Review of Accelerator based Short-Baseline Neutrino oscillation searches

DBD23
International Workshop on “Double Beta Decay and Underground Science”
Dec 1st-3rd, 2023

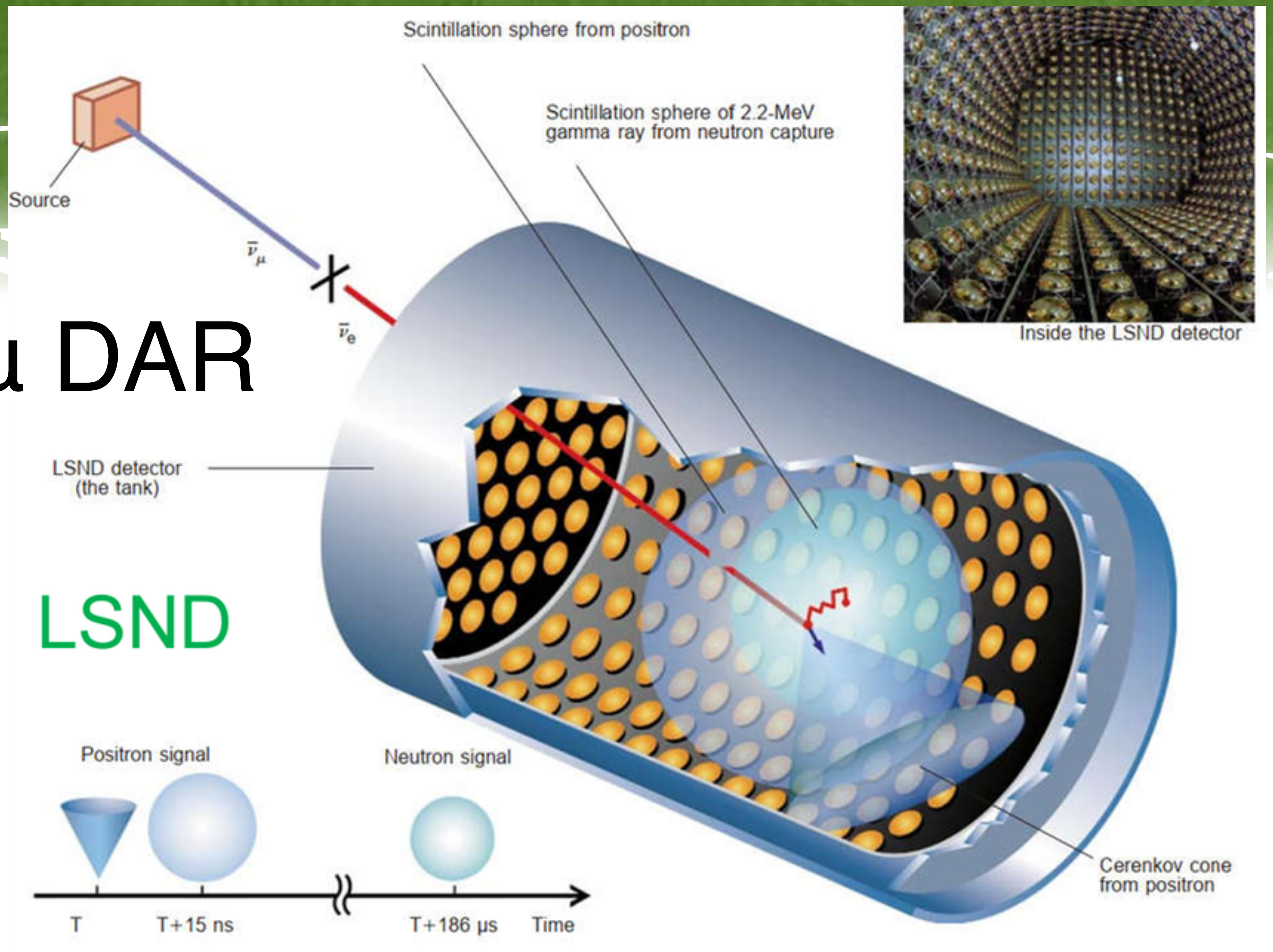
Dongha Lee, KEK

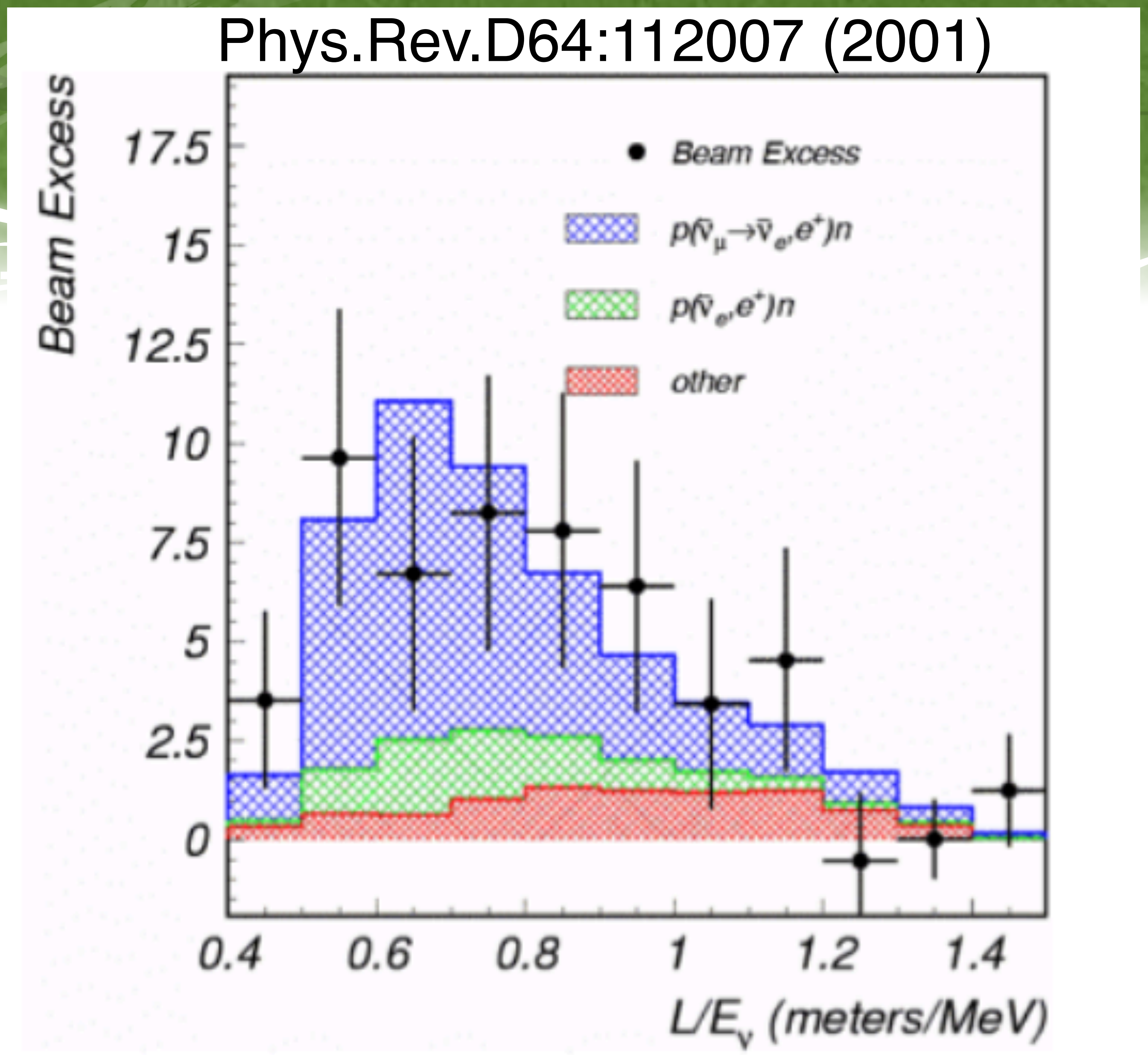
Indication of a sterile neutrino

Anomalies, which cannot be explained by standard neutrino oscillations for a few tens years are shown.

Experiments	Neutrino source	signal	significance	E(MeV),L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	4.5σ	800,600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ	
		combined	4.7σ	
BEST (Ga)	e capture	$\nu_e \rightarrow \nu_x$	$\sim 4.0\sigma$	<3,10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3,10-100

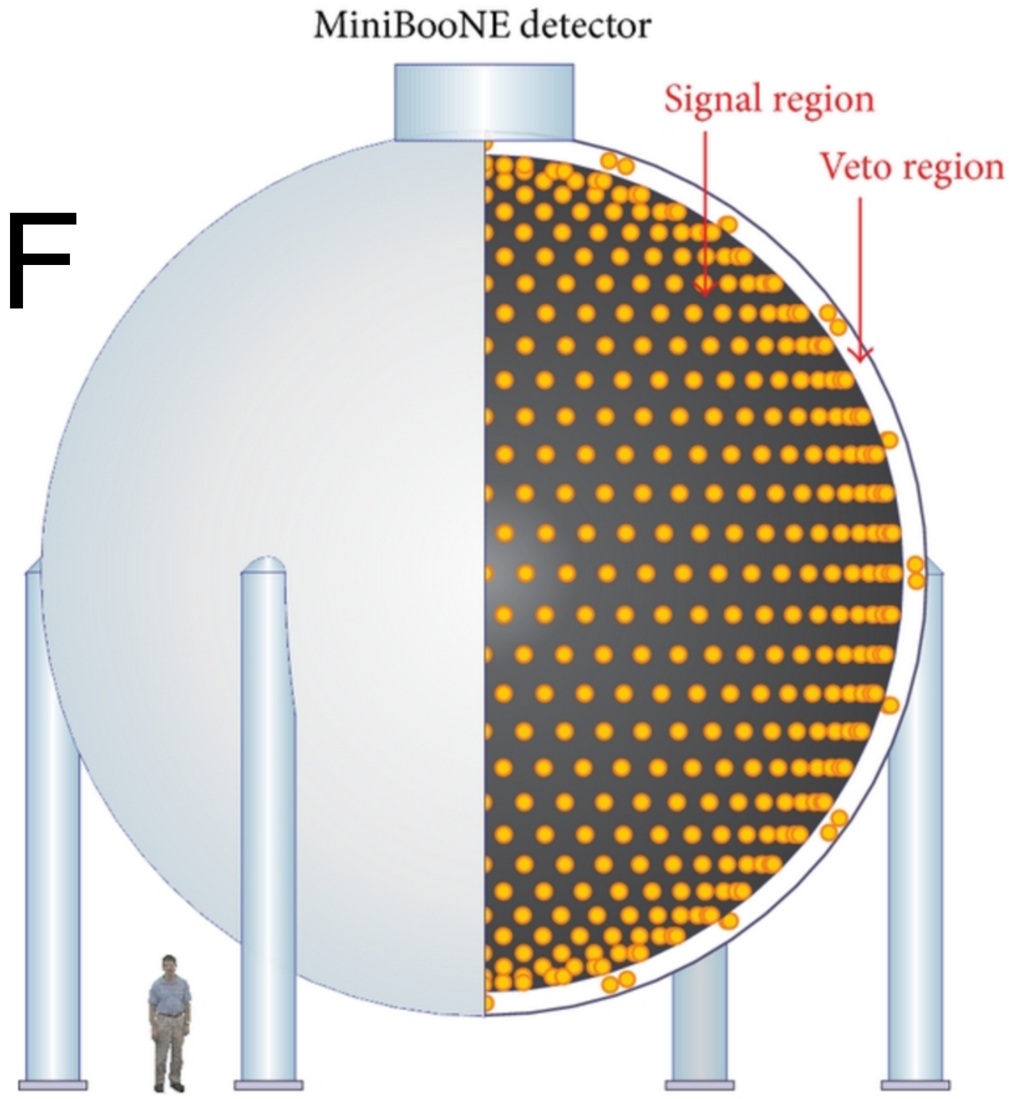
μ DAR

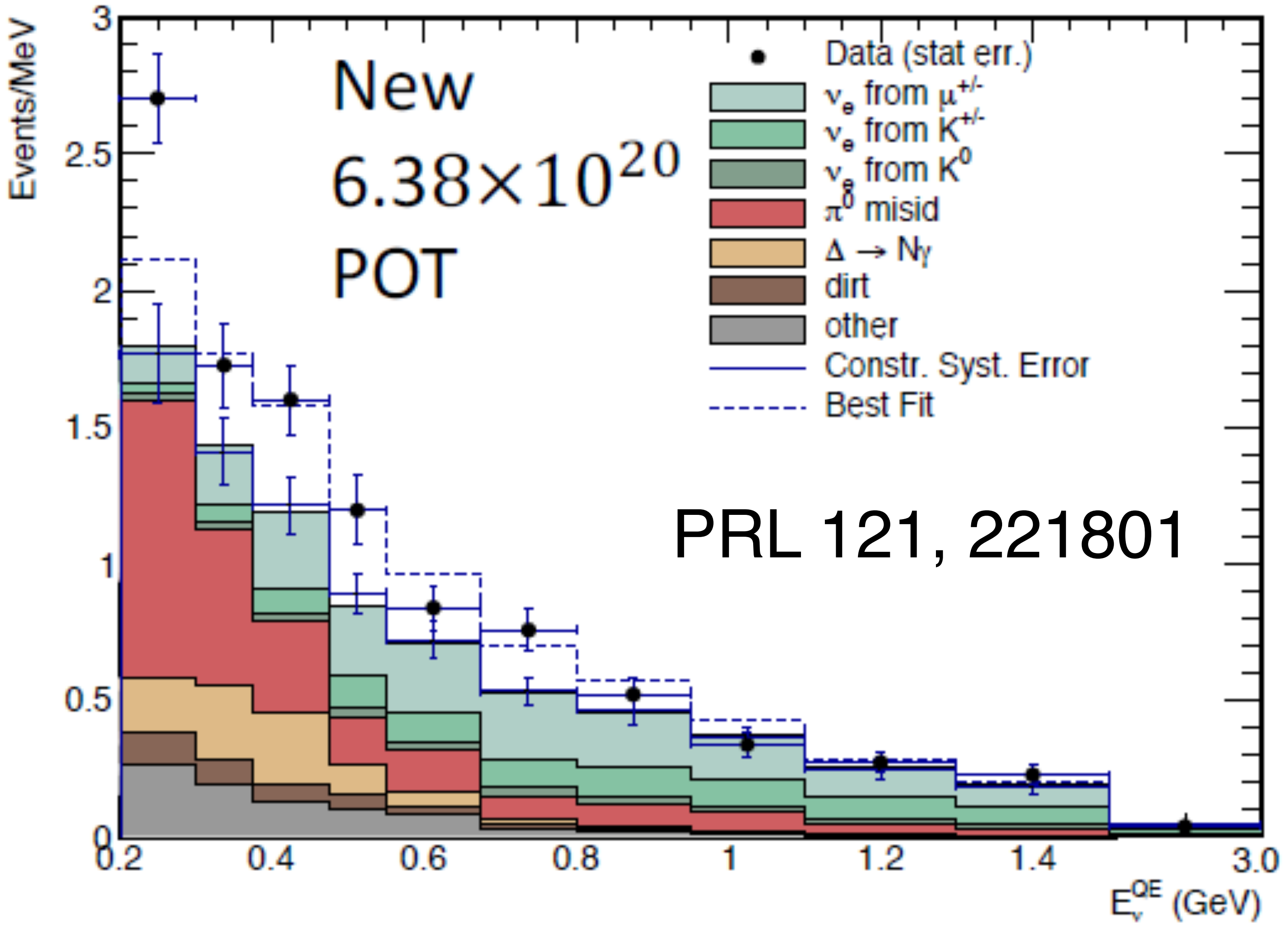




LSND
3.8sigma
$\bar{\nu}_e$ excess

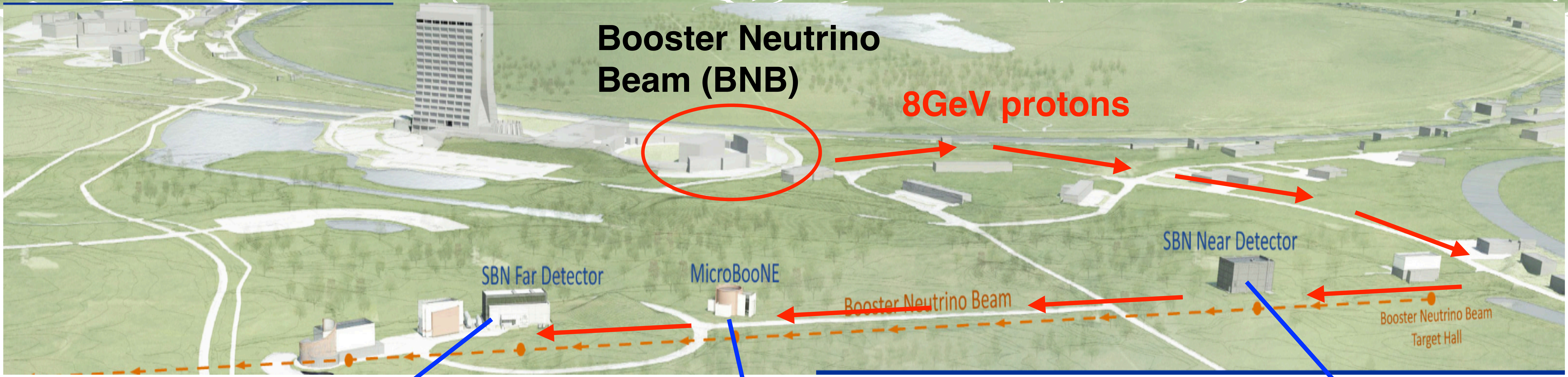
π DIF

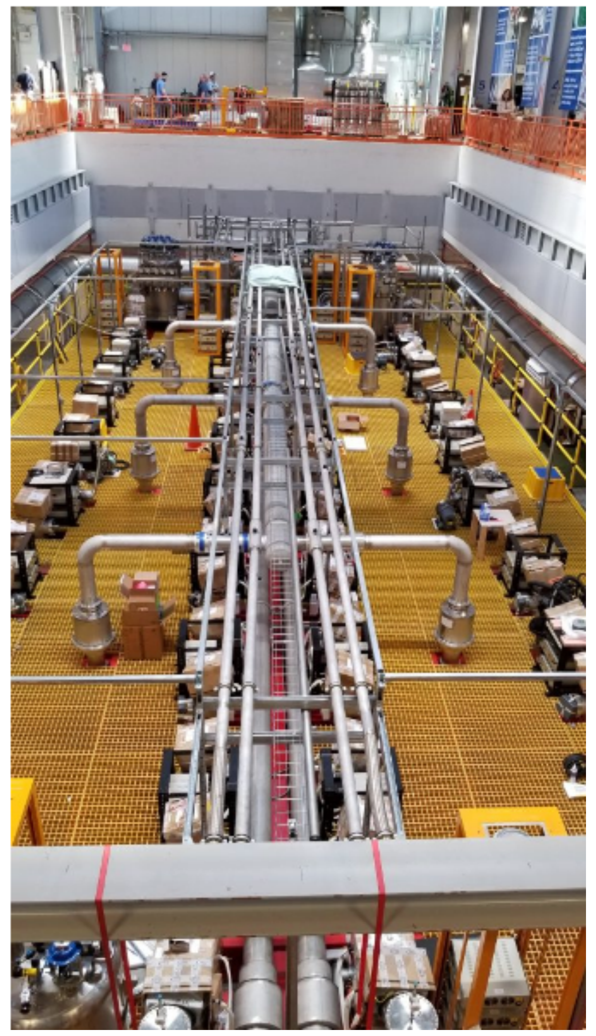




MiniBooNE
4.5sigma
ν_e excess

Short-Baseline Neutrino (SBN) program





ICARUS
476ton
LArTPC

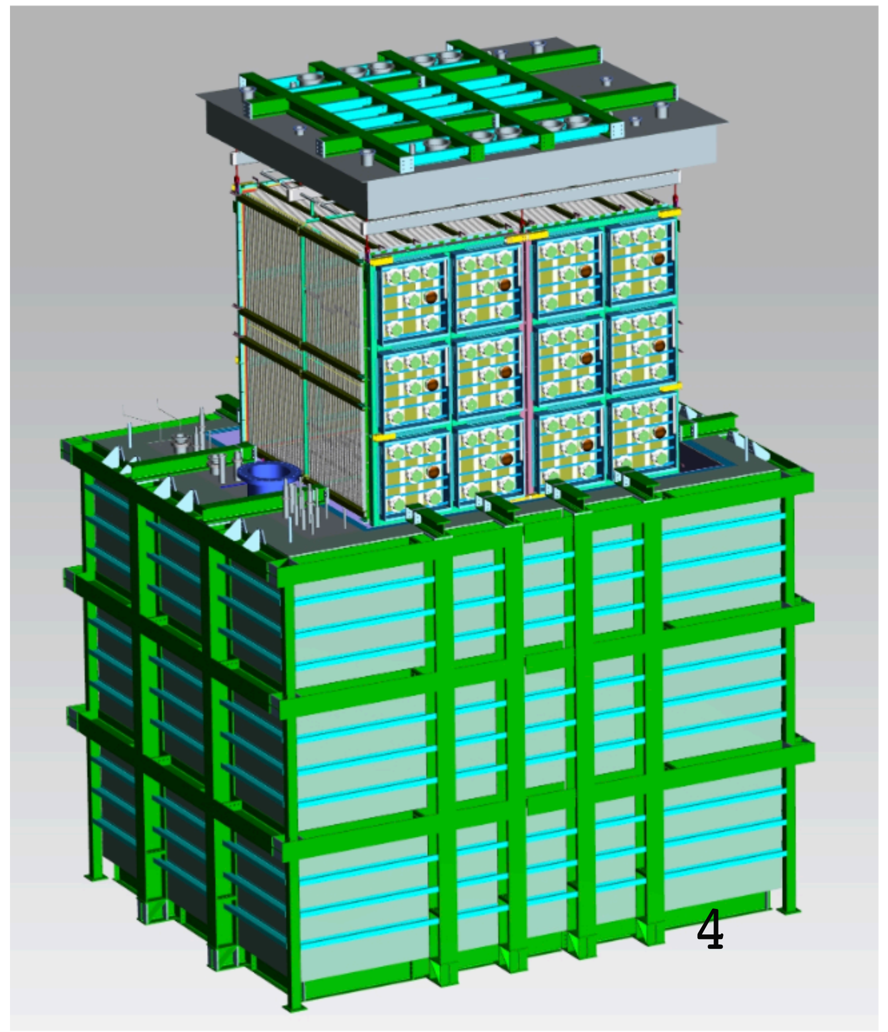
Operation
2022 Summer~

MicroBooNE
89ton
LArTPC

Data taking
2015-2021

Near Detector
112ton
LArTPC

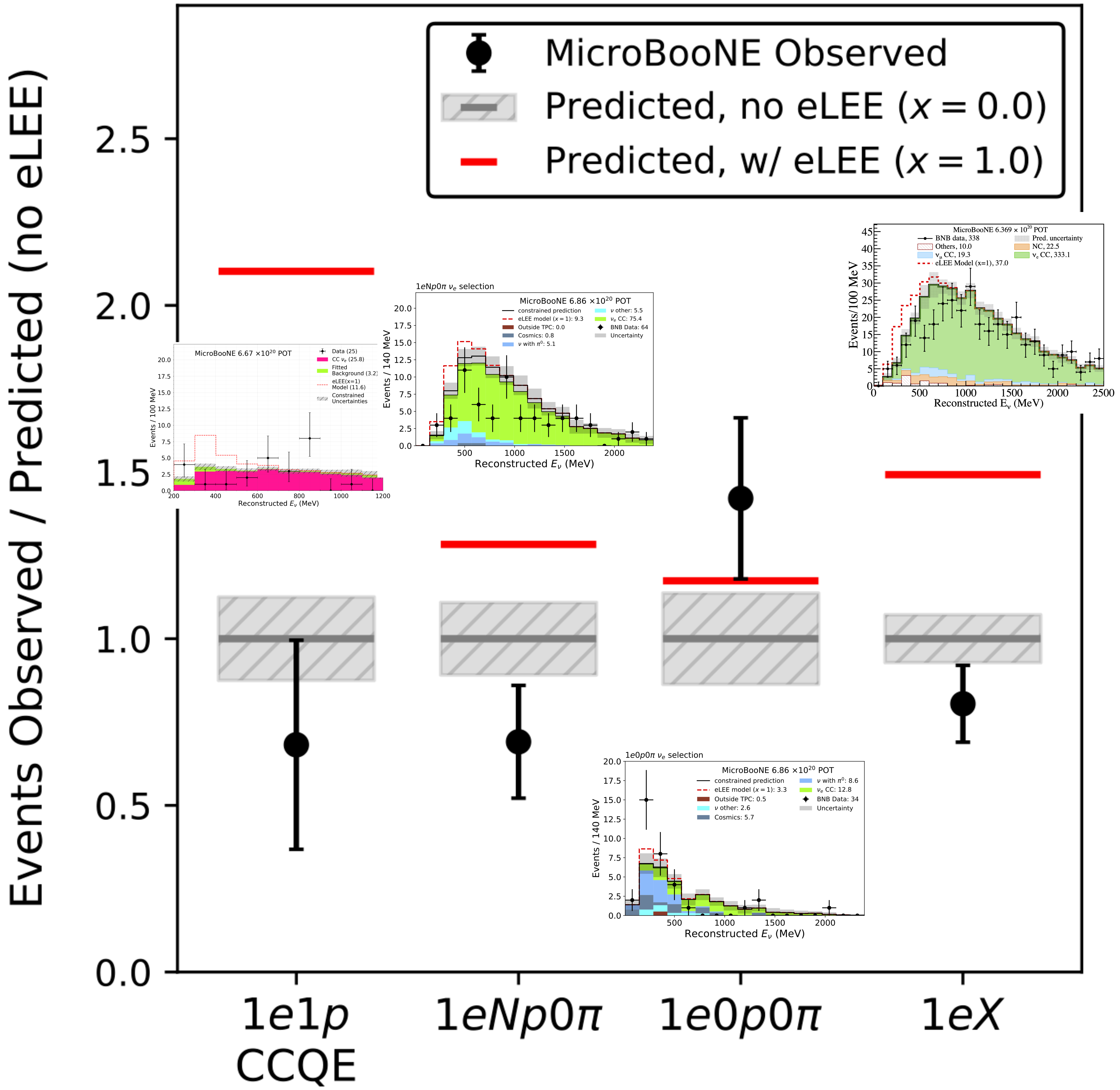
Anticipate
to begin
2023~

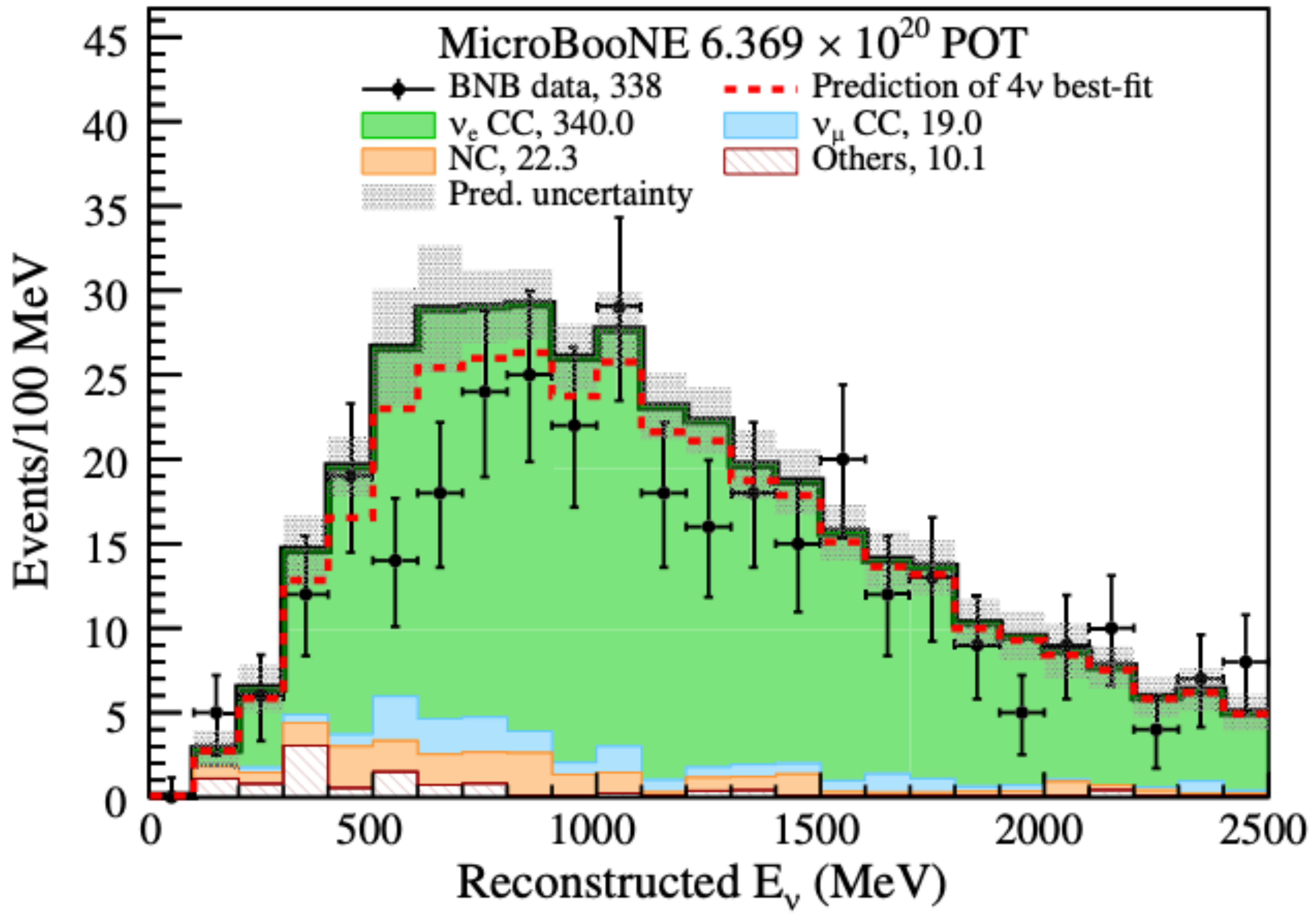


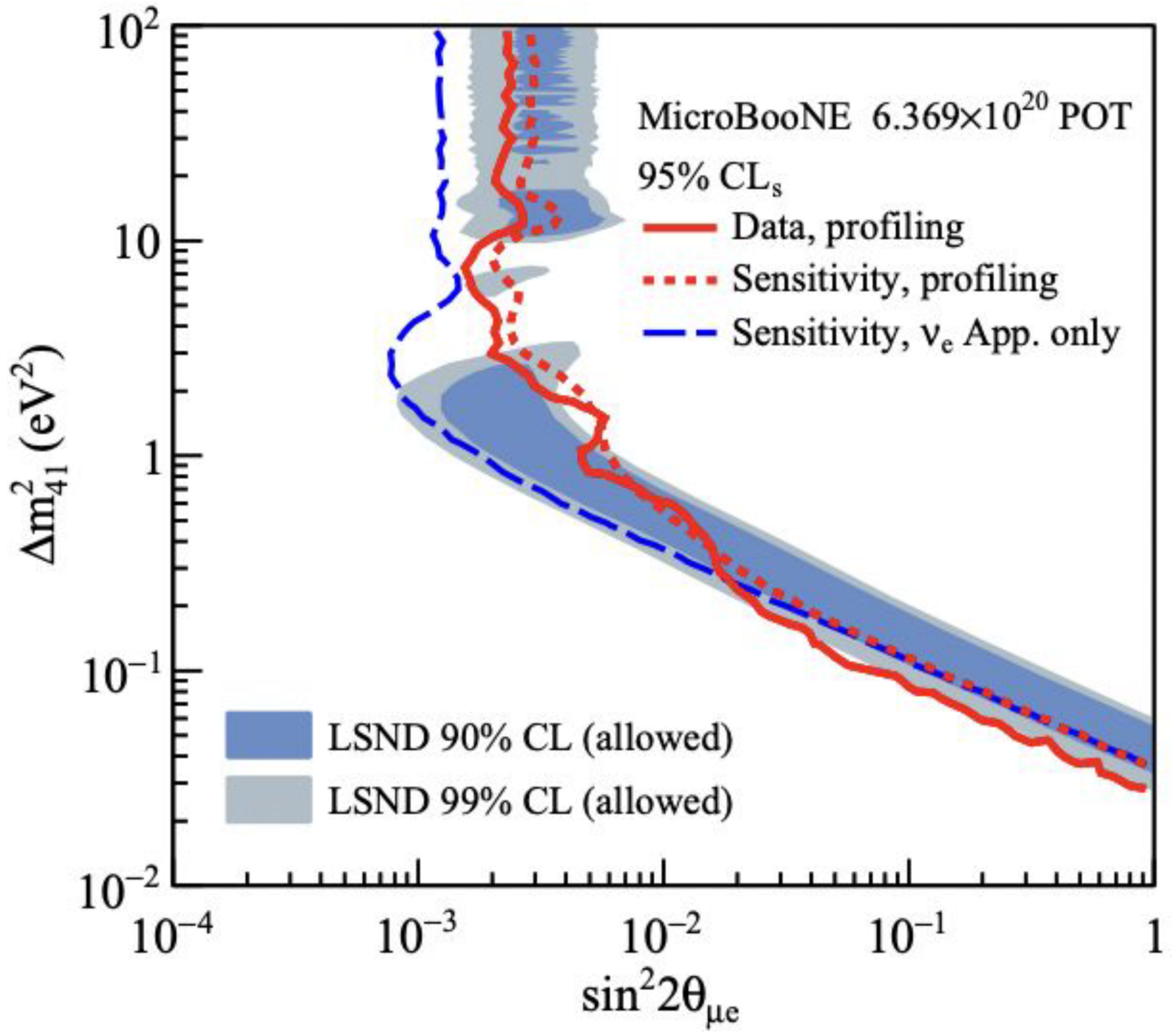
MicroBooNE results so far

- They put **89t fiducial LAr detector** at the neighborhood site of MiniBooNE
- Data taking 2015-2021
- eLEE search
  => **No excess is observed (right plots)**
- 3+1 Oscillation Analysis
  => **Exclude part of LSND allowed region (below plots)**

Phys. Rev. Lett. 128. 241801

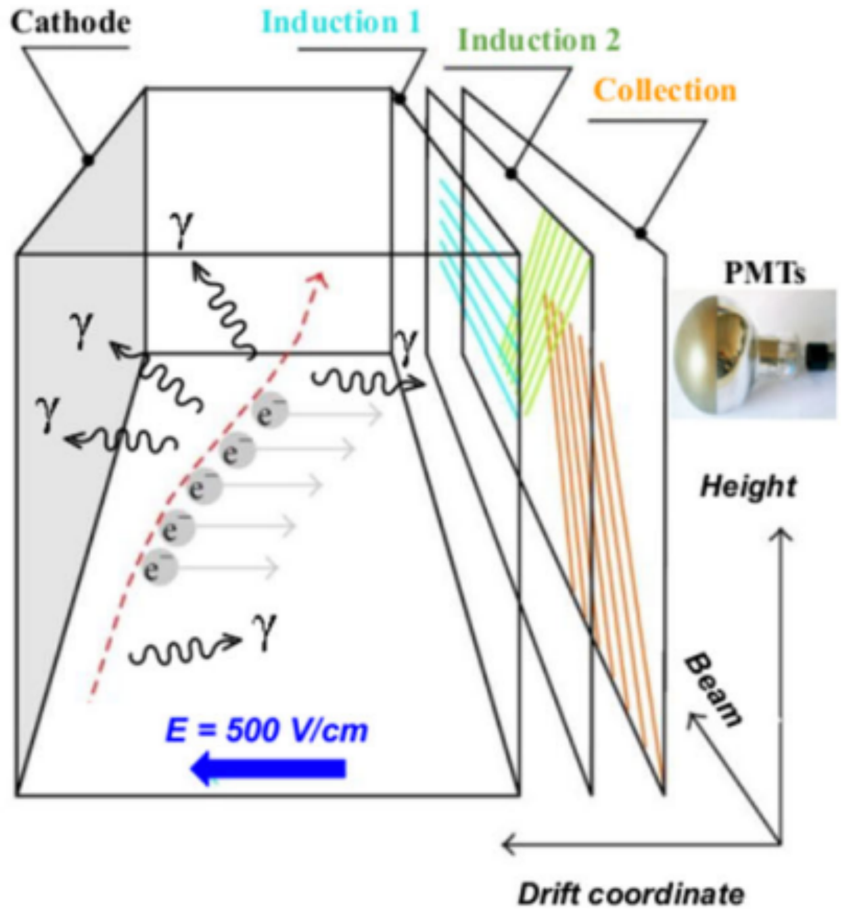






Phys. Rev. Lett. 130.011801

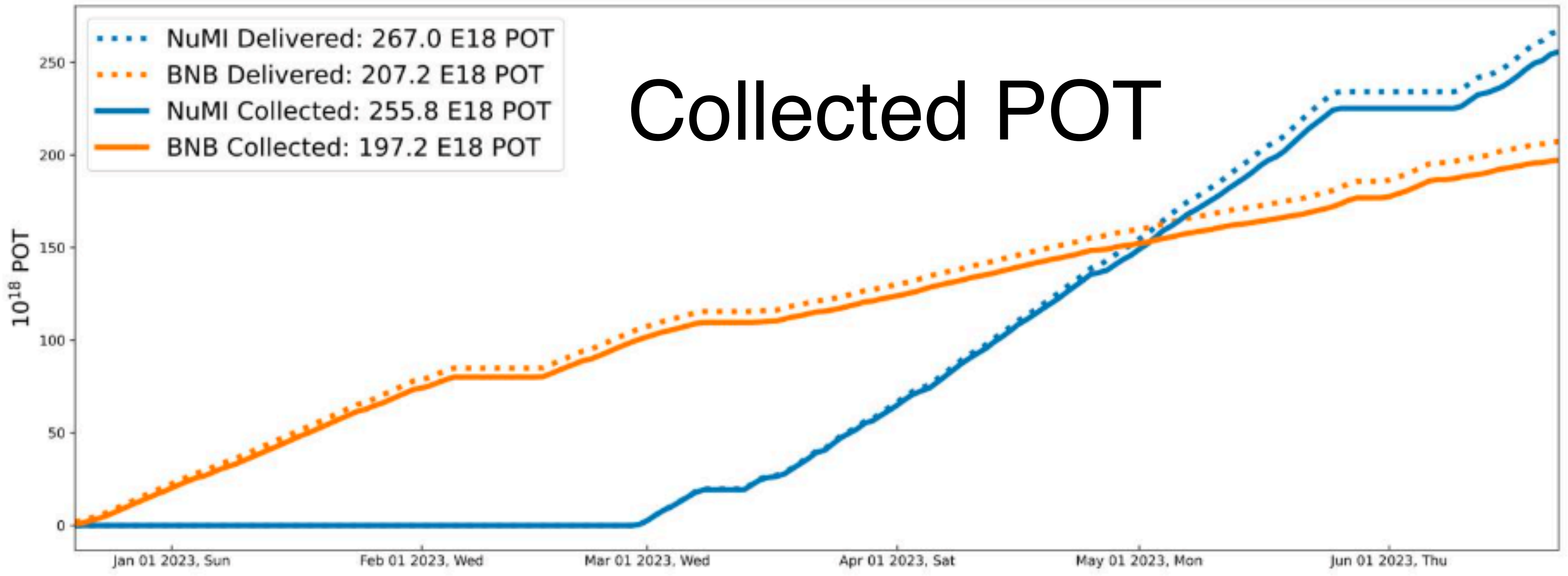
Status of ICARUS



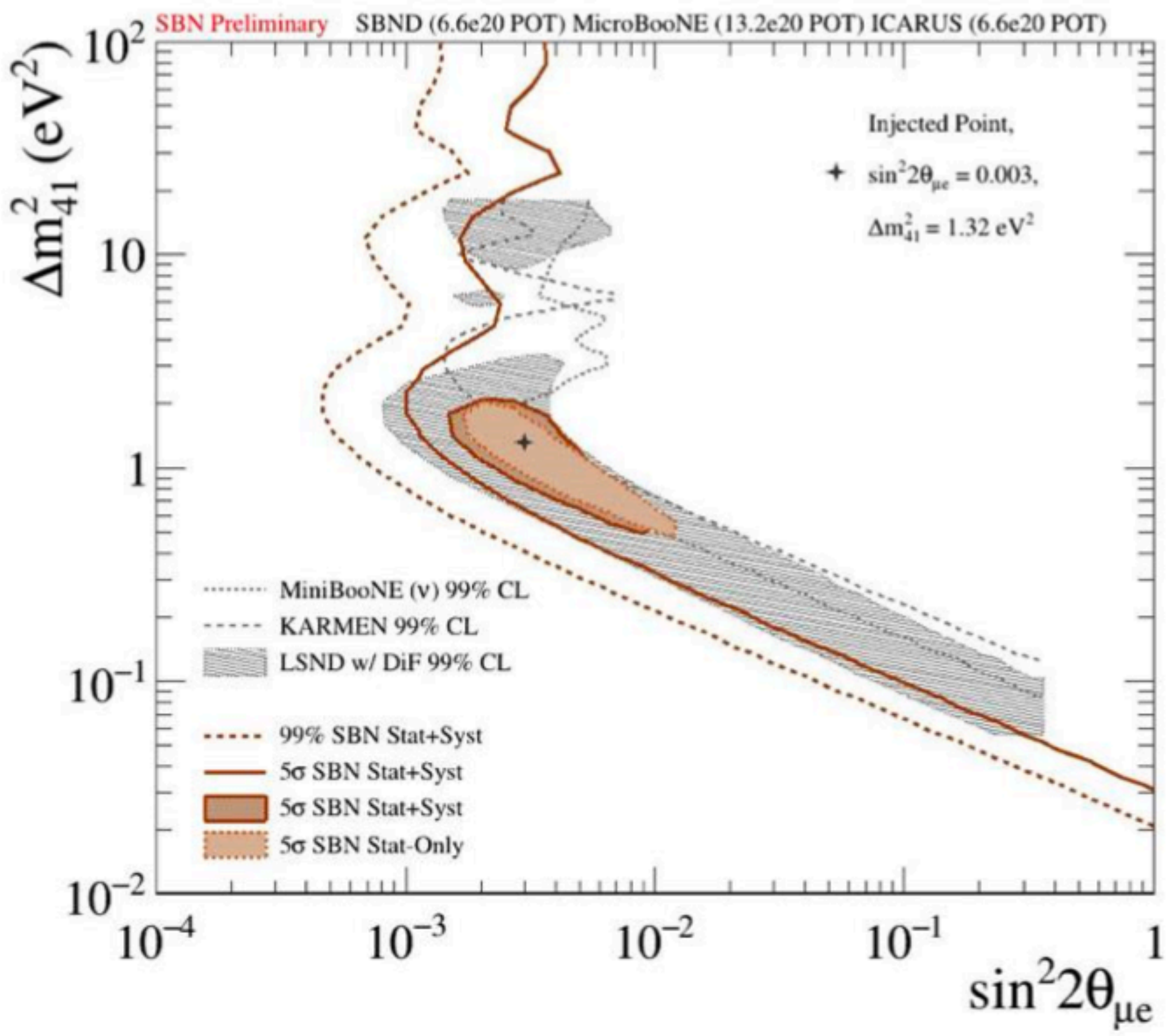
Eur.Phys.J.C 83 (2023) 6, 467

- ~600m from BNB, 476ton LArTPC
- First detector operation : 2022 Summer~

- Initial data has been used to perform detector physics measurements relevant for future LArTPC experiments



ν_e appearance

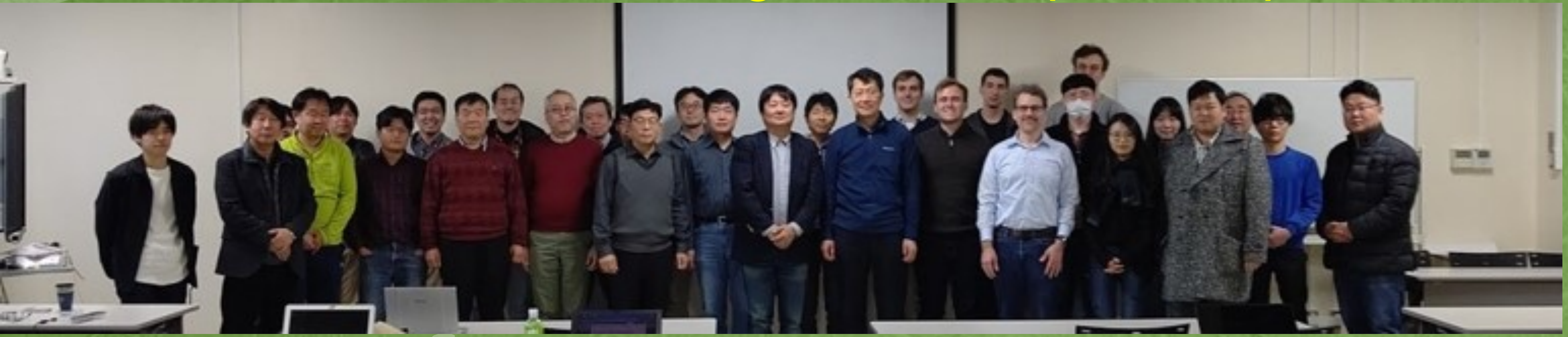


- Joint analysis for neutrino oscillation with SBND and MicroBooNE will be performed

JSNS^2 / JSNS^2-II Experiments

Direct test of LSND

Collaboration meeting @ J-PARC (2020/Feb)



JSNS^2 collaboration (~60 collaborators)

- 7 Japanese institutions (27 members)
- 10 Korean institutions (25 members)
- 1 UK institution (1 member)
- 3 US institutions (5 members)
- 1 China institution (3 members)

JAEA
KEK
Kitasato
Kyoto Sangyo
Osaka
Tohoku
Tsukuba

Chonnam National
Jeonbuk National
Dongshin
GIST
Kyungbook
Kyung Hee
Seoyeong
Soongsil
Sungkyunkwan
Seoul National of sci and tech

BNL
Florida
Michigan
Utah

Sussex

Sun Yat-sen
(Zhongshan)

Spokesperson: T.Maruyama (KEK)
Co-spokesperson: S.B.Kim (Sun Yat-sen)

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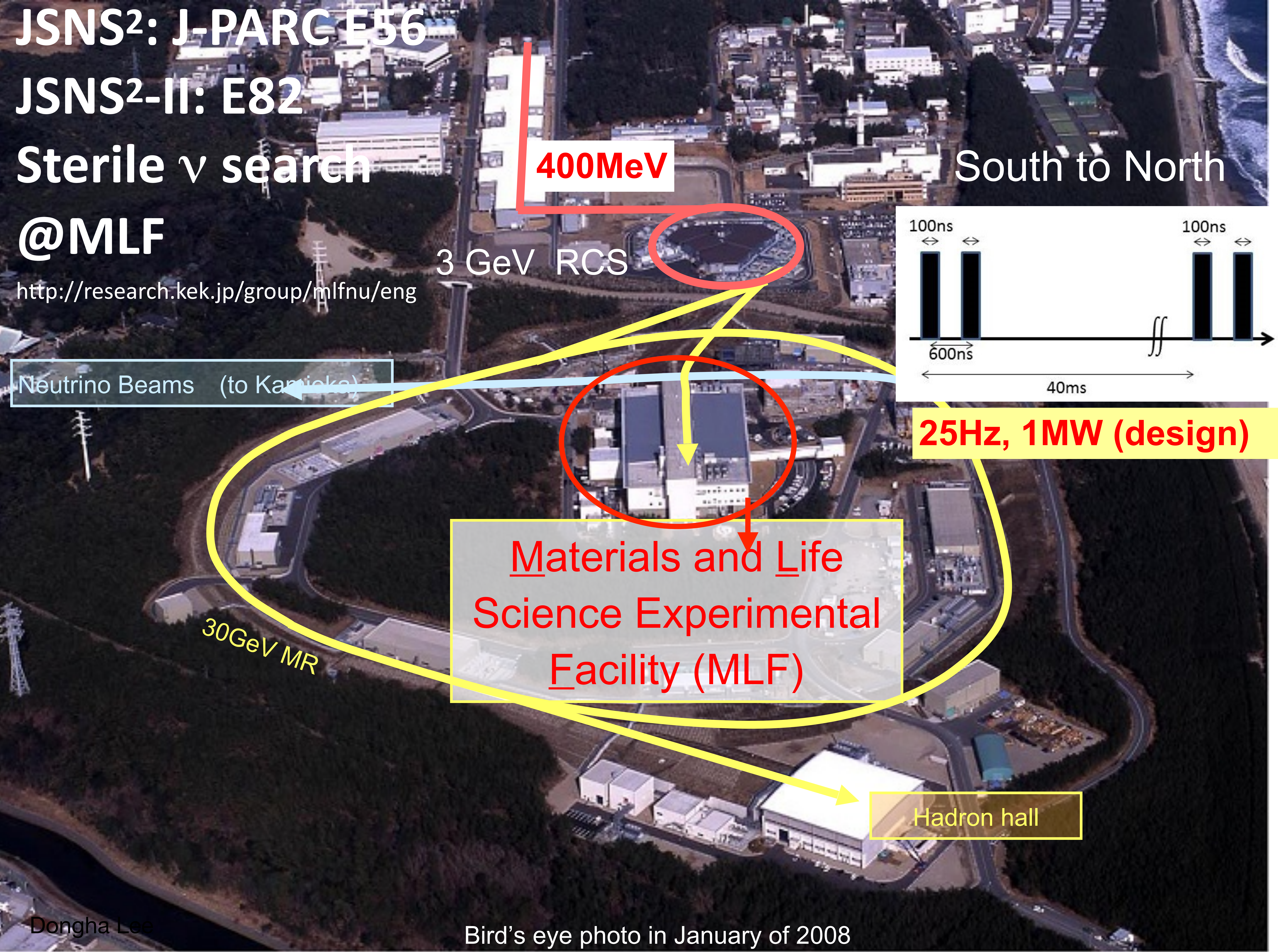
We aim to have a direct test for this

JSNS[2] uses the same neutron source(μ), target(H) and the detection principle (IBD) as the LSND.
=> Even if the excess is not due to the oscillation, we can catch this directly.
=> Two advantages : short-pulsed beam / Gd-LS give excellent S/N ratio.

JSNS^2: J-PARC E56
JSNS^2-II: E82
Sterile ν search @MLF

http://research.kek.jp/group/mlfnu/eng



25Hz, 1MW (design)

Bird's eye photo in January of 2008

J-PARC Facility (KEK/JAEA)

Low duty factor beam (short pulse + small repetition rate) gives excellent S/N ratio.

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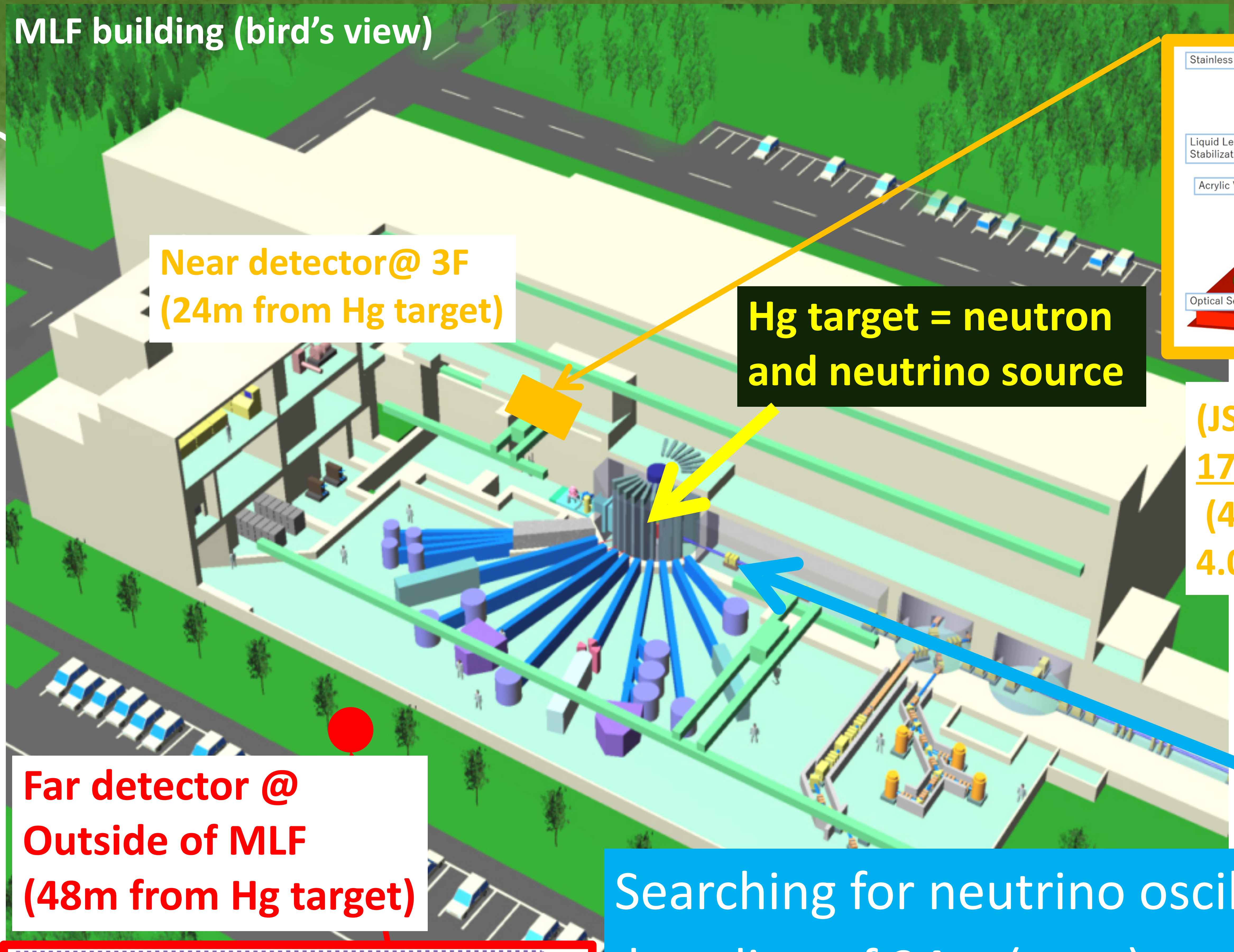
JSNS² / JSNS²-II : Sterile Neutrino Search

MLF building (bird's view)

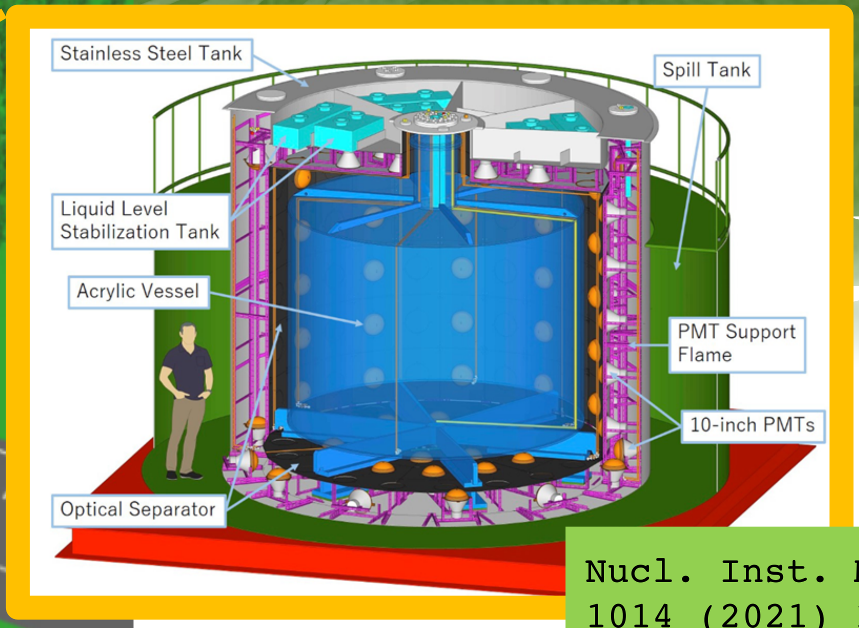


Near detector@ 3F
(24m from Hg target)

Hg target = neutron and neutrino source

Far detector @ Outside of MLF (48m from Hg target)

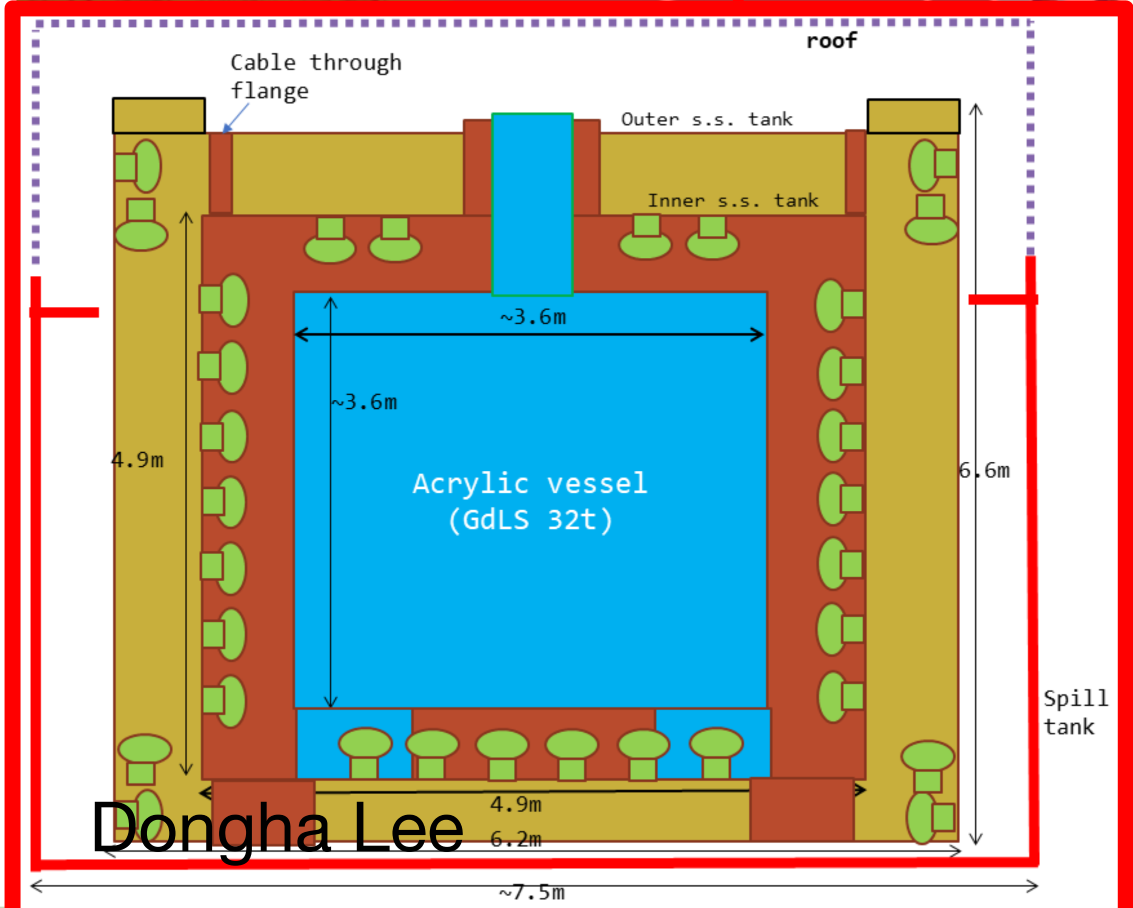
3GeV short pulsed beam



Nucl. Inst. Meth. A 1014 (2021) 165742

(JSNS2-I, JSNS²-II near detector
17t GdLS fiducial (target)
(4.6m diameter x
4.0m height, 120 10" PMTs)

Searching for neutrino oscillation : $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with baseline of 24m (near), and 48m (far detector)



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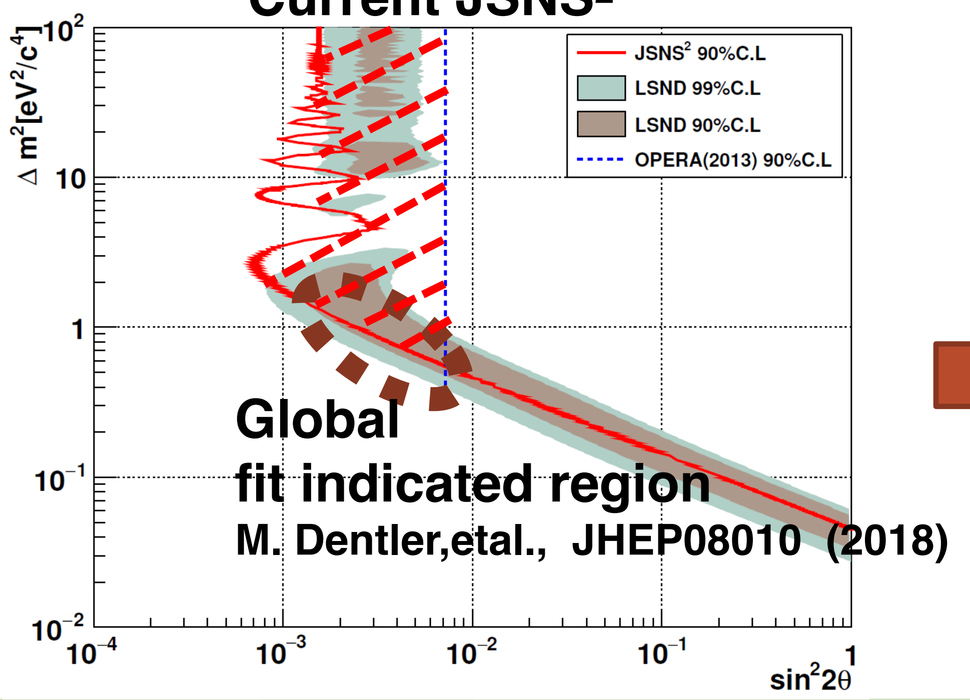
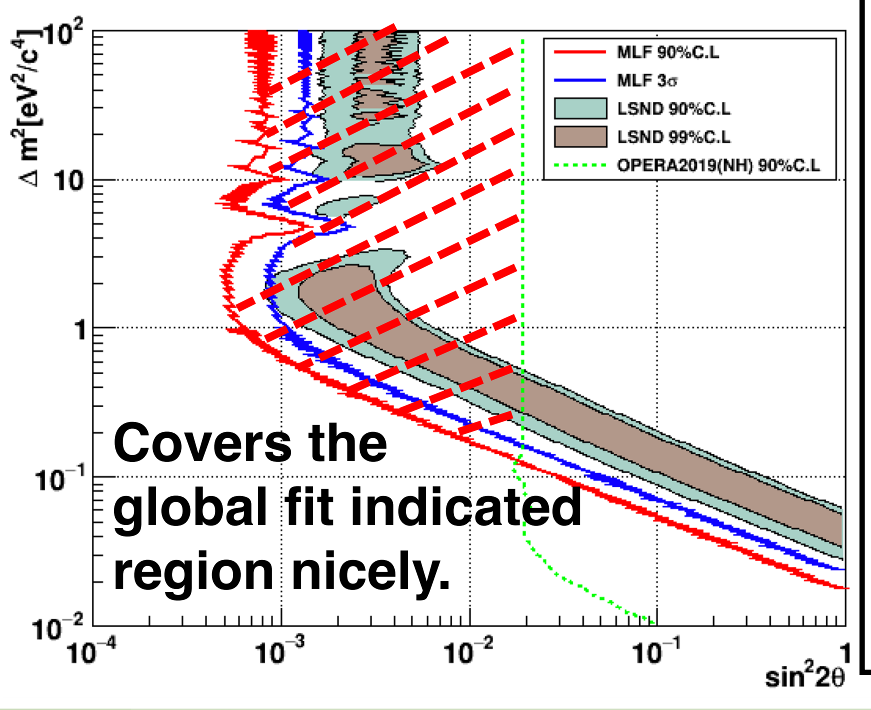
(JSNS²-II:
Far detector)
32t GdLS
(6.2m dia x
6.2m (h)
~228 10"
PMTs)

Current JSNS²



Global fit indicated region
M. Dentler,etal., JHEP08010 (2018)

JSNS²-II



Covers the global fit indicated region nicely.

JSNS²-I : 1MW x 3years (near only)
- commissioning (2020) :
  Eur. Phys. J. C (2022) 82:331
- 1st/2nd/3rd long physics run (2021,2022,2023)
  -> Smooth data taking
- 4th long physics run will be started from 2023 Dec

JSNS²-II : 1MW x 5years (near + far)
- Proposal (2020) : arXiv:2012.10807
- New far detector :
  32tons, 48m baseline
- Two detectors with different baselines
  -> Good sensitivity on low Δm^2 region (a solid conclusion on LSND anomaly)
- J-PARC/KEK granted the stage-2 (out of 2) status

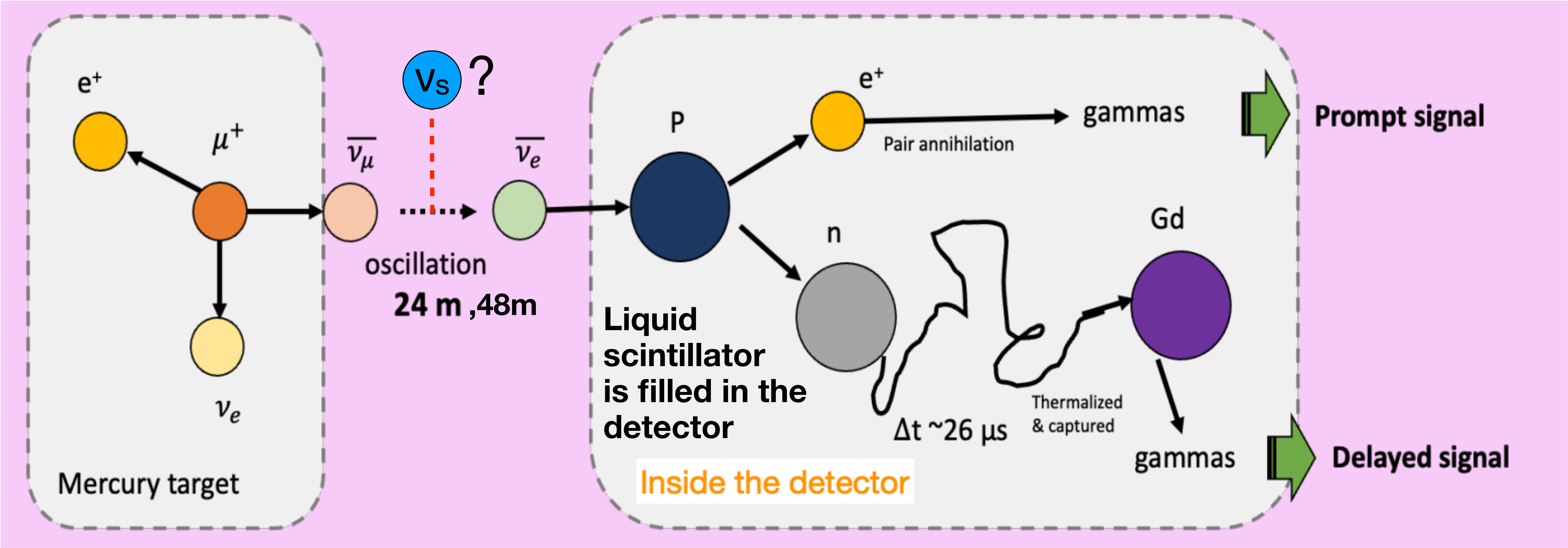
Strategy to search a sterile neutrino

Sterile neutrino oscillation during 24m,48m baseline.

Detection by coincidence of IBD (Inverse Beta Decay)
-> Prompt : e+ signal
-> Delayed : gammas from neutron capture on gadolinium (Gd)

	Timing	Energy
Prompt	2 ~10μs from beam	20~60 MeV
Delayed	$\Delta T_{p\text{-}d}$ <100μs	7~12 MeV

+ Spatial correlation cut
$\Delta VTX_{p\text{-}d} < 60$cm



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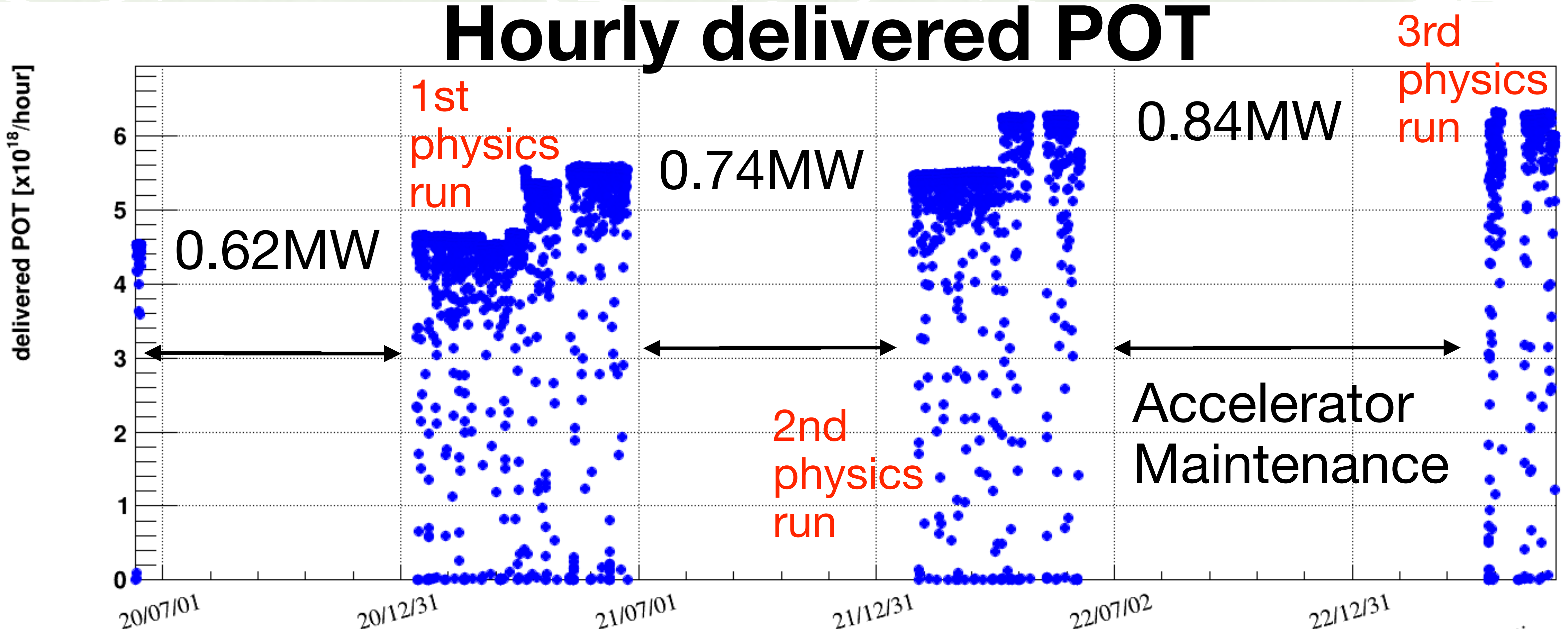
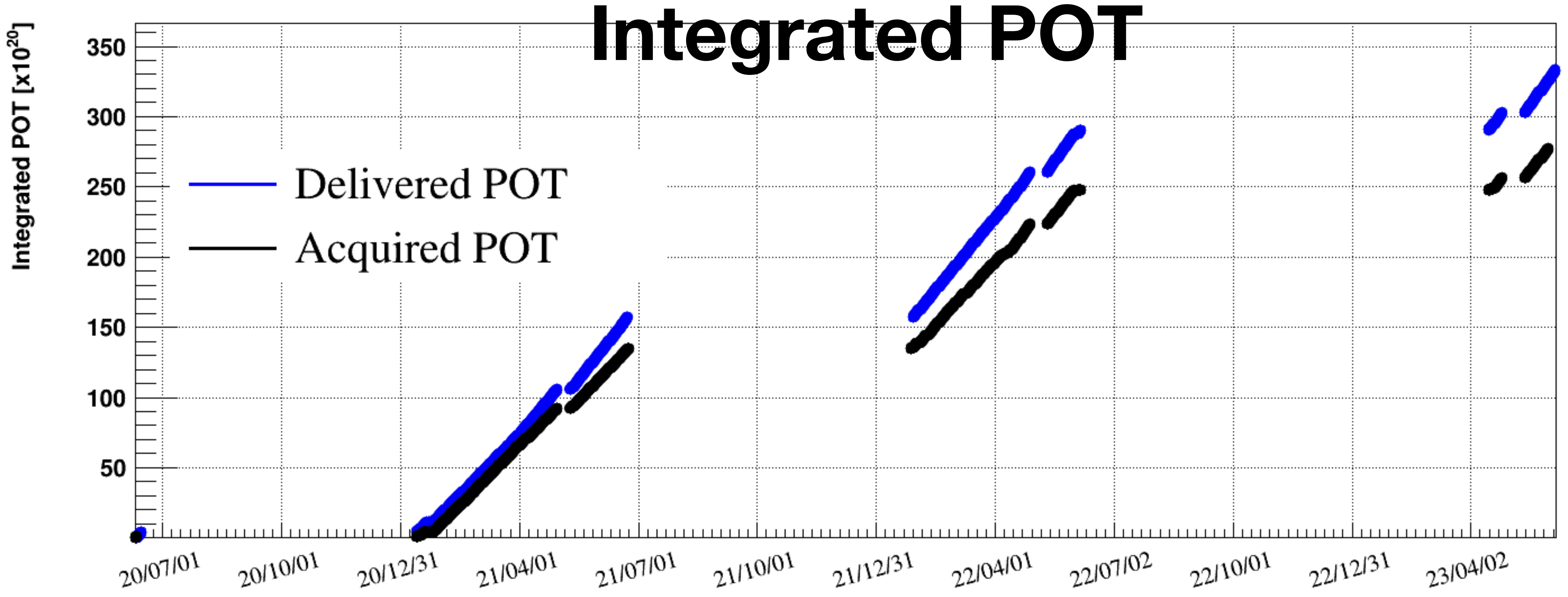
Operation of Near Detector

- Beam Power is **950kW from 2023 Spring** at exit point of RCS (design : 1MW)

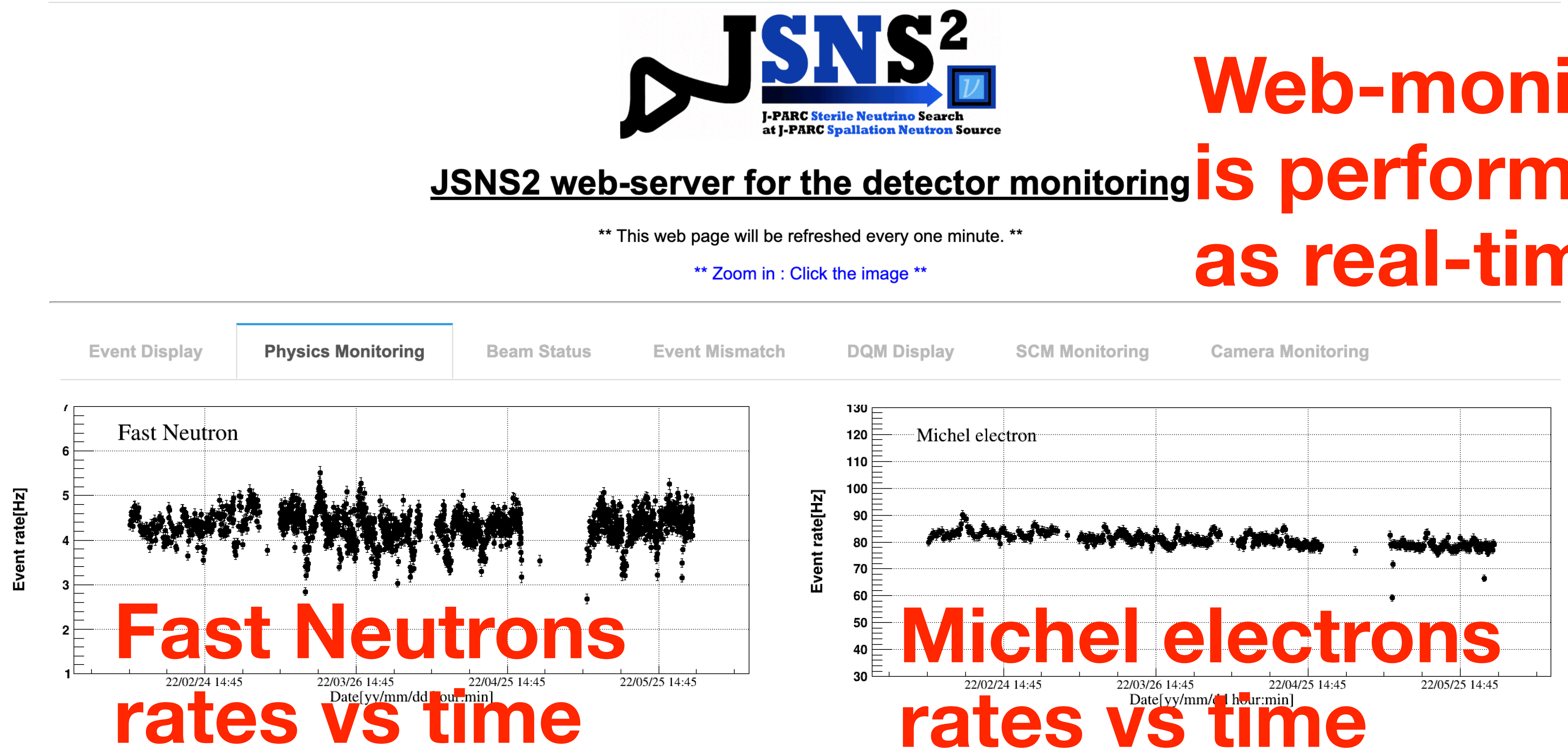
- Smooth data taking so far

- There is an accelerator maintenance in summer every year





Delivered POT so far : 3.28×10^{22}
(28.7% of approved POT(3y) for JSNS²)



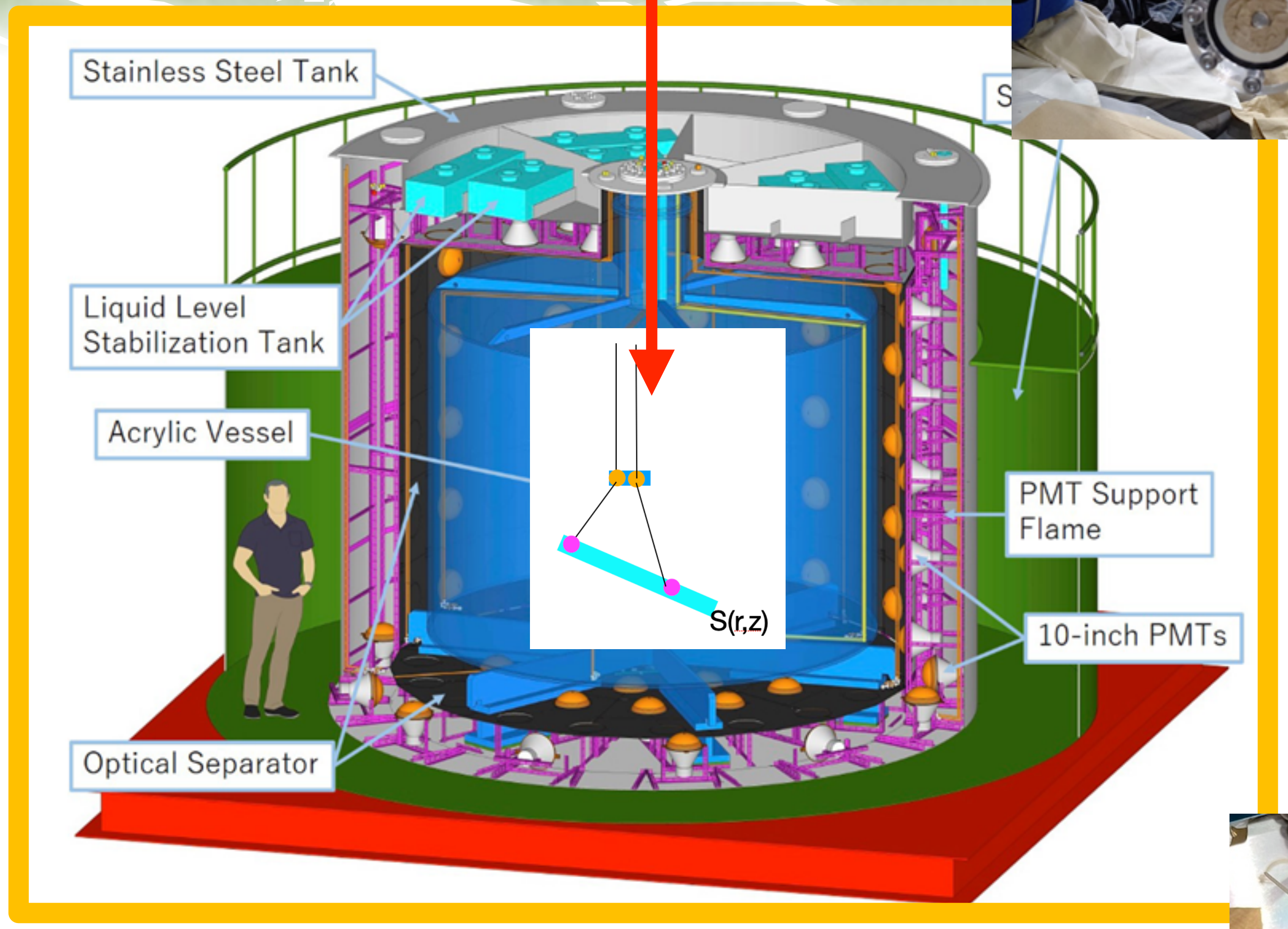
Web-monitoring is performed as real-time!!!

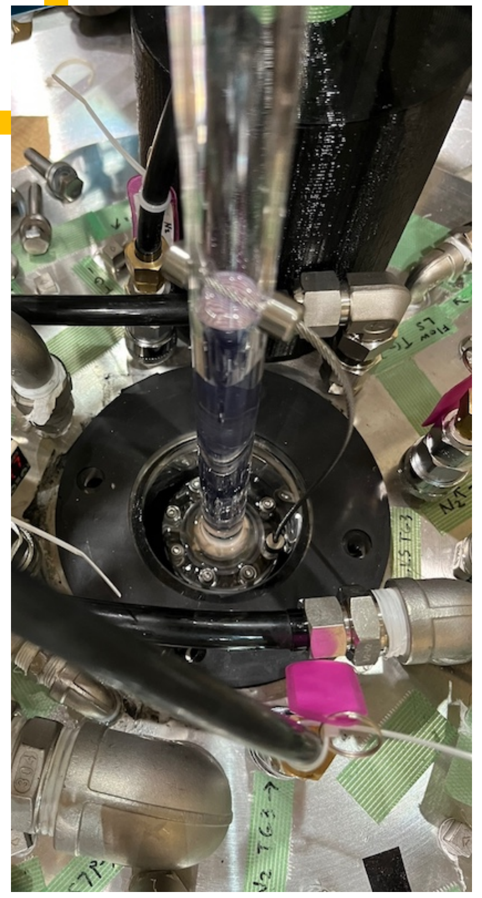
Fast Neutrons rates vs time

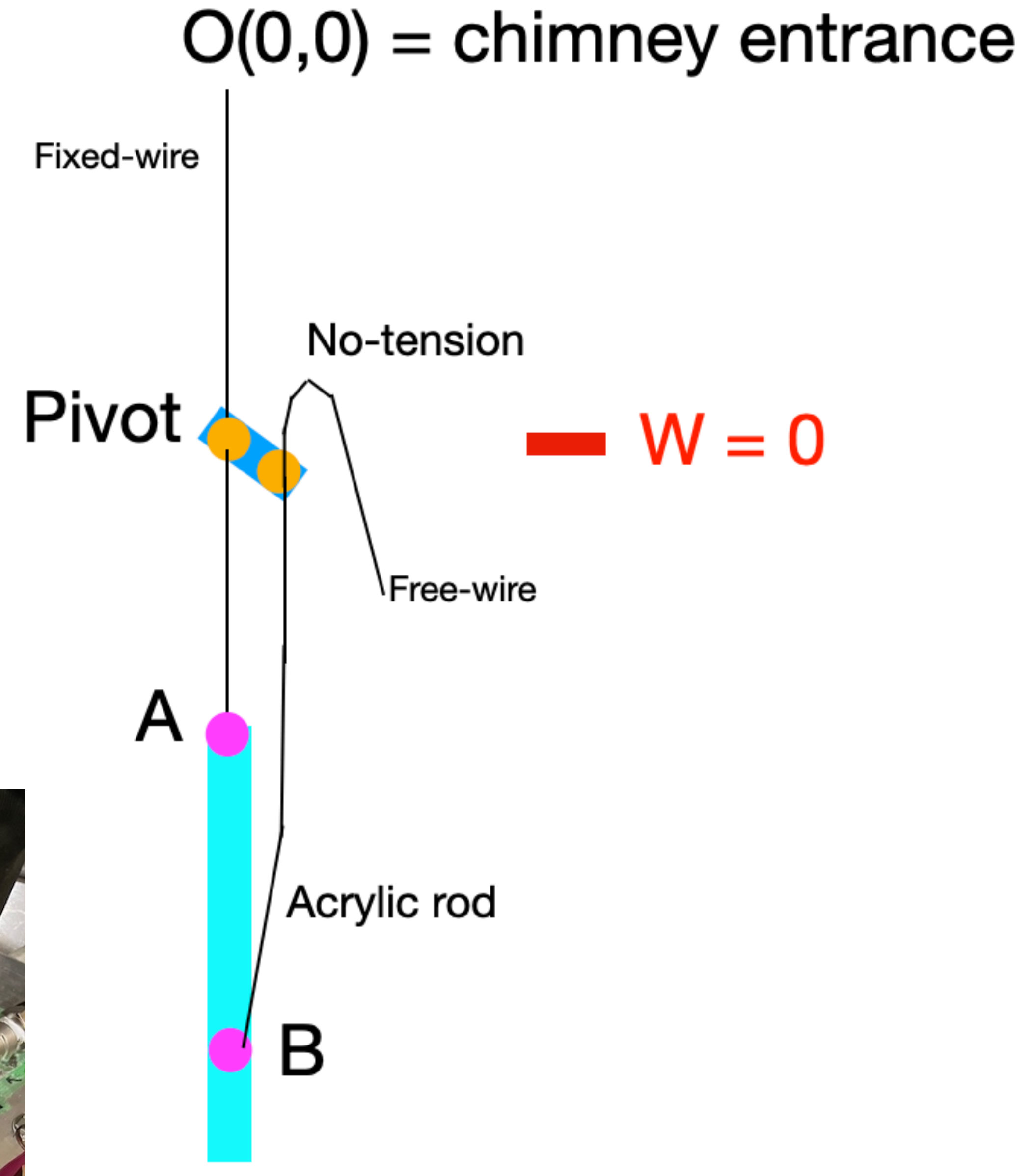
Michel electrons rates vs time

^{252}Cf 3D calibration : Study of Energy/Vertex reconstruction

^{252}Cf radioactive source







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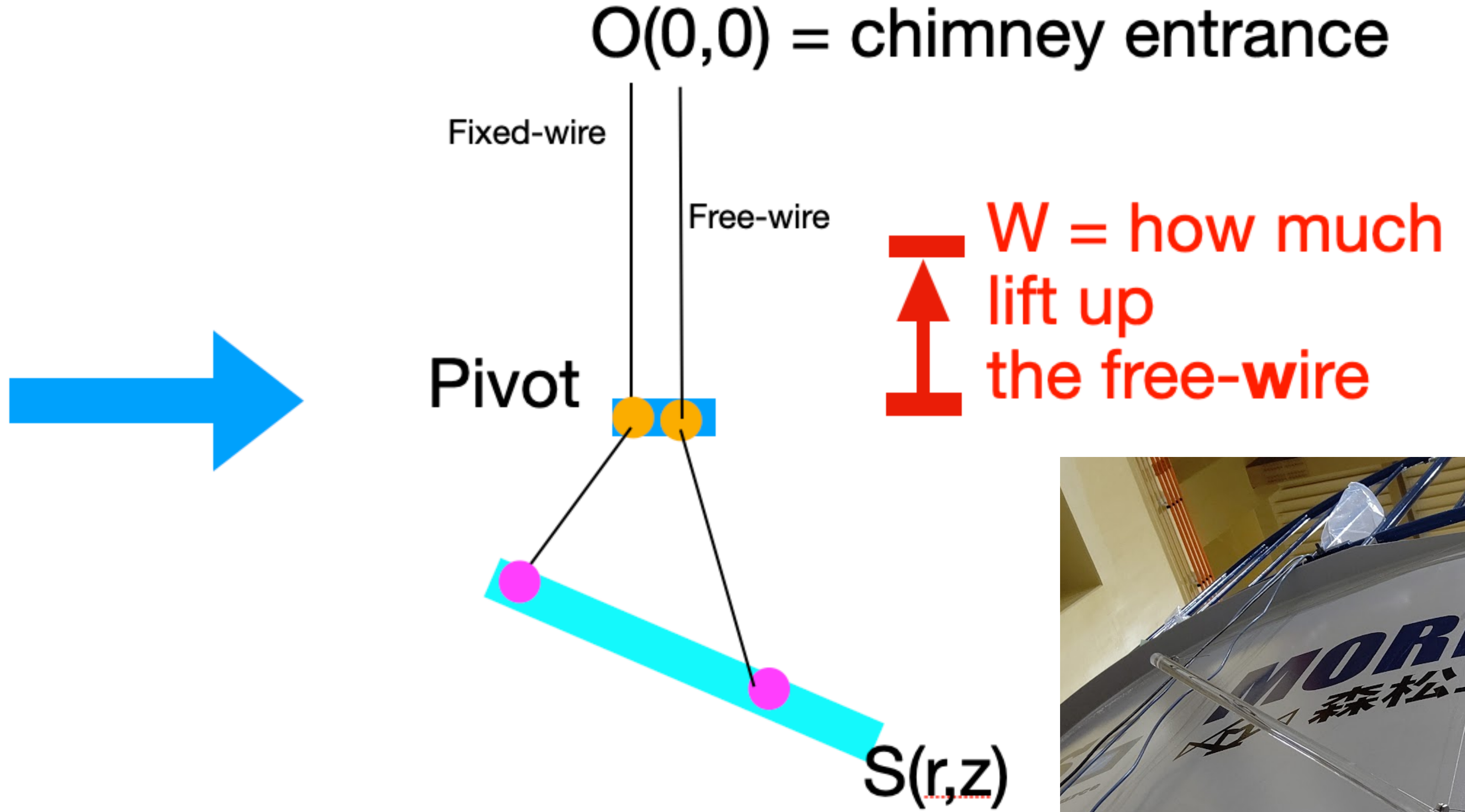
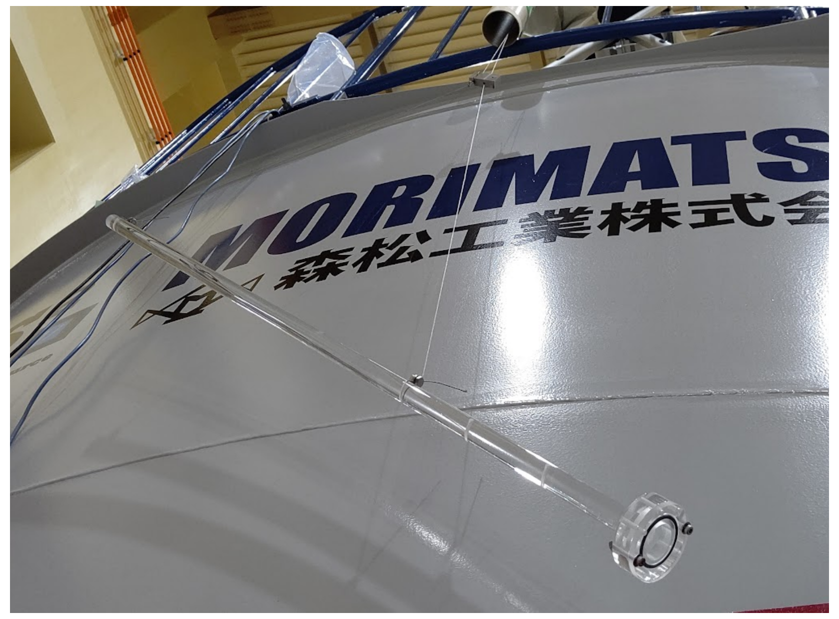
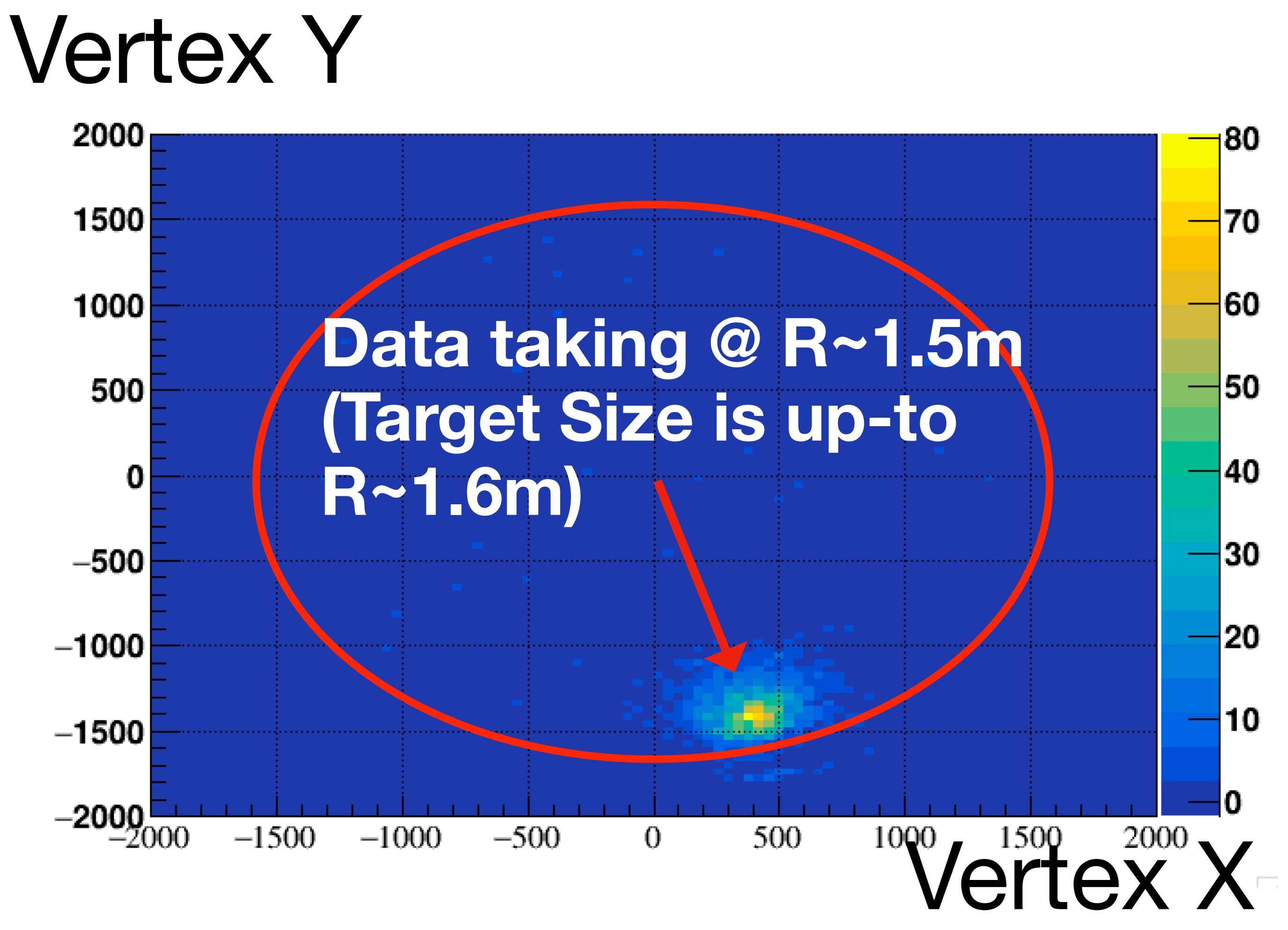


<manipulate the rod>





(NEW) ^{252}Cf 3D calibration system
-> **Any of position (R&Z)** can be covered!!!

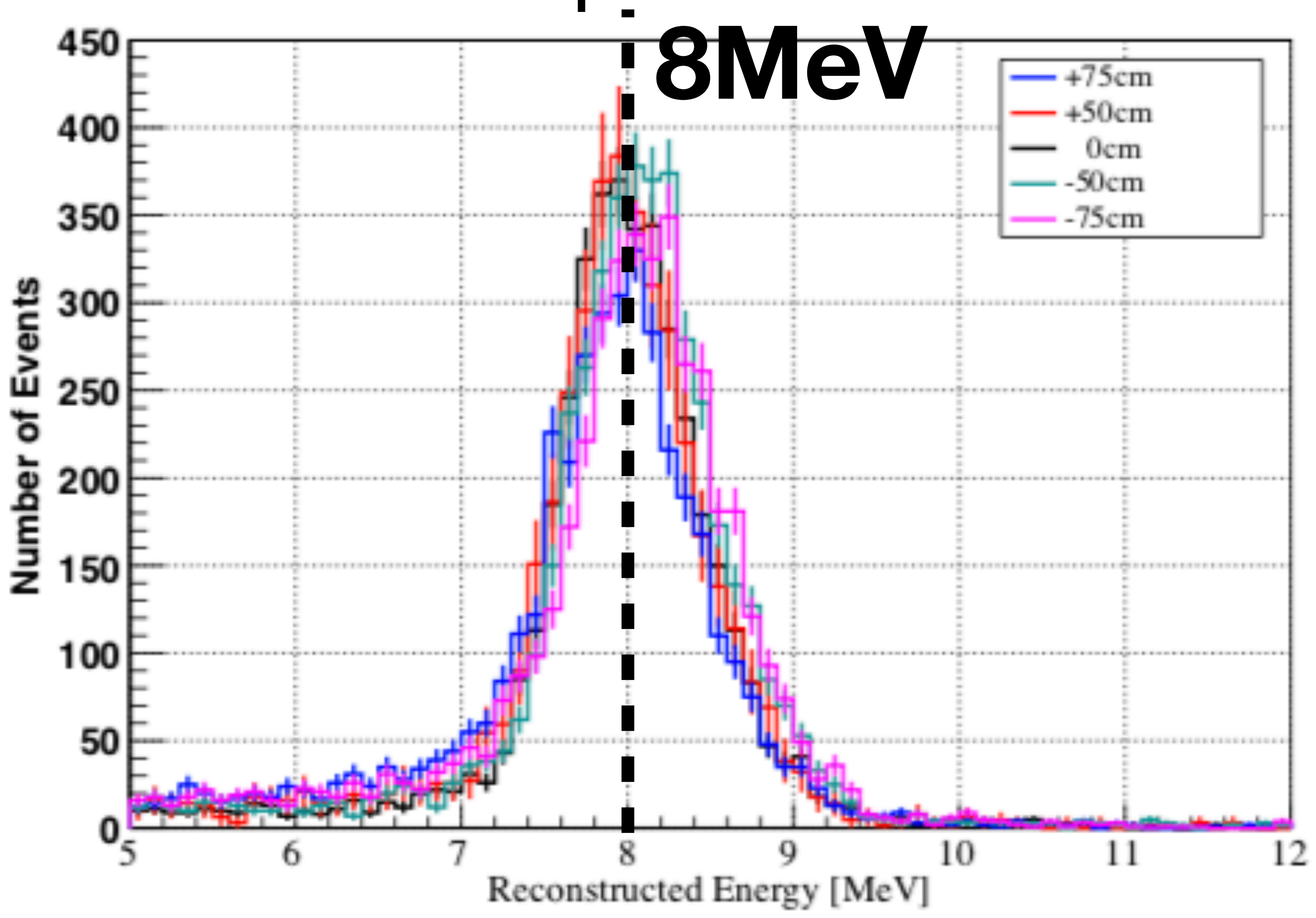
Reconstruction Parameters were studied based on this calibration
=> Reconstruction performances were checked using several data sample

Calibration using ^{252}Cf and Michel electrons are crucial!!!

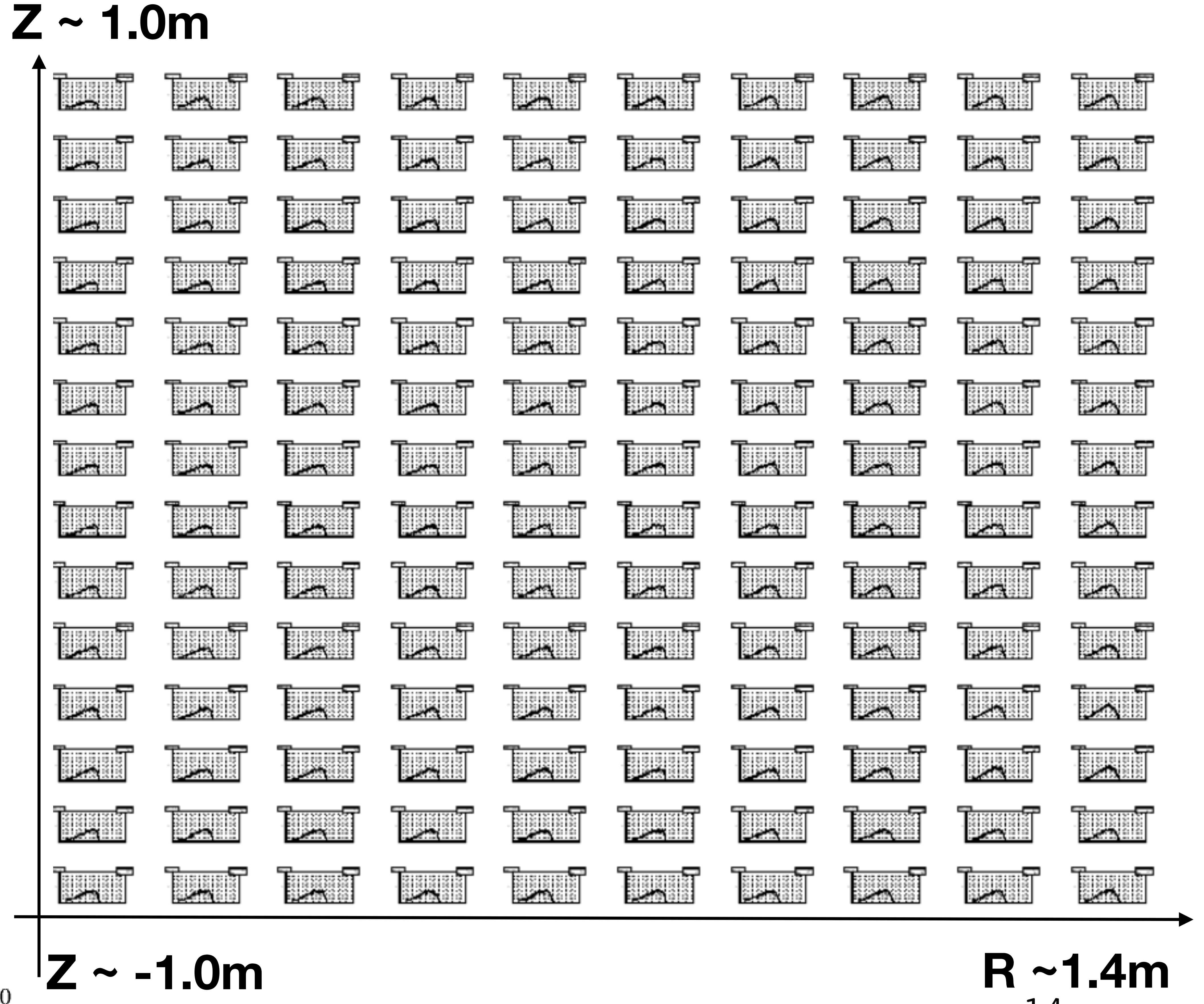
Energy/Vertex reconstruction performance

Energy/Vertex reconstruction performances are good (in fiducial)

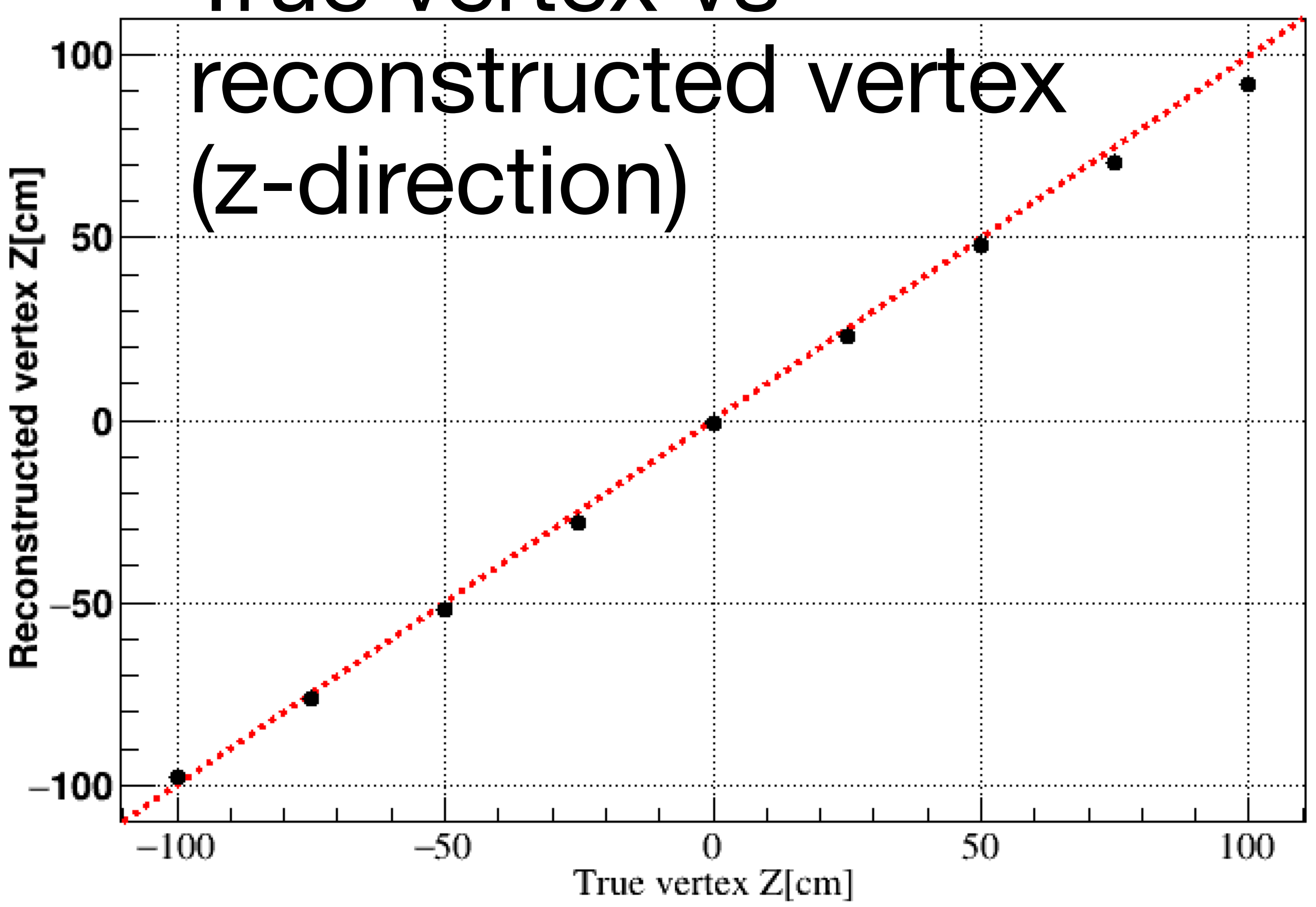
Reconstructed energy of n-Gd captured events



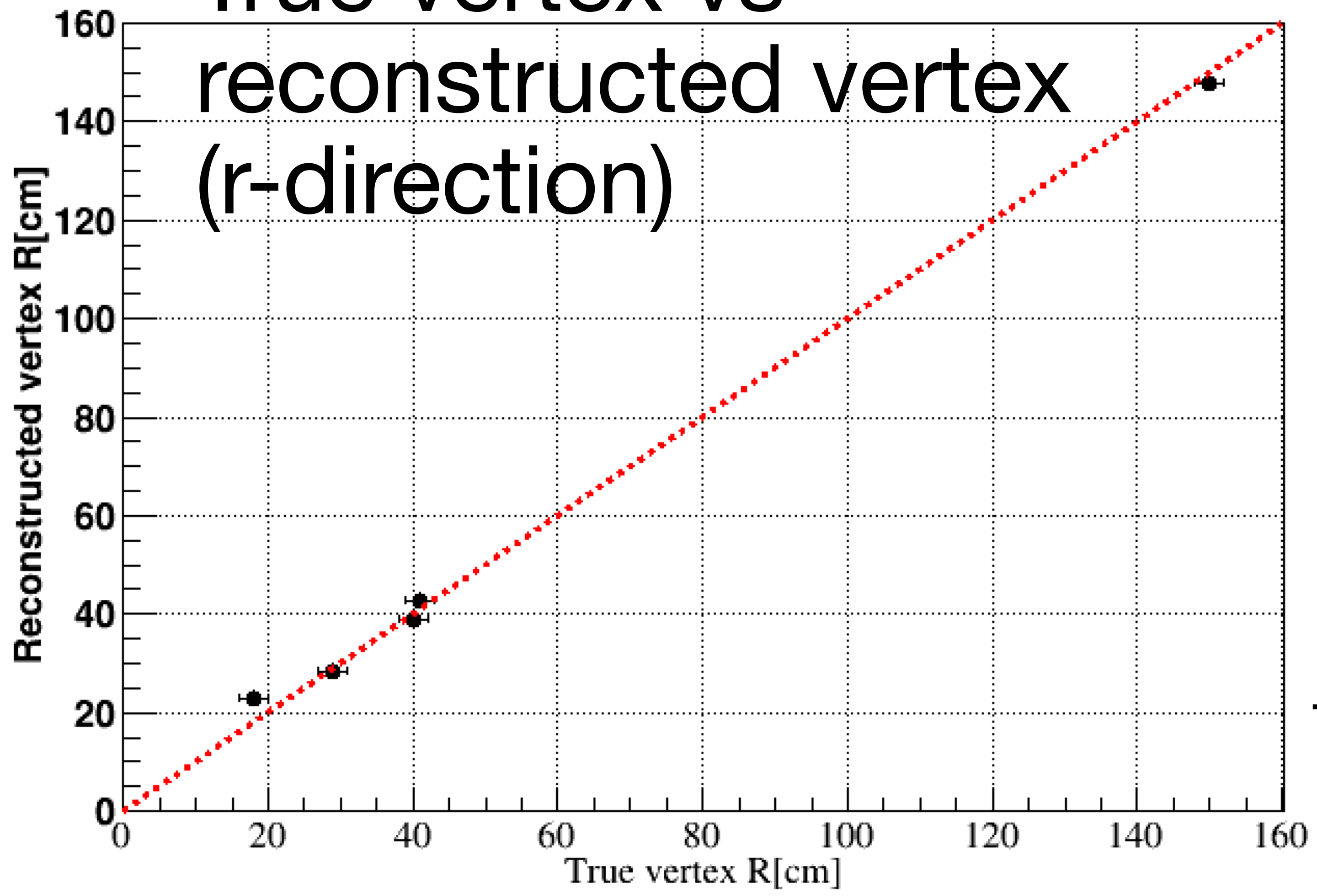
Reconstructed energy spectra of Michel electrons at each position



True vertex vs reconstructed vertex (z-direction)



True vertex vs reconstructed vertex (r-direction)



Blind analysis and Side-band study

Toward the sterile neutrino search (Blind analysis)

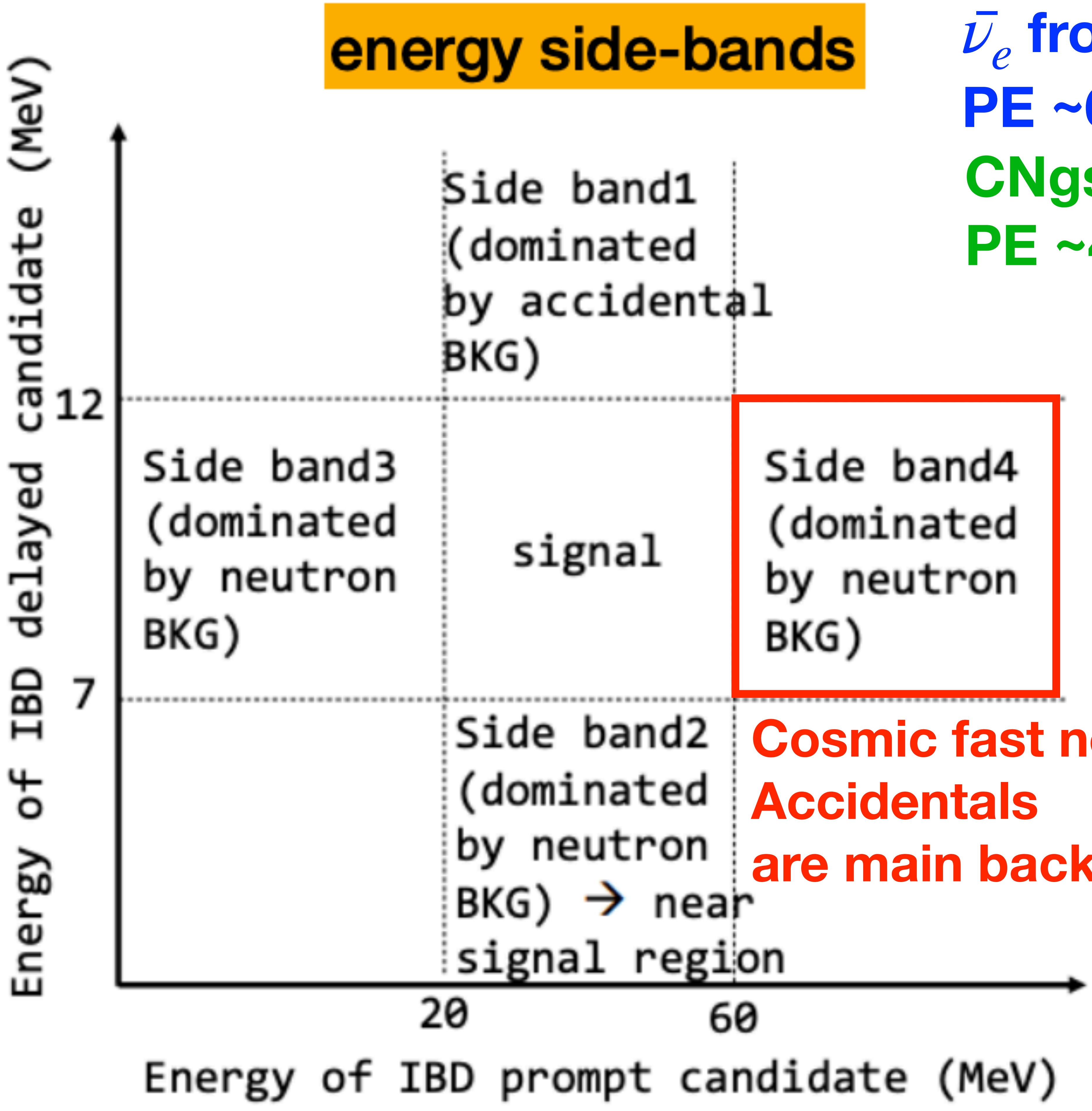
- We are doing the blind analysis to search a sterile neutrino.

- All energy side-bands should be understood before opening the signal region.

- Side-bands are defined by energies like right plot.

- The rates in the side-band regions will be predicted by the <u>control samples driven by data</u>

- Now, side-band 4 (prompt 60-100MeV) data are opened!!!



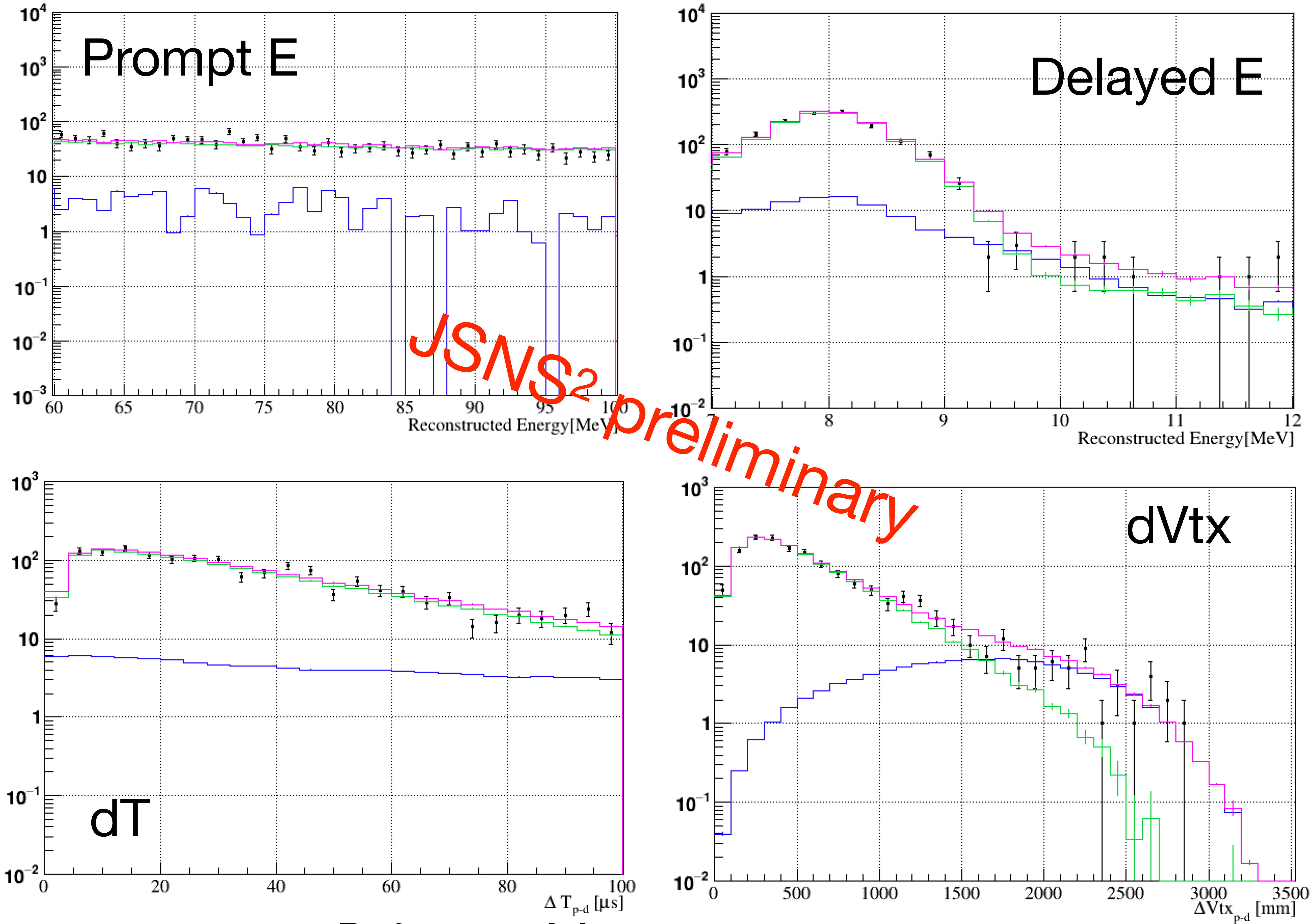
Cosmic fast neutrons, Accidentals are main backgrounds

Other Main Bkgs

$\bar{\nu}_e$ **from** μ^- **:**
PE ~60MeV

CNgs :
PE ~40MeV

The first comparison between the observation vs expectation ~Side-band4 (prompt 60-100MeV)~ 1



Before applying
Spatial correlation $\Delta VTX_{p\text{-}d}$ < 60cm

	Observed	Expectation
Total	**1498 +- 38.7**	**1528.5 +- 5.9**
Neutrons		**1421.7 +- 5.7**
Accidental		**106.8 +- 1.5**

- The **observed events** are compared with the background expectations (Cosmic fast Neutrons + Accidental)

=> well agreed.

=> Cosmic fast neutrons background is dominated.

    => **Pulse Shape Discrimination(PSD)** would reject them. (Goal : 99% rejection)

    => Study is on-going.

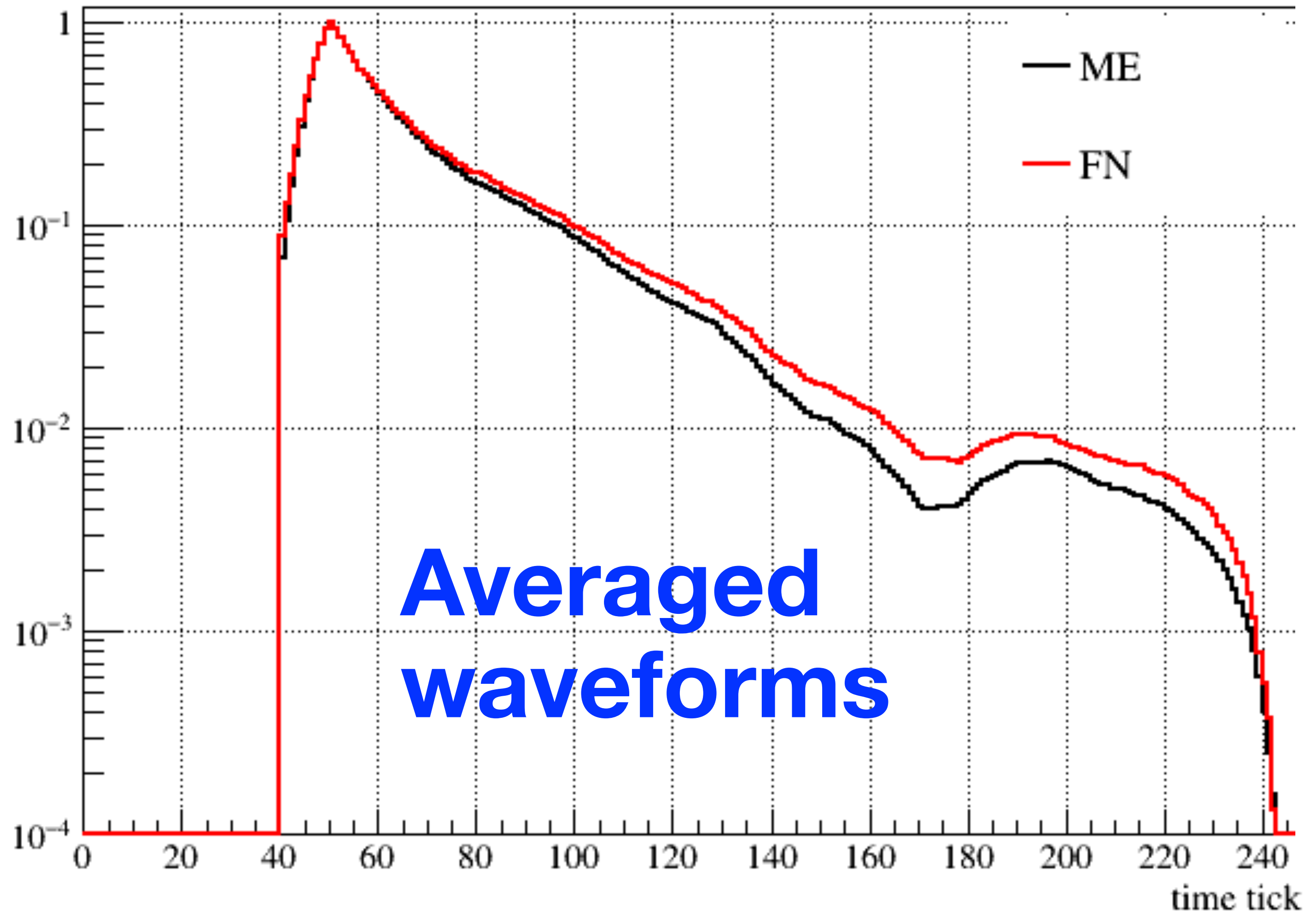
=> After applying PSD, the accidental will be dominated.

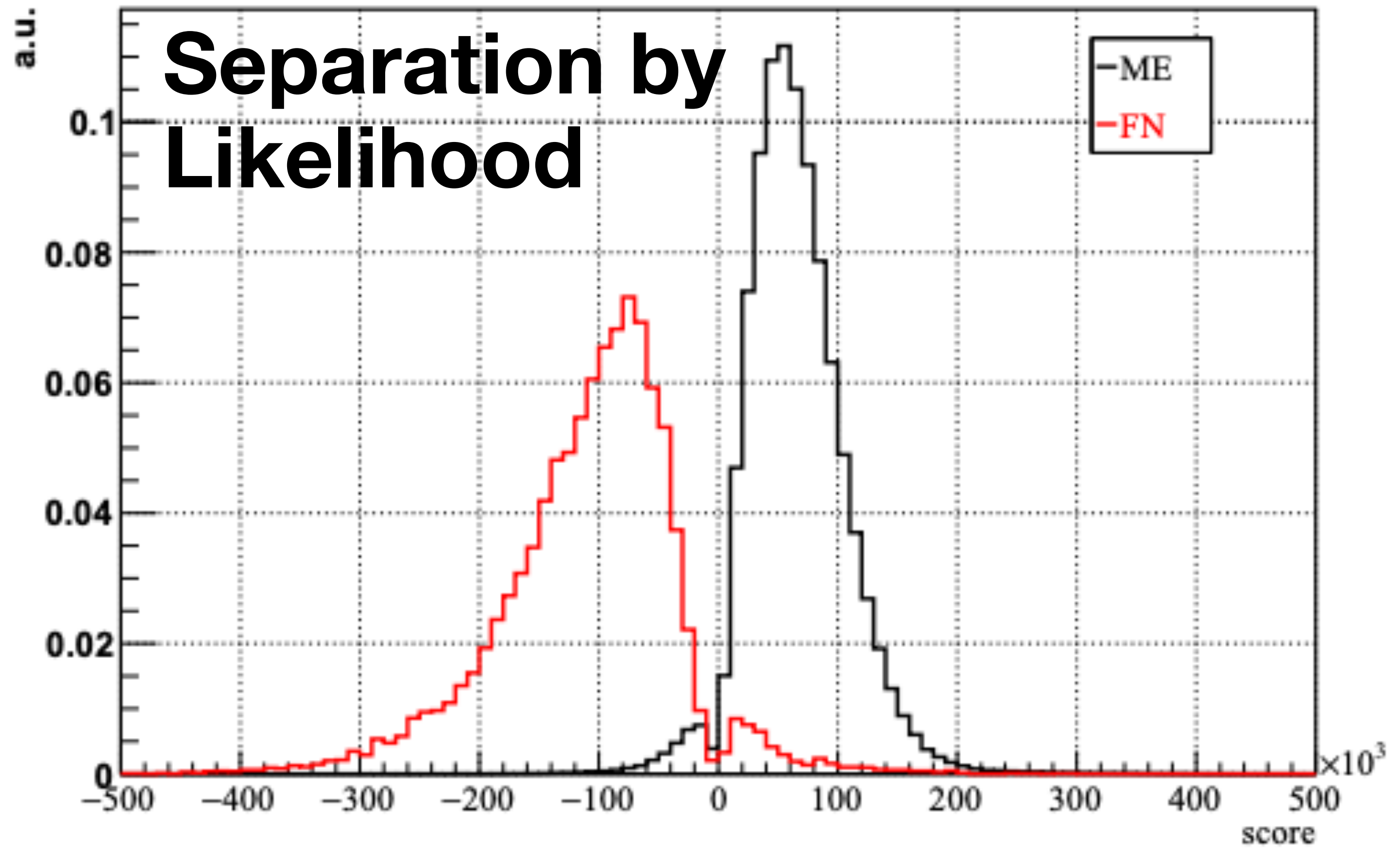
=> **Understanding of accidental** is much improved recently. arXiv 2308.02722

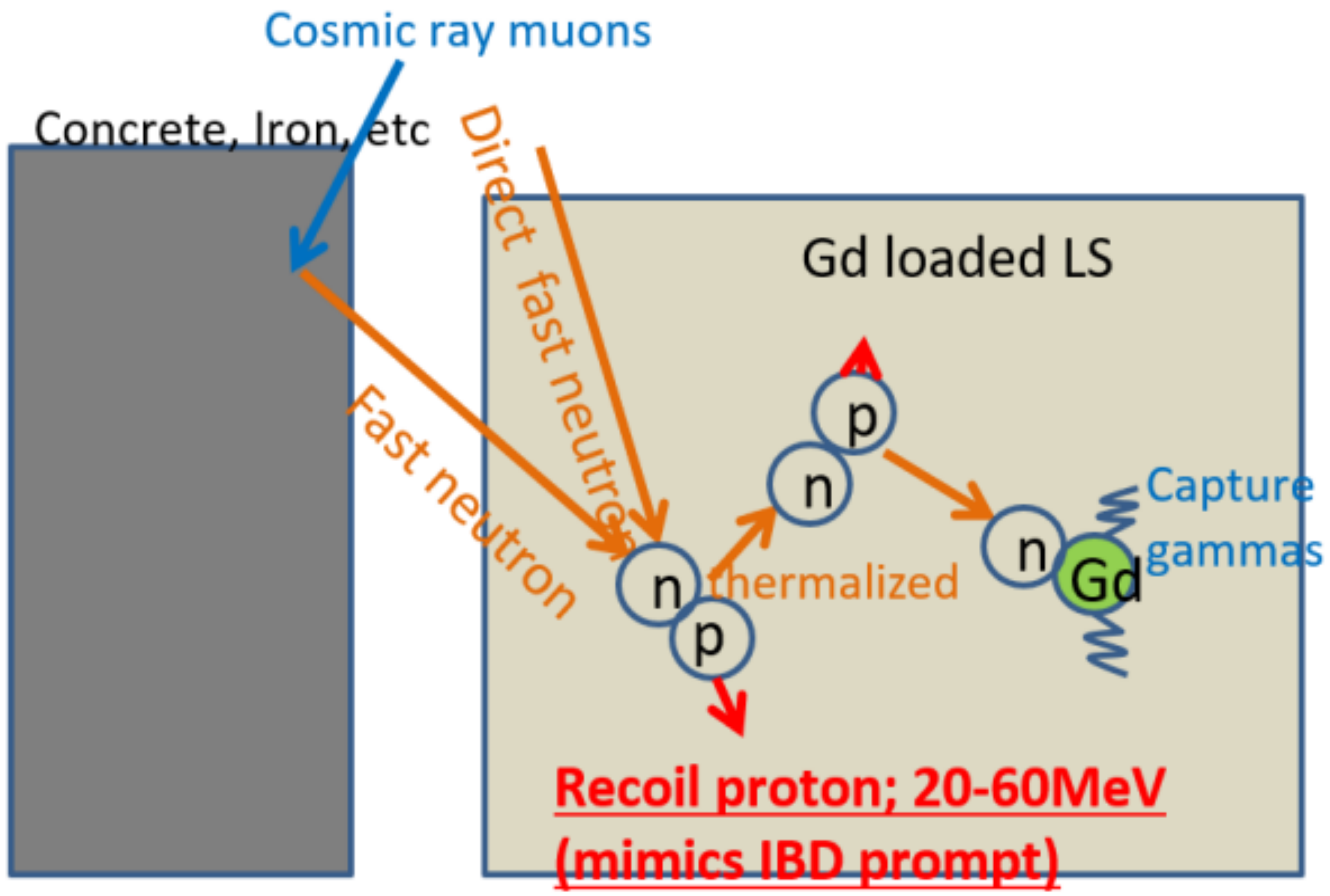
Study on the fast neutron background - PSD

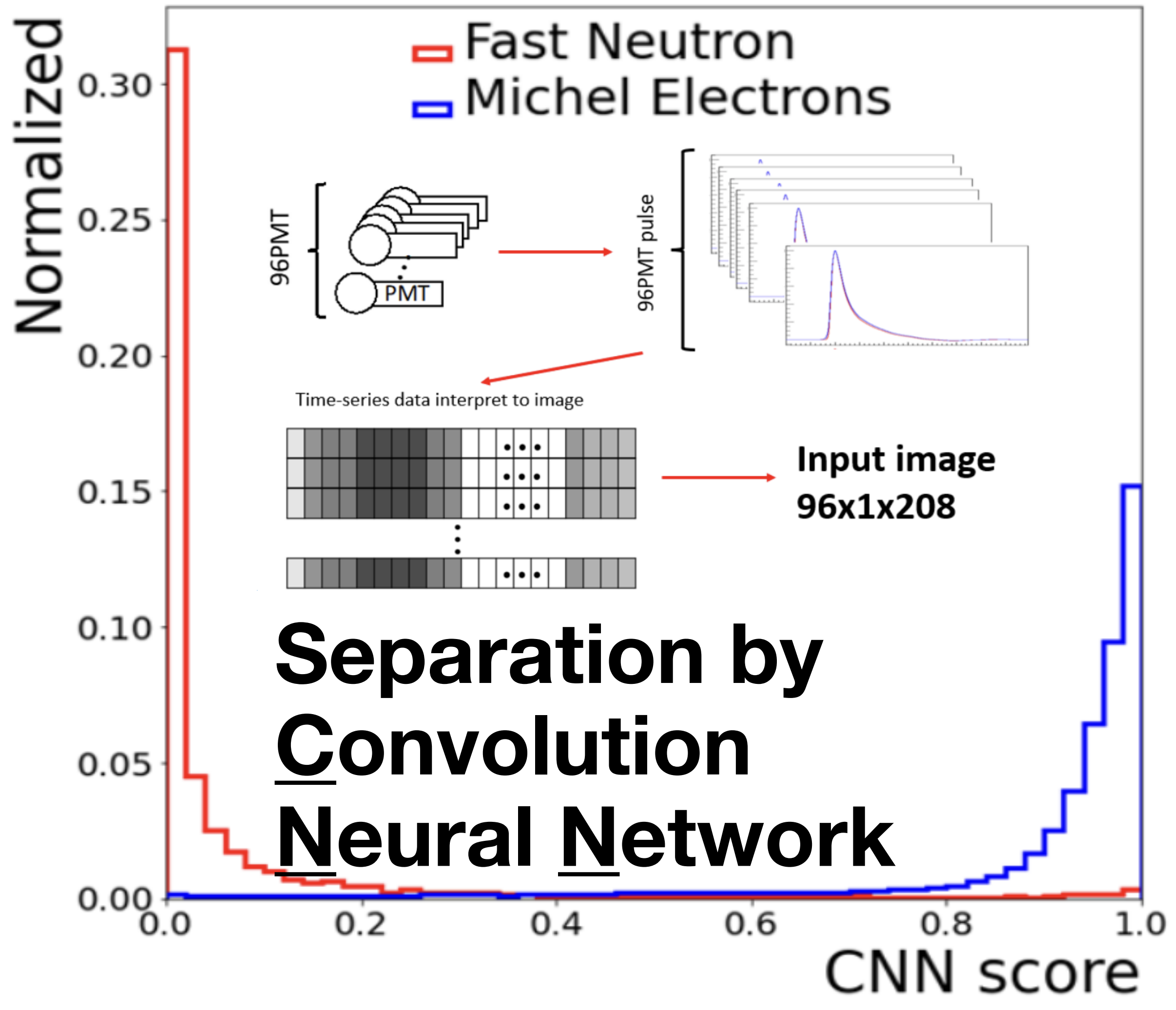
- **Fast neutrons** can mimic the **IBD signals** from electron anti-neutrino.

- Those two will be separated by the **PSD method**.
   => using the neutron-like/electron-like templates (**averaged waveforms from data**).









- Both of Likelihood team / Machine-learning(CNN) team work independently.
=> progress is on-going.

(Goal : 99% rejection of fast neutrons)

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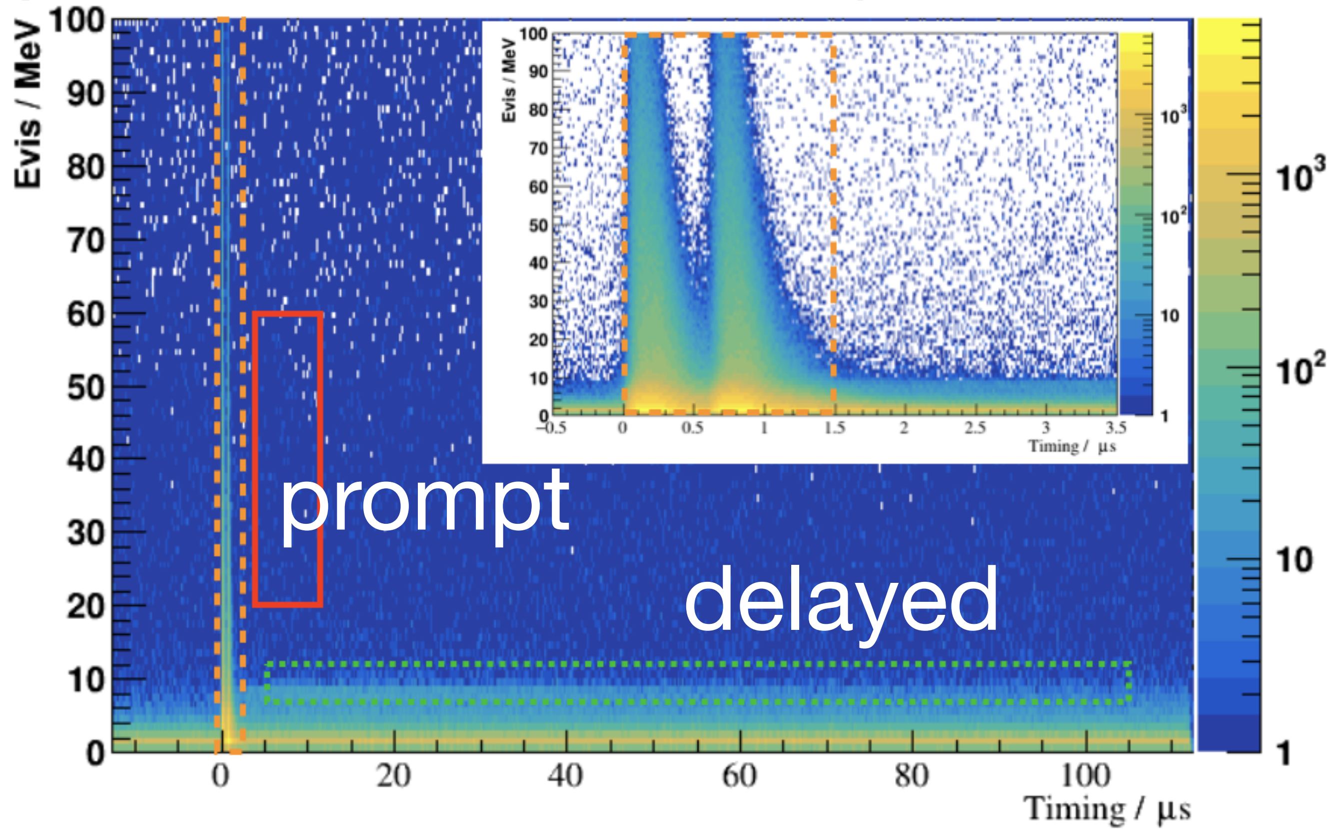
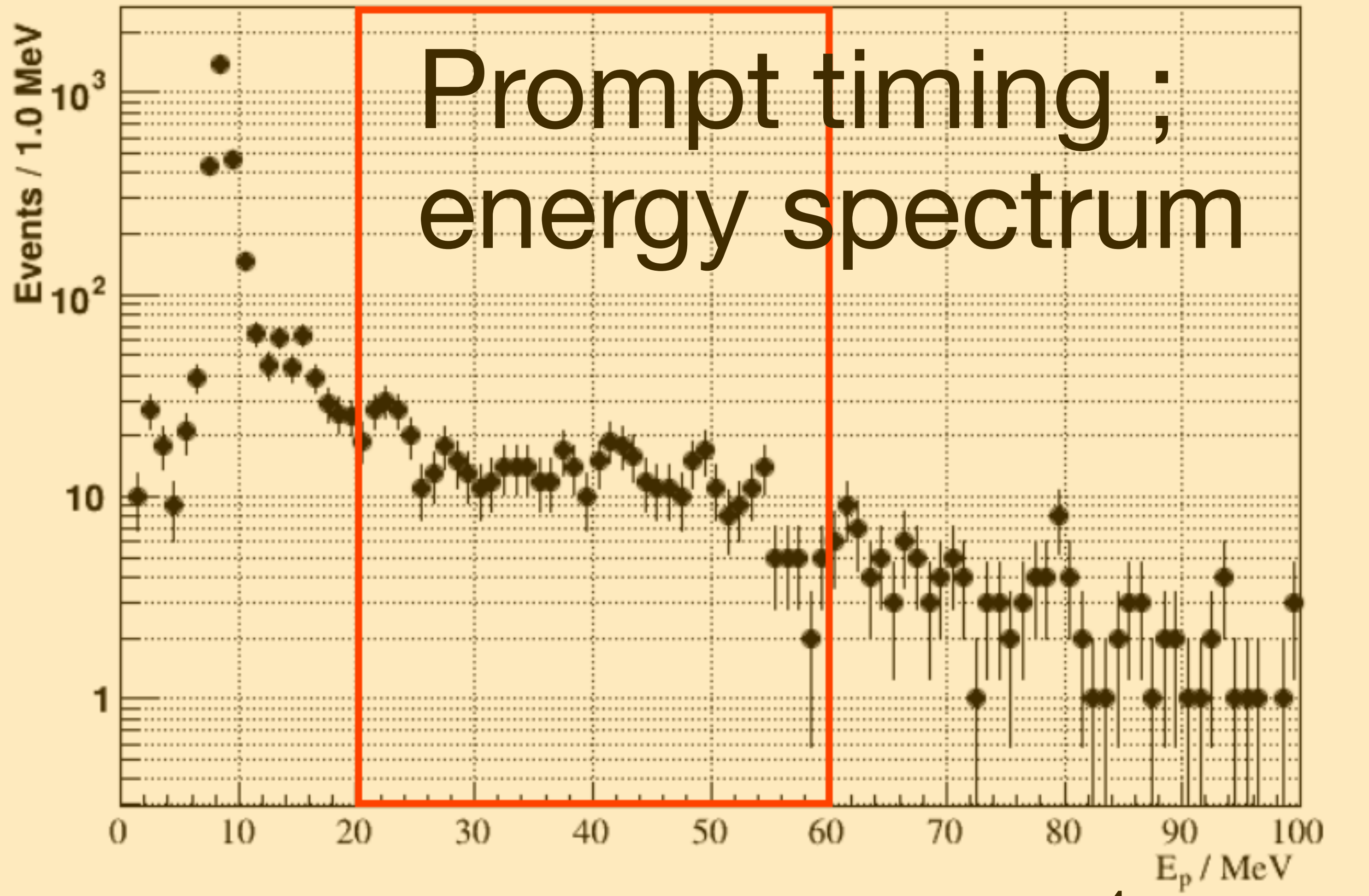
Study on the accidental background - 1

arXiv 2308.02722

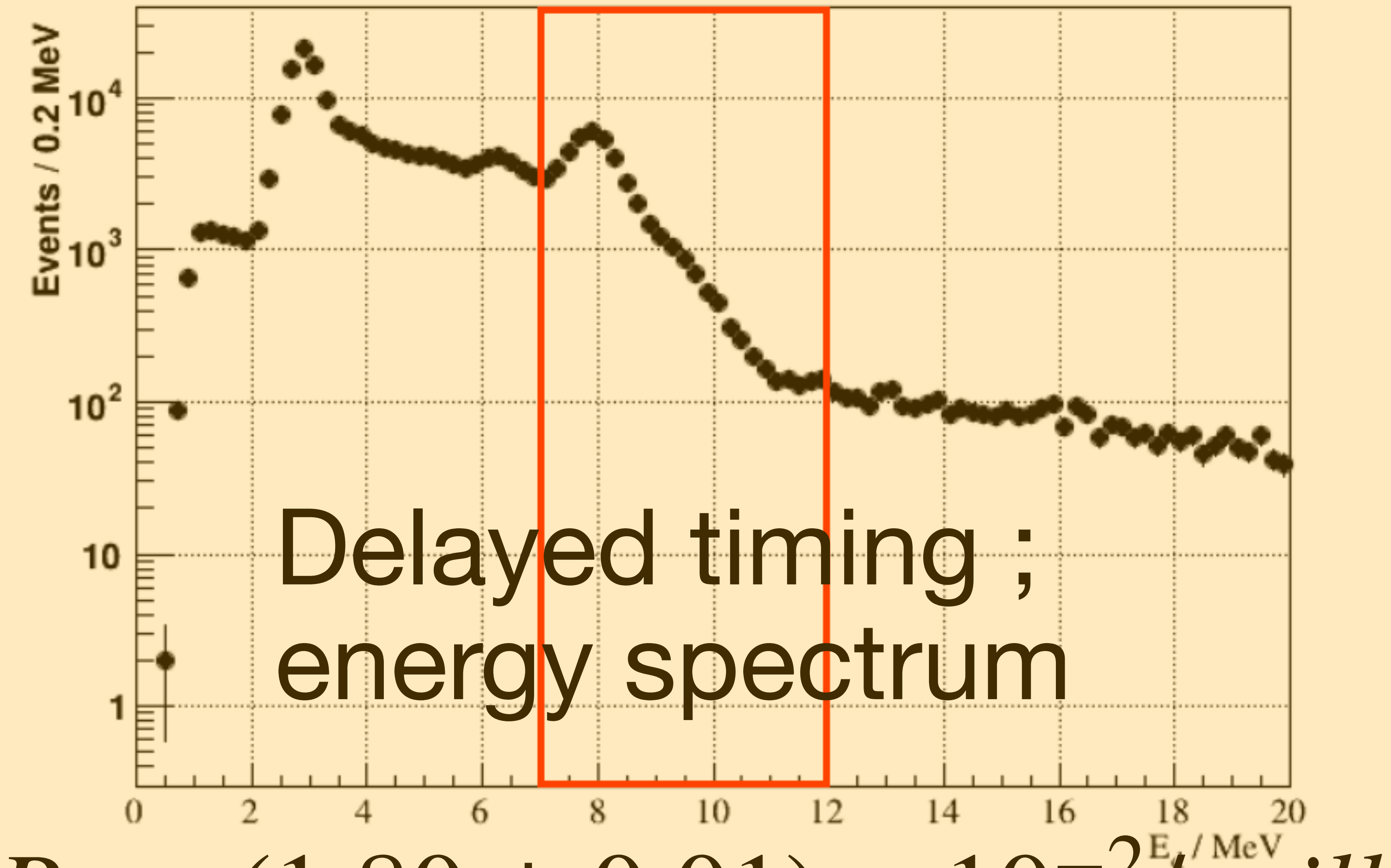
125μs time window triggered data
(special calibration run)



125μs fully covers
the timing structure for IBD



$R_p = (2.20 \pm 0.09) \times 10^{-4}/spill$



$R_d = (1.80 \pm 0.01) \times 10^{-2}/spill$

- The single rates of the prompt / delayed timing region were understood using 125μs time window special calibration data

- The prediction of the accidental background rate is calculated with multiplying these single rates.

$$R_{acci} = R_p \times R_d \times \varepsilon_{cut}$$

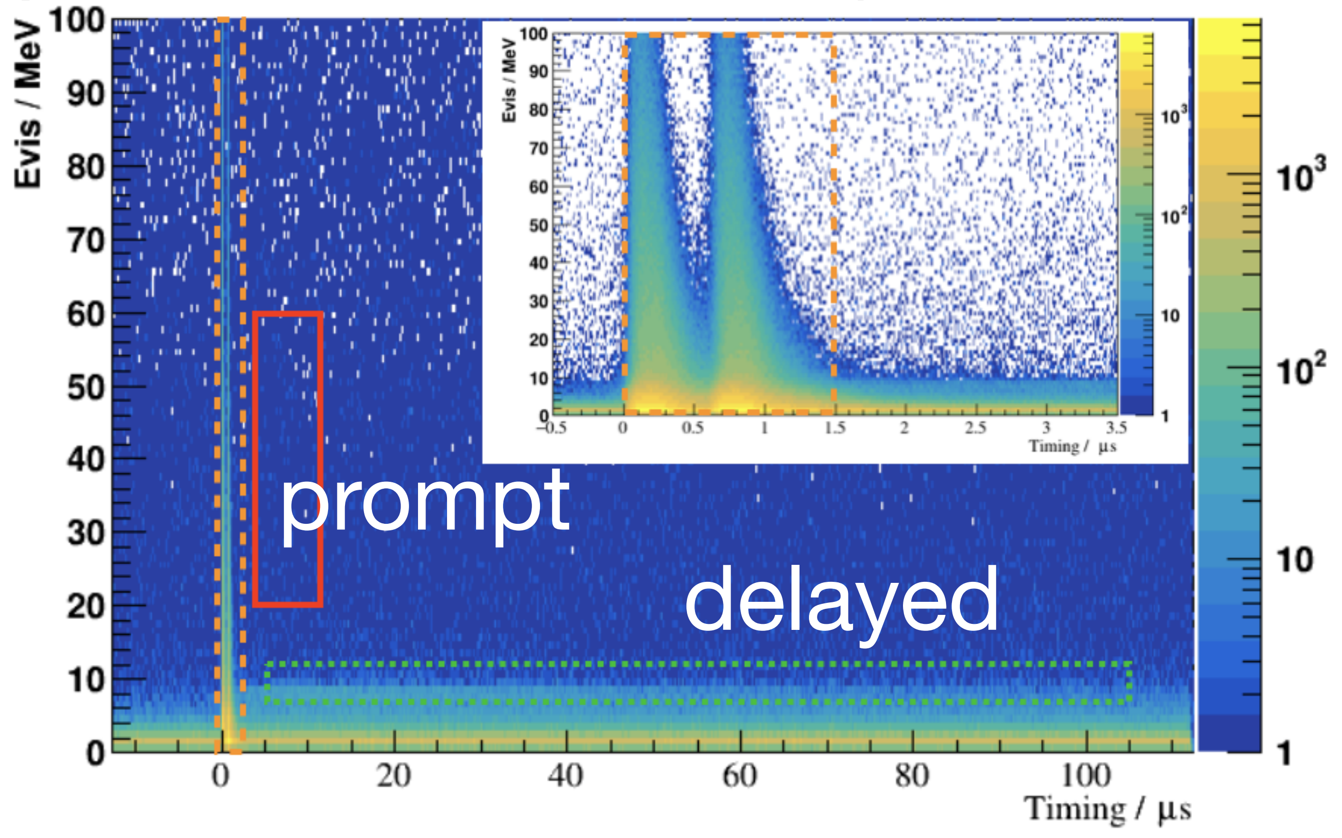
$\varepsilon_{\text{timing likelihood}} = 46\,\%$

$\varepsilon_{\Delta VTX} = 5.1 \pm 0.1\,\%$

Study on the accidental background - 2

arXiv 2308.02722

125μs time window triggered data
(special calibration run)



125μs fully covers
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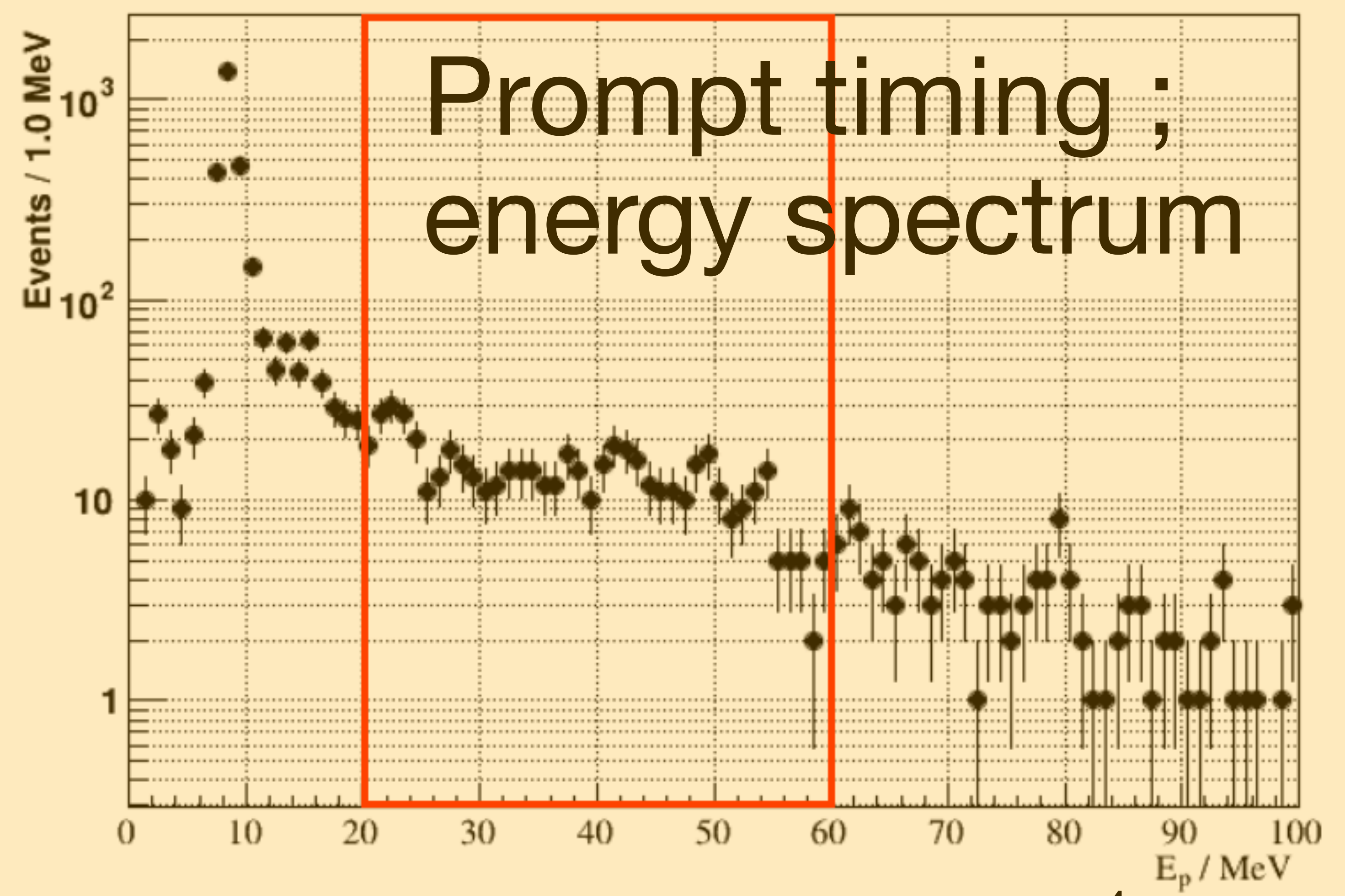
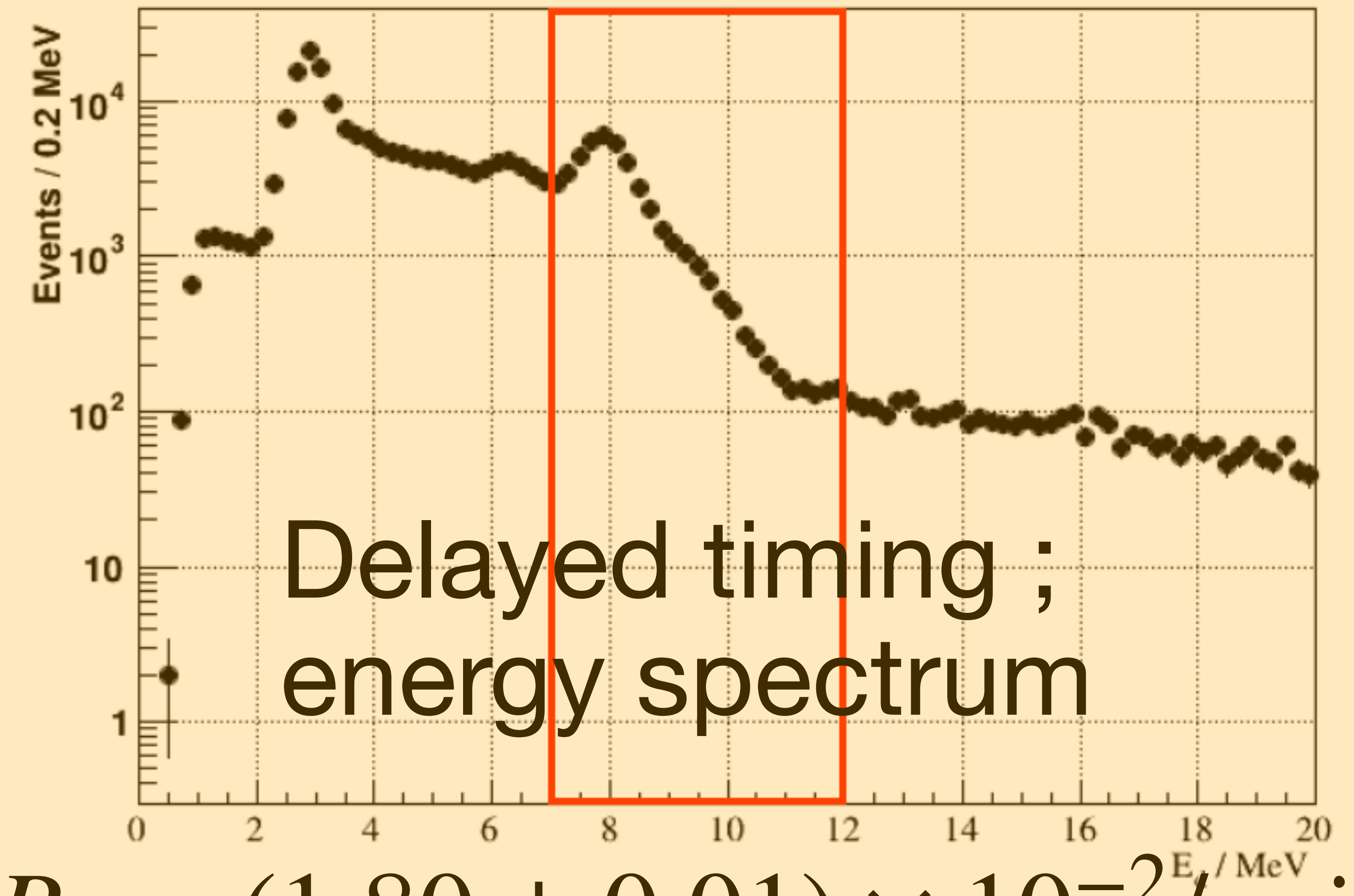


$R_p = (2.20 \pm 0.09) \times 10^{-4} / spill$

X



$R_d = (1.80 \pm 0.01) \times 10^{-2} / spill$

=

$R_{acci} = (9.29 \pm 0.42) \times 10^{-8}$
/spill /0.75MW

- The single rates of the prompt / delayed timing region were understood using 125μs time window special calibration data

- The prediction of the accidental background rate is calculated with multiplying these single rates.

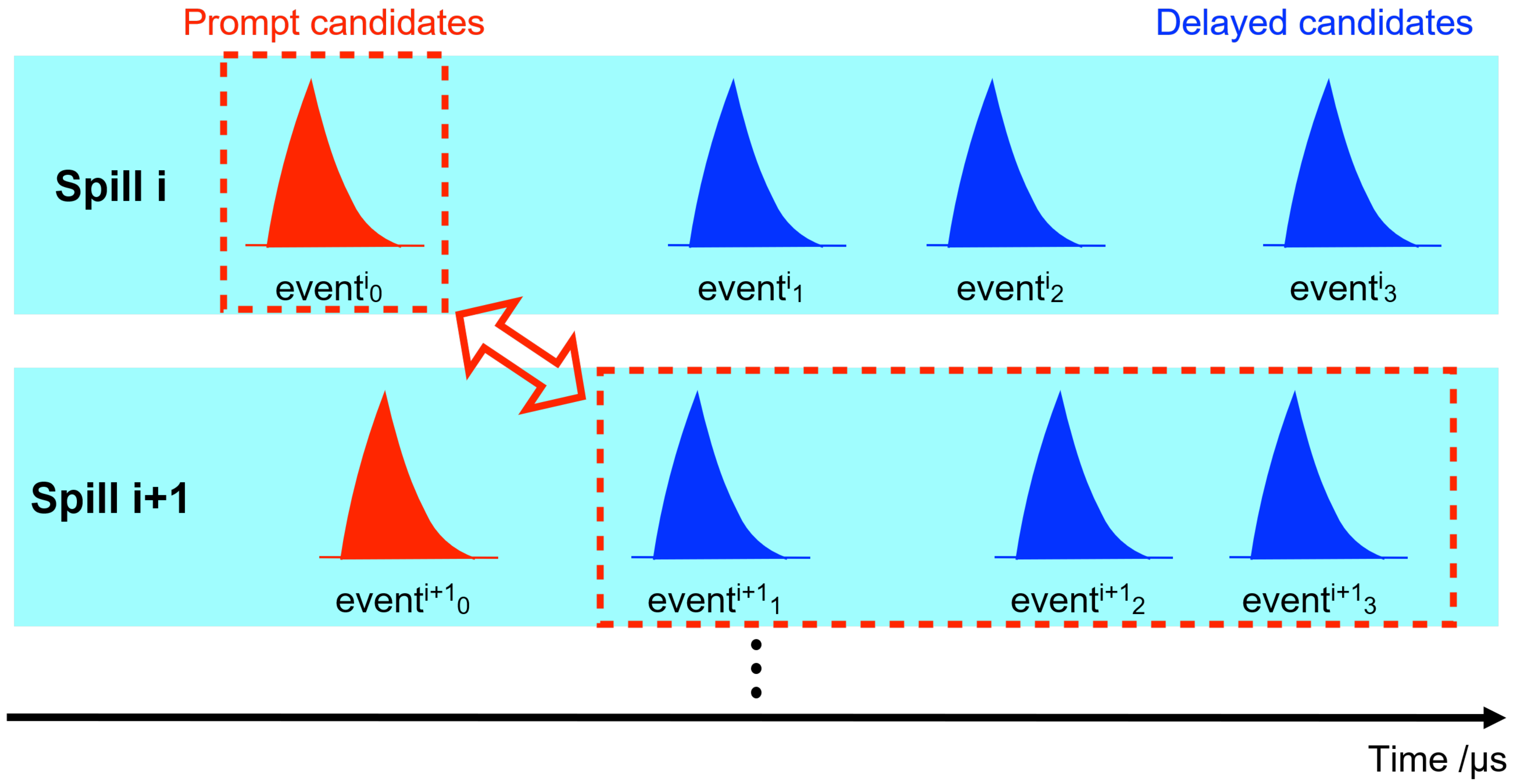
$R_{acci} = R_p \times R_d \times \varepsilon_{cut}$ $\varepsilon_{\Delta VTX} = 5.1 \pm 0.1\ \%$

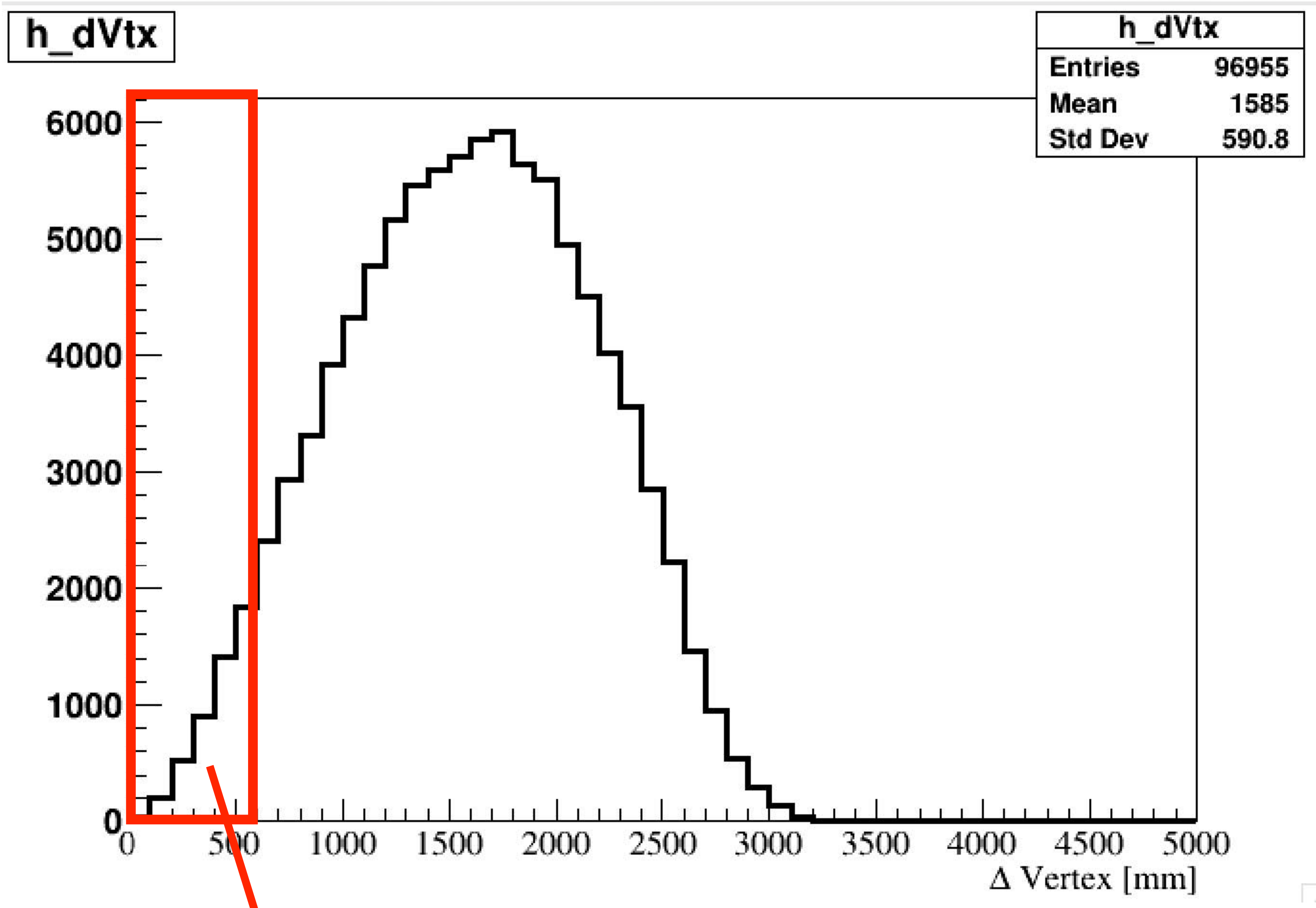
(ΔVTX cut will be explained in next page)

(Expected IBD signal is 4.59 x 10^{-8} /spill/MW
=>comparable)

Study on the accidental background - 3

arXiv 2308.02722





$$\varepsilon_{\Delta VTX} = 5.1 \pm 0.1\ \%$$

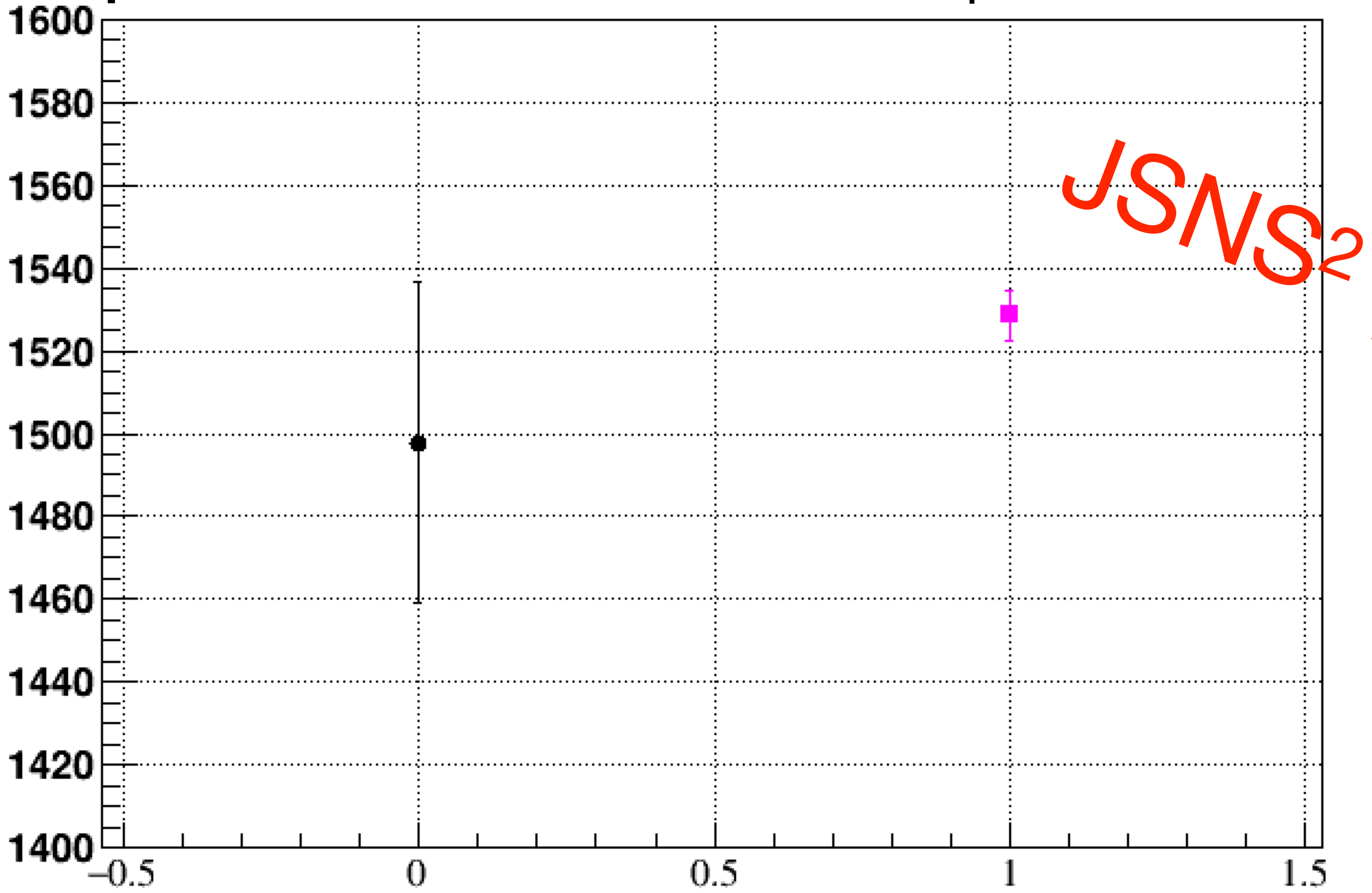
- Mimic IBD pair using prompt / delayed events at the different spills [**Spill-shift method**]
=> 1, 2, 3 … 10000th shifted spills
=> Accidental background control sample

- This method will be used for signals/side-bands

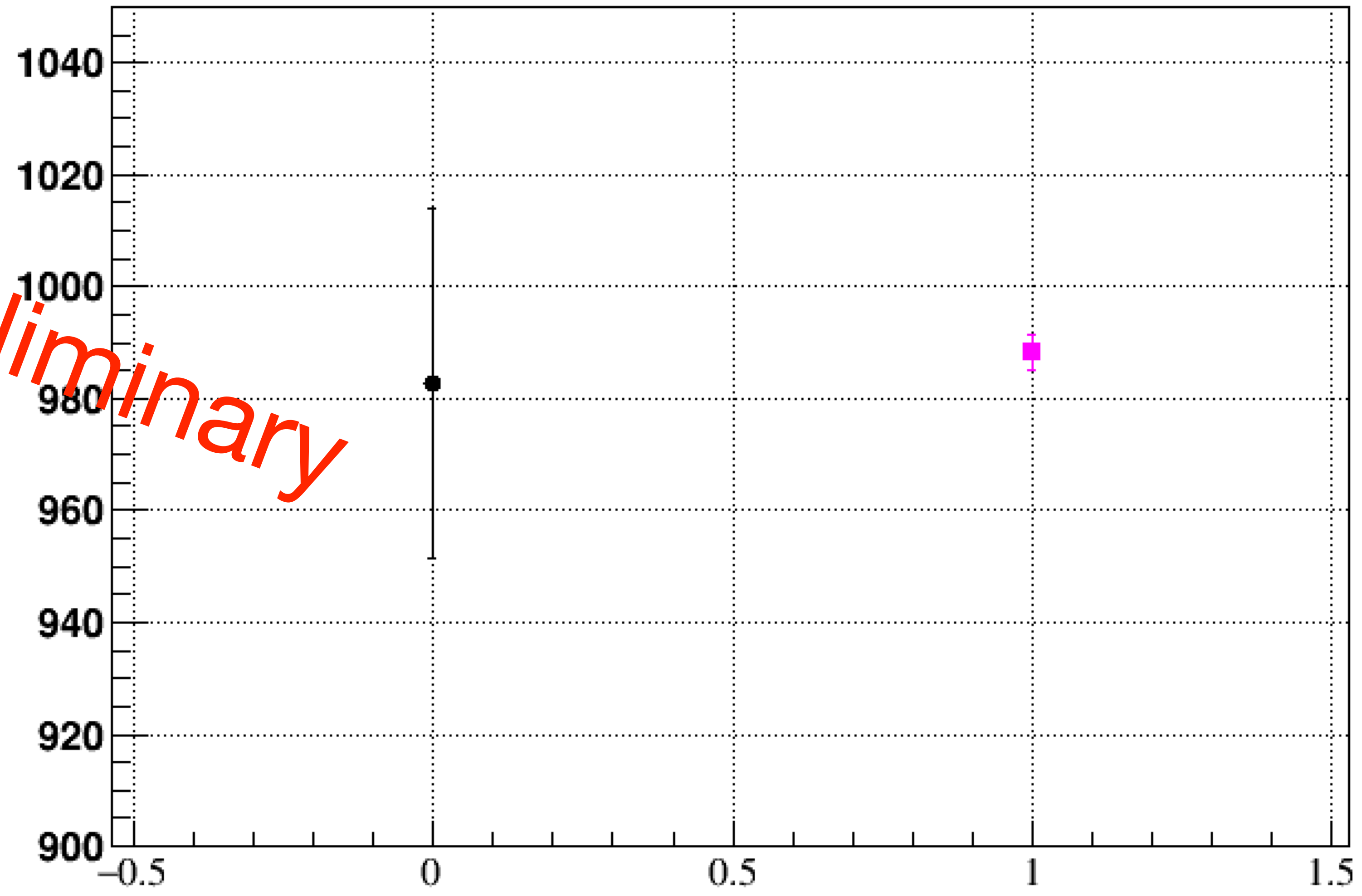
To reject accidental backgrounds, $\Delta VTX_{p\text{-}d}$ < 60cm is applied.
=> Side-band 4 is checked again.

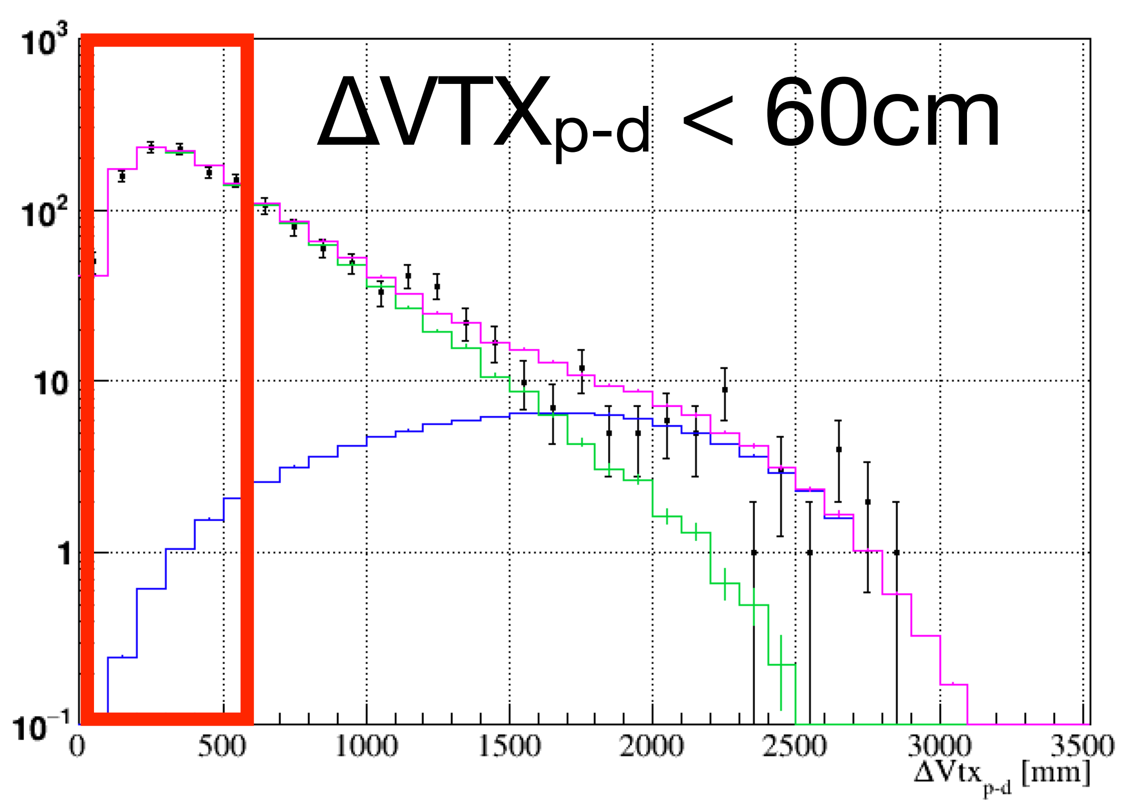
The first comparison between the observation vs expectation ~Side-band4 (prompt 60-100MeV)~ 2

Before applying
Spatial correlation $\Delta VTX_{p\text{-}d} < 60cm$



After applying
Spatial correlation $\Delta VTX_{p\text{-}d} < 60cm$





	Observed events	Expectation events
No $\Delta VTX_{p\text{-}d}$ Cut	**1498 +- 38.7**	**1528.5 +- 5.9**
$\Delta VTX_{p\text{-}d} < 60cm$	**983 +- 31.4**	**988.4 +- 3.2**

Neutrons 982.8 + Accidental 5.6
If PSD is applied, Neutrons ~10 events

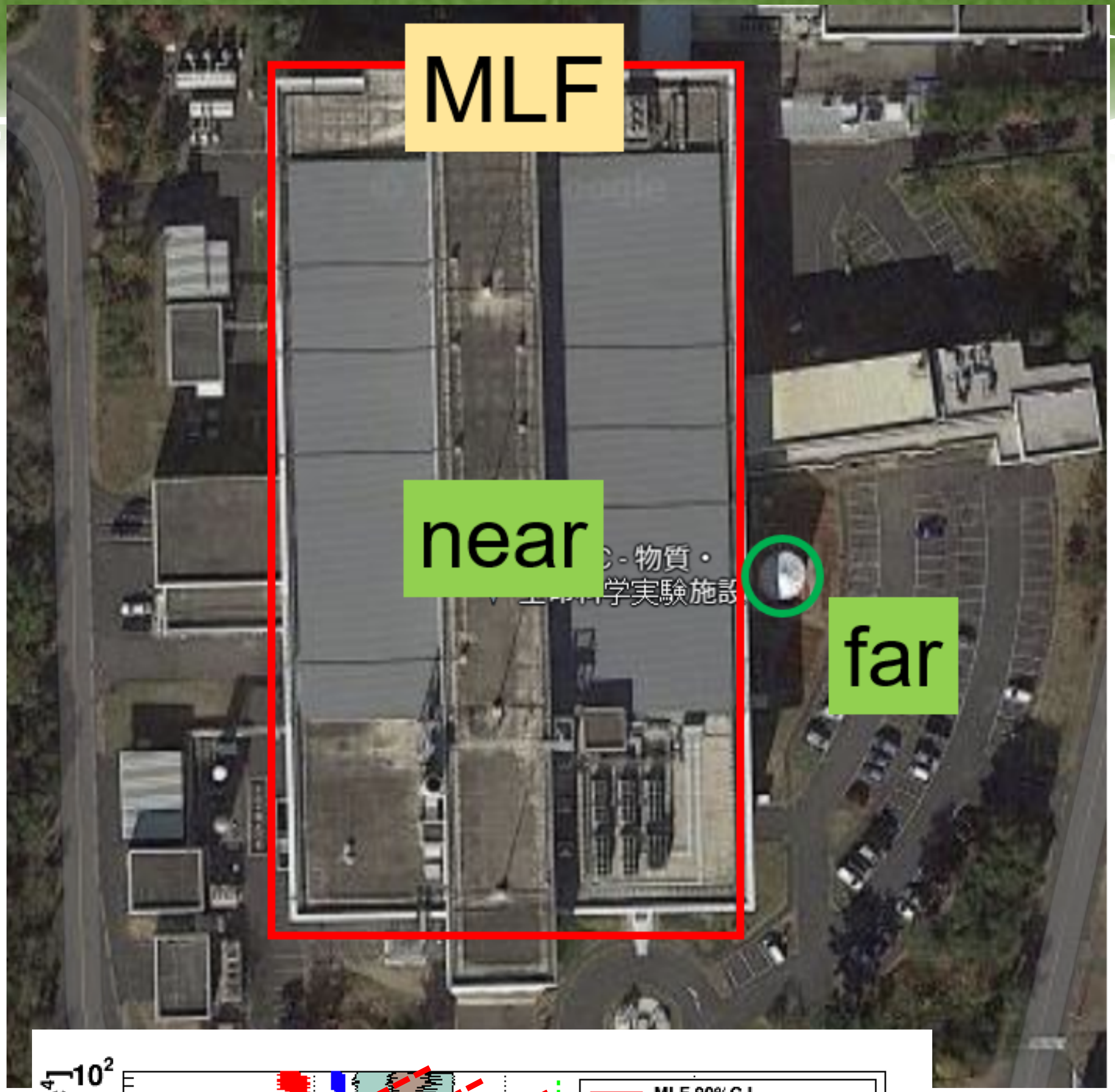
- The number of events for the observed & the expectations have good consistency, for both of the spatial correlation condition cases.

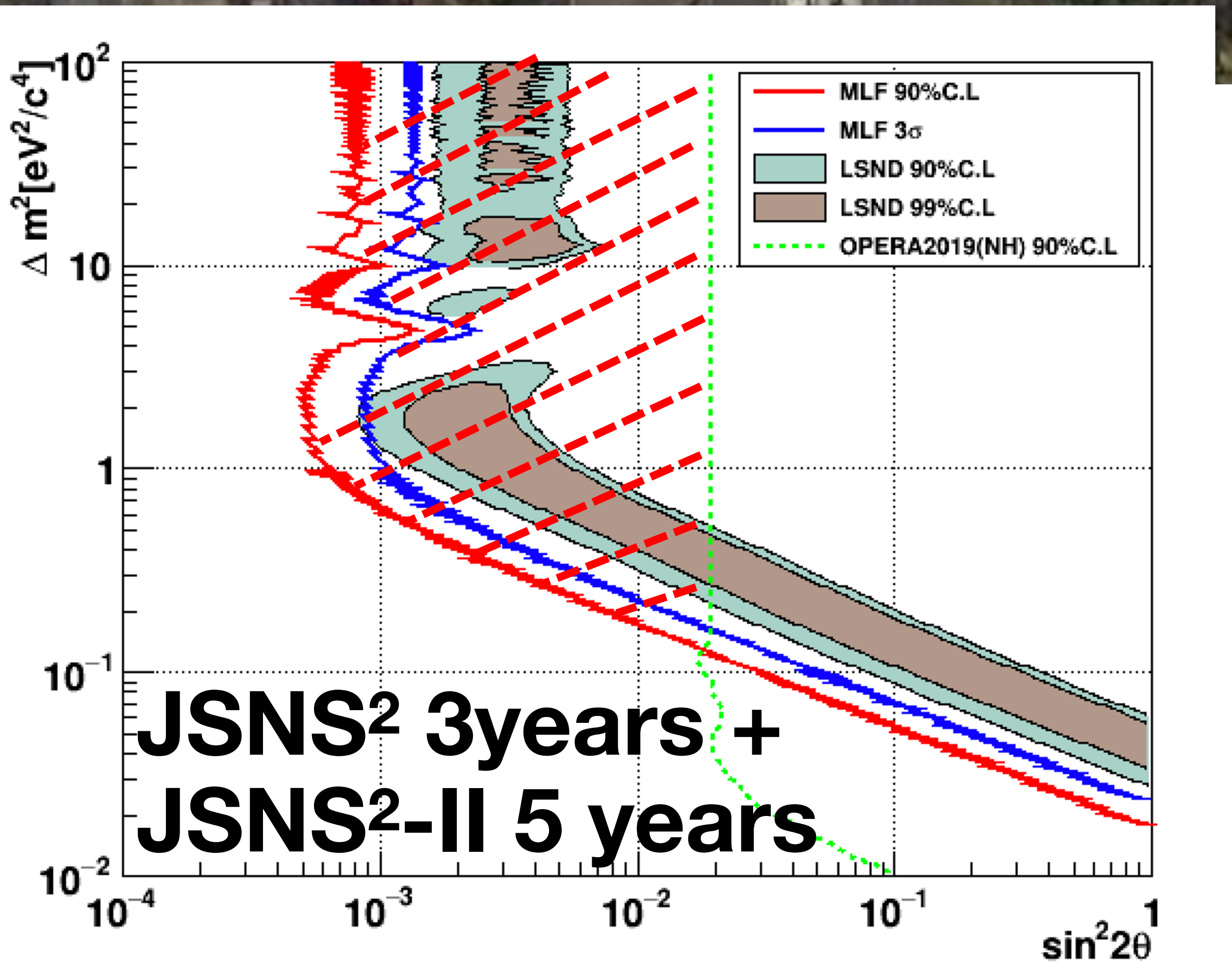
JSNS^2-II (2nd phase)

- New Far detector
=> Fiducial volume 32ton(37m^3) and 48m baseline.
=> 150m^3 for veto & Gamma-catcher.
=> 172(inner)+48(veto) PMTs.
=> Outside of MLF building.

- Two detectors (Near + Far) with two different baselines
=> The sensitivity at low Δm^2 region is much improved compared with only single 24m detector.
=> A sold conclusion on LSND anomaly.

- The construction work is being progressed rapidly.





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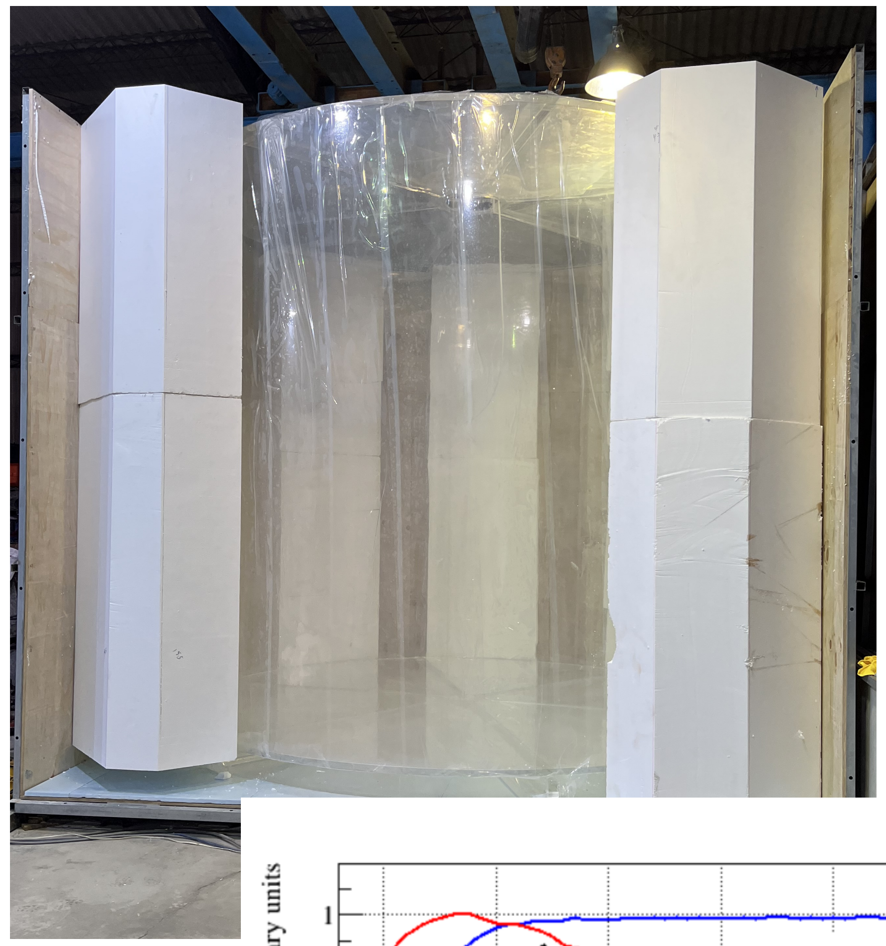
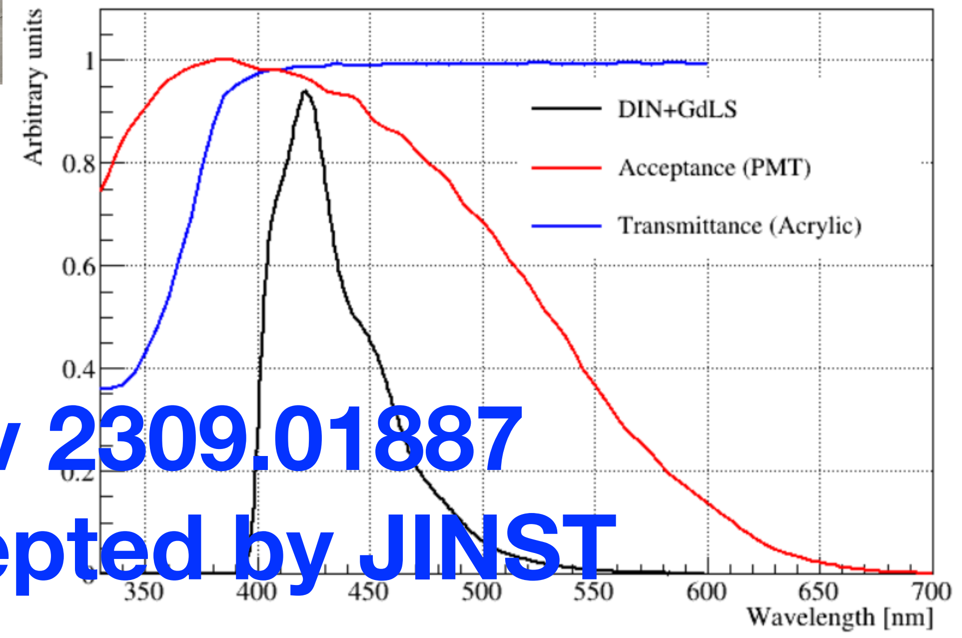
JSNS^2-II (2nd phase) - construction

- The construction of the stainless steal tanks was finished (2023 Mar)





arXiv 2309.01887
accepted by JINST

- The acrylic tank was made by Taiwan company.
- The transmittance of the acrylic => ~93% @ 400~600nm.

- 190 PMTs were donated from Double-Chooz.
- **<u>Installation of 172 PMTs for inner detector is finished!!!</u>**
- The calibration system was installed.
  -> LED / Temperature sensors

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Schedule of JSNS^2-II

Final step of the construction
-> Close to data taking!!!

Summary

- There have been **1st (2021), 2nd (2022)** and **3rd (2023)** long physics run.
  (JSNS2 single 24m detector)

- Analyses are on-going with the data.
  => **^{252}Cf 3D calibration** is developed.
    -> Good reconstruction performances in fiducial volume.
  => One side-band (prompt 60-100MeV) data are opened !!!
    -> Has been studying fast neutron background (with **PSD**).
    -> Study on the **accidental background** (using single rates).

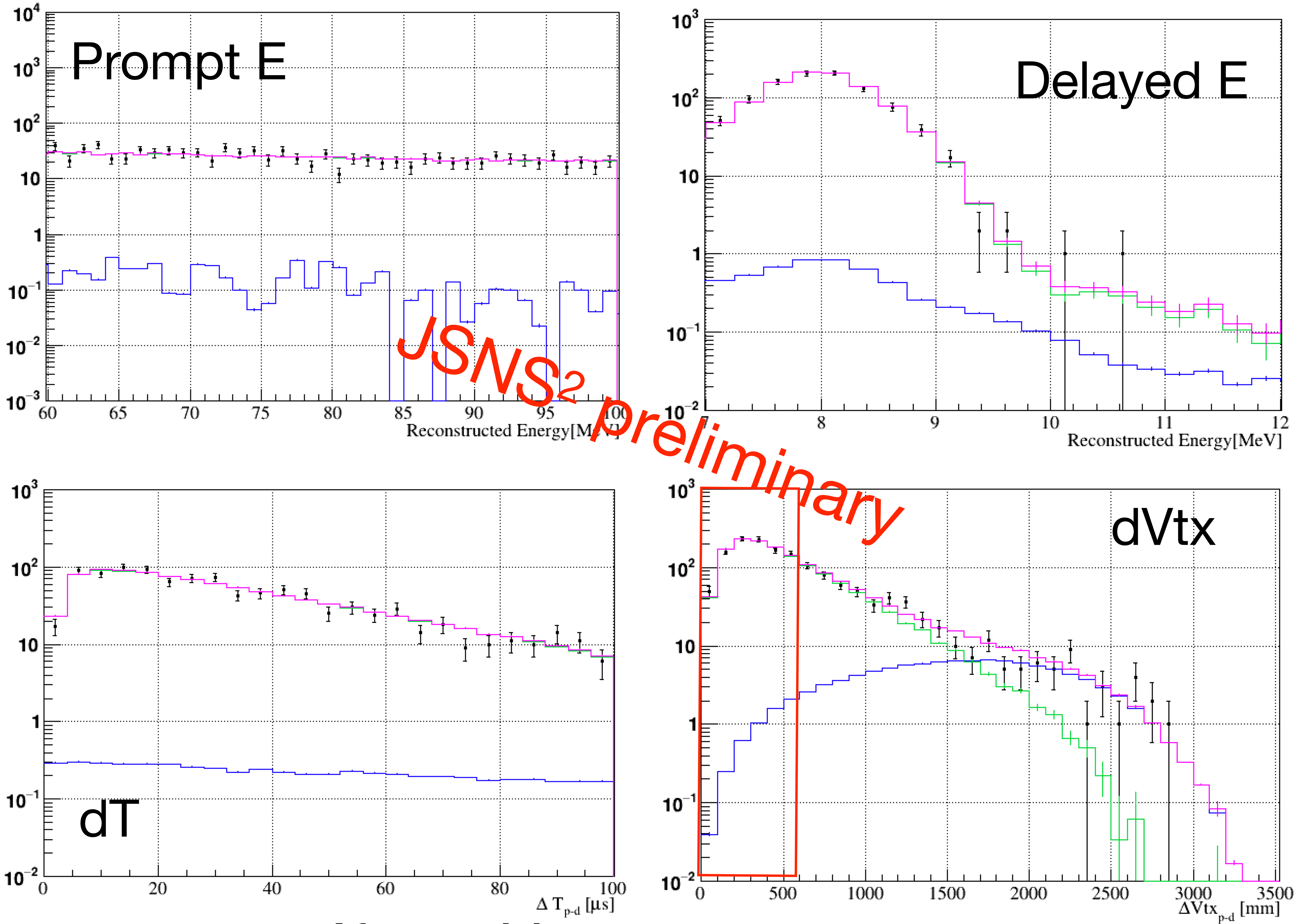
Accidental study
arXiv 2308.02722 / submitted to EPJC

- **JSNS^2-II (2nd phase) with new far detector** (48m, 32tons of GdLS)
  -> Construction works are on-going rapidly.
  -> Plan to data taking in next year.

Acrylic tank :
arXiv 2309.01887
accepted by JINST

BACKUP

First comparison of the observed vs expected events ~Side-band4 (prompt 60-100MeV)~ 1



After applying
Spatial correlation $\Delta VTX_{p\text{-}d}$ < 60cm

	Observed	Expectation
Total	**983 +- 31.4**	**988.4 +- 3.2**
Neutrons		**982.8 +- 3.2**
Accidental		**5.6 +- 0.1**

- The **observed events** are compared with the background expectations (Cosmic fast Neutrons + Accidental)
=> well agreed.
=> Cosmic fast neutrons background is dominated.
  => **Pulse Shape Discrimination(PSD)** would reject them. (Goal : 99% rejection)
  => Study is on-going.

=> After applying PSD, the accidental will be dominated.
=> **Understanding of accidental** is much improved recently. arXiv 2308.02722

Expected visible energy and Sensitivity (1st phase)

Signal	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 2.5 eV^2$ (Best fit values of MLF)	87
	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 1.2 eV^2$ (Best fit values of LSND)	62
background	$\overline{\nu}_e$ from μ^-	43
	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	3
	beam-associated fast n	$\lesssim 2$
	Cosmic-induced fast n	negligible
	Total accidental events	20

- Expected signals/bkgs for only single 24m detector (JSNS^2 TDR, arXiv:1705.08629)

- Spectral fit is sensitive to the difference of energy spectrum