The Data Acquisition System for the KOTO Detector

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On behalf of

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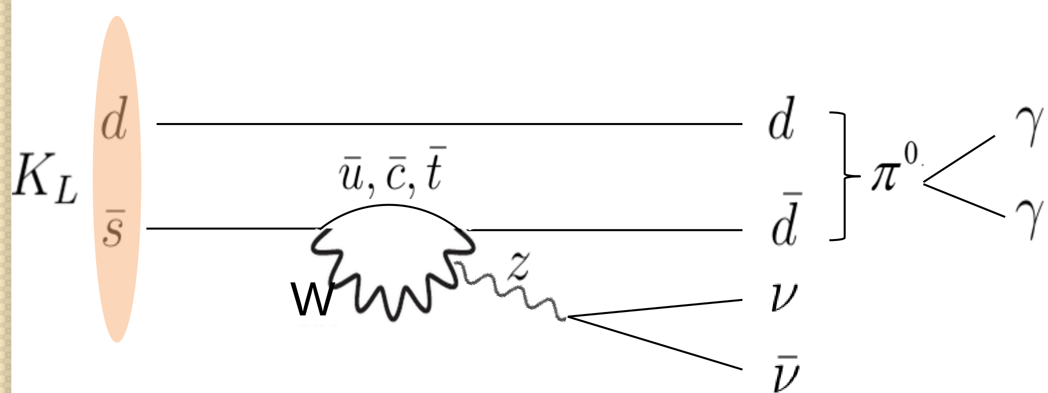
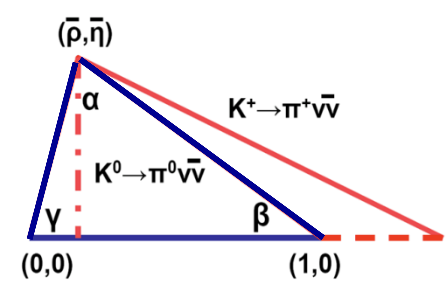
The KOTO Experiment

- Study of rare K_L^0 decay at **To**kai, Japan
  - Measure the branching ratio of $K_L \rightarrow \pi^0 \nu\bar{\nu}$ decay
    Standard model: $(2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$ [J.Brod, *et al.* PRD 83, 034030 (2011)]
  - Direct CP violating process $\propto \eta^2$
  - Study FCNC and probe for new physics





Previous Results

Direct Limit:

- E391a at KEK [PRD 81, 072004, 2010]

  $BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ at 90% CL

Indirect Limit:

- E949 at BNL [PRL 101, 191802, 2008]

  Measure $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (17.3 \pm 11.0) \times 10^{-11}$

  Grossman-Nir Relation [Y. Grossman and Y. Nir, Phys. Lett. B 398, 163 (1997)]

  $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.4 \times BR(K^+ \to \pi^+ \nu\bar{\nu})$

  $\rightarrow BR(K_L \rightarrow \pi^0 \nu\bar{\nu}) < 1.7 \times 10^{-9}$ at 90% CL

Goal:

- Standard model: $(2.4 \pm 0.4) \times 10^{-11}$ [J.Brod, *et al.* PRD 83, 034030 (2011)]

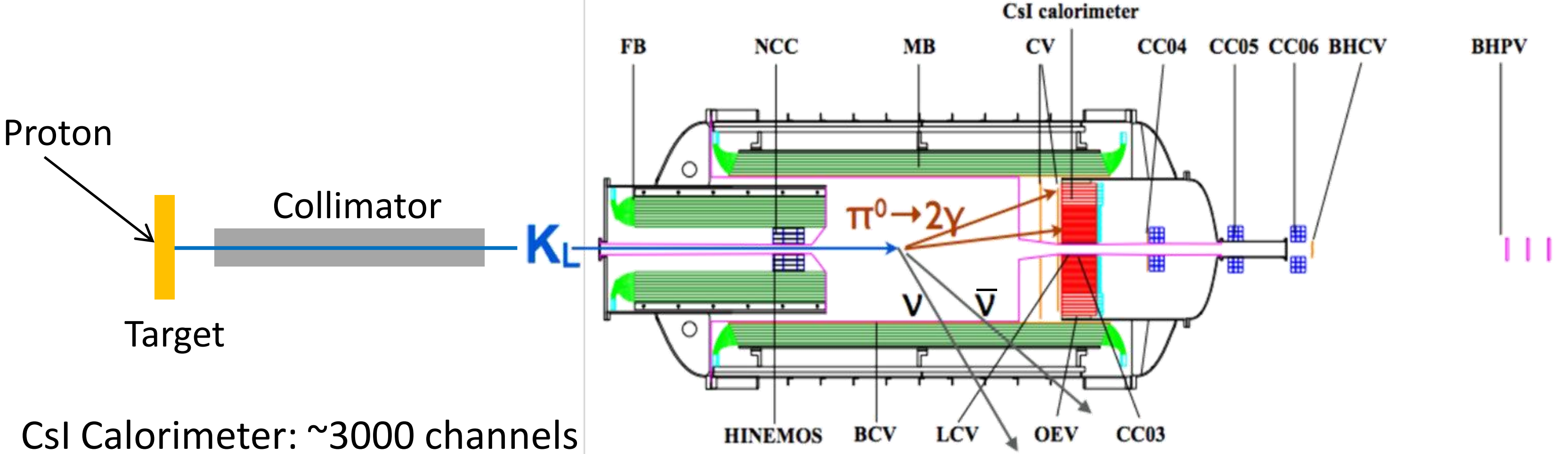
The KOTO Experiment

At J-PARC 30GeV Main Ring

May, 2013

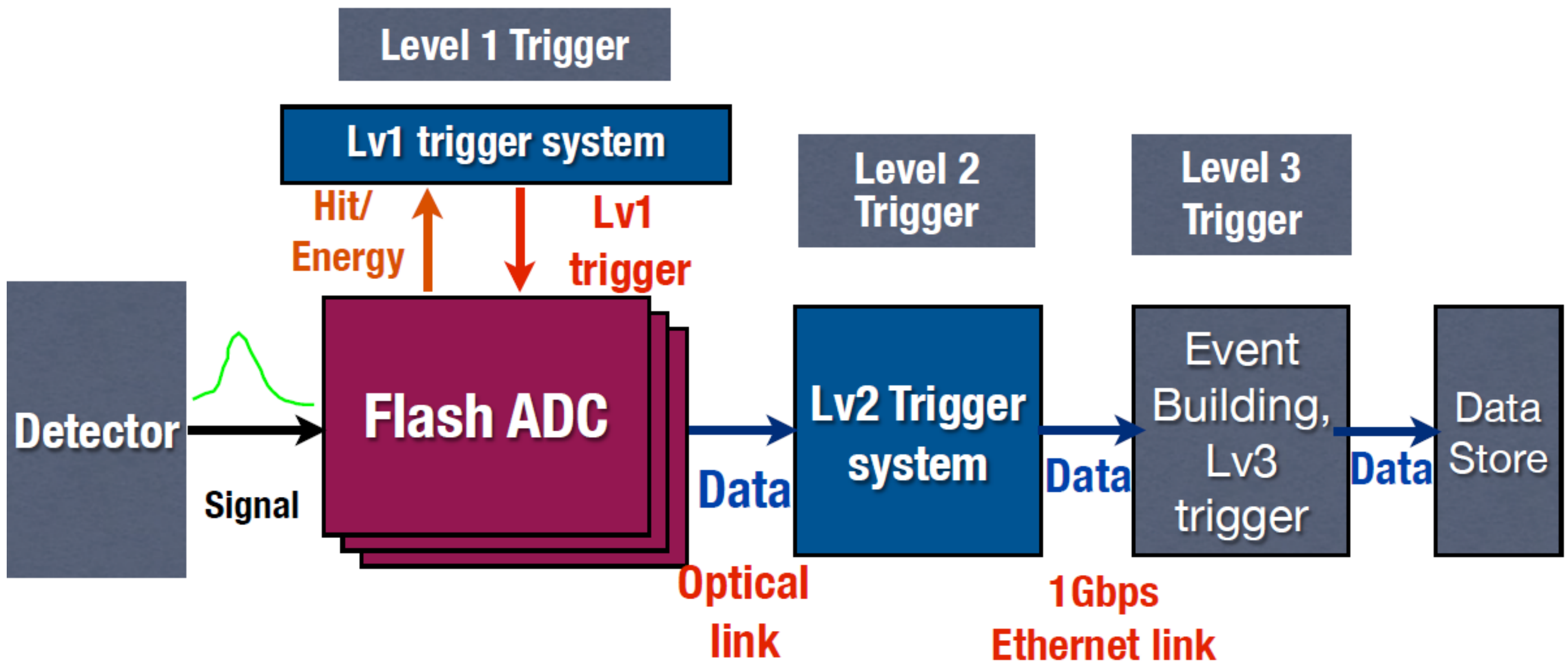
- 24kW proton beam power
- Slow extraction with spill time: 2s/6s
- 3×10^{13} POT/spill → 6.3×10^{6} K_L/spill

[preliminary, T. Masuda, 2014, *Development and Experimental Study of the KOTO Detector System using Three KL Neutral Decay Modes*, Kyoto University, Japan]

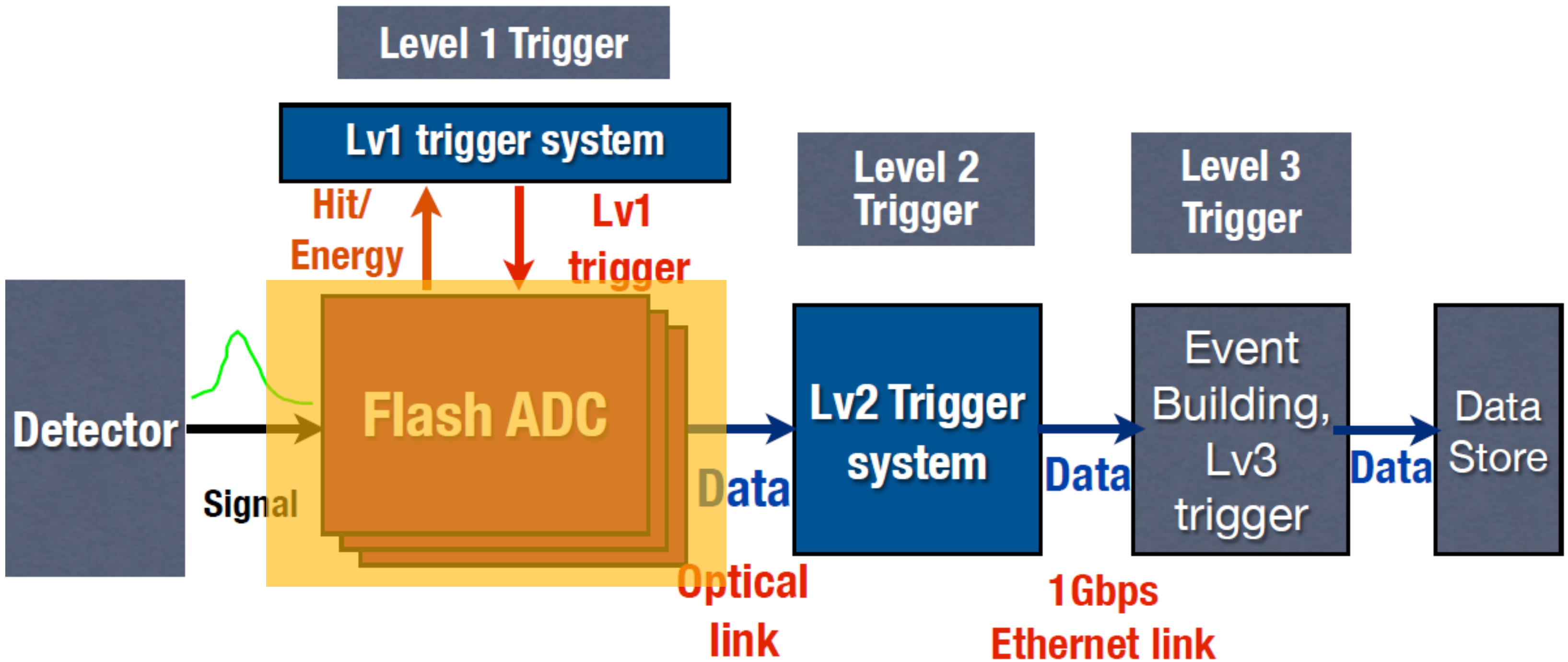


CsI Calorimeter: ~3000 channels
Other detectors: ~1000 channels

Overview of KOTO DAQ System

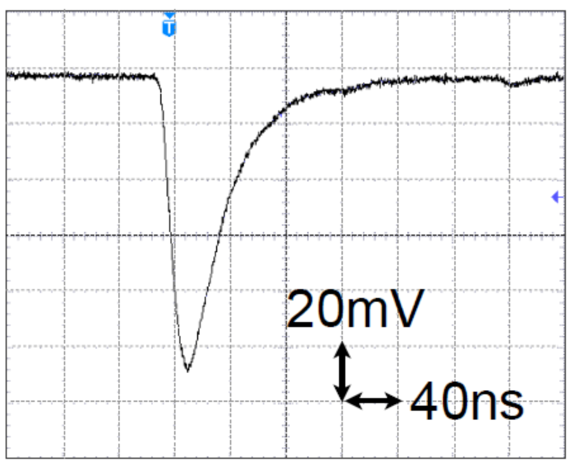


Overview of KOTO DAQ System

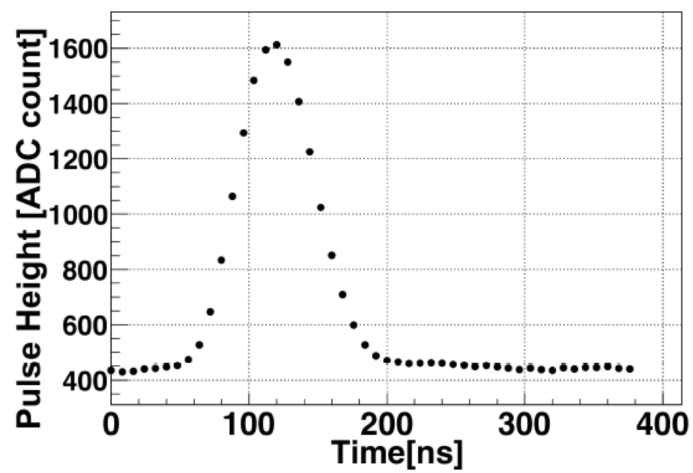


ADC

- Each ADC module has 16 channels
- Shape the analog input into Gaussian of 100ns at FWHM
- Digitize the shaped signal with 14-bit at 125MHz



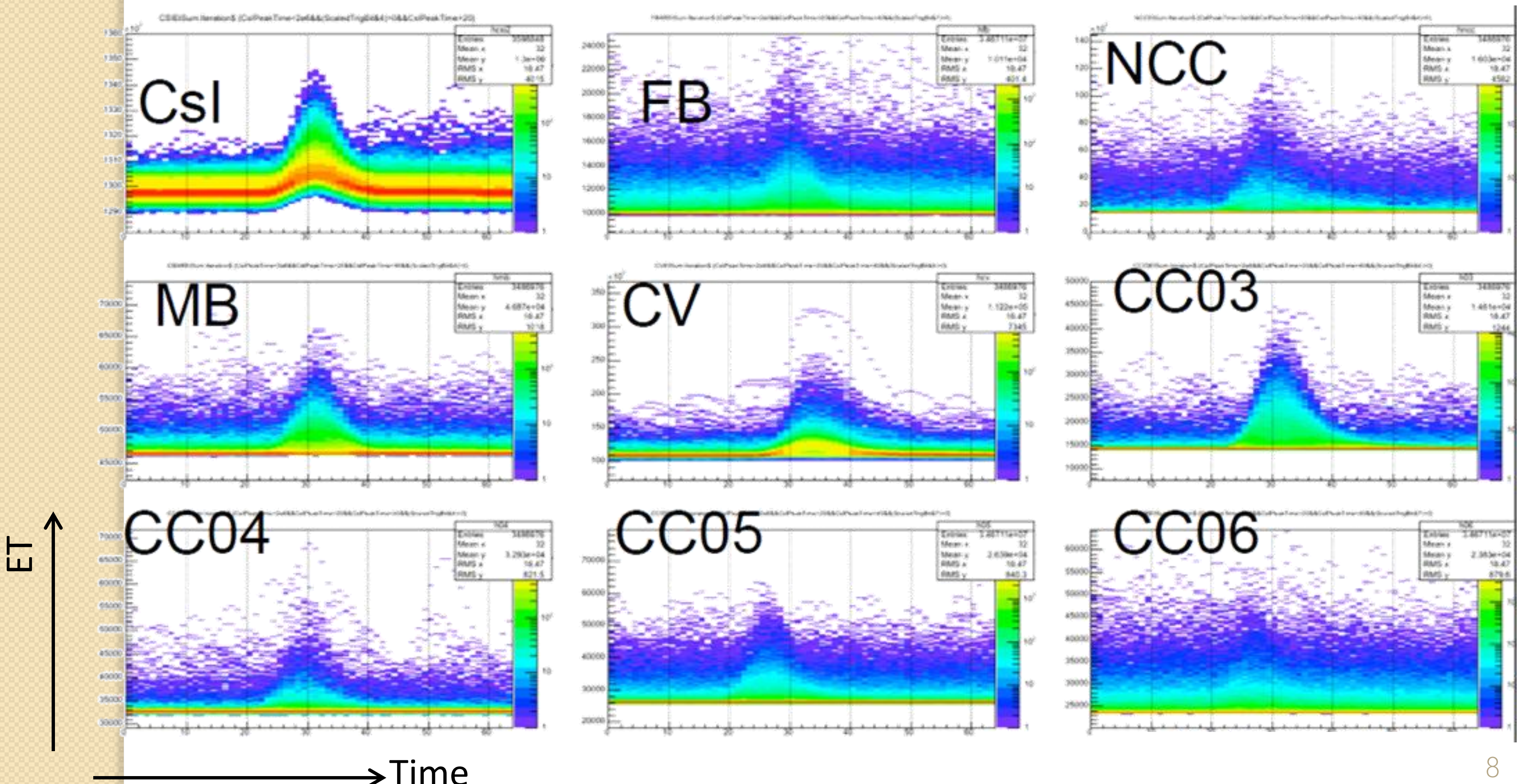
PMT Signal

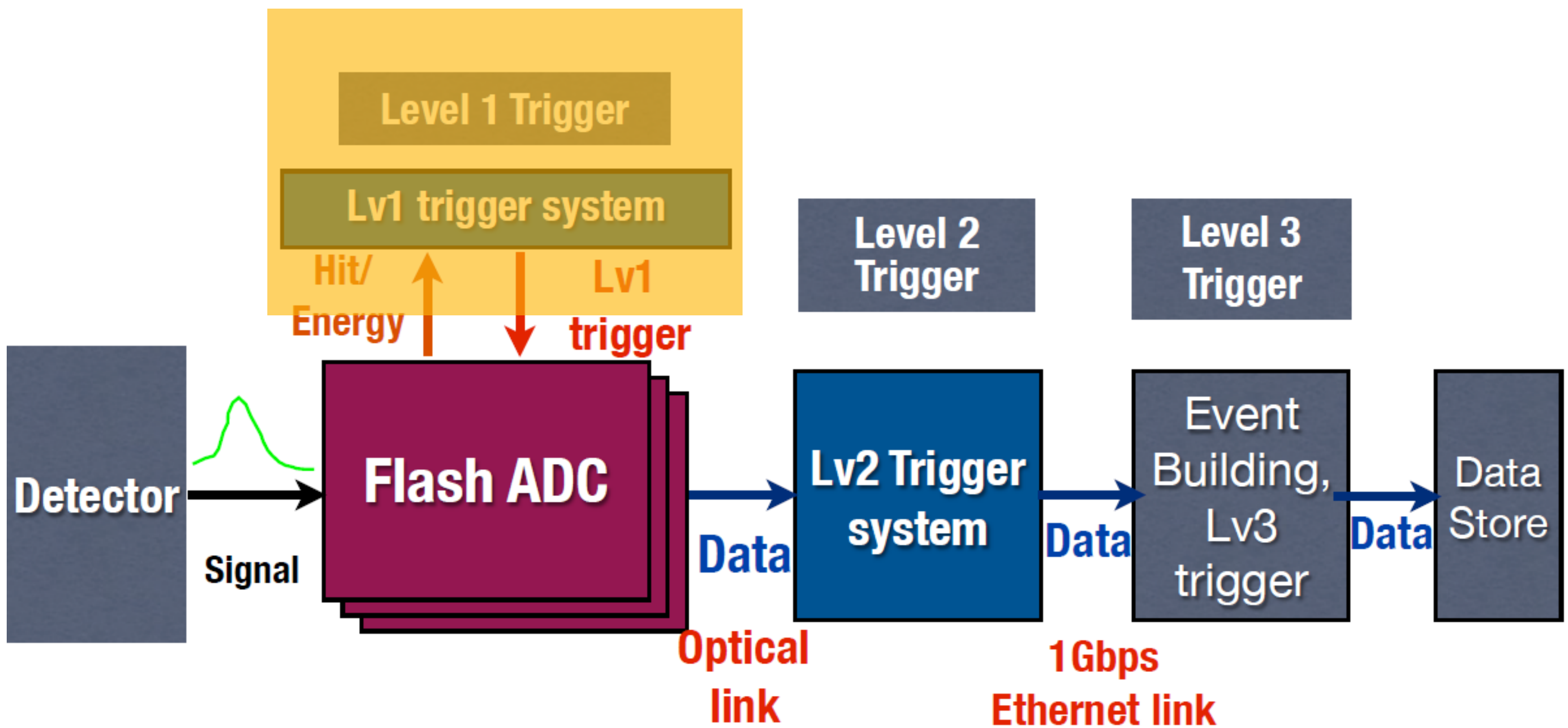


Digitization

Timing Alignment

- Most of the detectors are aligned with the CSI calorimeter and in the event window (64 clock width)

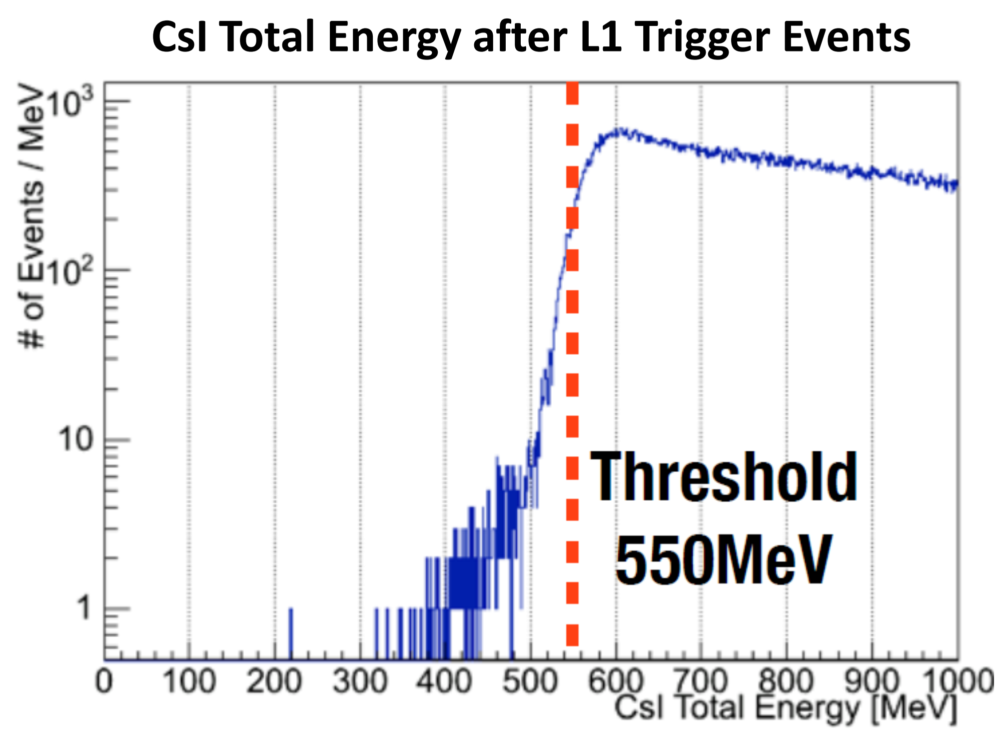




Level 1 Trigger
Lv1 trigger system
Hit/ Energy
Lv1 trigger
Level 2 Trigger
Level 3 Trigger
Detector
Signal
Flash ADC
Data
Optical link
Lv2 Trigger system
Data
1Gbps Ethernet link
Event Building, Lv3 trigger
Data
Data Store

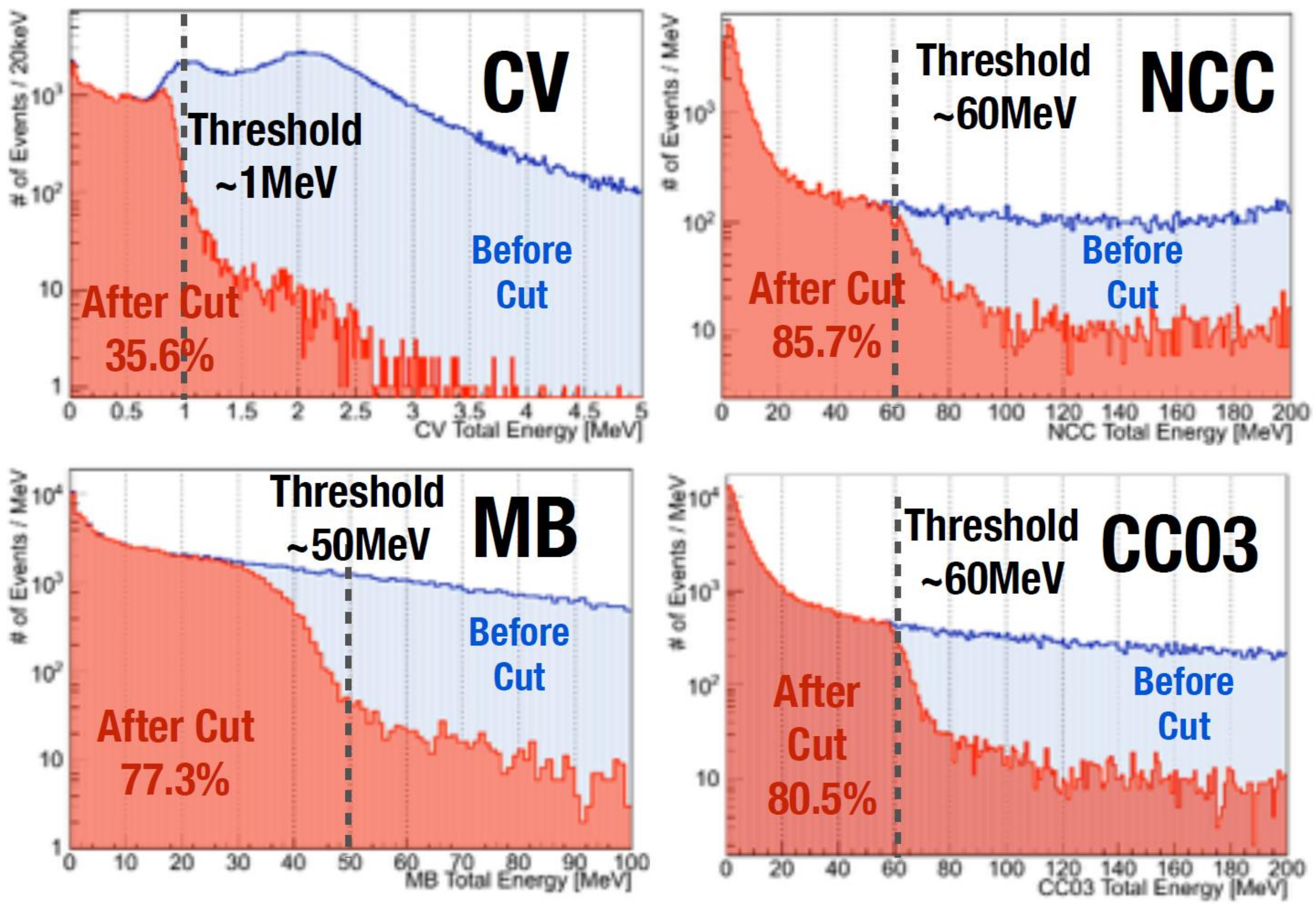
L1 Trigger

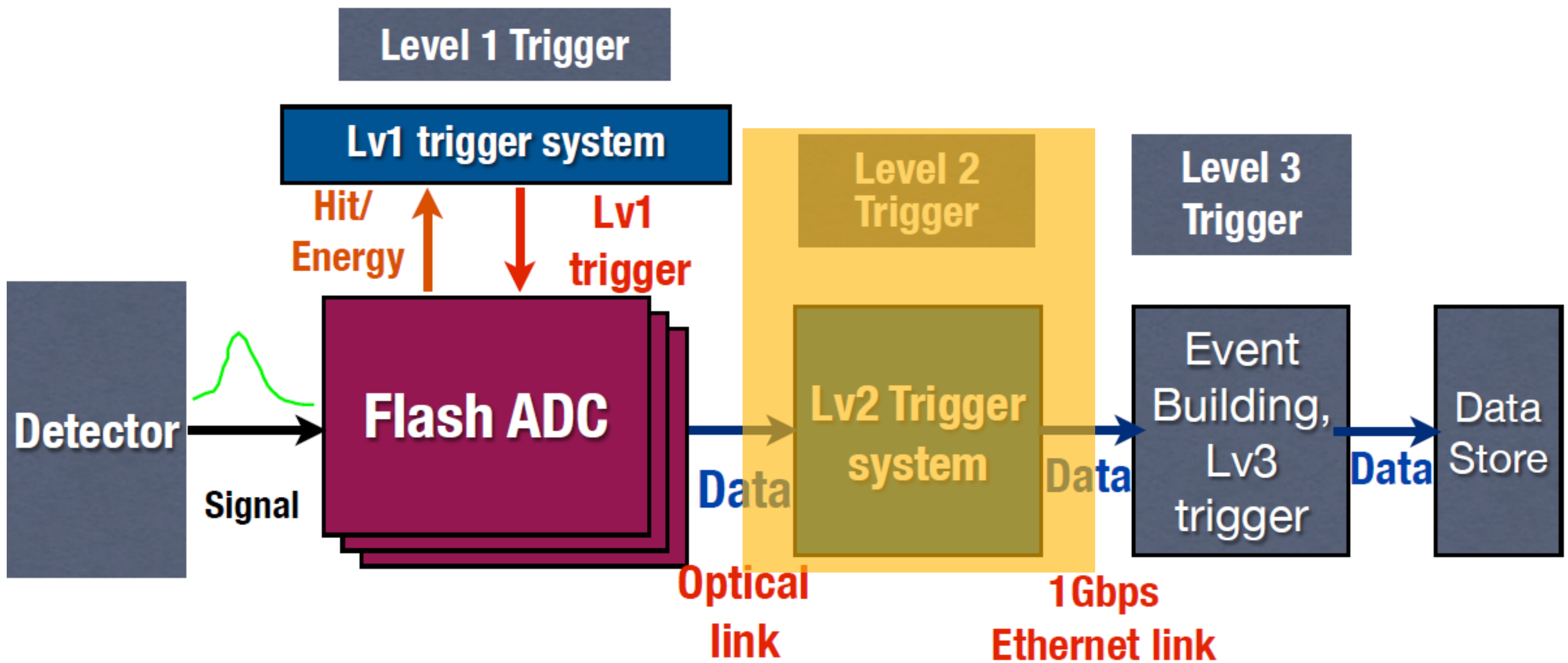
- Energy cut on sum of the CsI calorimeter energy



L1 Trigger

- Energy cut on sum of the CsI calorimeter energy
- Low energy cut for veto detectors

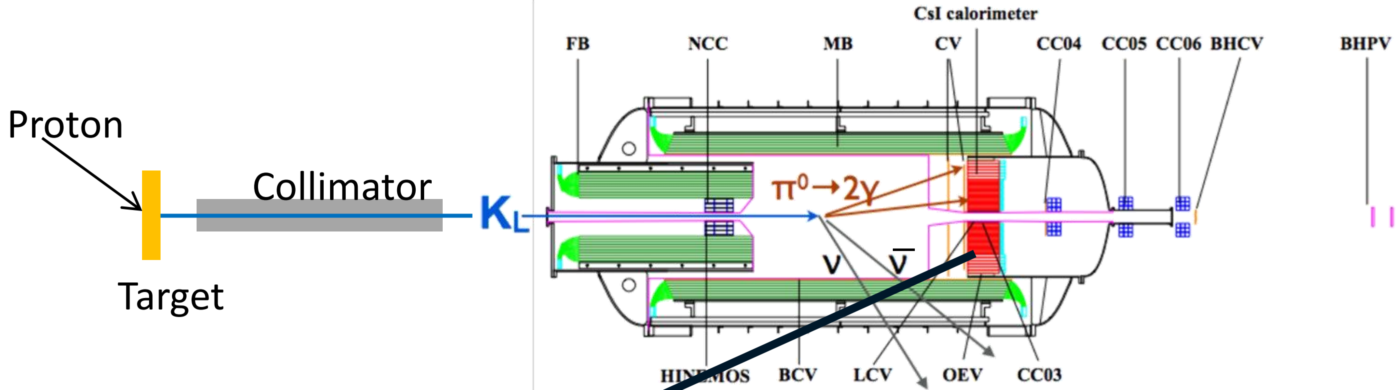



Level 1 Trigger
Lv1 trigger system
Hit/
Energy
Lv1
trigger
Level 2
Trigger
Level 3
Trigger
Detector
Signal
Flash ADC
Lv2 Trigger
system
Event
Building,
Lv3
trigger
Data
Store
Data
Data
Data
Optical
link
1Gbps
Ethernet link

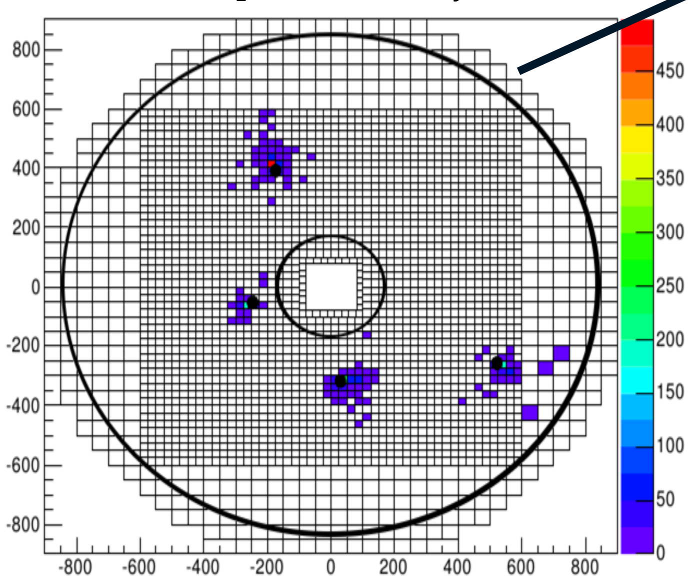
L2 Trigger

- Perform Center Of Energy (COE) radius cut
  - $K_L \rightarrow \pi^0 \nu \bar{\nu}$ has large COE radius

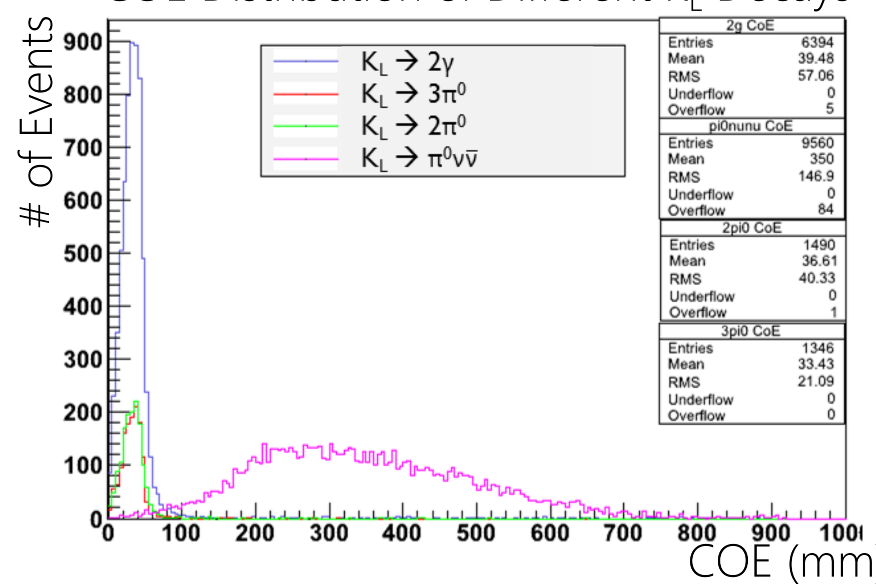
$$COE = \frac{\sqrt{(\sum_i E_i x_i)^2 + (\sum_i E_i y_i)^2}}{\sum_i E_i}$$



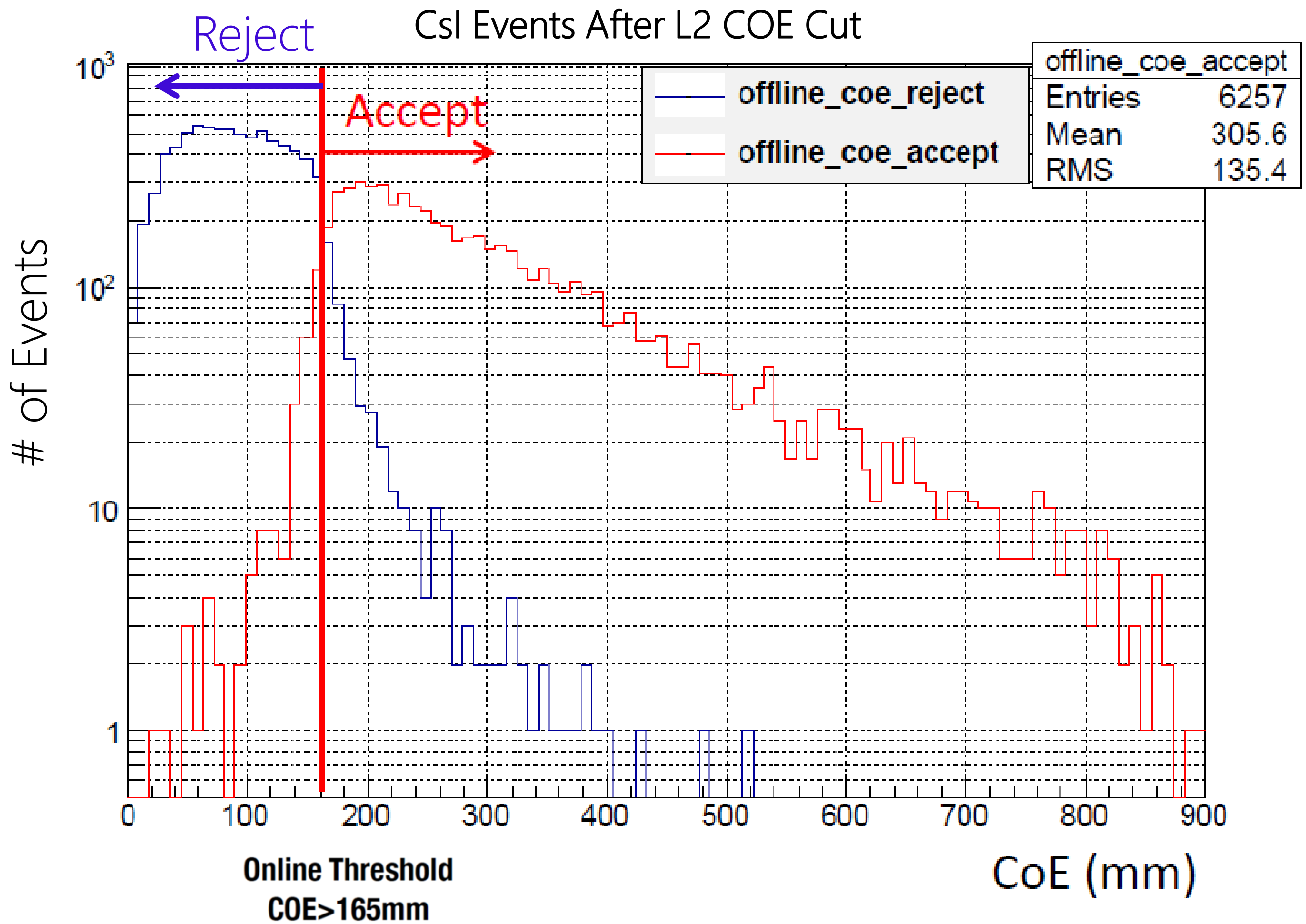
Event Display of CsI Calorimeter for $K_L \rightarrow 2\pi^0$ decay



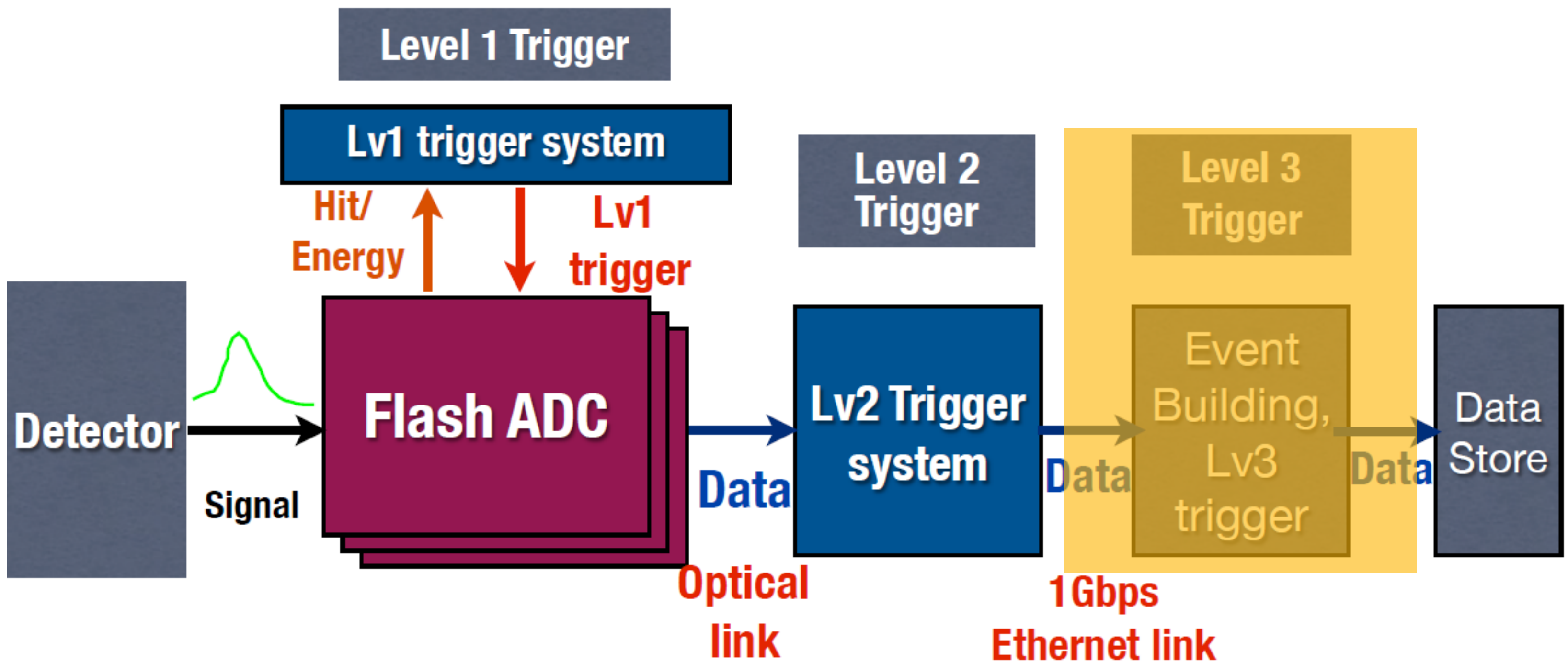
COE Distribution of Different K_L Decays



L2 COE Cut



Reject
CsI Events After L2 COE Cut
Accept
offline_coe_reject
offline_coe_accept
offline_coe_accept
Entries 6257
Mean 305.6
RMS 135.4
# of Events
10³
10²
10
1
0
100
200
300
400
500
600
700
800
900
Online Threshold
COE>165mm
CoE (mm)


Level 1 Trigger
Lv1 trigger system
Hit/
Energy
Lv1
trigger
Level 2
Trigger
Level 3
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Detector
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Flash ADC
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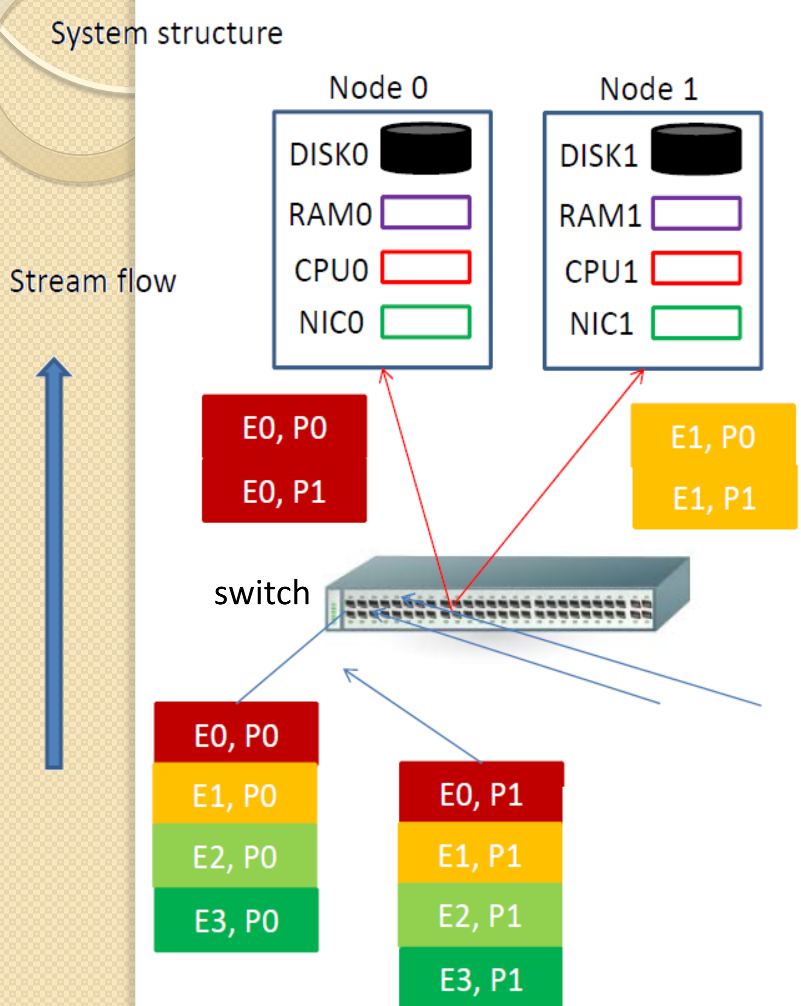
Optical
link
Lv2 Trigger
system
Data
1Gbps
Ethernet link
Event
Building,
Lv3
trigger
Data
Data
Store

L3 Trigger

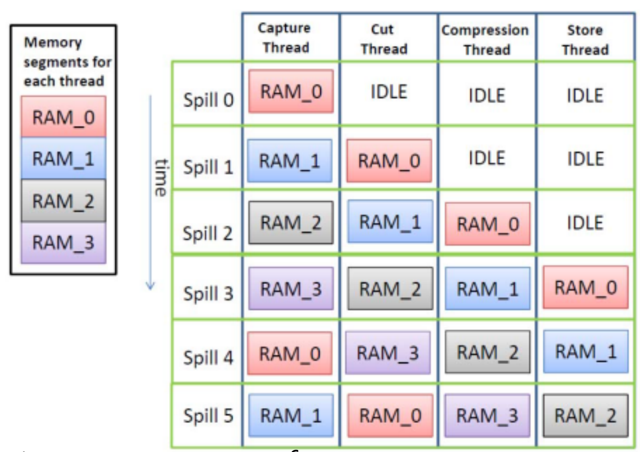


- Computer clusters
- Backend switch do the routing of fragments of single events to the nodes
- Parallel processing using multi-thread
  - 4-thread scheme

L3 Trigger

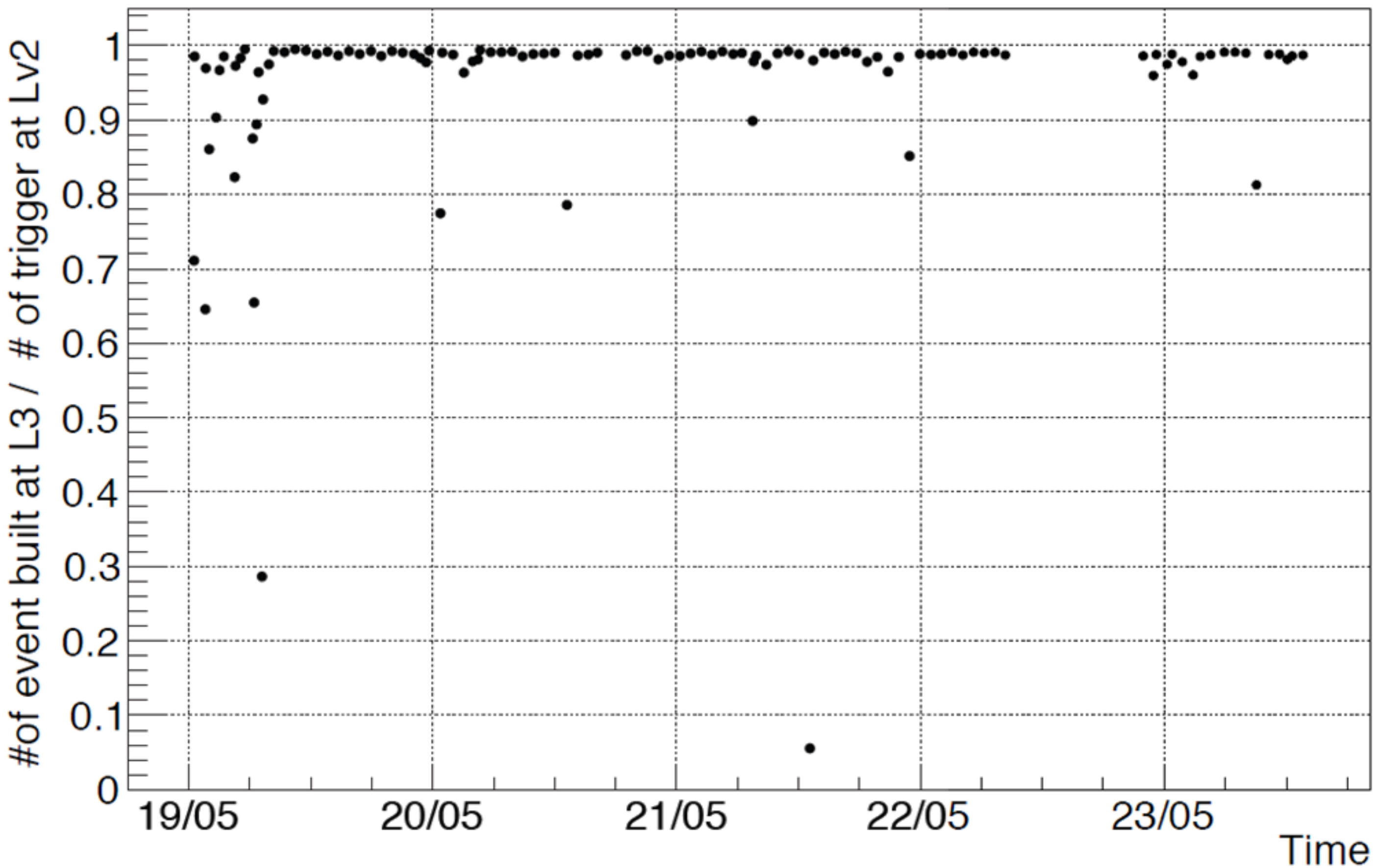
- Multi-thread structure

Threads	What thread does	Physical memory operation
Capture thread	Capture events from Ethernet card	NIC → RAM_0
Cut thread	Throw away uninterested events	RAM_0 → RAM_1
Compression on thread	Compression	RAM_1 → RAM_2
Store thread	Copy events into run file in the hard disk	RAM_2 → hard disk



The time sequence of memory segments and multi-thread

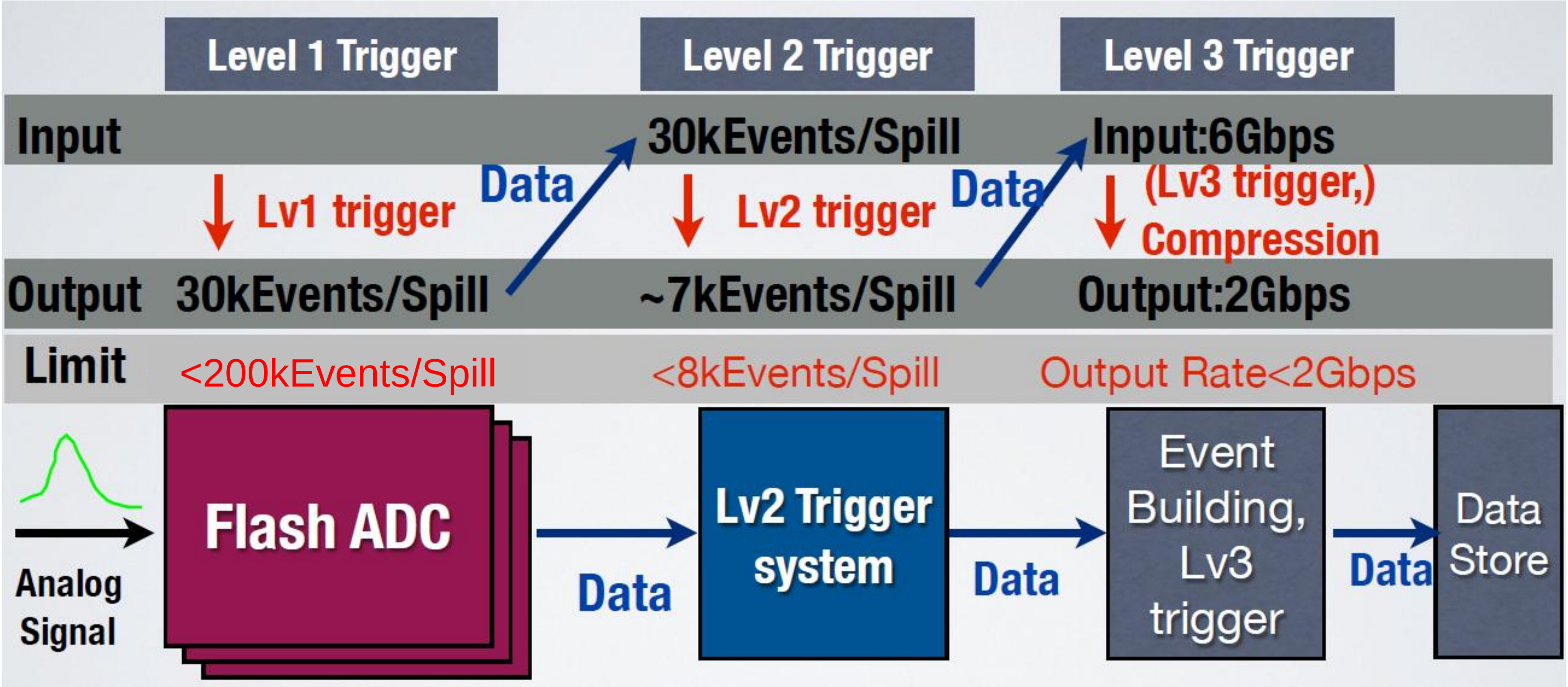
L3 Trigger



#of event built at L3 / # of trigger at Lv2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
19/05
20/05
21/05
22/05
23/05
Time

Data Transfer Rates

- May, 2013
- Spill: 2s/6s

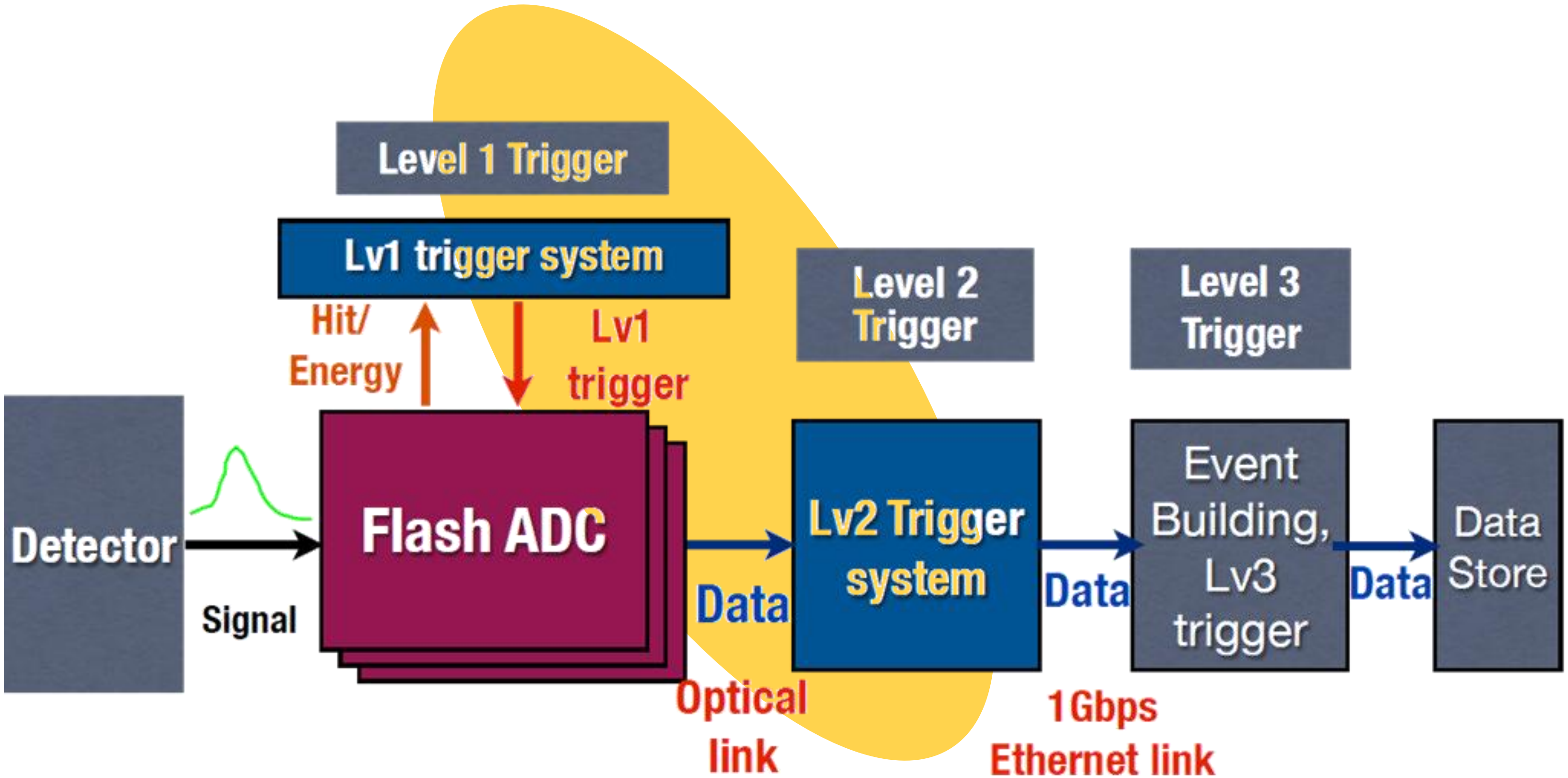


Standard model

$$(2.4 \pm 0.4) \times 10^{-11}$$

[J.Brod, *et al*. PRD 83, 034030 (2011)]

L1, L2 DAQ Simulation

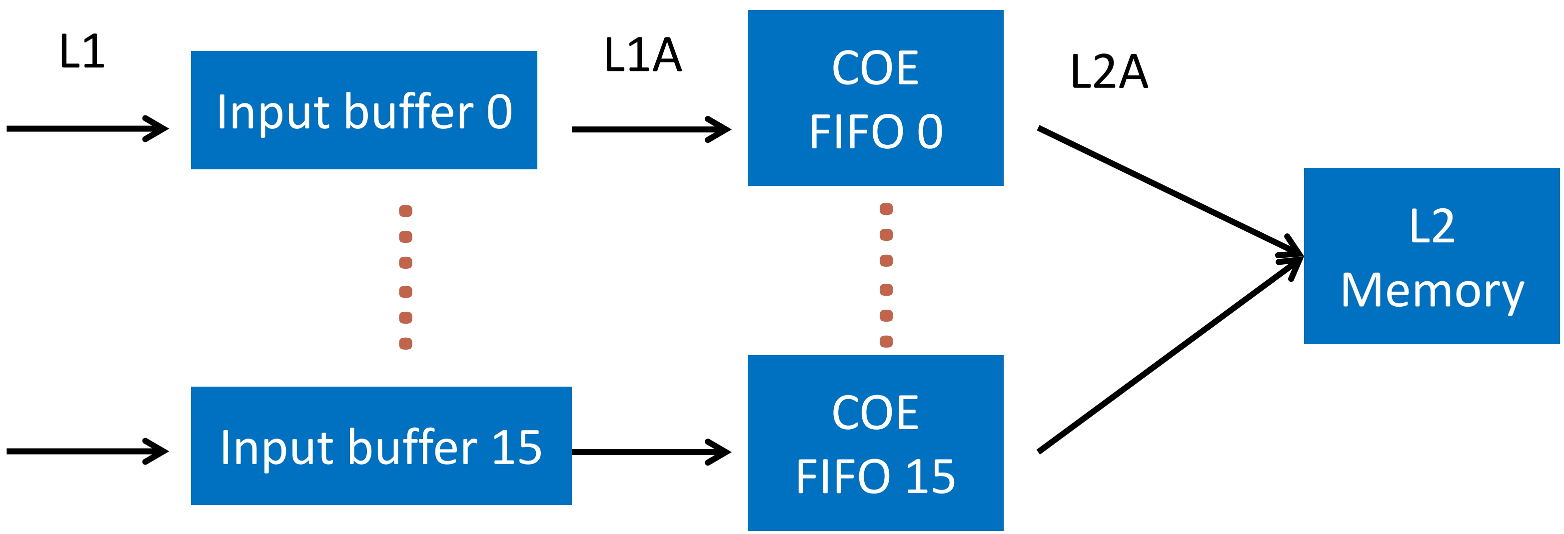


L1→L2 DAQ Simulation

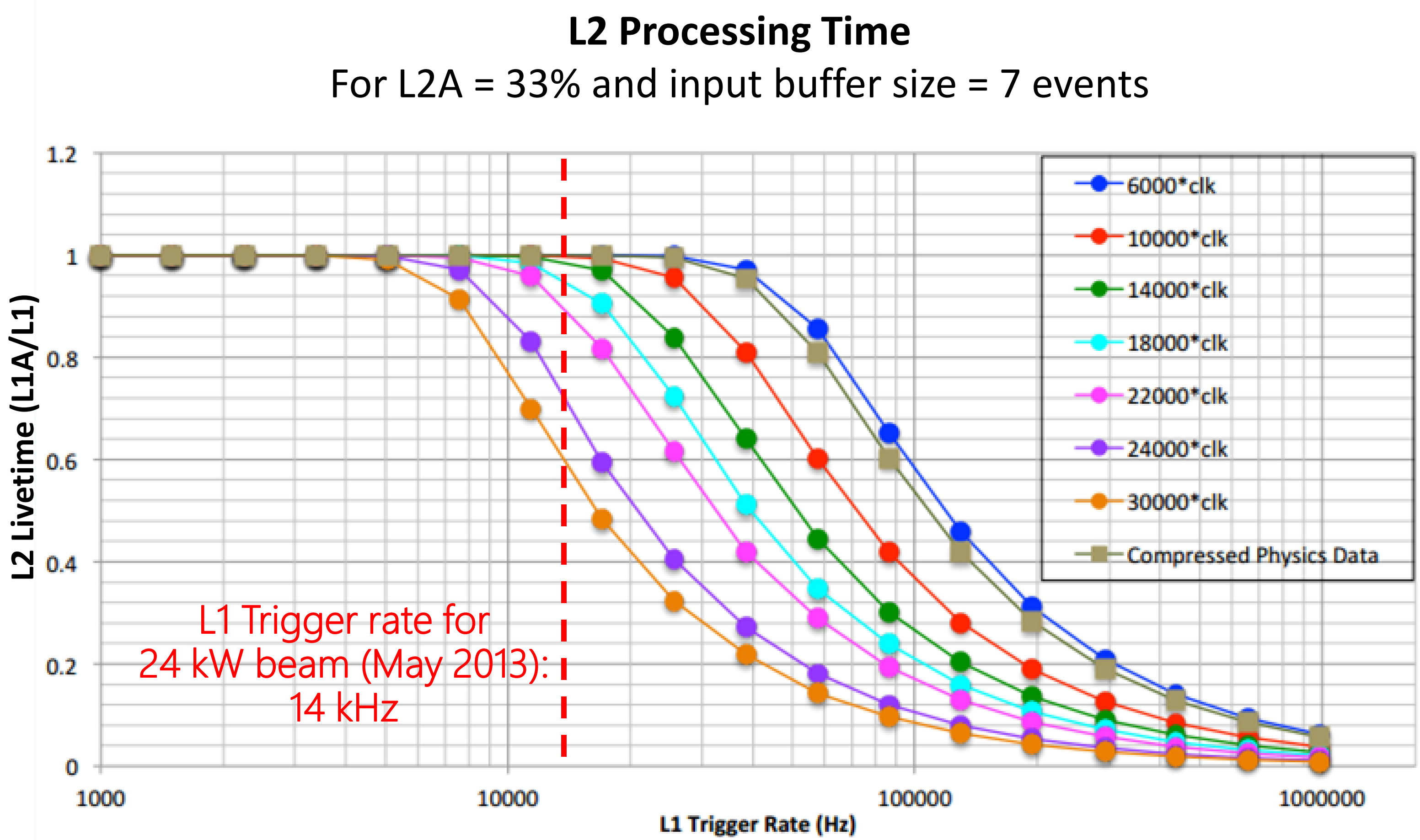
L2 Trigger Model

- L1 event from ADC enters input buffer and is accepted (L1A) if buffer is not full
- L1A event wait in COE FIFO for L2 decision
- L2A event is moved from 16 COE FIFOs into single memory
- L2 processing time for uncompressed event (~250kb) is 18000 clock cycles

Simulation studies L2 livetime dependence on input buffer size, COE acceptance rate and L2 processing time as a function of L1 trigger rate.



L1→L2 Simulation Result



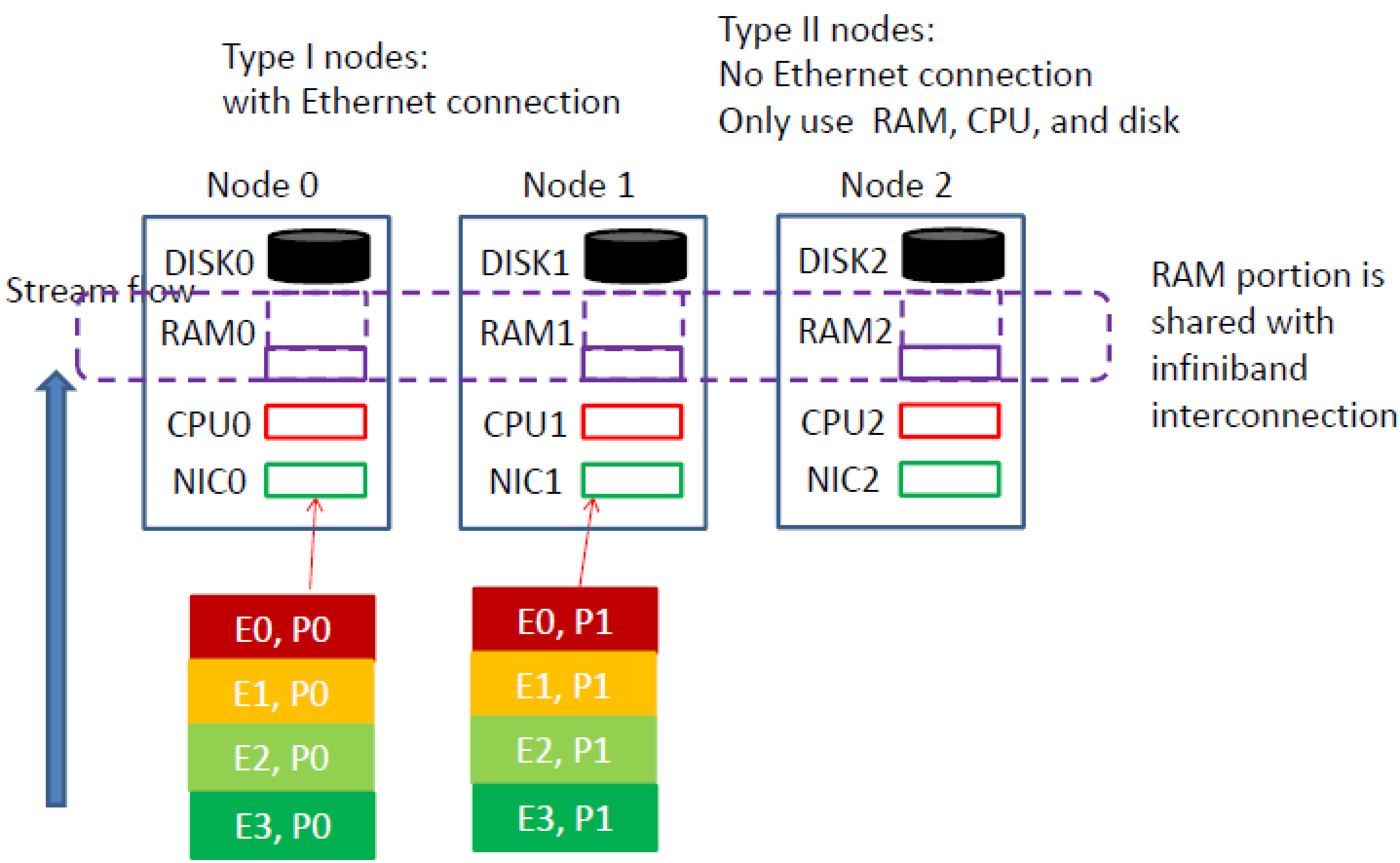
May 2013 DAQ implementation: Cyan points

Compressed data: Brown squares

KOTO DAQ Upgrade

New L3 Architecture

- Event Building: Ethernet → Infiniband
  - Remote direct memory access
  - TCP based connection
  - Uses API



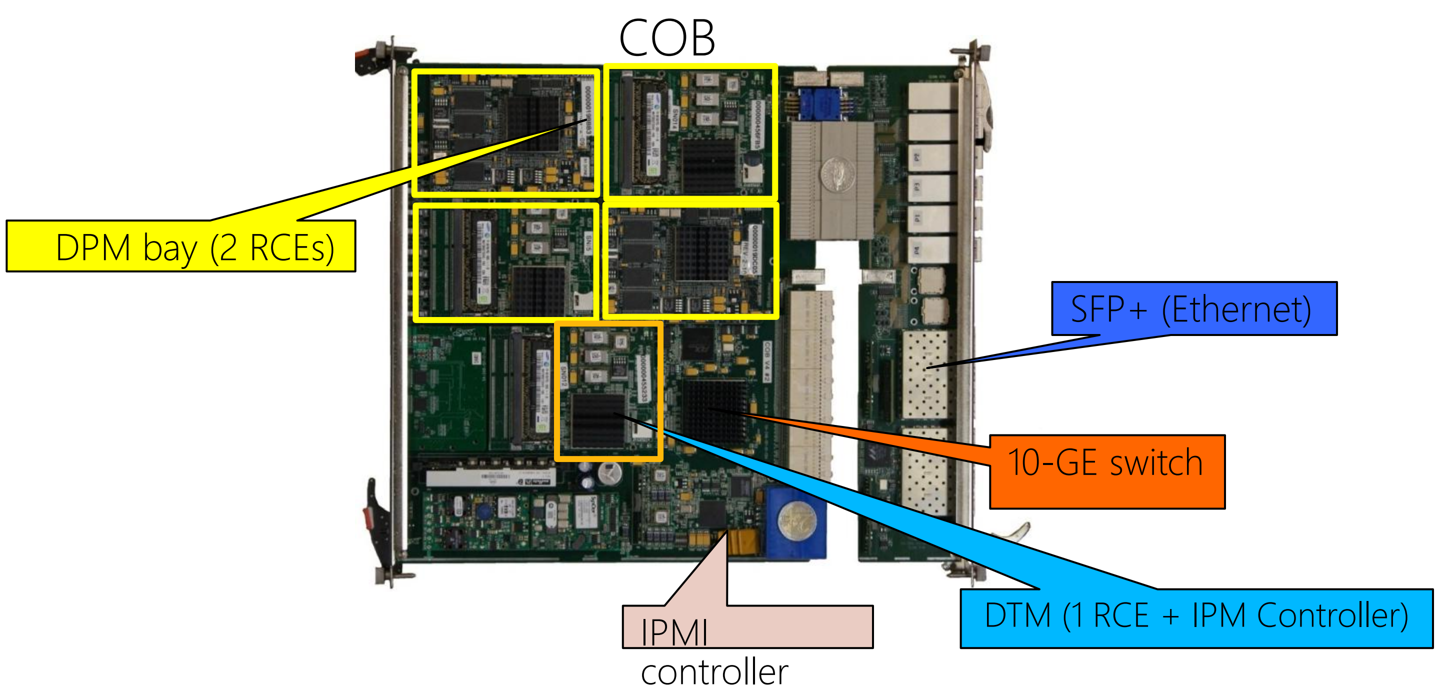
New L3 Architecture

- Both Type I and Type II nodes can have the same multi-thread structure.

Threads	What thread does	Physical memory operation
Capture thread	Capture events from Ethernet card	NIC → RAM_x
Switching thread	Target data segments to designated nodes	RAM_x → Whoever's RAM_0 it should go to
Cut thread	Throw away uninterested events	RAM_0 → RAM_1
Compression on thread	Compression	RAM_1 → RAM_2
Store thread	Copy events into run file in the hard disk	RAM_2 → hard disk

L2 Trigger Upgrade

- Advanced Telecommunication Computing Architecture (ATCA)
  - Allow backend communication (each board can talk to each other)
- Reconfigurable Cluster Element (RCE)
  - Dense and fast connection across different parts of the system (R&D undergoing at SLAC)
- Cluster-On-Board (COB)
  - Dense and fast connection across different parts of the system (R&D undergoing at SLAC)



Conclusion

Current DAQ: Functioned well at 24kW in May, 2013

Short-term upgrade (up to 100kW):

- Online compression to increase L2 Livetime
- New L3 architecture with Infiniband

Long-term upgrade (up to 300kW):

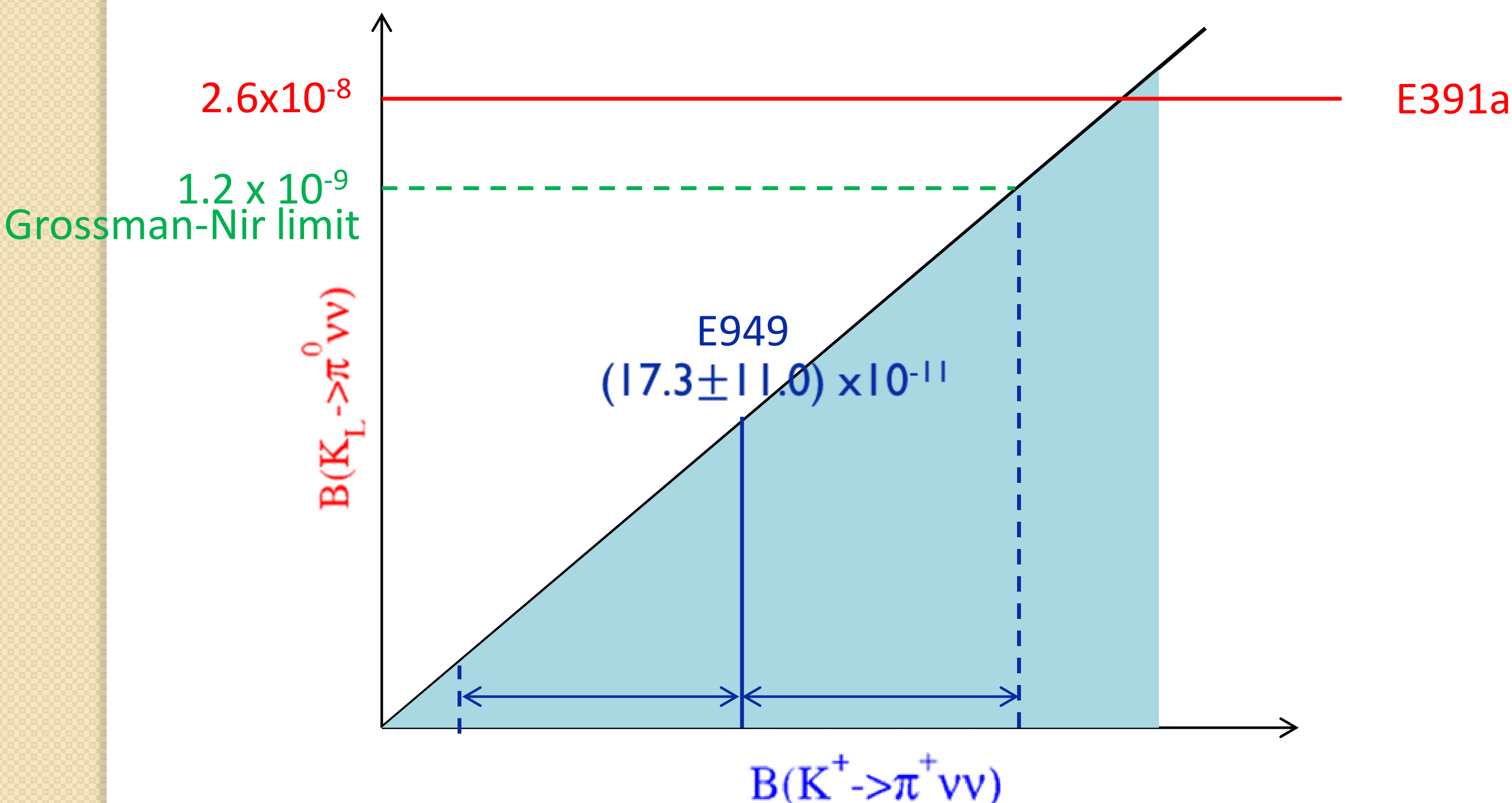
- Use L2 trigger with RCE

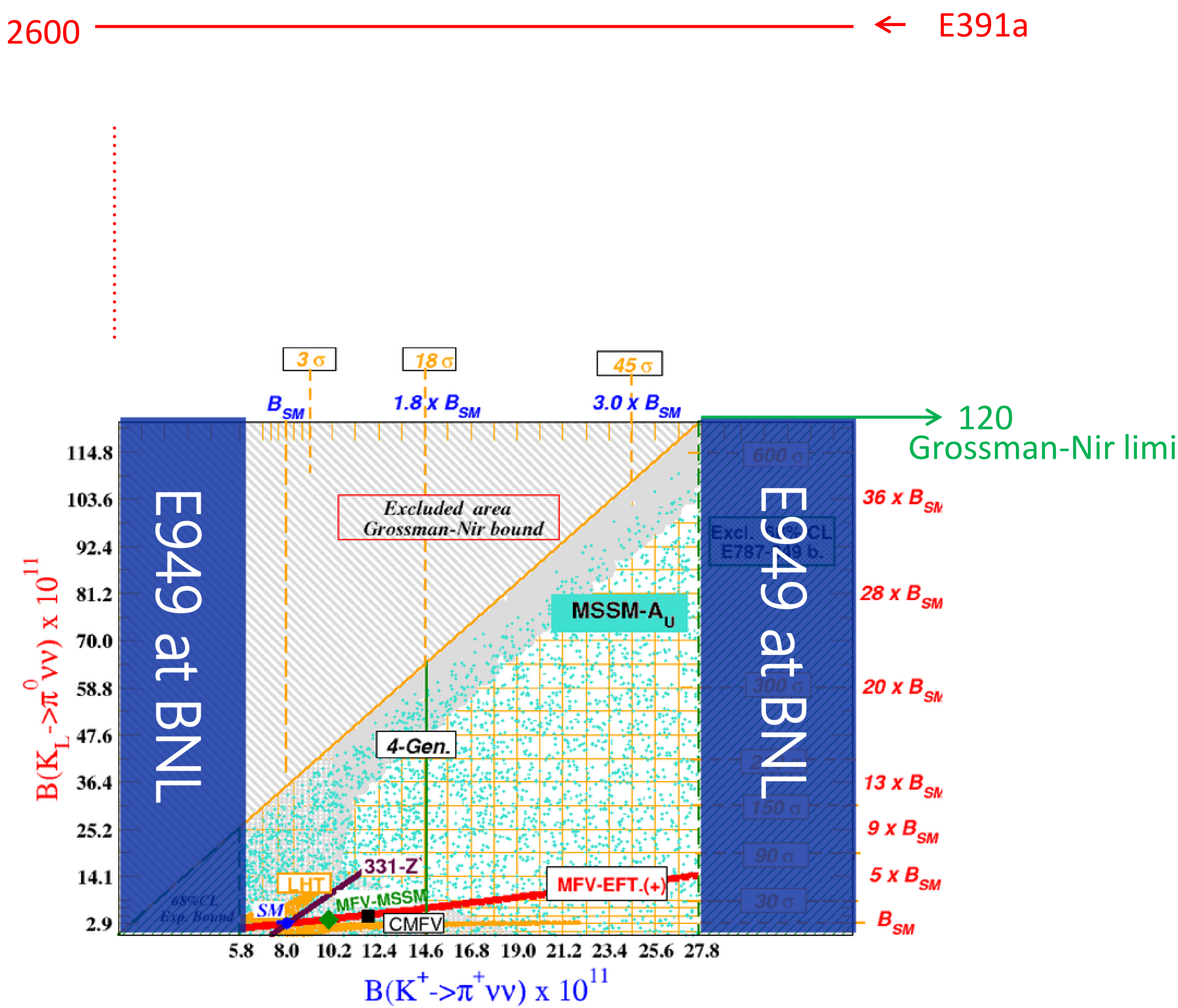
Backup Slides

Grossman-Nir Limit

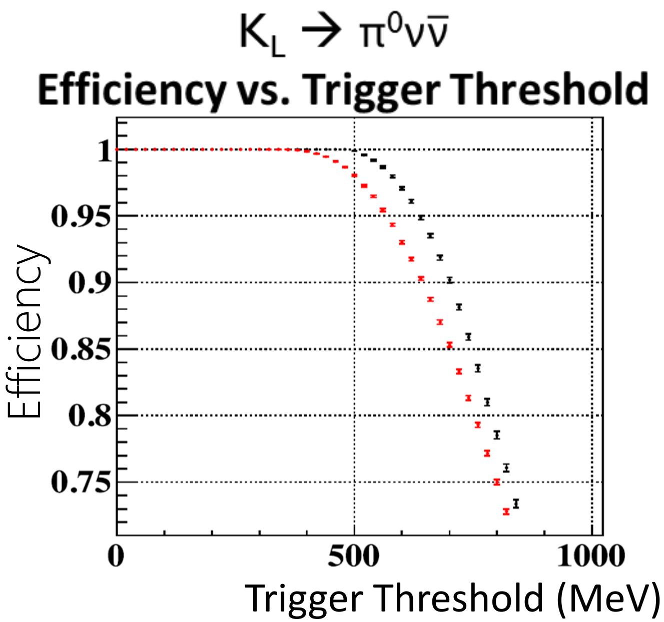
- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.4 \times BR(K^+ \to \pi^+ \nu\bar{\nu})$

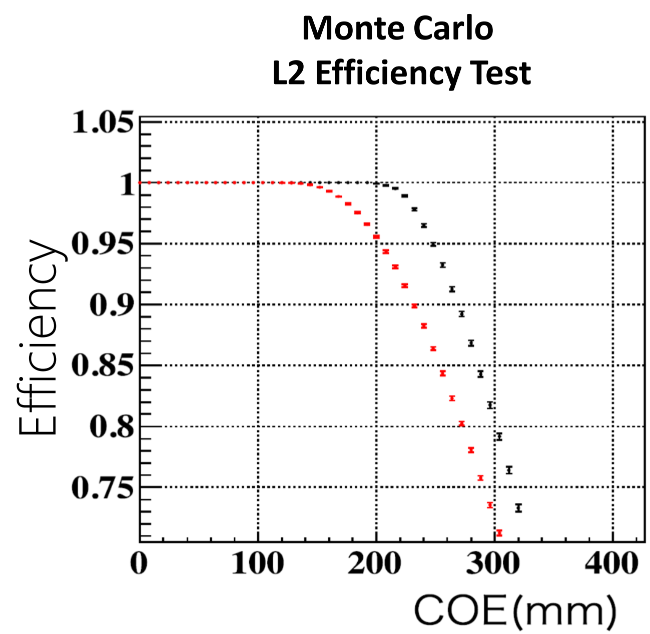
[Y. Grossman and Y. Nir, Phys. Lett. B 398, 163 (1997)]




2600
E391a
120
Grossman-Nir limit
3 σ
18 σ
45 σ
B_SM
1.8 x B_SM
3.0 x B_SM
E949 at BNL
E949 at BNL
Excluded area
Grossman-Nir bound
MSSM-A_U
4-Gen.
331-Z'
LHT
SM
MFV-MSSM
CMFV
MFV-EFT.(+)
68%CL
Exp. Bound
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
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_L^0->π^0 νν) x 10^11
B(K^+->π^+ νν) x 10^11

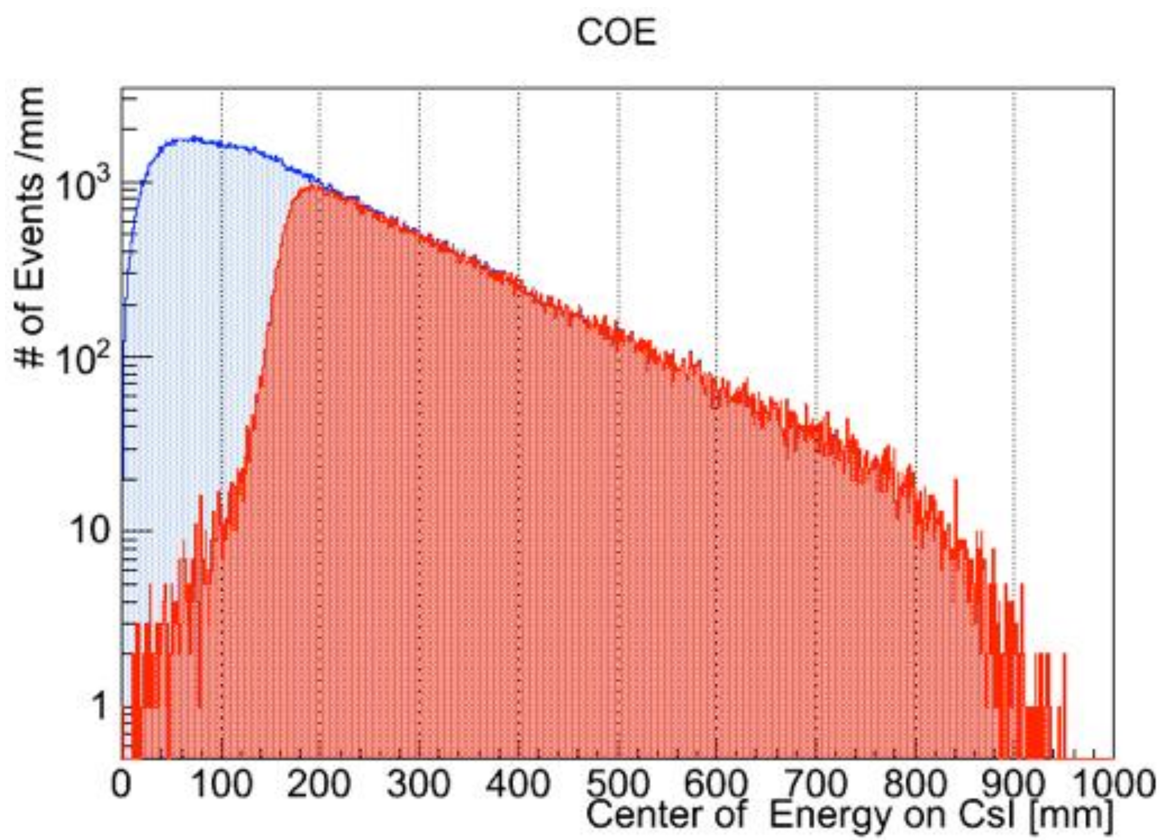
Trigger Efficiency - Monte Carlo





Black: All K_L events after reconstructions
Red: K_L events in our signal region

L2 COE Cut


COE
# of Events /mm
10^3
10^2
10
1
0
100
200
300
400
500
600
700
800
900
1000
Center of Energy on CsI [mm]

L1→L2 DAQ Simulation

- Simulate 2 second spill with rates between 1kHz and 1MHz
  - In 24 kW physics run (Apr. 2013), the L1Req was 14kHz
- Make a decision for L1Req every clock cycle (8ns)
- Each L1Req dumps one packet into the buffer
  - Current DAQ can hold max of 7 packets
  - L1Req is not accepted (L1A) if the input buffer is full
- L2A: 17000 clock cycles
  - Models the time it takes to move 64-sampling uncompressed trigger from 16 fibers (256 ADC)
- L2R: instant
  - Models 10 clock cycles