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Search for  $K_L \rightarrow \pi^0 \nu \nu$   
at KOTO experiment

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The University of Chicago

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# Outline

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- ❖ Introduction
- ❖ 2015 Data Results
- ❖ Improvements after 2015
- ❖ Projection of Sensitivity

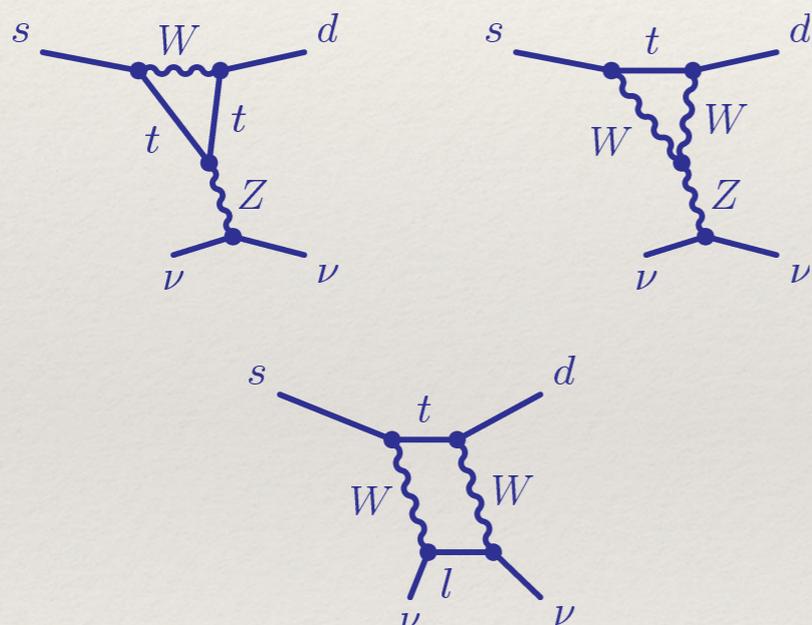
# KOTO Experiment

- ❖ Dedicated experiment for  $K_L \rightarrow \pi^0 \nu \nu$
- ❖ Located at J-PARC, Japan
- ❖ ~50 people from US, Japan, Taiwan & Korea

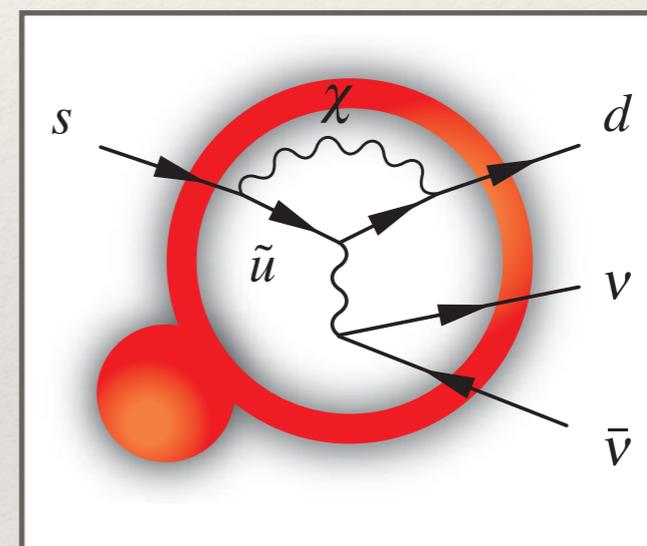


$$K_L \rightarrow \pi^0 \nu \nu$$

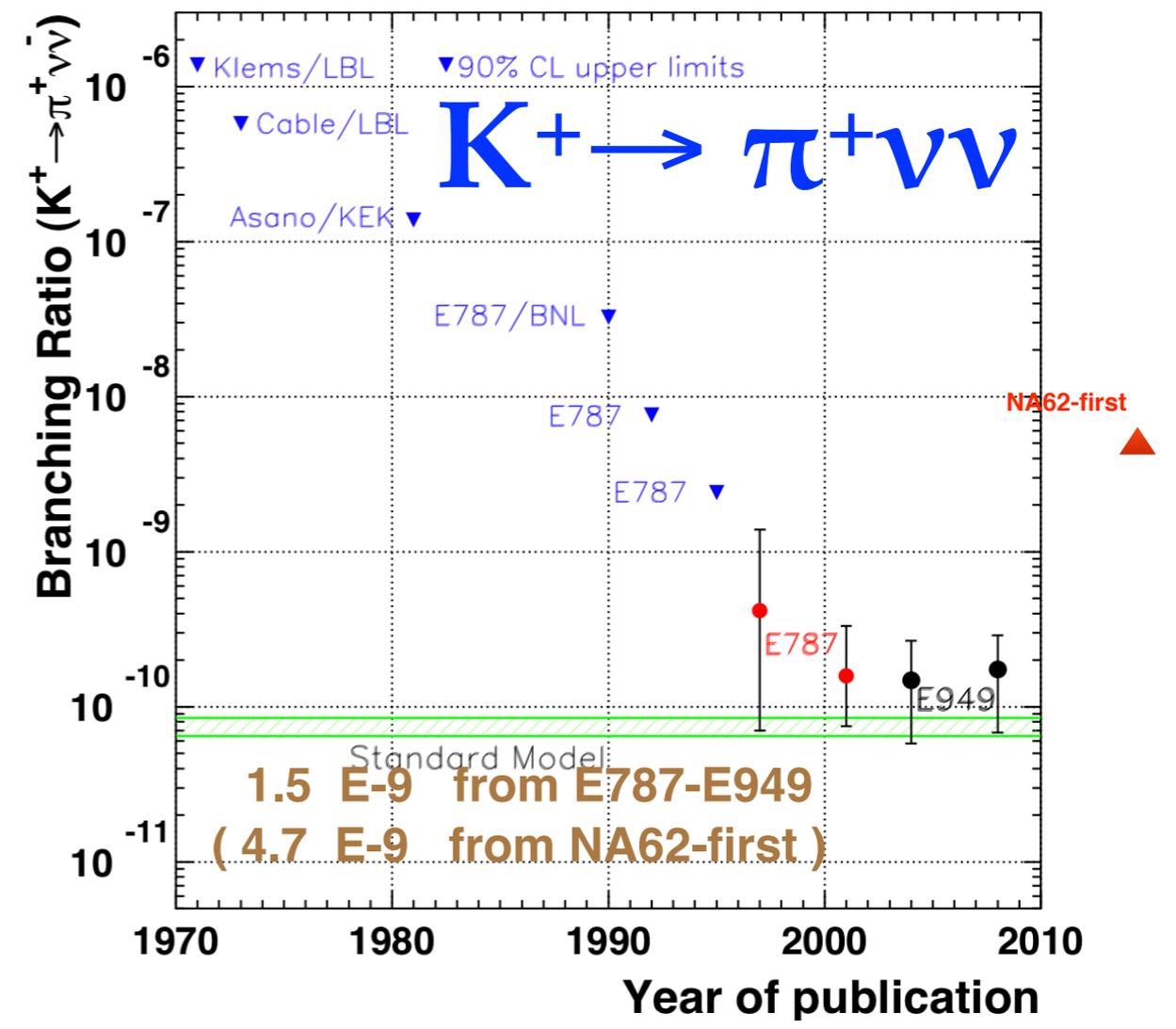
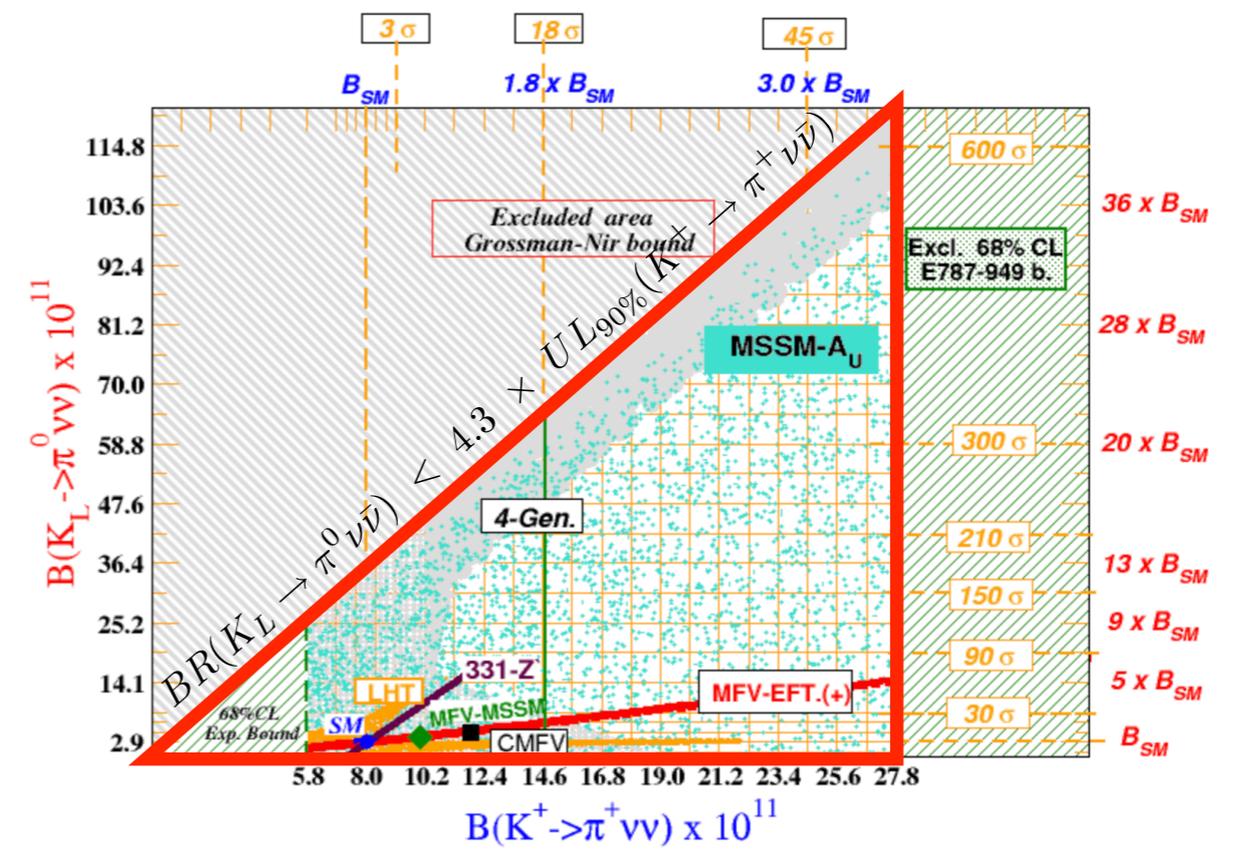
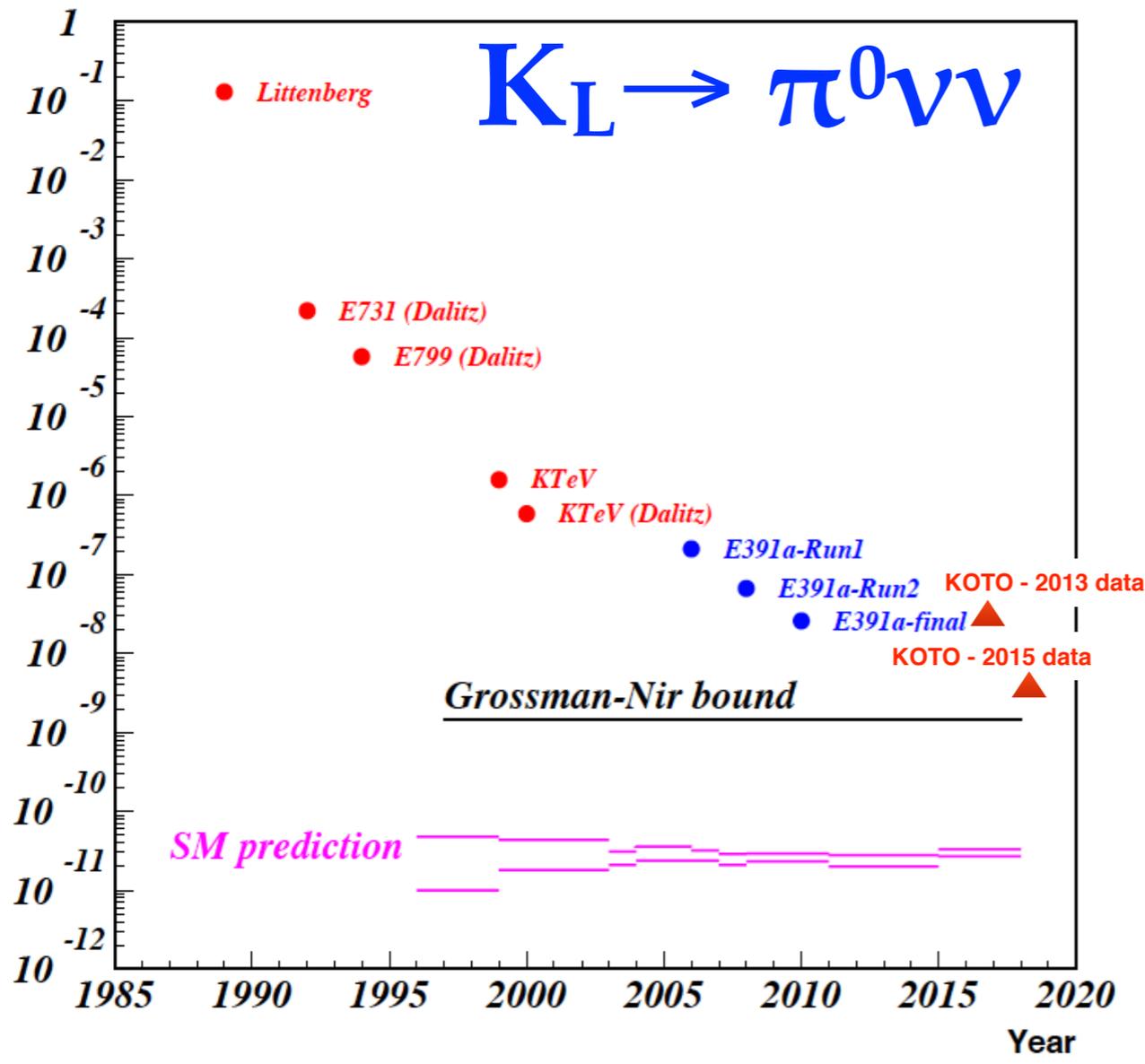
- ❖ Direct CP violating process
- ❖ Theoretically clean: small uncertainty in BR(SM)



+ ?



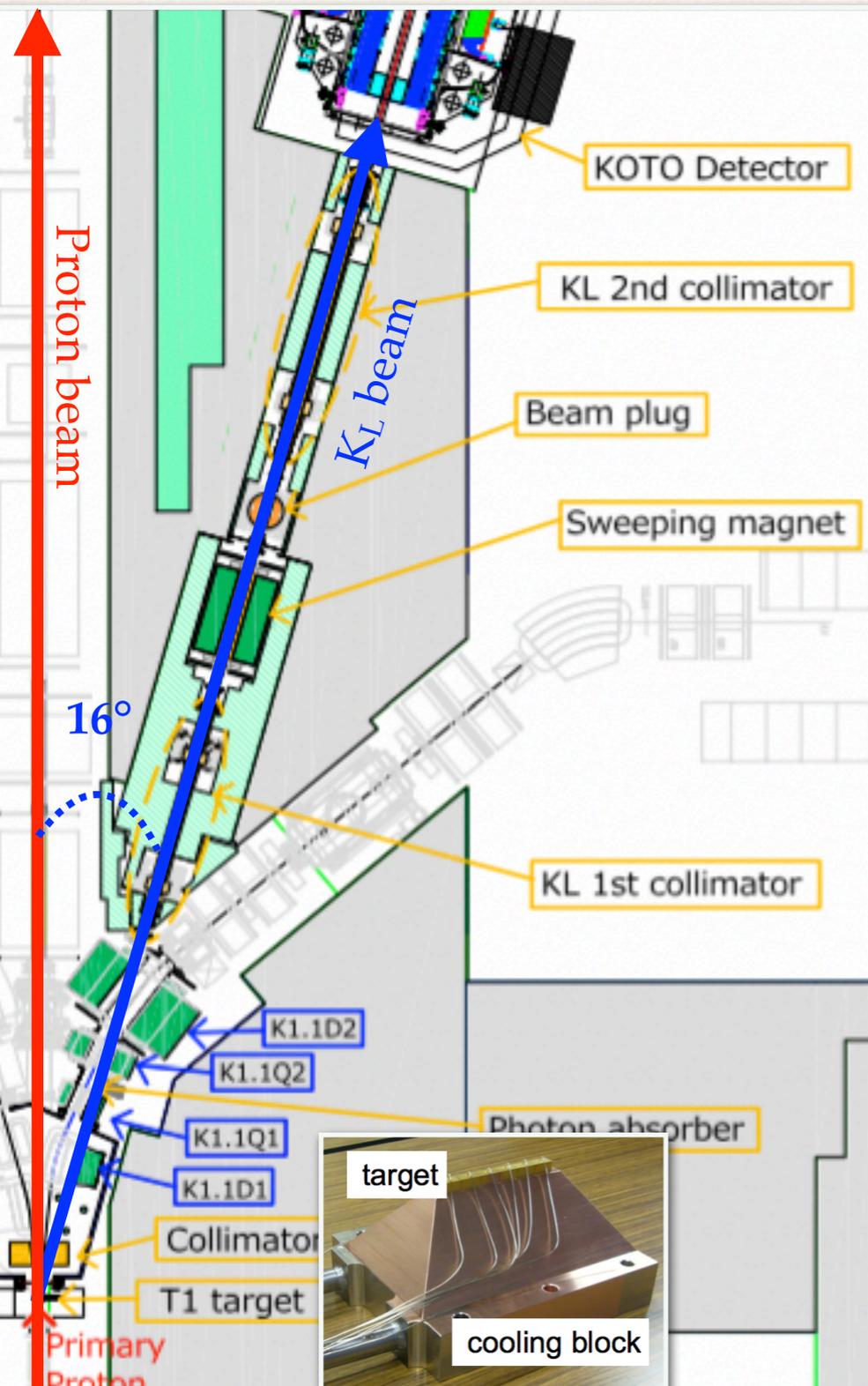
- ❖ Sensitive to New Physics
- ❖ But, rare:  $BR(SM) = (3.00 \pm 0.30) \times 10^{-11}$



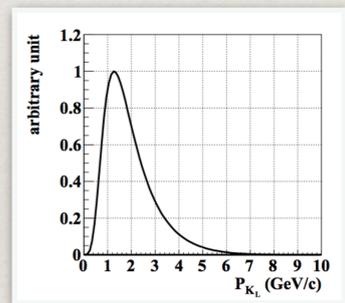
**CERN NA62 ( $K^+ \rightarrow \pi^+ \nu \nu$ )**

**J-PARC KOTO ( $K_L \rightarrow \pi^0 \nu \nu$ )**

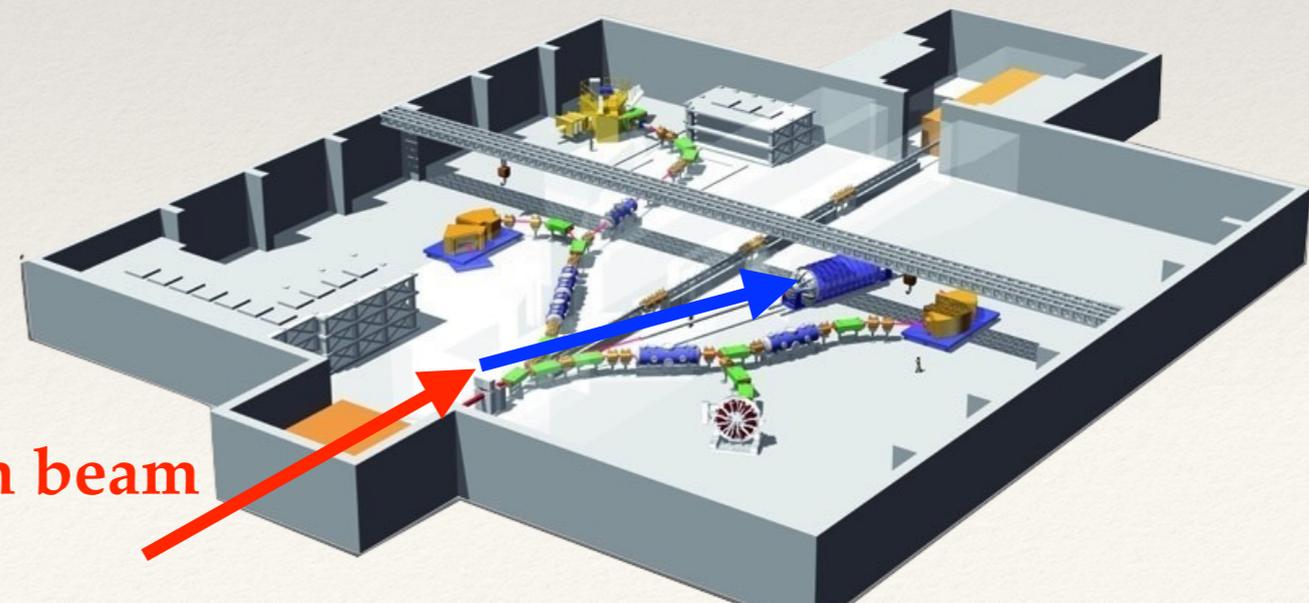
# Beam Line



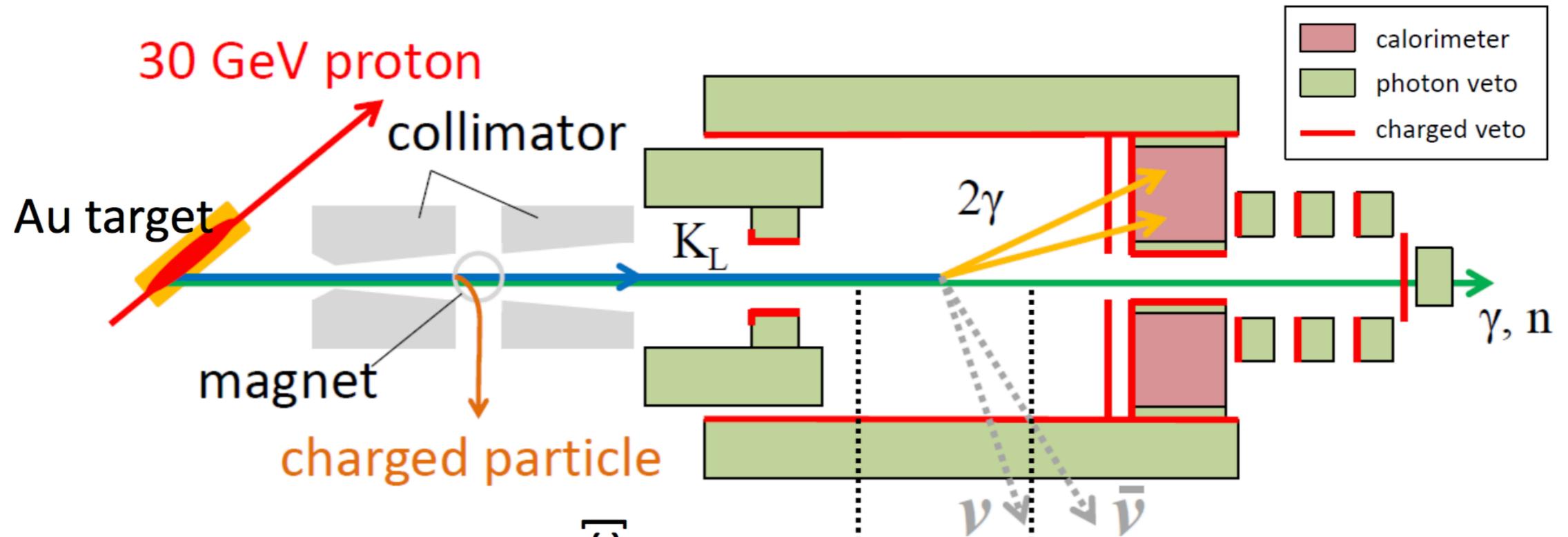
- ❖ KL beam extracted at 16 degree angle.
- ❖ Two stages of collimators.
  - ❖ Beam size  $\sim 3.5$  cm at detector exit.
- ❖ A magnet sweeps out charged particles.
- ❖ Detector entrance at 21m from the target.
- ❖ Kaon momentum peaked at 1.5 GeV



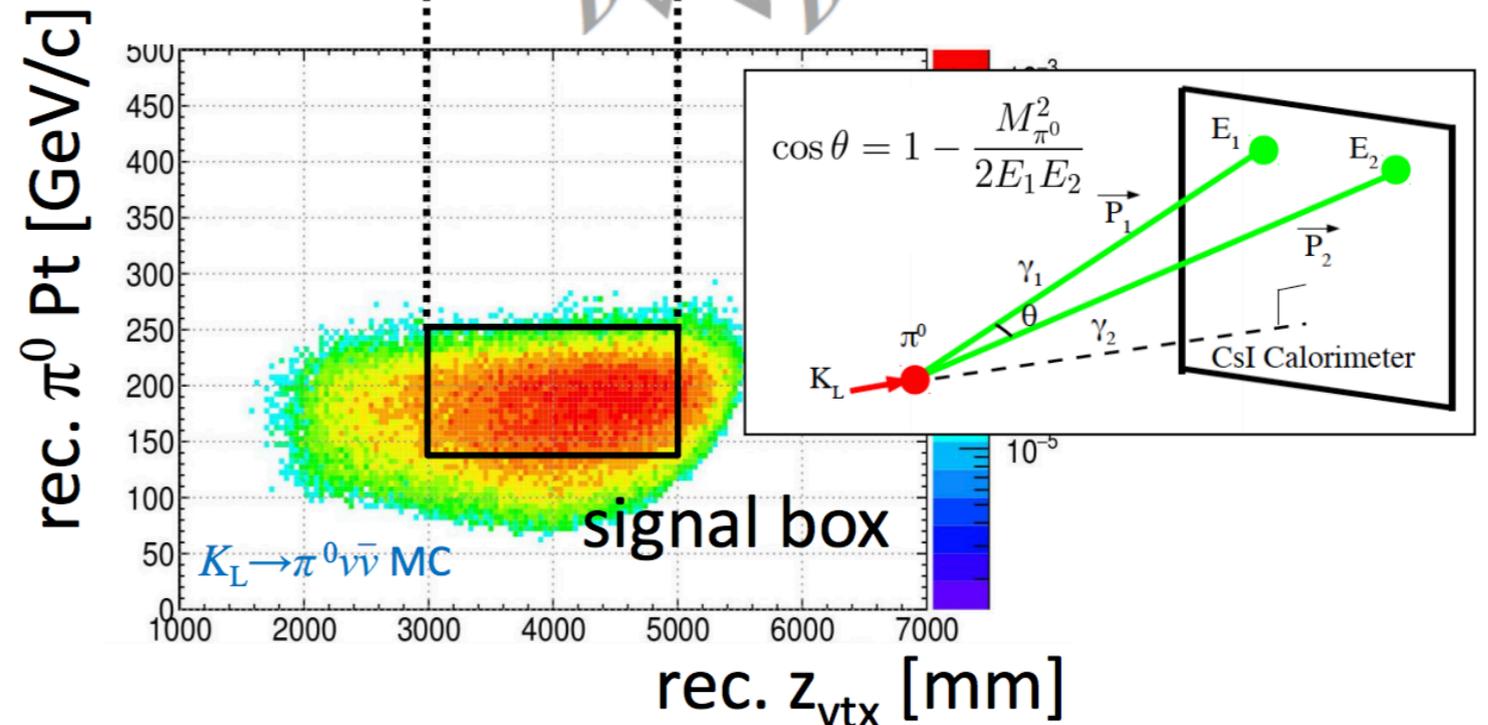
30GeV Proton beam



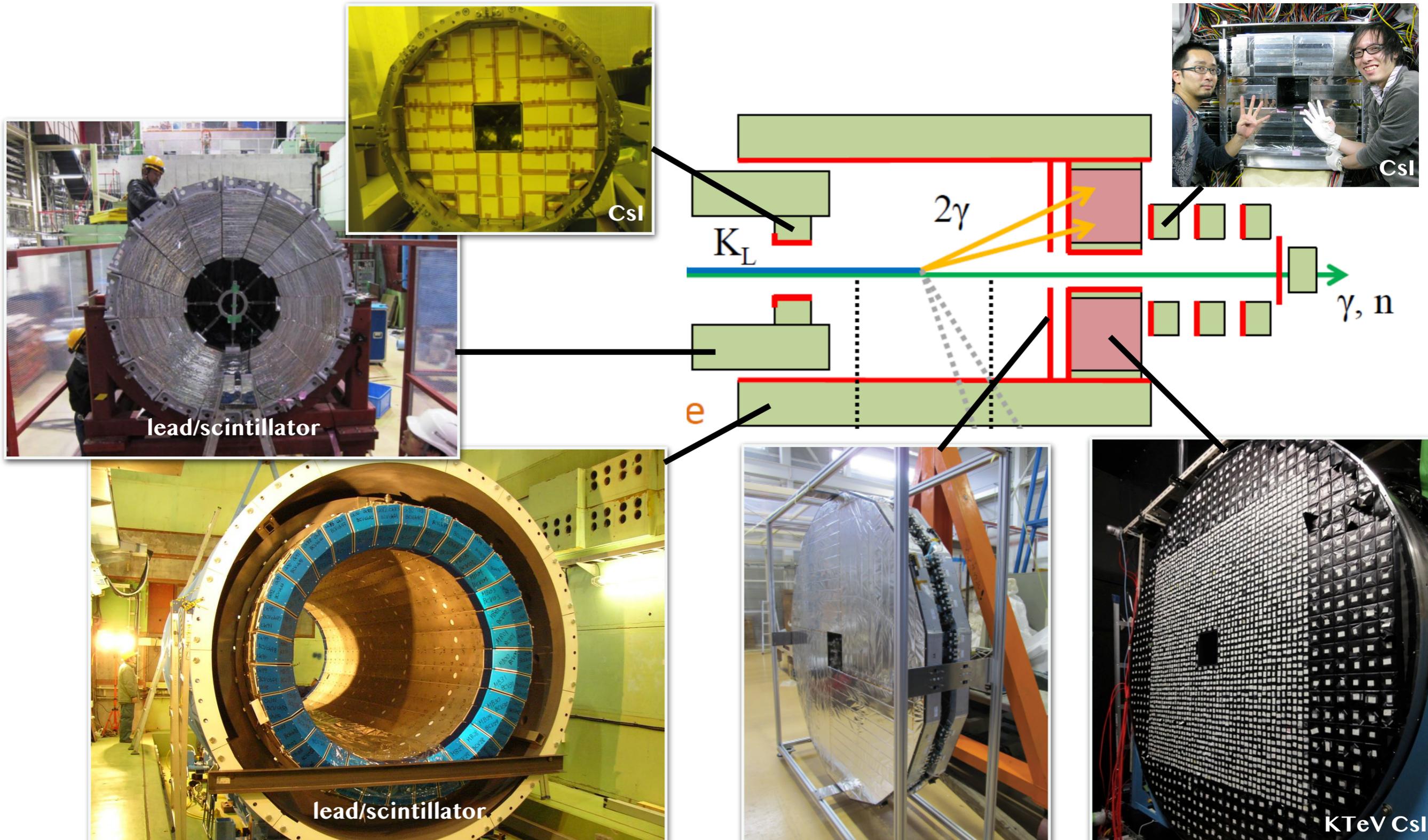
# Concept of Signal Detection



- ❖ Event Signatures:
  - ❖  $2\gamma$  on CsI
  - ❖ nothing elsewhere

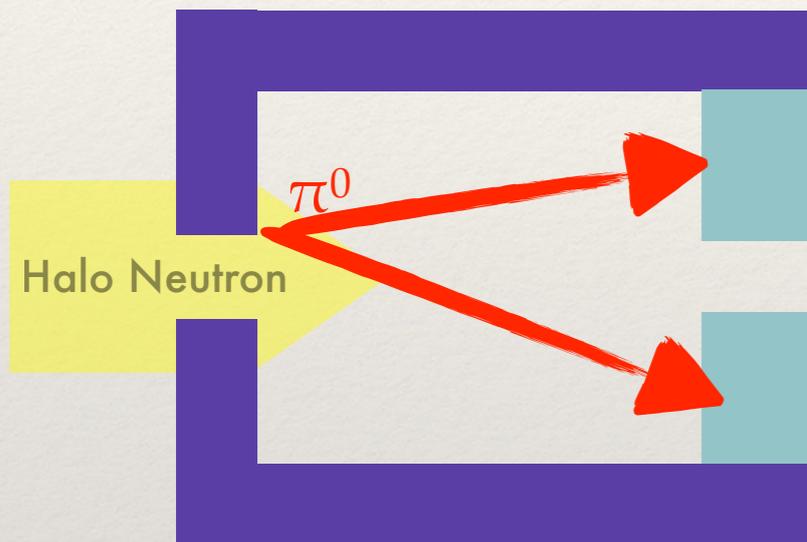


# Detector

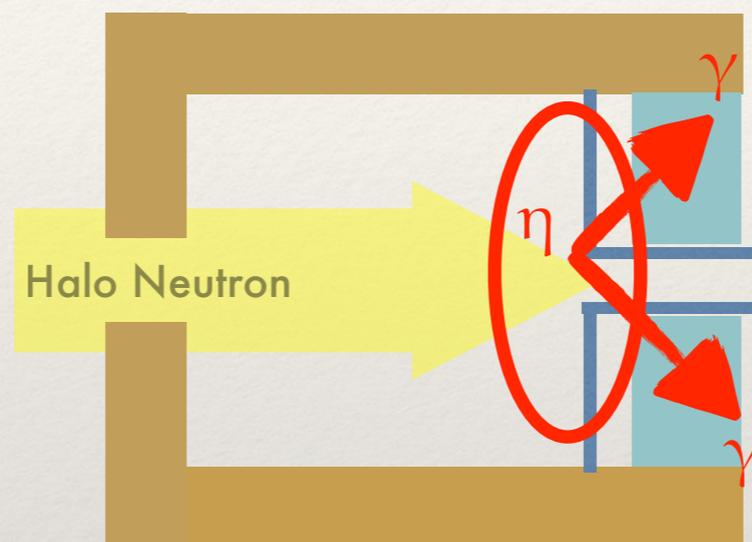


# Background Sources - Neutron

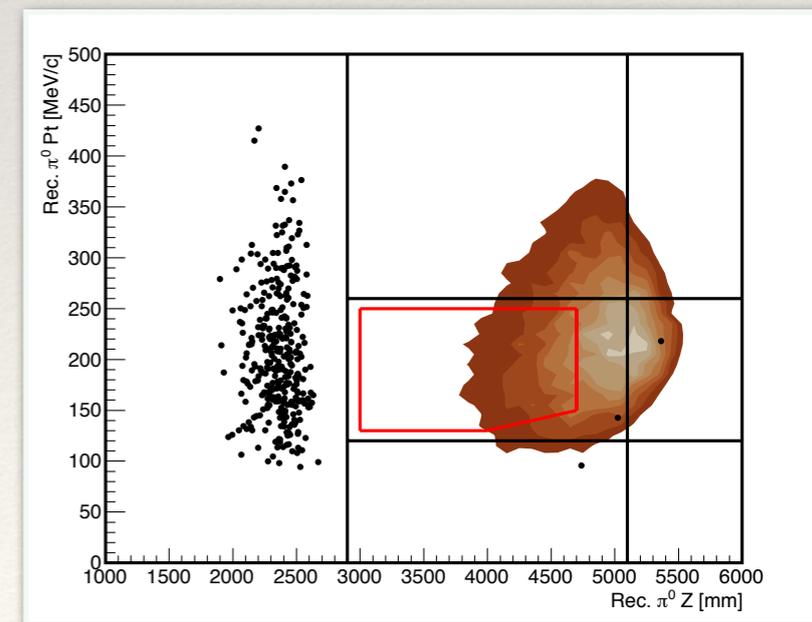
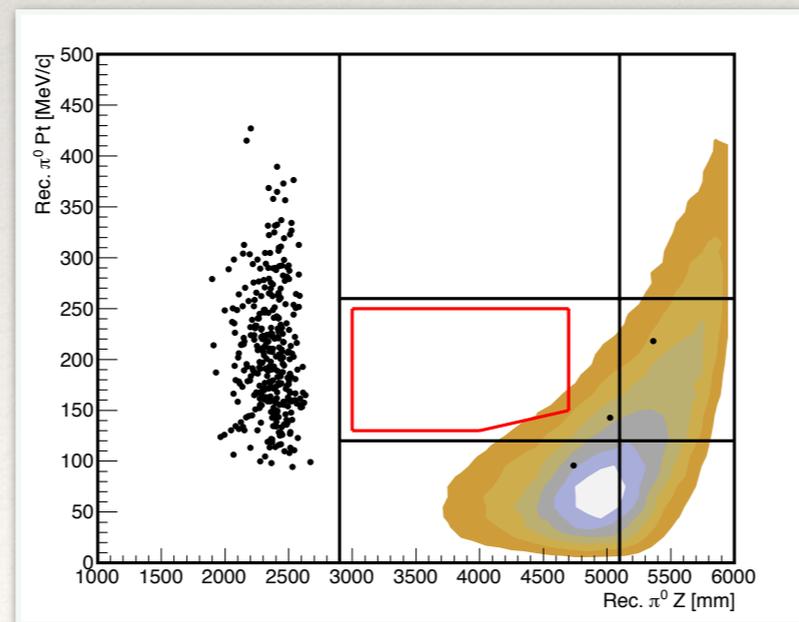
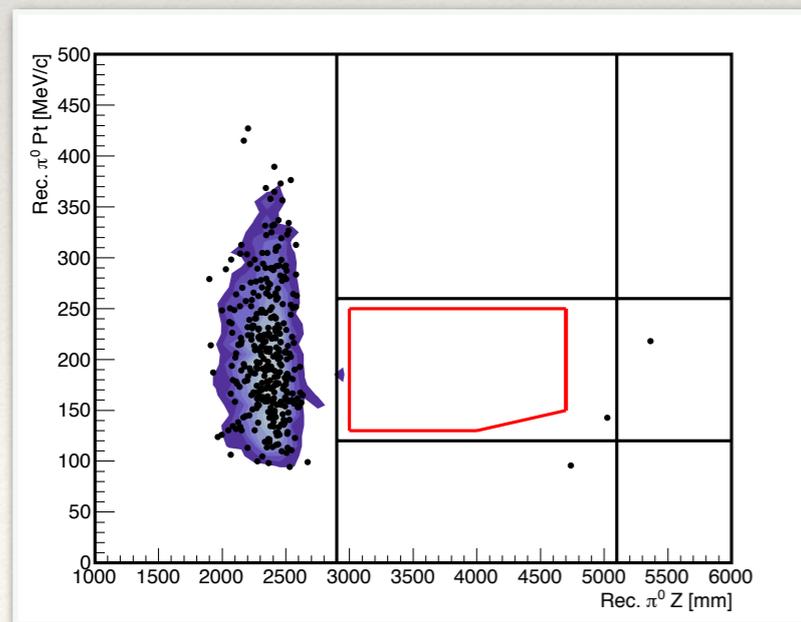
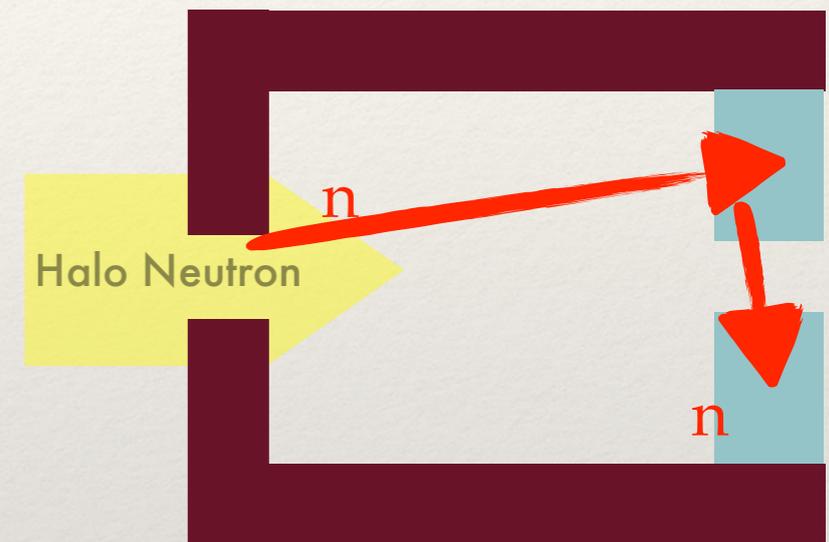
Upstream- $\pi^0$



CV- $\eta$

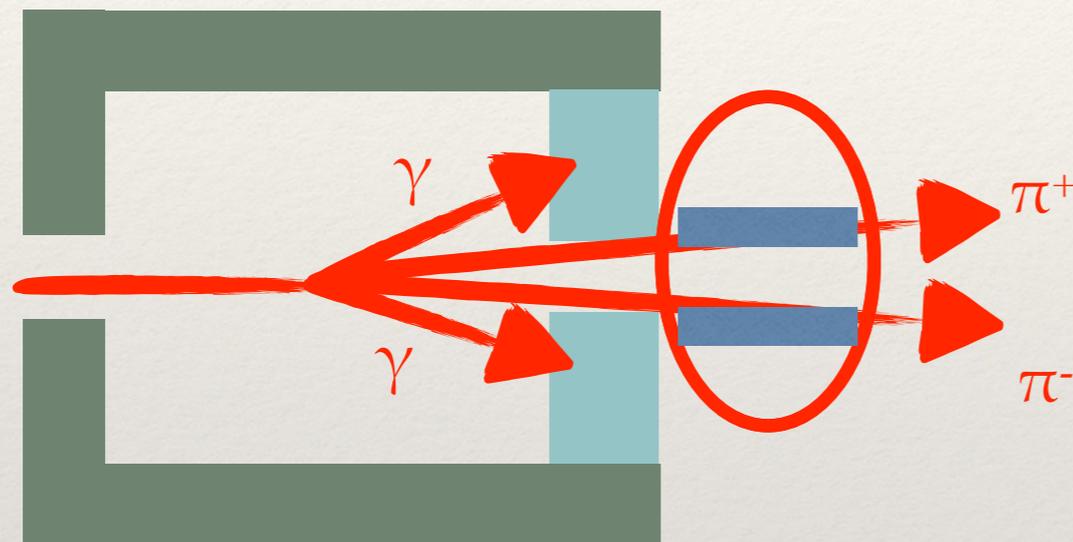


Hadron Cluster

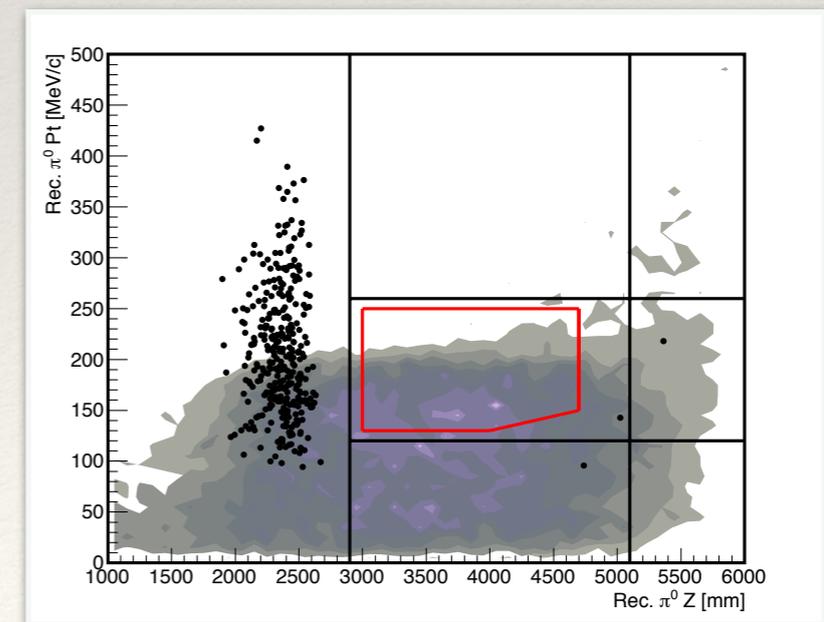
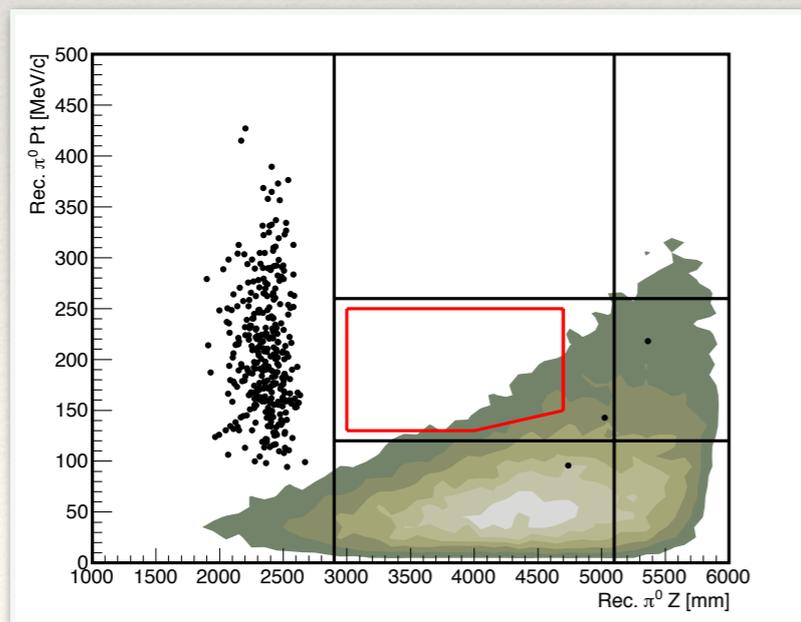
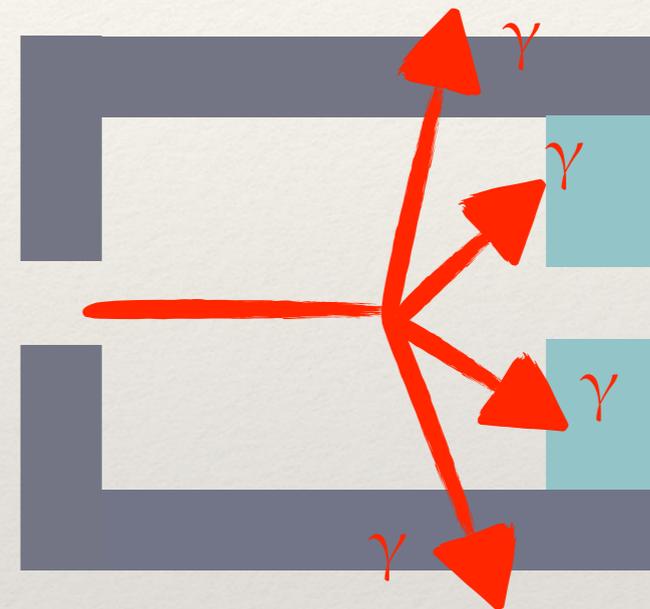


# Background Sources - Kaon

$$K_L \rightarrow \pi^+ \pi^- \pi^0$$



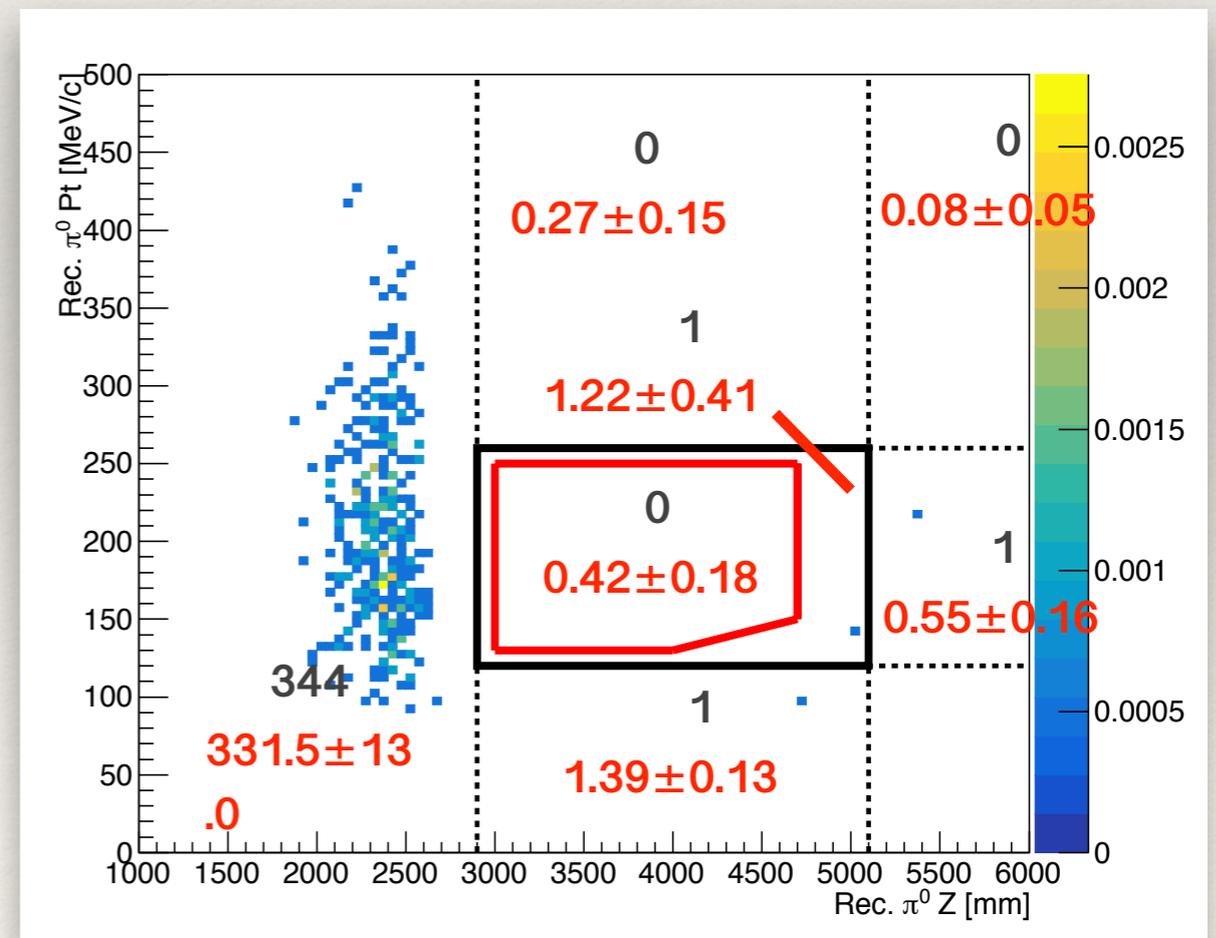
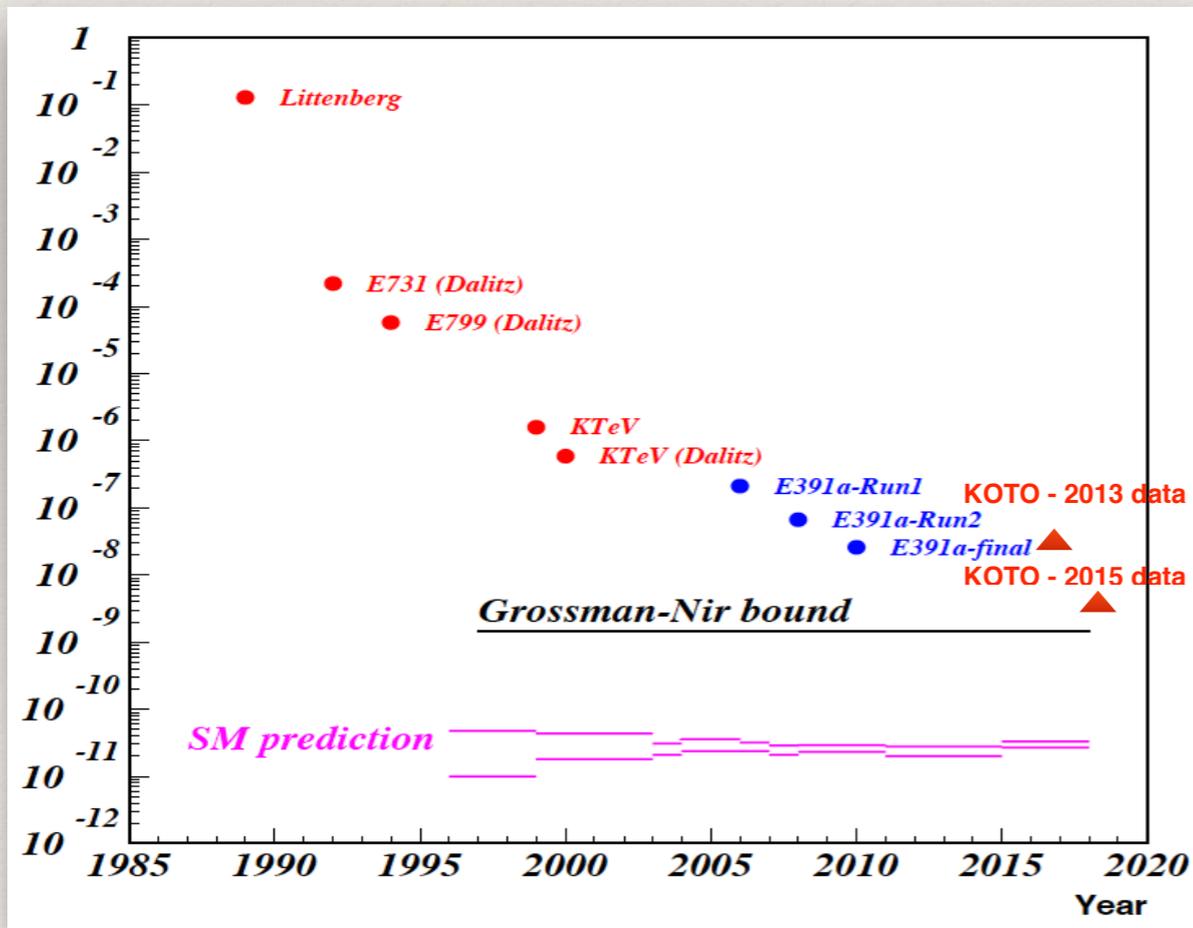
$$K_L \rightarrow \pi^0 \pi^0$$



# 2015 Data Results

- ❖ ~40% total collected data
  - ❖ S.E.S. =  $1.3 \times 10^{-9}$
- ❖ BR <  $3.0 \times 10^{-9}$  (90% C.L.)

	BG Prediction
Hadron Cluster	$0.24 \pm 0.17$
$K_L \rightarrow \pi^+ \pi^- \pi^0$	$0.05 \pm 0.02$
CV- $\eta$	$0.04 \pm 0.02$
Upstream- $\pi^0$	$0.04 \pm 0.03$
$K_L \rightarrow \pi^0 \pi^0$	$0.02 \pm 0.02$
Other $K_L$ decays	$0.03 \pm 0.01$

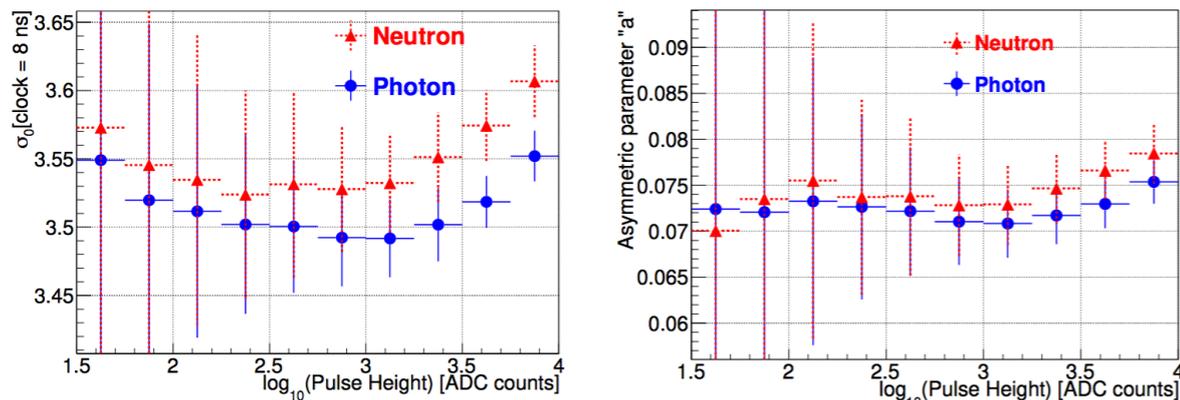
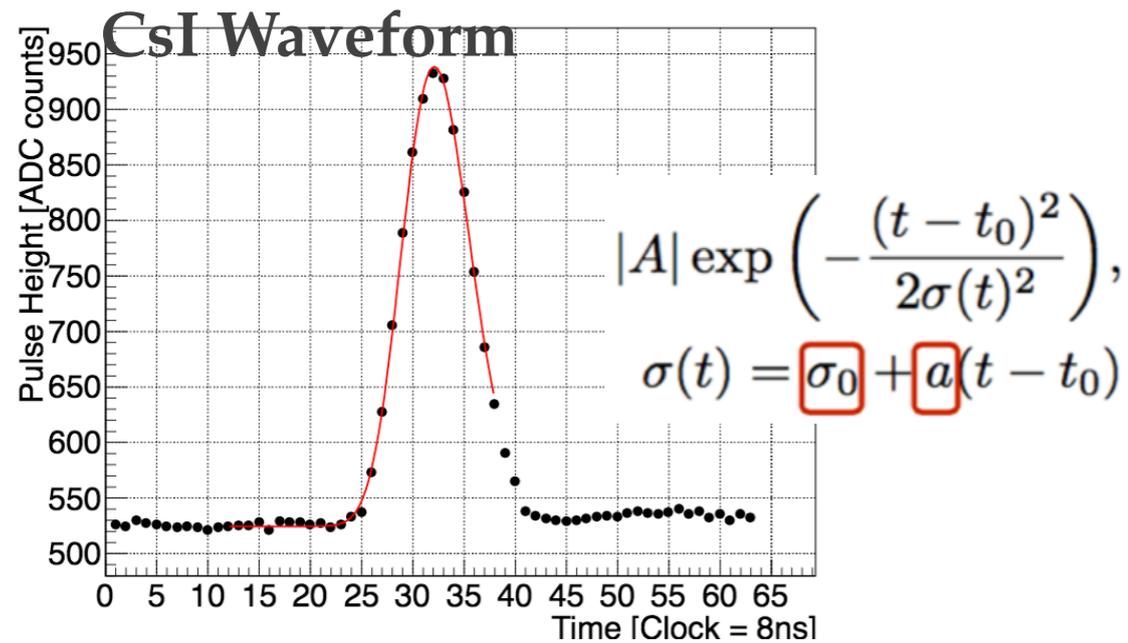


# Background Level at SES( $10^{-11}$ )

- ❖ 2015 SES =  $1.3 \times 10^{-9}$ , a factor of 130 from SES= $10^{-11}$
- ❖ 2015 Background Level (BGL) scaling to SES= $10^{-11}$

	2015 BGL	2015 BGL @ SES= $10^{-11}$
Hadron Cluster	$0.24 \pm 0.17$	31
$K_L \rightarrow \pi^+ \pi^- \pi^0$	$0.05 \pm 0.02$	6.5
CV- $\eta$	$0.04 \pm 0.02$	5.2
Upstream- $\pi^0$	$0.04 \pm 0.03$	5.2
$K_L \rightarrow \pi^0 \pi^0$	$0.02 \pm 0.02$	2.6

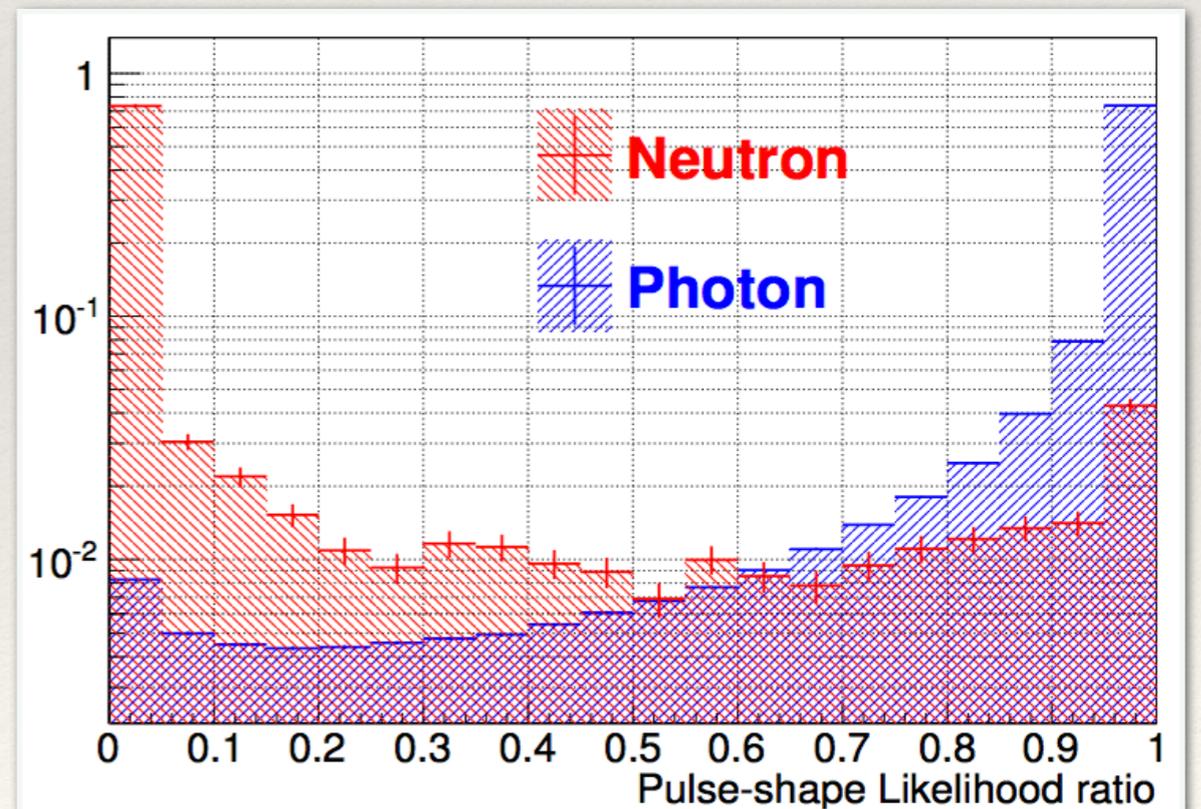
# Hadron Cluster



**Wider Pulse in hadronic shower**

## Pulse Shape Discrimination

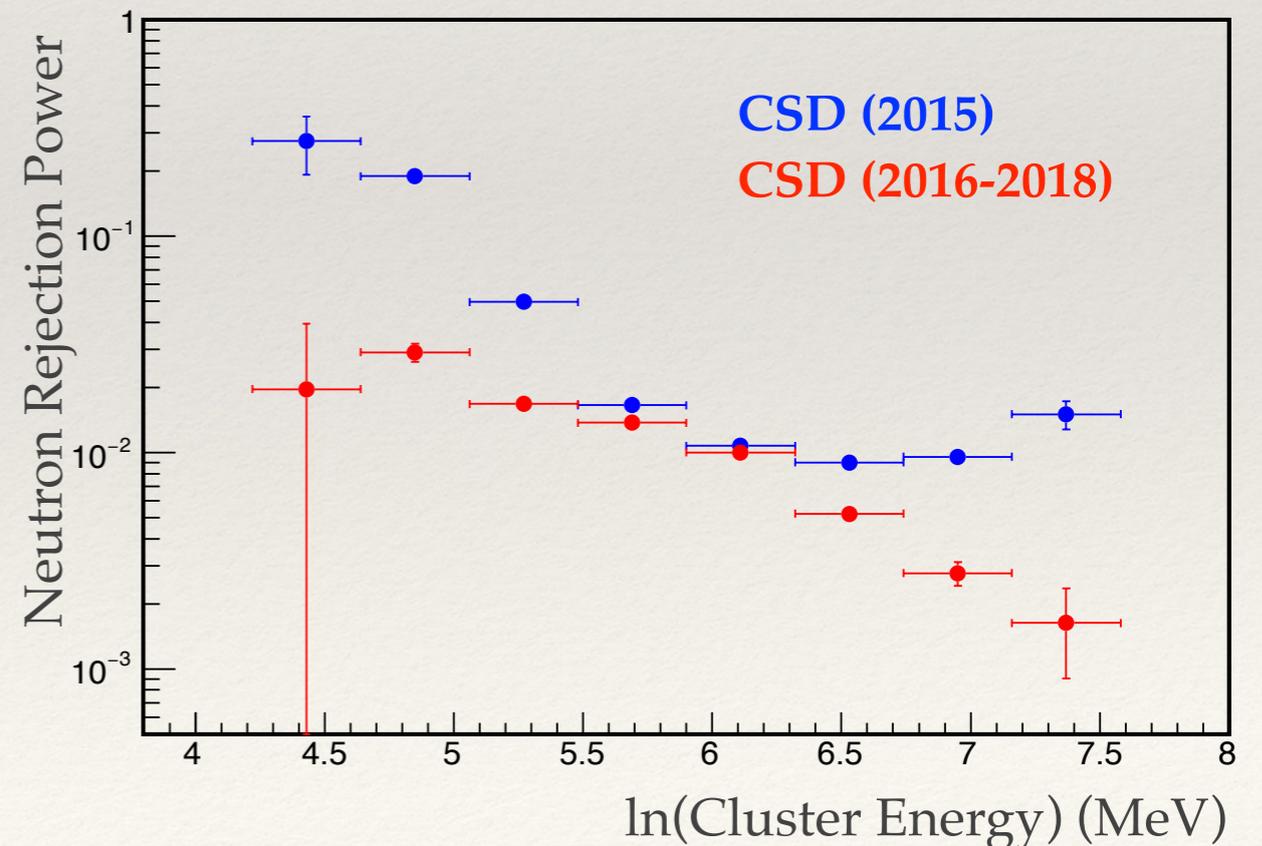
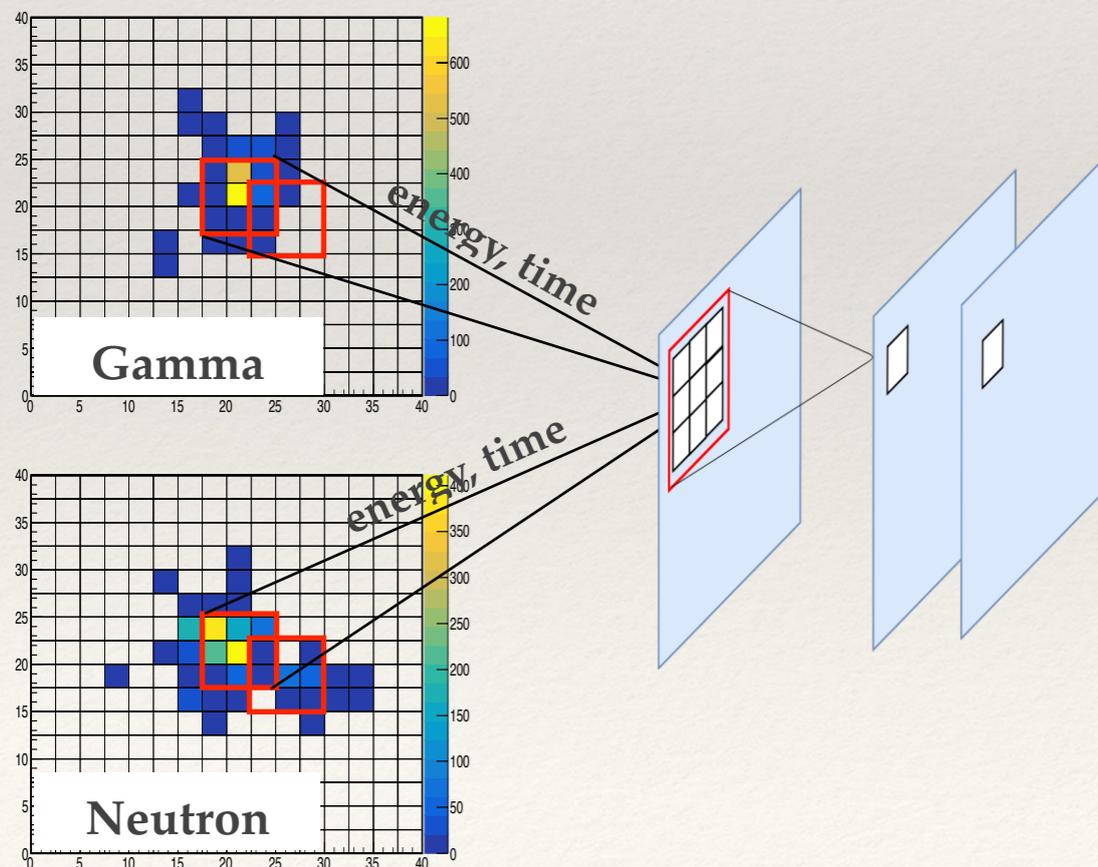
- ❖ used in 2015 data analysis
- ❖ 1/10 reduction with 90% signal eff.



# Hadron Cluster

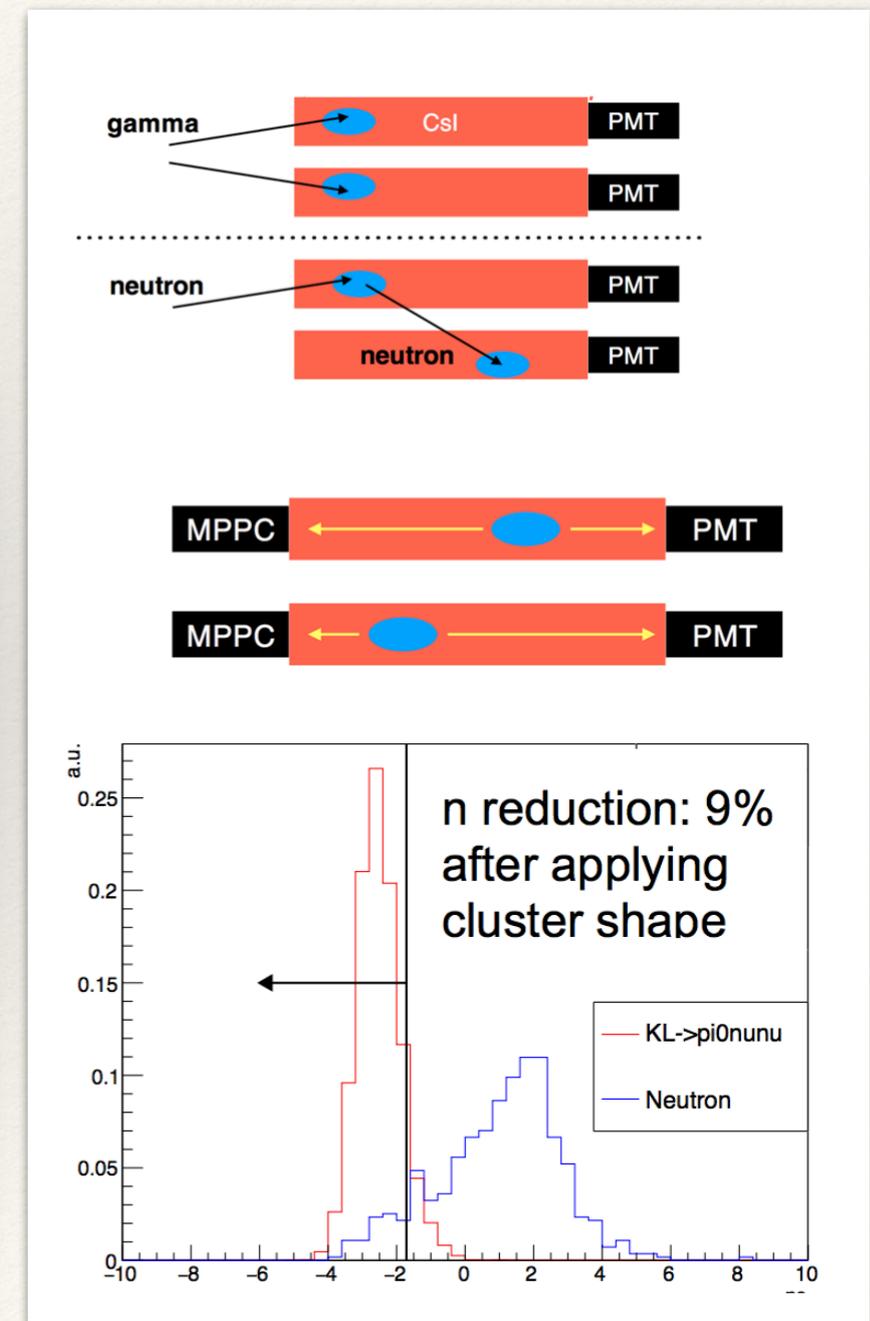
## Cluster Shape Discrimination (neural net variable)

- ❖ 2015 analysis: MC based inputs with TMVA neural net
- ❖ 2016 - 2018 analysis: pixel inputs with deep learning neural net
  - ❖ Neutron BG  $\times 1/4$



# Hadron Cluster

- ❖ CsI both-end readout to measure shower depth
  - ❖  $BG \times 1/10$
- ❖ Complete by early 2019

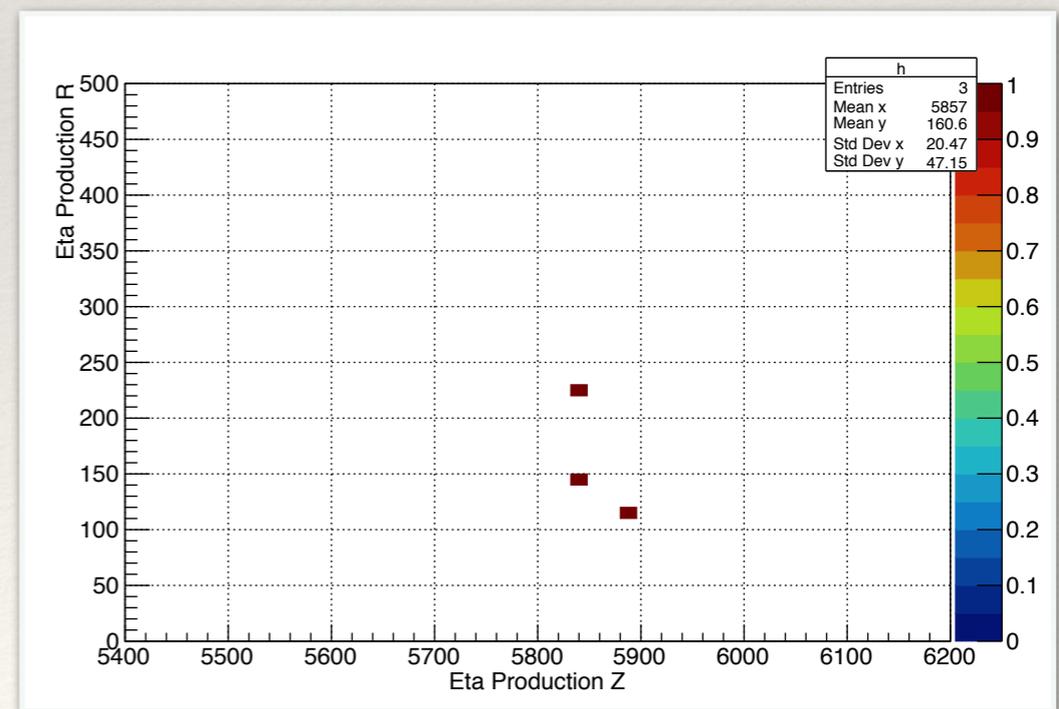
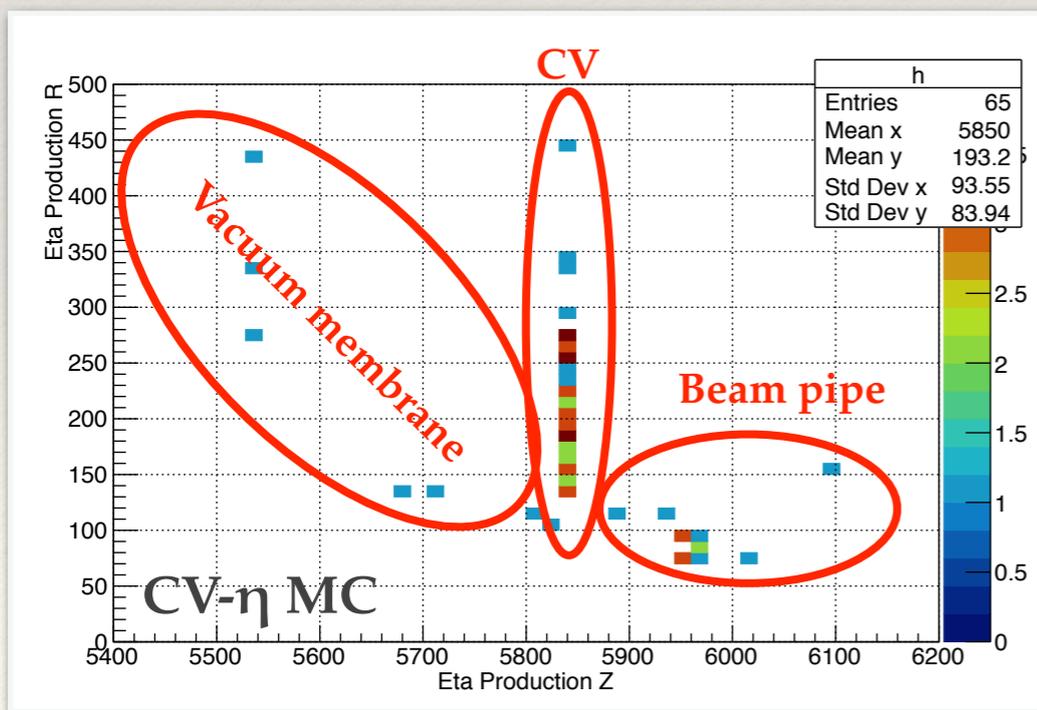
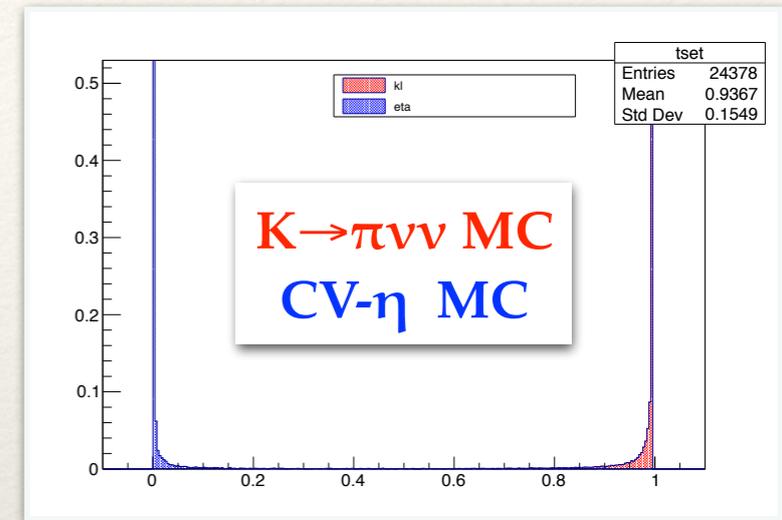


# CV- $\eta$

❖ Cluster shape analysis by neural net

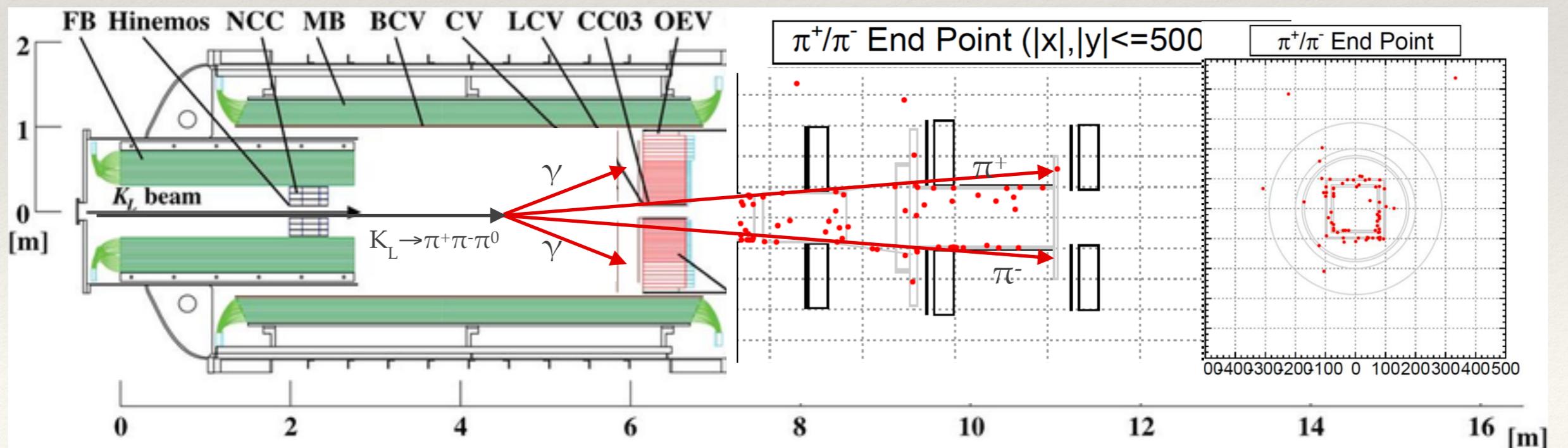
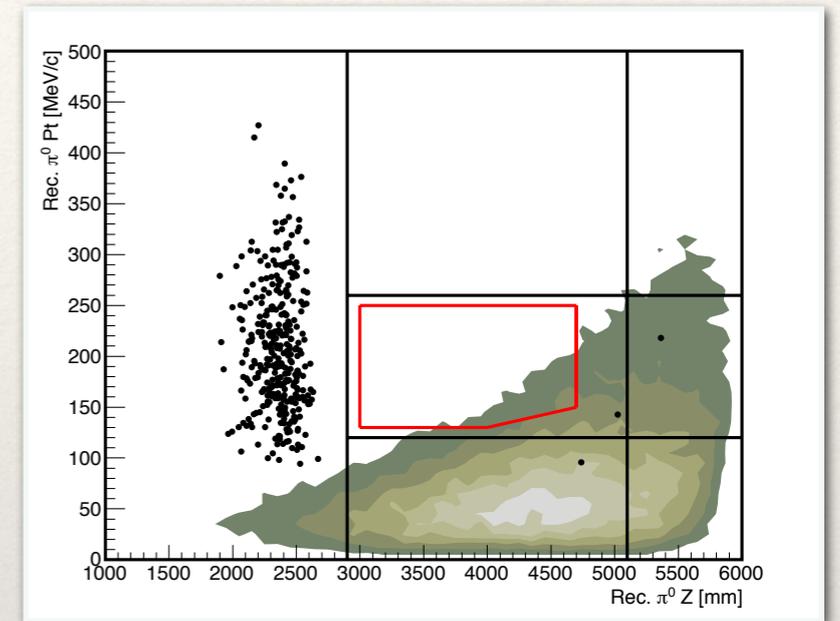
❖ BG x 1/6

❖ BG x 1/2 by changing downstream supporting-structure



# $K_L \rightarrow \pi^+ \pi^- \pi^0$

- ❖ New Charged veto inside the beam pipe
- ❖ Installation in early 2019
- ❖ better coverage  $\Rightarrow$  BG  $\times 1/50$



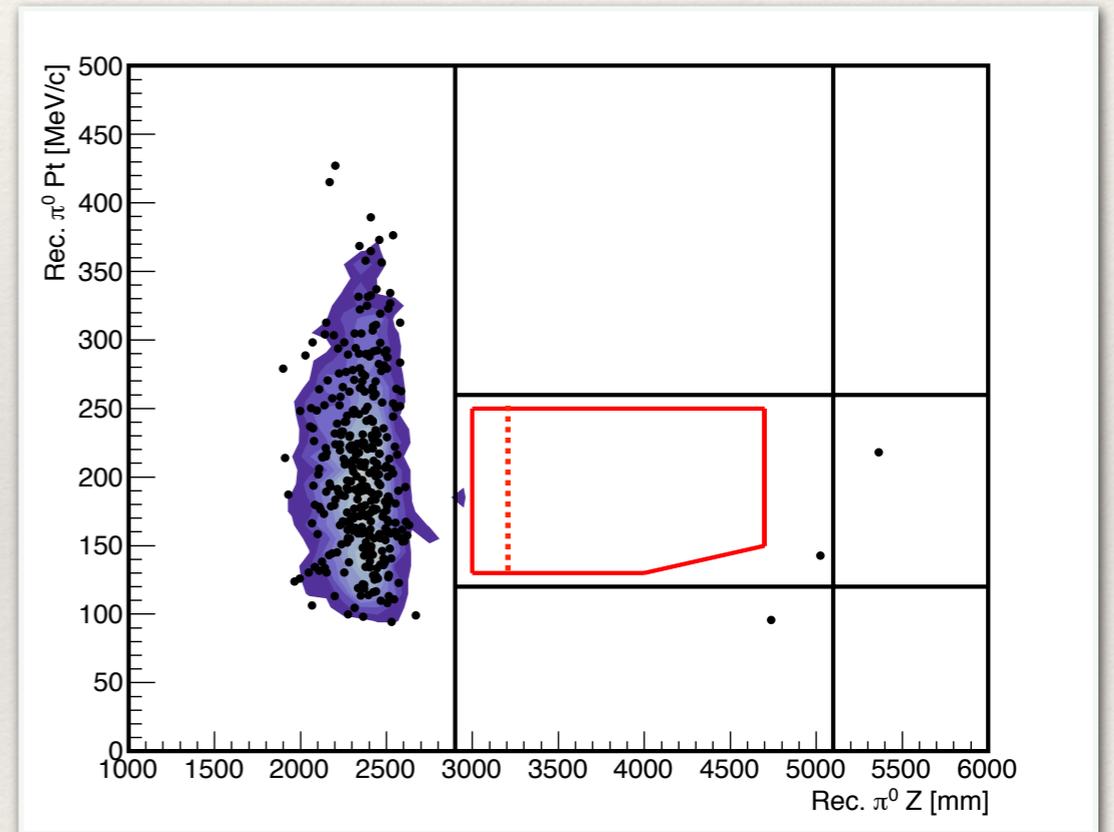
# Upstream- $\pi^0$

## Background mechanism:

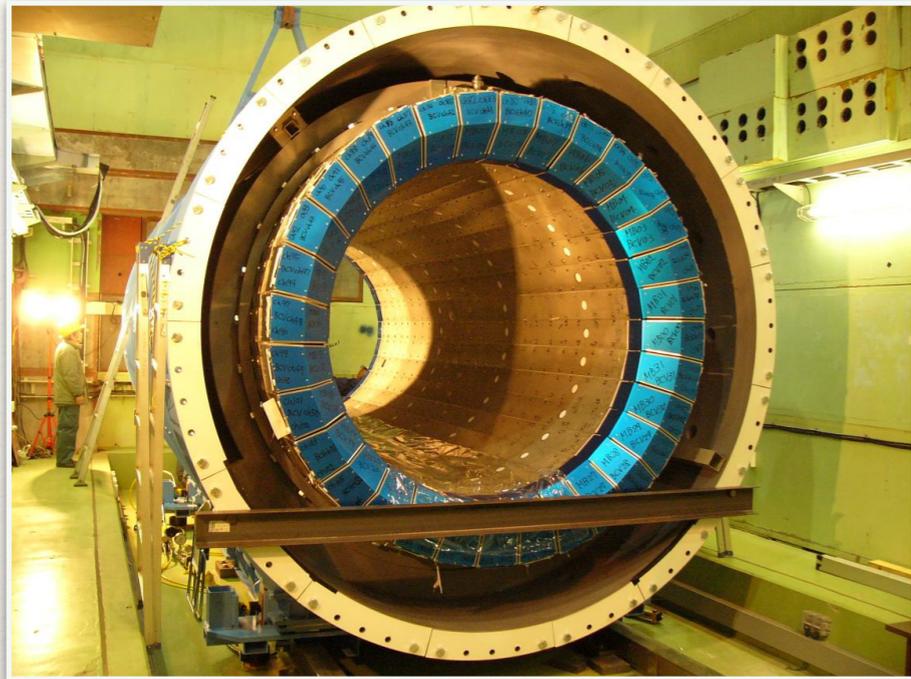
- ❖ 50%:  $\Upsilon + \Upsilon$  (less E in CsI)
  - ❖ BG  $\times 1/6$  by cutting upstream 20 cm
- ❖ 50%:  $\Upsilon + n$ 
  - ❖ BG  $\times 1/4$  by PSD & CSD
  - ❖ BG  $\times 1/3$  by CsI front-end readout

## Expected background level:

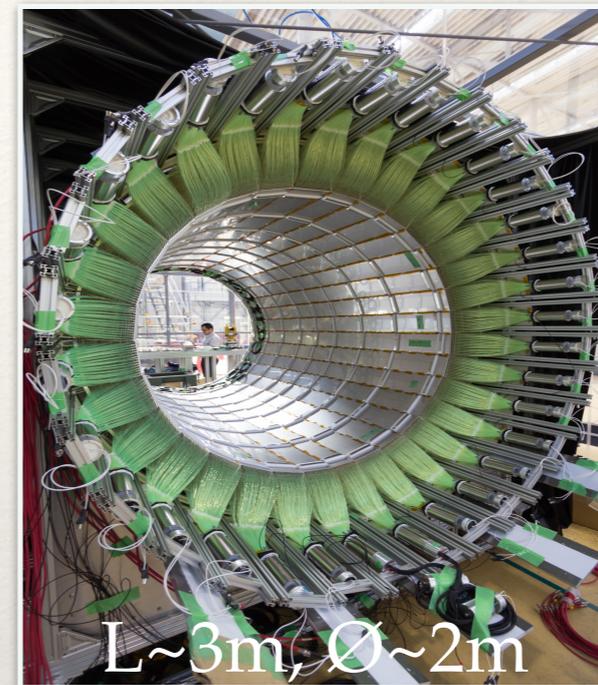
- ❖  $\times 1/5$  for 2016-2018 data
- ❖  $\times 1/8$  for 2019- data



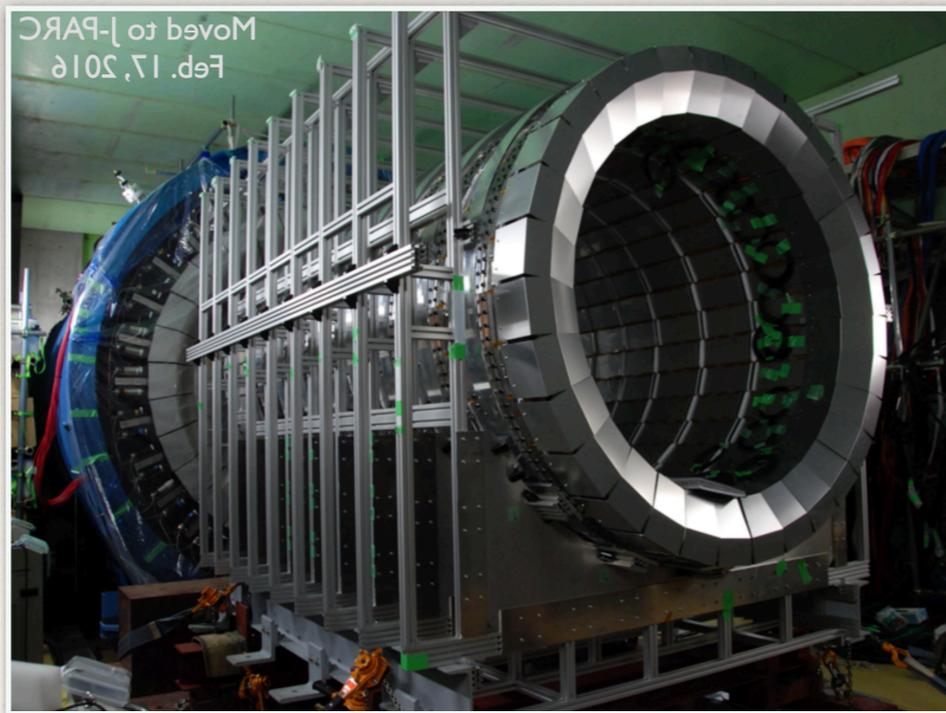
$$K_L \rightarrow \pi^0 \pi^0$$



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- ❖ Radiation  $13.5 + 5 X_0$
- ❖  $K_L \rightarrow \pi^0 \pi^0$  BG  $\times 1/3$ 
  - ❖  $\sim 1$  events in SES( $10^{-11}$ )

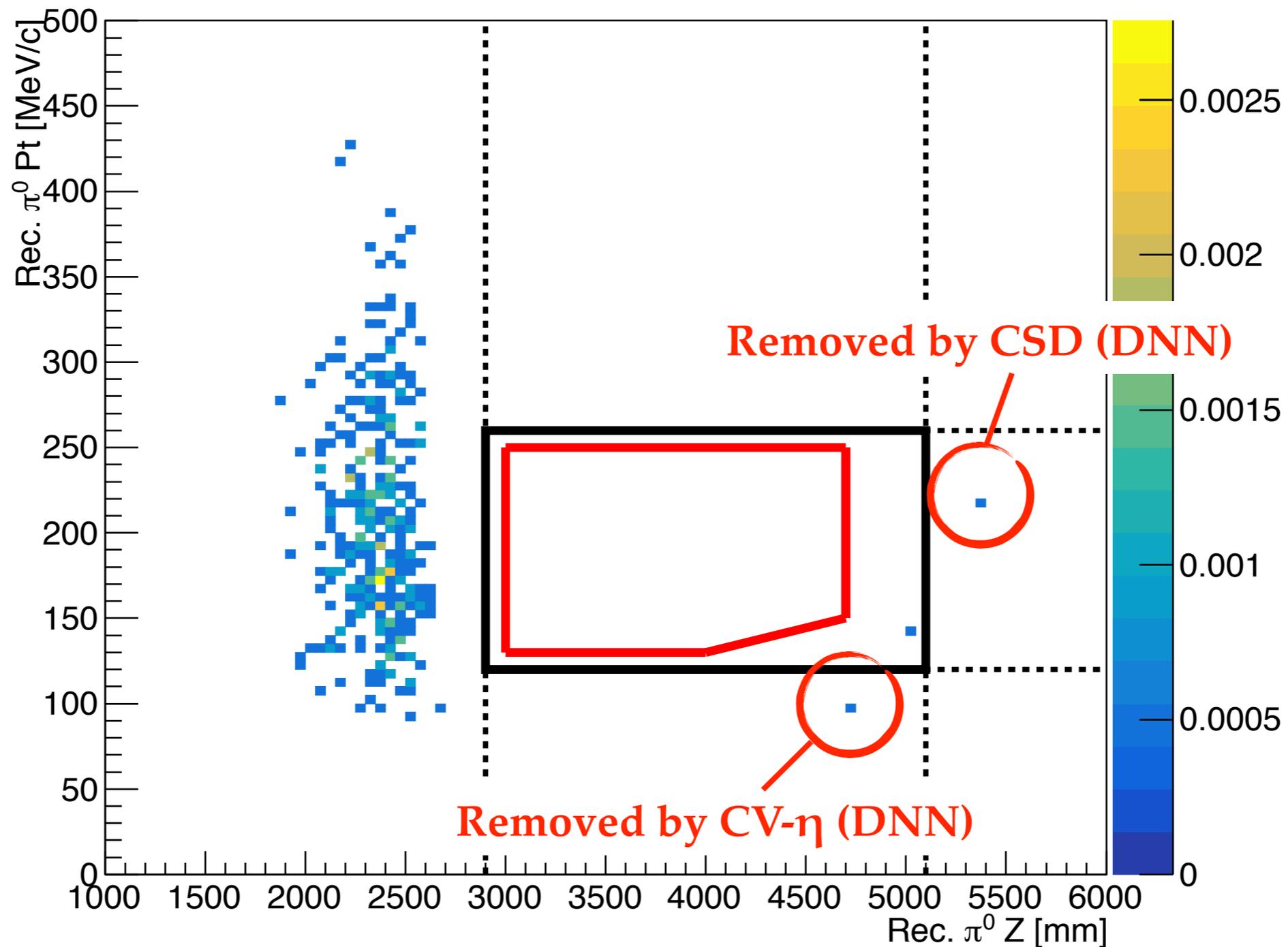
# Improvement after 2015

- ❖ 2016-2018 data:
  - ❖ new analysis methods
  - ❖ thicker barrel detector
- ❖ 2019 data:
  - ❖ CsI front-end readout
  - ❖ new beam pipe charged veto

**Background Level scaled to SES=10<sup>-11</sup>**

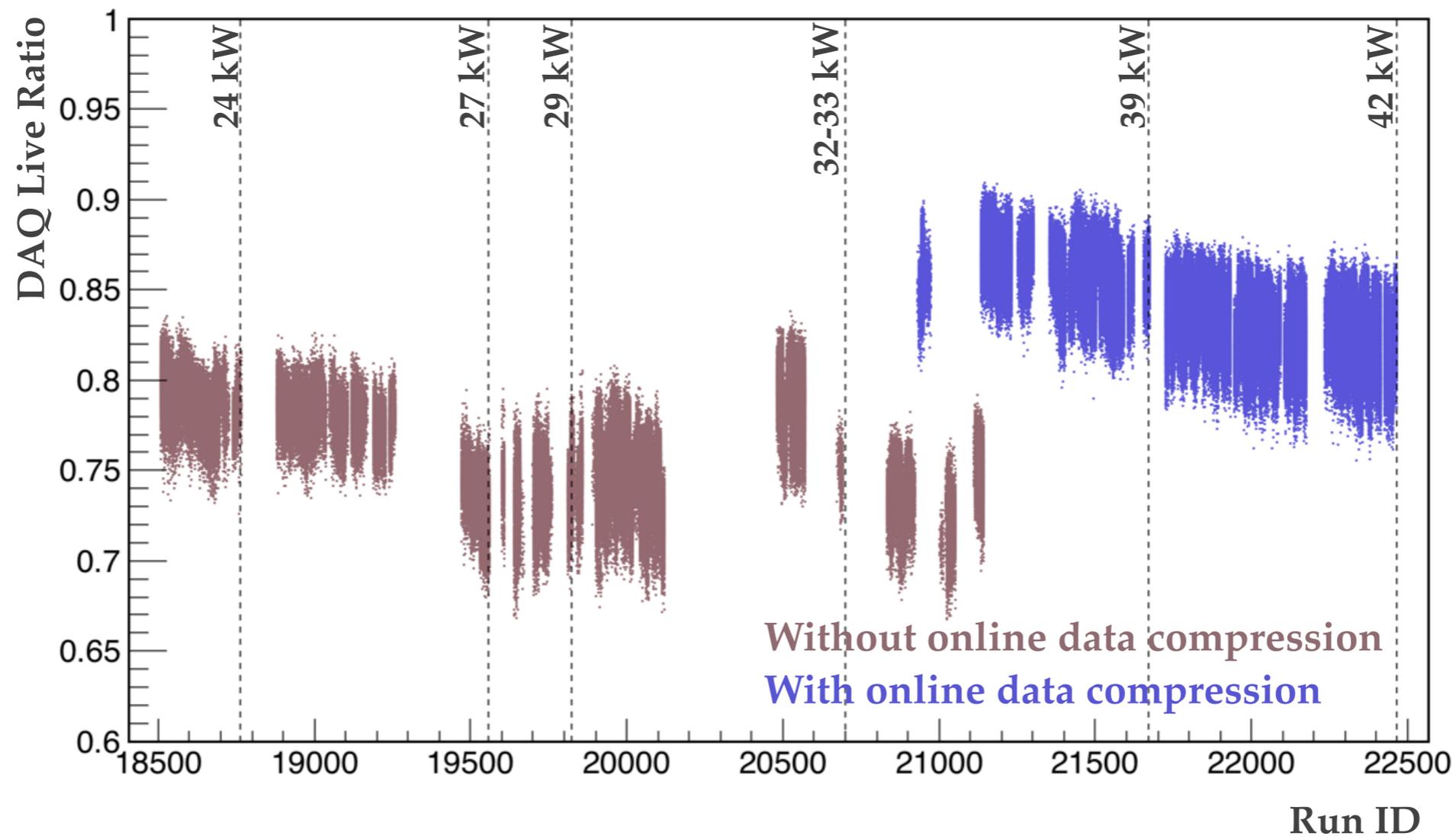
	2015 BGL	2016-2018 BGL	2019-
Hadron Cluster	31	8	0.8
$K_L \rightarrow \pi^+ \pi^- \pi^0$	6.5	6.5	0.1
CV- $\eta$	5.2	< 0.9	< 0.9
Upstream- $\pi^0$	5.2	1.3	0.7
$K_L \rightarrow \pi^0 \pi^0$	2.6	0.9	0.9

# 2015 Data with New Cuts



# DAQ Performance (2015)

- ❖ DAQ avg. Live ratio  $\sim 83\%$  @ 42kW beam power
- ❖ Need upgrade for future 100kW beam power



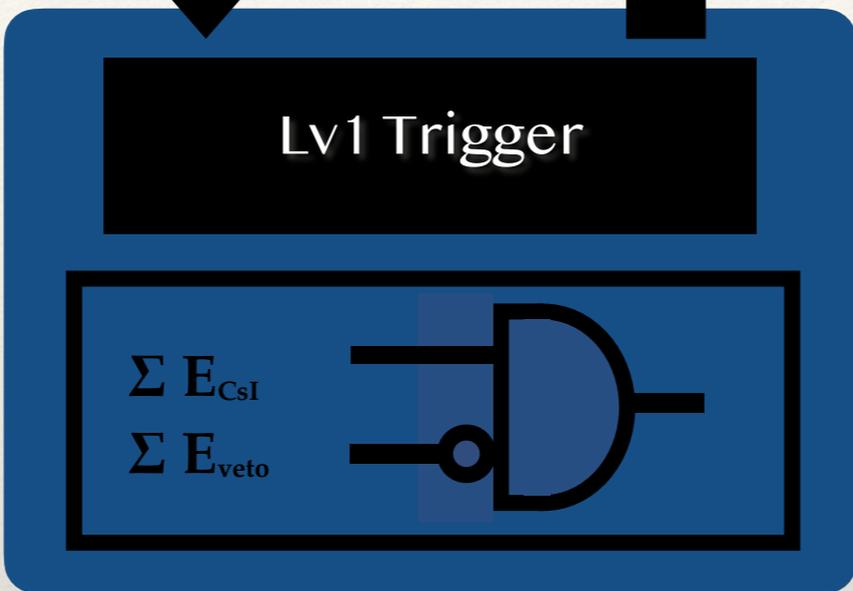
  
(Analog Pulse)



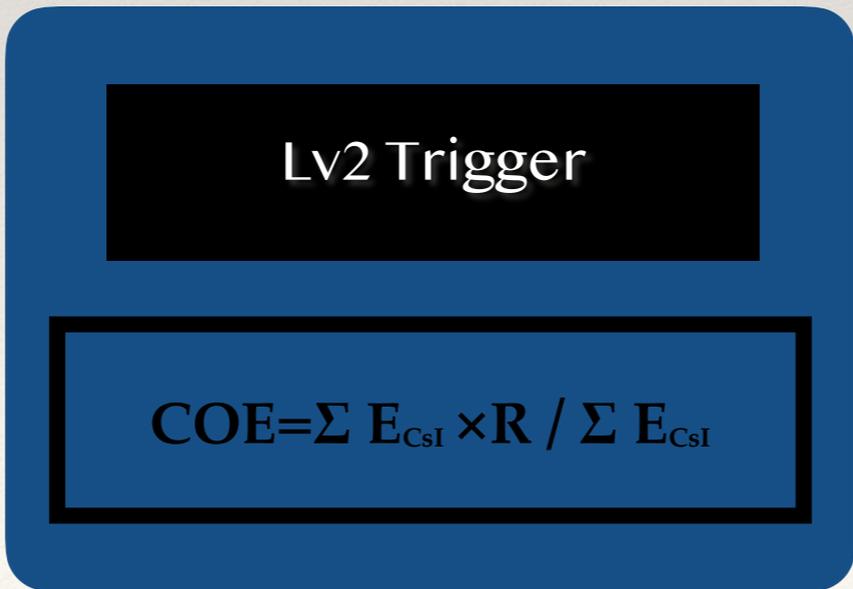
(Digital Data)

37K evts/spill

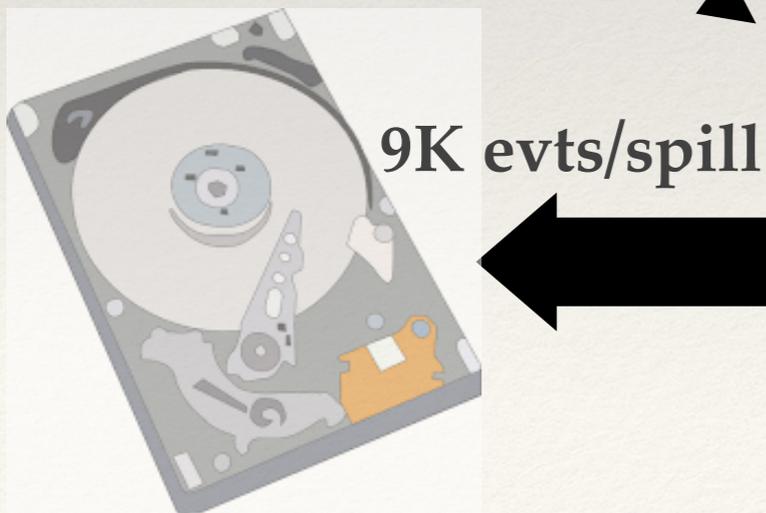
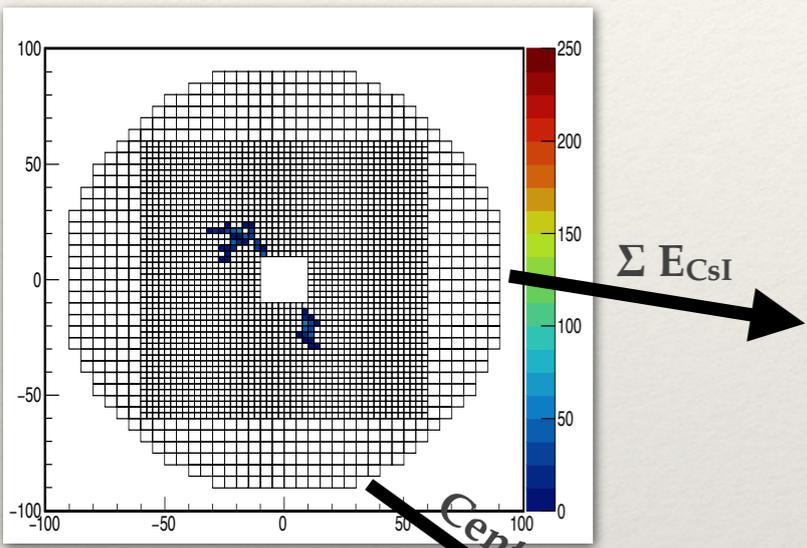
37K evts/spill



Calculation done through custom-made 9U backplane



30K evts/spill accepted  
(~20% deadtime)



- \* Trigger rate at 40kW beam power
- \* Spill length ~ 2 sec

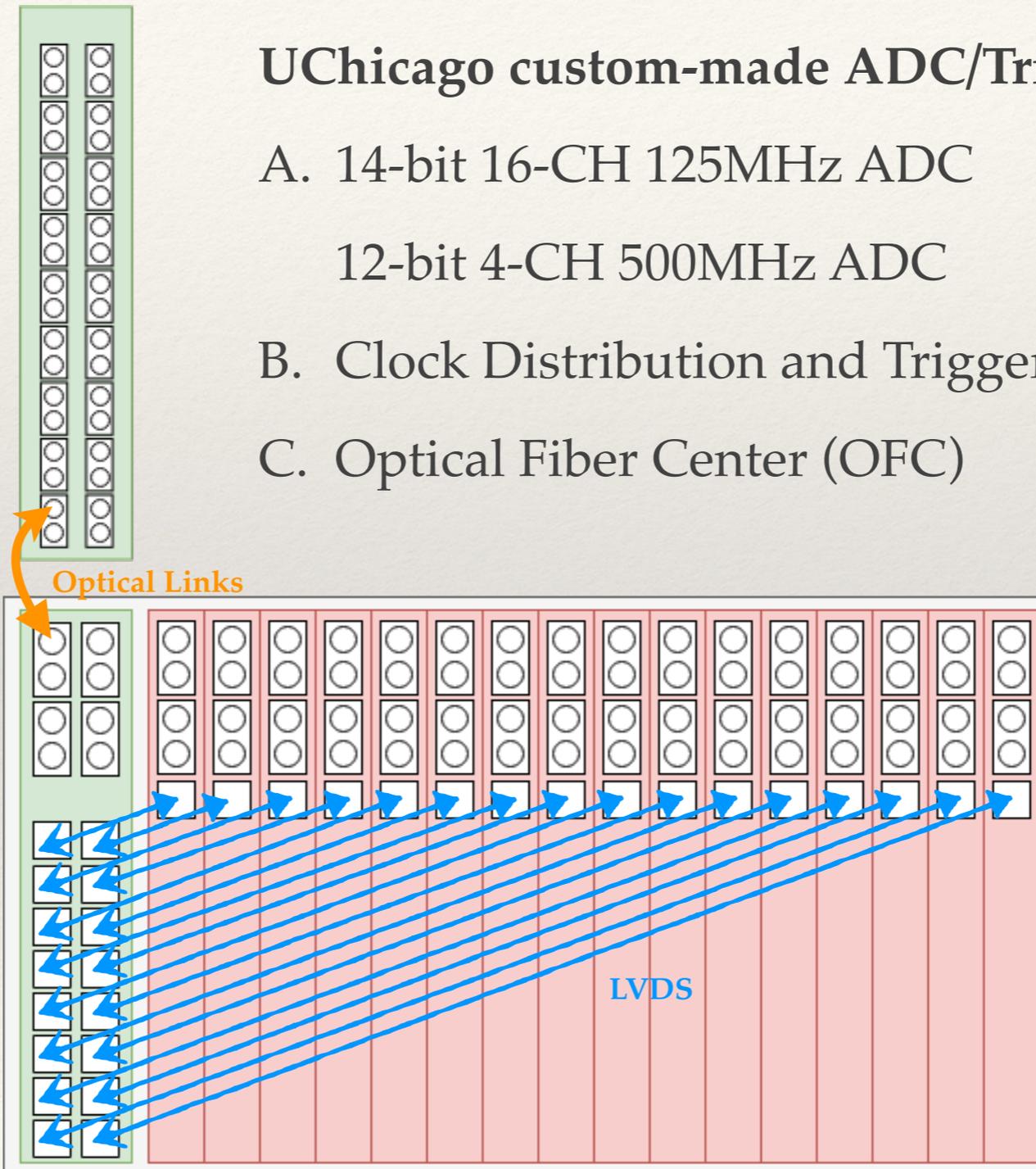
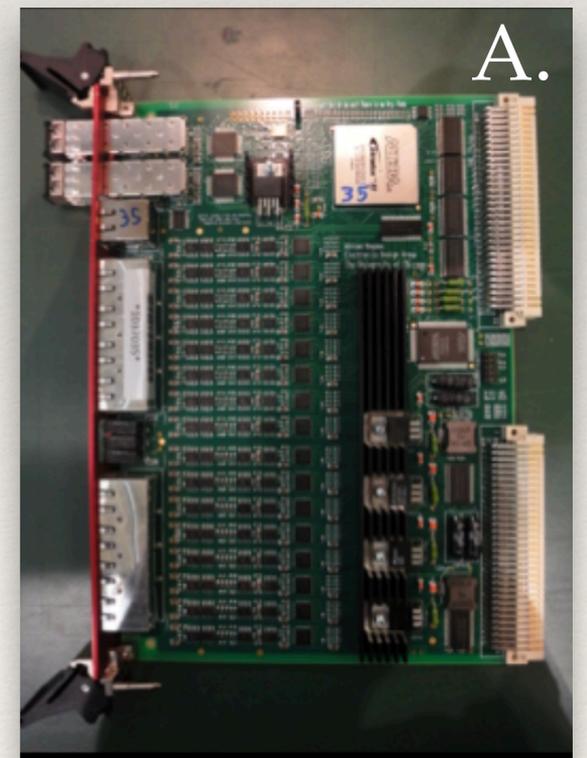
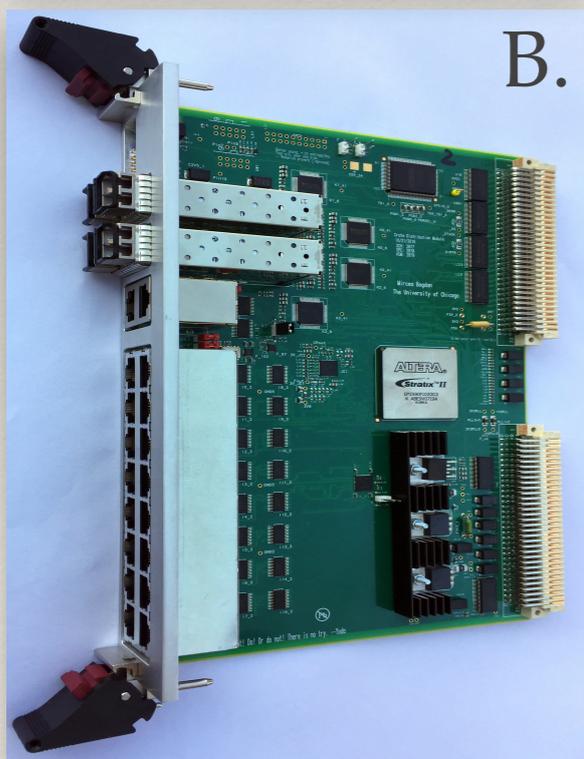
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# Requirements of Trigger System

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- ❖ Should be able to handle trigger rate  $> 100\text{kW}$  beam power
- ❖ Lv1 trigger/veto
  - ❖ better trigger rate control
- ❖ Lv2 trigger
  - ❖ flexibility:
    - ❖  $K_L \rightarrow \gamma\gamma\gamma$ ,  $K_L \rightarrow \pi^0\gamma$ ,  $K_L \rightarrow \pi^0\gamma\gamma$ ,  $K_L \rightarrow \pi^0\pi^0\gamma$
    - ❖ no more COE trigger

# Trigger Modules



UChicago custom-made ADC/Trigger modules:

A. 14-bit 16-CH 125MHz ADC

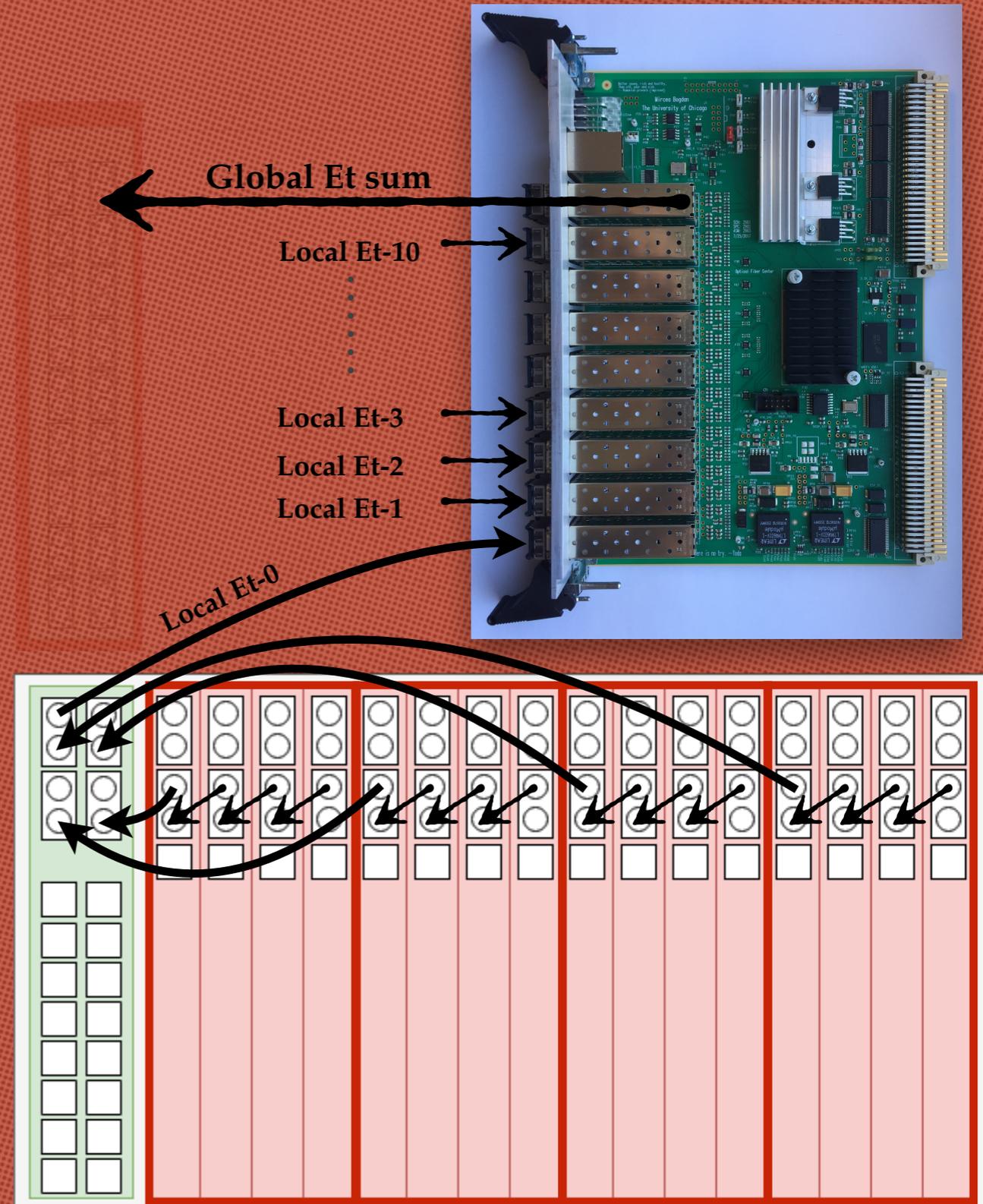
12-bit 4-CH 500MHz ADC

B. Clock Distribution and Trigger Processor (CDT)

C. Optical Fiber Center (OFC)

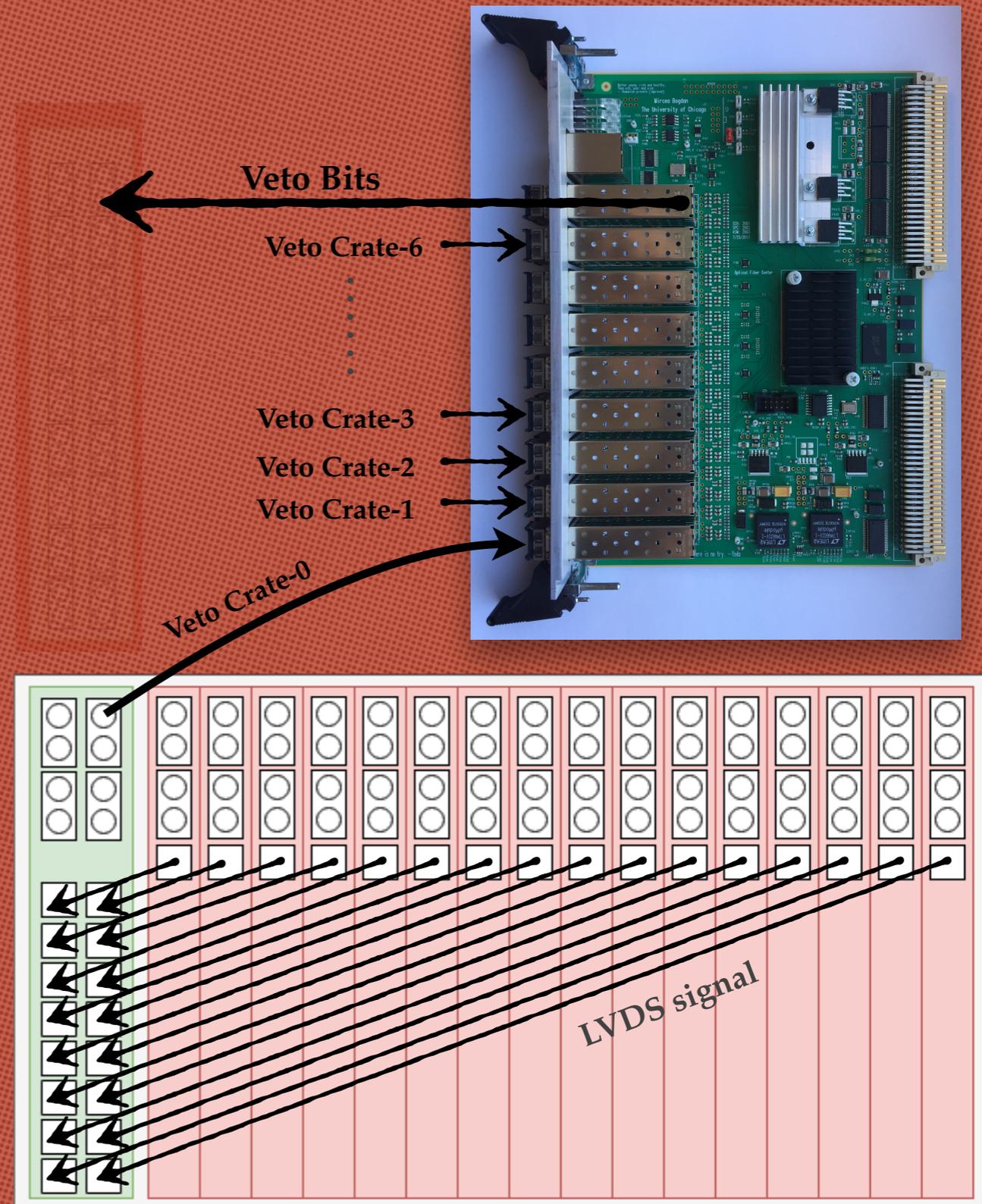
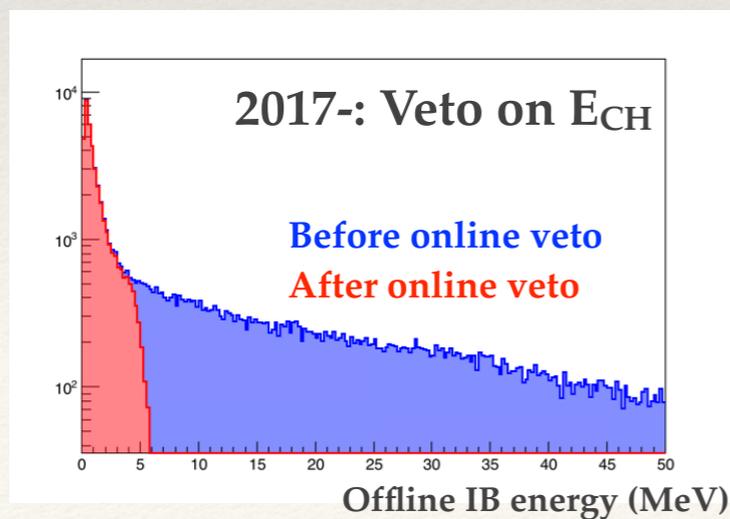
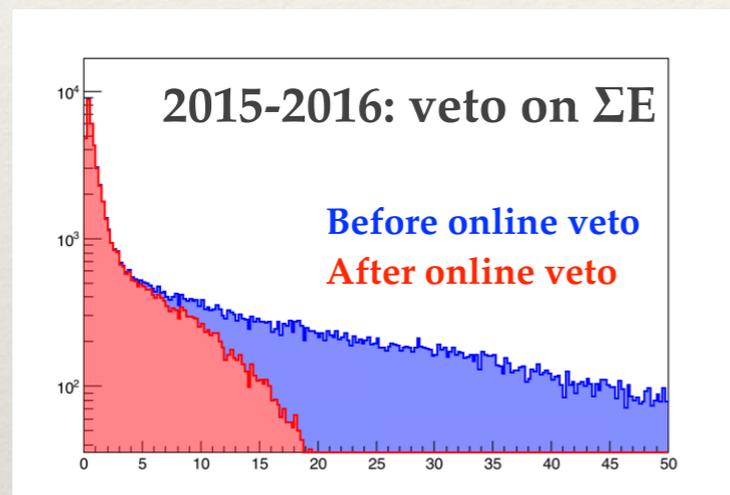
# Lv1 Et Trigger

- ❖  $\Sigma E$  daisy-chain via optical fiber
- ❖  $\sim 2.5 \mu s$  latency



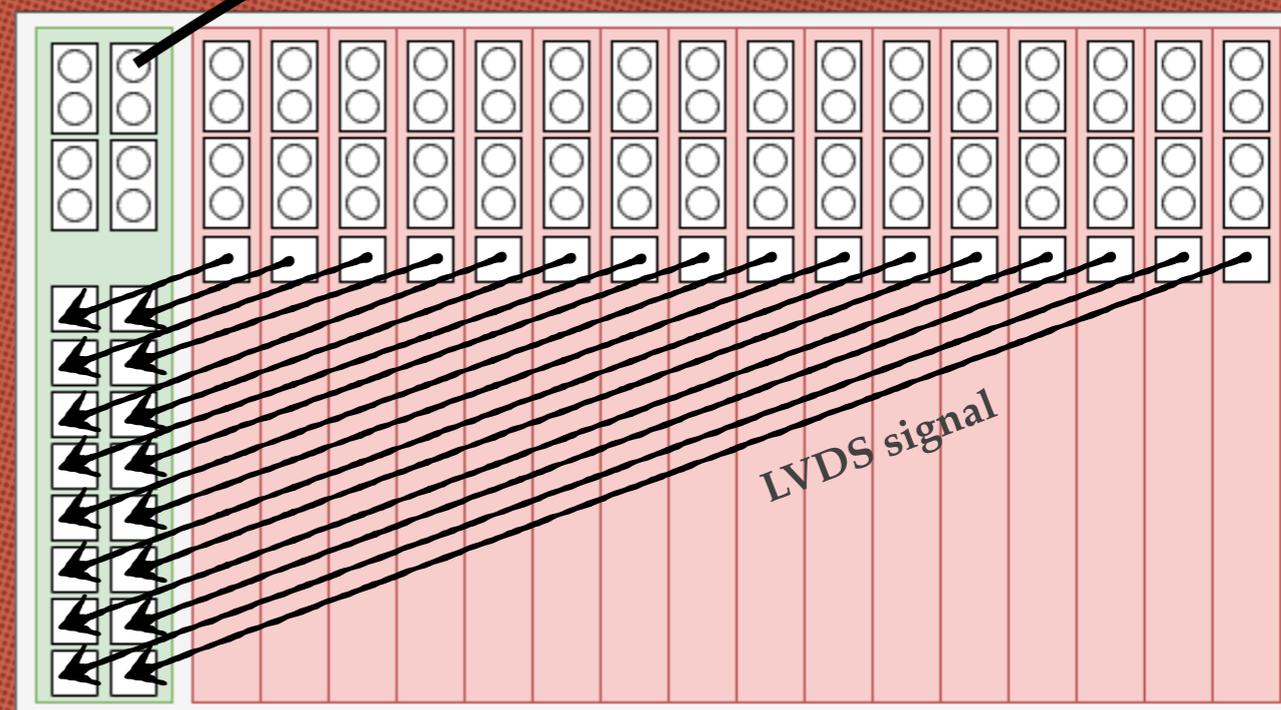
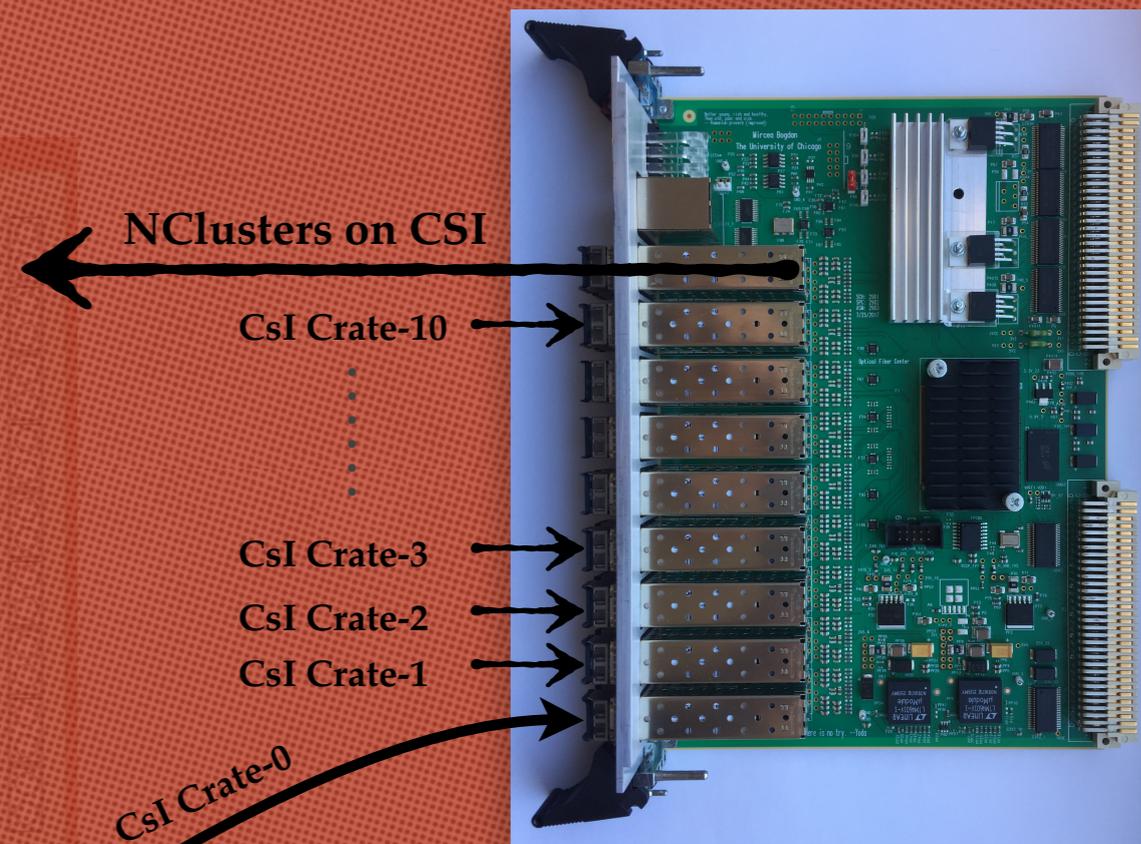
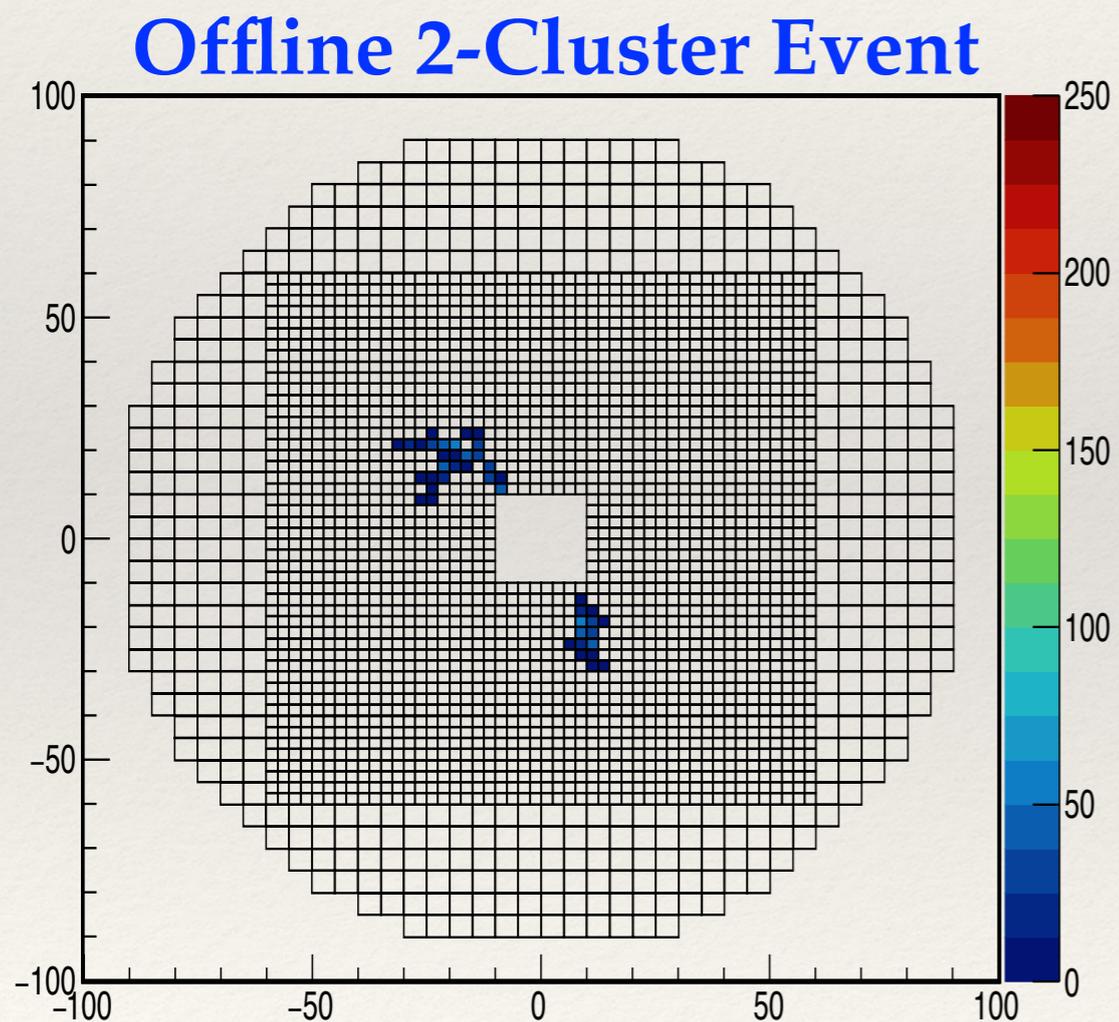
# Lv1 Veto

- ❖ Veto/Trigger based on  ~~$\Sigma E$~~   $\Rightarrow E_{CH}$
- ❖ A factor of 4 trigger reduction



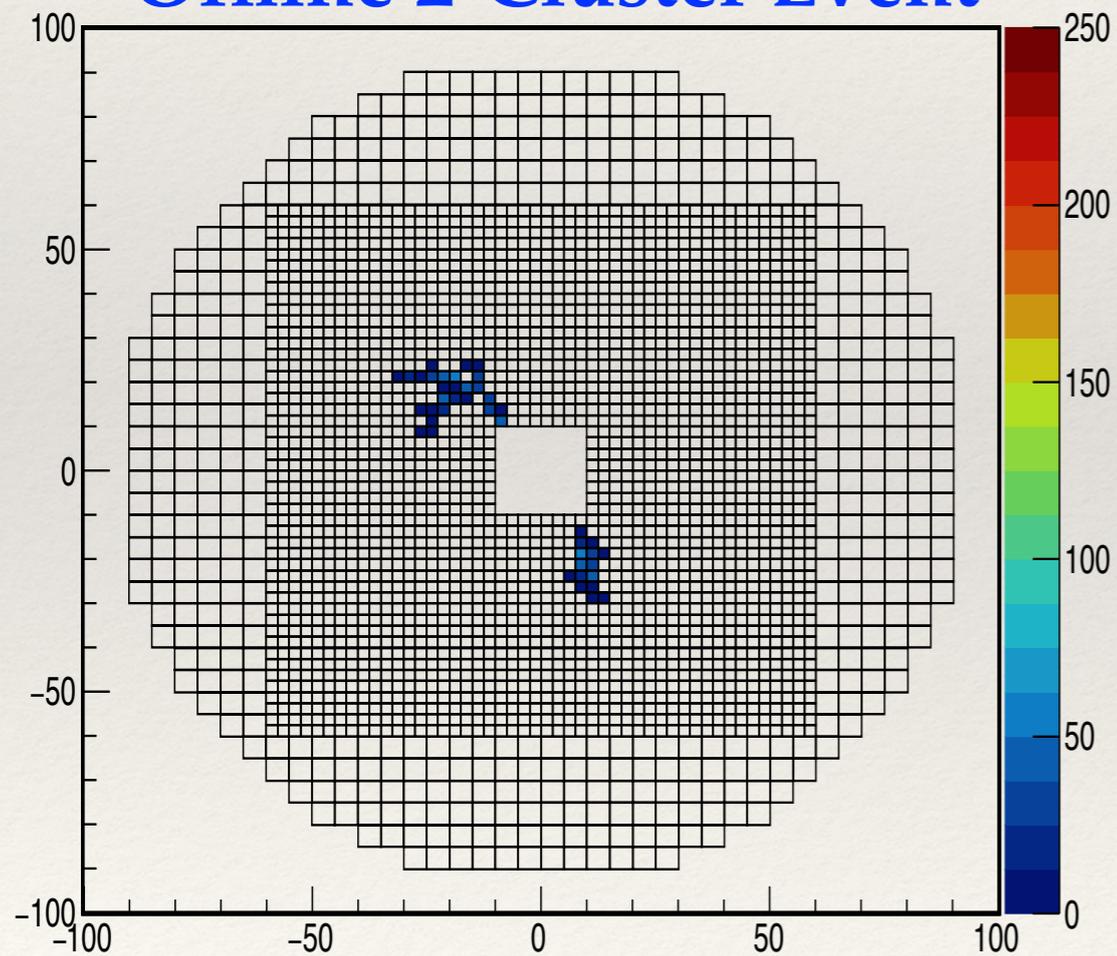
# Lv2 Trigger

- ❖ Trigger based on number of clusters



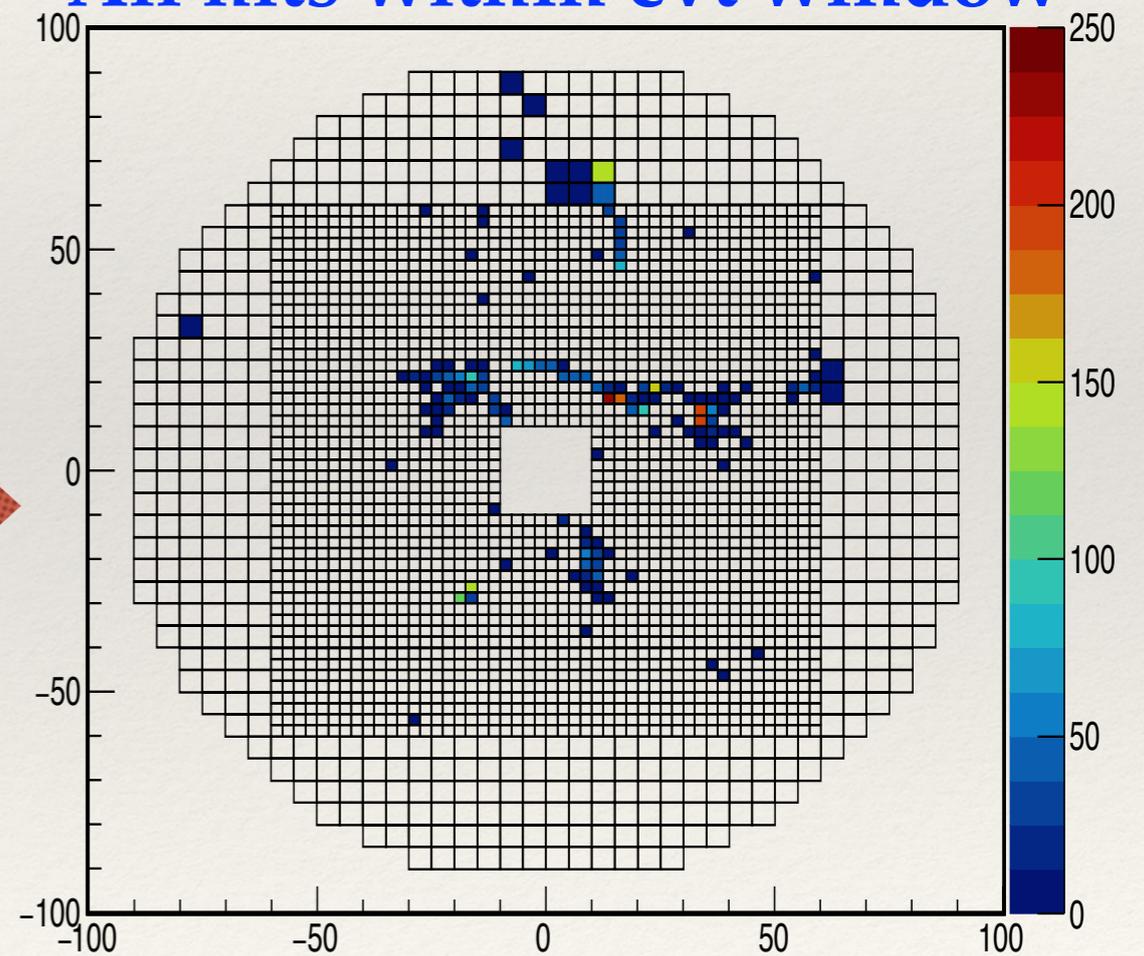
# Lv2 - Cluster Trigger

Offline 2-Cluster Event

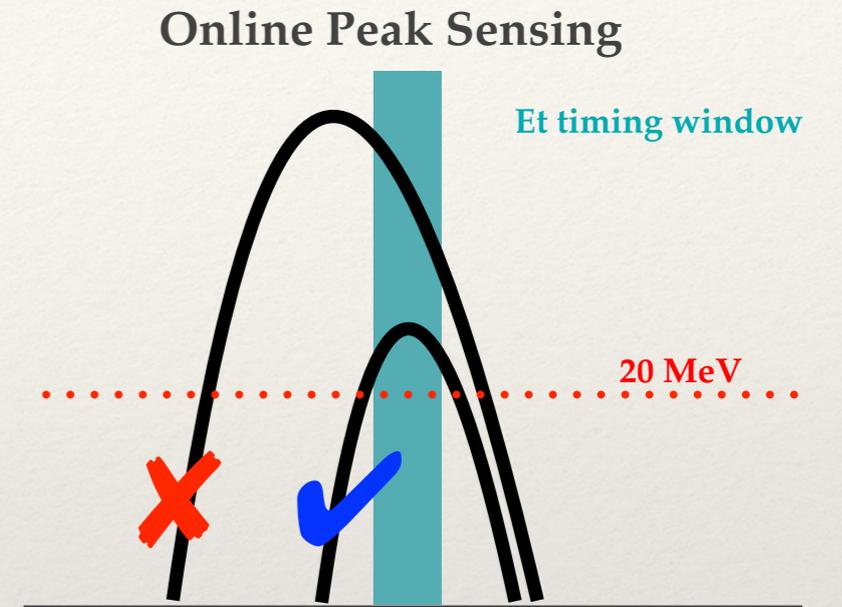
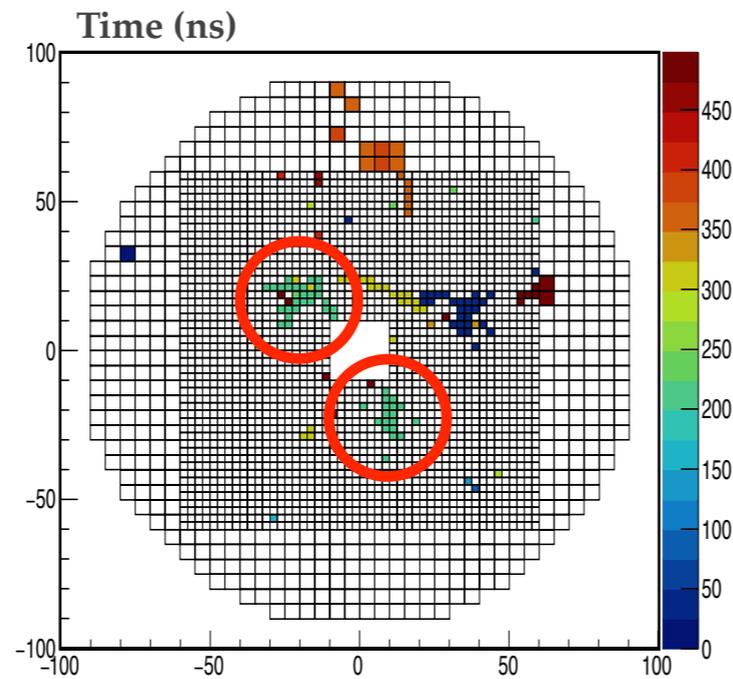
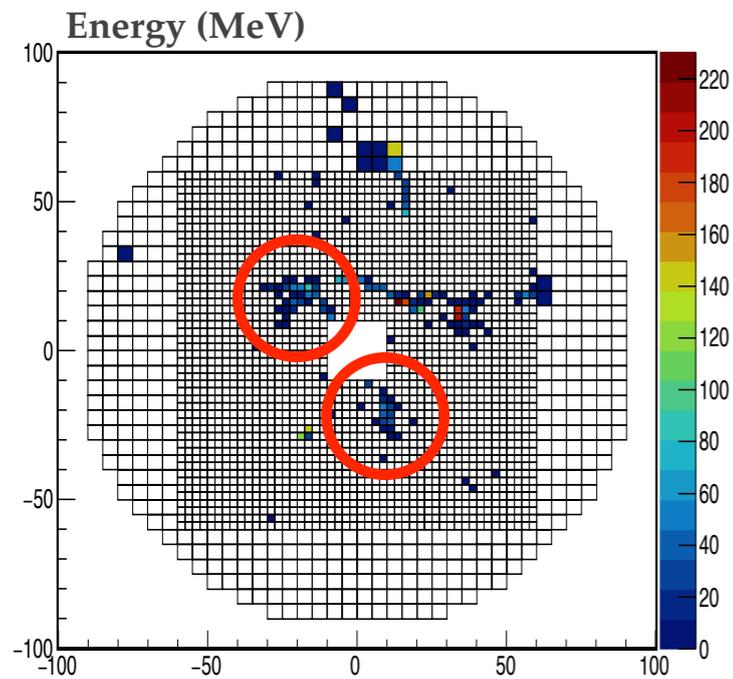


Online  
→

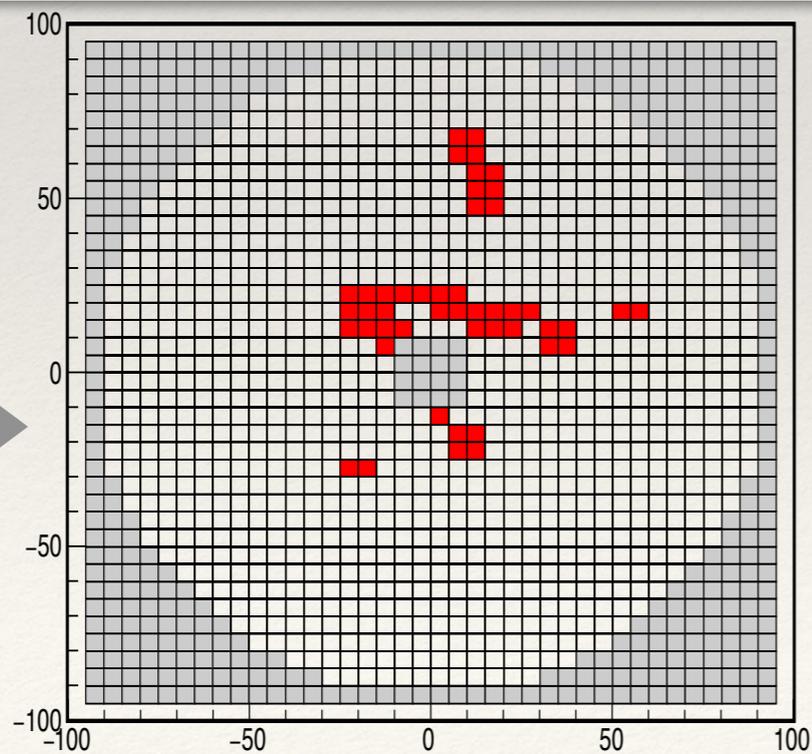
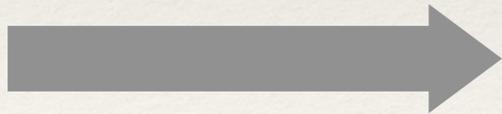
All hits within evt window



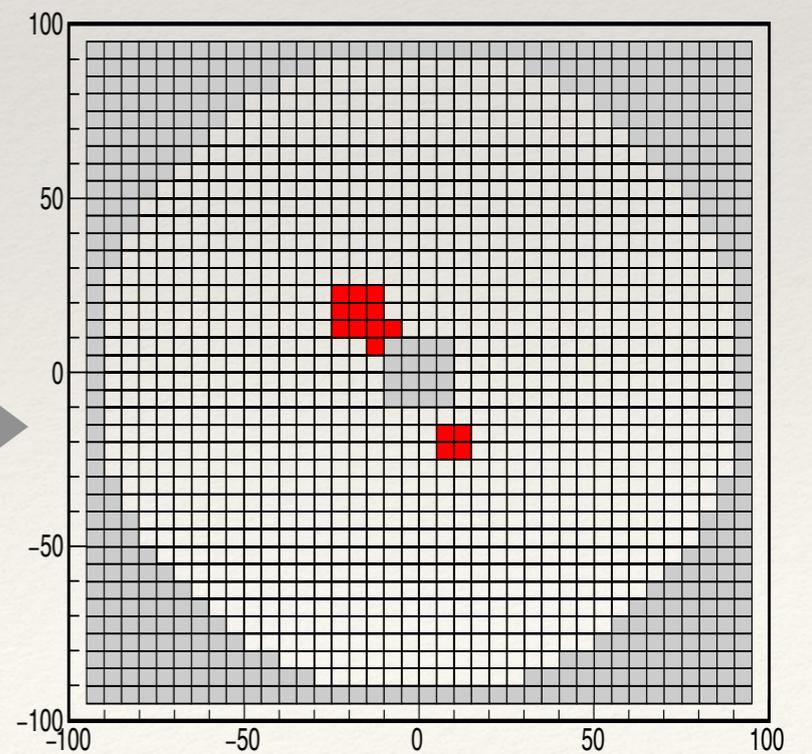
# Lv2 - Cluster Trigger



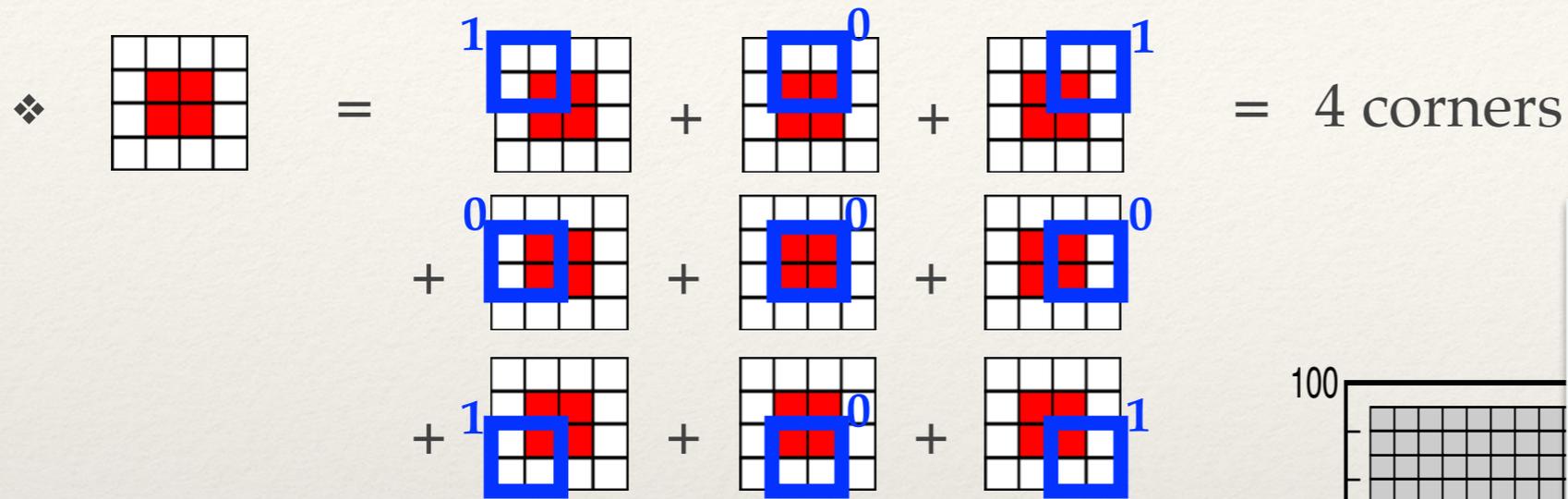
20 MeV Theshold



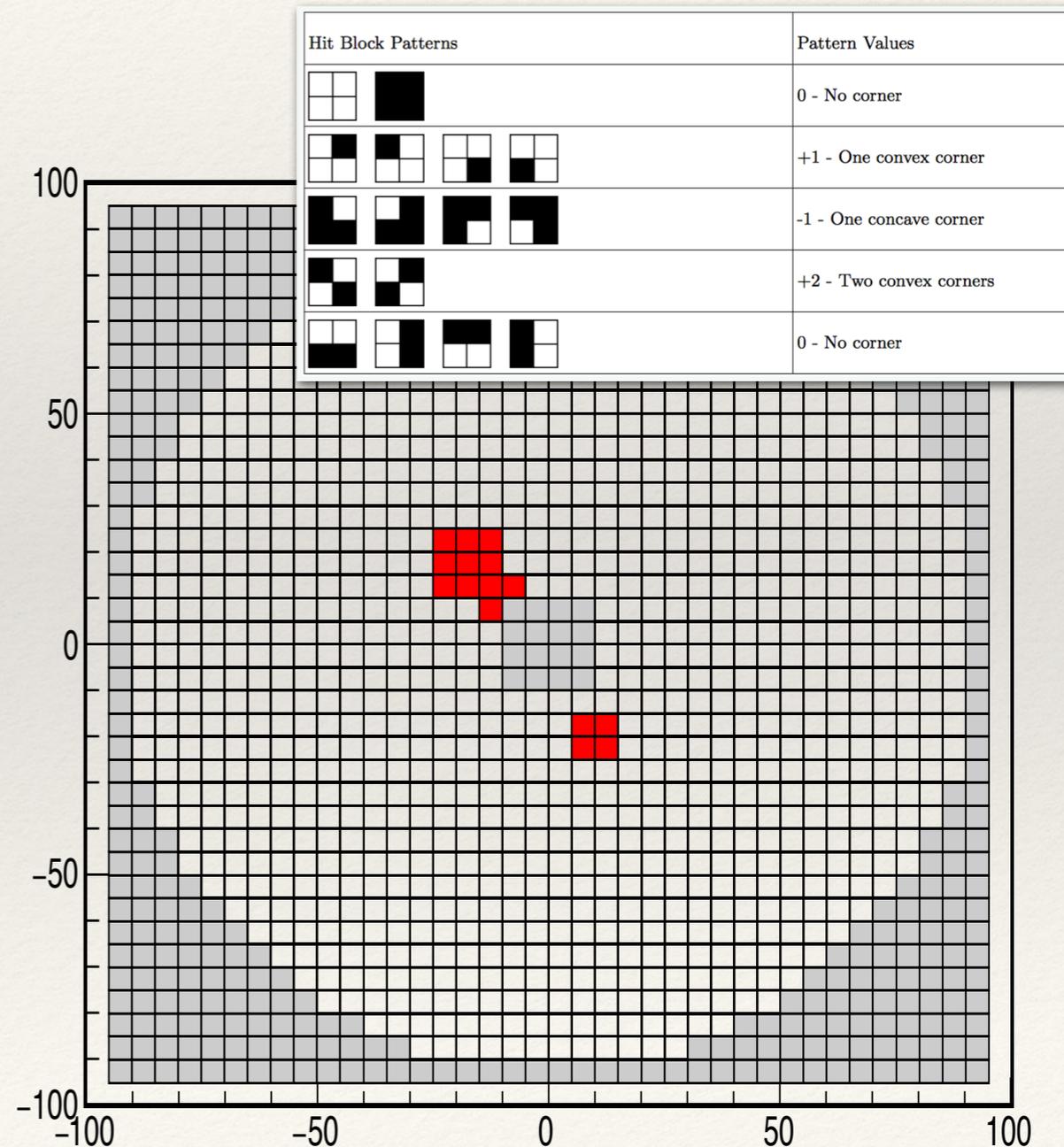
Trigger Timing



# Lv2 - Cluster Trigger

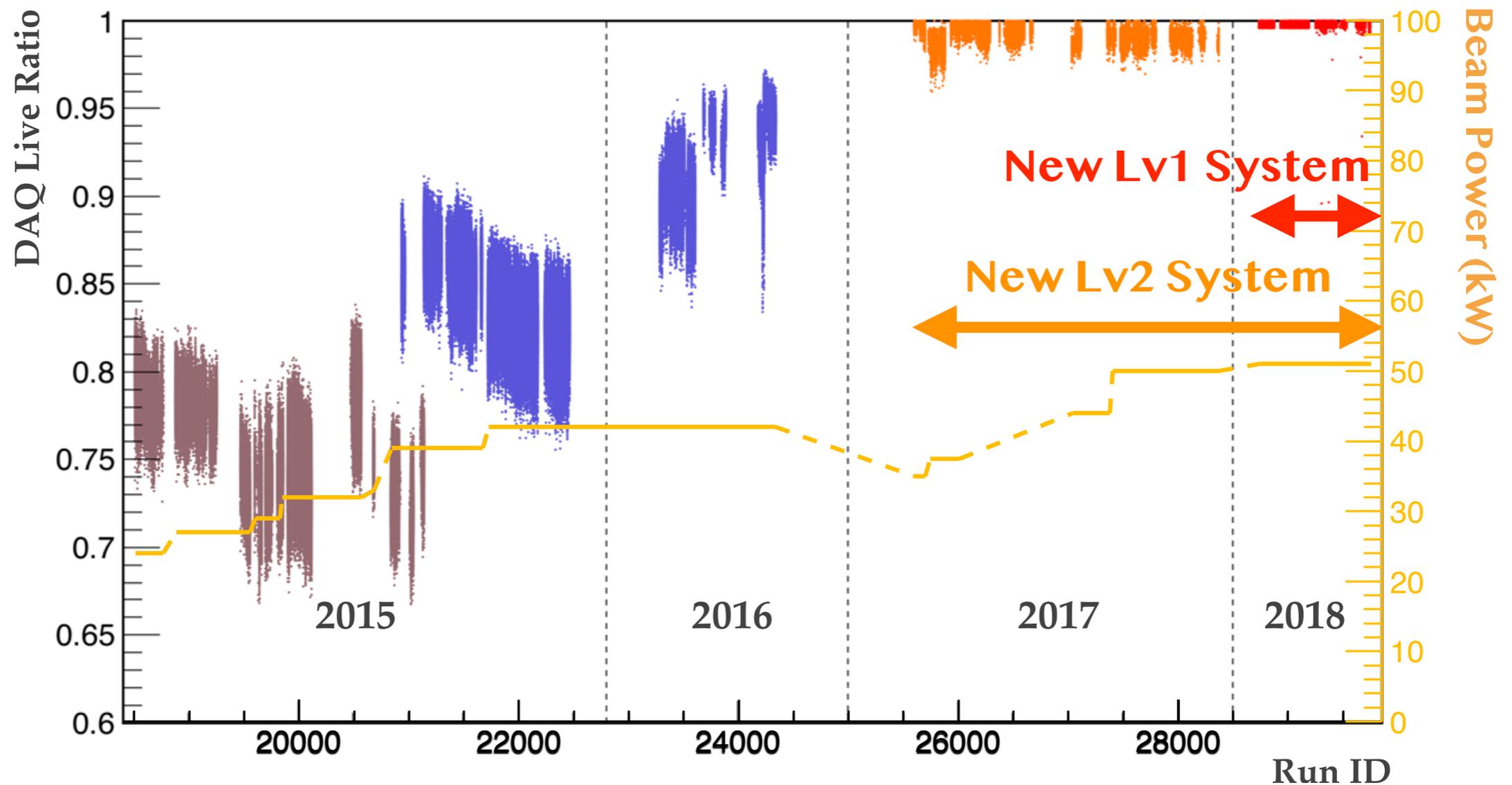


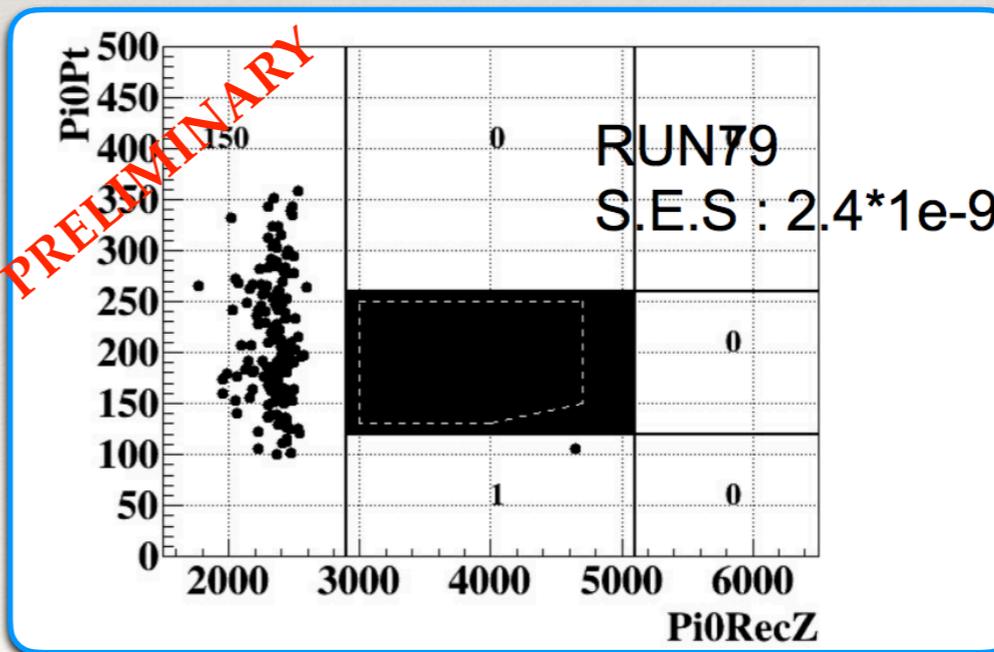
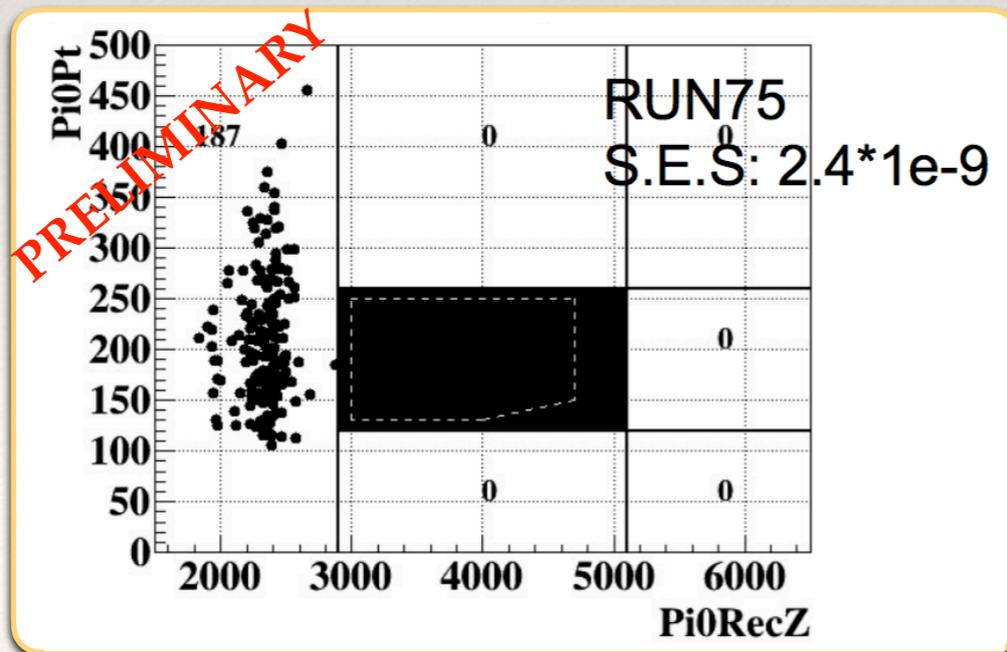
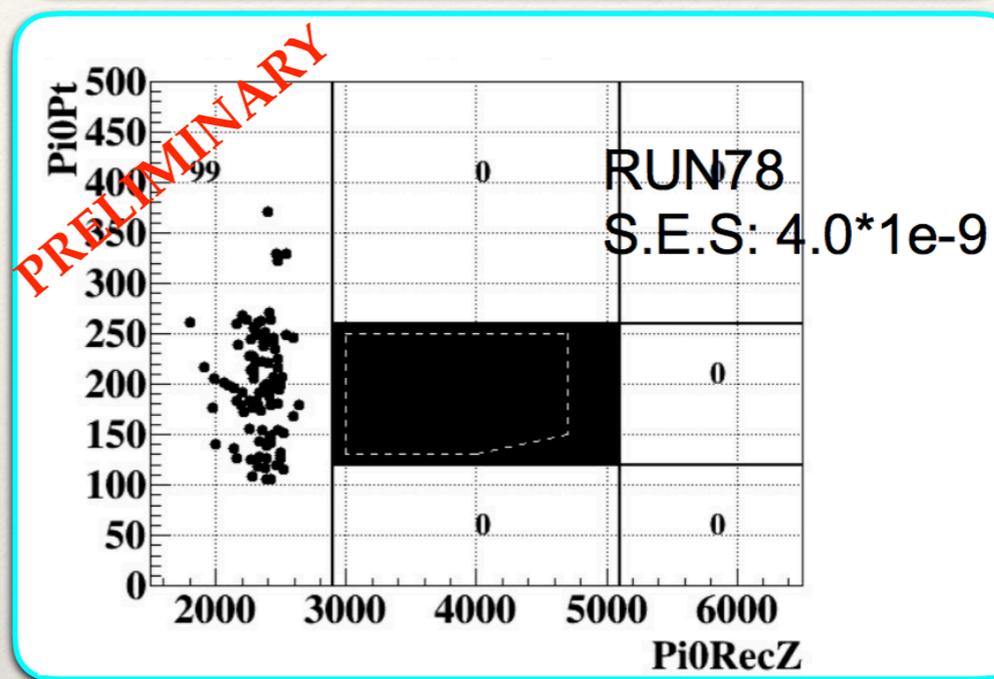
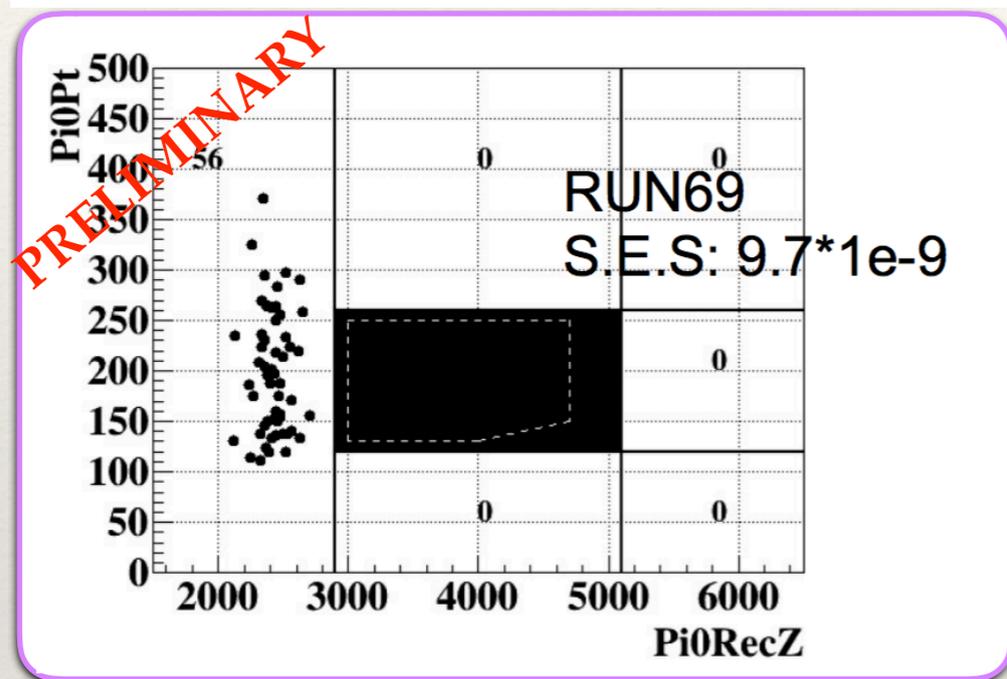
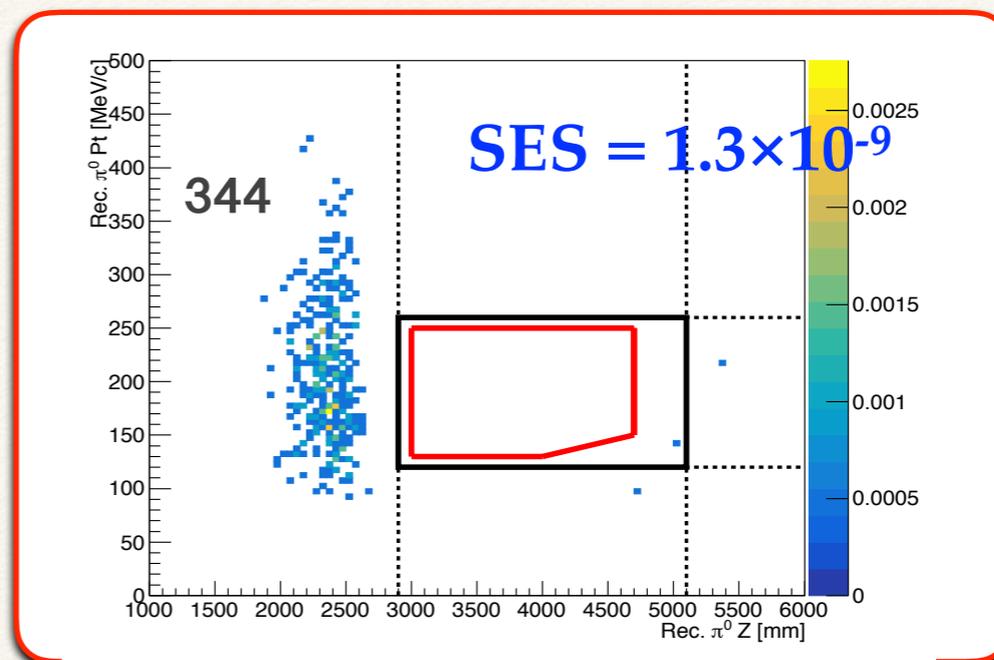
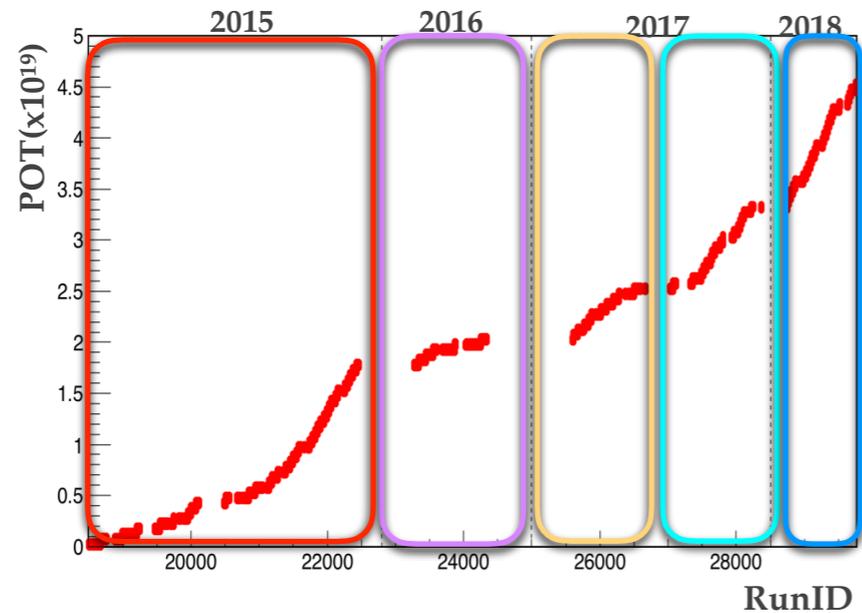
- ❖ Total corners / 4 = Num. of Clusters
- ❖ Trigger efficiencies:
  - ❖  $K_L \rightarrow \pi^0 \nu \nu \sim 99.6\%$
  - ❖  $K_L \rightarrow \gamma \gamma, K_L \rightarrow 2\pi^0, K_L \rightarrow 3\pi^0 \times 30$
  - ❖ neutron study trigger eff.  $\times 4$
- ❖ Dead time  $\sim 150$  ns



# DAQ Performance

- ❖ Lv1 & Lv2 upgrade was completed in 2018
  - ❖ DAQ Live ratio ~100%
- ❖ System is ready for 100kW beam power





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# Projection of Sensitivity

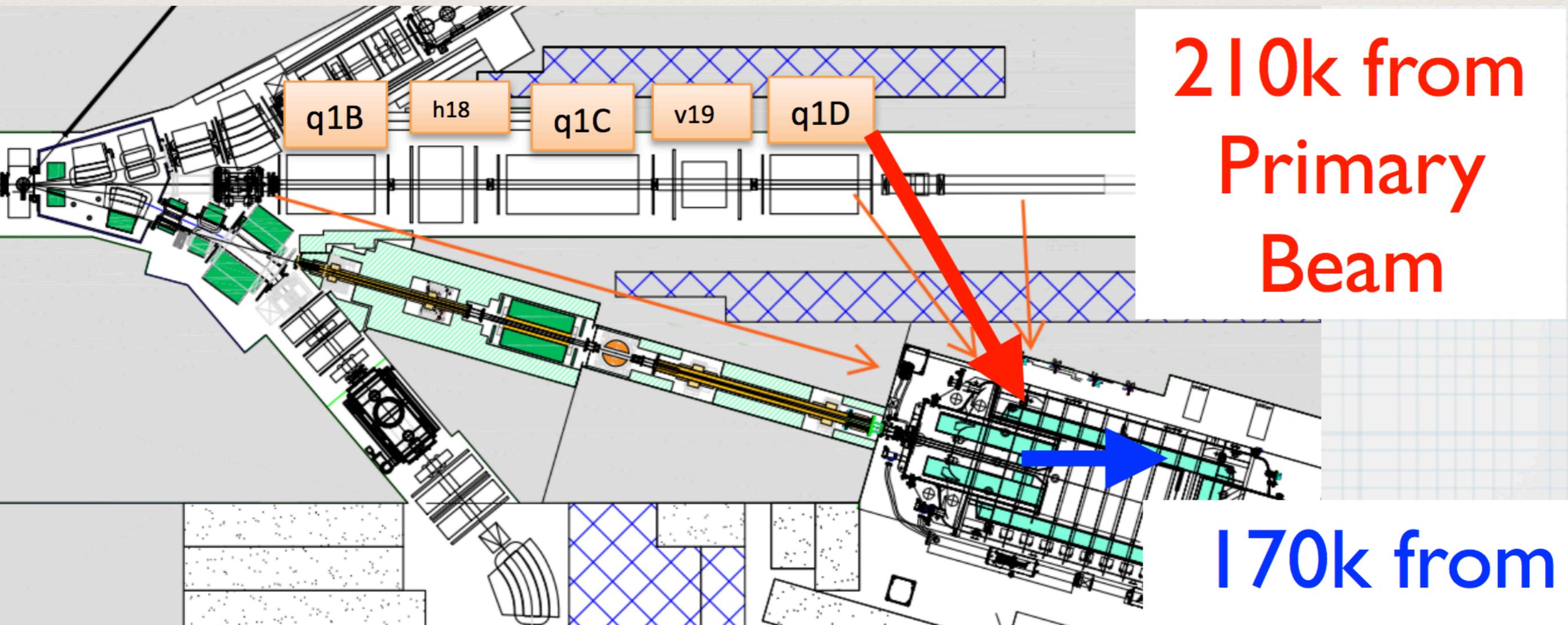
---

$$SES = \frac{1}{N_{KL} \times P_{decay} \times A_{sig}}$$

- ❖  $N_{KL}$  is proportional to beam power & run time
- ❖  $P_{decay}$ : 3.2 %
- ❖  $A_{sig}$ : signal acceptance
  - ❖ width of veto timing window
  - ❖ accidental rate

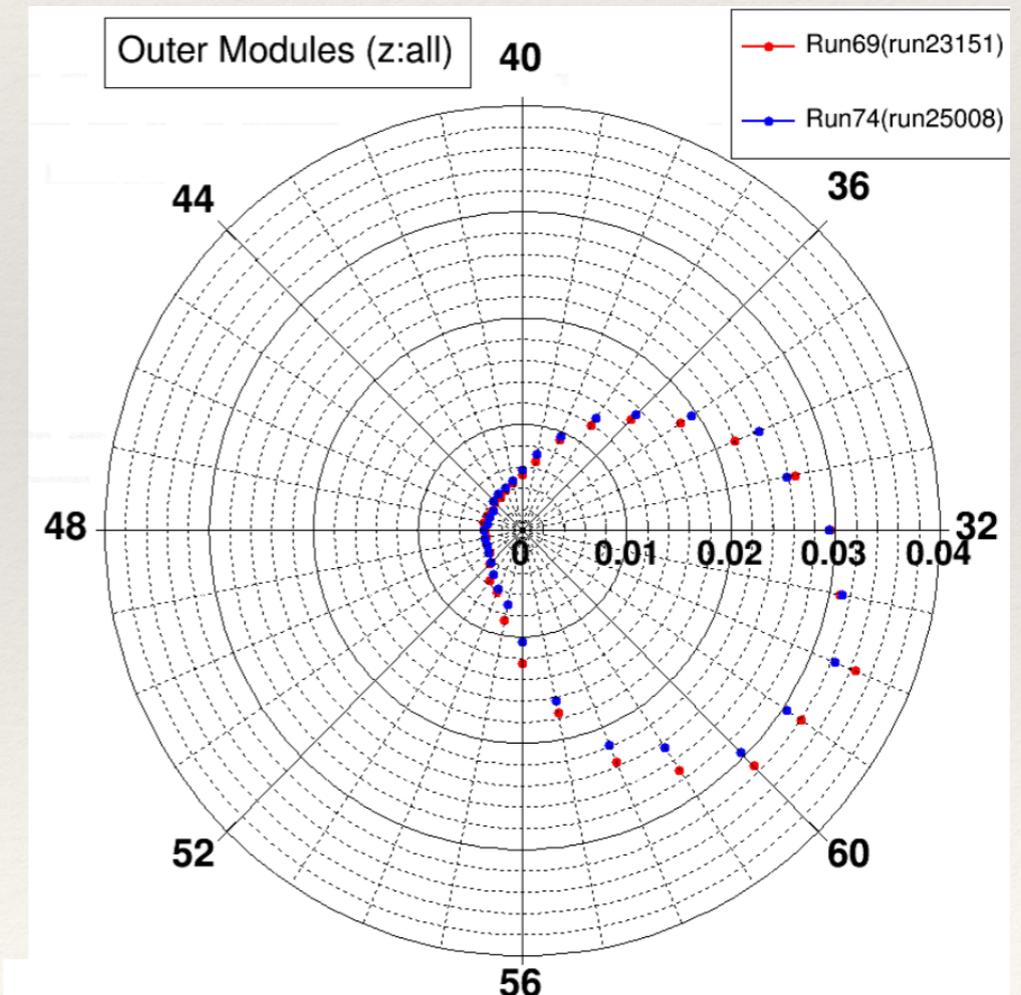
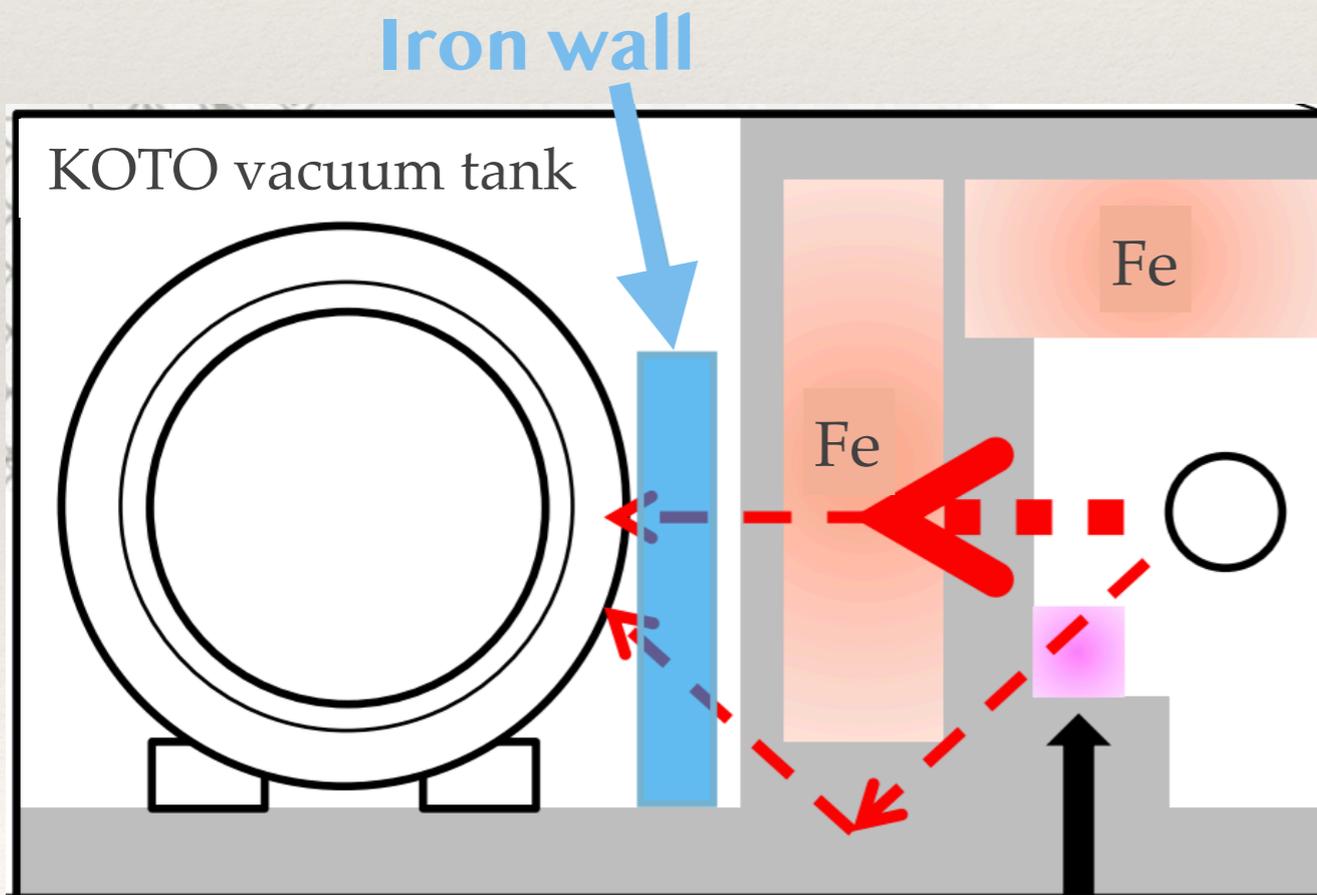
# External Accidental

- Neutrons from primary proton beam



# External Accidental

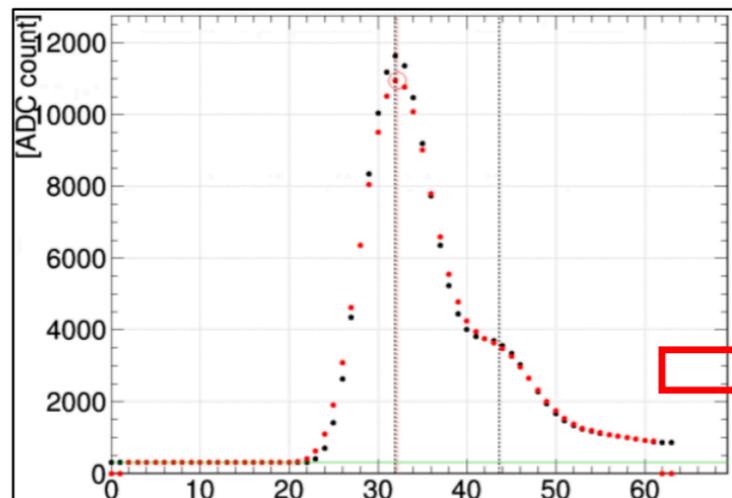
- Add a 20-cm ( $1.2\lambda_D$ ) iron wall before 2020
- Expect external rate  $\times 0.05$



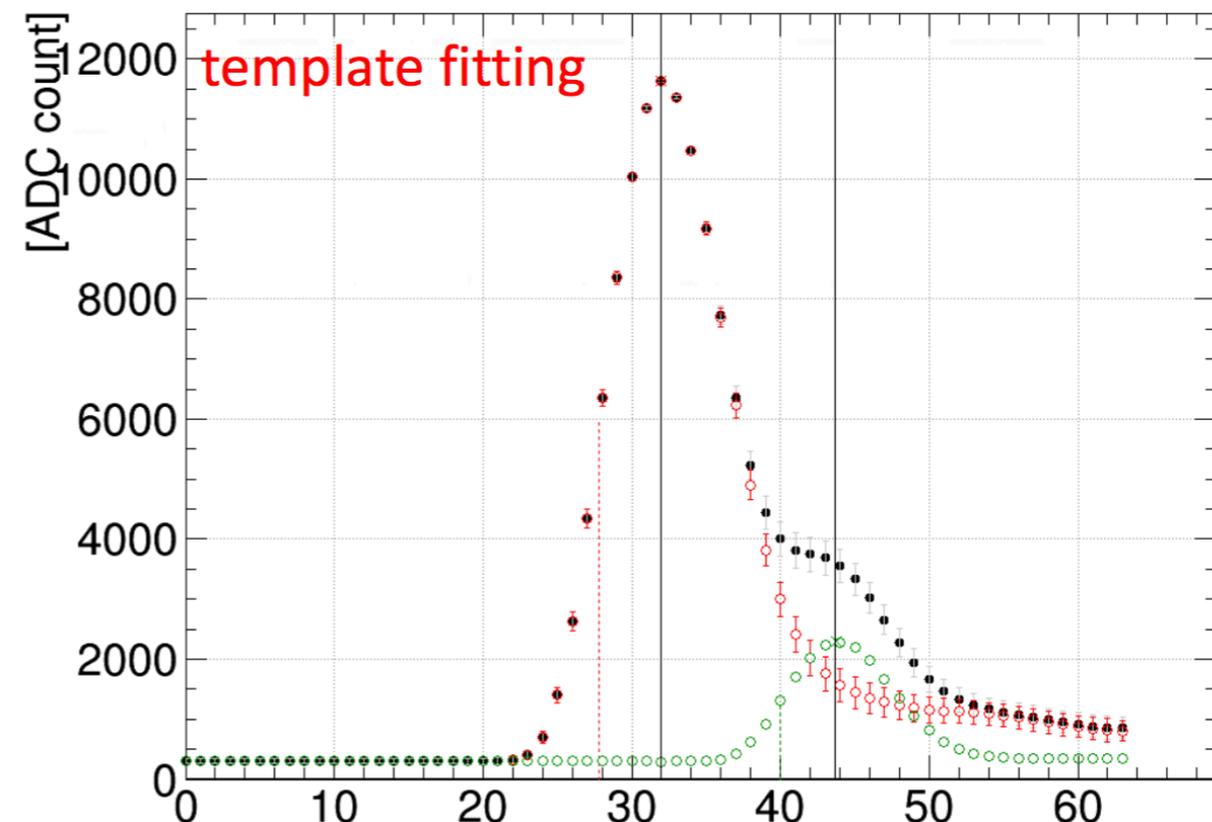
# Internal Accidental

- ❖ Wide veto window because of double pulses
- ❖ Expect to recover 50% signal by window  $\times 1/2$ 
  - ❖ waveform analysis

parabolic fitting

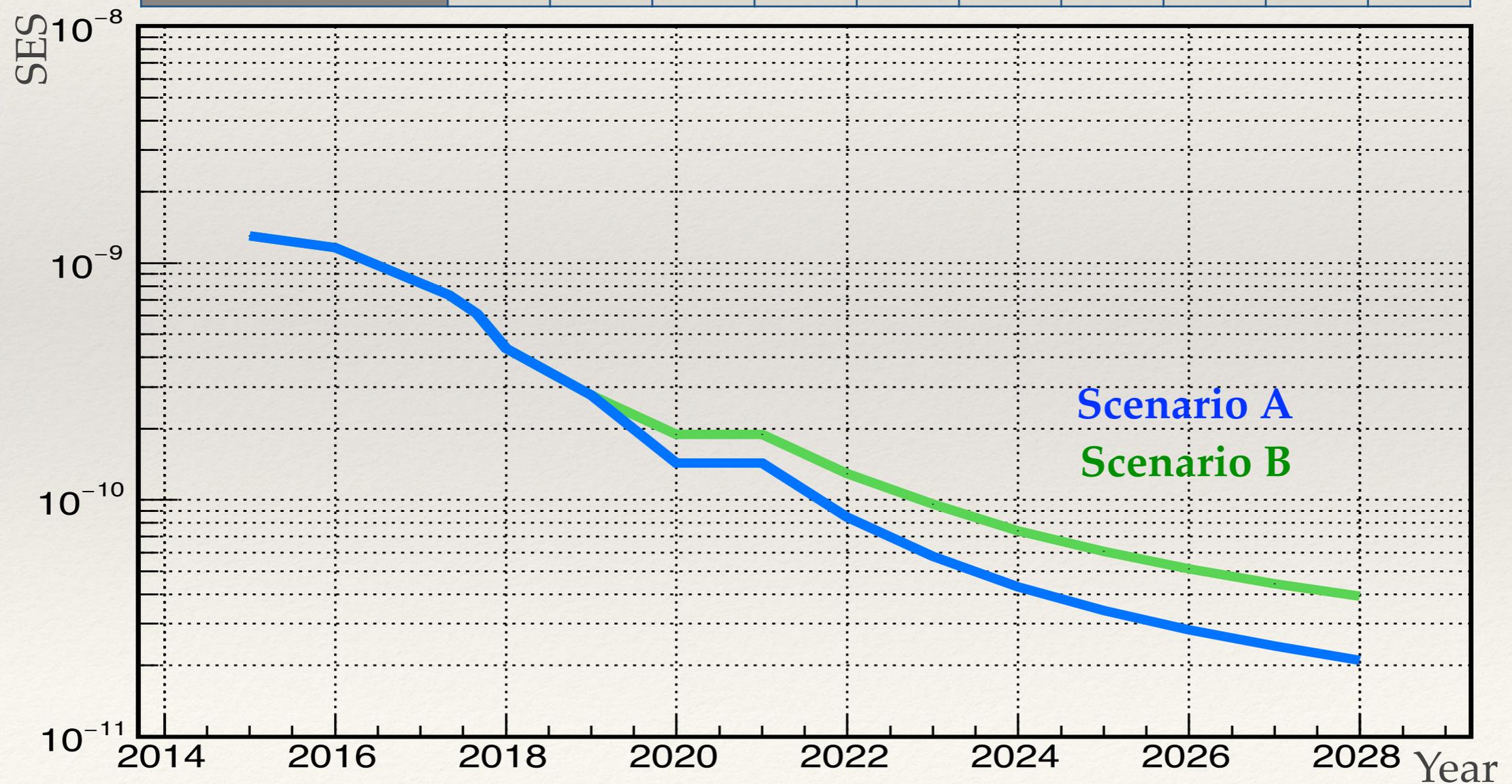


Better pulse separation ability is expected in template fitting



# Projection of Sensitivity

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024-
Avg. Beam Power (kW)	38	42	43	50	50	70	-	80	90	100
Run Time (month)	3.1	1	1.3	2.2						
Scenario A					2	4	-	4	4	4
Scenario B					2	2	-	2	2	2



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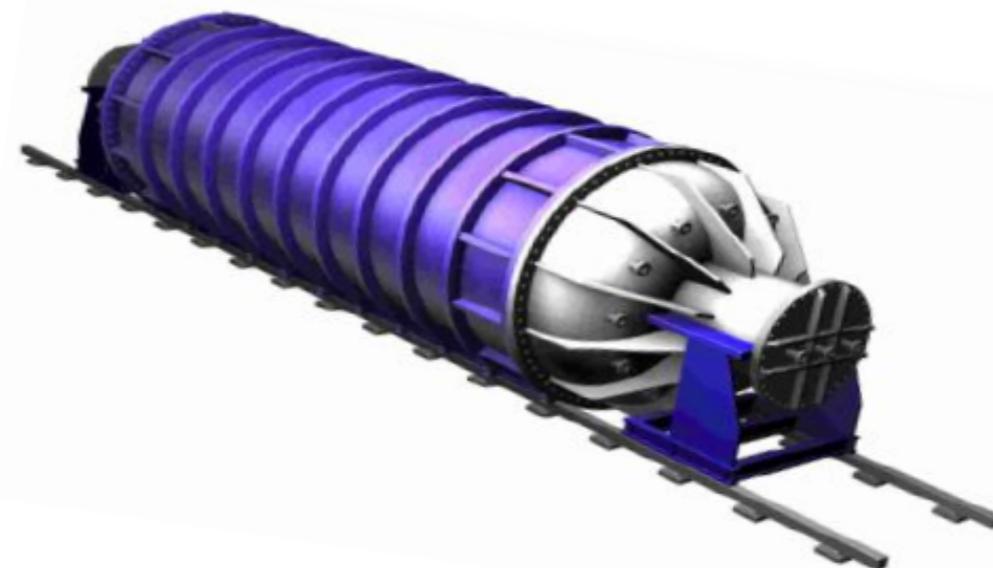
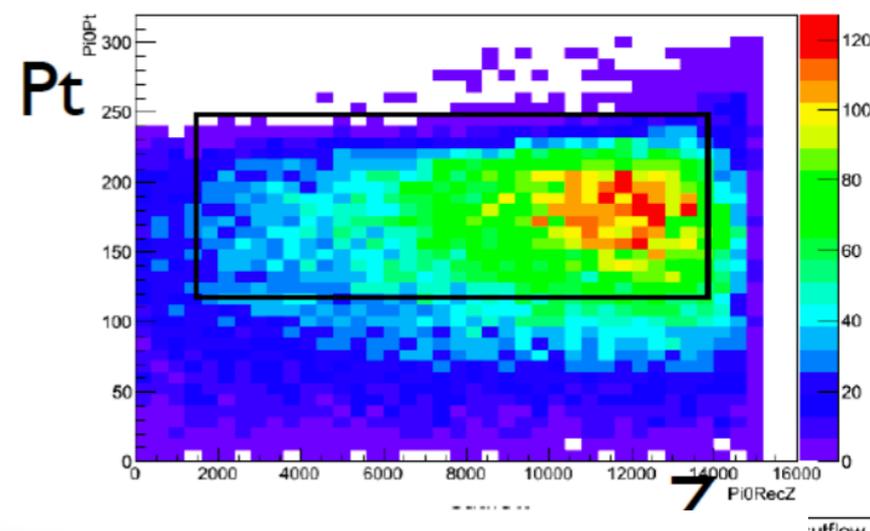
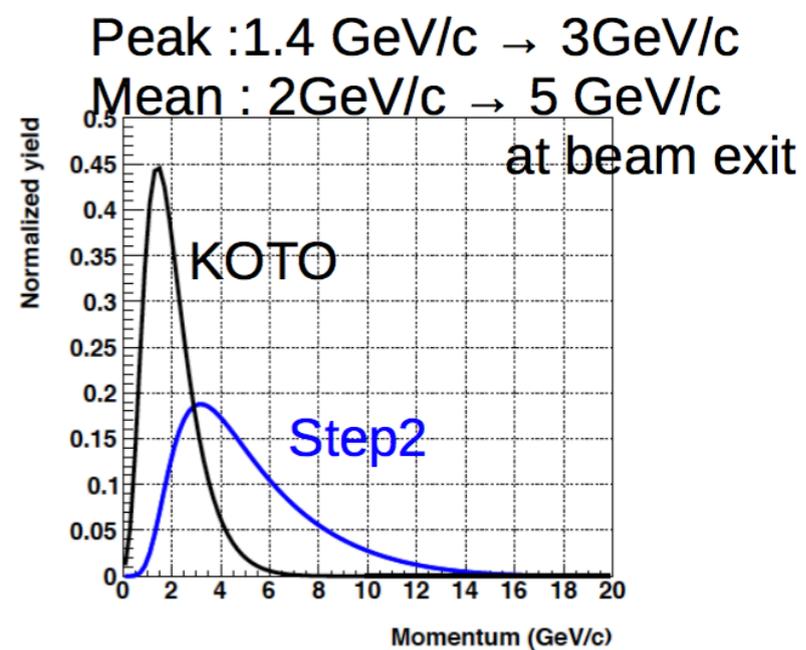
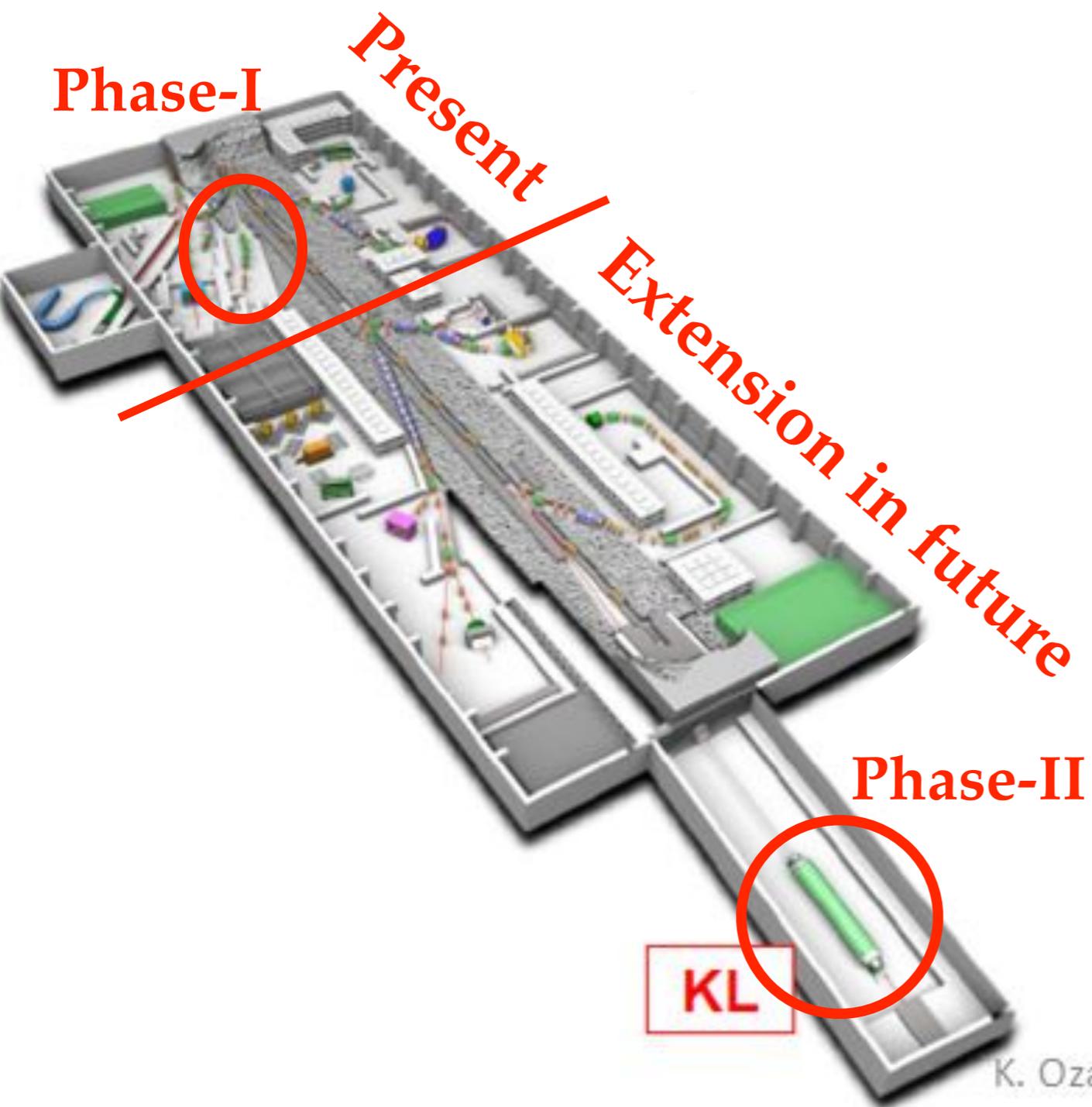
# Summary

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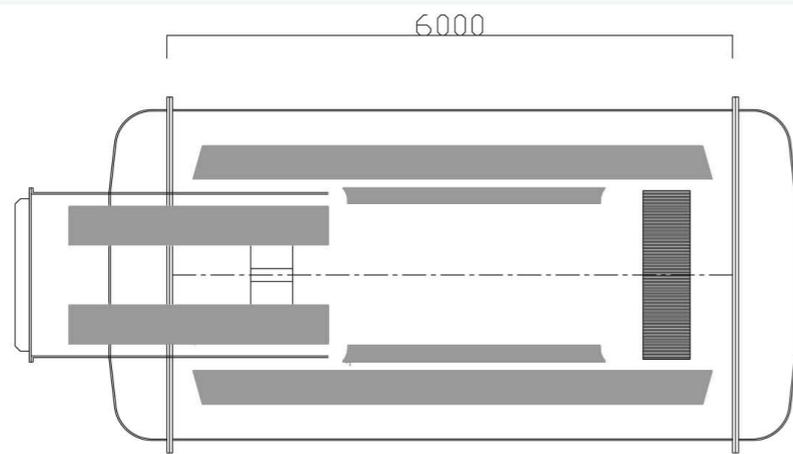
- ❖ New Result  $\text{BR}(\text{K}_L \rightarrow \pi^0 \nu \nu) < 3.0 \times 10^{-9}$  (90% C.L.)
  - ❖ based on 40% of collected data.
- ❖ Background is under control.
- ❖ DAQ is ready for 100kW beam power.
- ❖ Future sensitivity depends on run time (not fixed).

extraction angle to gain  $K_L$  yield

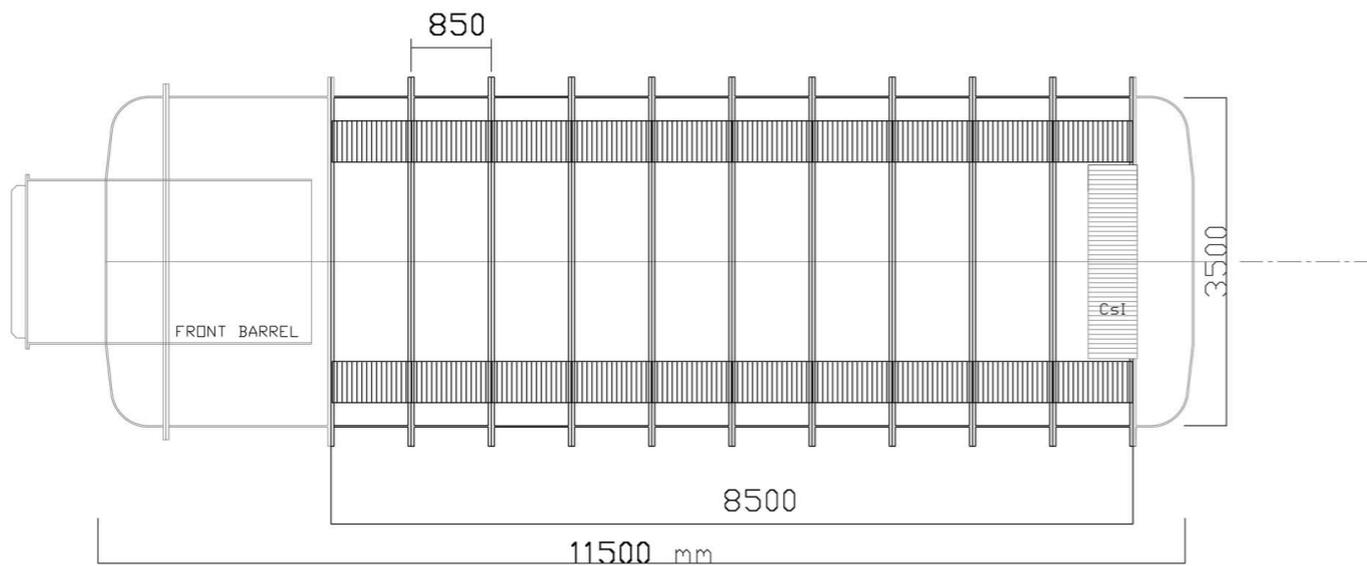
detector to increase acceptance



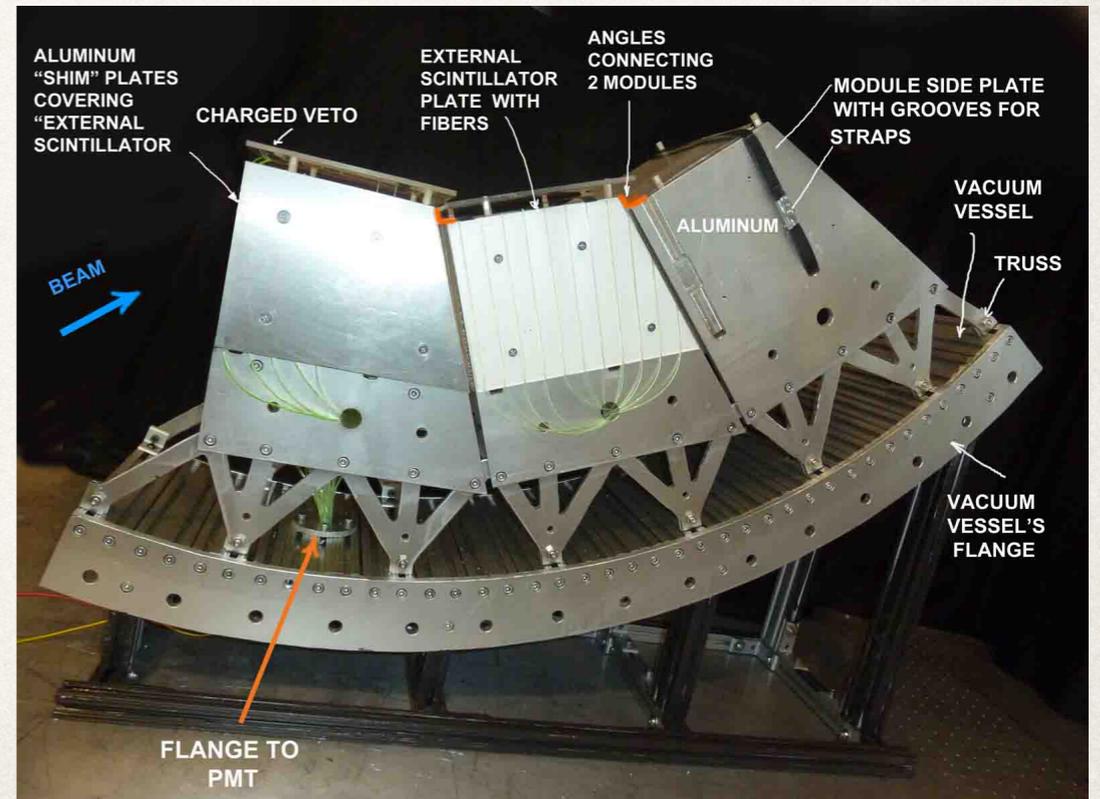
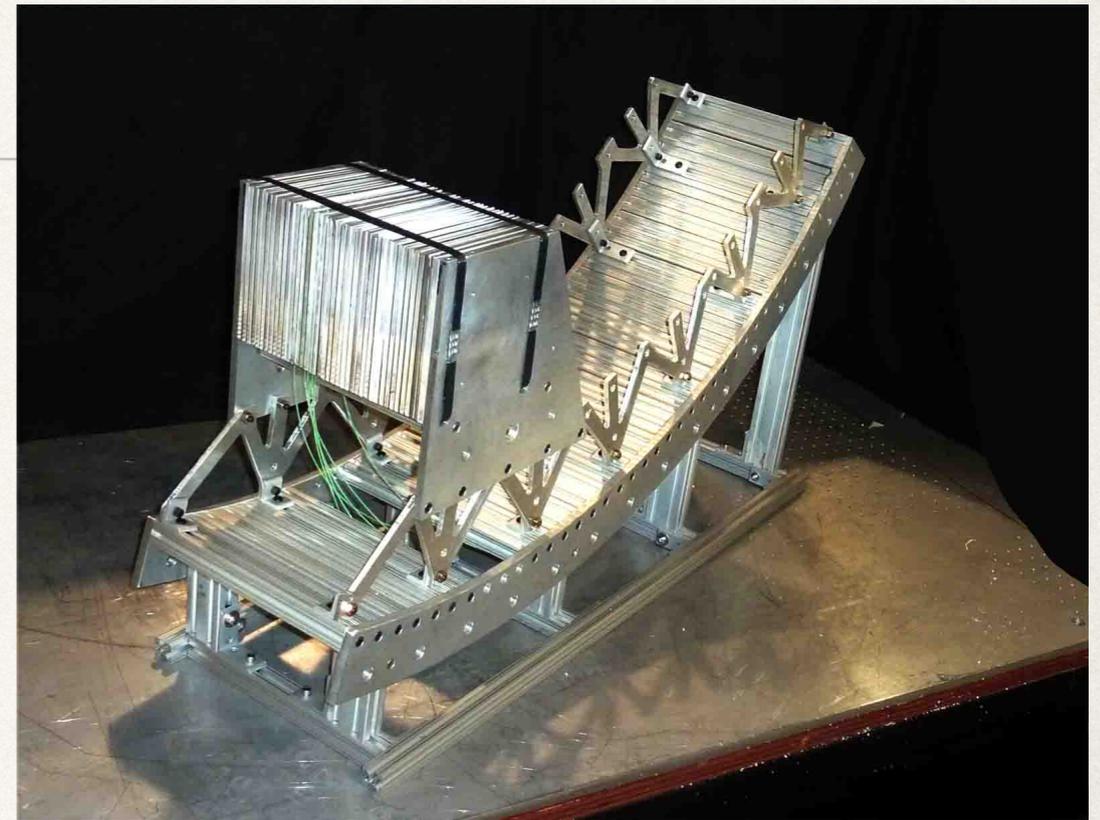
# New MB R&D



**KOTO**  
SCINTILLATORS PARALLEL  
TO THE BEAM



**KOTO II** -- SCINTILLATORS PERPENDICULAR TO THE BEAM



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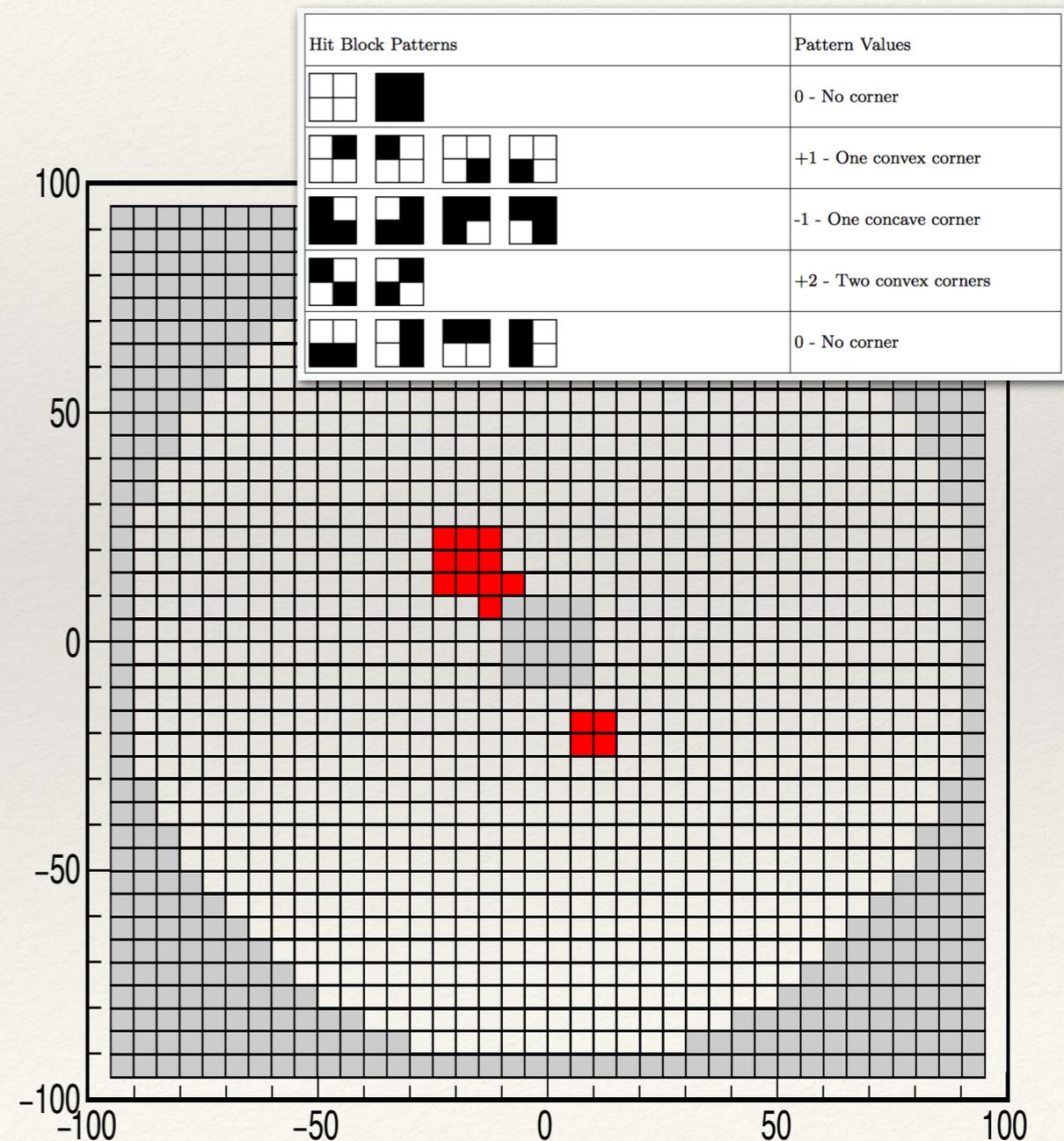
# Backup

---

# Lv2 - Cluster Trigger

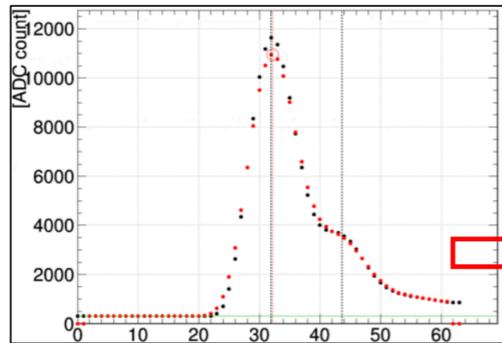
## Hardware Performance OFC with Altera Arria-V FPGA

- Scan all 1369 2-by-2 blocks in parallel
- calculation done within 10 clks (80 ns)
- System dead time ~150 ns
- limited by data transfer rate

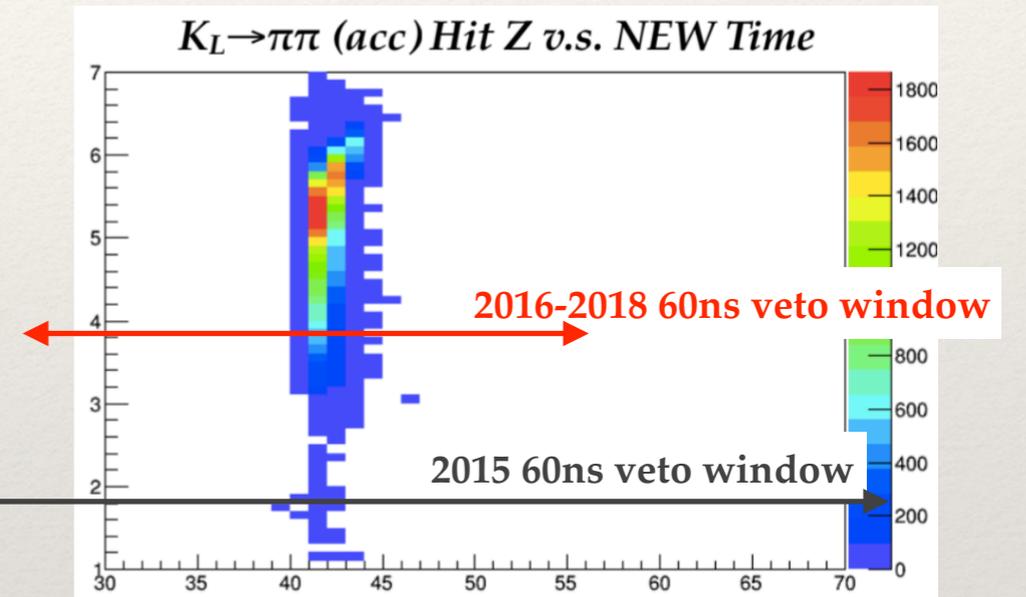
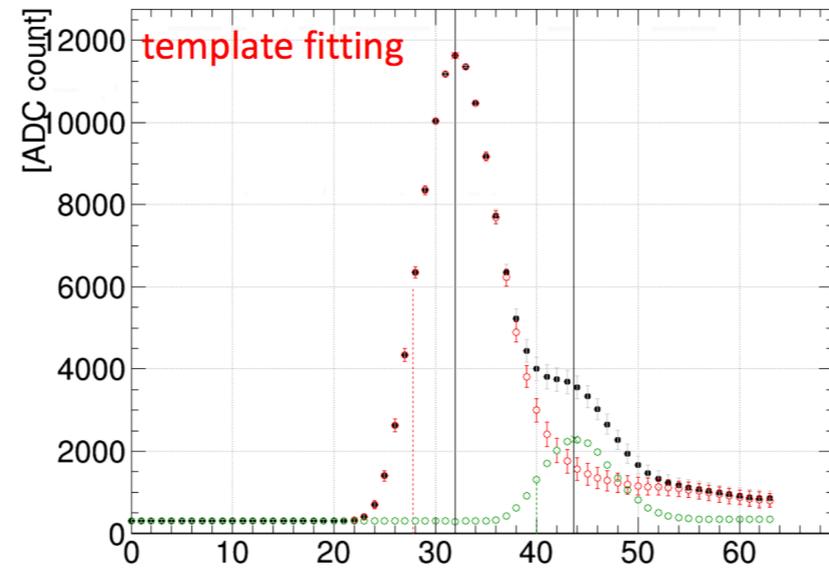


# Internal Accidental

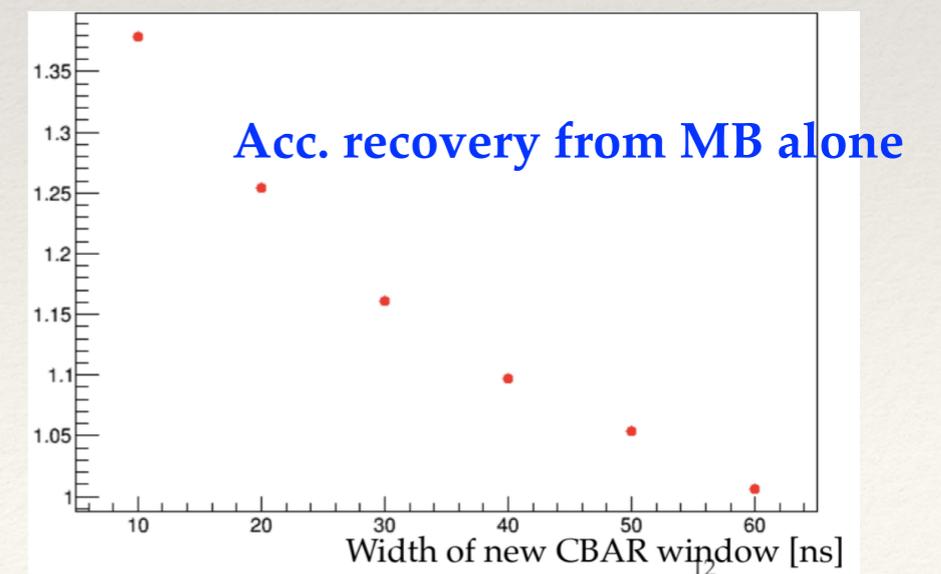
parabolic fitting



Better pulse separation ability is expected in template fitting

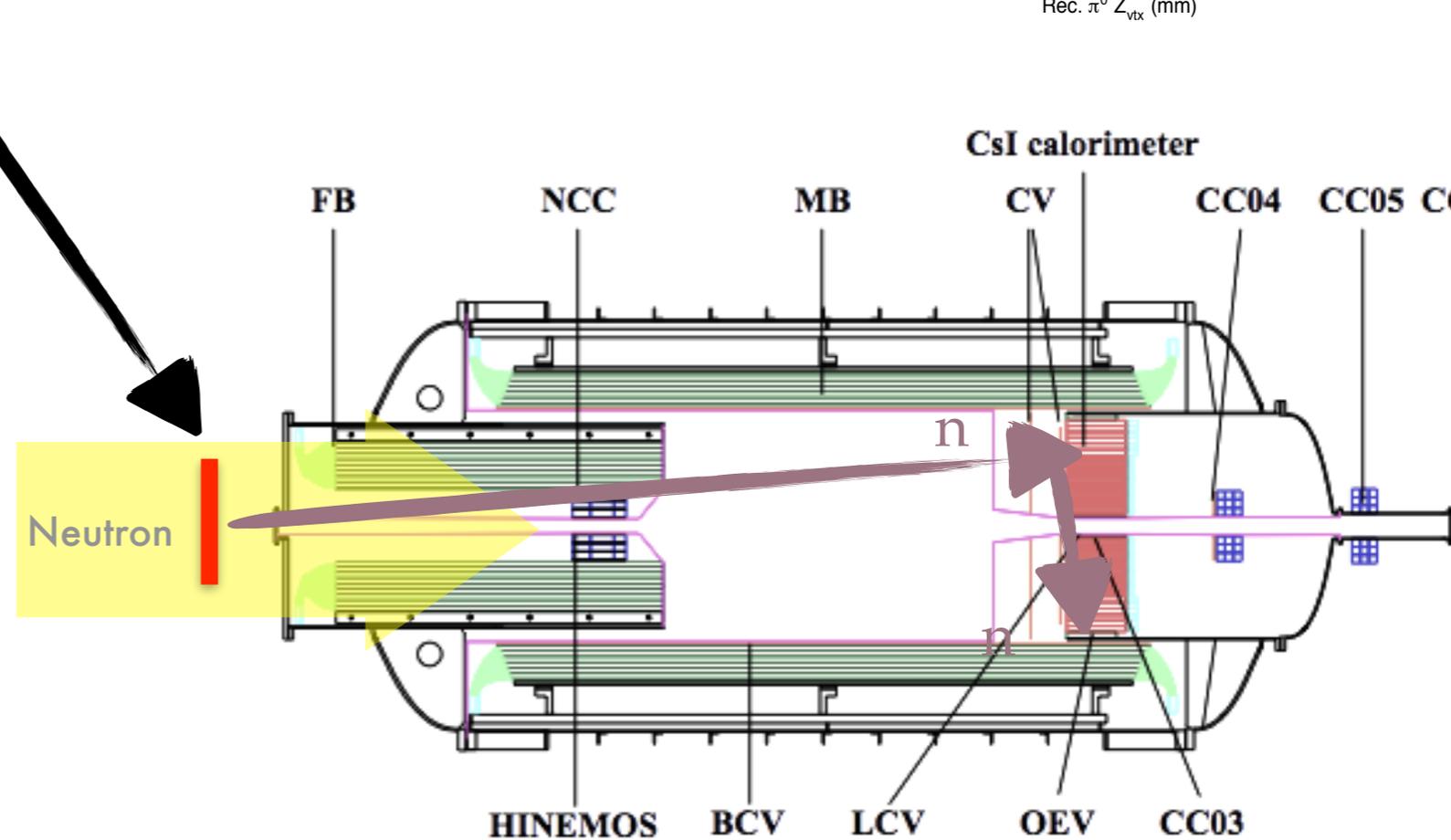
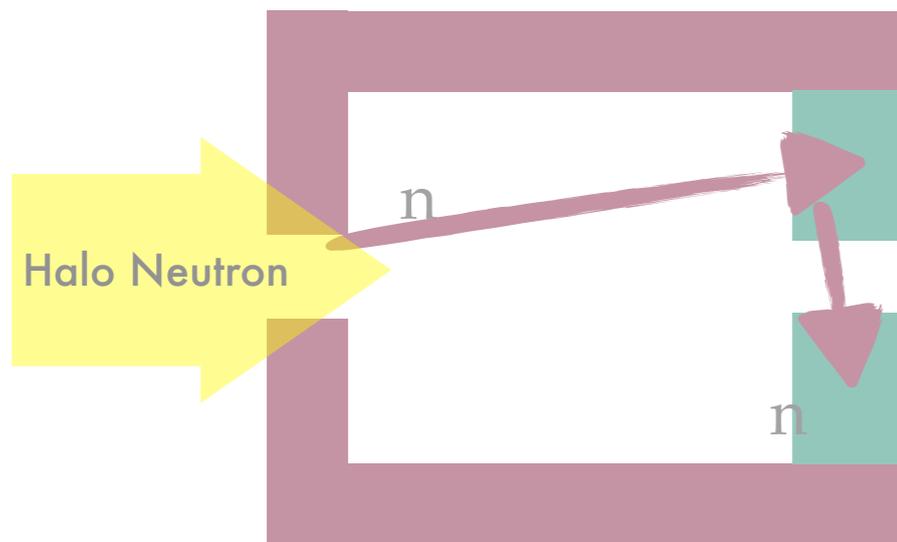
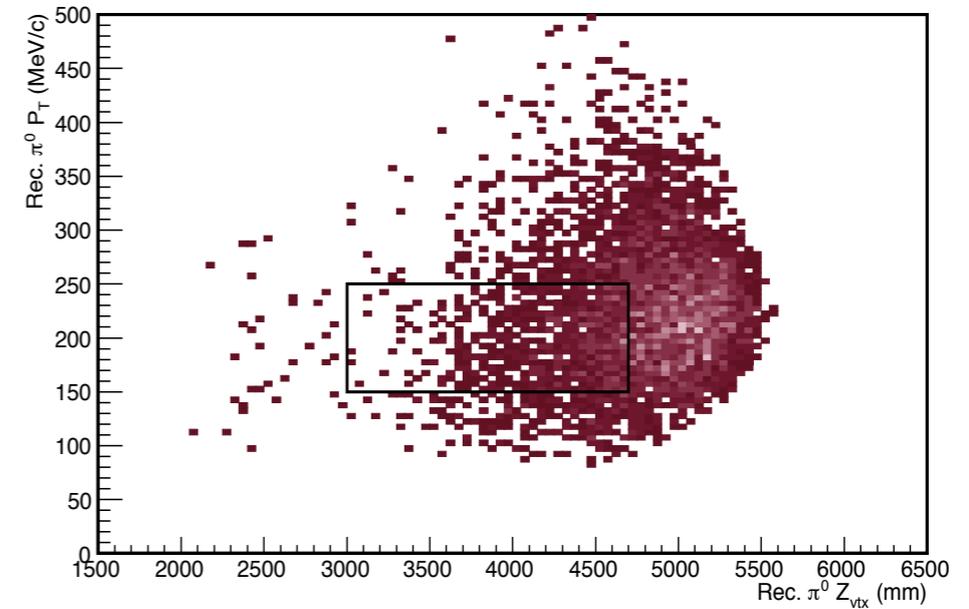


- Wide veto window because of double pulses
- Expect to recover 50% signal from window  $\times 1/2$ 
  - waveform analysis



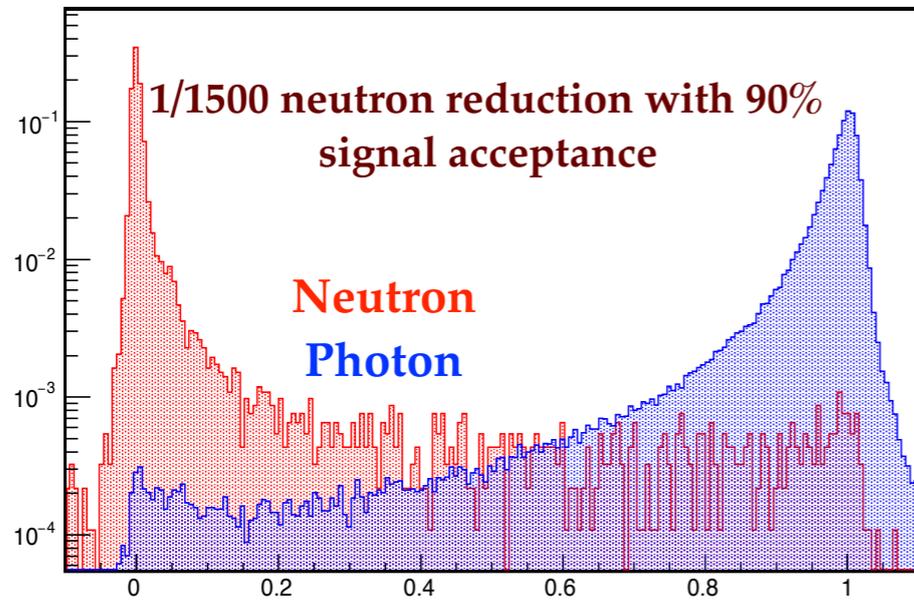
# Neutron Run

Special Al target run to collect  
neutron rich events

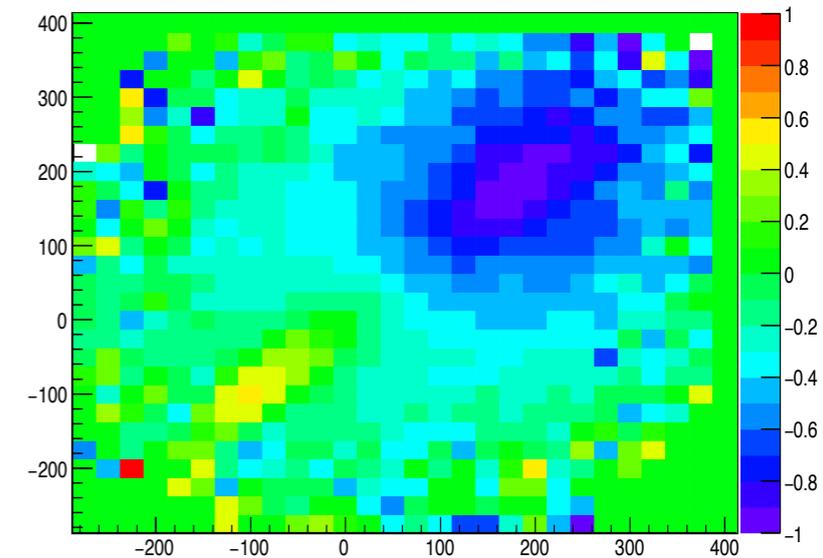
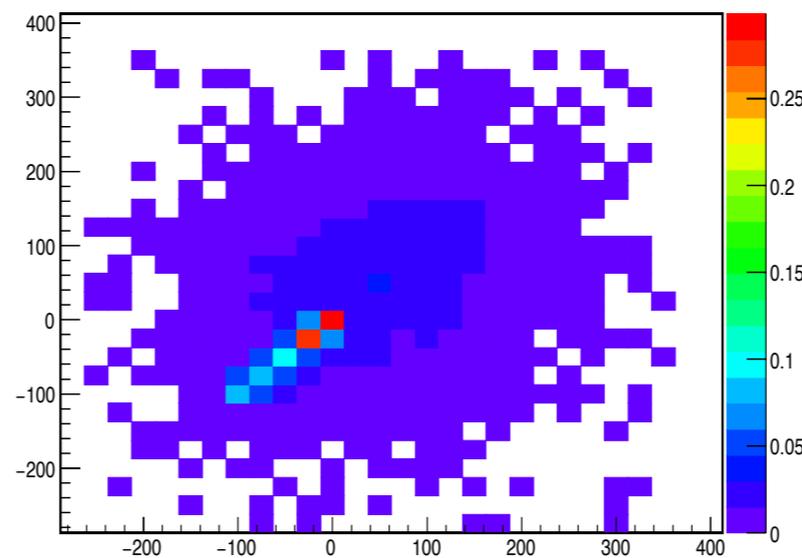
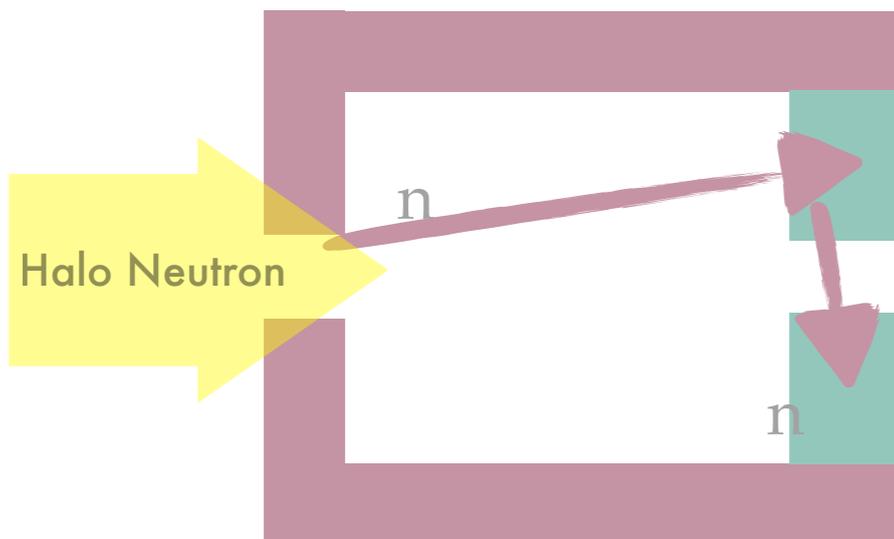


# CSD

- Cluster Shape Discrimination

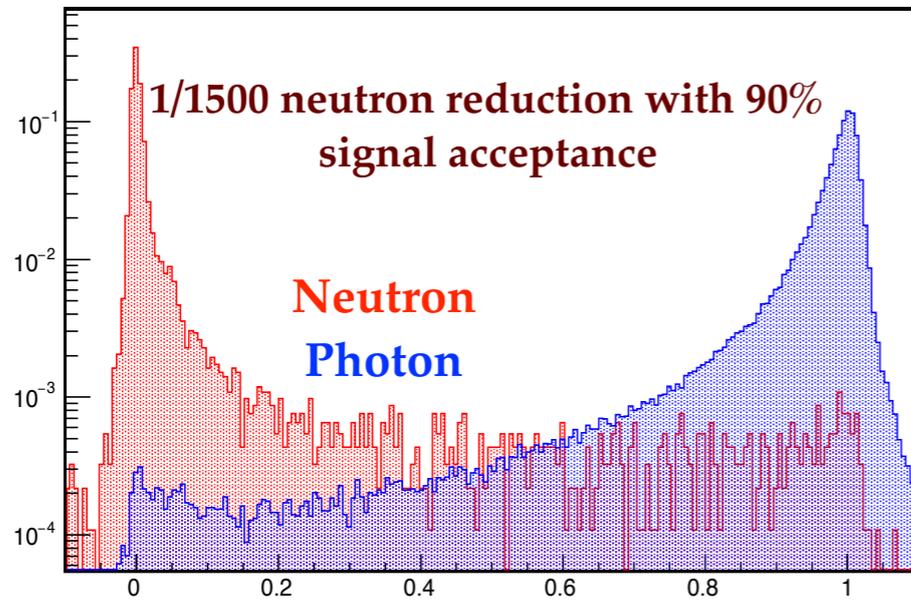


$\Upsilon/n$  identification by using cluster energy & timing information

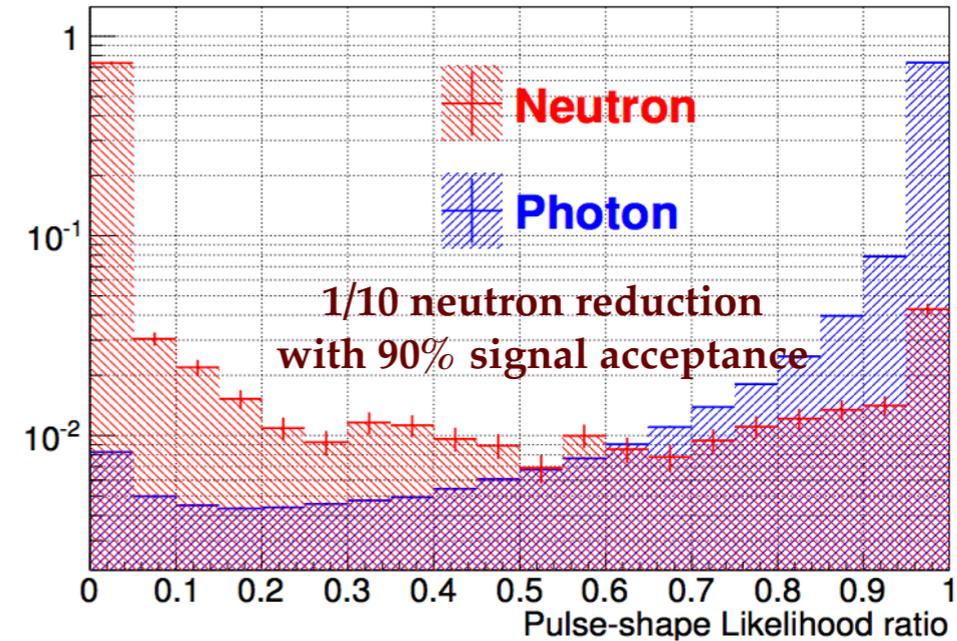


# PSD

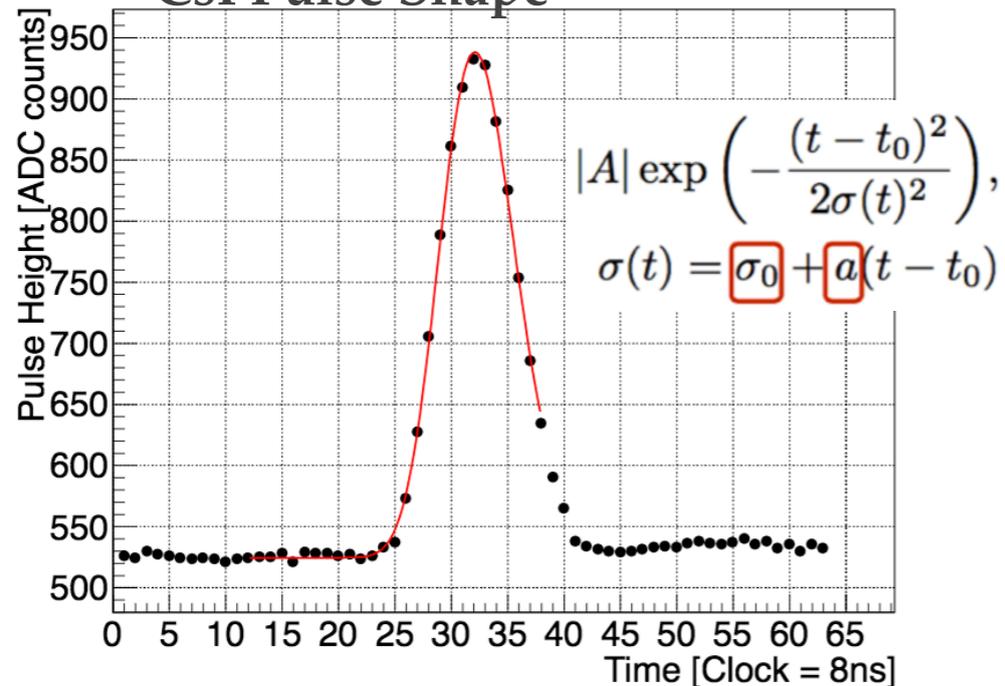
- Cluster Shape Discrimination



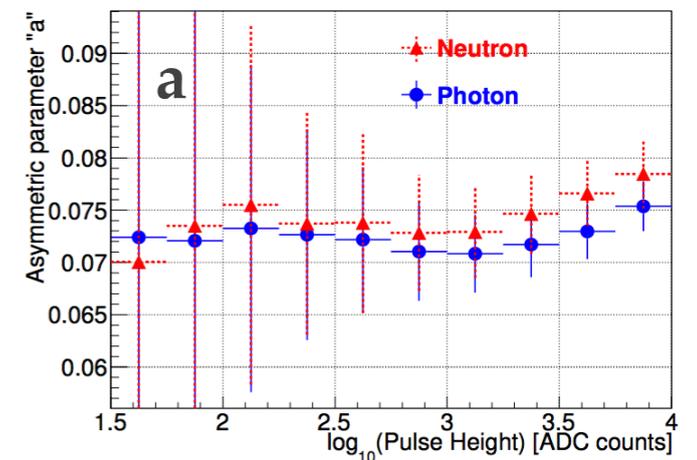
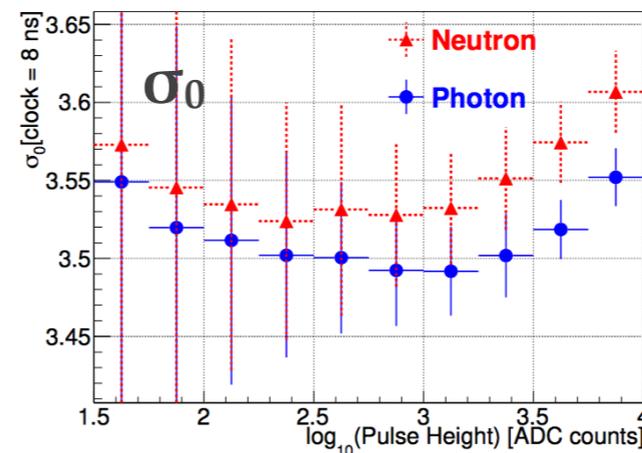
- Pulse Shape Discrimination



## CsI Pulse Shape

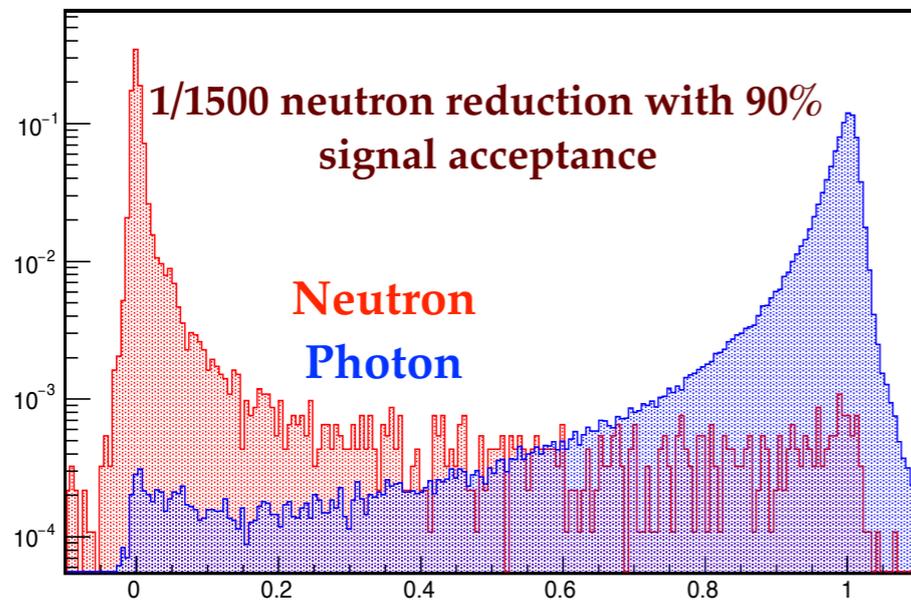


## Wider Pulse from hadronic shower



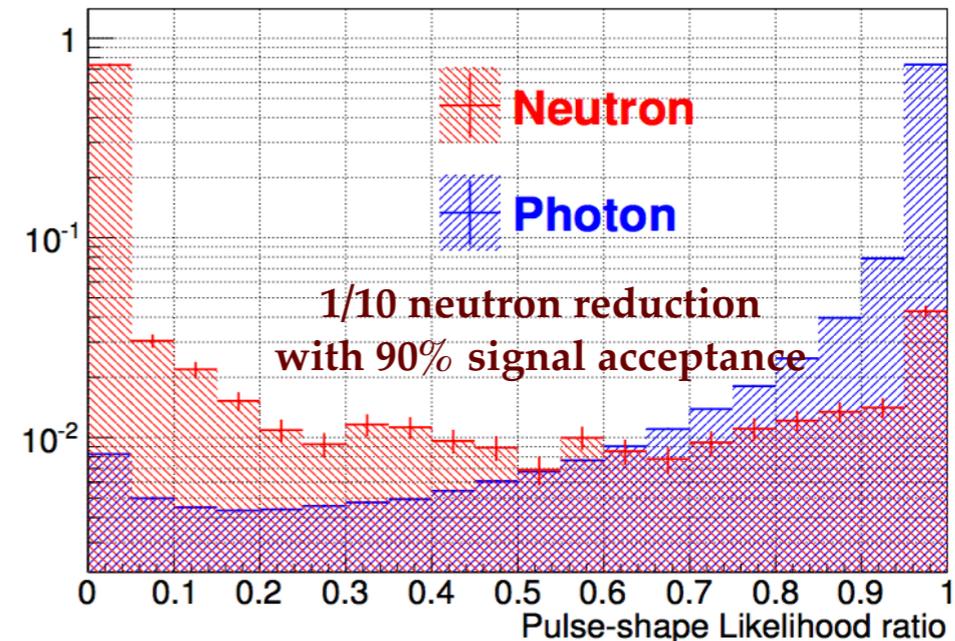
# Neutron Reduction

- Cluster Shape Discrimination

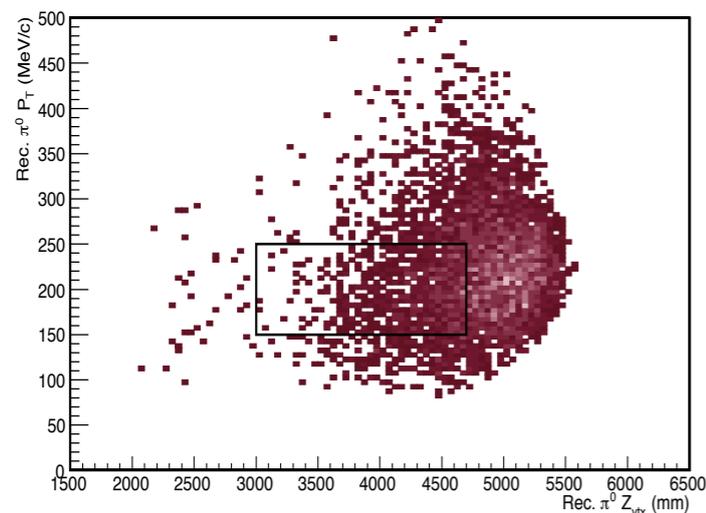


+

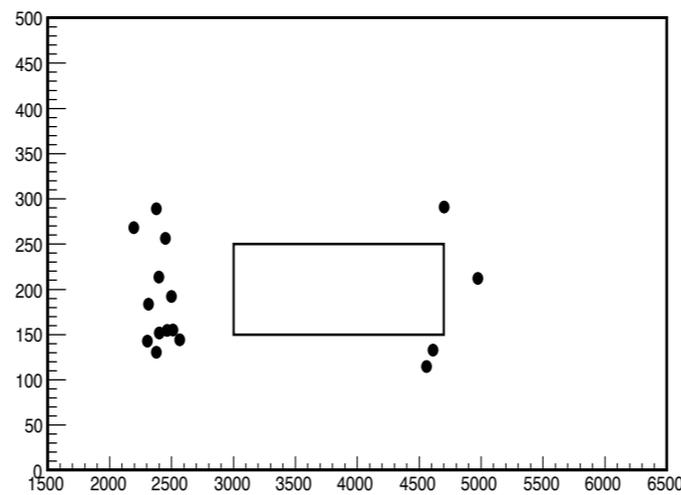
- Pulse Shape Discrimination



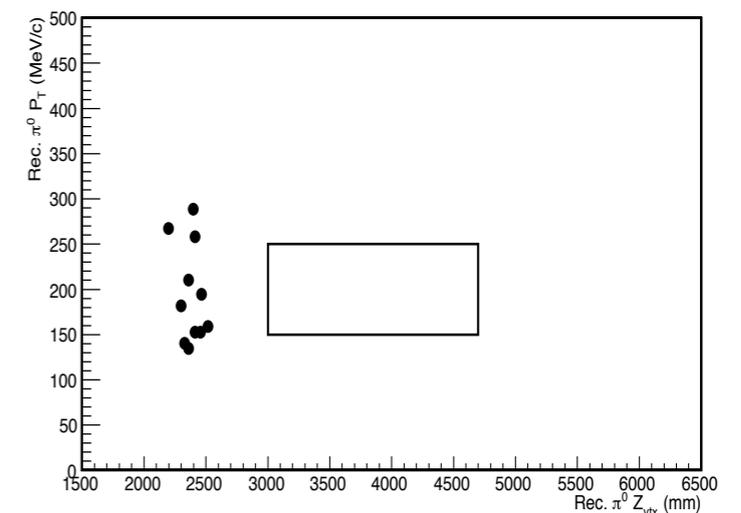
Neutron reduction improved by O(2)



Neutron Sample



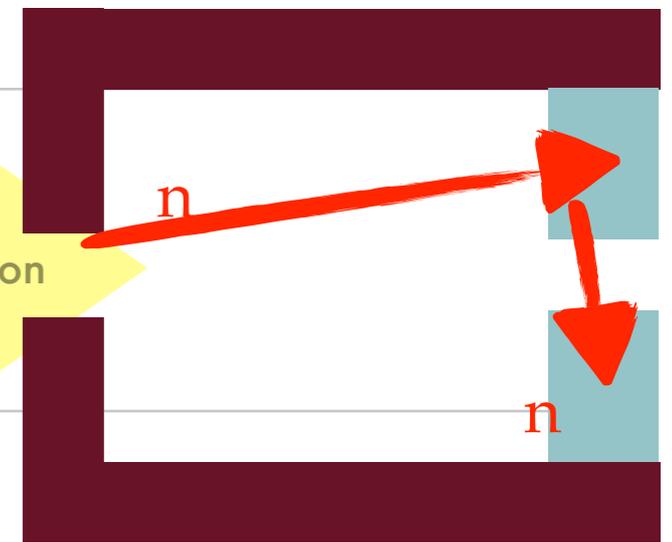
2013 Selection



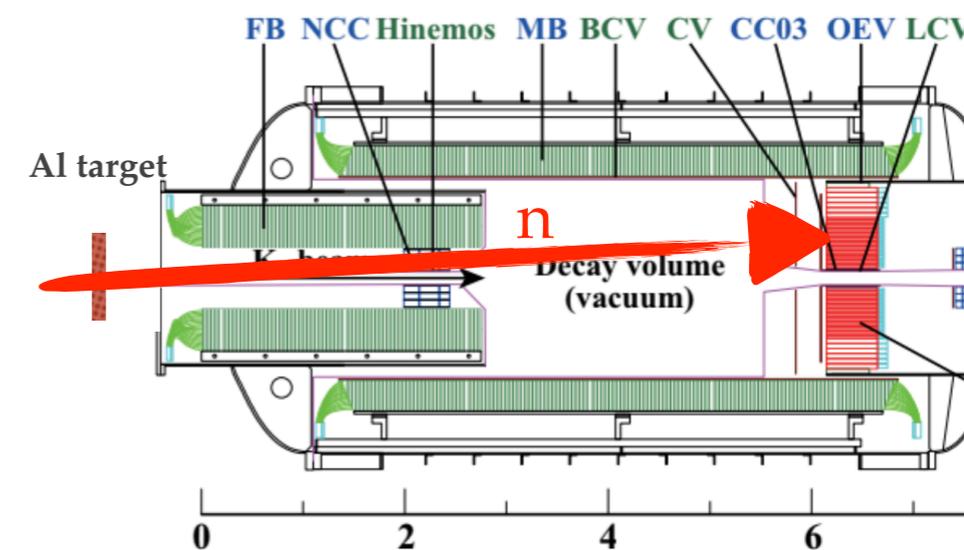
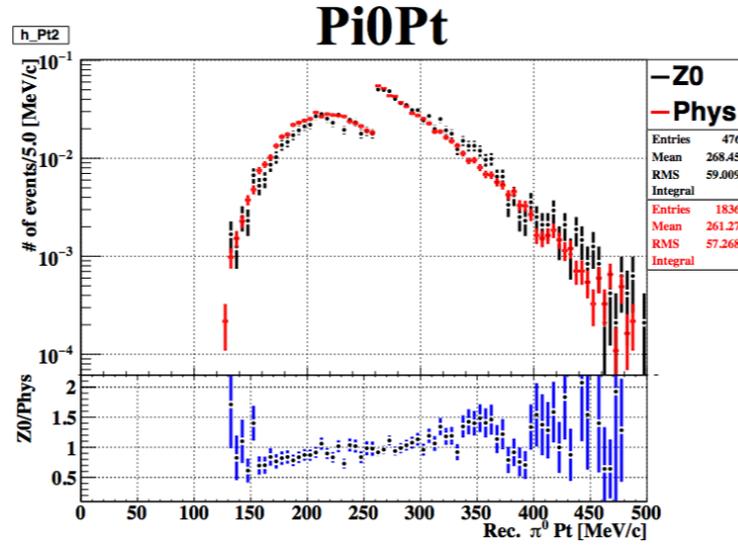
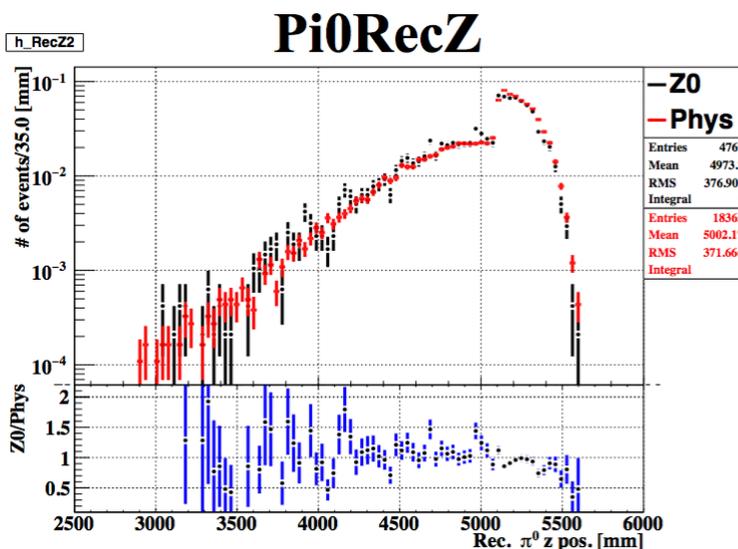
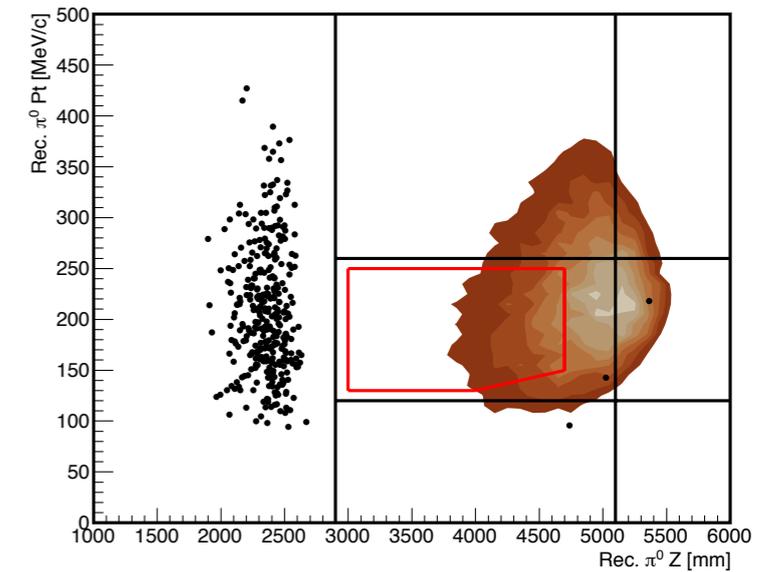
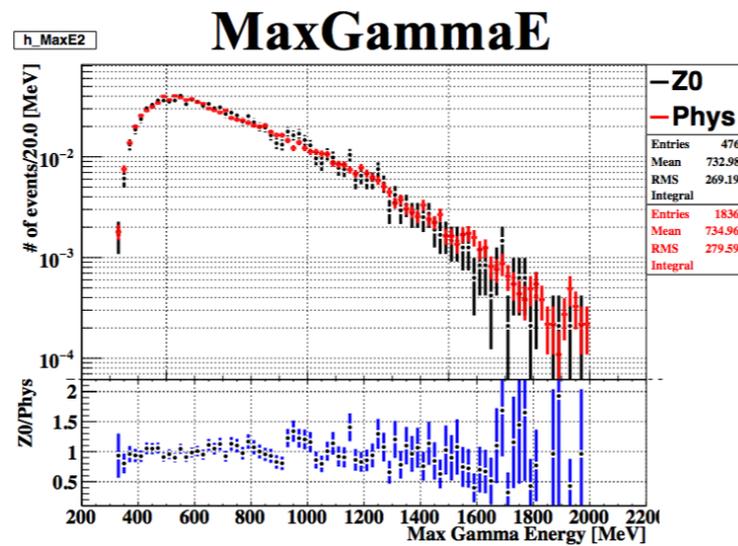
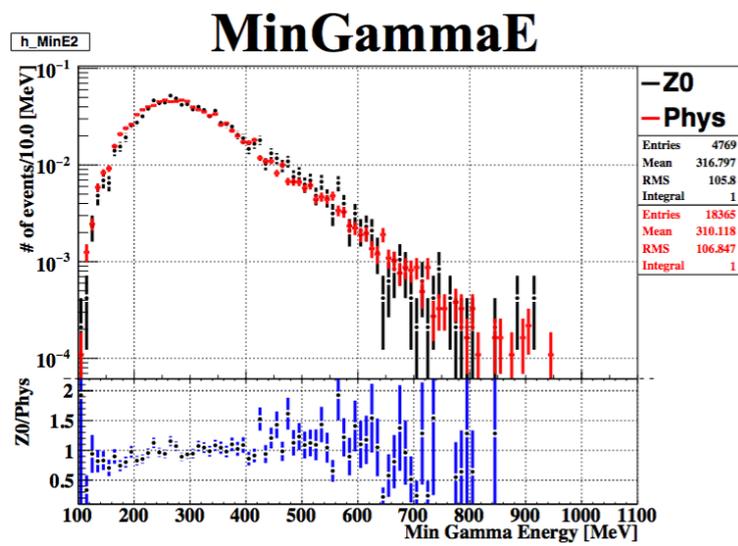
Present Selection

# Hadron Cluster

Halo Neutron

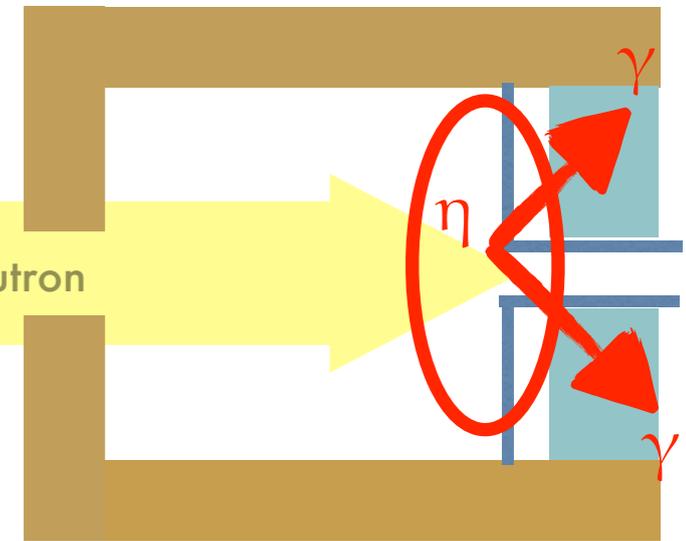


- Dedicated run to collect neutron samples.
- Good agreement between neutron & physics runs.

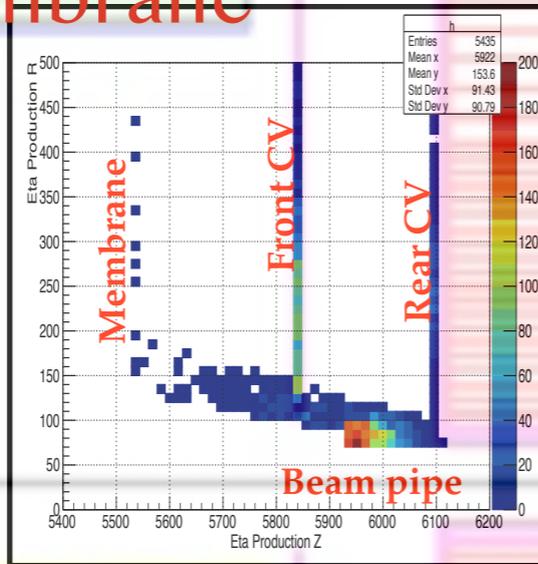


# CV- $\eta$

Halo Neutron

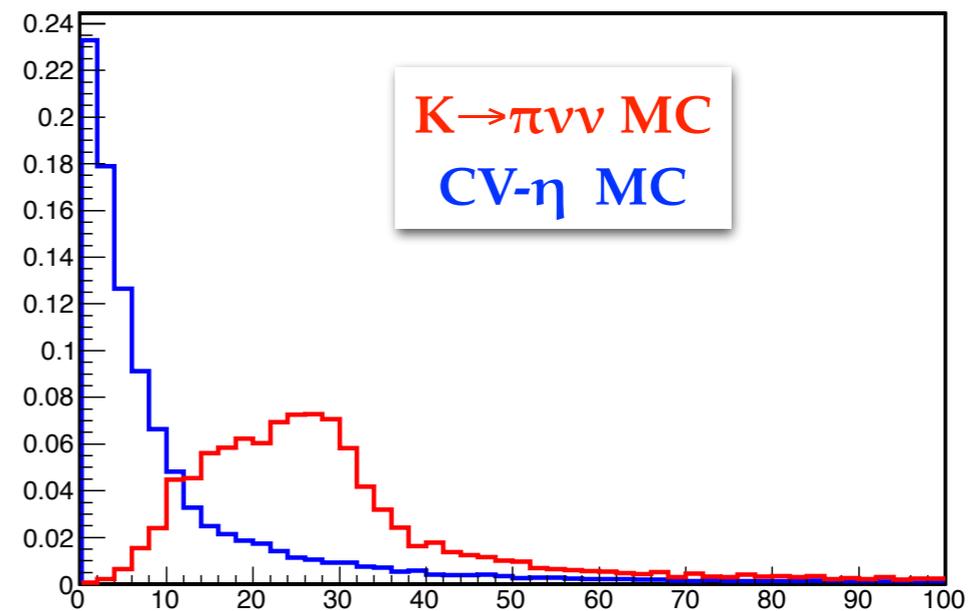
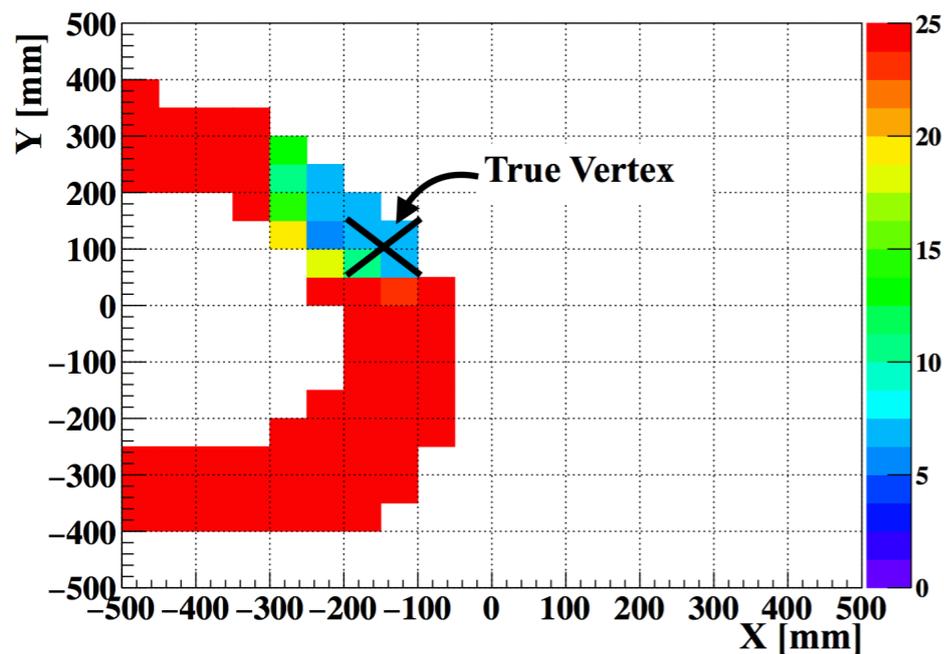
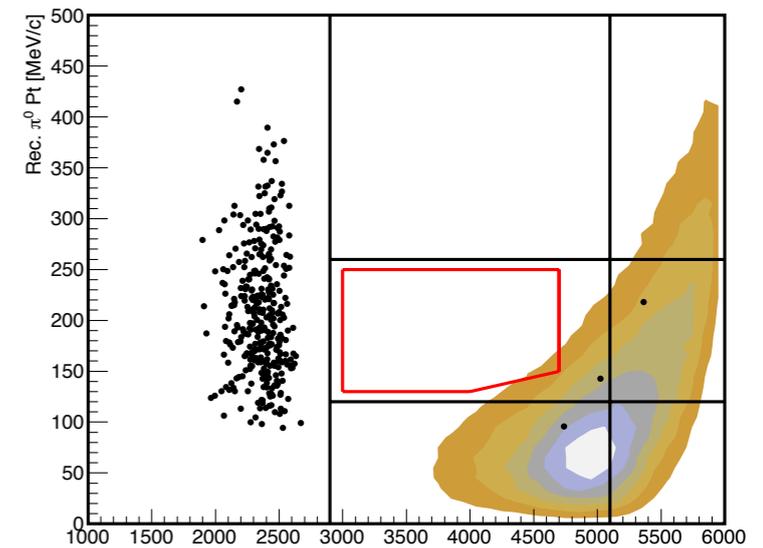


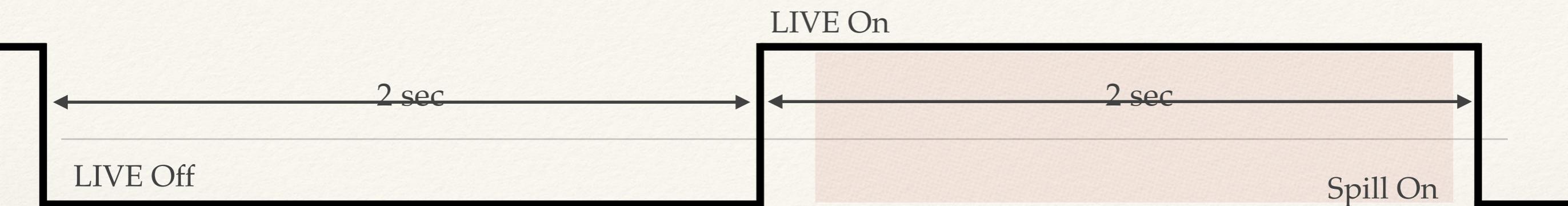
pe & vacuum membrane



data analysis:

ct by angle consistency  $\Rightarrow$  CV- $\eta \times 1/10$





Trigger Table	
1000	Lv1 w/o PS
1100	Lv1 w/ PS
1110	Cluster Bit
1010	Alignment
1001	Test trigger
1111	Reset

LIVE Off

optical link and test optical transmission

LIVE rising edge and Before spill on

system checks the result of optical link test

system issues alignment trigger

issues out one clock signal simultaneously for alignment

DCs set the delay for Et daisy-chain

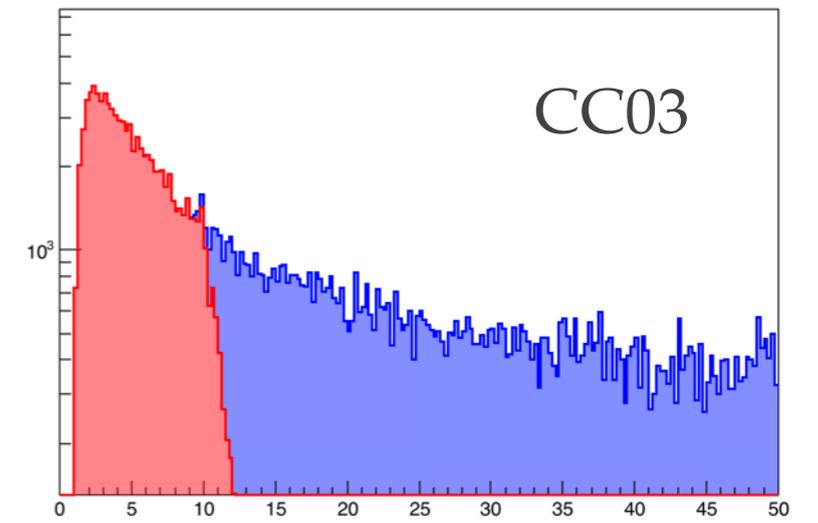
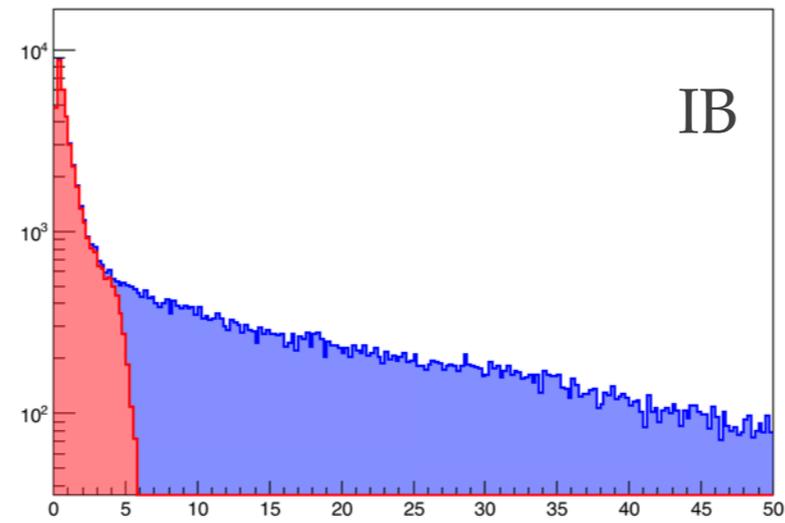
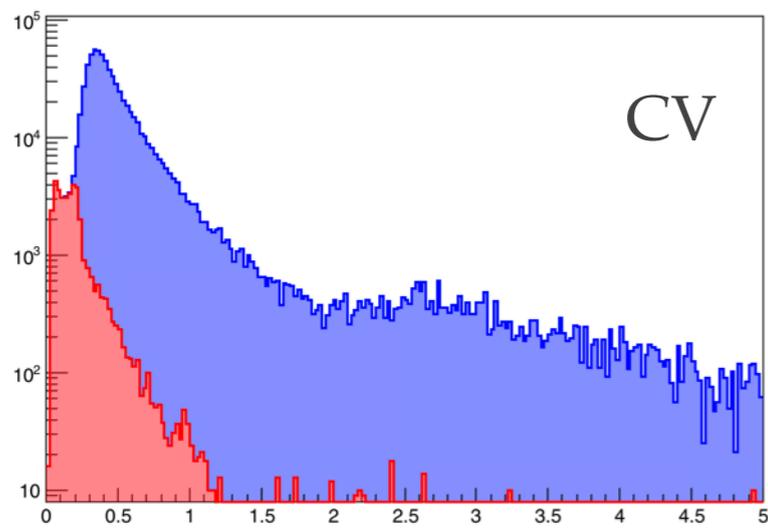
sets the global delay between CsI and veto crates

issues a test trigger to check Lv2 clustering system

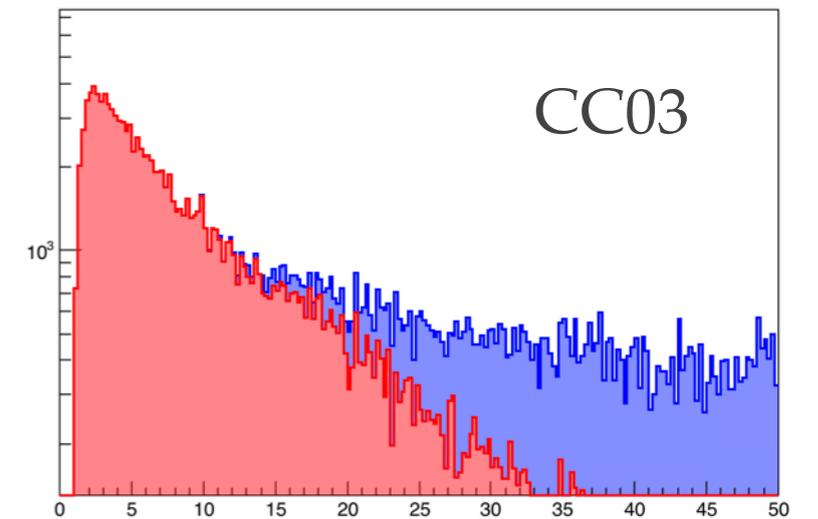
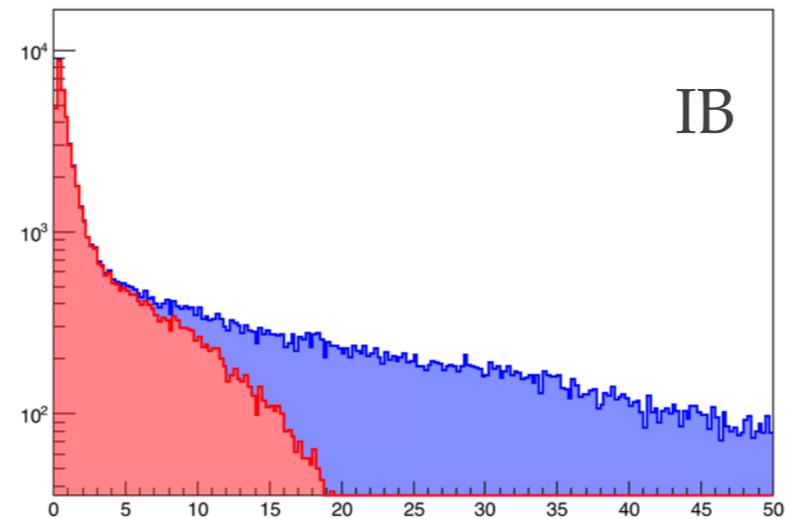
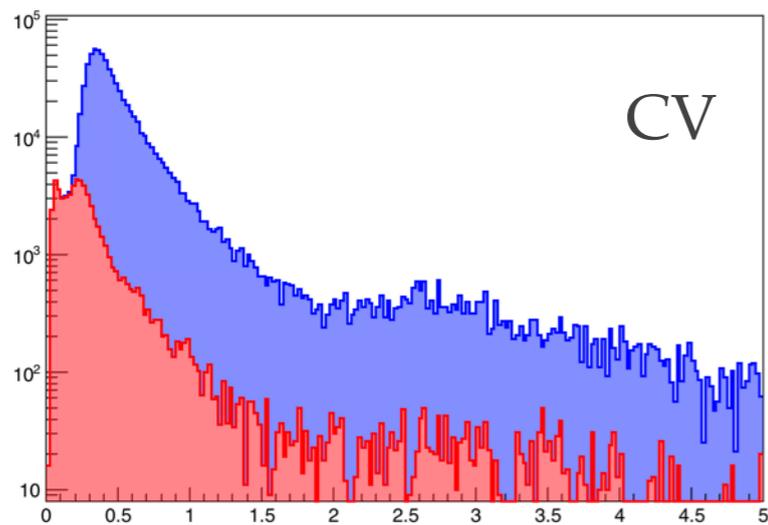
system is ready for spill on

# Maximum Energy Distribution Before/After Veto

## CDT Veto



## L1 Veto



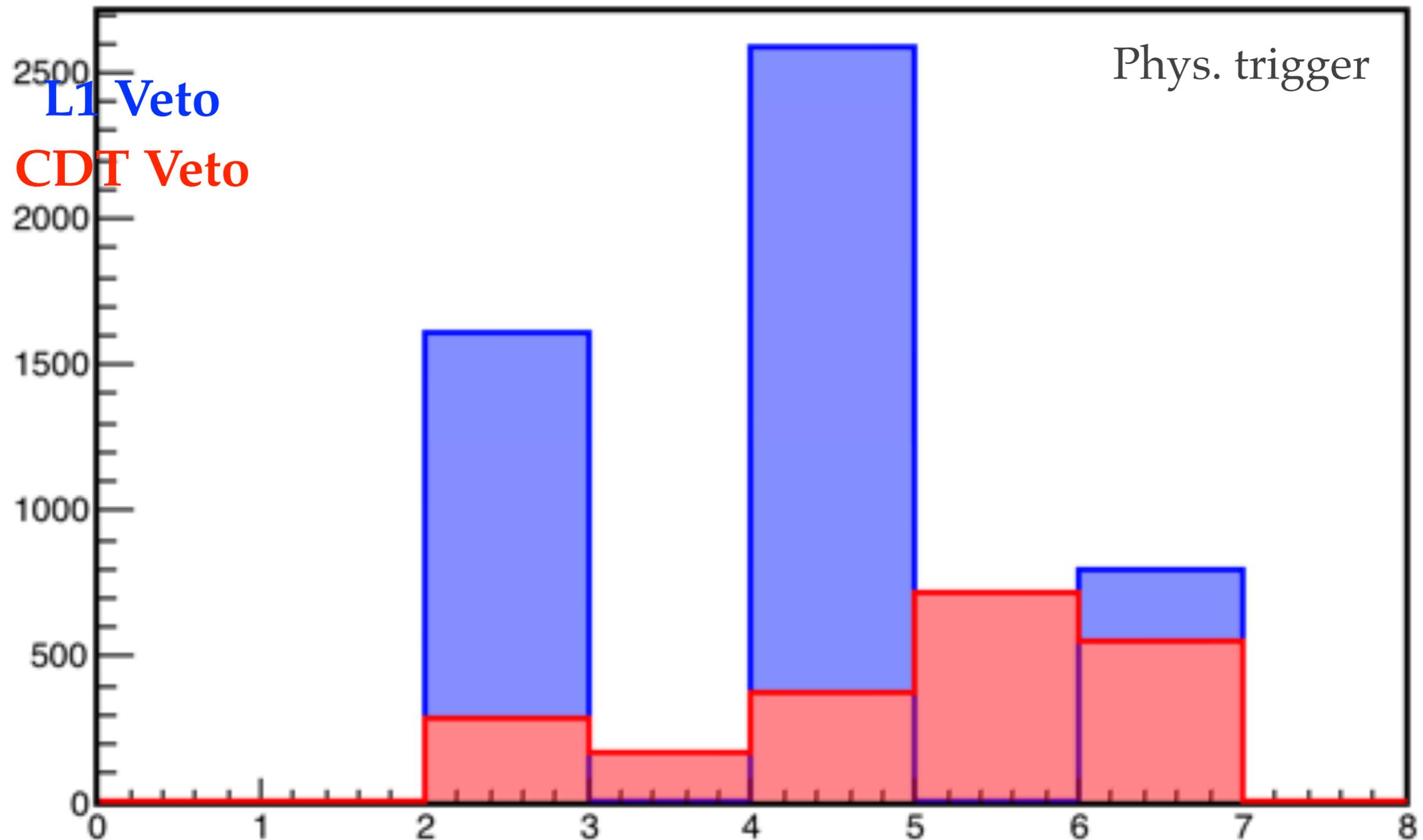
# L1A Reduction

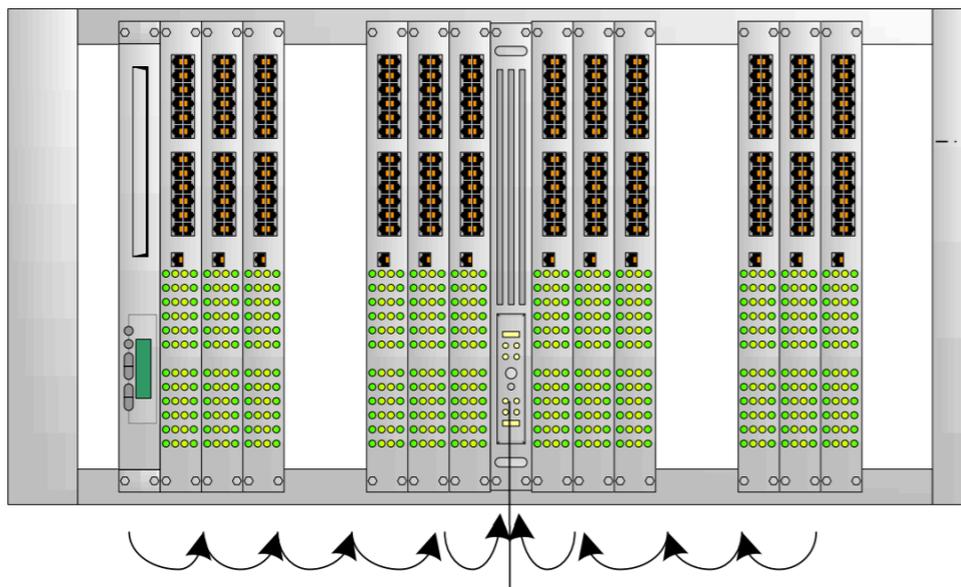
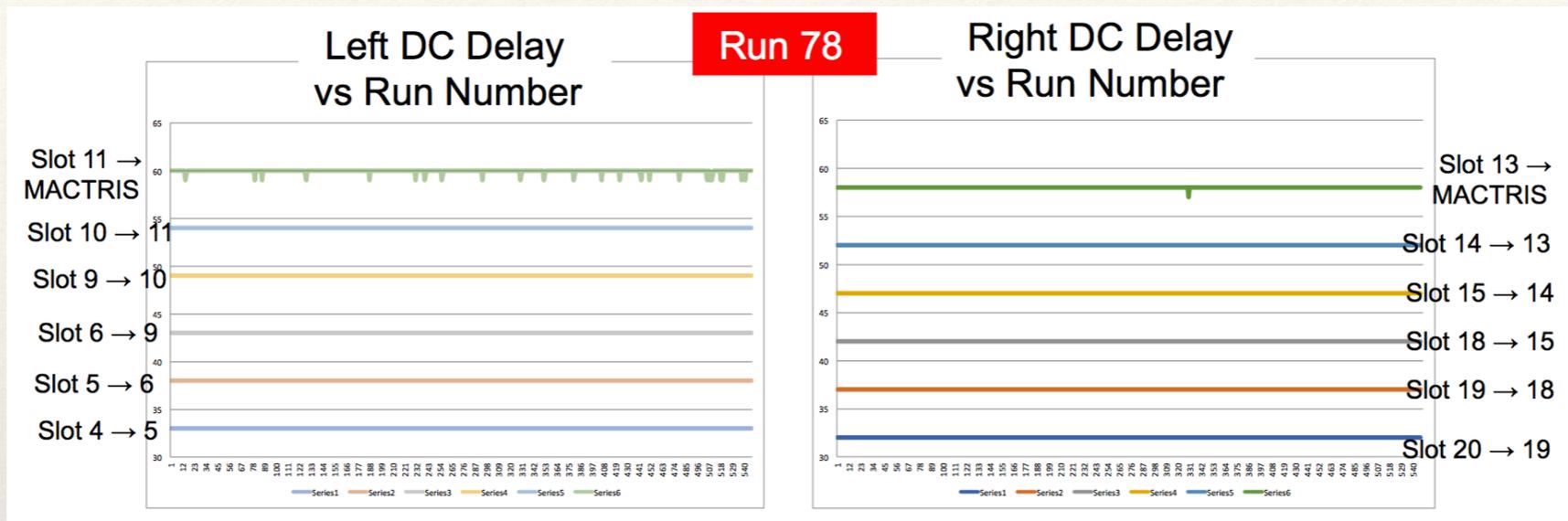
- Estimated by using dst data with CDT trigger and without L3 veto (run26060-26066).
- Two cluster events are normalized to no CoE rate.
- CDT veto is applied to only physics and normalization events.
- L1A rate with CDT veto: 3.5K/spill in 37.5kW beam power.
- L1A rate extrapolated to 150kW beam power = 14.2K ~ current L2 output limit.
- Pedestal subtraction can improve L2 output limit by another factor of 2  $\Rightarrow$  300kW?

L1A Reduction in each Detector

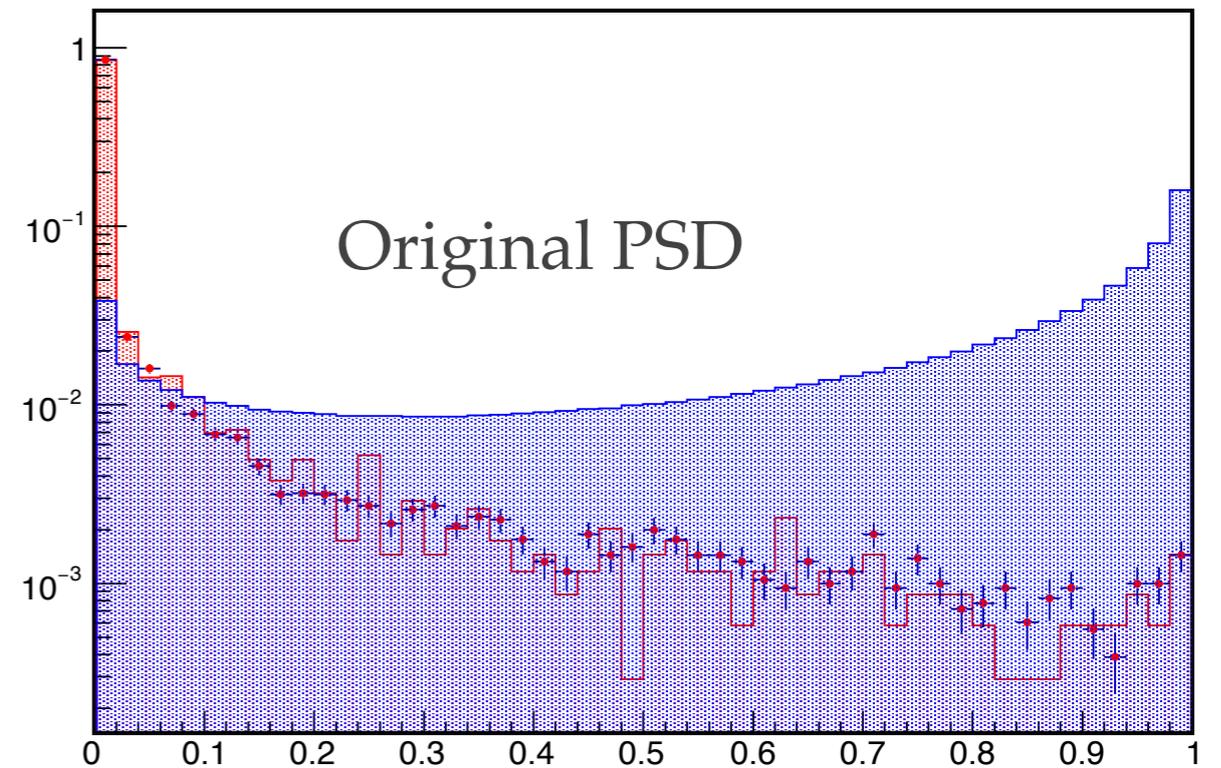
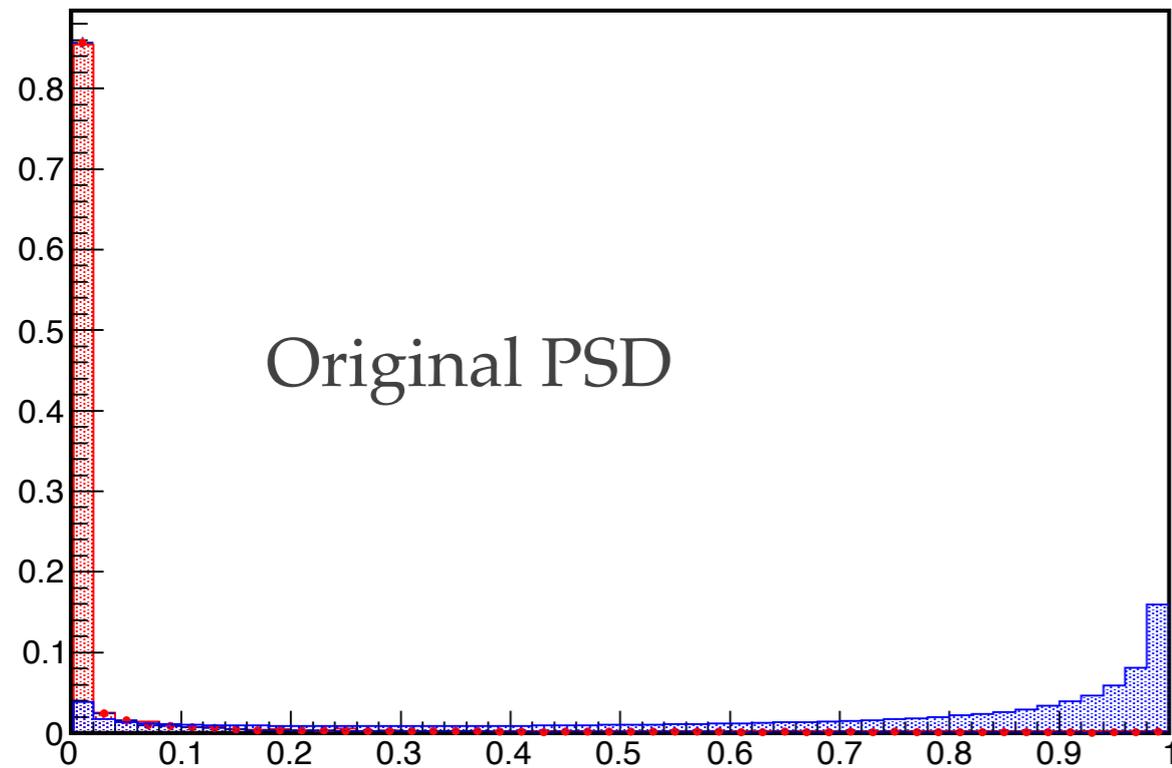
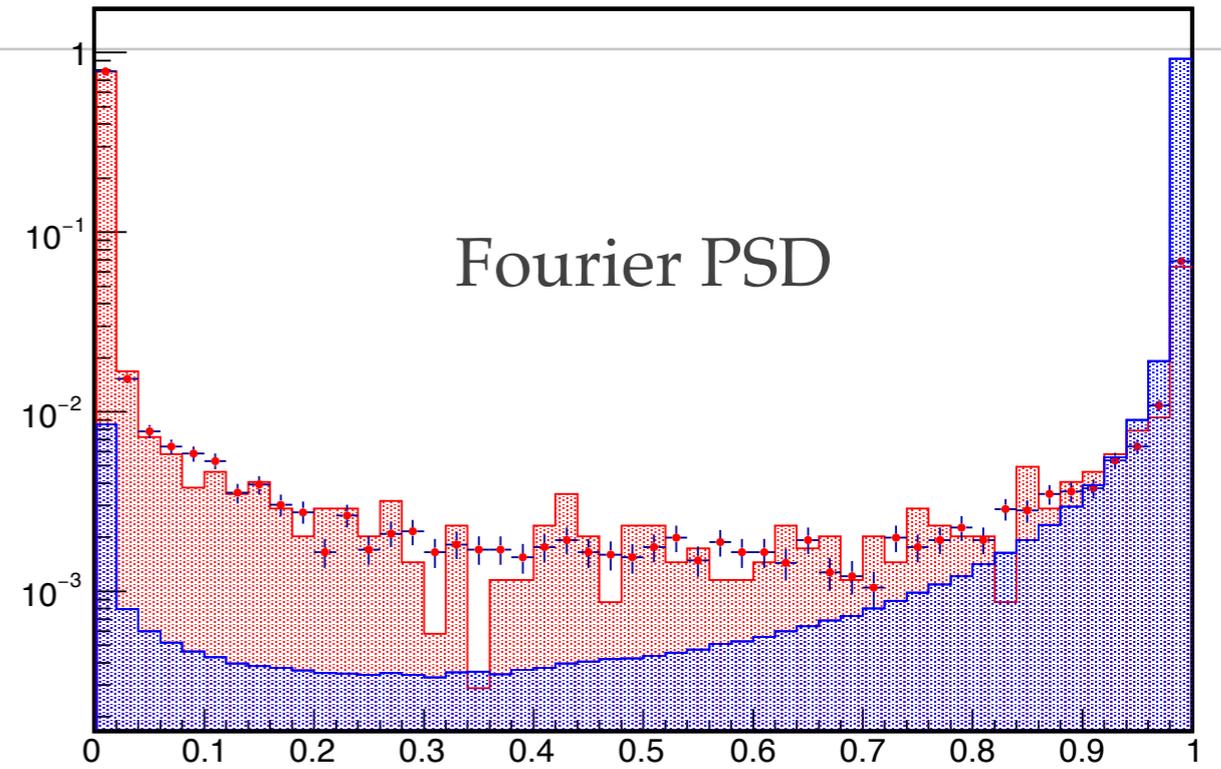
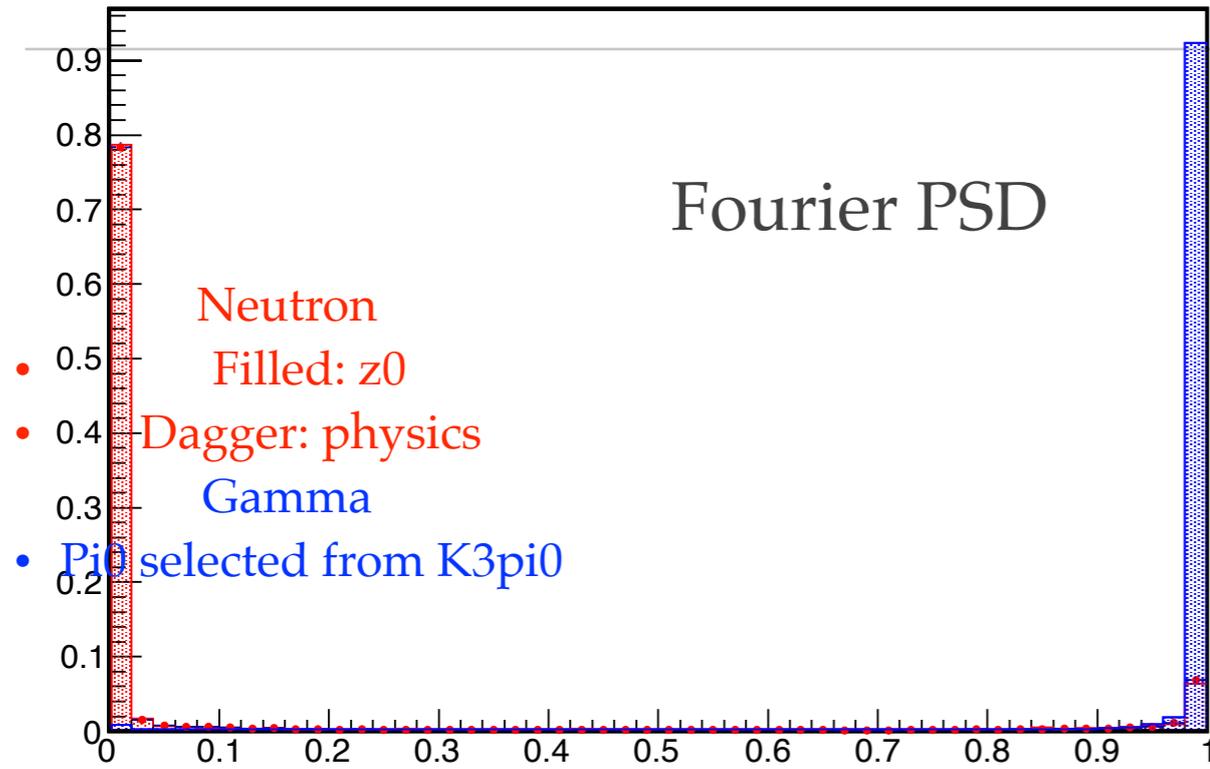
	CV	LCV	IB	CBAR	FBAR	NCC	CC03	CC04	CC05	CC06	BPCV	L1A
L1 Veto (%)	66.7	-	24.9	5.4	-	13.8	20.8	-	-	-	-	14.5K
CDT veto (%)	71.8	18.2	34.7	18.0	8.8	17.4	26.1	12.7	5.9	4.9	2.3	3.5K

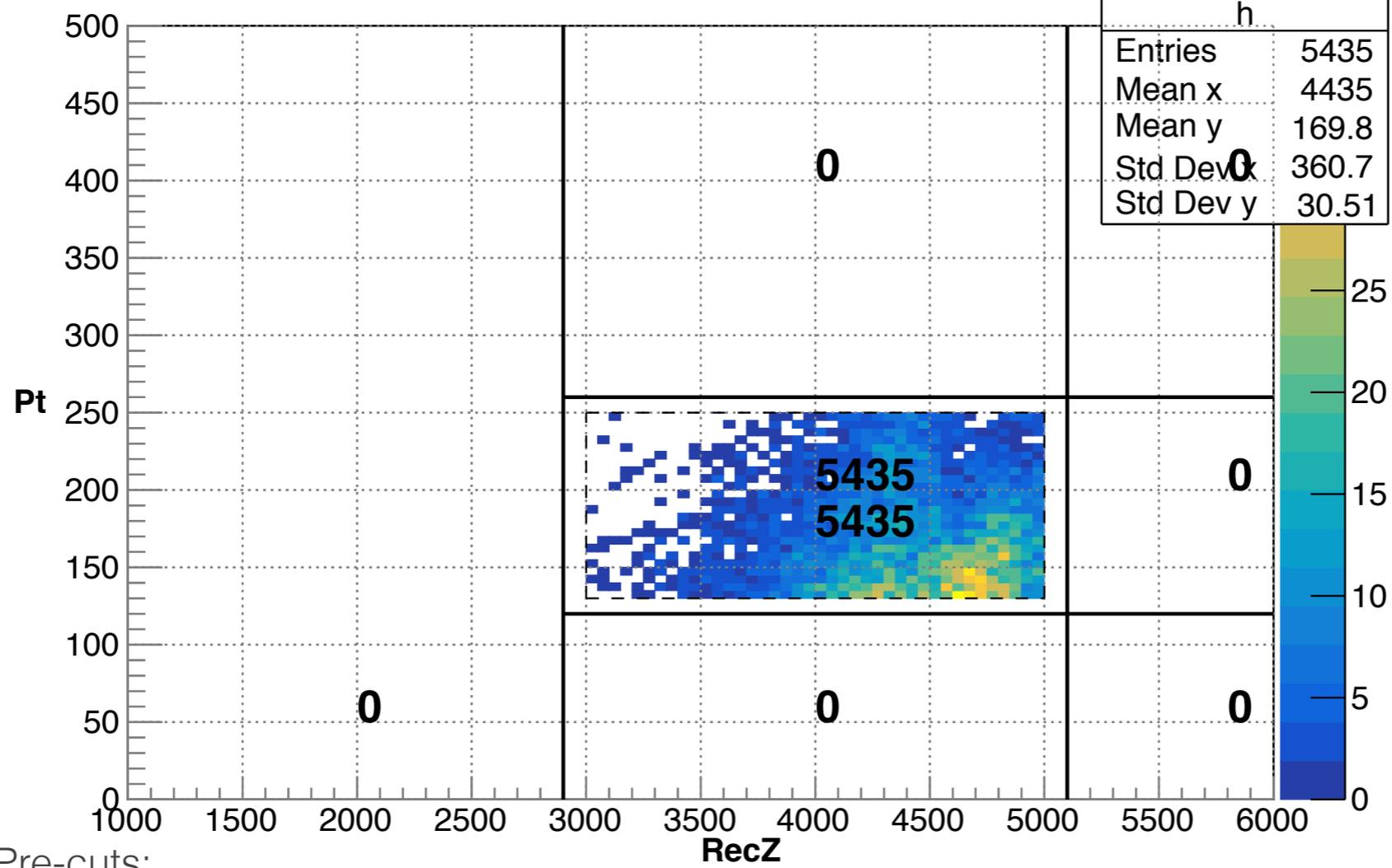
# We Can even Take 3 & 5 Cluster





# Likelihood of two-cluster System





← Eta MC after pre-cuts

*Lorem Ip*

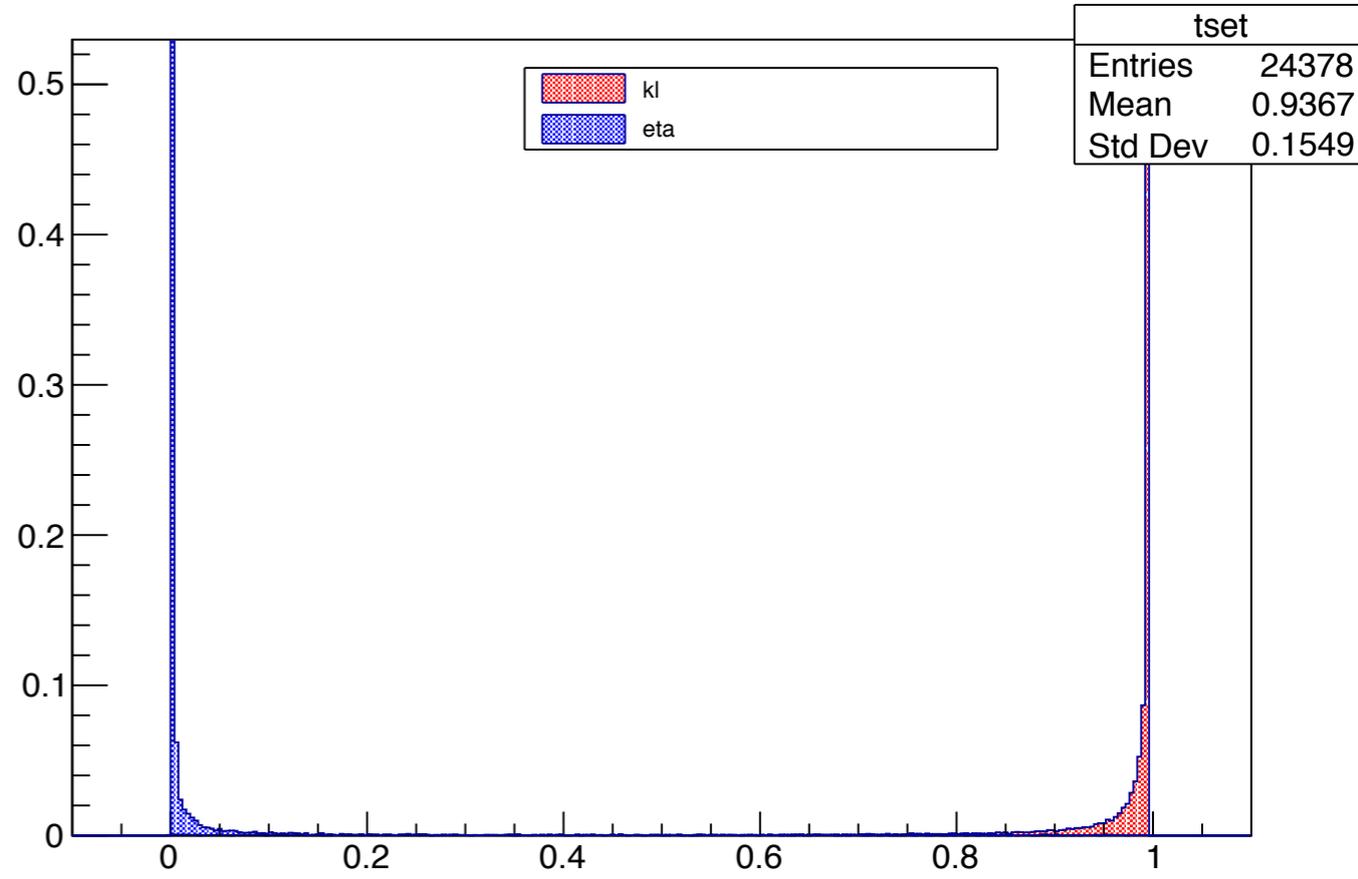
Pre-cuts:

```

(CutCondition==0 &&
(AddCutCondition|0xd0)==0xd0 &&
(MyVetoCondition|0x1120)==0x1120
&& CC06E391VetoEne<=3 &&
CC06ScintiVetoEne<=1 &&
CSIVetoFlag==0 &&
!(newBHCVMModHitCount>1 &&
newBHCVVetoEne>884.e-6/4.) &&
CBARMod39VetoEne<=2 &&
FBARNewVetoEne<=2 &&
BPCVVetoEne<=1

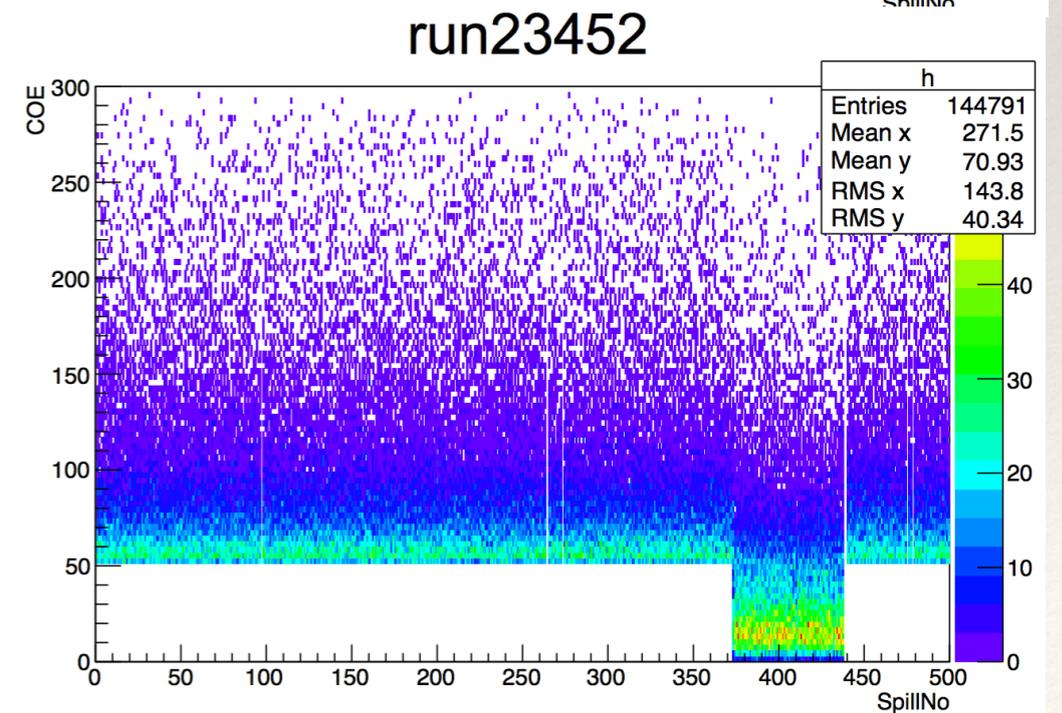
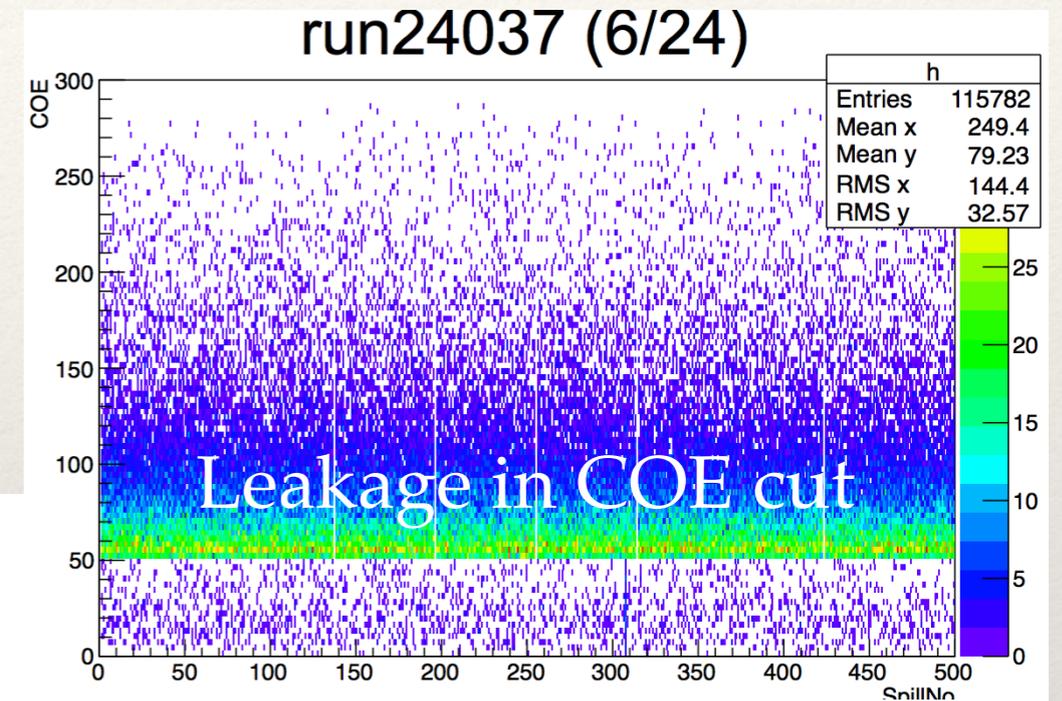
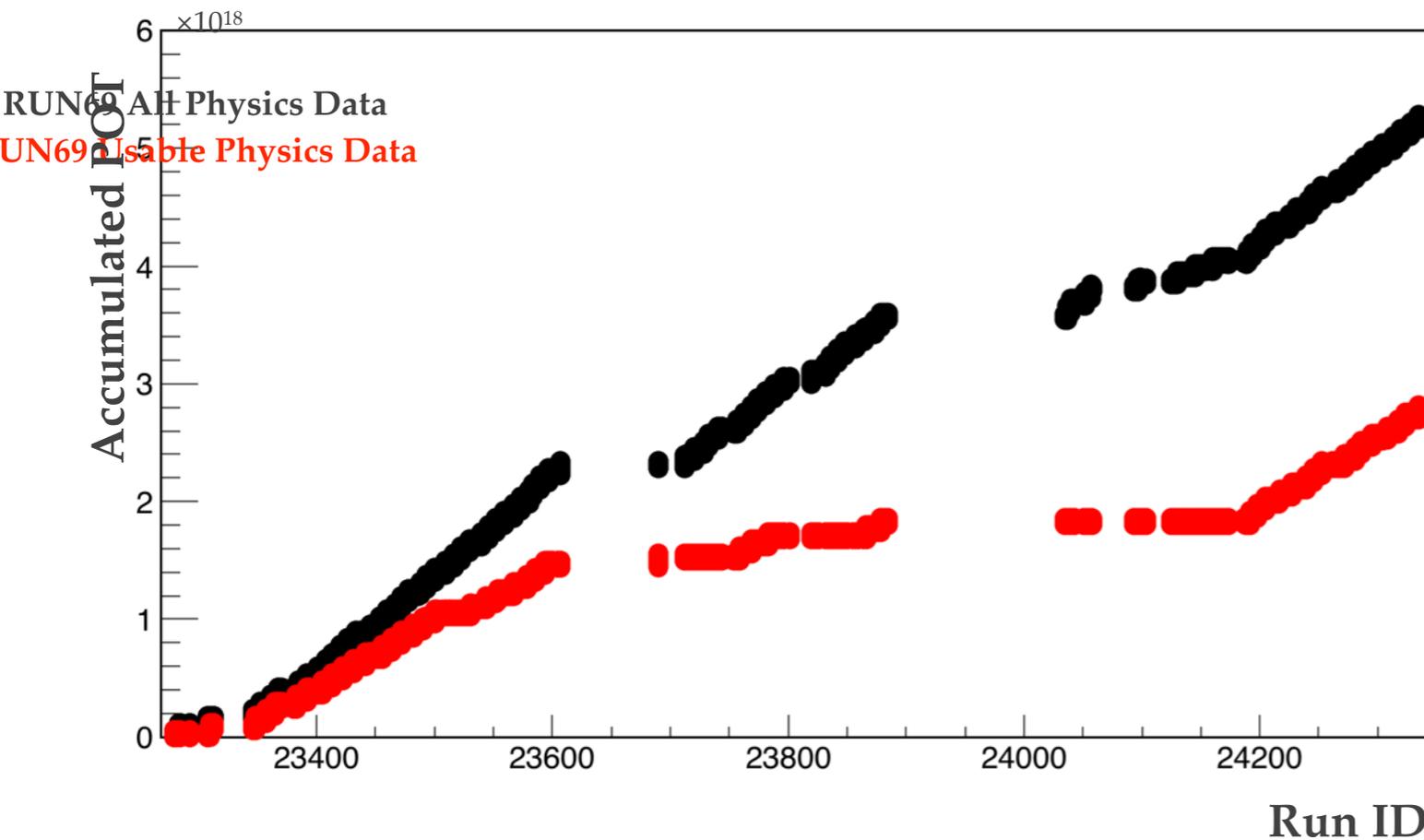
```

Eta CSD distribution  
on KL and Eta MC samples  
after pre-cuts



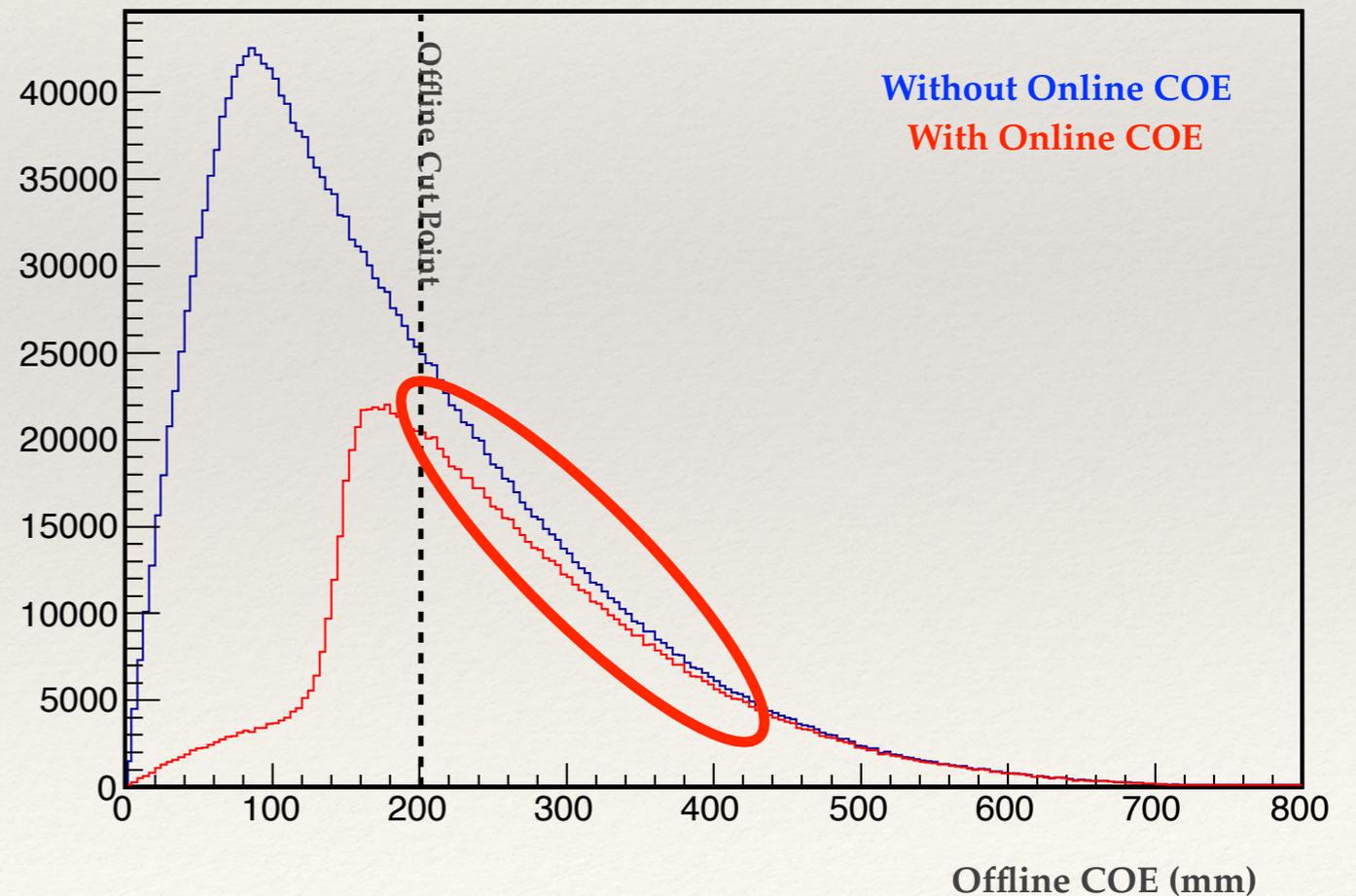
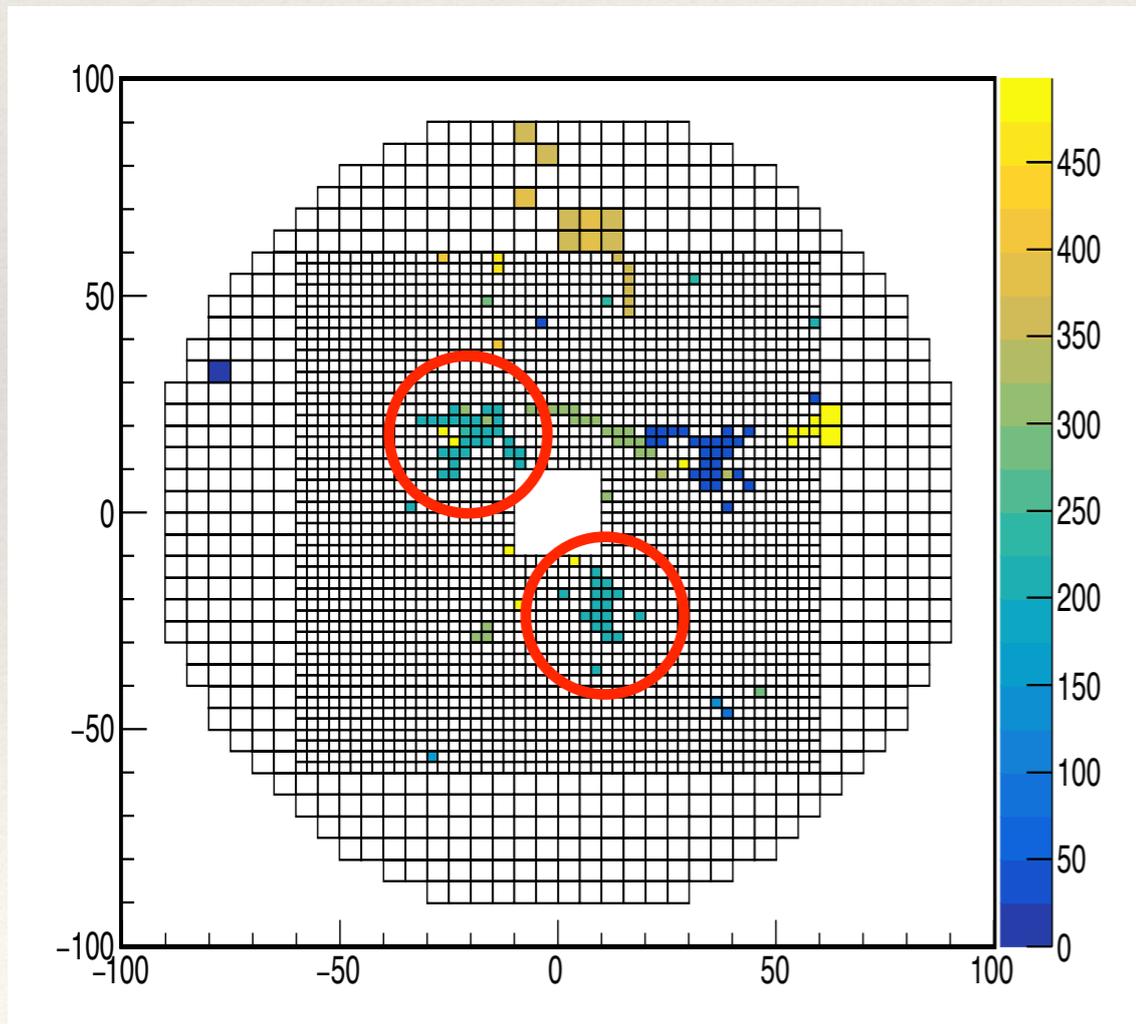
# DAQ Performance (2016)

2016 after IB installation.  
lected data is bad.

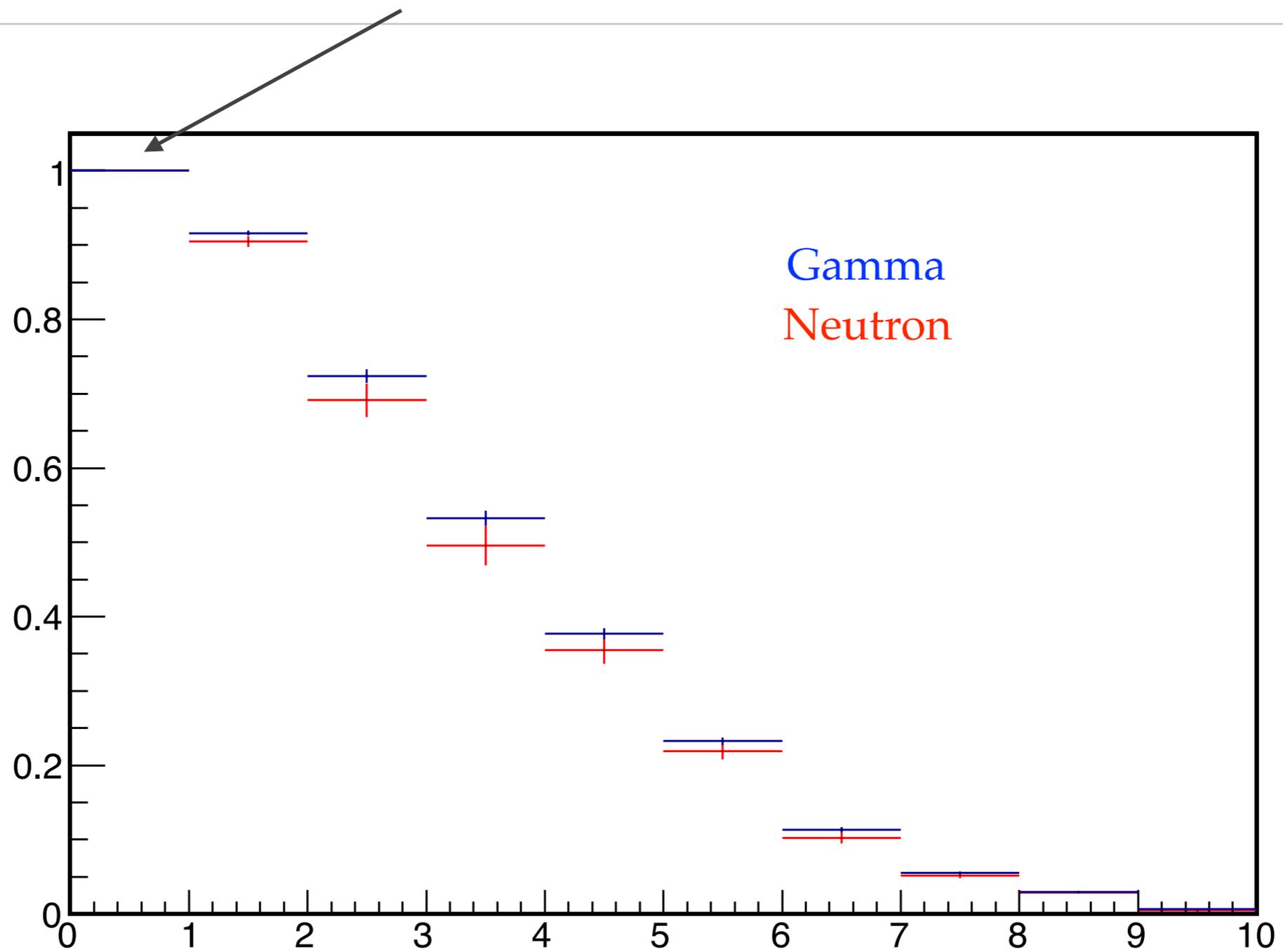


# Online COE Trigger

from all 2716 crystals disregarding the timing  
s between CsI channels were ignored  
COE online  $\neq$  COE offline



Normalized by the first bin



# Anomaly

Experimental result:

$$\frac{\epsilon'}{\epsilon} = (16.6 \pm 2.3) \times 10^{-4} \quad \mathbf{7\sigma \text{ above } 0}$$

from KTeV and NA48

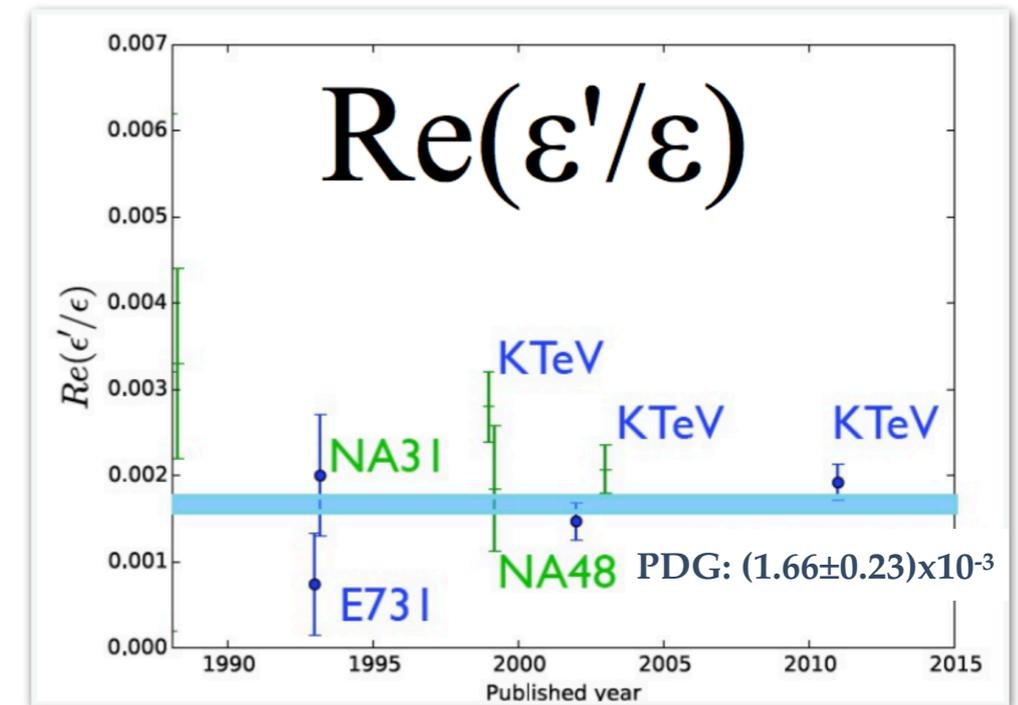
Theory (SM):

$$\frac{\epsilon'}{\epsilon} = (1.1 \pm 4.7_{lattice} \pm 1.9_{NNLO} \pm 0.6_{isosp. \text{ br.}} \pm 0.2_{mt}) \times 10^{-4}$$

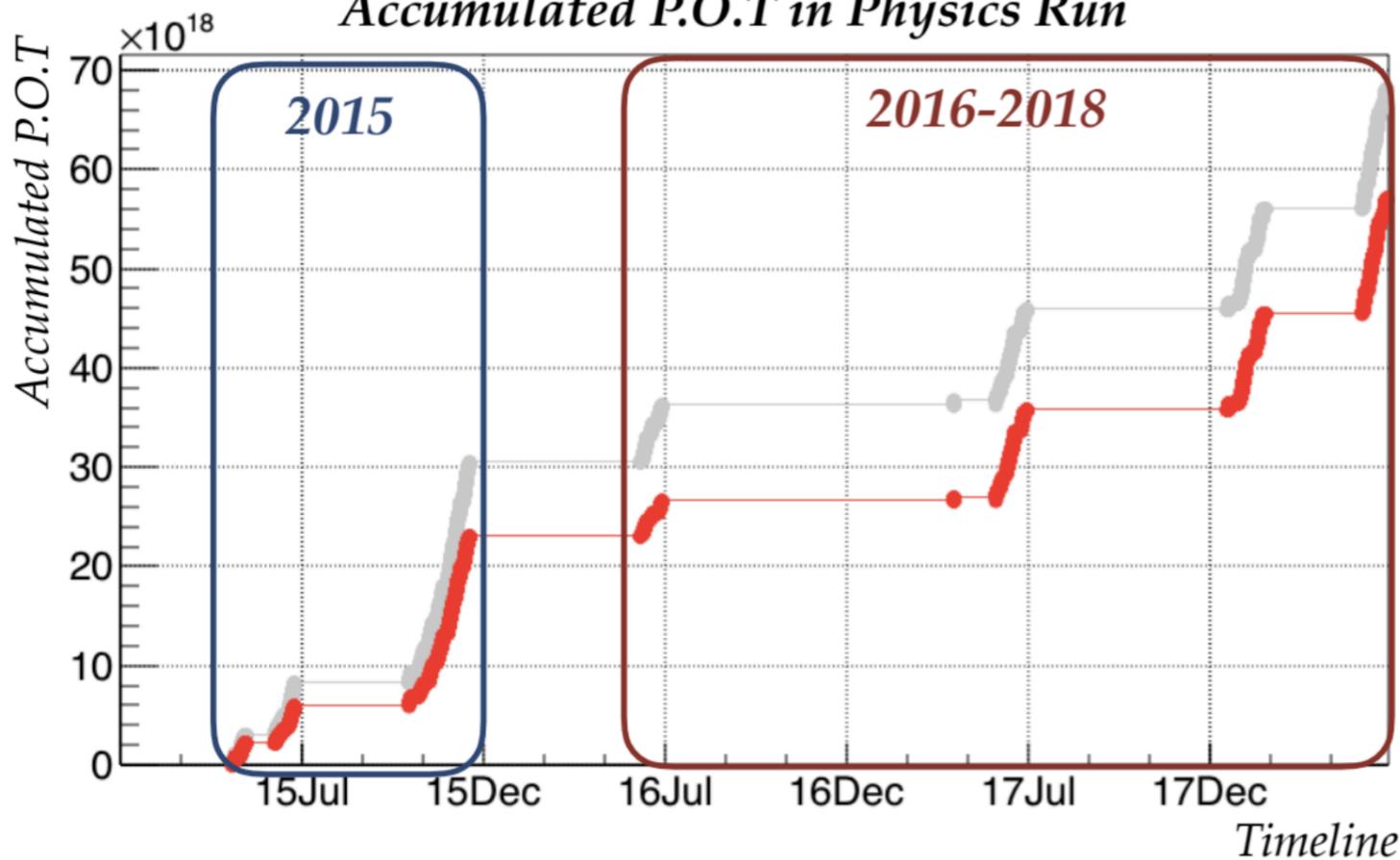
from Kitahara, *et al*, JHEP 1612 (2016) 078

$$\frac{\epsilon'}{\epsilon} = (1.9 \pm 4.5) \times 10^{-4} \quad \mathbf{A \text{ } 2.9\sigma \text{ deviation from the measurement!}}$$

from Buras, *et al*, JHEP 1511 (2015) 202



Accumulated P.O.T in Physics Run

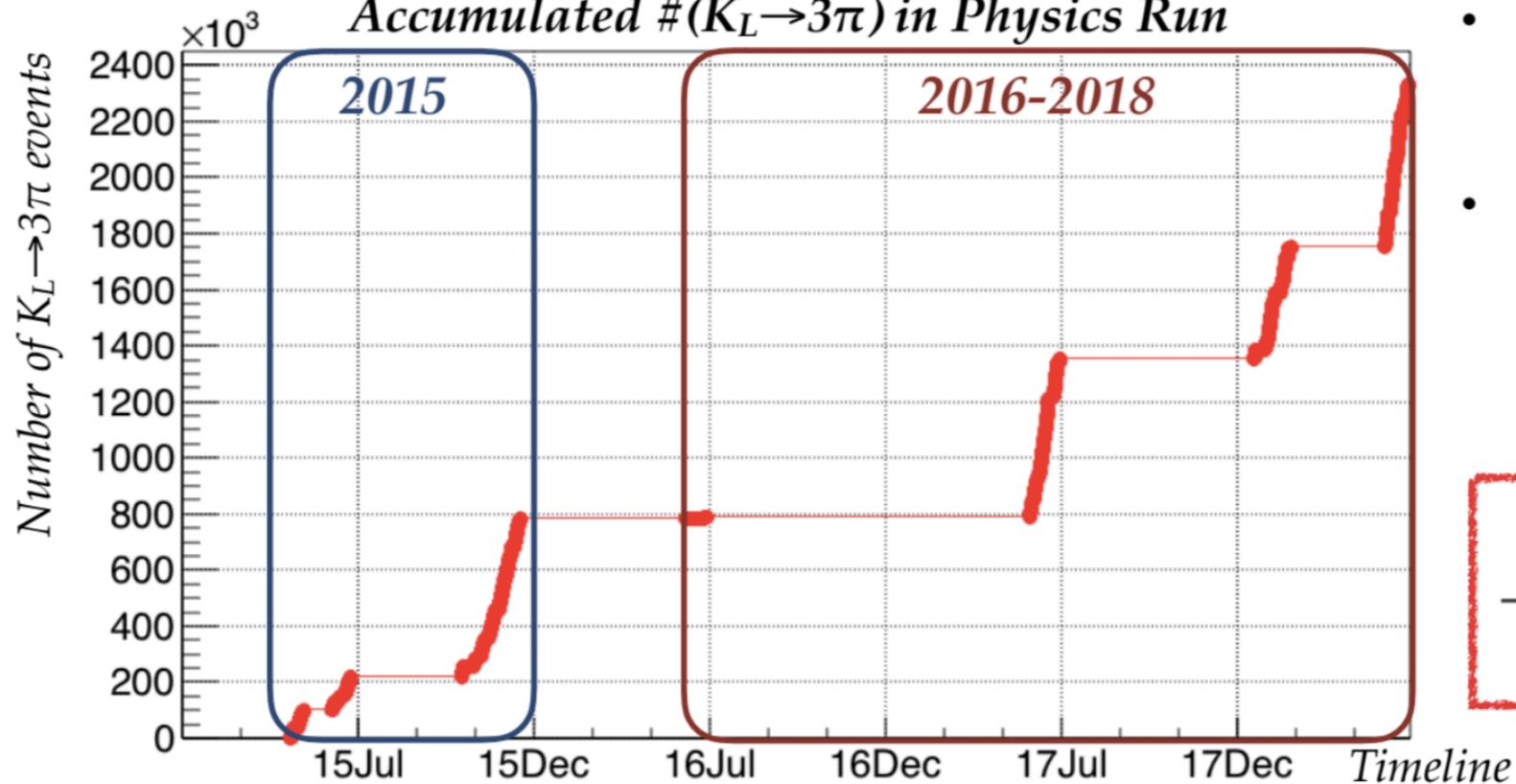


● → ●  
 + Spill quality selection  
 + Live time correction

$$\frac{\square + \square}{\square} = 2.24$$

$$\frac{\square + \square}{\square} = 2.48$$

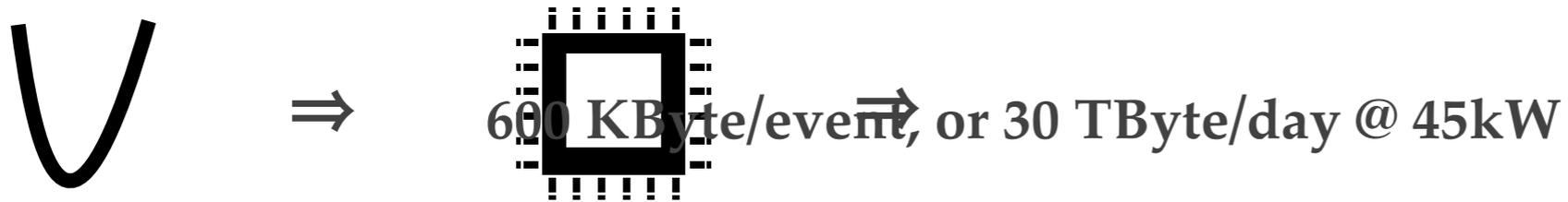
Accumulated #( $K_L \rightarrow 3\pi$ ) in Physics Run



- Norm. trigger (pre-scale = 30)
- + kin. cuts
- + vetoes
- + IB veto (after 2016)

$$\frac{\square + \square}{\square} = 2.98$$

# Lv0 Data Suppression

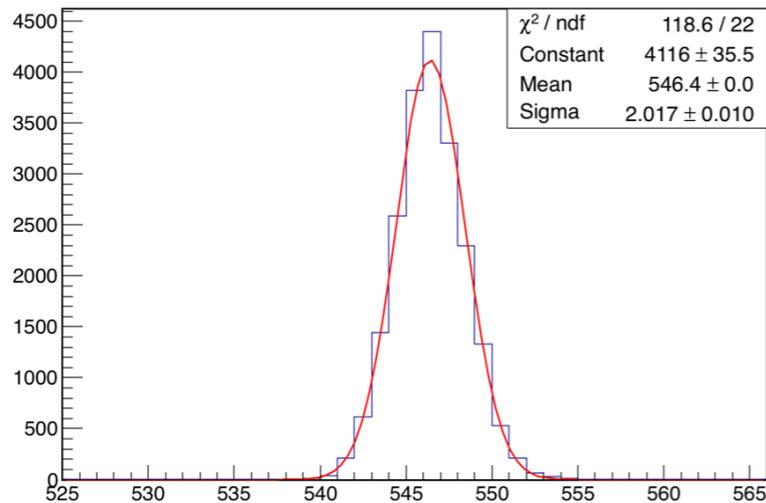


~4000 channels  
 95% 125MHz ADC  
 5% 500MHz ADC

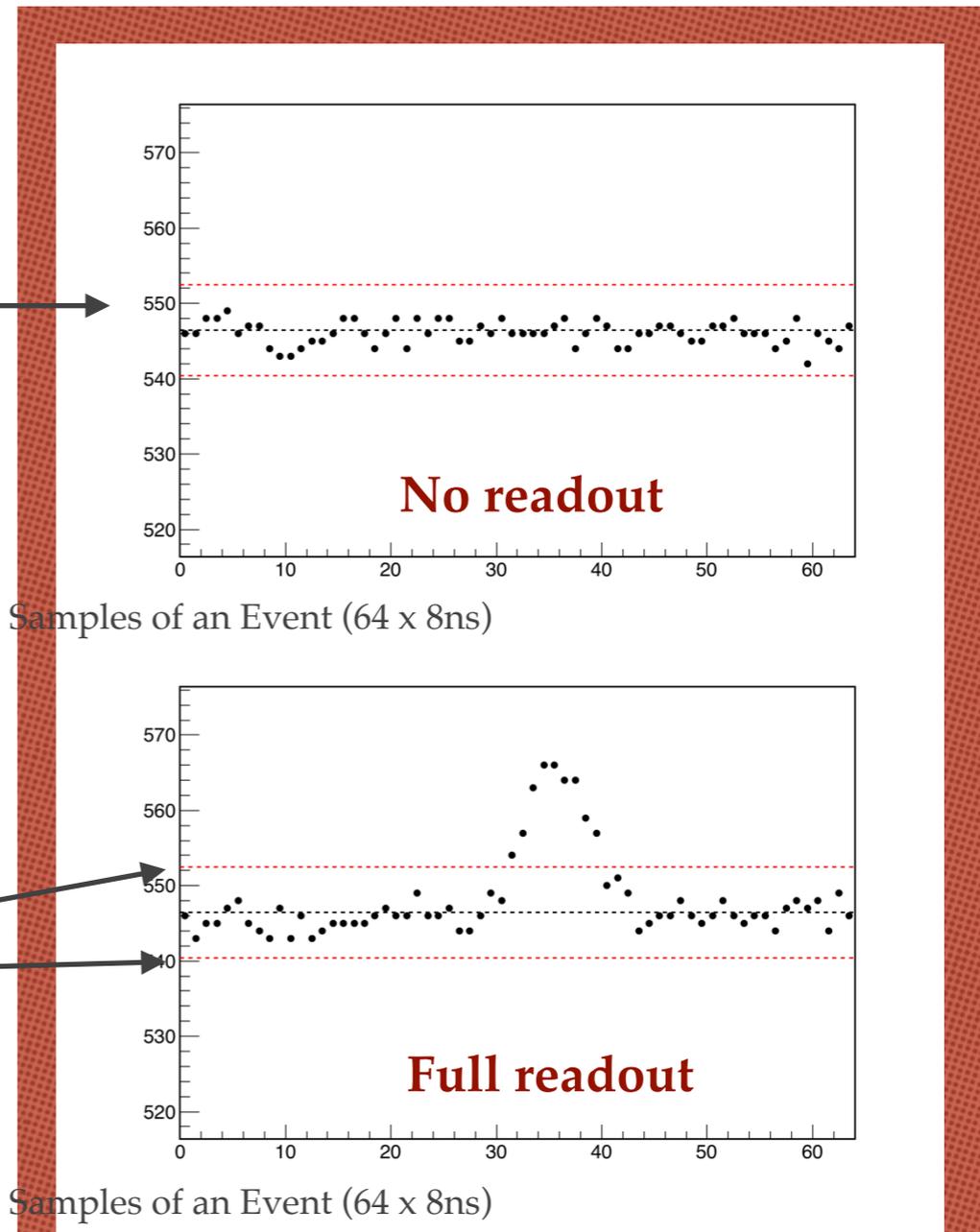
Readout of all samples within  $\mu \pm 3\sigma$

Data size  $\times 1/3$

Event throughput  $\times 3$

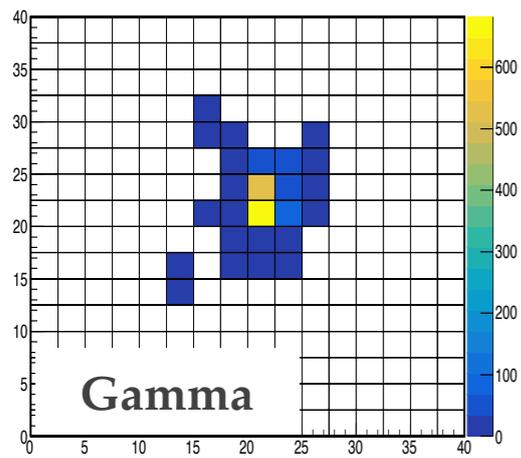
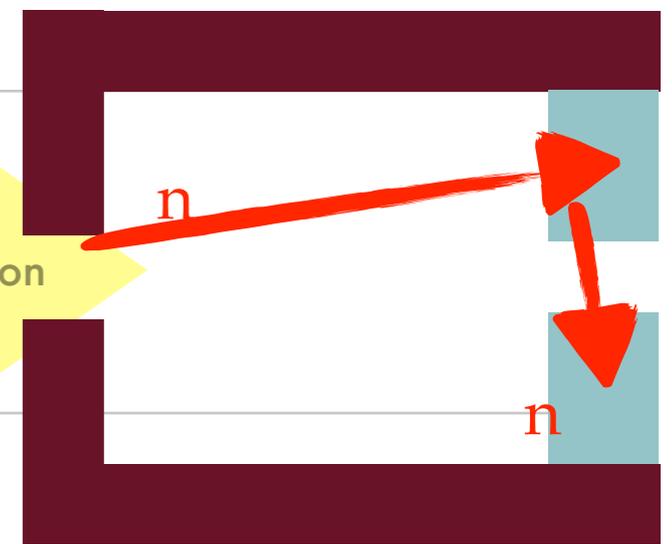


Crystal fluctuation  $\sigma \sim 2$  counts

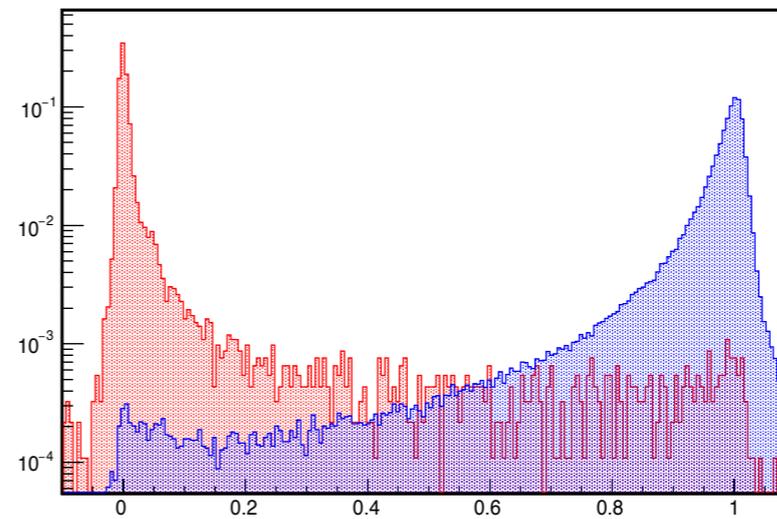
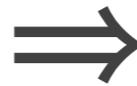
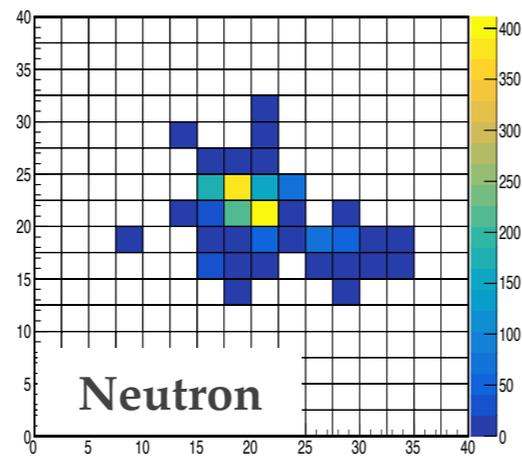


# Hadron Cluster

Halo Neutron

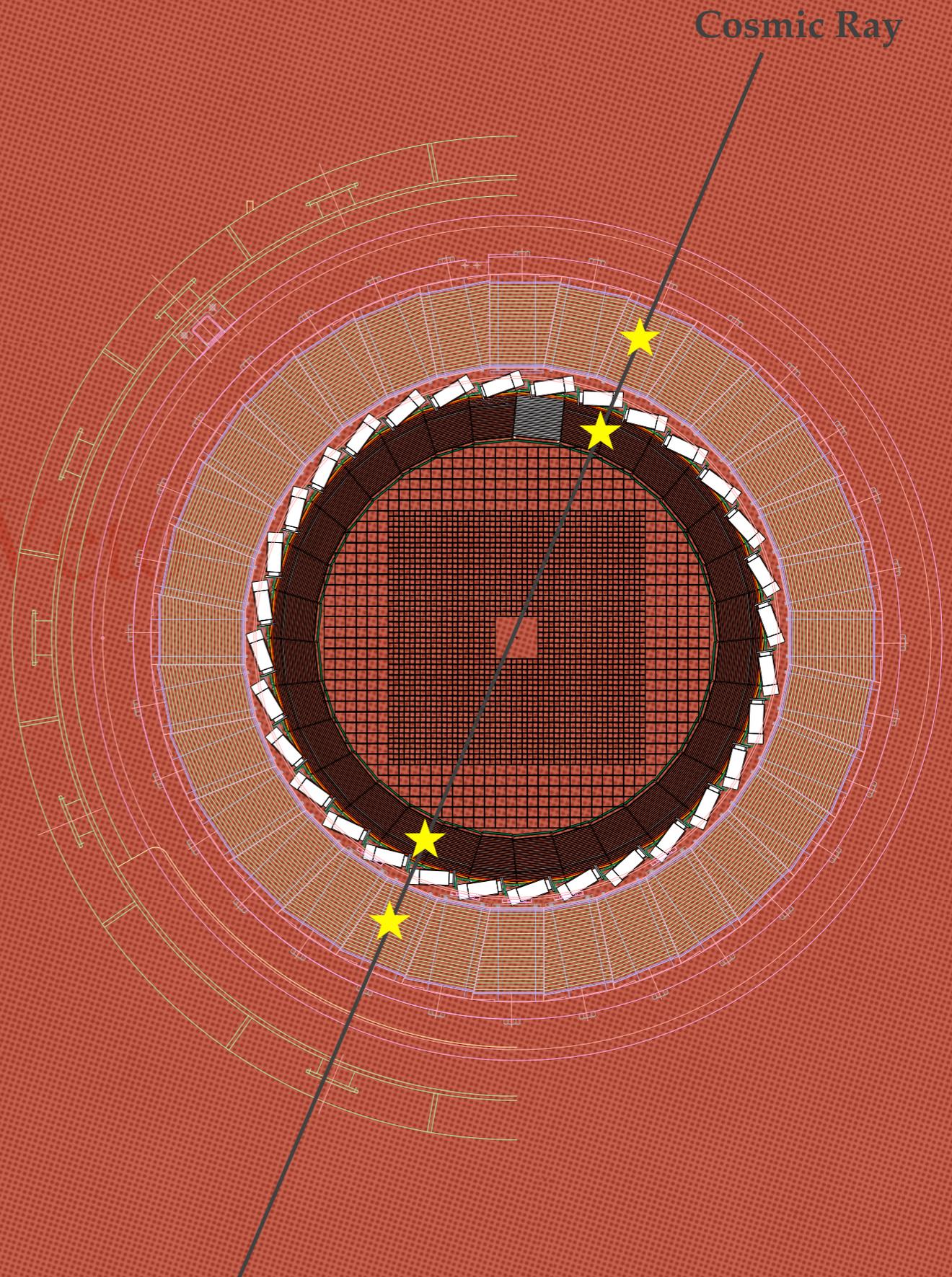


vs.

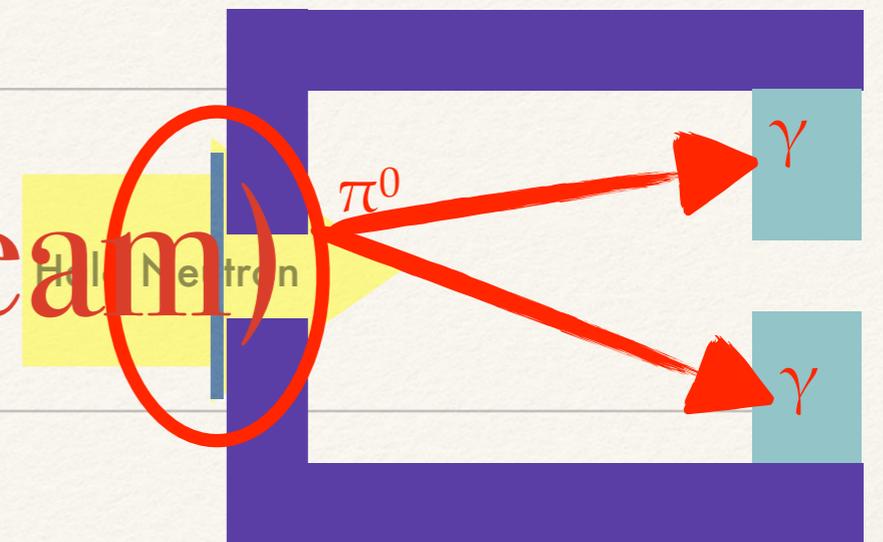


**Combined Rejection Power:  $2.2 \times 10^{-5}$**

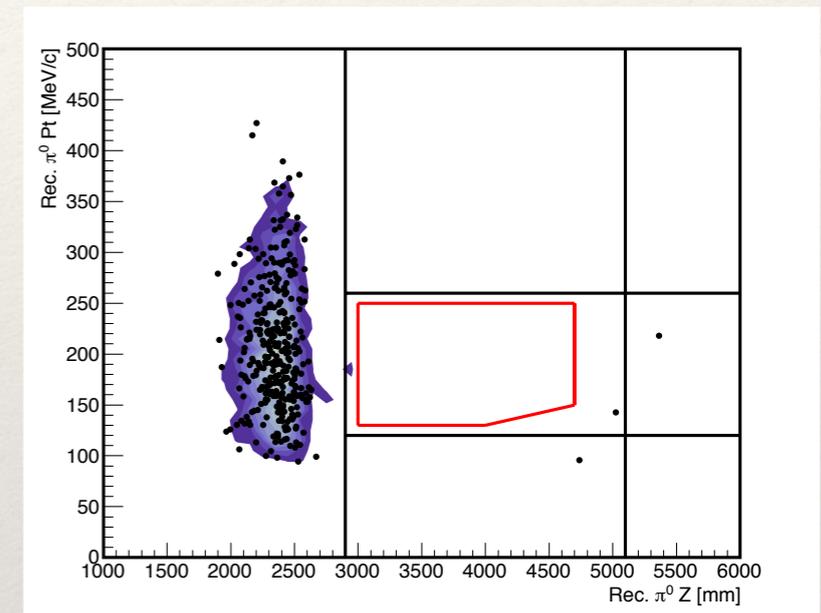
- Veto/Trigger based on  $E_{CH}$
- A factor of 4 trigger reduction. **LV1**
- Flexible trigger logic:
  - e.g. 2 hits in upper barrel channels & 2 hit in lower barrel channels.
  - pickup cosmic ray in physics run.



# Neutron (Upstream)



background mechanism  
%:  $\Upsilon + \Upsilon$  (less E in CsI)  
/6 (cut upstream 20 cm)  
50%:  $\Upsilon + n$   
3 (CsI front-end readout)



# Models and Correlations

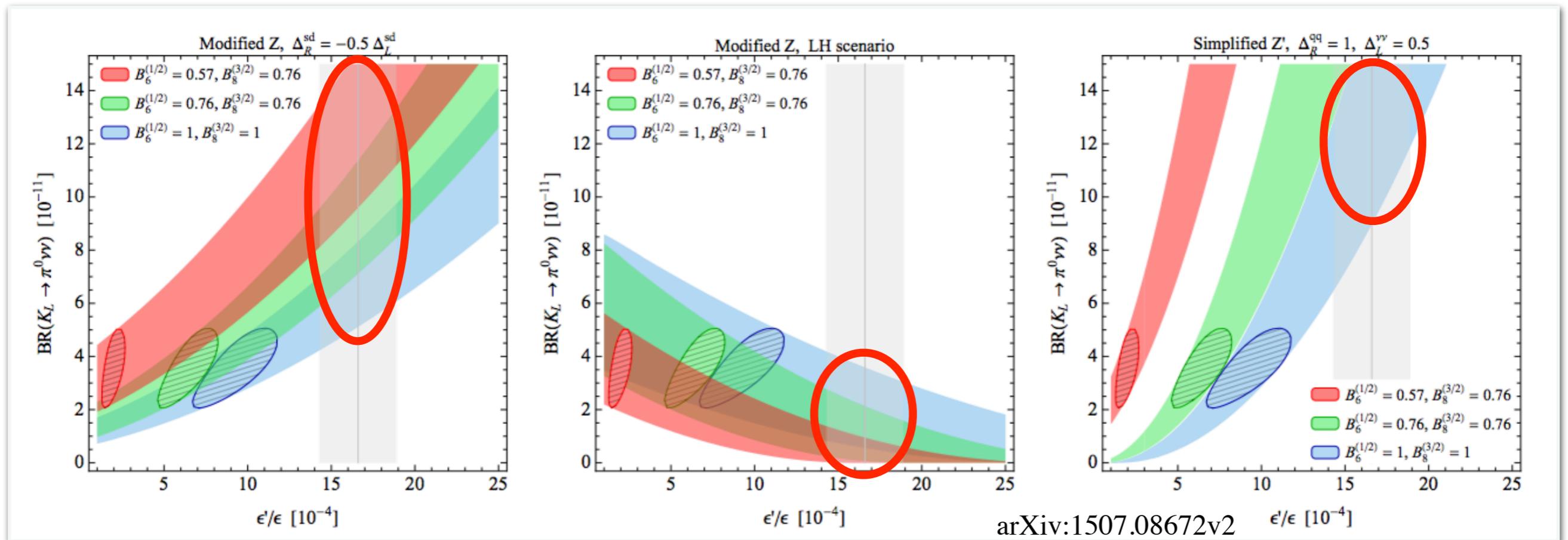
Rare  $K_L \rightarrow \pi^0 \nu \nu$ ,  $\text{BR}_{\text{SM}} = 3 \times 10^{-11}$

CPV process.

theoretically clean, 2% uncertainty.

“gold mode” for probing deviation from SM.

enhancement or suppression from new physics?



# DAQ Electronics

UChicago custom-made ADC/Trigger modules

- A. 14-bit 16-CH 125MHz ADC
- B. 12-bit 4-CH 500MHz ADC
- C. Clock Distribution and Trigger Processor (CDT)
- D. Optical Fiber Center (OFC)

