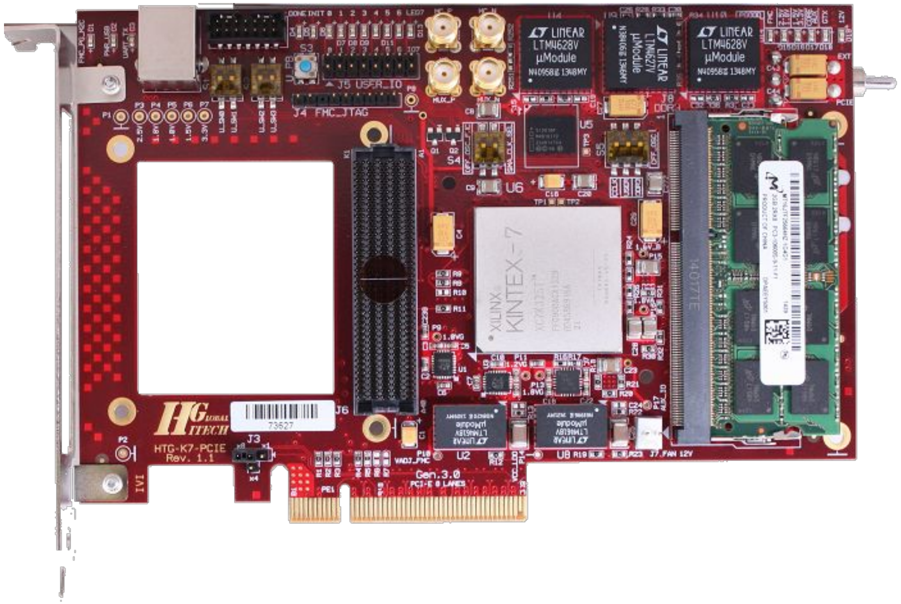
| PROMPT | 1 | 2,32 | 5 | 200 | 1000 | 2000 | 30 | 66 | 40 | 20 | 0.2 |

# Future Projects
# (Things I’m Working On)

# FPGA Use

- For the PIONEER DAQ, we plan to use FPGAs to digitize data
- A PCIe card with an FPGA will replace the waveDREAM in our test stand picture
- Why?
  - Can use PCIe for fast data transfer
  - Able to transfer data directly to GPU
  - More flexible signal triggers

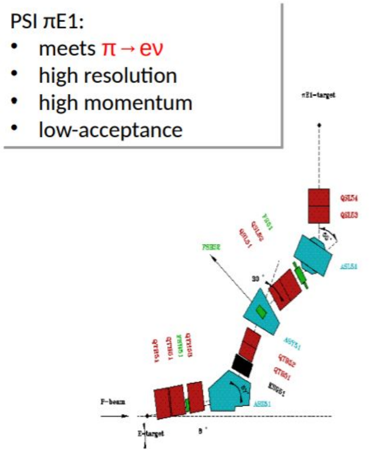


# November PSI beam time

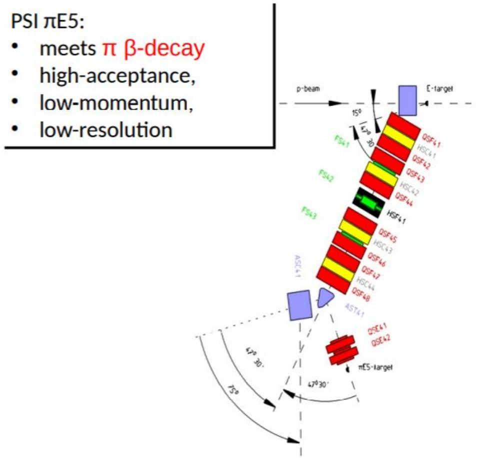
- Need a functioning one crate DAQ by November in order to test equipment

- Equipment tests (Calo, ATAR, etc.)

- Will have to “build” DAQ onsite




@75 MeV/c, **2x10$^5$ Hz**, dp/p=1%




@75 MeV/c, **3x10$^7$ Hz**, dp/p=2%

# Auxiliary Slides

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# Common Pion Decay Channels

(highlighted box) = Most Common

**Leptonic Decay**

- $\pi^+ \rightarrow e^+ + \nu_e$
- $\pi^- \rightarrow e^- + \bar{\nu}_e$
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (most common)
- $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ (most common)

**Beta Decay**

- $\pi^+ \rightarrow \pi^0 + e^+ + \nu_e$
- $\pi^- \rightarrow \pi^0 + e^- + \bar{\nu}_e$

**Photon Decay**
- $\pi^0 \rightarrow \gamma + \gamma$ (most common)

**Dalitz Decay**
- $\pi^0 \rightarrow \gamma + e^- + e^+$

**Double-Dalitz Decay**
- $\pi^0 \rightarrow e^- + e^+ + e^- + e^+$

**Electrons**
- $\pi^0 \rightarrow e^- + e^+$

[Note: Dalitz Decays are like photon decays, except the photon(s) are virtual and immediately decay into electron/positron pairs]

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# Naive Pion Decay, 2-body decay

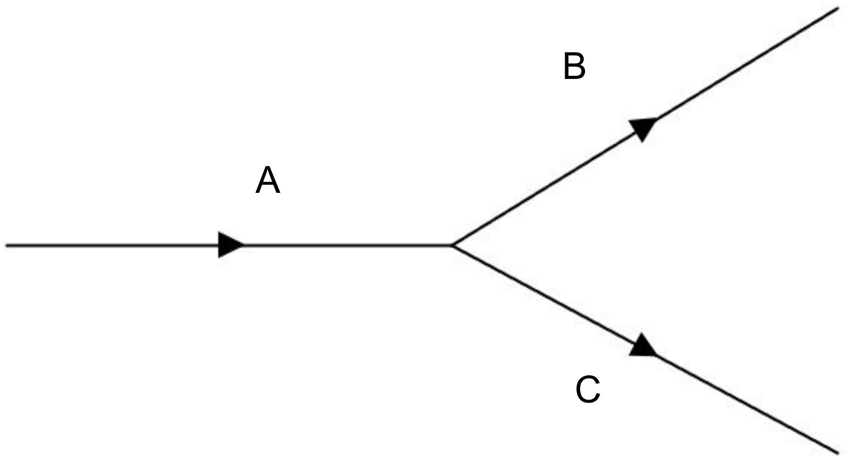
- Without getting into details of QCD, we can treat this as a 3 particle decay
- We can use Fermi's golden rule:

$$d\Gamma = |\mathcal{M}|^2 \cdot \frac{1}{2\hbar m_a} \cdot \left[ \frac{c d^3 \mathbf{p}_b^2}{(2\pi)^3 2E_b} \cdot \frac{c d^3 \mathbf{p}_c^2}{(2\pi)^3 2E_c} \right] \cdot (2\pi)^4 \delta^4 (p_a - p_b - p_c)$$

- After integration in the COM frame we find:

$$\Gamma = \frac{|\mathbf{p}|}{8\pi\hbar m_a^2 c} |\mathcal{M}|^2$$
$$\text{where } \mathbf{p} = \mathbf{p}_b = -\mathbf{p}_c$$

- $\longrightarrow \Gamma \propto$ p (not correct)
    - Details hidden in matrix element



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# Why Massless → Chirality States ~ Helicity States

- Massless → moves at c
- Moves at c → cannot reverse particle direction with Lorentz boost → helicity is Lorentz Invariant
- Chirality is a property of a particle, always Lorentz invariant! → helicity and chirality agree in direction in all inertial reference frames

$$(\gamma^\mu p_\mu - m)u(p) = 0$$ [Dirac Equation]

$$\Longrightarrow \begin{pmatrix} -mI_{2\times 2} & \sigma\cdot p \\ \bar{\sigma}\cdot p & -mI_{2\times 2} \end{pmatrix} \begin{pmatrix} u_L \\ u_R \end{pmatrix} = 0$$

[Chiral States]

$$\Longrightarrow \begin{cases} (\sigma\cdot p)u_R - mu_L = 0 \\ (\bar{\sigma}\cdot p)u_L - mu_R = 0 \end{cases}$$

$$m \to 0 \Longrightarrow \begin{cases} (p_0 - \boldsymbol{\sigma}\cdot\mathbf{p})u_R = 0 \\ (p_0 + \boldsymbol{\sigma}\cdot\mathbf{p})u_L = 0 \end{cases}$$

$$\Longrightarrow \begin{cases} \frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{|\mathbf{p}|}u_R = u_R \\ \frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{|\mathbf{p}|}u_L = -u_L \end{cases}$$

$$\hat{h} = \frac{\mathbf{S}\cdot\mathbf{p}}{|\mathbf{p}|} = \frac{1}{2}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{|\mathbf{p}|}$$ [Helicity operator]

$$\Longrightarrow \begin{cases} \hat{h}u_R = \frac{1}{2}u_R \\ \hat{h}u_L = -\frac{1}{2}u_L \end{cases}$$

[Chiral states are eigenstates of helicity operator]

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# LH (negative) helicity spinor to chiral components

An negative helicity antiparticle can be written as

$$v_{\downarrow} = \sqrt{E+m}\begin{pmatrix} \frac{|\mathbf{p}|}{E+m}\cos(\frac{\theta}{2}) \\ \frac{|\mathbf{p}|}{E+m}\sin(\frac{\theta}{2})e^{i\phi} \\ \cos(\frac{\theta}{2}) \\ \sin(\frac{\theta}{2})e^{i\phi} \end{pmatrix}$$

Where (θ,φ) define the direction of the momentum. Without loss of generality, assume the momentum is in the z direction

$$v_{\downarrow} = \sqrt{E+m}\begin{pmatrix} \frac{|\mathbf{p}|}{E+m} \\ \frac{|\mathbf{p}|}{E+m} \\ 1 \\ 1 \end{pmatrix} \equiv A\begin{pmatrix} \tau\xi_R \\ \xi_R \end{pmatrix}$$

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# LH (negative) helicity spinor to chiral components

We can use the chiral projection operations to project this helicity state to chiral state

$$v_\downarrow = P_L v_\downarrow + P_R v_\downarrow$$

$$P_R = \frac{I_{4\times4} + \gamma^5}{2} = \begin{pmatrix} I_{2\times2} & I_{2\times2} \\ I_{2\times2} & I_{2\times2} \end{pmatrix}$$

$$P_L = \frac{I_{4\times4} - \gamma^5}{2} = \begin{pmatrix} I_{2\times2} & -I_{2\times2} \\ -I_{2\times2} & I_{2\times2} \end{pmatrix}$$

$$v_\downarrow = \frac{A}{2}\left[(1-\tau)\begin{pmatrix} -\xi_R \\ \xi_R \end{pmatrix} + (1+\tau)\begin{pmatrix} \xi_R \\ \xi_R \end{pmatrix}\right] \equiv \frac{A}{2}(1-\tau)v_R - \frac{A}{2}(1+\tau)v_L$$

Where the left and right chiral anti-particle states are defined by

$$P_L v_R = v_R \text{ and } P_R v_L = v_L$$

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# LH (negative) helicity spinor to chiral components

Looking at the chiral projection of a negative helicity state, we can see in general there are left **and** right chiral components, so the weak force **can** act on a LH (negative) anti-particle helicity state

$$v_{\downarrow} = \frac{A}{2}\left[\left(1 - \frac{p}{E+m}\right)v_R - \left(1 + \frac{p}{E+m}\right)v_L\right]$$

It should also be clear as m→0, the LH (negative) helicity state coincides with the LH chiral state.

This means W boson decay to two massless leptons is forbidden! One of the particles must have the wrong chirality, and thus low mass decays will be suppressed.

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# Matrix Element Details

$$\mathcal{M}_{fi} = \left[\frac{g_W}{\sqrt{2}}\frac{1}{2}f_\pi p_\pi^\alpha\right] \cdot \left[\frac{g_{\alpha\beta}}{m_W^2}\right] \cdot \left[\frac{g_W}{\sqrt{2}} g_l \bar{u}(p_l)\gamma^\beta \frac{1}{2}(1-\gamma^5)v(p_\nu)\right]$$

Move to pion rest frame so only $p^0 = m_\pi$ remains:

$$\mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} m_\pi \bar{u}(p_l)\gamma^0 \frac{1}{2}(1-\gamma^5)v(p_\nu)$$

Using the identity: $\bar{u}(p_l)\gamma^0 = u^\dagger(p_l)\gamma^0\gamma^0 = u^\dagger(p_l) I_{4\times 4} = u^\dagger(p_l)$

$$\mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} m_\pi u^\dagger(p_l) \frac{1}{2}(1-\gamma^5)v(p_\nu)$$

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# Matrix Element Details

For a neutrino m << E so helicity eigenstate is essentially the chiral eigenstate:

$$\frac{1}{2}(1-\gamma^5)v(p_\nu) = v_\uparrow(p_\nu) \implies \mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} m_\pi u^\dagger(p_l) v_\uparrow(p_\nu)$$

By letting the lepton go in the z-direction we can write:

$$u(p_l) = u_\uparrow(p_l) + u_\downarrow(p_l) = \sqrt{E_l + m_l}\left[\begin{pmatrix} 1 \\ 0 \\ \frac{p}{E_l+m_l} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \\ 0 \\ \frac{-p}{E_l+m_l} \end{pmatrix}\right]$$ and $$v(p_\mu) = v_\uparrow(p_\mu) = \sqrt{p}\begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}$$

Negative helicity lepton down state disappears when “dotted” with the neutrino state:

$$\mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} m_\pi \sqrt{E_l + m_l}\sqrt{p}\left(1 - \frac{p}{E_l + m_l}\right)$$

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# Matrix Element Details

$$\mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} m_\pi \sqrt{E_l + m_l}\sqrt{p}\left(1 - \frac{p}{E_l + m_l}\right)$$

We can re-write $E_l$ and p in the limit where the neutrino mass is zero:

$$E_l = \frac{m_\pi^2 + m_l^2}{2m_\pi} \text{ and } p_l = \frac{m_\pi^2 - m_l^2}{2m_\pi}$$

$$\implies \mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} m_\pi \cdot \frac{m_\pi + m_l}{\sqrt{2m_\pi}} \cdot \left(\frac{m_\pi^2 - m_l^2}{2m_\pi}\right)^{\frac{1}{2}} \cdot \frac{2m_l}{m_\pi + m_l}$$

$$\implies \mathcal{M}_{fi} = \frac{g_W^2 f_\pi g_l}{4m_W^2} \cdot m_l (m_\pi^2 - m_l^2)^{\frac{1}{2}}$$

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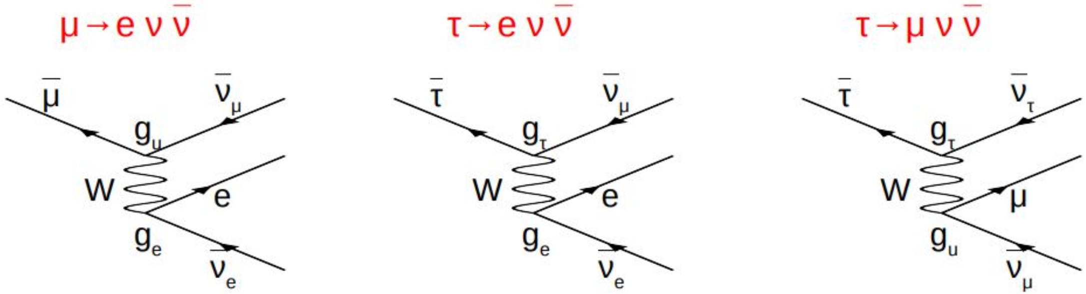
# Another Test for Lepton Universality




Fermi constant, $G_F = g^2 / 4\sqrt{2}M_W^{\,2}$

$G_{\mu e}$ = 1.166 378 7(6)x$10^{-5}$ GeV$^{-2}$ (0.5 ppm)

$G_{\tau\mu}$ = 1.1665(28)x$10^{-5}$ GeV$^{-2}$ (0.2%)

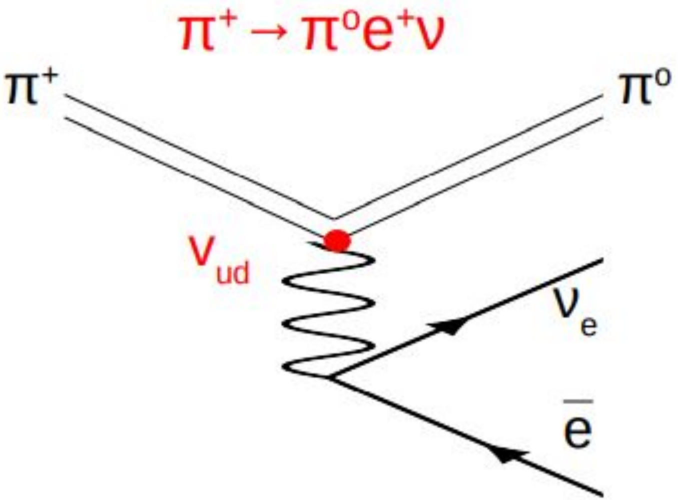
$G_{\tau e}$ = 1.1665(28) x $10^{-5}$ GeV$^{-2}$ (0.2%)

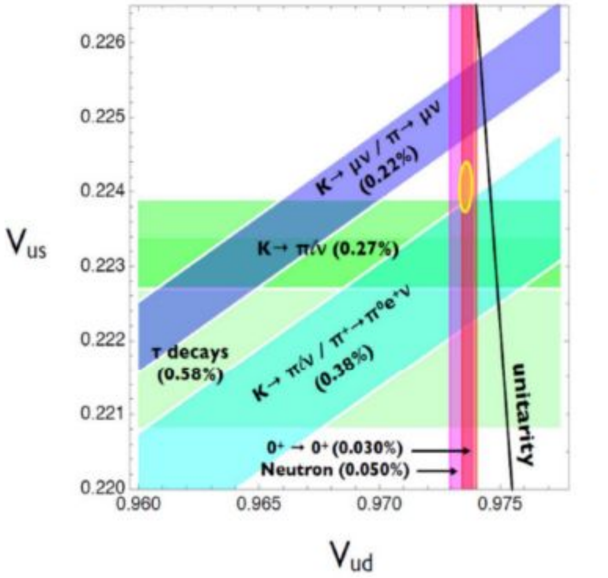
weak coupling, g

$g_e : g_\mu : g_\tau$ 1 : 1.0011(24) : 1.0006(24)

# CKM Unitary Test

arXiv:2203.05505




- Pion beta decay gives a precision measurement of $V_{ud}$
- These decays are lower rate than $\pi \rightarrow e\nu_e$ and $\pi \rightarrow \mu\nu_\mu$
- Experimental measurements do not agree

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# Some Information about LXe and NaI

- LXe has singlet and triplet state decay constants:
  - $\tau_S = 4.3 \pm 0.6$ ns
  - $\tau_T = 26.9^{+0.7}_{-1.1}$ ns
- LXe light yield:
  - ~29 photons/keV at room temp
- NaI decay constant:
  - ~ 250 ns
- NaI light yield:
  - 38 photons/keV at room temp

**Scintillation from excited Xe ($Xe^*$):**

$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* + \mathrm{Xe}\,,$$

$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu\,.$$

**Scintillation from ionized Xe ($Xe^+$):**

$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+\,,$$

$$\mathrm{Xe}_2^+ + e^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe}\,,$$

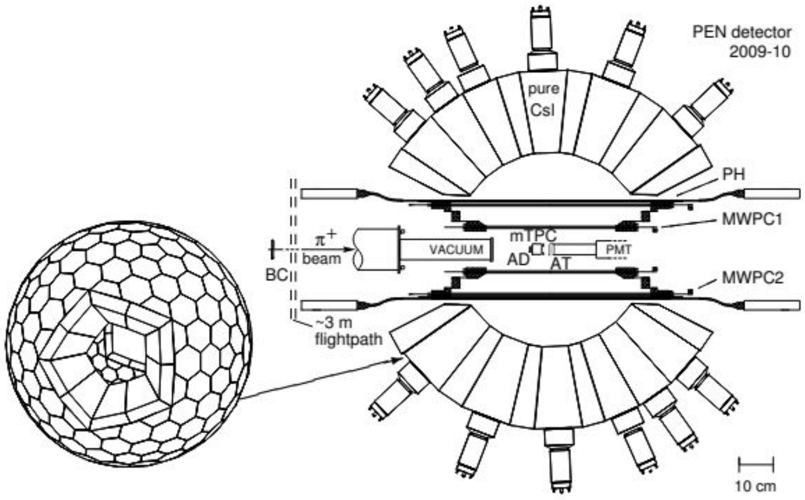
$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + heat\,,$$

$$\mathrm{Xe}^* + \mathrm{Xe} + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^* + \mathrm{Xe}\,,$$

$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu\,.$$

# PEN

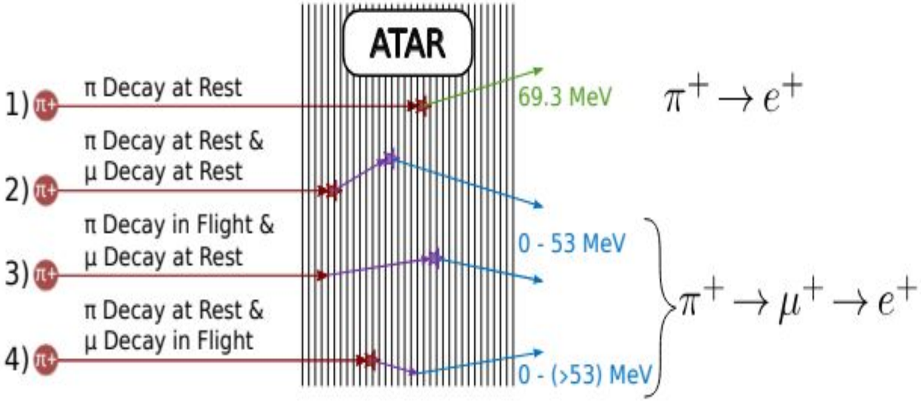
- Similar to PIENU
  - Segmented
  - Better timing
- Many channels of pure CSI
  - 240 channels
- Active target



# More ATAR details

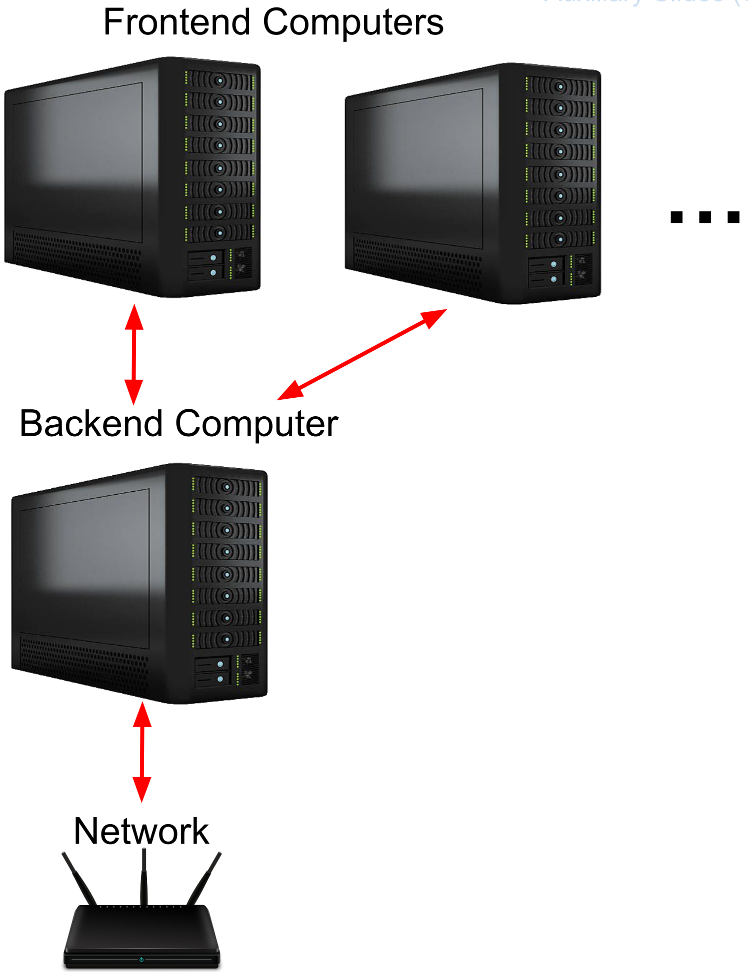
- Pion and muon decays deposit energy into ATAR
- Allow event types to be distinguished
- Muons decaying in flight can boost positron energy past 53 MeV (big issue!)
  - ATAR can give information to rebuild event, and correctly classify a muon decay

arxiv: 2203.01981



# Why two computers?

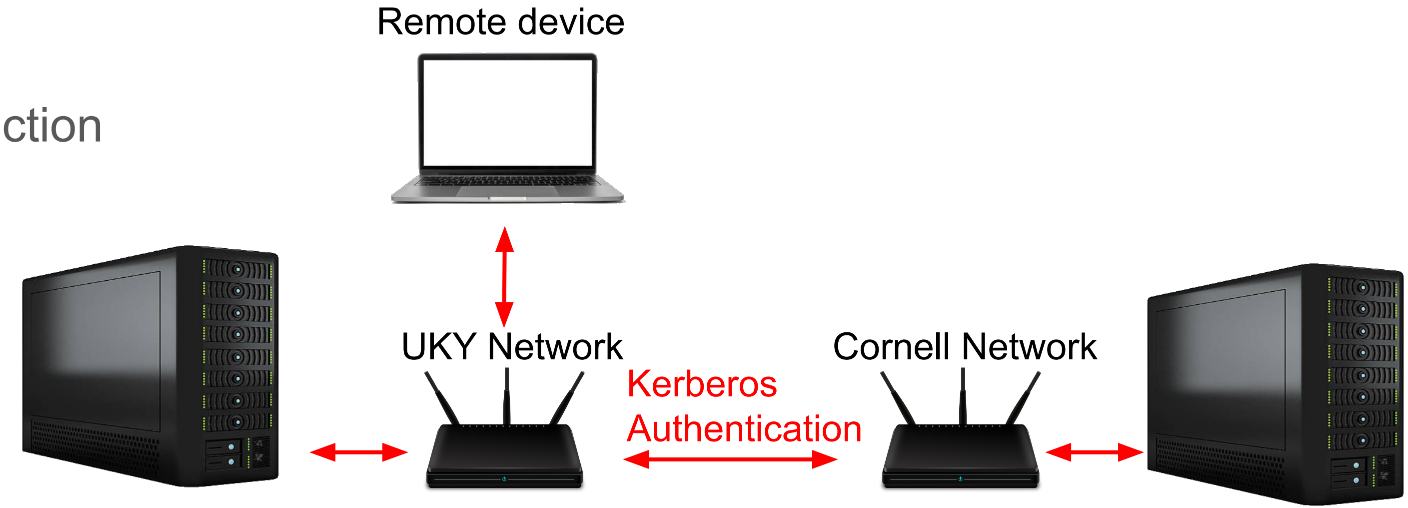
- Really just for practice
- Real experiment will likely have multiple FE computers, which will all communicate with one BE computer
- In real experiment, one computer is impractical



# Networking Machines Together

1. LAN connection
   a. dhcp
   b. ssh


2. Remote connection
   a. Kerberos
   b. ssh

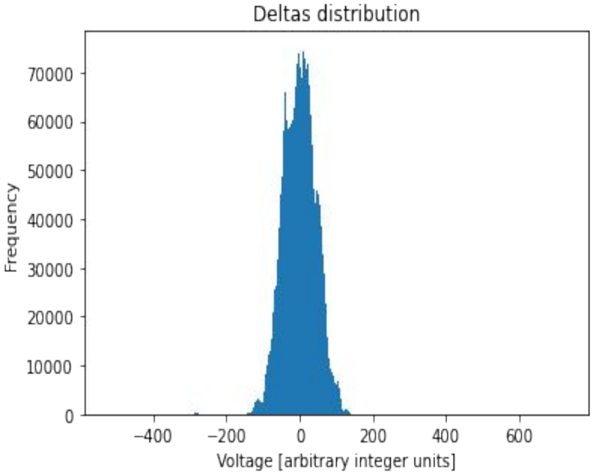


# Edits to MIDAS code

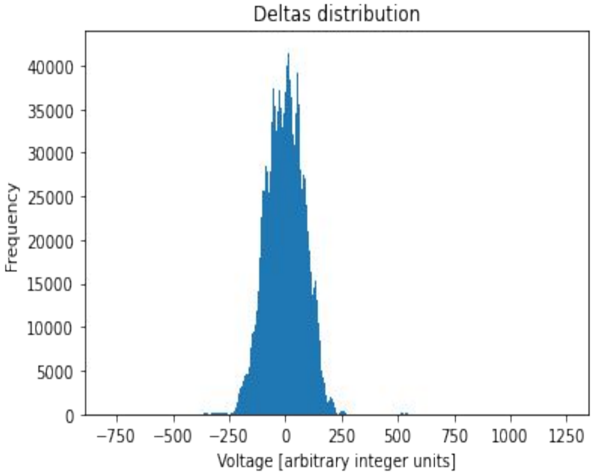
- Some edits were made to the MIDAS source code to make our frontends "work"
  - Increasing online database (ODB) maximum number of hotlink
  - Various "bug fixes" (i.e. things that made it so the g-2 daq would no longer compile)

# Other Conditioning Distributions

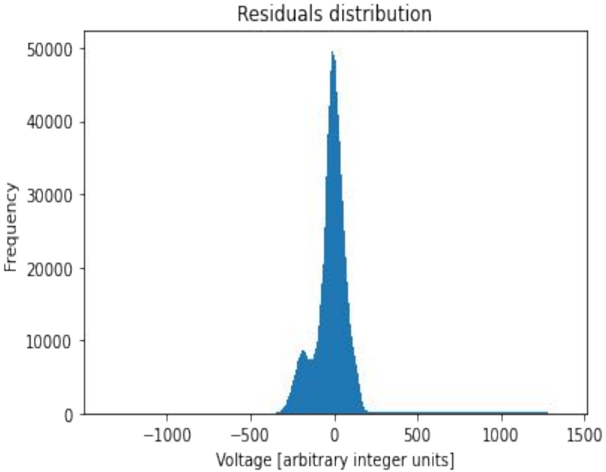
## Delta Encoding




## Twice Delta Encoding




## Double Exponential Fit



# Shape Fitting Details

Fit Function

$$X[i] = aT(t[i] - t_0) + b$$

Explicit $a(t_0)$ calc

$$a(t_0) = \frac{\sum_i^N X[i] \sum_i^N T(t[i]-t_0)^2 - \sum_i^N T(t[i]-t_0) \sum_i^N T(t[i]-t_0) X[i]}{N \sum_i^N T(t[i]-t_0)^2 - (\sum_i^N T(t[i]-t_0))^2}$$

Explicit $b(t_0)$ calc

$$b(t_0) = \frac{N \sum_i^N T(t[i]-t_0) X[i] - \sum_i^N T(t[i]-t_0) \sum_i^N X[i]}{N \sum_i^N T(t[i]-t_0)^2 - (\sum_i^N T(t[i]-t_0))^2}$$

Explicit $\chi^2$ calc

$$f(t_0) \equiv \chi^2 \propto \sum_i \{X[i] - a(t_0)T(t[i]-t_0) + b(t_0)\}^2$$

Newton's method

$$(t_0)_{n+1} = (t_0)_n - \frac{f'((t_0)_n)}{f''((t_0)_n)}$$

Threshold requirement

$$|(t_0)_{n+1} - (t_0)_n| < \epsilon \equiv \text{"Threshold"}$$

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# Golomb Encoding

- In general, M is an arbitrary choice
- Since computers work with binary, $M = 2^x$ such that x is an integer is a "fast" choice
  - This is called Rice-Golomb Encoding
- Self delimiting so long as the information M is provided

## Golomb Encoding Example

Choose M = 10, $b = \log_2(M) = 3$
$2^{b+1} - M = 16 - 10 = 6$
r < 6 → r encoded in b=3 bits
r ≥ 6 → r encoded in b+1=4 bits

| Encoding of quotient part | |
|---|---|
| *q* | output bits |
| 0 | 0 |
| 1 | 10 |
| 2 | 110 |
| 3 | 1110 |
| 4 | 11110 |
| 5 | 111110 |
| 6 | 1111110 |
| ⋮ | ⋮ |
| N | 111⋯1110 |

| Encoding of remainder part | | | |
|---|---|---|---|
| *r* | offset | binary | output bits |
| 0 | 0 | 0000 | 000 |
| 1 | 1 | 0001 | 001 |
| 2 | 2 | 0010 | 010 |
| 3 | 3 | 0011 | 011 |
| 4 | 4 | 0100 | 100 |
| 5 | 5 | 0101 | 101 |
| 6 | 12 | 1100 | 1100 |
| 7 | 13 | 1101 | 1101 |
| 8 | 14 | 1110 | 1110 |
| 9 | 15 | 1111 | 1111 |

Citation: Wikipedia
(https://en.wikipedia.org/wiki/Huffman_coding)

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# Huffman Encoding

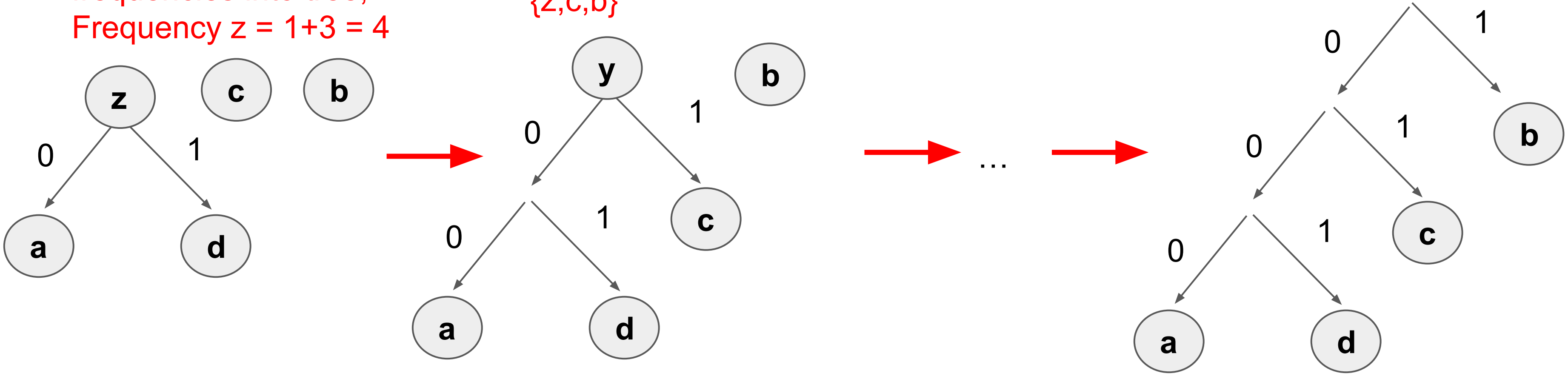
- Requires finite distribution
- Values treated as “symbols”
- Self-delimiting (sometimes called “greedy”)

## Huffman Encoding Example

| Value | Frequency | Encoding |
|---|---|---|
| -1 ≡ a | 1 | 000 |
| 0 ≡ b | 10 | 1 |
| 1 ≡ c | 5 | 01 |
| 2 ≡ d | 3 | 001 |

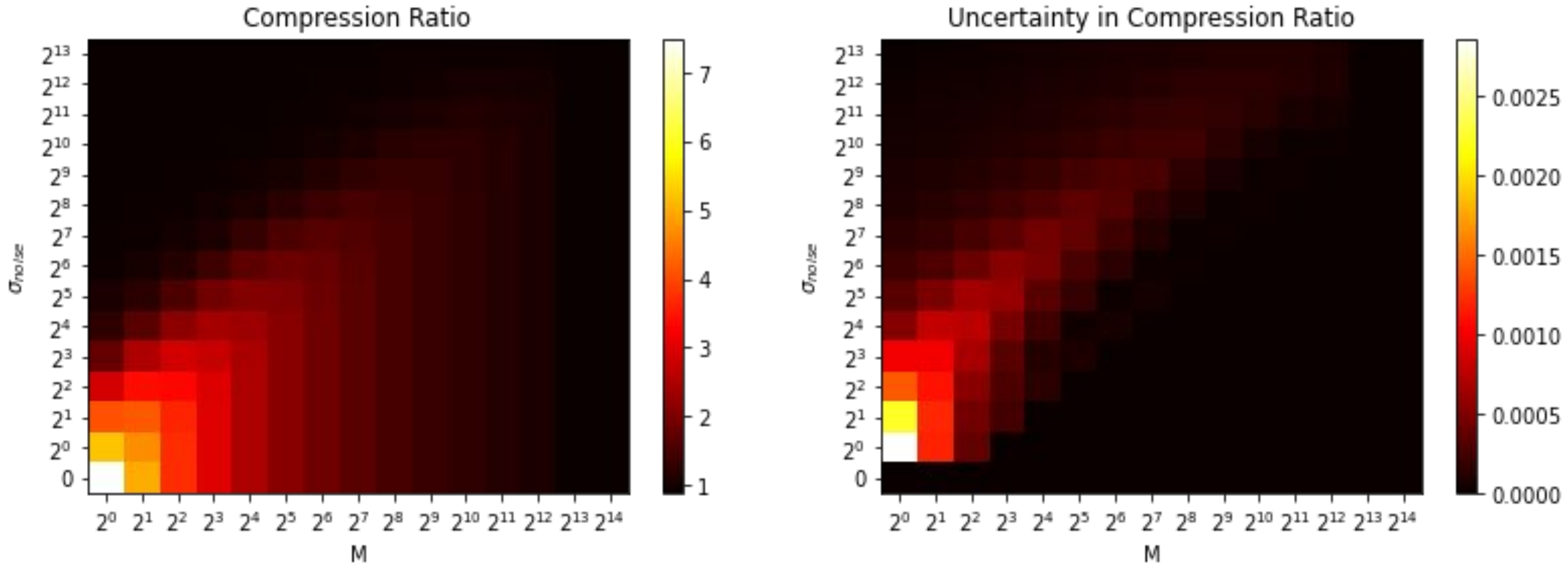
“Combine” two lowest frequencies into tree, Frequency z = 1+3 = 4

Repeat for set {z,c,b}



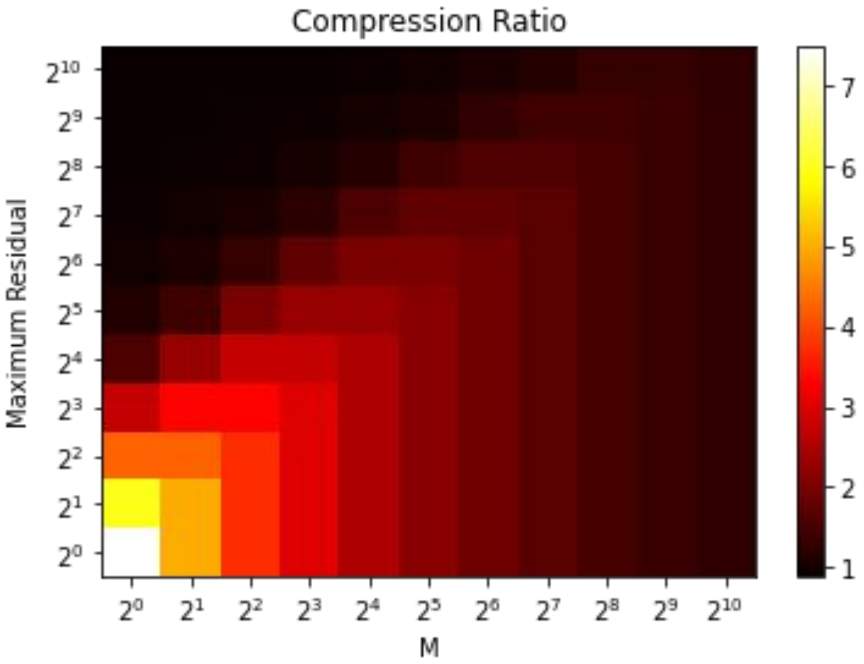
# Theoretical Uncertainty in Compression Ratio from Gaussian Noise

- ~ 0.1% relative error

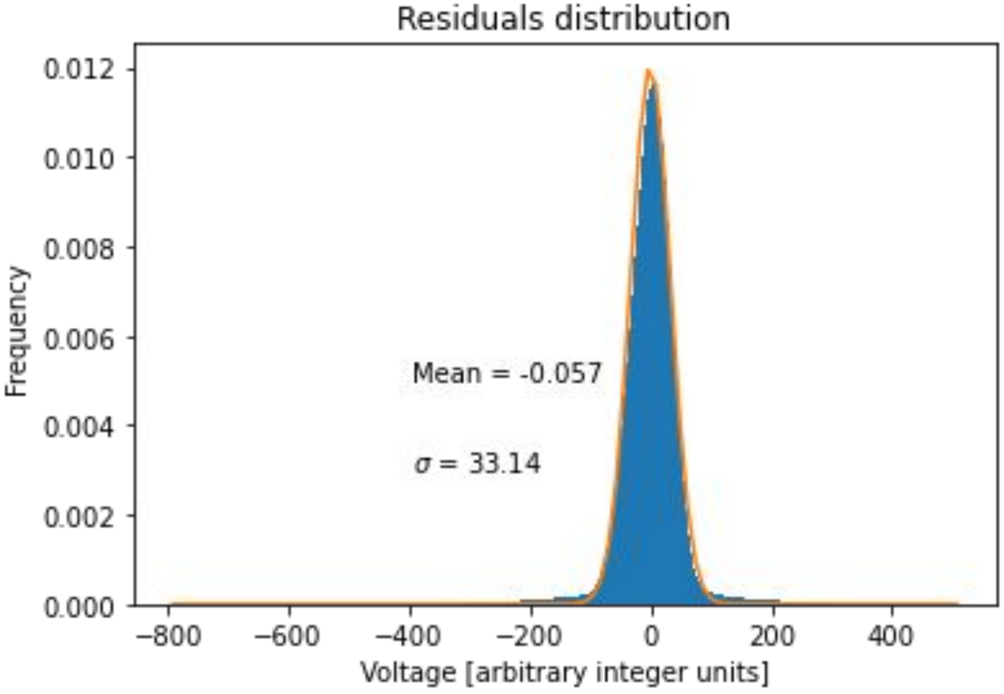


# Uniform Distribution of Noise effect on Compression Ratio

- Here instead we use a uniform distribution to generate the noise
- Not much different than gaussian noise, same conclusions really



# Residuals Distribution and Optimal M




| M | Compression Ratio |
|---|---|
| 1 | 1.04721105 |
| 2 | 1.21287474 |
| 4 | 1.53114598 |
| 8 | 1.92616642 |
| **16** | **2.09307249** |
| 32 | 2.02975311 |
| 64 | 1.86037914 |
| 128 | 1.66627451 |
| . . . | . . . |

# Lossy Compression Idea

- In lossless compression, Rice-Golomb encodes:
  1. Fit parameters
  2. Residuals

- If the residuals meet some criteria, we may choose to threw them out just keeping our fit of the signal.

  Example Criteria: $$\sum_i r[i] < \epsilon \equiv \text{"Threshold"}$$

# GPU Timing Breakdown

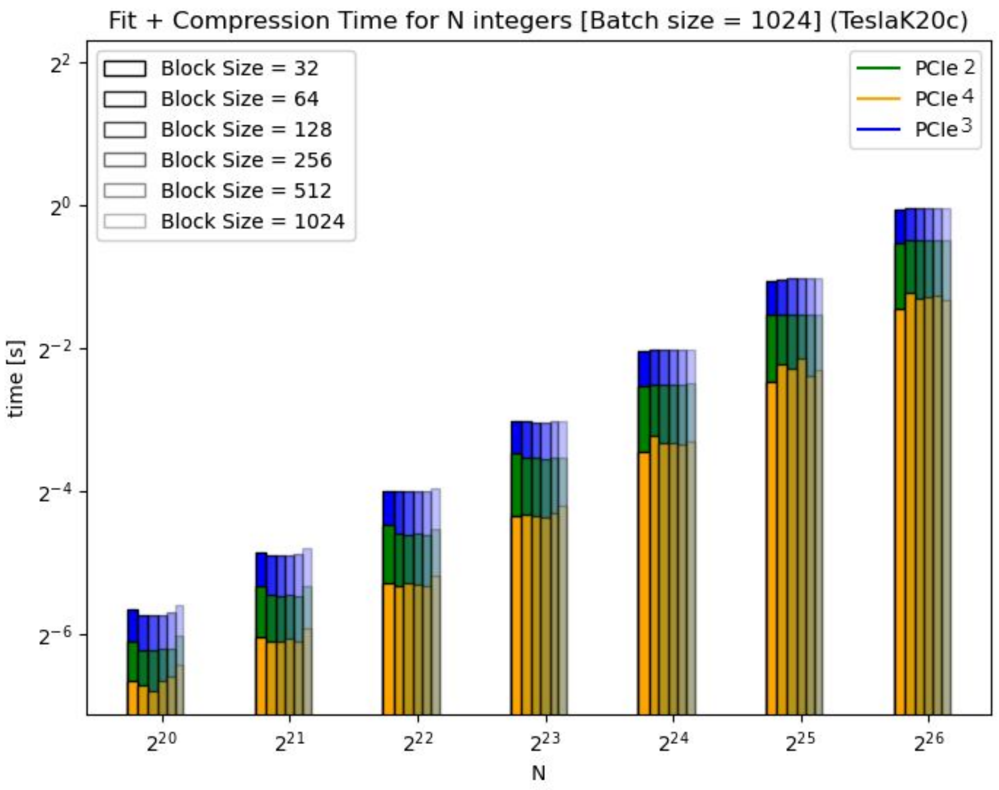
- Bottleneck is at the transfer between GPU and CPU
- This data transfer time decreases with PCIe gen
- Interfacing and Initialization should be 1 time operations

```
C:\Users\custo\Desktop\Scripts\CUDA>fitting_and_compression.out
Interfacing with GPU: 0.111413700 seconds.
Initializing arrays (CPU): 0.129644300 seconds.
Initializing arrays (GPU): 0.102764100 seconds.
Computing Fit Parameters (CPU): 0.010539800 seconds.
Allocate an array on GPU mem: 0.000347700 seconds.
Copy an array CPU->GPU mem: 0.073158300 seconds.
Calculate Residuals (GPU): 0.000018800 seconds.
Encode Integers (GPU): 0.000008000 seconds.
Copy an array GPU->CPU mem: 0.069847700 seconds.
Sew together encodings (CPU): 0.024214400 seconds.
Free an array from mem (GPU): 0.001255800 seconds.
Free an array from mem (CPU): 0.001255800 seconds.

N = 67108864, blockSize = 1024
Full Execution Time: 0.590825600 seconds.
Compression Ratio =  2.500000
--------------------------------------------
```

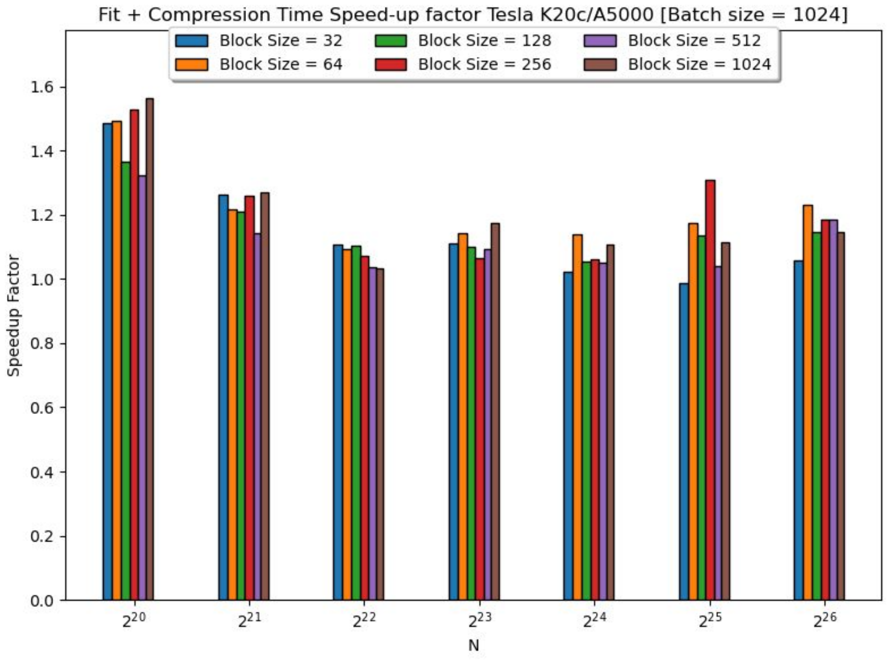
# PCIe Gen Speedup

- PCIe3 → PCIe4 gives a roughly factor of 2 speedup (expected)
- What's puzzling is that PCIe2 is faster than PCIe3
- PCIe2 test was done on different computer and OS, may be the cause



# Does the GPU Quality Matter?

- PCIe bus data transfer rate matters much more
- Tesla K20c (Released: November 12th, 2012)
- A5000 (Released: April 12th, 2021)
- Nearly a decade of improvement gives ~1.2x speedup. **Not cost efficient to use newest GPUs.**



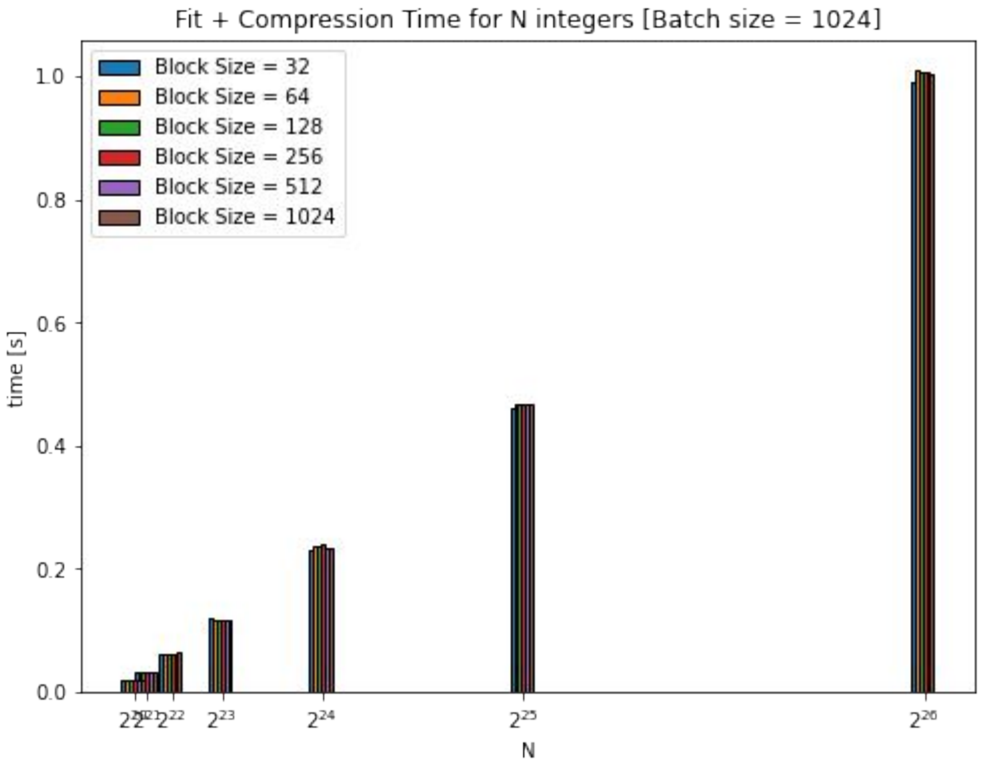
# Programing FPGAs

- To code our FPGAs, we will likely use *Vivado* and write our code in *Verilog*

- To the right is an example thermometer project I did to learn about programming FPGAs

# Computation Time scales O(n)

- Same plot as before, without x axis in log scale
- For sufficient N, the computational time scales linearly
- N too large, GPU runs out of memory
- N too small, GPU parallel computation not fully utilized



# Optimal Batching Choice

- There appears to be an optimal batching choice
- Small optimization, may not be worth worrying about
- Small batch sizes → CPU must do more “sewing” data back together.
- Large batch sizes → fewer GPU threads are utilized during compression