eRD22 GEM-based Transition Radiation Detector

Yulia Furletova (and eRD22 team)

eRD22 team:

- Jefferson Lab:
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  - ✓ Cody Dickover
  - ✓ Yulia Furletova
  - ✓ Sergey Furletov
  - ✓ Lubomir Pentchev
  - ✓ Chris Stanislav
  - ✓ Beni Zihlmann
- University of Virginia
  - ✓ Kondo Gnanvo
  - ✓ Nilanga K. Liyanage
  - ✓
- Temple University
  - ✓ Matt Posik
  - ✓ Bernd Surrow
- Old Dominion University
  - ✓ Lee Belfore

Many thanks to the Hall-D and GlueX teams!(in particular Eugene Chudakov and Tim Whitlatch)

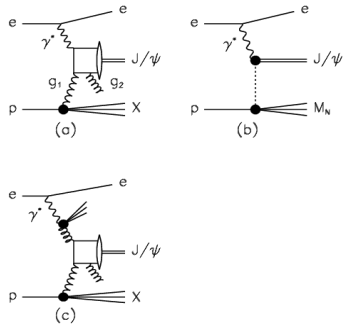
Electron identification (e/hadron separation)

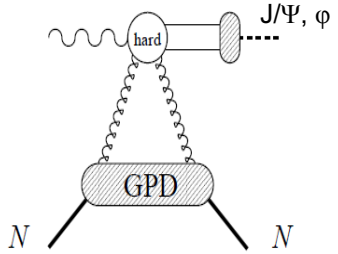
- **J/ψ identification**

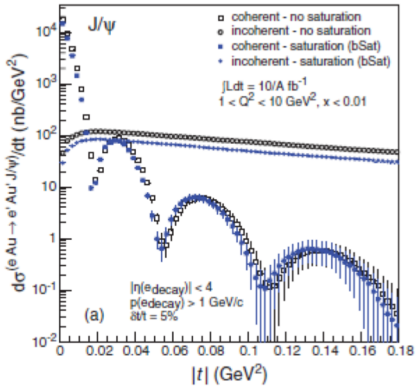
VM production

Br (J/ψ->e+e-) ~6%

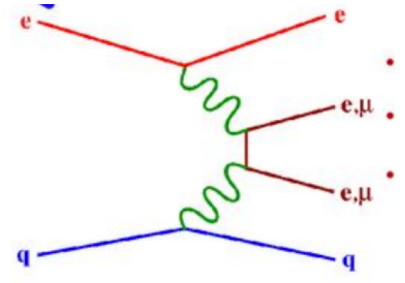
Br (J/ψ->μ+μ-) ~6%







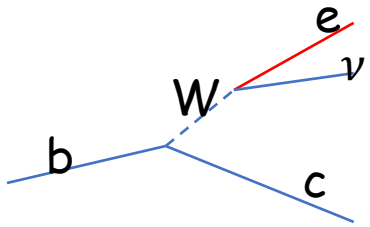
- **Multi-leptons**

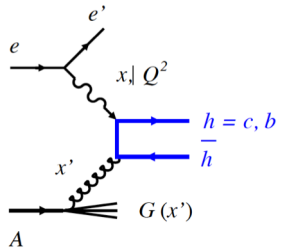


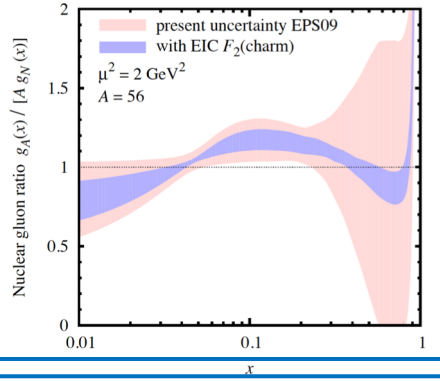
- **Heavy quark tagging**

Br ($D^{\pm}$->e+X) ~16%

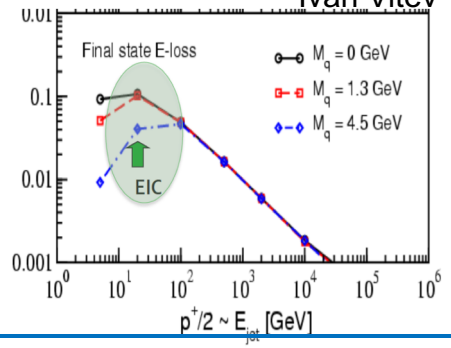
Br ($B^{\pm}$->e+ν+X_c) ~10%

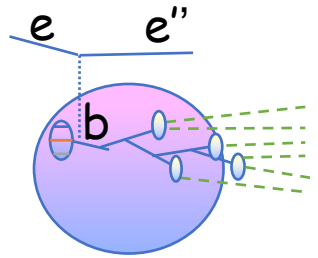




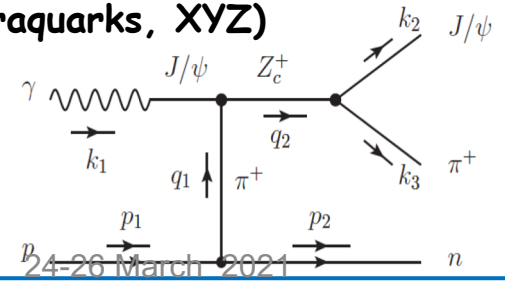


Ivan Vitev

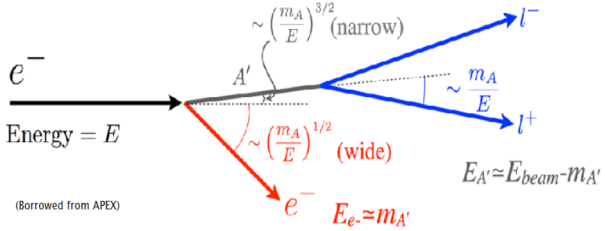




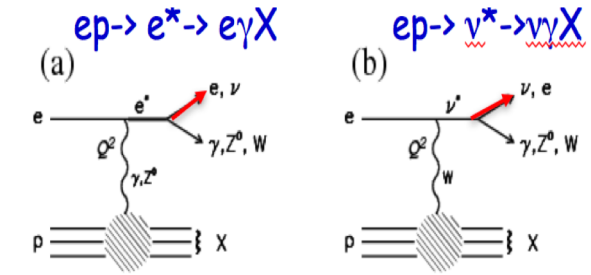
- **Exotic spectroscopy (pentaquarks, tetraquarks, XYZ)**



- **Heavy photon**

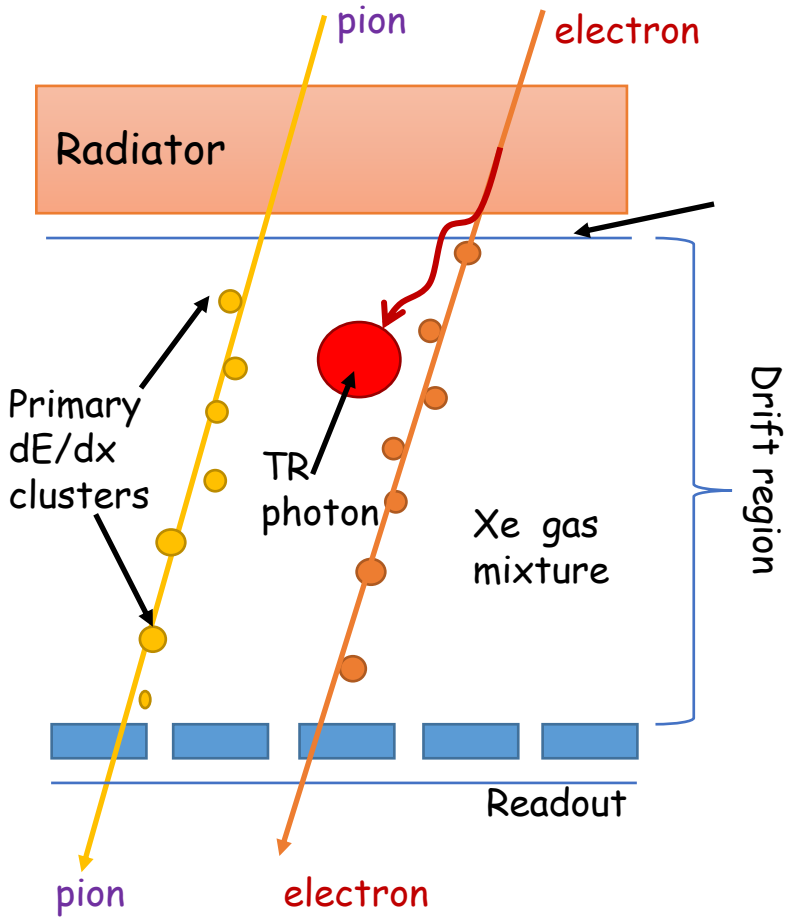


- **Other BSM physics**



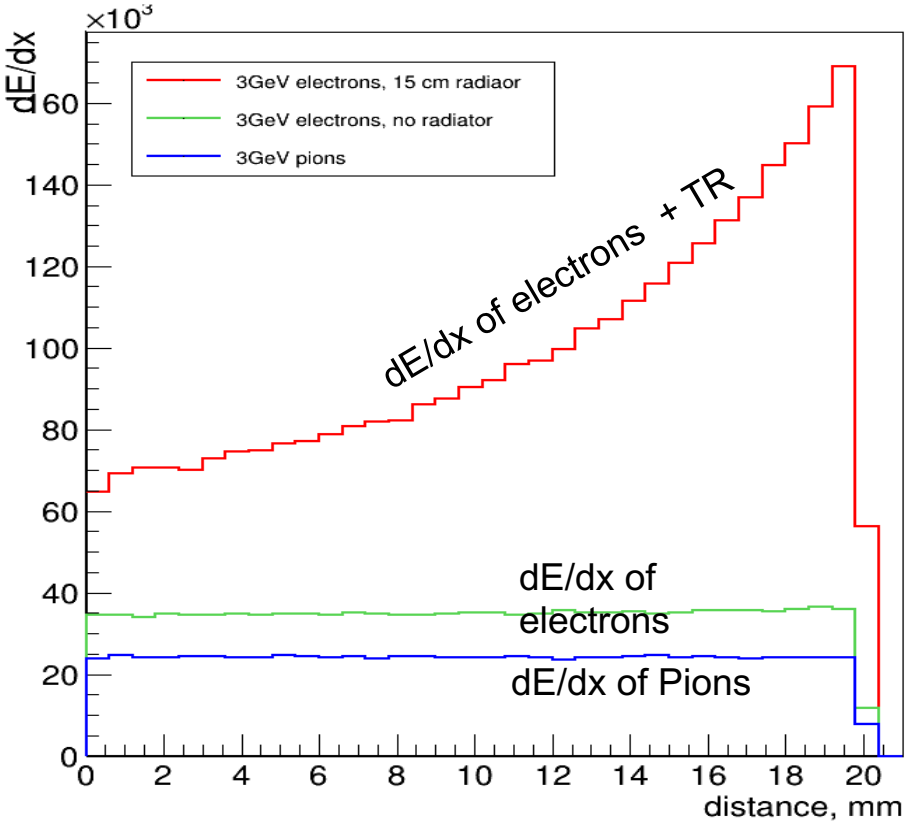
GEM as Transition Radiation detector and tracker for EIC (eRD22)

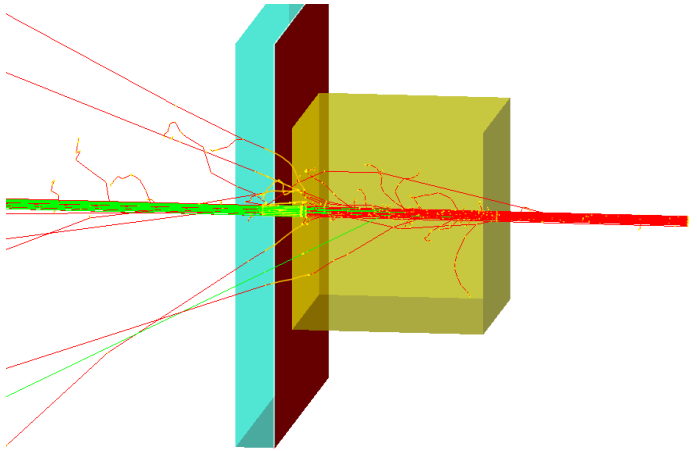
- High resolution tracker.
- Low material budget detector (tracker)
- How to convert GEM tracker to TRD:
  - ✓ Change gas mixture from Argon to Xenon (TRD uses a heavy gas for efficient absorption of X-rays)
  - ✓ Increase drift region up to 2-3 cm (for the same reason).
  - ✓ Add a radiator in the front of each chamber (radiator thickness ~5-10cm)
  - ✓ Number of layers depends on needs: Single layer could provide e/pi rejection at level of 10 with a reasonable electron efficiency (85-95%).



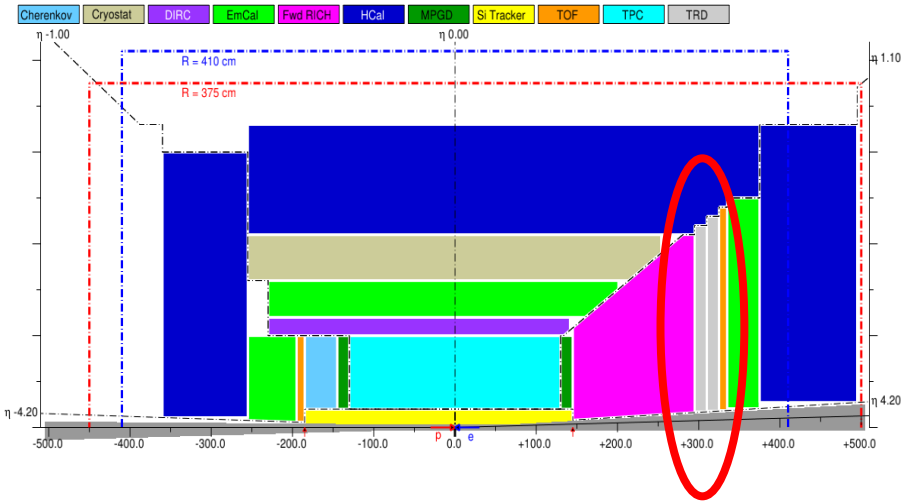
GEANT4: electron and pion comparison

Energy deposition (dE/dx + TR) vs drift distance





e,π ~3 GeV



Implemented in g4e

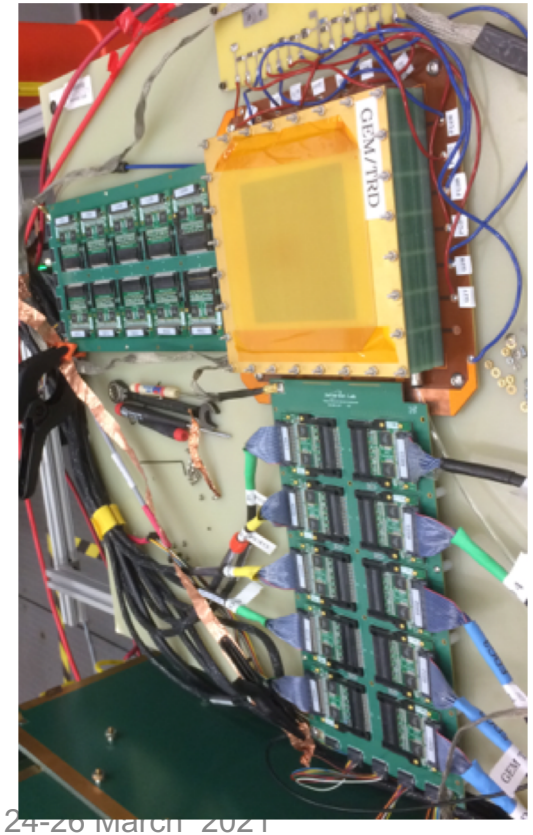
Parameters:

- ✓ Detector Gas Thickness (D) : 1 – 4 cm
- ✓ Radiator Thickness (R): 3-10 cm
- ✓ "Dead region":
  - ✓ cathode material(Al, Cu, Cr)
  - ✓ gap (Xe filled) 400um
- ✓ Gas mixture: Xe/CO_2 , Ar/CO_2 …
- ✓ # layers:1,2,3 …

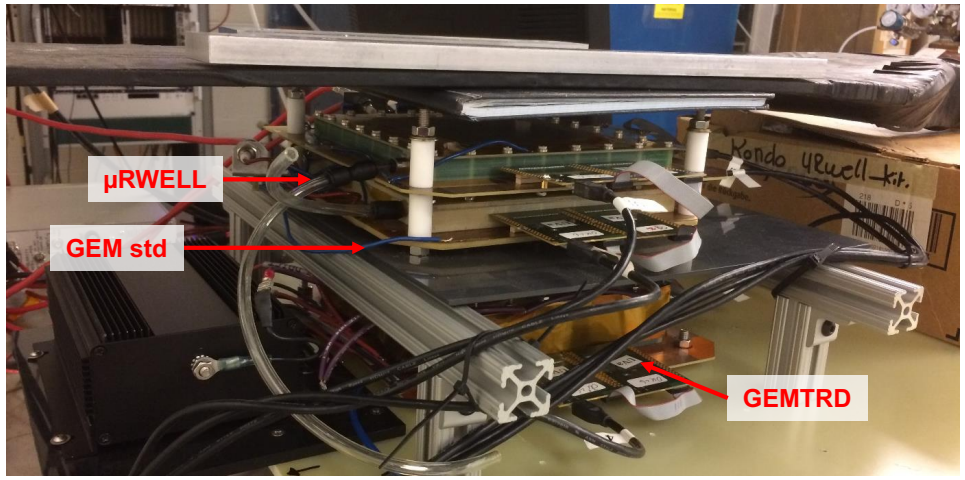
Prototypes

-10x10cm^2 prototypes assembled at Uva

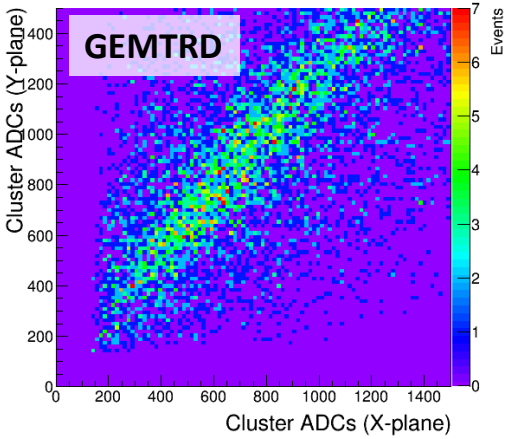
-Assembly and X-ray/cosmic tests of each prototype
-Noise, pedestal tests



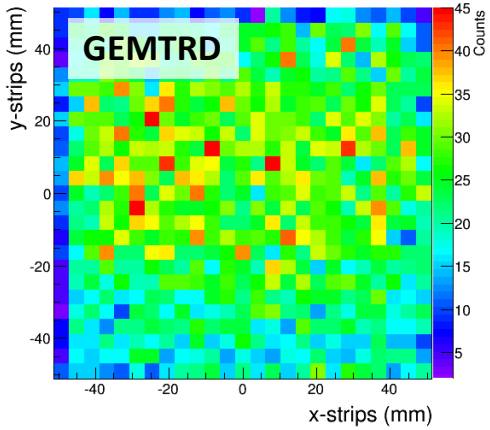
GEMTRD Test in cosmic setup @ UVa

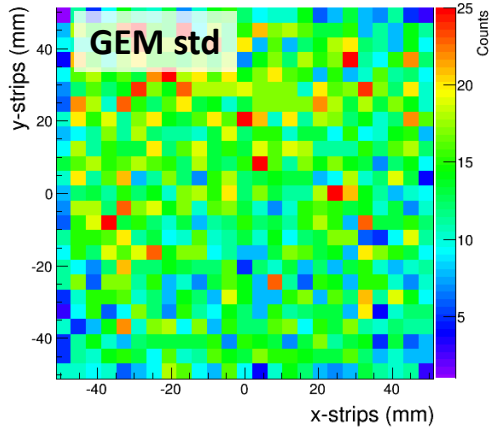


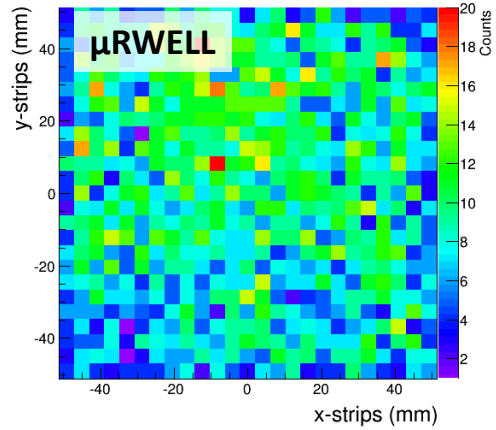
X-Y charge sharing



Reconstructed position hit map

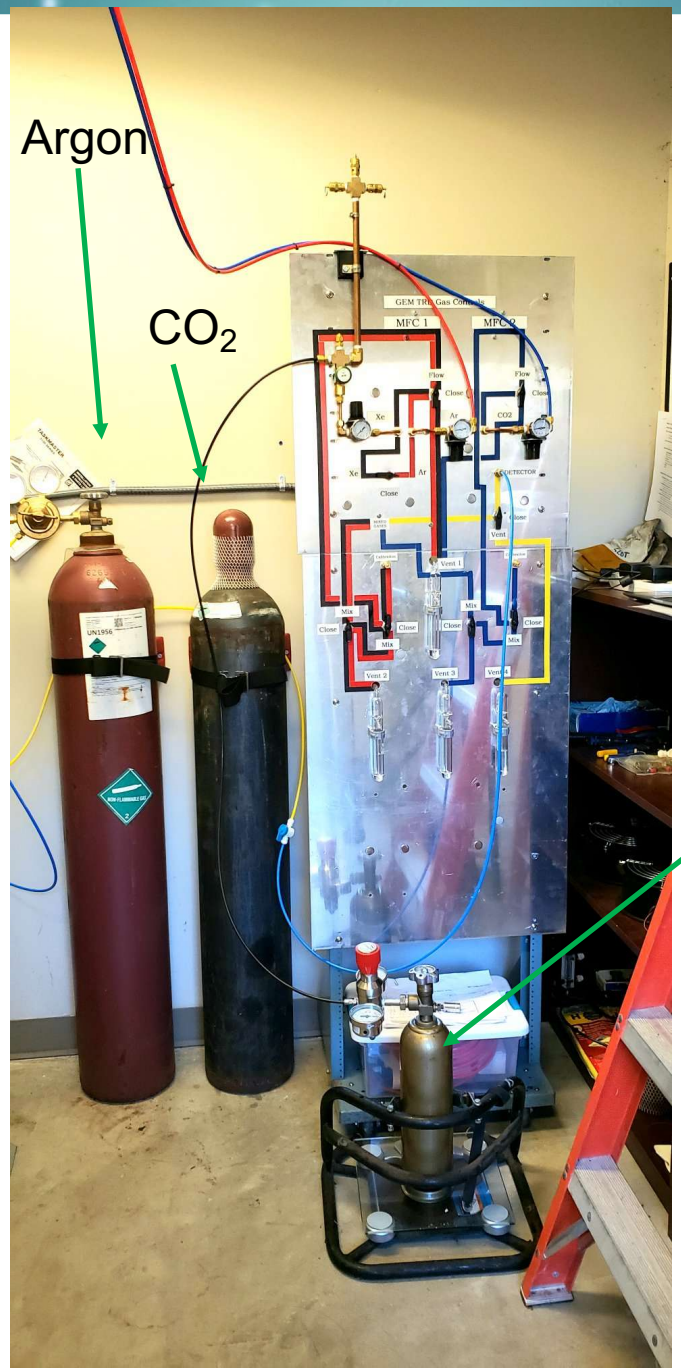


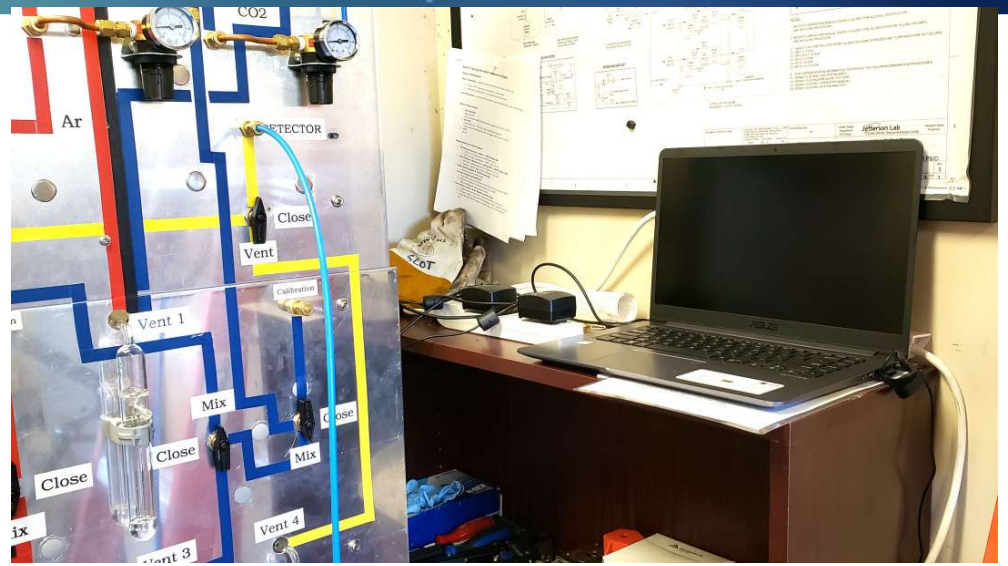




Gas system

- Assembled at Temple U.
- Delivered to JLAB (hall-D) in Jan 2019
- Approved for a safety and operation under pressure (took a bit longer due to the DIRC installations)





Gas system:

- Without a re-circulation and a purification system (too early stage of R&D)
- Gas mixing system
- Flow controller, CO_2 controller

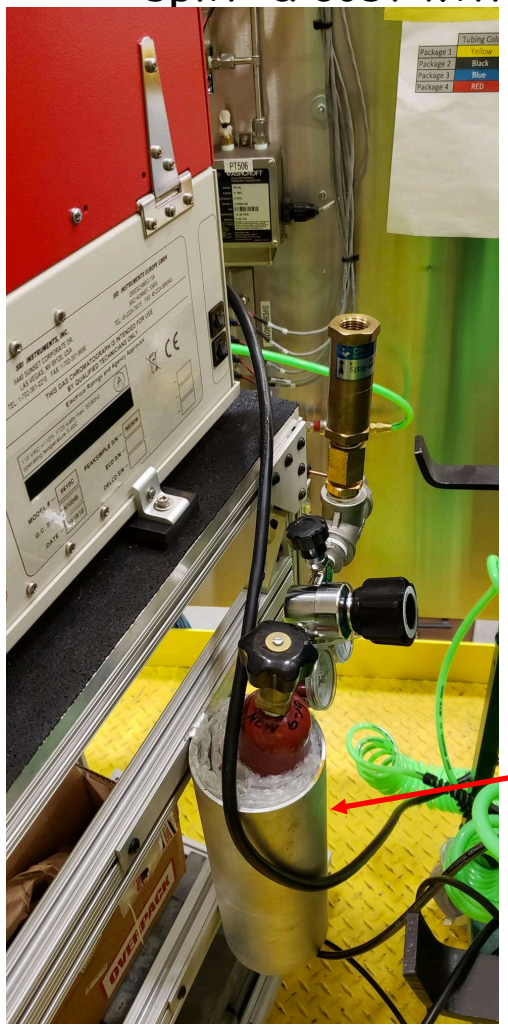
Gas mixing setup:
Xenon/CO2: 80/20 percent.

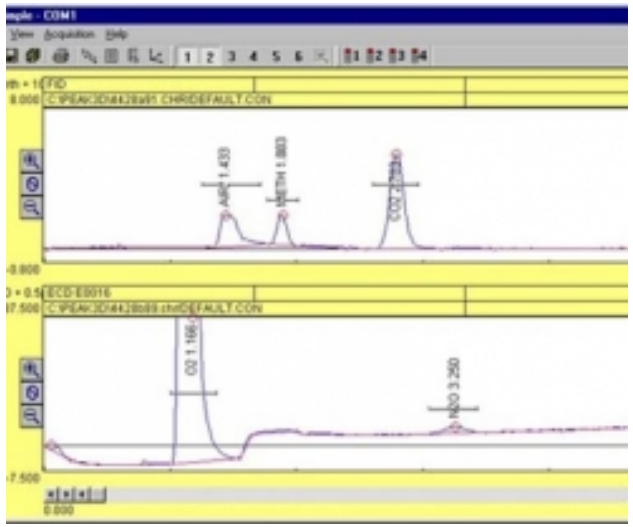
- Small Xe-gas bottle : $8k ! (need a good planning!!!)

Gas quality monitoring system

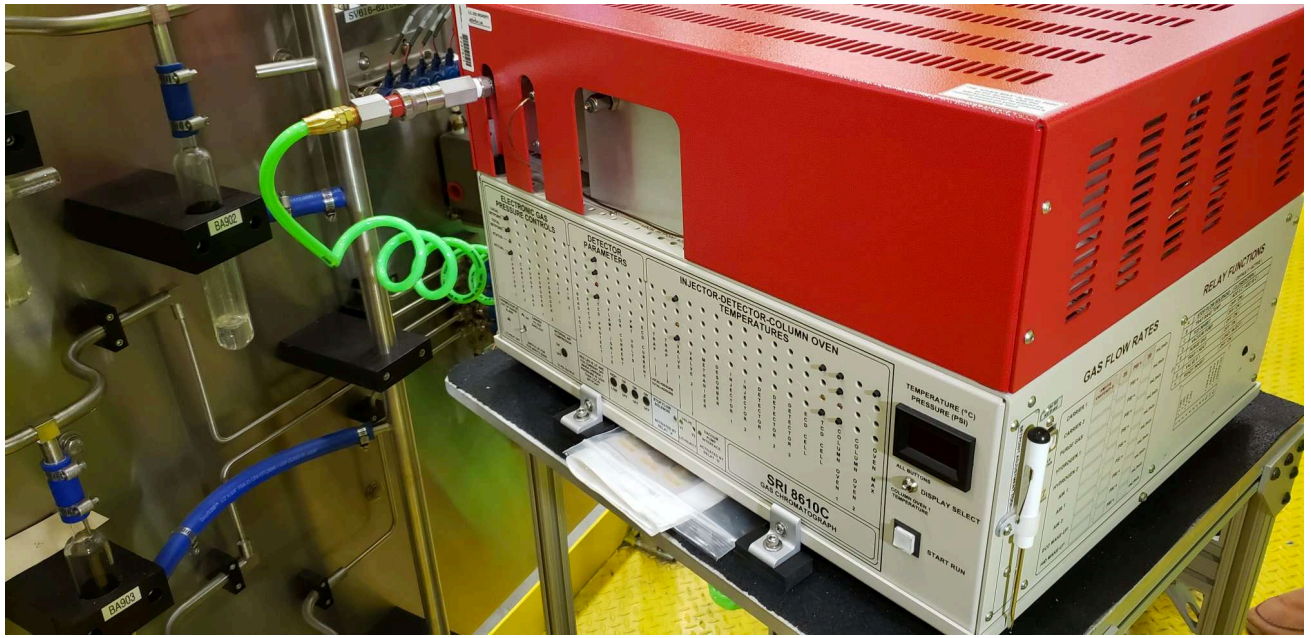
We purchased gas analyzer to begin quantifying and monitoring contaminations and to measure the concentrations of the Xe and CO_2 gasses.

-> split a cost with Hall-D : our contribution $7k (40%) to extend up to Xe





Helium gas as carrier

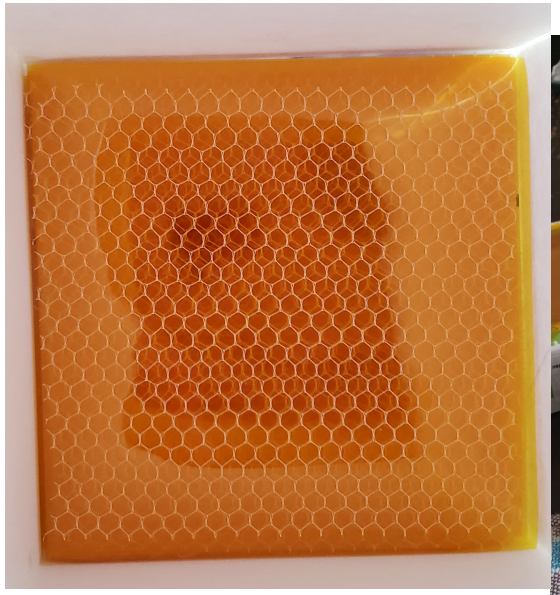


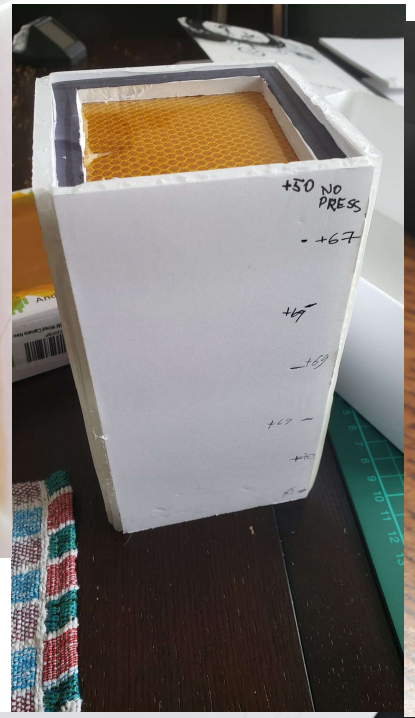
SRI 8610C

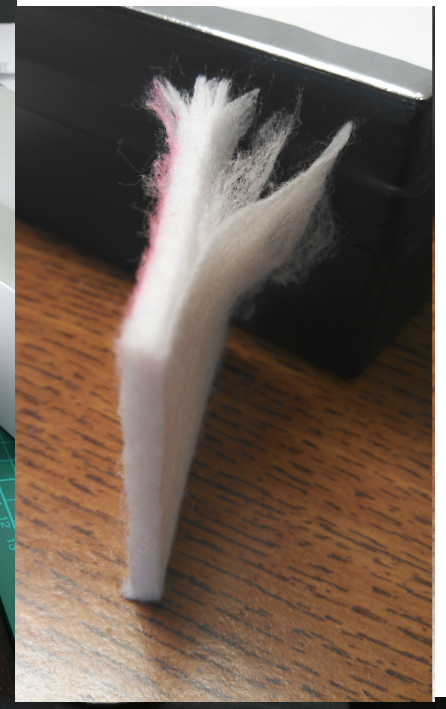
Different TR-radiators.

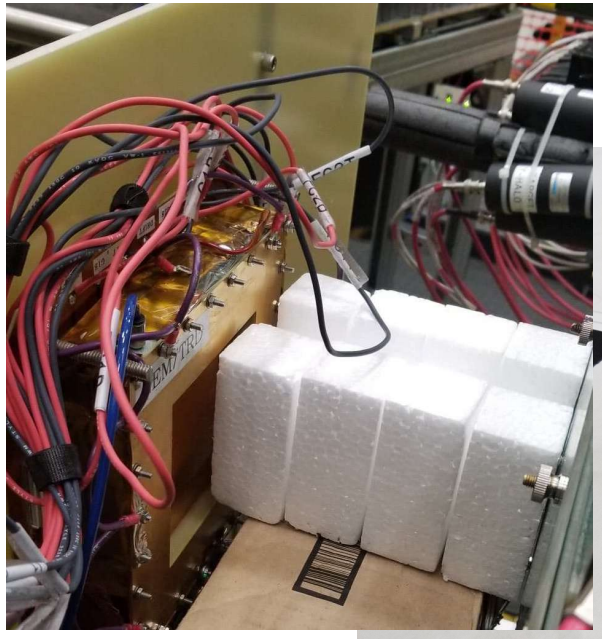
- We continue to search and test different types of radiators
- Goal: to find low material budget, but high TR-yield radiators
- The TR-energy spectrum is very important (minimum of self-absorption)

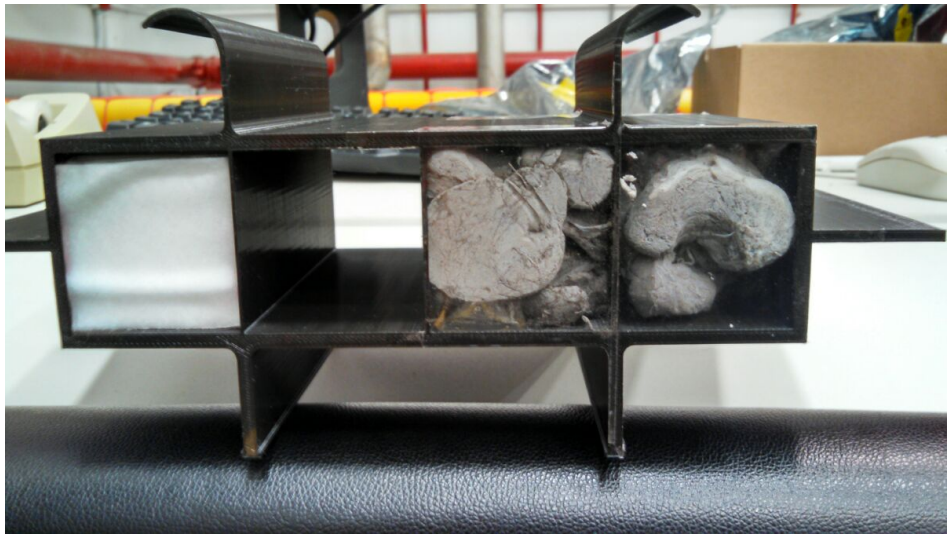
Single module (X/X0) :
Radiator (10cm) ~ 1.5 % X_0 for fleece (could go down with mylar foils)
Xenon gas (2.0 cm) ~ 0.1% X_0
Triple GEM with readout at active area ~ 0.7% X_0
(could go down to 0.4%, see current eRD6)

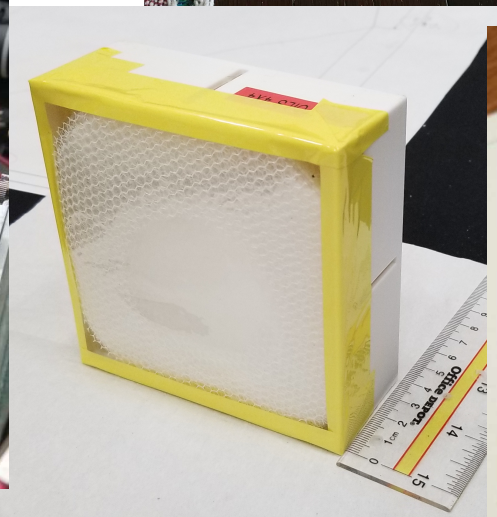






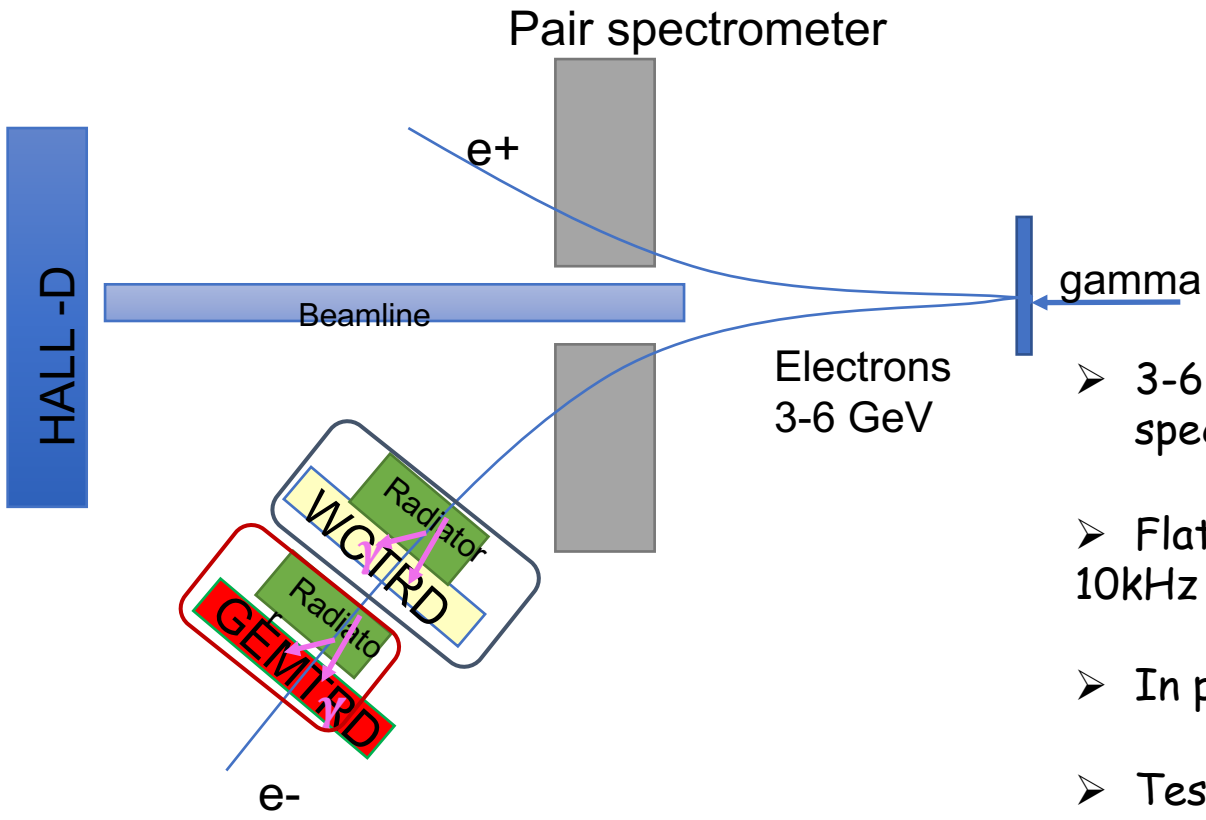


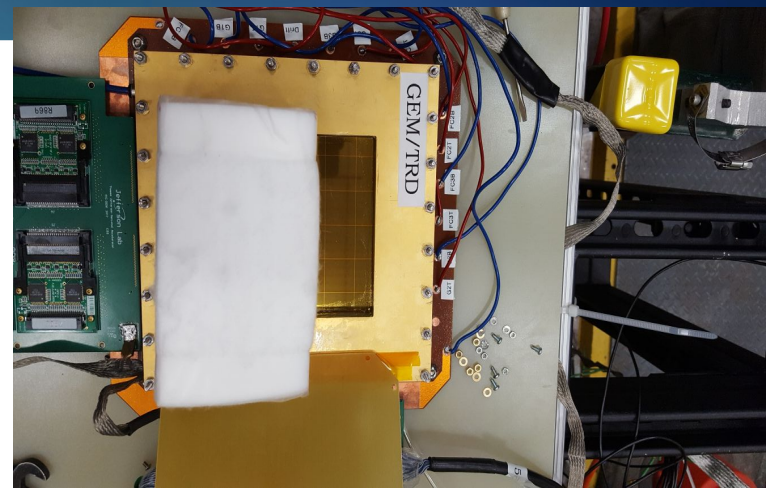


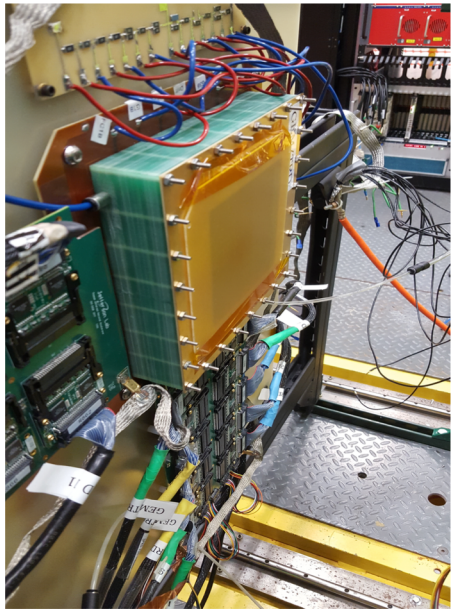


Test at the pair-spectrometer location

Outside of the Glue-X acceptance







- 3-6 GeV electrons in Hall-D from pair spectrometer
- Flat beam: in-plane(y spread ~ 5mm) 10kHz rate
- In parallel with other tracking detectors.
- Test with Ar/CO_2 and Xe/CO_2 mixtures
- Different radiators
- covered $\frac{1}{2}$ of the sensitive area with radiator (to compare with and without radiator)

Dedicated runs with GlueX DIRC (Feb-Mar 2020)

To measure a real e/π rejection factor we need a pion beam!!!

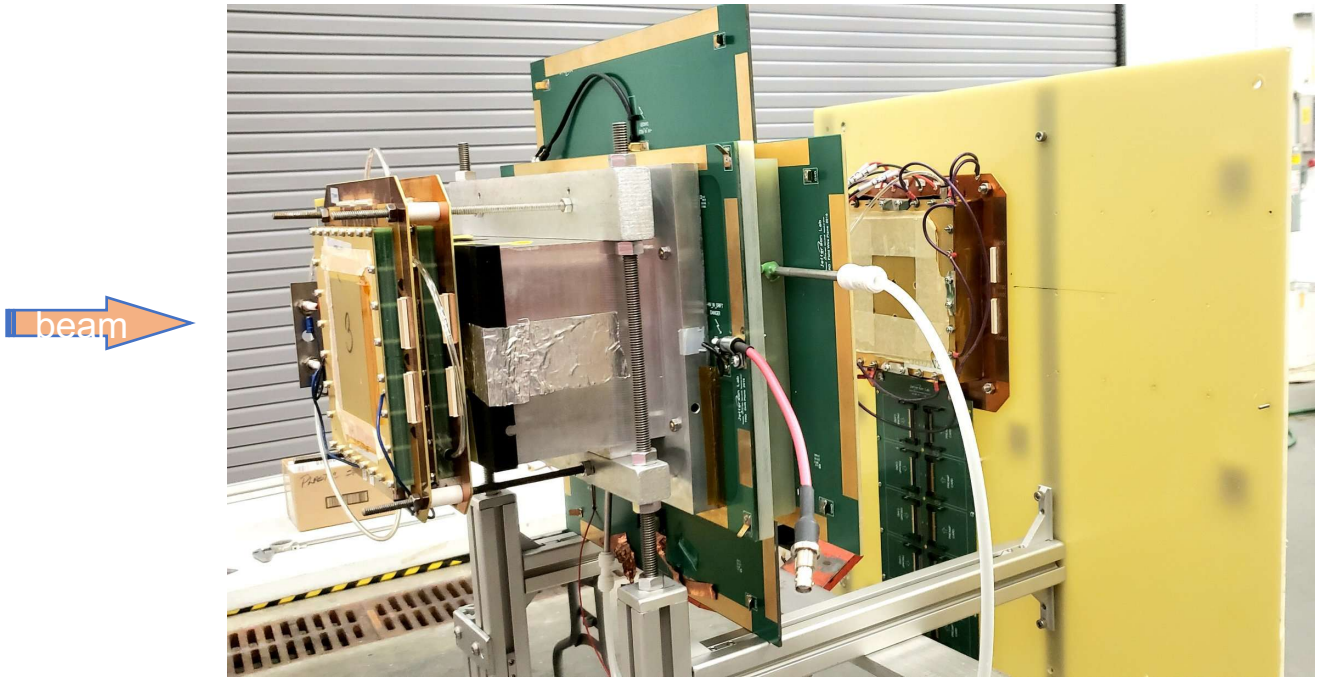
a) In collaboration with eRD6 we are working towards possible test beam at Fermilab
(Spring 2021 was cancelled due to COVID19 travel restrictions
=> hope to get it done during next year!)

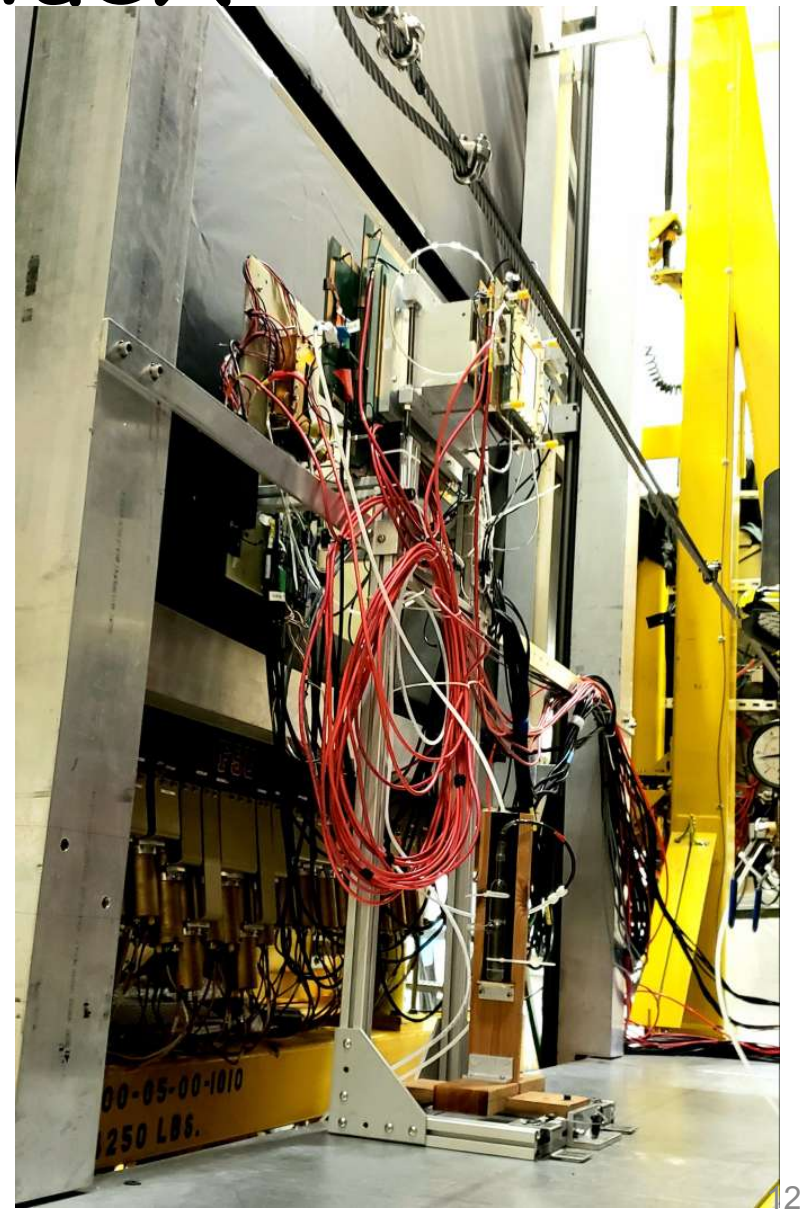
b) use pions from $\rho - meson$ decays (real GlueX/ Hall-D physics !)
Used dedicated/commissioning runs (with DIRC at Glue-X) .

- Installation of GEM-TRD setup in front DIRC detector (new mechanical support and alignment)
- Integration of GEM-TRD into GlueX DAQ
- Integration of GEM-TRD into the GlueX post-processing analysis.

GEMTRD test setup with GlueX

- Motivation:
- To check for real e/pi rejection (detector response on pions)
- Also important for DIRC (precise tracking in front of the detector)

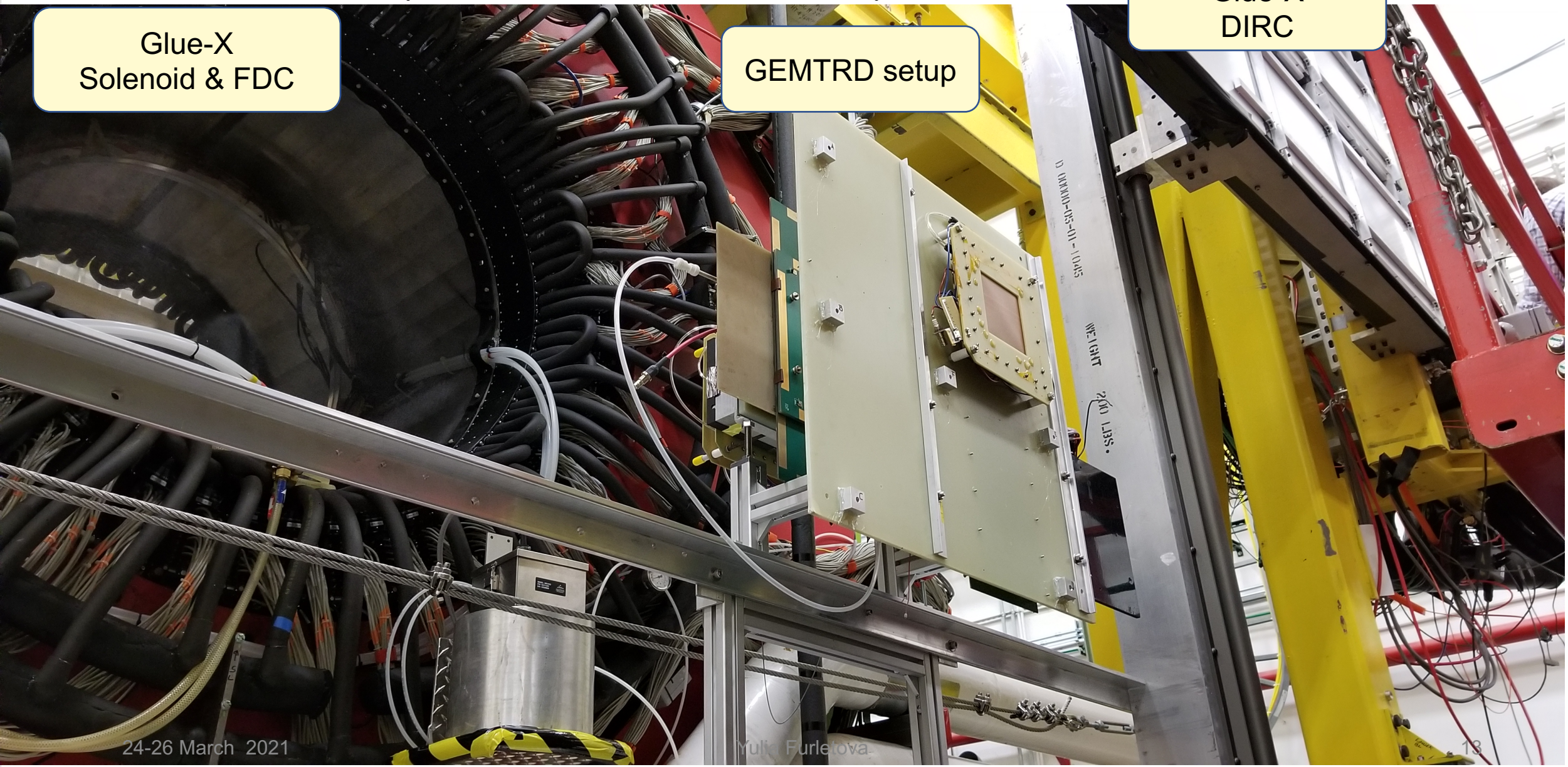




Setup: 5 tracking detectors(counting from the target): Standard GEM, uRWELL, TRD Multi wire chamber (TRD-MW), GEM-TRD, Standard GEM plane.

Yulia Furletova

GEMTRD setup at the GlueX experiment



COVID19 summer 2020 run

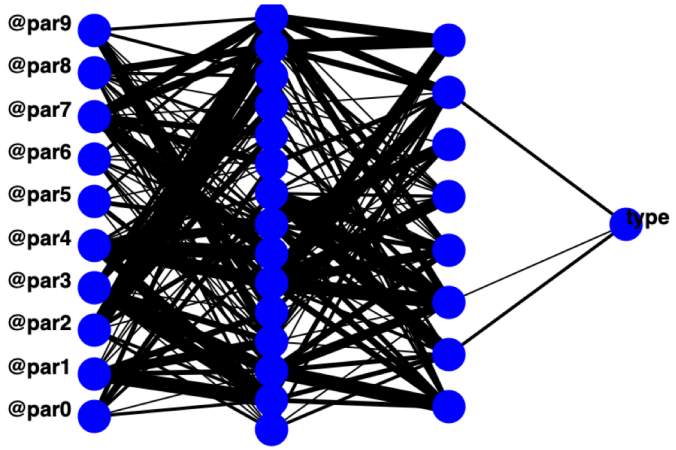
Due to the lab and facilities closures in March we were not able to finish our test

During this summer 2020 test with pions at the Glue-X location.

Currently postponed (planning to resume as soon as possible): a joint beam test with the EMCAL (eRD1) and mRICH (eRD14) to get global PID estimates.

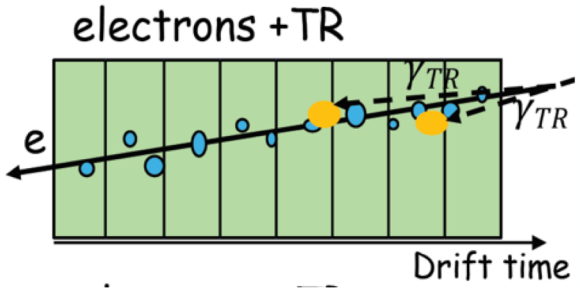
Moving GEMTRD/TRD setup to the DIRC location at GlueX (summer 2020)

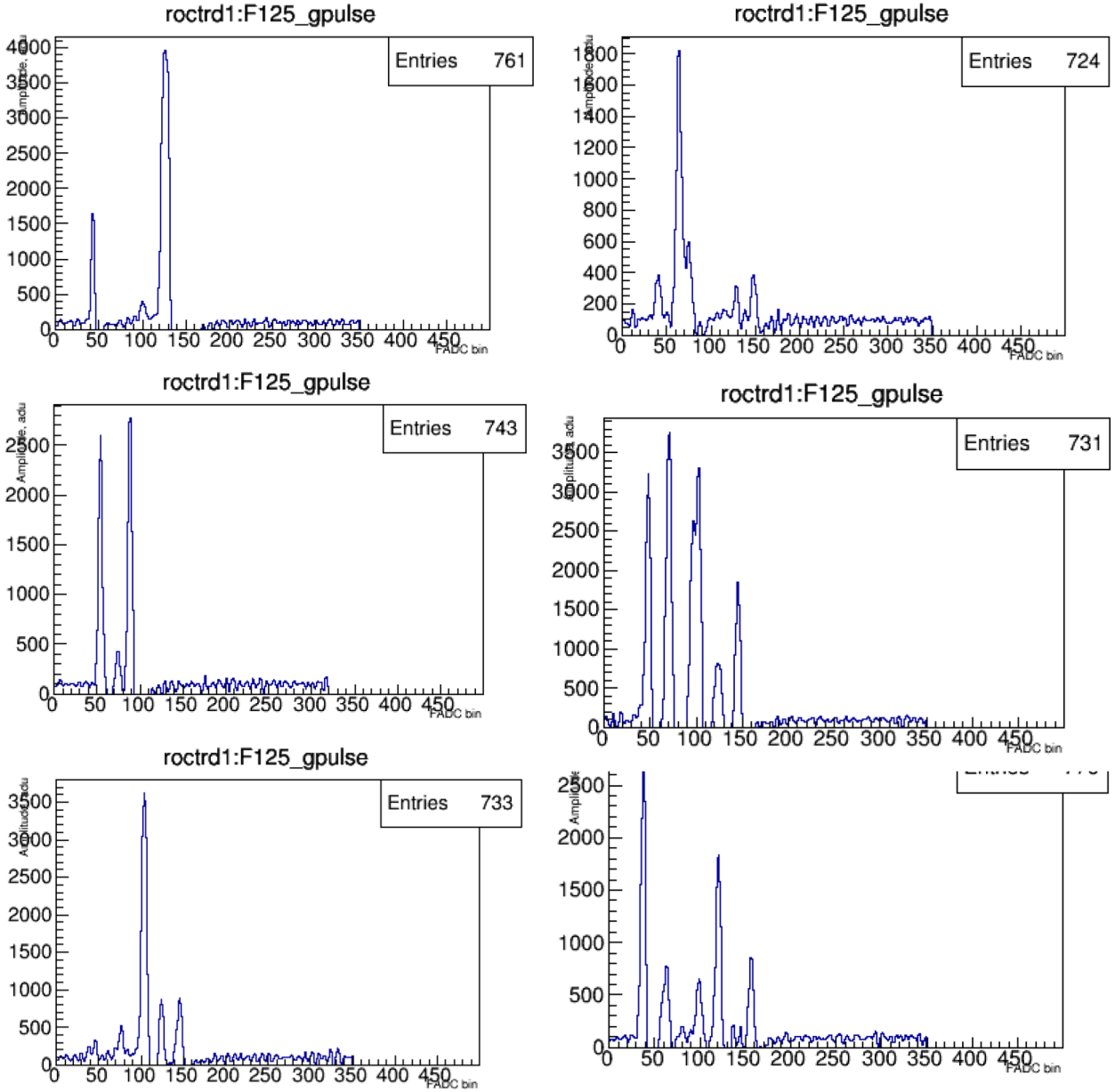
Machine learning technique



Used different methods/programs (JETNET, Root based-TMVA, etc) for cross-check.

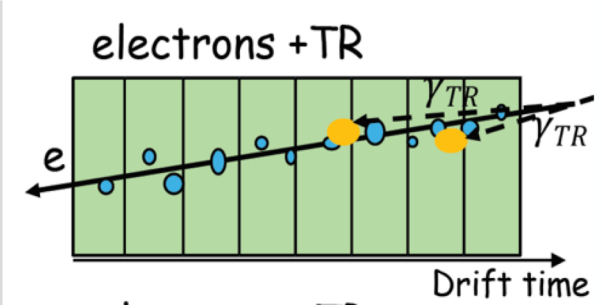
Cluster counting method (Time, Amplitude, number of clusters)

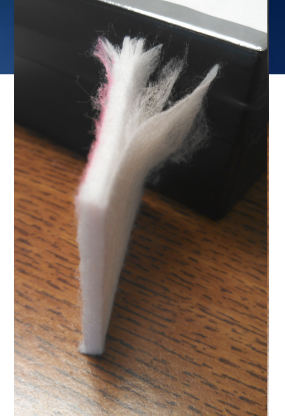


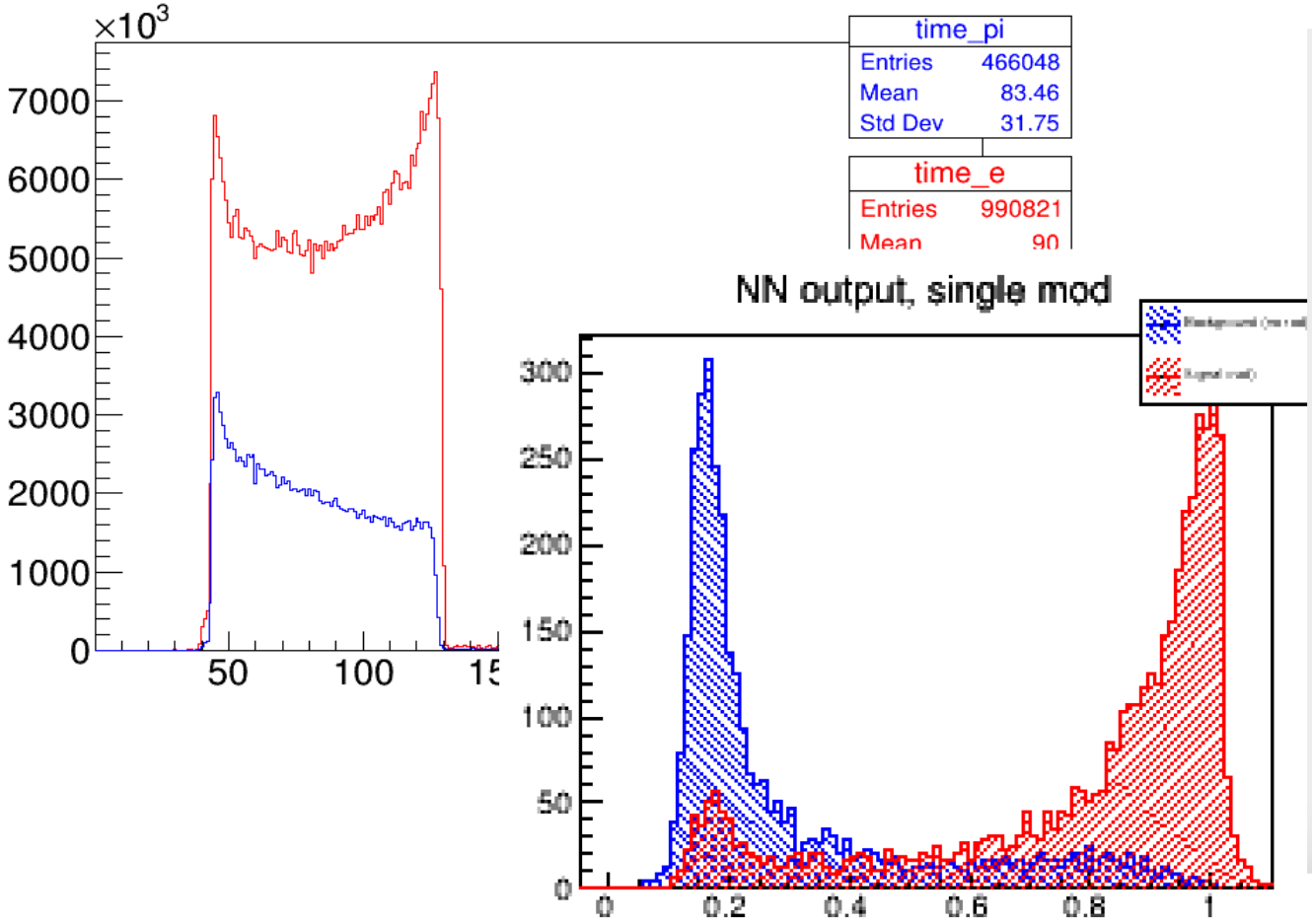


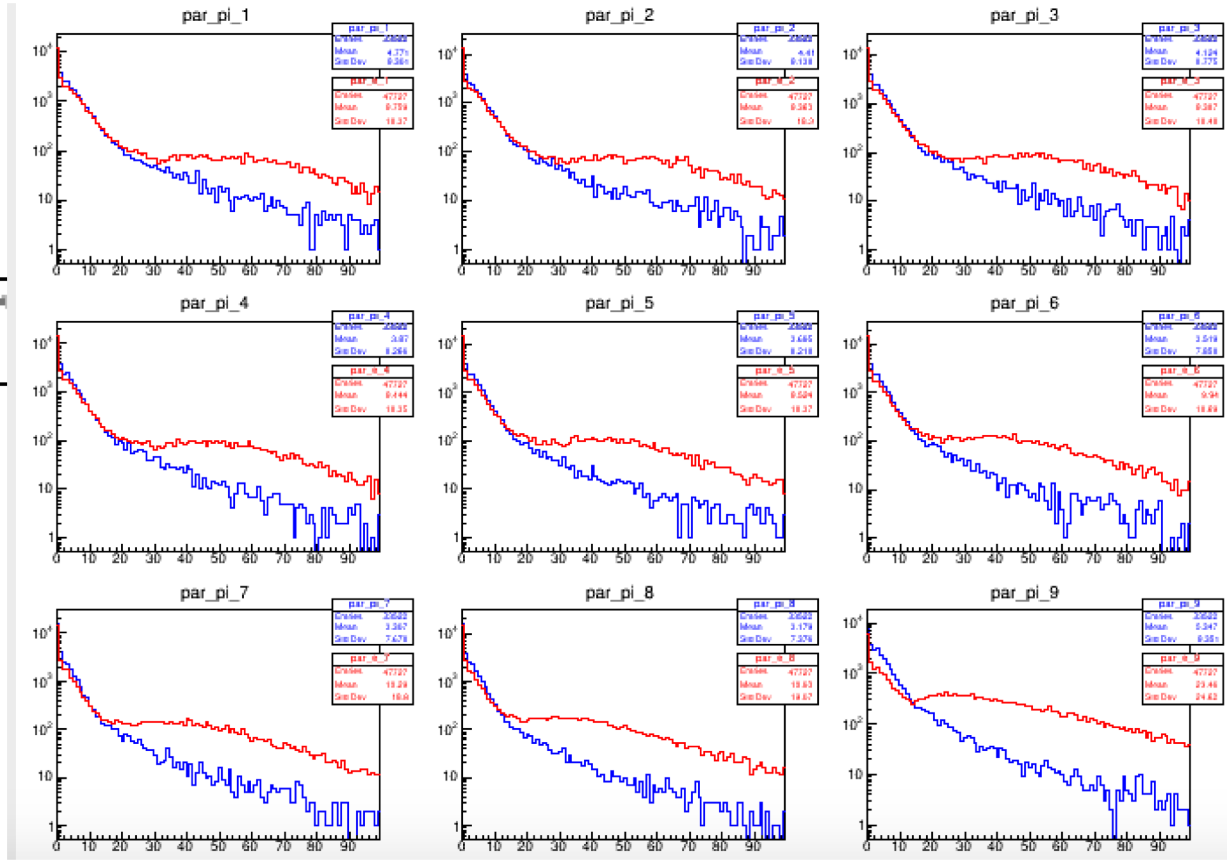
Results: Fleece

Beautiful response, High TR-yield, soft and hard TR photon's spectrum



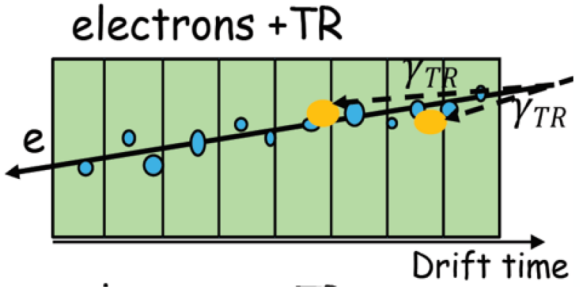


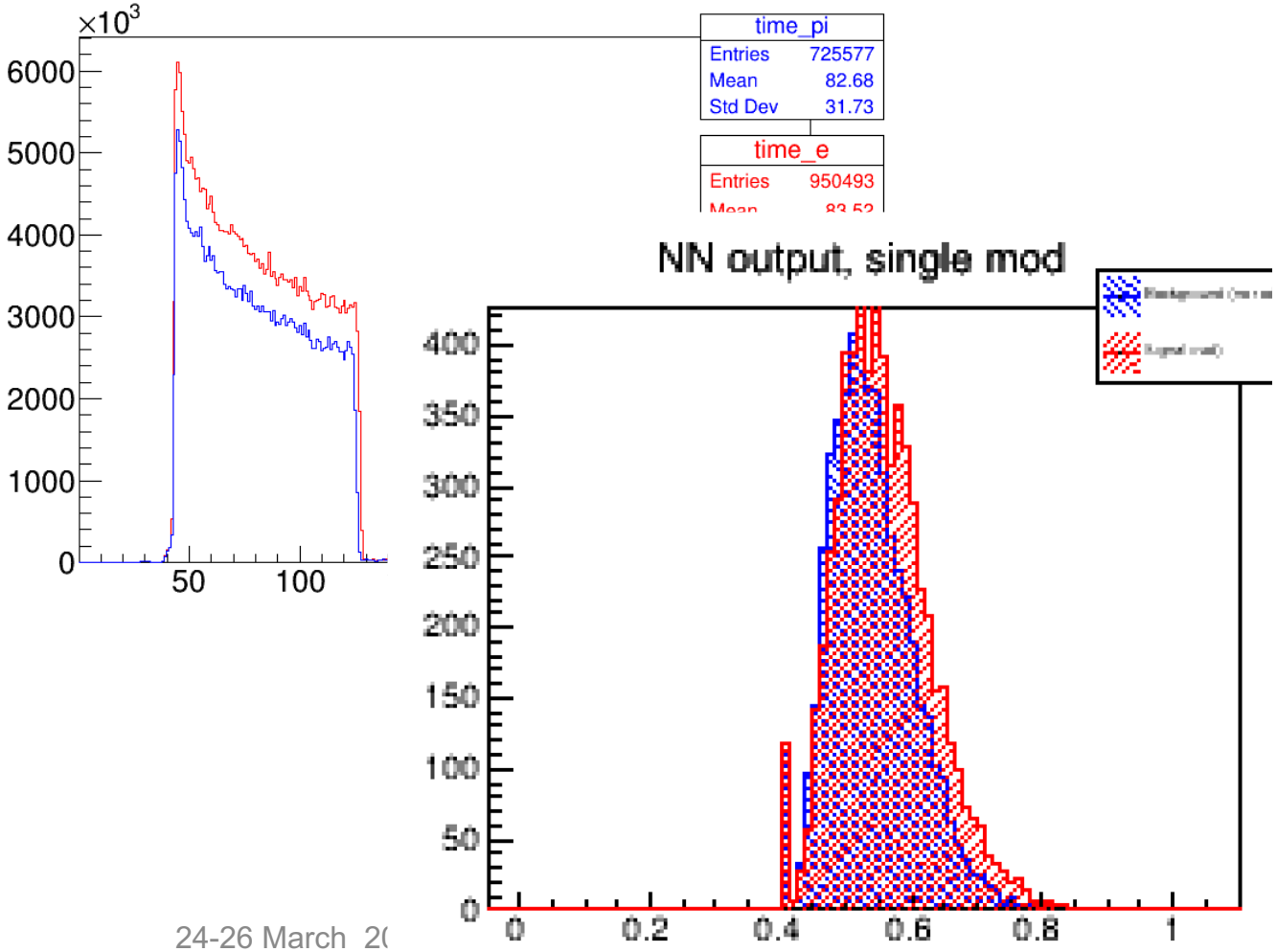


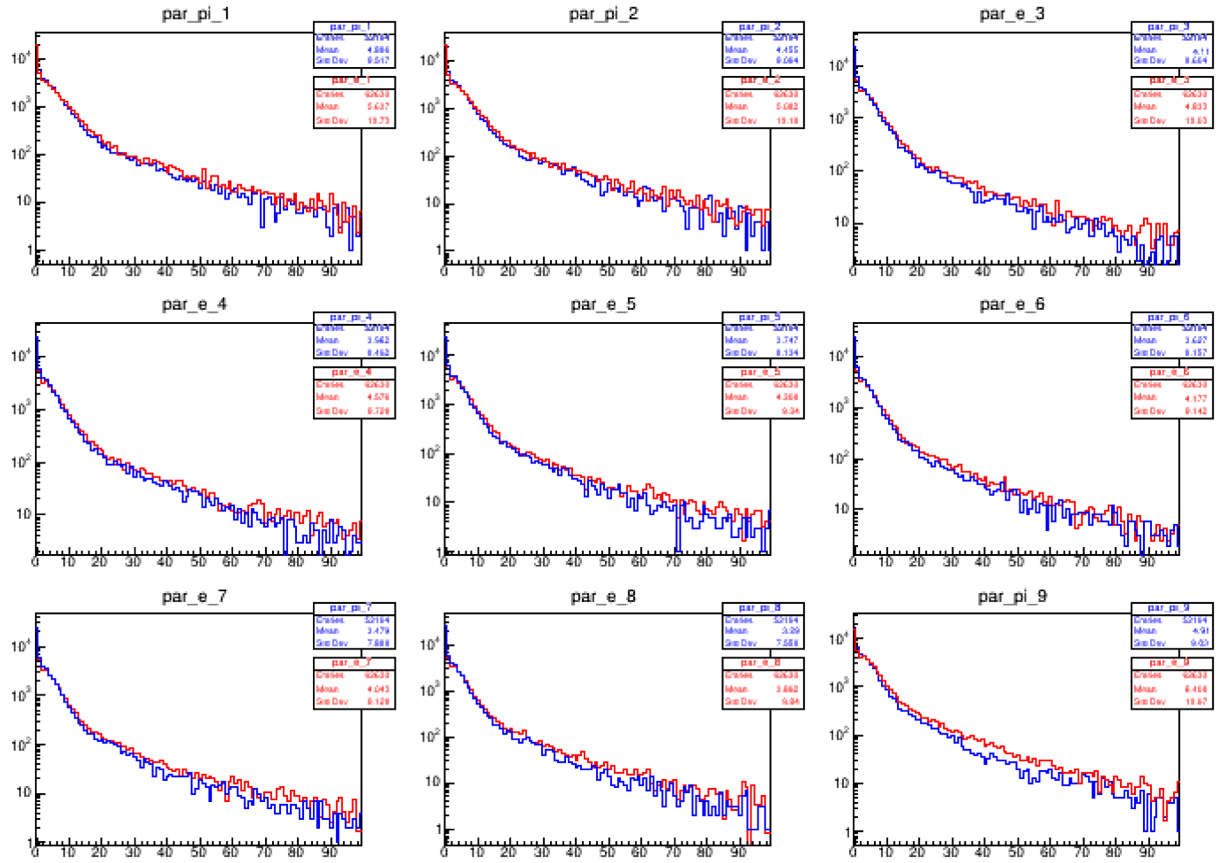


Radiator: Aerogel

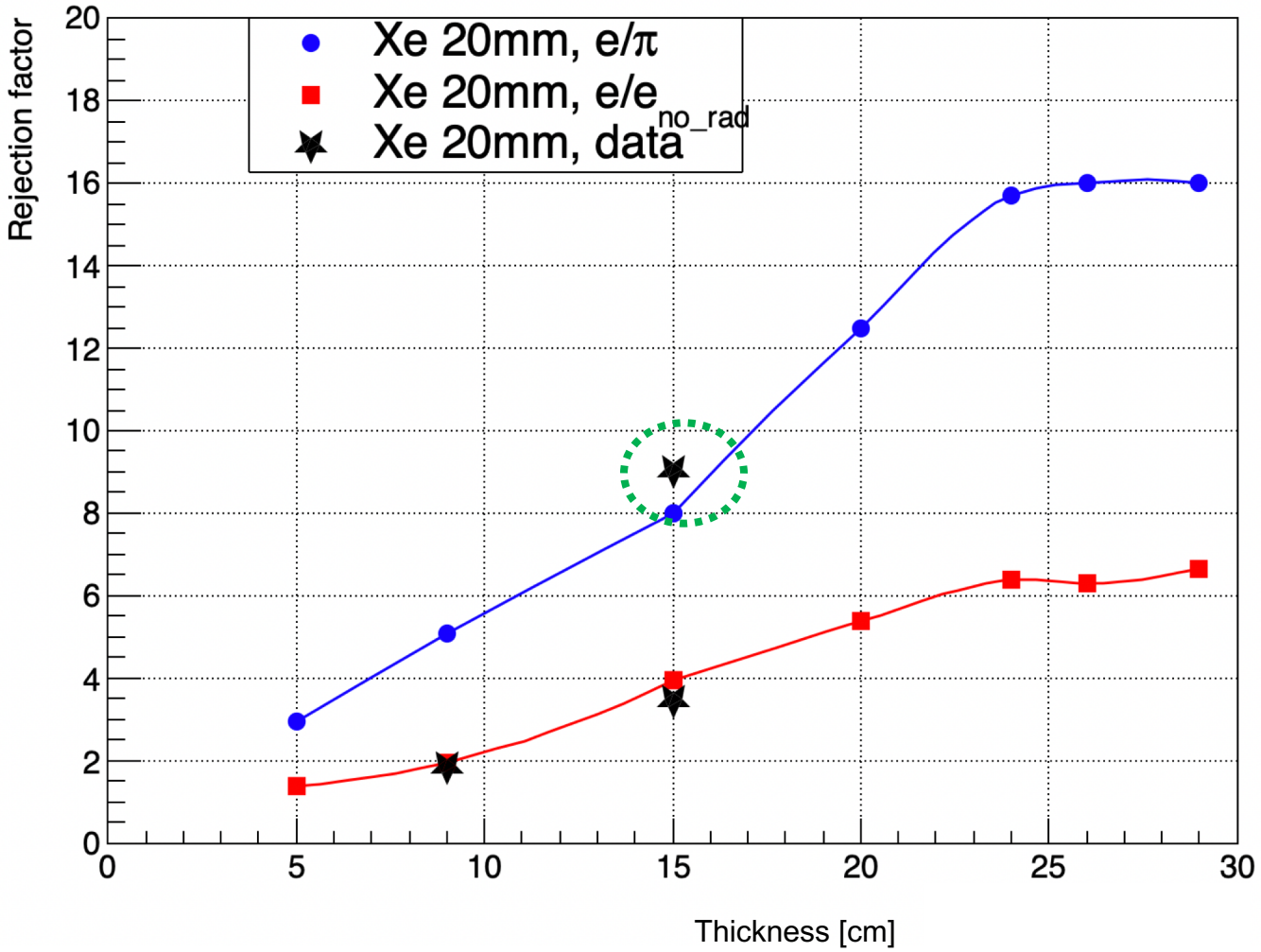
No TR yield is seen







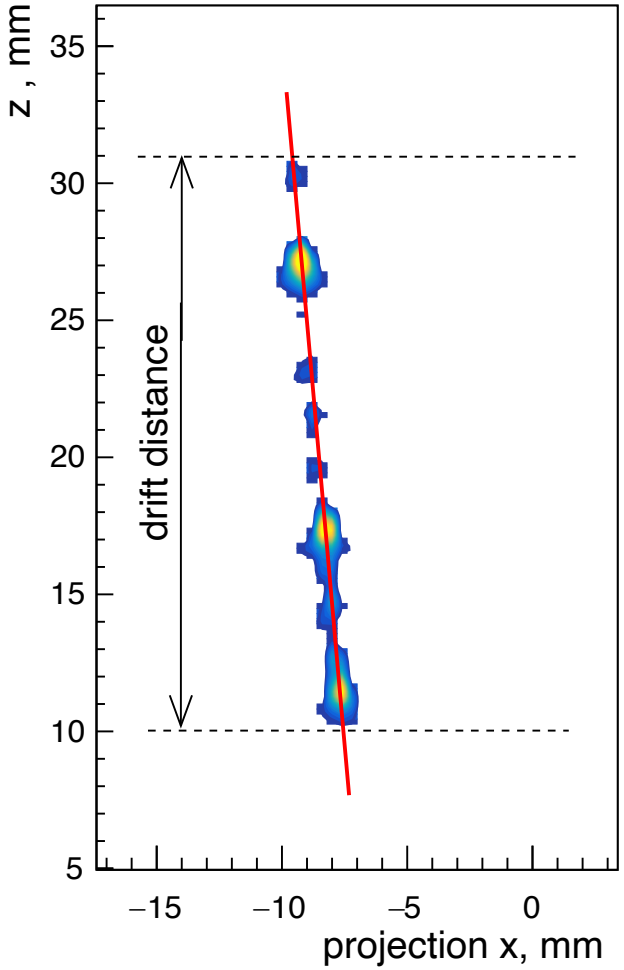
GEMTRD performance

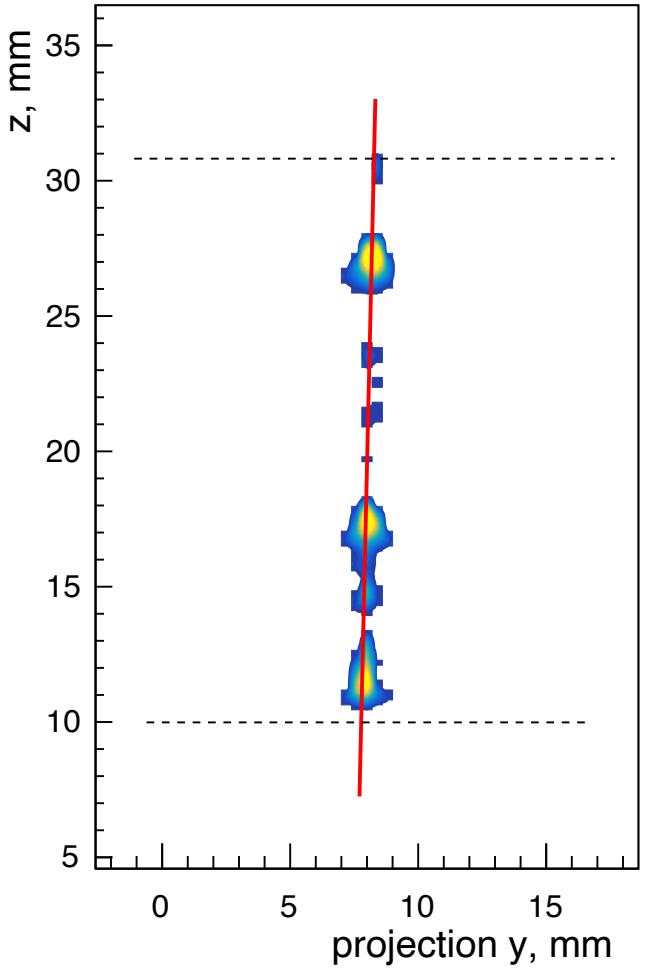


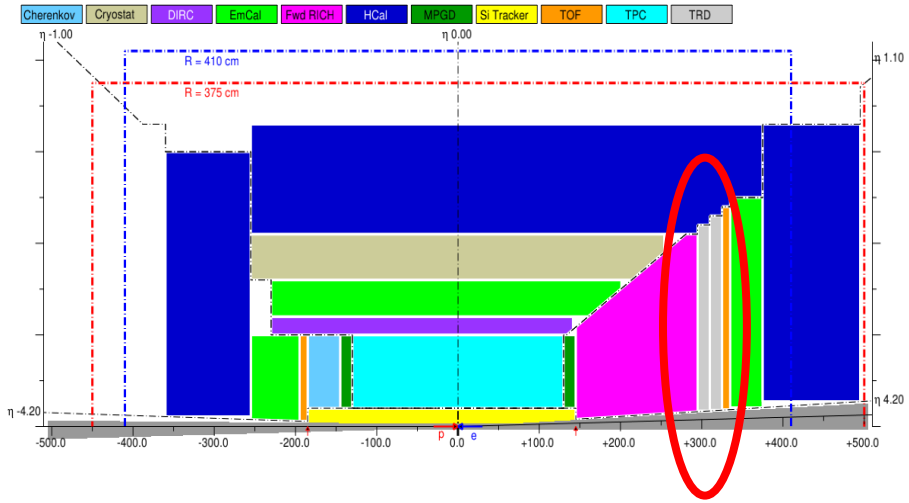
- Few runs with the fleece radiator 9 cm and 15 cm
- Data points are in a good agreement with MC predictions
- For e/π data point : compared data at the different locations: pair-spectrometer (e-beam only) vs Glue-X setup (mainly hadrons) .
- Need to validate this point at the Fermilab with e and pion test beams.

GEMTRD tracking

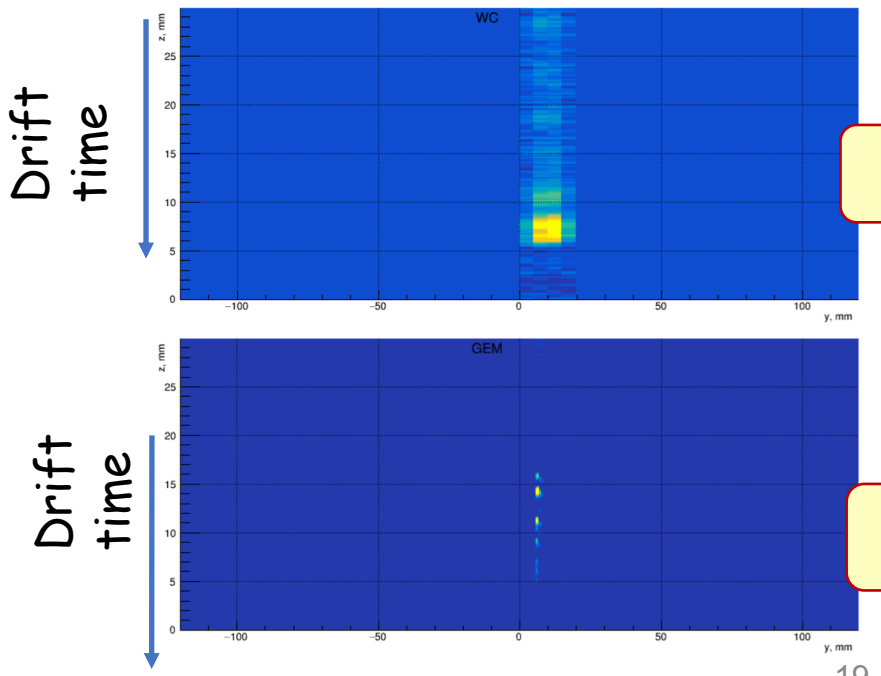
In addition to e/pi PID: Very precise track segment (drift time 2.1cm) will improve tracking behind dRICH





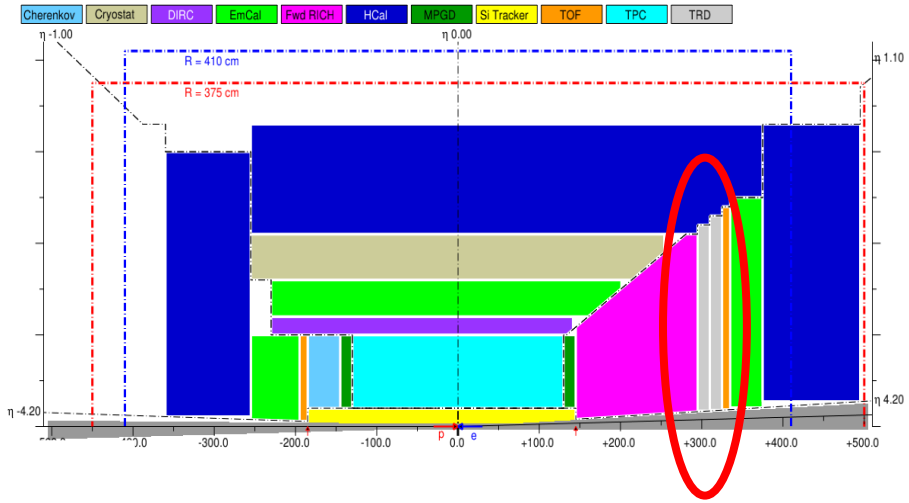


Resolution comparison

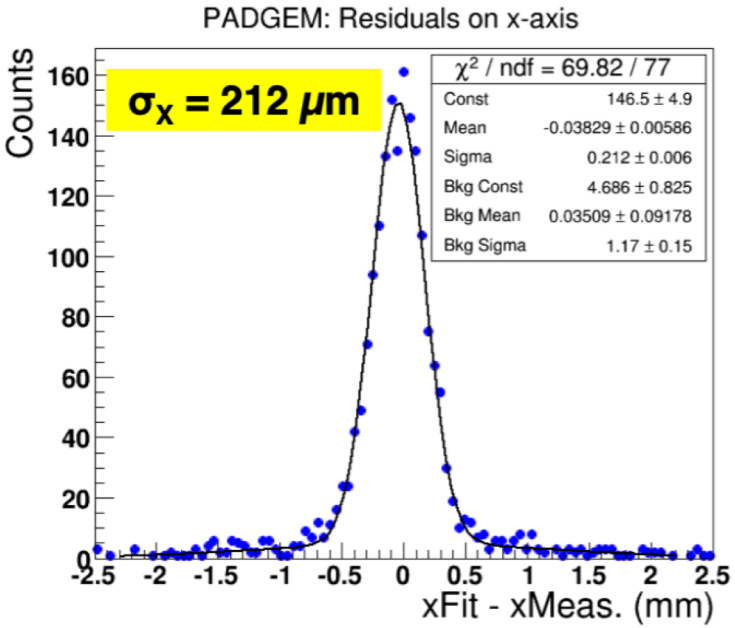


GEMTRD tracking

In addition to e/pi PID: Very precise track segment (drift time 2.1cm) will improve tracking behind dRICH



1 cm x 1 cm capacitive-sharing pad readout



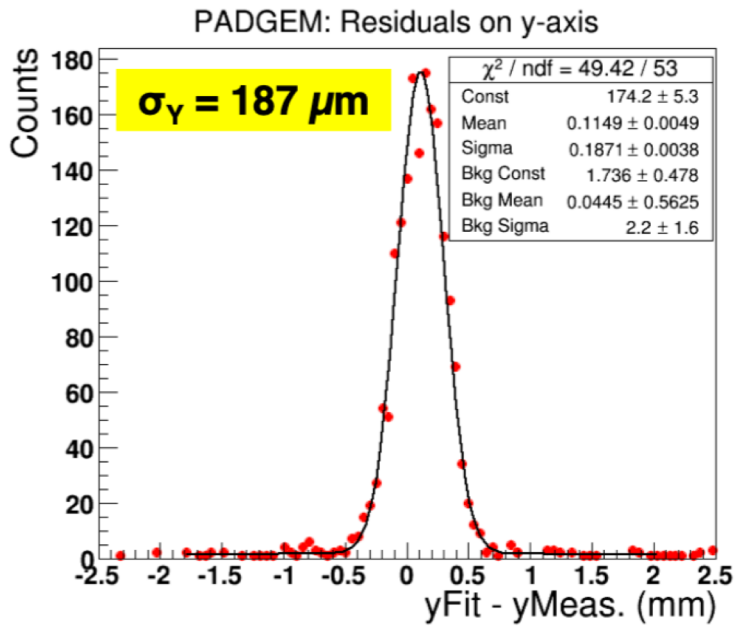


Figure 7: Spatial resolution in x (left) and y (right) for 1 cm × 1 cm pad readout prototype.

Readout issues towards streaming readout applications

	MHz	ns/bin	Peaking time	Range	Channels/chip cost	ADC bits	Shaper
FlashADC125	125	8	30ns	$1\mu s$ or stream	$50/channel	12bit	-GAS2-preamp : Undershooting , No baseline restorer
APV25	40	25	50ns	625ns	128 chan/chip		Analog output (no digitalization)
DREAM (CLAS12)	40	25	50ns		64chan/chip		Analog output (no digitalization)
VMM3 (ATLAS)	4	250	25-200ns		64chan/chip	10bit	L0 or continuous
SAMPA (ALICE)	10-20	100-50	160ns	Stream 3.2Gbit/s	32chan/chip 30$/chip 1$/channel	10bit	500ns- return to baseline Baseline restorer, DSP (zero-suppression, thr)

Current setup

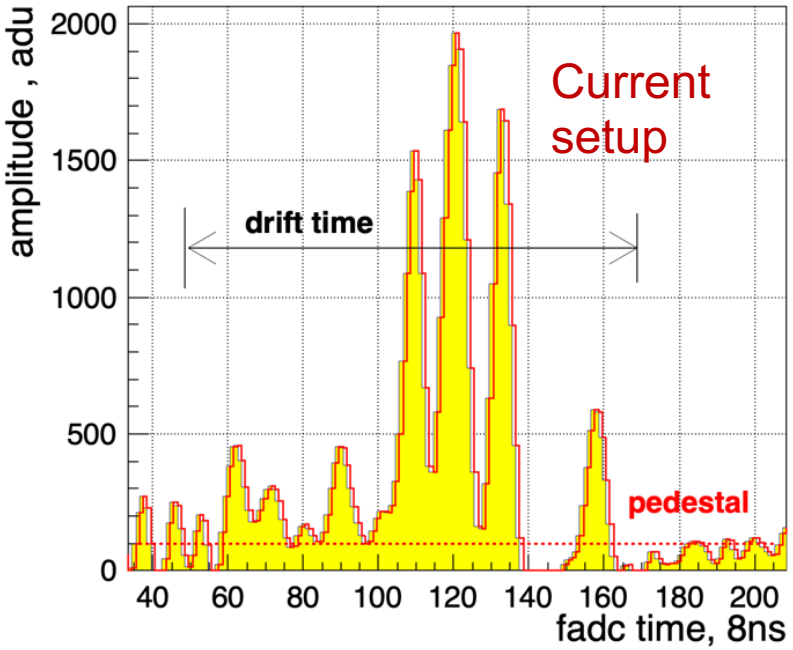
Yulia Furletova

Readout

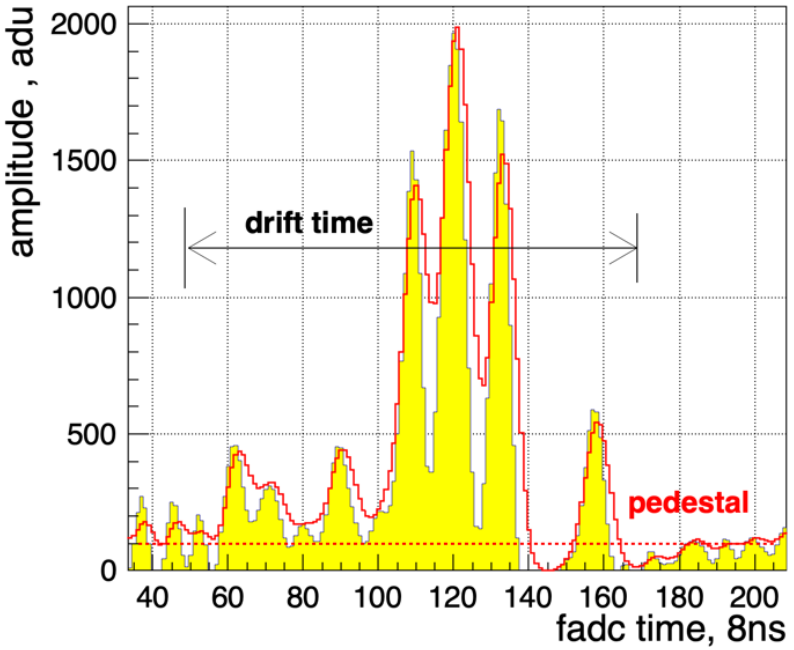
Current setup: preamplifiers (GAS2 ASIC chip) with shaping times of~10-12ns.
The flash ADC has a sampling rate of 125 MHz and 12 bit resolution but provides only pipe-lined triggered readout (price ~50$/channel)

Shaping time:
For TRD applications not only raising time is important, but also full width (tails, return to baseline)
In Xe – high density clusters (ionization density)

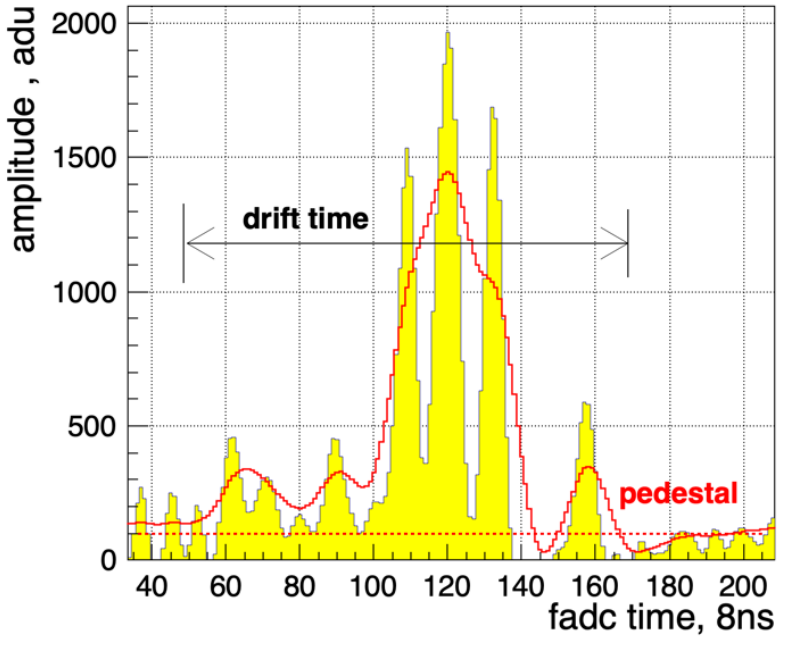
~ 20ns shaping time



~ 40ns shaping time

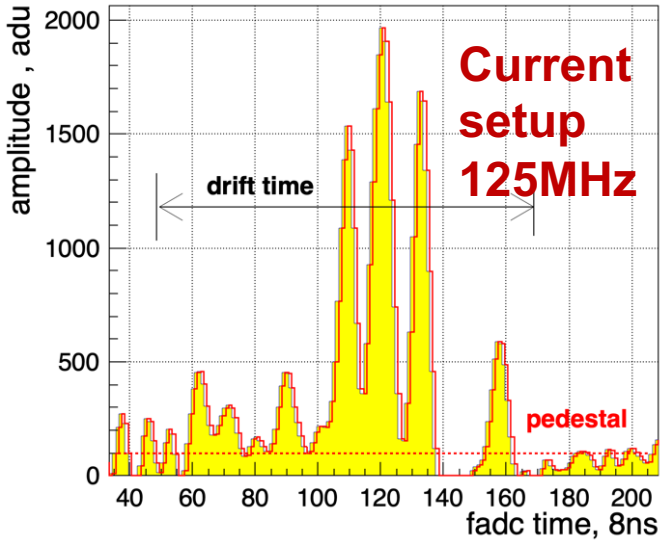


80ns (Sampa) shaping time

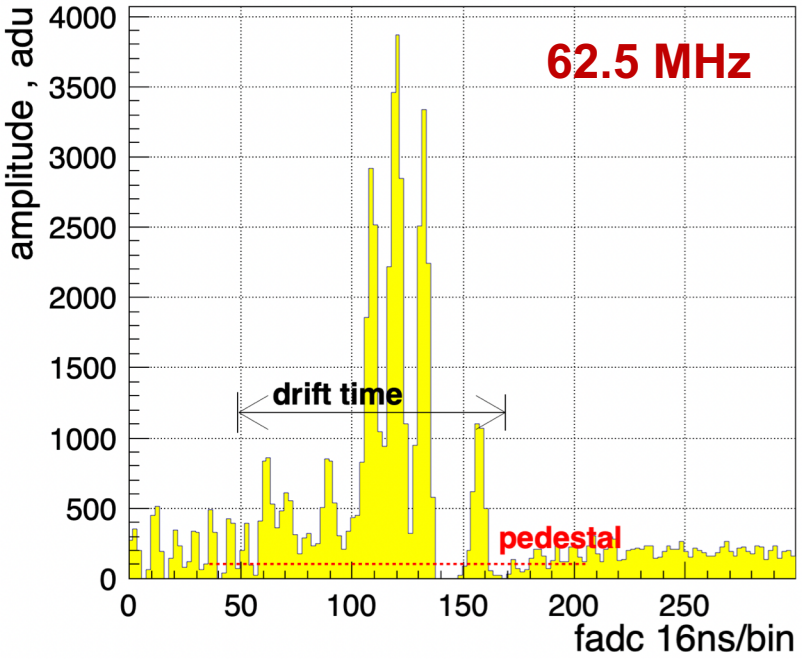


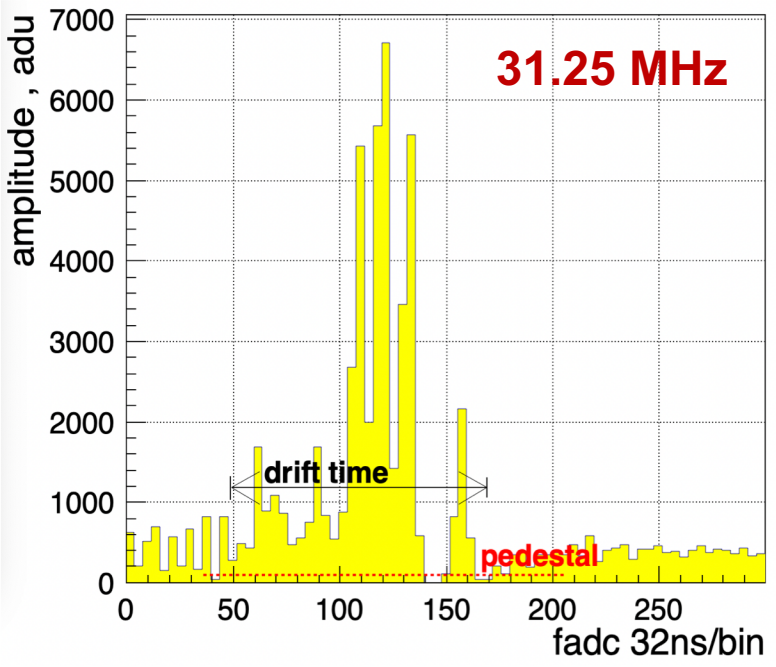
Readout

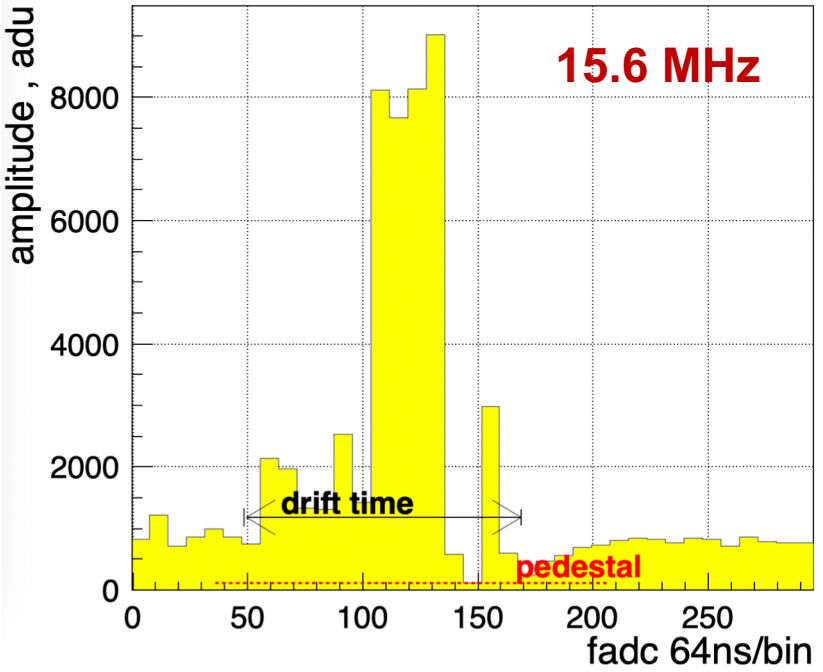
a preamplifier (GAS2 ASIC chip) with shaping times of~10-12ns. The flash ADC has a sampling rate of 125 MHz and 12 bit resolution but provides only pipe-lined triggered readout (price ~50$/channel)



Sampling frequency:

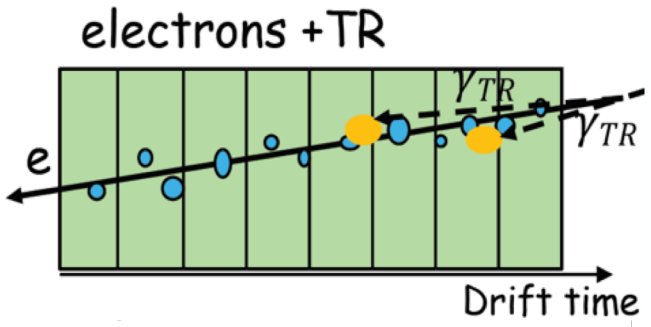


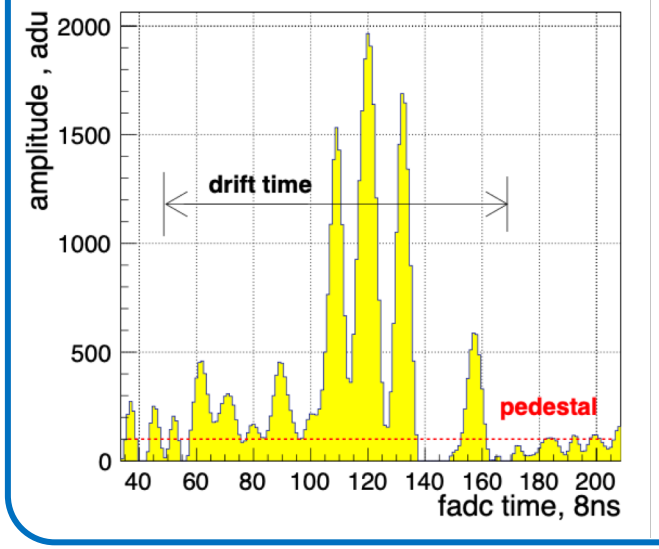




Machine Learning on FPGA

For OFF-line data analysis we are using neural network library provided by root /TMVA package : MultiLayerPerceptron (MLP)



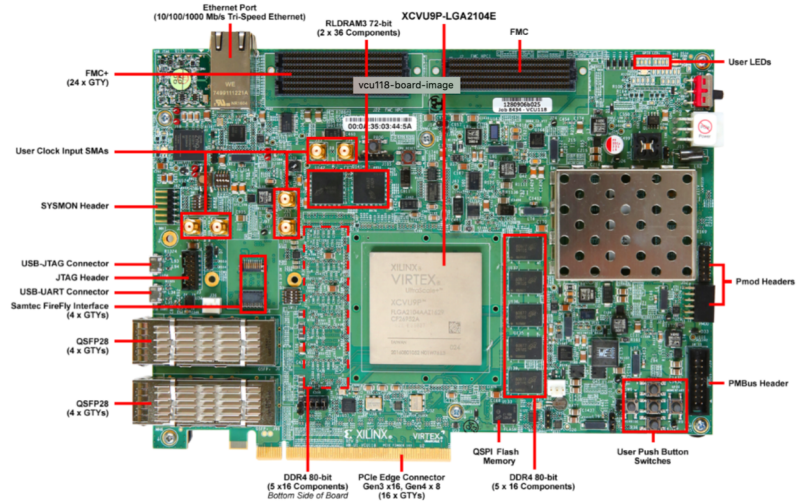


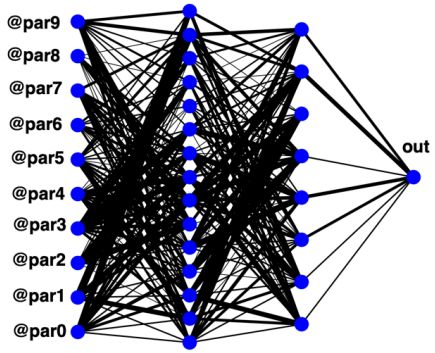
Moving towards ON-line data processing

In a collaboration with GlueX, PANDA and ODU

ML FPGA Core for TRD

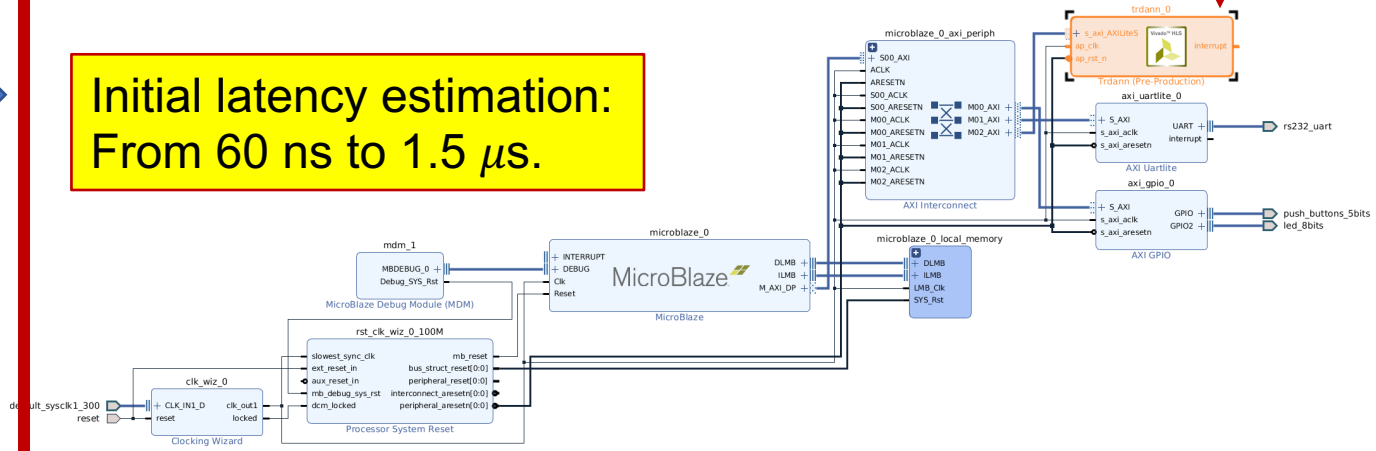
Xilinx Virtex® UltraScale+™





TRD ML Core

Initial latency estimation: From 60 ns to 1.5 μs.



The setup is ready and we are waiting for the next beam opportunity to test this system

Optimization using hls4ml

Performance Estimates

Timing (ns)

Summary

Clock	Target	Estimated	Uncertainty
ap_clk	4.00	3.466	0.50

Latency (clock cycles)

Summary

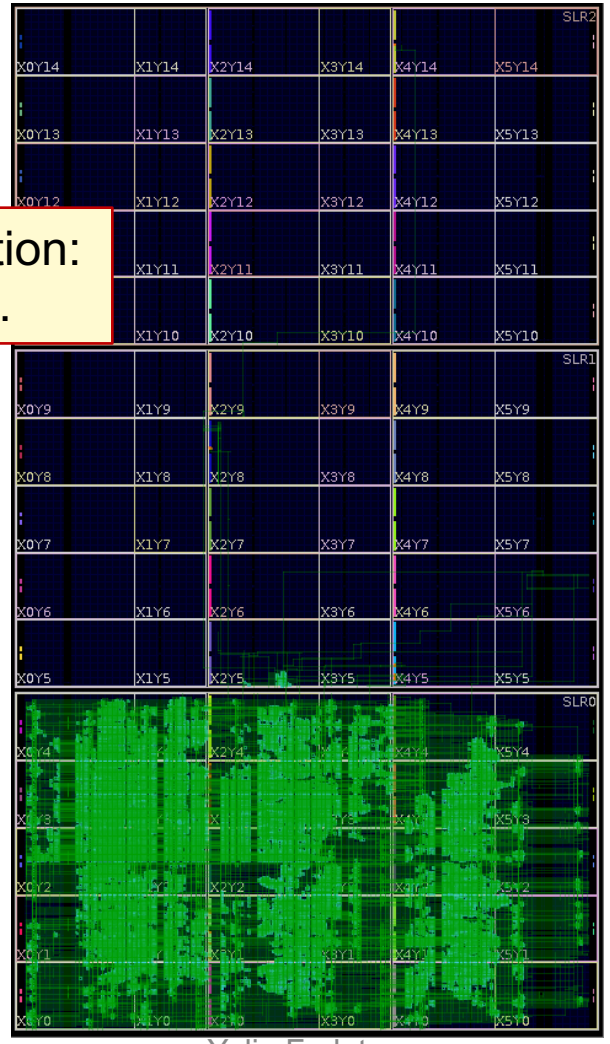
Latency		Interval		
min	max	min	max	Type
15	381	15	381	none

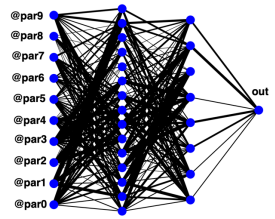
Initial latency estimation:
From 60 ns to 1.5 μs.

Utilization Estimates

Summary

Name	BRAM_18K	DSP48E	FF	LUT	URAM
DSP	-	7	-	-	-
Expression	-	40	40	8082	-
FIFO	-	-	-	-	-
Instance	510	1415	142176	199915	-
Memory	-	-	-	-	-
Multiplexer	-	-	-	181	-
Register	-	-	2350	-	-
Total	510	1462	144566	208178	0
Available	4320	6840	2364480	1182240	960
Available SLR	1440	2280	788160	394080	320
Utilization (%)	11	21	6	17	0
Utilization SLR (%)	35	64	18	52	0






```
================================================
== Performance Estimates
================================================
+ Timing (ns):
    * Summary:
    +--------+-------+----------+------------+
    |  Clock | Target| Estimated| Uncertainty|
    +--------+-------+----------+------------+
    |ap_clk  |   5.00|     3.883|        0.62|
    +--------+-------+----------+------------+

+ Latency (clock cycles):
    * Summary:
    +-----+-----+-----+-----+----------+
    |  Latency  |  Interval | Pipeline |
    | min | max | min | max |   Type   |
    +-----+-----+-----+-----+----------+
    |    1|   11|    1|    1| function |
    +-----+-----+-----+-----+----------+
```

After optimization
latency estimation: 55 ns

```
================================================================
== Utilization Estimates
================================================================
* Summary:
+-----------------+---------+-------+--------+--------+-----+
|       Name      | BRAM_18K| DSP48E|    FF  |   LUT  | URAM|
+-----------------+---------+-------+--------+--------+-----+
|DSP              |        -|      2|       -|       -|    -|
|Expression       |        -|      -|       0|      24|    -|
|FIFO             |        -|      -|       -|       -|    -|
|Instance         |        -|    695|    3731|   12612|    -|
|Memory           |        2|      -|       0|       0|    -|
|Multiplexer      |        -|      -|       -|      36|    -|
|Register         |        -|      -|    1125|       -|    -|
+-----------------+---------+-------+--------+--------+-----+
|Total            |        2|    697|    4856|   12672|    0|
+-----------------+---------+-------+--------+--------+-----+
|Available SLR    |     1440|   2280|  788160|  394080|  320|
+-----------------+---------+-------+--------+--------+-----+
|Utilization SLR (%)|     ~0|     30|      ~0|       3|    0|
+-----------------+---------+-------+--------+--------+-----+
|Available        |     4320|   6840| 2364480| 1182240|  960|
+-----------------+---------+-------+--------+--------+-----+
|Utilization (%)  |      ~0 |     10|      ~0|       1|    0|
+-----------------+---------+-------+--------+--------+-----+
```

Next steps

Generic R&D:

- Test of **different readout architecture** (strips, pad,zig-zag) to minimize the noise level, number of readout channels, and spatial resolution. This would require use to build several small(10x10 cm2) prototypes with different readouts options and test them at JLAB and Fermilab.
- Tests of a new **streaming readout** architecture hardware (SRO125) and ML-FPGA –based data reduction concepts.
- Test of different **TR-radiators**

Targeted R&D:

- Build and test **large-size modules** in order be able to workout possible issues: like noise, gain-uniformity, drift-time issues, HV stability, etc. A field/gas-cage needs to be developed and optimized for TRD applications.
- **Test beams** at Fermilab with electron and pion beams (once per year)
- Design and development of a **recirculation gas** system to purify, distribute, circulate, and recover the gas (in collaboration with other labs/universities).
- Development of final design specifications for the **streaming readout architecture** as input to a coordinated ASIC design program

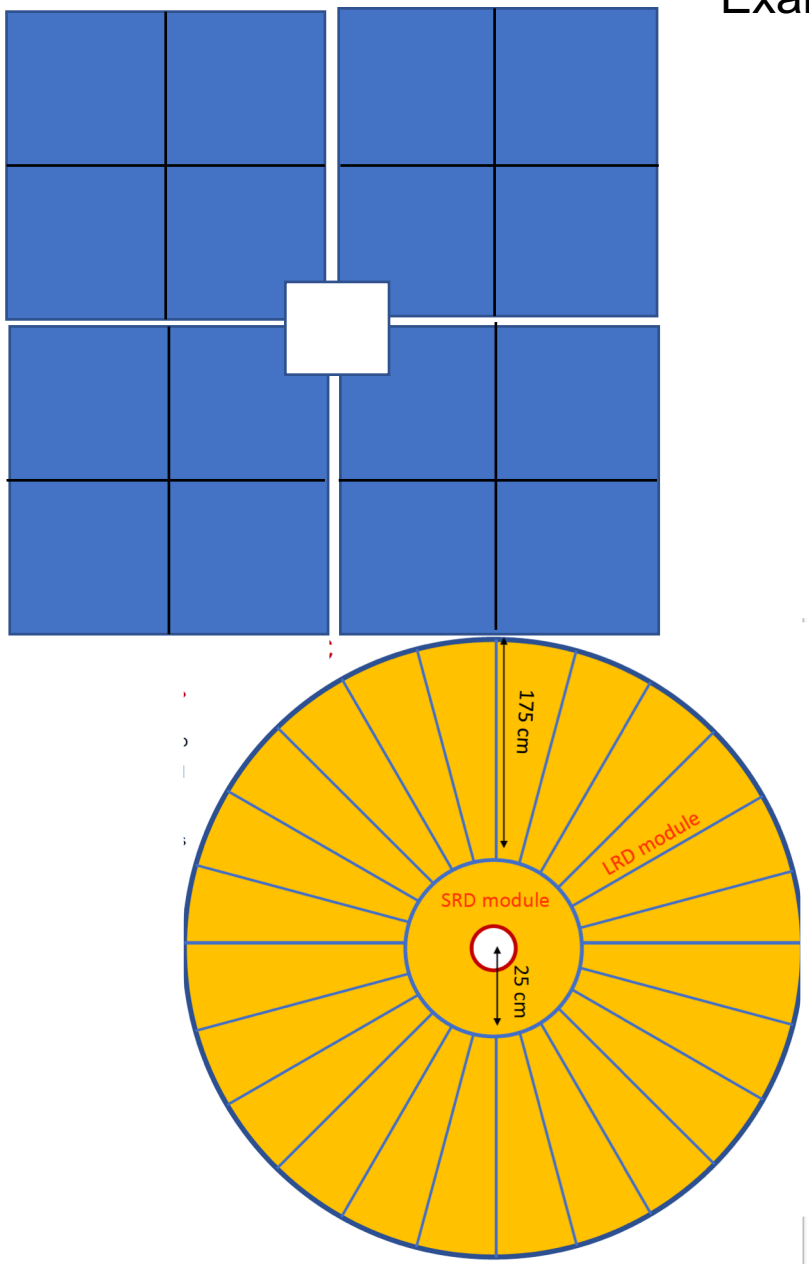
Next steps

Come up with a design for large scale modules (and optimize in terms of material budget and r/o channels)

Table 1: **A preliminary estimates for eRD22 R&D**

	FY22	**FY23**	**FY24**
Prototyping	SRD $25k		LRD $30k
Readout electronics	$20k	$ 20k	
Gas, gas system	$20k		
Travel Testbeam	$5k	$10k	$10
Total	**$70**	**$ 30**	**$60**

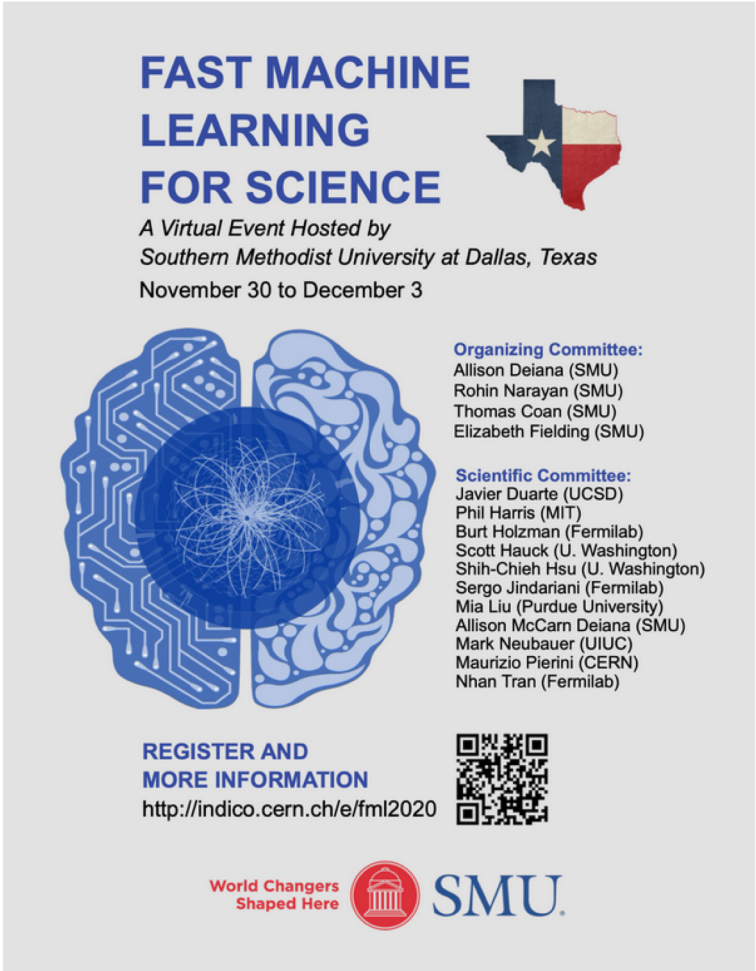
Examples



Conferences

A new Transition Radiation detector based on GEM technology
https://doi.org/10.1016/j.nima.2019.162356

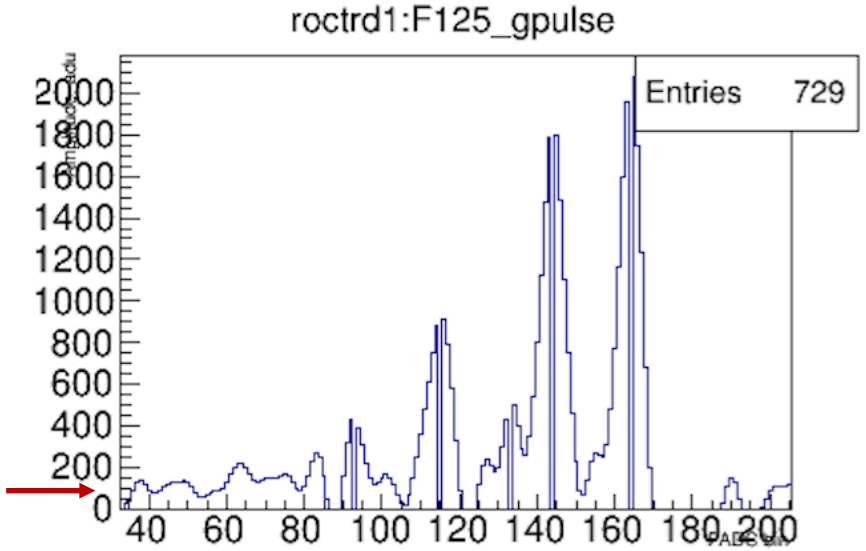
- ✓ ML workshop of the GlueX, EIC and PANDA collaboration.
- ✓ Streaming readout VII workshop



Thank you!

Backup

Readout hardware: find a cheaper solution/replacement of FlashADC125 (<<$50/channel): FADC125 have a timing resolution of 8ns/bin, and covers a whole drift time range >1μs .



FADC 125MHz == 8ns/bin
Preamp peaking time: 3-4 bins ~ 20-30ns
need better
Problems: undershooting (base at 100ADU),
loosing signal =>
need better shaper and
need also baseline restorer
Need: dE/dx, Cluster counting + timing
Coverage ~ 1μs

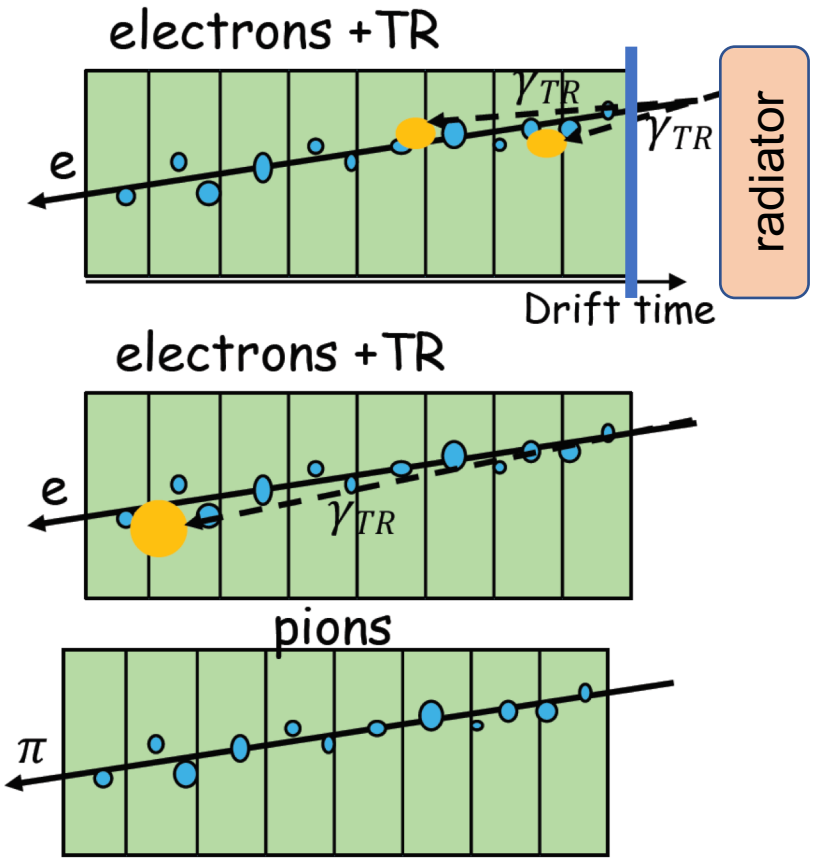
Available electronics for GEM

-APV25: too few bins, coverage x
-VMM3 : 200ns/bin x
-SAMPA: 10-20 MHz only x but…

lots of good features inside SAMPA:
- 32channels/chip 30$/chip => 1$/channel v
- Shaper/preamps v
- Baseline restorer v
(similar to ASDBLR/ATLAS)
- DSP: Zero suppression, thresholds v
- ASICs : could implement later any PID algorithms v

Yulia Furletova

GEANT4: electron and pion comparison



Soft TR-photons:

- absorbs near entrance window, therefore have large drift time
- sensitive to dead volumes, like Xe-gap, cathode material.
- **Increase** of radiator thickness does not lead to increase of number of soft-photons (radiator self-absorption)

Hard TR-photons:

- Depending on energy of TR-photons, could escape detection (depends on detection length)
- **Increase** of radiator leads to **increase** of hard TR-spectra.

Separation/ Identification of TR-clusters and dE/dx clusters

e/π rejectrion

Detector	Dead material in front	Radiator	e/π	$e/e_{no\ radiator}$	$DATA_{e/e_{noR}}$
20 mm	no dead material	20 cm	14.4	6.3	
20 mm	400 μm Xe, Kapton 75μm	20 cm	12.5	5.38	
20 mm	as above	5 cm	2.94	1.37	
20 mm	as above	9 cm	5.07	1.97	1.8
20 mm	as above	15 cm	8.0	3.94	
20 mm	as above	26 cm	16.0	6.3	
20 mm	as above	29 cm	16.1	6.66	
29 mm	400 μm Xe, Kapton 75μm	15 cm	11.5	4.22	
25 mm	as above	15 cm	11.55	4.62	
15 mm	as above	15cm	7.54	3.33	
10 mm	as above	15 cm	4.01	1.97	
5 mm	as above	15 cm	1.96	1.38	

Table 1: Rejection factor corresponding to 90% of electron efficiency

3. Test of different TR-radiators.

- We continue to search and test different types of radiators
- Goal: to find low material budget, but high TR-yield radiators

- The TR-energy spectrum is very important (minimum of self-absorption)

Single module (X/X0) :
Radiator (10cm) ~ 1.5 % X_0 for fleece (could go down with mylar foils)
Xenon gas (2.0 cm) ~ 0.1% X_0
Triple GEM with readout at active area ~ 0.7% X_0
(could go down to 0.4%, current eRD6)

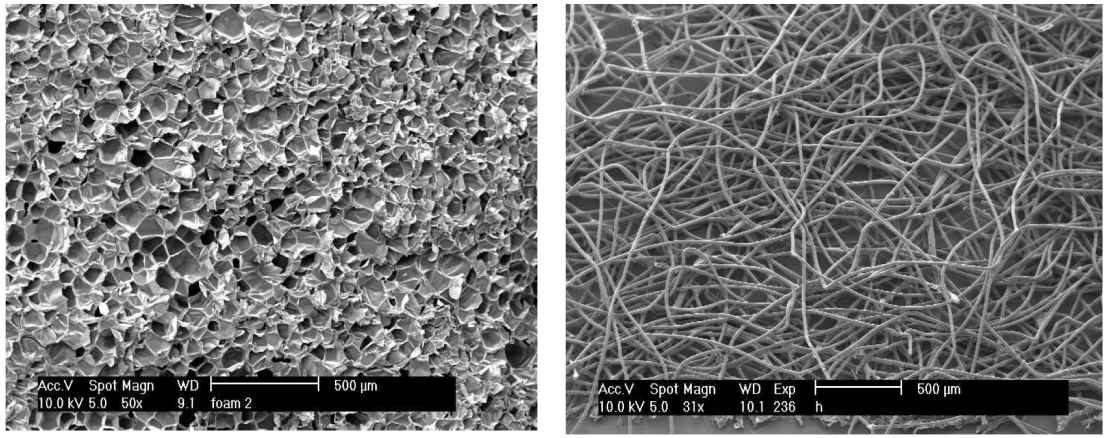
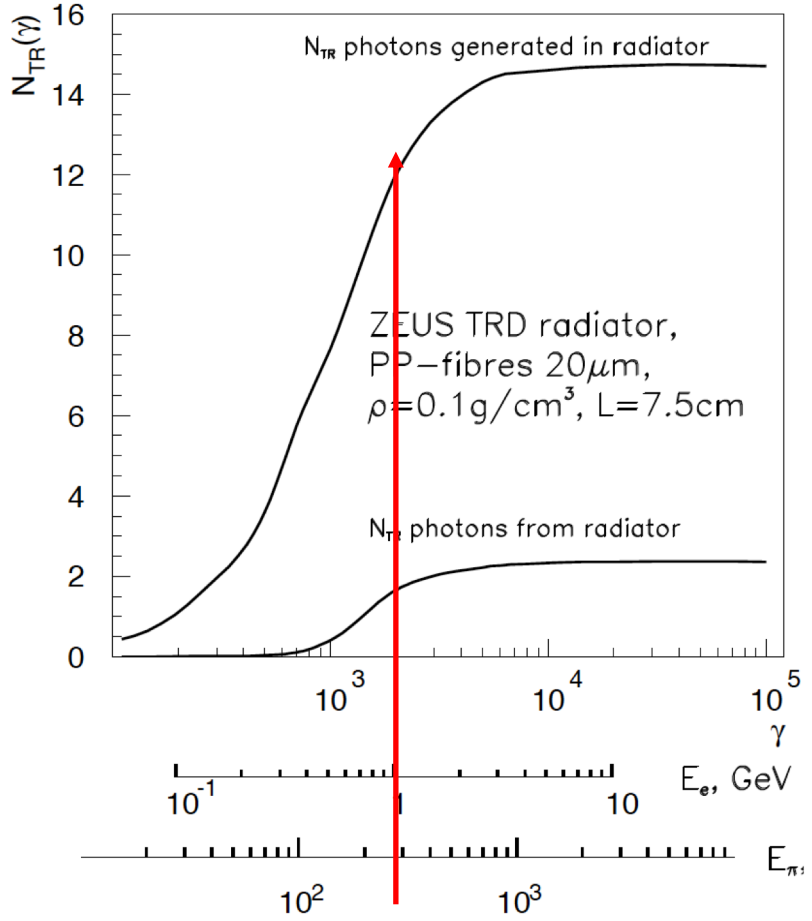


Figure 2: Electron microscope images of a polymethacrylimide foam (Rohacell HF71)(left) and a typical polypropylene fiber radiator (average diameter ≈ 25 μm) (right) [52].

J.Tandler



Only e produce TR photons (E>1GeV)
Pions only start to produce TR at E > 100-150 GeV

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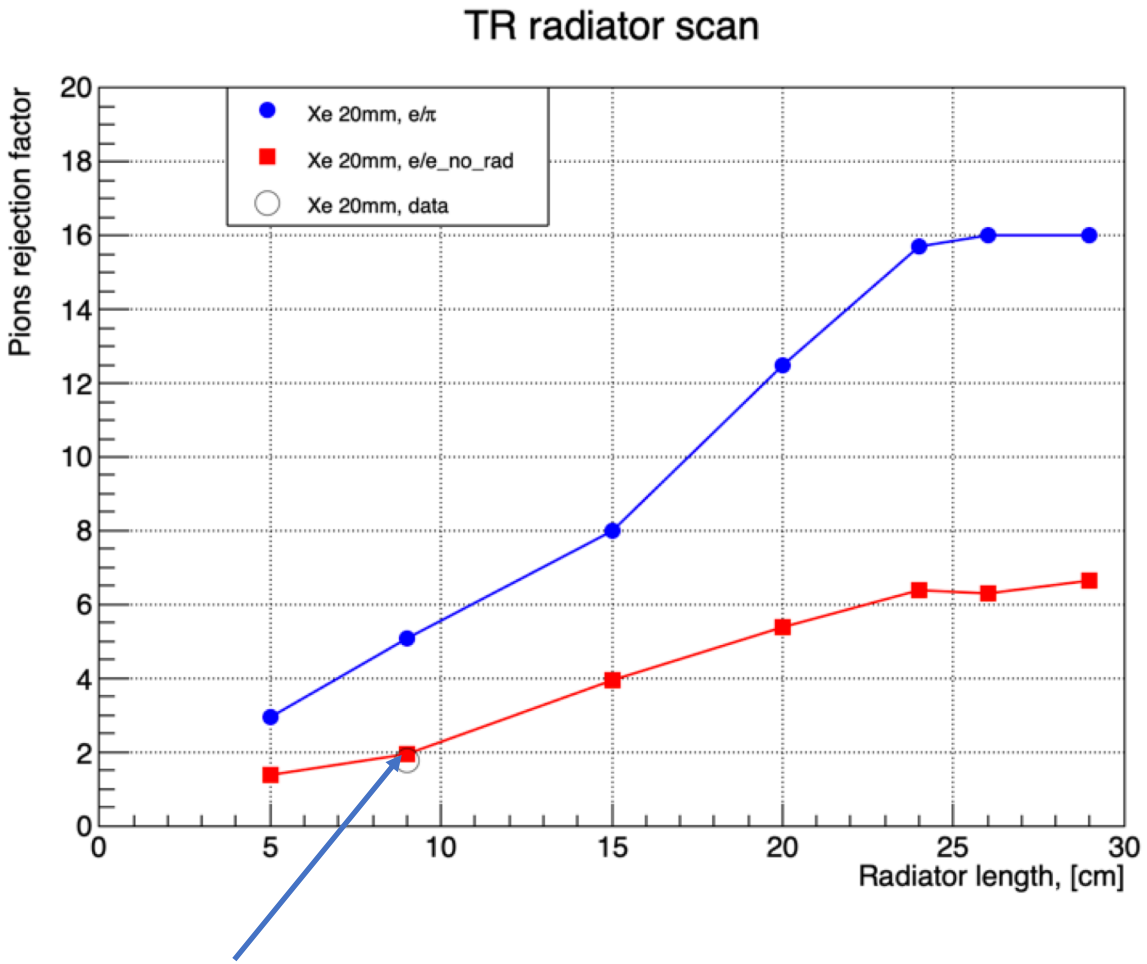
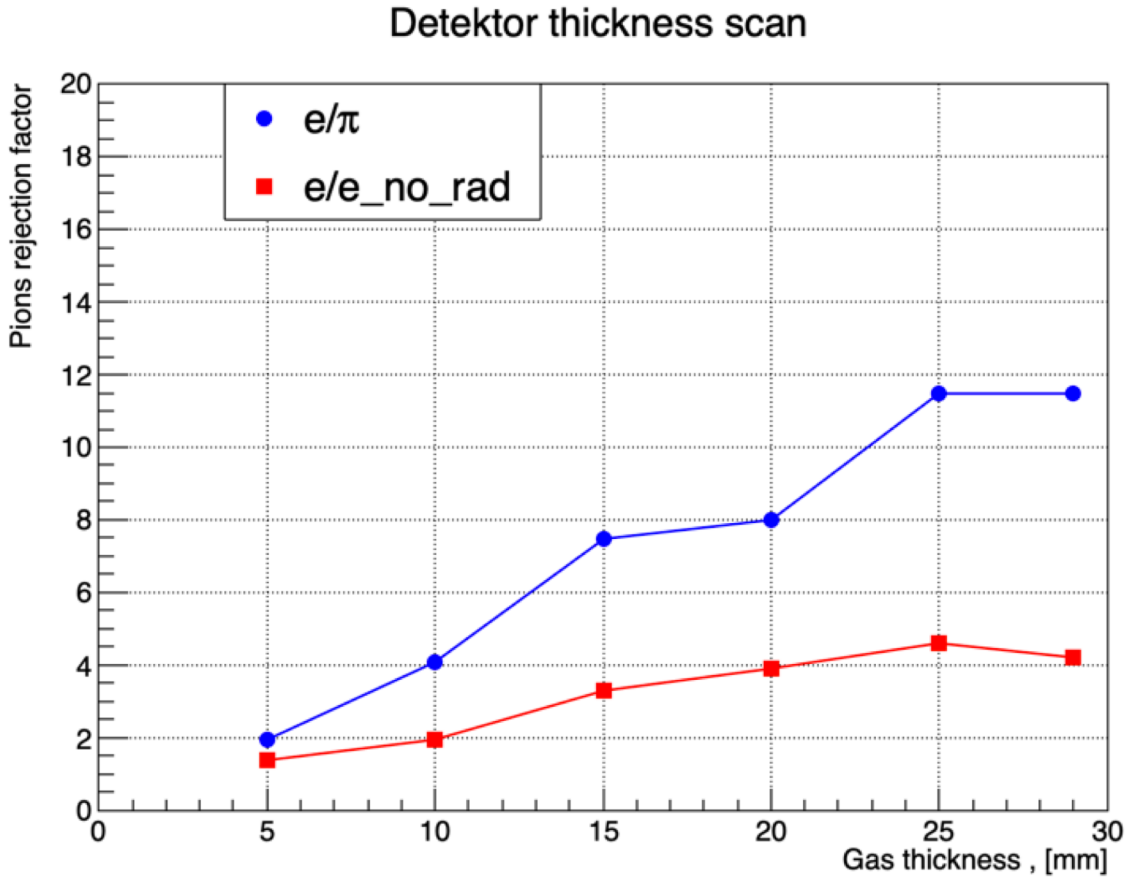
e/π rejection (MC and Data)

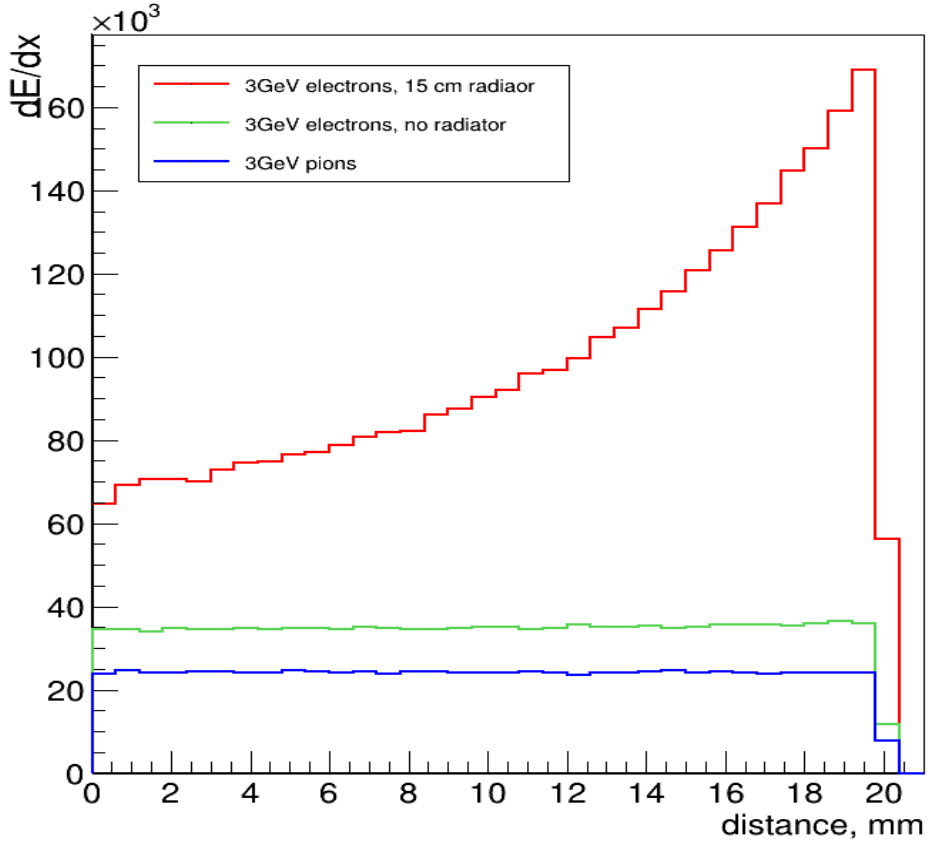


DATA point



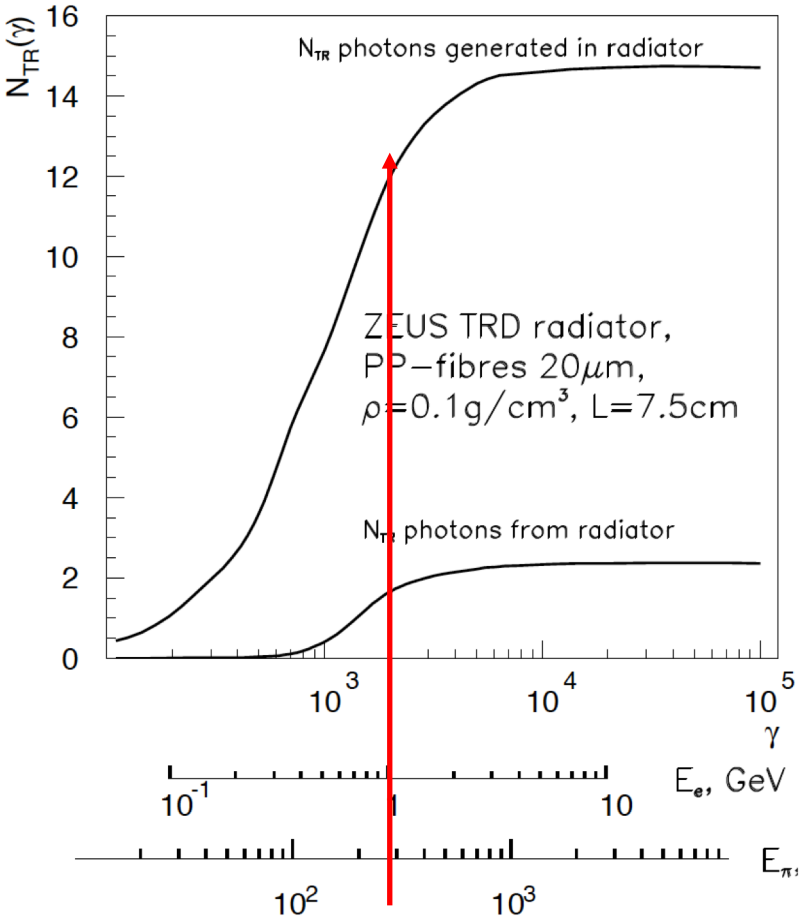
GEANT4: electron and pion comparison

Energy deposition (dE/dx + TR) vs distance



e,π ~3 GeV

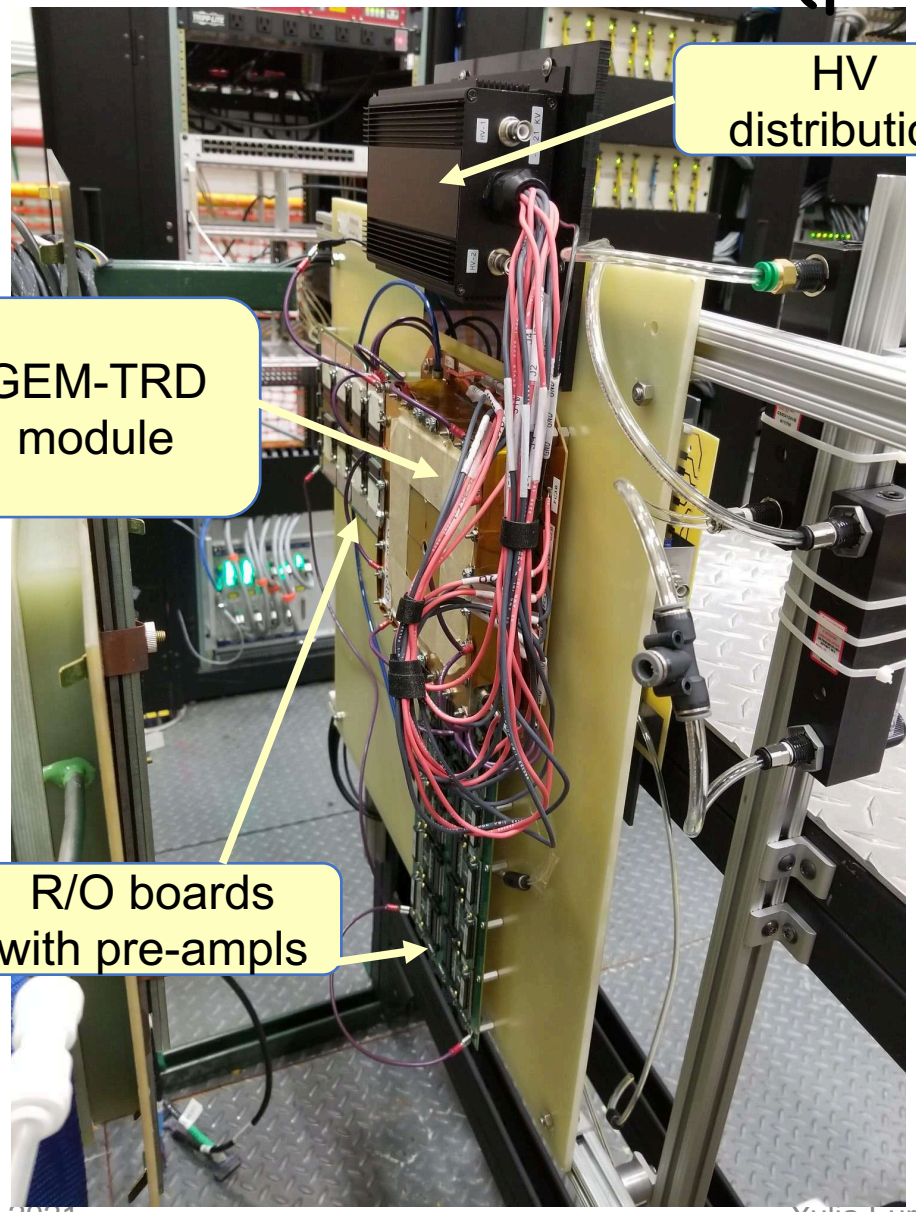
J.Tandler

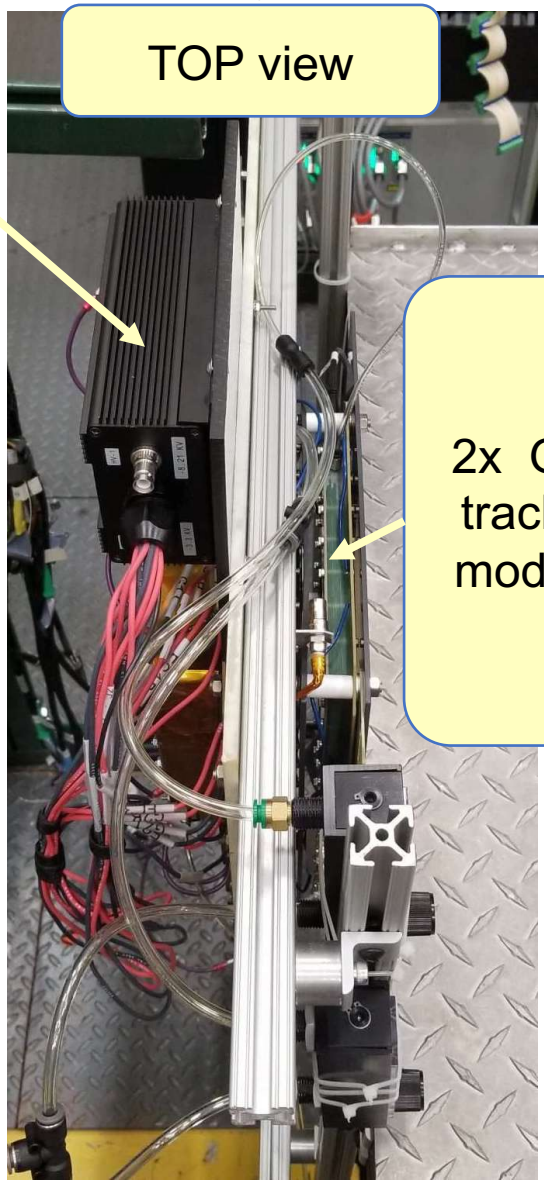


Only e produce TR photons (E>1GeV)
Pions only start to produce TR at E > 100-150 GeV

Preparation for the test (pair-spectrometer location)

Preparation for the test (pair-spectrometer location)





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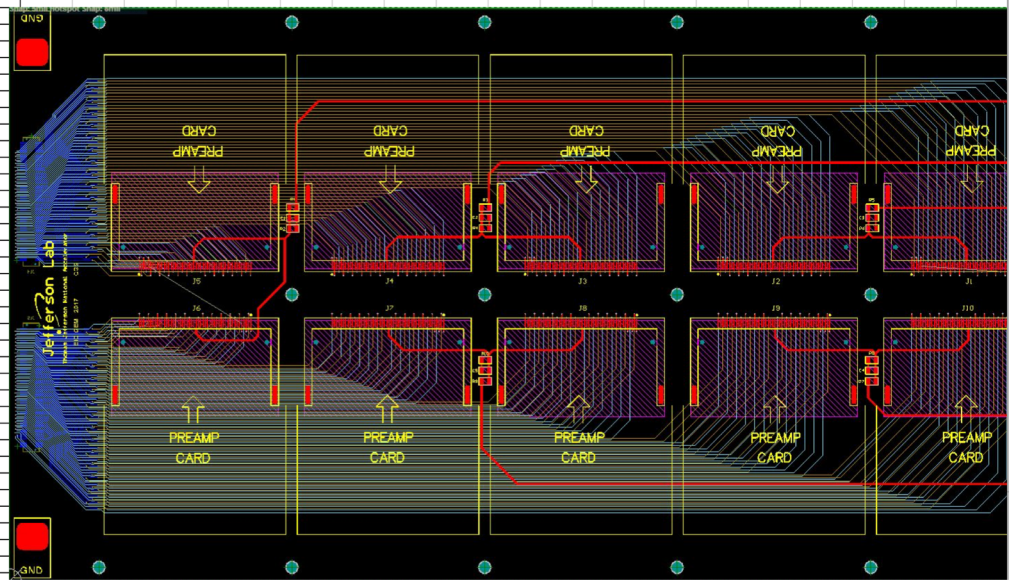
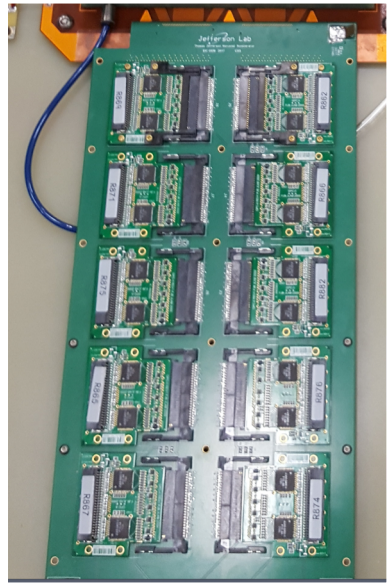
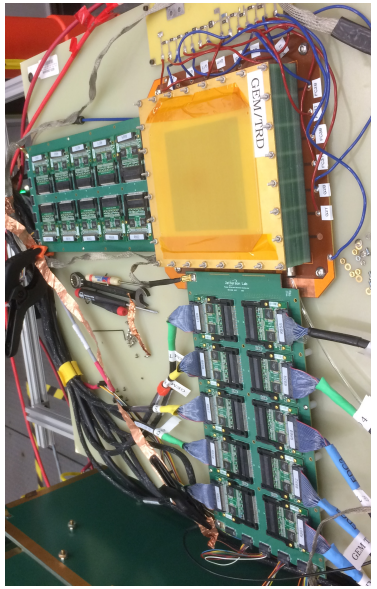
New interface board

J15	Channel	Pre-Amp	Pre-Amp Pin
1	GND		
2	CH121	J6	50
3	CH122	J6	49
4	CH123	J6	48
5	CH124	J6	47
6	CH125	J6	46
7	CH126	J6	45
8	CH127	J6	44
9	CH128	J6	43
10	CH129	J6	42
11	CH130	J6	41
12	CH131	J6	40
13	CH132	J6	39
14	CH133	J6	37
15	CH134	J6	36
16	CH135	J6	35
17	CH136	J6	34
18	CH137	J6	33
19	CH138	J6	32
20	CH139	J6	31
21	CH140	J6	30
22	CH141	J6	29
23	CH142	J6	28
24	CH143	J6	27
25	CH144	J6	26
26	CH145	J7	50
27	CH146	J7	49
28	CH147	J7	48
29	CH148	J7	47
30	CH149	J7	46
31	CH150	J7	45
32	CH151	J7	44
33	CH152	J7	43
34	CH153	J7	42
35	CH154	J7	41

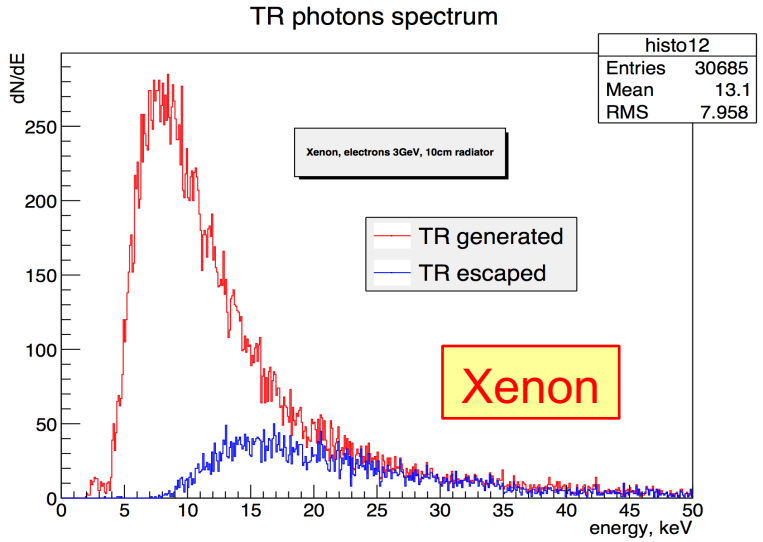


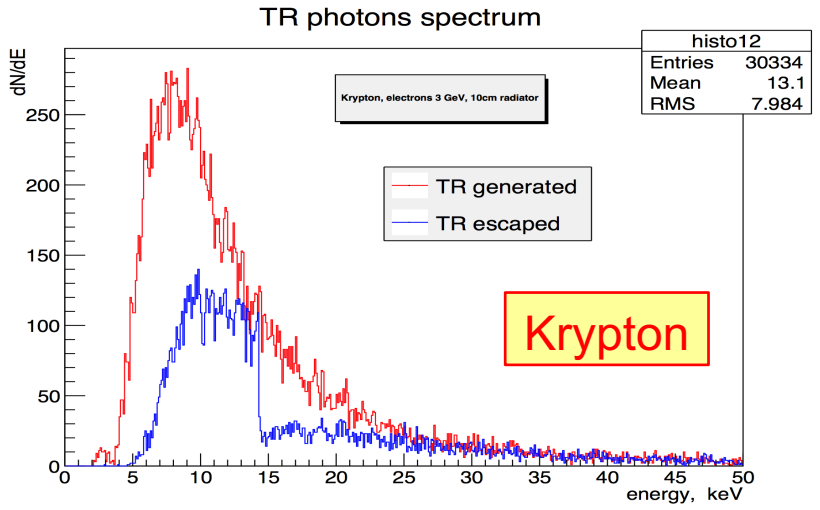


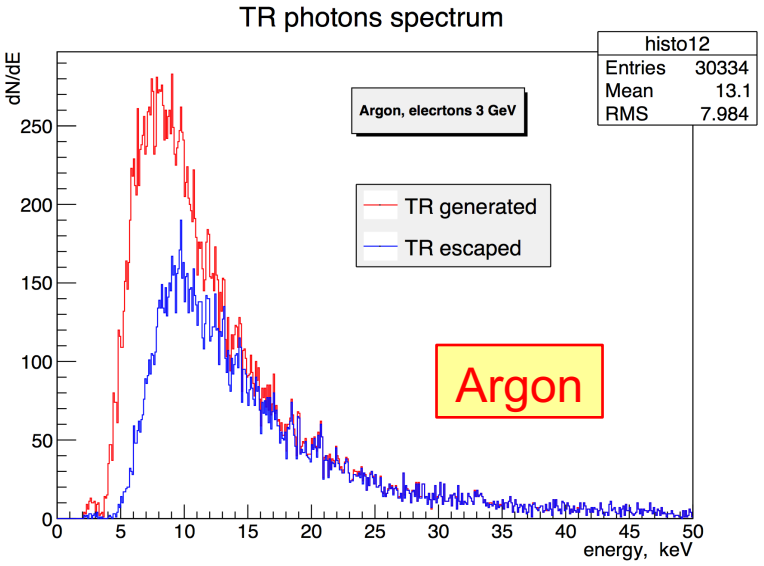


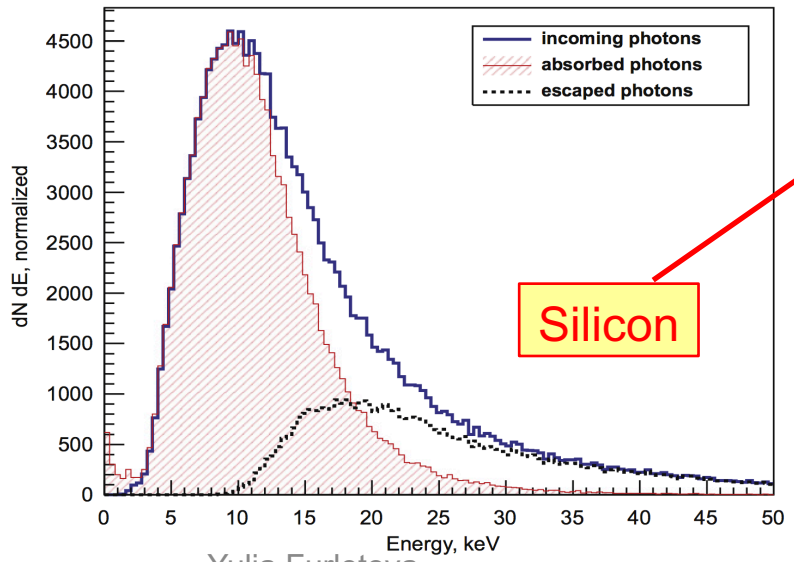
- compatible with JLAB Flash-ADC system
- Each board holds 10 preamplifiers, each preamplifier connects to 24 GEM strips resulting on a readout of 240 GEM strips per each readout board or X/Y coordinate.
- A pre-amplifier has GAS-II ASIC chips (3 chips per each preamplifier card) and provides 2.6 mV/fC amplification. A preamplifier has a peaking time of 10 ns. It consumes 50 mWatt/channel and has a noise <0.3 fC. The dynamic range of preamplifiers (where it is linear) is about 200 fC.
- Covers up to 2.4 (32) μs of a drift time.

TR absorption





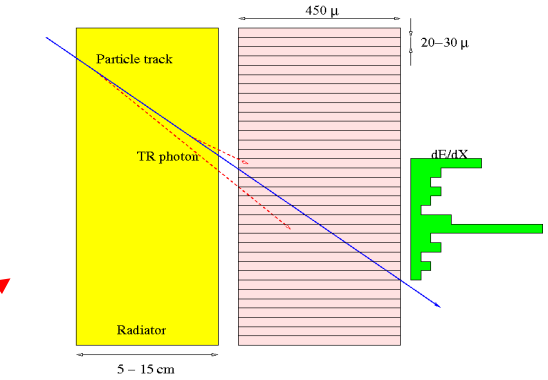


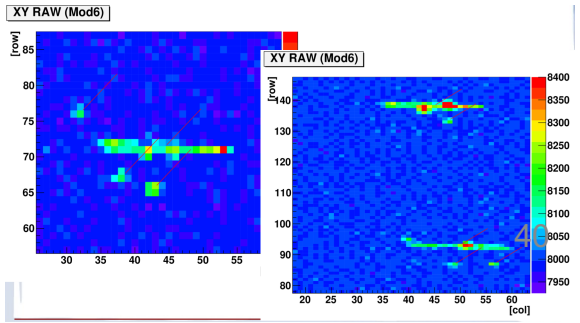


New transition radiation detection technique based on DEPFET silicon pixel matrices

https://doi.org/10.1016/j.nima.2010.06.342

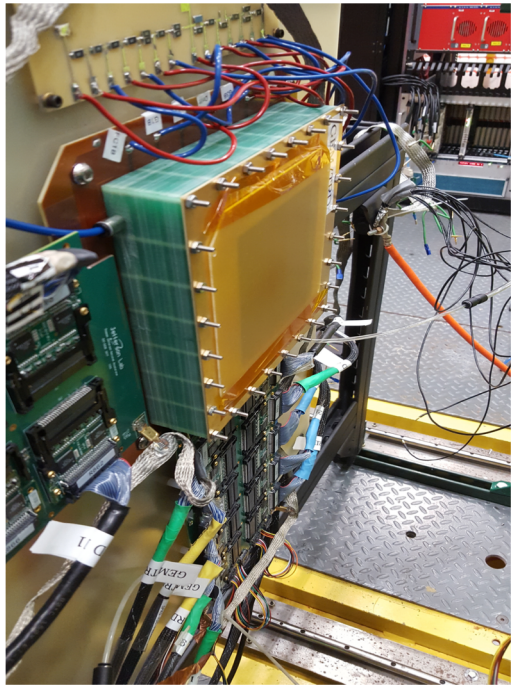
JuliaFurletova, SergeyFurletov

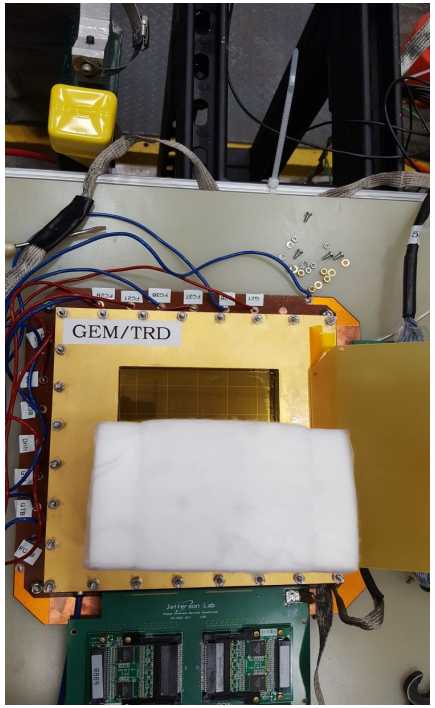




GEMTRD (e/π separation)

Single module (X/X0) :
Radiator (10cm) ~ 1.5 % X_0 (for fleece, could go down with mylar foils)
Xenon gas (2.0 cm) ~ 0.1% X_0
Triple GEM with readout at active area ~ 0.7% X_0
(could go down to 0.4%, current eRD6)



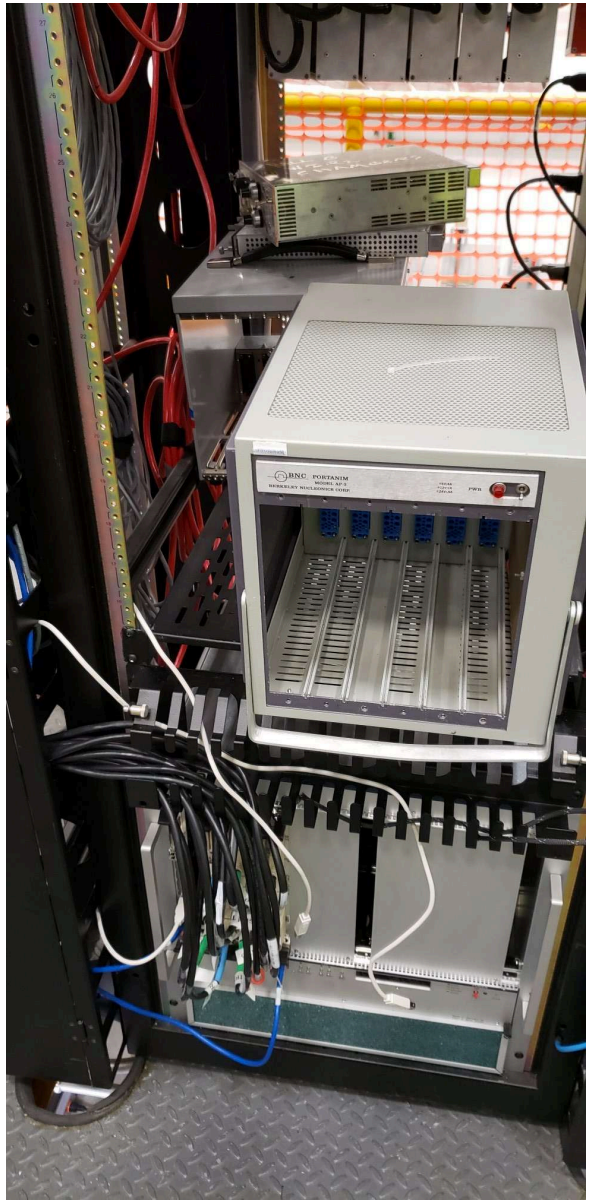


HV and readout

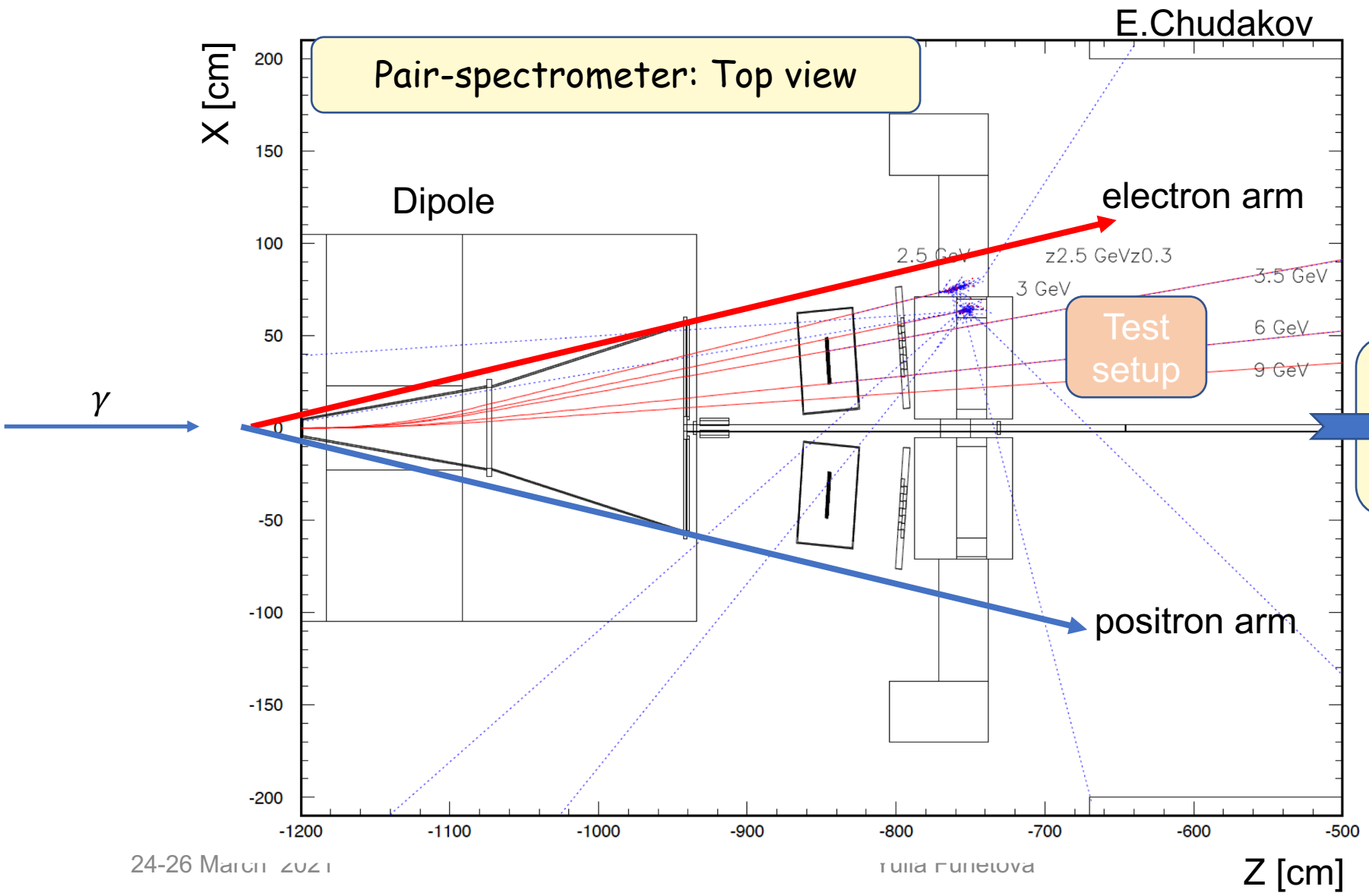
HV1 (amplification): -3.3kV
HV2 (drift): -8.21kV

DAQ:
FlashADCs 125
Crate is located nearby

Safety first !



Hall-D pair spectrometer

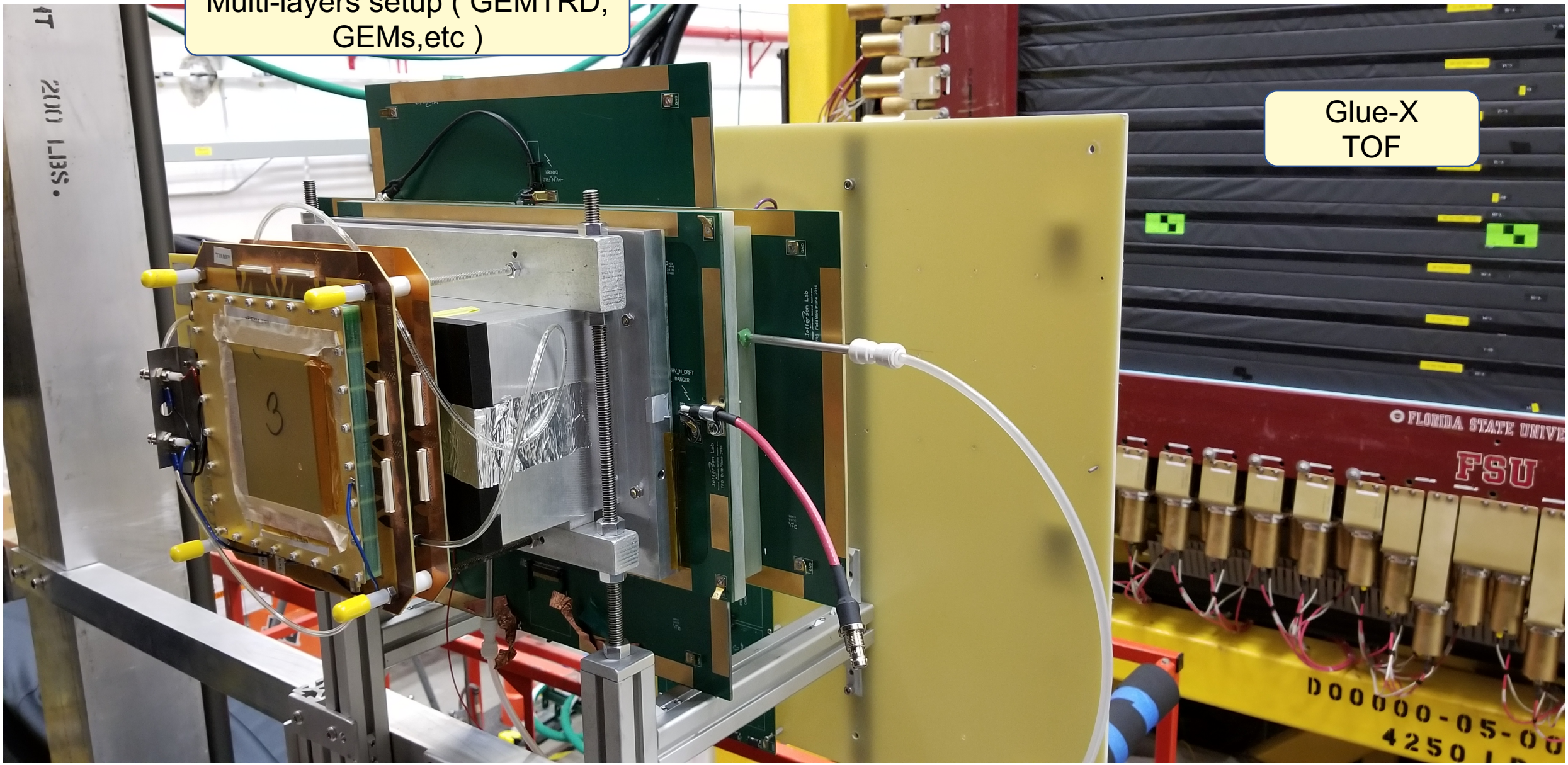


Electrons with 3.5-6 GeV, the energy is measured with a ~0.5-1% resolution.

Flat beam: in-plane(y spread ~ 5mm)

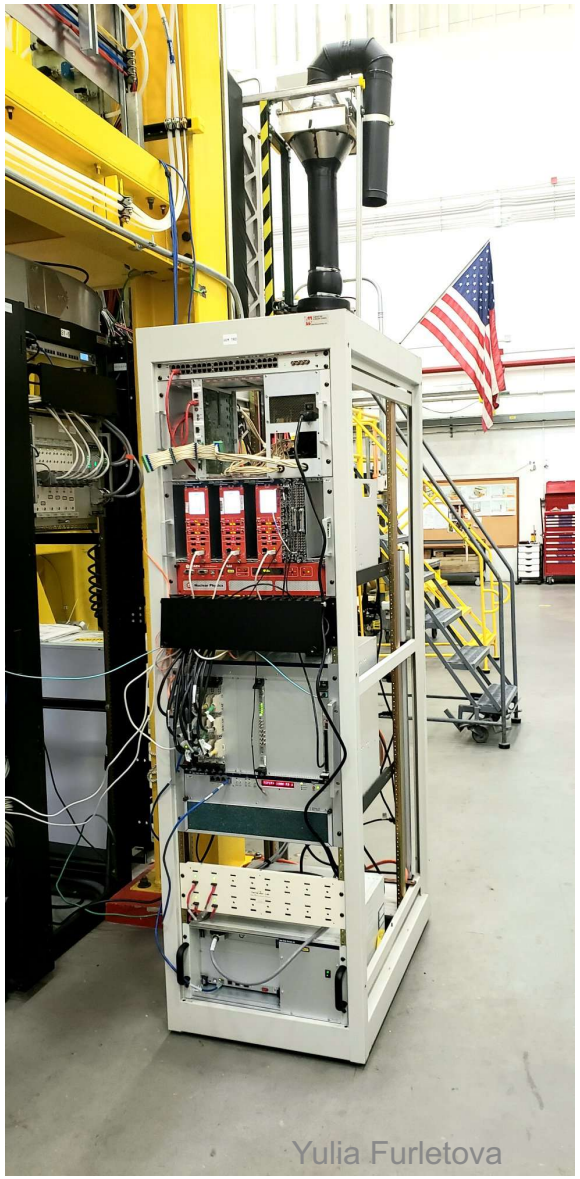
10kHz rate

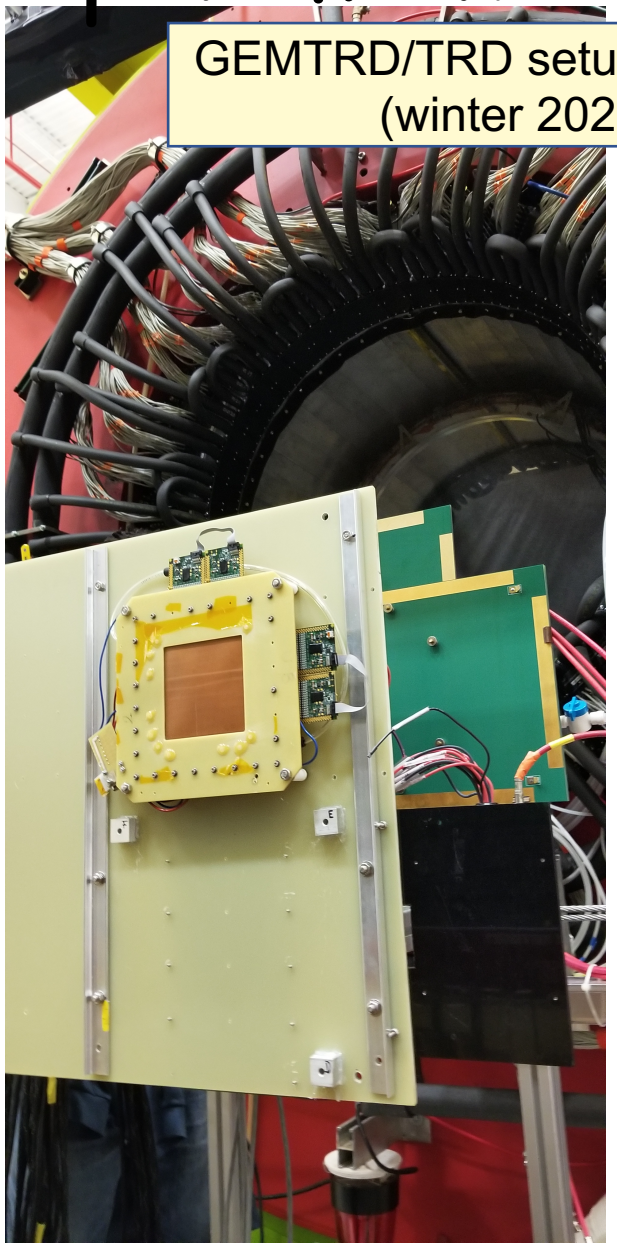
Multi-layers setup (GEMTRD, GEMs,etc)



Glue-X TOF

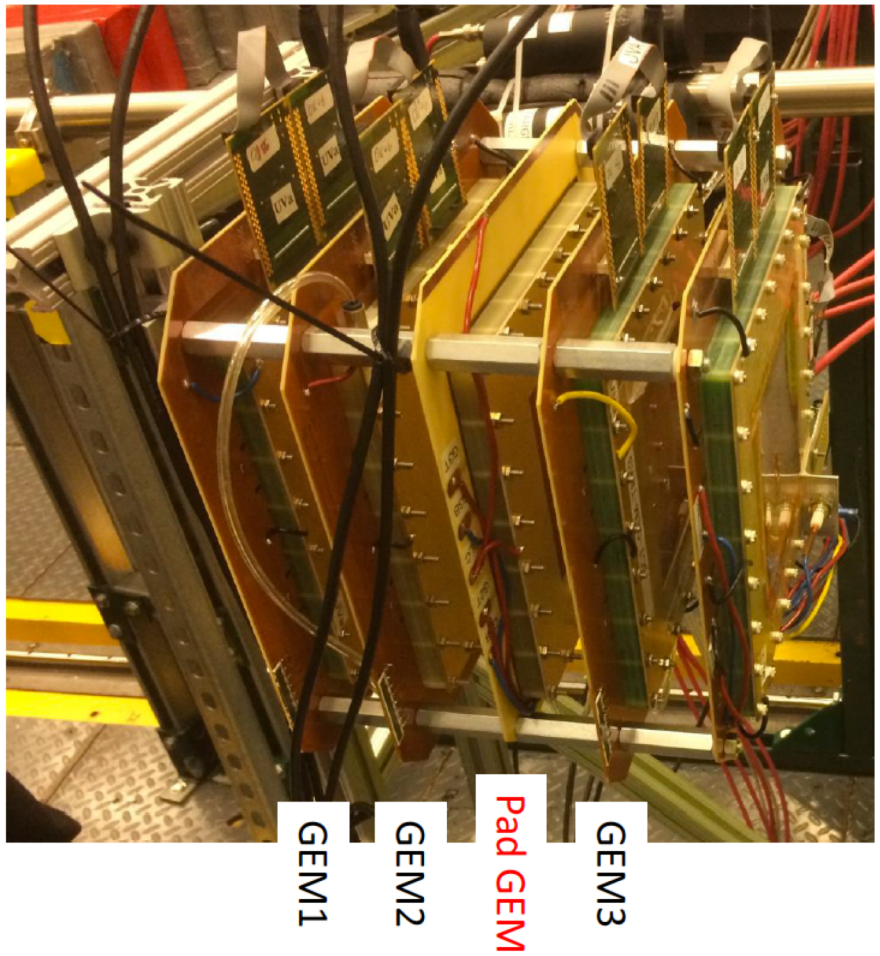
Integration into GlueX experiment



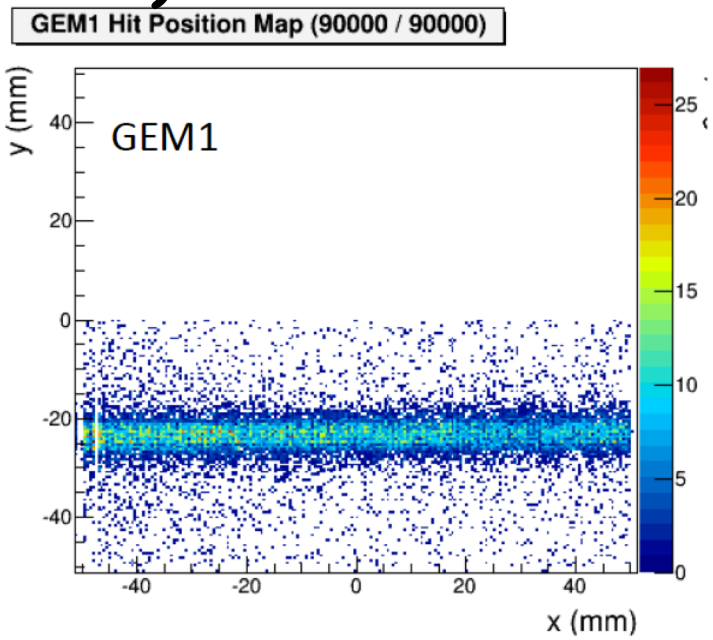


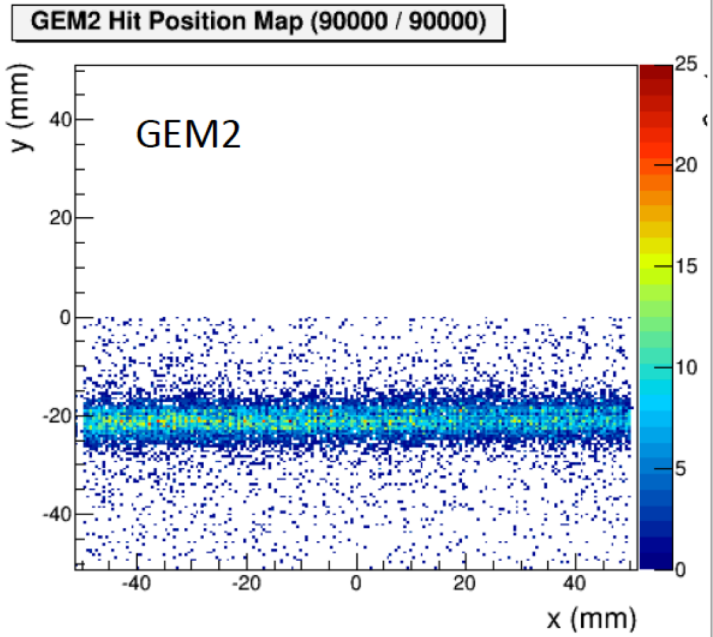
GEMTRD/TRD setup at GlueX
(winter 2020)

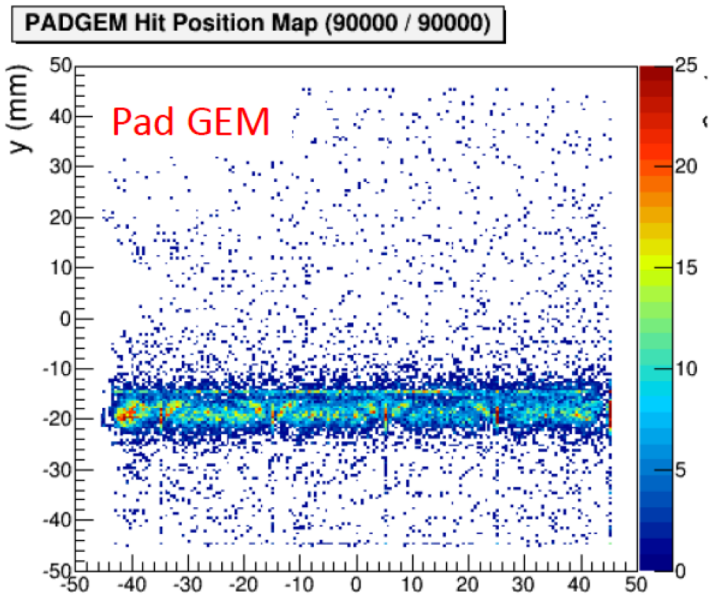
XY hit-map (beam is flat)

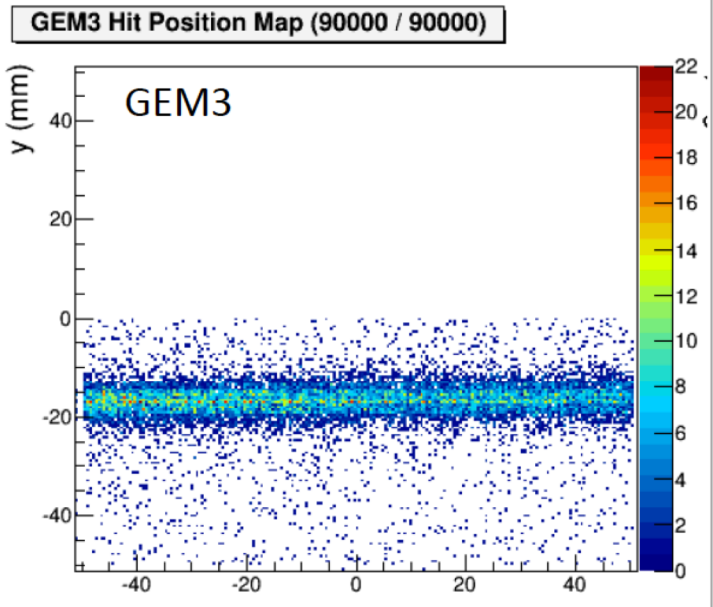


Moving stages are needed!









Conclusions

- Very challenging!