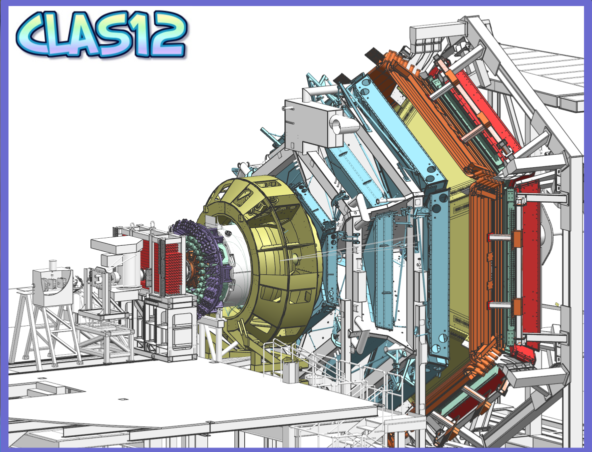
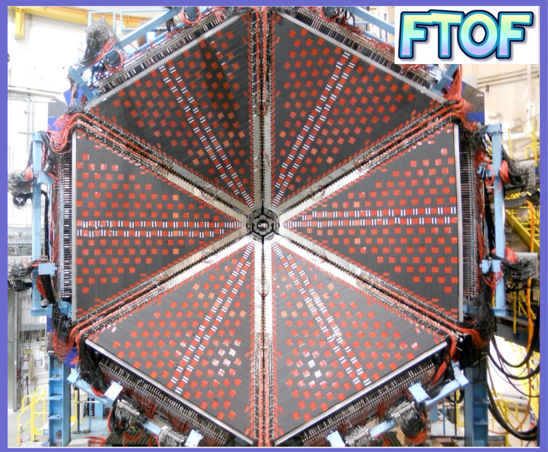
Detector Technology for High Resolution TOF

Some Thoughts and Considerations





Daniel S. Carman
Jefferson Laboratory

clas
CEBAF Large Acceptance Spectrometer

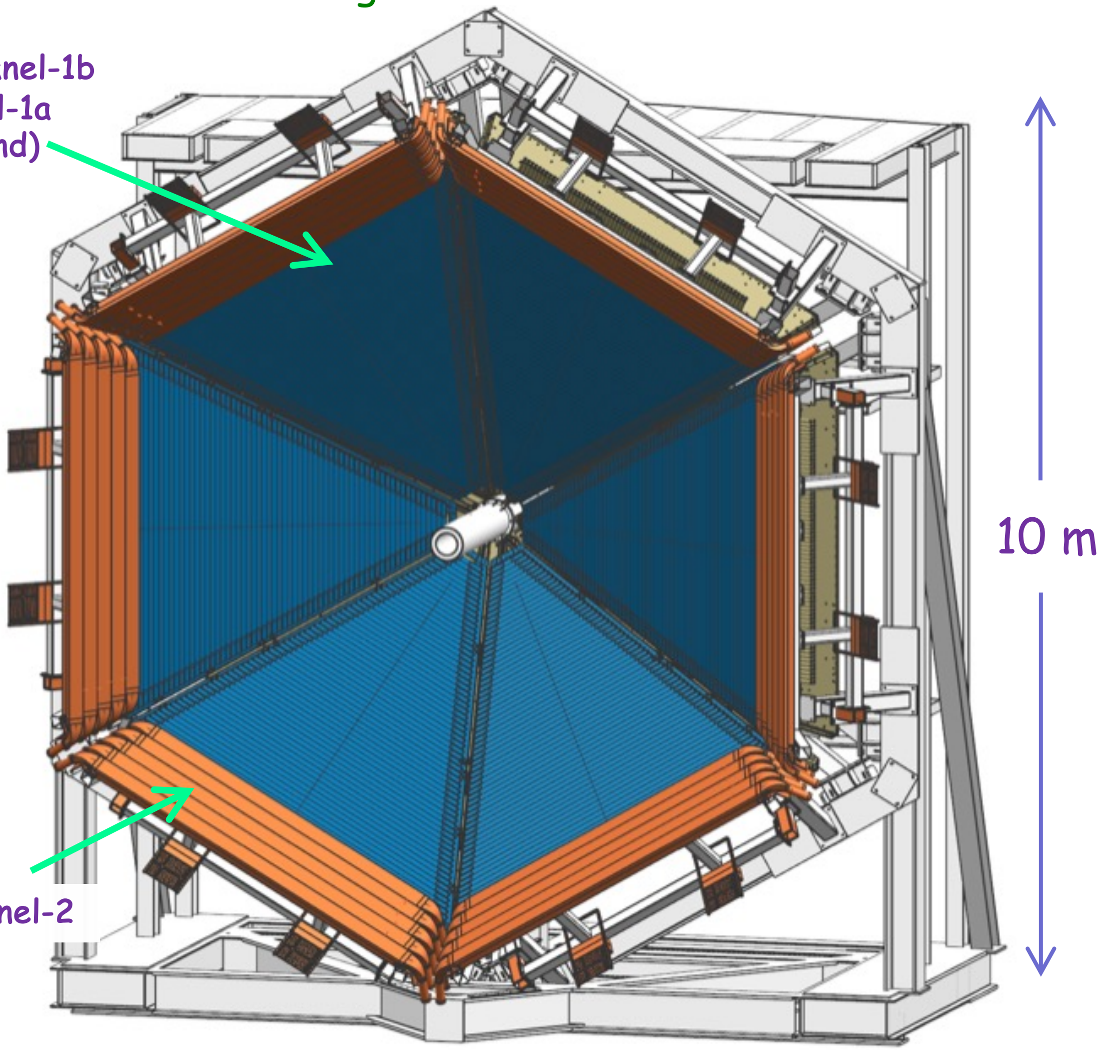
SBS Collaboration Meeting
Sep. 12-14, 2024

Outline:

- CLAS12 FTOF Detector
- CLAS12 Particle Identification
- Design Considerations
- Calibration Approach
- Concluding Remarks

FTOF System Overview

CLAS12 Forward Carriage

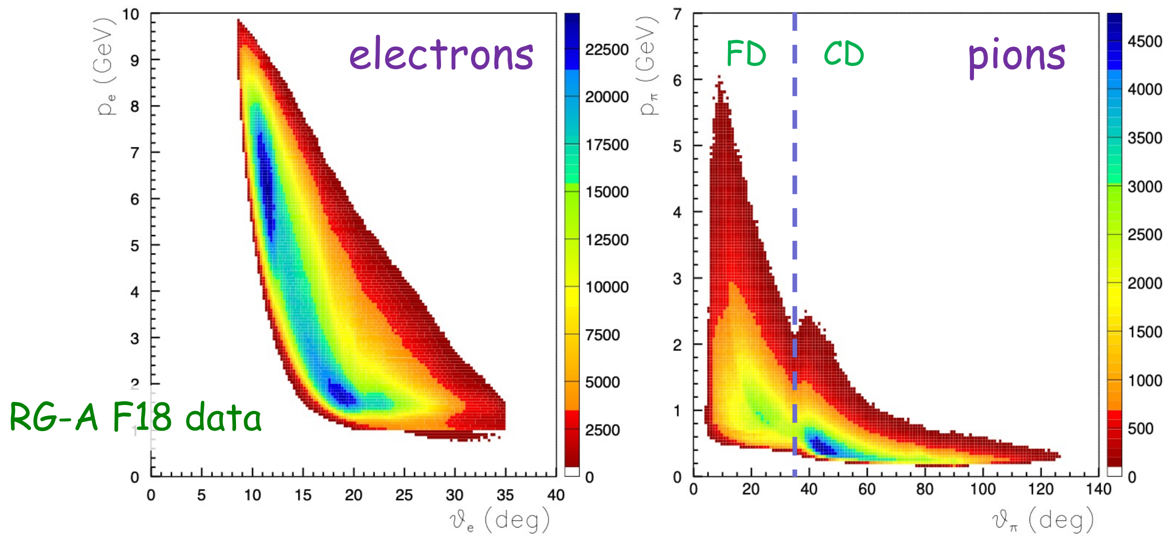


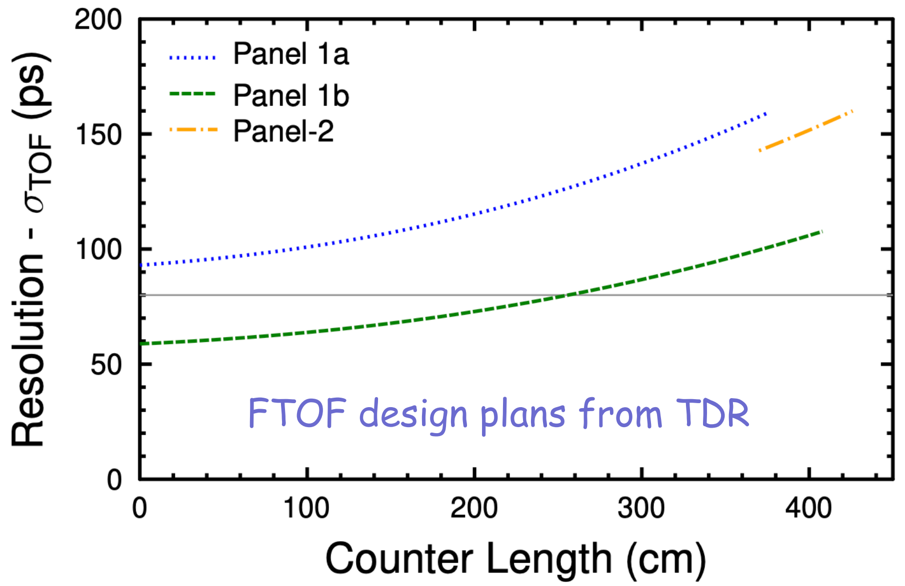
540 counters

PARAMETER	DESIGN VALUE
Panel-1a:	23 counters/sector
Angular Coverage	θ: 5° → 35°, ϕ: 50% at 5° → 85% at 35°
Counter Dimensions	L = 32.3 cm → 376.1 cm, w x h = 15 cm x 5 cm
Scintillator Material	BC-408
PMTs	EMI 9954A, Philips XP2262
Design Resolution	90 ps → 160 ps
Panel-1b:	62 counters/sector
Angular Coverage	θ: 5° → 35°, ϕ: 50% at 5° → 85% at 35°
Counter Dimensions	L = 17.3 cm → 407.9 cm, w x h = 6 cm x 6 cm
Scintillator Material	BC-404 (#1 → #31), BC-408 (#32 → #62)
PMTs	Hamamatsu R9779
Design Resolution	60 ps → 110 ps
Panel-2:	5 counters/sector
Angular Coverage	θ: 35° → 45°, ϕ: 85% at 35° → 90% at 45°
Counter Dimensions	L = 371.3 cm → 426.2 cm, w x h = 22 cm x 5 cm
Scintillator Material	BC-408
PMTs	EMI 4312KB, Philips XP 4312B
Design Resolution	140 ps → 165 ps

FTOF Design Time Resolution

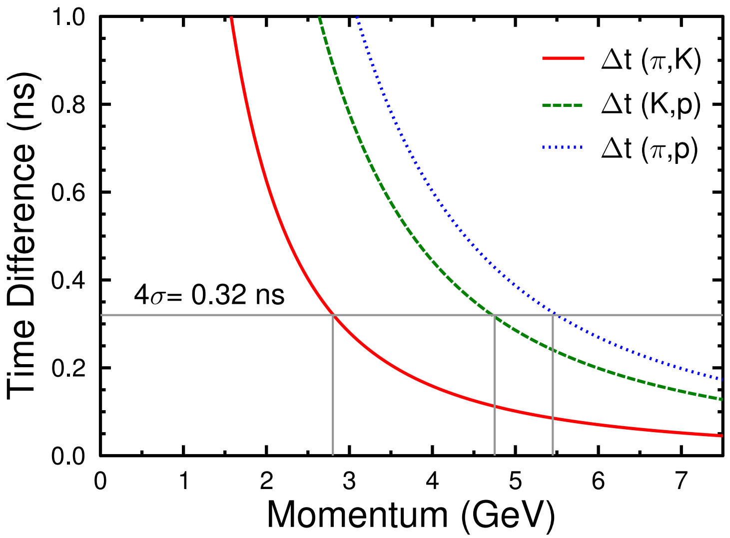
Kinematic Coverage E_b=11 GeV





Calculation based on t_{res} = 80 ps

⇒



⇒

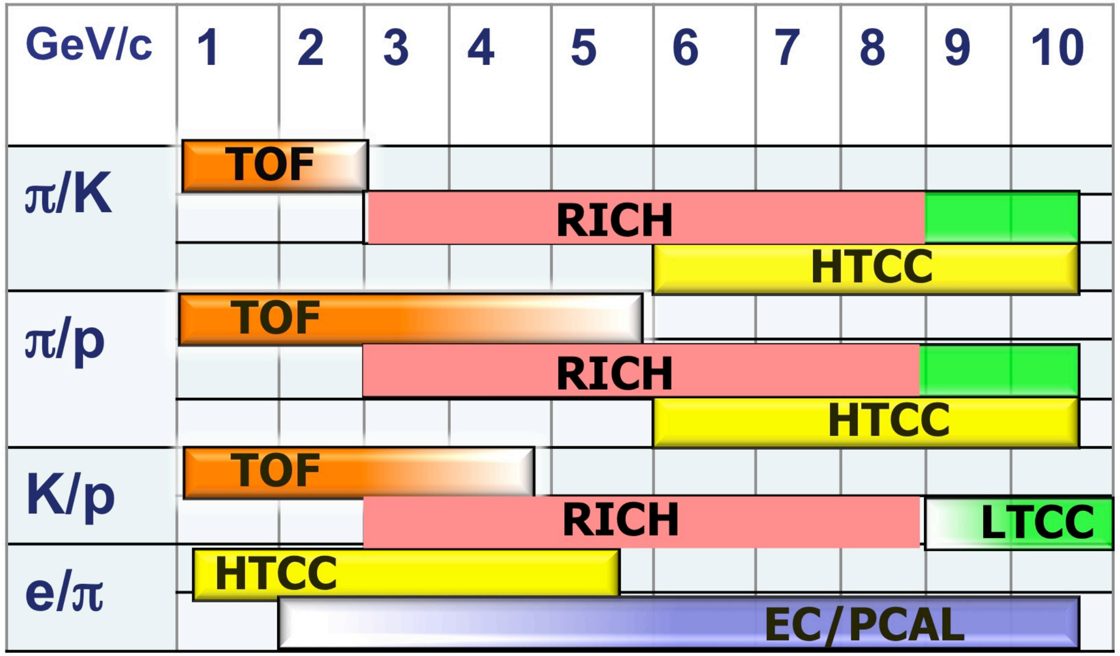
	π/K to 2.8 GeV
4σ	K/p to 4.8 GeV
	π/p to 5.4 GeV

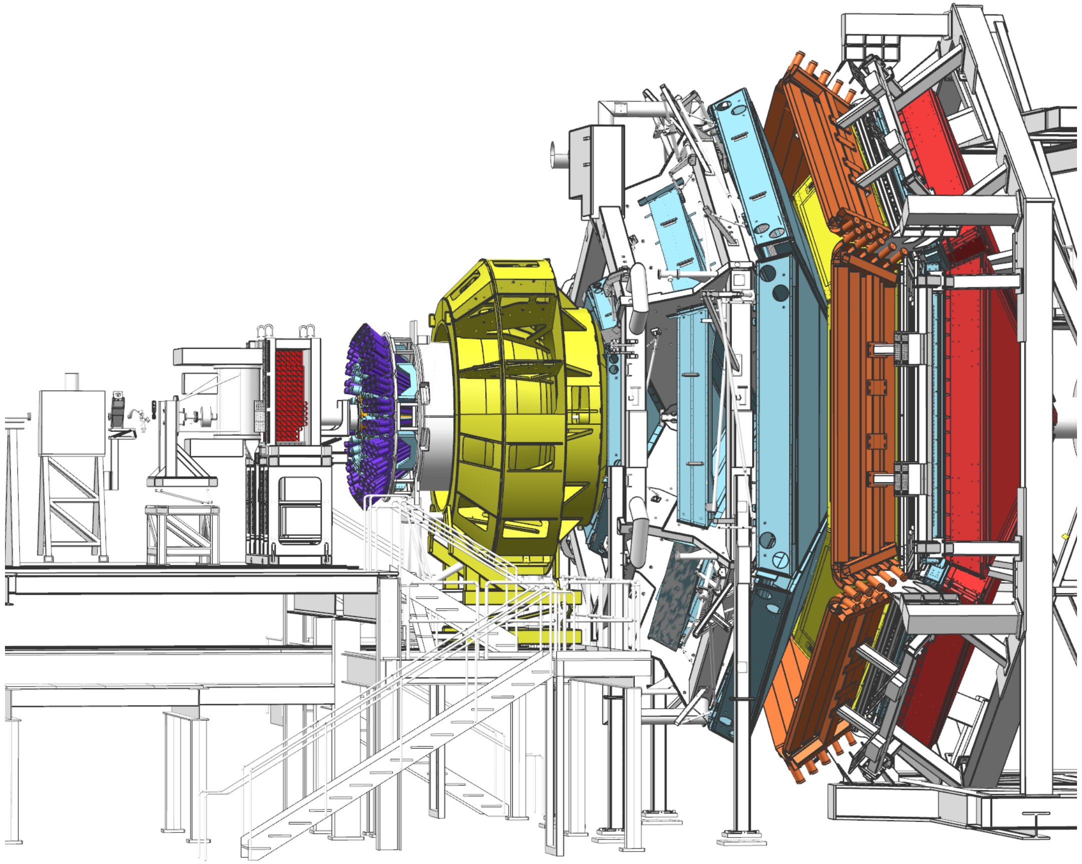
Design specifications

CLAS12 Charged Particle PID

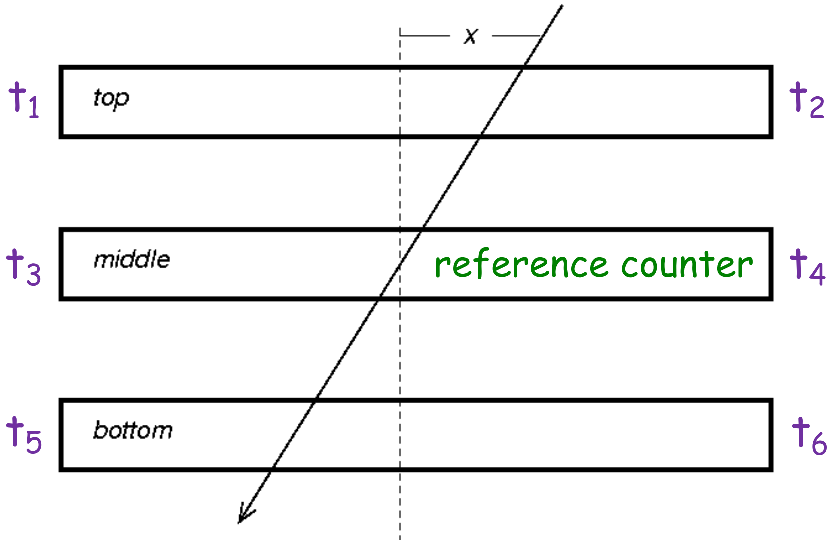
Particle identification in CLAS12 is accomplished through the use of multiple subsystems

FTOF is one part of CLAS12 PID system





Bench Testing – Triplet Method



- Scintillator hit times:

$$t_t = \frac{1}{2}(t_1 + t_2) \qquad t_m = \frac{1}{2}(t_3 + t_4) \qquad t_b = \frac{1}{2}(t_5 + t_6)$$

(hit times relative to trigger)

- Define time residual:

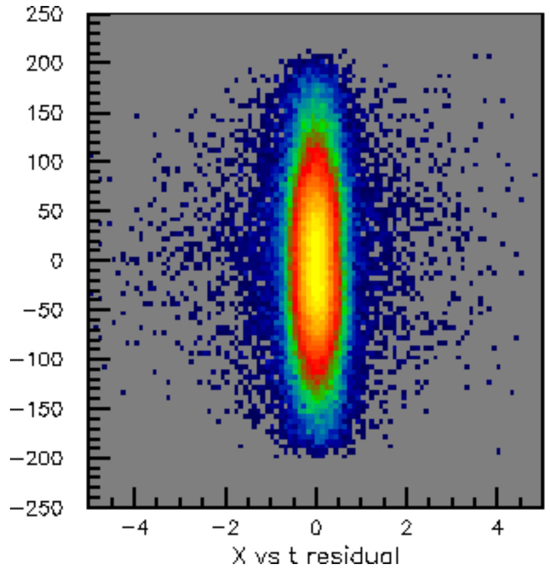
$$t_r = t_m - \frac{1}{2}(t_t + t_b)$$

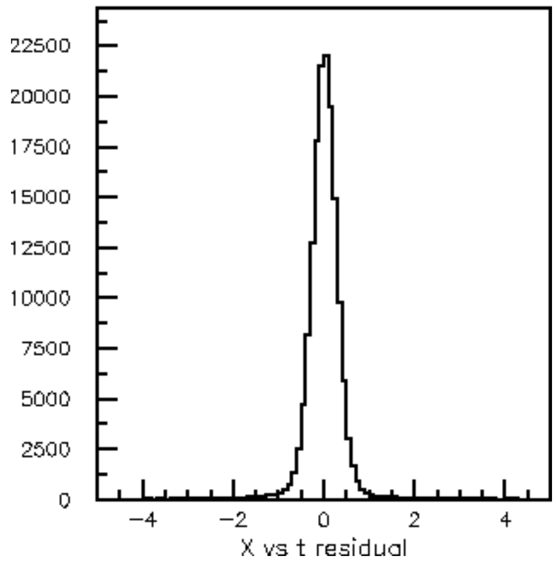
- Compute variance:

$$(\delta t_r)^2 = \sum_{i=1}^{6} \left(\frac{\partial t_r}{\partial t_i} \right)^2 \Delta t_i^2$$

$$\delta t_r = \frac{\sqrt{3}}{2} \Delta t_i = \frac{\sqrt{3}}{2} \sigma_{PMT} = \frac{\sqrt{3}}{2} \left(\sqrt{2} \sigma_{counter} \right)$$

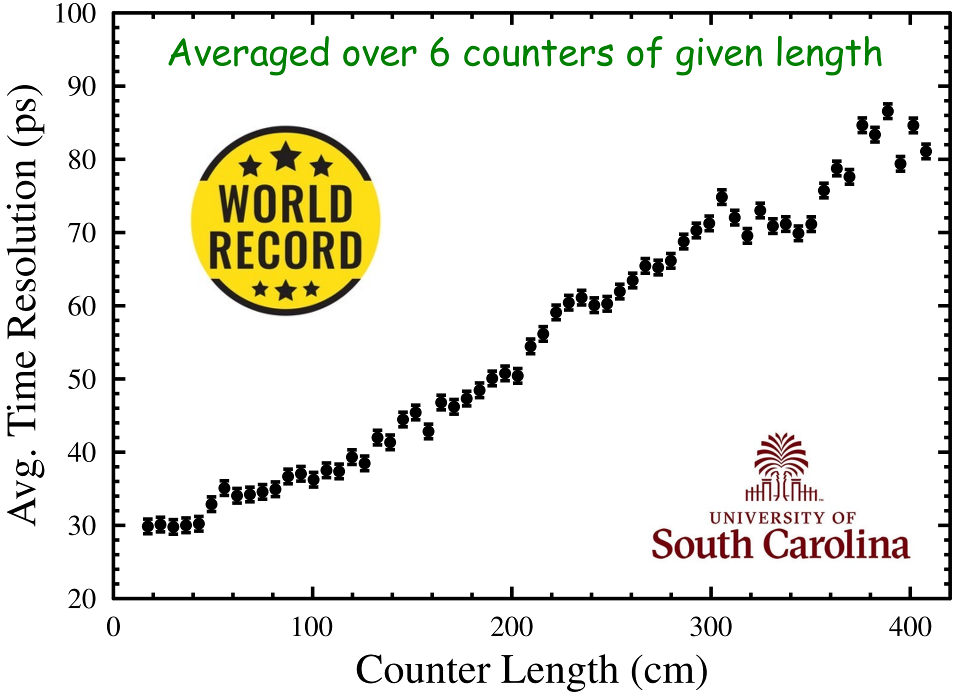
$$\sigma_{counter} = \frac{2}{\sqrt{6}} \delta t_r$$

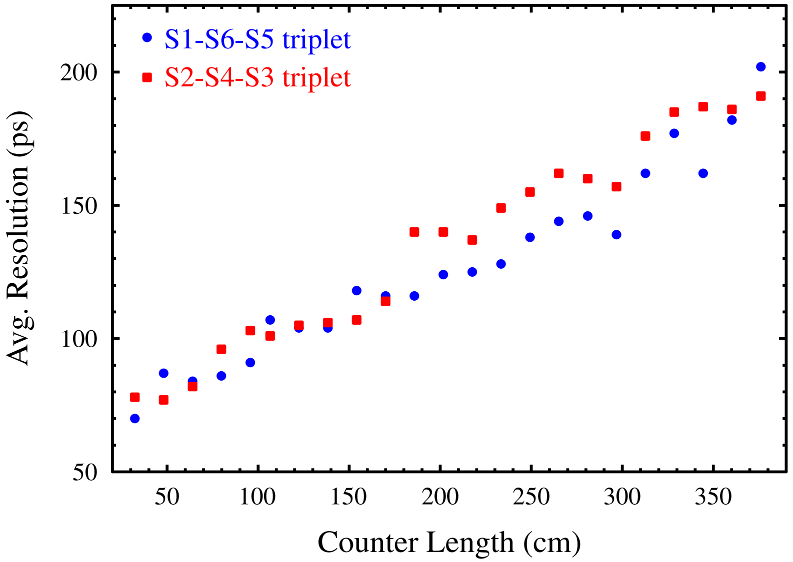




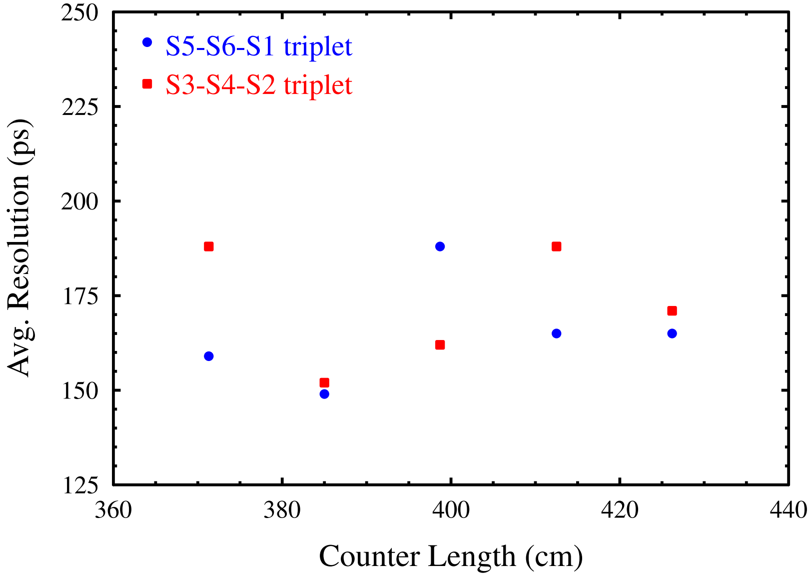
Bench Testing Results

panel-1b





panel-1a

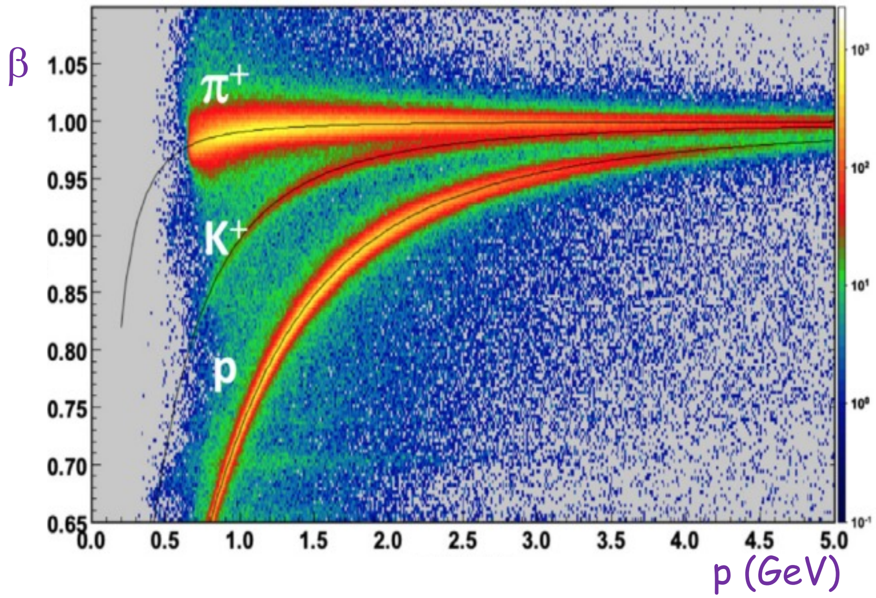


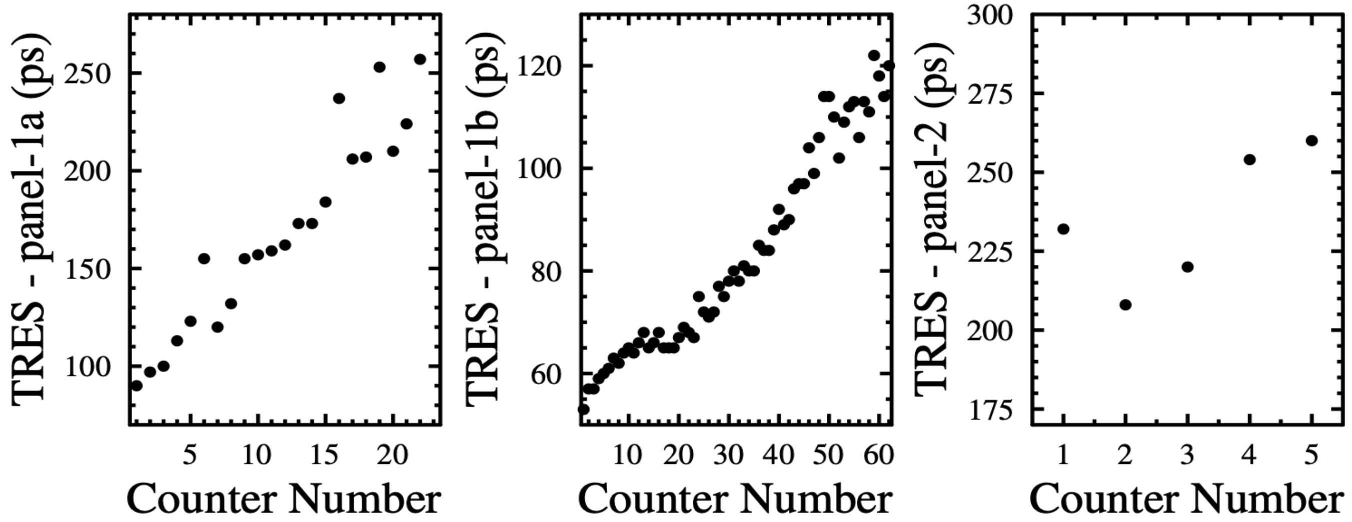
panel-2

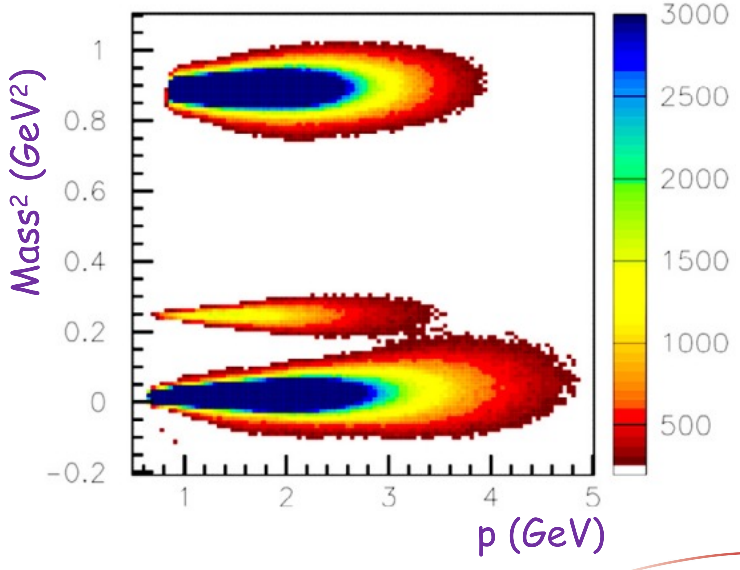
This is what is measured on the bench – what is seen in the "real world"?

Intrinsic vs. effective time resolution

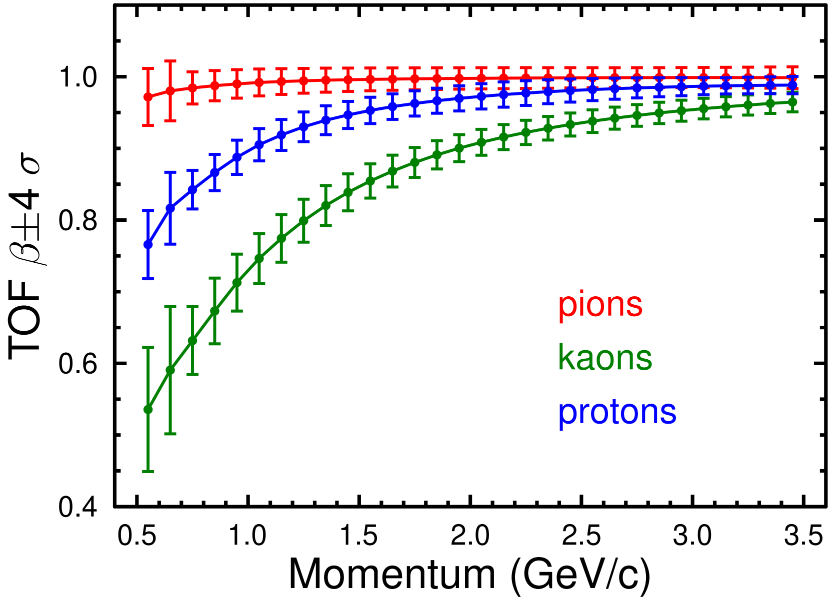
CLAS12 FTOF Performance



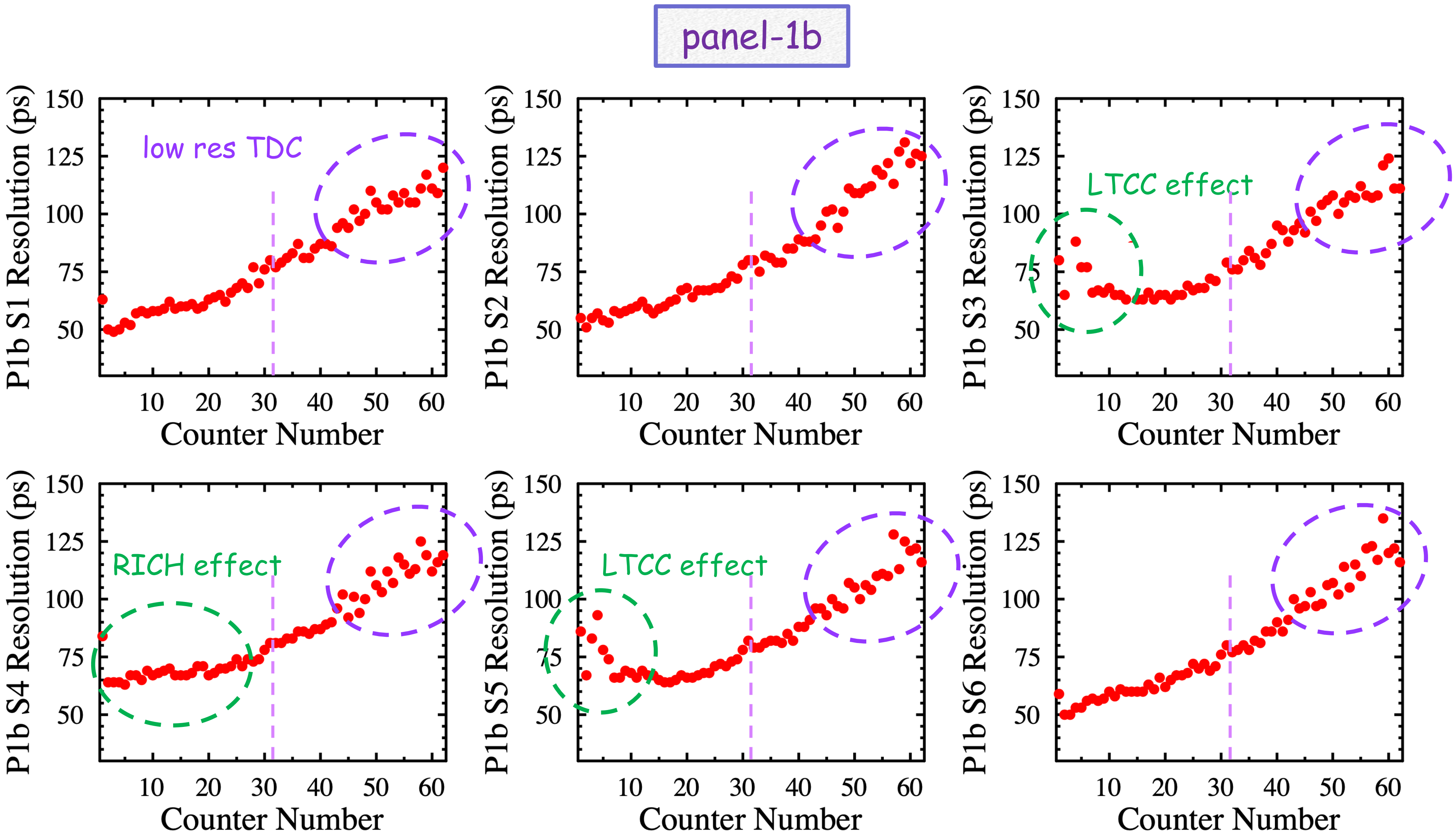




Studies of FTOF performance from E_b=11 GeV data



CLAS12 FTOF Performance



Timing Resolution

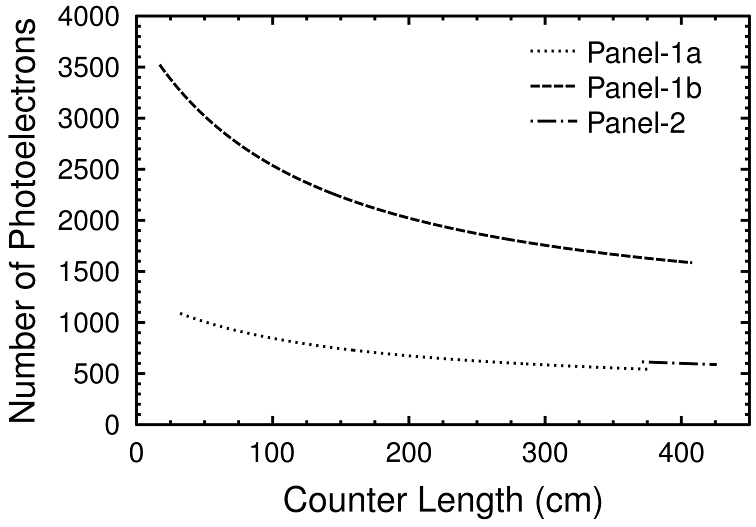
The counter timing resolution has been parameterized as:

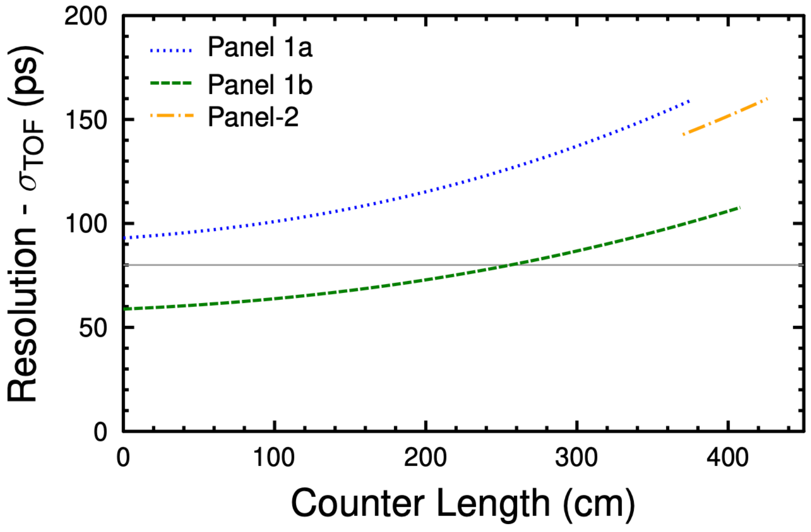
$$\sigma_{TOF} = \sqrt{\sigma_0^2 + \frac{\sigma_1^2 + (\sigma_2 L/2)^2}{N_{pe}}}$$

$$N_{pe} = N_{pe}^0 \exp\left(\frac{L_0}{2\lambda_0} - \frac{L}{2\lambda}\right)$$

σ_0 = electronics contribution
σ_1 = scintillator and PMT
σ_2 = path length variation
L = scintillator length
QE · N_γ = number of primary p.e.
λ = attenuation length

Parameter	Nominal Value
σ_0	0.040 ns
σ_1	2.1 ns
σ_2	2.0 ns/m
N_{pe}^0	918
λ	0.358 L + 81.725 cm

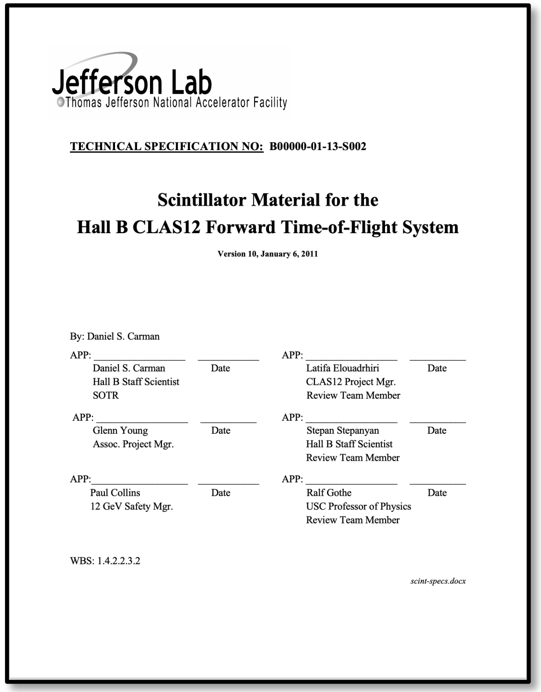




But this is still not the whole story when it comes to effective timing resolution:

- Material effects
- Calibration reliance on other detectors (e.g. track reconstruction)
- Backgrounds

Scintillator Specifications


Jefferson Lab
Thomas Jefferson National Accelerator Facility

TECHNICAL SPECIFICATION NO: B00000-01-13-S002

Scintillator Material for the
Hall B CLAS12 Forward Time-of-Flight System

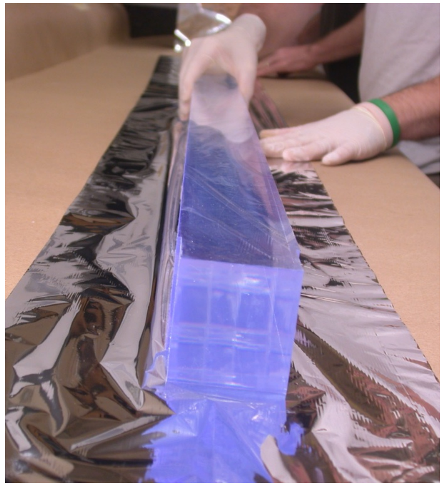
Version 10, January 6, 2011

By: Daniel S. Carman

APP: Daniel S. Carman, Hall B Staff Scientist, SOTR — Date
APP: Latifa Elouadrhiri, CLAS12 Project Mgr., Review Team Member — Date
APP: Glenn Young, Assoc. Project Mgr. — Date
APP: Stepan Stepanyan, Hall B Staff Scientist, Review Team Member — Date
APP: Paul Collins, 12 GeV Safety Mgr. — Date
APP: Ralf Gothe, USC Professor of Physics, Review Team Member — Date

WBS: 1.4.2.2.3.2

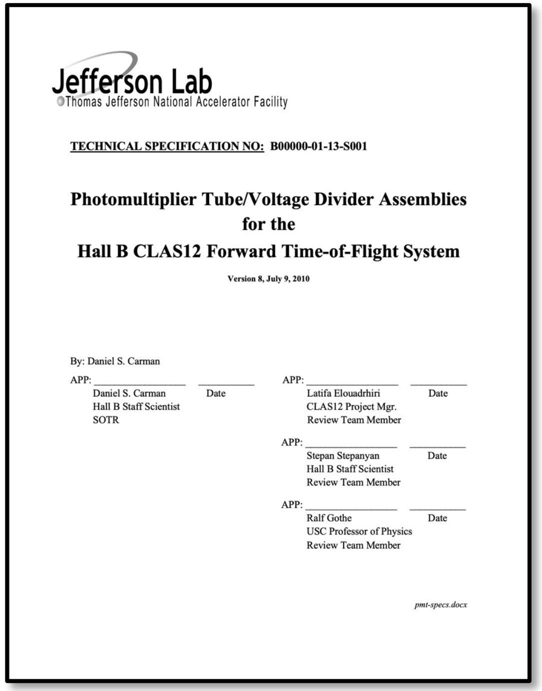
scint-specs.docx



	Category	Specification
1	Base Material	Polyvinyltoluene, r = 1.023 gm/cm^3, n=1.58
2	Appearance	No visual inclusions or air bubbles
3	Surface Preparation	Faces glass cast or diamond-tool milled
4	Length Tolerance	±1 mm
5	Straightness Tolerance	0.5 mm
6	Rise Time	< 0.7 ns (FRT), < 0.9 ns (LAL)
7	Decay Time	< 1.8 ns (FRT), < 2.1 ns (LAL)
8	Max Signal Pulse Width	~ 2.2 ns (FRT), ~ 2.5 ns (LAL)
9	Max Emission Wavelength	408 nm (FRT), 425 nm (LAL)
10	Bulk Attenuation Length	> 160 cm (FRT), > 380 cm (LAL)
11	Technical Attenuation Length	> 140 cm (FRT), > 280 cm (LAL)

Saint-Gobain Crystals: BC-404, BC-408

PMT/Voltage Divider Specifications


Jefferson Lab
Thomas Jefferson National Accelerator Facility

TECHNICAL SPECIFICATION NO: B00000-01-13-S001

Photomultiplier Tube/Voltage Divider Assemblies for the Hall B CLAS12 Forward Time-of-Flight System

Version 8, July 9, 2010

By: Daniel S. Carman

APP: ____ Daniel S. Carman, Hall B Staff Scientist, SOTR ____ Date

APP: ____ Latifa Elouadrhiri, CLAS12 Project Mgr., Review Team Member ____ Date

APP: ____ Stepan Stepanyan, Hall B Staff Scientist, Review Team Member ____ Date

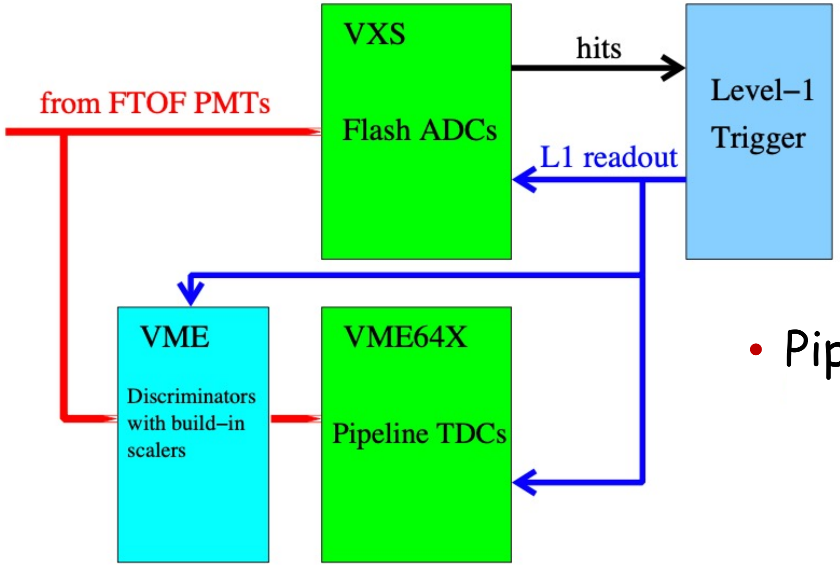
APP: ____ Ralf Gothe, USC Professor of Physics, Review Team Member ____ Date

pmt-specs.docx

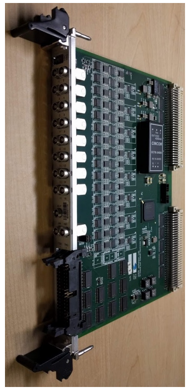
	Category	Specification
1	Spectral Response	300 – 600 nm
2	PMT Window	Planar, borosilicate glass
3	Photocathode	Bi-alkali
4	Dynode	Linear-focused
5	Minimum/Average Gain	5e5/1e6 at 85% of max HV
6	Anode Dark Current	< 50 nA
7	Anode Pulse Rise Time	< 2 ns
8	Electron Transit Time	< 20 ns
9	Transit Time Spread	< 250 ps
10	Pulse Linearity	~50 mA up to 1 MHz
11	Cathode/Anode Sensitivity	~100 μA/lm / ~100 A/lm
12	B-Shield	0.2 mm μ-metal
13	Anode+Dynode Cables	RG-174, 25 cm long, BNC connectors
14	HV Cable	HV rated, 25 cm long, SHV connectors

Hamamatsu – R9779 2-in diameter, 8-stage, head-on type

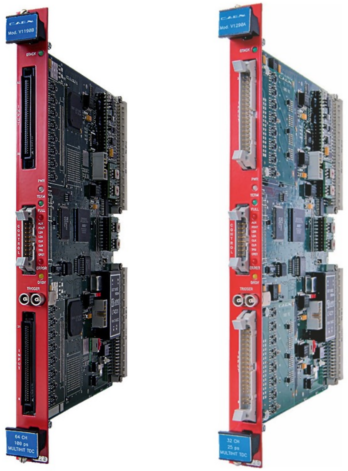
Readout Electronics



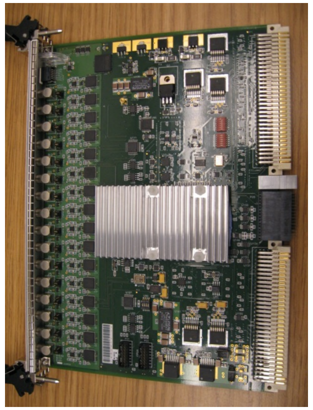
- Discriminator/Scaler:
  - JLab DSC – 16 channel VME, leading-edge type



- Pipeline TDCs:
  - CAEN V1290 - 32 channel VME, 25 ps LSB
  - CAEN V1190 - 128 channel VME, 110 ps LSB



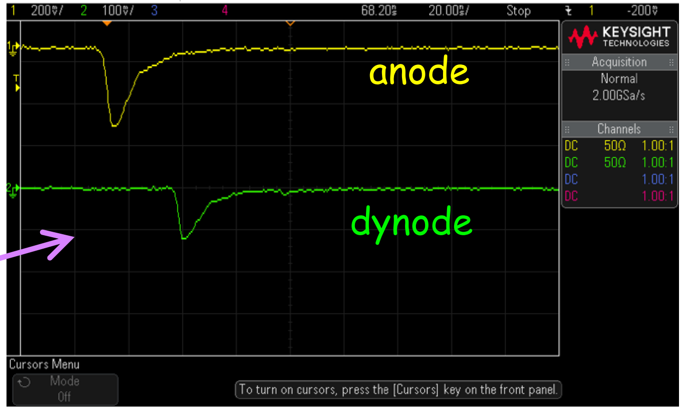
- Flash ADCs:
  - JLab 250 – 16 channel VME, 12 bit, 250 MHz



PMT anode goes to disc/TDC

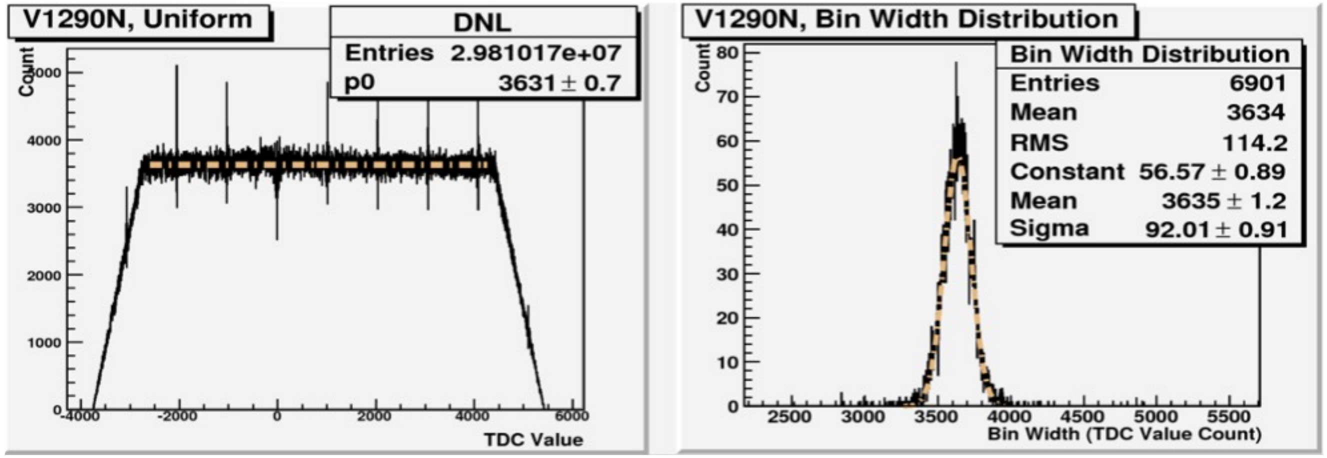
PMT dynode goes to FADC

Anode is 3x bigger than dynode signal



TDC Calibration

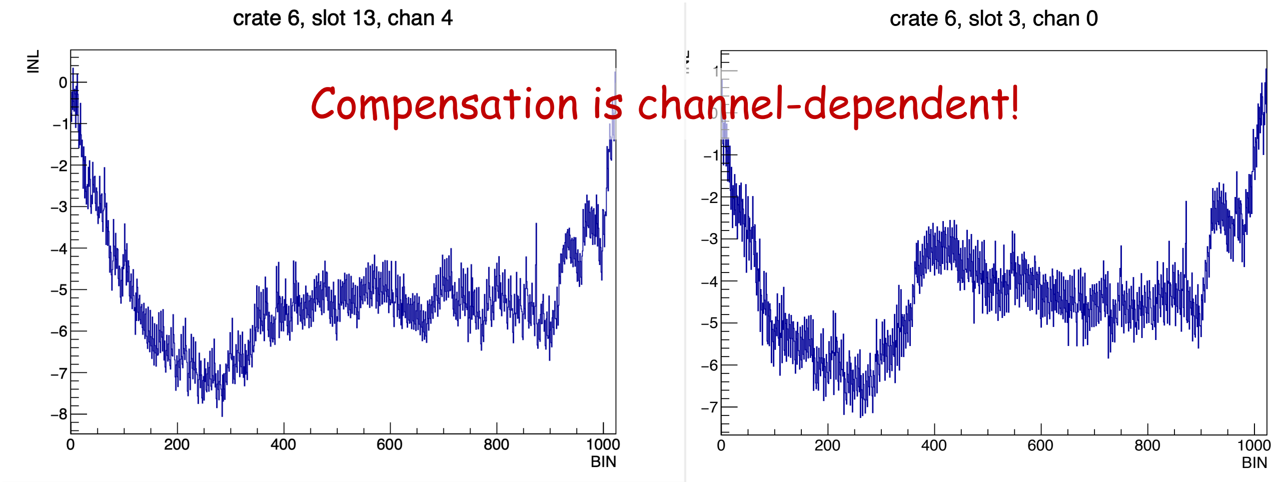
Differential Non-linearity



CAEN TDC characterization studies:

- Differential non-linearity (< 3 LSB)
- Integral non-linearity (< 2.5 LSB)
  - Channel-by-channel compensation tables stored in SRAM memory
  - Boards run on external 41.666 MHz clock rather than internal 40 MHz clock
- TDC conversation factor
  - 23.45 ps/ch

Integral Non-linearity

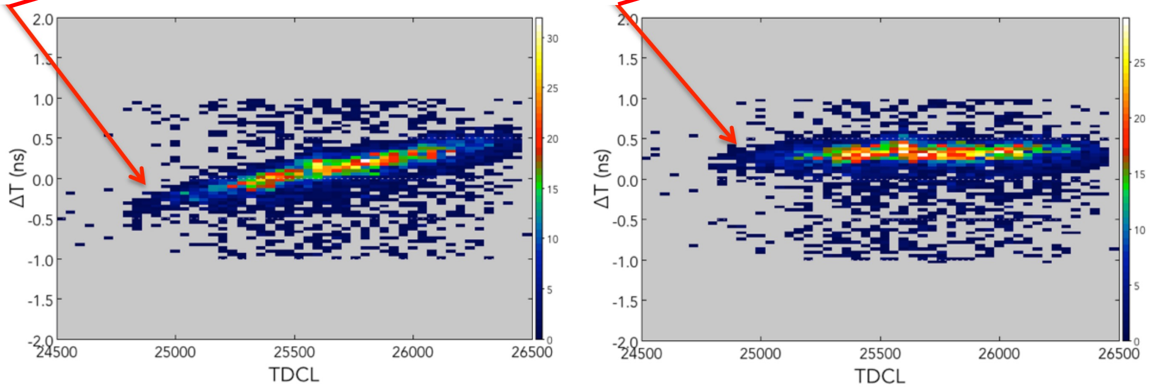


Compensation is channel-dependent!

Vertex time vs. TDC

24.0 ps/ch

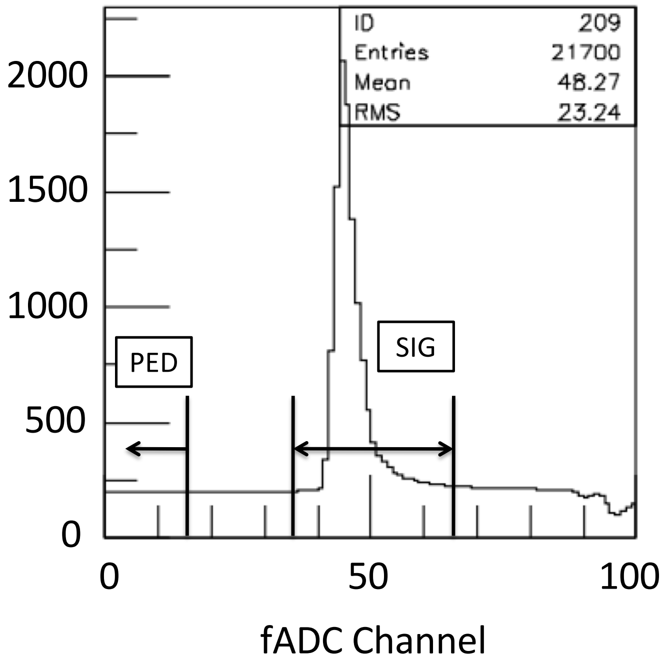
23.5 ps/ch



ADC Calibration

JLab FADC characterization studies:

- Differential non-linearity (±0.8 LSB)
- Integral non-linearity (±0.5 LSB)
- Clock jitter 350 fs
- SNR 56.8 dB @ 100 MHz input

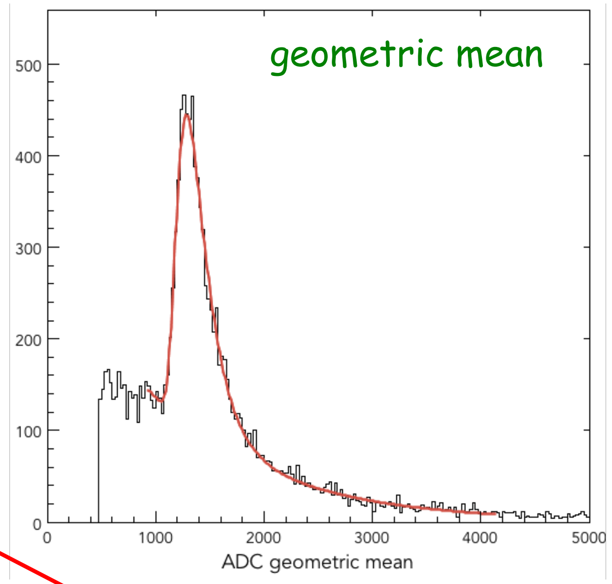


- PMT gain depends exponentially on the applied voltage. For two settings

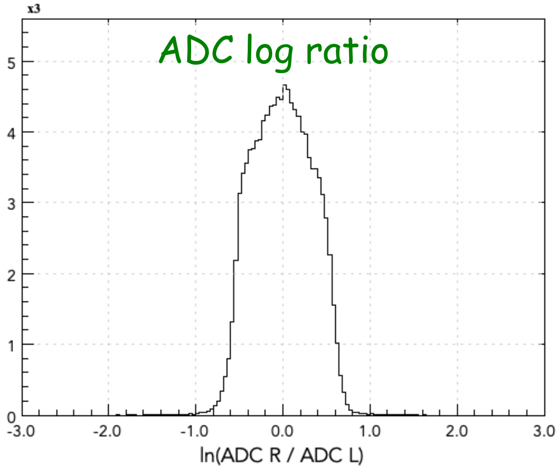
$$\frac{G_1}{G_2} = \left(\frac{V_1}{V_2}\right)^{\alpha}, \quad \frac{\Delta G}{G_1} = \alpha \frac{\Delta V}{V_1}$$

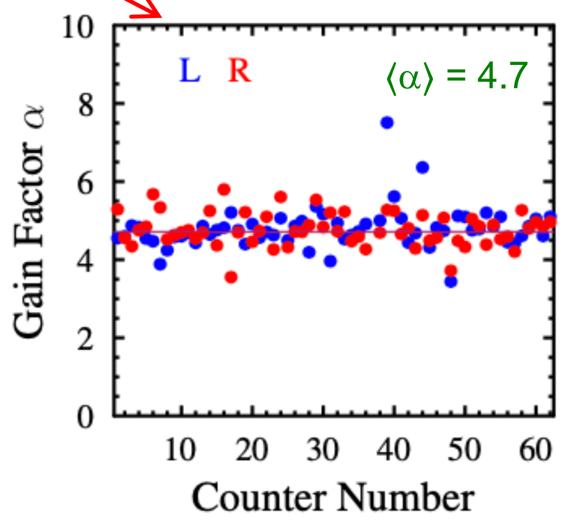
$$\Delta V_{L,R} = \frac{V_{L,R}^{orig} \cdot (\text{ADC shift})}{(\text{ADC mean}) \cdot \alpha}$$

- Adjust PMT HV settings to put ⟨ADC⟩ for min-i particles in desired channel

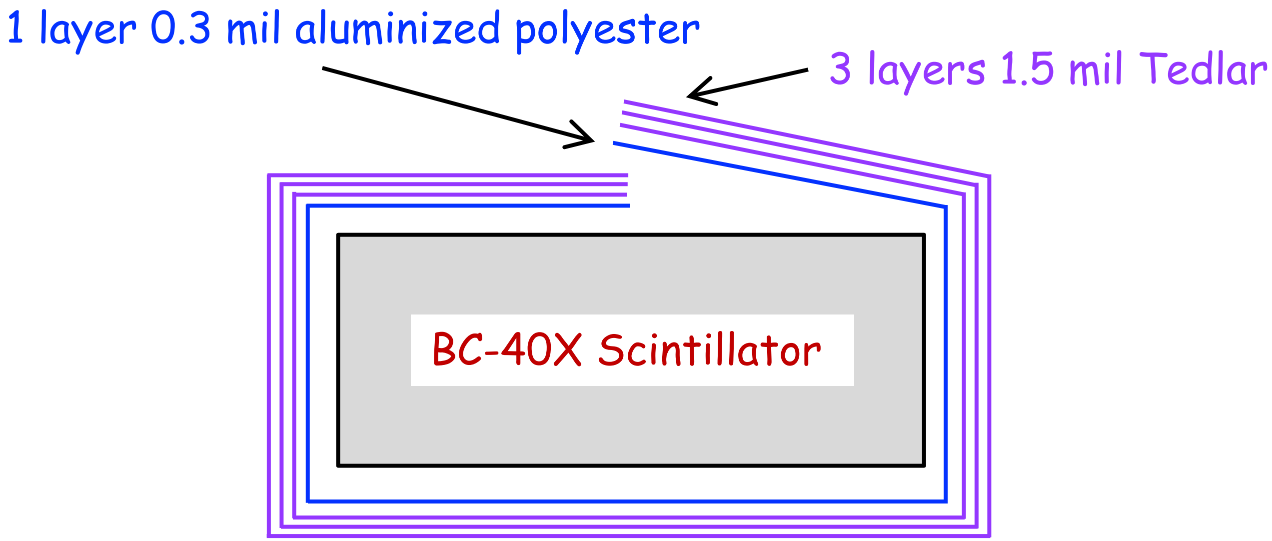


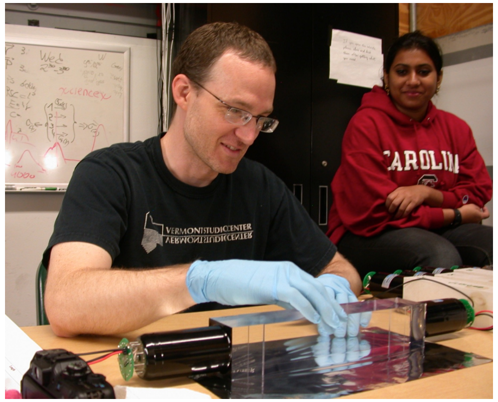
Use log ratio plots to check L/R gain balancing





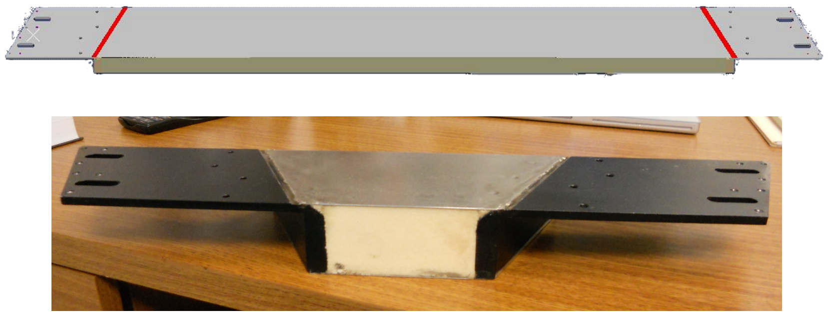
Scintillator Preparations



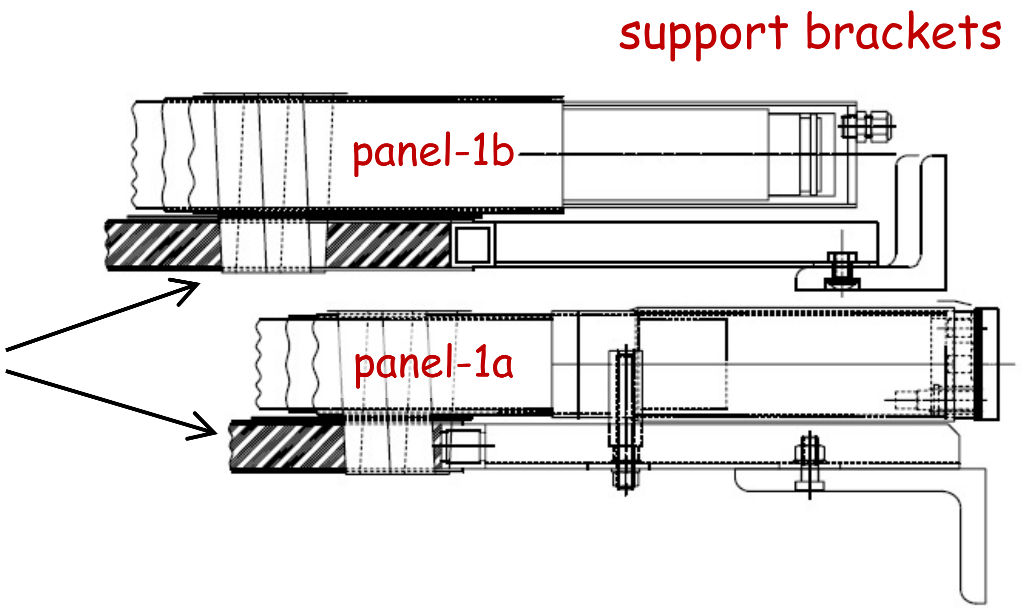


Wrapping in progress @ USC

backing structures



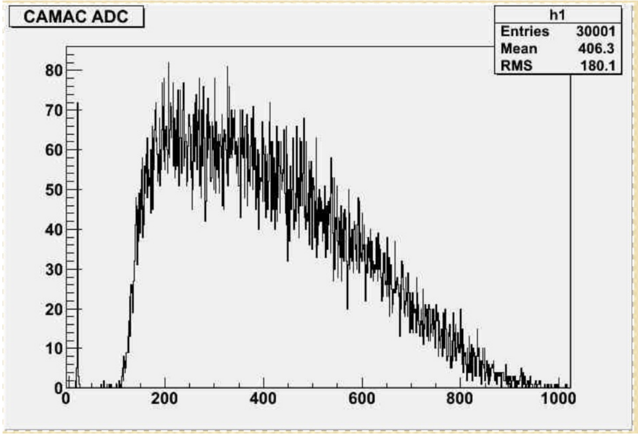
st.st. skins + foam core



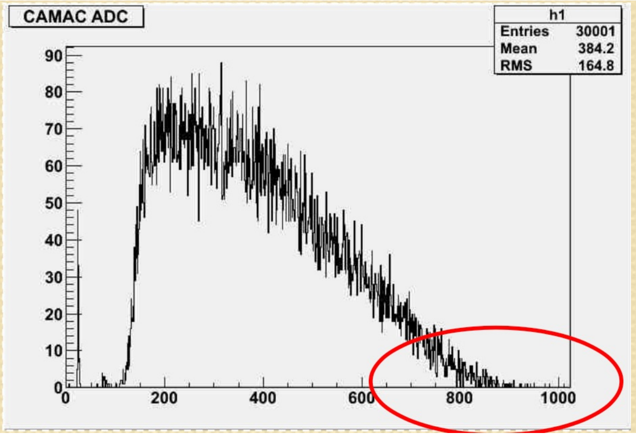
Magnetic Shielding

TOSCA calculations show field at PMT location < 30 G (mostly axial)

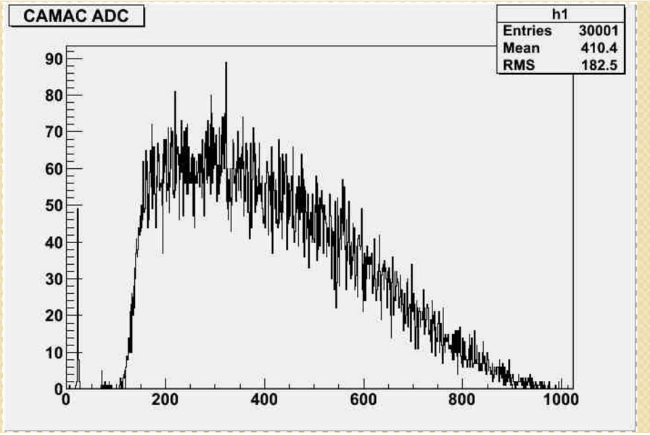
No Magnetic Field

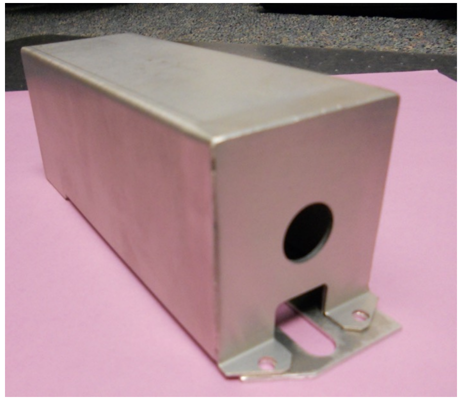


10 G Axial Field

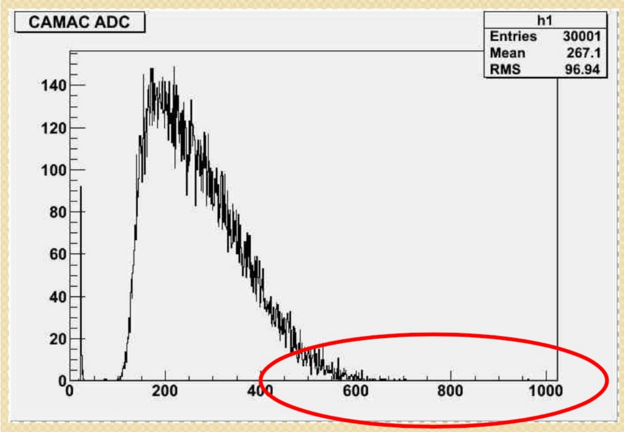


10 G Transverse Field

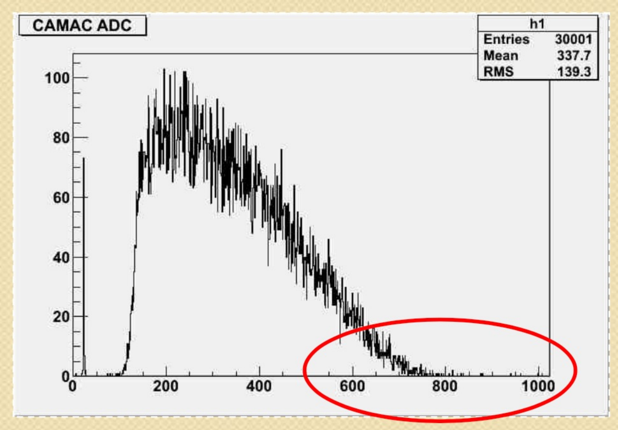




20 G Axial Field



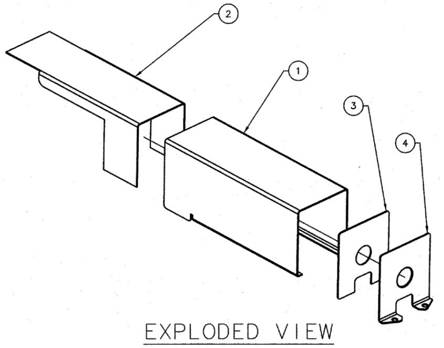
20 G Transverse Field



	< 10 Gauss	< 20 Gauss	> 25 Gauss
Axial Field	Shielding in tube is enough	Steel frame and possible active shielding	Active shielding
Transverse Field	Shielding in tube is enough	Shielding in tube is enough	Additional shielding required

Tests with nominal PMTs 0.2 mm μ-metal

2 mm μ-metal



Signal Cables

	RG-58	RG-9913	RG-8	RG-214	RG-174
Cable Length (ft)	200	251.5	202.2	95.3	128.2
Rise Times 30/70 (ns) 10/90	5.67 22.04	1.78 10.55	2.69 12.69	1.36 7.01	4.3 18.03
Amplitude (V)	1.32	1.4	1.432	1.464	1.072
Resolution (ps)	36.13	19.64	19.9	18.36	59.4
Charge (pC)	1078	1110	1123	1139	952

Long cable runs could benefit from alternative cable type choices, *e.g.* RG-9913

PMT BNC M
Anode

Cable RG-58 frame-mounted
BNC F ⟷ BNC M

Cable RG-58 patch cable
BNC F ⟷ BNC F
bulkhead type bulkhead type

Cable RG-174 electronics
BNC M ⟷ Lemo M

FTOF signal cables
52 – 64 ft

PMT BNC M
Dynode

Cable RG-58 frame-mounted
BNC F ⟷ BNC M

Cable RG-58 patch cable
BNC F ⟷ BNC M
bulkhead type

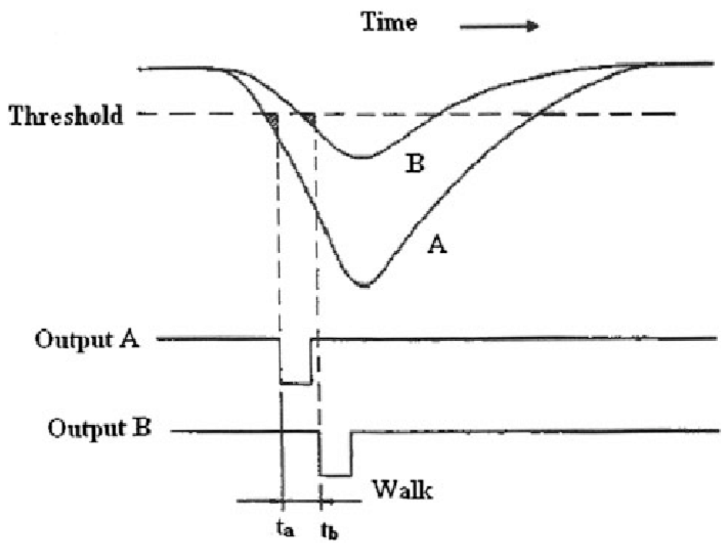
460 IT

BNC F BNC F
bulkhead type

Cable RG-174 electronics
BNC M ⟷ Lemo M

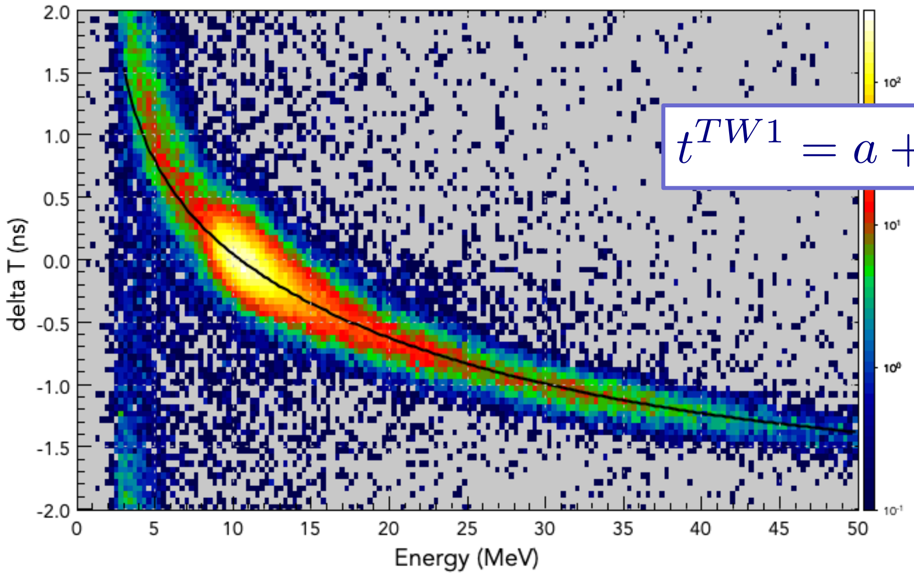
Time Walk Corrections

Time-walk effects are inherent in the use of leading-edge discriminators

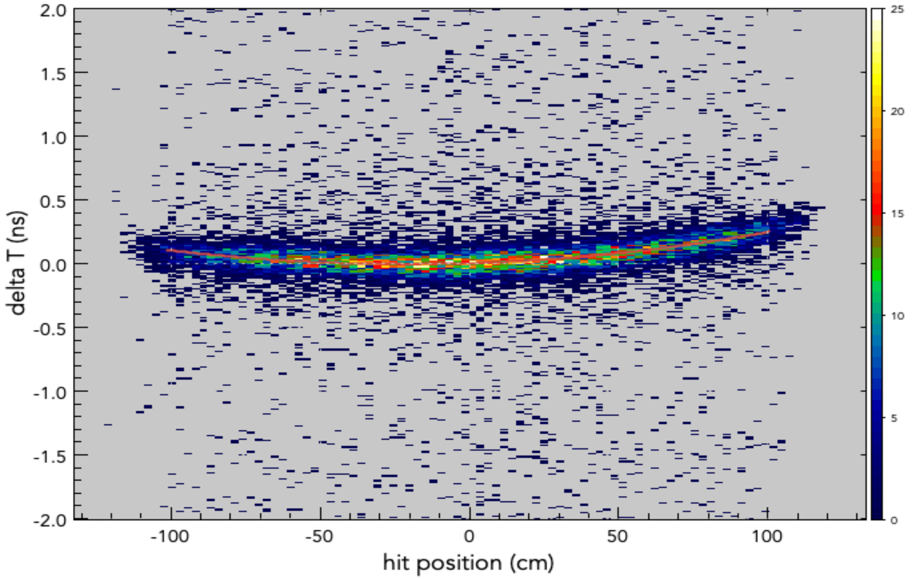


Ortec- Fast-Timing Discriminator Introduction

Also account for 2nd-order correction for hit-position-dependence of TW functional – distance from PMT location



$$t^{TW1} = a + b \cdot \exp(c \cdot \Delta E) + d/\Delta E$$



$$t^{TW2} = \alpha \cdot y + \beta \cdot y^2$$

Time Walk Corrections

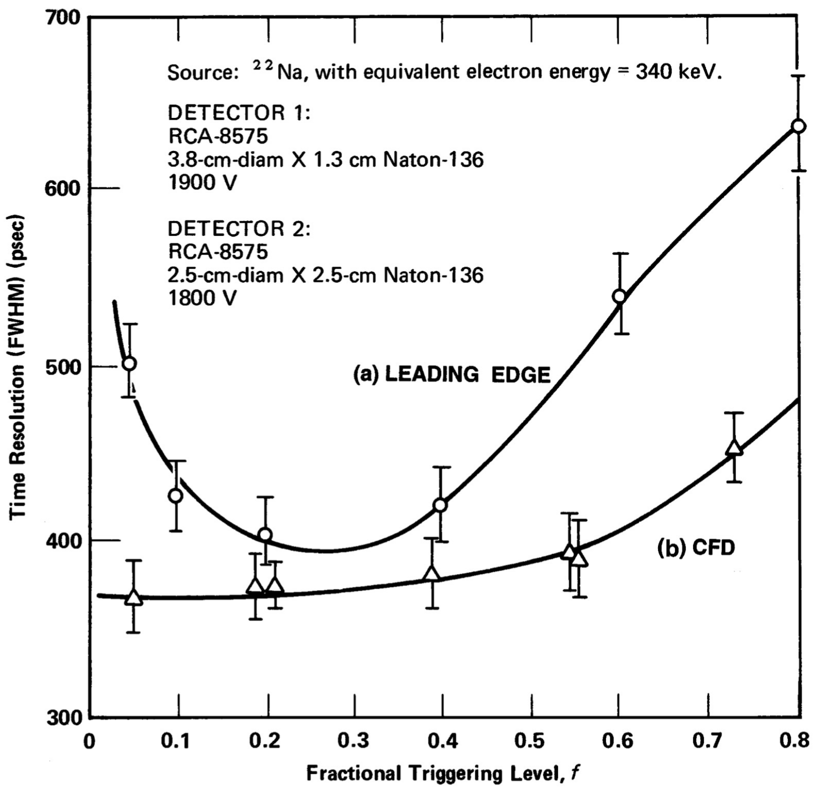
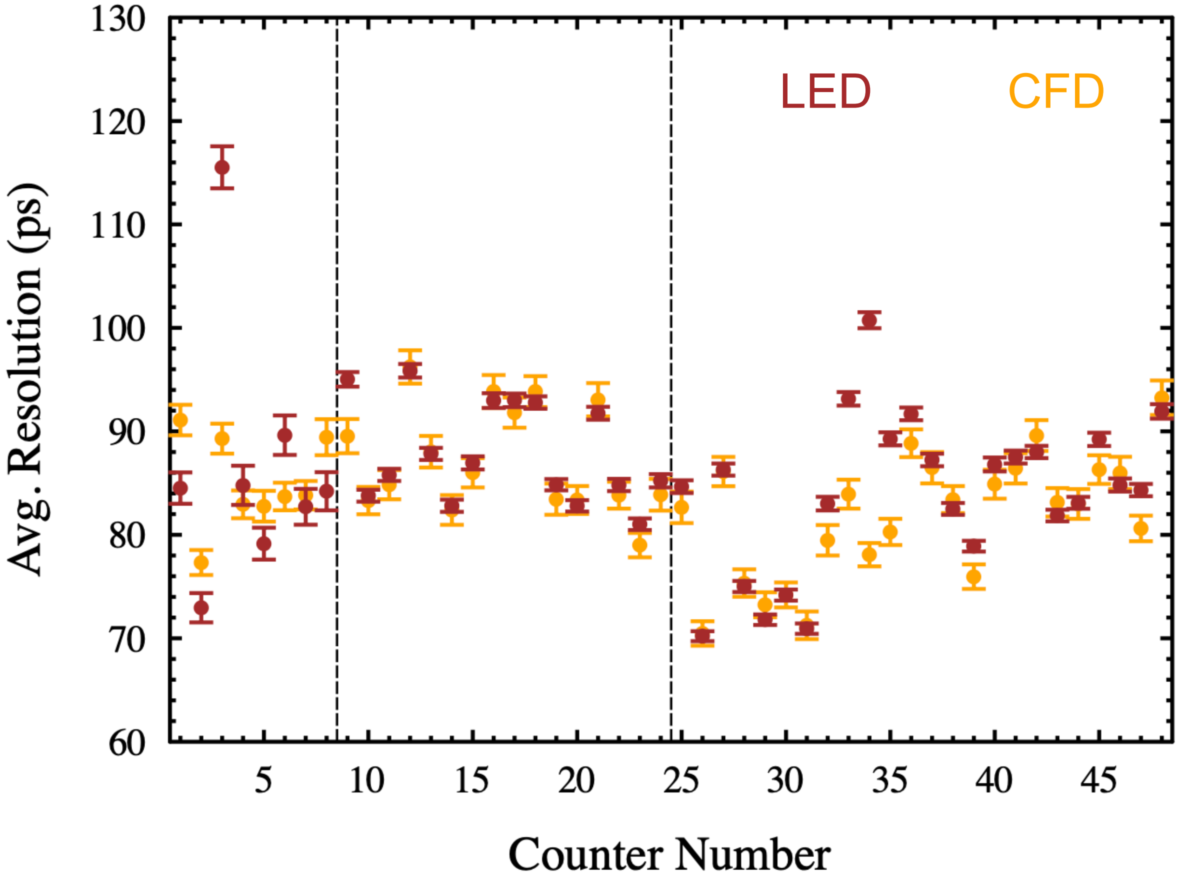


Fig. 2. A Comparison of Leading-Edge Timing with Constant-Fraction Timing for a Narrow Pulse-Height Range. The source was ^{22}Na, with the selected equivalent electron energy in the scintillator = 340 keV. The time resolution (FWHM) is Δt.



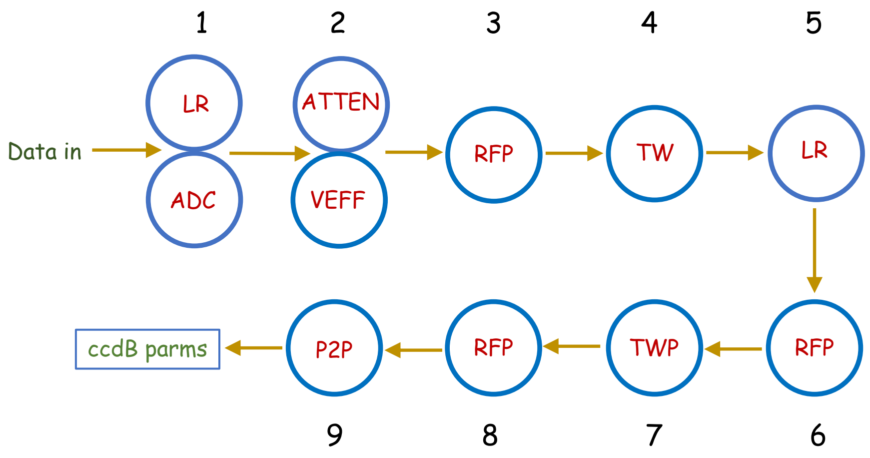
Ortec- Fast-Timing Discriminator Introduction

"the timing resolution from a CFD is better than from a LED"

However, in reality, the LED vs. CFD comparison depends on the dynamic range of the pulses and their pulse shape – in some cases timing with LED (with corrections) can give better results!

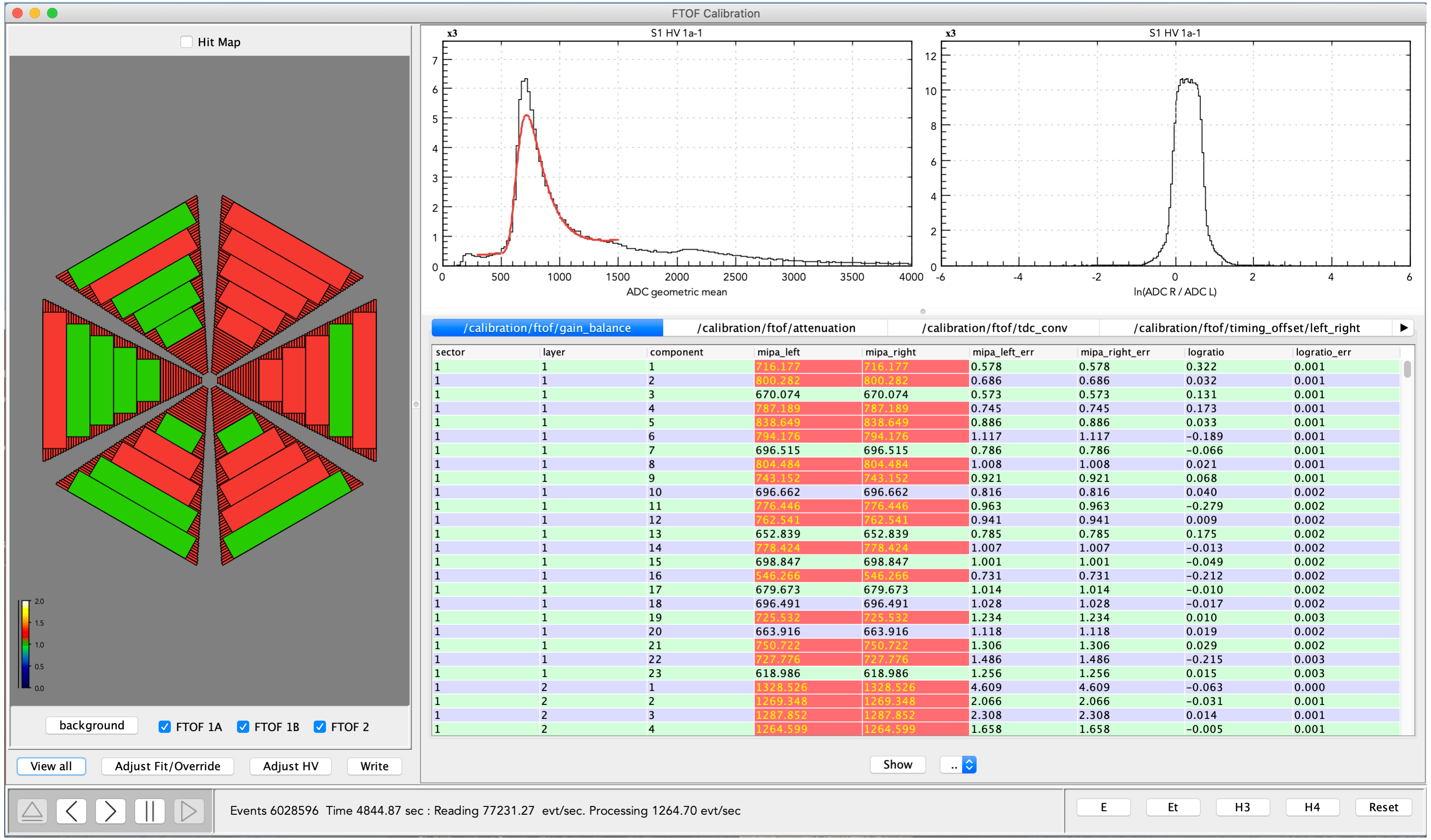
Calibration Software

Calibration Sequence



Java-based suite writes out constants to upload to ccdb

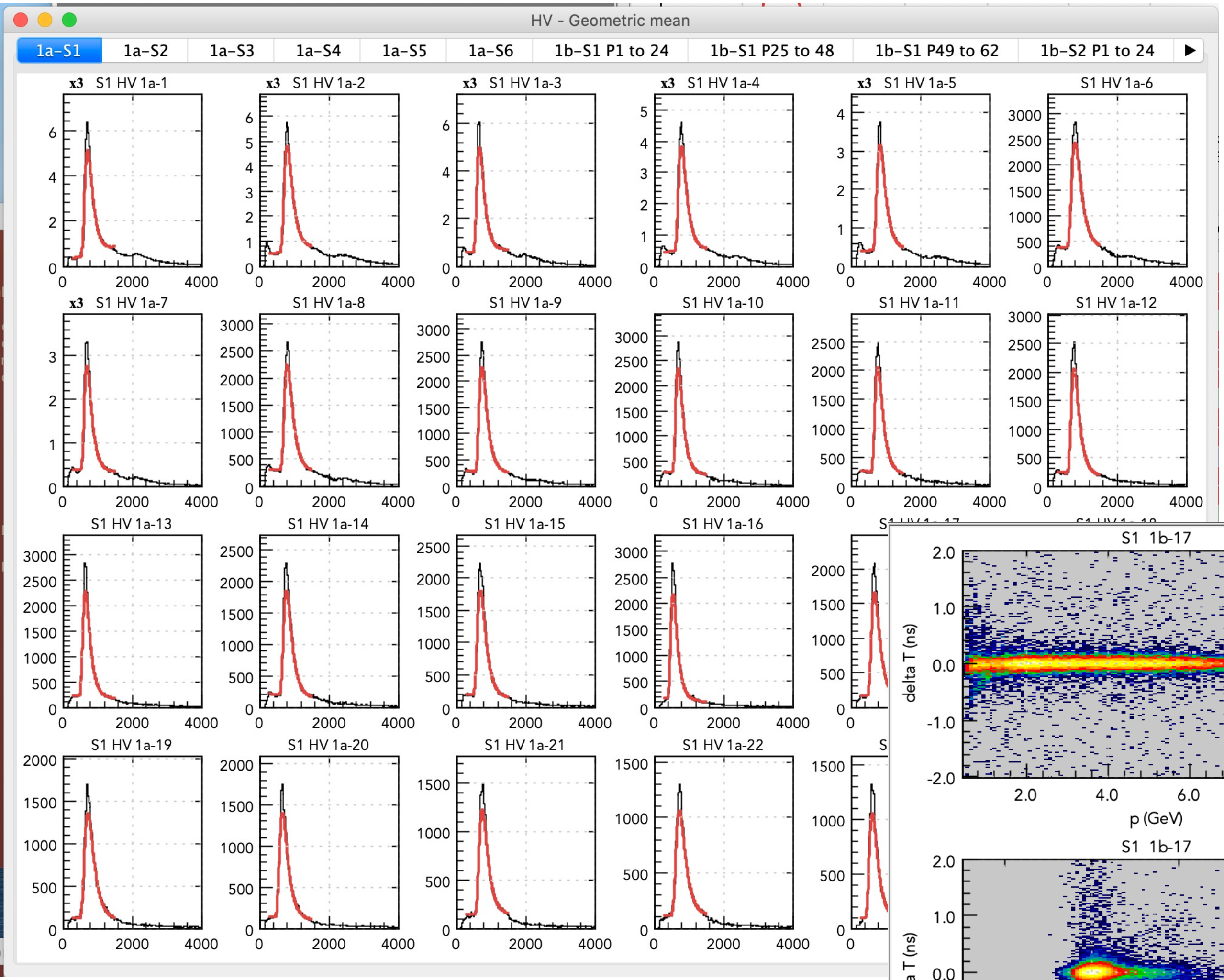
Calibration Suite



sector	layer	component	mipa_left	mipa_right	mipa_left_err	mipa_right_err	logratio	logratio_err
1	1	1	716.177	716.177	0.578	0.578	0.322	0.001
1	1	2	800.282	800.282	0.686	0.686	0.032	0.001
1	1	3	670.074	670.074	0.573	0.573	0.131	0.001
1	1	4	787.189	787.189	0.745	0.745	0.173	0.001
1	1	5	838.649	838.649	0.886	0.886	0.033	0.001
1	1	6	794.176	794.176	1.117	1.117	-0.189	0.001
1	1	7	696.515	696.515	0.786	0.786	-0.066	0.001
1	1	8	804.484	804.484	1.008	1.008	0.021	0.001
1	1	9	743.152	743.152	0.921	0.921	0.068	0.001
1	1	10	696.662	696.662	0.816	0.816	0.040	0.002
1	1	11	776.446	776.446	0.963	0.963	-0.279	0.002
1	1	12	762.541	762.541	0.941	0.941	0.009	0.002
1	1	13	652.839	652.839	0.785	0.785	0.175	0.002
1	1	14	778.424	778.424	1.007	1.007	-0.013	0.002
1	1	15	698.847	698.847	1.001	1.001	-0.049	0.002
1	1	16	546.266	546.266	0.731	0.731	-0.212	0.002
1	1	17	679.673	679.673	1.014	1.014	-0.010	0.002
1	1	18	696.491	696.491	1.028	1.028	-0.017	0.002
1	1	19	725.532	725.532	1.234	1.234	0.010	0.003
1	1	20	663.916	663.916	1.118	1.118	0.019	0.002
1	1	21	750.722	750.722	1.306	1.306	0.029	0.002
1	1	22	727.776	727.776	1.486	1.486	-0.215	0.003
1	1	23	618.986	618.986	1.256	1.256	0.015	0.003
1	2	1	1328.526	1328.526	4.609	4.609	-0.063	0.000
1	2	2	1269.348	1269.348	2.066	2.066	-0.031	0.001
1	2	3	1287.852	1287.852	2.308	2.308	0.014	0.001
1	2	4	1264.599	1264.599	1.658	1.658	-0.005	0.001

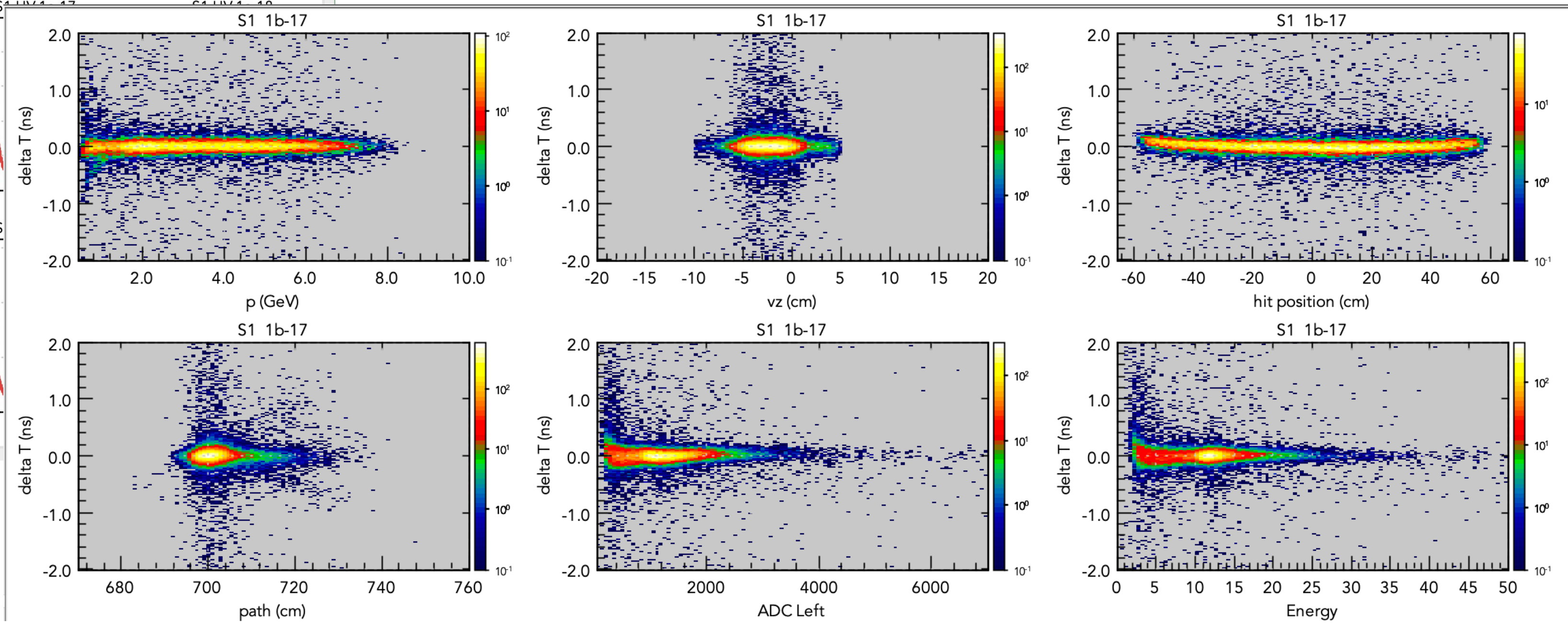
https://www.jlab.org/Hall-B/ftof/notes/ftof_calib.pdf

Calibration Software



All FTOF channels checked for each step

Final "check plots" step after completed sequence



Calibrated Energy and Time

Measured energy @ PMT

$$E_{L,R} = ADC_{L,R} \cdot \left[\frac{\left(\frac{dE}{dx}\right)_{MIP} \cdot t}{ADC_{MIP}} \right] \exp\left(\frac{d_{L,R}}{\lambda}\right)$$

Counter energy deposited

$$E_{dep} = \sqrt{E_L \cdot E_R}$$

Corrected PMT time

$$t_{L,R} = (CONV \cdot TDC_{L,R}) - t^{walk}_{L,R} \mp \frac{C_{LR}}{2} + C_{RF} + C_{p2p}$$

Counter hit time

$$\bar{t}_{hit} = \frac{1}{2}(t_L + t_R)$$

Particle time-of-flight

$$t_{TOF} = \bar{t}_{hit} - t_{ST}$$

Effective counter time resolution

↳ width of vertex time distribution

vertex time

$$t_{res} = mod\left[\left\{\left(\bar{t}_{hit} - \frac{P_L}{\beta c}\right) - \left(t_{RF} + \frac{z_{vert}}{\beta_e c}\right)\right\}, T_{RF}\right]$$

Concluding Remarks

- The Forward Time-of-Flight (FTOF) system is the main system for charged particle identification in the CLAS12 Forward Detector https://www.jlab.org/Hall-B/ftof/index.html
- The FTOF panel-1b counter arrays were constructed as part of the JLab 12-GeV Upgrade project and have provided world-record timing resolutions for scintillation detectors of these lengths
- I have not covered all features/considerations – *see technical papers for more details*

Nuclear Inst. and Methods in Physics Research, A 960 (2020) 163629

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

The CLAS12 Forward Time-of-Flight system

FTOF

D.S. Carman et al., NIM A 960, 163629 (2020)

Nuclear Inst. and Methods in Physics Research, A 960 (2020) 163626

Contents lists available at ScienceDirect

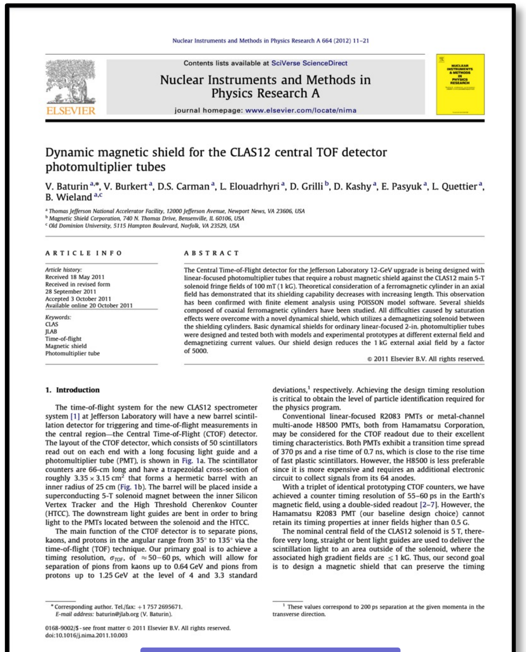
Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

The CLAS12 Central Time-of-Flight system

CTOF

D.S. Carman et al., NIM A 960, 163626 (2020)



Nuclear Instruments and Methods in Physics Research A 664 (2012) 11–21

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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Dynamic magnetic shield for the CLAS12 central TOF detector photomultiplier tubes

1 kG shields

V. Baturin et al., NIM A 664, 11 (2012)

BACKUP SLIDES

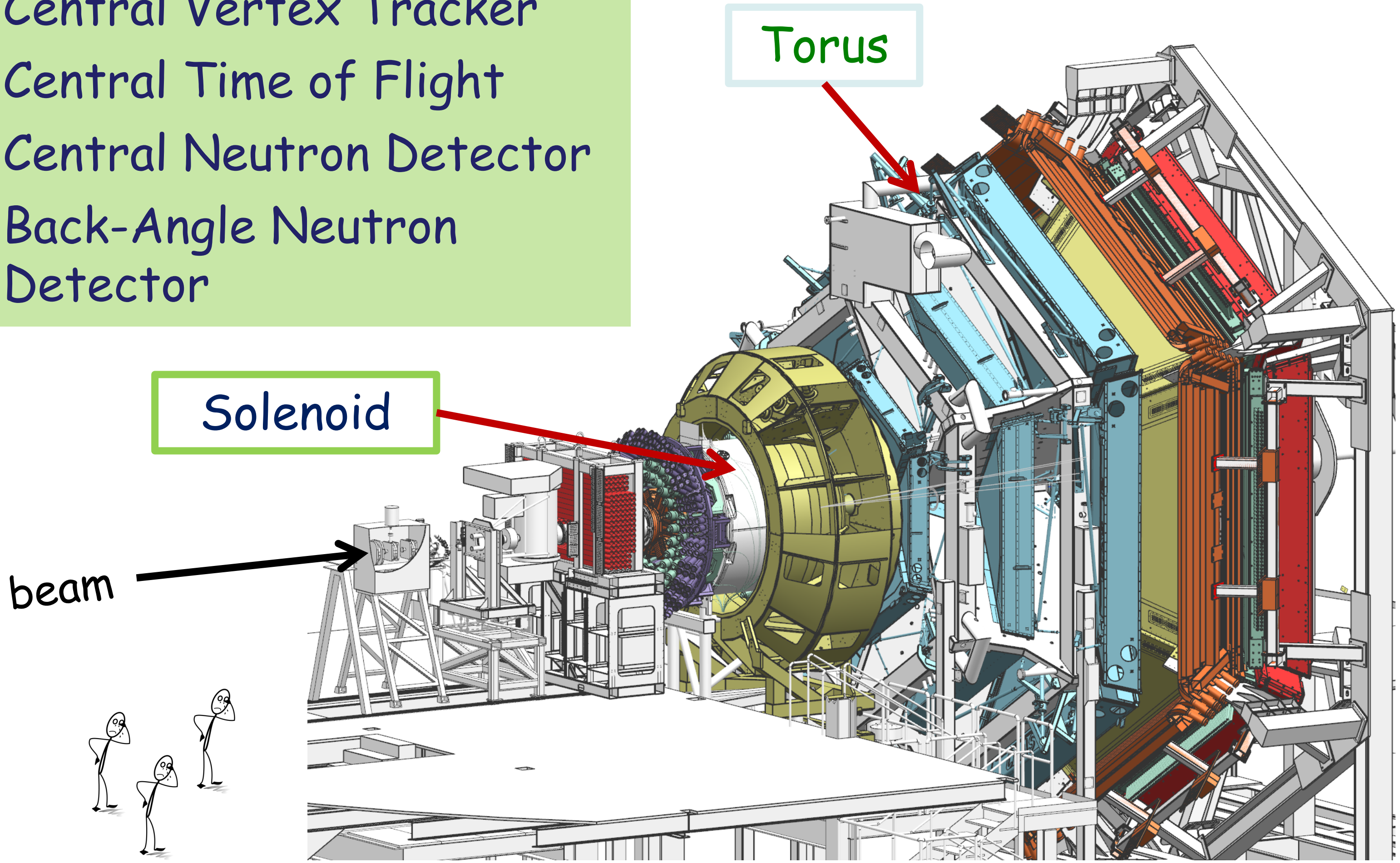
CLAS12 Spectrometer Model

C E N T R A L

- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Detector
- Back-Angle Neutron Detector

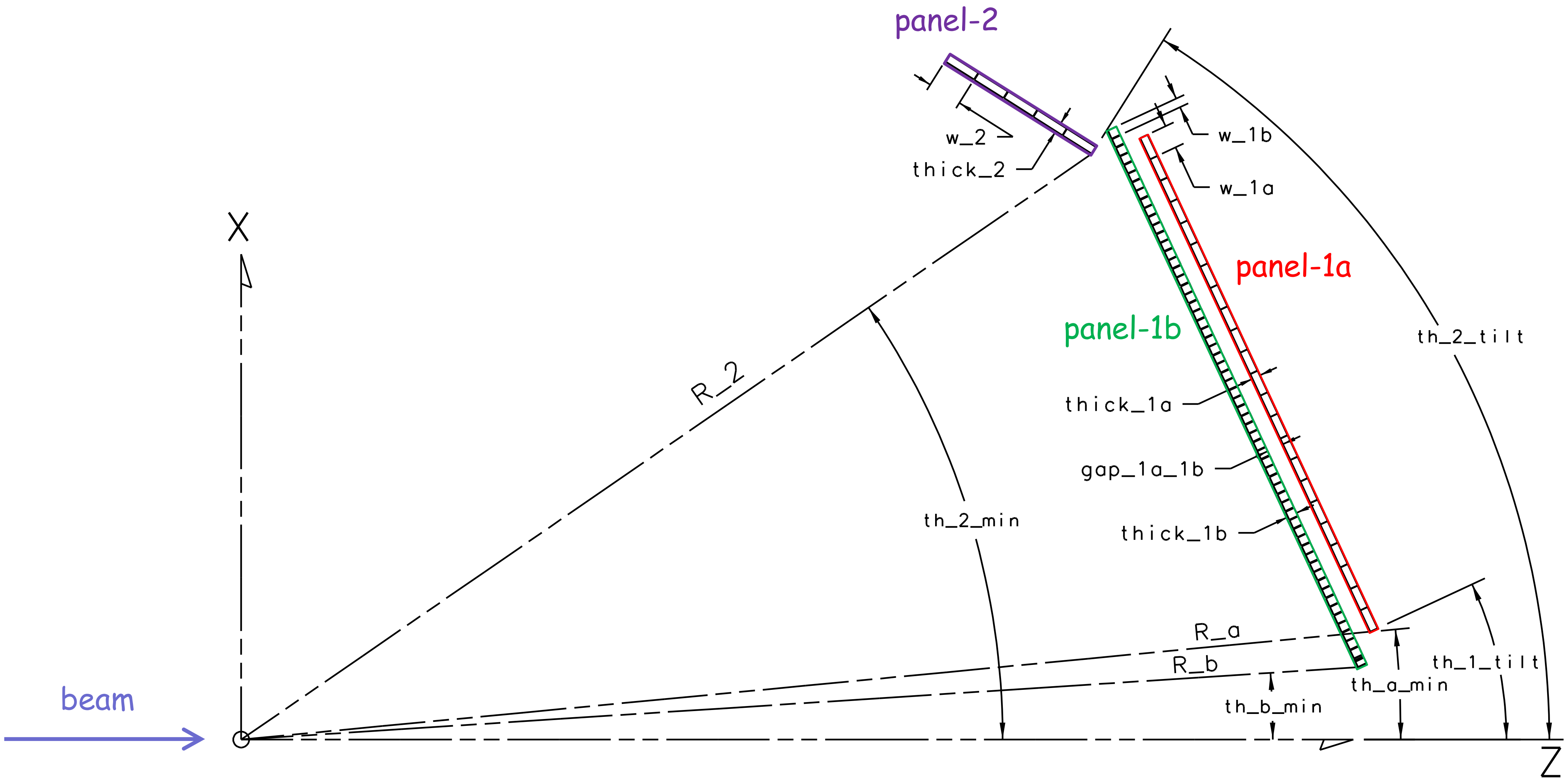
FORWARD

- High Threshold Cherenkov
- Forward Tagger
- Drift Chambers
- Low Threshold Cherenkov
- Ring Imaging Cherenkov
- Forward Time of Flight
- EM Calorimeter



	Forward	Central
Angular coverage	$5^{o} - 35^{o}$	$35^{o} - 135^{o}$
Momentum resolution	$\delta p/p < 1\%$	$\delta p/p < 5\%$
θ resolution	1 mrad	5 – 10 mrad
ϕ resolution	1 mrad/sinθ	5 mrad/sinθ

FTOF System Overview



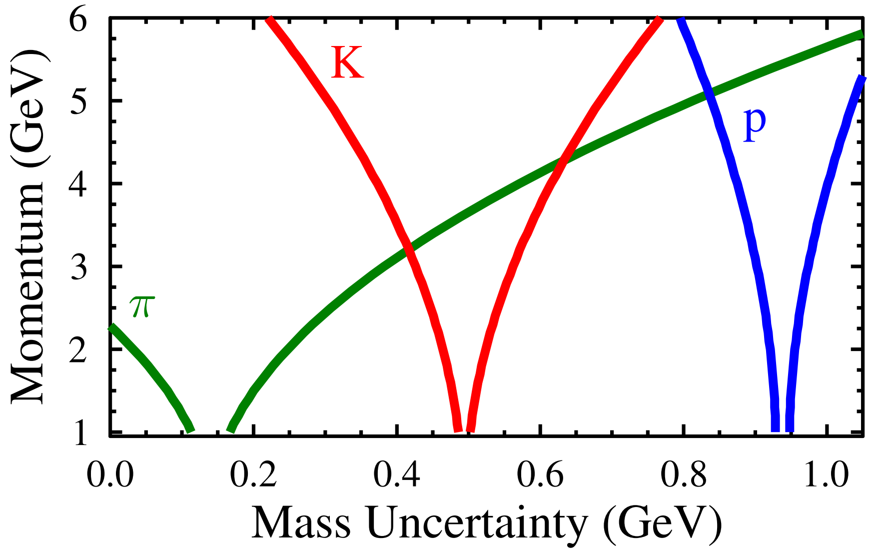
FTOF Mass Resolution

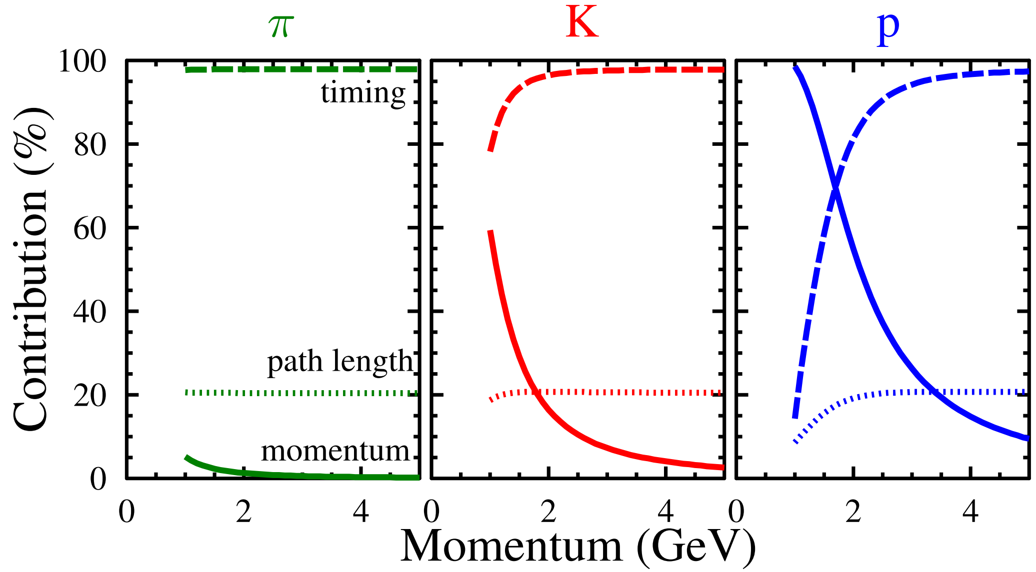
CLAS12 charged hadron identification below 5 GeV in the forward direction relies on the FTOF system

- Nominal (average) timing resolution is 80 ps
- Path length uncertainty of 5 mm from target to FTOF hit is 5 mm
- DC track momentum uncertainty is 1%

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta p}{p}\right)^2 + \gamma^4 \left[\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2\right]$$

with $m = \frac{p}{\beta\gamma}$

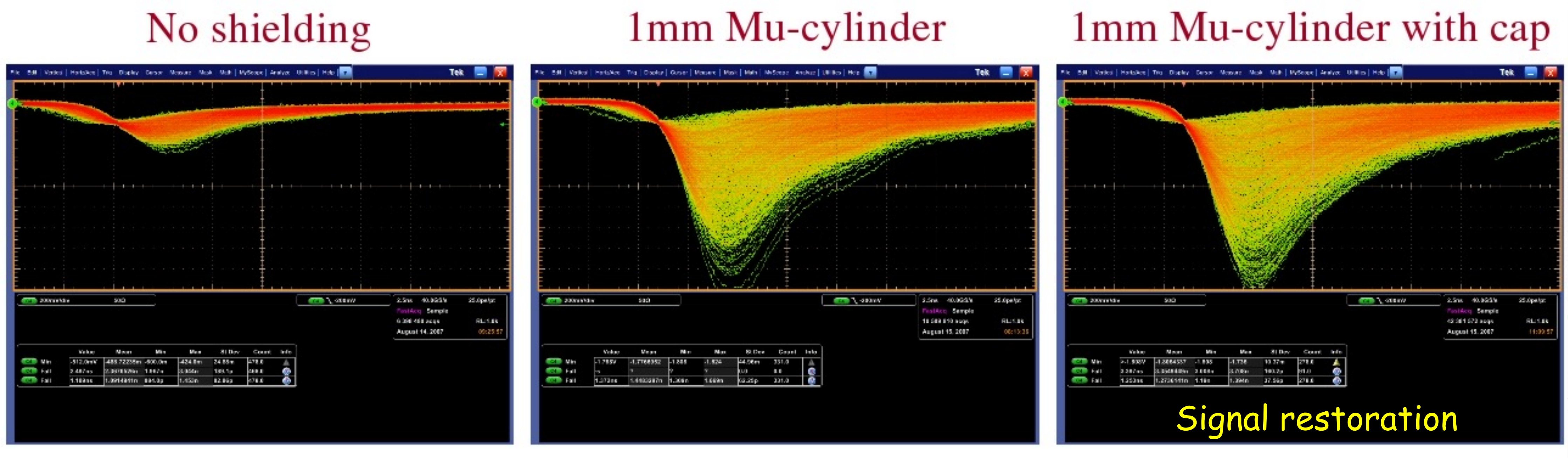




Magnetic Shielding

TOSCA calculations show field at PMT location < 30 G (mostly axial)

10 G Axial Field



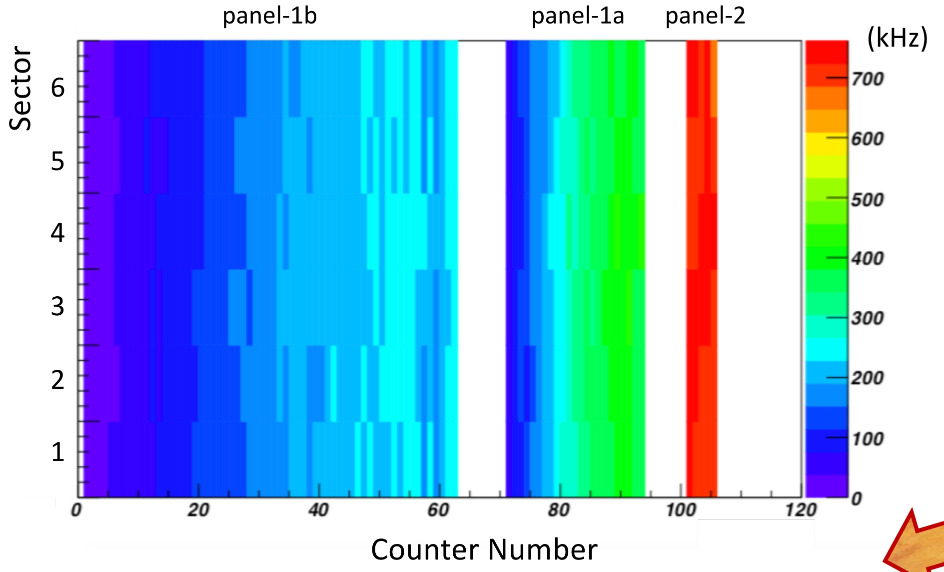
Axial Fiel

Transverse Field	Shielding in tube is enough	Shielding in tube is enough	Additional shielding required

Tests with nominal PMTs 0.2 mm μ-metal

EXPLODED VIEW

FTOF Rate Studies

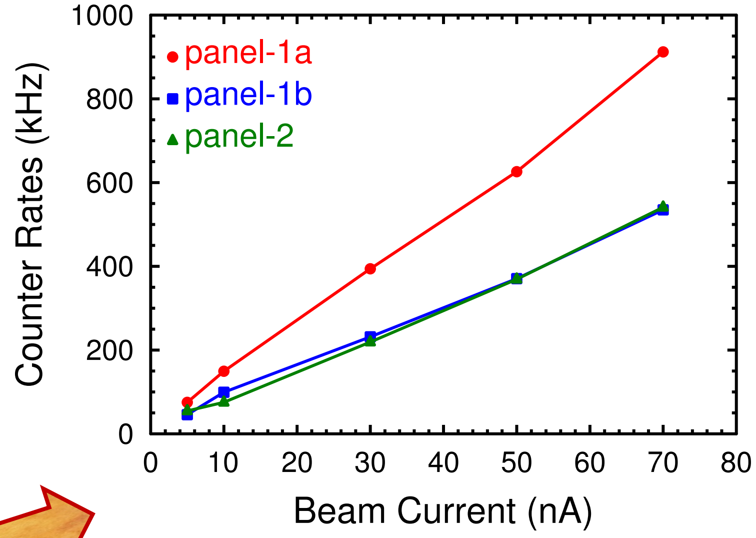


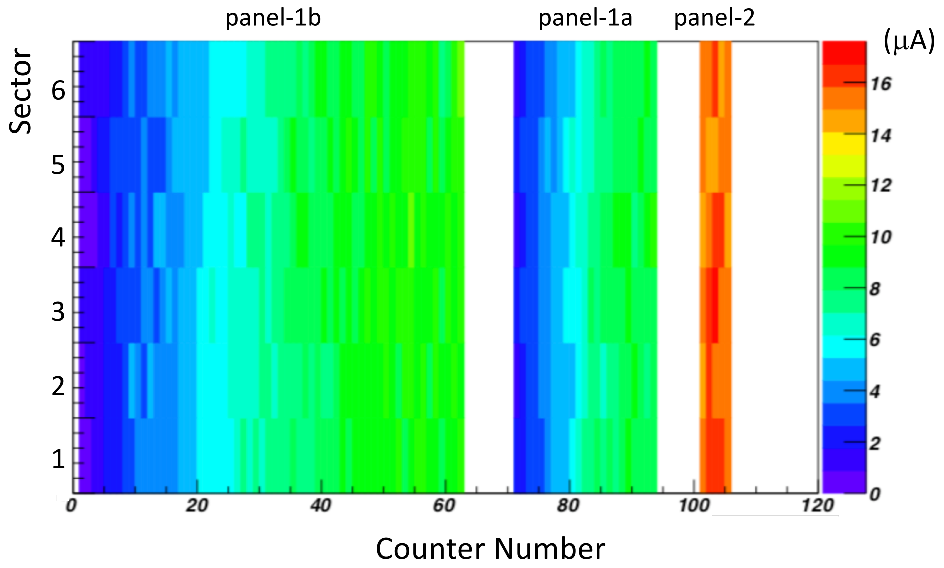
GEMC simulations:

- $\mathcal{L} = 10^{35}\ cm^{-2}s^{-1}$

(i=70 nA on 5-cm LH_2)

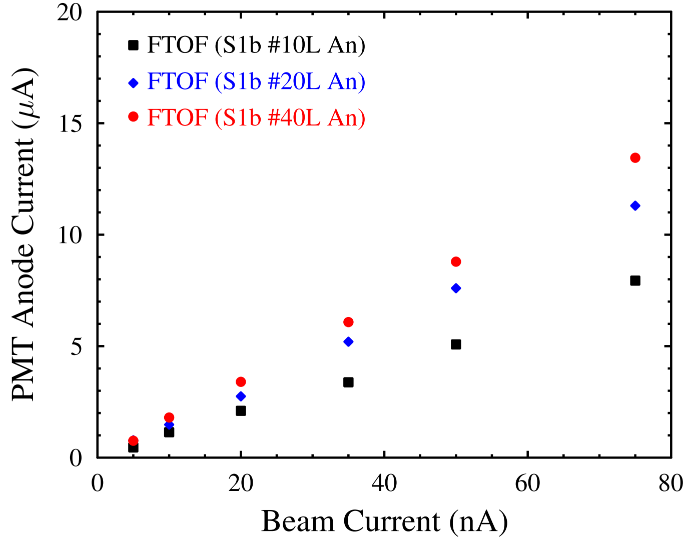
- E_b = 10.6 GeV
- 1 MeV threshold





Data Measurements:

- E_b = 10.6 GeV
- 5-cm LH_2
- 1 MeV threshold



Optimizing FTOF Time Resolution

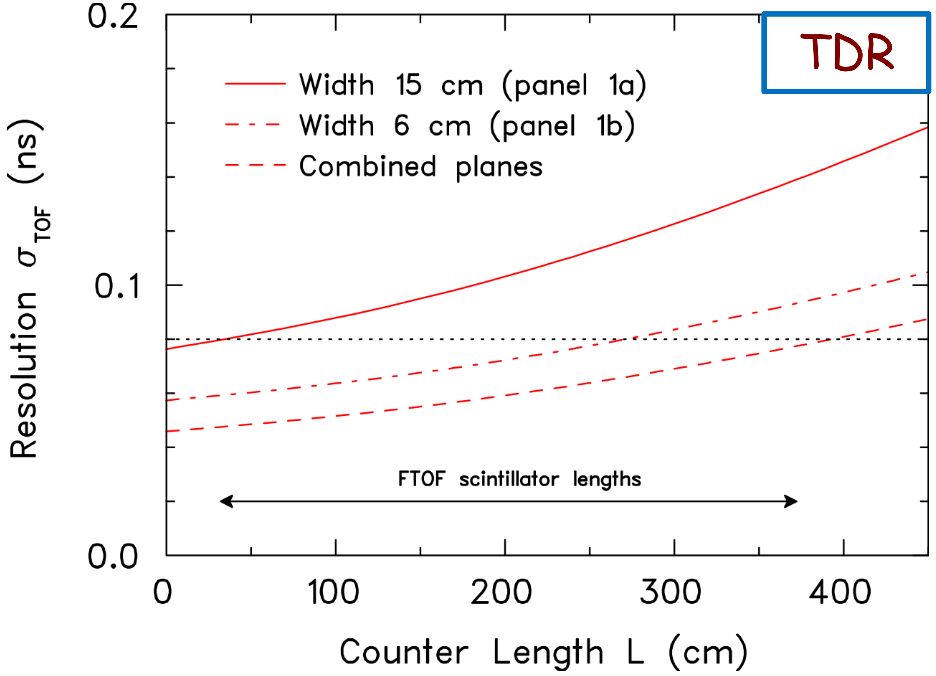
Combine the measured times from the FTOF panel-1a and panel-1b to optimize the resolution

$$t_{corr} = \frac{\frac{t_{1b}^{cluster}}{\delta_{1b}} + \frac{(t_{1a}^{cluster} - \Delta r/\beta)}{\delta_{1a}}}{\left(\frac{1}{\delta_{1b}} + \frac{1}{\delta_{1a}}\right)}$$

Algorithms for cluster > 1:

- use hit with t_{min}
- use hit with E_{max}
- use weighted average

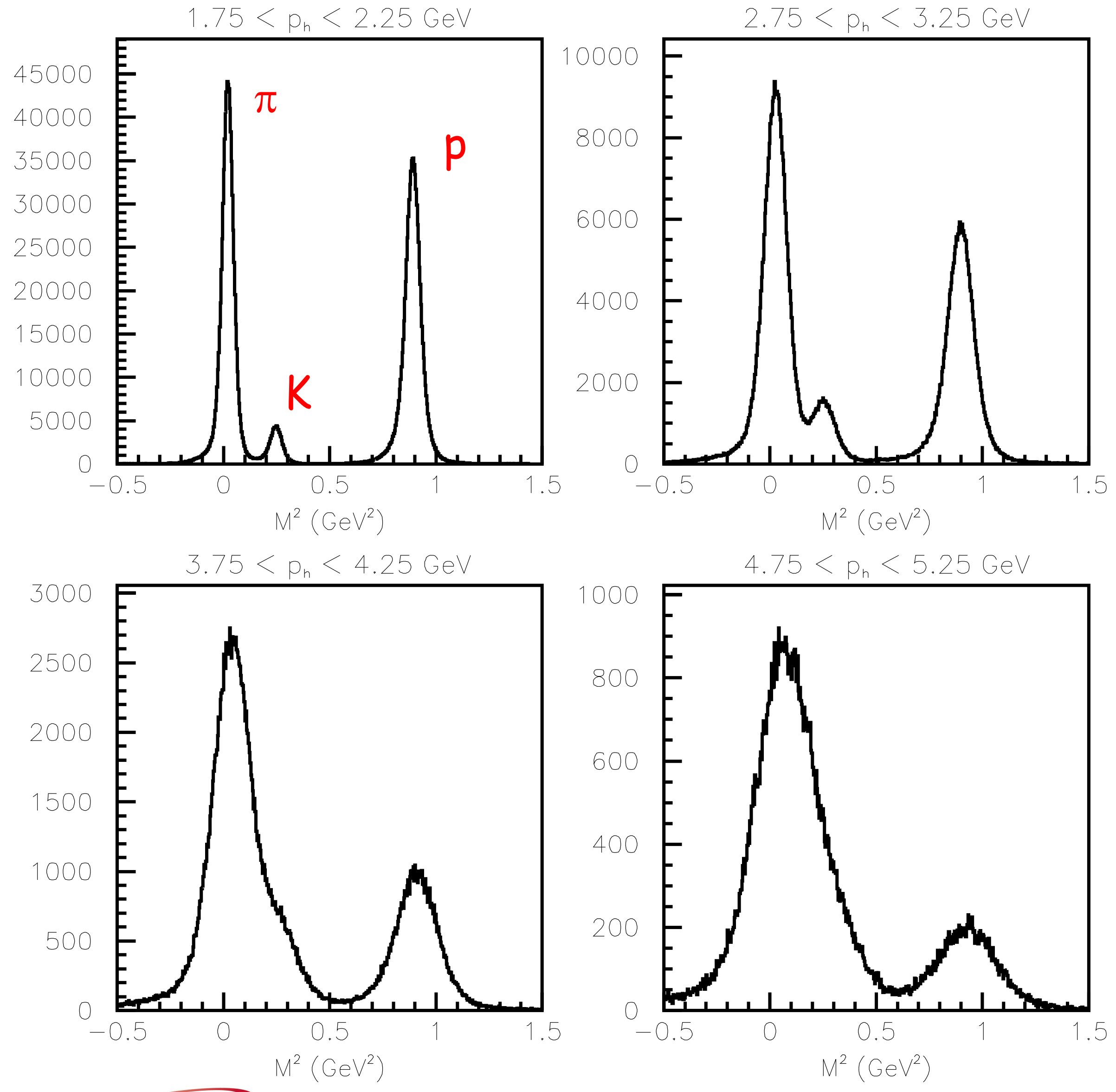
Upgrade to future EB PID



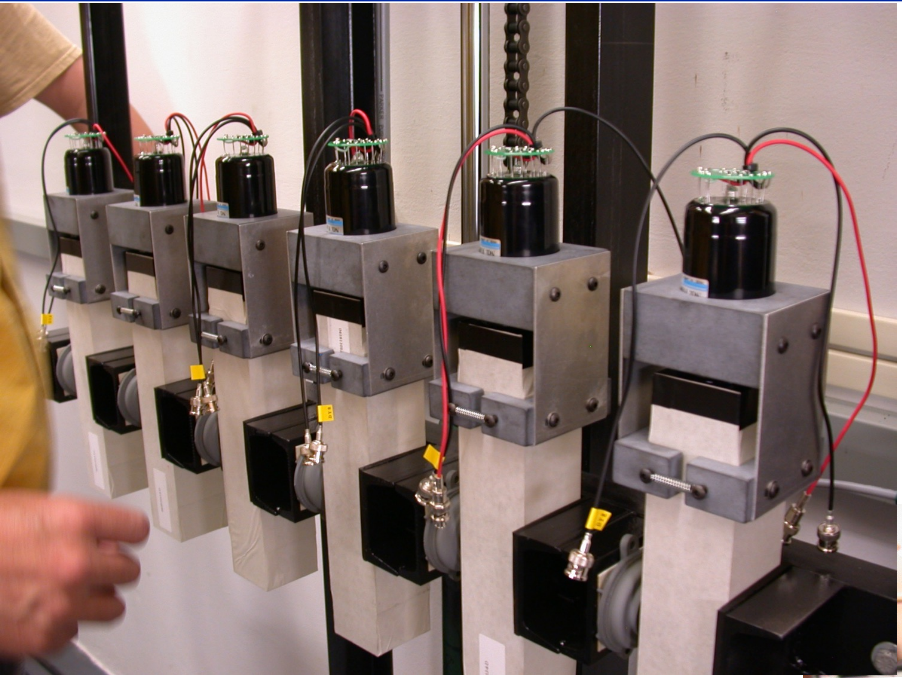
GEMC Studies with cluster=1

(20% gain)	e	p	π^+	π^-
FTOF 1a	152 ps	164 ps	160 ps	151 ps
FTOF 1b	62 ps	67 ps	65 ps	61 ps
FTOF 1a+1b	49 ps	54 ps	54 ps	51 ps

CLAS12 FTOF Performance



FTOF Panel-1b Assembly Area at USC



FTOF Panel-1b Assembly Area at JLab