Status of KOTO Experiment

Yu-Chen Tung for the KOTO collaboration

University of Chicago

KOTO Experiment

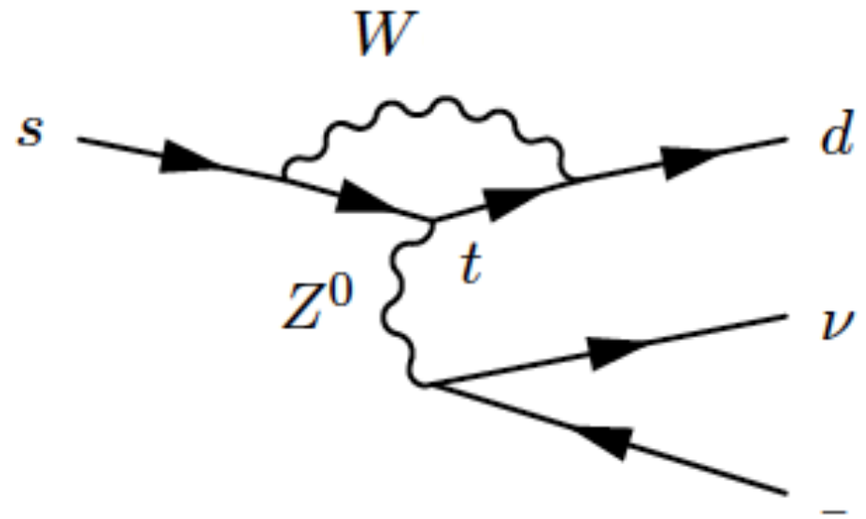
50 collaborators from 16 institutes

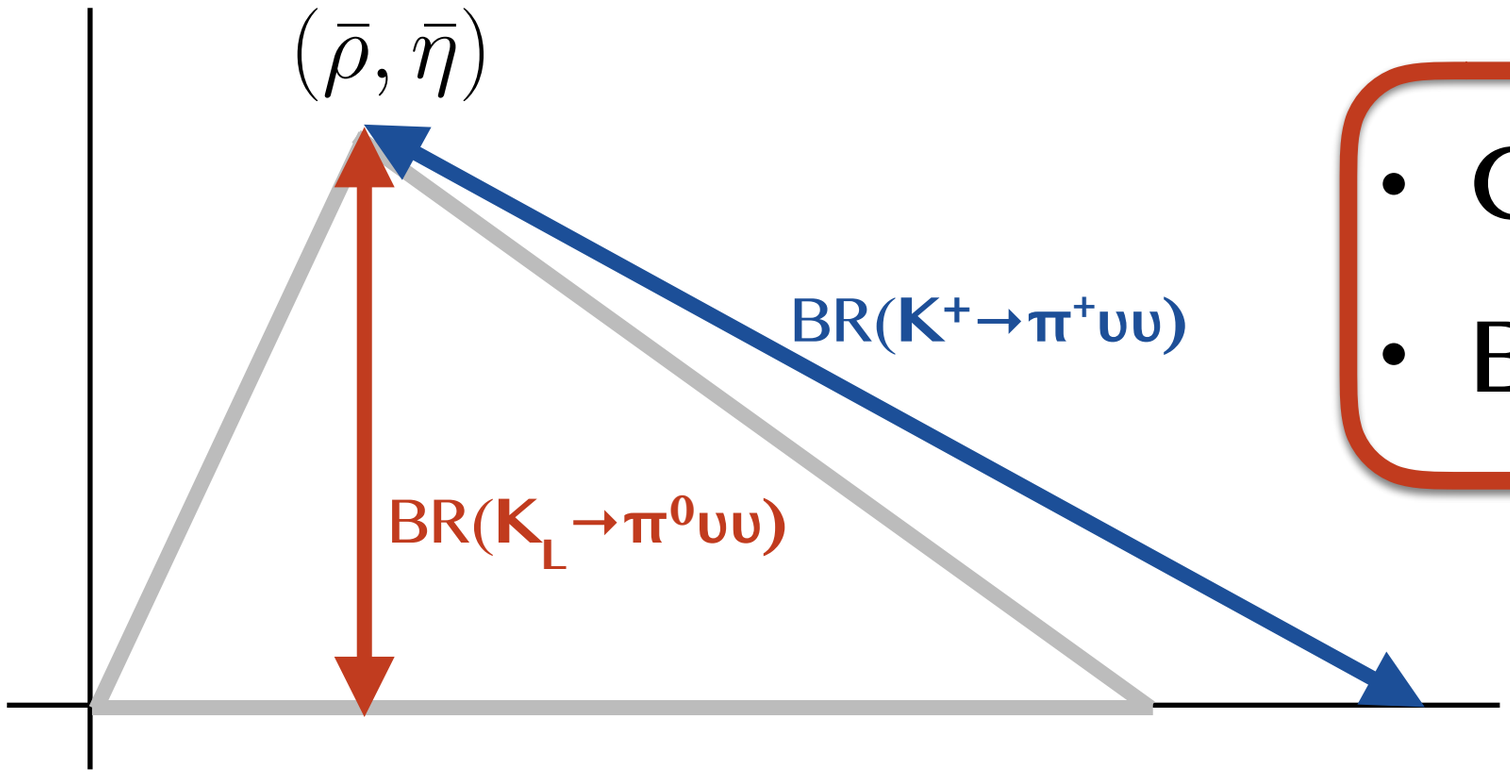
Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto,
Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata

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

- Direct CPV
- BR(SM)=3.0×10^{-11}

Ultra Rare





- Clean: ~2%
- BR ∝ CKM height

Golden Decay

Sea of Japan

Sapporo
札幌

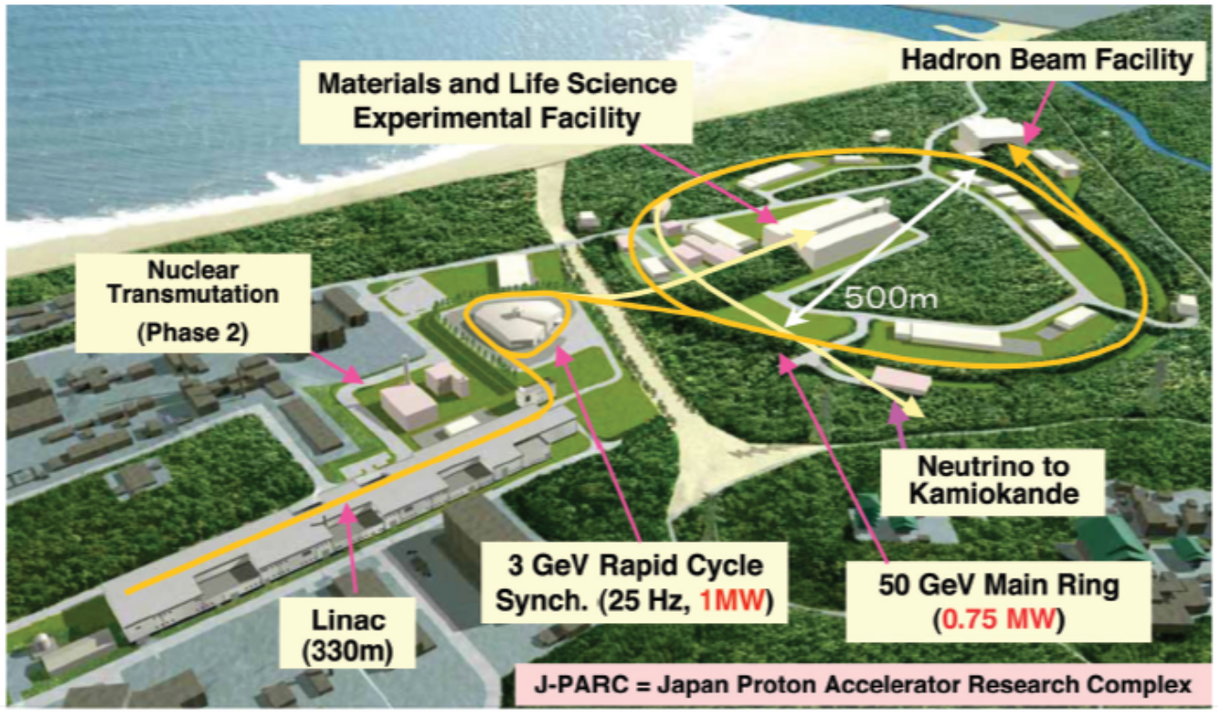
Sendai
仙台

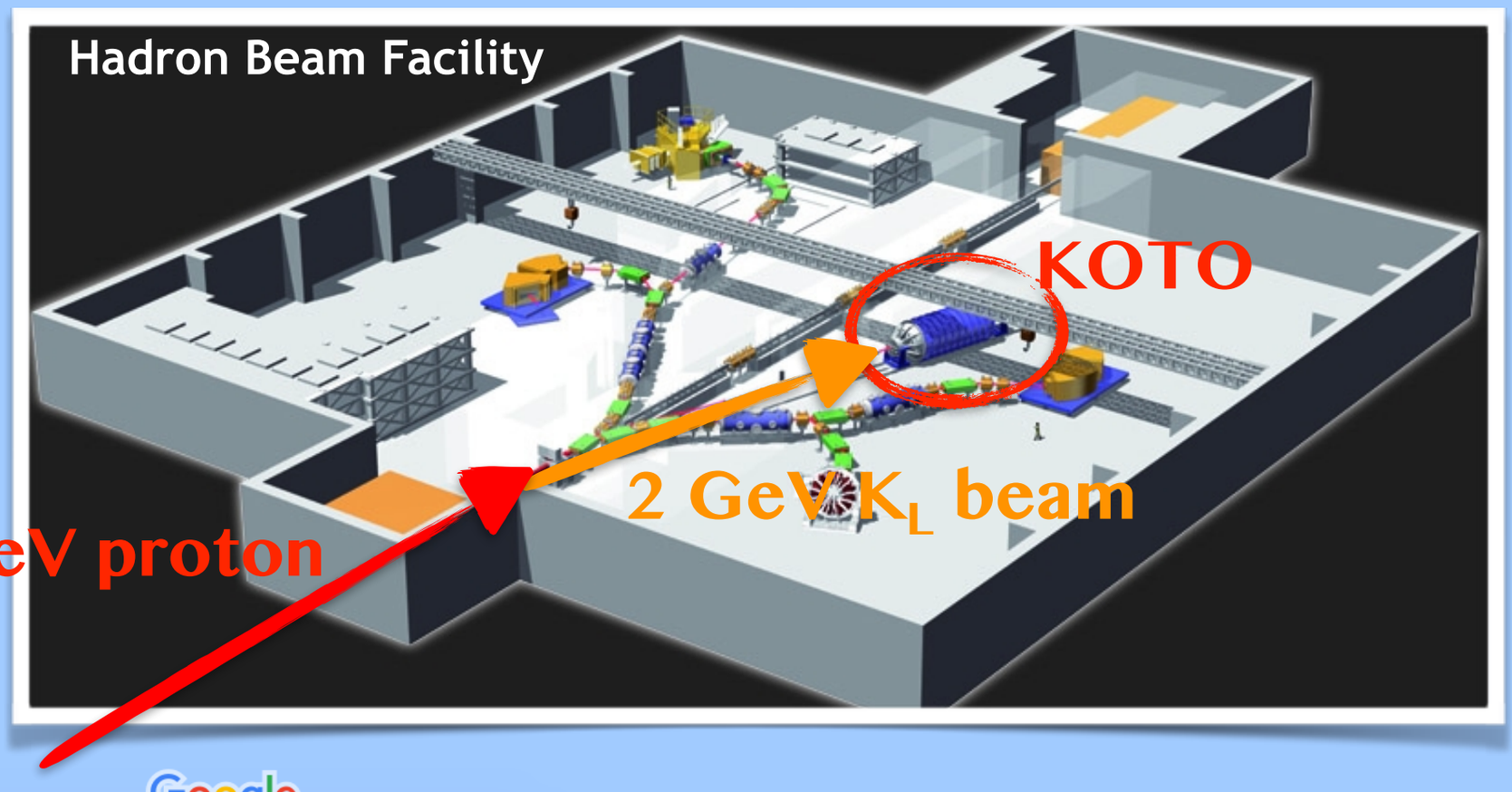
Japan

Tokyo
東京

Nagoya
名古屋

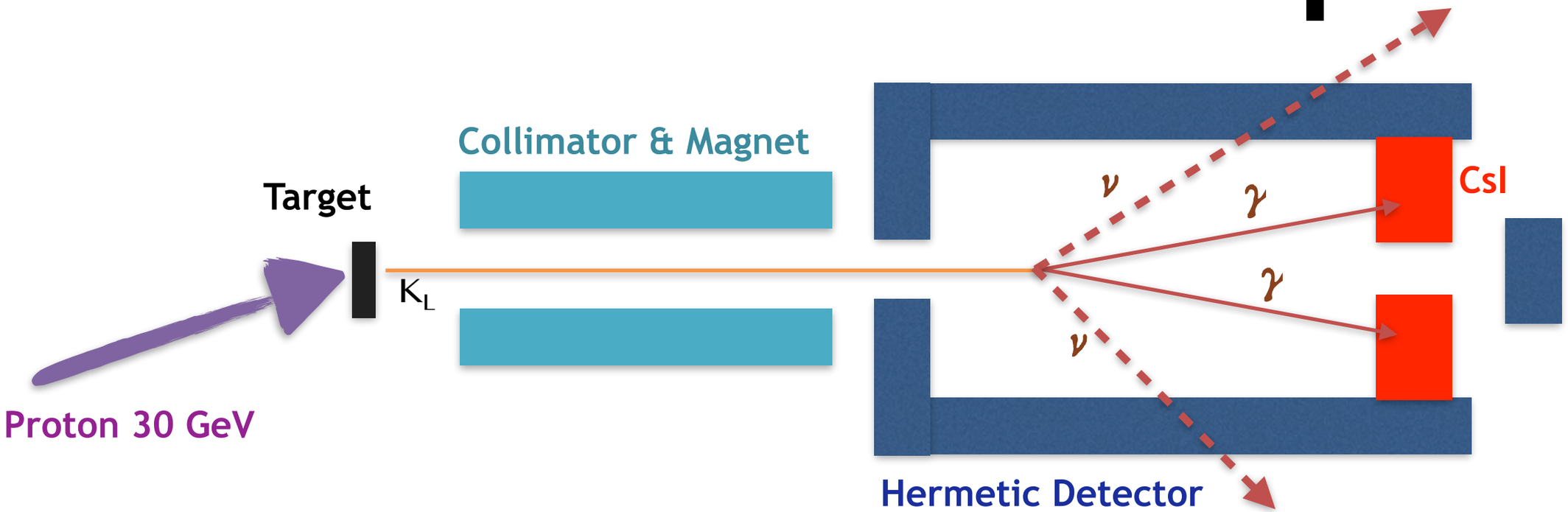
Osaka
大阪



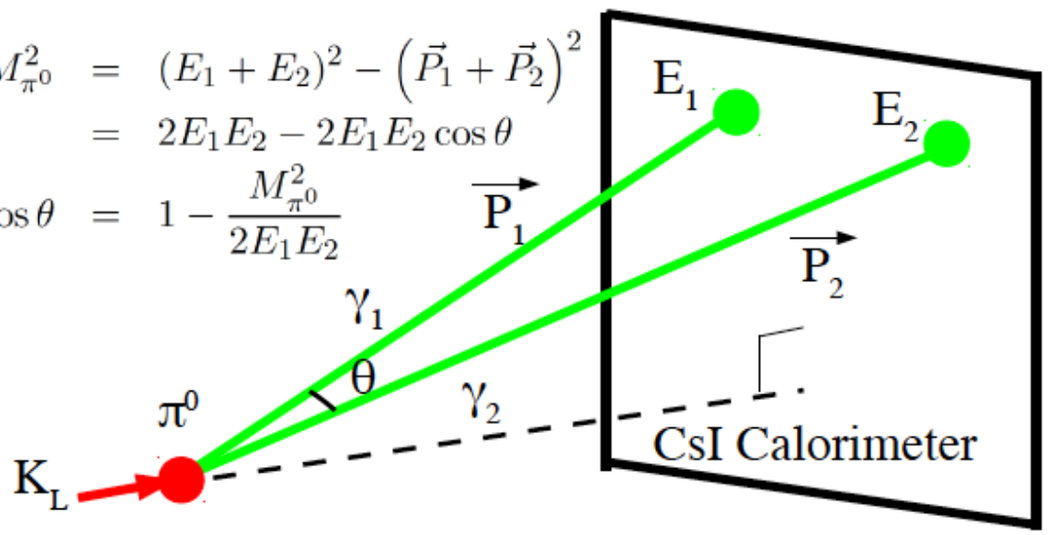


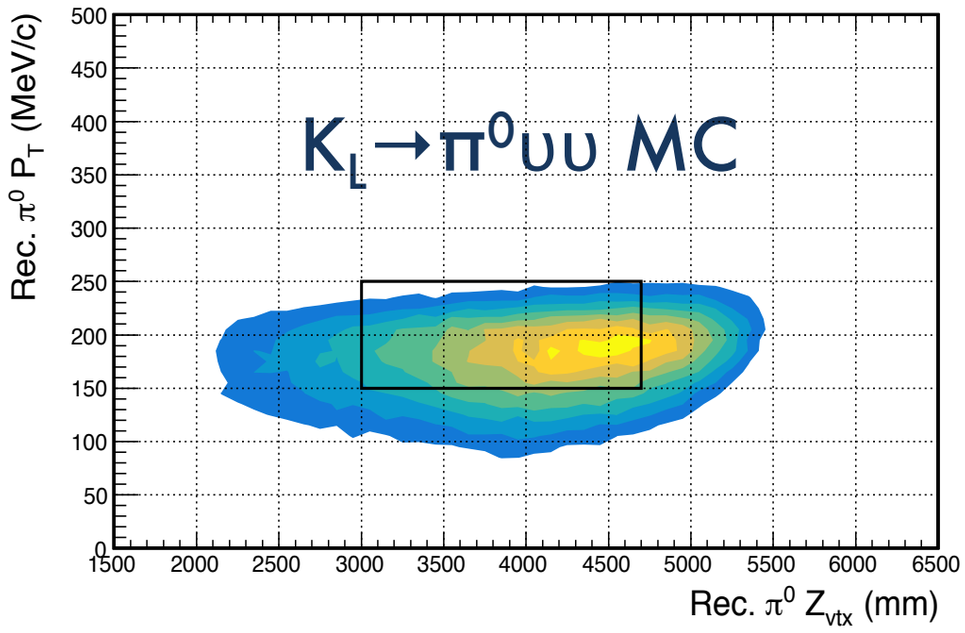
Google

Detection Principle

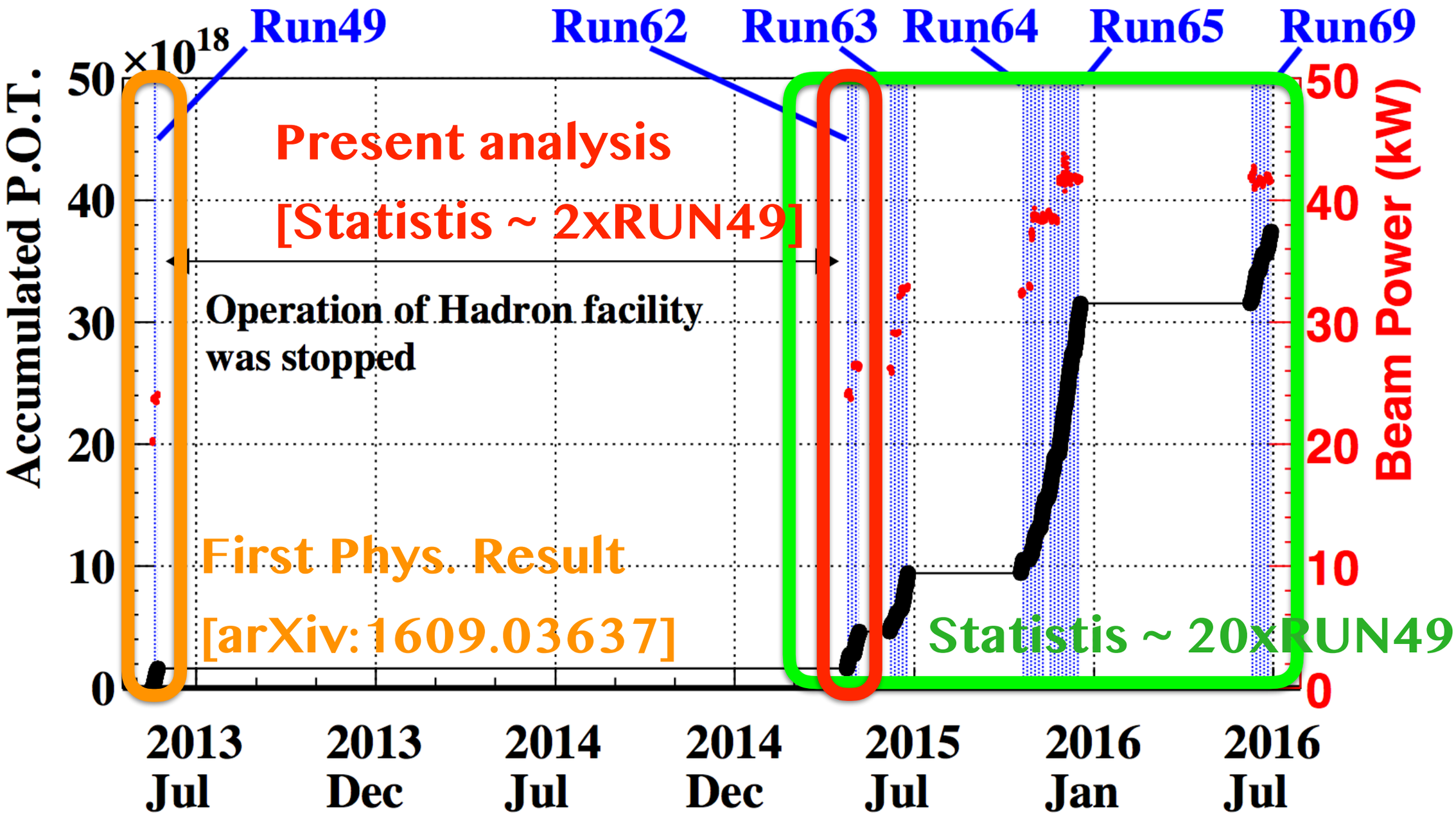


$$
\begin{aligned}
M_{\pi^0}^2 &= (E_1+E_2)^2 - \left(\vec{P}_1+\vec{P}_2\right)^2 \\
&= 2E_1E_2 - 2E_1E_2\cos\theta \\
\cos\theta &= 1 - \frac{M_{\pi^0}^2}{2E_1E_2}
\end{aligned}
$$



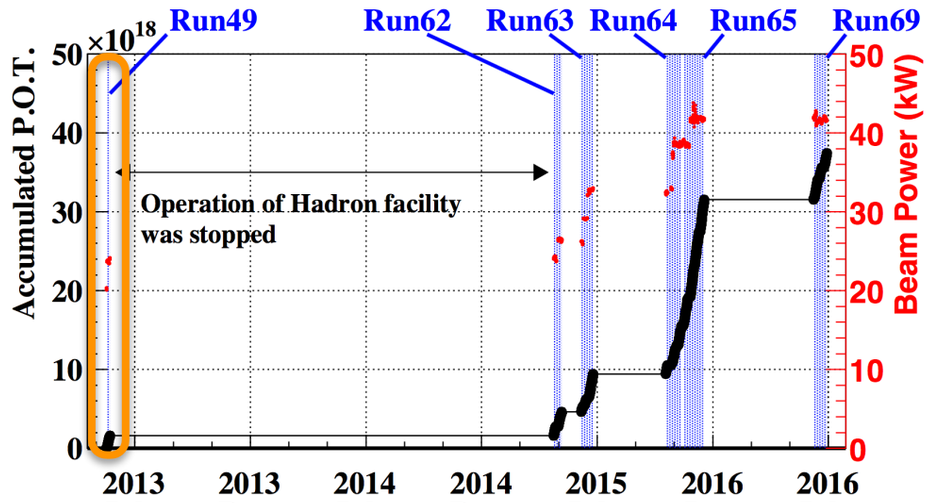


Data Taking


Run49
Run62
Run63
Run64
Run65
Run69
Accumulated P.O.T.
×10^18
50
40
30
20
10
0
Beam Power (kW)
50
40
30
20
10
0
Present analysis
[Statistis ~ 2xRUN49]
Operation of Hadron facility
was stopped
First Phys. Result
[arXiv:1609.03637]
Statistis ~ 20xRUN49
2013 Jul
2013 Dec
2014 Jul
2014 Dec
2015 Jul
2016 Jan
2016 Jul

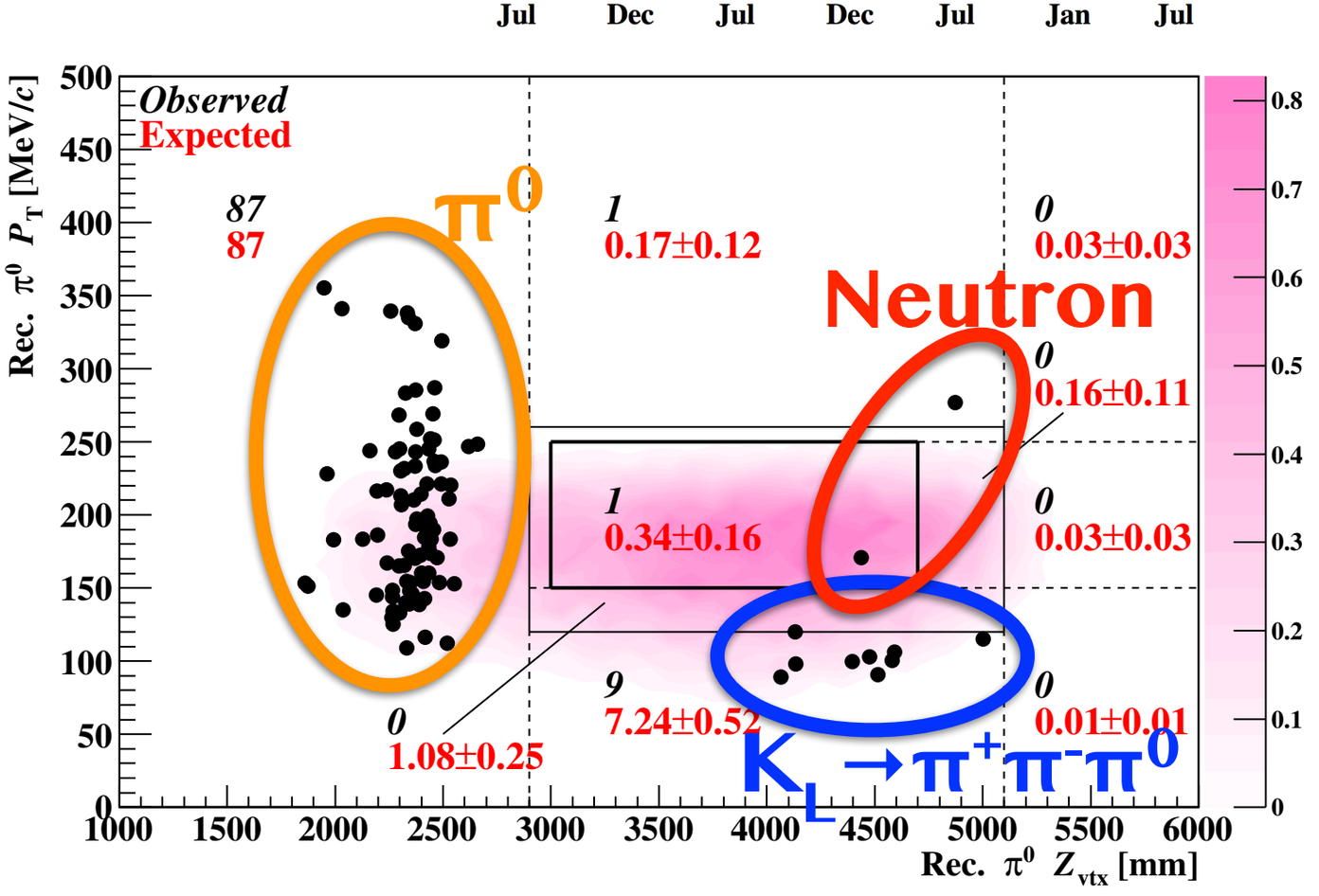
First Phys Results

- Predict/Observe: 0.34/1
  - Background: 70% neutron
- BR < 5.1×10^{-8} (90% CL)
- arXiv:1609.03637



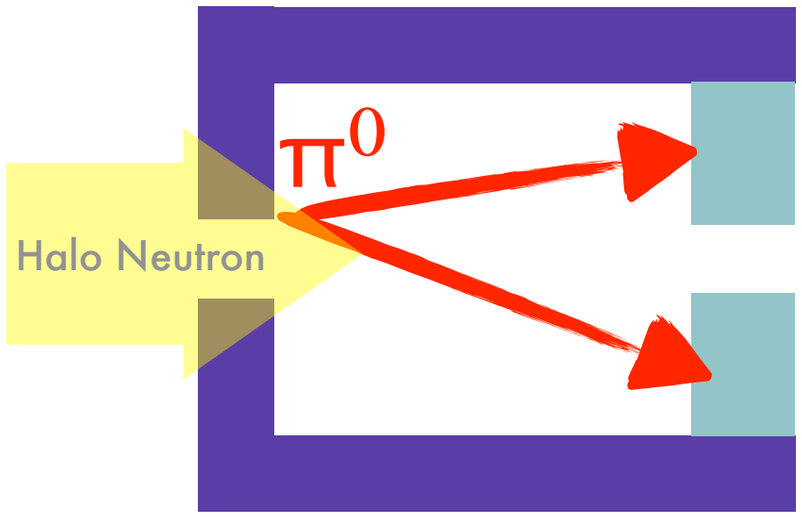
background source	number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
pileup of accidental hits	0.014 ± 0.014
other K_L background	0.010 ± 0.005
halo neutrons hitting NCC	0.056 ± 0.056
halo neutrons hitting the calorimeter	0.18 ± 0.15
total	0.34 ± 0.16

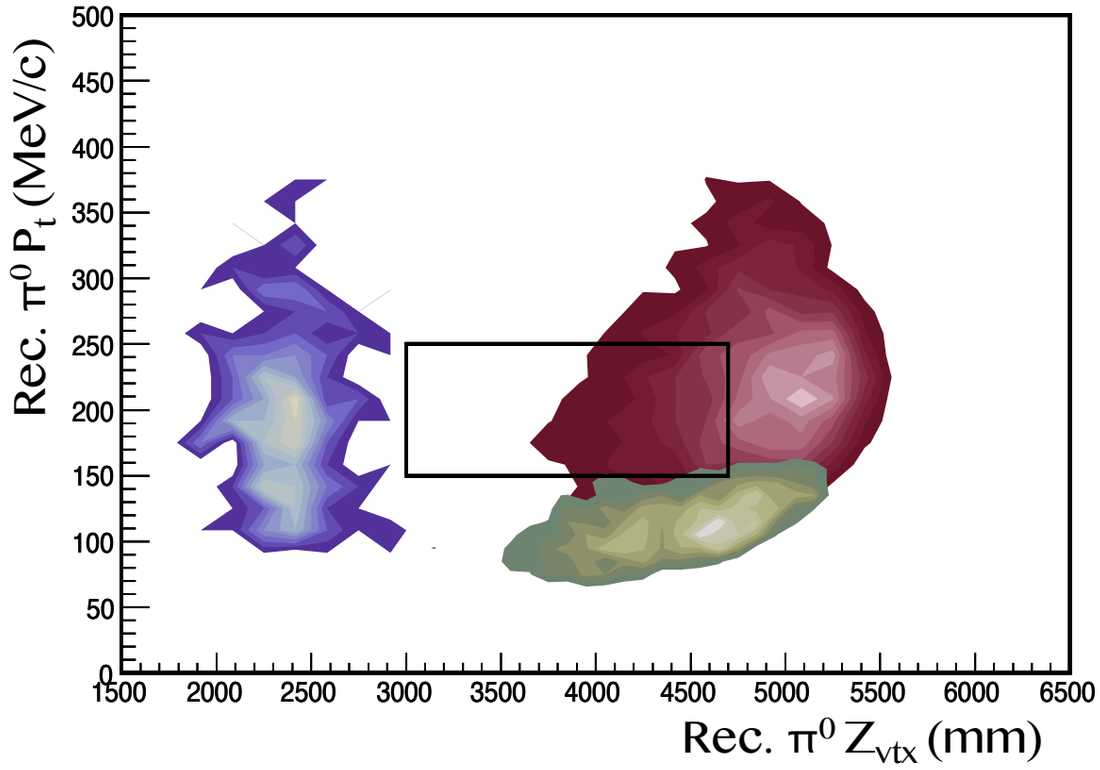
dominated by neutron



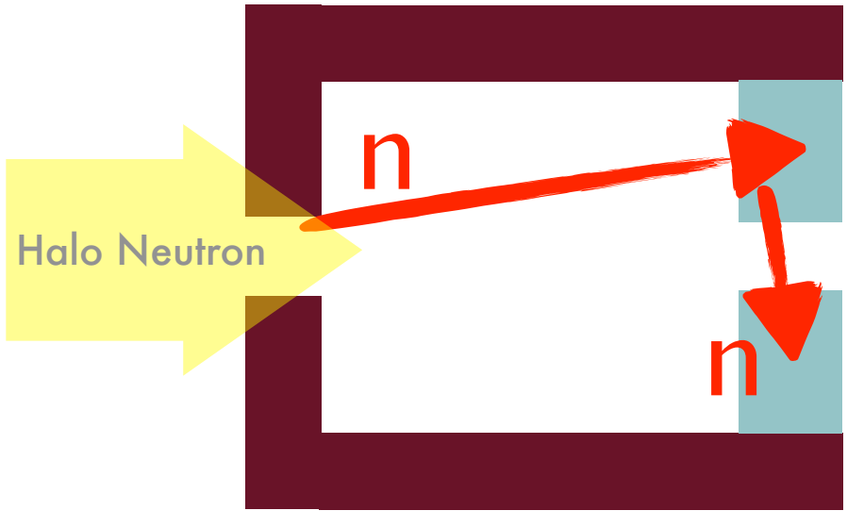
Major Background

Pion produced at detector upstream

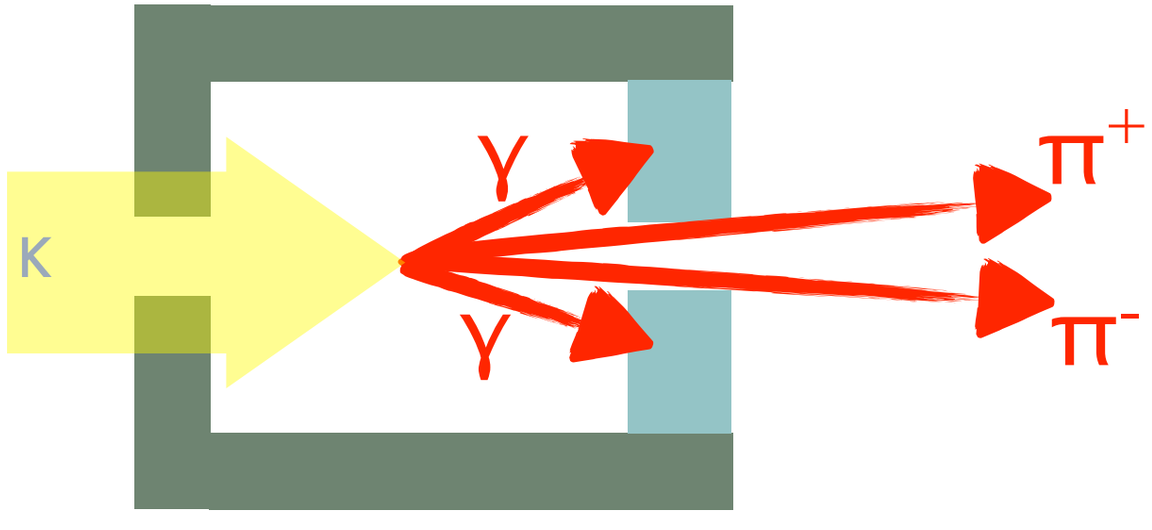




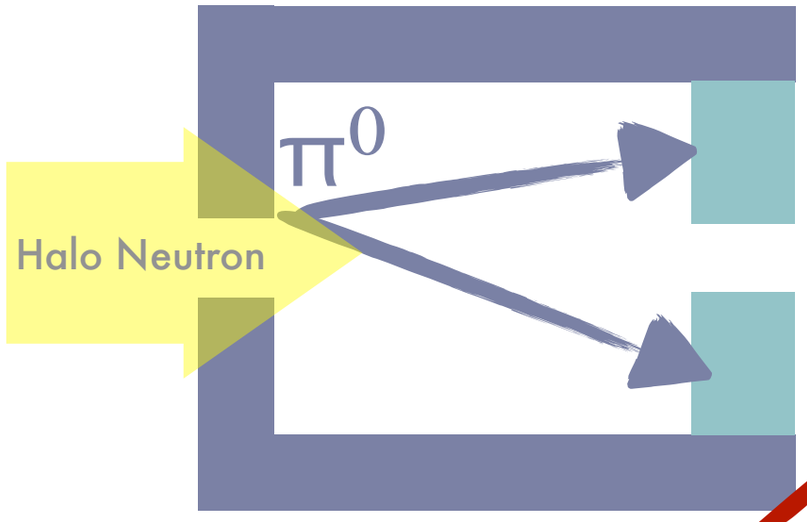
Neutron directly hit on CsI



Particles missing in the downstream gap



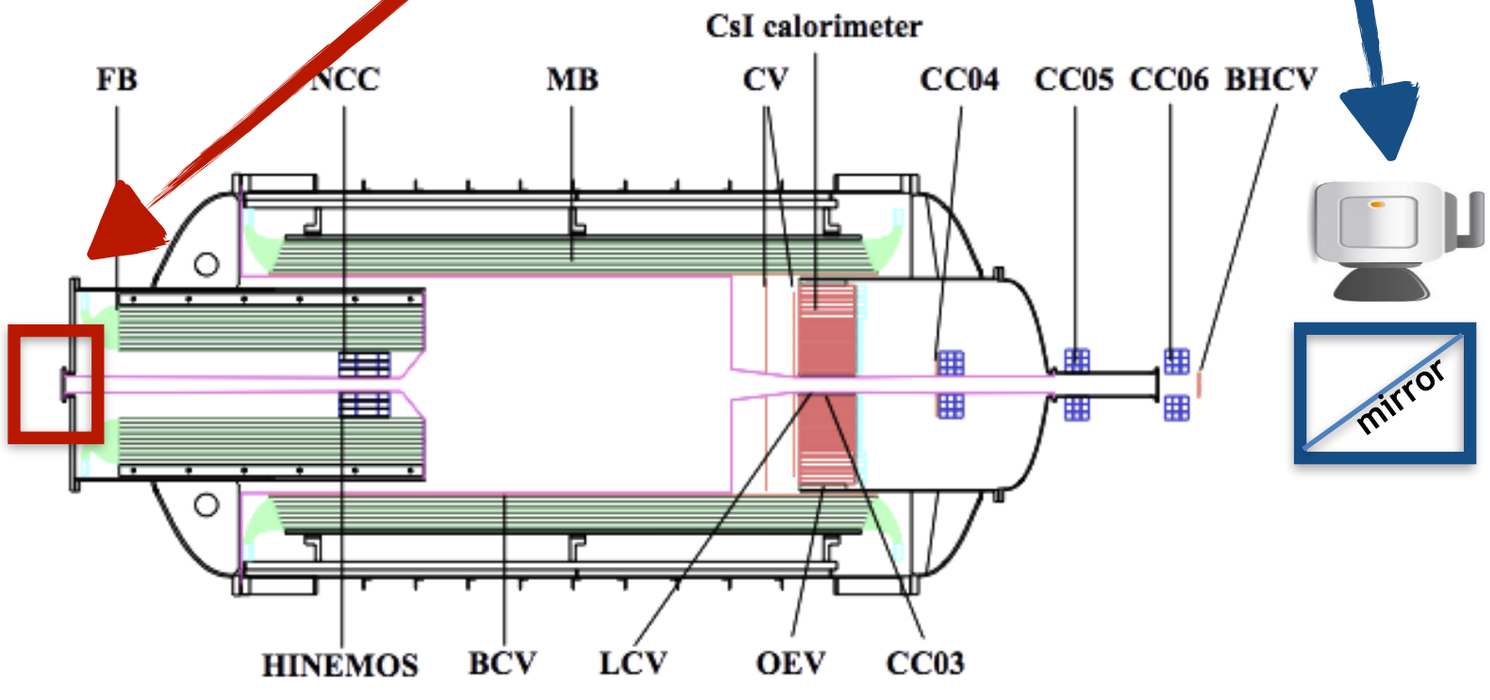
Improvements after 2013

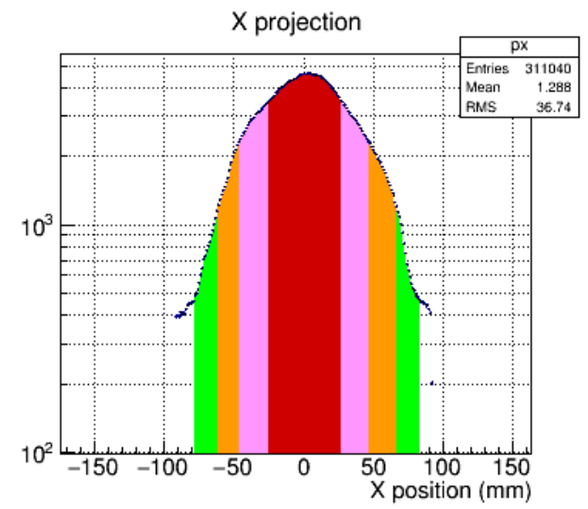


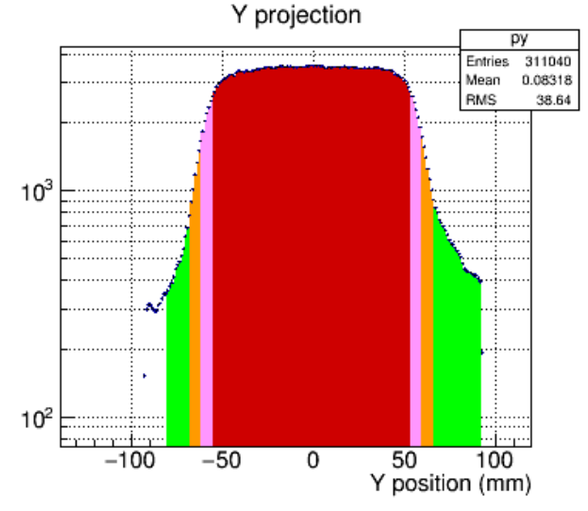
Thinner vacuum window (125μm ⇒ 12.5μm)

to reduce neutron interaction.

Beam Profile Monitor for better beam alignment.

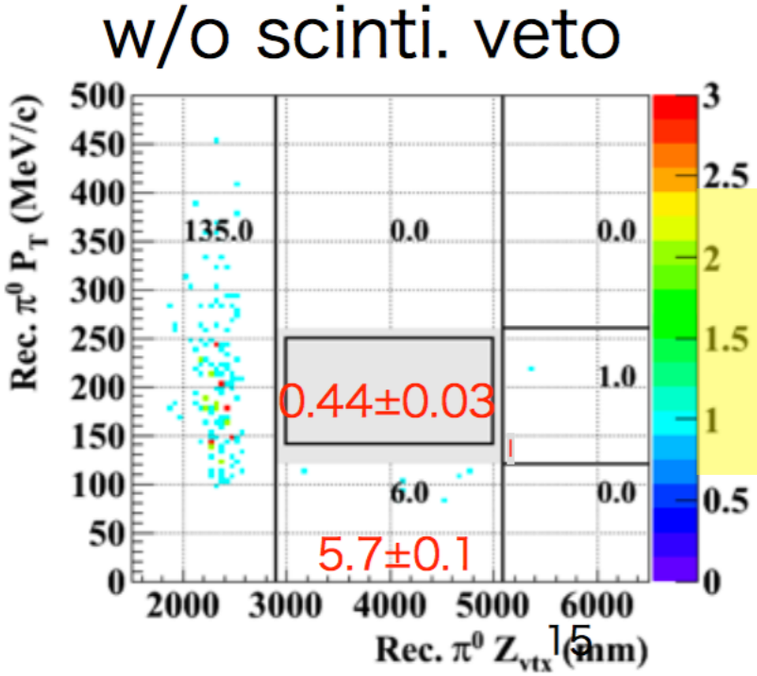


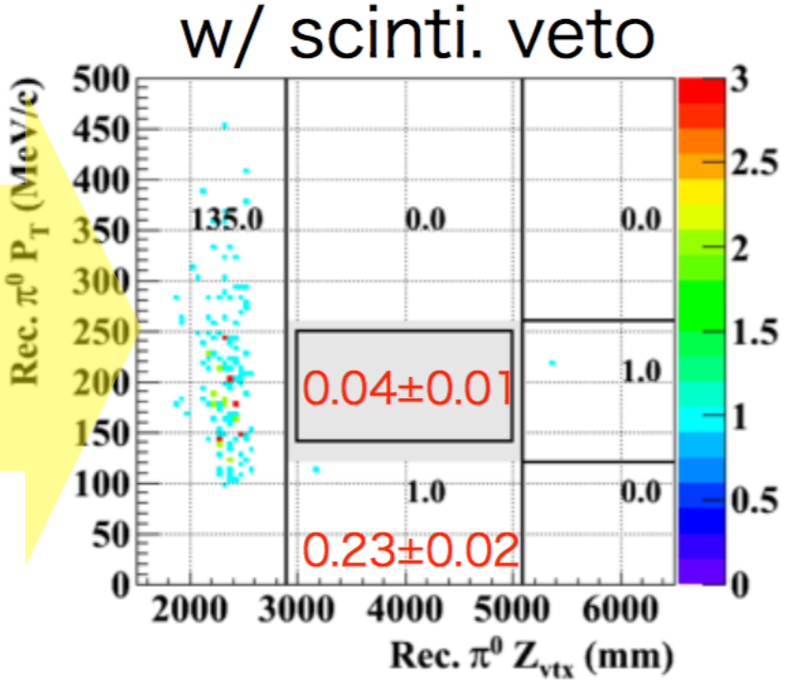




Improvements after 2013

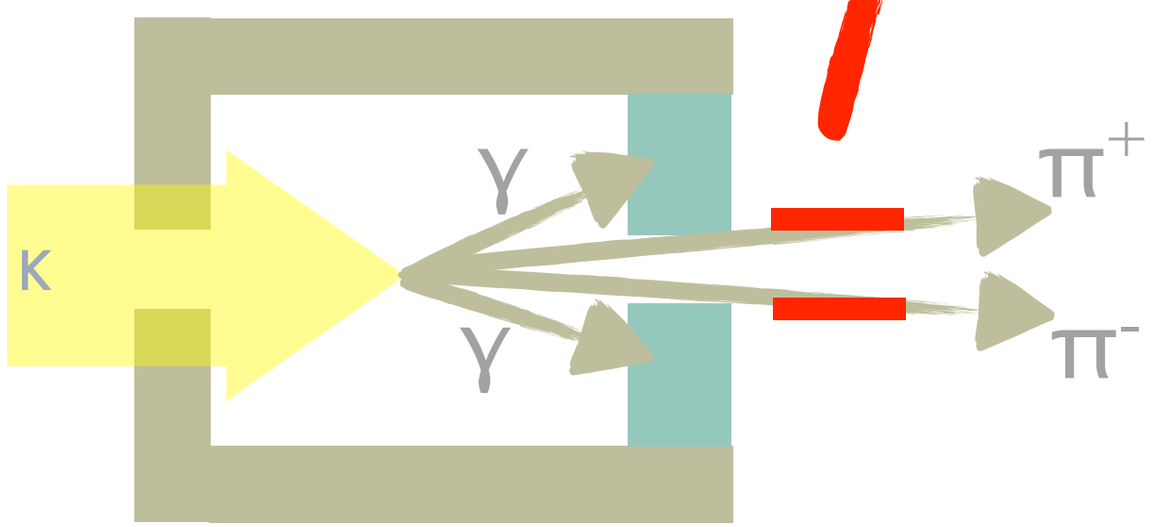
Beam Pipe Charged Veto (BPCV)





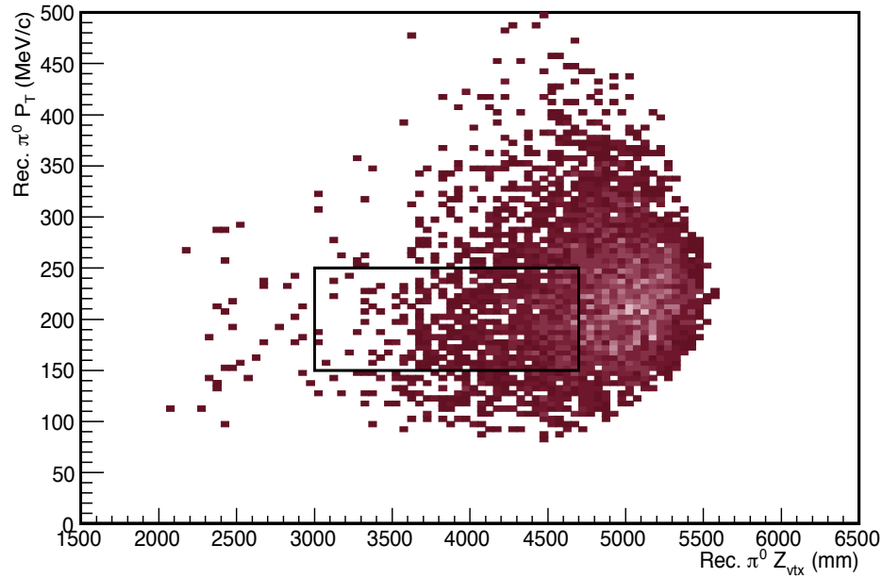
1/10 Reduction of

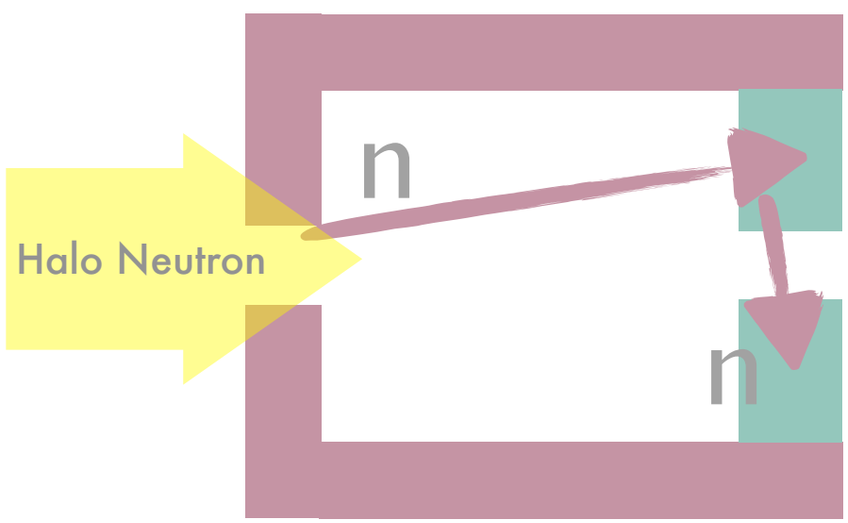
$K_L \rightarrow \pi^+\pi^-\pi^0$ Background

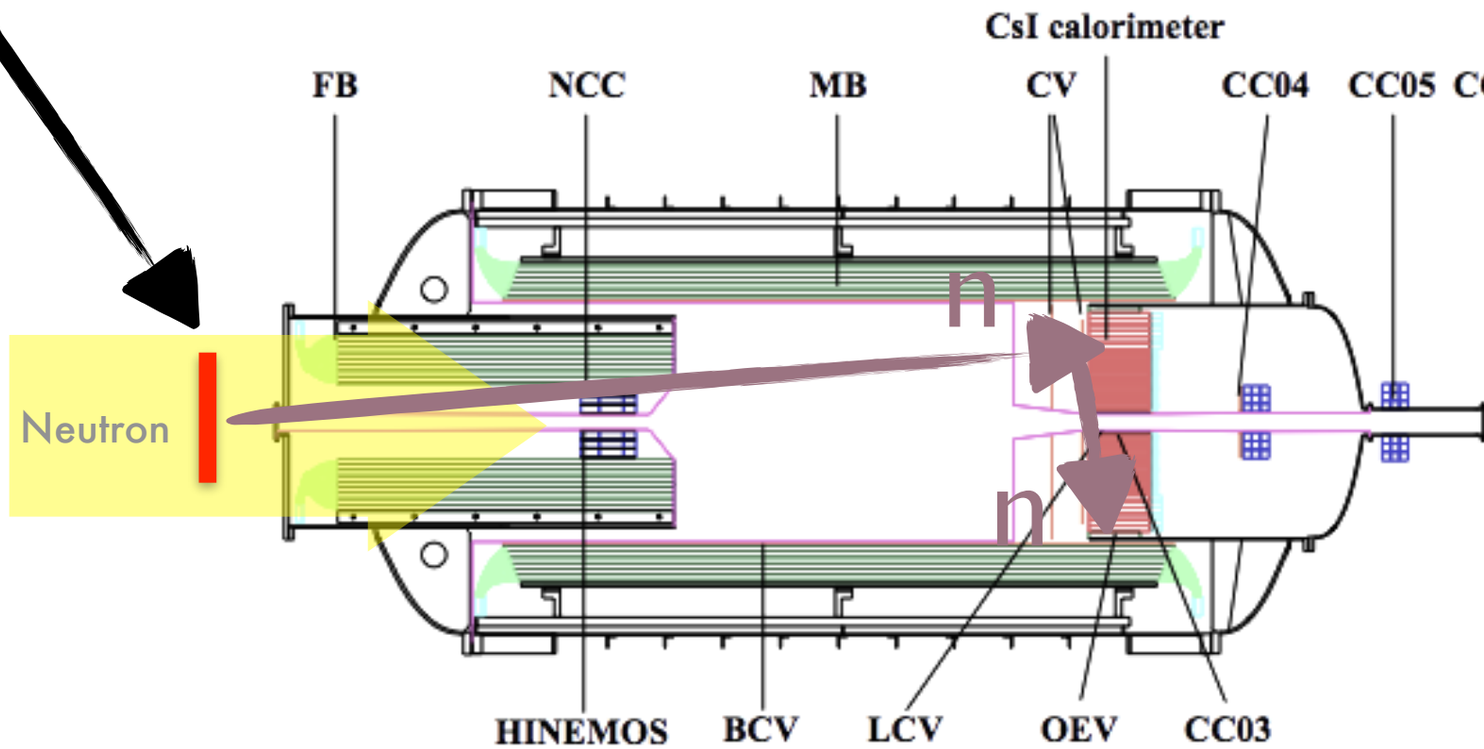


Improvements after 2013

Special Al target run to collect neutron rich events

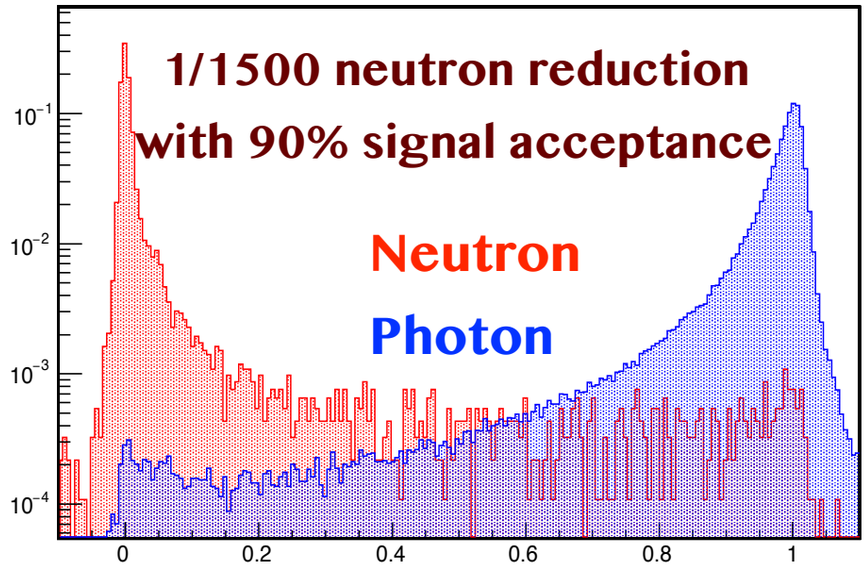




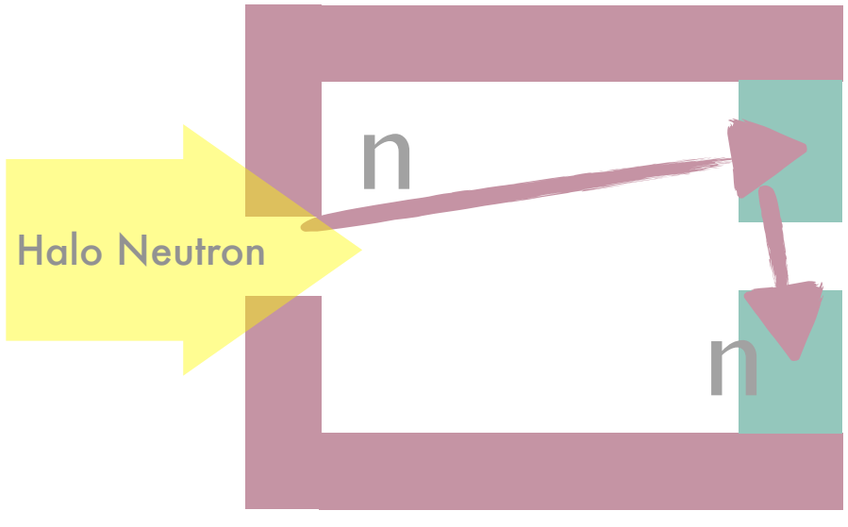


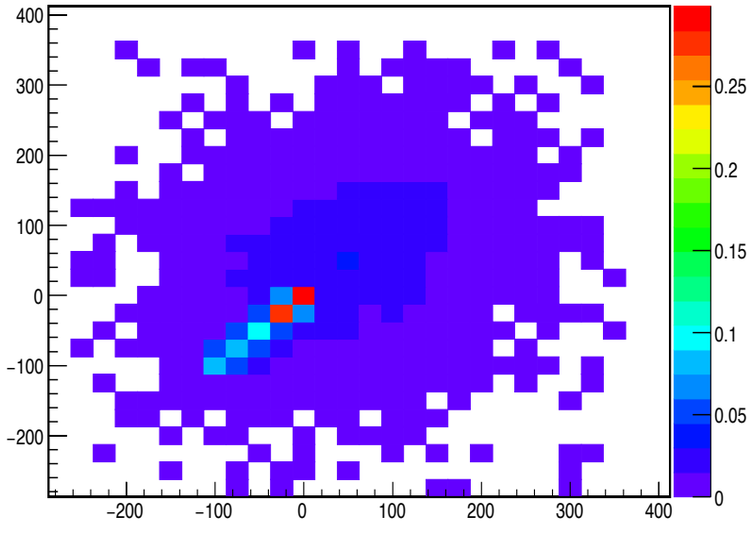
Improvements after 2013

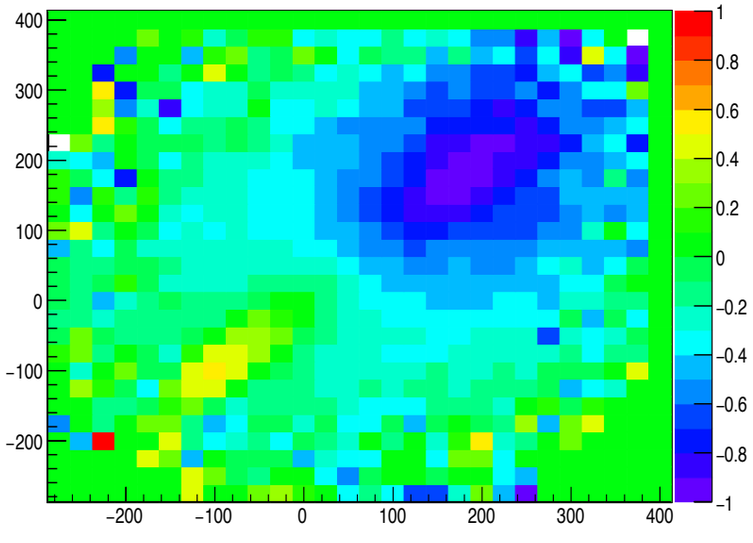
- **Cluster Shape Discrimination**



ϒ/n identification by using cluster energy & timing information

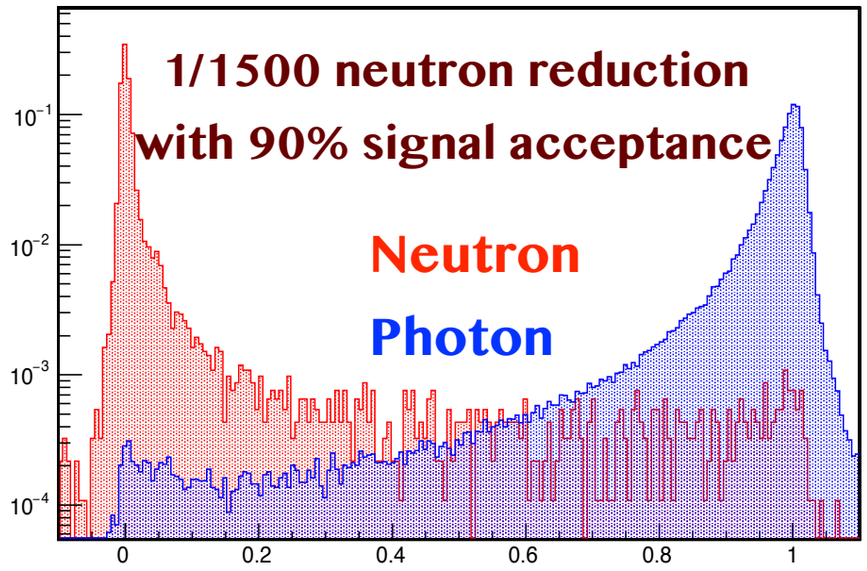




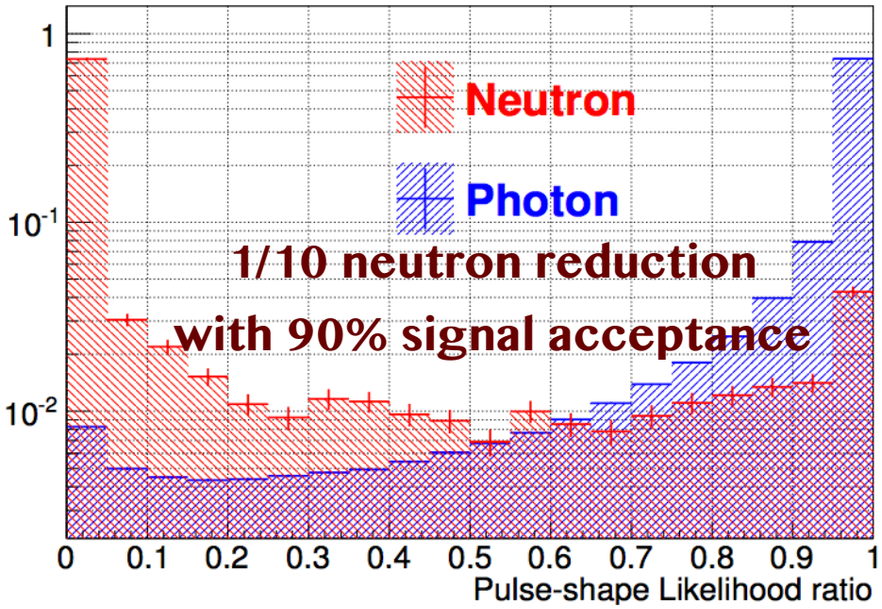


Improvements after 2013

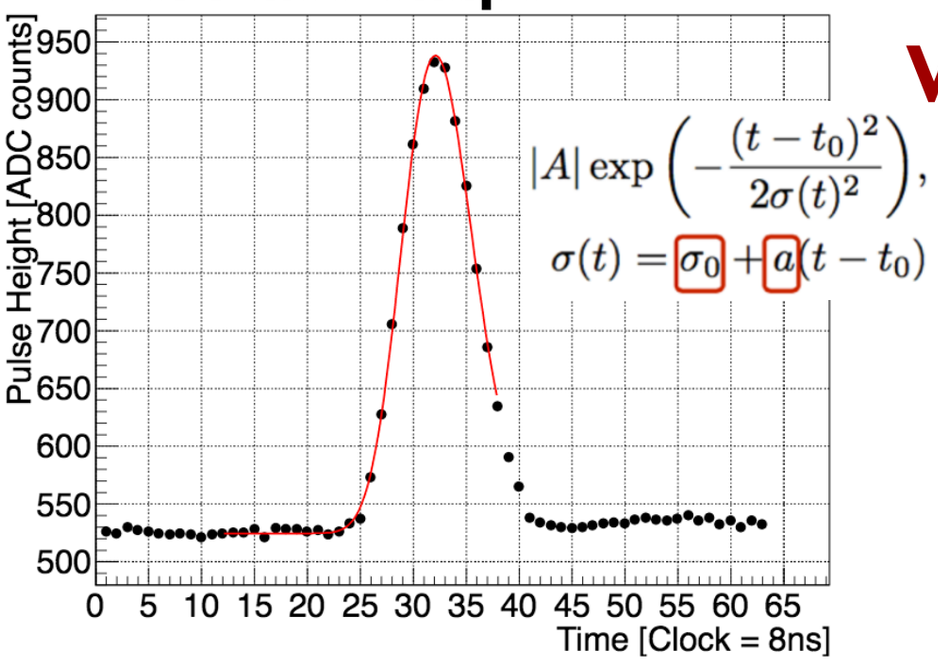
- **Cluster Shape Discrimination**



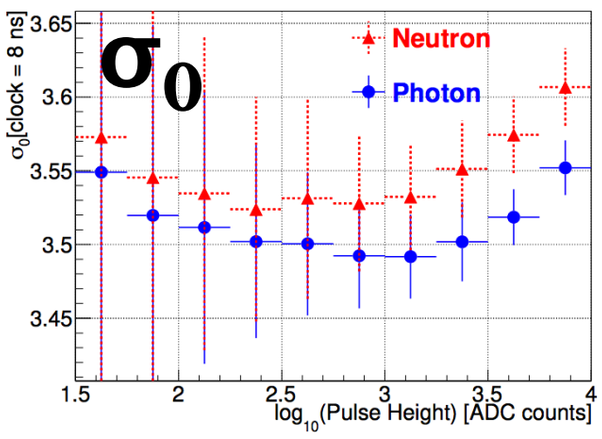
- **Pulse Shape Discrimination**

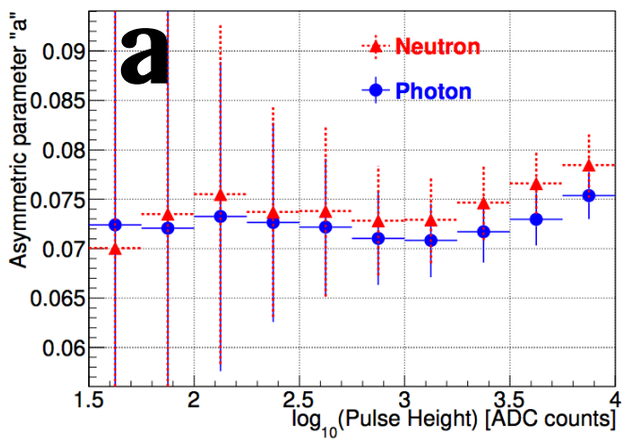


CsI Pulse Shape



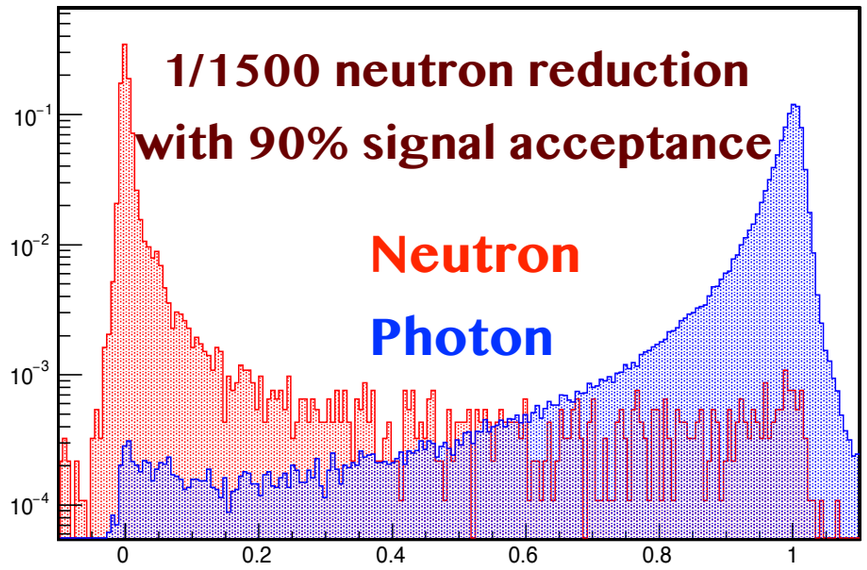
Wider Pulse from hadronic shower





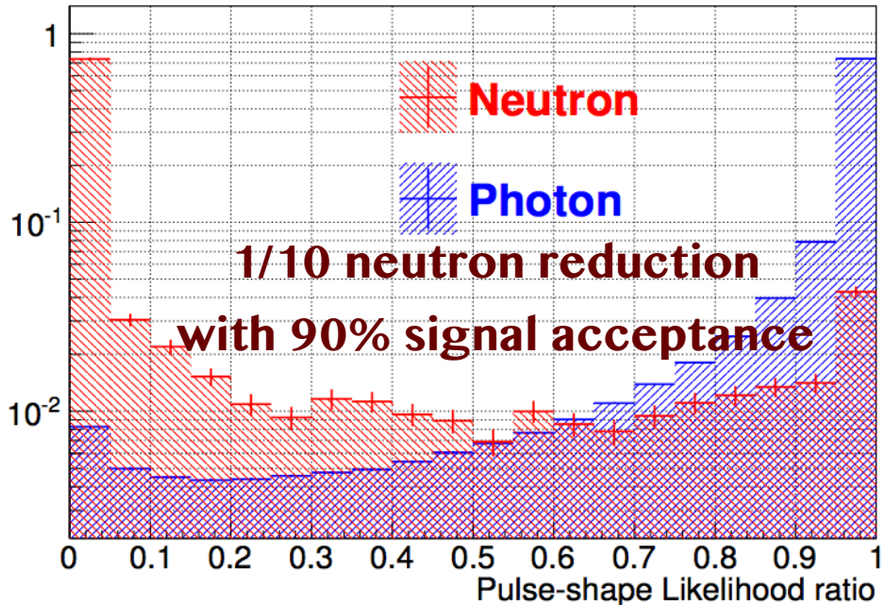
Improvements after 2013

- **Cluster Shape Discrimination**

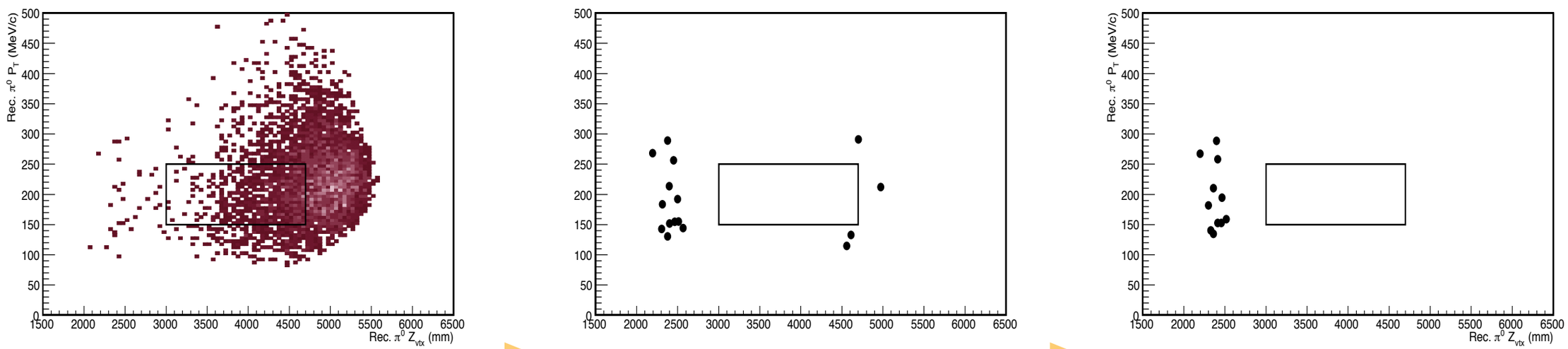


+

- **Pulse Shape Discrimination**

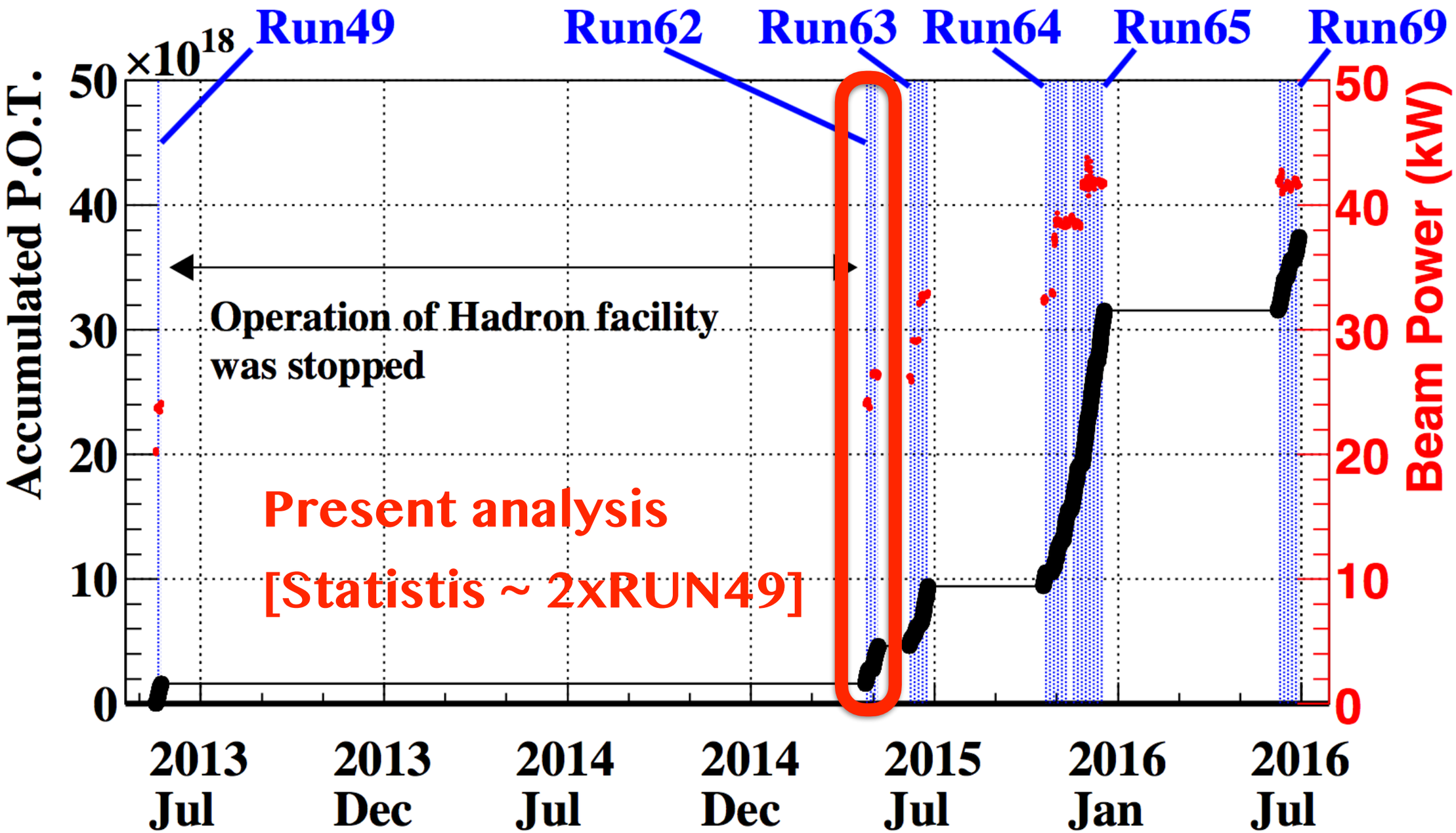


= Neutron reduction improved by O(1)



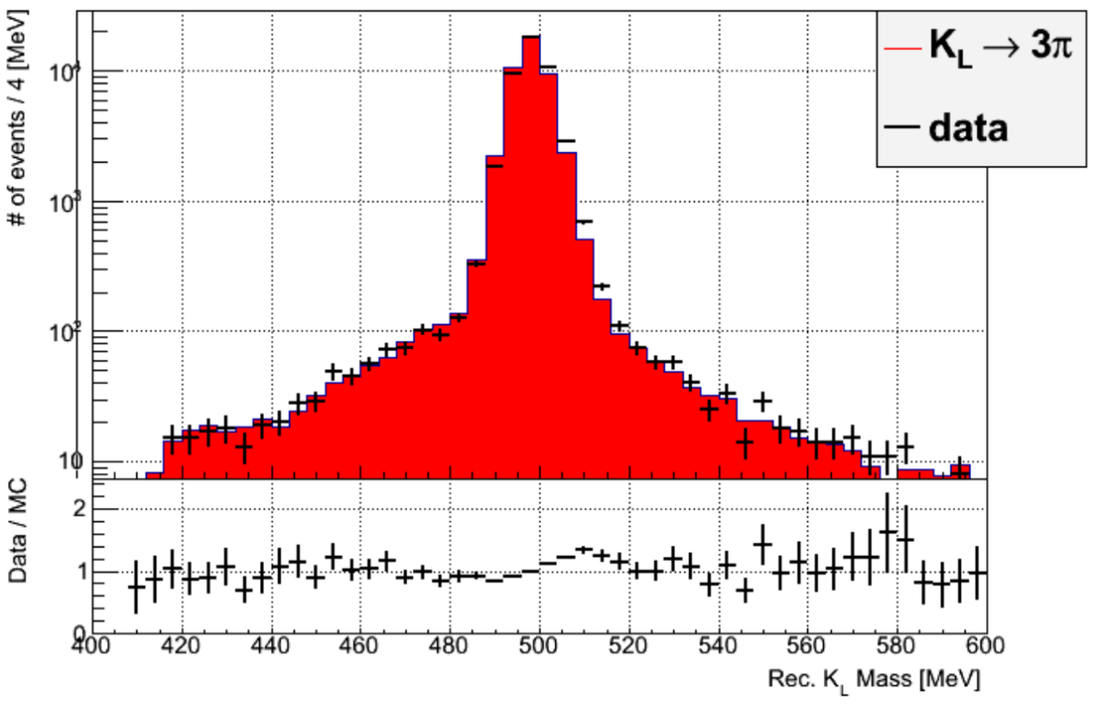
Neutron Sample → **2013 Selection** → **Present Selection**

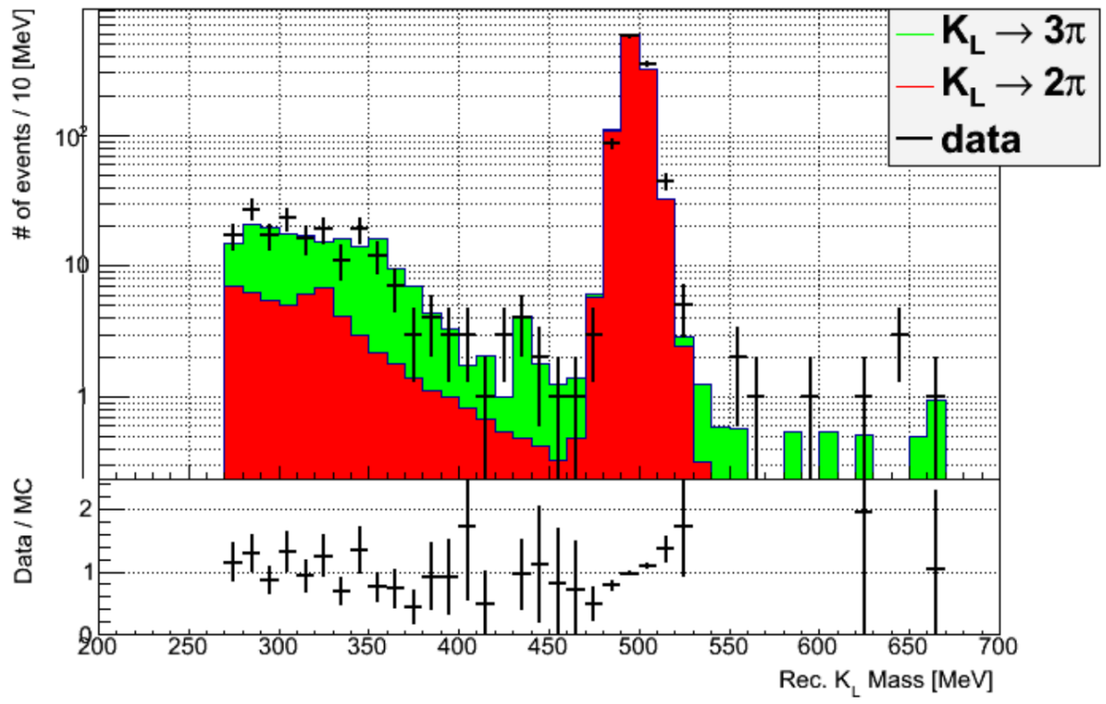
Present Analysis



Present Analysis

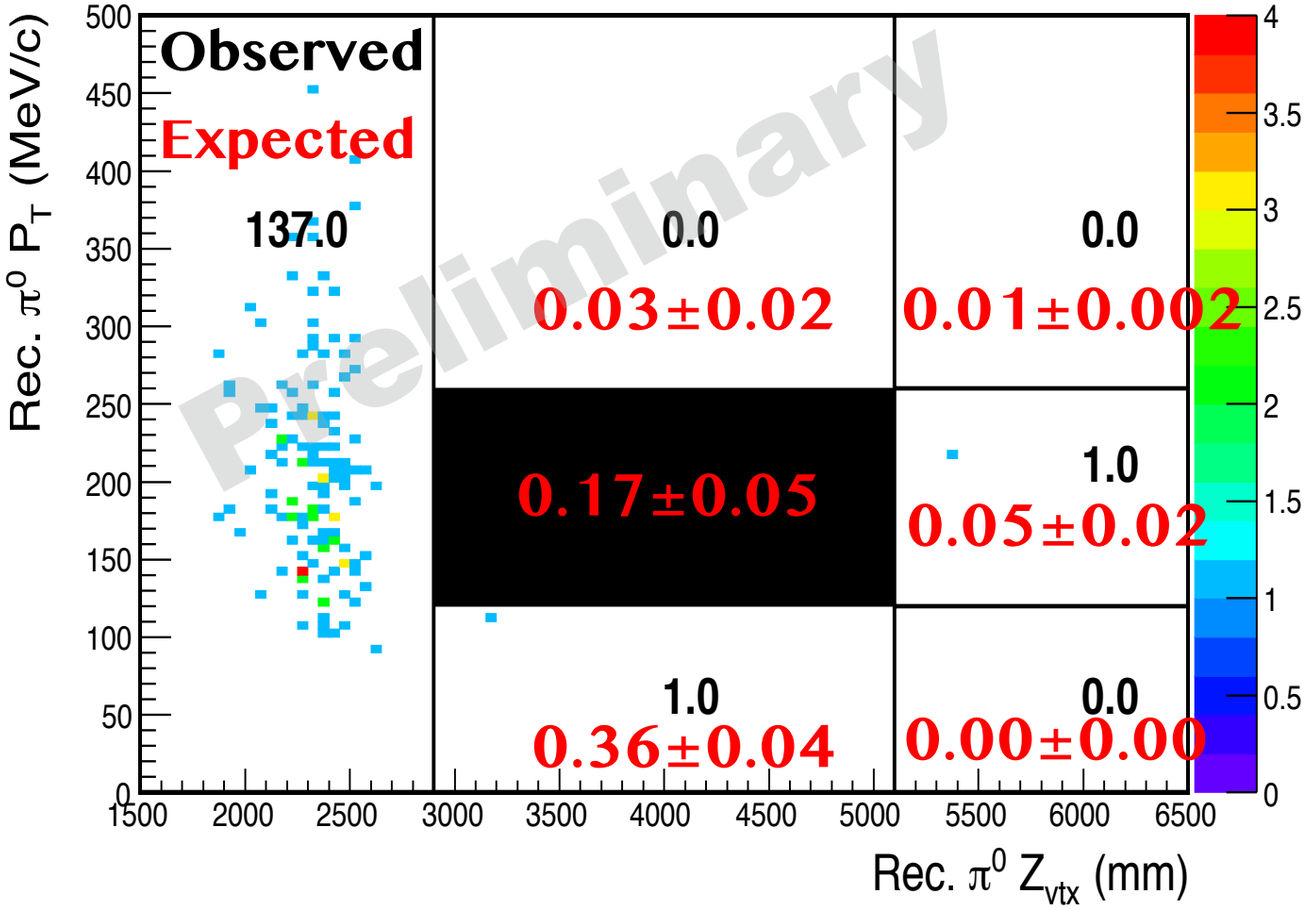
Mode	N_{KL} @ beam exit	S.E.S.
$K_L \to 3\pi^0$	$(3.60\pm0.02)\times10^{11}$	5.9×10^{-9}
$K_L \to 2\pi^0$	$(3.72\pm0.07)\times10^{11}$	
$K_L \to \gamma\gamma$	$(3.43\pm0.04)\times10^{11}$	





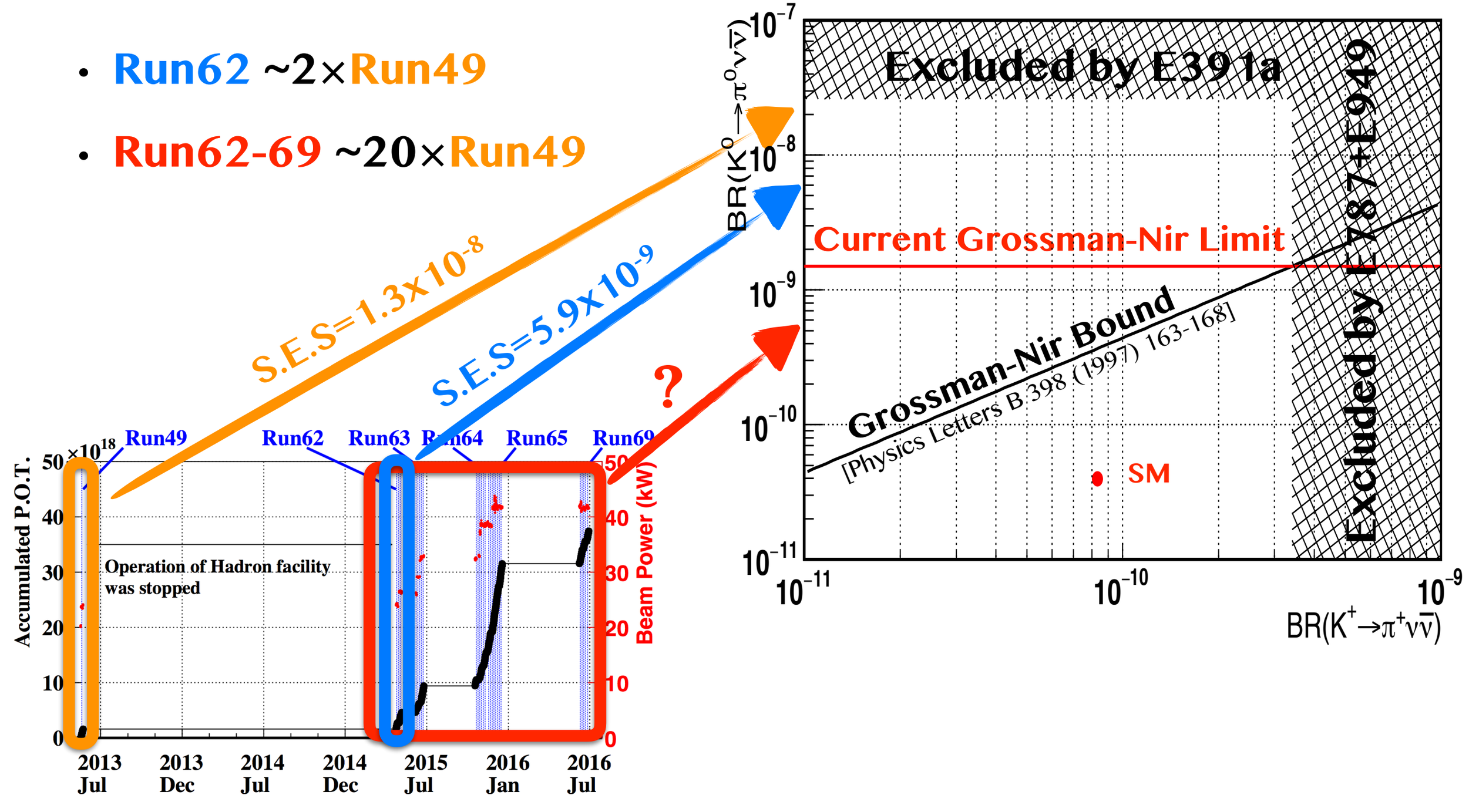
Present Analysis

BG in Box	#BG
$K_L \to \pi^0\pi^0$	0.04±0.03
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01
Upstream Events	0.04±0.04
Neutron Events	0.05±0.02
Other BG	Under Estimation



Sensitivity

- **Run62** ~2×**Run49**
- **Run62-69** ~20×**Run49**

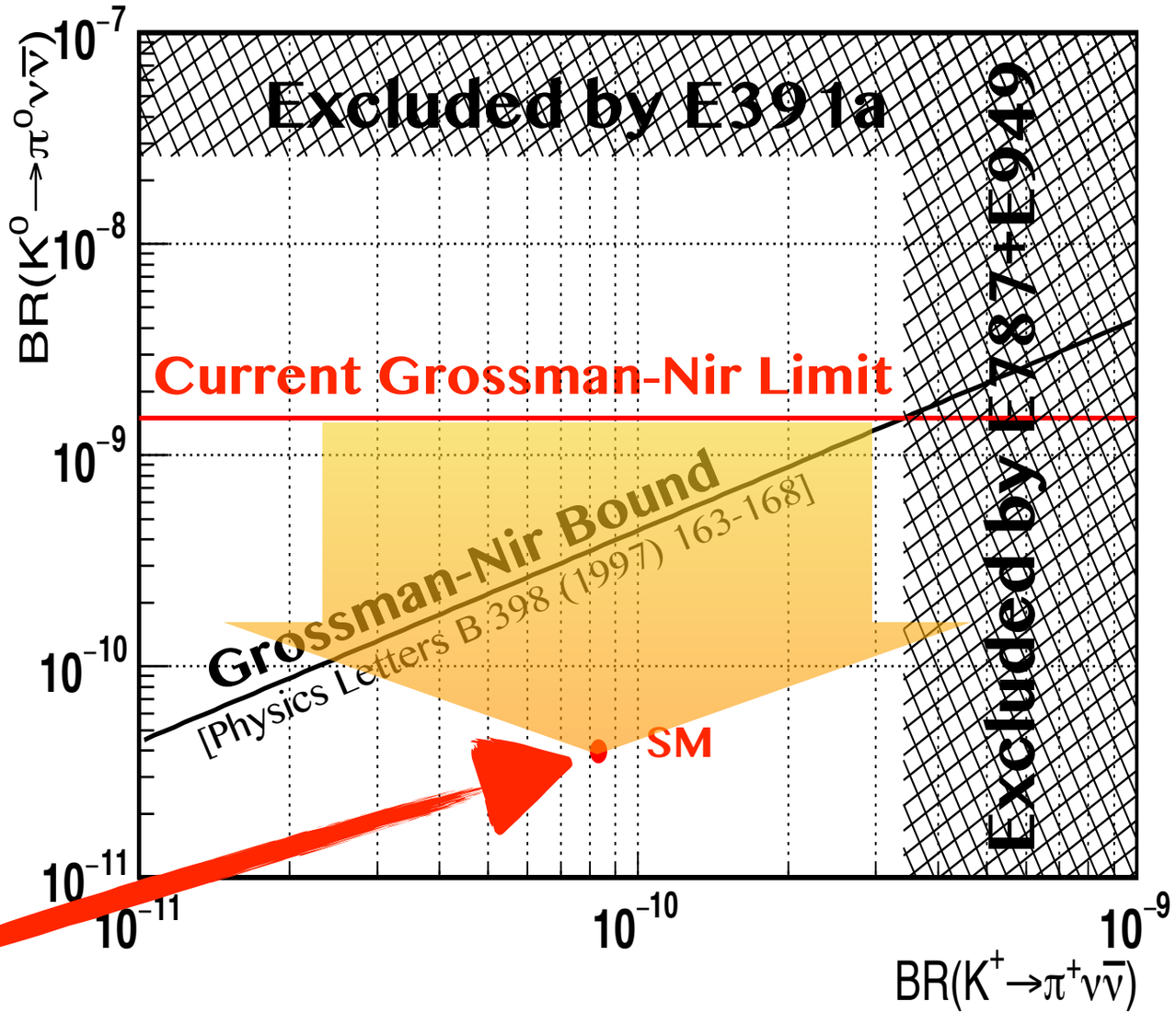


Beyond G-N Limit

Upgrade is Needed!!

BG in Box	Run62 #BG	Projected #BG
$K_L \to \pi^0\pi^0$	0.04±0.03	7.86
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01	7.86
Upstream	0.04±0.04	7.86
Neutron	0.05±0.02	9.83

Preliminary



Upgrades

Upgrade is Needed!!

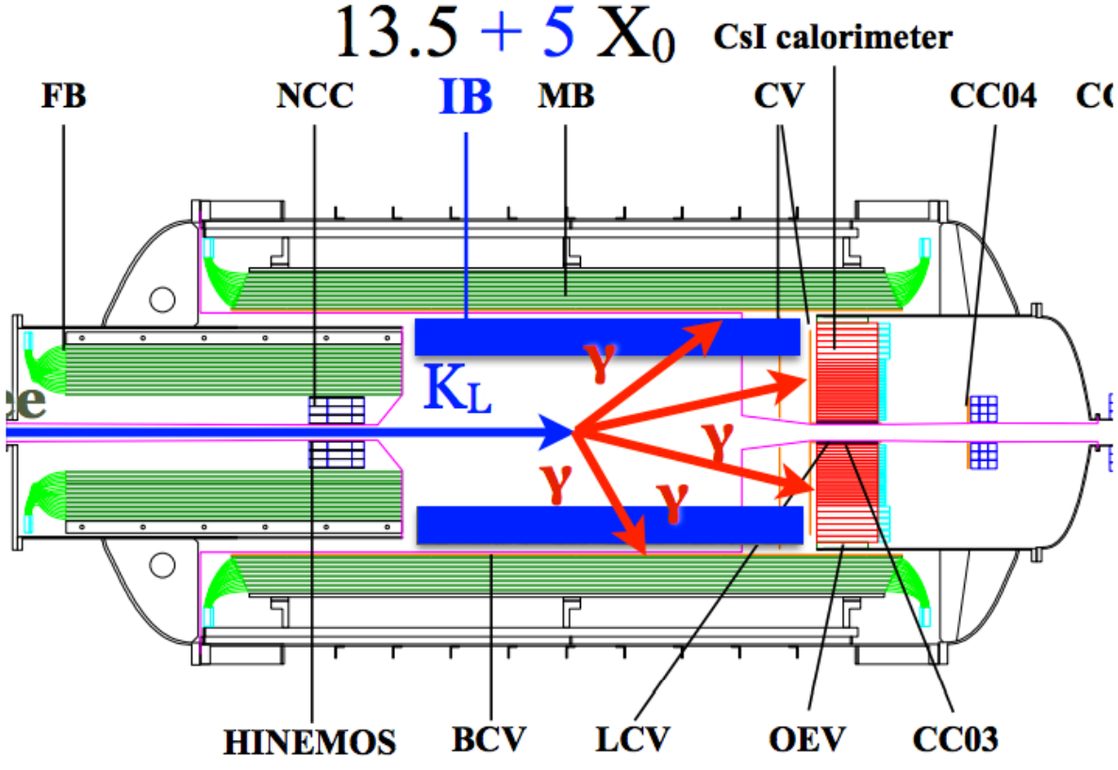
BG in Box	Run62 #BG	Projected #BG
$K_L \to \pi^0\pi^0$	0.04±0.03	7.86
$K_L \to \pi^+\pi^-\pi^0$	0.04±0.01	7.86
Upstream	0.04±0.04	7.86
Neutron	0.05±0.02	9.83

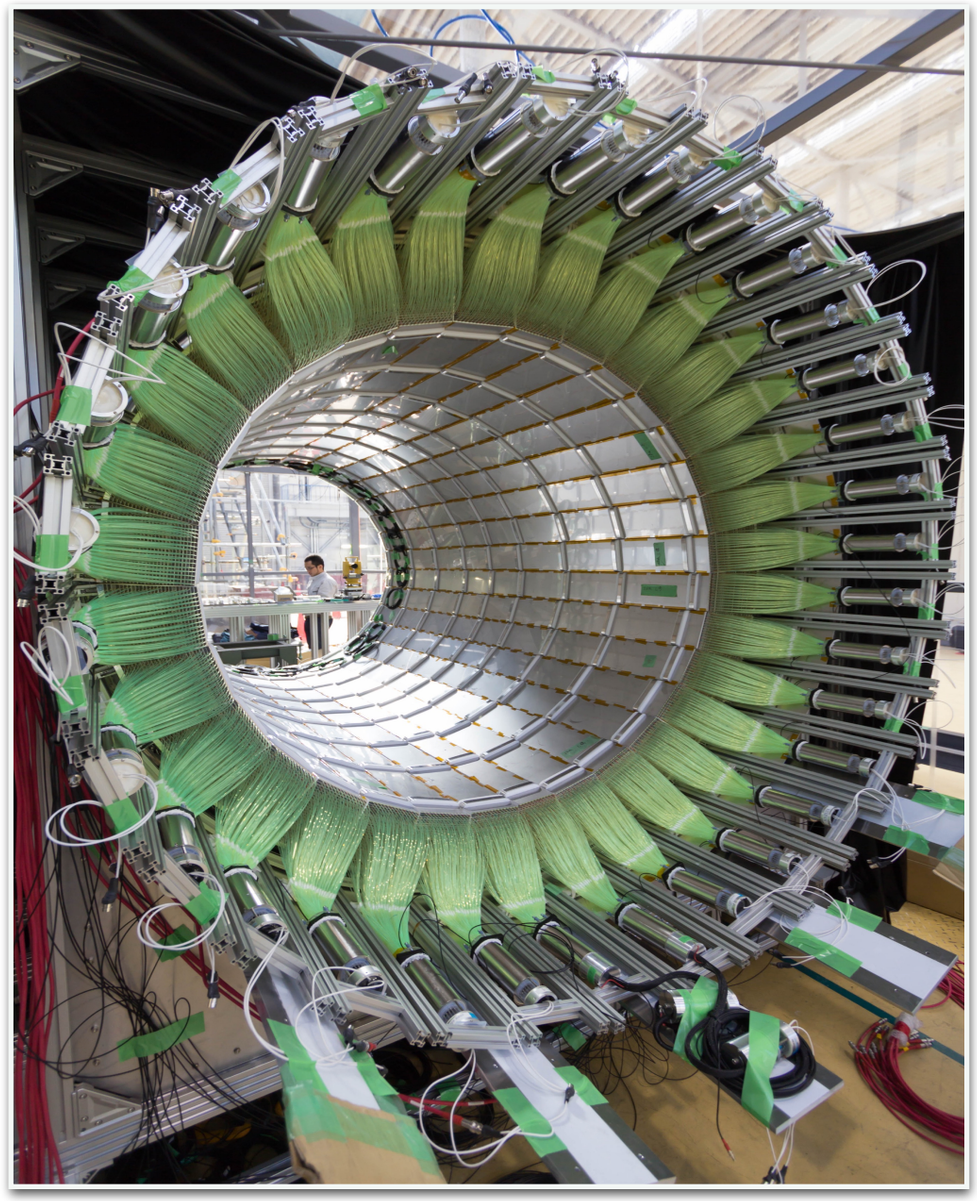
Preliminary

- **New Barrel Detector**
  - installation completed
- **Beam Pipe Modification**
  - study on-going
- **CsI Both-end Readout**
  - validated in beam test
  - upgrade scheduled in 2018

New Barrel Detector

- **Installed in April 2016**
- **Radiation length: 13.5+5X_0**
- **Reduction: 1/3 x $K_L \to \pi^0\pi^0$**



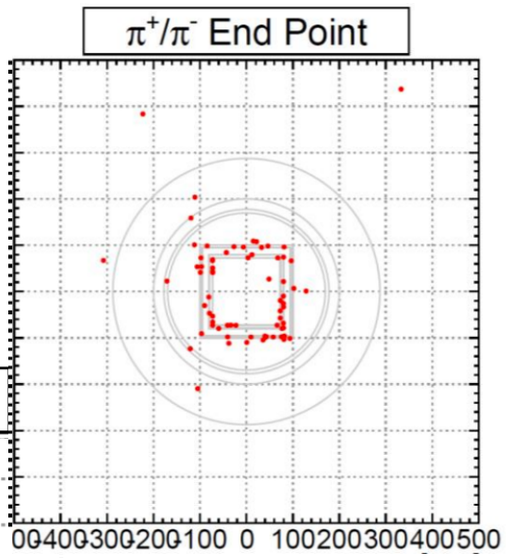


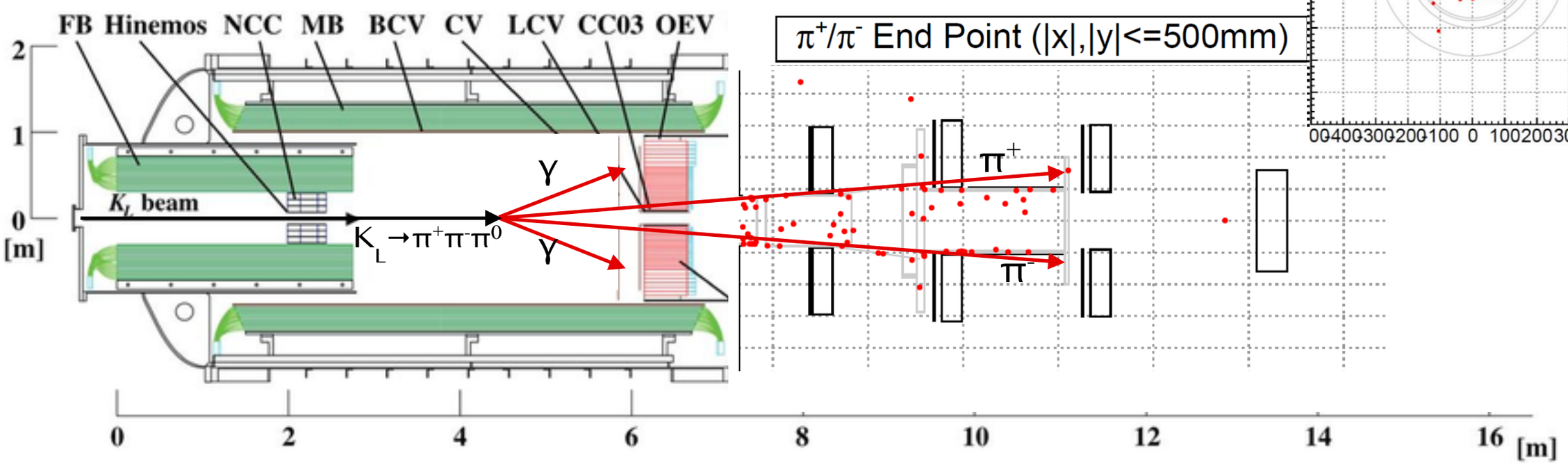
L~3m, Ø~2m

Beam Pipe Modification

Conceptual Modification: (study on-going)

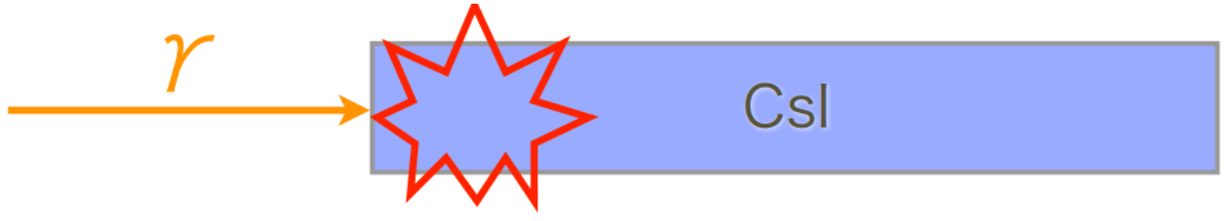
- reduce dead material in the beam pipe
- install charged veto with better coverage

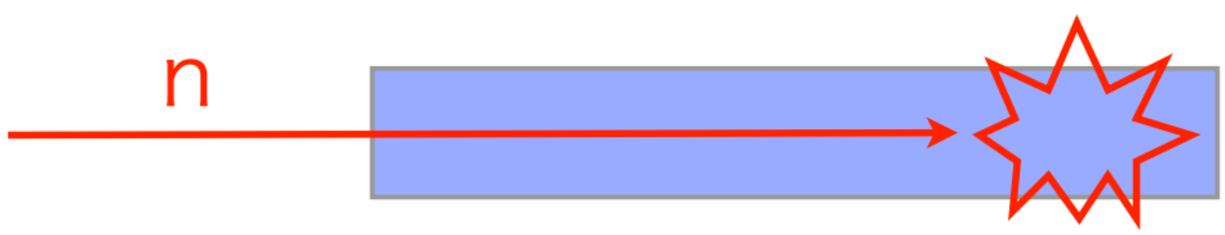


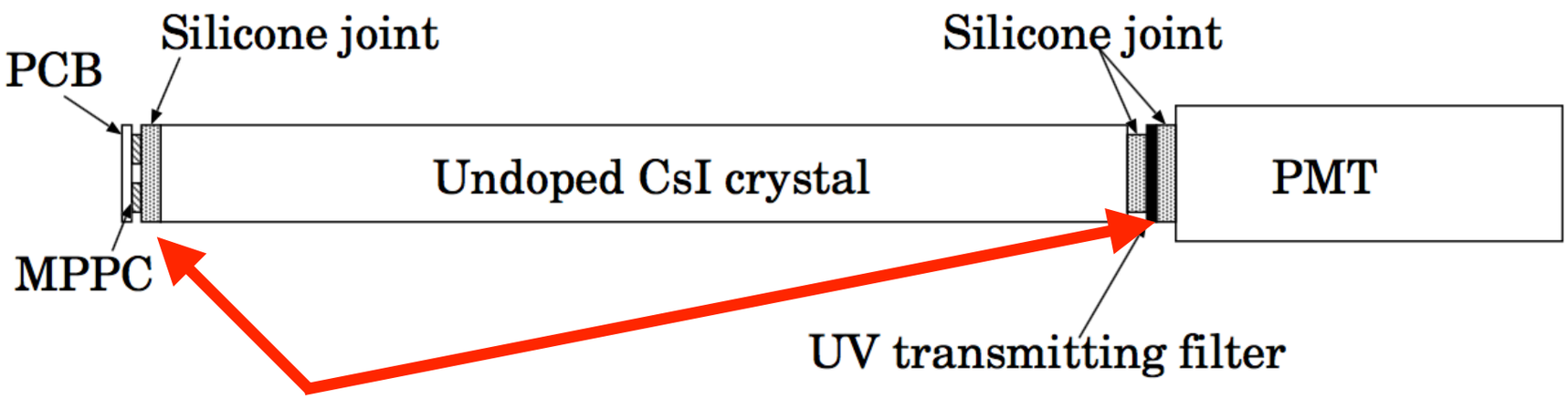


CsI Both-end Readout

Both-end readout to measure the shower depth



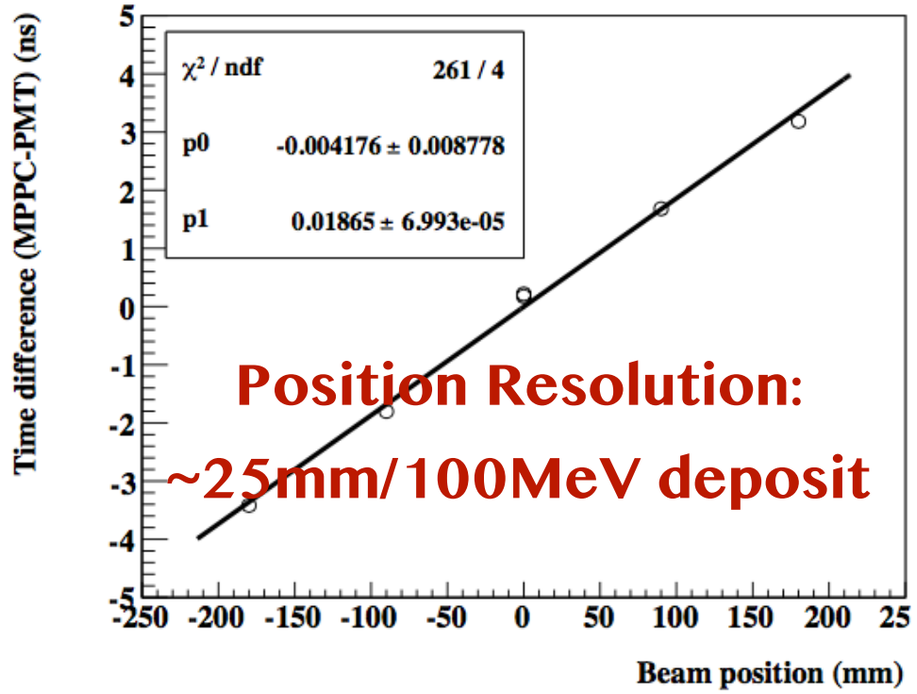


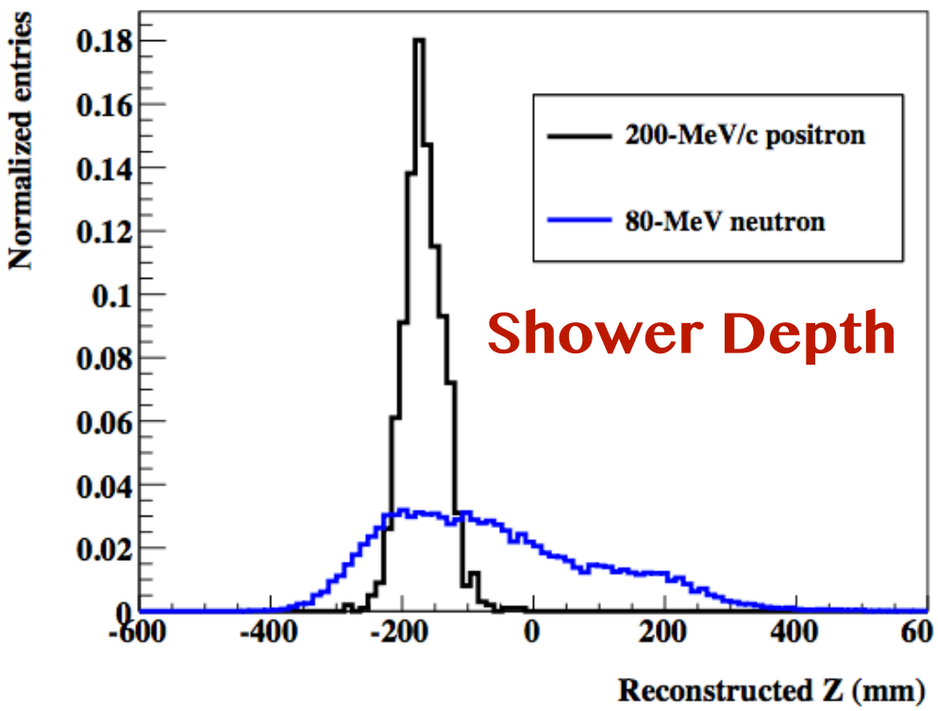


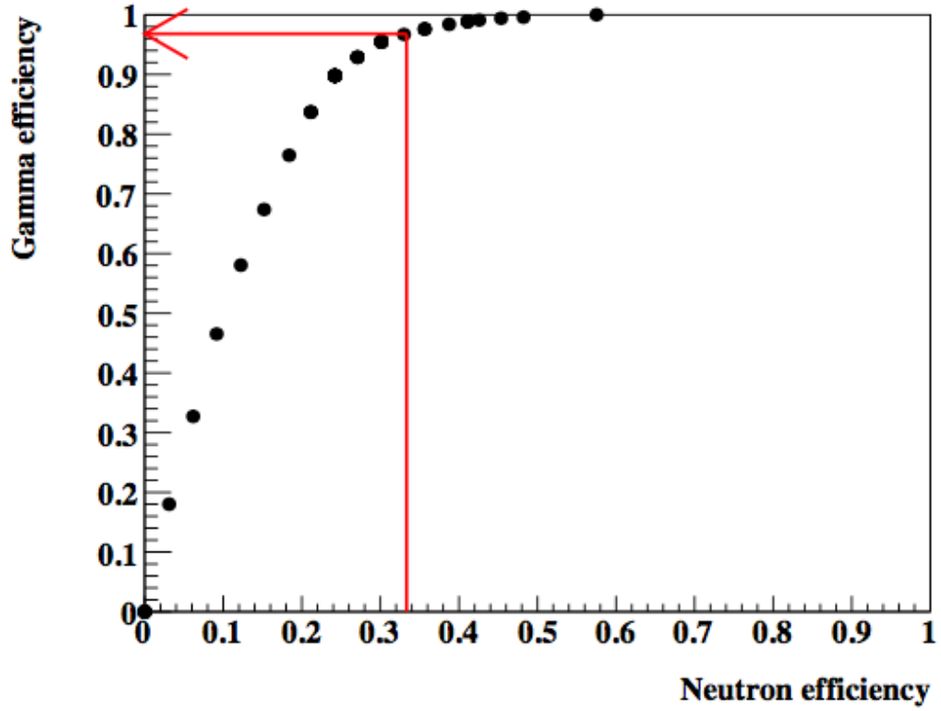
Reconstruct shower depth by using timing difference

CsI Both-end Readout

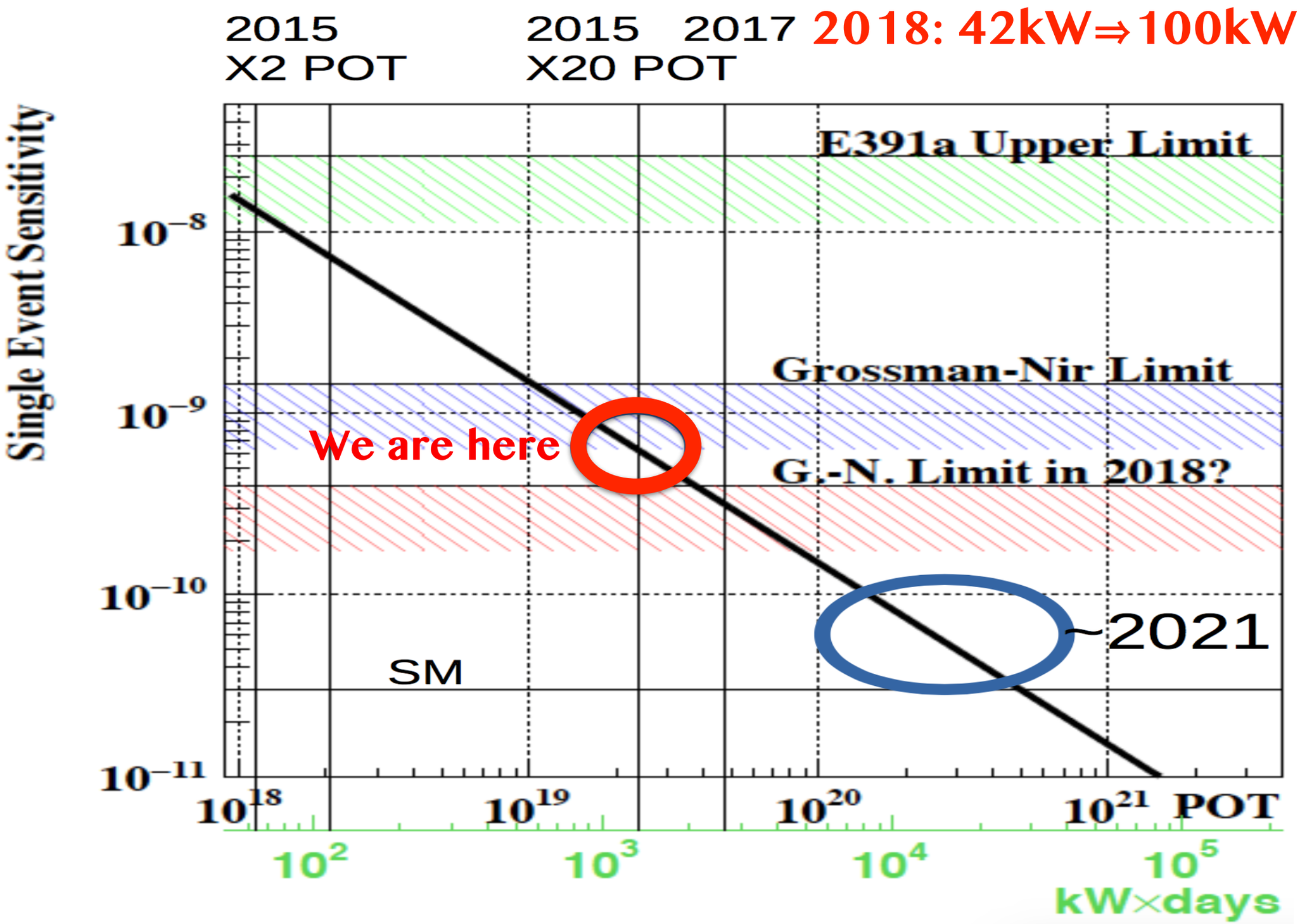
Expect 1/10 reduction
or better







Prospect


2015
X2 POT
2015 2017
X20 POT
2018: 42kW⇒100kW
Single Event Sensitivity
E391a Upper Limit
Grossman-Nir Limit
We are here
G.-N. Limit in 2018?
~2021
SM
POT
kW×days

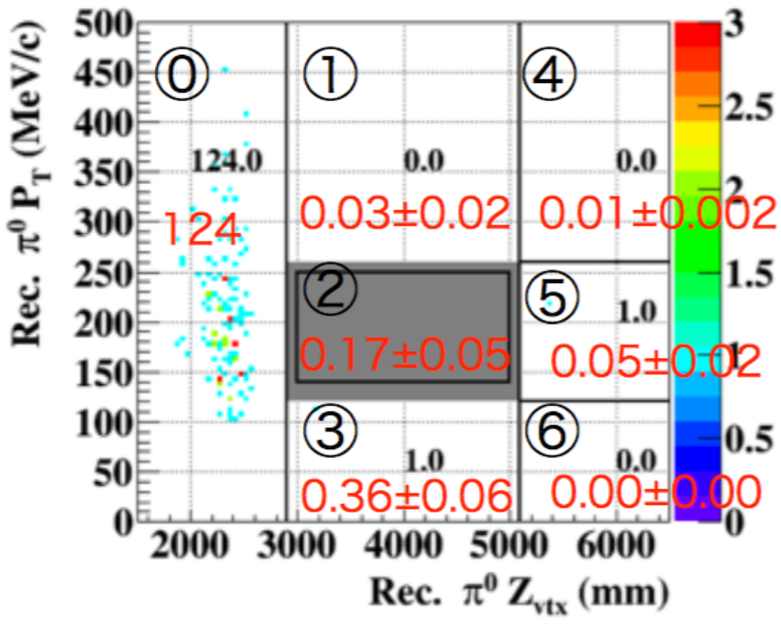
Summary

- First analysis result is released [arXiv:1609.03637].
- With new detector and new analysis technique, major background sources are within control.
- Present analysis with 20 times more data is on-going.
- Detector upgrade in 2018 to improve S.E.S.
- Expect to reach S.E.S. of O(-11) after 2021.

Backup

Background Estimation

	Upstream	Neutron	KL→2π^0	KL→$\pi^+\pi^-\pi^0$
Region0	124	0.025±0.019	0	0
Region1	0	0.025±0.019	0	0
Region2	0.04±0.04	0.049±0.019	0.04±0.03	0.04±0.01
Region3	0.04±0.04	0.003±0.001	0.09±0.04	0.23±0.02
Region4	0	0.006±0.002	0	0
Region5	0	0.021±0.008	0.02±0.02	0.01±0.01
Region6	0	0	0	0



Improvement after 2013

Cluster Shape X^2 (used in 2013) = 3.1×10^{-3}

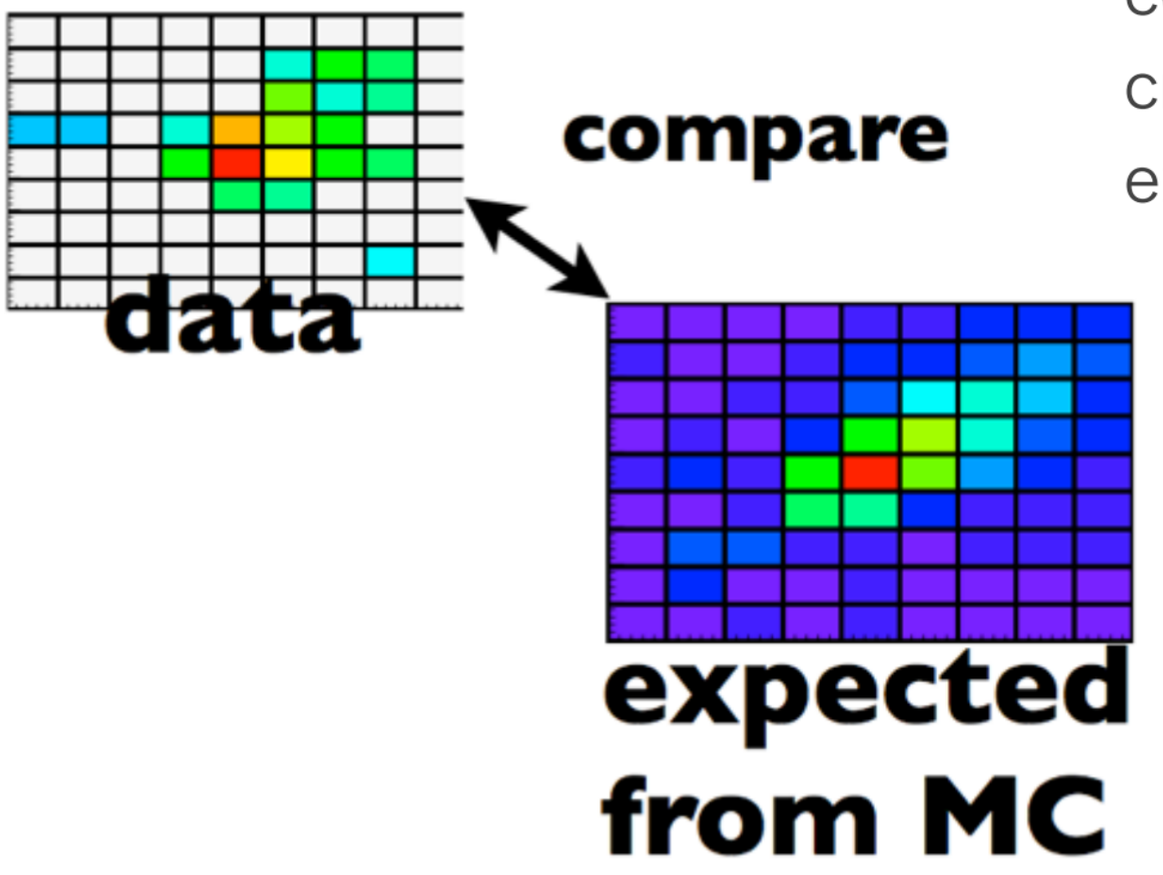
+ Cluster Shape Discrimination (CSD) = 2.9×10^{-4}
(new cut)

+ Pulse Shape Discrimination (PSD) = 2.6×10^{-5}
(new cut)

= Neutron reduction improved by O(2)

Improvement after 2013

Cluster Shape X^2 (used in 2013)



compare the observed Edep. in each crystals in a cluster with its expected energy derived from MC

$$\chi^2 \equiv \frac{1}{N} \sum_{i}^{\text{in } 27\times 27 \text{ region}} \left(\frac{e_i/E_{inc} - \mu}{\sigma} \right)^2$$

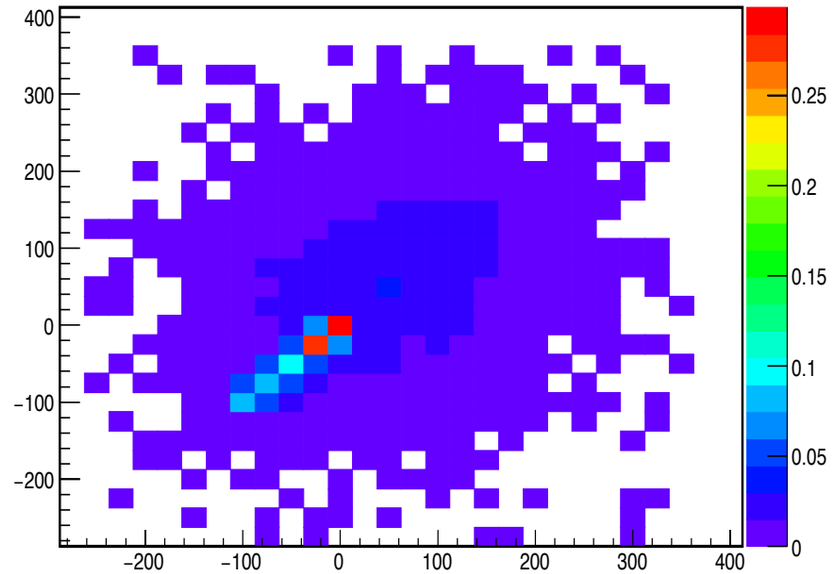
E_{inc} : measured photon energy
e_i : measured deposit energy in ith crystal in a cluster
μ : expected mean e/E
σ : expected RMS of e/E

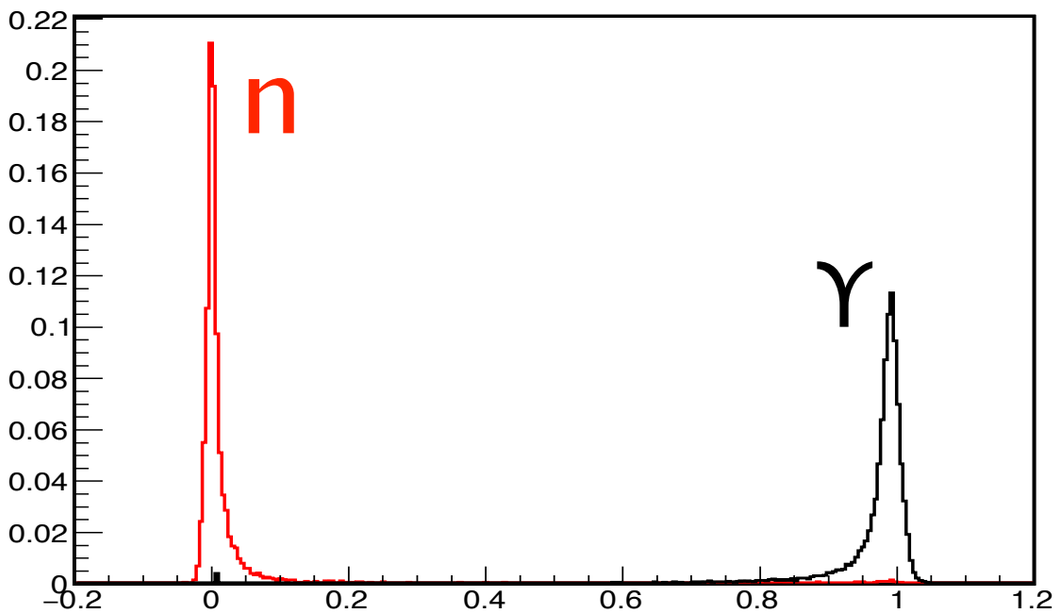
1/300 neutron reduction & 80% signal acceptance

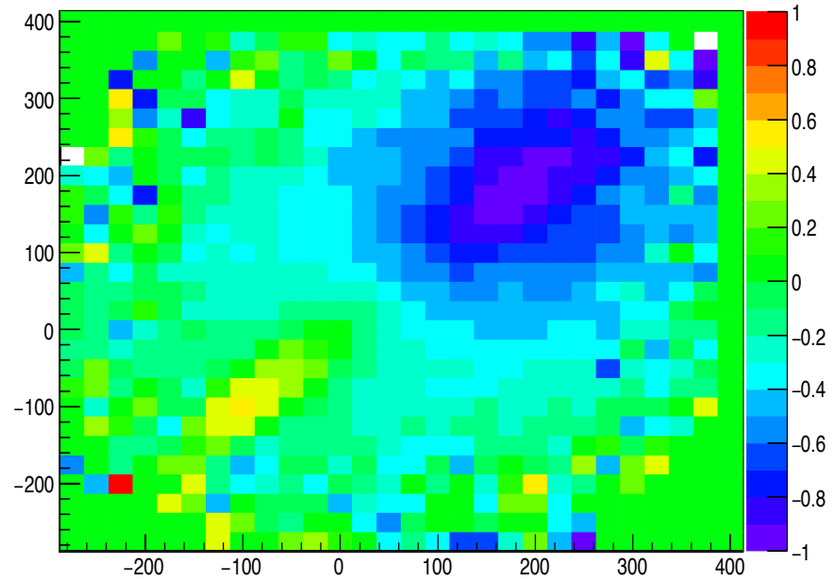
Improvement after 2013

Cluster Shape Discrimination (CSD)

- Use cluster energy & timing info.
- + Neural Net

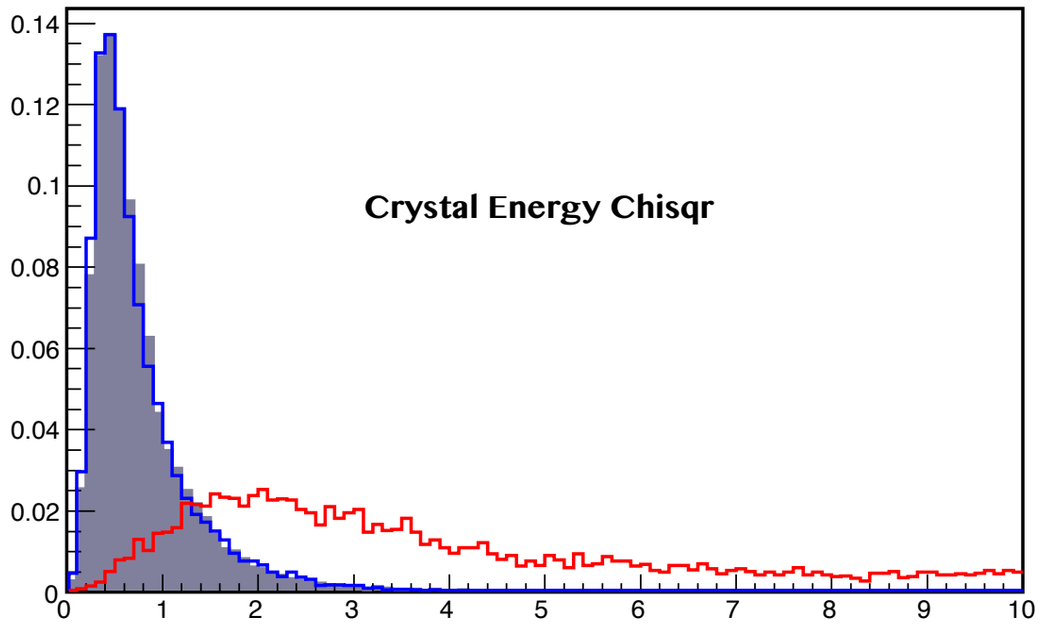


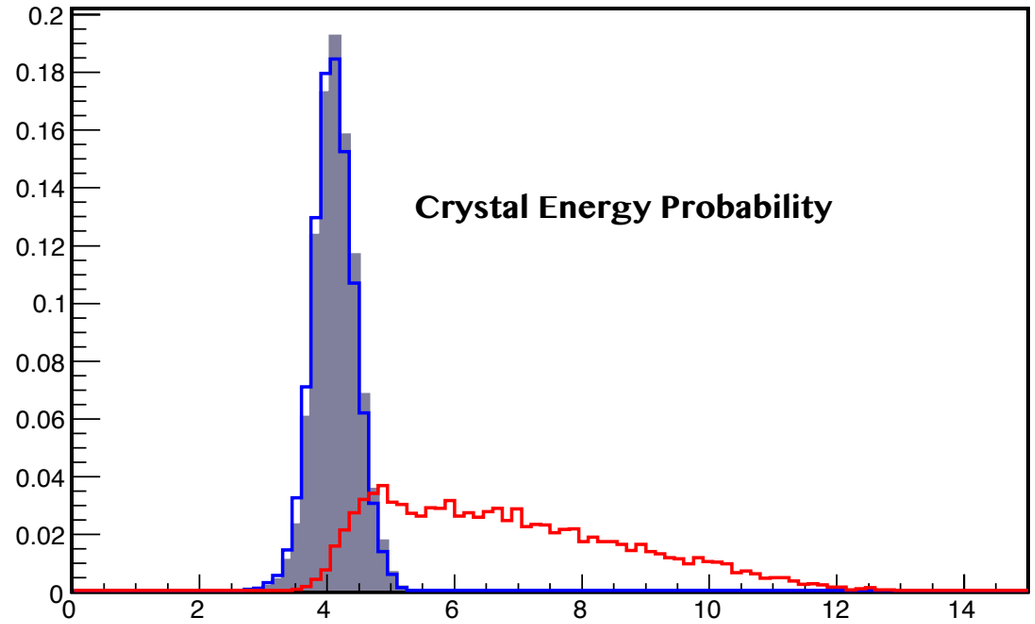


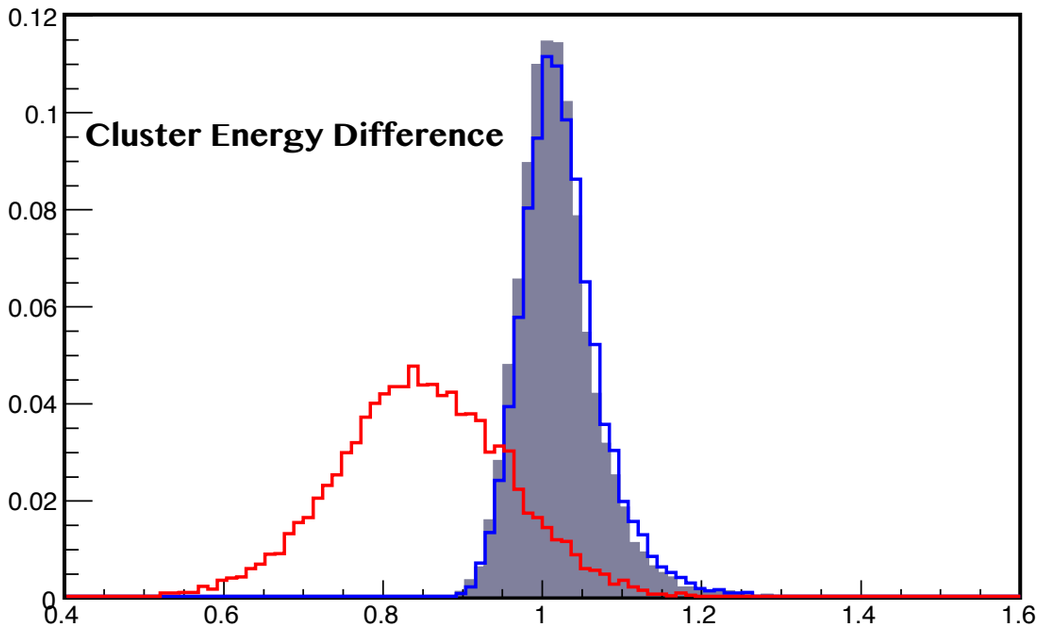


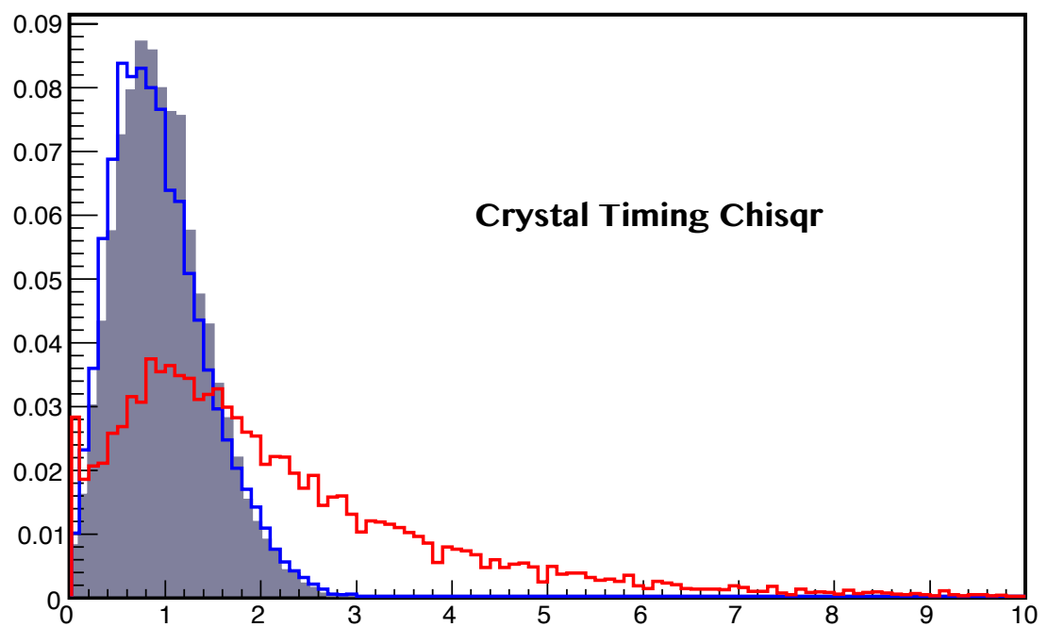
1/1500 neutron reduction & 90% signal acceptance

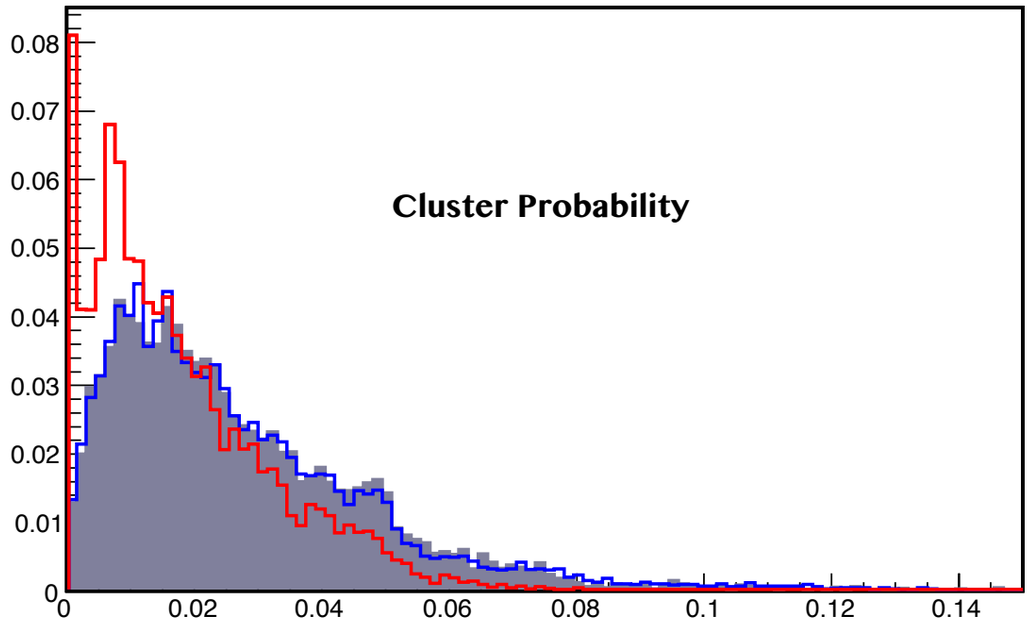
Run62 K3pi0
Run62 Z0
Run62 K3pi0 MC

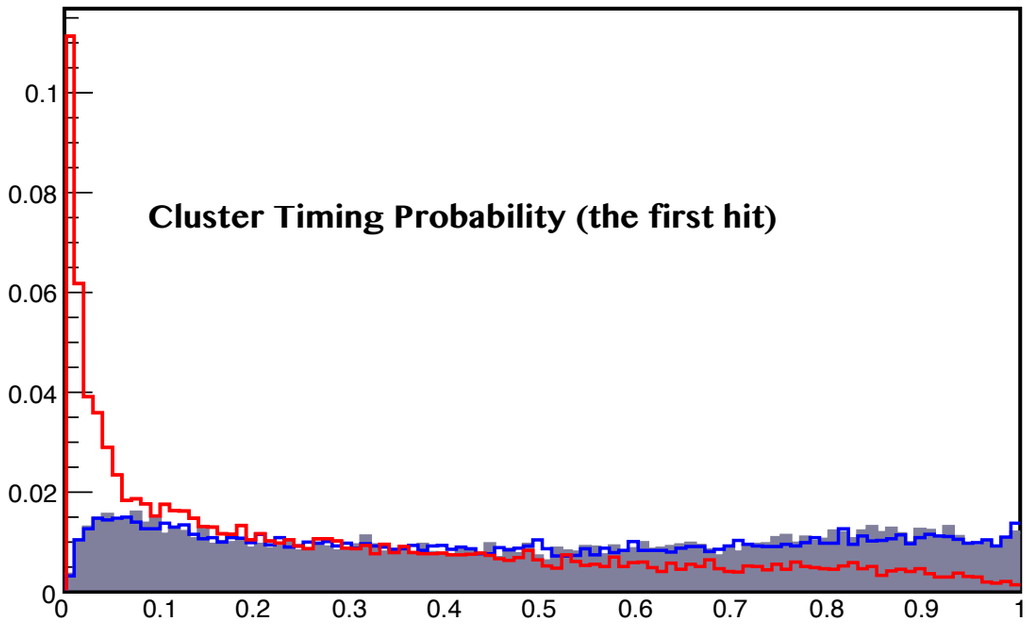


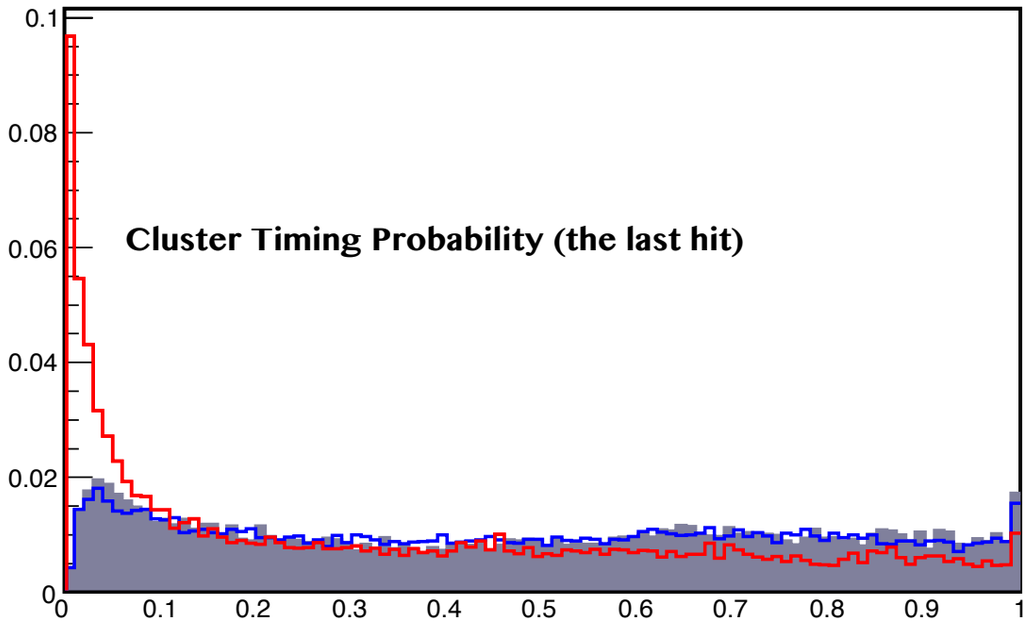


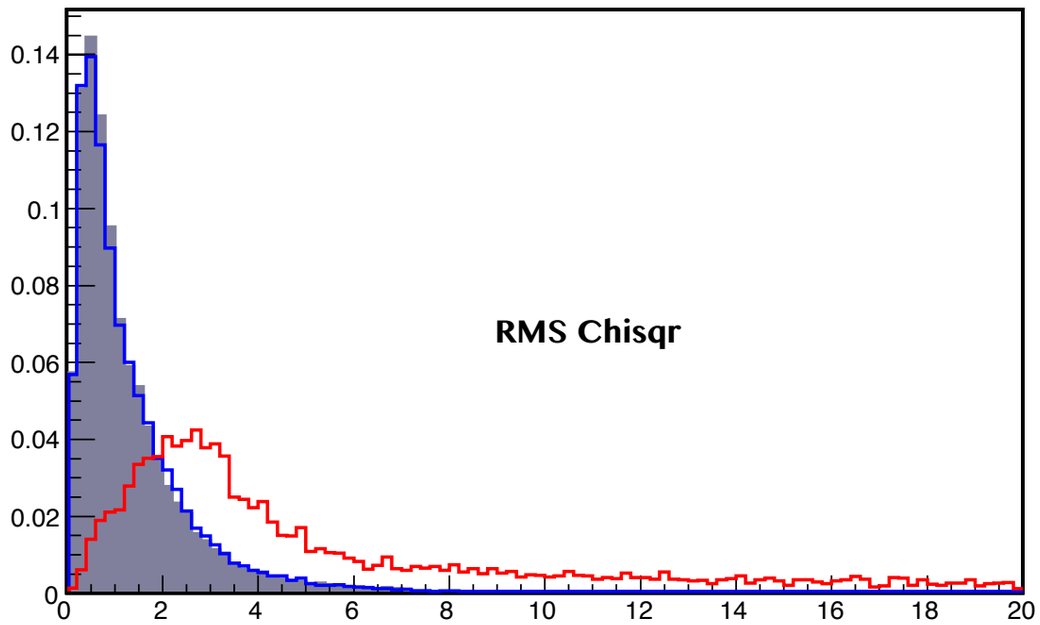


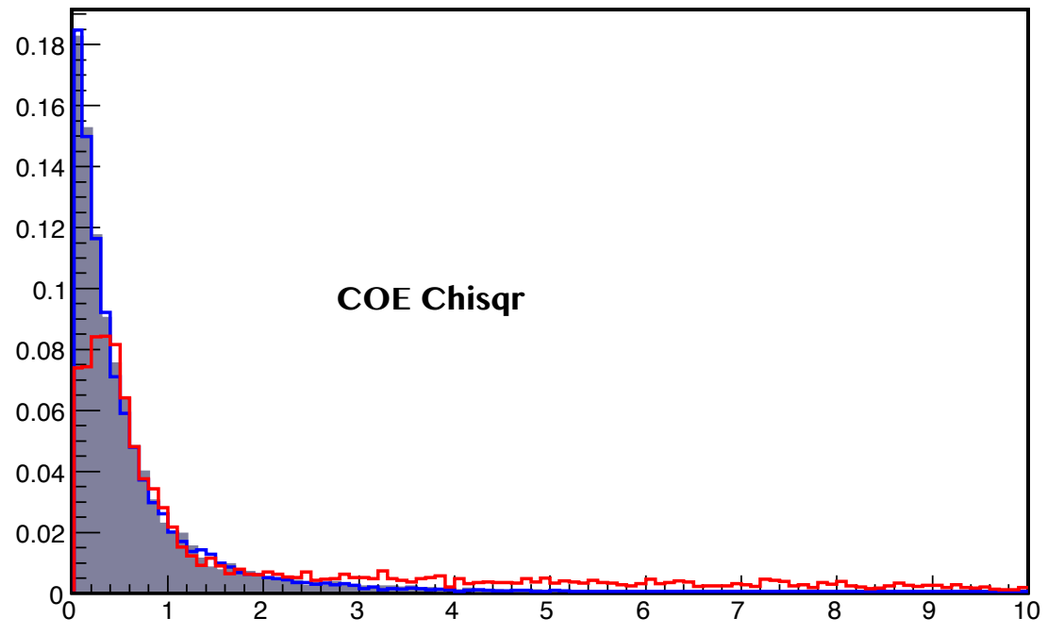


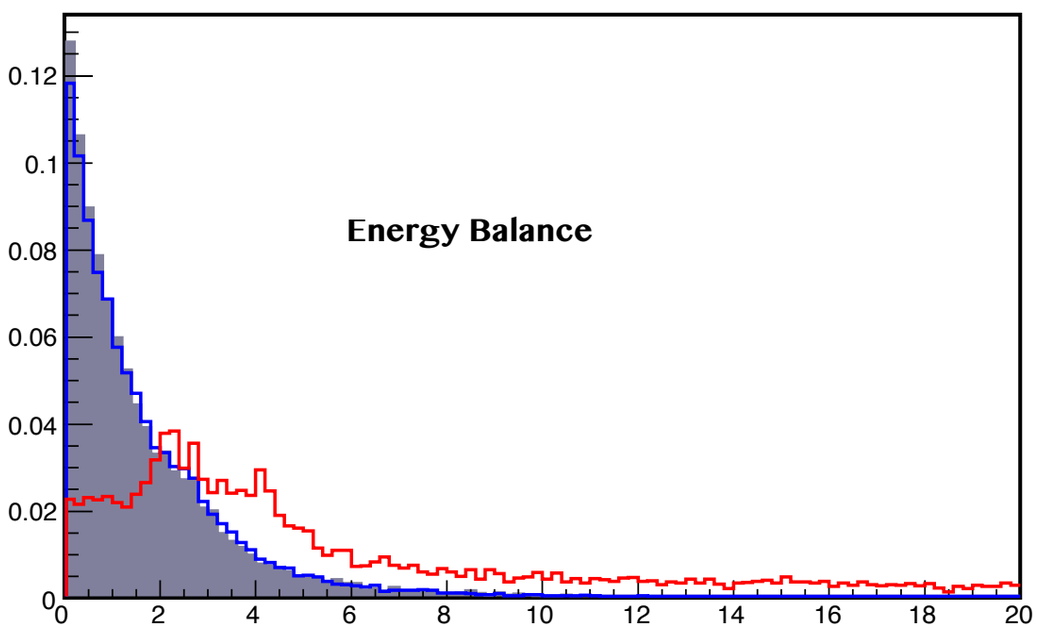

Cluster Probability
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14

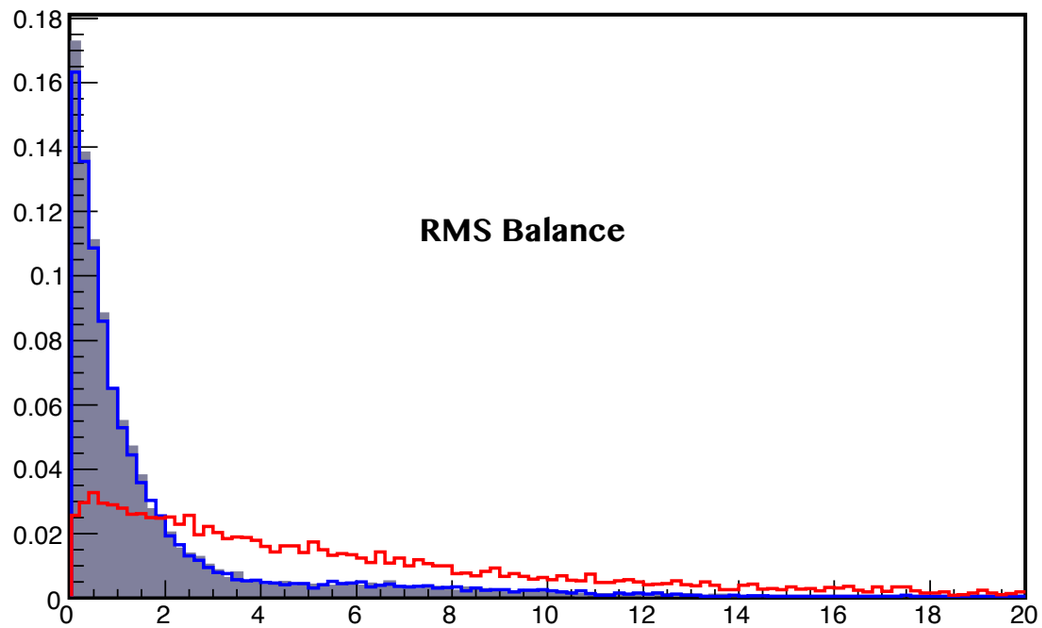

Cluster Timing Probability (the first hit)
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

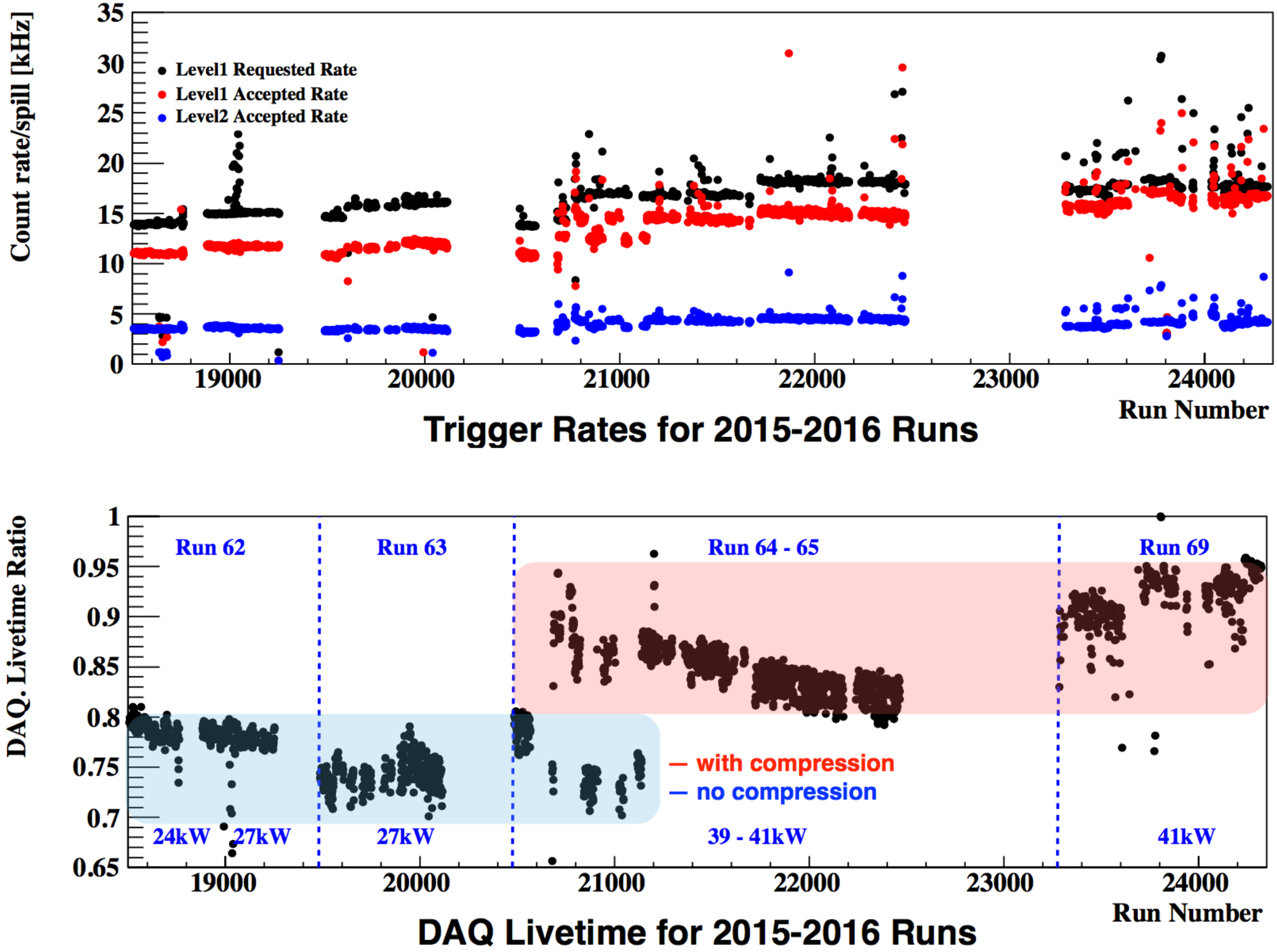

Cluster Timing Probability (the last hit)
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


RMS Chisqr

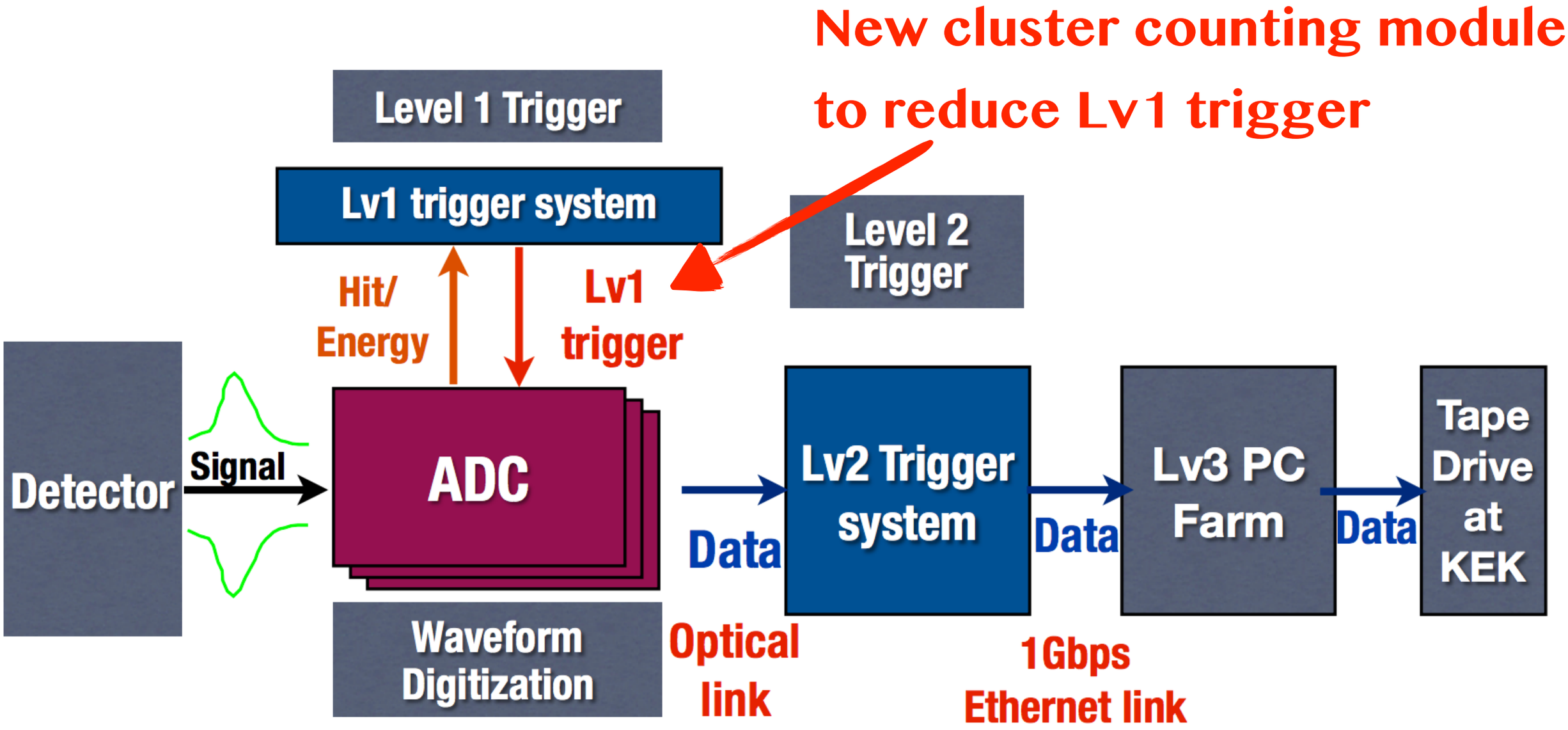

COE Chisqr


Energy Balance


RMS Balance

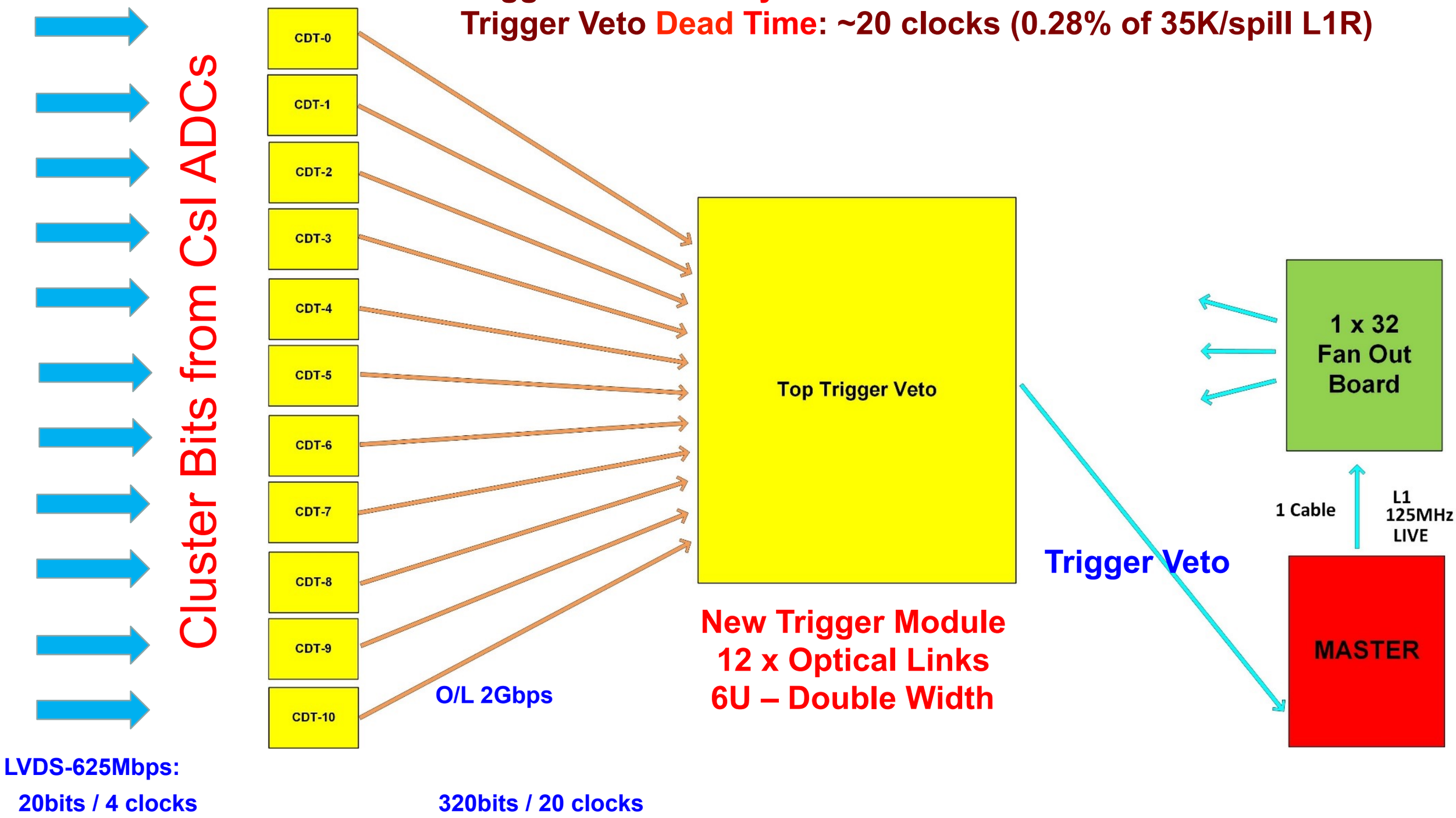

Count rate/spill [kHz]
35
30
25
20
15
10
5
0
Level1 Requested Rate
Level1 Accepted Rate
Level2 Accepted Rate
19000
20000
21000
22000
23000
24000
Run Number
Trigger Rates for 2015-2016 Runs
DAQ. Livetime Ratio
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
Run 62
Run 63
Run 64 - 65
Run 69
with compression
no compression
24kW
27kW
27kW
39 - 41kW
41kW
19000
20000
21000
22000
23000
24000
Run Number
DAQ Livetime for 2015-2016 Runs

DAQ Upgrade


New cluster counting module
to reduce Lv1 trigger
Level 1 Trigger
Lv1 trigger system
Level 2
Trigger
Hit/
Energy
Lv1
trigger
Detector
Signal
ADC
Waveform
Digitization
Data
Optical
link
Lv2 Trigger
system
Data
1Gbps
Ethernet link
Lv3 PC
Farm
Data
Tape
Drive
at
KEK

CLUSTER Trigger with the new CDT Module

Trigger Veto Latency: 60-80 clocks
Trigger Veto Dead Time: ~20 clocks (0.28% of 35K/spill L1R)



L1R Reduction

Assuming original L1R = 35k/spill (42kW),
the reduction of L1R estimated by using norm data.

Scenario-A

NCluster	1	2	3	4	5	6
Percentage	14.7%	14.5%	18.6%	24.3%	19.0%	7.2%
Prescale	∞	1	10	1	∞	1
L1R	35k*(14.5%+1.86%+24.3%+7.2%)=16.8k/spill					

Scenario-B

NCluster	1	2	3	4	5	6
Percentage	14.7%	14.5%	18.6%	24.3%	19.0%	7.2%
Add COE		5.8%				
Prescale	∞	1	10	1	∞	1
L1R	35k*(5.8%+1.86%+24.3%+7.2%)=13.7k/spill					