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

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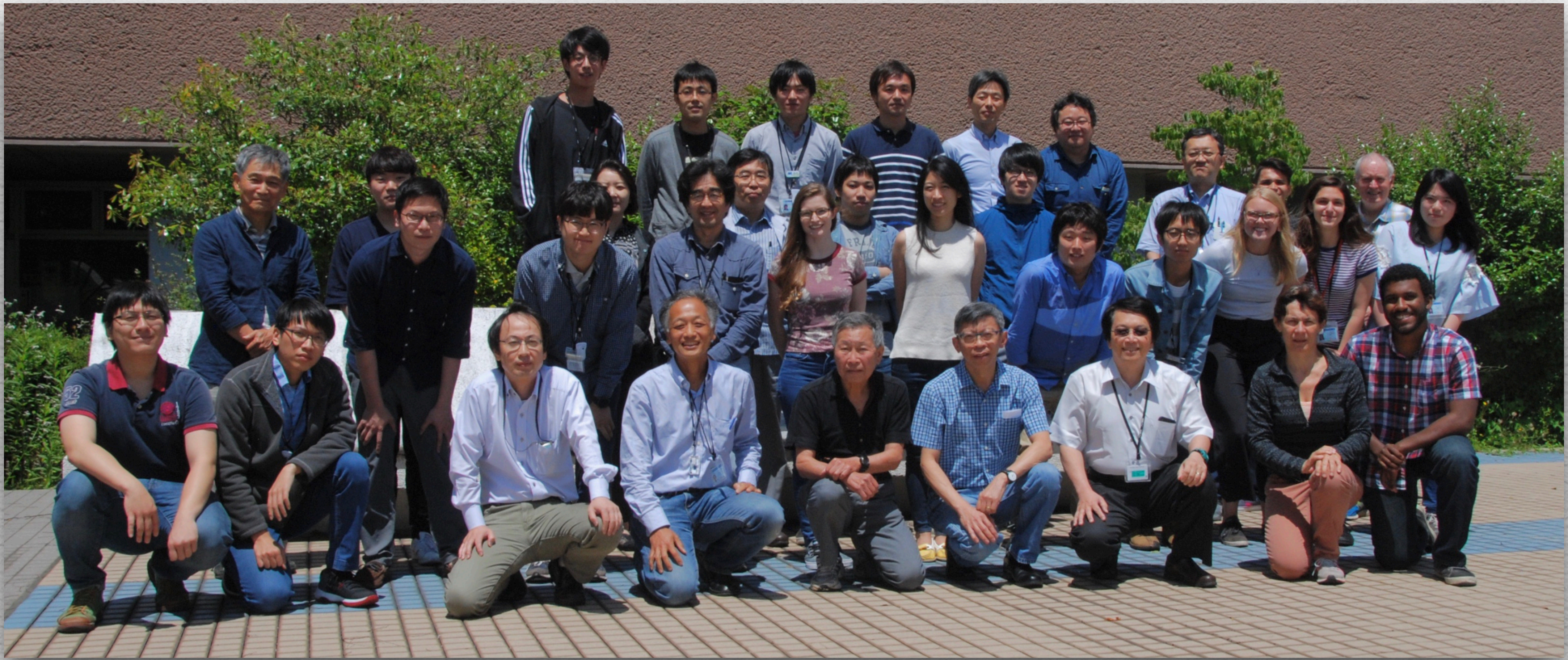
Outline

- Introduction of KOTO
- Results of 2015 Data
- Improvements after 2015
    - Detector, DAQ, Analysis
- Current Status and Future

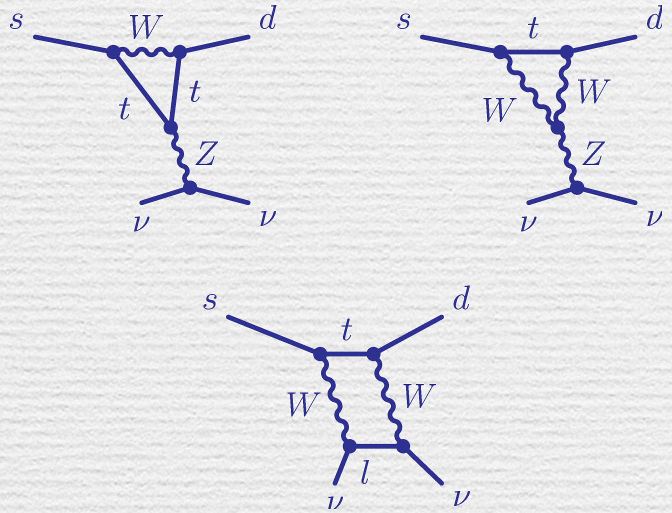
KOTO Experiment

- Dedicated Experiment for $K_L \rightarrow \pi^0 \nu\nu$ @J-PARC, Japan
  - proposed in 2006, approved in 2009, first physics run in 2013
- ~50 people from 16 Institutes in US, Japan, Korea & Taiwan



The Golden Mode: $K_L \rightarrow \pi^0 \nu\nu$

- Direct CP violating process
    - sensitive to New Physics related to CPV
- FCNC process purely dominated by



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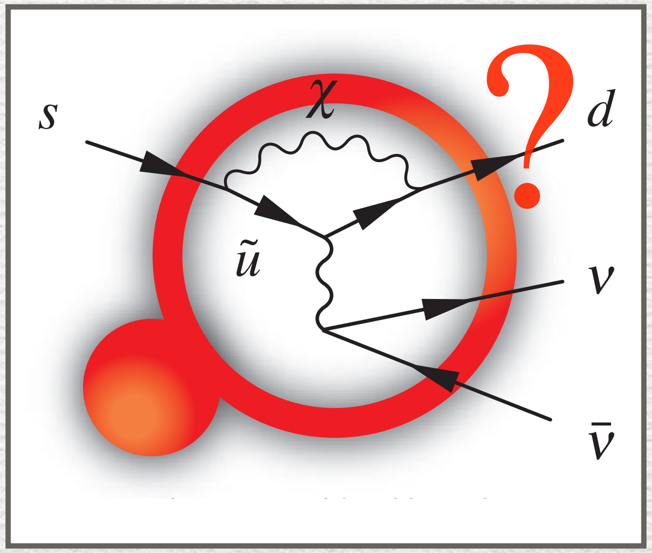


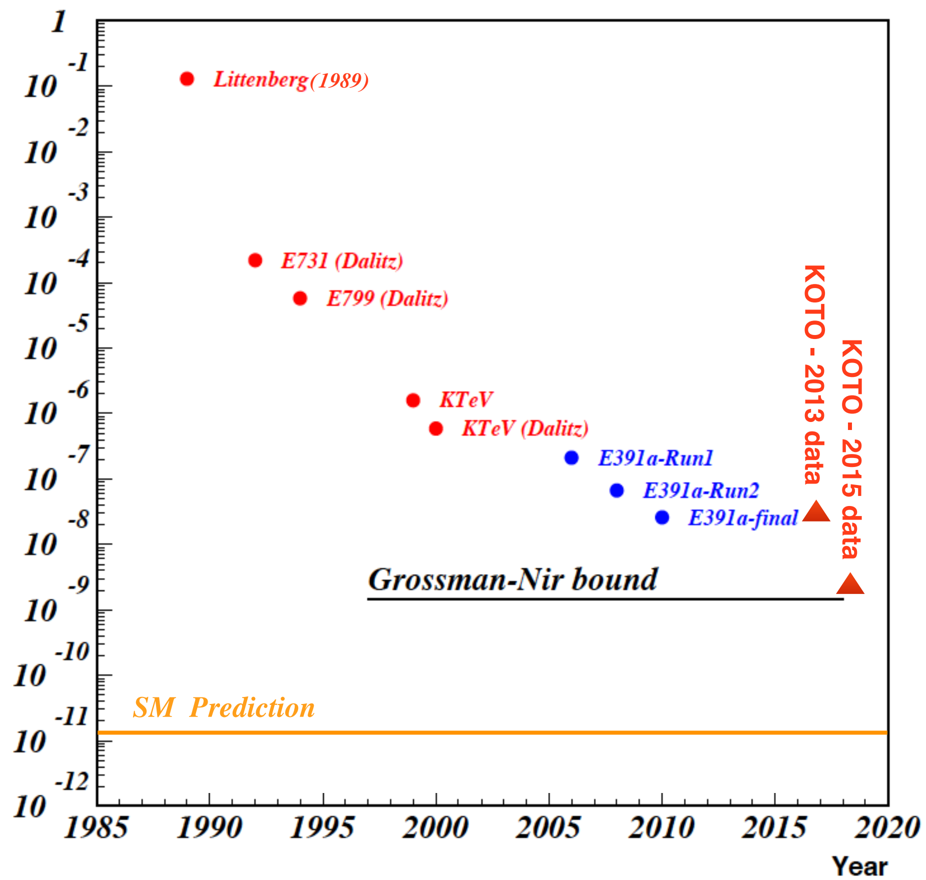
- Rare and clean: BR(SM) = 3×10^{-11} with < 2% uncertainty
    - sensitive to New Physics contributions

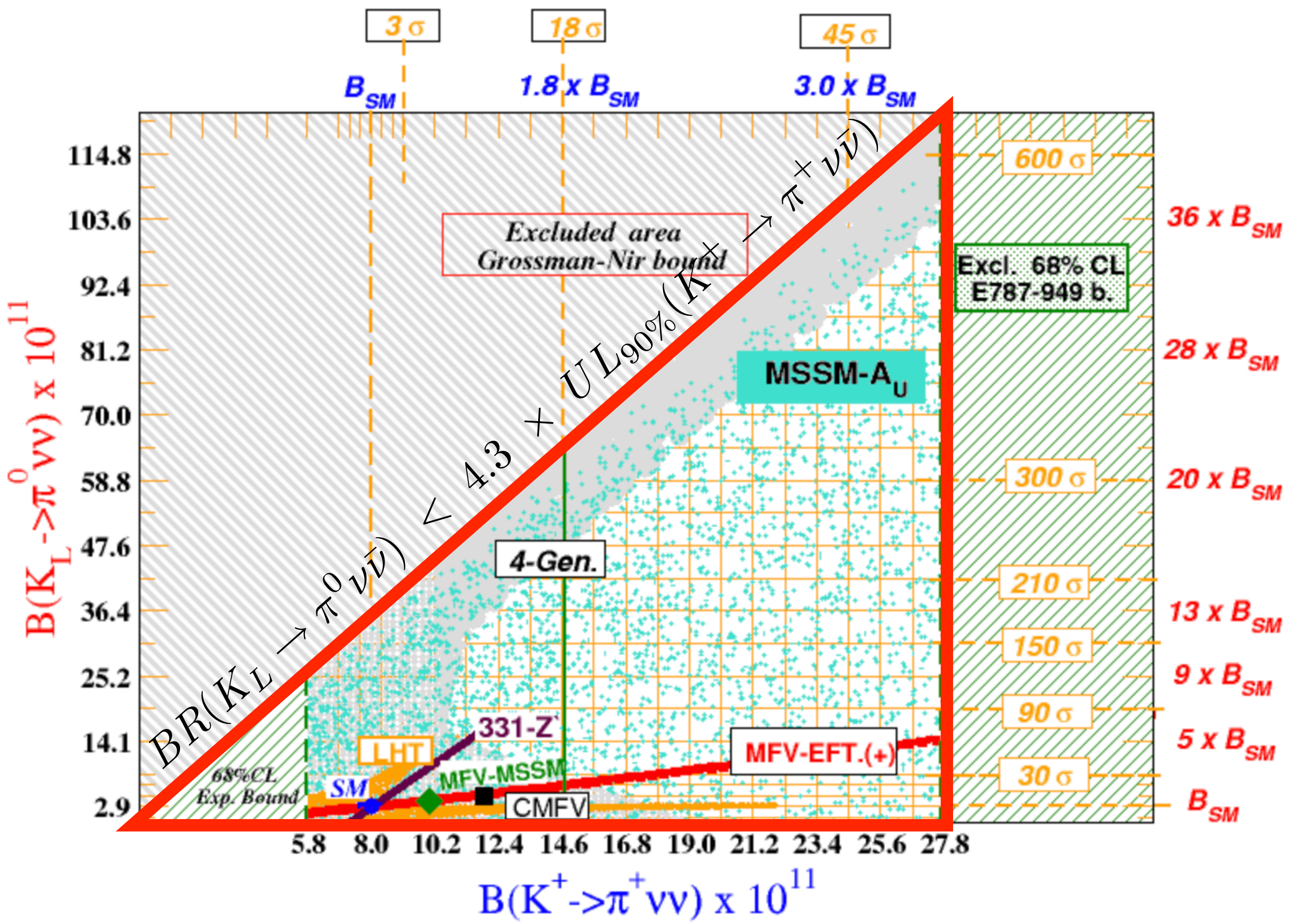
http://www.lnf.infn.it/wg/vus/content/Krare.html

Past and Future

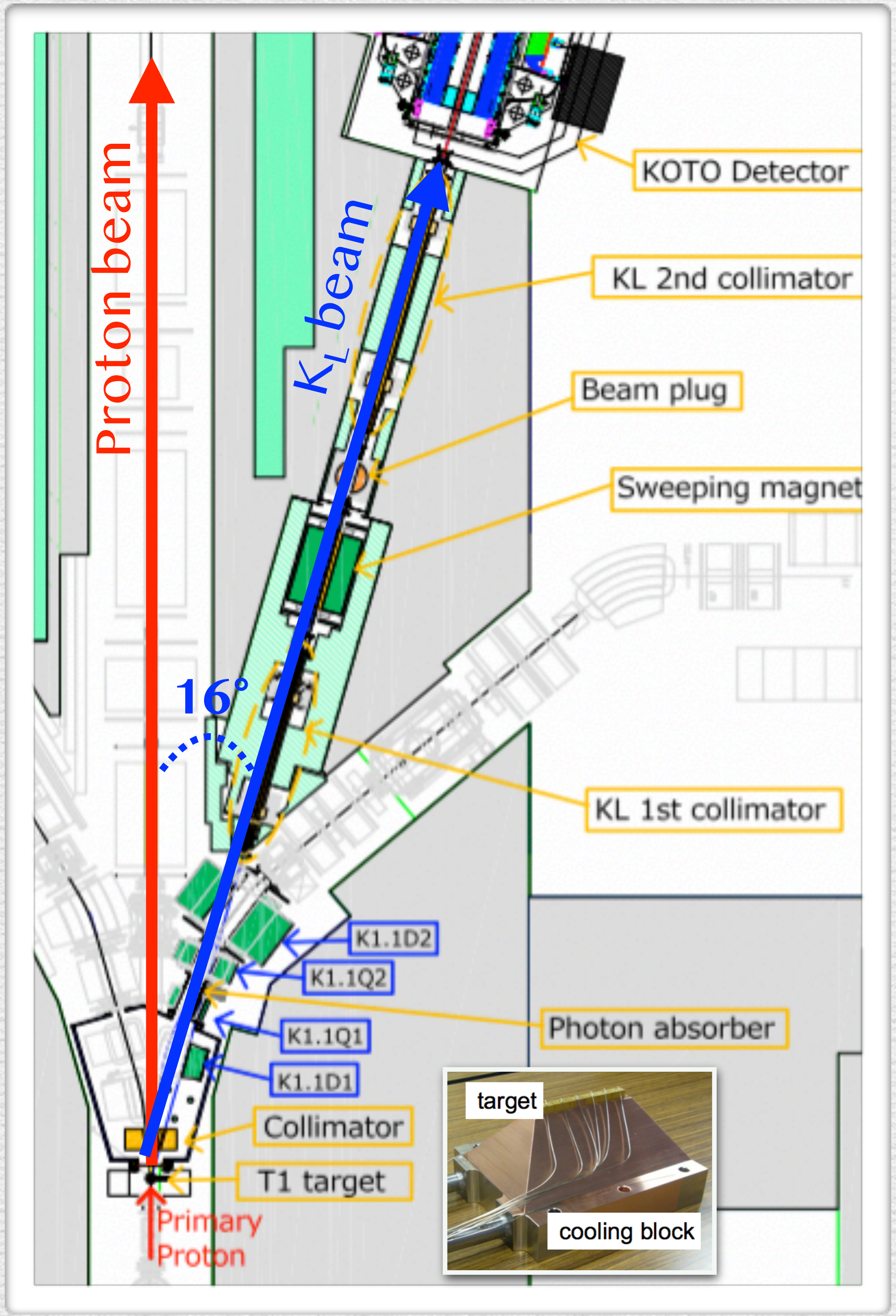
KOTO Two-Stage Approach to Discover $K_L \rightarrow \pi^0 \nu\nu$

- Stage-I: reach sensitivity of $O(10^{-11})$
- Stage-II: precise measurement with sensitivity of $O(10^{-13})$

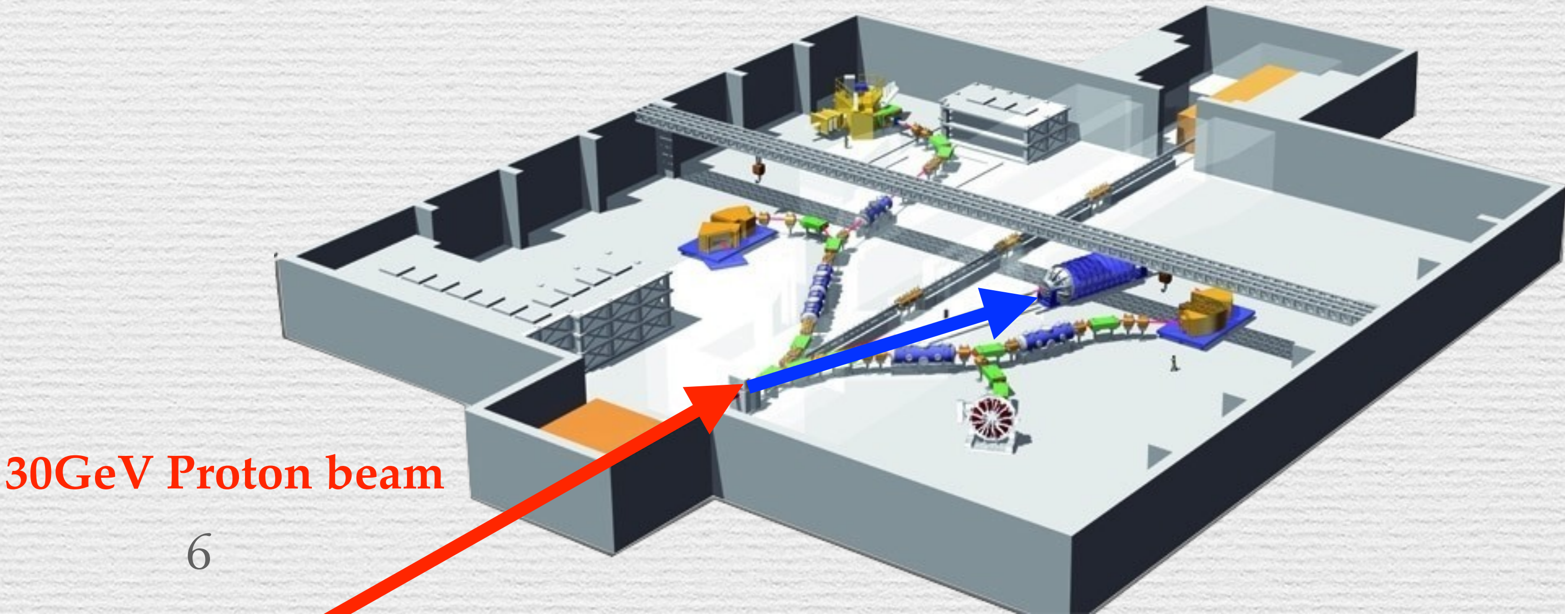




Kaon @ J-PARC



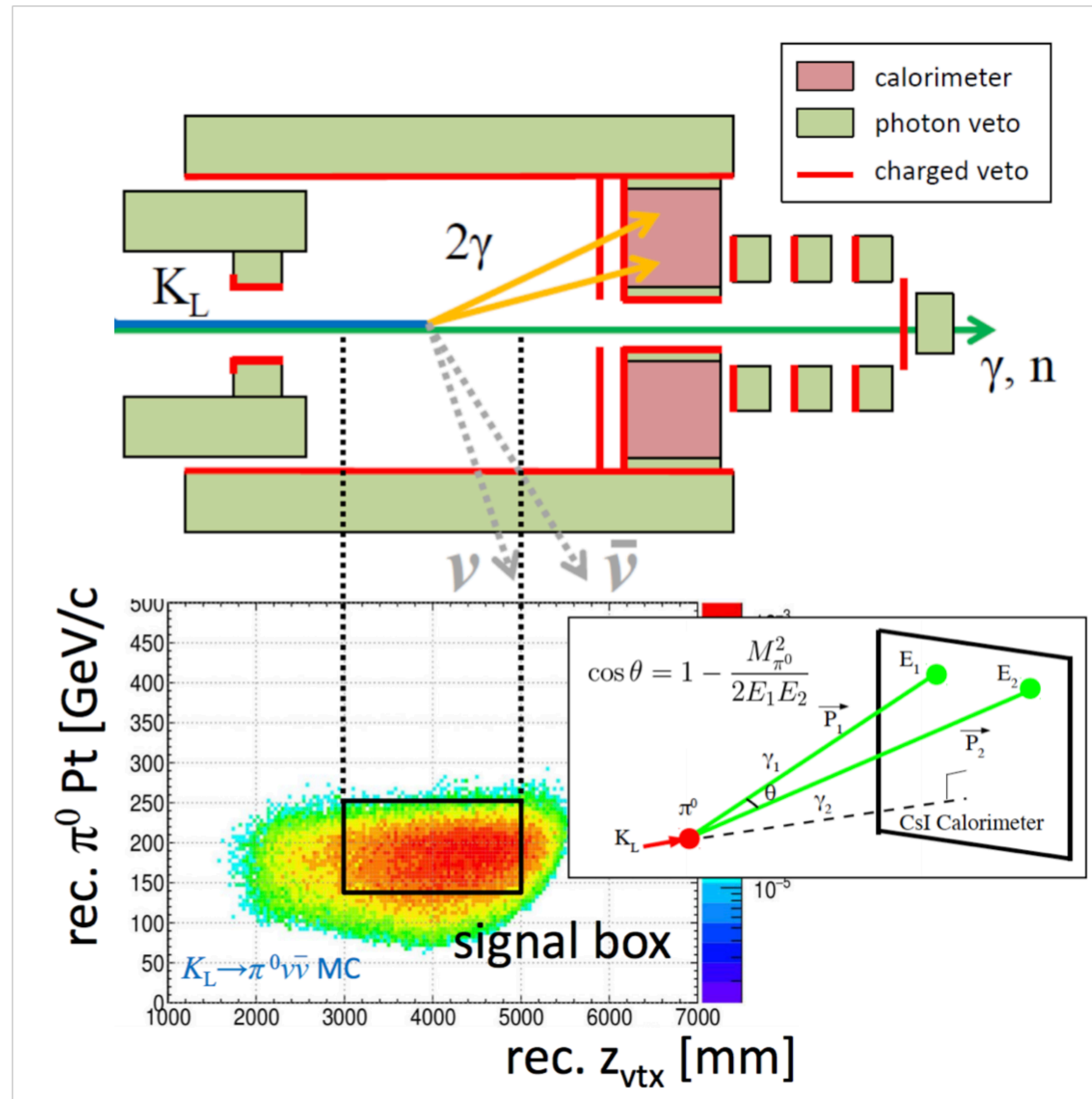
- Proton
  - come in a bundle of 2sec spill
  - ~5×10^{13} protons on target @ 50kW B.P.
- Detector located at 21m from target
- Beam size ~ 8×8 cm^2 @ detector
- Kaon
  - kaon yield: ~10^8 per spill @ 50kW B.P.
  - momentum peaked @ 1.4 GeV



Signal Detection

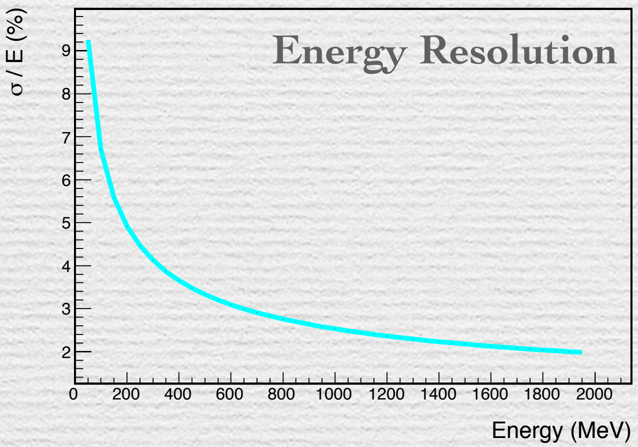
- $K_L \to \pi^0 \nu \nu$ Invisible
  - 2γ with high P_T = signal
- Hermetic Detector
  - no signal in veto detectors

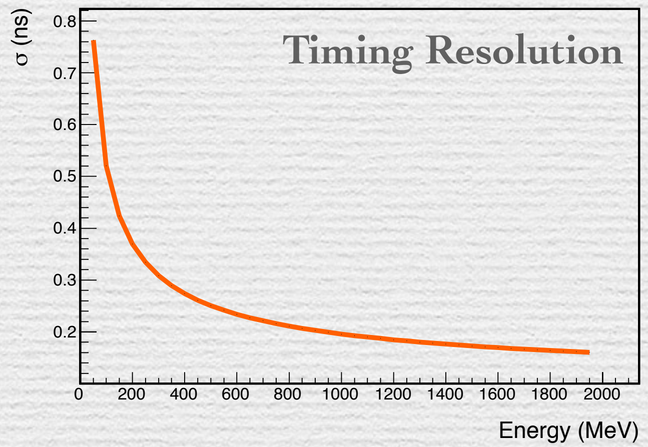
Mode	BR	Handles
$K_L \to \pi^{\pm} e^{\mp} \nu$	40.6%	charged (x2), non-EM (x1)
$K_L \to \pi^{\pm} \mu^{\mp} \nu$	27.0%	charged (x2), non-EM (x1)
$K_L \to \pi^{+} \pi^{-} \pi^{0}$	12.5%	charged (x2), low π^0 Pt
$K_L \to \pi^{0} \pi^{0} \pi^{0}$	19.5%	extra photon (x4)
$K_L \to \gamma\gamma$	5.5×10^{-4}	low Pt, back-to-back symmetry
$K_L \to \pi^{+} \pi^{-}$	2.0×10^{-3}	charged (x2), non-EM (x2)
$K_L \to \pi^{0} \pi^{0}$	8.6×10^{-4}	extra photon (x2)

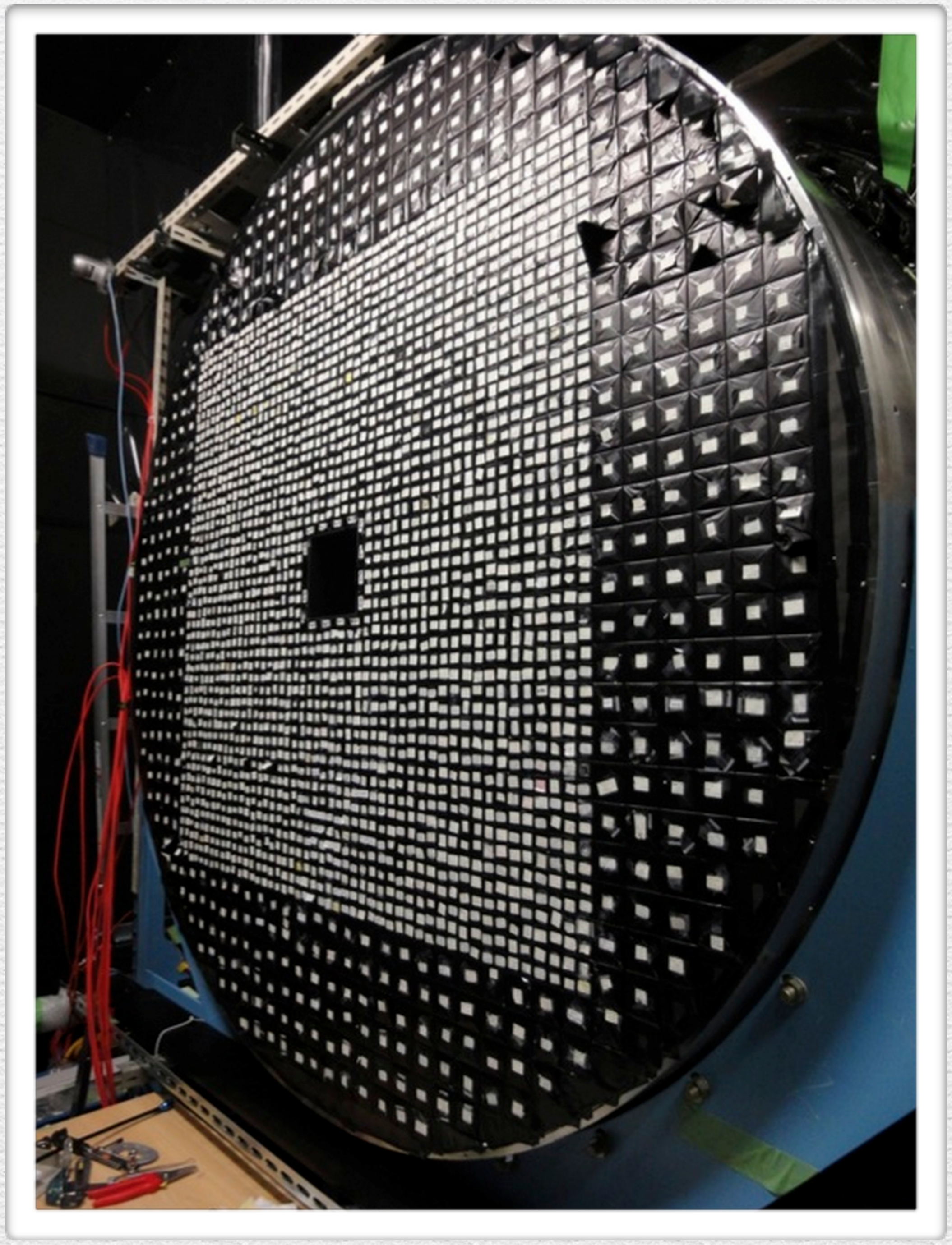


Detector - Photon Calorimeter

- KTeV CsI crystals:
  - small: 2.5×2.5×50 cm
  - large: 5.0×5.0×50 cm
  - full scale:
    - 200 cm in diameter
    - 15×15 cm² beam hole
- Resolution:
  - σ_E=3%, σ_T=0.25ns for 500MeV signal



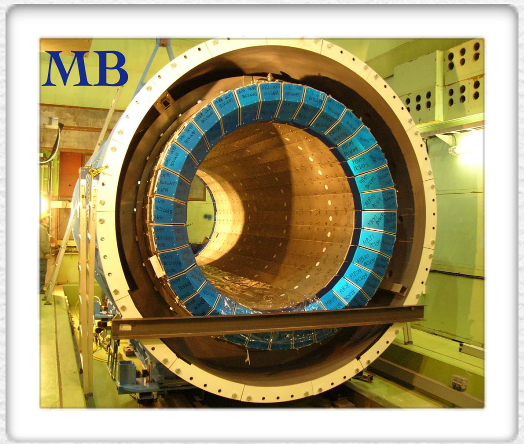


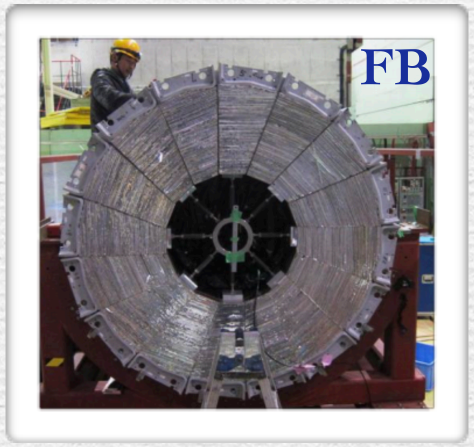


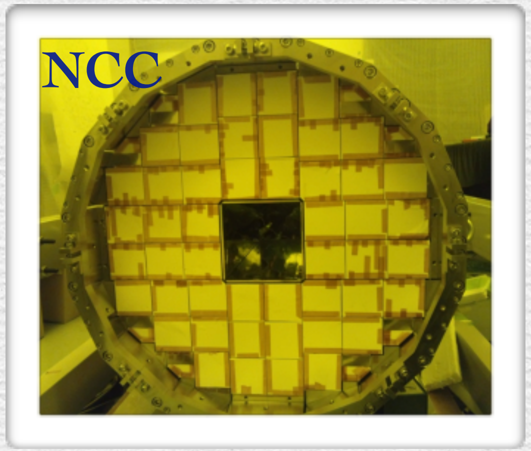
Detector - Photon Veto

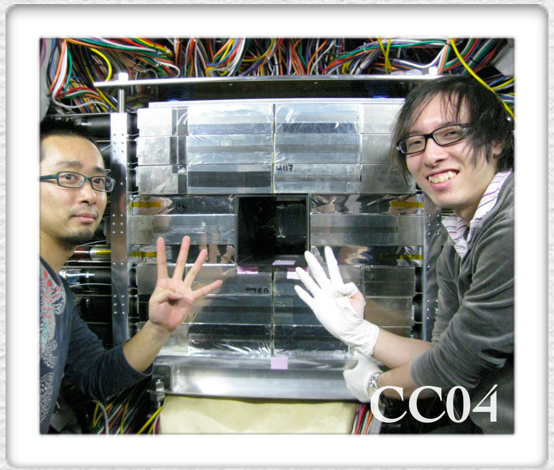
Photon Veto Detectors:

- Barrel Region (MB, FB):
  - Scintillator/lead sandwich
- Along Beam (NCC, CC0X):
  - CsI crystals + Scintillator
- In Beam (BHPV):
  - Aerogel Cherenkov detector
  - Lightest solid material on earth



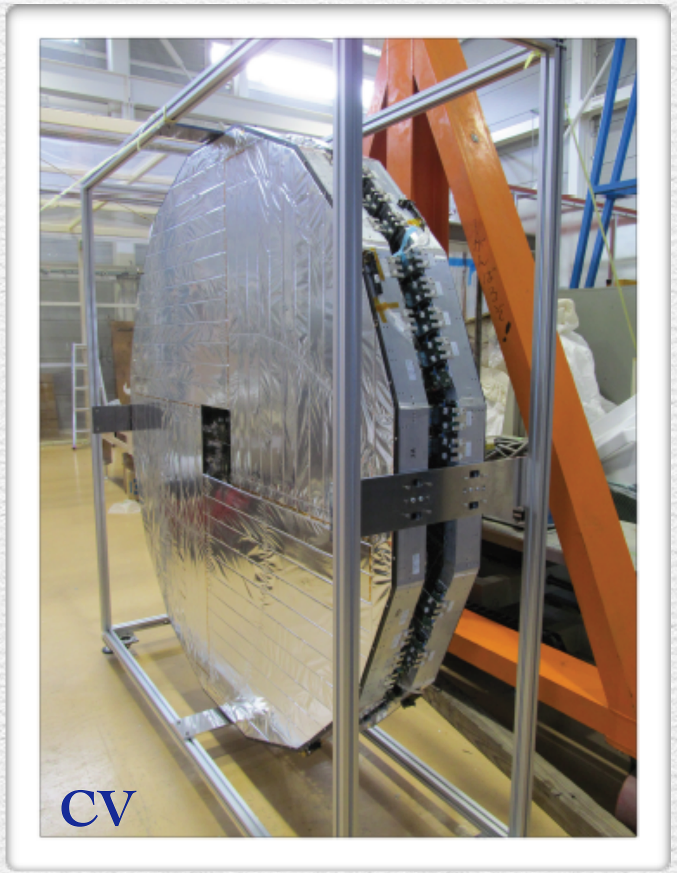


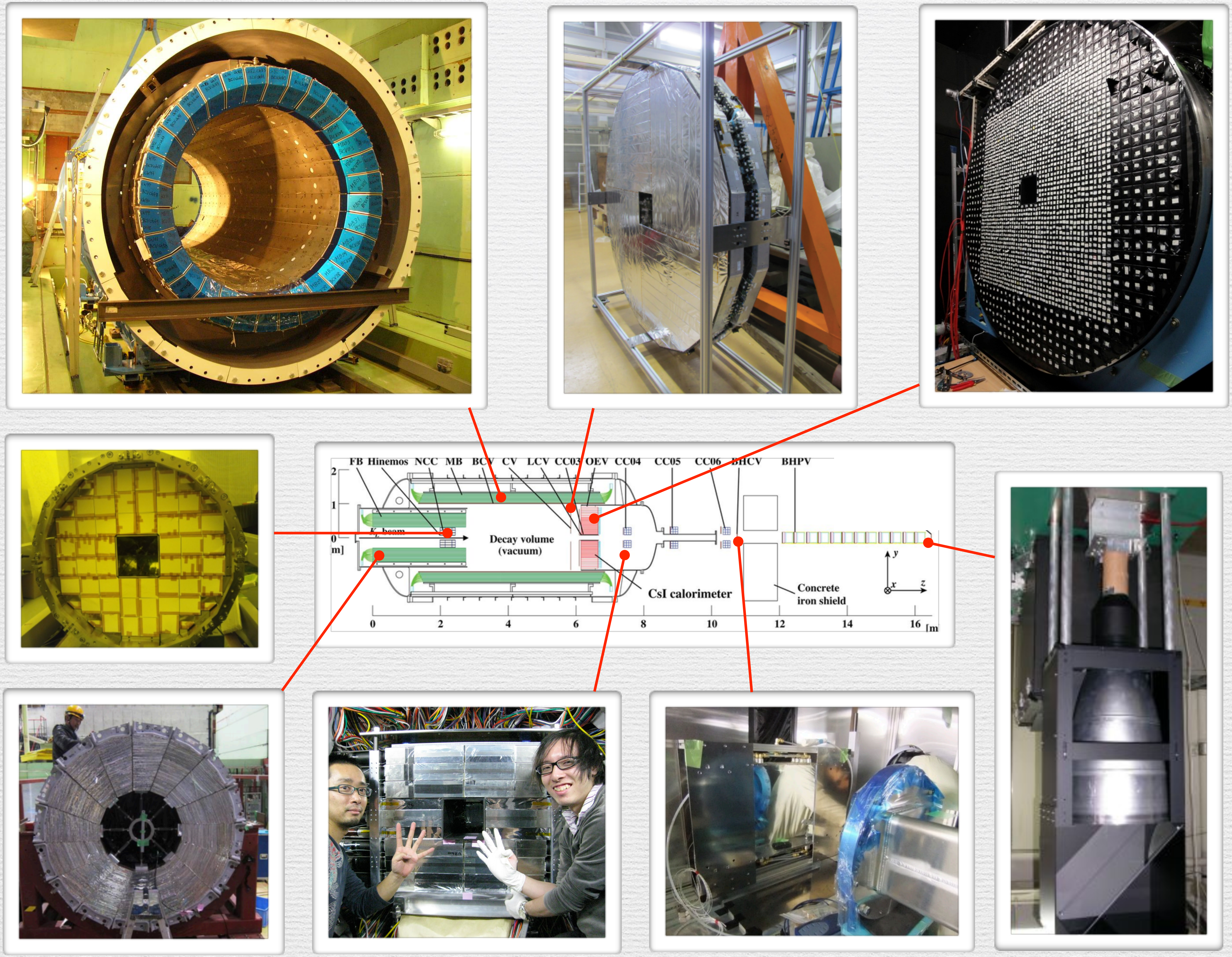




Detector - Charged Veto

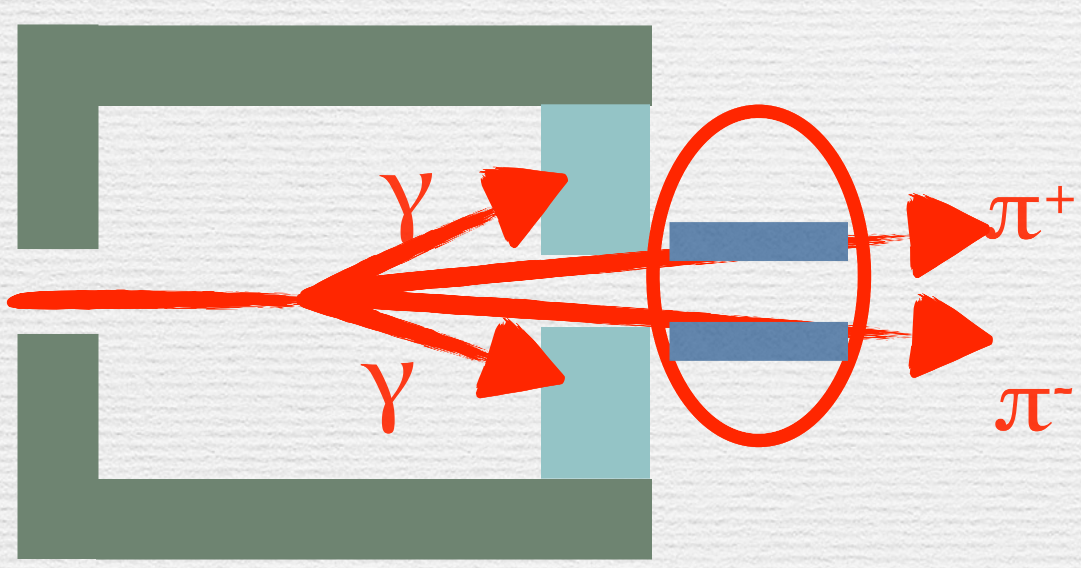
- CV in front of CsI grid (CV)
  - 2 layers of plastic scintillator
  - detection inefficiency ~$O(10^{-10})$
- CV in beam (BHCV)
  - gas chamber (CF_4 + n-Pentane)
  - detection inefficiency < $O(10^{-3})$
- And, CV everywhere else

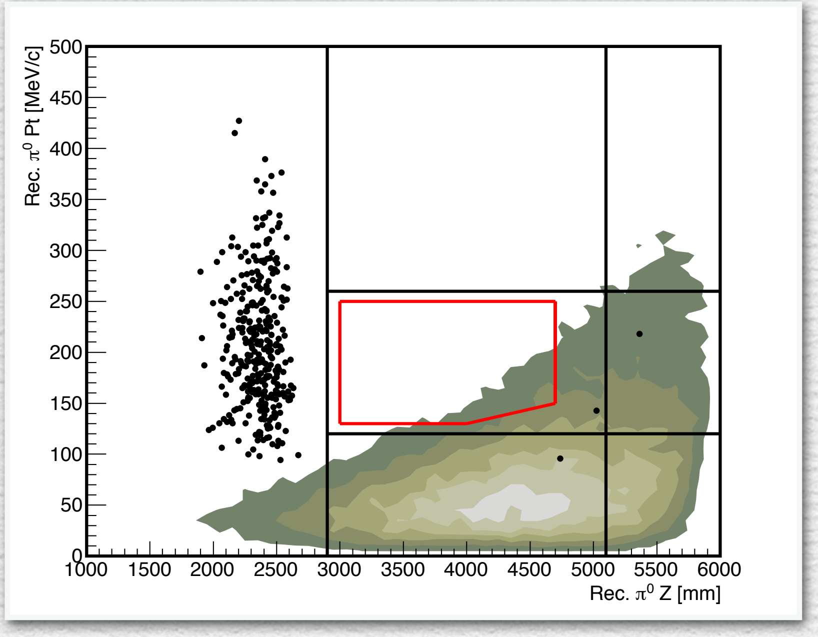



FB Hinemos NCC MB BCV CV LCV CC03 OEV CC04 CC05 CC06 BHCV BHPV
2
1
0
[m]
K_L beam
Decay volume
(vacuum)
CsI calorimeter
Concrete
iron shield
y
x
z
0 2 4 6 8 10 12 14 16 [m]

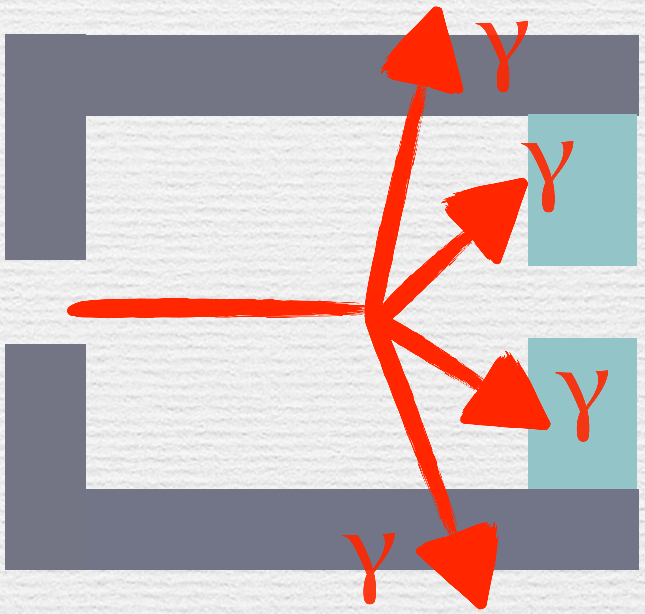
Background - Kaon

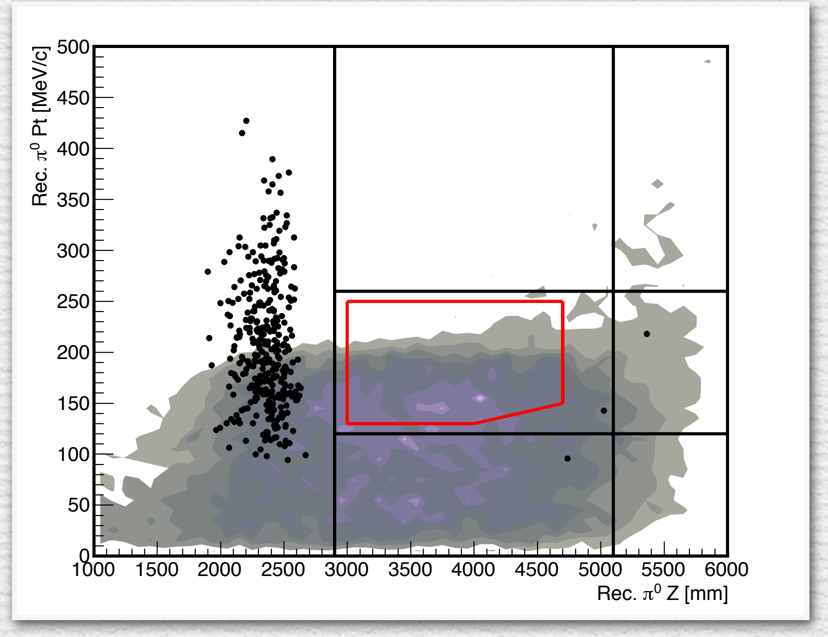
$K_L \rightarrow \pi^+\pi^-\pi^0$





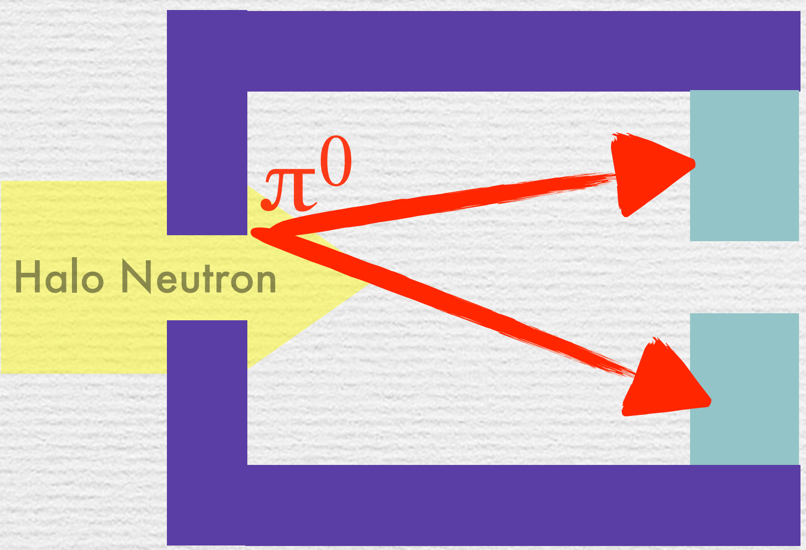
$K_L \rightarrow \pi^0\pi^0$

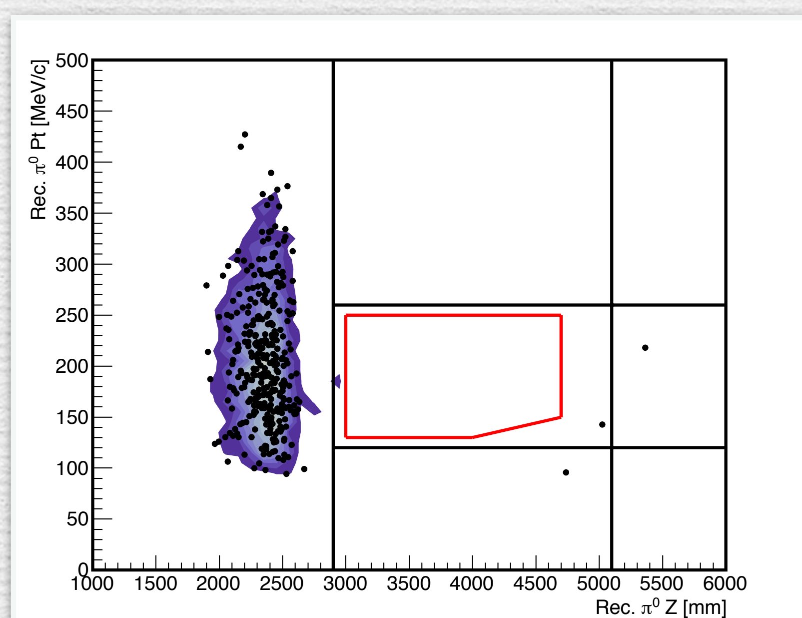




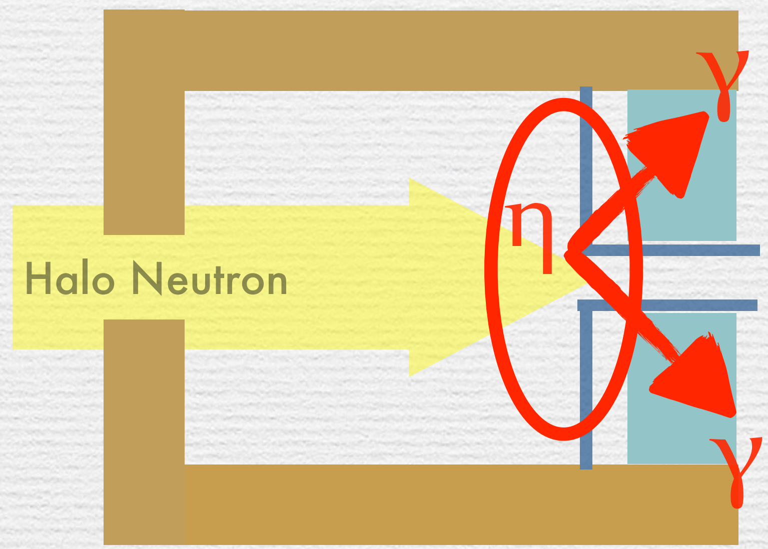
Background - Neutron

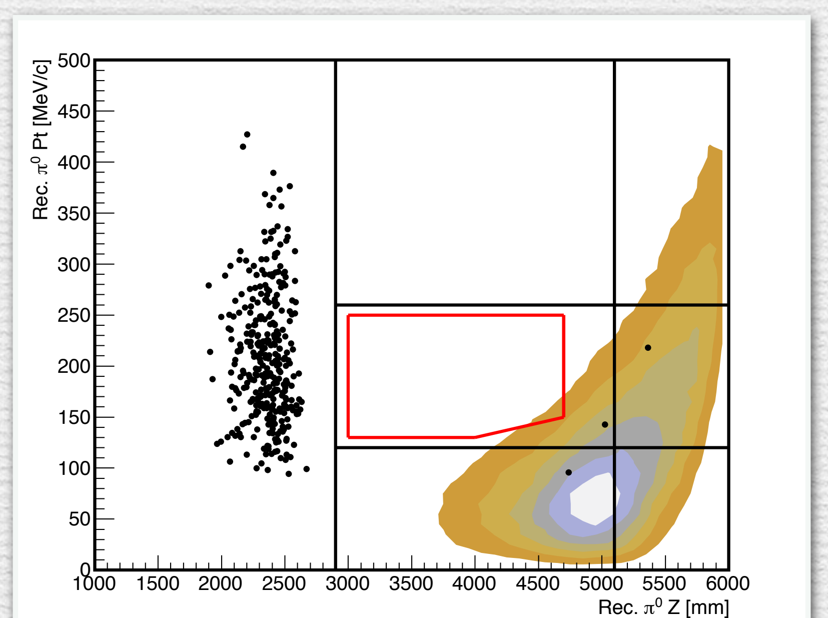
Upstream-π^0



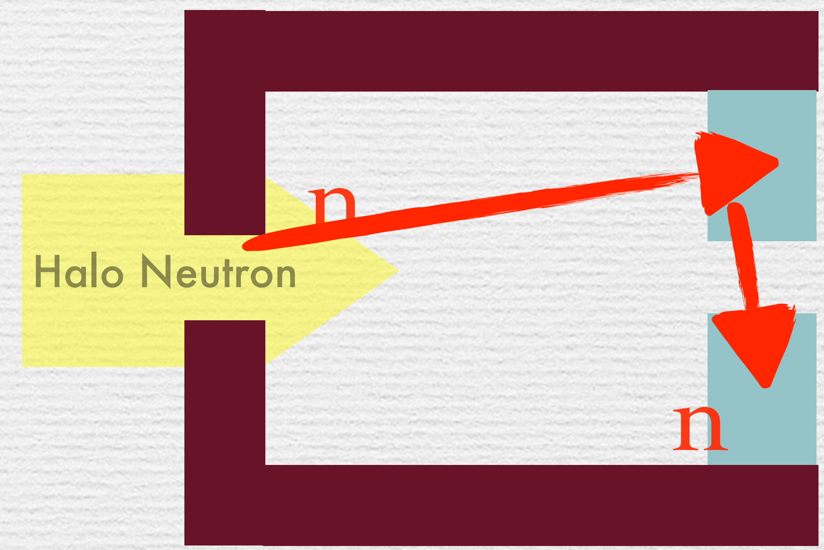


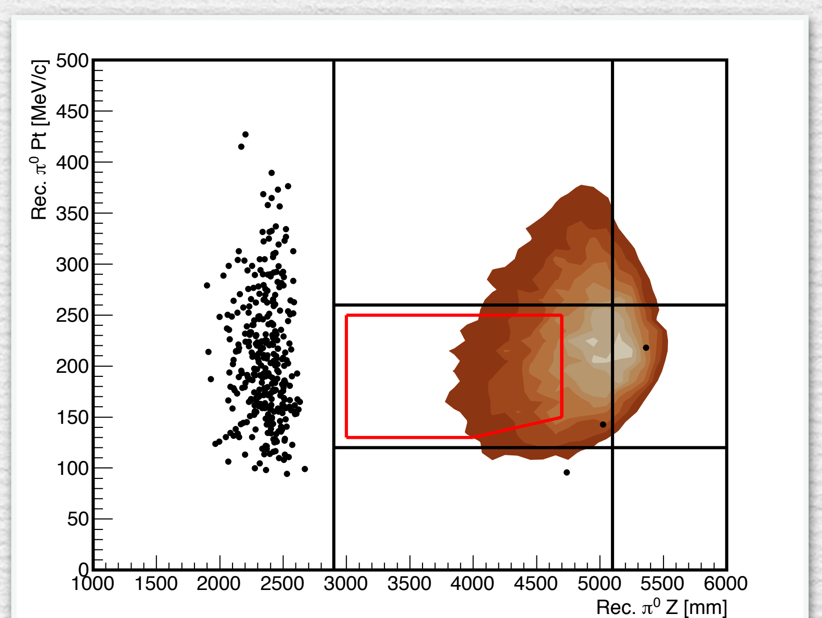
CV-η





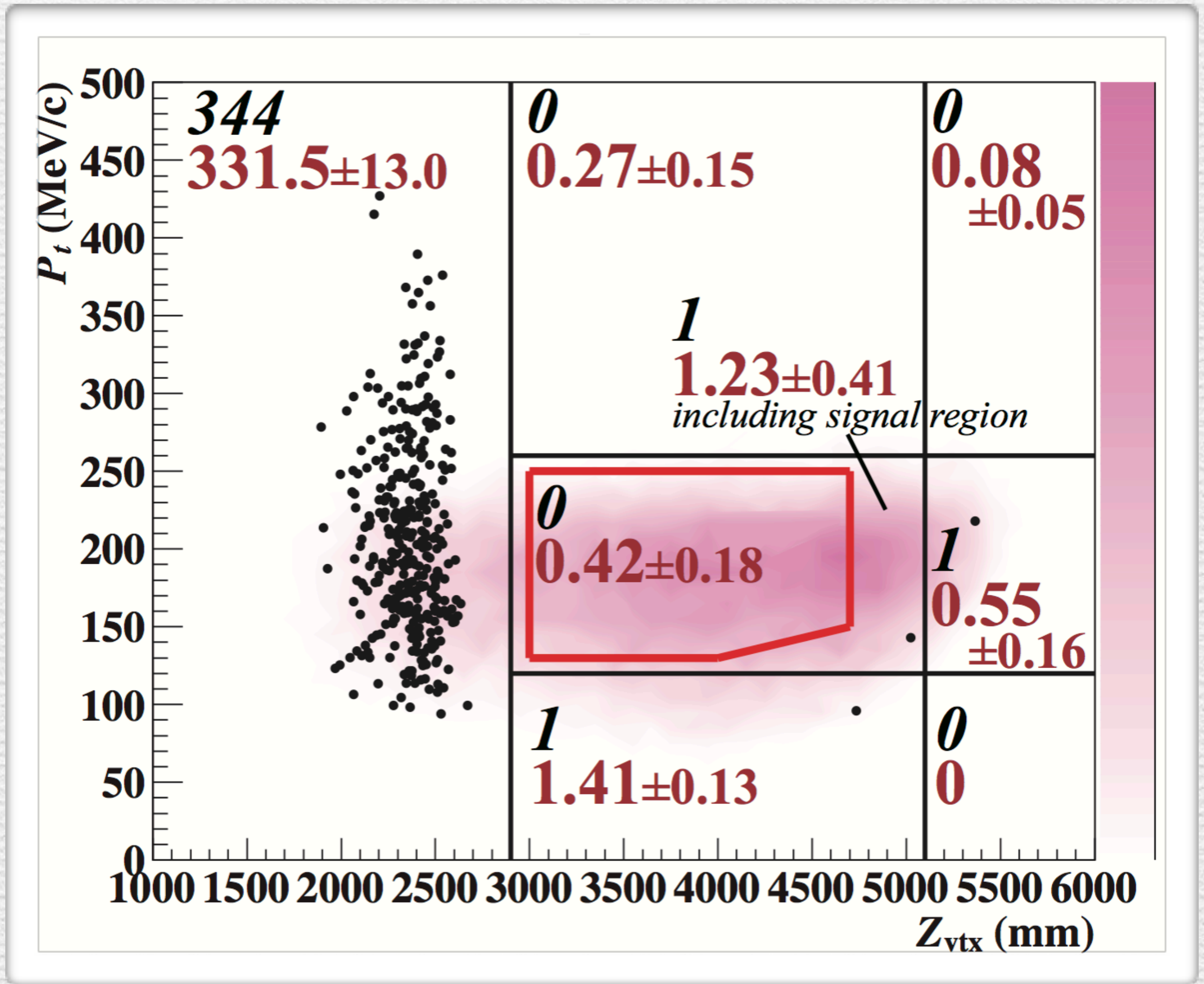
Hadron Cluster





Results of 2015 Data

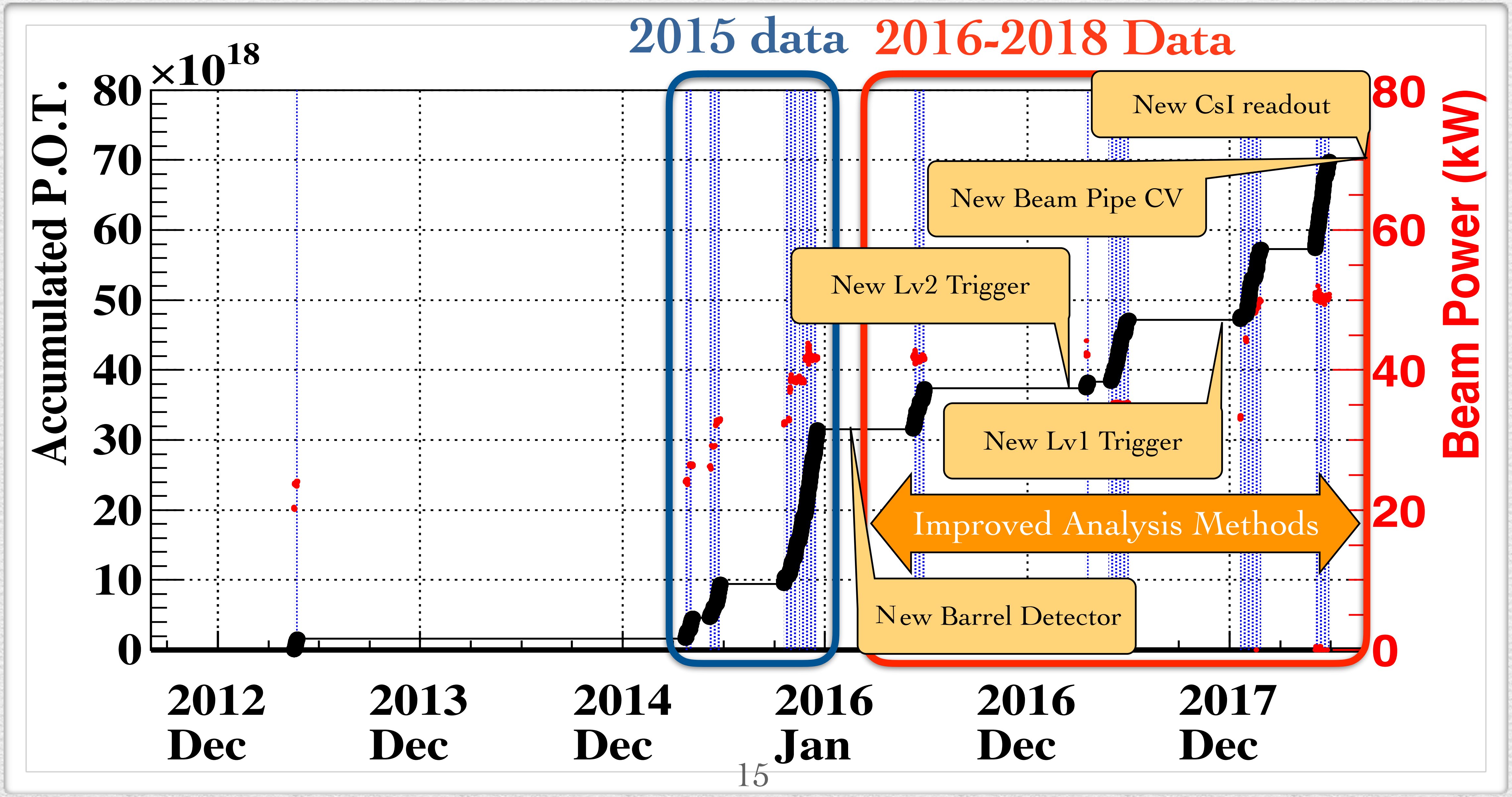
- Based on 40% data collected before major upgrades
  - SES = 1.3×10^{-9}
  - BR[$K_L\to\pi^0\nu\nu$] < 3.0×10^{-9}
  - Published in PRL.122.021802



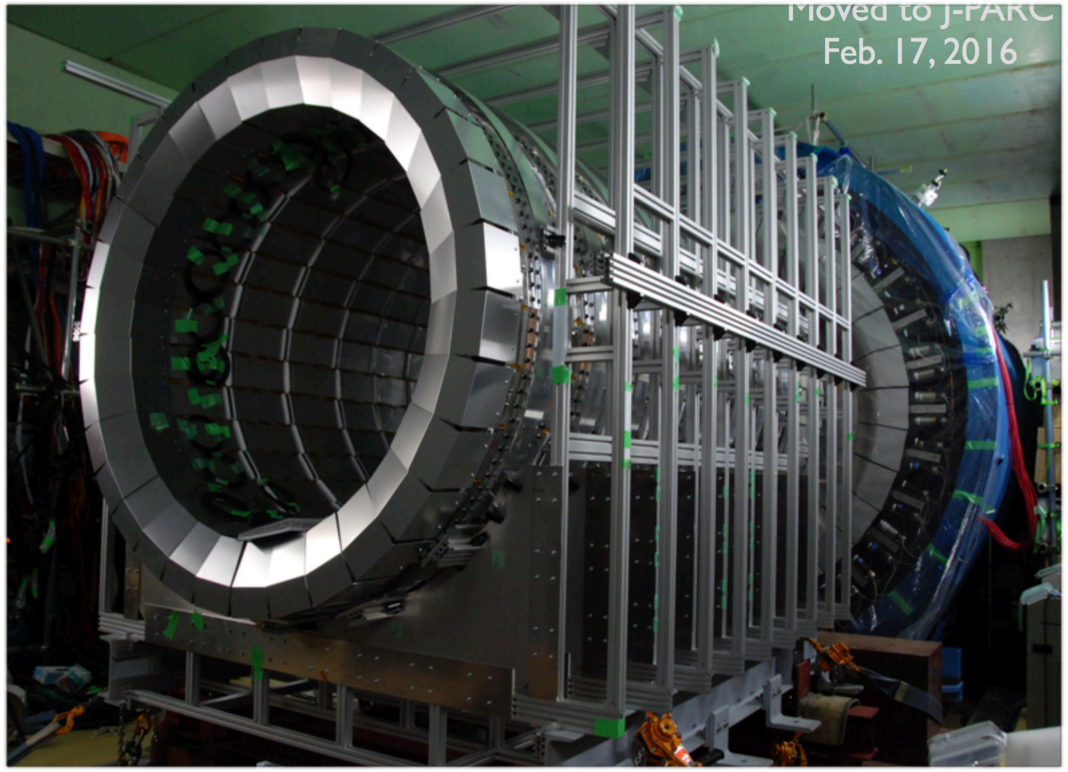
source		Number of events
K_L decay	$K_L\to\pi^+\pi^-\pi^0$	0.05 ± 0.02
	$K_L\to2\pi^0$	0.02 ± 0.02
	other K_L decays	0.03 ± 0.01
neutron-induced	hadron-cluster	0.24 ± 0.17
	upstream-π^0	0.04 ± 0.03
	CV-η	0.04 ± 0.02
total		0.42 ± 0.18

Detector/DAQ Upgrades

- Several major upgrades after 2015
- 2016-2018 result is coming out this summer
  - expect combined U.L. to cross G-N limit

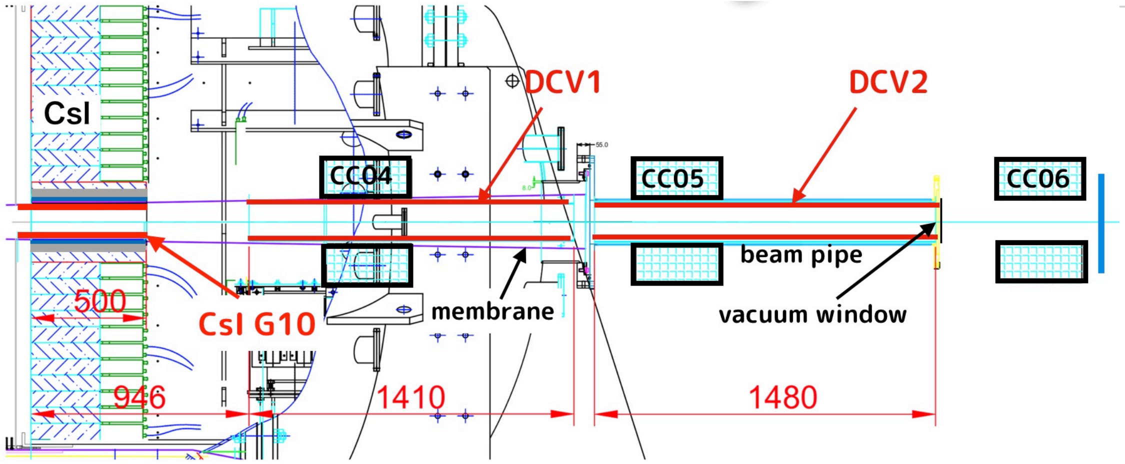


Detector Upgrades



Ticker Barrel Veto (2016-)

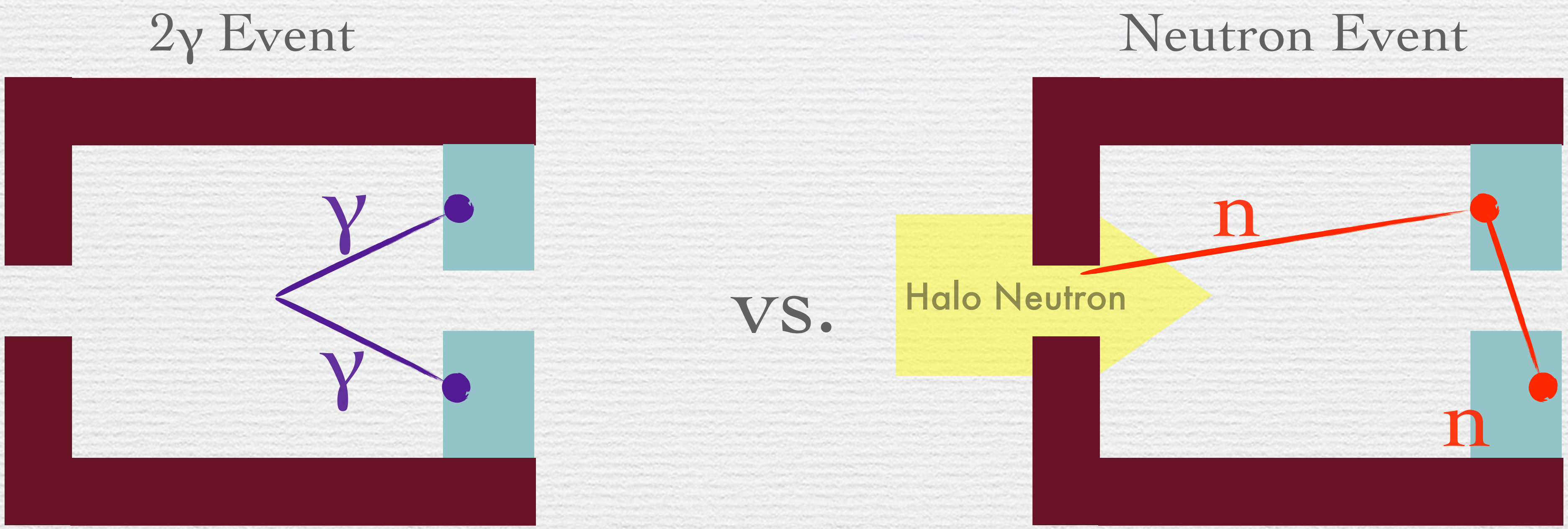
- $13.5 + 5\ X^0$
- $K_L \to \pi^0\pi^0$ / 3



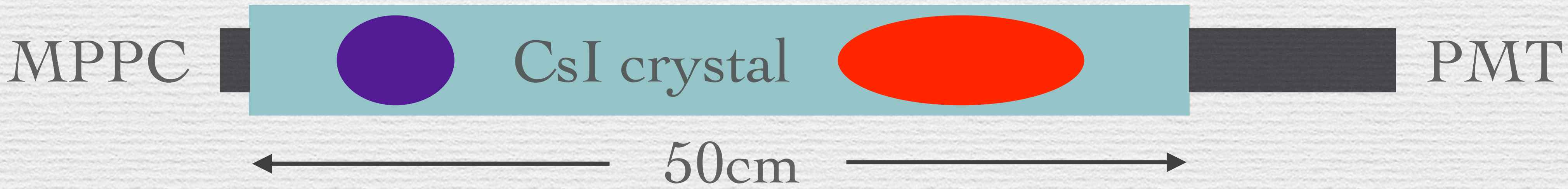
Downstream Charged Veto (2019-)

- inside vacuum with better coverage
- $K_L \to \pi^+\pi^-\pi^0$ / 50

Detector Upgrades



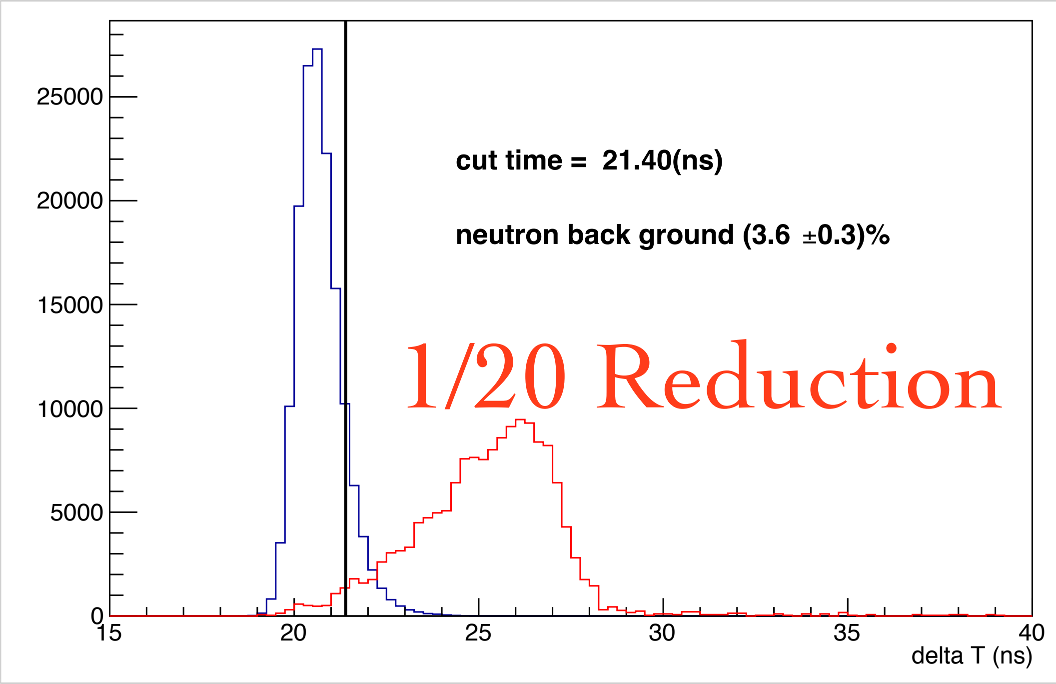
- Neutron interaction deeper than gamma
- Measure shower depth through Δt
  - Front: MPPC (Multi-Pixel Photon Counter)
  - Back: PMT

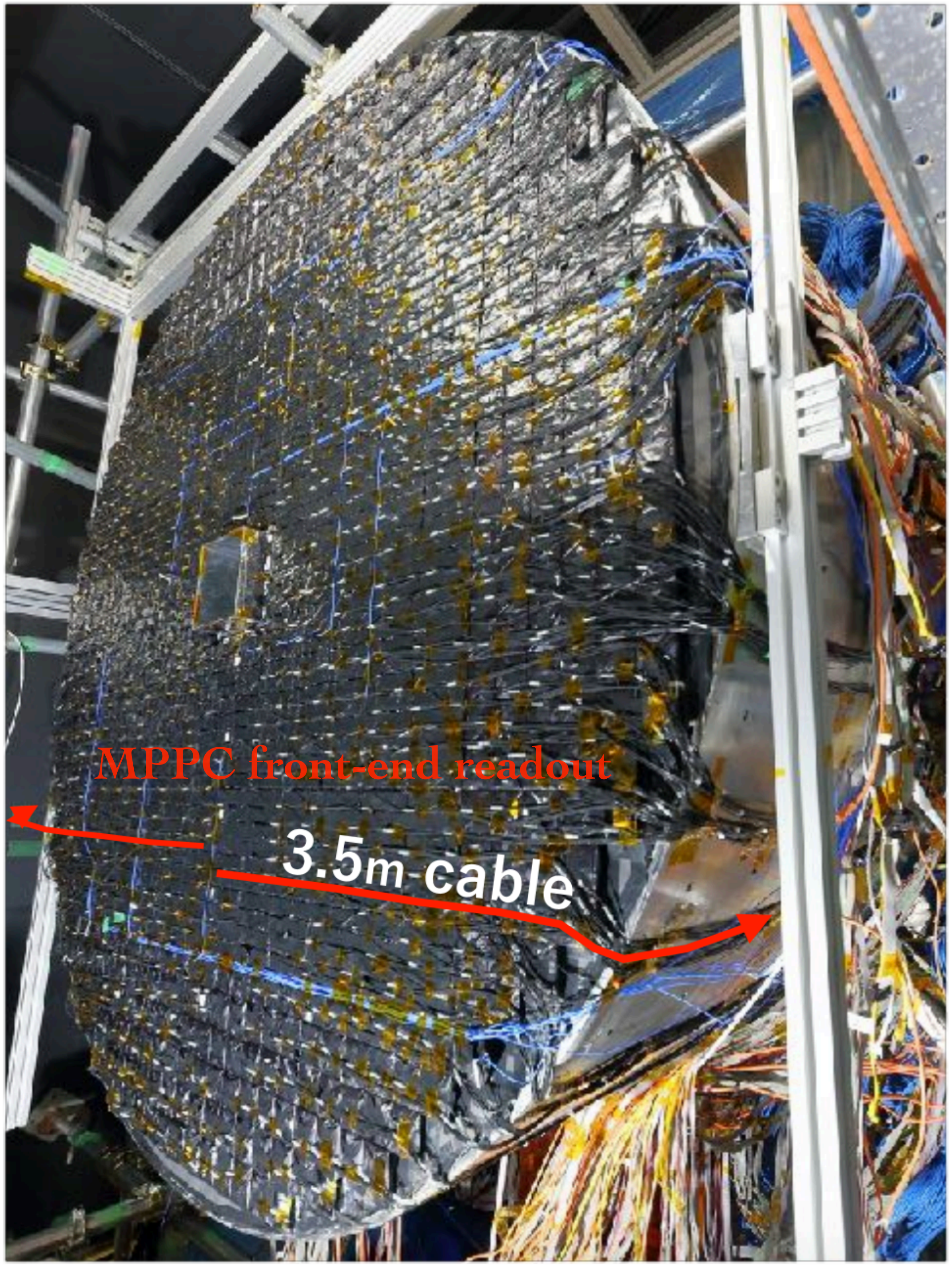


Detector Upgrades

CsI dual-sided readout (2019-)

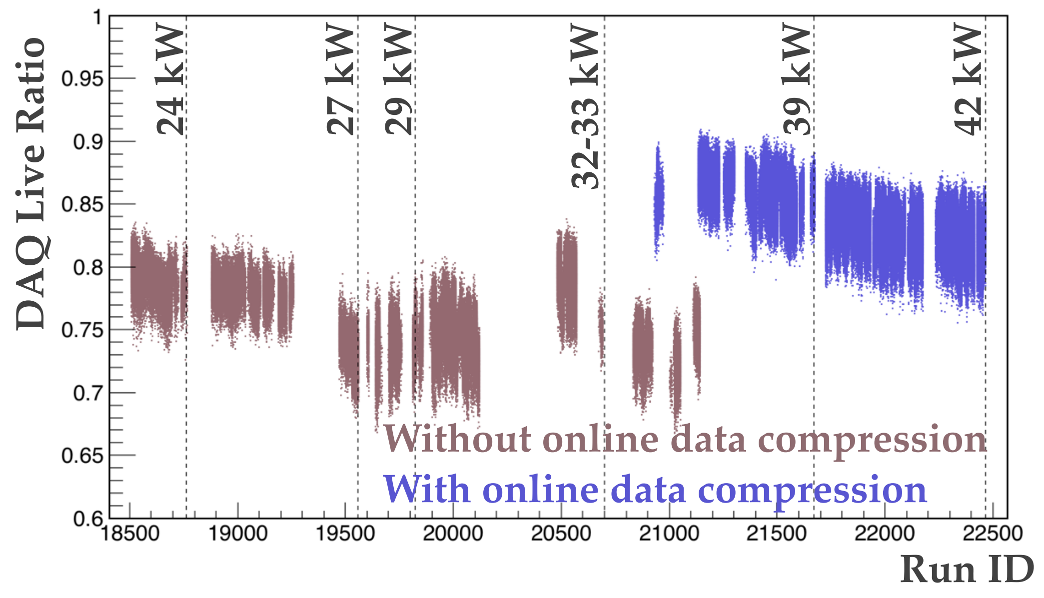
- MPPC (front) + PMT (back)
- Acceptance:
  - 90% signal events
  - 4% neutron events

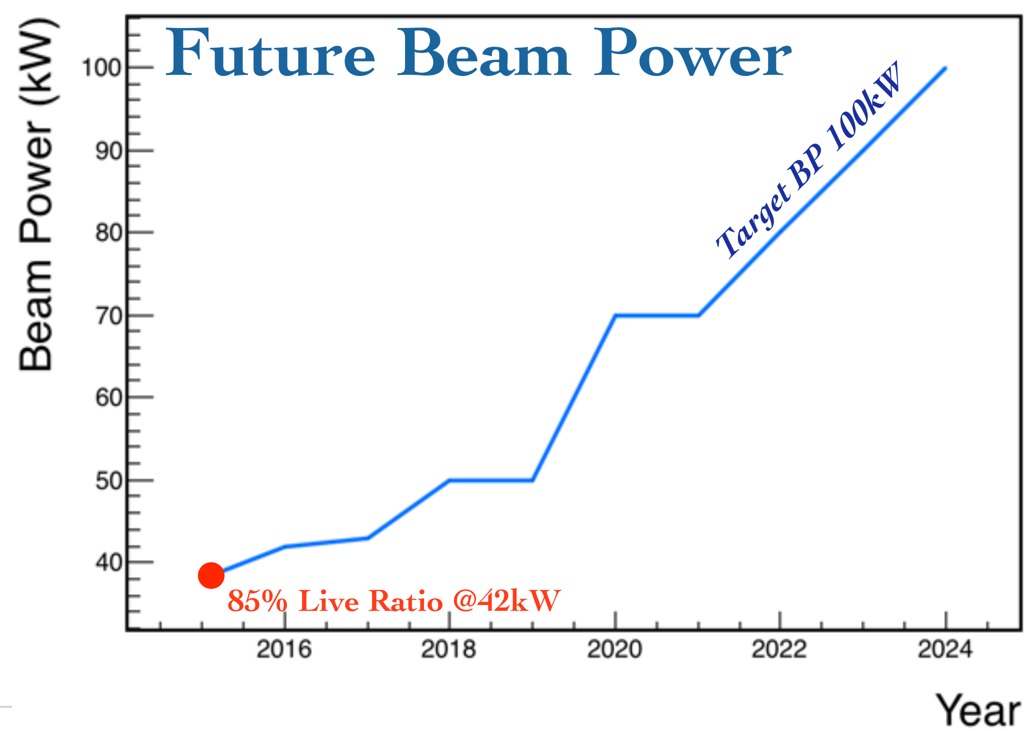




DAQ in 2015

- Detector with near 4000 Channels :
  - Full waveform readout by FADC
- 2015 DAQ Performance @ 42 kw:
  - Spill Length: 2 sec
  - Level-I Trigger: 37K events/spill
    - E_{sum} on CsI + Loose veto
  - Level-II Trigger: 9K events/spill
    - Center of Energy (C.O.E.) on CsI
  - Avg. of 85% DAQ Live Ratio
  - DAQ reached its Limitation

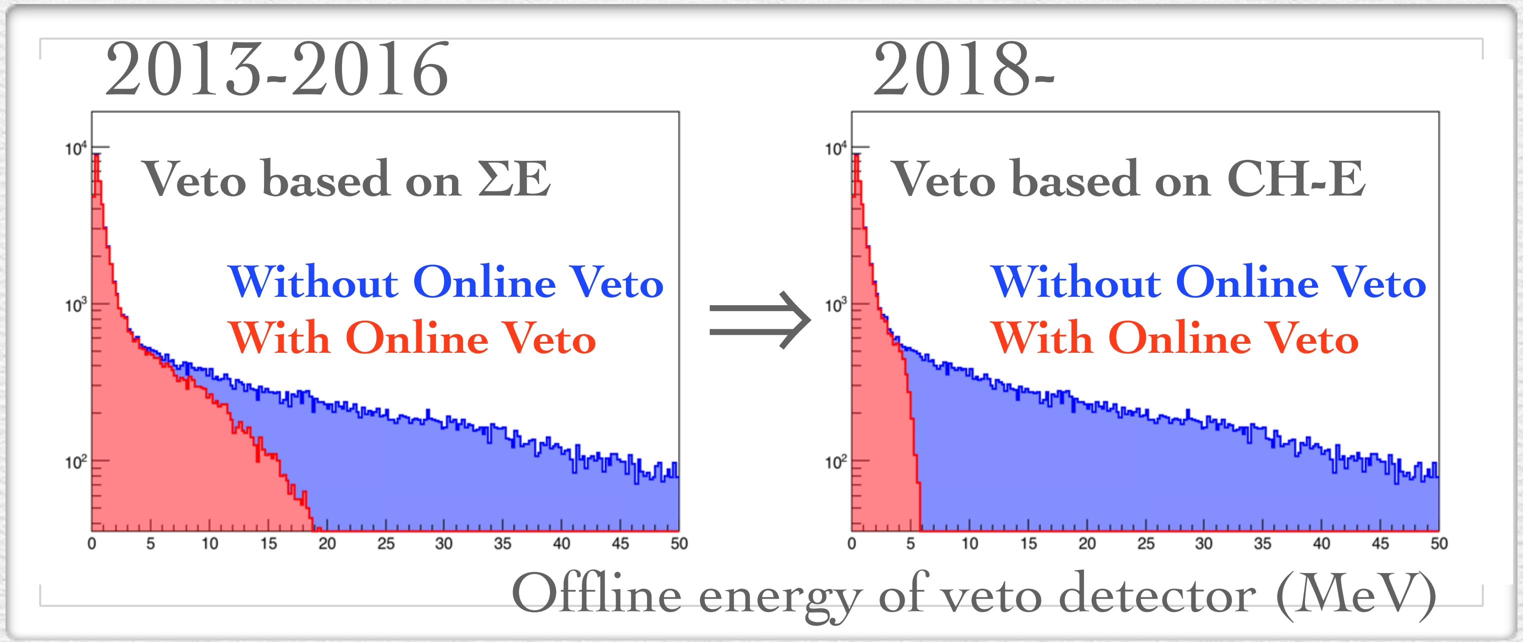


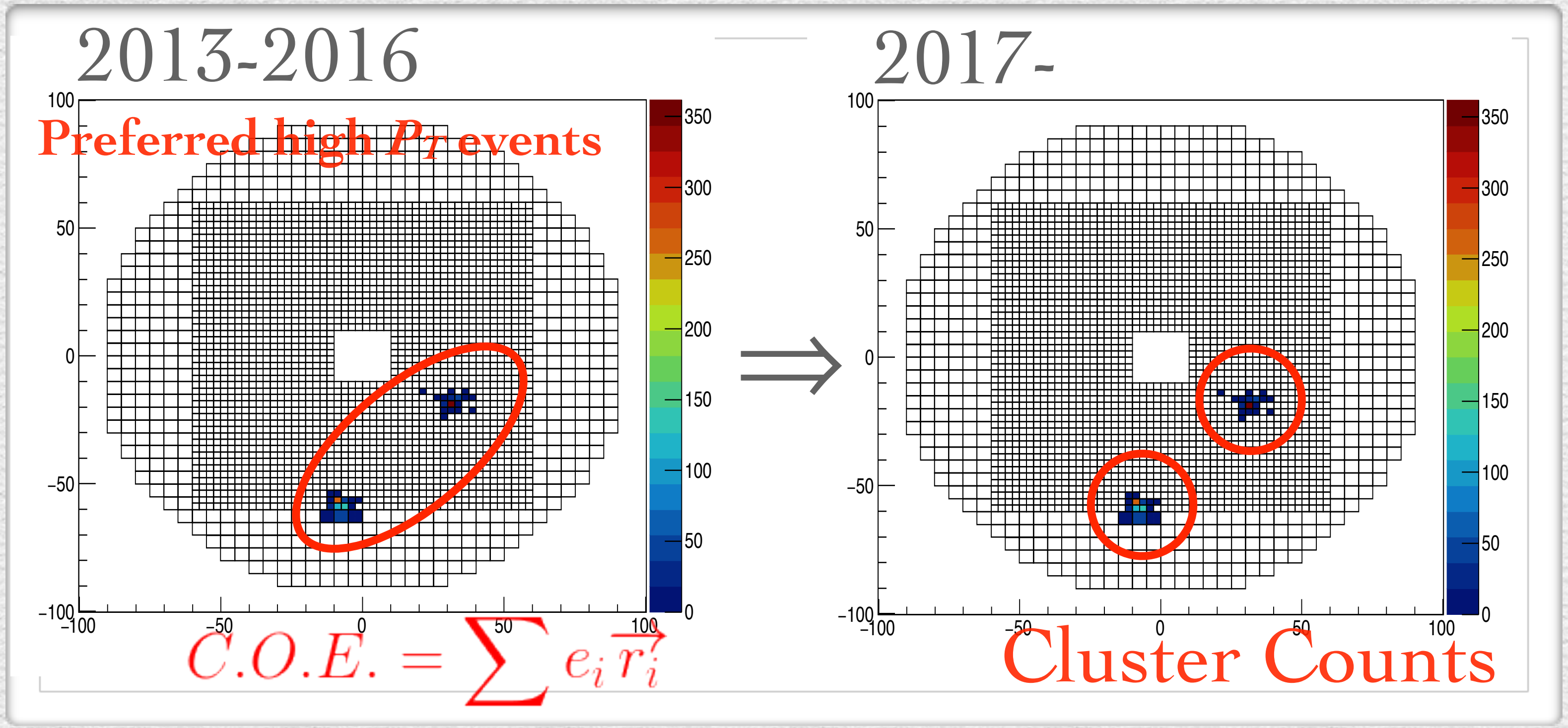


DAQ Upgrades - Trigger

New Level-I (UChicago/NTU) :

- Implemented in 2018
- Veto based on individual CH energy
  - Online pulse peak sensing
  - CH-by-CH calibrated threshold



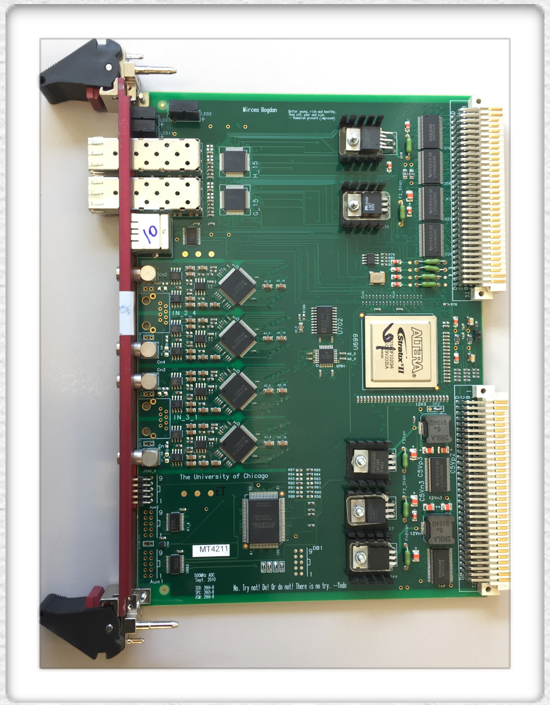


New Level-II (UChicago/NTU) :

- Implemented in 2017
- Based on cluster counts in CsI
- Broader analysis programs
  - $K_L \rightarrow \gamma\gamma\gamma$, $K_L \rightarrow \pi^0\gamma$, $K_L \rightarrow \pi^0\gamma\gamma$ …

DAQ Upgrades - Electronics

Univ. of Chicago Custom-Made ADC/Trigger Modules :

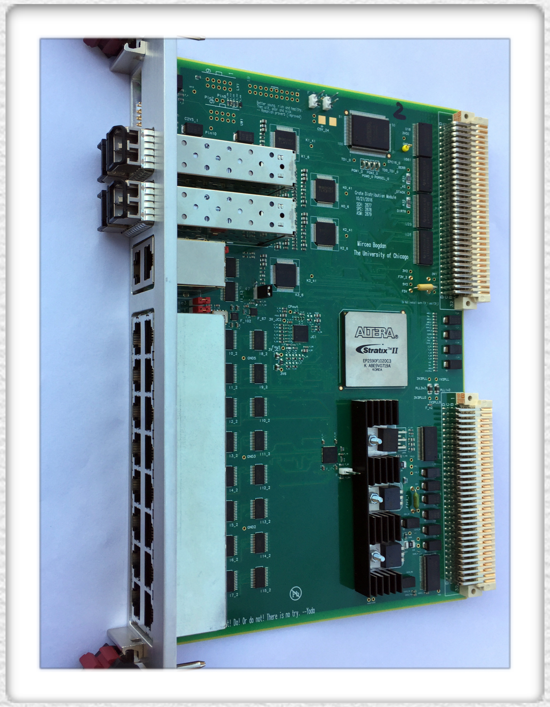


Flash ADC moduls:

- Stratix-II FPGA; Fully digital pipeline
- 125MHz 14-bit ADC for CsI/veto CHs
  - dynamic range covers several GeV to sub-MeV
  - Gaussian Shaper
- 500MHz 12-bit ADC for veto CHs
  - better timing resolution for vetos

Trigger Processor:

- Clock Distribution and Trigger
  - Stratix-II FPGA
  - 16 sets of LVDS I/O
  - ADC interface module
- Optical Fiber Center
  - Arria-V FPGA
  - 18 Optical Links up to 6 Gbs
  - Leve-I & Level-II module

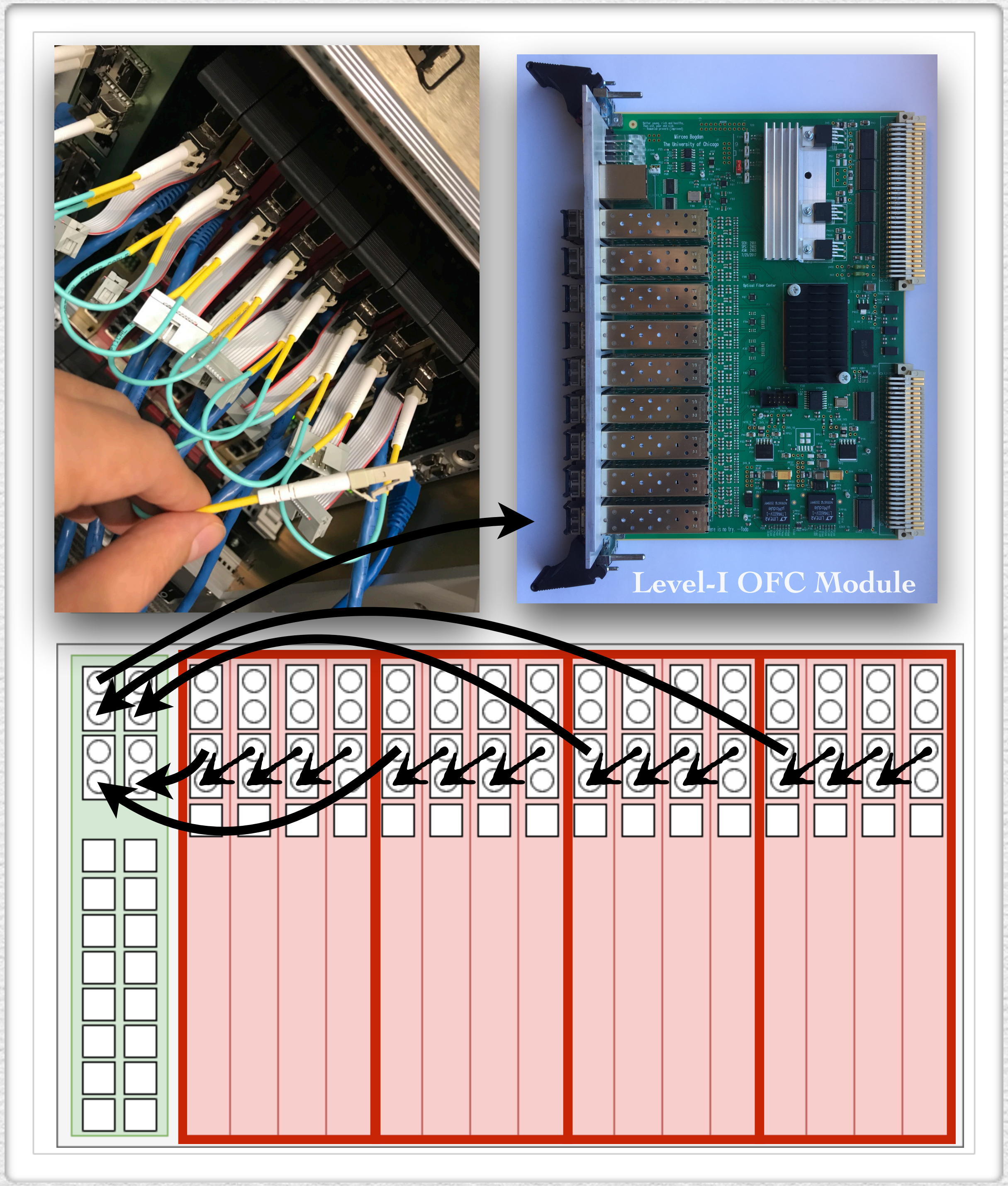


Reference: https://edg.uchicago.edu/~bogdan/

Trigger: Level-I (2018-)

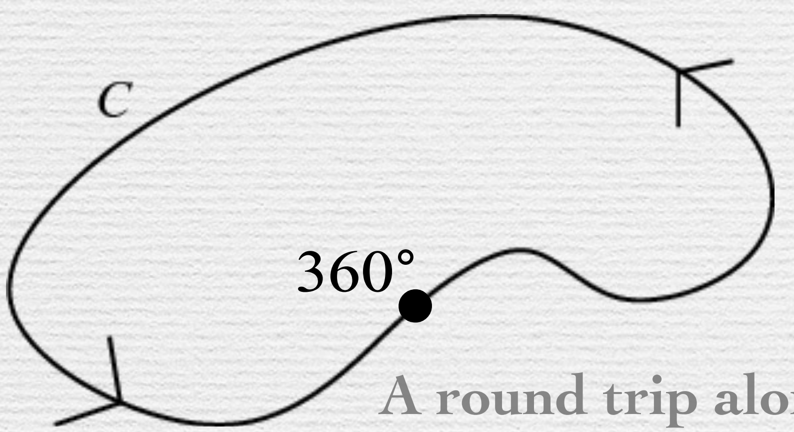
Level-I Trigger based on:

- ΣE of 2716 CsI Channels
  - daisy-chain/pyramid via optical fibers
  - 2.5 μs latency
- Veto on in-time CH-energy
- Trigger rate ~40K per spill @ 50kW
  - further reduction can be achieved
  - maximum ×3 reduction w/o sig. loss



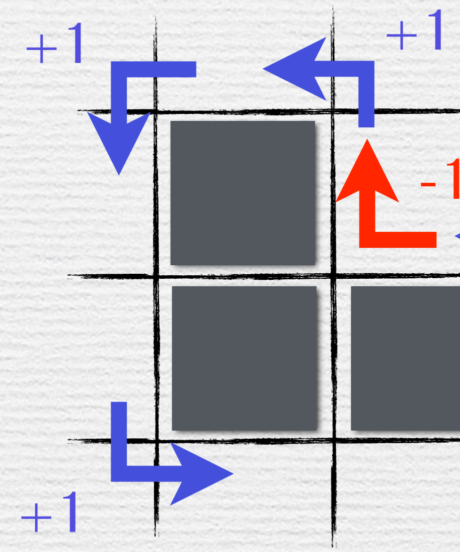
Trigger: Level-II (2017-)

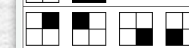
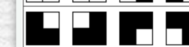
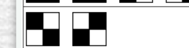
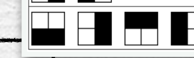
- **Clustering Algorithm:**



A round trip along any closed curve = 360°

⇒



Hit Block Patterns	Pattern Values
	0 - No corner
	+1 - One convex corner
	-1 - One concave corner
	+2 - Two convex corners
	0 - No corner

A completed cluster has 4 "net" corners

- **Number of net corners / 4 = Number of Clusters**

CLUSTER COUNTING FOR E799/E832 AT FERMILAB

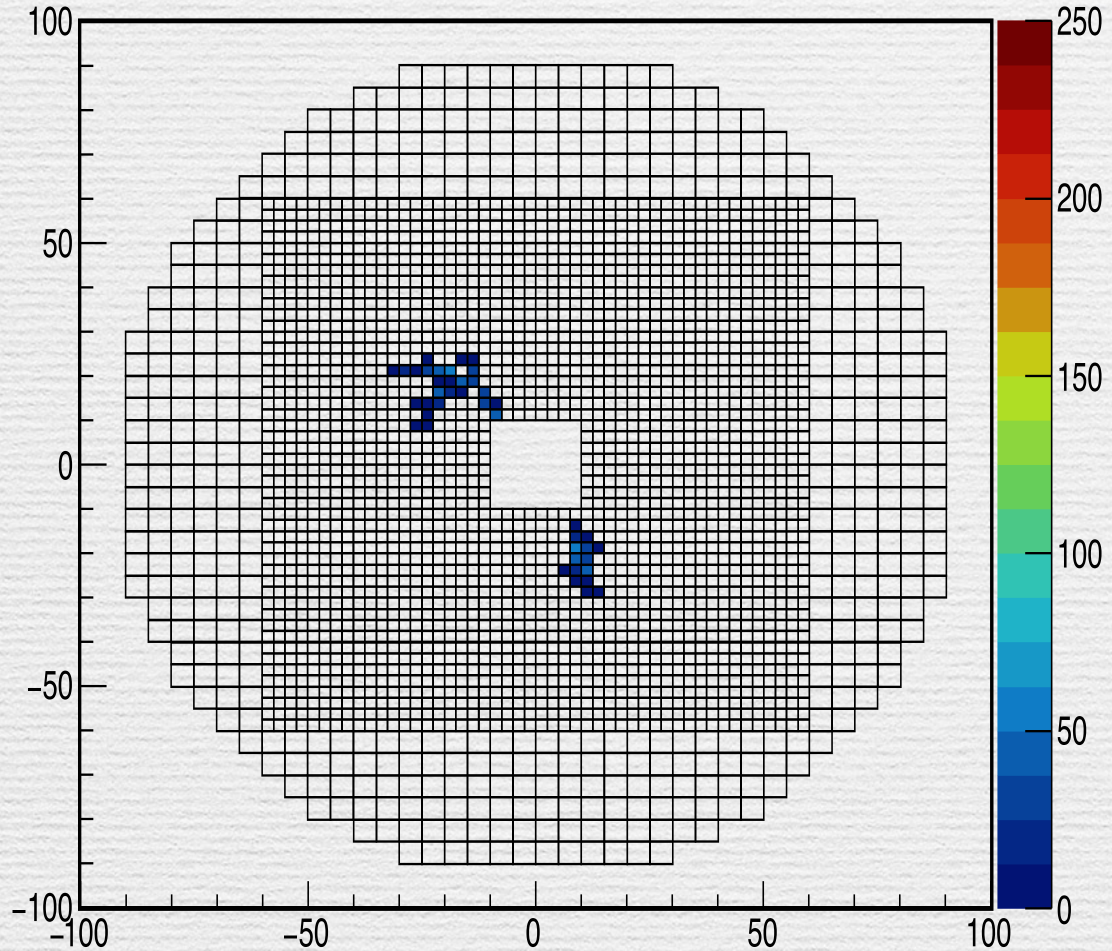
M. J. Haney and G. D. Gollin[1],
University of Illinois, 1110 W. Green St., Urbana, IL 61801 USA

T. Yamanaka,
Osaka University, Toyonaka, Osaka 560, Japan

Published in 1992

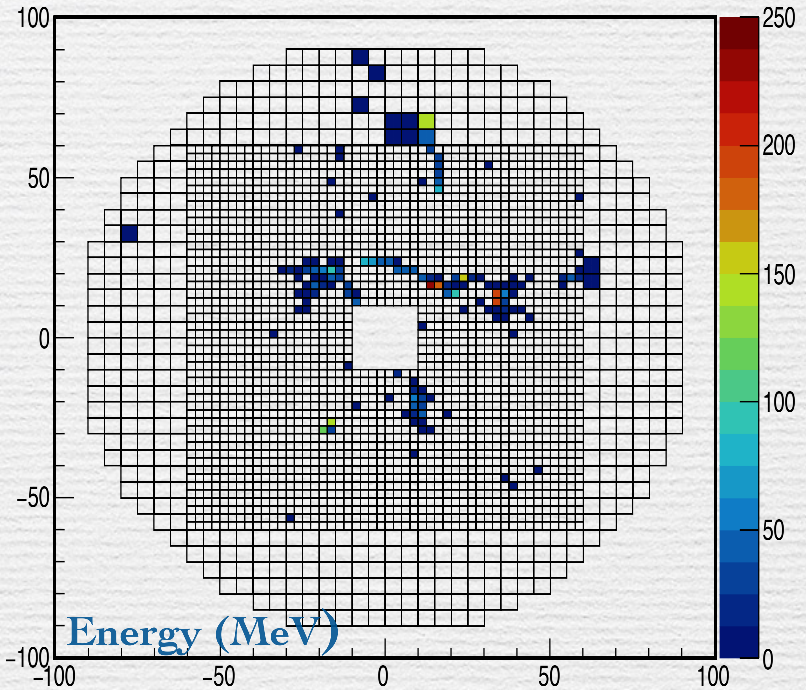
Trigger: Level-II (2017-)

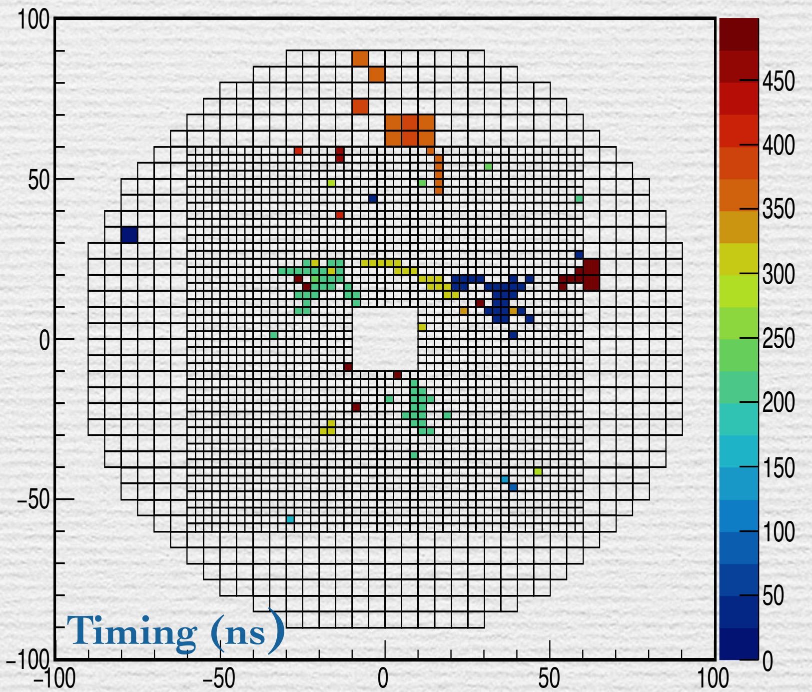
Offline Two-Cluster Event



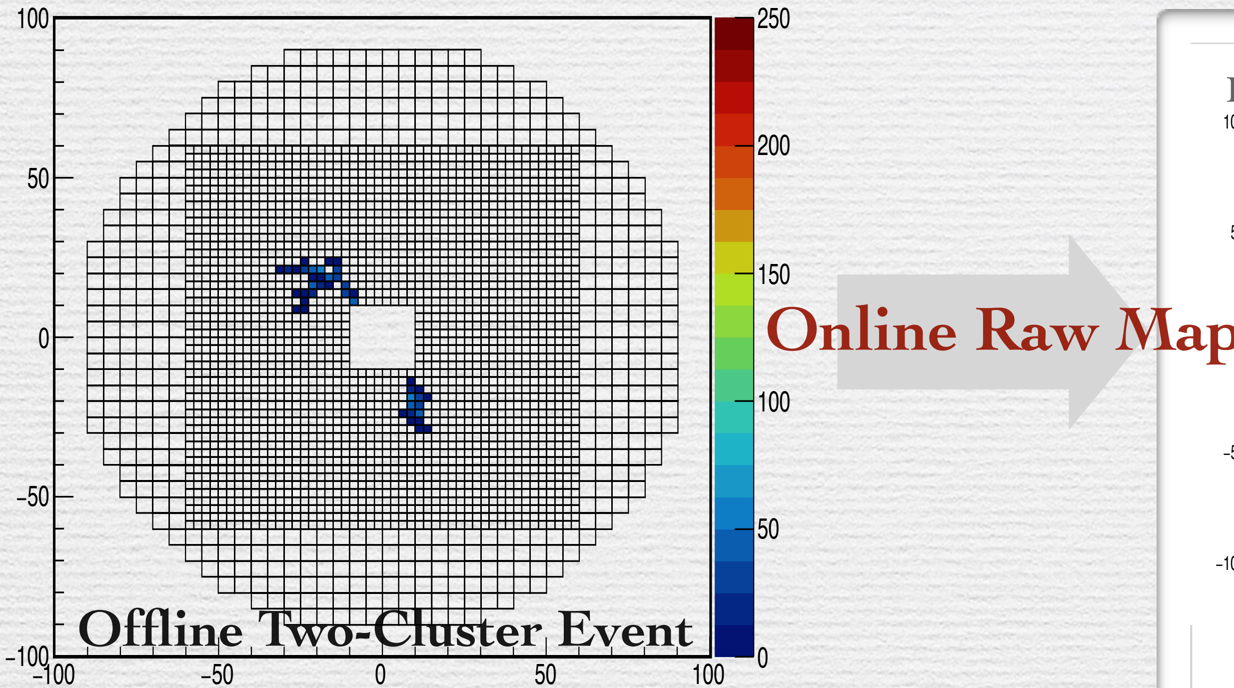
Online

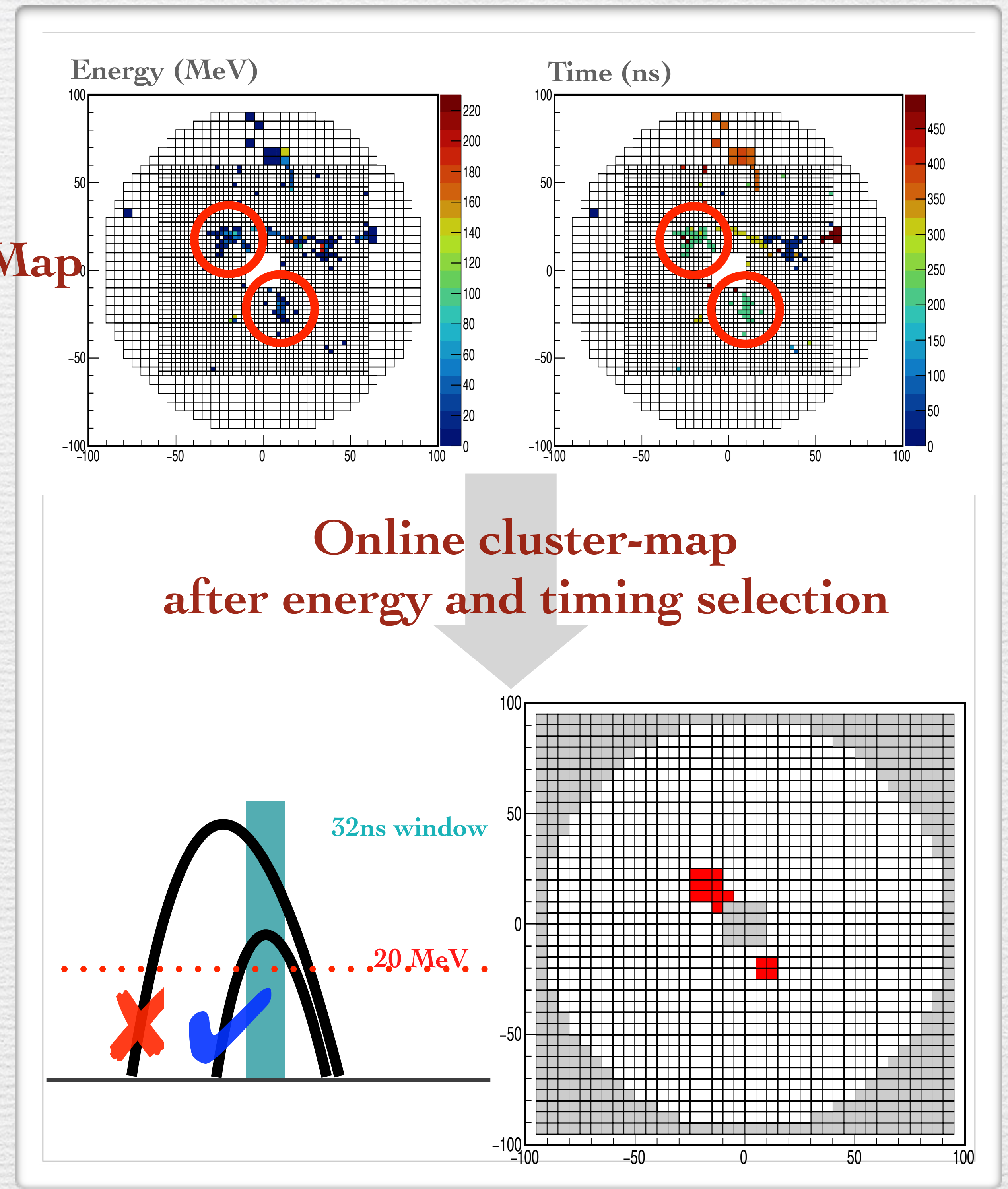
All Hits within Event Window (512ns)





Trigger: Level-II (2017-)





- Online pulse peak sensing
  - count clusters within 32ns window
- High E-threshold to suppress satellite hits

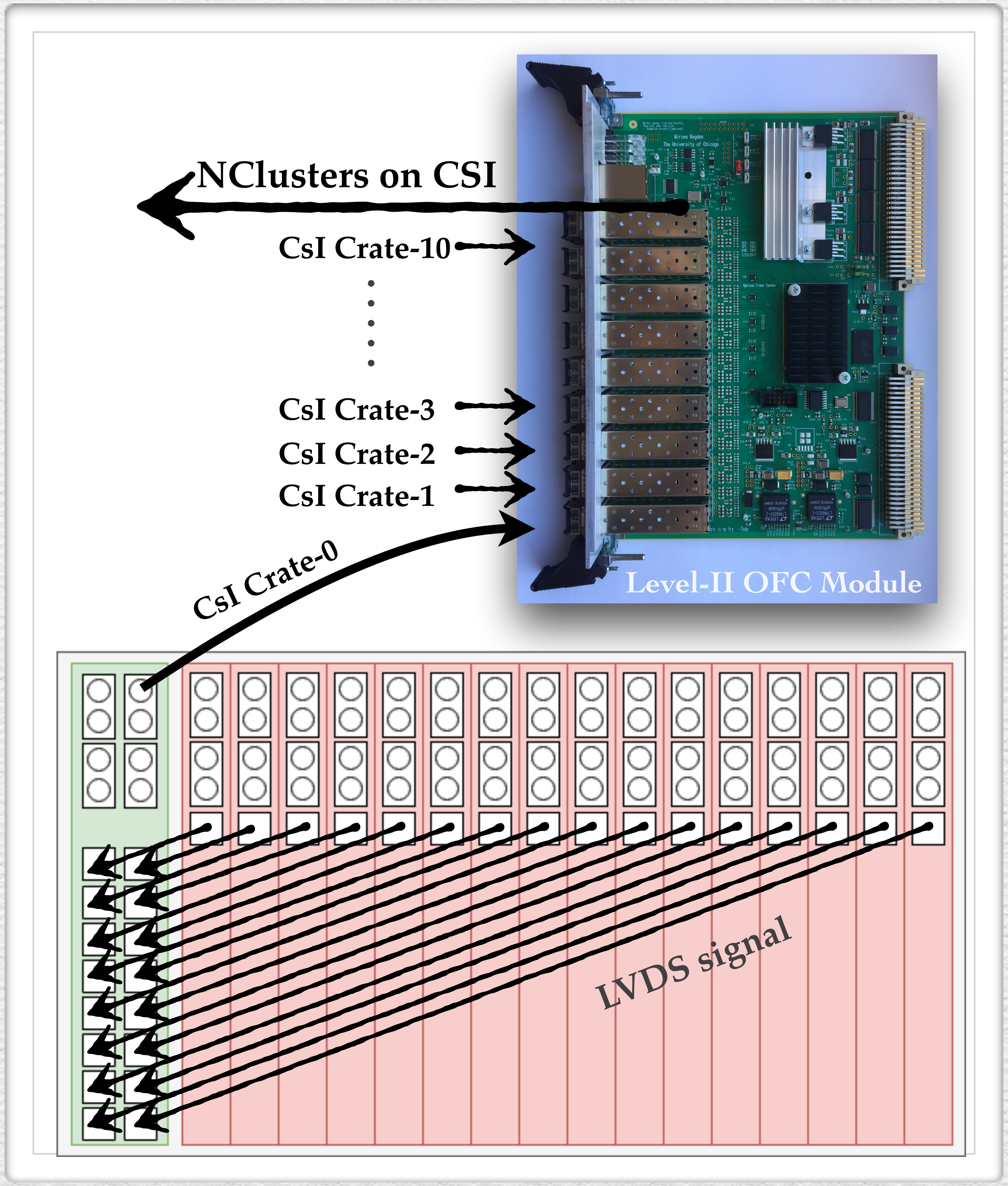
Trigger: Level-II (2017-)

Parallel counting in Lv-II OFC

- negligible dead time (~150ns)
- latency: 2.0 μs

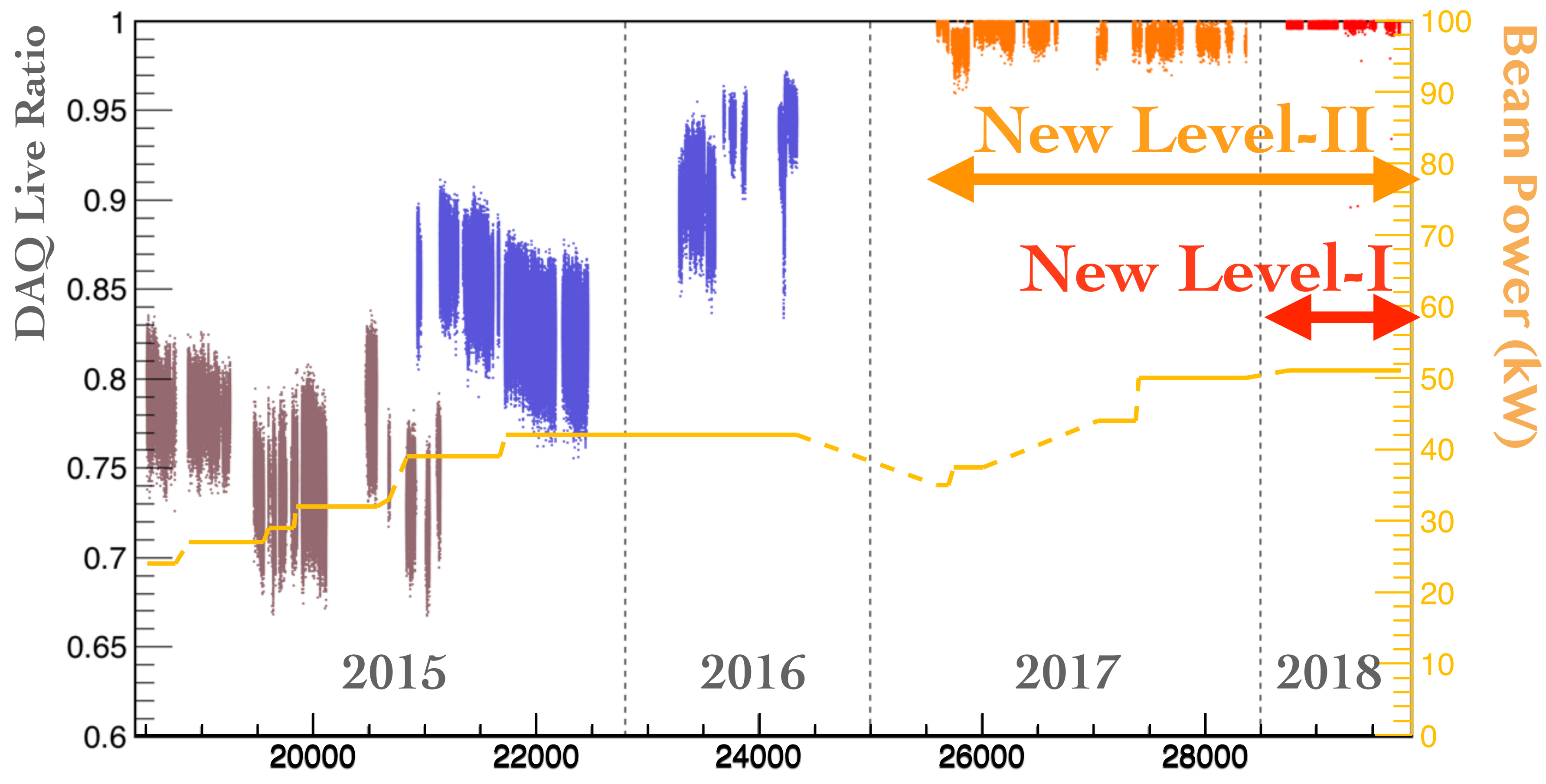
Trigger efficiency:

- 99.6% for $K_L \to \pi^0 \nu\nu$
- ×30 efficient for low P_T modes
  - $K_L \to \pi^0\pi^0$, $K_L \to \pi^0\gamma\gamma$, $K_L \to \pi^0\pi^0\pi^0$…
- ×4 efficient for neutron study samples
  - ×9 neutron data in 2016-2018 than 2015



DAQ Performance

- DAQ Live ratio ~100%
- System is ready for 100kW beam power



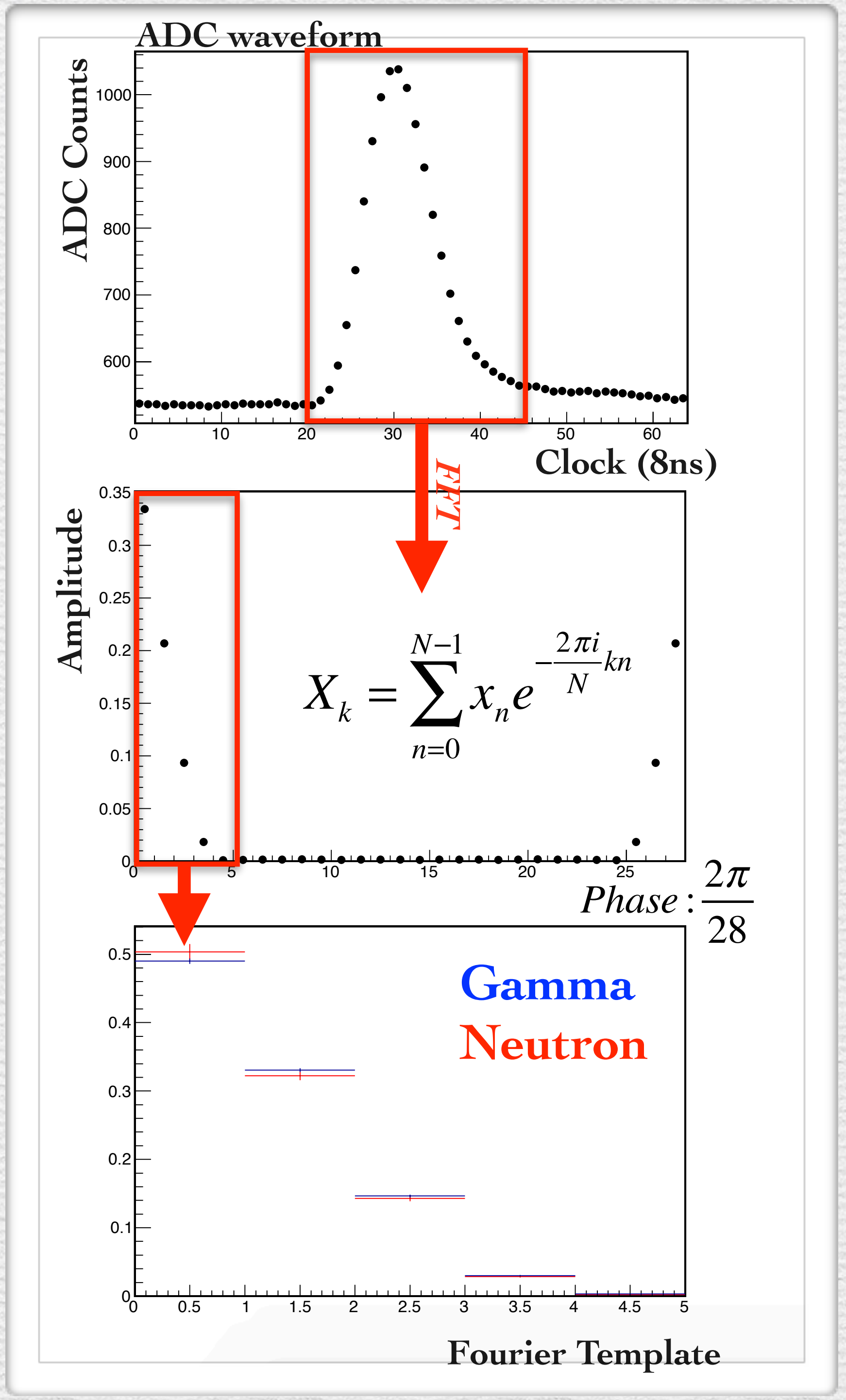
New Algorithms - Neutron PSD

Pulse Shape Discrimination

- Hadronic pulse wider than EM pulse

Fourier Analysis on ADC waveform

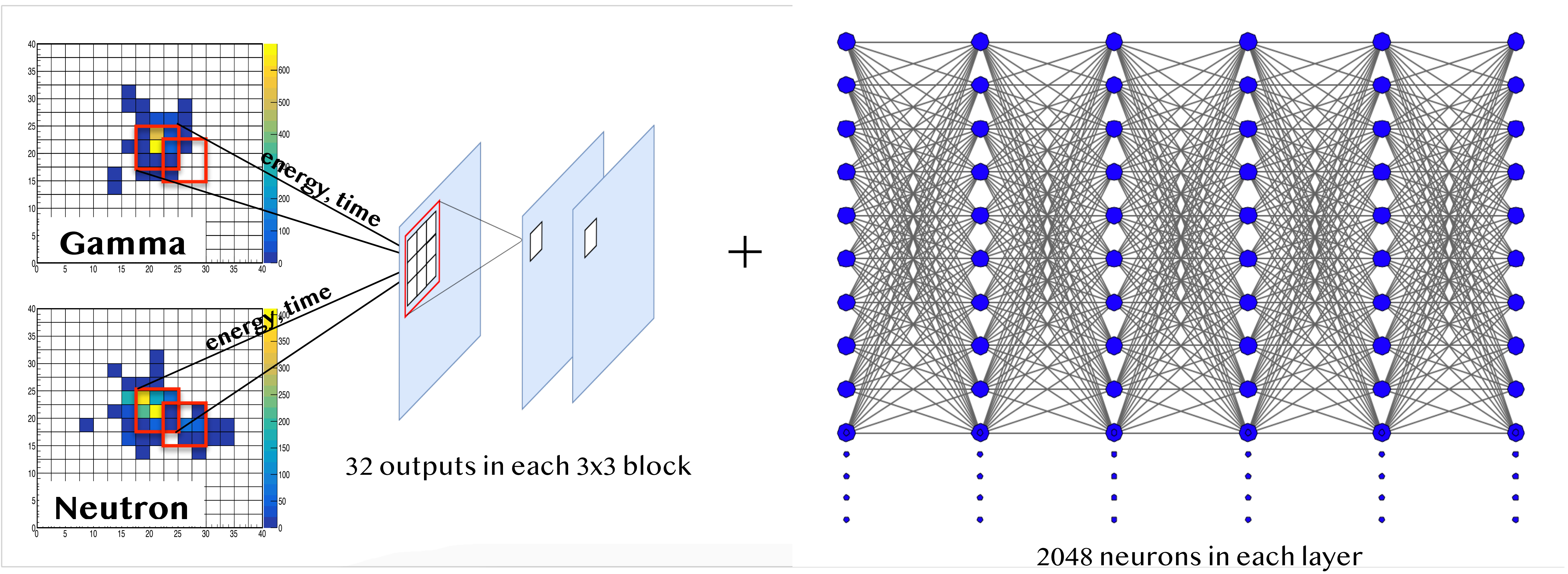
- Neutron Acceptance: 3.2%
- $K_L \to \pi^0 \nu\nu$ acceptance: 90%
- ×3 reduction over 2015 results



New Algorithms - Neutron CSD

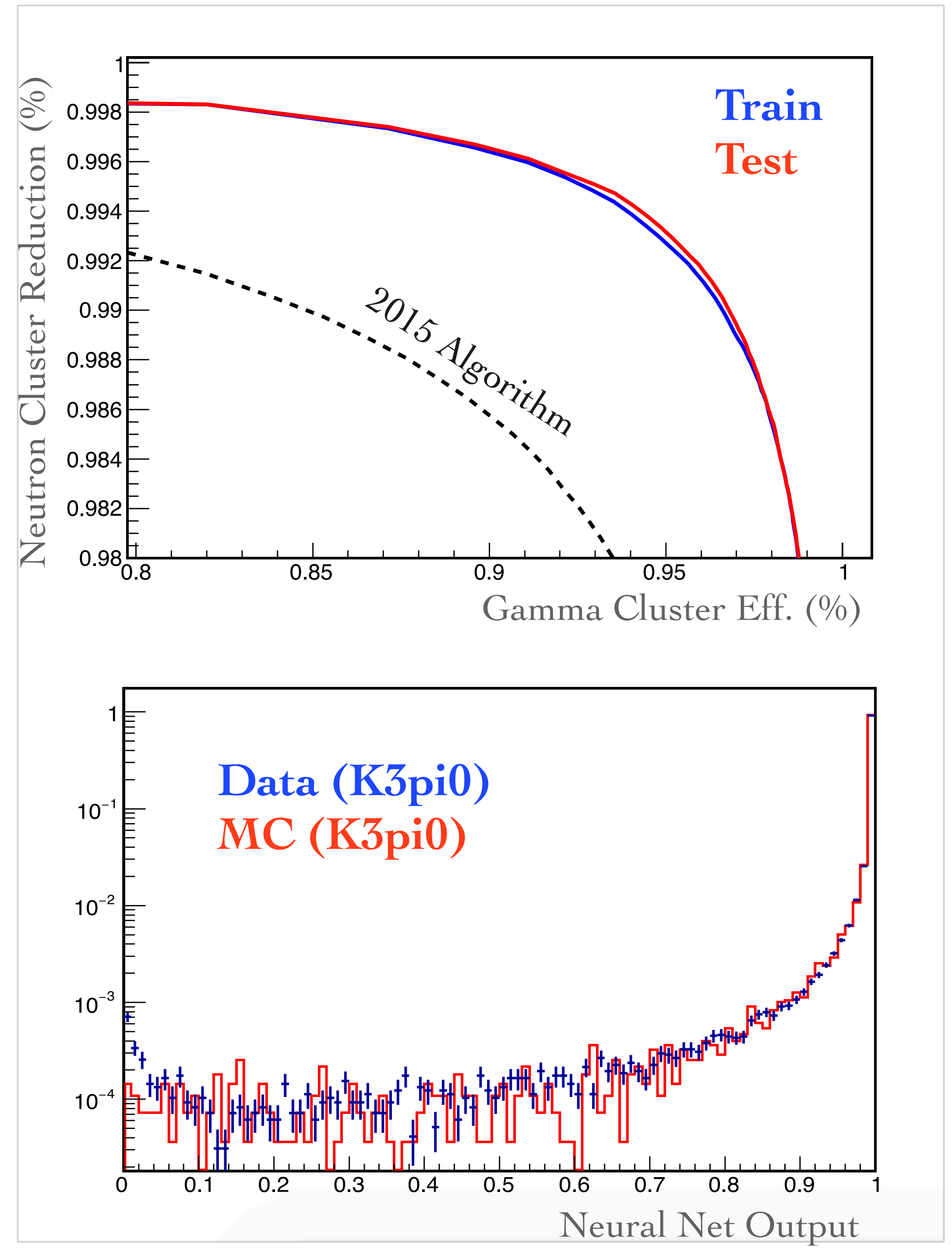
Cluster Shape Discrimination

- Convolutional Neural Net with deep learning
- Input: energy and timing of crystals
- 4 conv. layers + 6 fully connected layers



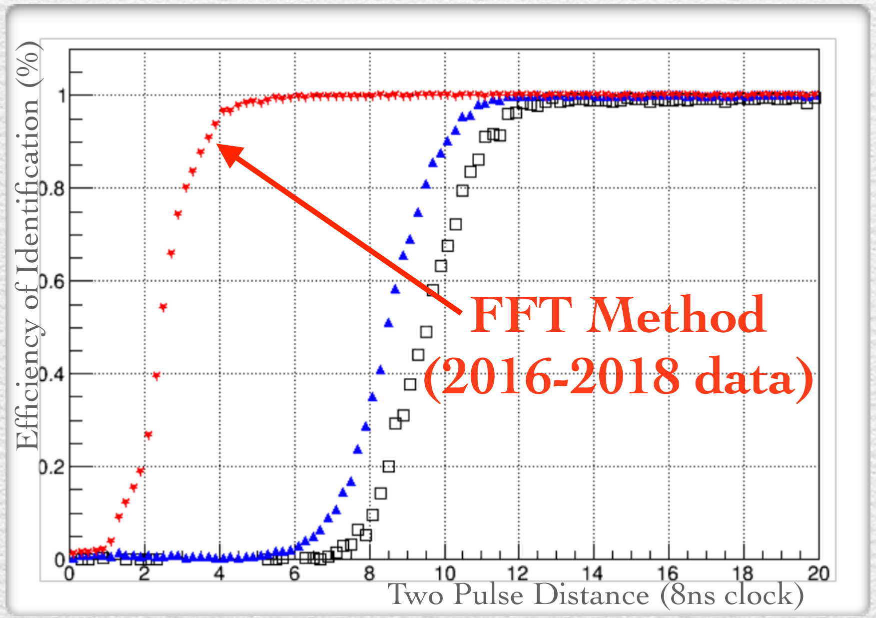
New Algorithms - Neutron CSD

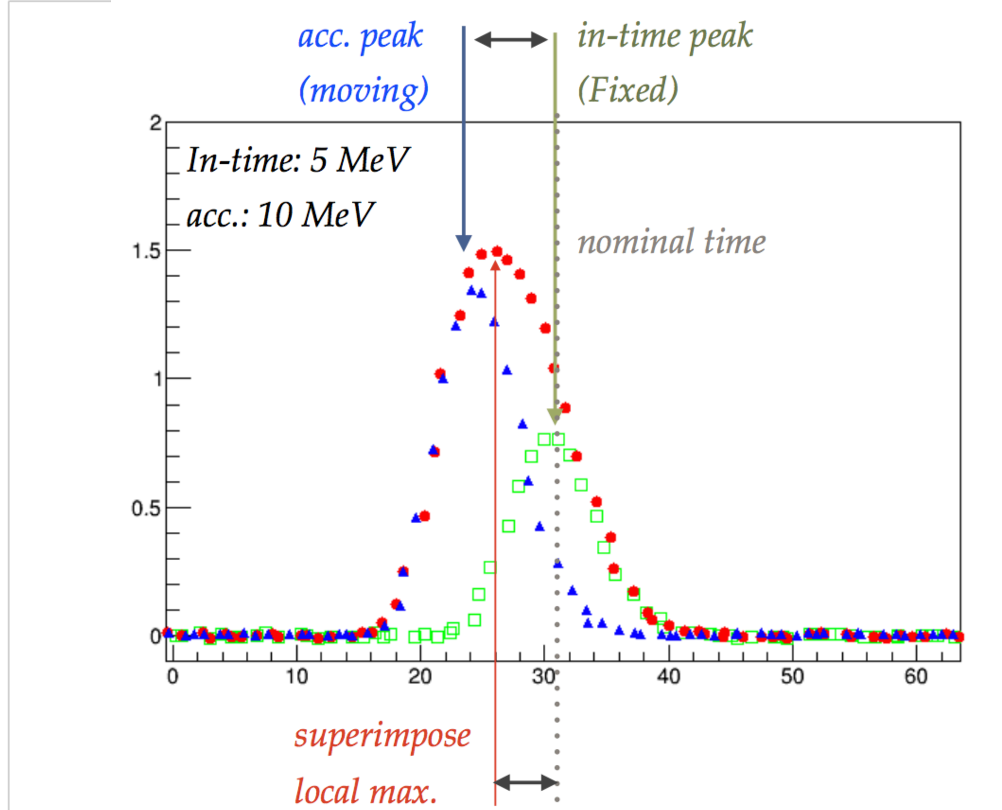
- Neutron Samples:
  - special Al run
- Gamma Samples:
  - $K_L \to \pi^0 \nu \nu$ MC
- Data/MC good consistency
  - Checked by $K_L \to \pi^0 \pi^0 \pi^0$
- Combined Reduction (PSD+CSD)
  - $\sim \mathcal{O}(10^{-6}\text{-}10^{-5})$

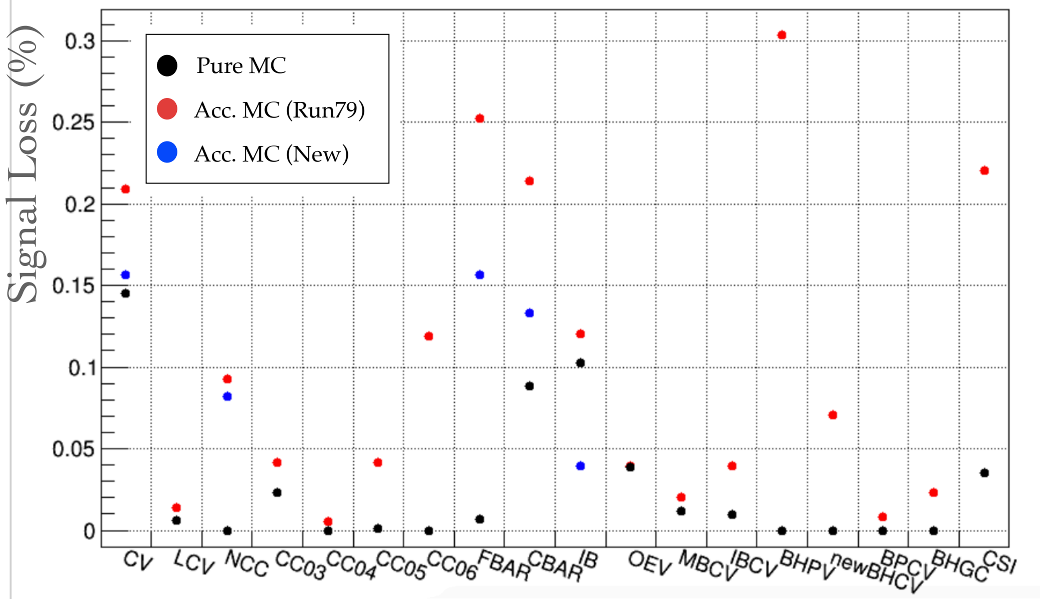


New Algorithms - Double Pulse

- **Double Pulse:**
  - True signal overlapped by accidental
  - Pulse timing deviated from true value
- **2015 Data Analysis:**
  - Wide veto window to cover double pulse
  - Large acceptance loss of signal
- **2016-2018 Data Analysis:**
  - Fourier analysis to identify double pulse
  - Signal acceptance × 1.38

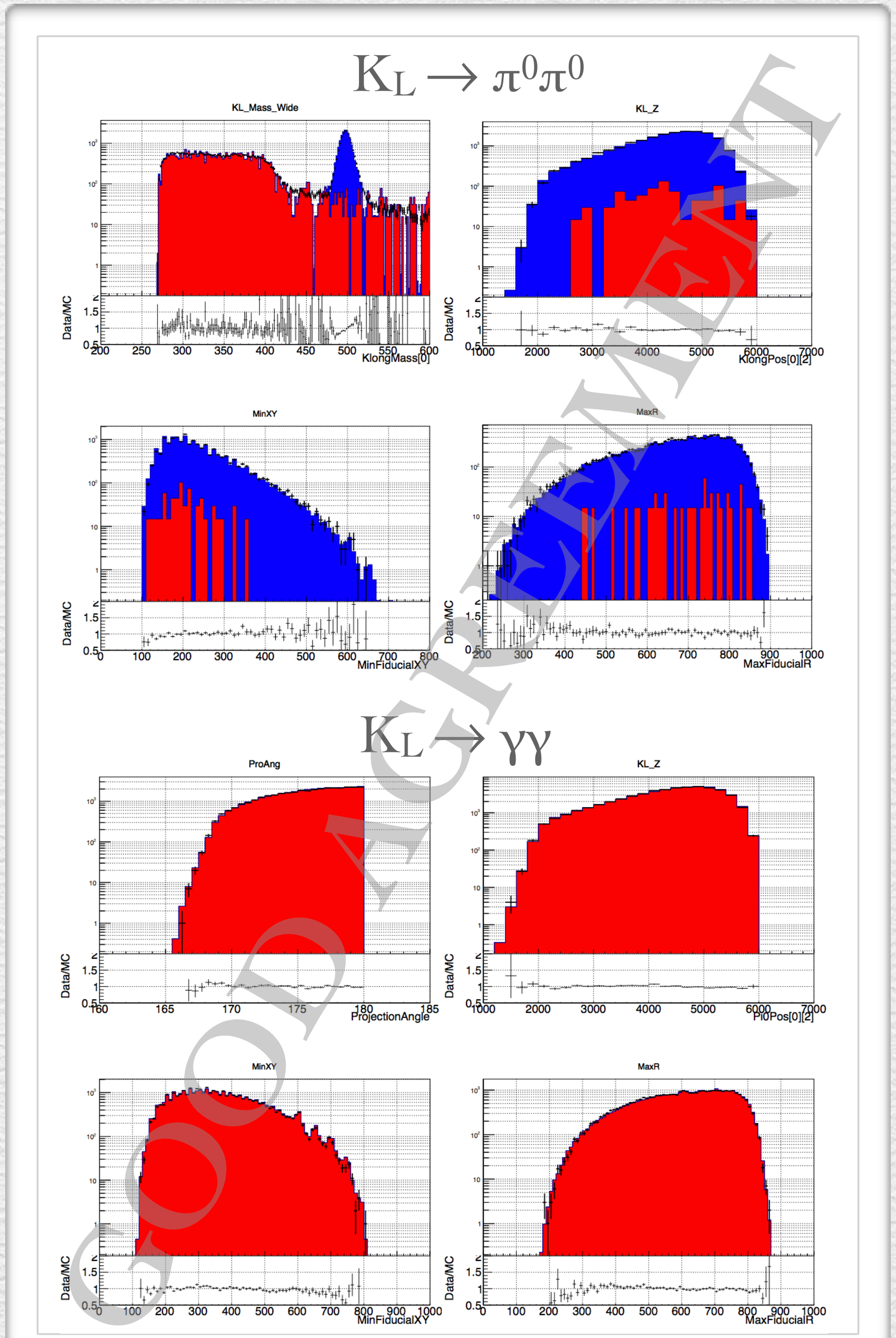






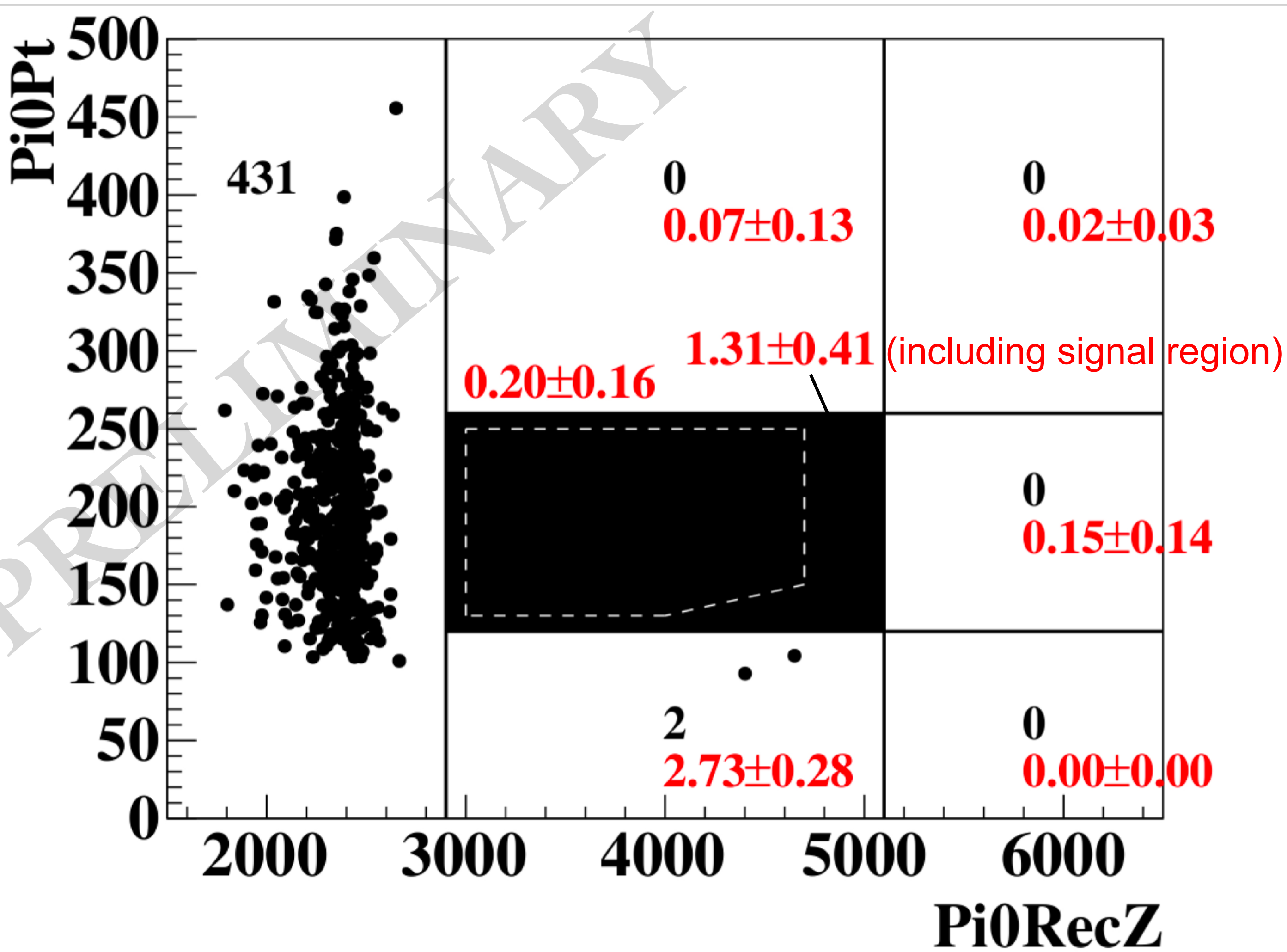
Analysis Status: 2016-2018 Data

- ×1.4 more data in 2016-2018
  - combined UL($K_L \to \pi^0 \nu\nu$) < G-N limit
- Better background control
  - new detectors and analysis methods
- By-products benefited from new DAQ:
  - $K_L \to \pi^0\gamma\gamma$
  - $K_L \to \pi^0\pi^0\nu\nu$
  - $K_L \to \pi^0\gamma$
  - $K_L \to \gamma\gamma\gamma$



Analysis Status: 2016-2018 Data

- S.E.S. = 8.2×10^{-10} (without new veto window)
- Background under control
- Results coming soon in summer 2019



	# of BG inside signal region
$K_L \to 2\pi^0$	0.09±0.09
$K_L \to \pi^+\pi^-\pi^0$	0.02±0.02
Hadron cluster	0.07±0.13
CV-pi0	< 0.19
CV-eta	0.02±0.01
Total	**0.20±0.16**

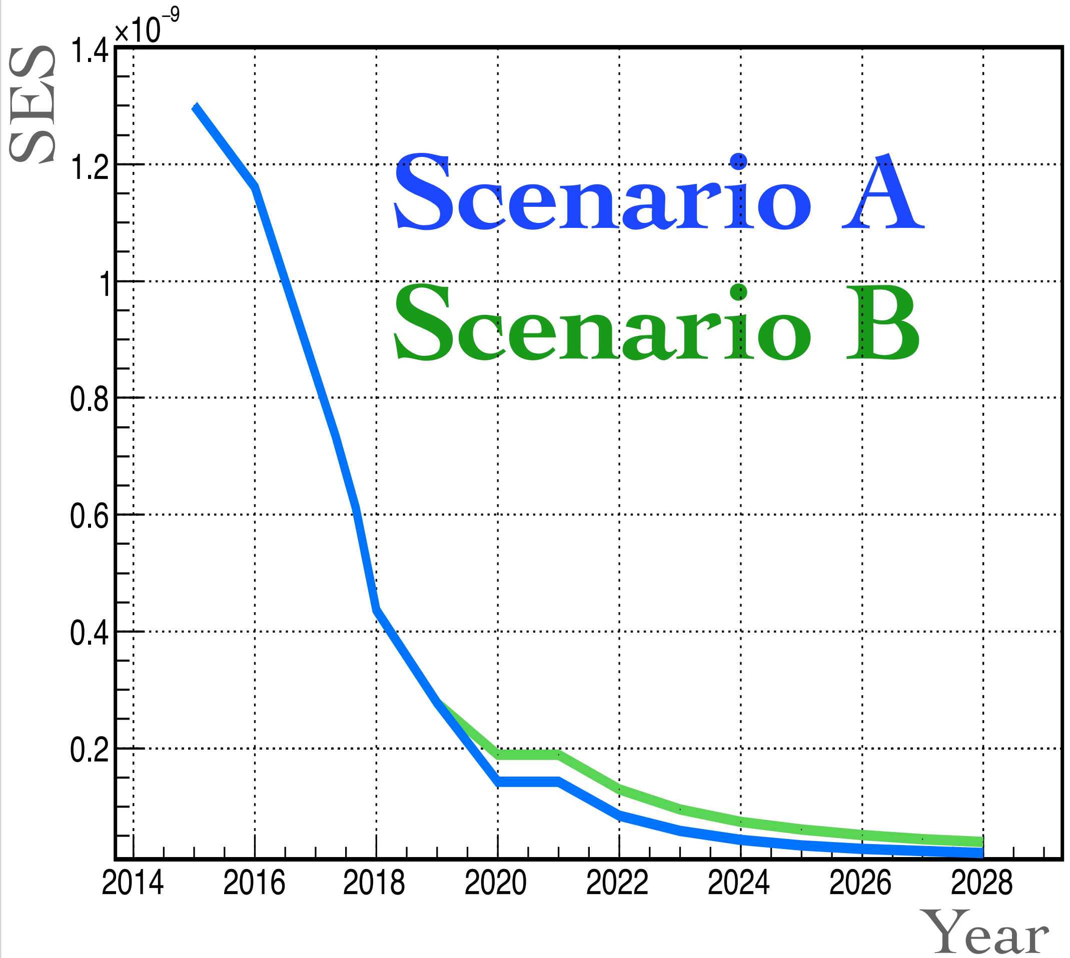
PRELIMINARY

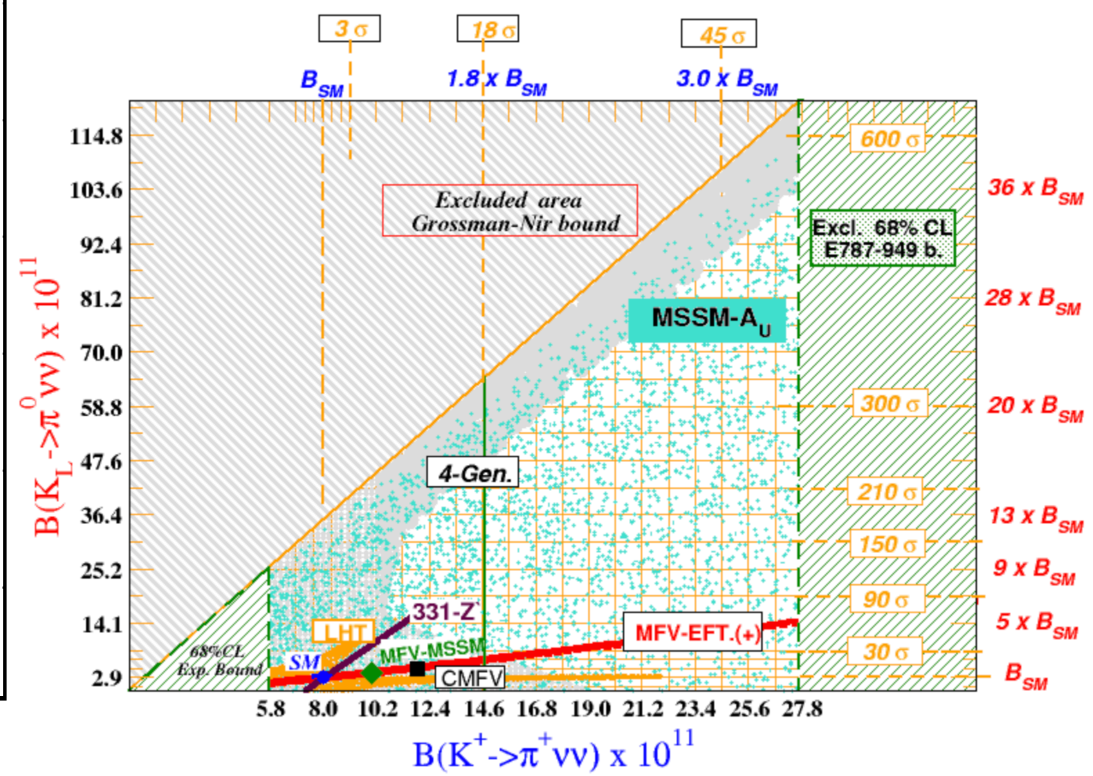
Future Runs

New Main Ring Power Supply

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 (month)					2	4	-	4	4	4
Scenario B (month)					2	2	-	2	2	2

New Target for Higher B.P.
Add Shielding to Reduce Acc.





Summary

Recent Result: U.L.[$K_L \to \pi^0 \upsilon\upsilon$] = 3.0×10^{-9} (90% C.L.)

- Based on Data Collected in 2015
- Before several Major Detector/DAQ Upgrades

Status of 2016-2018 Data Analysis

- Better Detector, DAQ & Analysis Methods
- Expect U.L. to Cross G-N Limit
- Results Coming Soon in Summer 2019
- By-product Analysis is on-going

Future Run toward SES(10^{-11}) with 100kW Beam Power

- Detector/DAQ is Ready
- Background under Control