# JUNO Top Tracker

João Pedro Athayde Marcondes de André
for the JUNO Collaboration

IPHC/IN2P3/CNRS

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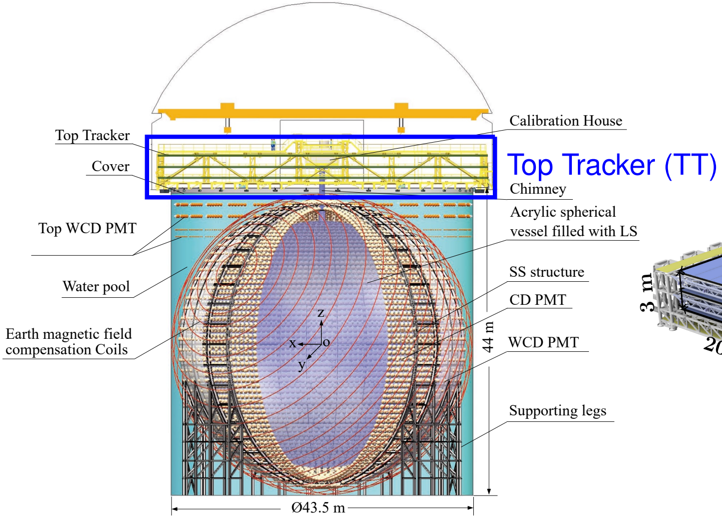
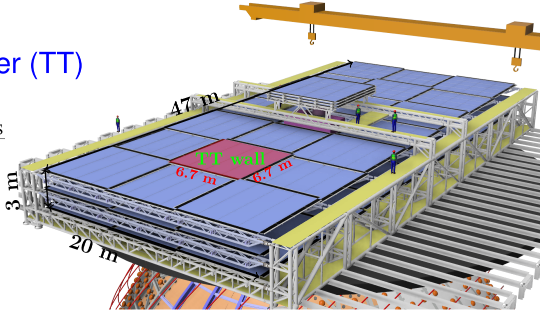
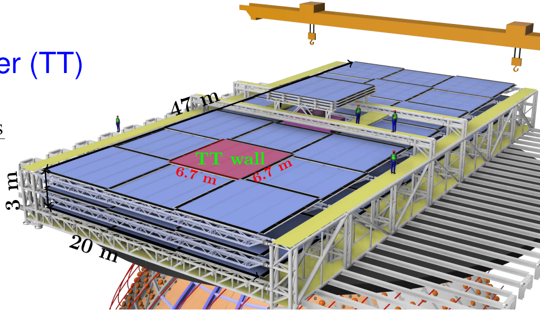
# The JUNO Detector



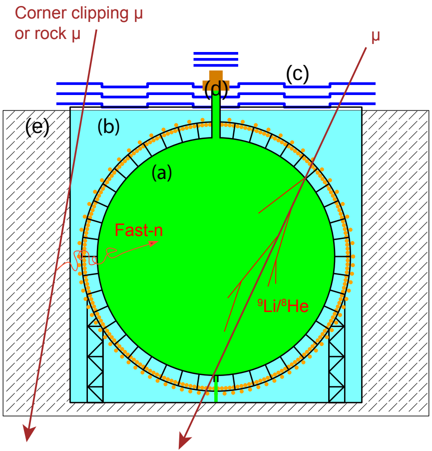



# The JUNO Detector

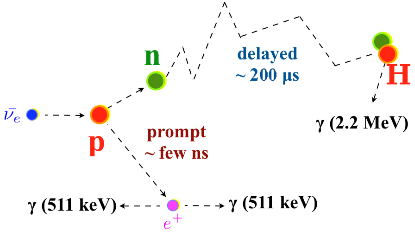

cker (TT)



# Cosmogenic background



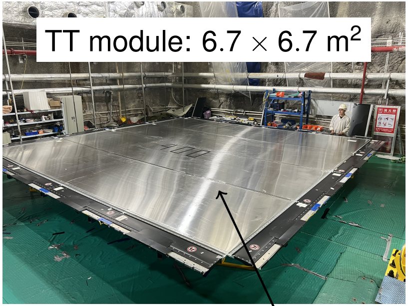

- Inverse Beta Decay (IBD) – ∼50/day in JUNO
  - Main channel to detect reactor antineutrinos

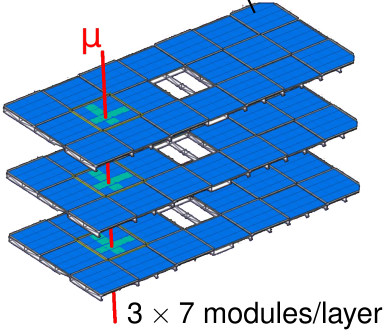



- Cosmogenic bkg. hard to distinguish from IBD
  - $^9$Li & $^8$He have decays with $e^- + n$
    - ∼60 ($^9$Li + $^8$He) per day
  - As IBD has prompt-delayed signature
  - Tagged using parent $\mu$
  - JUNO needs good muon tracking capabilities
- Fast-n can also be issue, but lower rate expected
  - Control it with good $\mu$ tracking outside CD

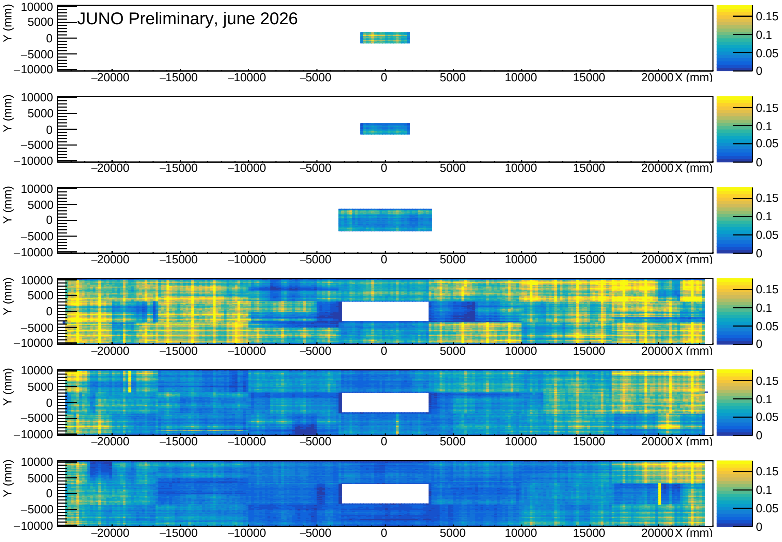
# JUNO Top Tracker (TT): Overview

- TT refurbished from OPERA Target Tracker
- 62 walls measuring $(6.7 \times 6.7)$ m$^2$ of plastic scintillator available
- Walls distributed in $3 \times 7$ horizontal grid in 3 layers $\rightarrow$ cover $\sim$ 60% of surface above WCD
- Upgrades realized on several systems: electronics, mechanical structure, ...



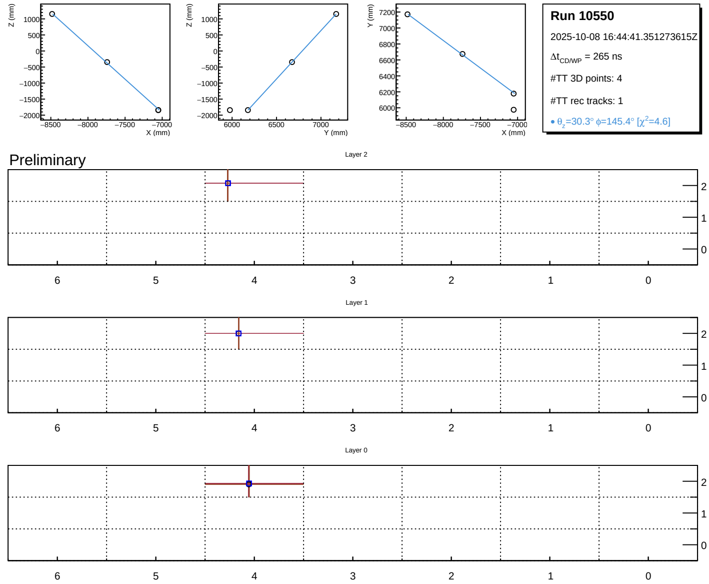



# Top Tracker status



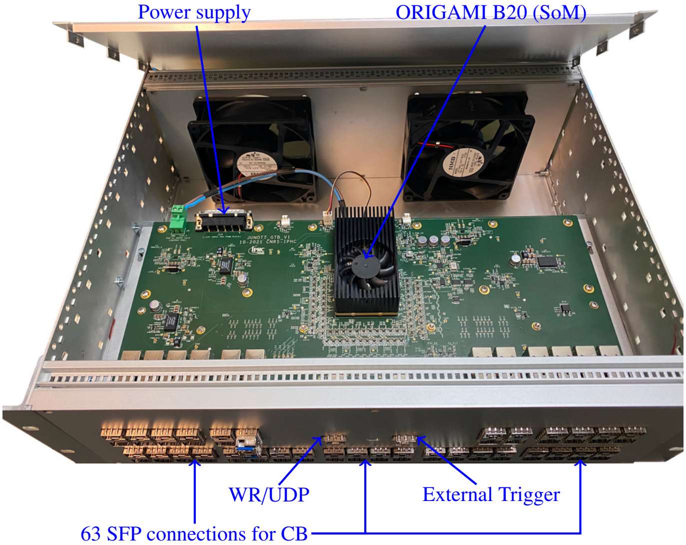

- Detector globally working well since August 2025
- Larger rates per strip @ top & sides: more exposed to rock radioactivity
- Some non-uniformity related to different aging of scintillator strips
- Total rate: $\sim$100 kHz
- $\mu$ rate: 1.7–1.8 Hz

# Example event from Top Tracker



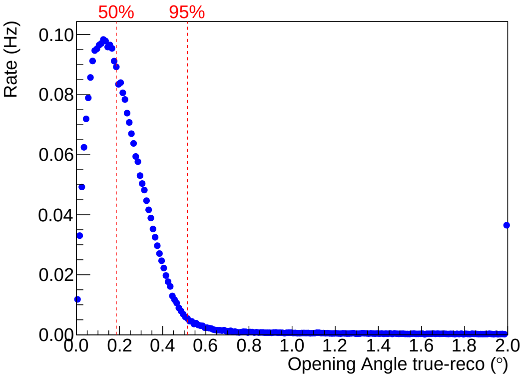

- Hits grouped in 300 ns time-windows to make 'event'
- Only few hits per event in most cases
- Reconstruct events by fitting line with 1 point/layer
  - Reject events with bad $\chi^2$: likely radioactivity
- Any missing PMT trigger $\rightarrow$ cannot reconstruct $\mu$
- Note: in this case has associated CD/WP trigger

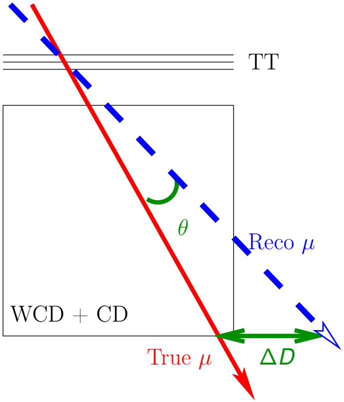
# Still missing working Global Trigger Board




- Function: check wall-triggers (L1) for alignment to reject radioactivity.
  - Reduce data rate (factor 20–400$\times$)
  - Reduce electronics deadtime from 10 $\mu$s $\rightarrow$ 1 $\mu$s on rejected events
- Hardware ready and onsite
- Firmware not ready yet
- Working to finalise this soon

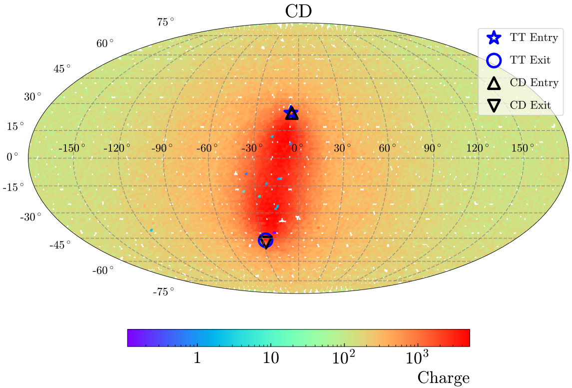
# TT $\mu$ reconstruction capabilities

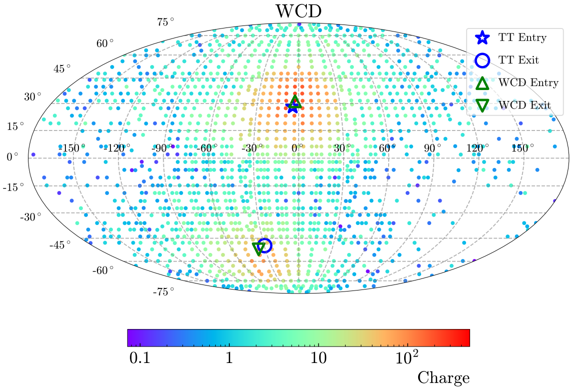



- Median resolution to track $\mu$ of 0.2° (from simulation)
- Projected to the bottom of WCD, corresponds to median $\Delta D = 20$ cm
- Excellent $\mu$ tracking capabilities to help veto $\mu$ and associated cosmogenics
- Also provides well reconstructed $\mu$ sample for CD + WCD tuning/calibration

# First verification of muon reconstruction performance



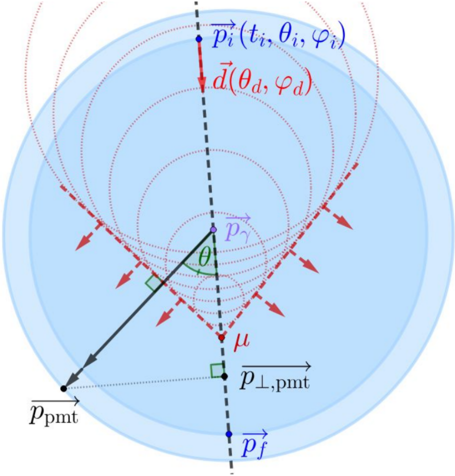

- Muons can be tracked crossing all sub-components of JUNO: TT, WCD, CD

# Muon reconstruction in JUNO: Traditional methods

See T. Raymond talk @ Blois 2026 and J. Wei, X. Lu poster @ Neutrino 2026

**Joint $\chi^2$**

- Minimize $\chi^2$ of first hit time in CD and WCD
- LS-Acrylic-Water boundary $\rightarrow$ needs correction
  - Use pre-computed tables to evaluate impact
  - Tables created assuming TT tracks are correct
- Final version can also include $\chi^2$ term from TT in fitting

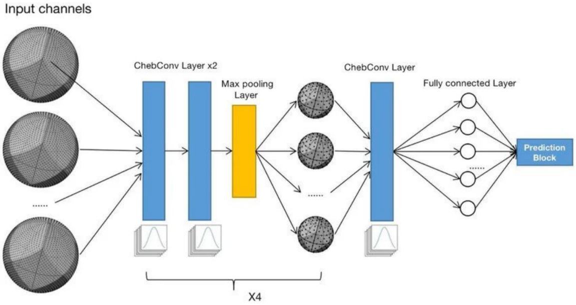


# Muon reconstruction in JUNO: Machine Learning based methods

See T. Raymond talk @ Blois 2026 and J. Wei, X. Lu poster @ Neutrino 2026

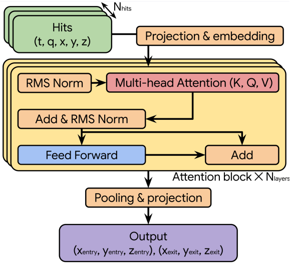
## Deep Sphere: EDWIN

- Use spherical graph CNN
- Features: charge, first hit time




## Transformer: AMBER

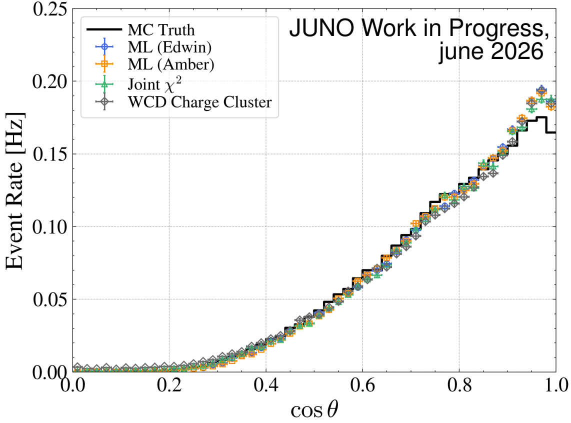
- Transformed based on self-attention mechanism
- Hit times & charges as input features

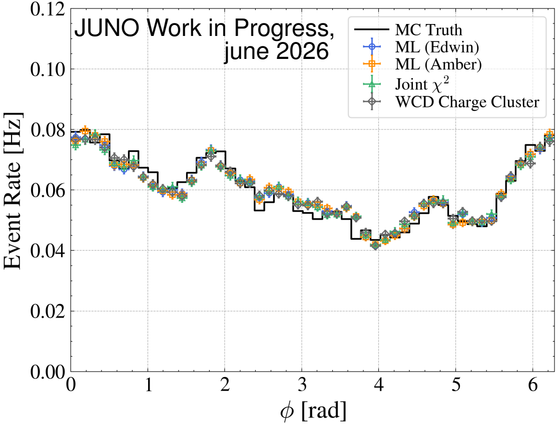



- In both cases: use TT-annotated data to train single-$\mu$ reconstruction
- Data is augmented by performing random rotations to compensate for TT limited size

# Reconstruction performance: angular distribution

See T. Raymond talk @ Blois 2026 and J. Wei, X. Lu poster @ Neutrino 2026

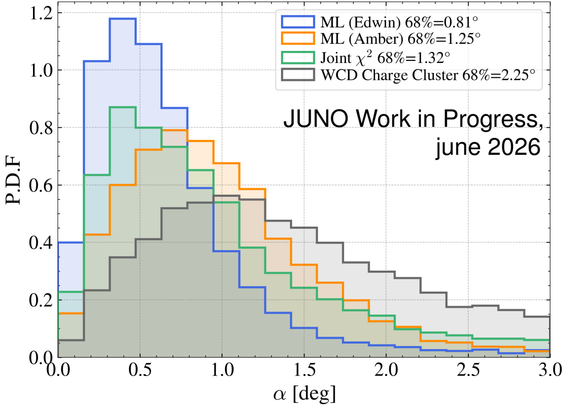


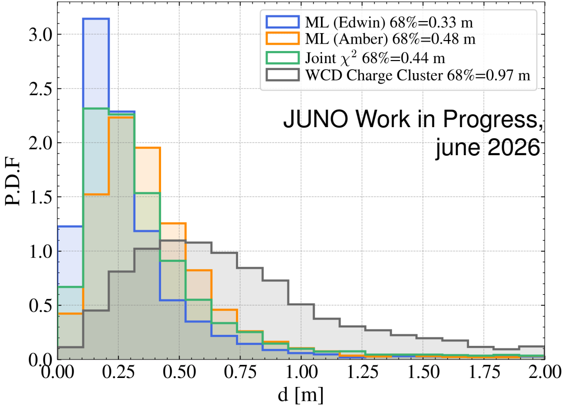




- Good overall agreement between μ direction from data and simulation
- Simulation strongly depends on mountain profile above JUNO
- Top Tracker cannot be compared here because limited angular coverage

# Reconstruction performance: comparing with TT tracks

See T. Raymond talk @ Blois 2026 and J. Wei, X. Lu poster @ Neutrino 2026

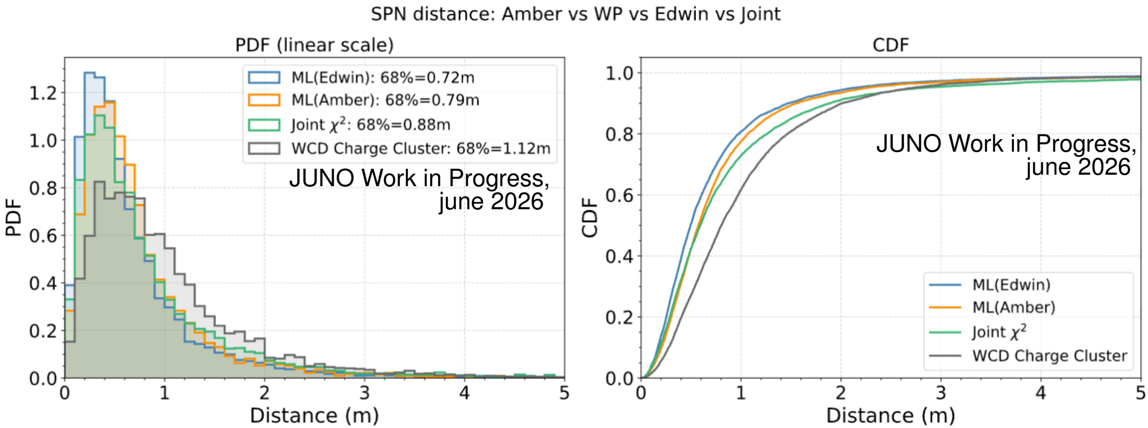



- Compare angle and distance between TT and CD/WCD muon reconstruction
- Good performance obtained from all methods; significantly better than charge cluster

# Reconstruction performance: spallation neutron rejection

See T. Raymond talk @ Blois 2026 and J. Wei, X. Lu poster @ Neutrino 2026



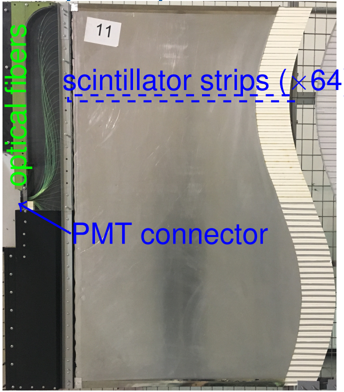

- EDWIN & AMBER used for latest oscillation results to reject cosmogenic $^{9}Li/^{8}He$
- In oscillation analysis $1.41 \pm 0.26$ cpd of $^{9}Li/^{8}He$ (post fit)

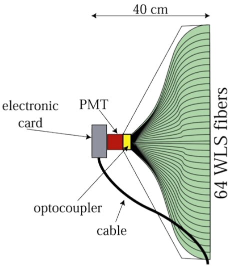
# Summary

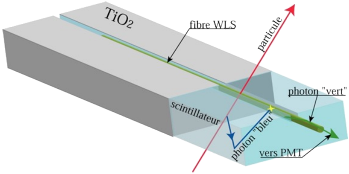
- Top Tracker installed and operating in JUNO
  - All modules working properly
  - Muon rate: 1.7–1.8 Hz
  - Finalizing Global Trigger Board firmware
    - Reject online radioactivity – reduce deadtime
    - Likely reason for some of missing $\mu$ rate @ TT
  - Planning to estimate radioactivity rate in surrounding rock using TT data
- Top Tracker already being used for $\mu$ tracking
  - 1 classical $\mu$ reconstruction uses corrections from TT data
  - 2 ML-based $\mu$ reconstructions trained using TT data
  - Very good performance from these 3 reconstructions!
  - Currently already being used for rejecting $^{9}$Li/$^{8}$He!

# Backup

# Detection principle

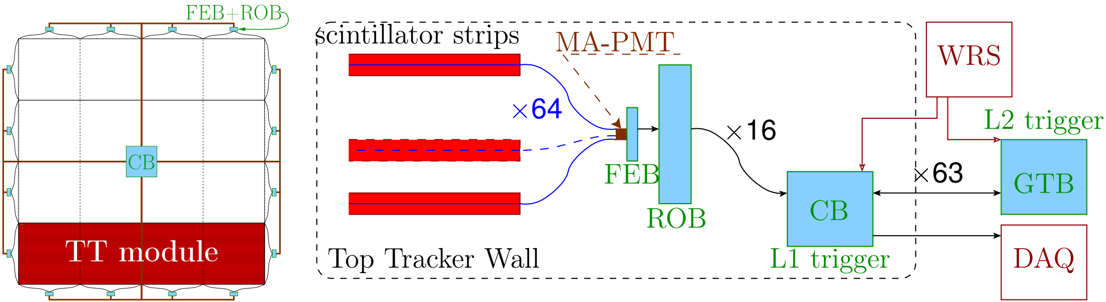



- Charged particle crosses scintillator strip $\rightarrow$ scintillation light
- Light captured by optical fibers and guided to MA-PMT
- Signal from PMT processed by electronics

# TT Electronics: Schematic View




Front-End Board (FEB): PMT interface and part of the PMT readout.

Read-Out Board (ROB): slow control, power supply, and finish PMT readout.

Concentrator Board (CB): gathers hits related to each wall, and create L1 trigger. Also time-stamps of all hits with a nanosecond precision.

Global Trigger Board (GTB): combine information of all L1 triggers from CB and produce a L2 trigger.

# L1 and L2 trigger views