Recent Results from KOTO Experiment

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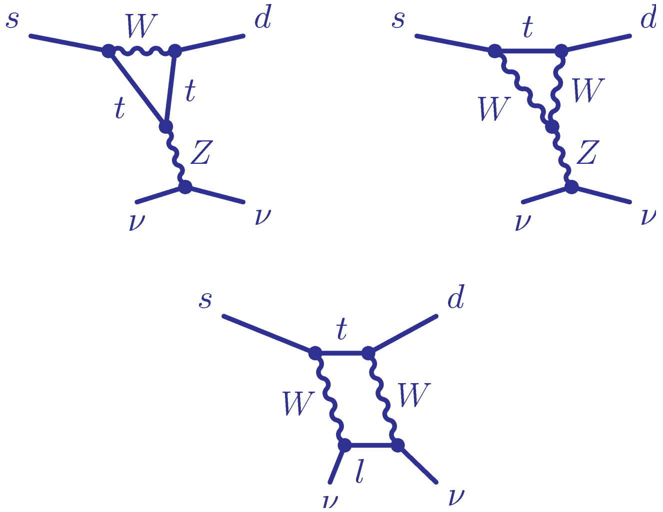
J-PARC E14 KOTO collaboration

- Japan
    - KEK
    - Kyoto Univ.
    - NDA
    - Okayama Univ.
    - Osaka Univ.
    - Saga Univ.
    - Yamagata Univ.
- USA
    - Arizona State Univ.
    - Univ. of Chicago
    - Univ. of Michigan, Ann Arbor
- Russia
    - JINR
- Taiwan
    - National Taiwan Univ.
- Korea
    - Chonbuk National Univ.
    - Jeju National Univ.
    - Korea Univ.

36 experimental physicists from the institutes in Japan
and 36 from abroad
participate in the KOTO experiment.

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

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



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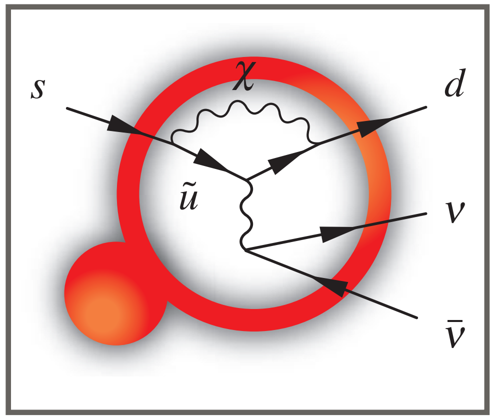


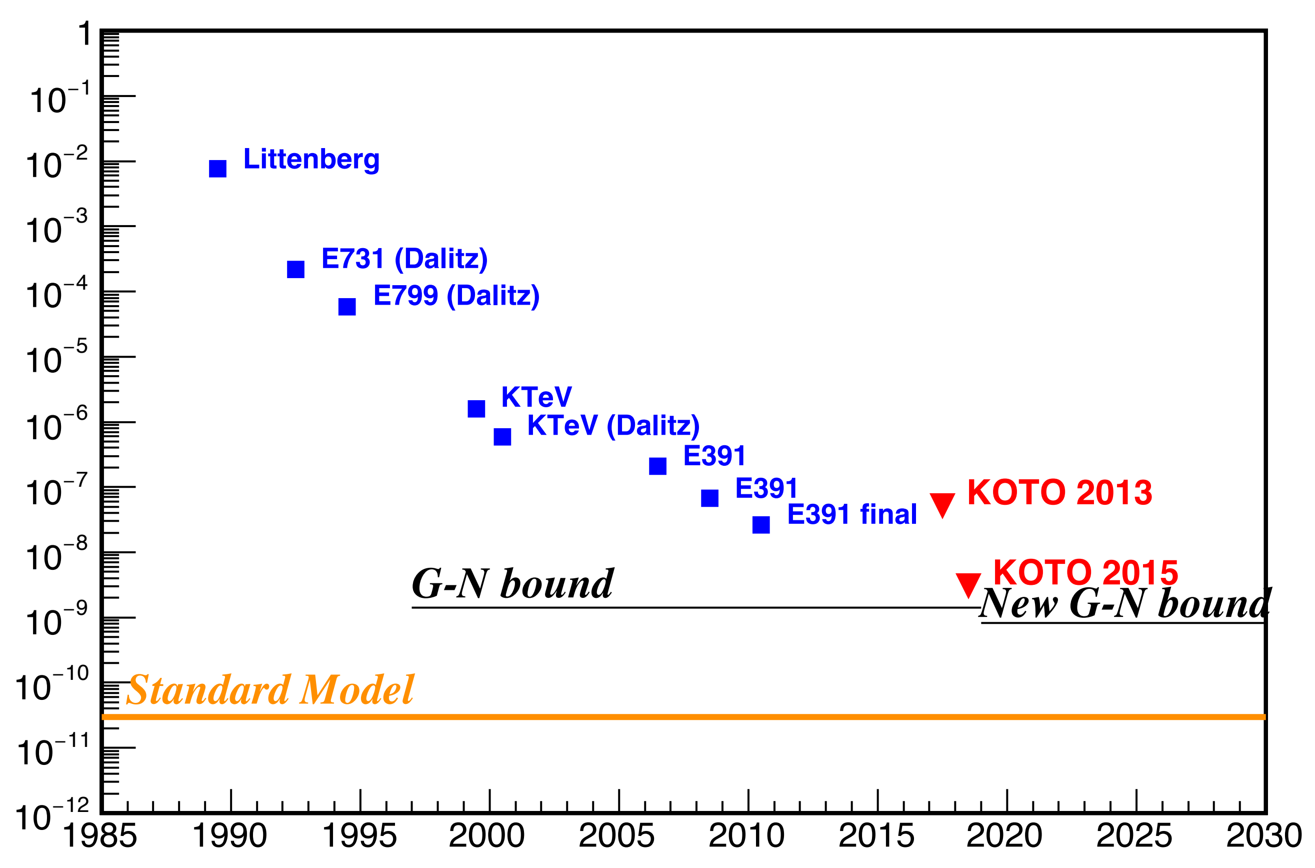
?

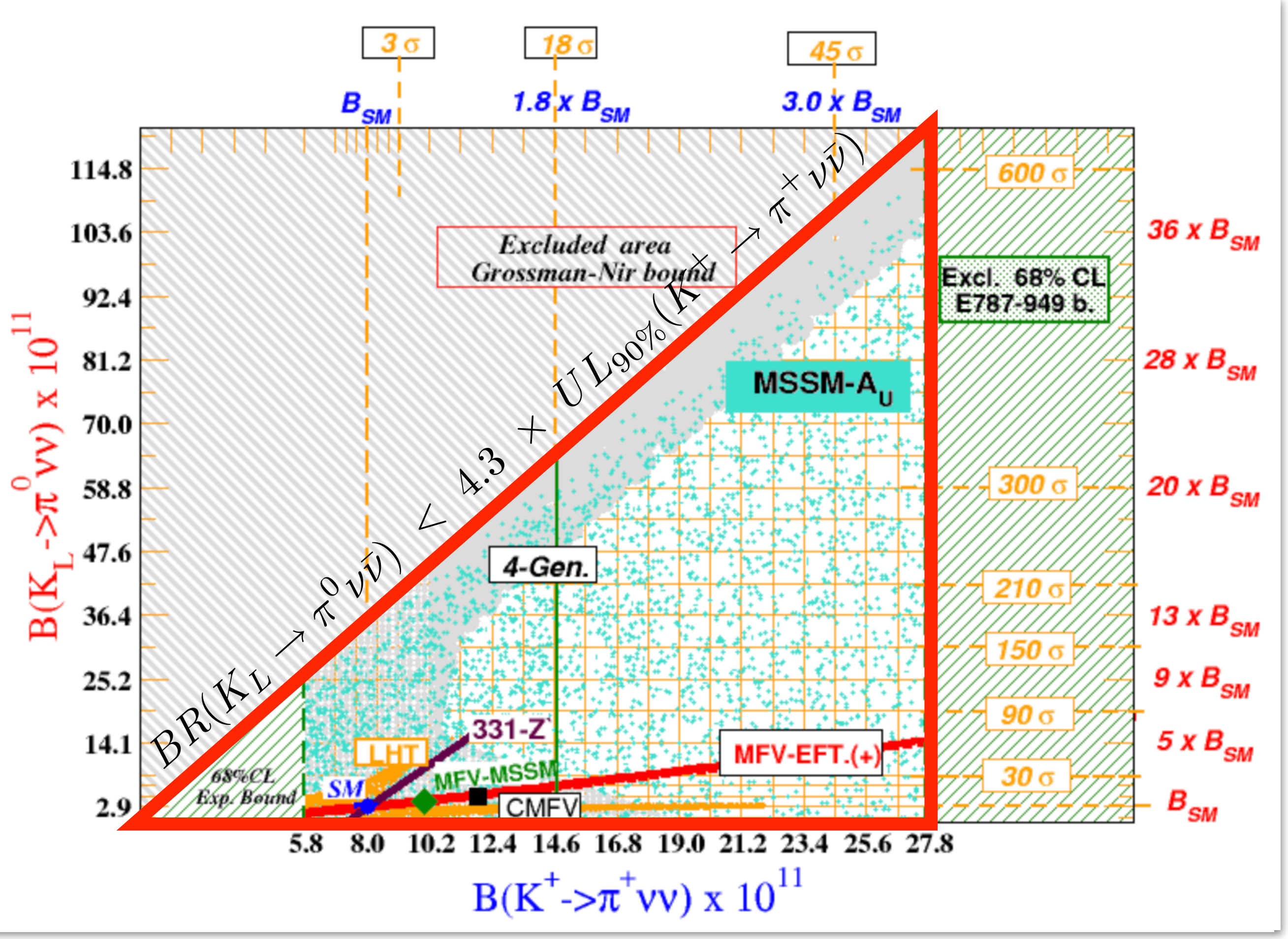
- BR(SM) = 3×10^{-11} with less than 2% theoretical uncertainty
  - clean window for probing New Physics contributions

Historical Limits

KOTO-I:

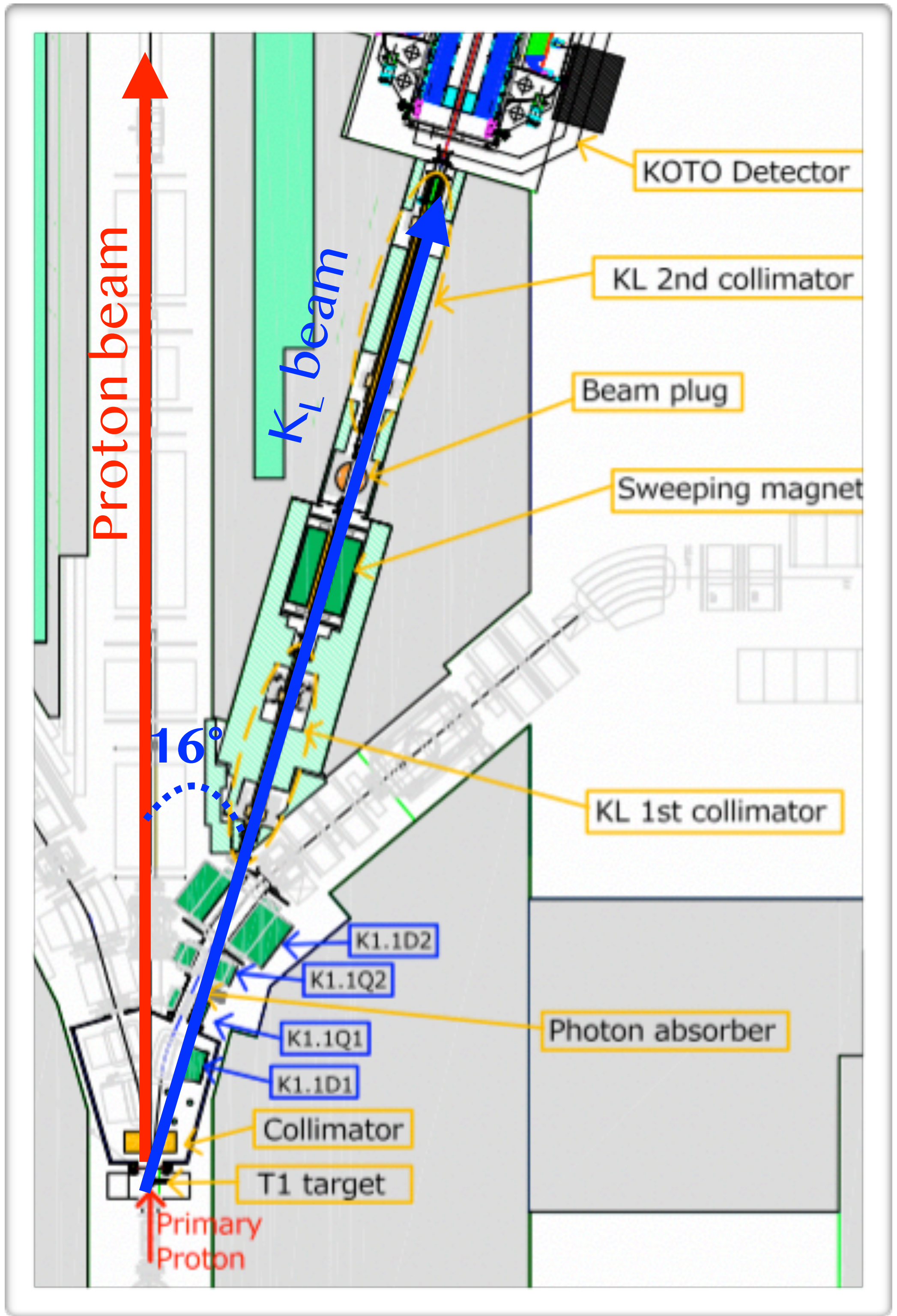
- The first experiment with the designed sensitivity of ~O(-11) for $K_L \rightarrow \pi^0 \nu\nu$
- The current world best limit by KOTO (2015 result) is right above Grossman-Nir bound.
- Will perform critical tests of standard and NP models in the near future.



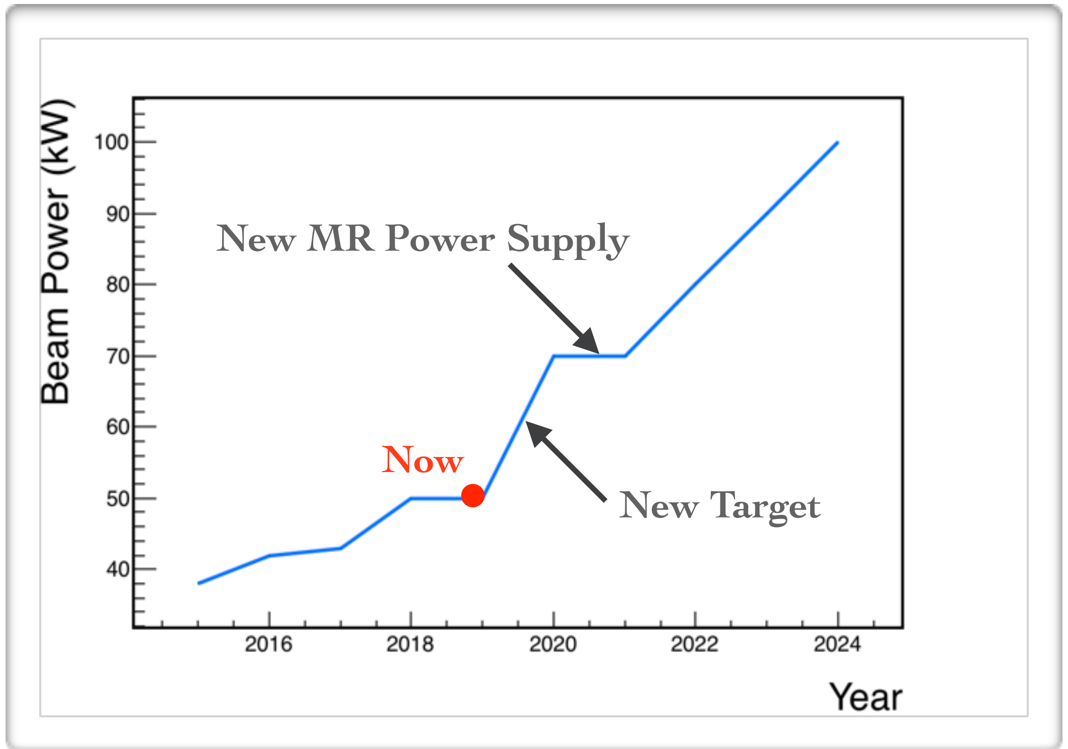


http://www.lnf.infn.it/wg/vus/content/Krare.html

Kaon @ J-PARC



- Proton
  - ~5×10^{13} protons per 2s spill @ 50kW beam power
  - Target beam power: 100kW
- Kaon
  - Momentum peaked @ 1.4 GeV



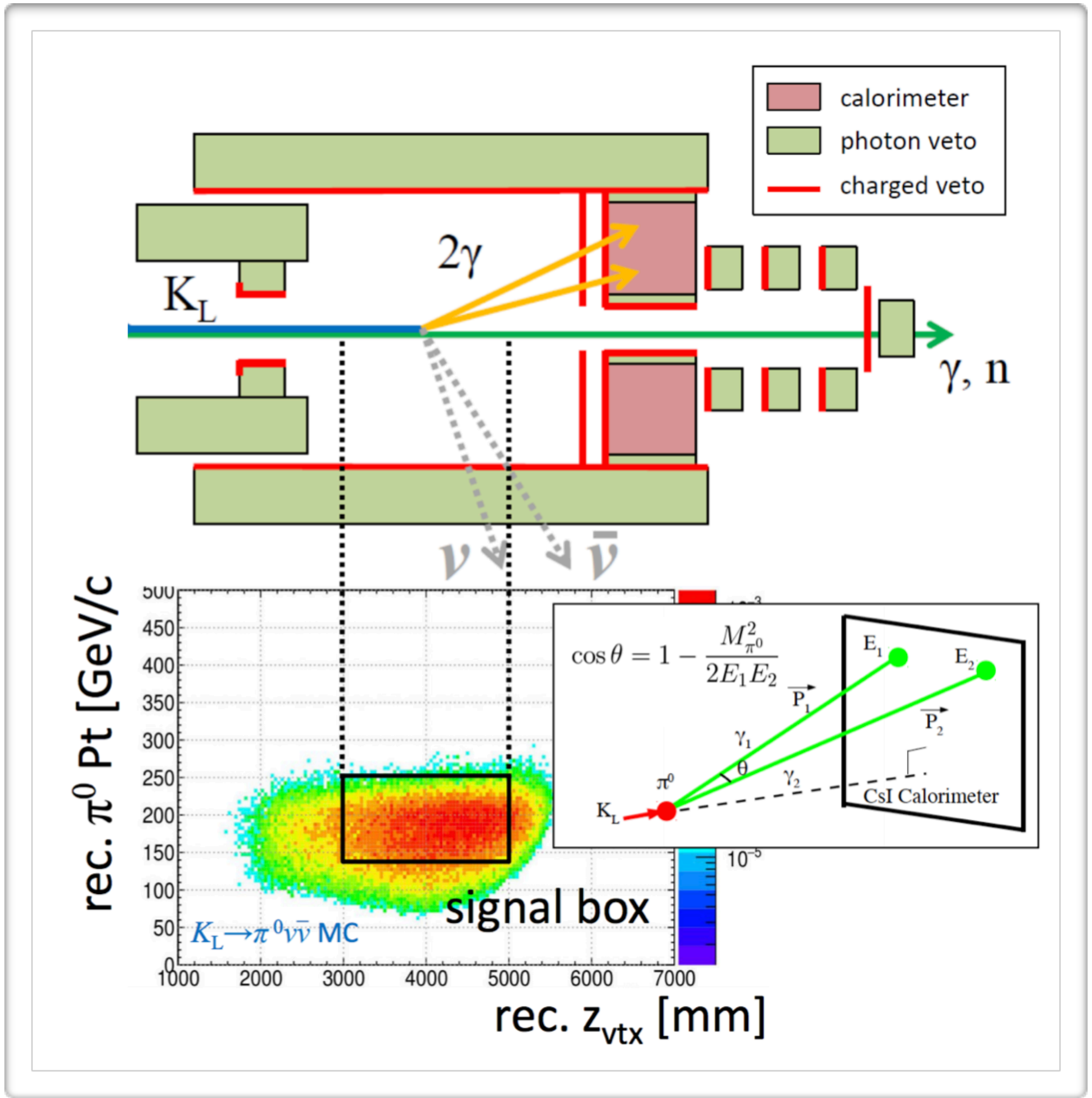
Signal Detection

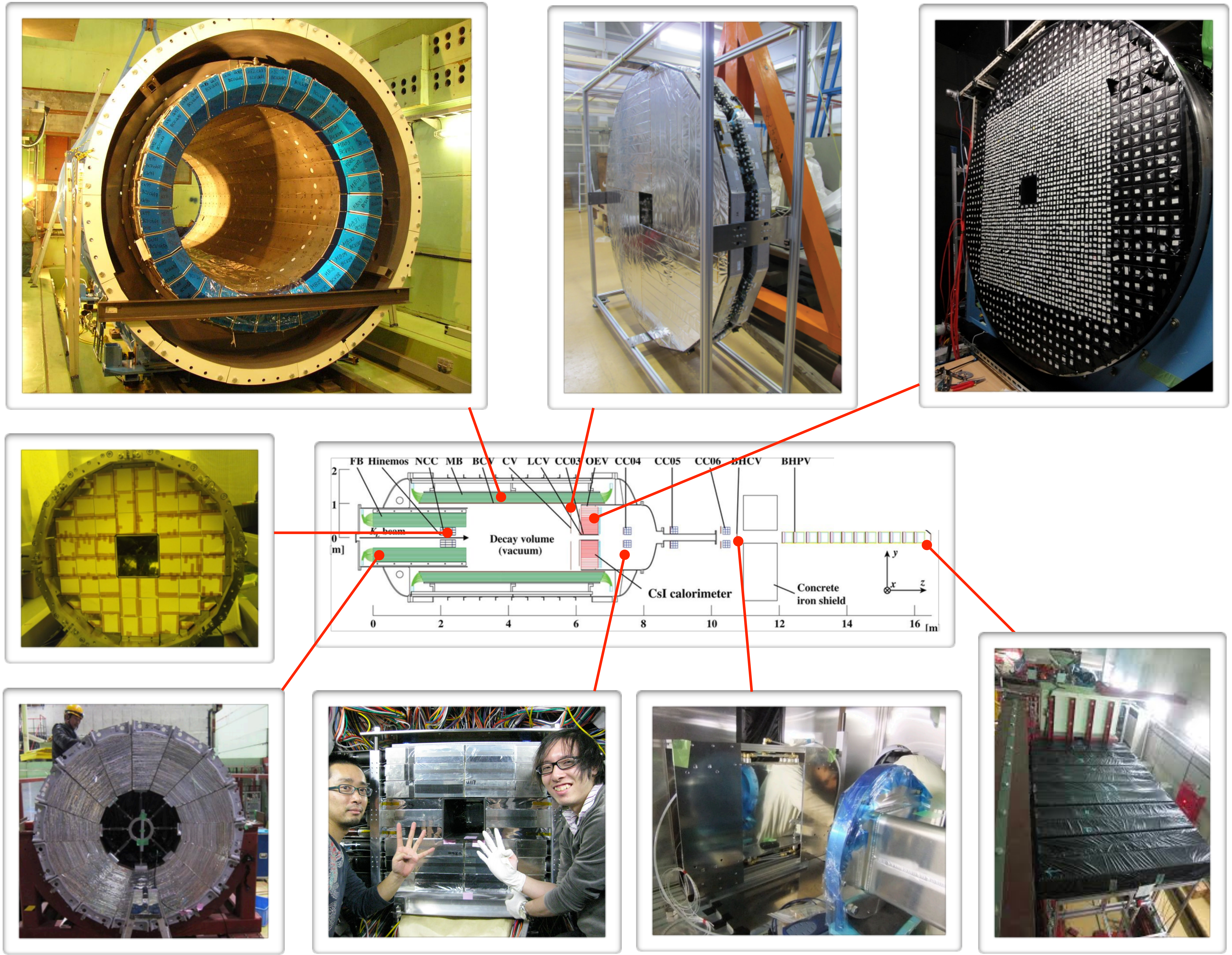
- $K_L \rightarrow \pi^0 \nu\ \nu$

Invisible

  - 2γ with high P_T = signal
- Hermetic Detector
  - no signal in veto detectors

Mode	BR	Handles
$K_L \rightarrow \pi^{\pm}e^{\mp}\nu$	40.6%	charged (x2), non-EM (x1)
$K_L \rightarrow \pi^{\pm}\mu^{\mp}\nu$	27.0%	charged (x2), non-EM (x1)
$K_L \rightarrow \pi^{+}\pi^{-}\pi^{0}$	12.5%	charged (x2), low π^0 Pt
$K_L \rightarrow \pi^{0}\pi^{0}\pi^{0}$	19.5%	extra photon (x4)
$K_L \rightarrow \gamma\gamma$	5.5x10-4	low Pt, back-to-back symmetry
$K_L \rightarrow \pi^{+}\pi^{-}$	2.0x10-3	charged (x2), non-EM (x2)
$K_L \rightarrow \pi^{0}\pi^{0}$	8.6x10-4	extra photon (x2)

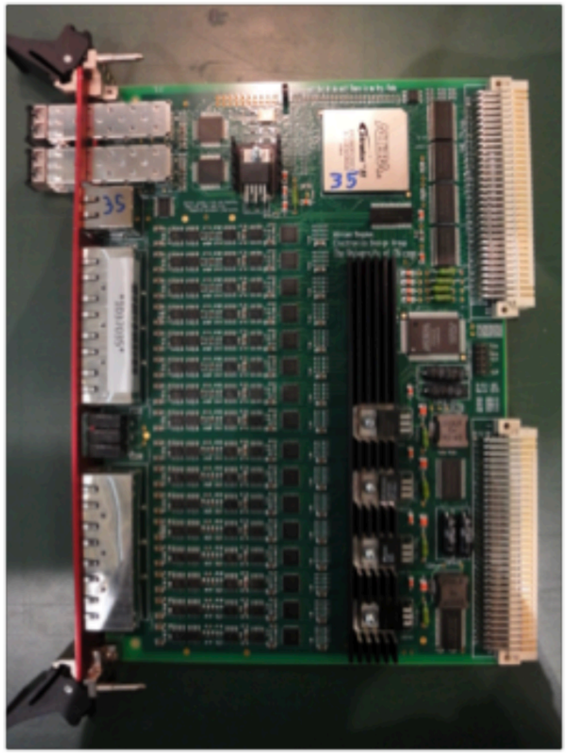



FB
Hinemos
NCC
MB
BCV
CV
LCV
CC03
OEV
CC04
CC05
CC06
BHCV
BHPV
2
1
0
[m]
K_L beam
Decay volume
(vacuum)
CsI calorimeter
Concrete
iron shield
y
x
z
0
2
4
6
8
10
12
14
16
[m]

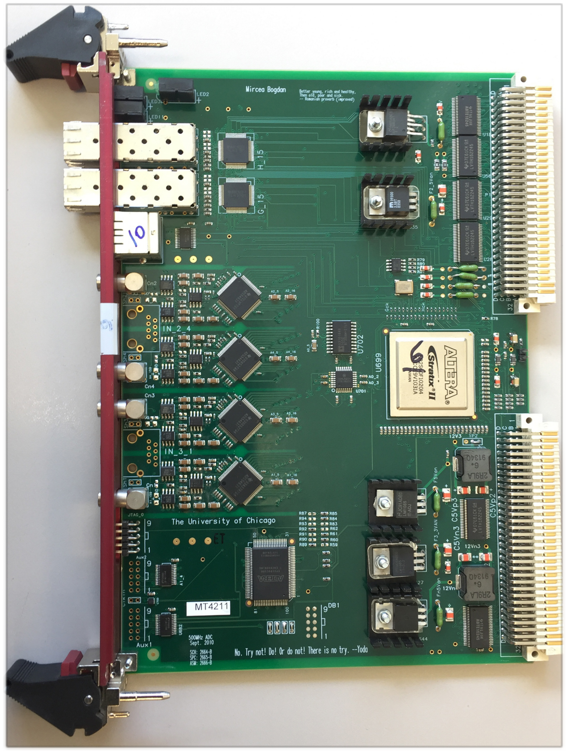
Custom-made DAQ Modules by UChicago E-Shop

(Ref: https://edg.uchicago.edu/~bogdan/)

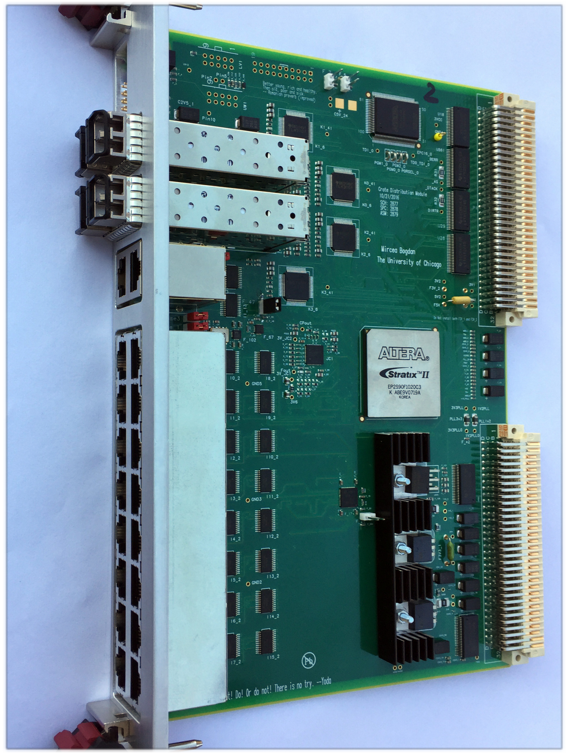
14-bit 16CH 125MHz ADC
- Stratix-II FPGA



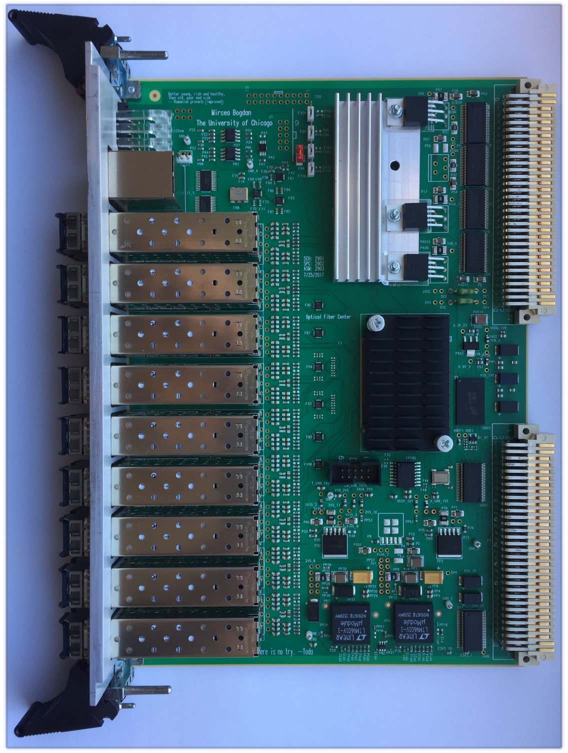
12-bit 4CH 500MHz ADC
- Stratix-II FPGA



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
- Leve-I & Level-II module



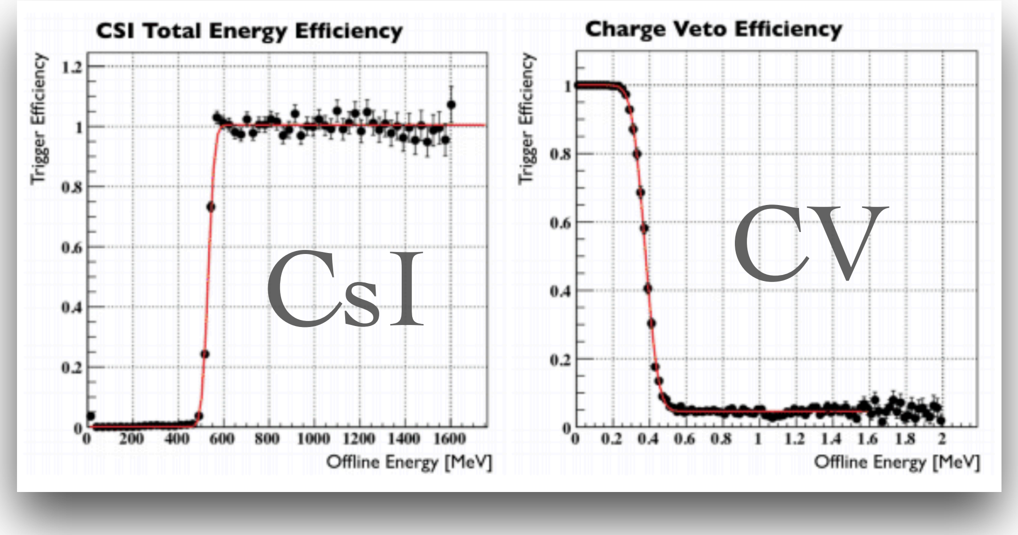
Level-I Trigger (2018-)

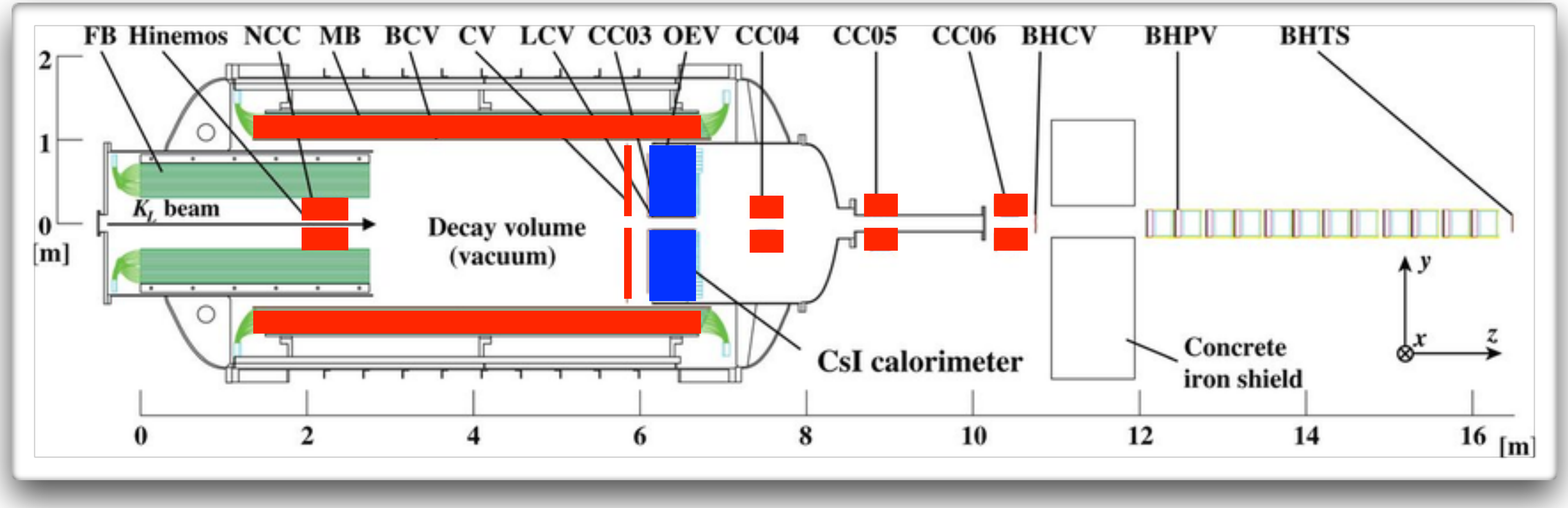
Triggering on:

🟦 CsI energy sum, and

🟥 No energy in veto counters

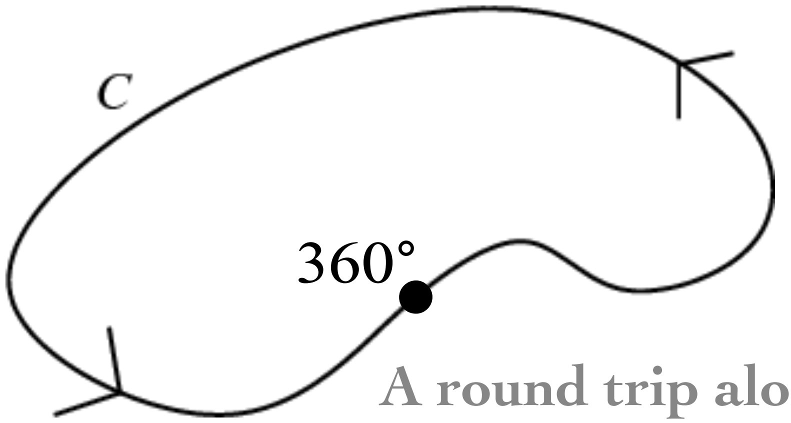
Offline Energy distribution after online cut





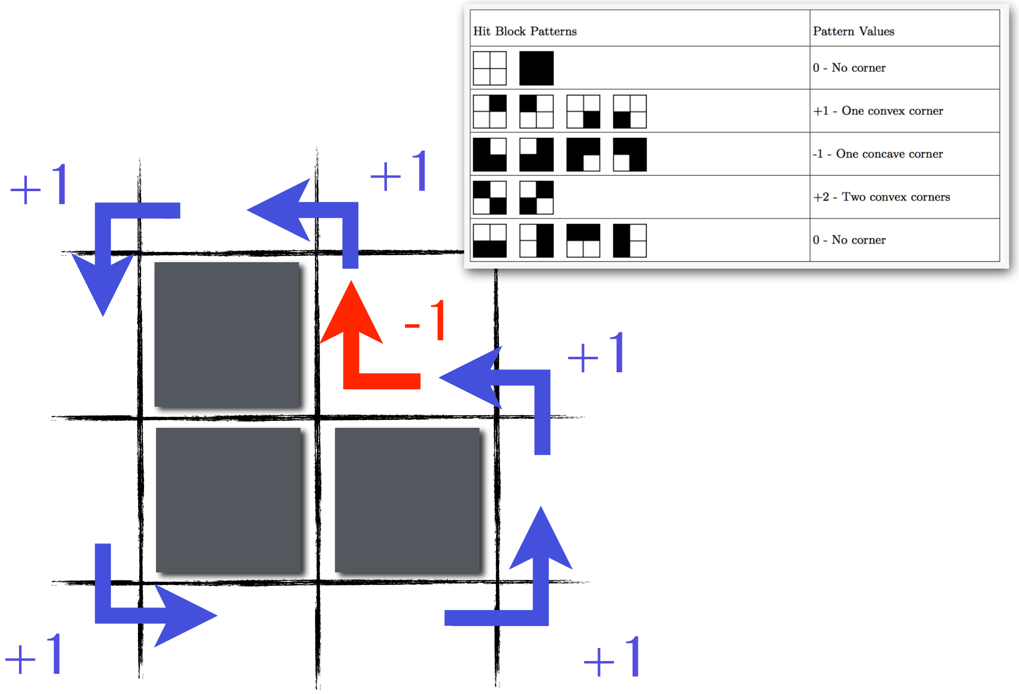
Level-II Trigger (2017-)

- 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
- Trigger Efficiency:

Lv2 Trig.	Trigger Eff.
2	99.6%
3	96.8-99.6%
4	96.8%
6	92.2%

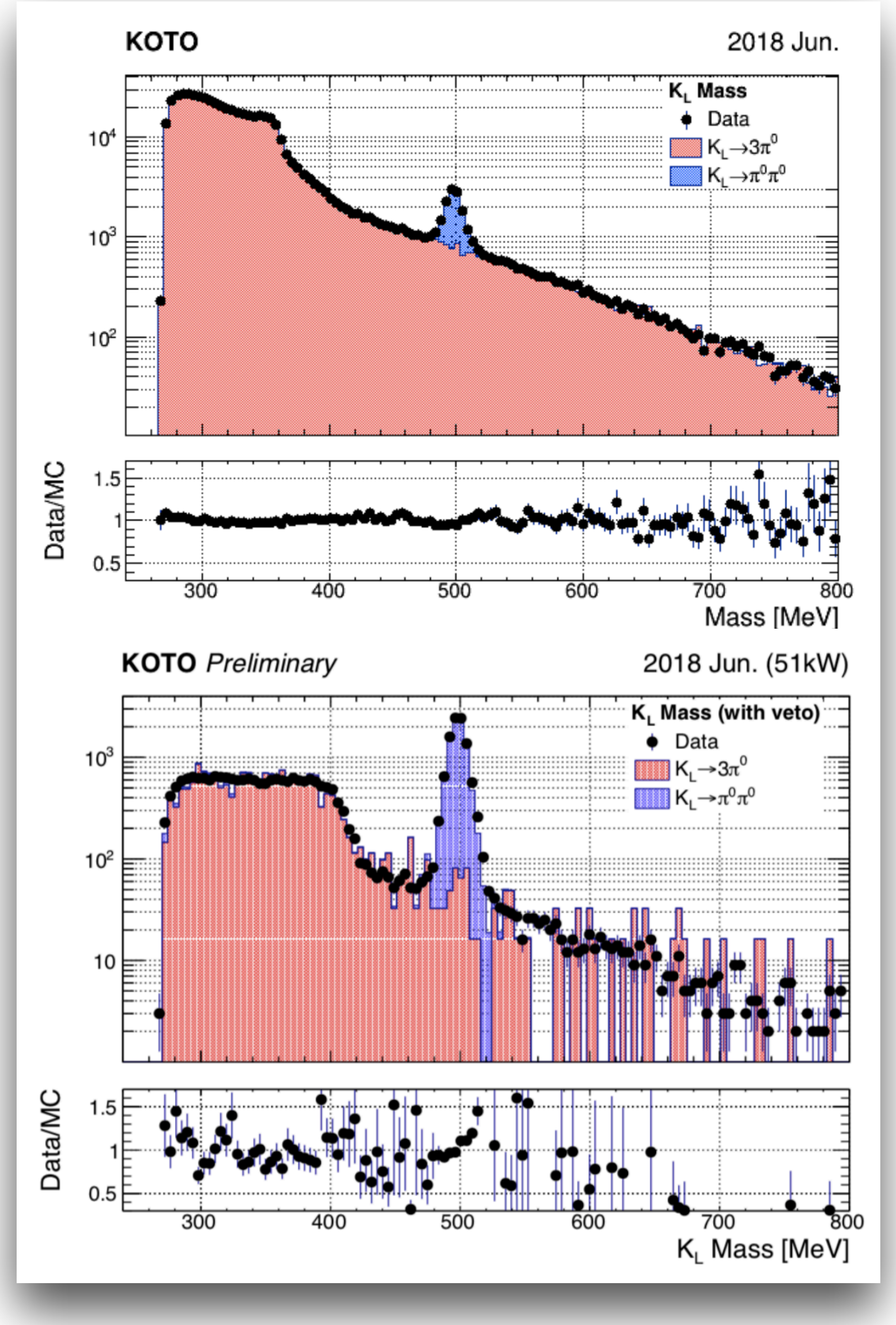
$K_L \rightarrow \pi^0 \nu\nu$ Analysis

Kaon Background

- Kaon backgrounds were studied based on the MC simulation.
- MC's were overlapped by accidental data (target monitor) taken along with physics run.
- Kaon background is negligible at current data statistics based on the MC study.

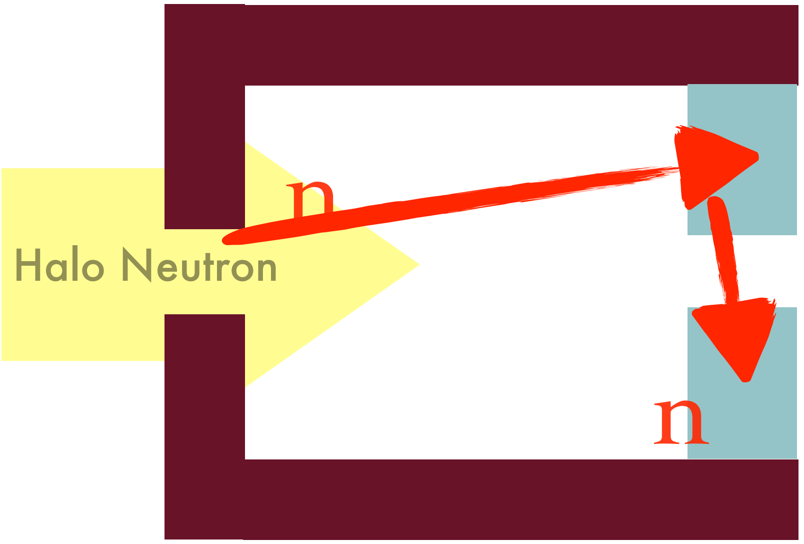
Decay Mode	Stat. (MC/data)	#BG
$K_L \to \pi^0\pi^0$	~13	<0.18
$K_L \to \pi^0\pi^0\pi^0$	~59	<0.04
$K_L \to \pi^+\pi^-\pi^0$	~87	<0.02
$K_L \to \pi^\pm e^\mp \nu$	~28	<0.09
$K_L \to \gamma\gamma$	~189	0.005

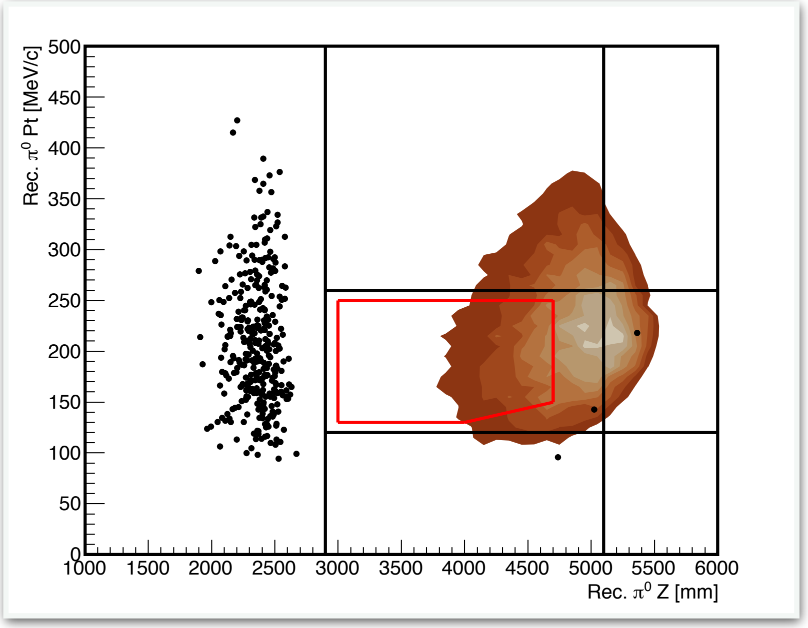
Data/MC Comparison



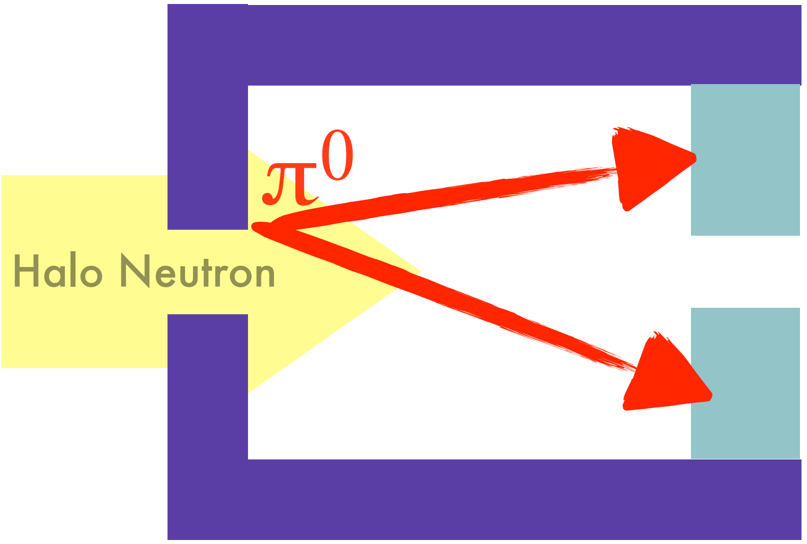
Neutron Background

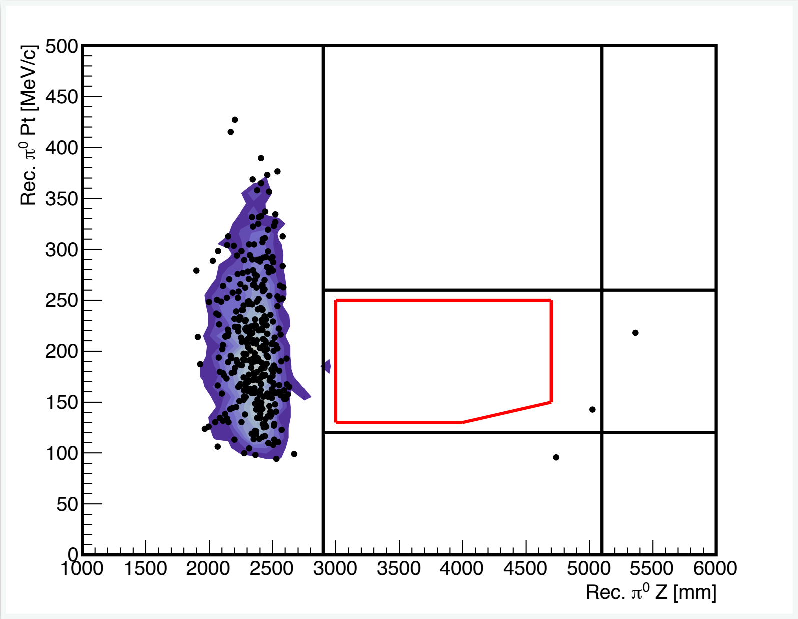
Hadron Cluster



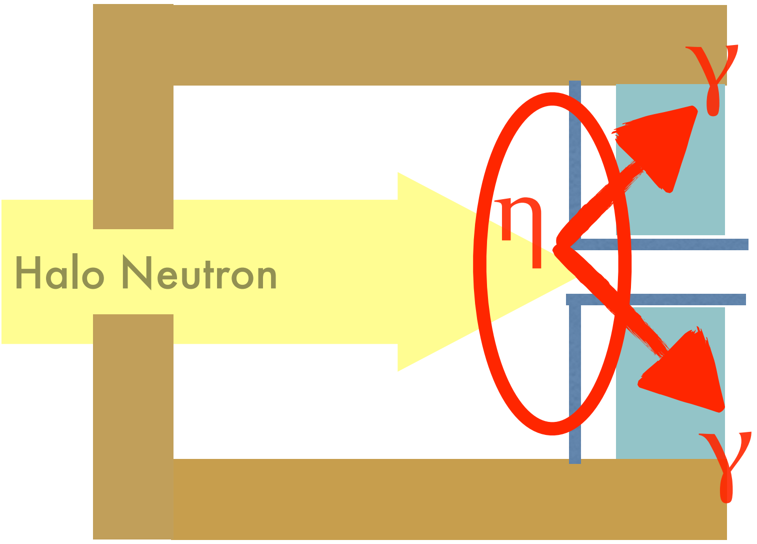


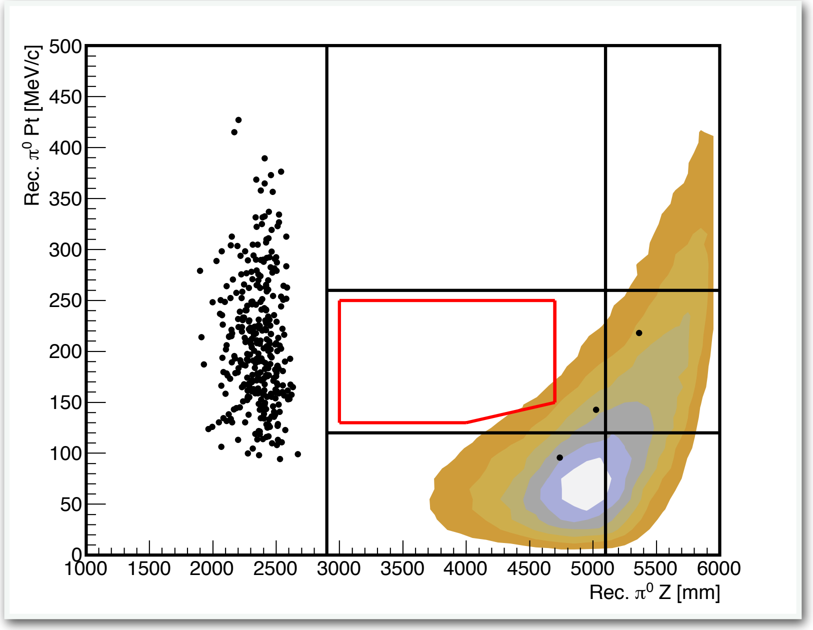
Upstream-π^0





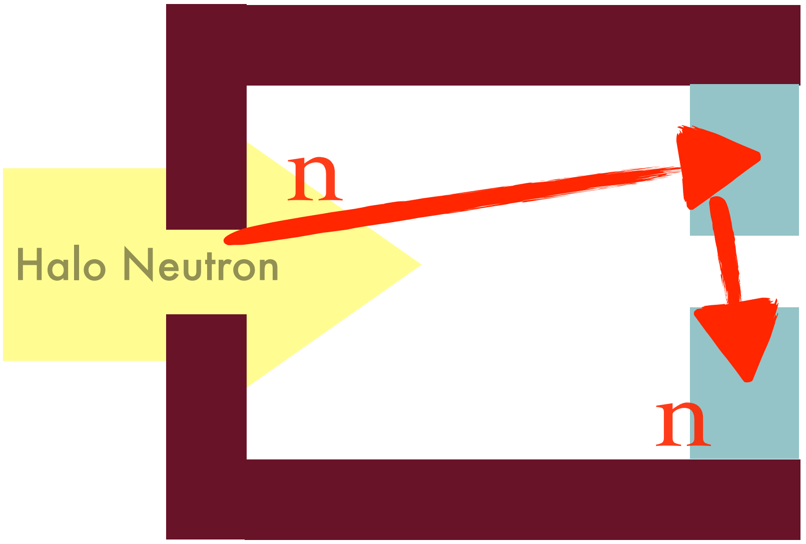
CV-η



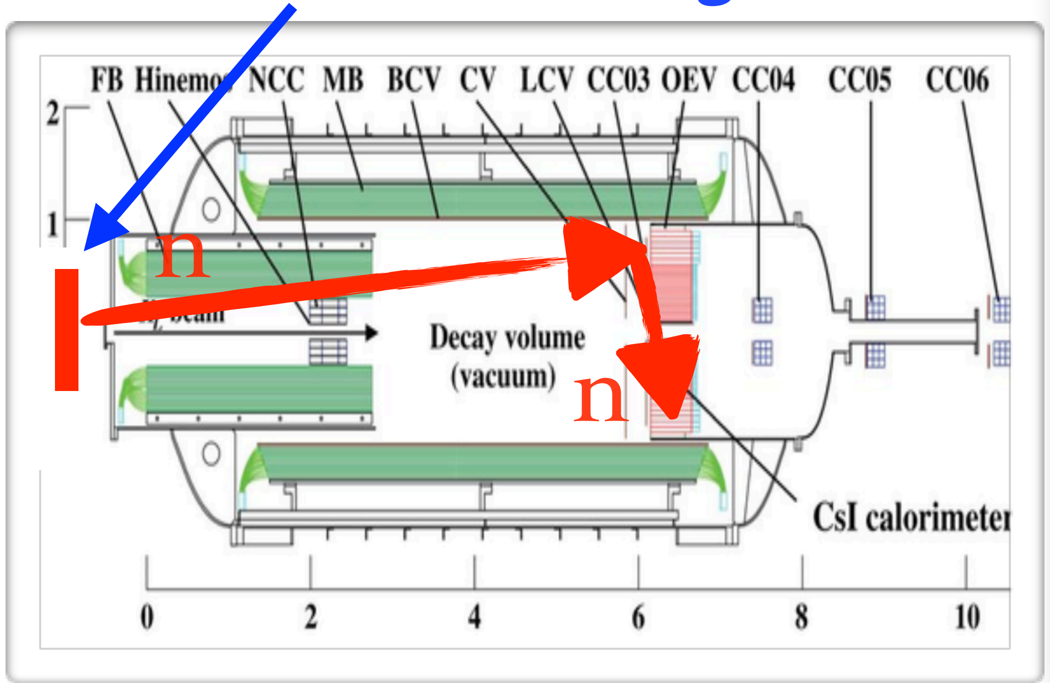


Neutron Background

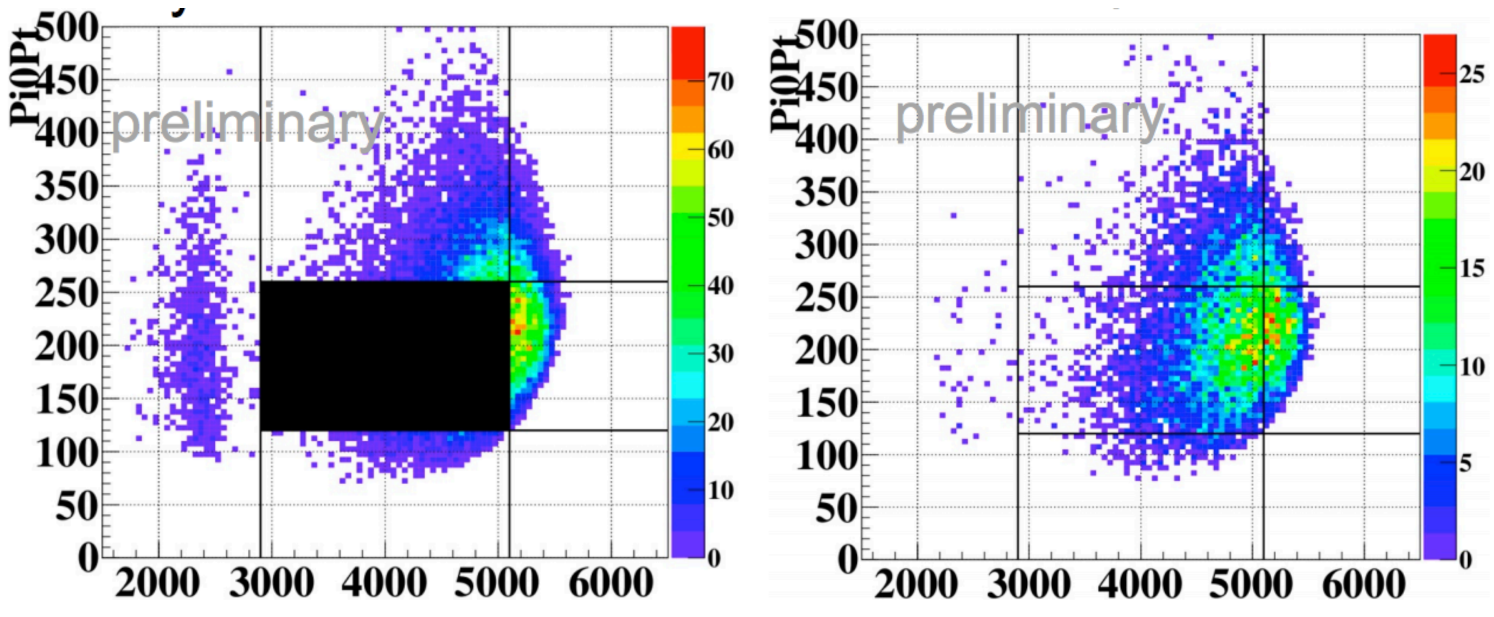
Hadron Cluster



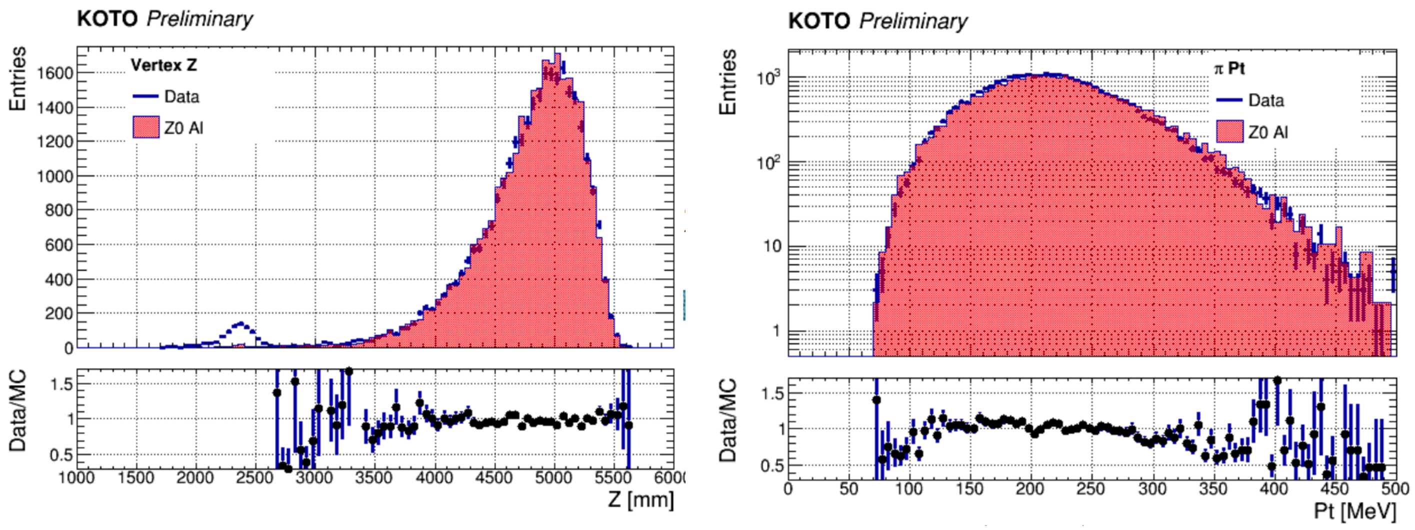
Aluminum Target



Physics vs. Neutron data



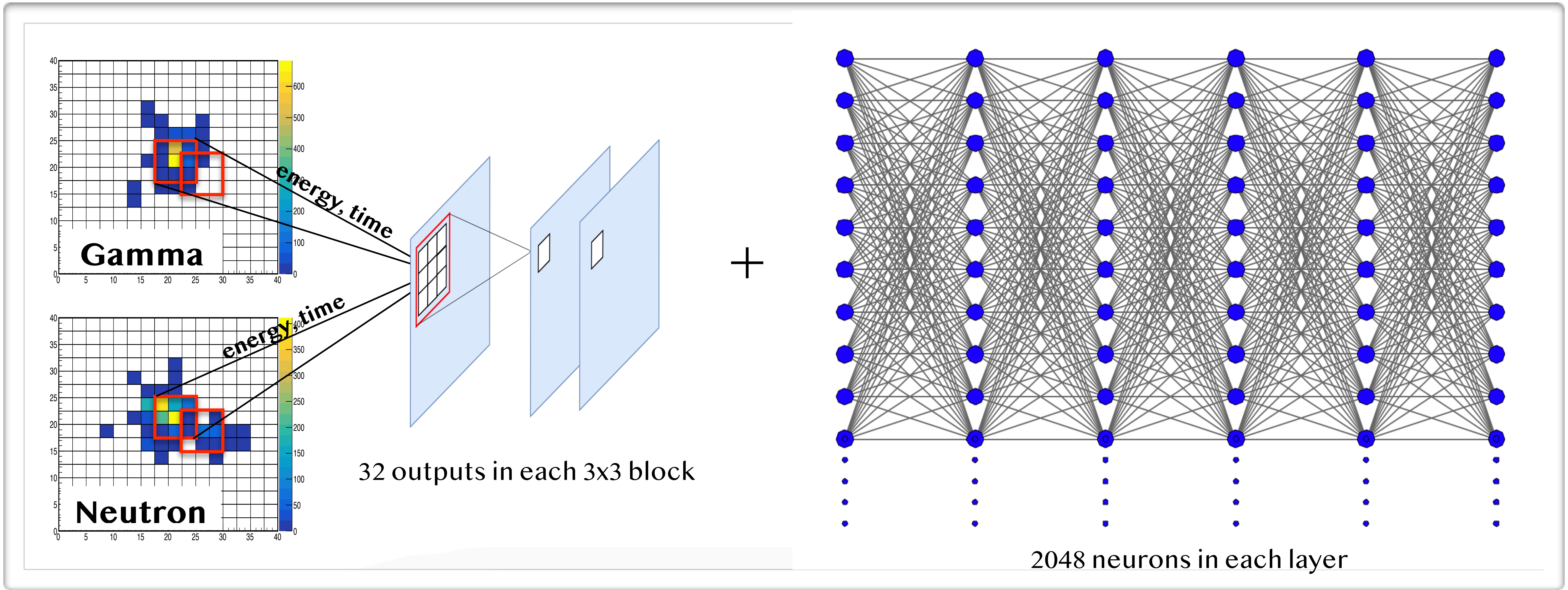
Physics (unblinded) vs. Neutron data



Neutron Background - CSD

Cluster Shape Discrimination (CSD)

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

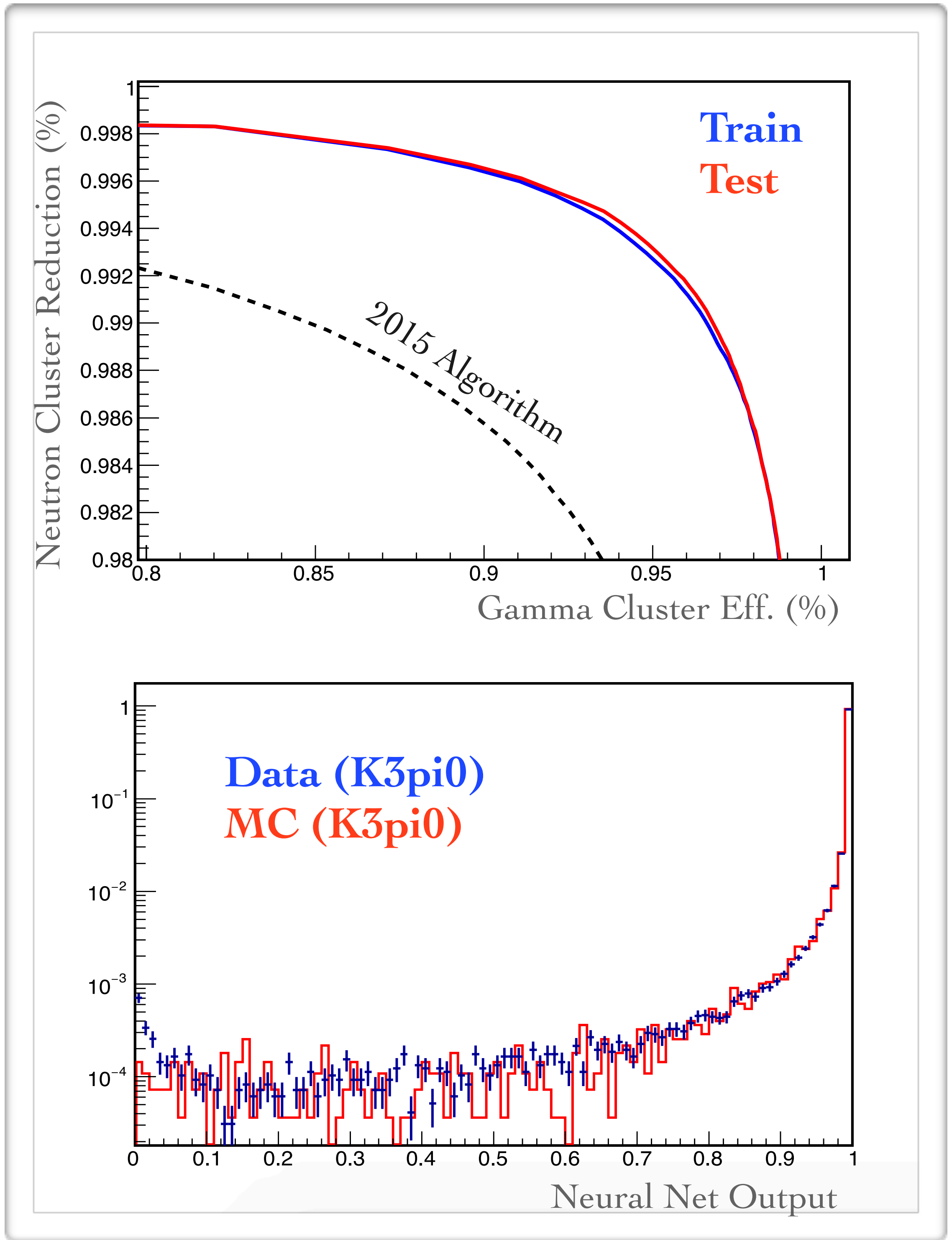


32 outputs in each 3x3 block

2048 neurons in each layer

Neutron Background - CSD

- Neutron Samples:
  - special neutron run
- Gamma Samples:
  - $K_L \to \pi^0 \nu\nu$ MC
- Data/MC good agreement
  - checked by $K_L \to \pi^0 \pi^0 \pi^0$
- Neutron BG reduction from CSD
  - ~$\mathcal{O}(10^{-5})$



Neutron Background - PSD

Pulse Shape Discrimination (PSD)

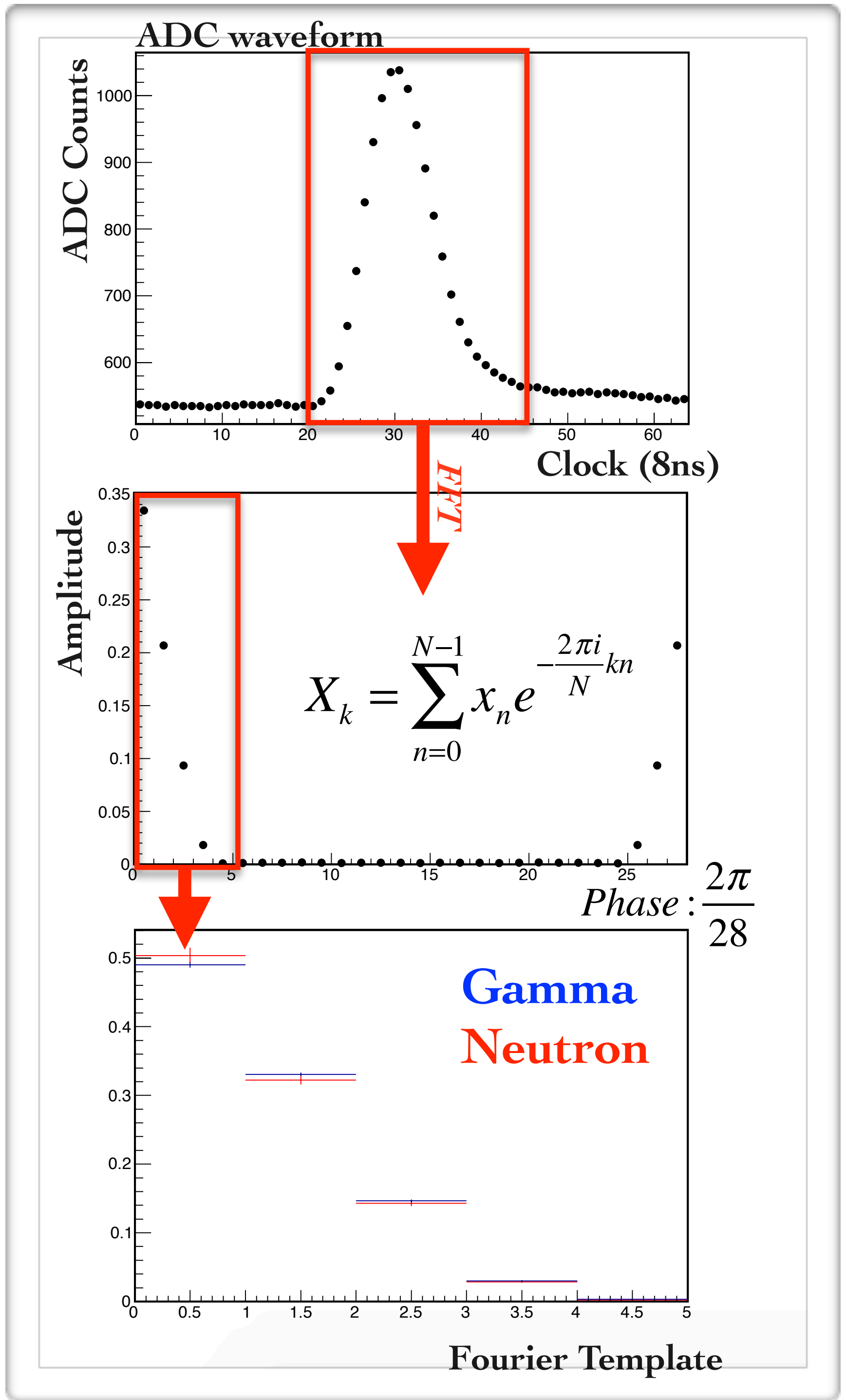
- Hadronic pulse wider than EM pulse

Fourier Analysis on ADC waveform

- Neutron Acceptance: 3.2%
- $K_L \to \pi^0 \nu\nu$ acceptance: 90%

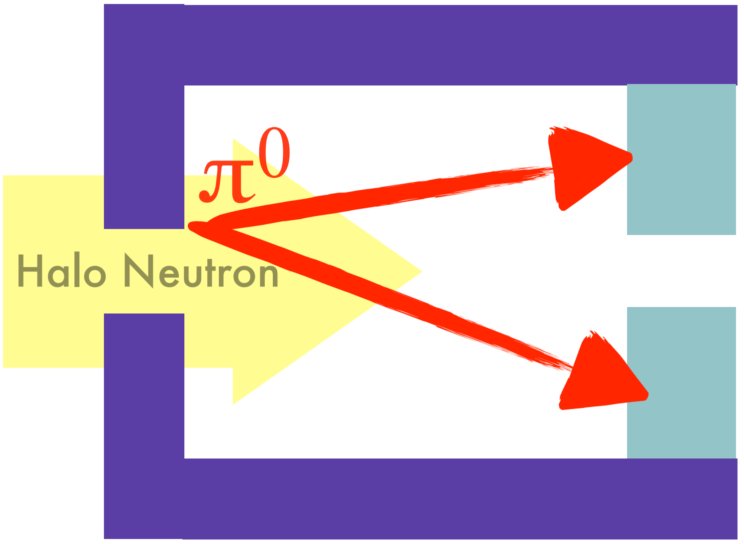
Combined Reduction of CSD+PSD

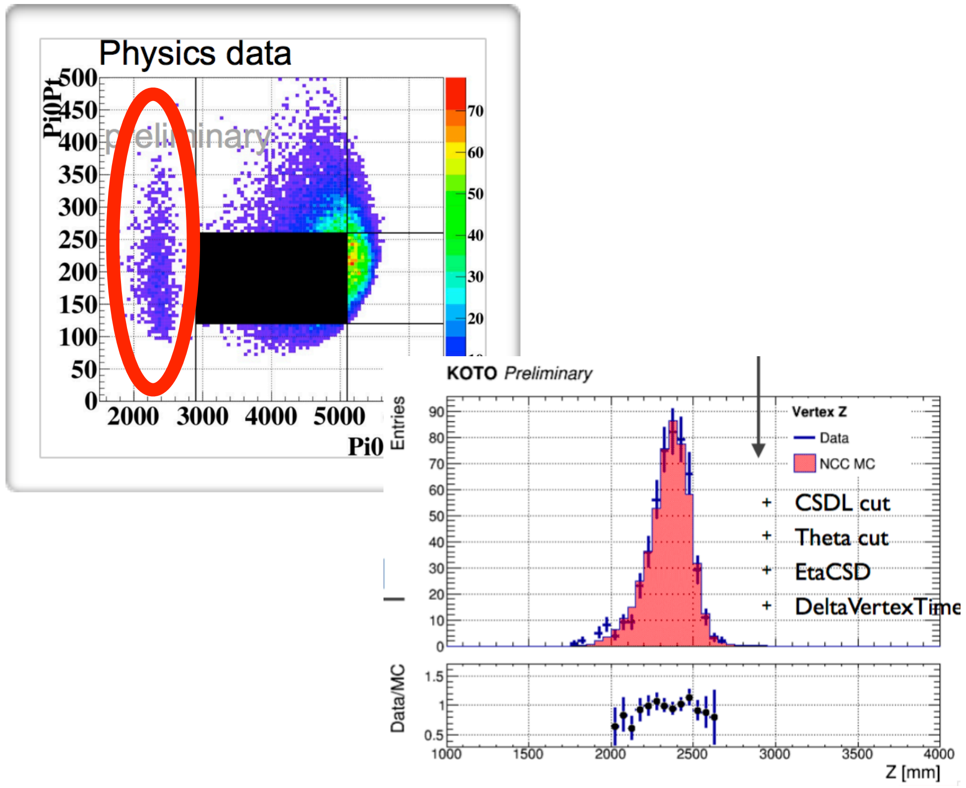
- $\sim O(10^{-6})$

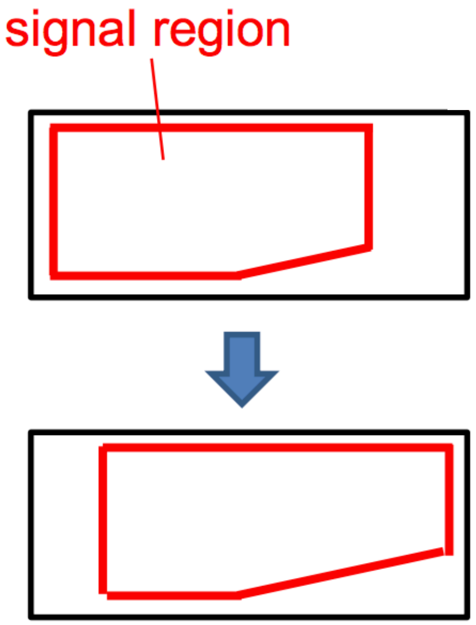


Neutron Background

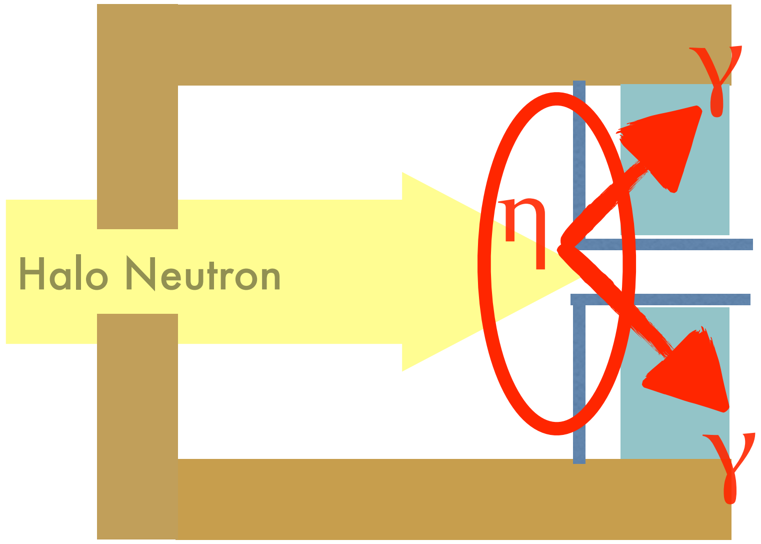
Upstream-π^0

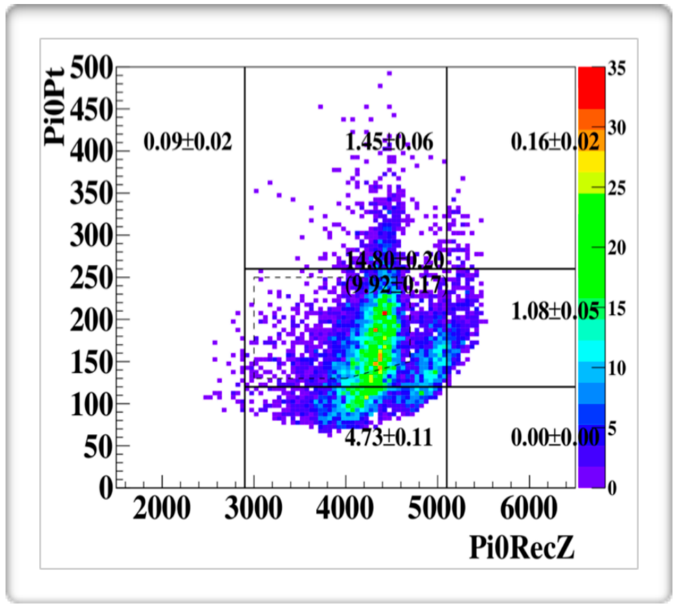


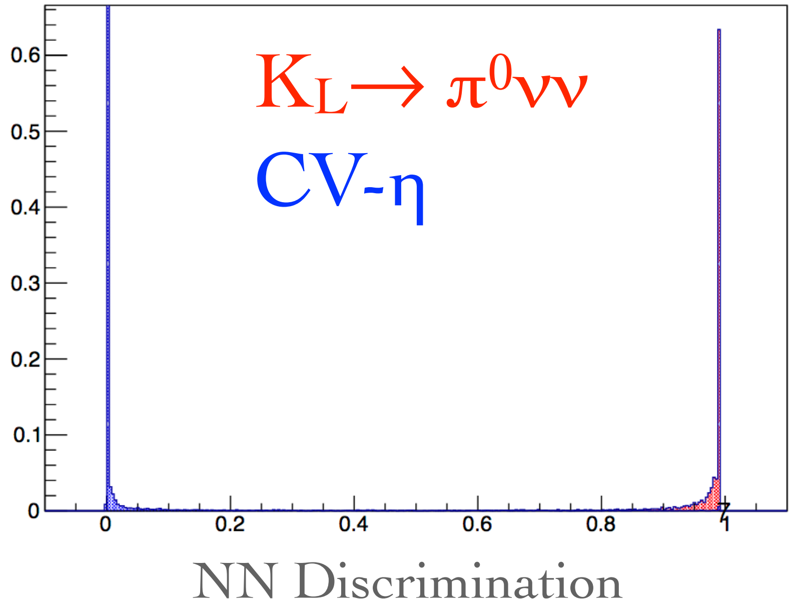




CV-η

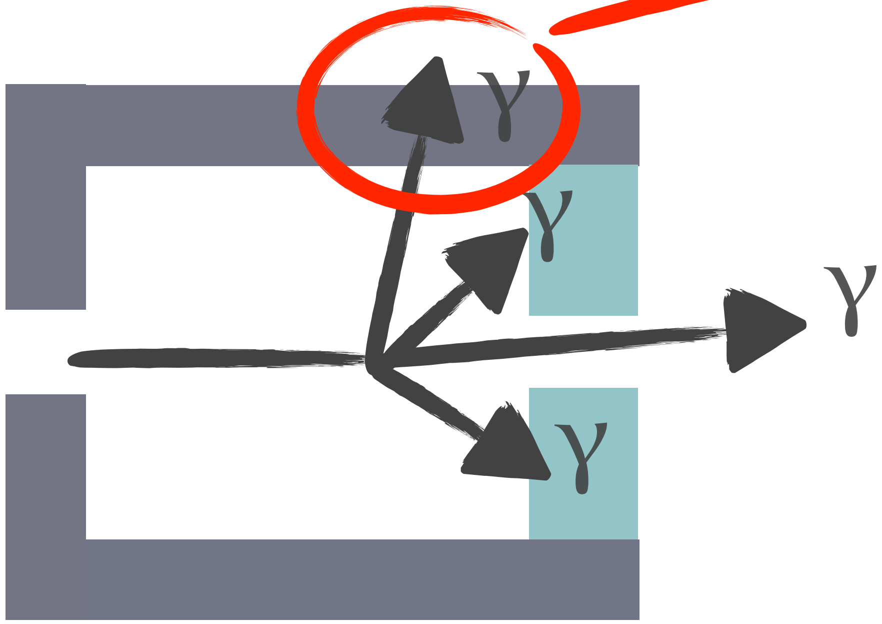


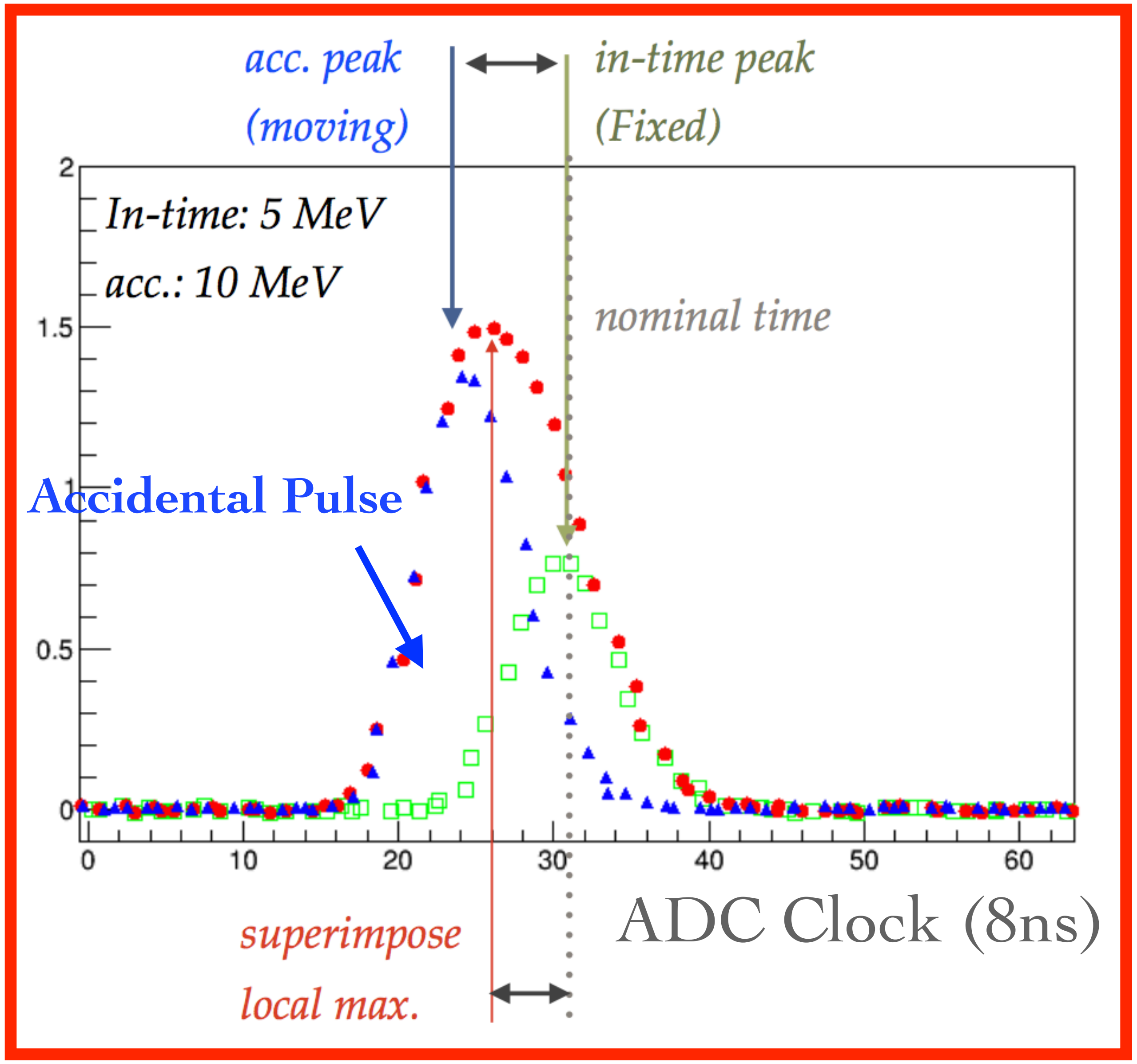




Accidental Background

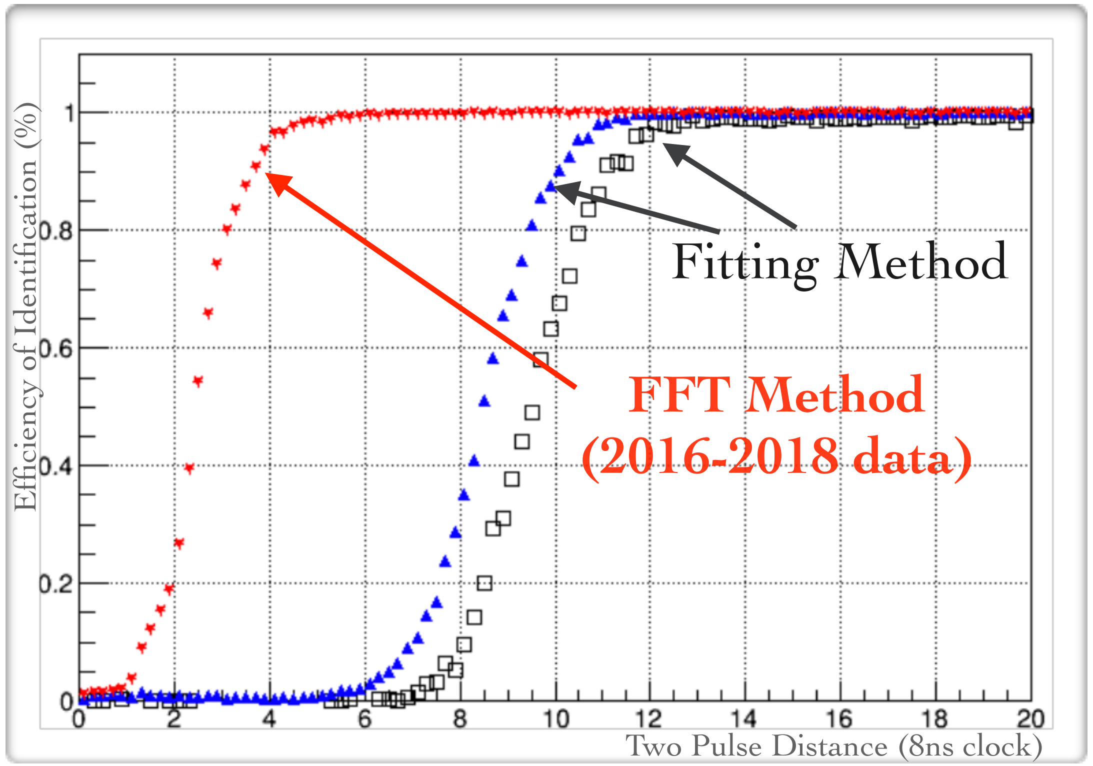
An in-time hit overlapped by an accidental pulse resulting in the measured timing outside the veto window.

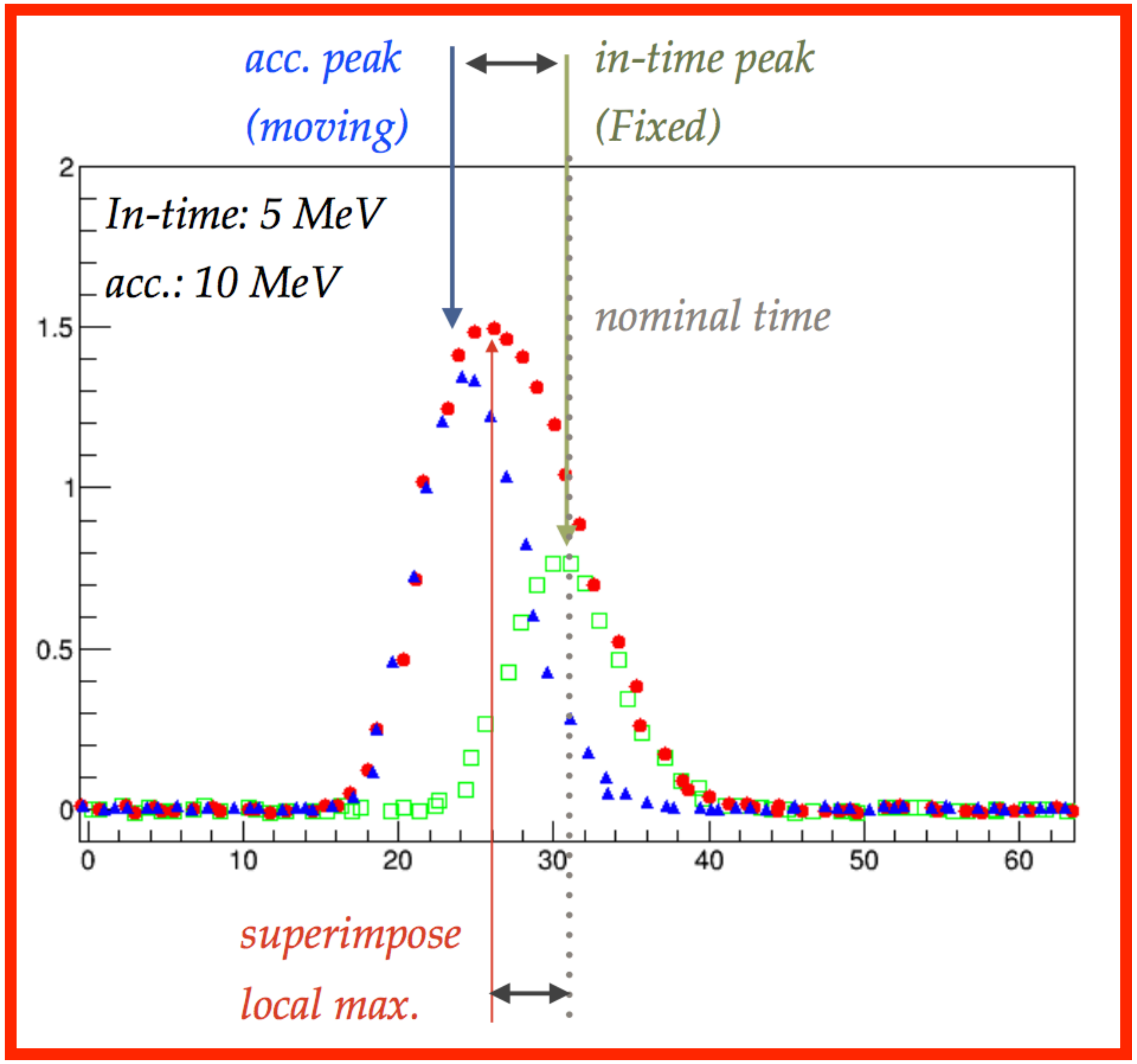




Accidental Background

Single/Double pulse discrimination
on frequency domain using Fourier analysis

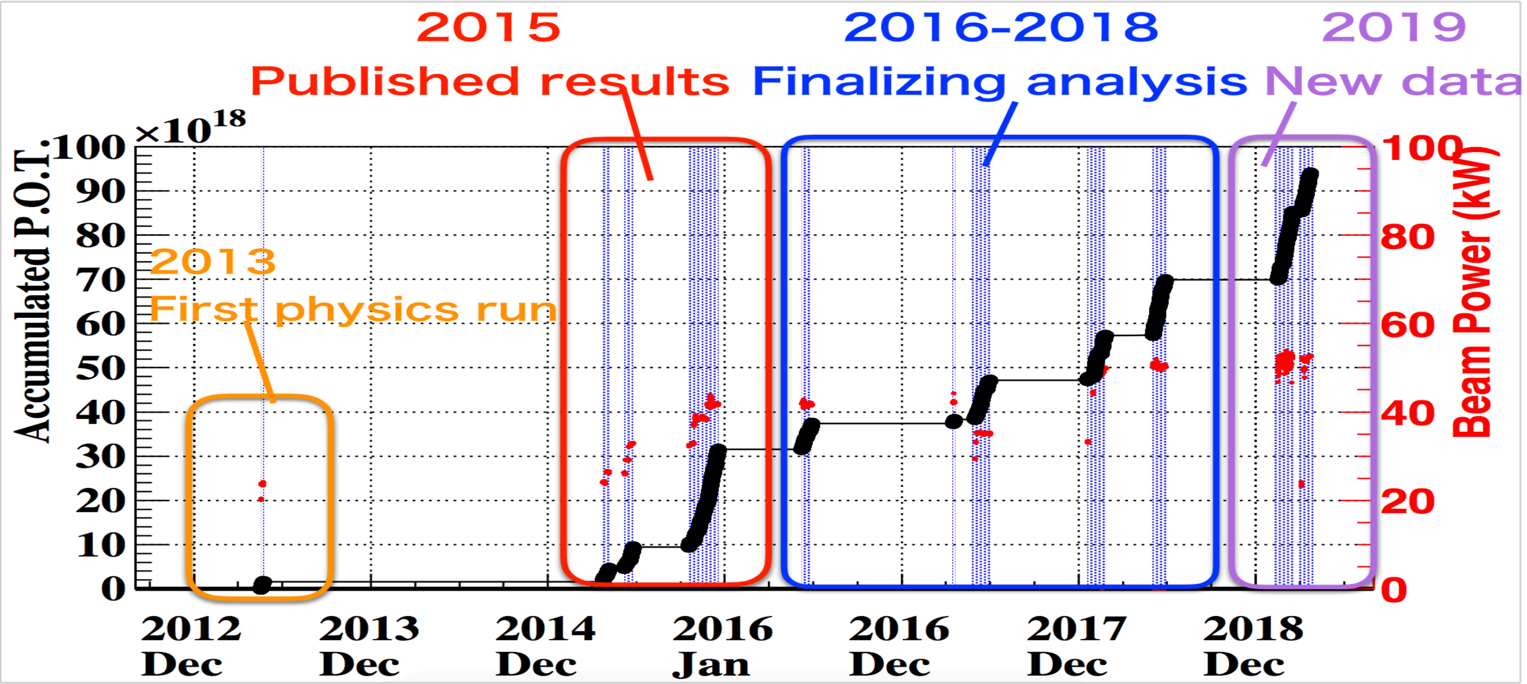




Apply :

- Narrow window for single pulse
- Wide window for double pulse

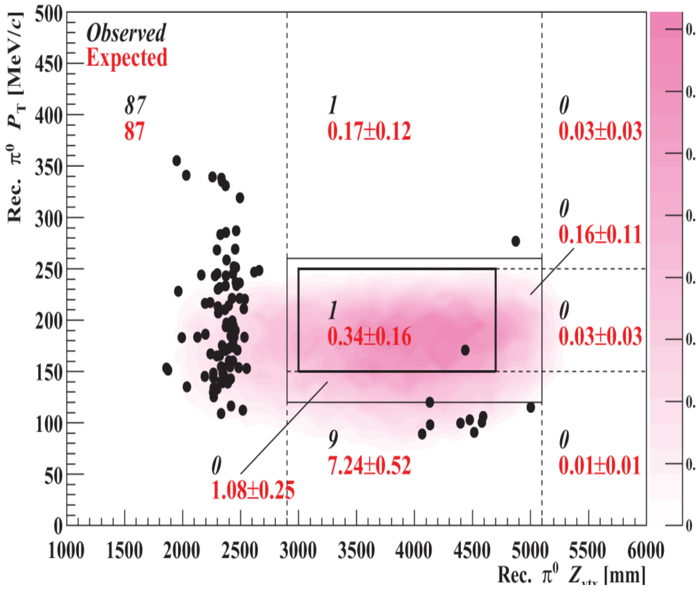
$K_L \to \pi^0 \nu\nu$



🟧 : PTEP, 2017, 021C01

🟥 : Phys. Rev. Lett., 122, 021802

🟦 = 1.57× 🟥



PTEP, 2017, 021C01

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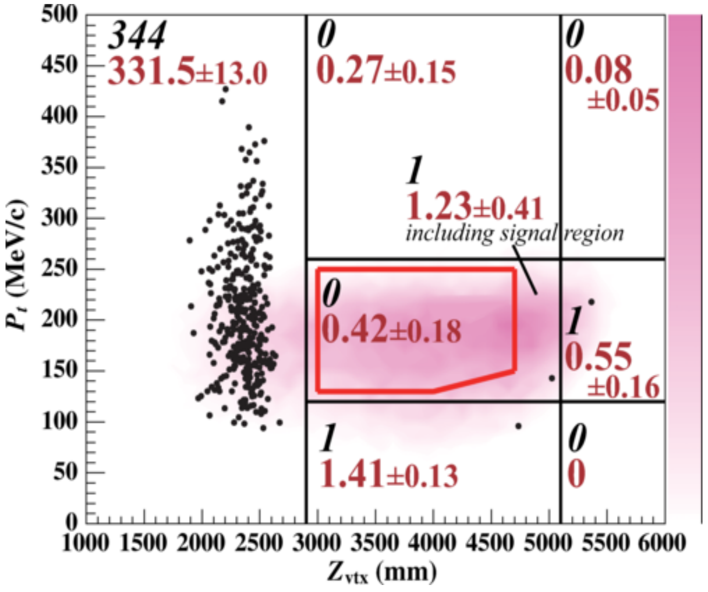
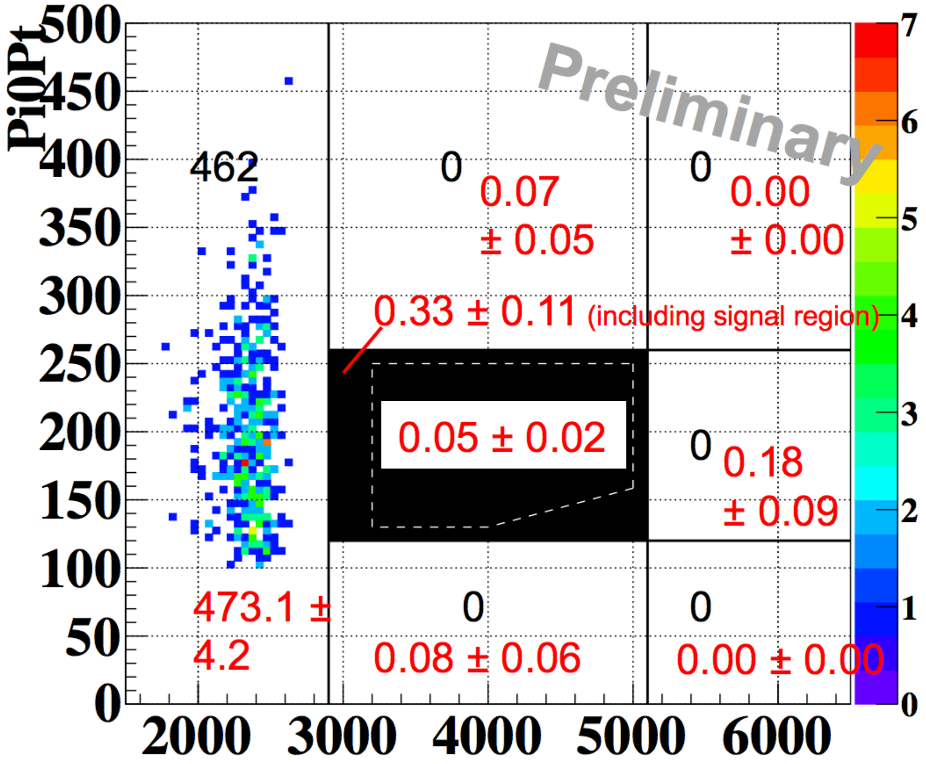
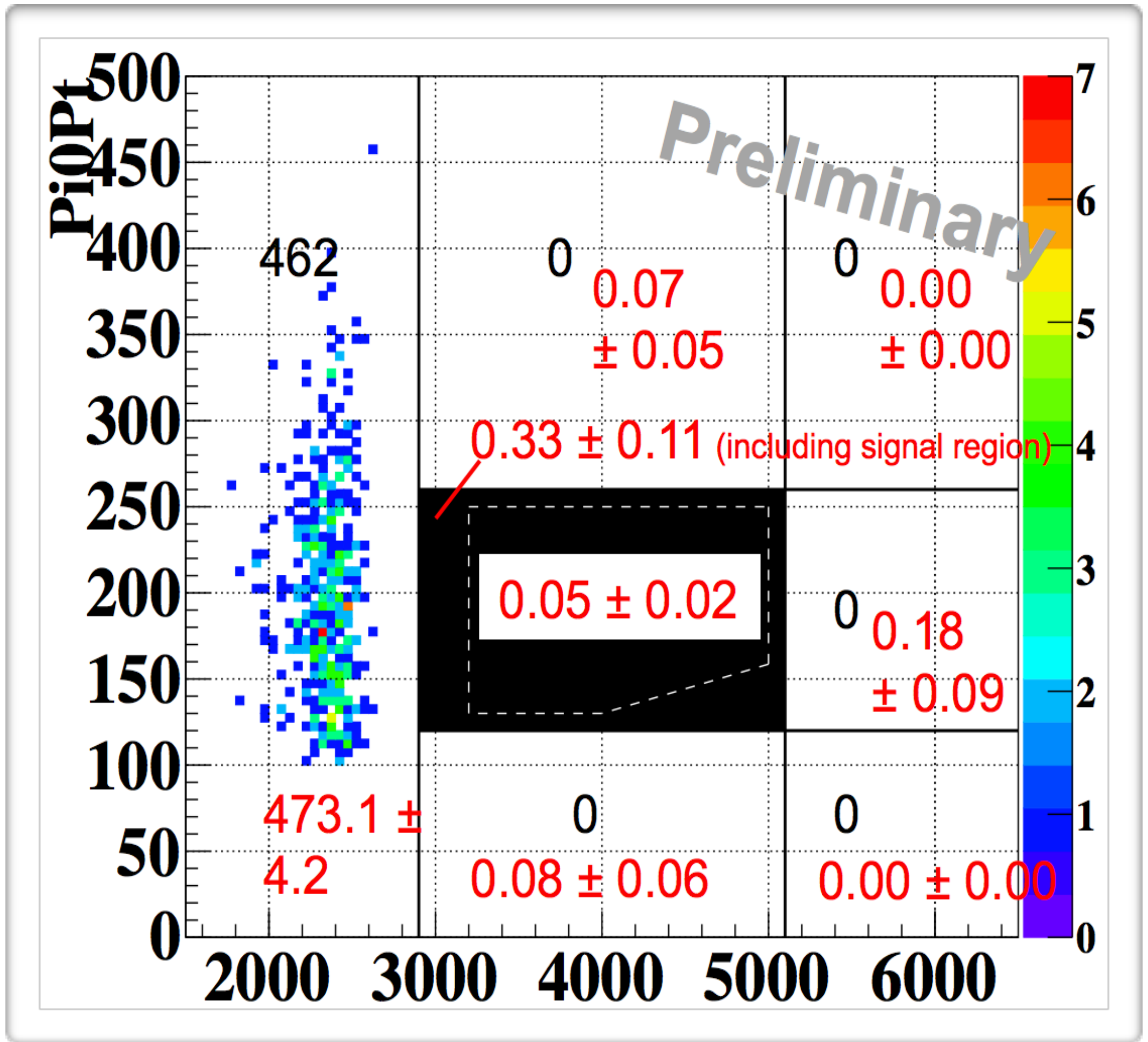


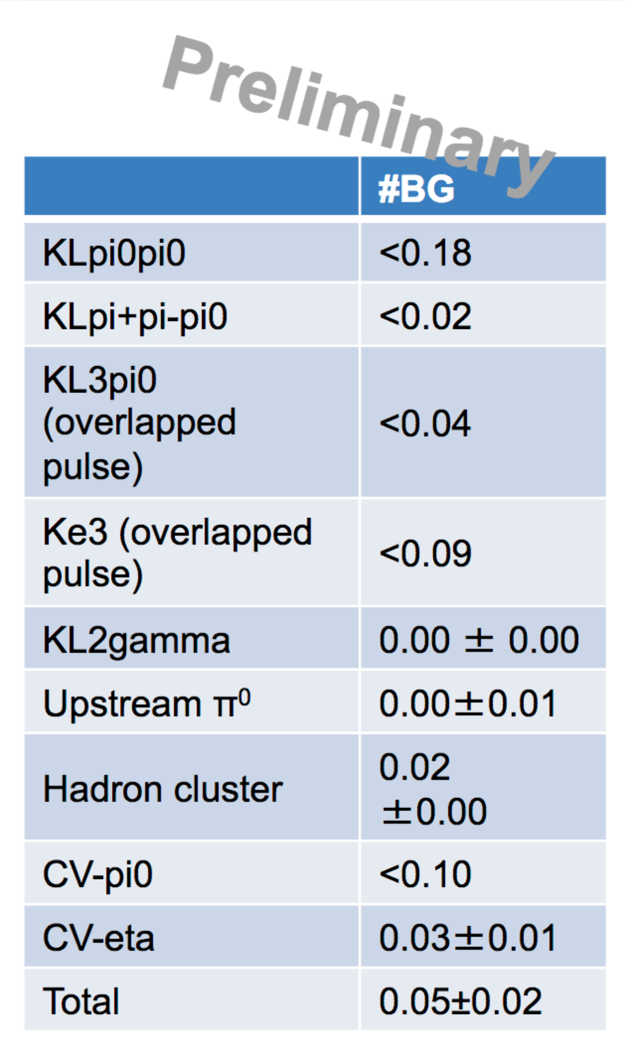
Phys. Rev. Lett., 122, 021802



$K_L \to \pi^0 \nu\nu$ (2016-2018 data)

- SES = 6.9×10^{-10}

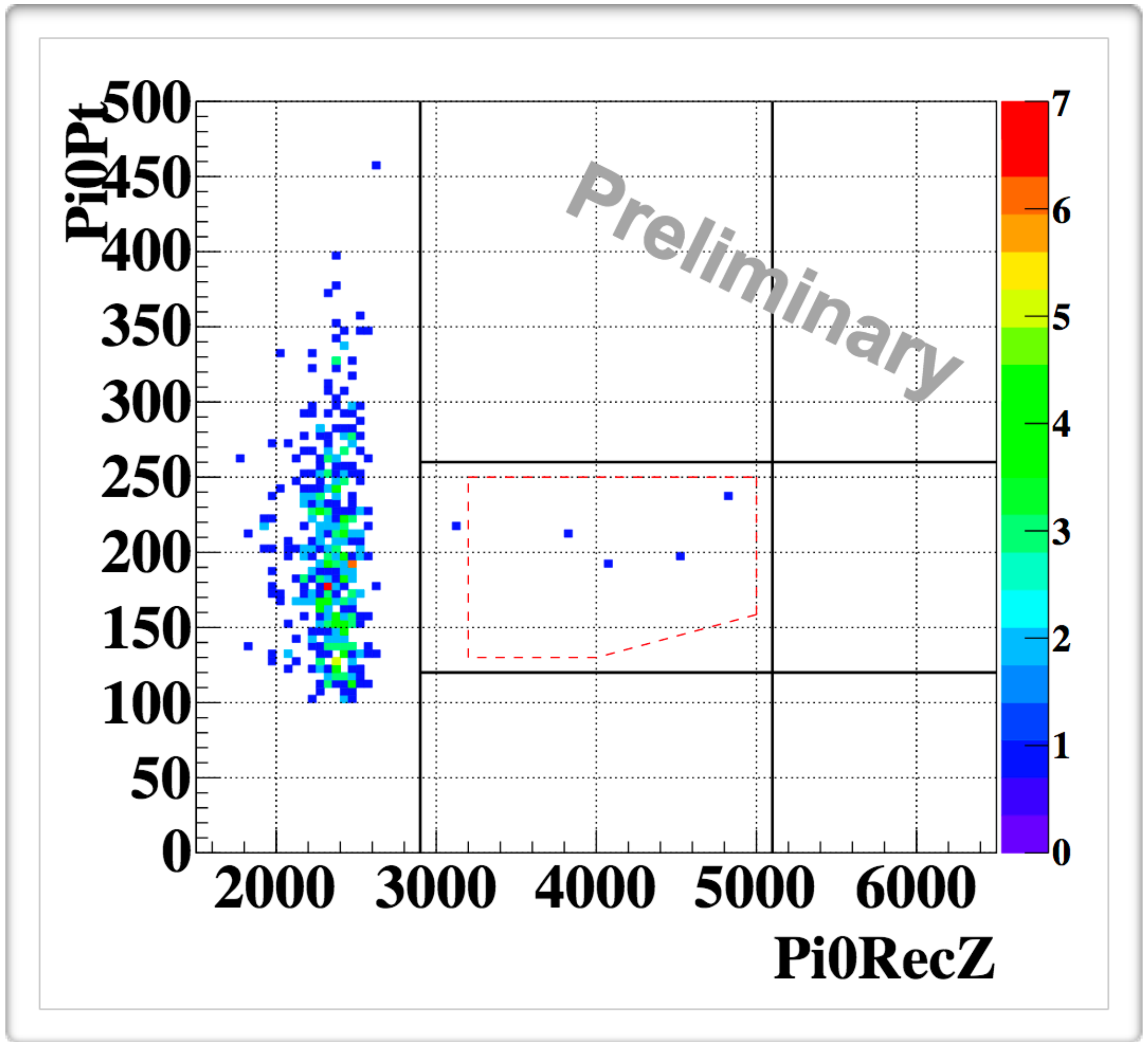


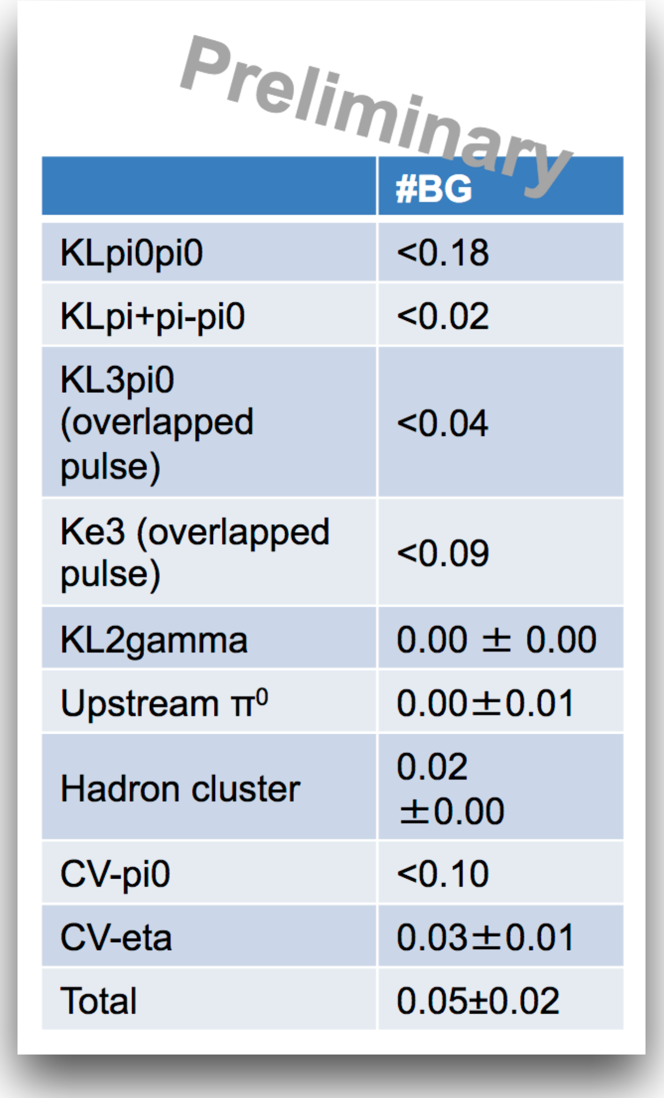


	#BG
KLpi0pi0	<0.18
KLpi+pi-pi0	<0.02
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09
KL2gamma	0.00 ± 0.00
Upstream π^0	0.00±0.01
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02

$K_L \rightarrow \pi^0 \nu\nu$ (2016-2018 data)

- SES = 6.9×10^{-10}
- Four candidate events observed in the signal region.
- Will study the nature of the events inside the box.





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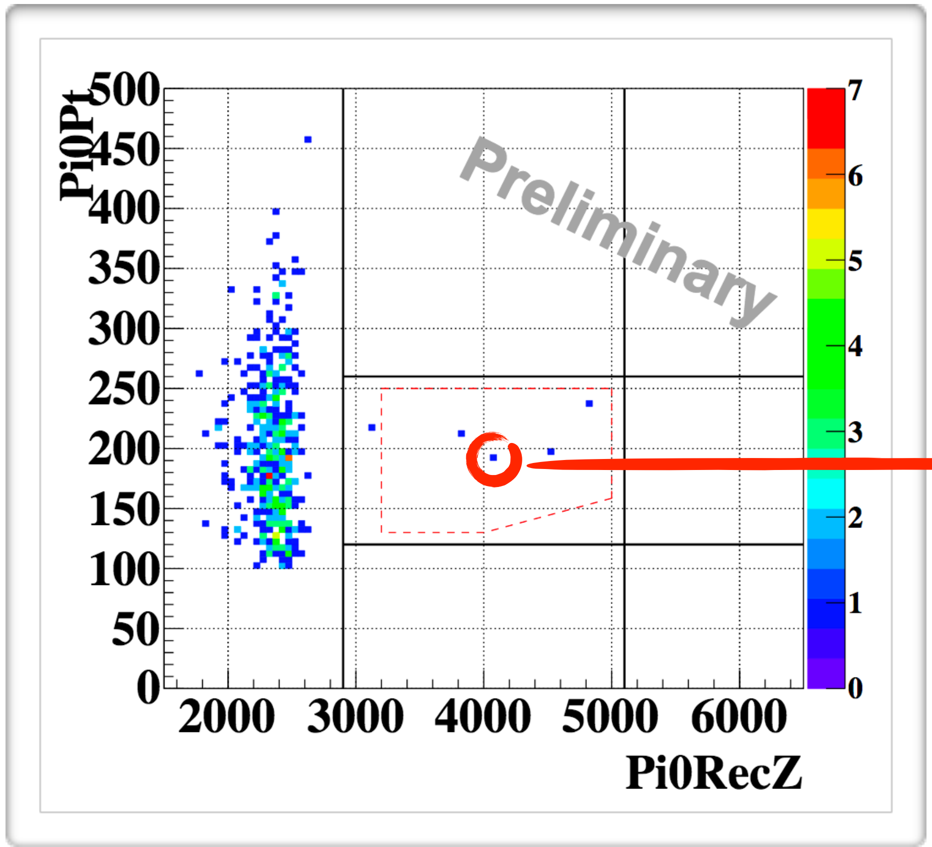
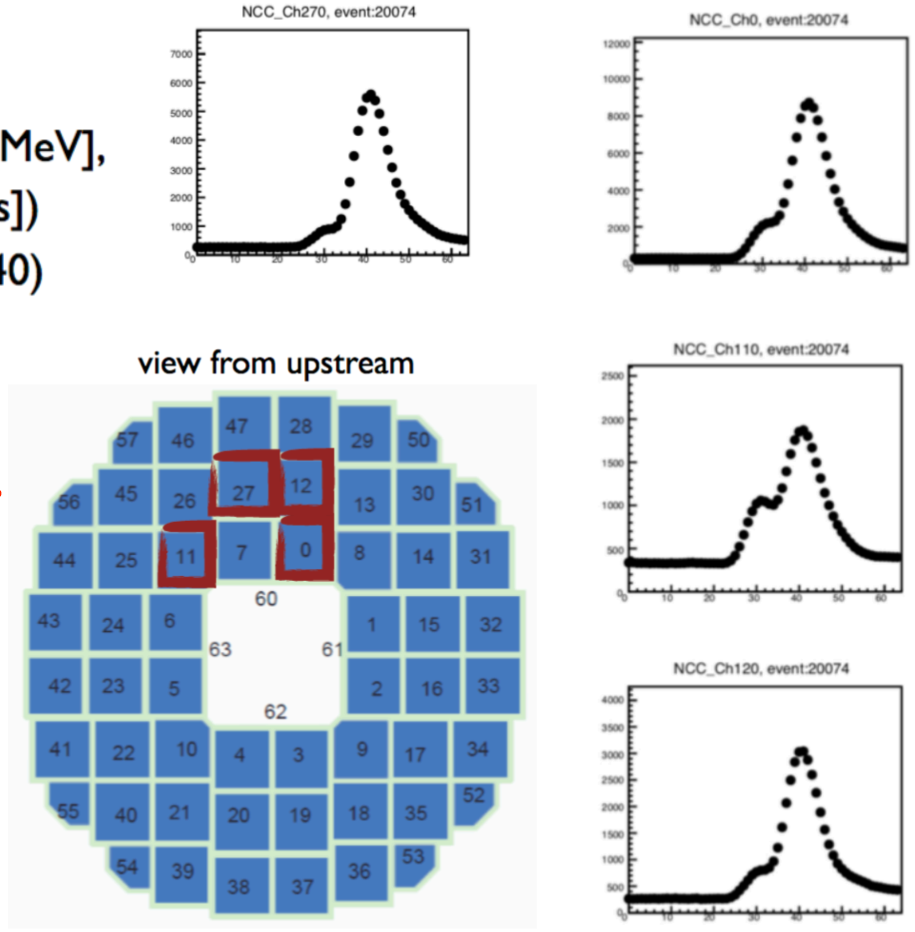
$K_L \to \pi^0 \nu\nu$ (2016-2018 data)



* NCC Veto Energy = 55.8 [MeV],
T = 82.3 [ns], (T0 = 9.1 [ns])
FTT = 99.3 (Threshold = 40)



- In one out of four candidate events:
  - A double was observed in NCC (upstream veto counter).
  - Measured timing was ~70ns away from the nominal time.
- The rest of events are still under investigation.

$K_L \rightarrow \pi^0\gamma$ Analysis

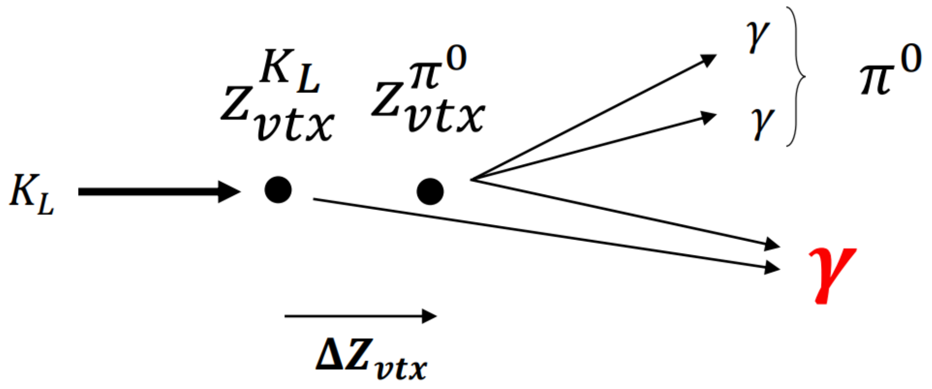
$K_L \rightarrow \pi^0\gamma$

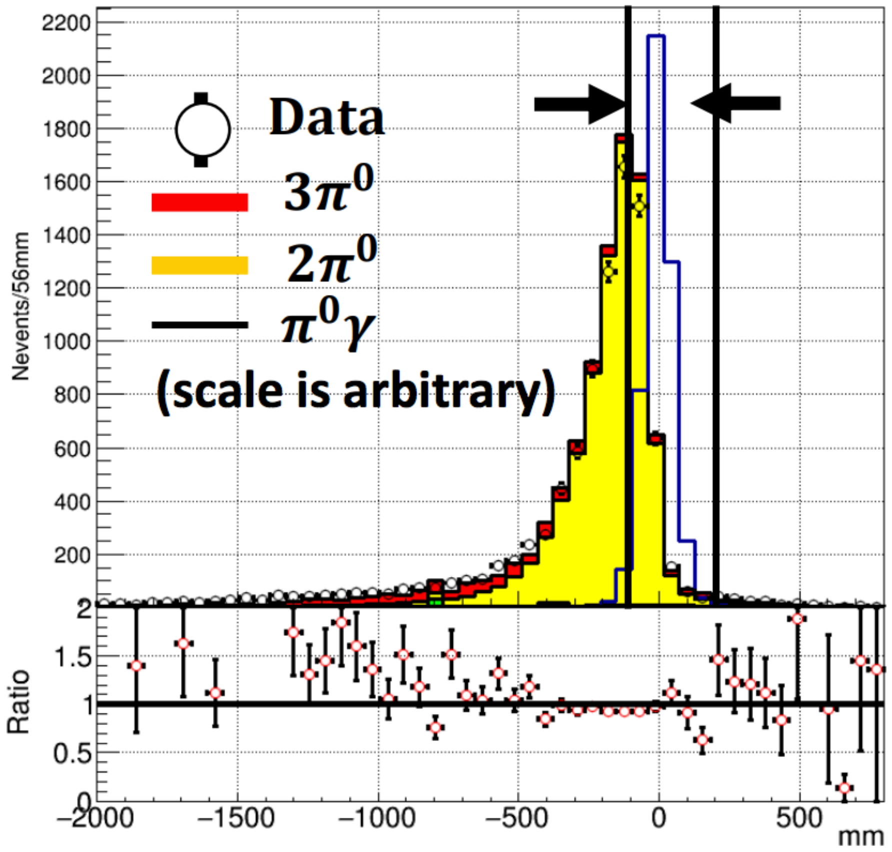
$K_L \rightarrow \pi^0\gamma$

- The decay is a CP violating process and is forbidden by the law of angular momentum conservation.
- No measurements up to now.
- KOTO with hermetic veto system is the best place to test this decay.

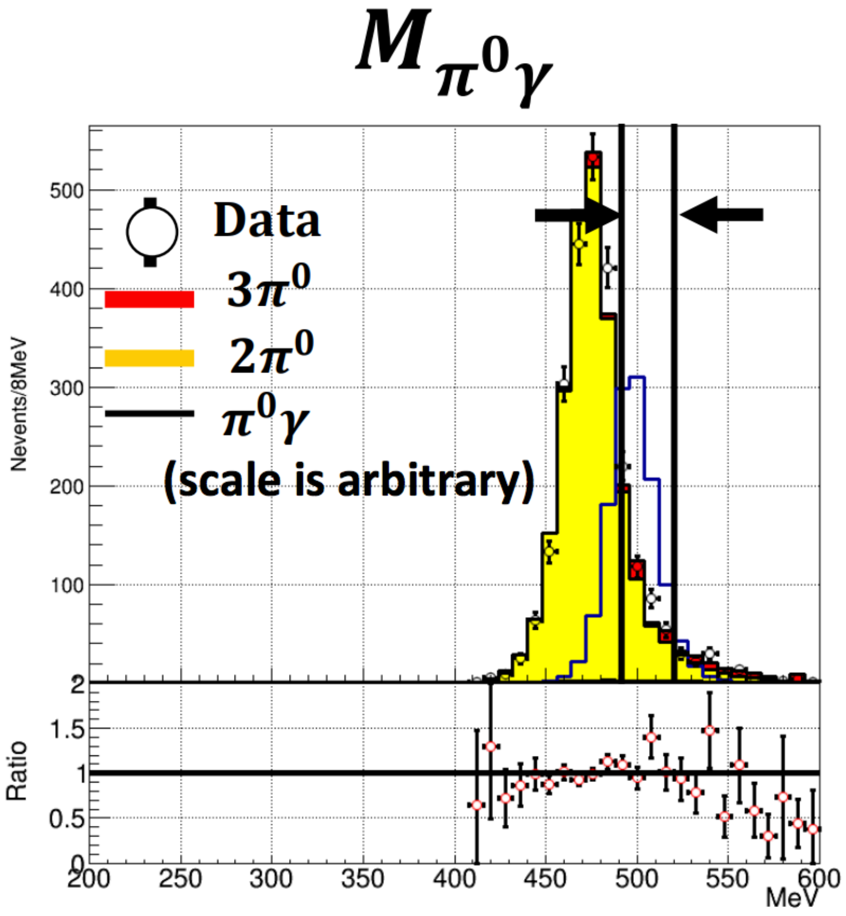
Reconstruction

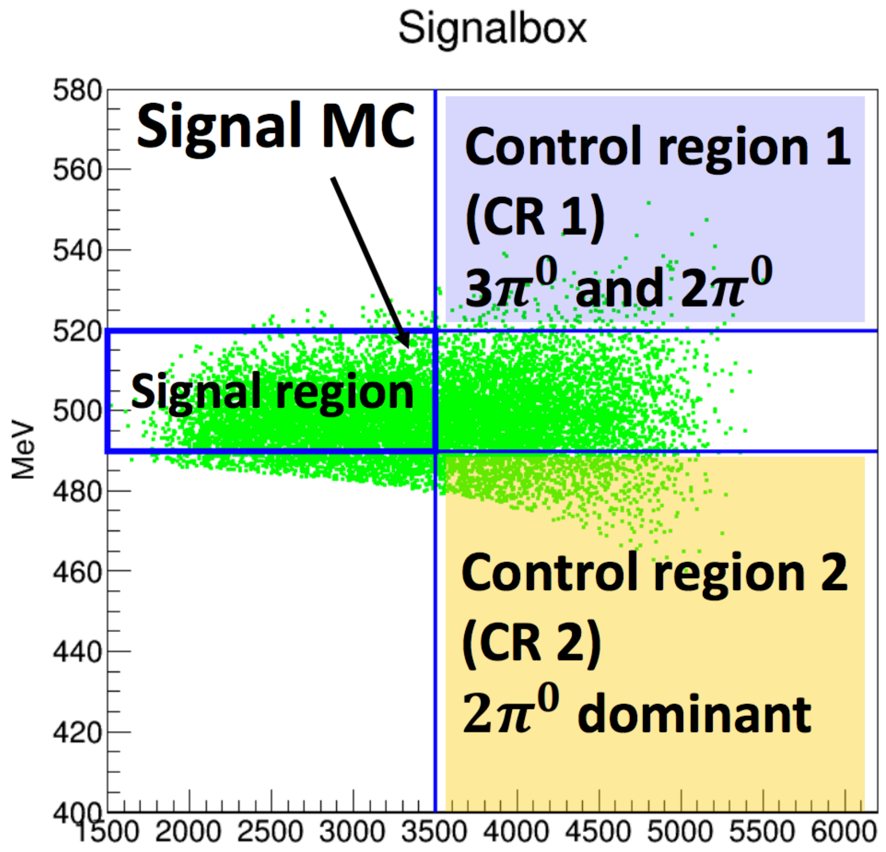
- $K_L \rightarrow \pi^0\gamma$ was reconstructed by finding a common decay vertex under nominal kaon and pion mass assumptions.
- The pairing with the minimum ΔZ was chosen.

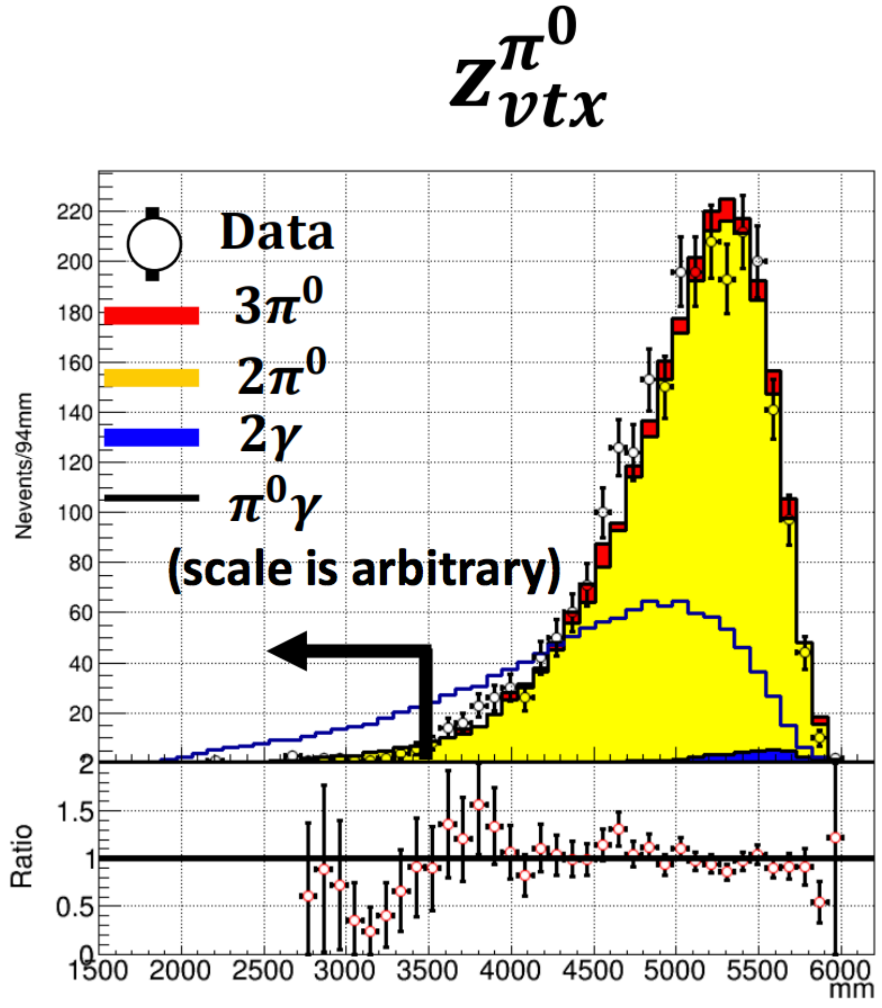




Signal Region



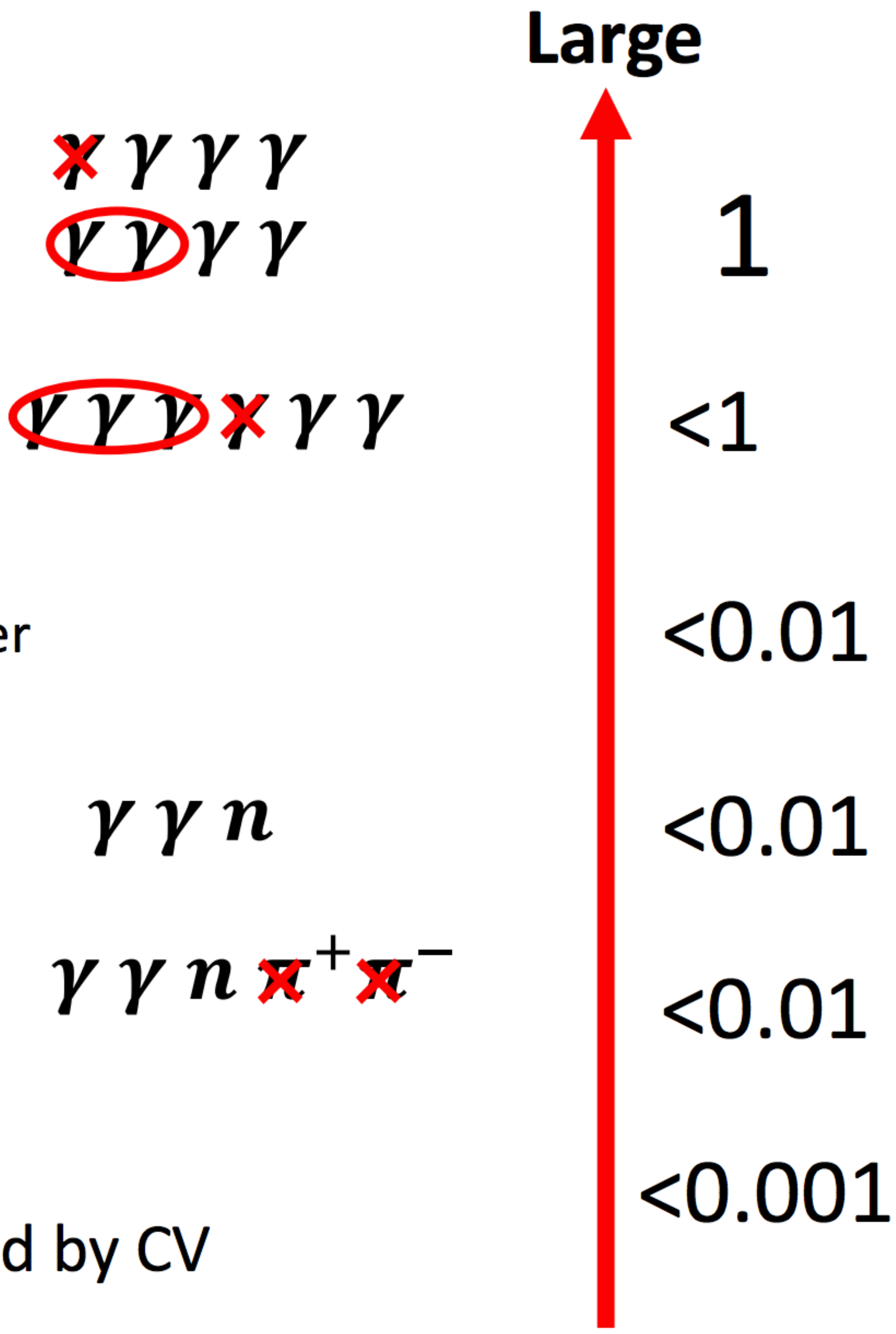




- Signal region was defined on M(πγ) and vertex-z plane.
- Control region-2 was used for MC/data normalization.

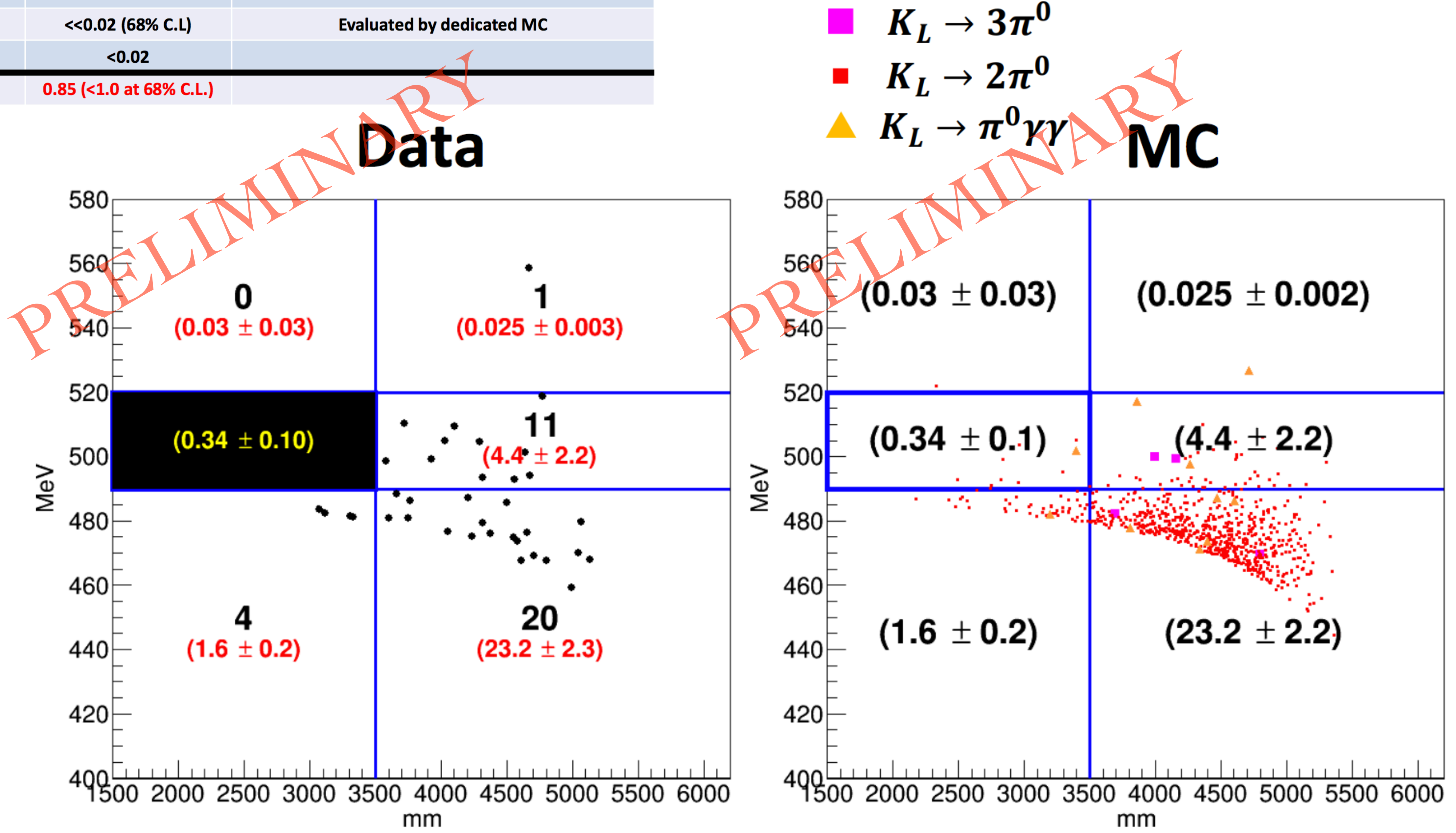
Background Sources

- $K_L \rightarrow 2\pi^0$
  1. a photon missed by some way
  2. two photons fuse
- $K_L \rightarrow 3\pi^0$
  mechanisms similar to $2\pi^0$
- Neutron induced BG
  π^0 produced from *n* and a single acc. cluster
- $K_L \rightarrow 2\gamma$
  combines with neutrons
- $K_L \rightarrow \pi^+\pi^-\pi^0$
  combines with neutrons
- $K_L \rightarrow \ell\pi\nu$ ($\ell = e$ or μ)
  e.g., $e^+e^-_{\text{detector}} \rightarrow 2\gamma$ and π^- missed by CV



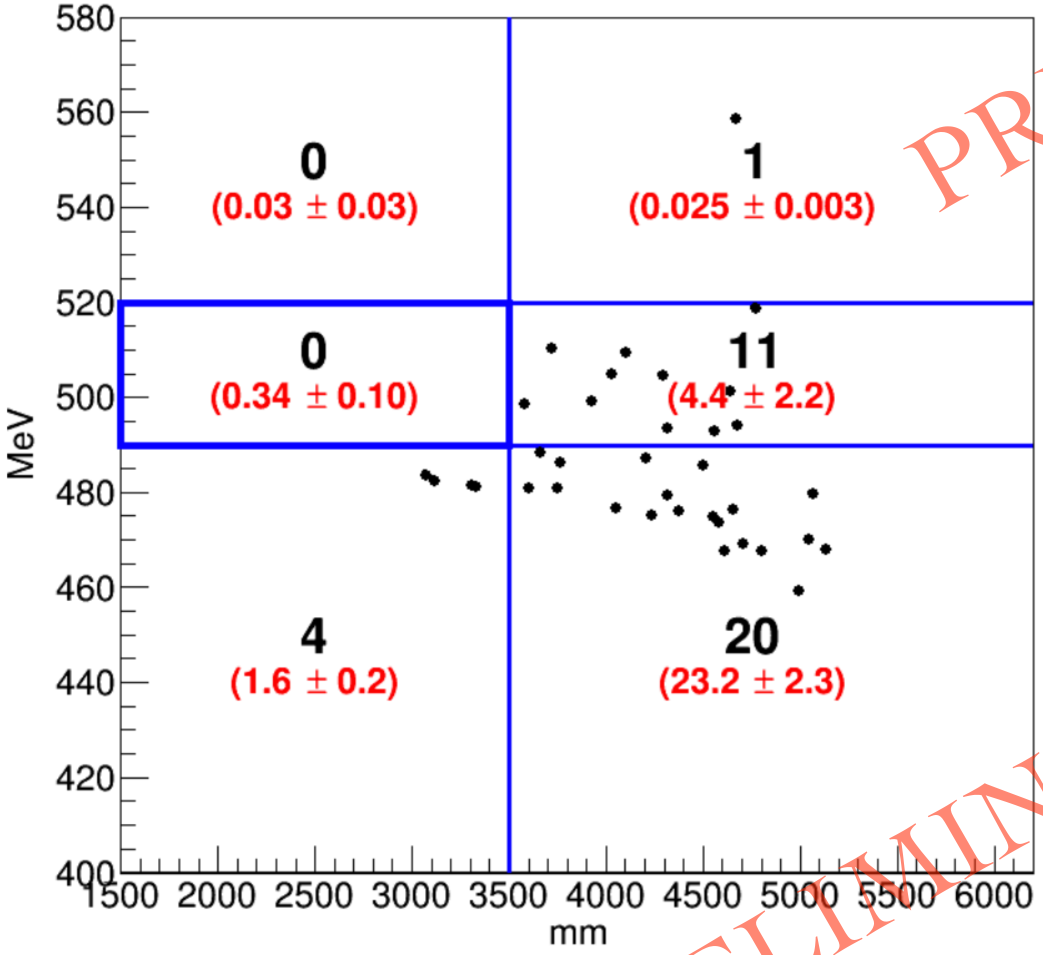
Background Predictions

Sources	Expected in signal box	Comment
$K_L \to 2\pi^0$	0.32 ± 0.11	Evaluated by MC
$K_L \to 3\pi^0$	<0.5 (68% C.L)	Data driven estimation
$K_L \to 2\gamma$	<< 0.06 (68% C.L)	Evaluated by full MC
Neutron induced BG	<<0.02 (68% C.L)	Evaluated by dedicated MC
Other K_L decays	<0.02	
Sum	0.85 (<1.0 at 68% C.L.)	



Results of $K_L \rightarrow \pi^0\gamma$

$$B(K_L \rightarrow \pi^0\gamma) < 1.7 \times 10^{-7} \text{ at } 90\,\%\ C.L.$$



Single event sensitivity of signal:

$$\frac{\mathbf{1}}{N_{K_L}\epsilon(K_L\rightarrow\pi^0\gamma)} = (\mathbf{6.9} \pm \mathbf{0.3}_{\mathbf{stat}} \pm \mathbf{1.5}_{syst}) \times \mathbf{10^{-8}}$$

Summary

- U.L.[$K_L \to \pi^0 \upsilon\upsilon$] = 3.0×10^{-9}, based on 2015 data.
- Unblinded the 2016-2018 data in the end of Aug.
  - Four candidate events found inside the signal box.
    - Under Investigation.
- First measurement of $K_L \to \pi^0 \gamma$ was performed.
  - No event observed.
  - U.L.[$K_L \to \pi^0 \gamma$] = 1.7×10^{-7} at 90% C.L.

Backup

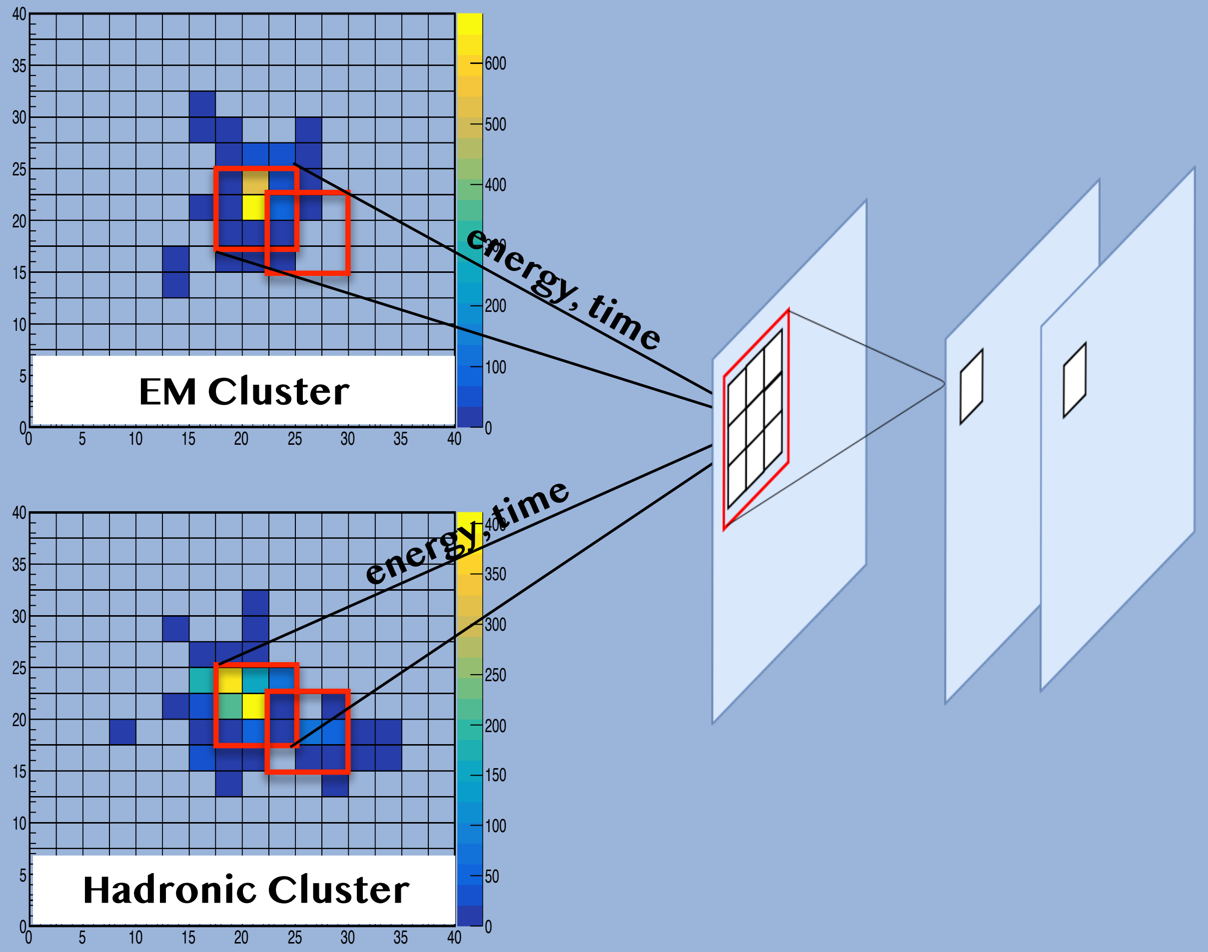
Physics Trigger Table

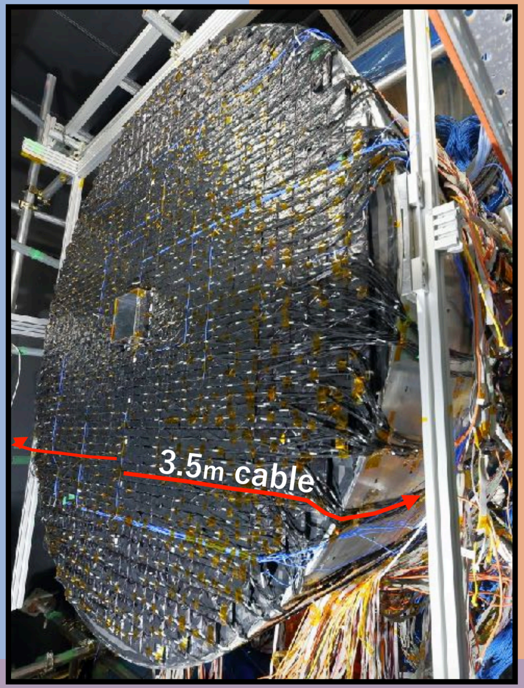
Veto	Cluster Counts	Modes	Trigger Eff.	Online Prescale
Photon & Charge	2	(*)$K_L \rightarrow \pi^0 \nu\nu$	99.6%	1
Photon & Charge	3	$K_L \rightarrow \gamma\gamma\gamma$, (**)$K_L \rightarrow \pi^0\gamma$	96.8-99.6%	3
Photon & Charge	4	$K_L \rightarrow \pi^0\pi^0\nu\nu$, $K_L \rightarrow \pi^0\gamma\gamma$	96.8%	1
Photon	4	$K_L \rightarrow \pi^0 e^+ e^-$	96.8%	20
Photon & Charge	6	$K_L \rightarrow \pi^0\pi^0\pi^0$	92.2%	3

*Satoshi Shinohara's Talk
**Nobuhiro Shimizu's Talk

Cluster Shape Discrimination

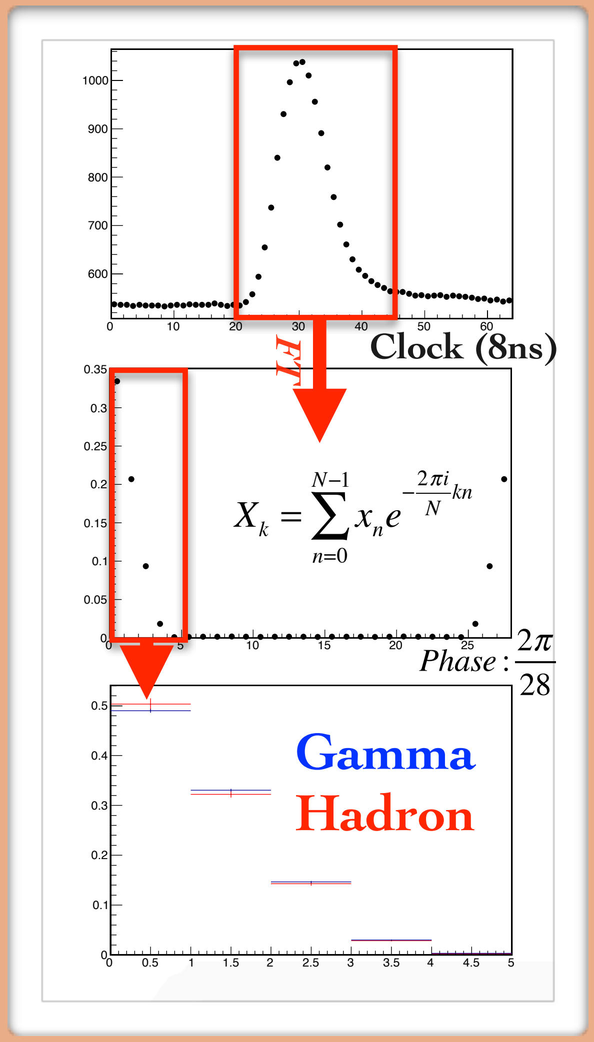
Pattern Classification
using Deep Learning Neural Network





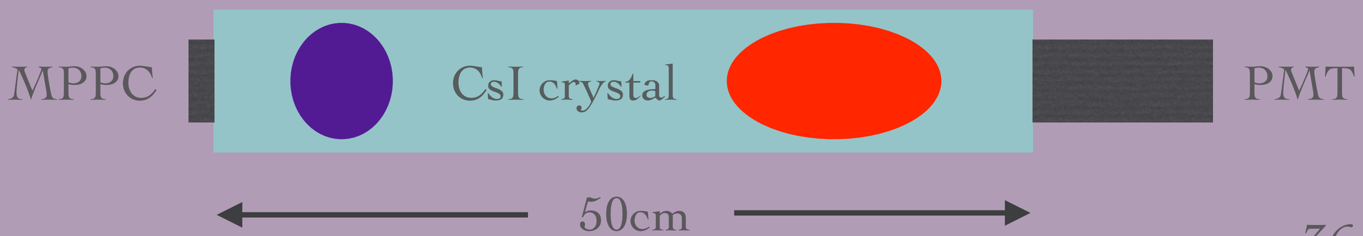
Pulse Shape Discrimination

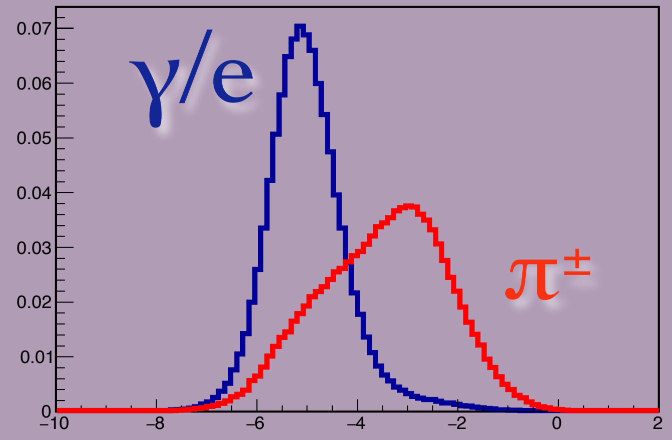
Fourier Analysis on Waveform



Shower Depth Discrimination

Reconstruct Shower Depth using timing

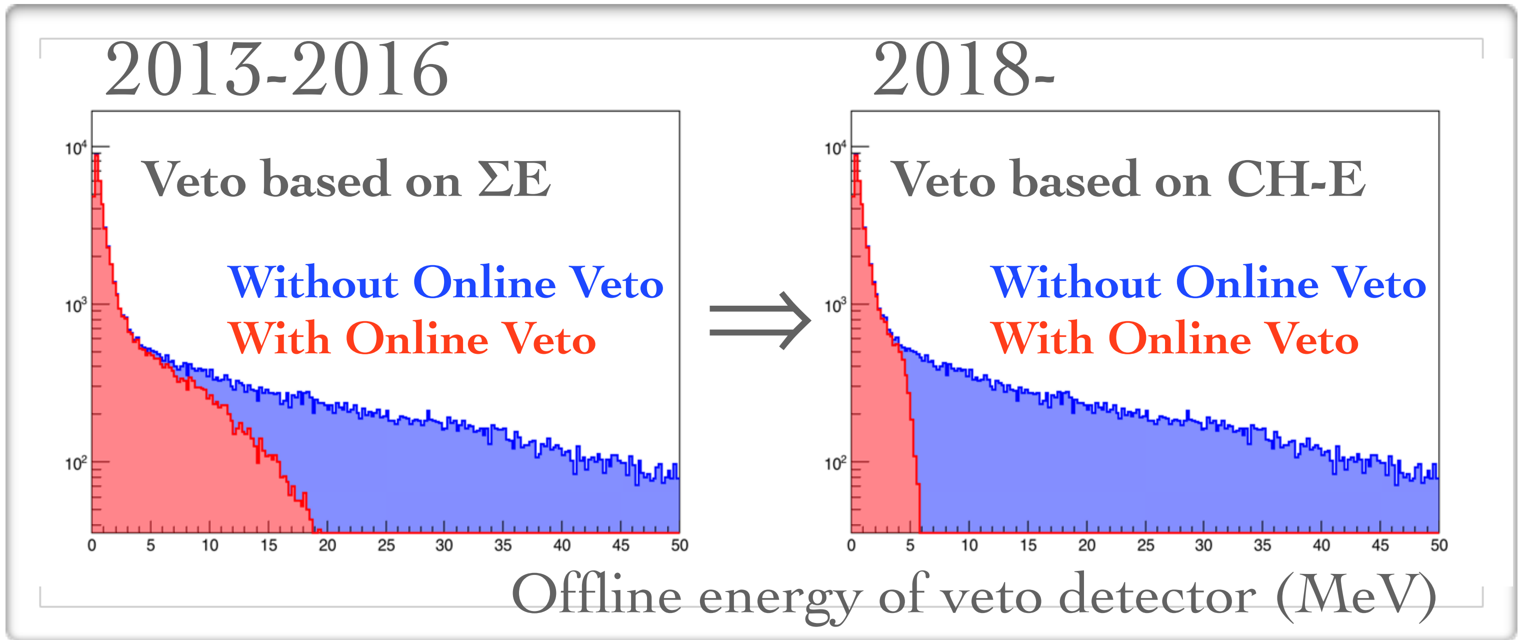


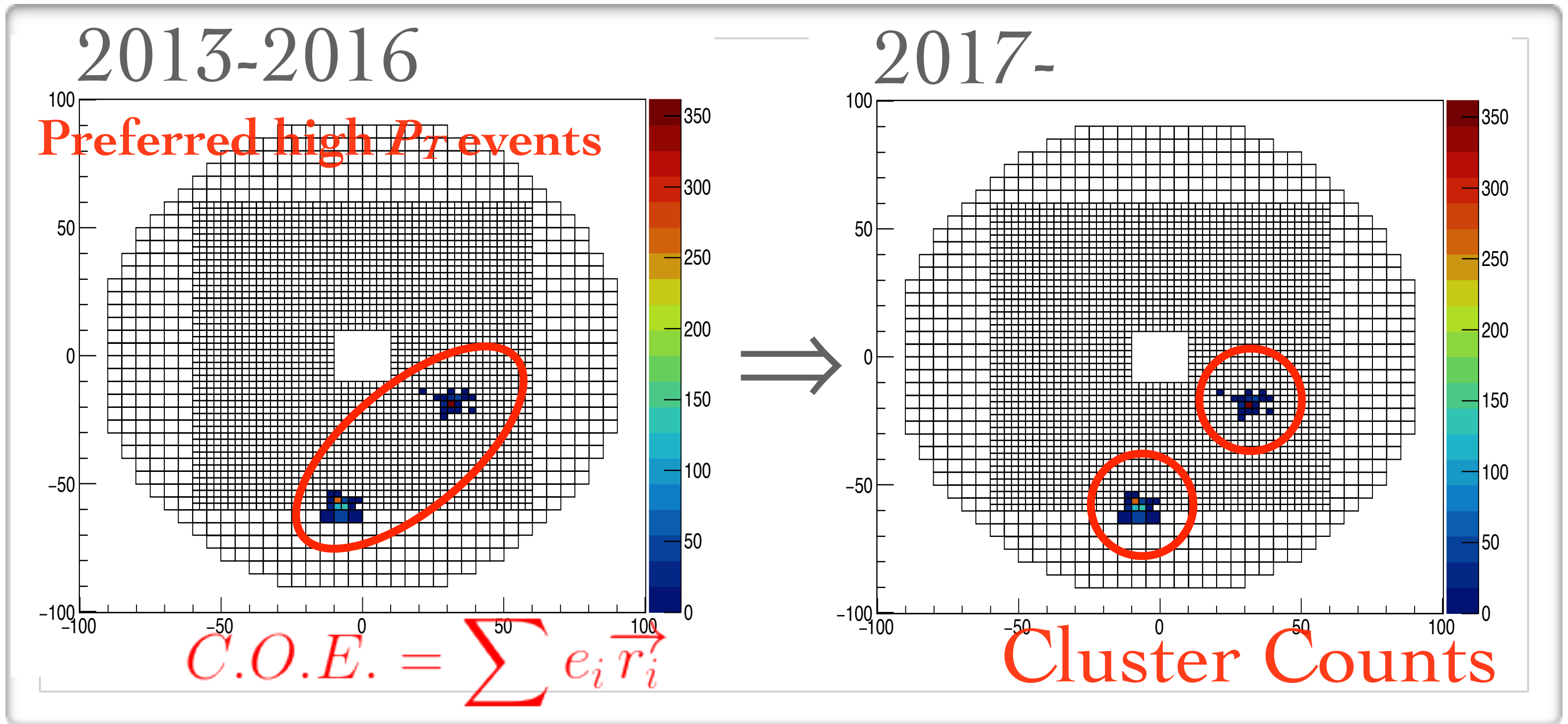


DAQ Upgrades - Trigger

New Level-I (UChicago/NTU) :

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

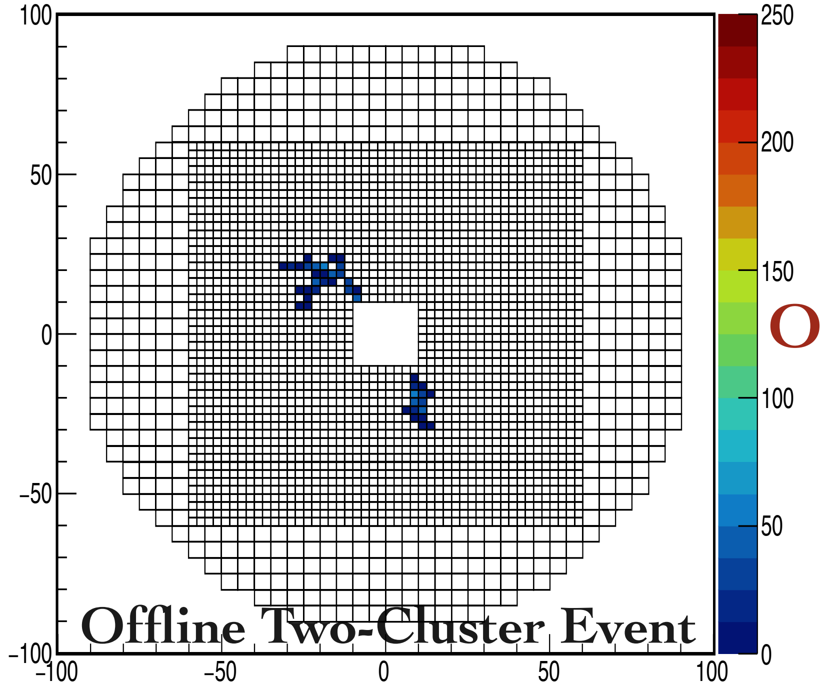




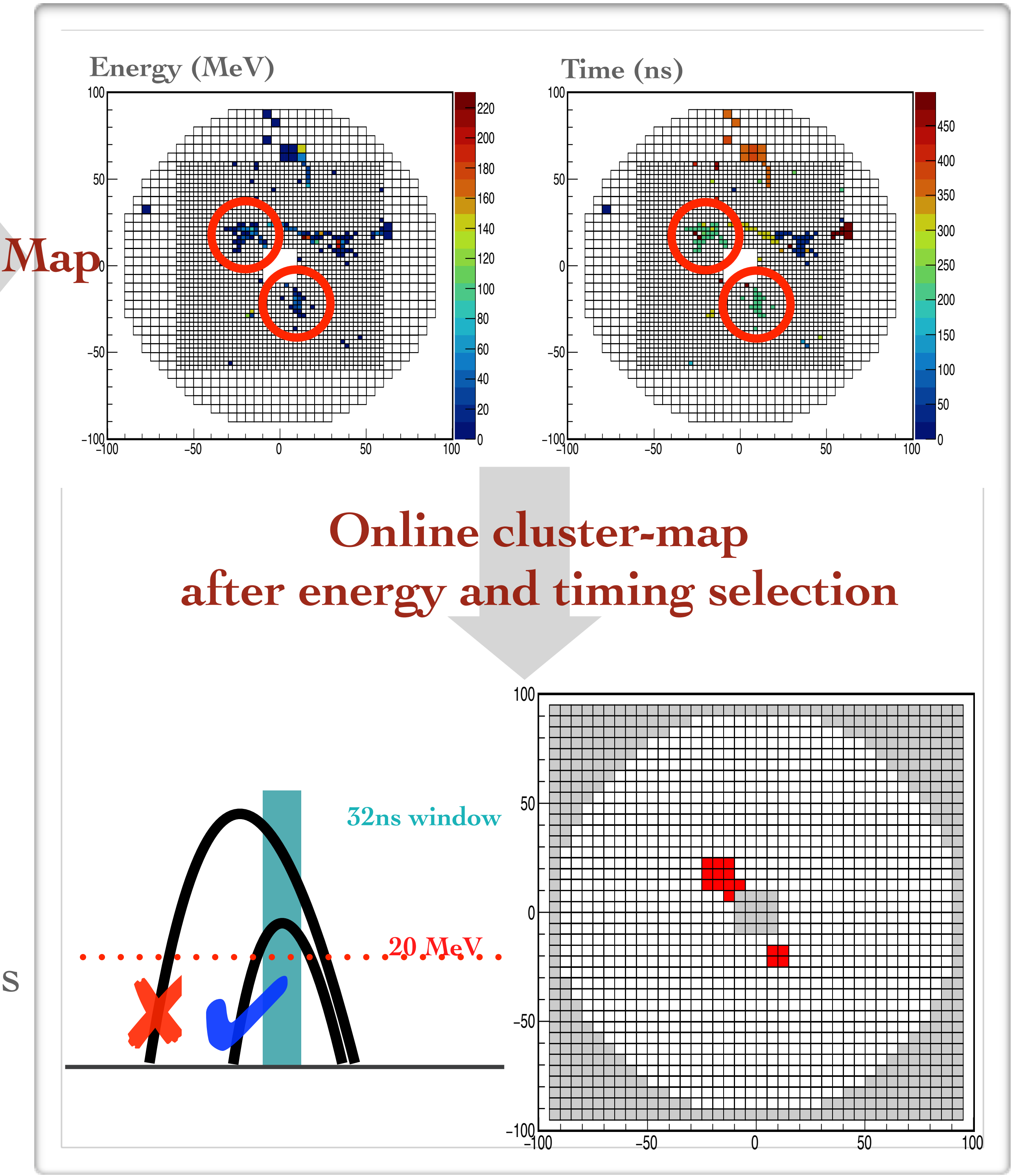
New Level-II (UChicago/NTU) :

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

Trigger: Level-II (2017-)



Online Raw Map

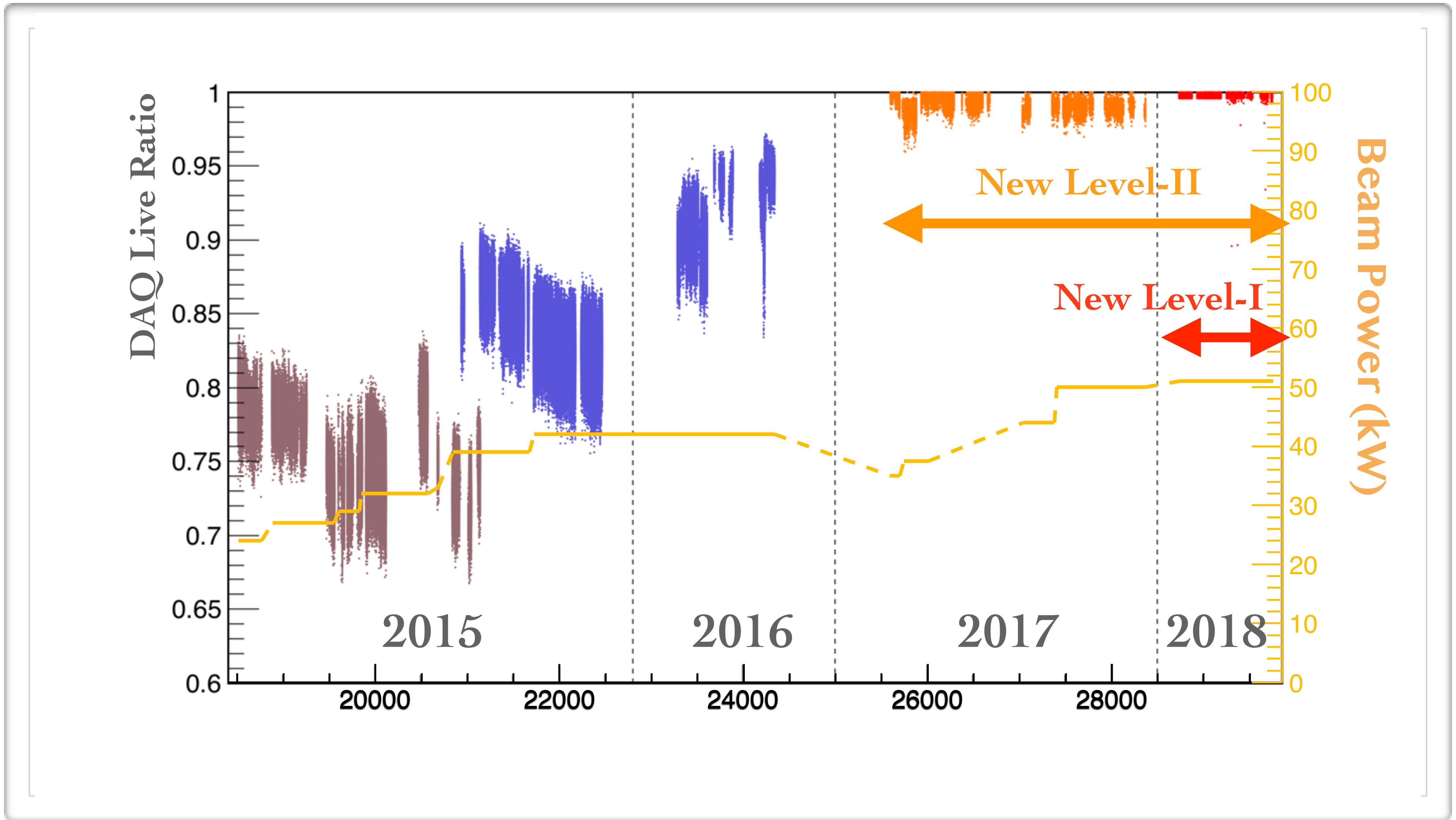


Online cluster-map
after energy and timing selection

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

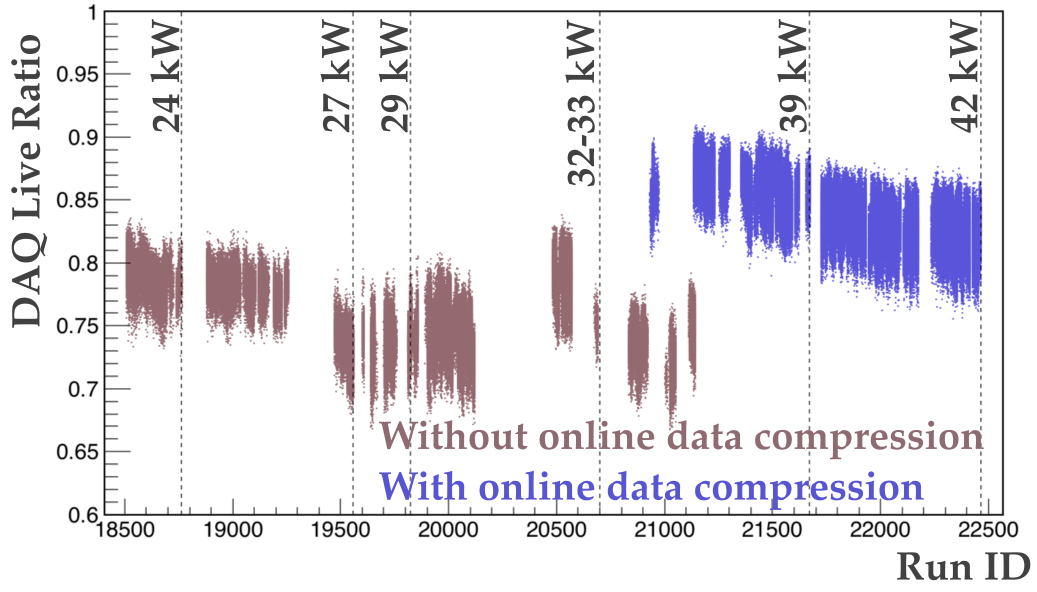
DAQ Performance

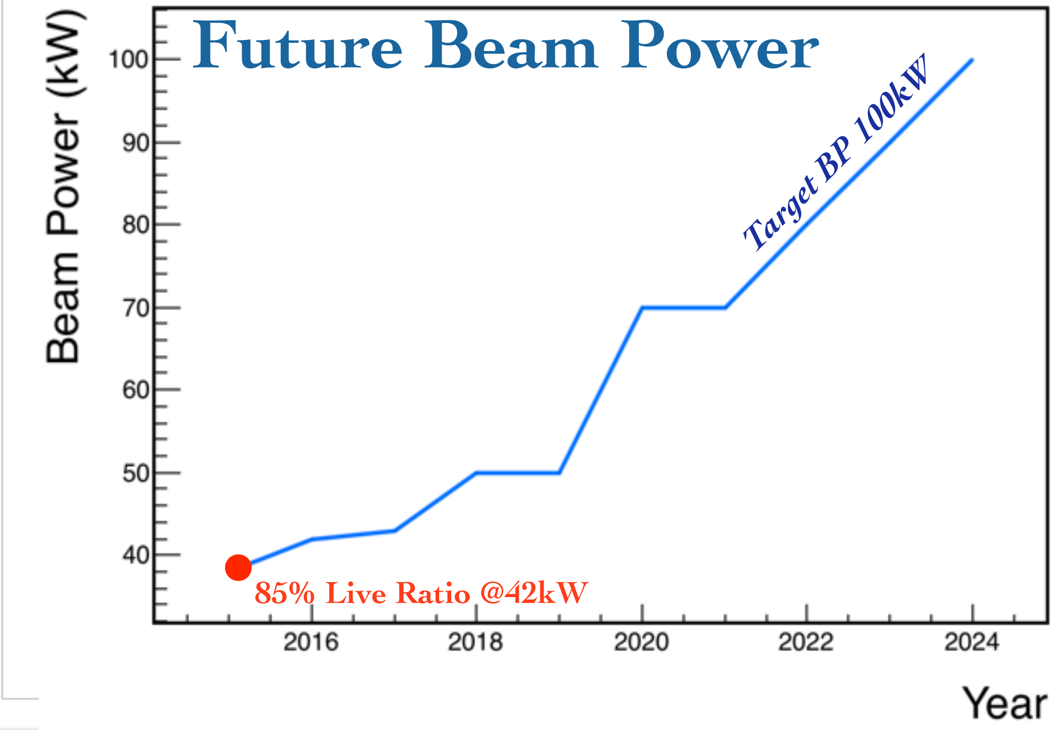
- New Lv1/Lv2 trigger system resolved the DAQ dead time issues.
- Planning on Lv3 upgrade to increase the downstream data throughputs.



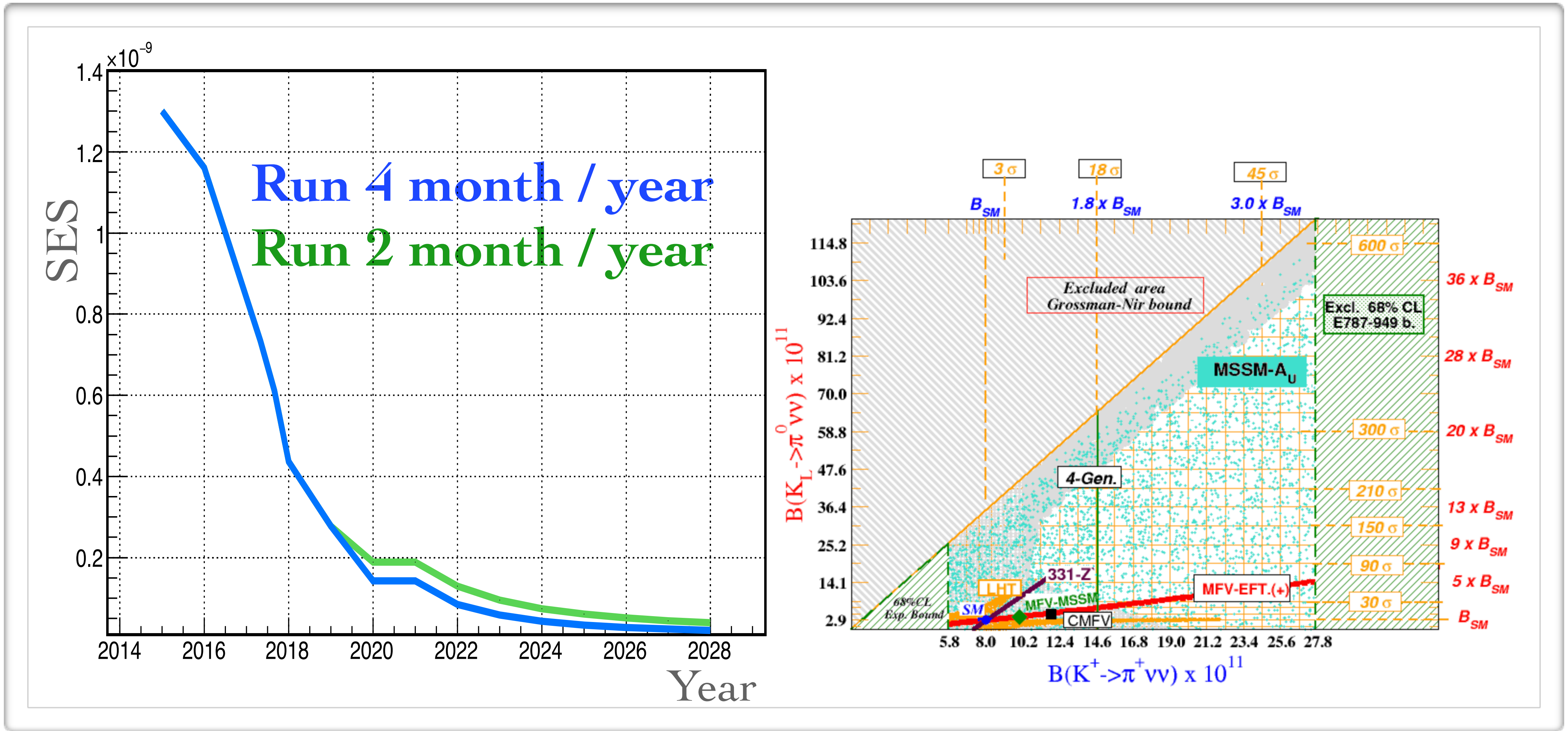
DAQ in 2015

- 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





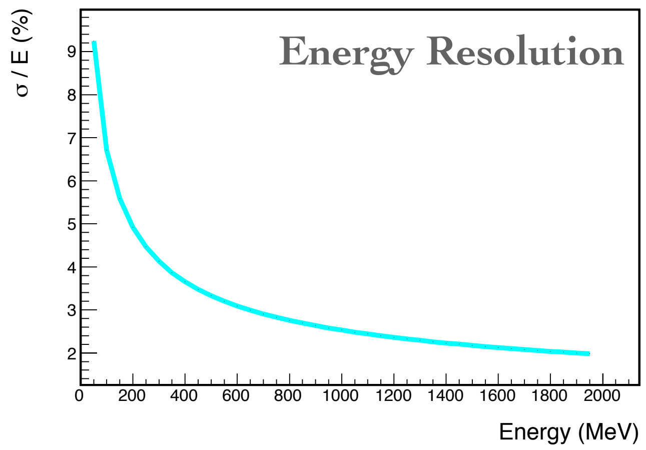
Future Runs

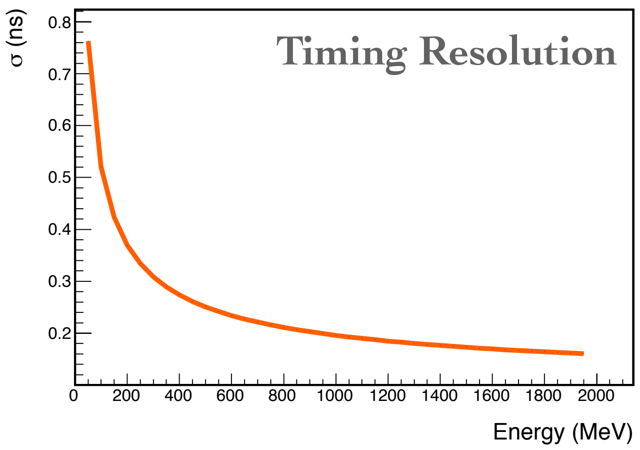


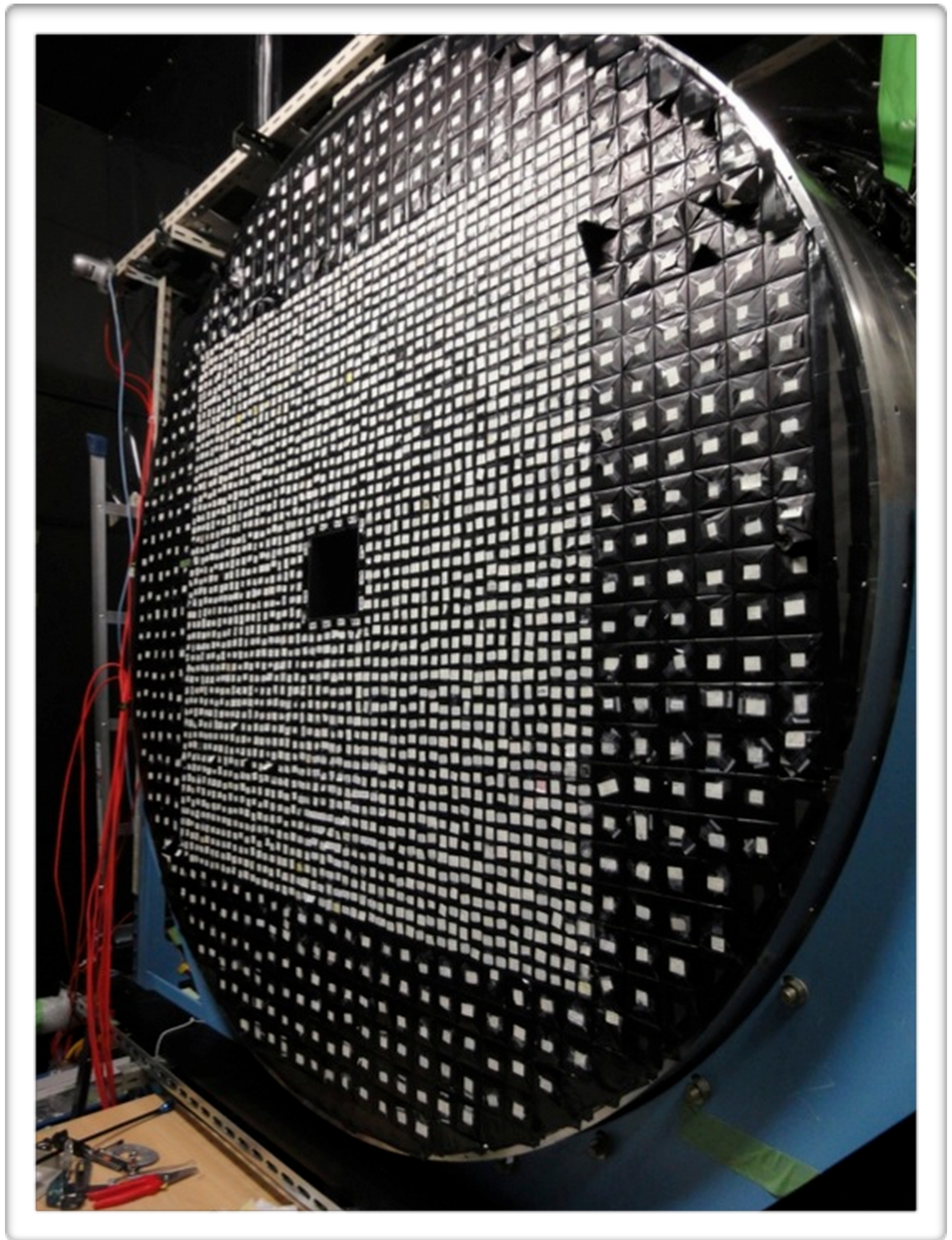
Run 4 month / year
Run 2 month / year
SES
x10^{-9}
1.4
1.2
1
0.8
0.6
0.4
0.2
2014
2016
2018
2020
2022
2024
2026
2028
Year
3 σ
18 σ
45 σ
B_{SM}
1.8 x B_{SM}
3.0 x B_{SM}
Excluded area
Grossman-Nir bound
Excl. 68% CL
E787-949 b.
MSSM-A_U
4-Gen.
331-Z'
LHT
SM
MFV-MSSM
CMFV
MFV-EFT.(+)
68%CL
Exp. Bound
600 σ
300 σ
210 σ
150 σ
90 σ
30 σ
36 x B_{SM}
28 x B_{SM}
20 x B_{SM}
13 x B_{SM}
9 x B_{SM}
5 x B_{SM}
B_{SM}
$B(K_L^0 \to \pi^0 \nu\nu) \times 10^{11}$
114.8
103.6
92.4
81.2
70.0
58.8
47.6
36.4
25.2
14.1
2.9
5.8
8.0
10.2
12.4
14.6
16.8
19.0
21.2
23.4
25.6
27.8
$B(K^+ \to \pi^+ \nu\nu) \times 10^{11}$

Detector - Photon Calorimeter

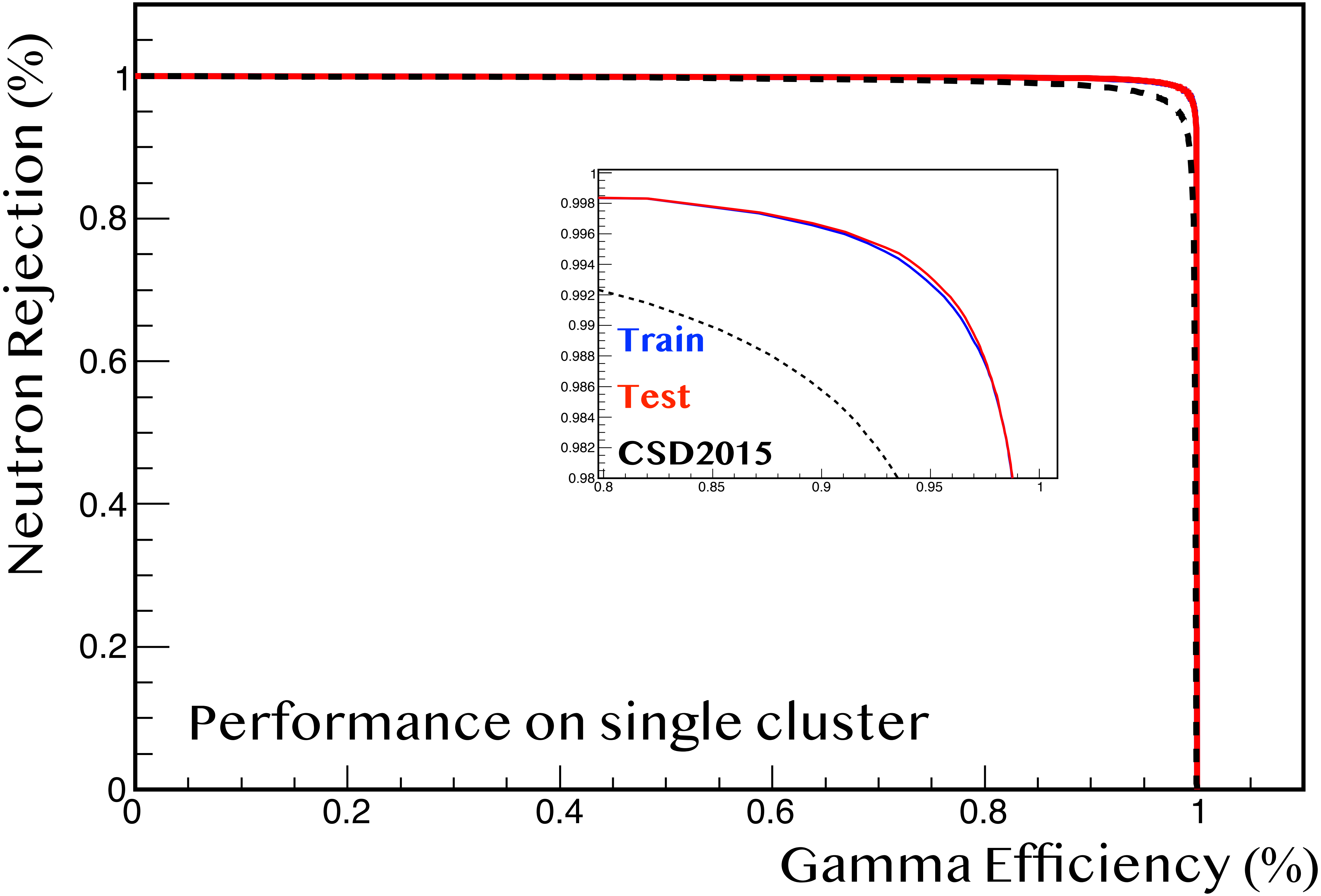
- KTeV CsI crystals:
  - small: 2.5×2.5×50 cm
  - large: 5.0×5.0×50 cm
  - full scale:
    - 200 cm in diameter
    - 15×15 cm^2 beam hole
- Resolution:
  - σ_E=3%, σ_T=0.25ns for 500MeV signal







Train vs. Test

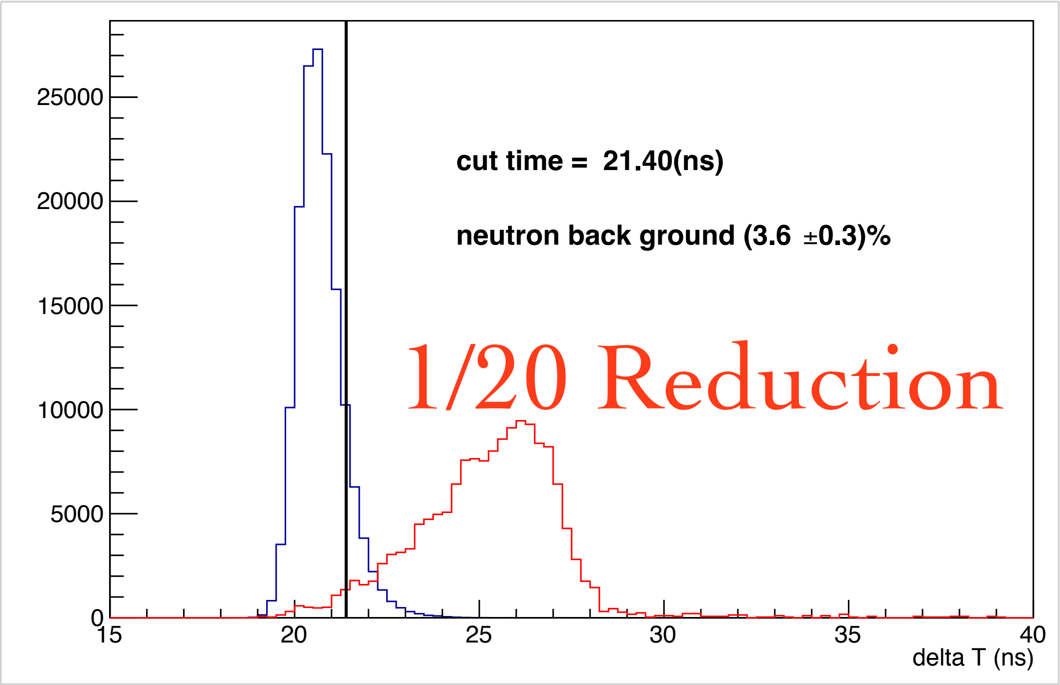


Performance on single cluster

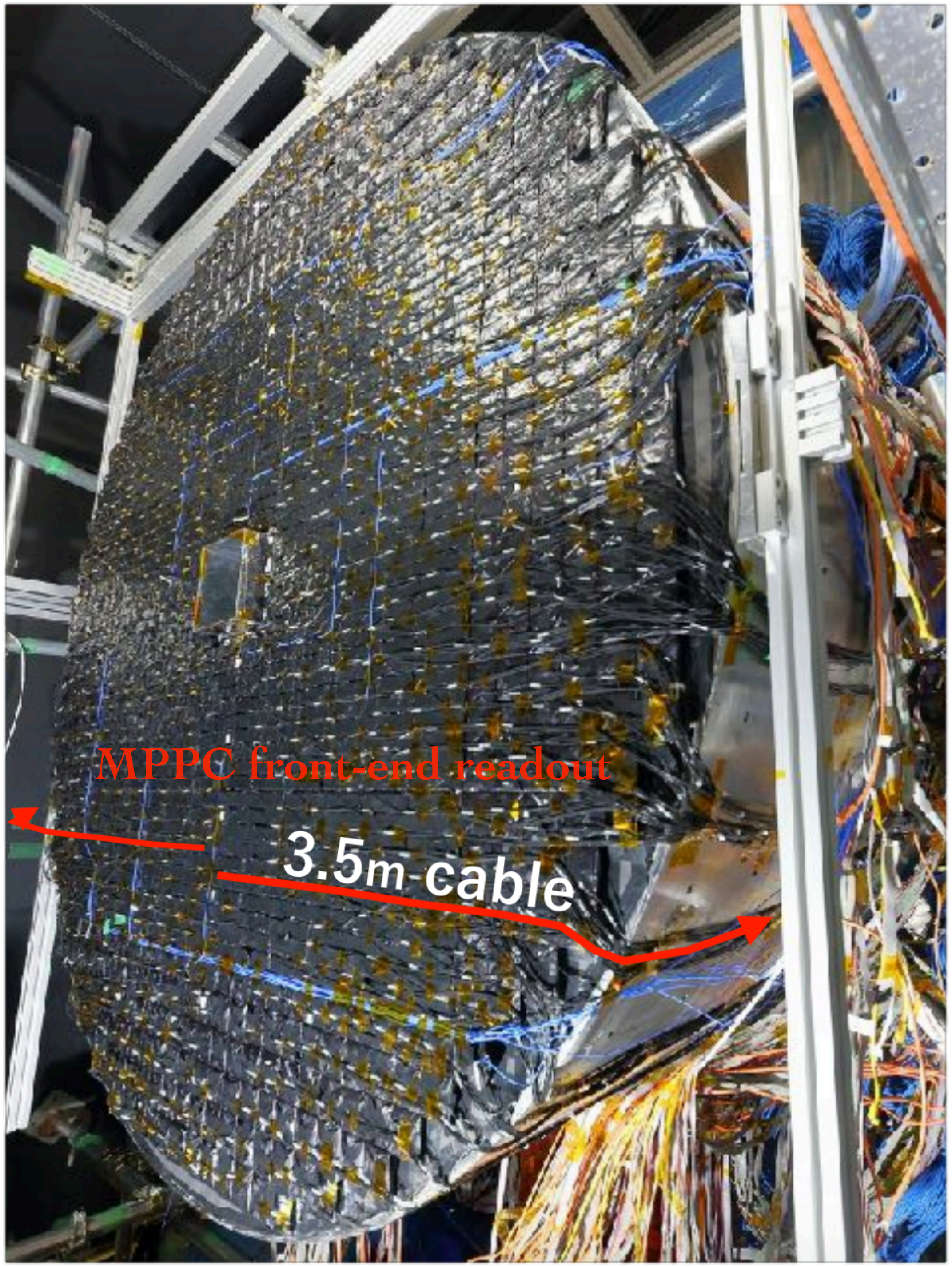
Detector Upgrades

CsI dual-sided readout (2019-)

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

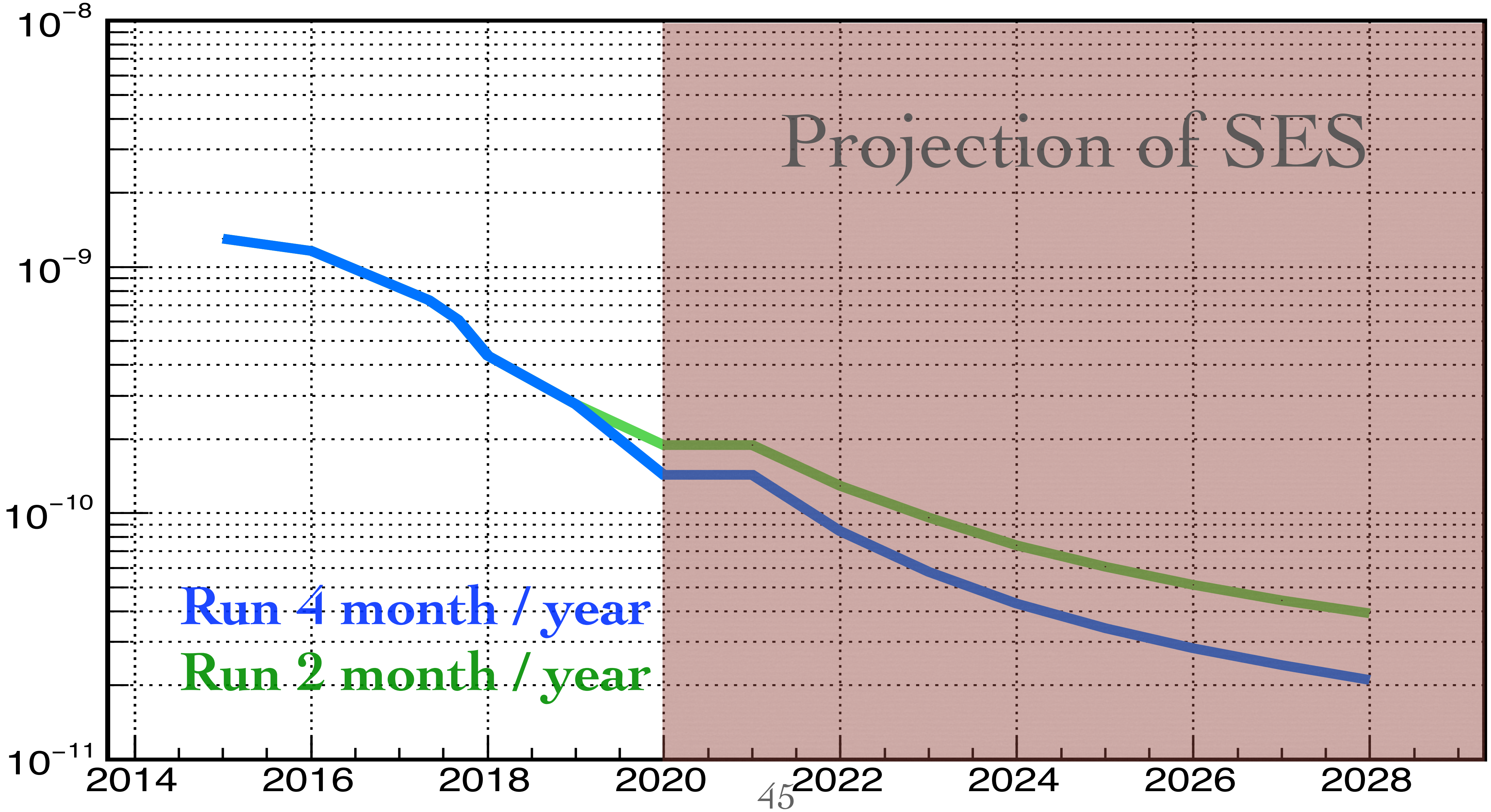


1/20 Reduction



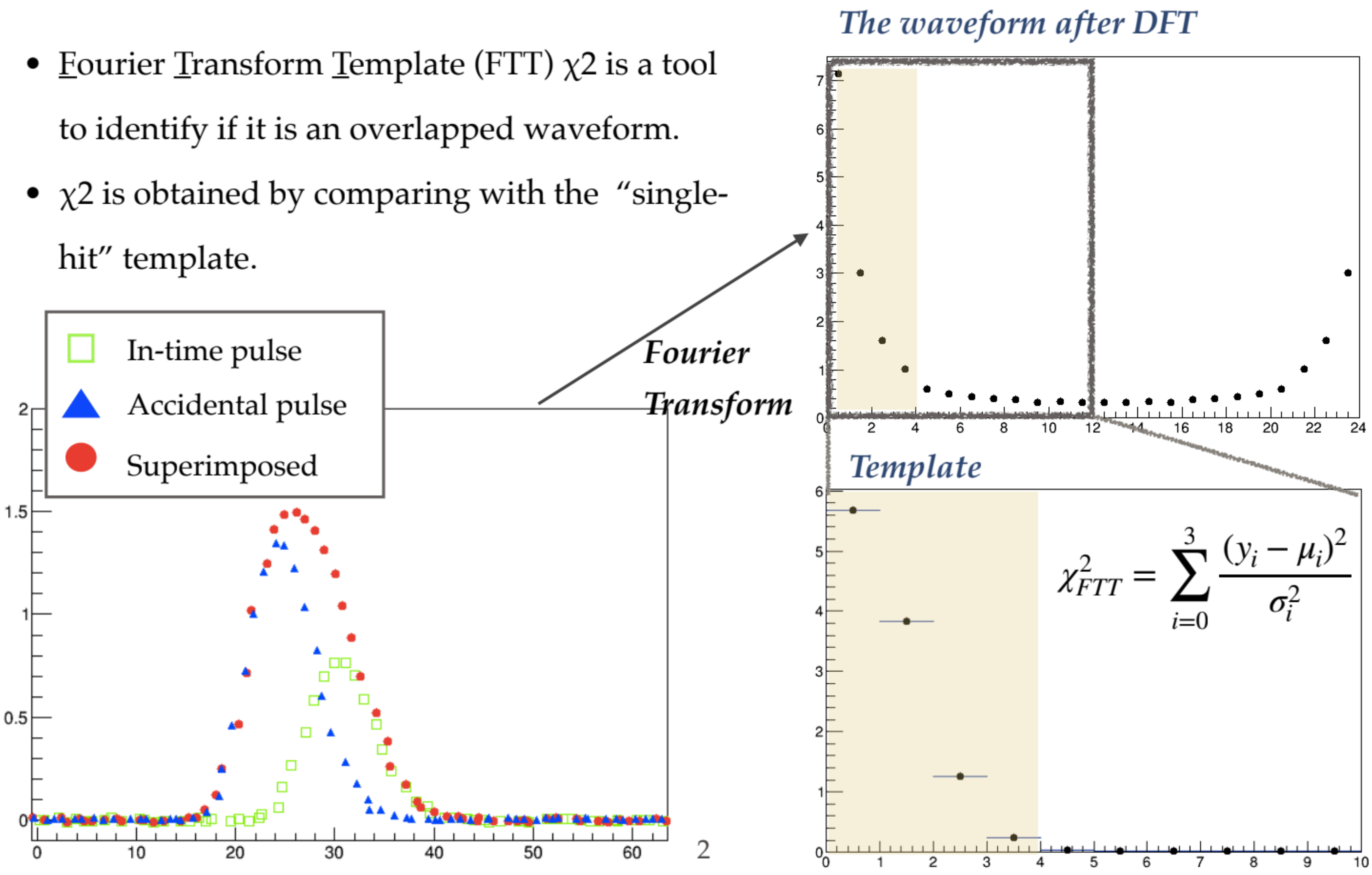
Single Event Sensitivity

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



FTT χ2 in a Nutshell

- Fourier Transform Template (FTT) χ2 is a tool to identify if it is an overlapped waveform.
- χ2 is obtained by comparing with the “single-hit” template.

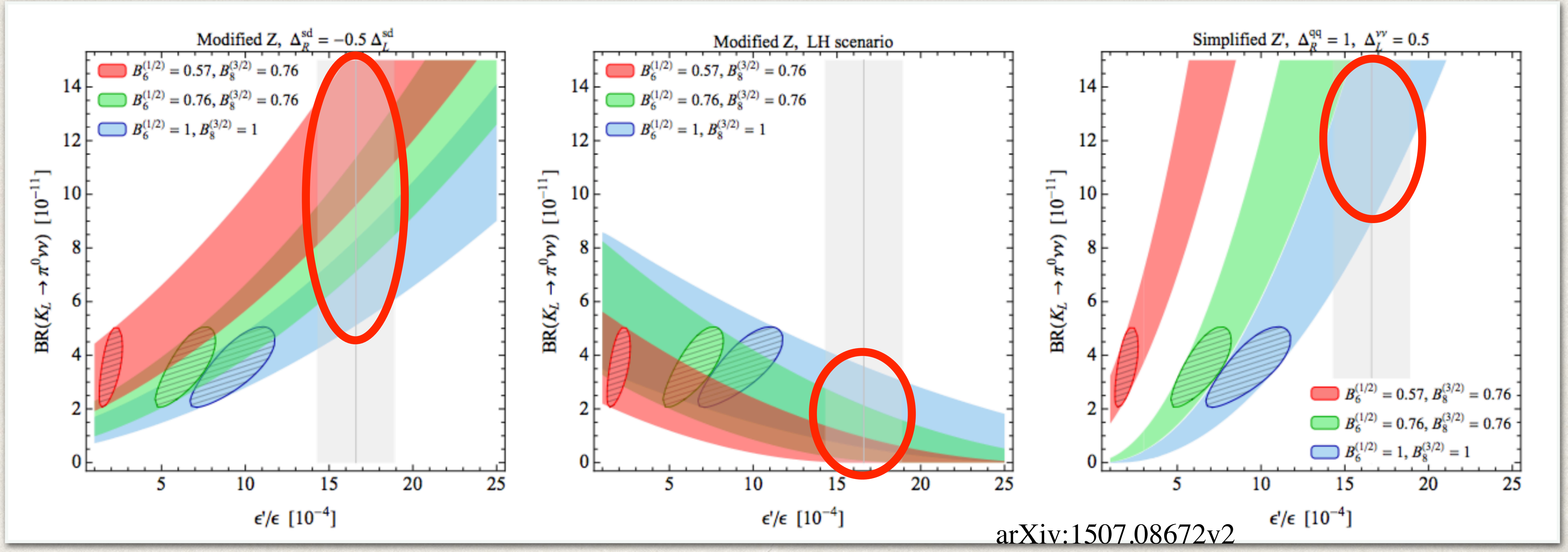


$$\chi^2_{FTT} = \sum_{i=0}^{3} \frac{(y_i - \mu_i)^2}{\sigma_i^2}$$

Models and Correlations

Rare $K_L \rightarrow \pi^0\nu\nu$, $BR_{SM} = 3x10^{-11}$

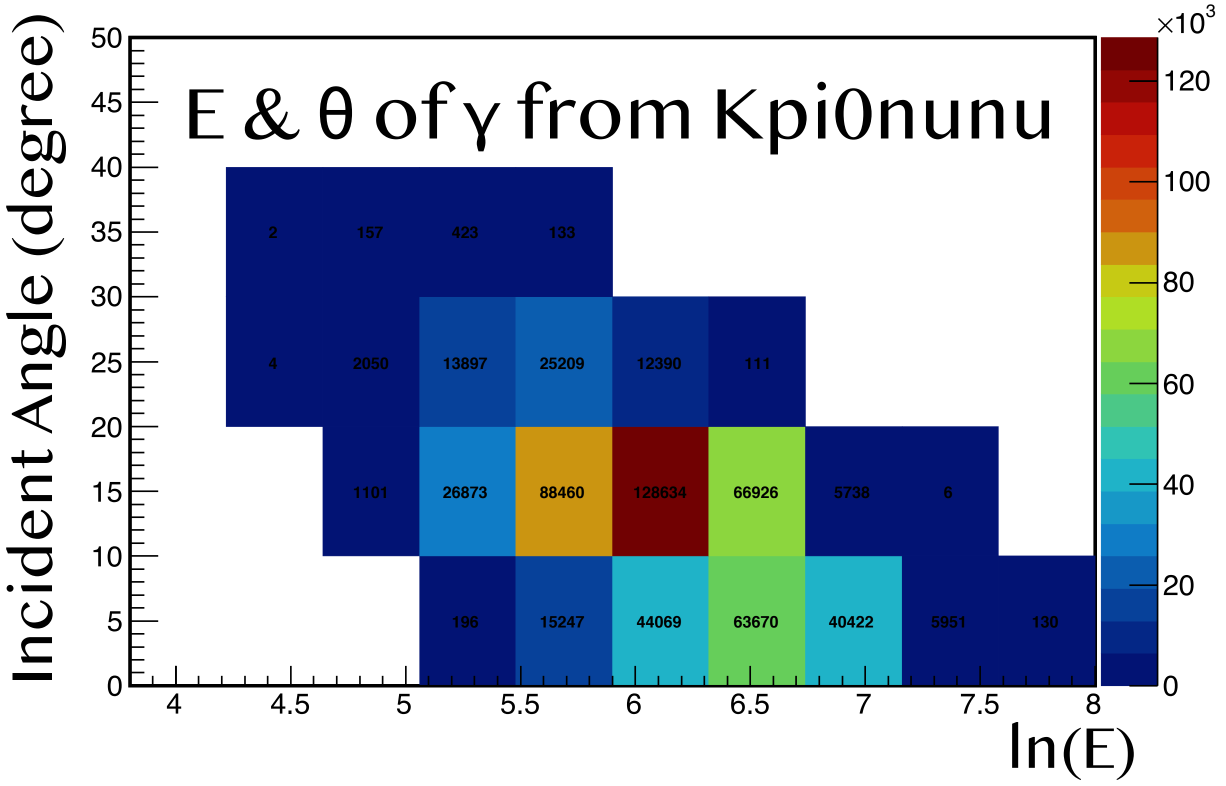
- CPV process.
- theoretically clean, 2% uncertainty.
- "gold mode" for probing deviation from SM.
- enhancement or suppression from new physics?

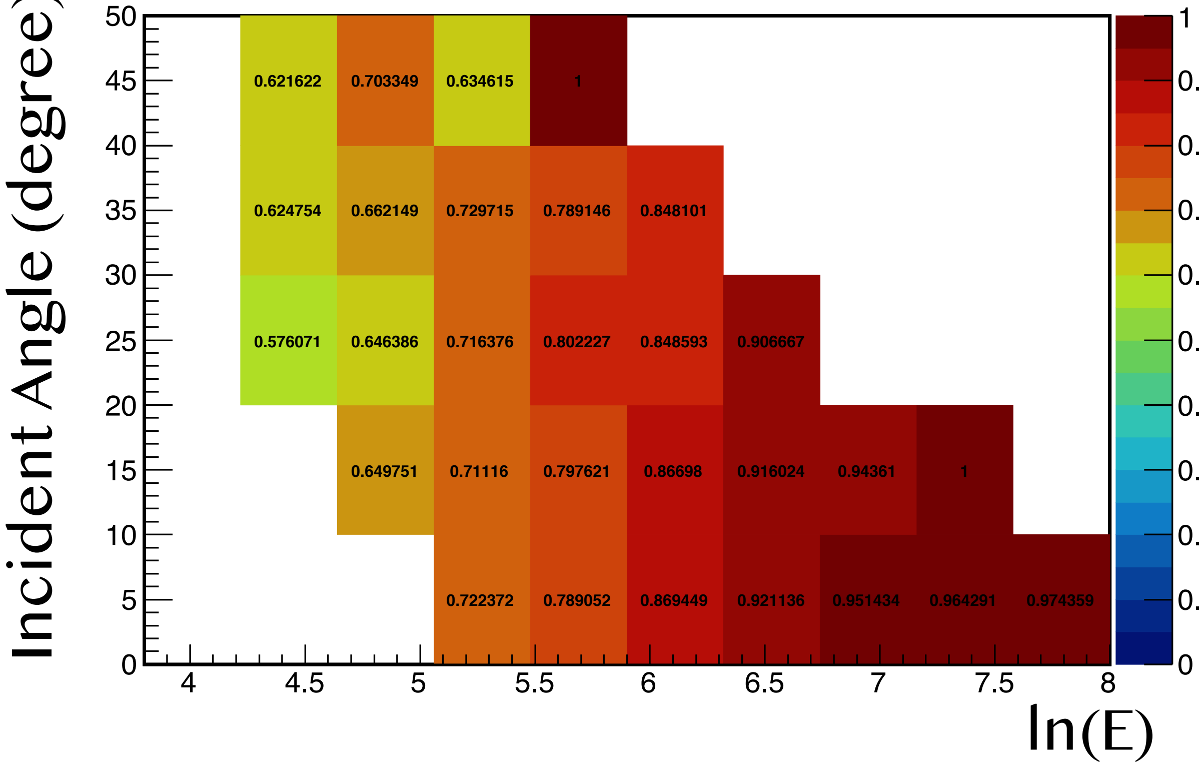


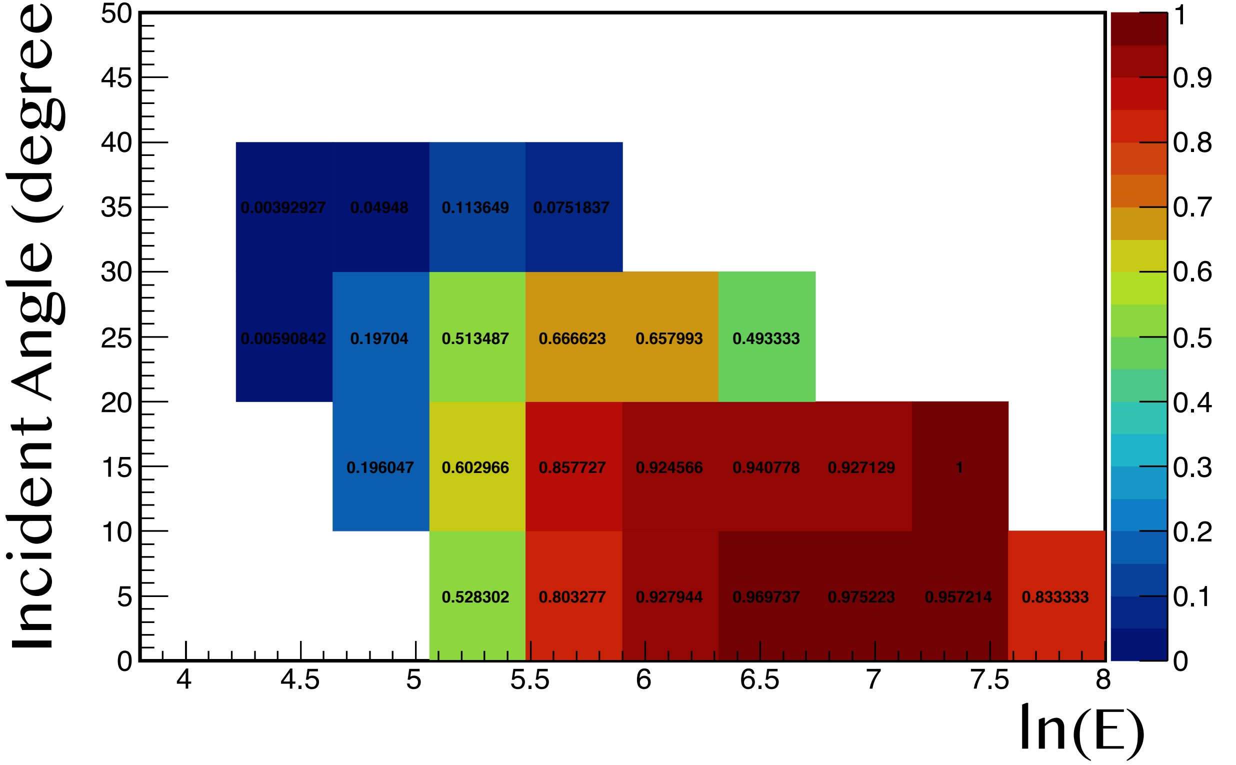
arXiv:1507.08672v2

Gamma Acceptance

- Acceptance by shape X² and CSD2015 is sort of uniform in θ
- CSD_DL rejected more on large angles

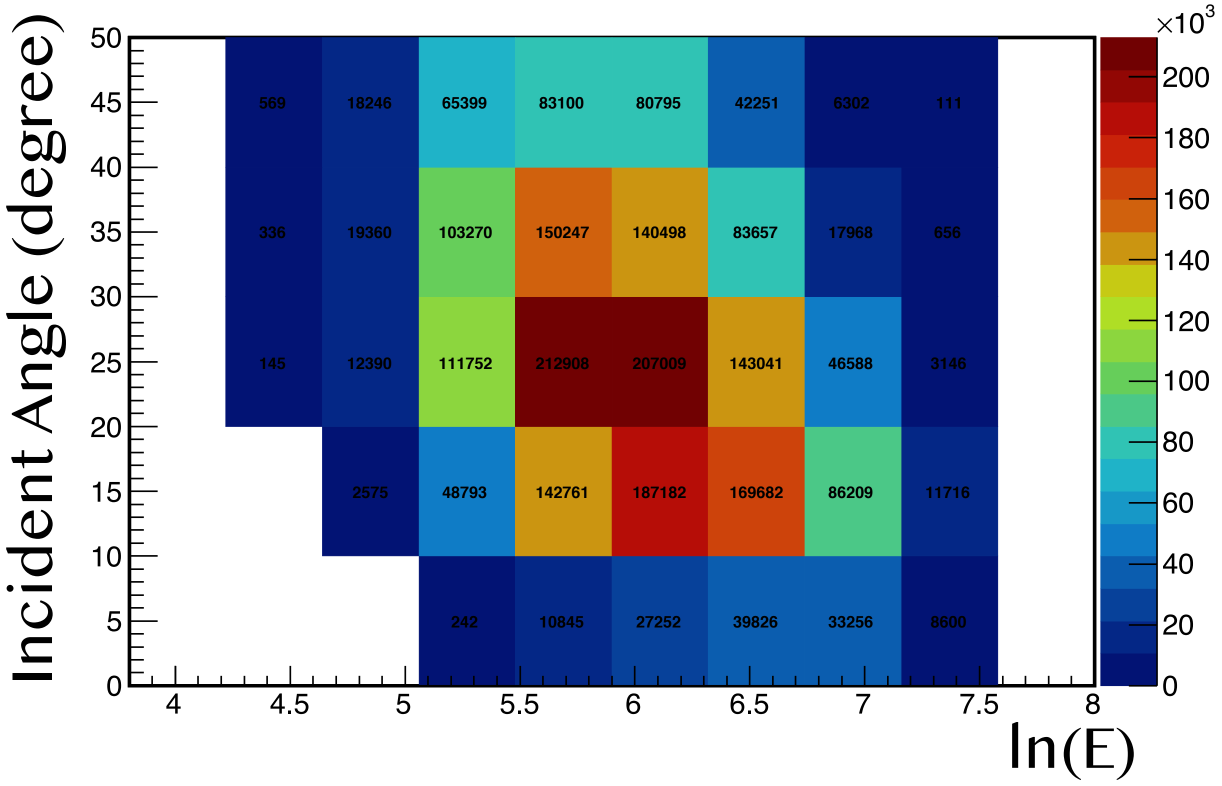



Shape X² & CSD2015 Acceptance

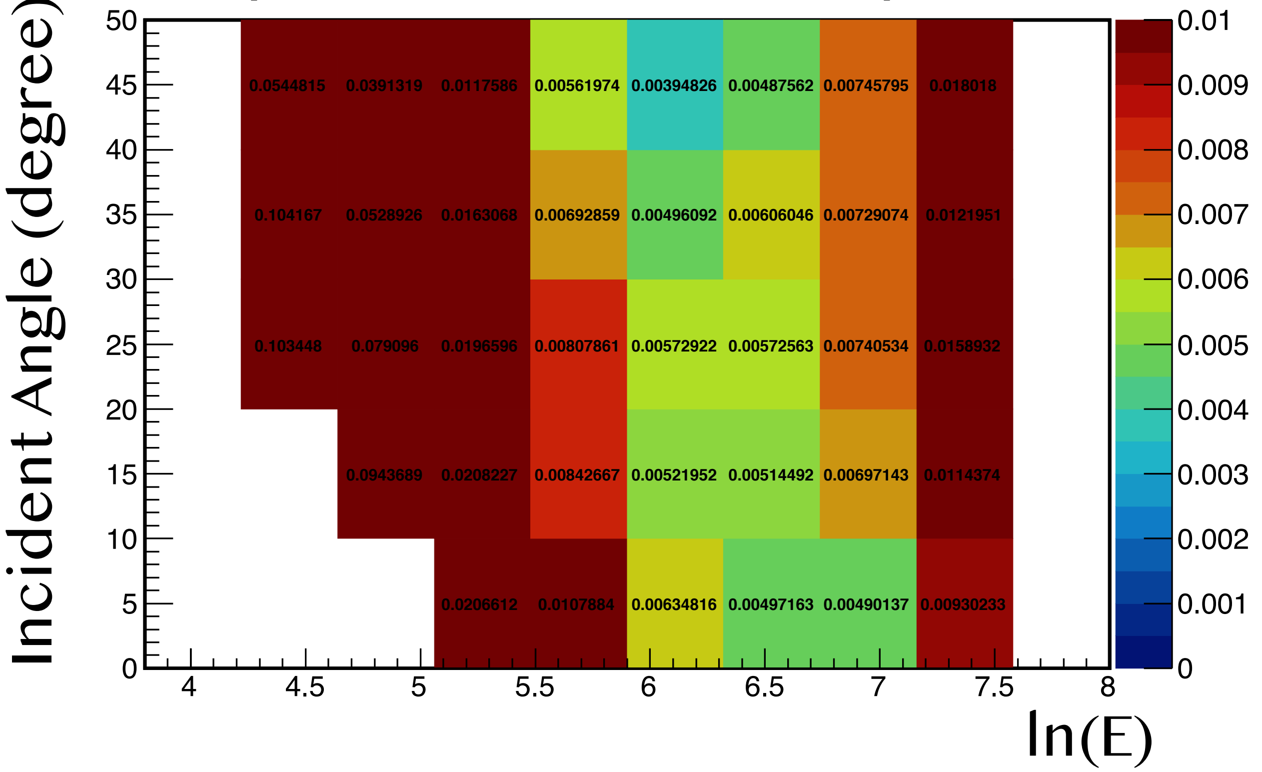

CSDDL Acceptance

Neutron Acceptance

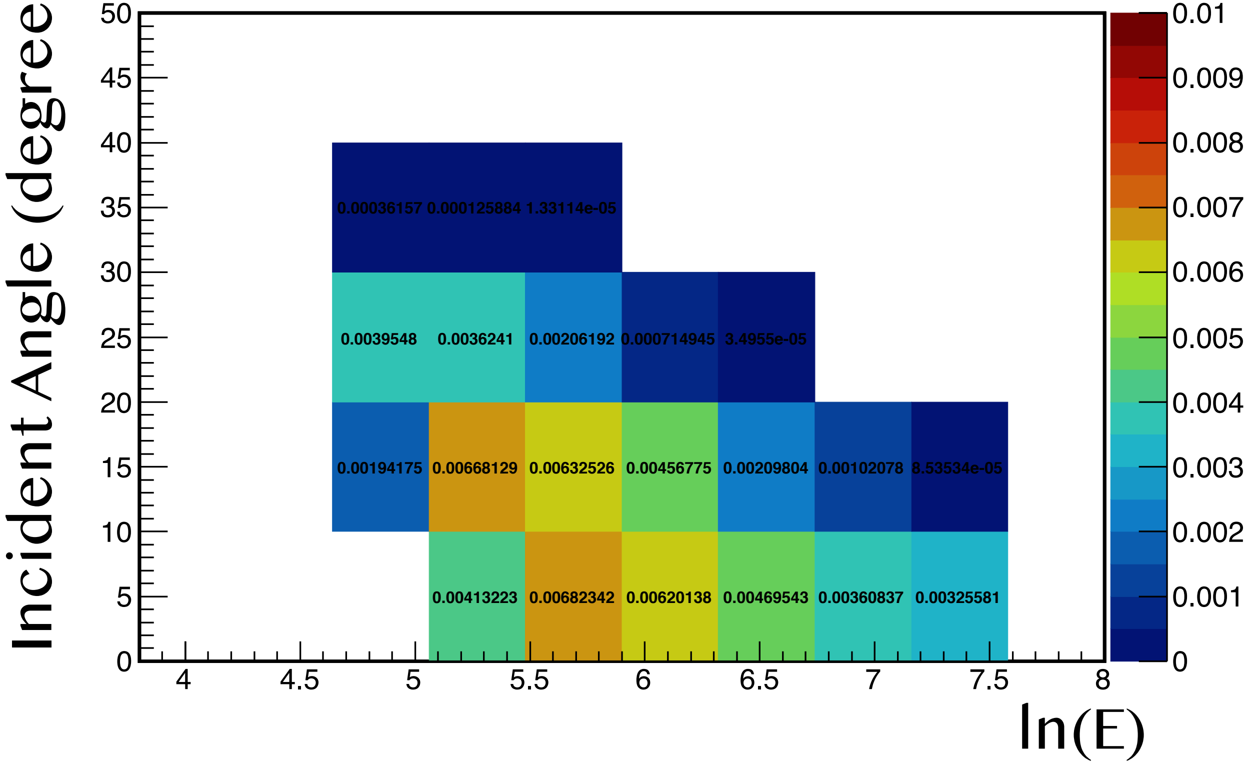
- Pi0 kinematic cut was removed
- Acceptance by shape X2 and CSD2015 is uniform in θ
- CSD_DL rejected more on large angles



Shape X² & CSD2015 Acceptance

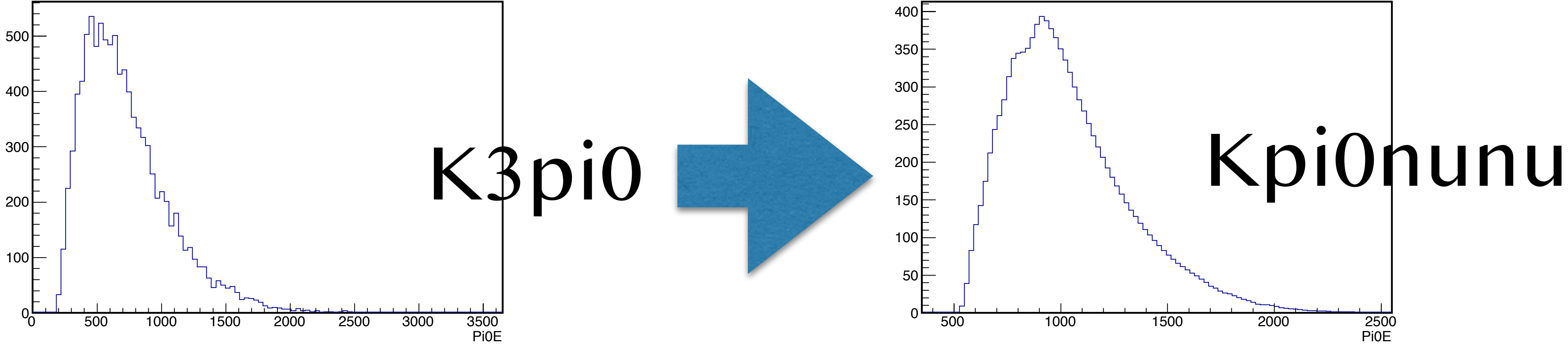


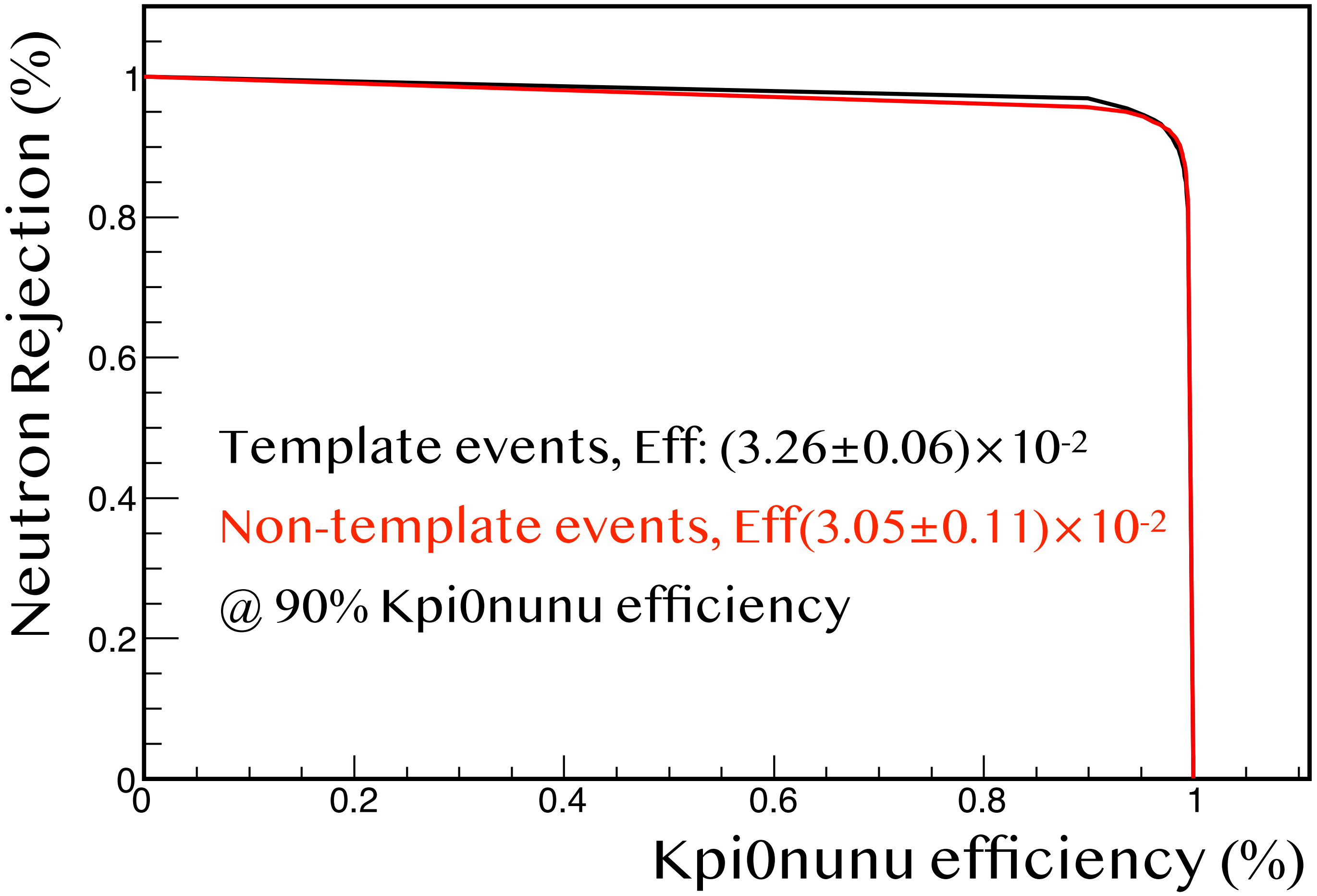
CSDDL Acceptance



Fourier PSD

Kpi0nunu efficiency was studied through gammas from K3pi0





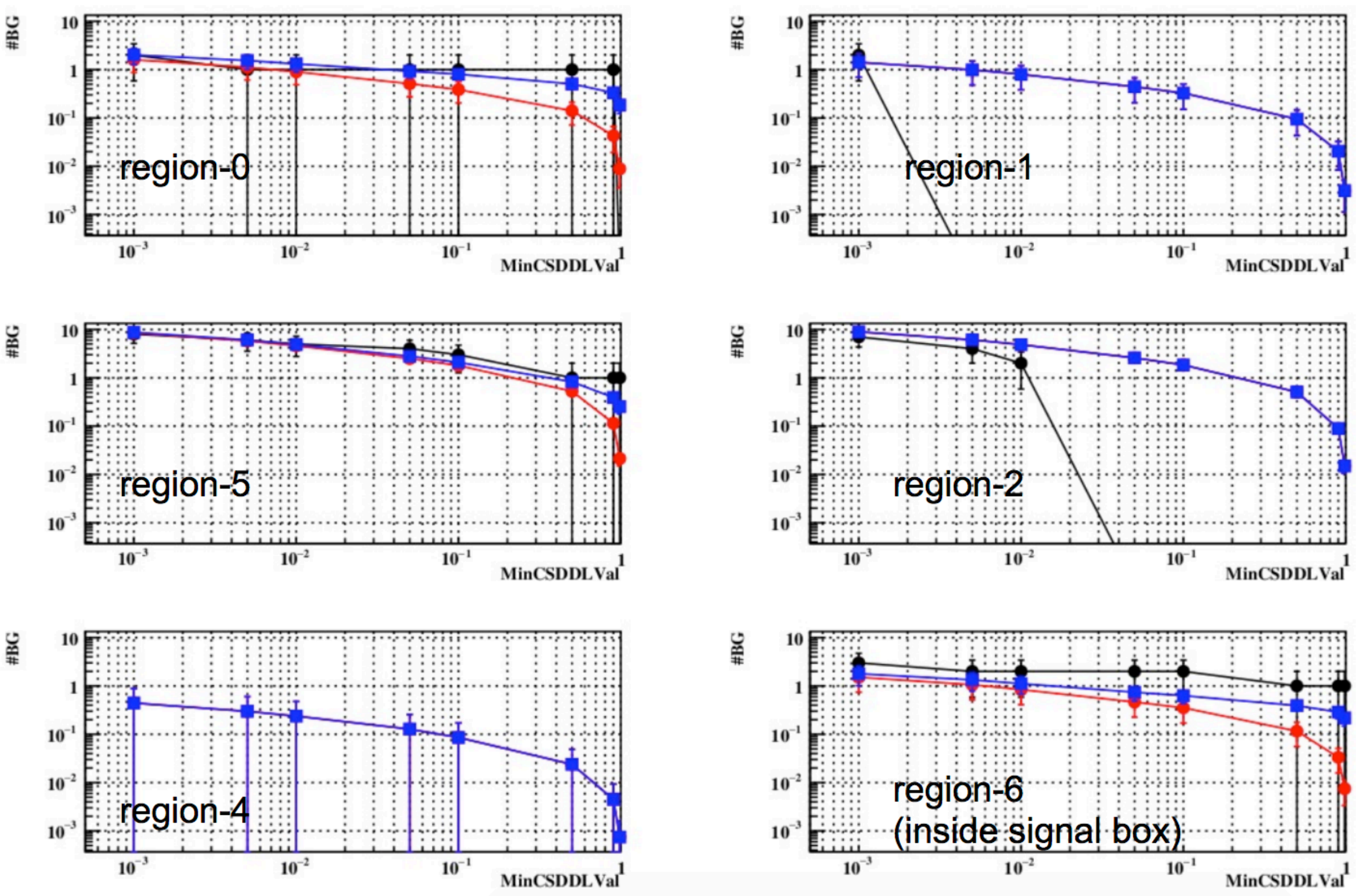
Template events, Eff: $(3.26\pm0.06)\times10^{-2}$

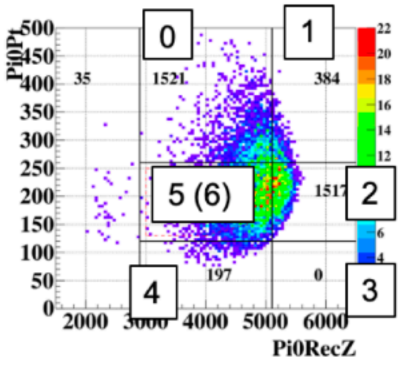
Non-template events, Eff$(3.05\pm0.11)\times10^{-2}$

@ 90% Kpi0nunu efficiency

Observed vs. expectation

w/o FPSD, tight veto condition





black : observed
blue: expectation (weighted + KL2gamma)
red : expectation (weighted only)