TEXONO and Neutrino-Nucleus Coherent Scattering - Results and Status

Venktesh Singh/ वेंकटेश सिंह

(TEXONO Collaboration)

Central University of South Bihar, Gaya (India)

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OUTLINE

- TEXONO-ν @ KSNL
- νA_{el} (Neutrino-nucleus elastic scattering) @ KSNL : Evolution
- νAel with EC-PCGe @ KSNL : Latest Updates
- Moving On ….

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May 30, 2023

AS,
KSNPS,
NTU,
NDHU,
[Taiwan]
IHEP,
CIAE,
THU,
SCU,
[China]
METU,
DEU,
[Turkey]
~~BHU,~~
CUSB,
GLAU,
HNBGU,
[India]

❖ TEXONO Program [since 1997] : AS, KSNPS, NTU, NDHU,

❖ Low Energy Neutrino (SM+EM) physics at Kuo-Sheng Neutrino Laboratory (KSNL), 28 m from 2.9 GW(Th) reactor core, $\varphi_\nu \sim 6 \text{ X } 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$

❖ Founding partner of CDEX@CJPL Dark Matter Experiment [since 2008]

❖ Theory Program [since 2010]

Arctic Ocean
Norwegian Sea
UNITED STATES
NORWAY
SWEDEN
FINLAND
DENMARK
Helsinki
Stockholm
Murmansk
Barents Sea
Kara Sea
Laptev Sea
East Siberian Sea
Bering Sea
Anadyr'
Cherskiy
Tiksi
Saint Petersburg
Arkhangel'sk
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East China Sea
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Faisalabad
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Indore
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Mandalay
Hanoi
Haiphong
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ChiLung
Taipei
HsinChu
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CHUNGYANG SHANMO
Hualien
Penghu Islands
Choshui River
Makung
Yushan
Alishan
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Taipei
ACADEMIA SINICA
NPS-IV
Hsinchu
Ilan


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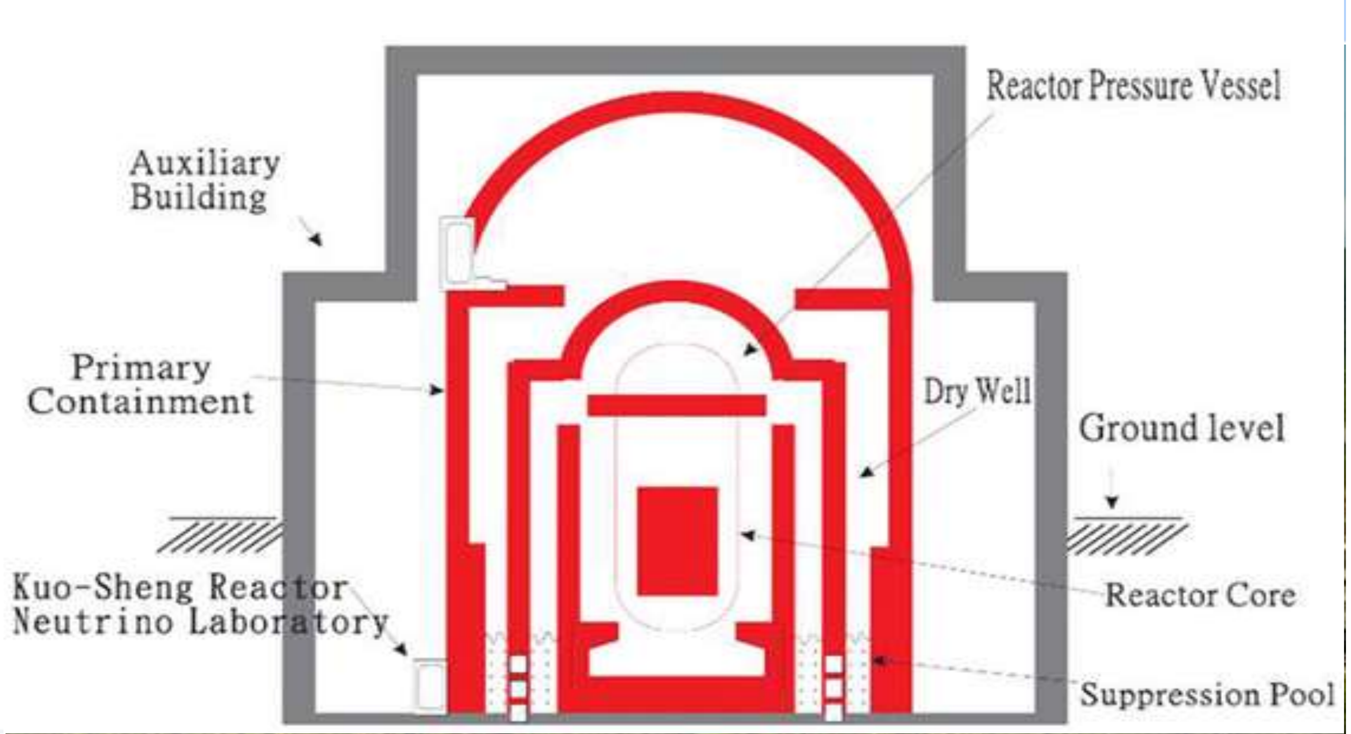
Kuo-Sheng Nuclear Power Station : Reactor Building



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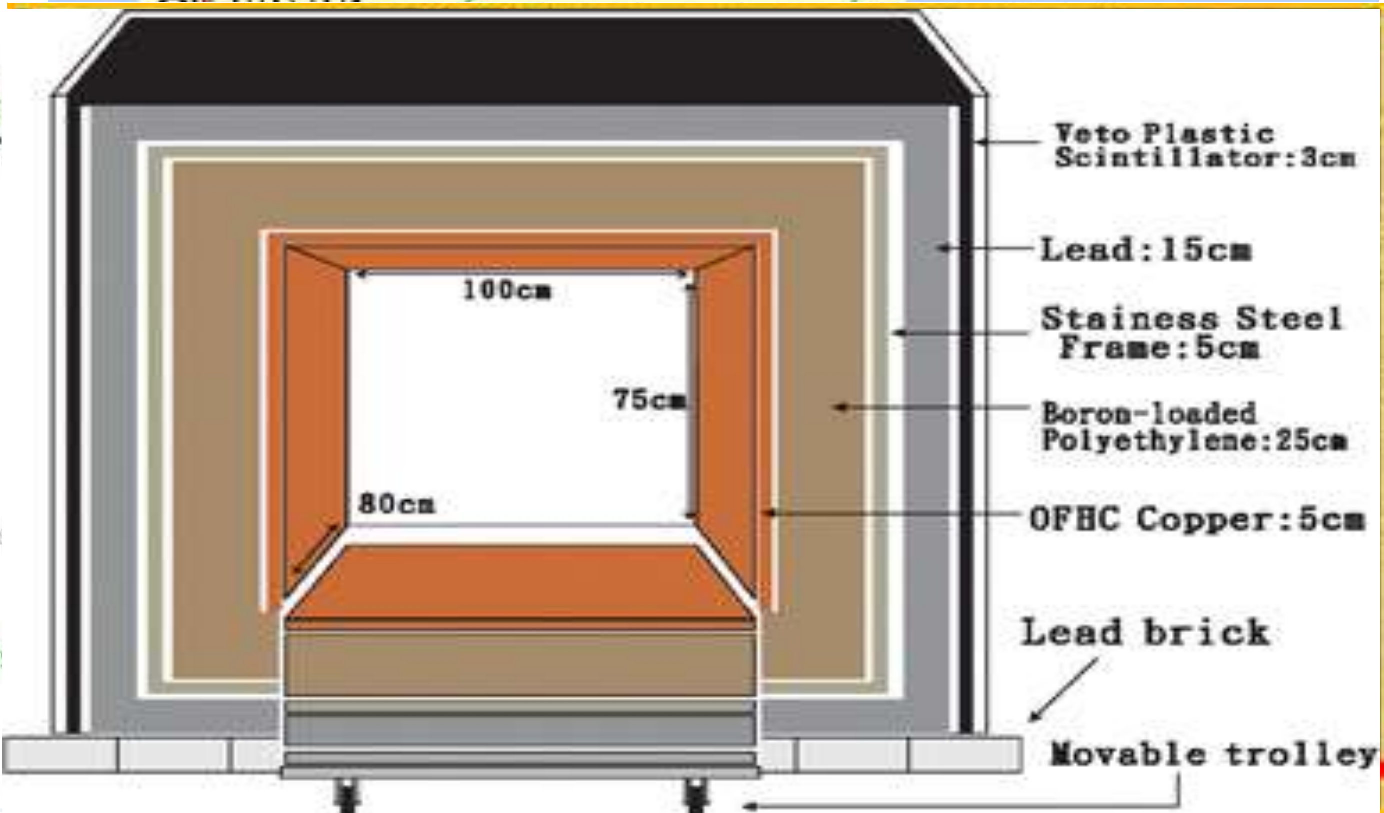
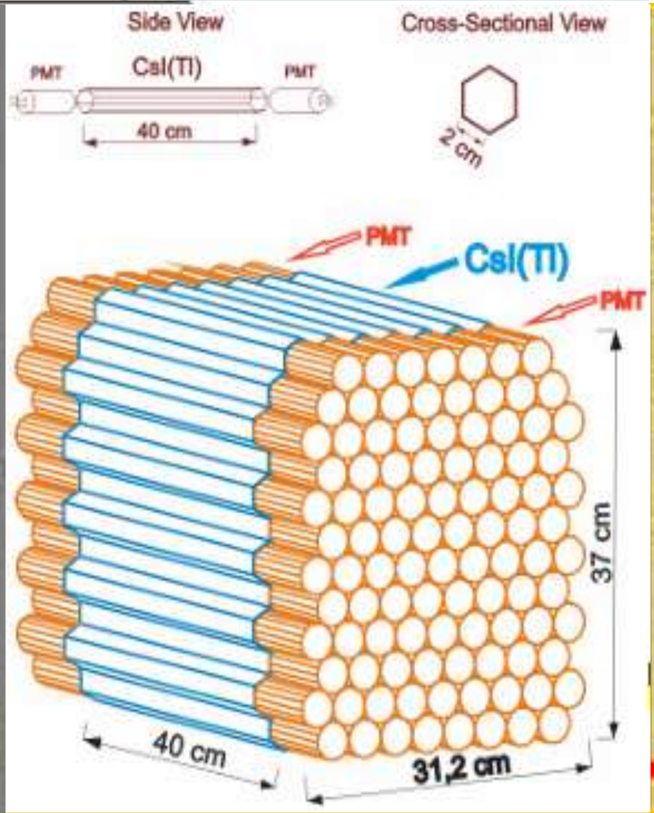

Veto Plastic
Scintillator:3cm
Lead:15cm
100cm
Stainess Steel
Frame:5cm
75cm
Boron-loaded
Polyethylene:25cm
80cm
OFHC Copper:5cm
Lead brick
Movable trolley

CsI(Tl) Detector
9×12 Array ~200 kg

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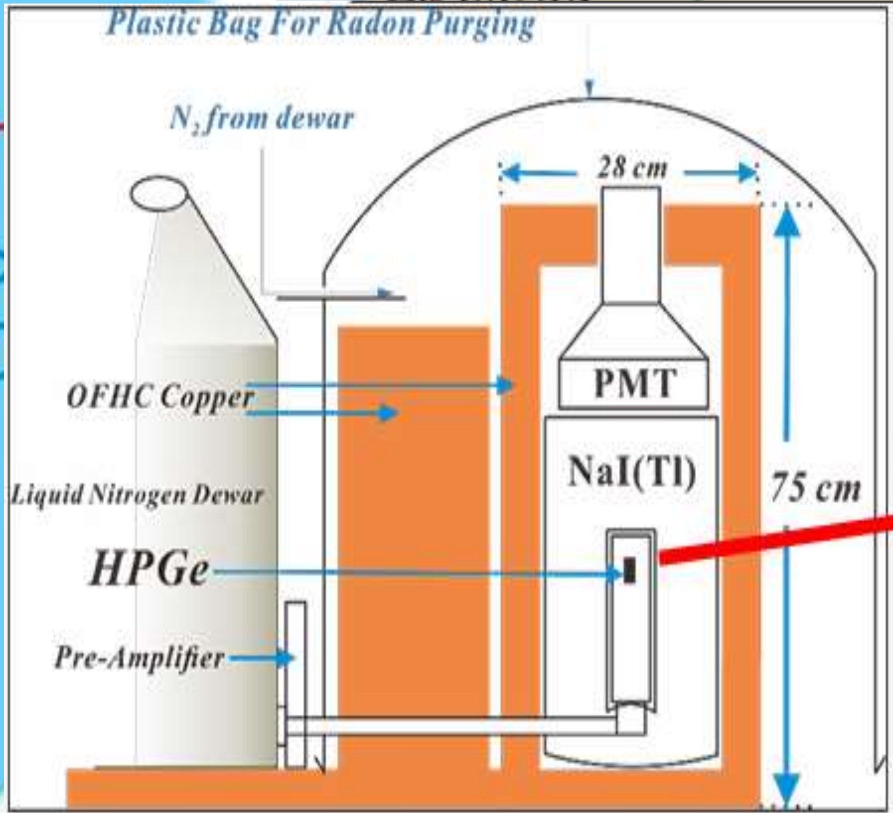
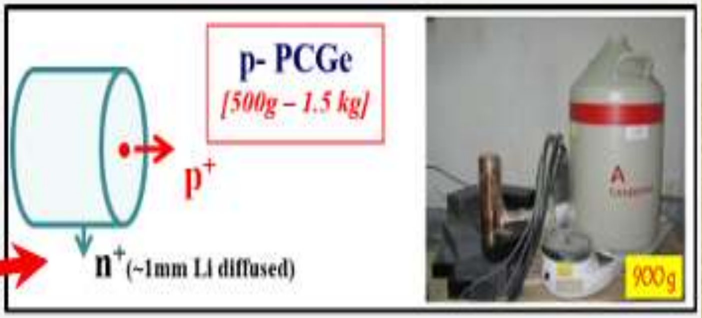
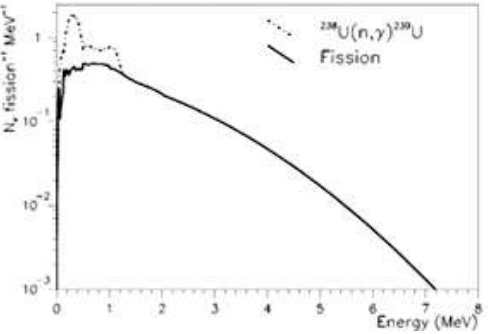

Plastic Bag For Radon Purging
N2 from dewar
28 cm
PMT
OFHC Copper
NaI(Tl)
Liquid Nitrogen Dewar
75 cm
HPGe
Pre-Amplifier

p- PCGe
[500g – 1.5 kg]
p+
n+(~1mm Li diffused)
900g

Neutrino Properties & Interactions at Reactor

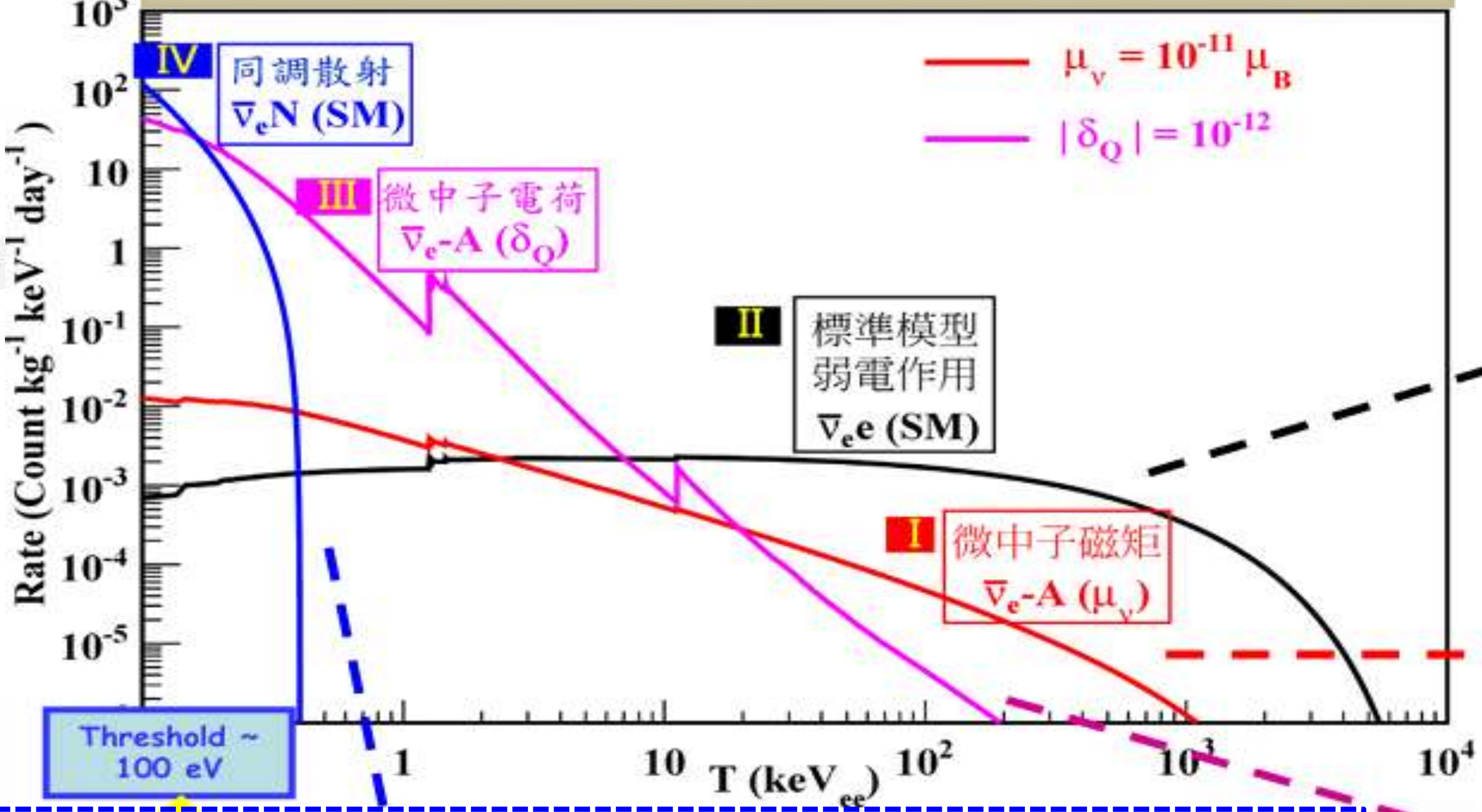
Reactor Neutrino Spectrum



KSNL: $\phi_\nu \sim 6 \times 10^{12}\ cm^{-2}\ s^{-1}$

Quality ⇐ Detector Requirements ⇒ Mass

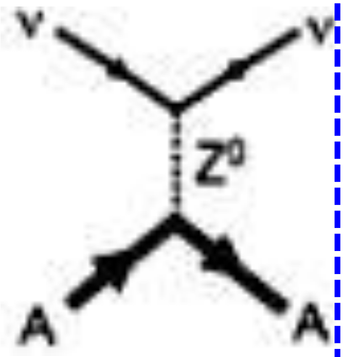
Observable Spectra with Reactor Neutrino "Beam"



ν-e Scattering SM
[PRD10] & *NSI/BSM*
[PRD10,PRD12,PRD15,PRD17]
⇨ 200 kg CsI(Tl)

Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ 1 kg HPGe

Neutrino Milli-charge
[PRD14]
⇨ sub-keV O(kg) PCGe



νN Coherent Scattering [Recent Theme; PRD16, PRD21]

- Pioneered sub-keV ULB-ULEGe / PCGe [MPLA08, NIMA16]
  - Light Dark Matter Searches @ KSNL [PRD09, PRL13, AP14, PRD19]
  - CDEX Dark Matter @ CJPL [PRD13, ……]
  - Theory Program [PLB14, …….]

sub-keV PCGe

Evolution

- "CEvNS" theoretically considered, Freedman 1974

- **TEXONO @ KSNL:**
  - Idea (Ge for reactor νA_{el}) first raised in TAUP2003 etc., following μ_ν results with threshold MeV→10 keV ,
  - Requiring "sub-keV" sensitivities (Ge Detectors)
  - Spin-off to "Light Dark Matter" searches, first results (20g ULEGe @ 220eV) 2007
  - Inspire theory program on ($\nu/\chi/\alpha$) - Atom cross - sections

- **CEνNS proposed with ν @ π-DAR, Scholberg 2006**
  - Experimental Observations since 2017, and BEYOND.

- **CoGeNT:**
  - Demonstration of "Point-Contact Ge" 2007
  - large modular mass detectors → νA_{el} + LDM + $0\nu\beta\beta$

- **CDEX @ CJPL:**
  - Ge for νA_{el}: catalyzed foundation of CJPL in China & CDEX program
  - Dedicated LDM experiment with Ge, starts 2010
  - ~2015: explore future $0\nu\beta\beta$ with Ge
  - ~2023: return to NG Reactor νA_{el} at Sanmen (China).

QM Coherency as a Qualifier for νA_{el} [PRD16; PRD21]

- Coherency in QM superpositions among scattering amplitudes from individual nucleons is central to νA_{el} interactions. $\nu A_{el}: \quad \nu + A(Z,N) \to \nu + A(Z,N)$

- Coherent Vs Elastic are TWO distinct aspects of C+E-νNS !!

- QM Coherency (for EW-process) is central

- Coherency is a continuous variable dependent on q^2 via E_ν & Target A(Z, N) in νA_{el}

- Define a quantifiable parameter beyond qualitative descriptions

- Parameterize: $\alpha(q^2) \equiv \cos\langle\phi\rangle \in [0, 1]$, i.e., (the degree of coherency in νA_{el}) where $\langle\phi\rangle(q^2)$ is the QM phase misalignment angle between two non-identical nucleons in A(Z, N)

- Unified Description for all A(Z, N) ; consistent comparison possible.

Coherency in Neutrino-Nucleus Elastic Scattering

- ❖ Quantify transitions between QM Coherency & Decoherency
- ❖ Universal Characterization between different Sources & Target

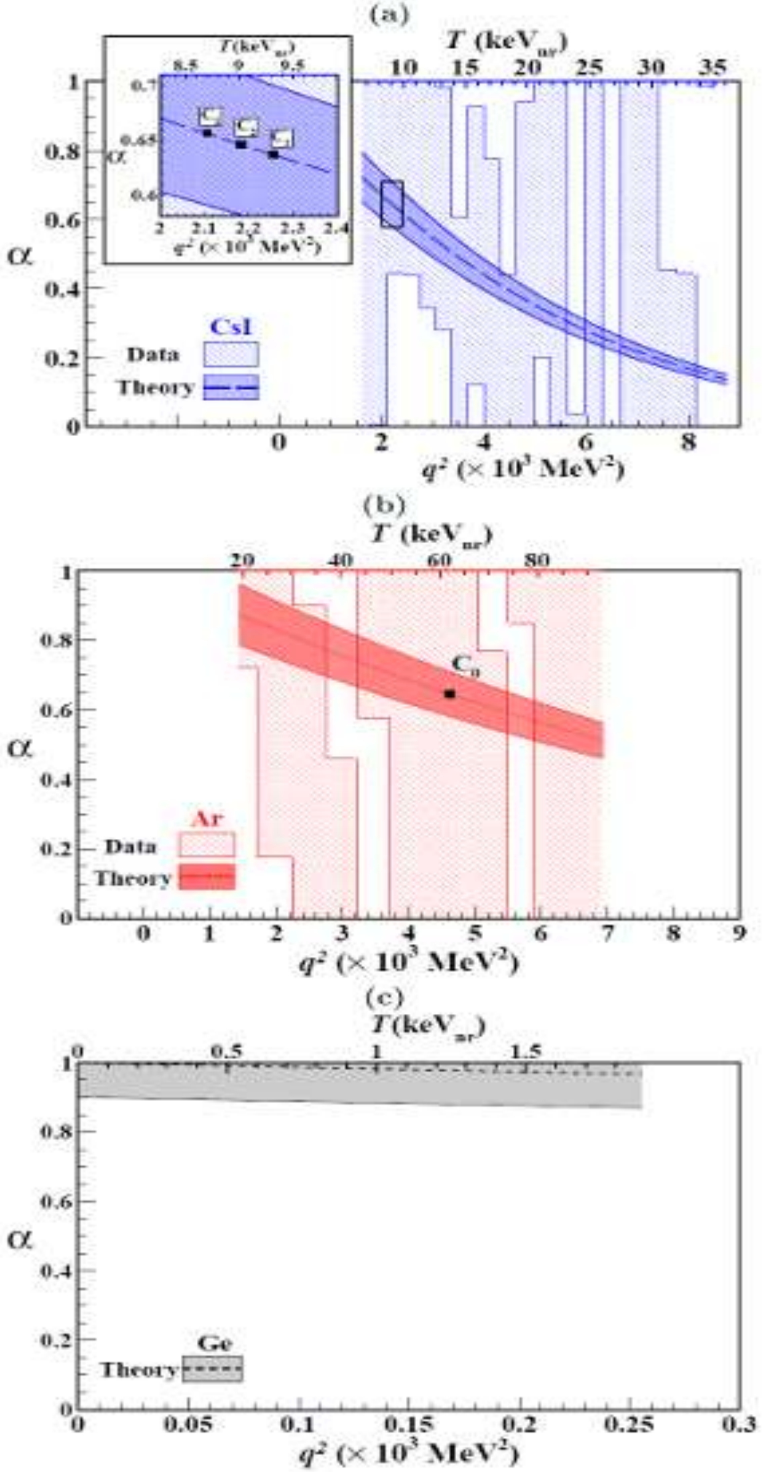
νA_{el} with Reactor Neutrinos:

- ➢ Different kinematics regimes : $q^2 \rightarrow 0$; Form Factor $F(q^2) = 1$
- ➢ Full QM Coherency **[DAR-νN @ ~0.6 - 0.7]**
- ➢ BSM/NSI Searches → **no degeneracy** with nuclear physics FF uncertainties

Measurements on α from COHERENT (a) CsI and (b) Ar data with DAR-π-ν. **The stripe-shaded areas are the 1-σ allowed regions derived from the reduction in cross-section relative to the complete coherency conditions independent of nuclear physics input.**
The dark-shaded regions are the theoretical expectations adopting the nuclear form factor formulation of Eq. with a ±1σ uncertainty of 10%.

$$F_A(q^2) = \left[\frac{3}{qR_0}\right] \, j_1(qR_0) \, \exp\left[-\frac{1}{2}q^2 s^2\right]$$

The α(q²) -values for different nuclei can be consistently compared. Labels C0,1,2,3 correspond to the configurations, where α0<α1, α0=α2 and α0>α3 despite having ξ0>ξ1,2,3 in all cases.
(c) The sensitivity with the theoretical projections applied to reactor-ν on Ge covering the complete q² -range for nuclear recoils.



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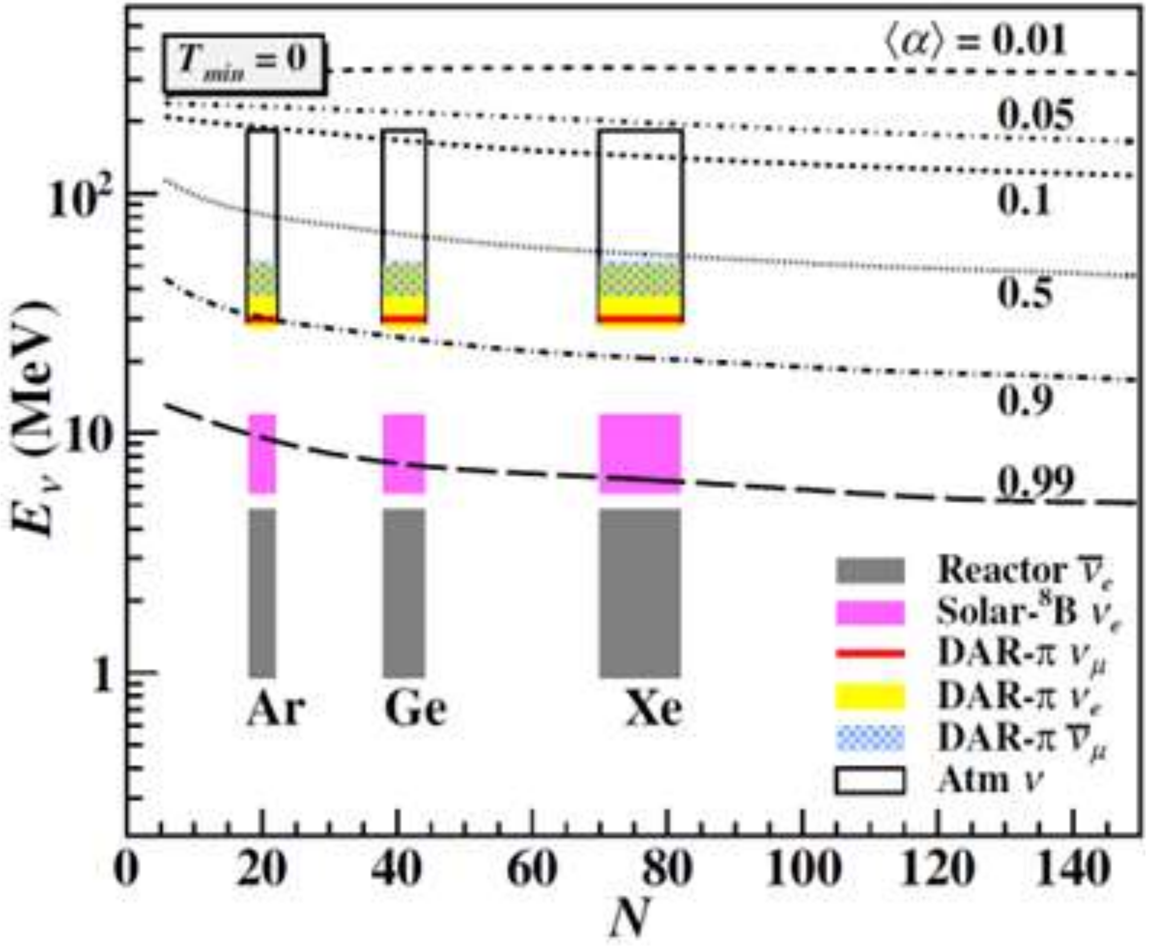


$$\alpha \equiv \cos\langle\phi\rangle \in [0,1]$$

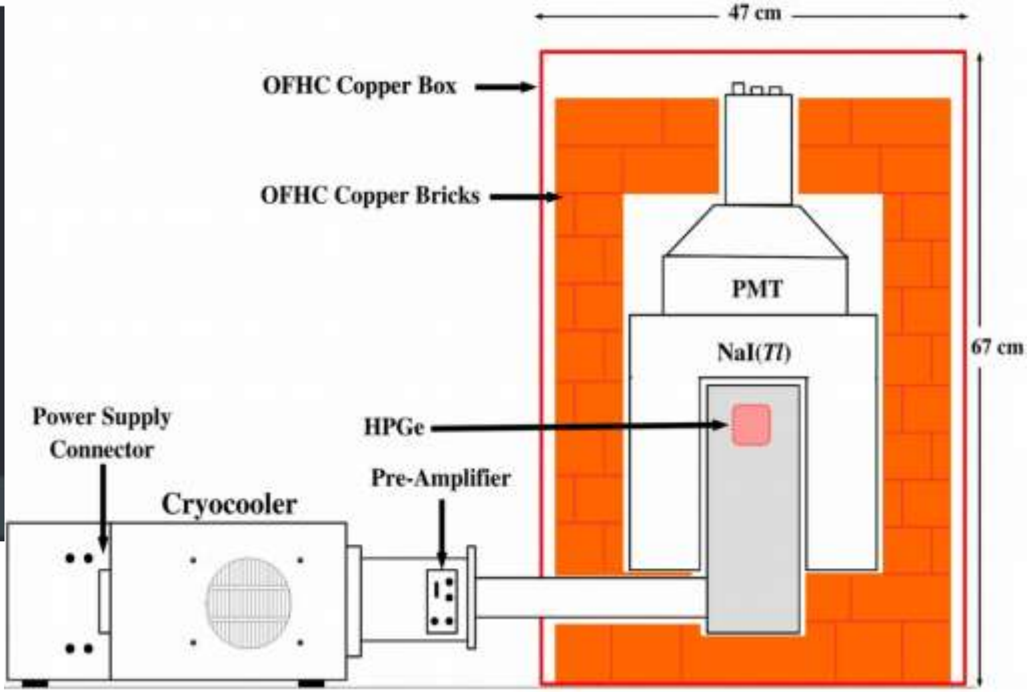
$\langle\phi\rangle$: Averaged Decoherency Angle

The contours of the mean degree of coherency <α> on the (N, E_ν) plane at zero minimum observable energy (T_{min}=0), with bands of neutrino sources and target nuclei superimposed. The ranges in E_ν correspond to FWHM in [$\Phi_\nu . \sigma \nu A_{el}$].

Seek Input / Inspirations:

❖ **Derive α from basics QM & Relate to nuclear physics**

νA_{el} with Electro-cooled PCGe



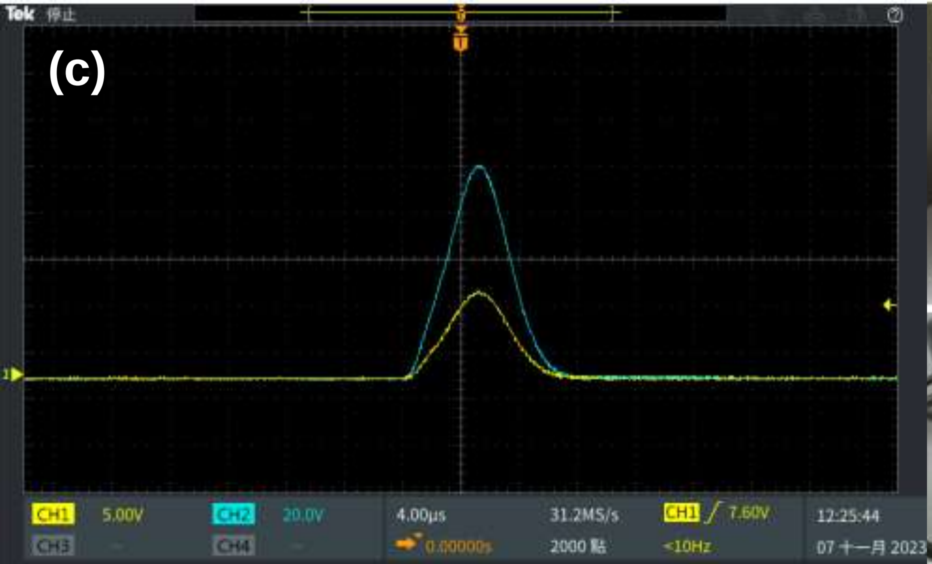
(a) Output of the preamplifier without applying the high voltage for the two-output channel is shown in blue and yellow, whereas the signal inhibit is shown in red.

(b) Output of the preamplifier after applying the high voltage.

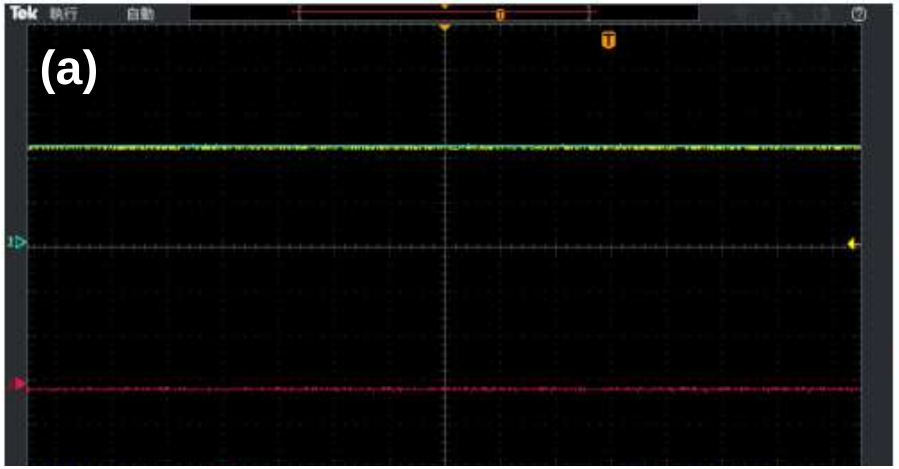
(c) Shaping amplifiers output of the preamplifier pulse.

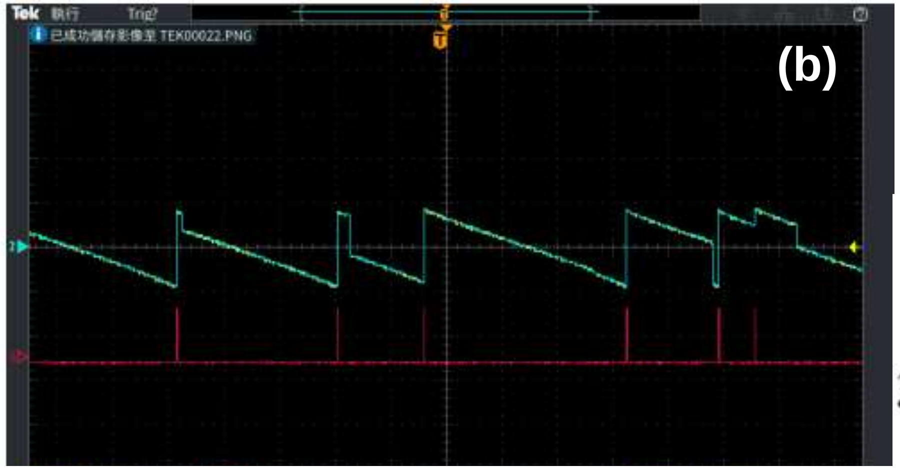
Experimental detector shielding (50 ton) along with NaI (Tl) ACV detector. The EC-pPC is kept inside the shielding.

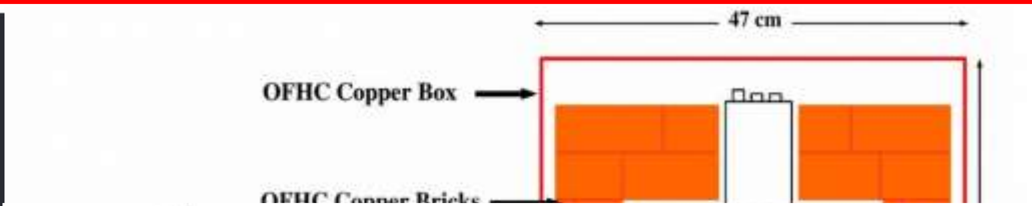
EC-pPC HV = +3300V, Power = 80 watt. T= –190 ^{0}C, Room T= 19^{0}C Power <80 watt.



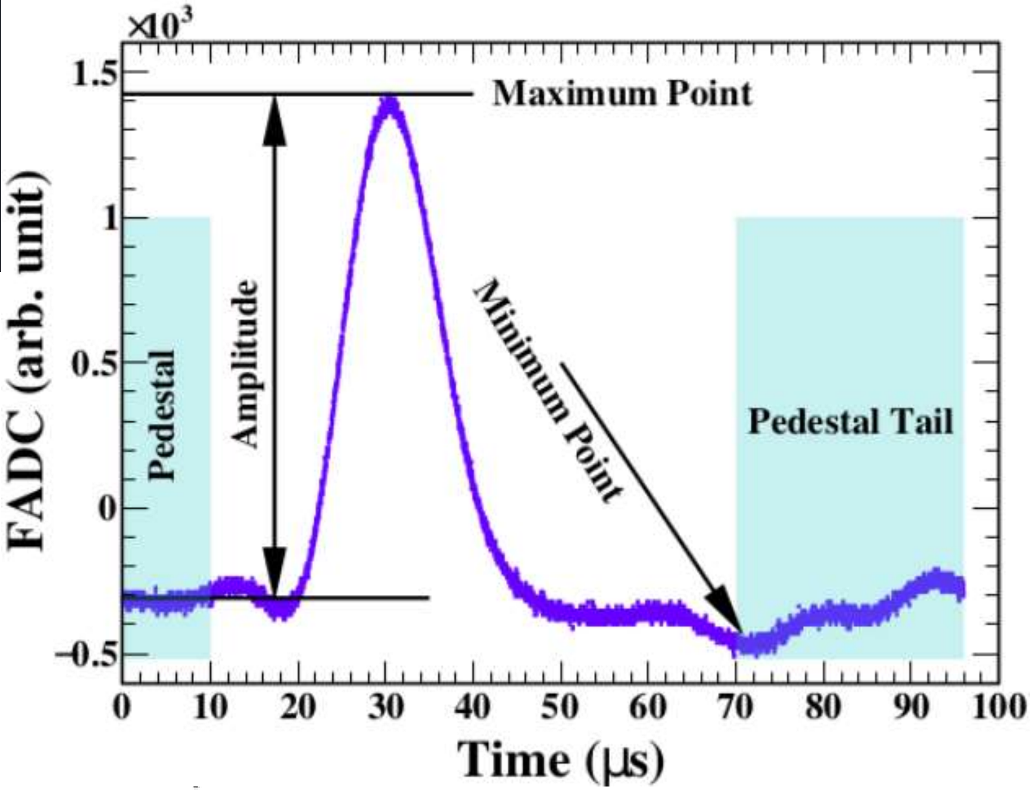
νA_{el} with Electro-cooled PCGe

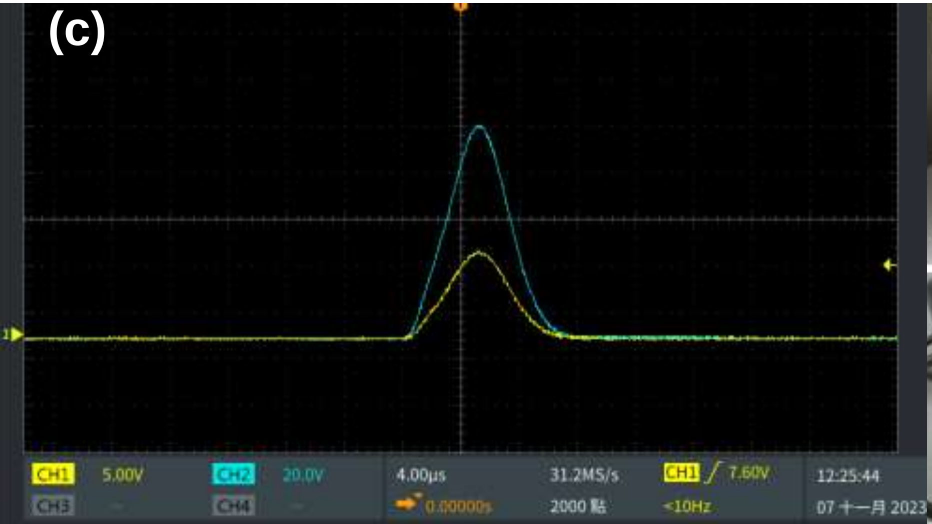




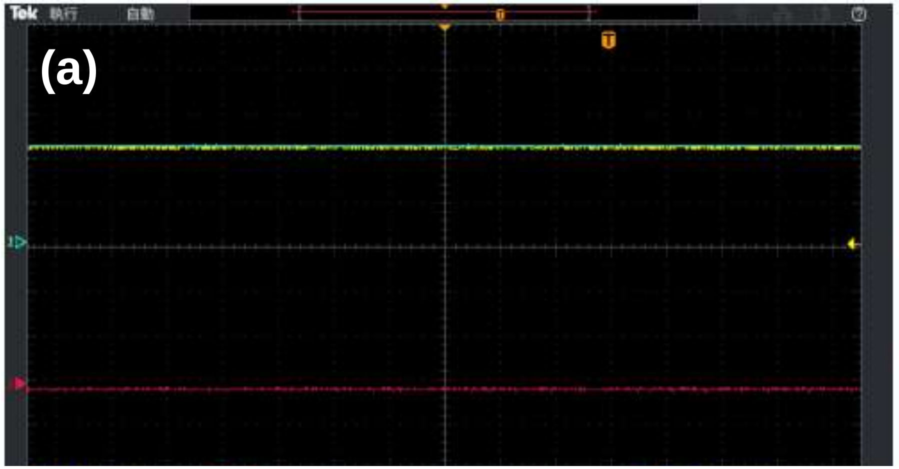


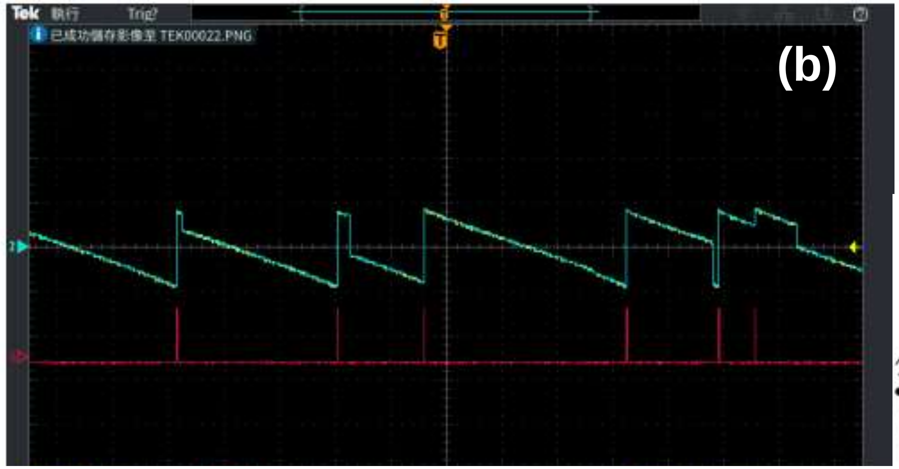
When charge deposition in the detector above a pre-established threshold, or after a predetermined time interval, the saw-tooth waveform represents the temporal structures of "RESETs" Physics signals with energy proportional to step size are represented by the steps between RESETs. This output of the preamplifier is then sent to the SA and TA. The SA output after giving the input of preamplifier pulse is shown (c). The shaping time is kept at 2μs. The pulse form TA helps in understanding the estimation of rise time and versus energy plot which helps in separation bulk and surface events. These SA and TA pulses were digitized with 200 MHz and 60 MHz flash analog-to-digital converters.

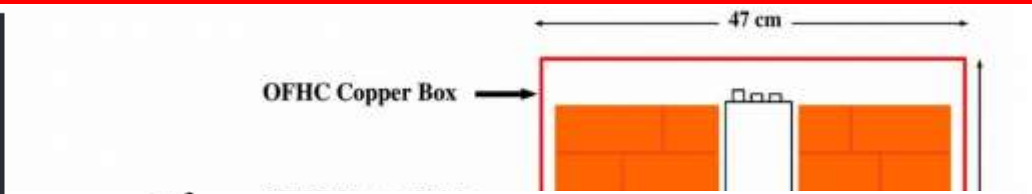


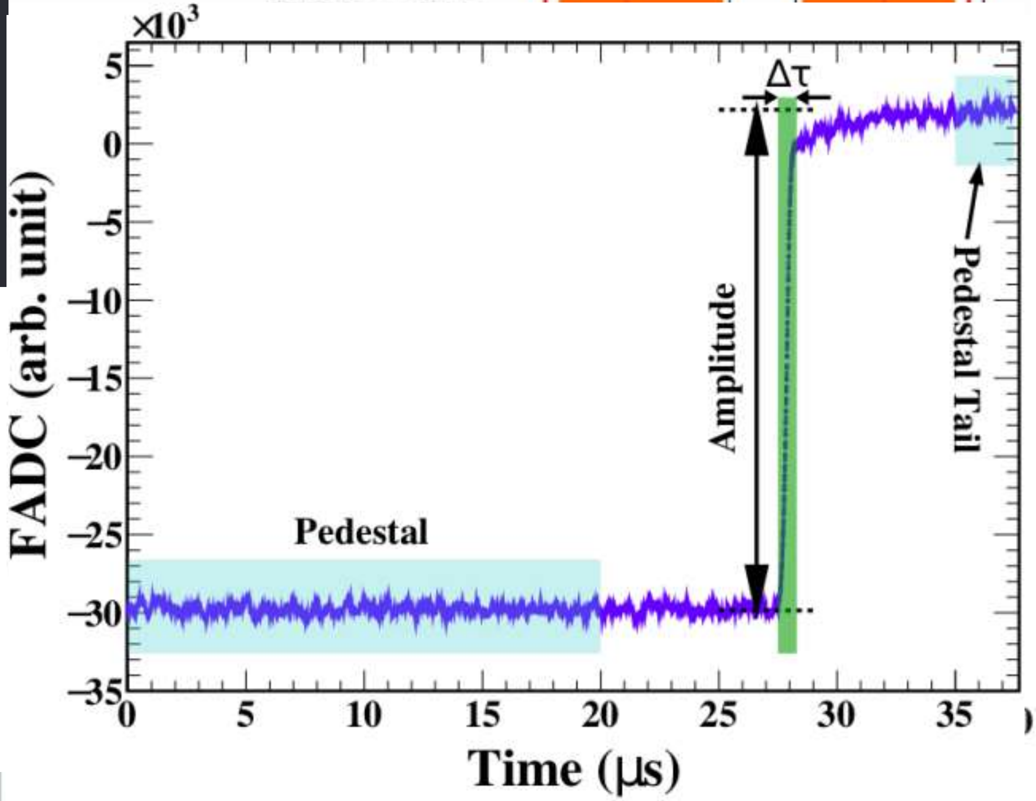


νA_{el} with Electro-cooled PCGe









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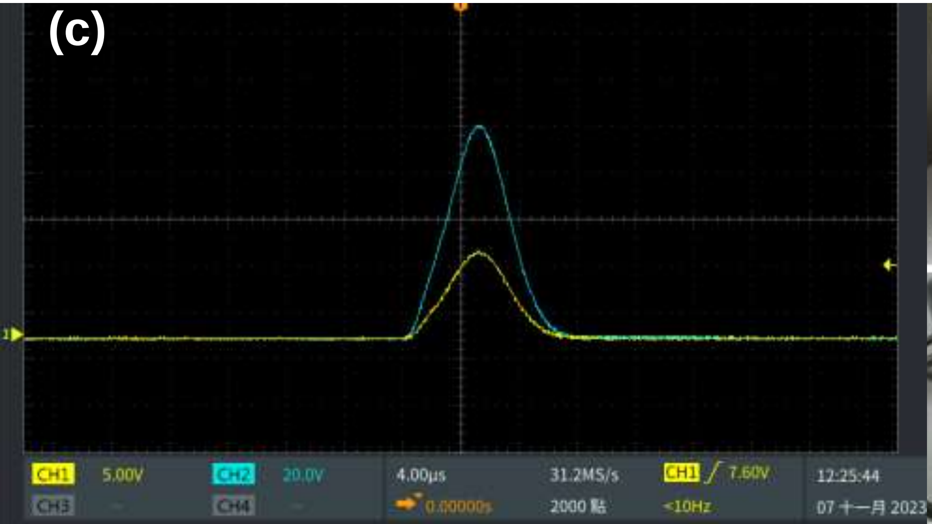
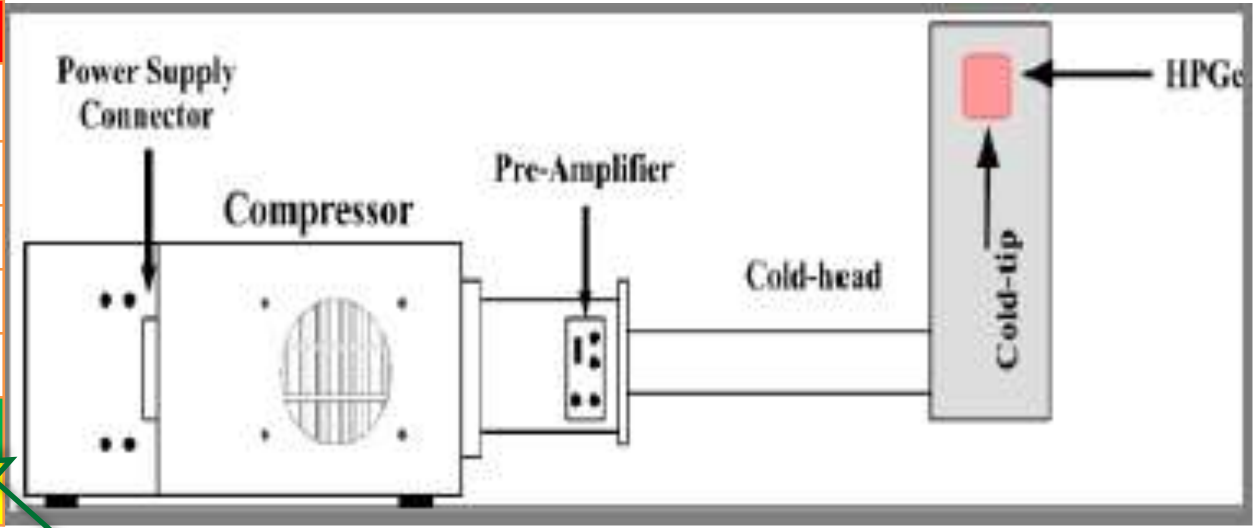


νA_{el} with Electro-cooled PCGe

	Generation	Mass (g)	Pulsar FWHM (eV_{ee})	Threshold (eV_{ee})
LN_2	G1	500	130	500
	G2	900	100	300
Electro-cool	G3	500	70	200
		900	70	~230
	G3+	1430	~60	~160
	G3++	1430	70	200
	G4	900	~50	~150

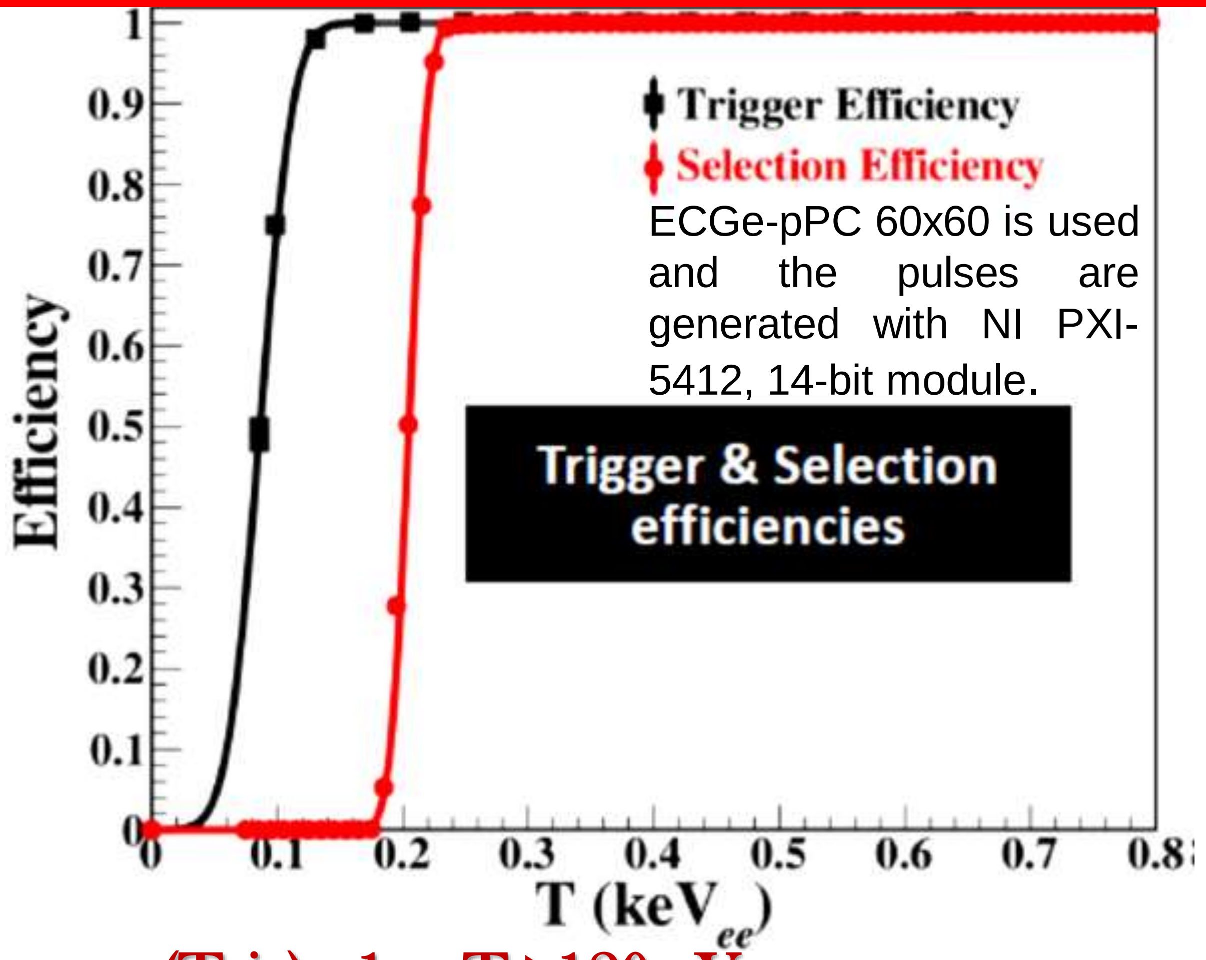


this analysis

νA_{el} Data Analysis Strategies:

- Events identified in 8 categories
  - ✓ $CR^{\pm} \otimes AC^{\pm} \otimes BS$ [Cosmic – Ray / anti-Compton / Bulk or Surface]
  - ✓ $CR^{-} \otimes AC^{-} \otimes B$ are PHY candidate (ν/χ) events, uncorrelated with other signals
  - ✓ Others are "background / benchmark" samples, In situ with PHYS data
- Benchmark samples for optimizing analysis parameters & procedures, monitor stability & performance, measuring efficiencies, & reducing systematic uncertainties
- Optimized procedures & parameters applied to analysis of PHYS samples

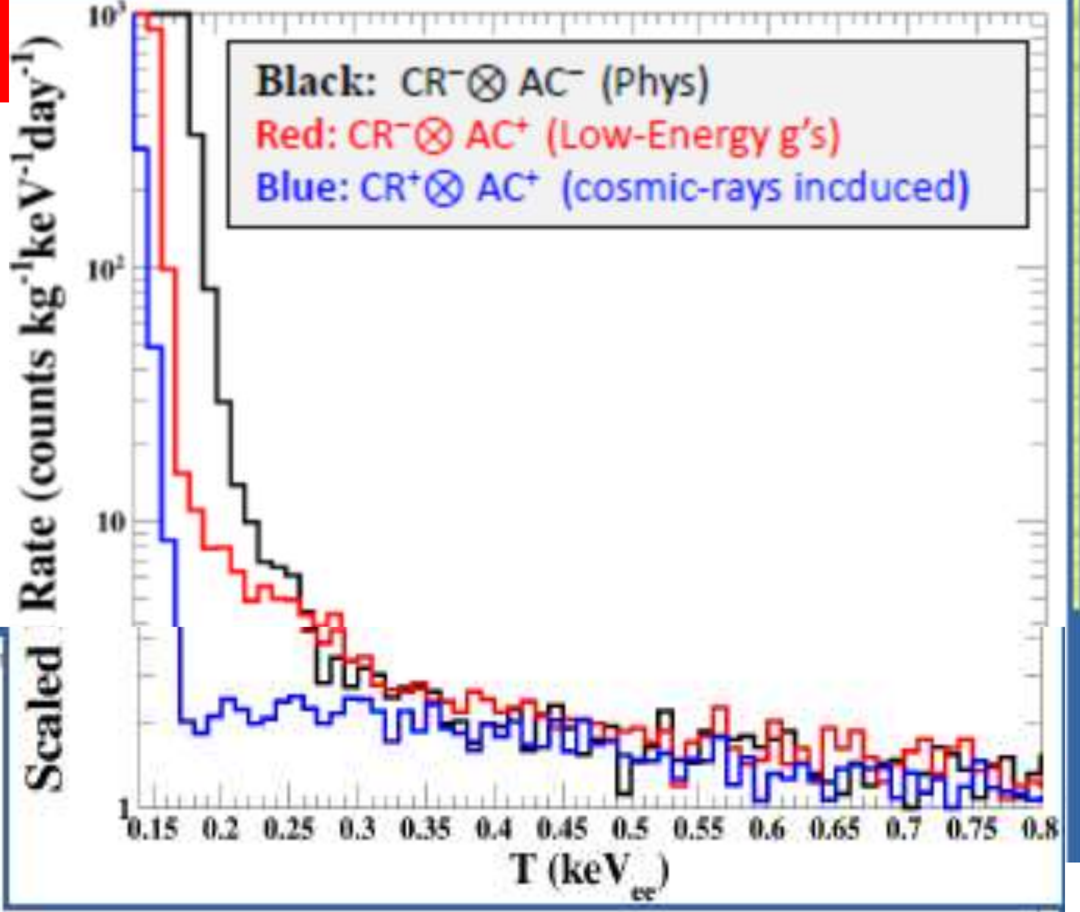
Analysis and Preliminary Results

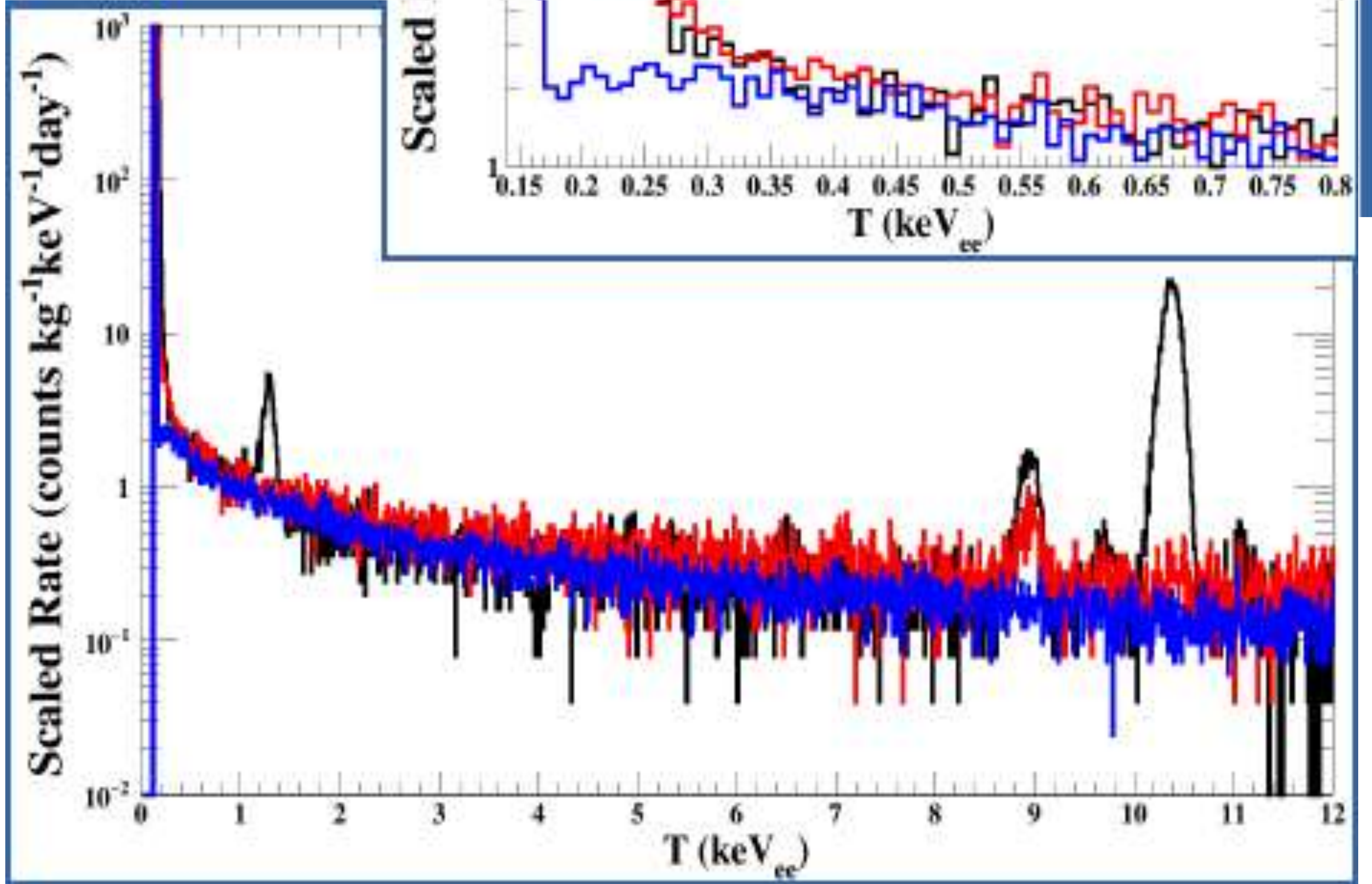


ε(Trig) ~1 at T >120 eV$_{ee}$

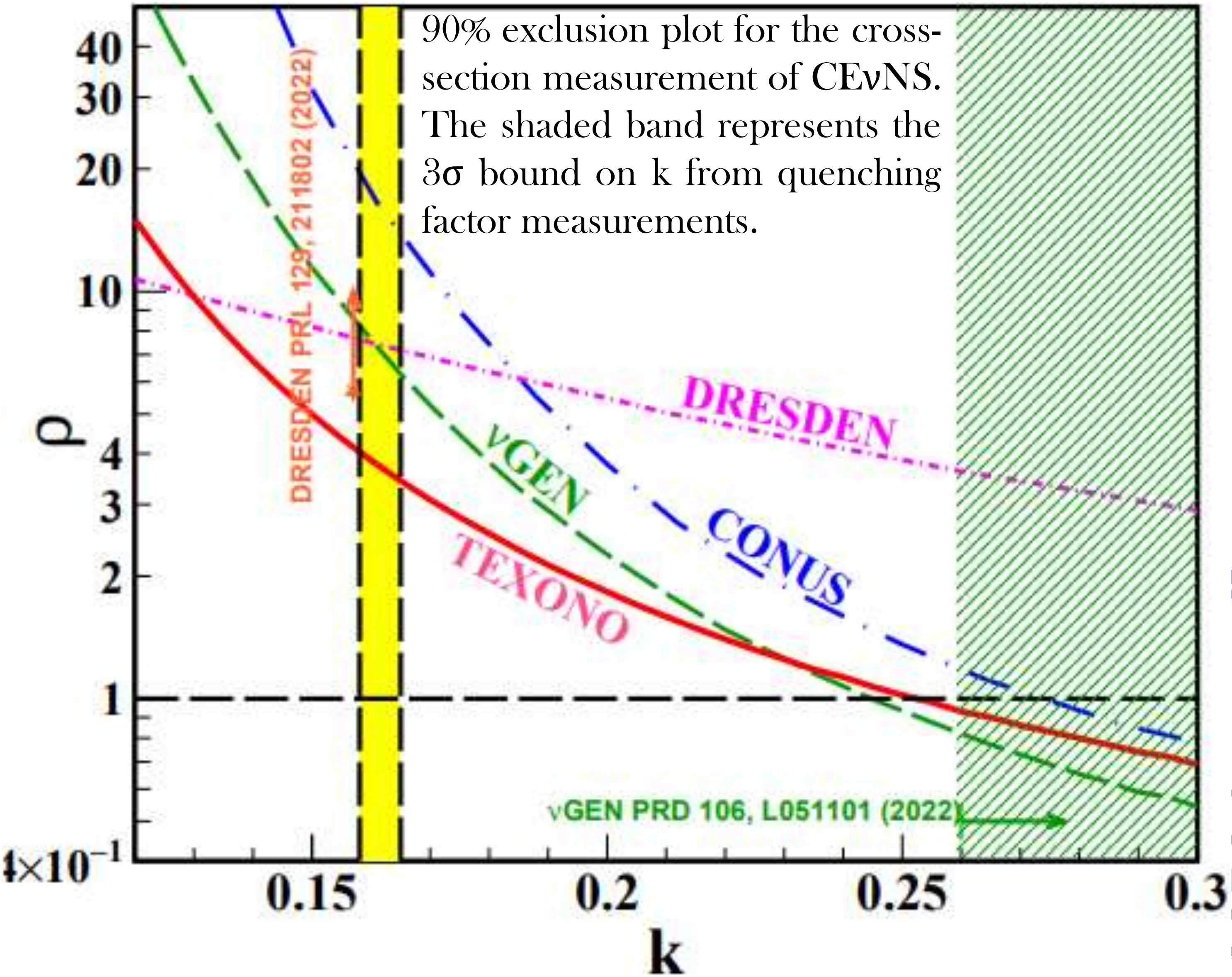
- Room to reduce threshold on ε(selection) with improving new software
- Improve PHYS reach of same data

Coincidence in Benchmark Samples
⇒ **Background Lower Threshold than Phys.**
⇒ **Improve in PSD B/S/Noise ID**





"Preliminary" Results Presented at TAUP-2023



- **Reactor ON/OFF:** 65/438 kg-days G3++
- **ρ:** Ratio of measured to SM cross-sections
- **3σ allowed** for k from QF measurement data
- **TEXONO** [with 200eV threshold]

@ 90% CL Upper Limit: $\rho = \frac{\sigma_{Measured}}{\sigma_{SM}}$

ρ < 4.2

@Lindhard SM-k= 0.157

CONUS recent Results [arXiv2401]:

ρ < 2 at SM-k

Similar experimental performance, but T with lower flux, less mass]

$$\chi^2 = \sum_i \left(\frac{N_i - \rho\mu_i(k) - Xe_{Th}}{\sigma_i}\right)^2 + \left(\frac{Xe - Xe_{Th}}{\sigma_{Th}}\right)^2$$

Where the N_i, σ_i are the experimentally measured counts and the corresponding error for i^{th} bin. $\mu_i(k)$ is the theoretical calculated count rate. The predicted contribution of ^{135}Xe and its corresponding error at threshold, denoted by Xe_{Th} and σ_{Th} respectively. Here ρ estimate the measured νA_{el} cross section compared to the SM prediction.

In order to estimate the ρ for a particular value of Lindhard k, χ^2_{min} was searched by varying the two free parameter ρ and Xe. After getting the χ^2_{min} it was found that data is favoring negative ρ for the k values (0.120-0.300) as we have not observed

August 2024: Despite being an original target and hard efforts by the team towards completing 245 / 560 kg - days G3++ ON / OFF data, we are not ready to update these results.

Near-threshold Analysis Procedures Require

- Produce Numerous Expected Features with in situ Benchmark samples

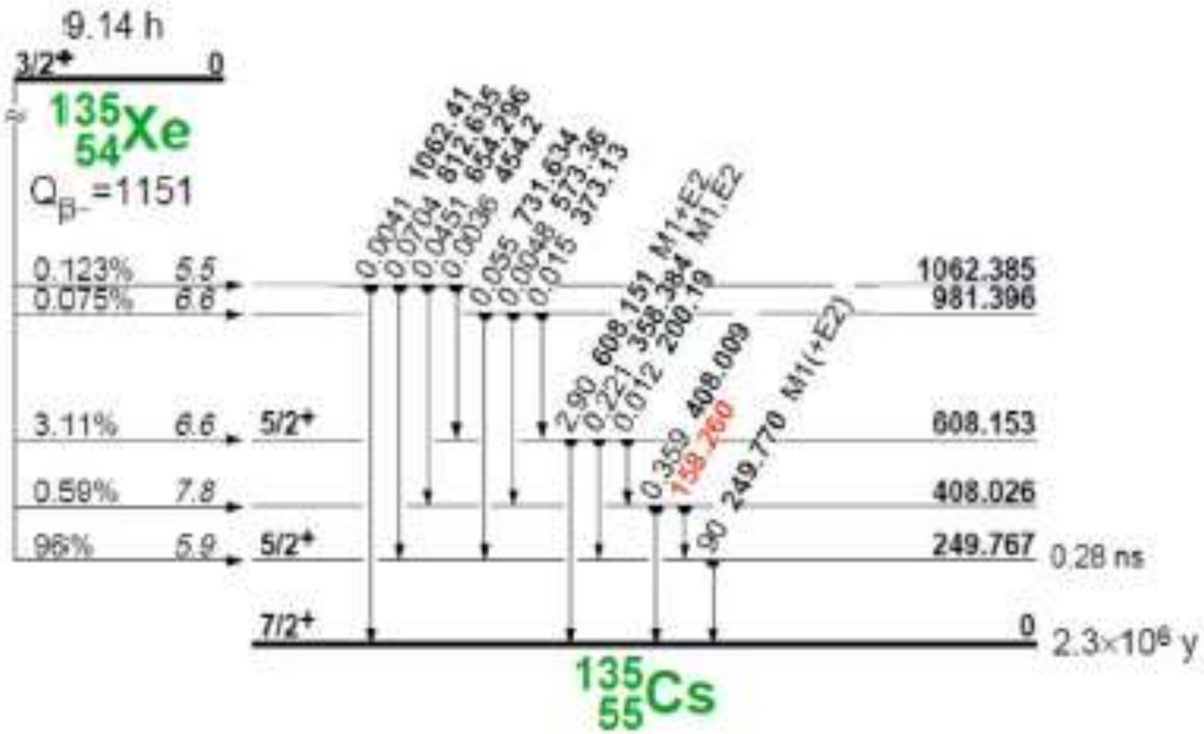
Challenges for THIS analysis:

- Most data taken during the difficult times of COVID lockdown
- DAQ @ KSNL are unattended and hardware operating at sub-optimal conditions without repairs for long time
- Workable DAQ Live Time-to-Real Time Ratio ~ only 1/2 to 2/3
- Instabilities detection and correction with subsequent analysis requires big efforts

Status:

- Not all analysis of all benchmark data sets are producing expected features and uncertainties YET ......

Reactor ON – related ^{135}Xe Background: 250keV gamma (γ)



- A Decay Product of ^{235}U- β

  $^{135}Xe \longrightarrow {}^{135}Cs^{*} + \bar{\nu}_e + e^-$ *[Half-life = 9.14 h]*

  $^{135}Cs^{*} \longrightarrow {}^{135}Cs + \gamma$ (249.8 keV)

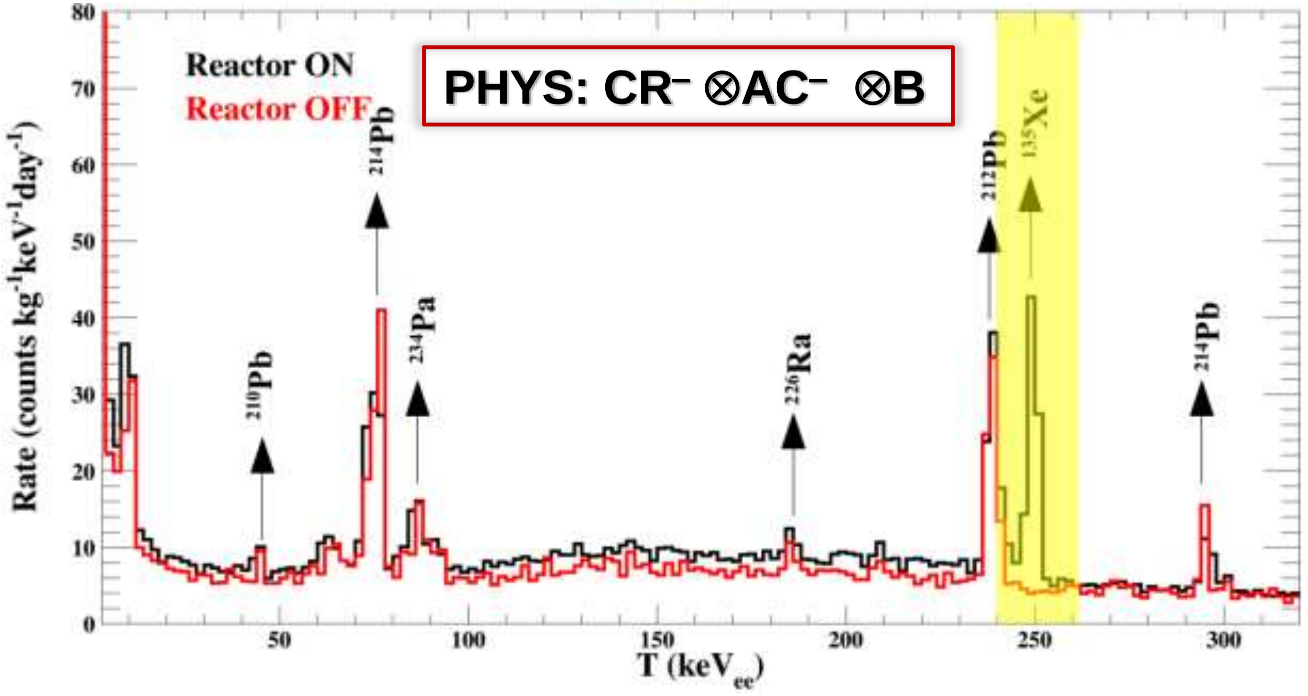
- Very Good Neutron Absorber Poison For Reactor
- Contributes 2.9 ± 0.8 counts.kg^{-1}.keV^{-1}.day^{-1}

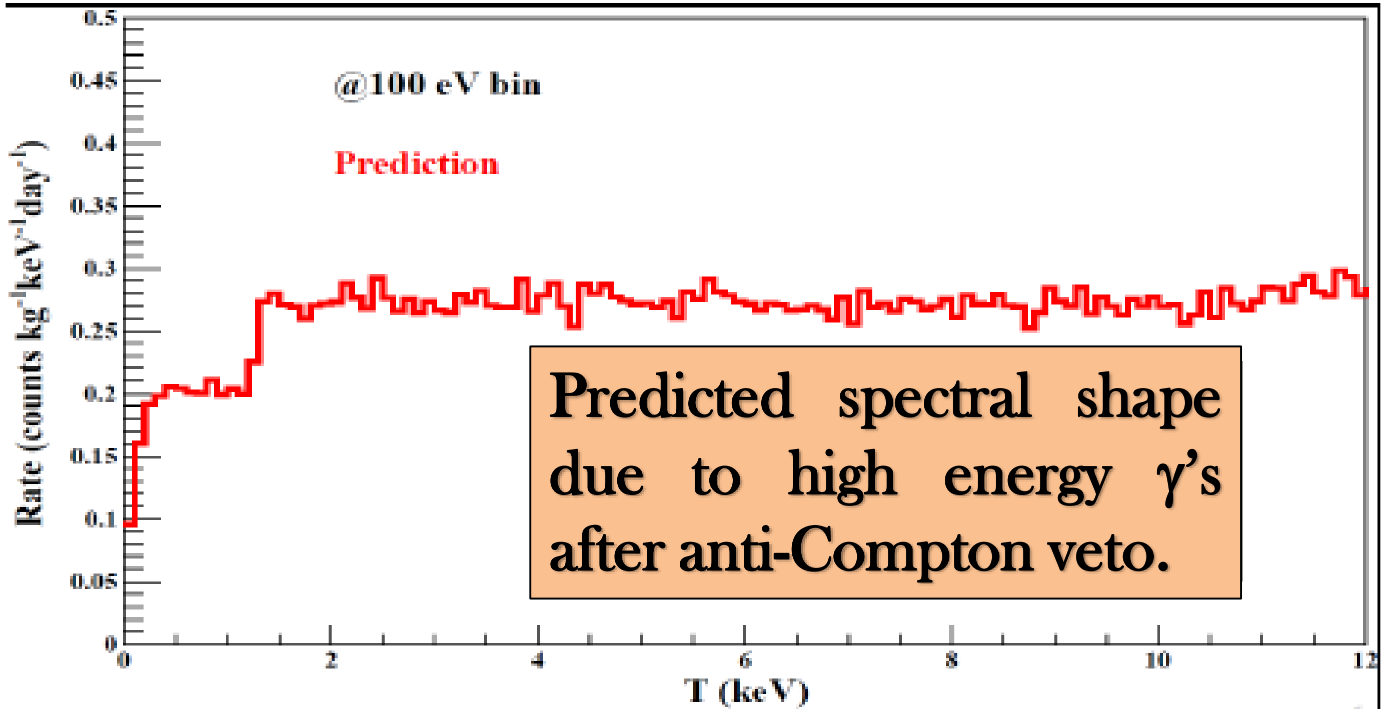
  @ sub-keV energy region

- Reactor ON PHYS background

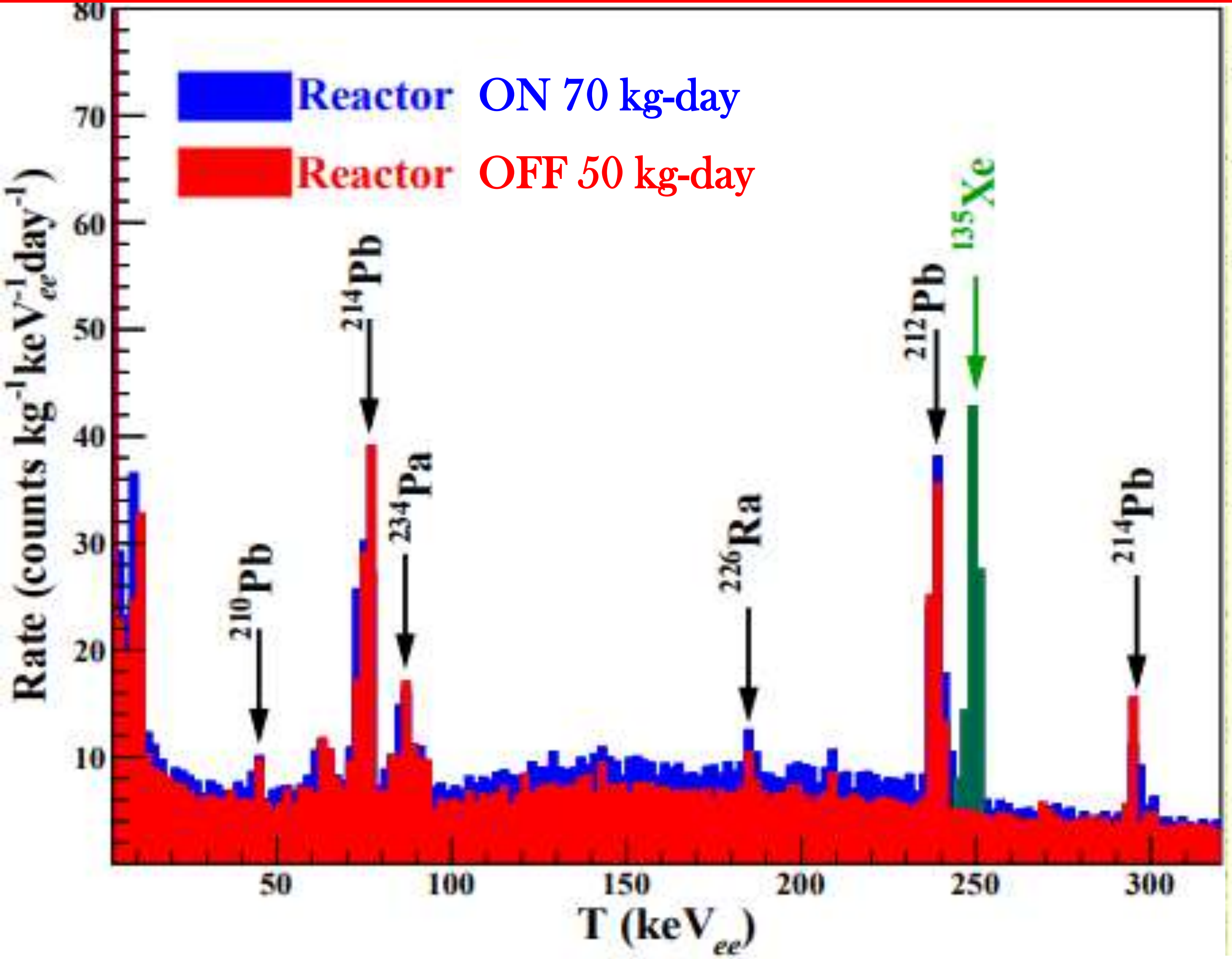
  ~90 counts.kg^{-1}.keV^{-1}.day^{-1}

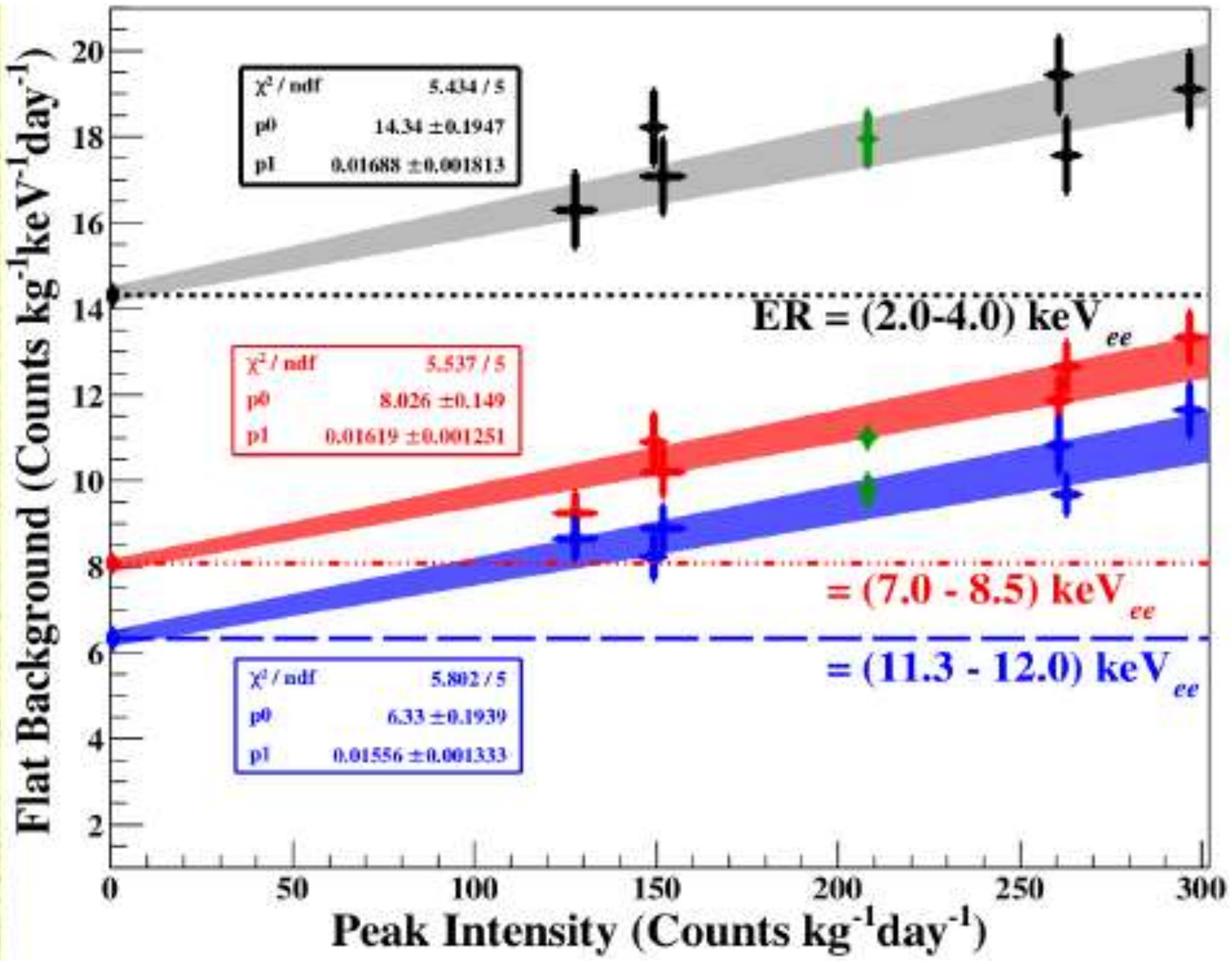
i.e. Minor and known background source.





^{135}Xe Background and Correction



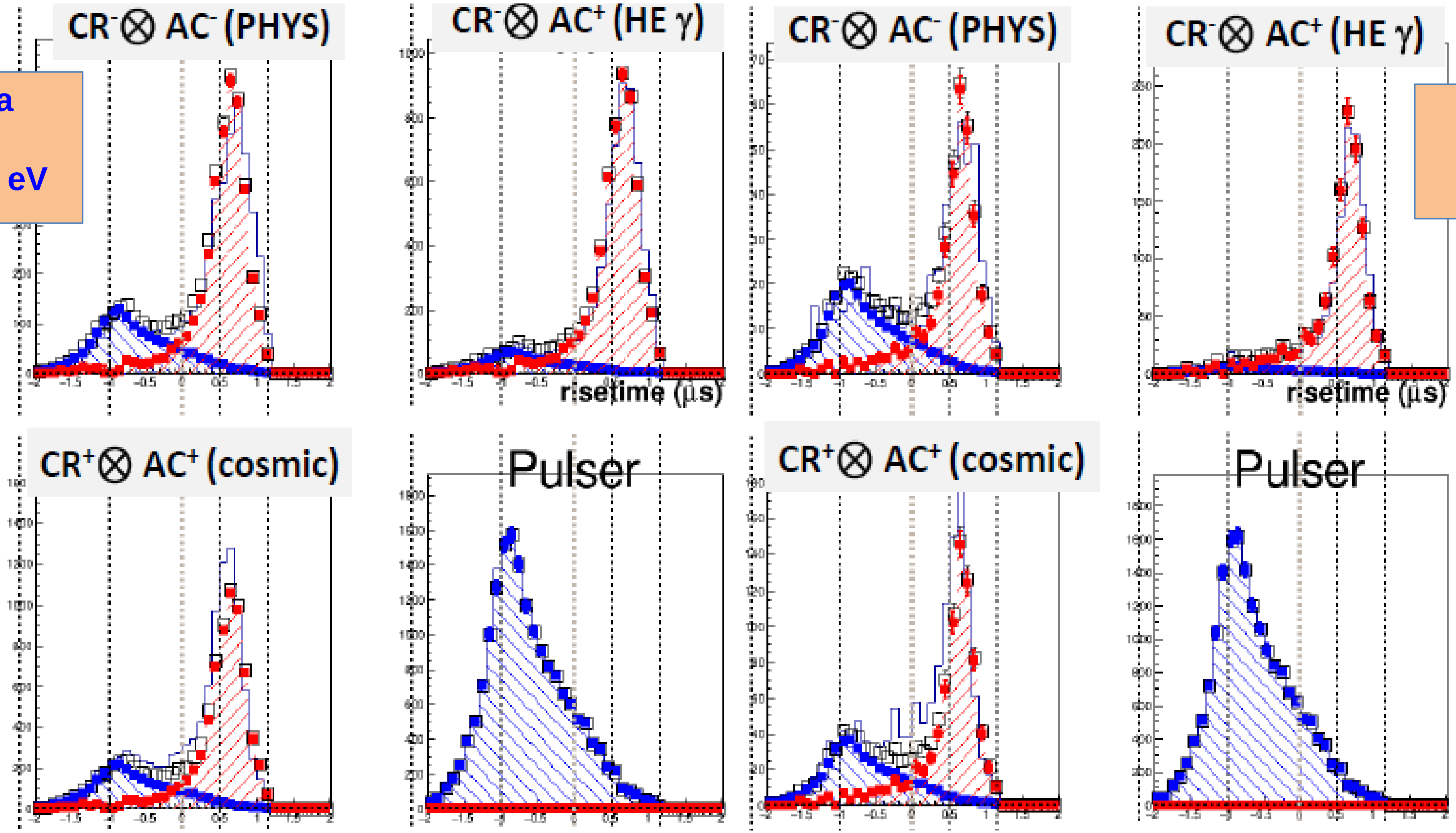


- ❖ Time variation of ^{135}Xe LE flat continuum background correlated with 250keV peak
- ❖ Accurately measured LE background to subtract in ON – OFF residual spectra
- ❖ At 200eV threshold, Xe continuum ~3% of PHYS – Reactor ON counts

Validity Checks: Rise – time distributions

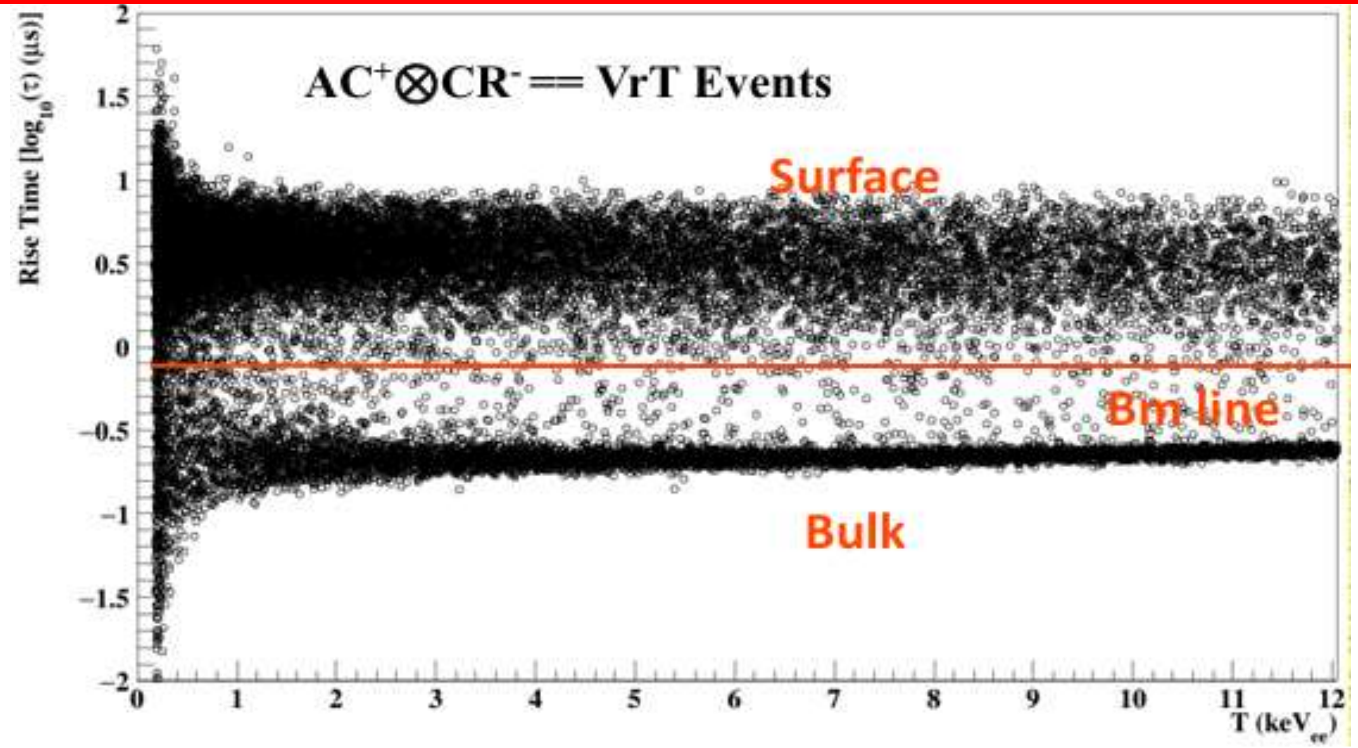
ON data (Total) 200 – 300 eV

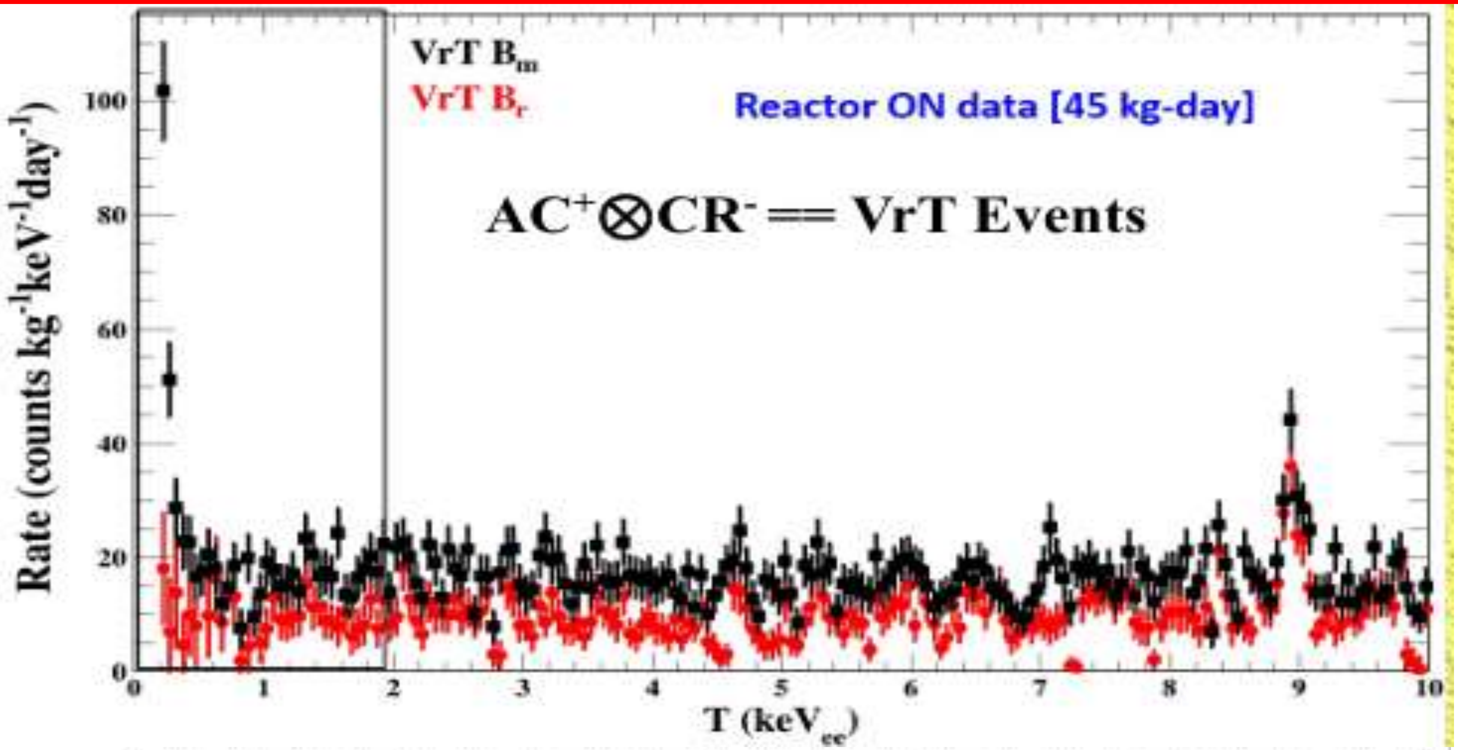
OFF data (Partial) 200 – 300 eV



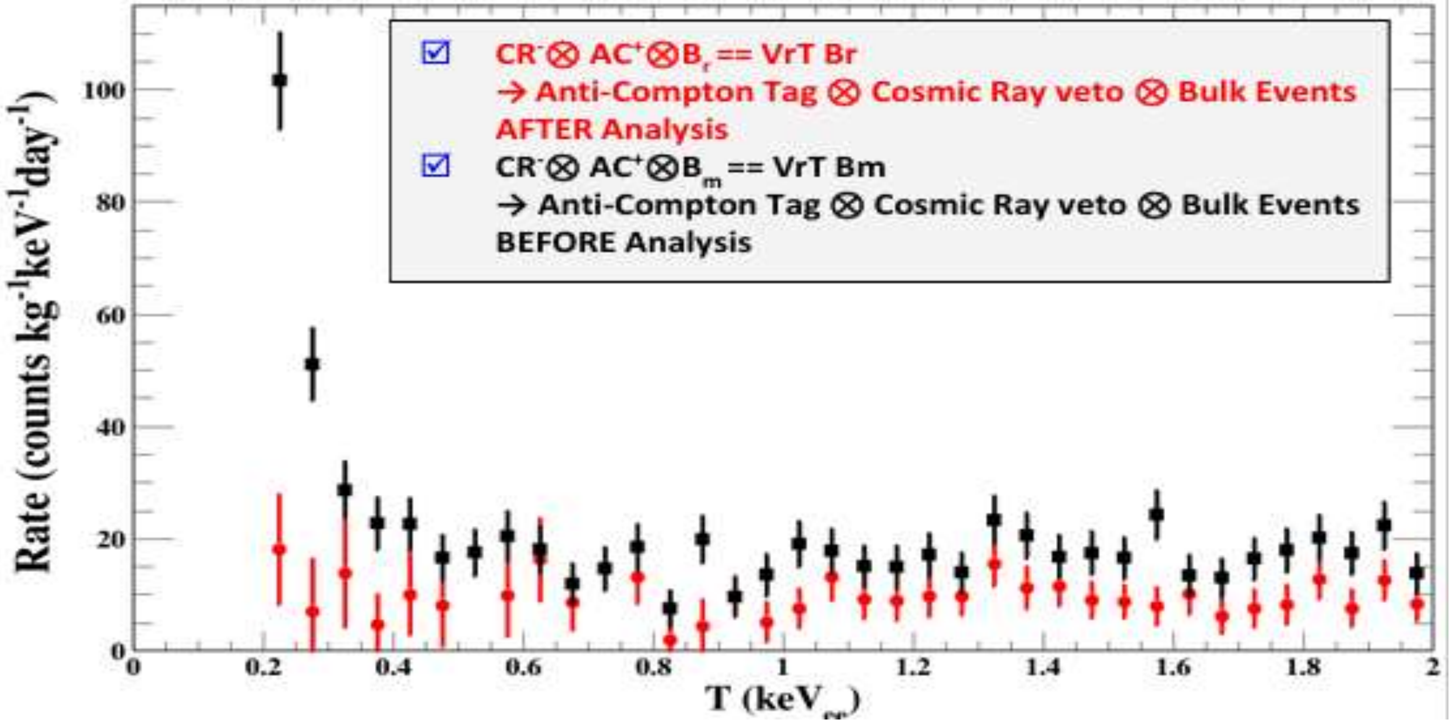
- ❖ **Global Bulk – Surface (B-S) Analysis with in situ data [NIM A 886, 13 (2018)]**
- ❖ **Validity: Benchmark data sets AND TEST Pulser events give consistent – distributions, per energy bin, as shown above.**
- ❖ **Status**: Some data set have NOT YET passed this criteria

Check: Validity of Bulk / Surface Fits



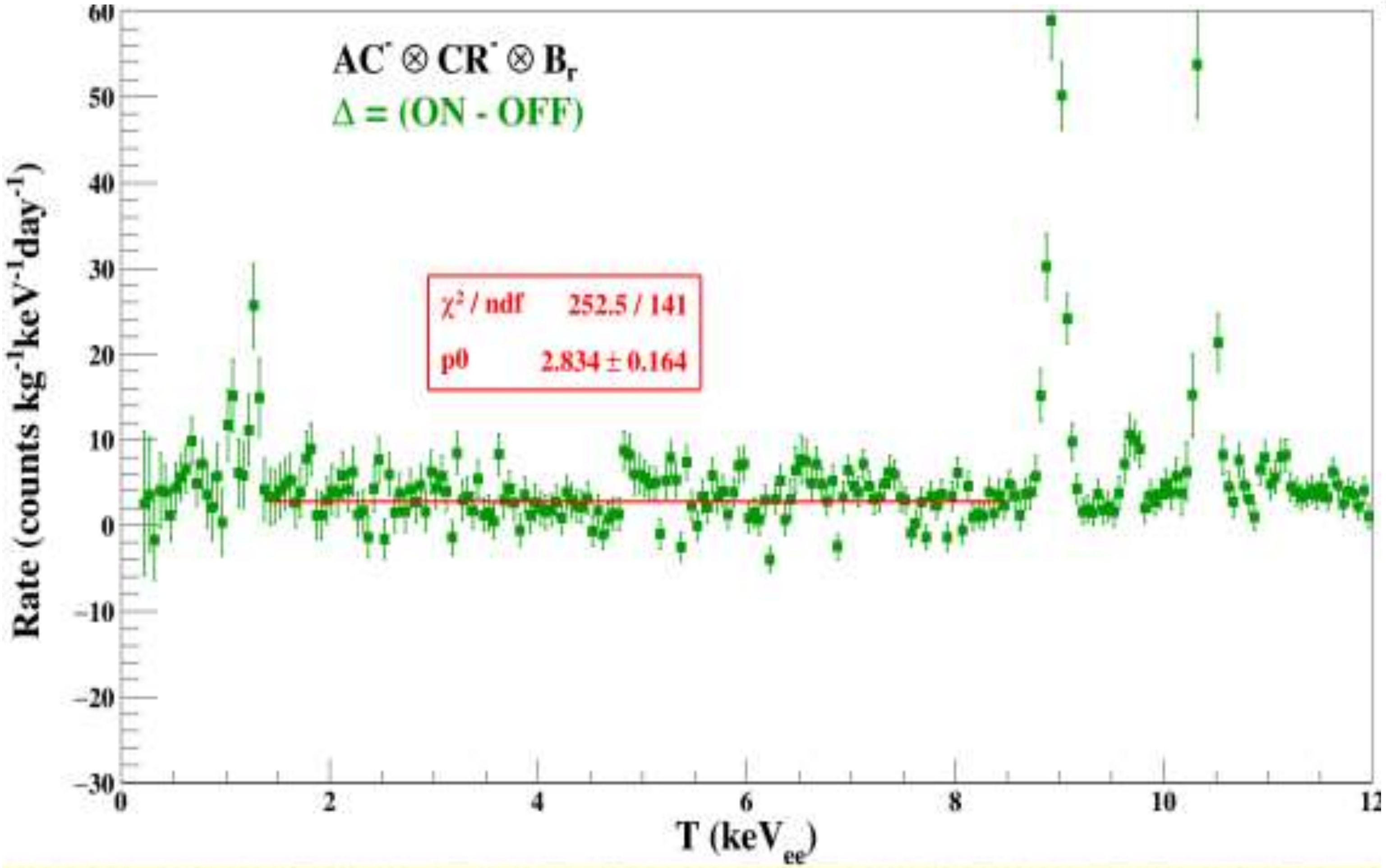


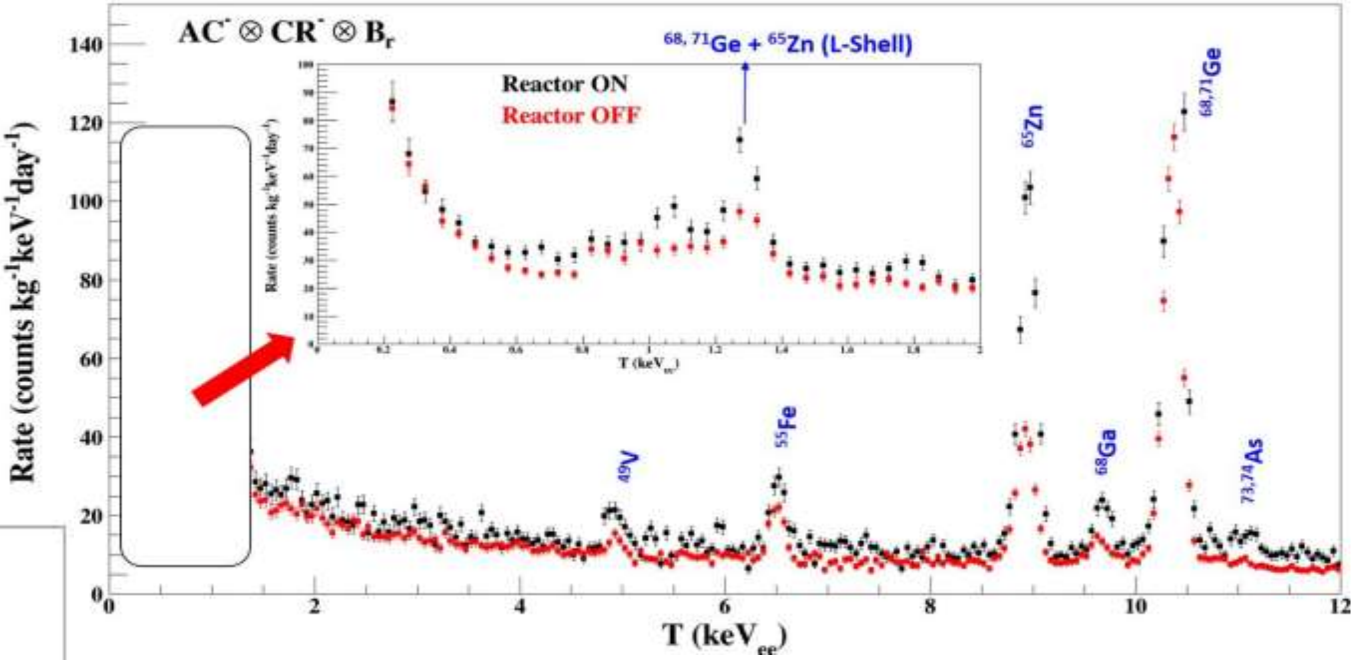
- ☑ $CR^- \otimes AC^+ \otimes B_r$ → high energy γ-induced Compton scattering, non-cosmic
- ☑ Valid analysis: should produce flat spectra (from input rising spectra with surface contaminated events)
- ☑ Status : Some data set not yet passed this criteria



Current Spectra on PHYS samples

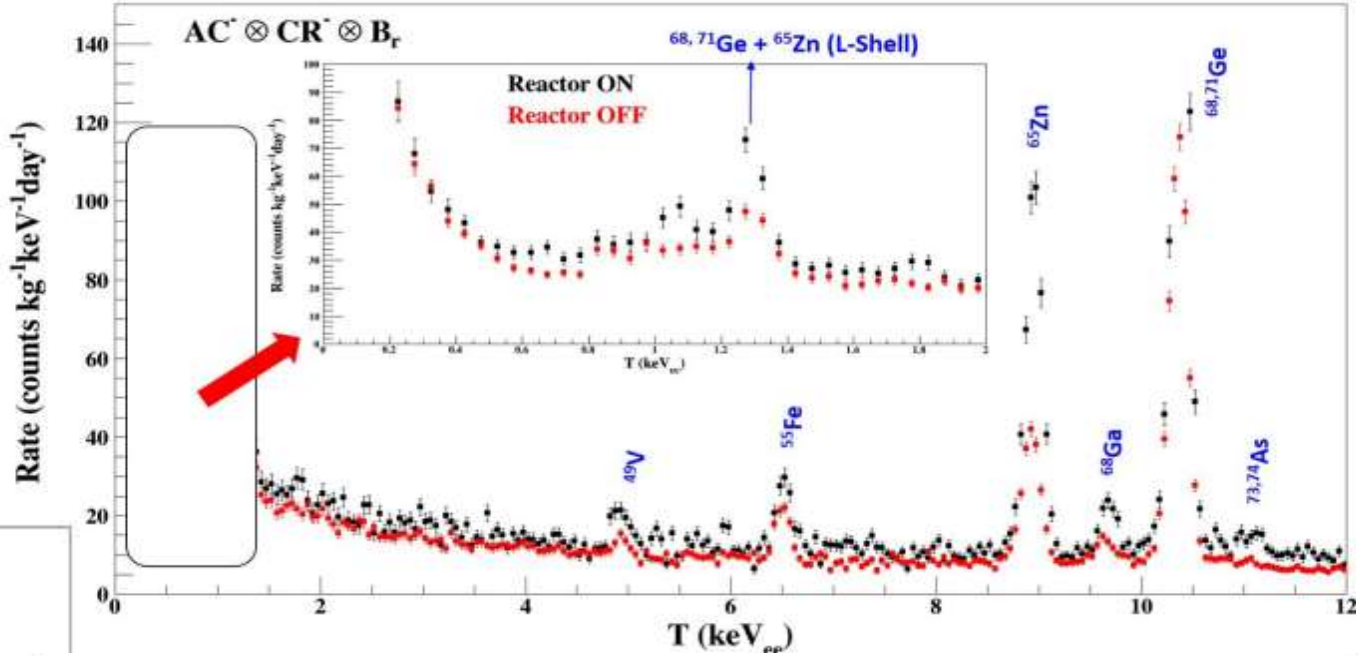
- $[CR^- \otimes AC^- \otimes B_r]$
- [ON/OFF = 245/560 kg-days]
- **Data Size** & **Details** & **Uncertainties** may evolve after benchmark samples passing validity tests.

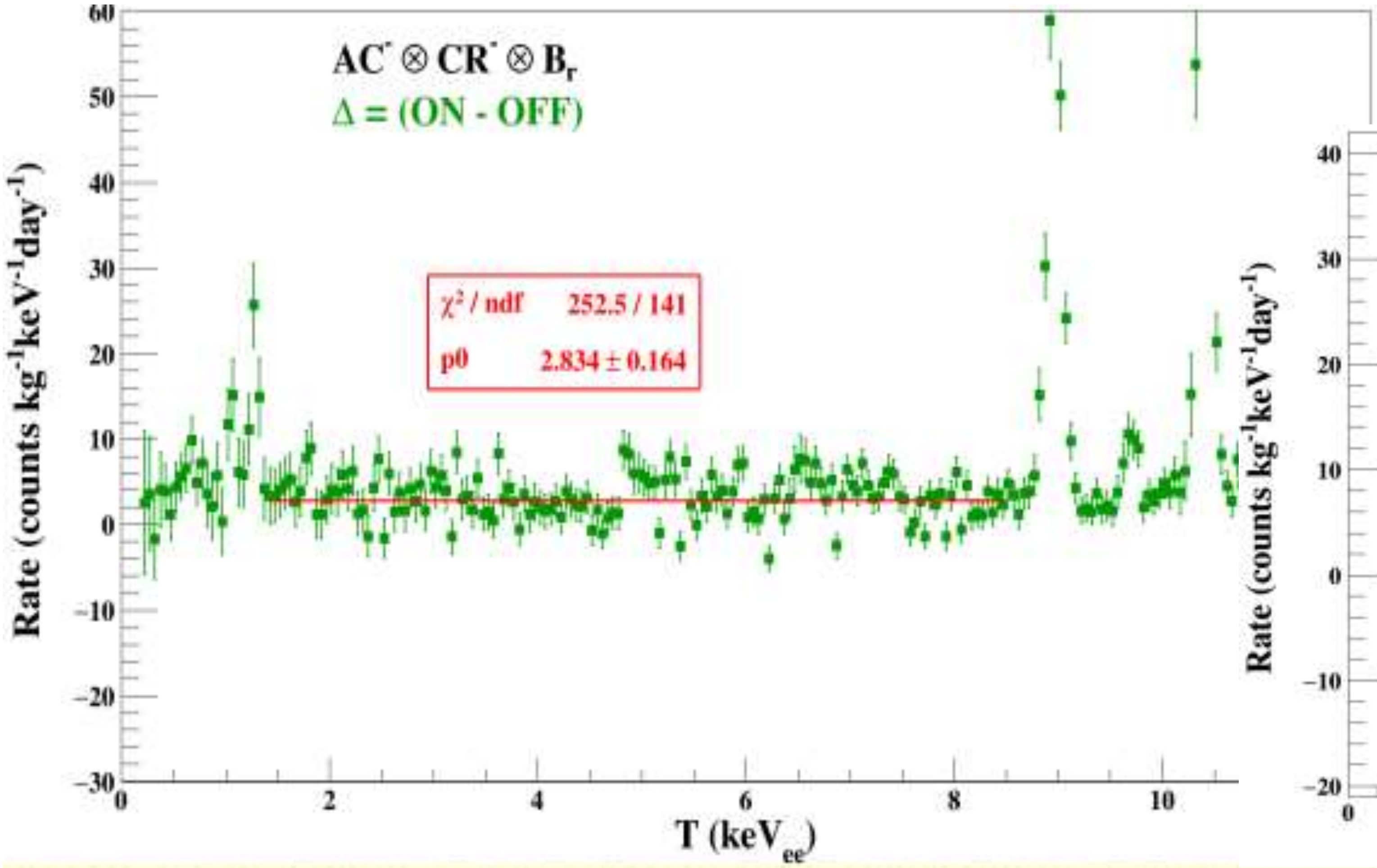


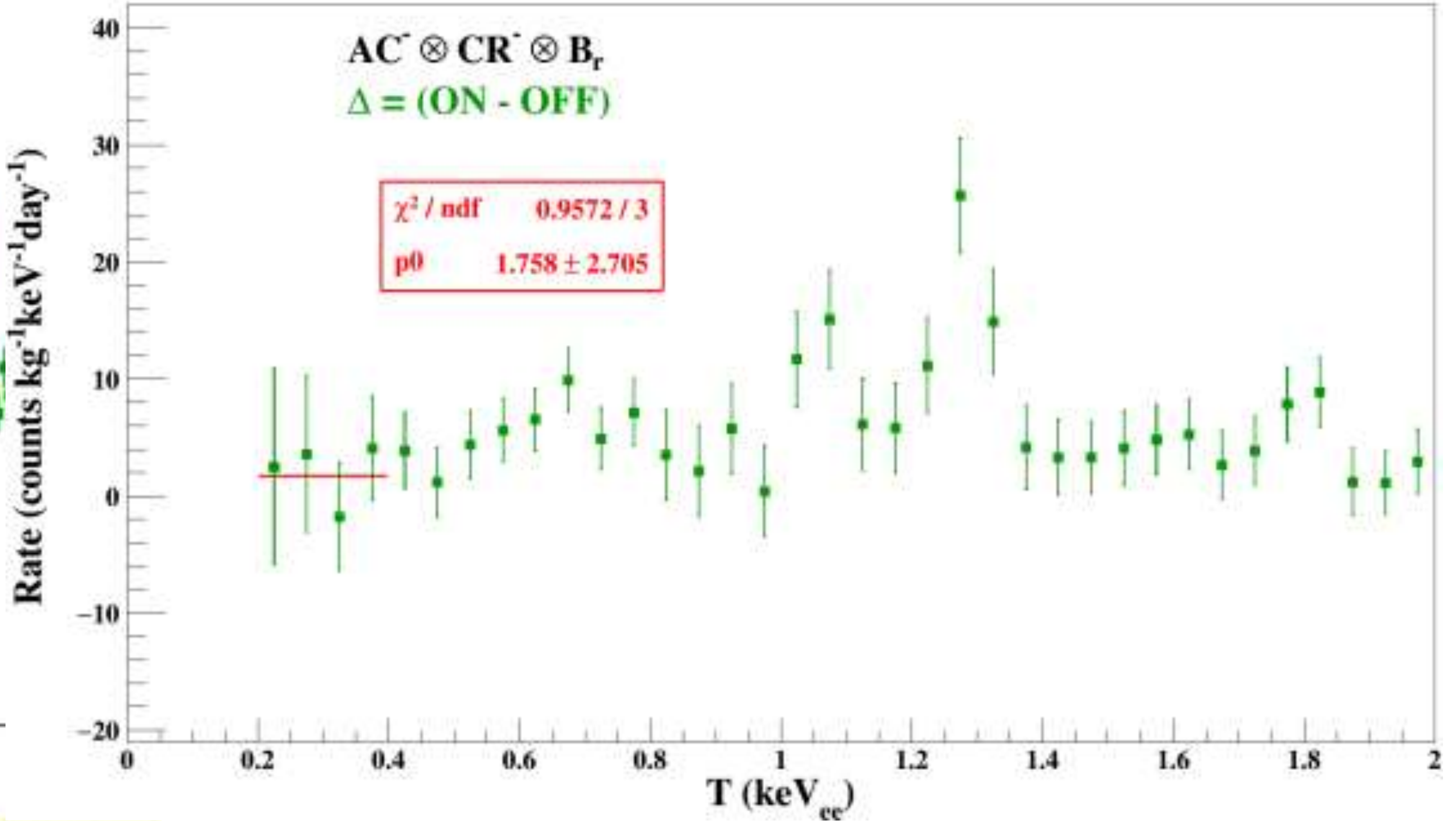


Current Spectra on PHYS samples

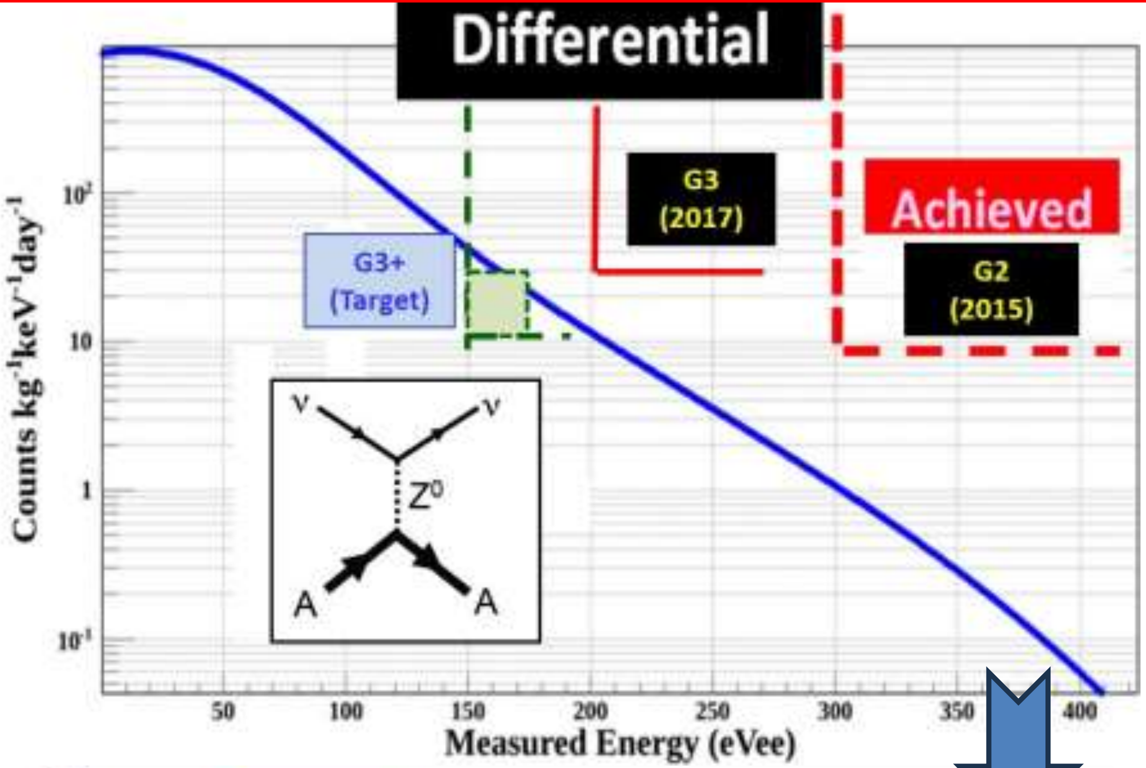
- [CR⁻ ⊗ AC⁻ ⊗ B_r]
- [ON/OFF = 245/560 kg-days]
- **Data Size** & **Details** & **Uncertainties** may evolve after benchmark samples passing validity tests.

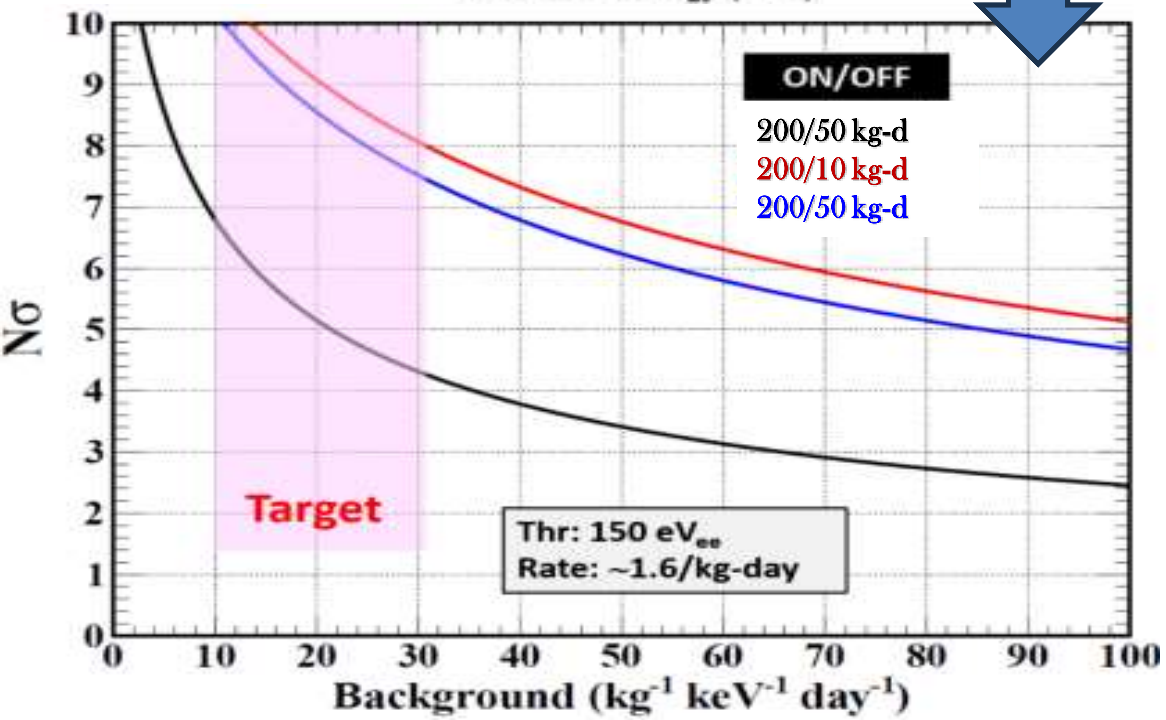






νA_{el} @ KSNL: Projected (Hypothetical) Sensitivities





Prospects:

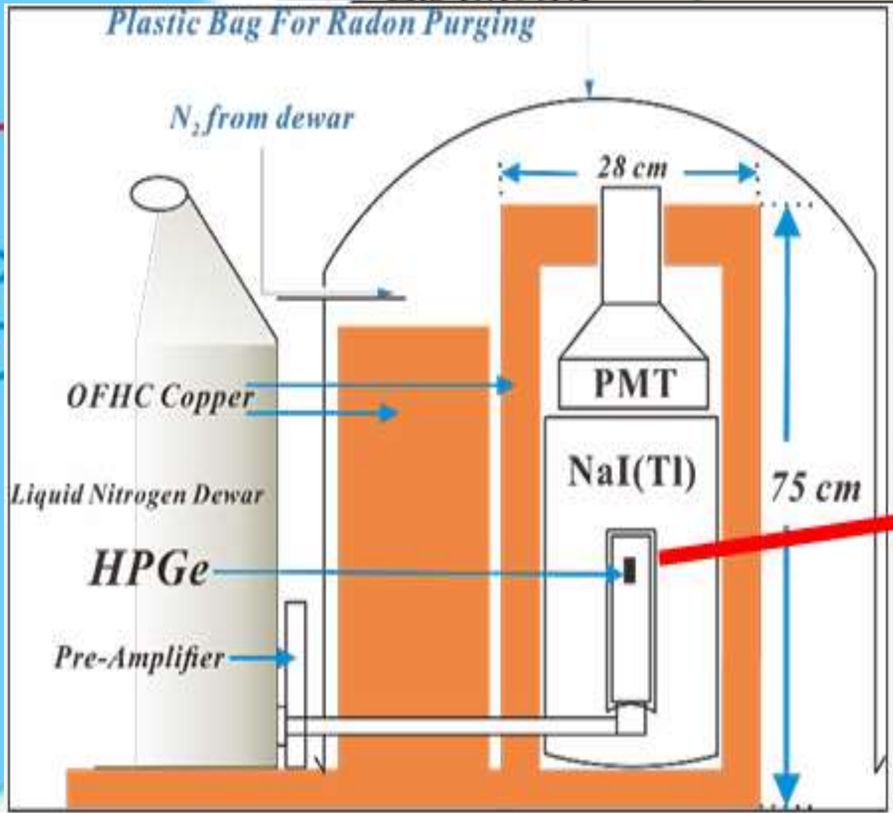
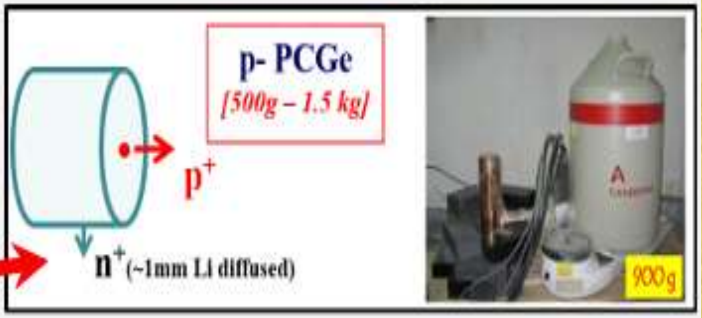
- KSNL (2.9GW, 28m):
  - G3 (200eV) Data ON/OFF ~ >500 / >800 kg-days
  - νDecommissioned: 2023, Access till at least end of 2025
- R & D: G4 (@ 150eV noise edge demonstrated) and PSD at threshold
- New site under preparation (under CDEX): Sanmen Reactor (3.4GW) @ Zhejiang
  - Possibility of site at ~11m !

Prospects & Outlook

- ❖ Our Pursuit of C+E νNS has convoluted evolutions & spinoffs
- ❖ νA_{el} @ KSNL with TEXONO
  - ❑ Complete G3+ & G3++ analysis
  - ❑ expecting ON/OFF [>500/>800 kg-day]
- ❖ New Reactor Site at Sanmen with CDEX
  - ❑ Complementing to/Enhancing CDEX DM & 0νββ @ CJPL with Ge
- ❖ Theory: LE ν/χ/ALP cross-sections, BSM searches, QM coherency, Follow our nose ...

Thank you so much


China
worldatlas
Yangmingshan N.P.
East China Sea
CKS International Airport
ChiLung
Taipei
HsinChu
Taiwan Strait
Taiwan
Suao
CHUNGYANG SHANMO
70 mi
70 km
Taichung
Hualien
Penghu Islands
Choshui River
Makung
Yushan
Alishan
Yushan N.P.
South China Sea
Tainan
Kaop'ing River
Taitung
Kaohsiung
Fengkang
Lan Yu
Oluanpi
TAIWAN
OW / HILLS / MOUNTAINS
Luzon Strait

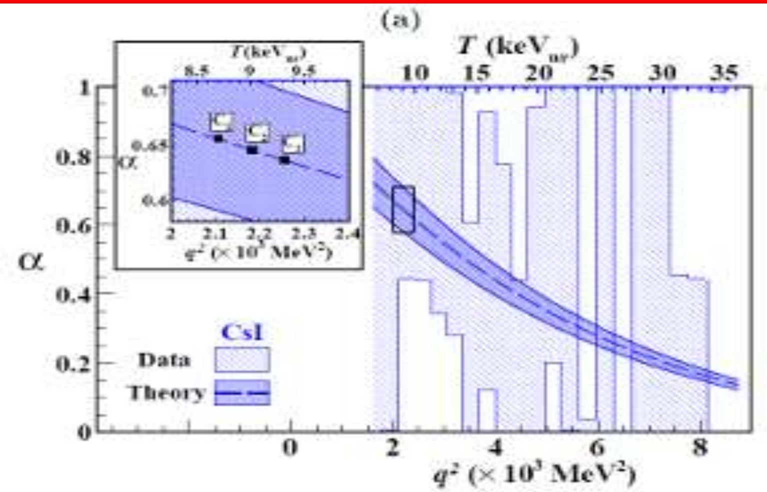
N
0
20mi
20km
NPS-I
NPS-II
Keelung
NPS-IV
Taipei
ACADEMIA SINICA
Hsinchu

Plastic Bag For Radon Purging
N2 from dewar
28 cm
PMT
OFHC Copper
NaI(Tl)
75 cm
Liquid Nitrogen Dewar
HPGe
Pre-Amplifier

p- PCGe
[500g – 1.5 kg]
p+
n+ (~1mm Li diffused)
900g

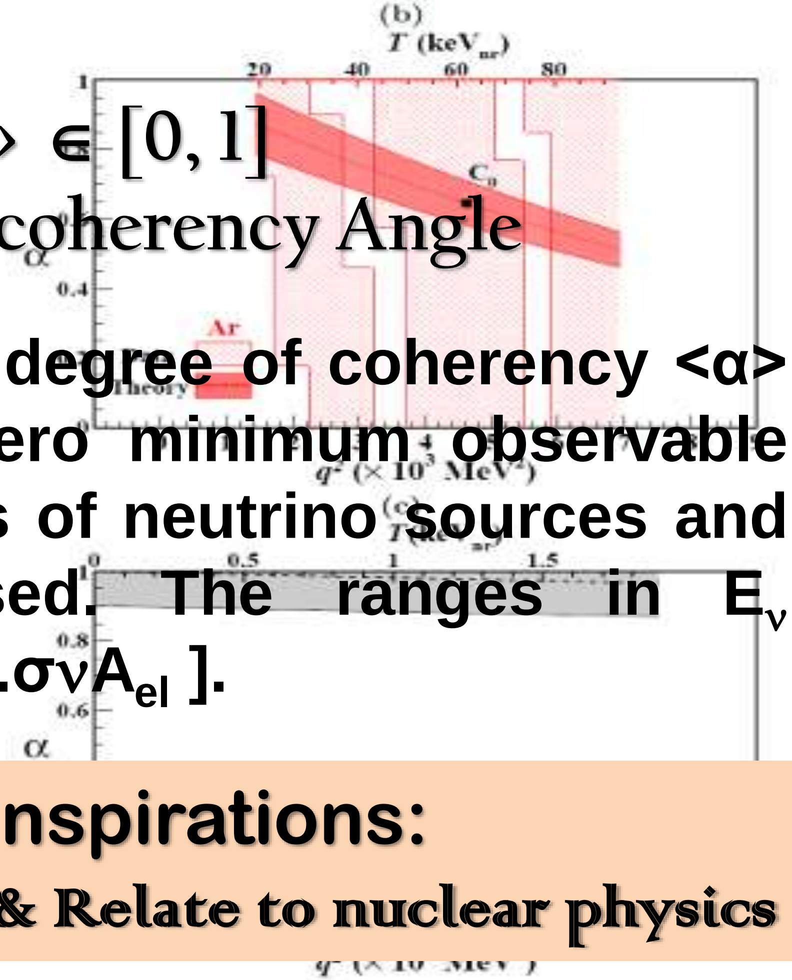
Coherency in Neutrino-Nucleus Elastic Scattering

- ❖ Quantify transitions between QM Coherency & Decoherency
- ❖ Universal Characterization between different Sources & Target

νA_{el} with Reactor Neutrinos:

- ➢ Different kinematics regimes : $q^2 \rightarrow 0$; Form Factor $F(q^2) = 1$
- ➢ Full QM Coherency **[DAR-νN @ ~0.6 - 0.7]**
- ➢ BSM/NSI Searches → **no degeneracy** with nuclear physics FF uncertainties





Measurements on α from COHERENT (a) CsI and (b) Ar data with DAR-π-ν. **The stripe-shaded areas are the 1-σ allowed regions derived from the reduction in cross-section relative to the complete coherency conditions independent of nuclear physics input.**
The dark-shaded regions are the theoretical expectations adopting the nuclear form factor formulation of Eq. with a ±1σ uncertainty of 10%.

$$F_A(q^2) = \left[\frac{3}{qR_0}\right] j_1(qR_0) \exp\left[-\frac{1}{2}q^2 s^2\right]$$

The $\alpha(q^2)$ -values for different nuclei can be consistently
compared. Labels C0,1,2,3 correspond to the configurations, where α0<α1, α0=α2 and α0>α3 despite having ξ0>ξ1,2,3 in all cases.
(c) The sensitivity with the theoretical projections applied to reactor-ν on Ge covering the complete q^2 -range for nuclear recoils.

$$\alpha \equiv \cos\langle\phi\rangle \in [0, 1]$$

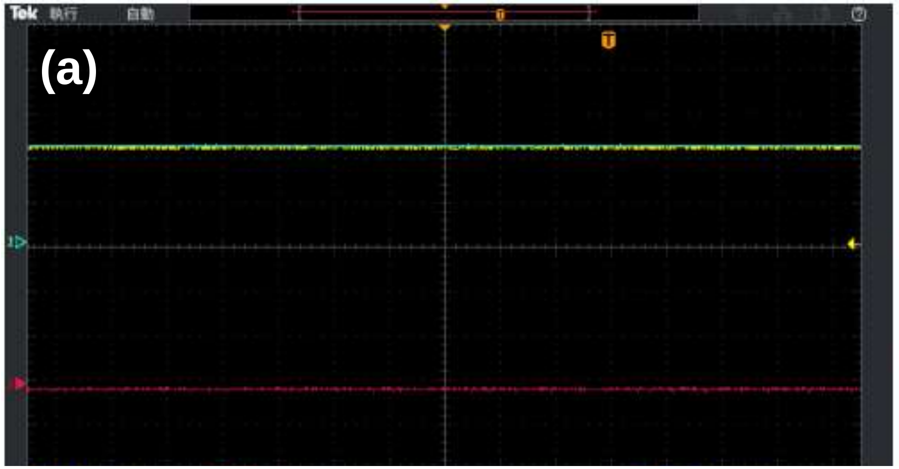
$\langle\phi\rangle$: Averaged Decoherency Angle

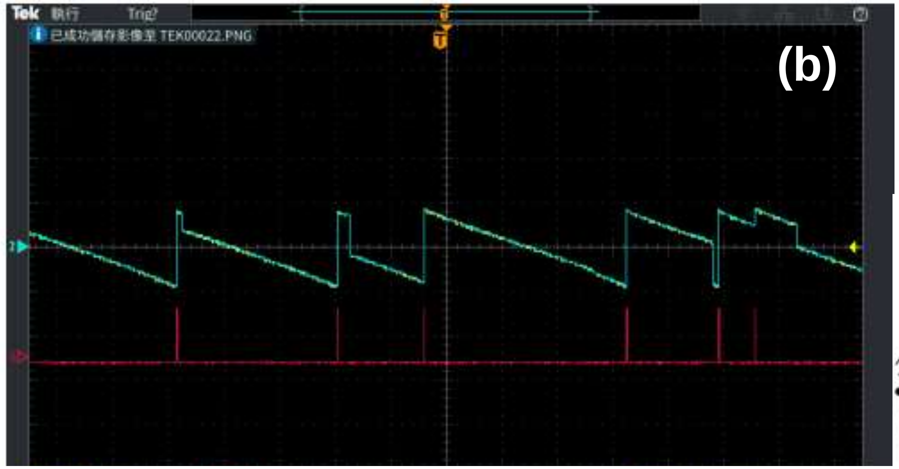
The contours of the mean degree of coherency <α> on the (N, E_ν) plane at zero minimum observable energy (T_{min}=0), with bands of neutrino sources and target nuclei superimposed. The ranges in E_ν correspond to FWHM in [$\Phi_\nu . \sigma\nu A_{el}$].

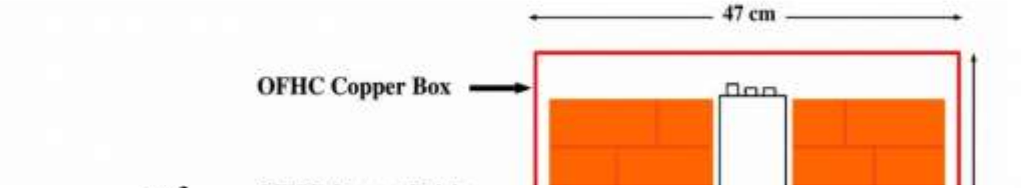
Seek Input / Inspirations:

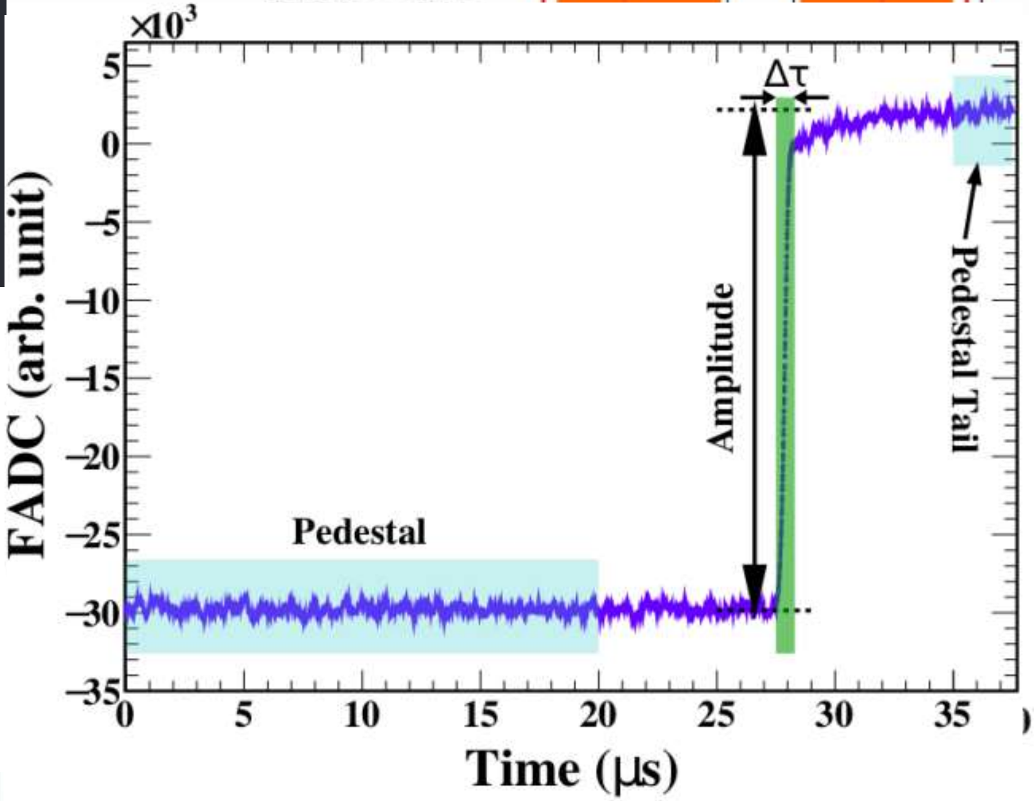
- ❖ **Derive α from basics QM & Relate to nuclear physics**

νA_{el} with Electro-cooled PCGe









When charge deposition in the detector above a pre-established threshold, or after a predetermined time interval, the saw-tooth waveform represents the temporal structures of "RESETs" Physics signals with energy proportional to step size are represented by the steps between RESETs. This output of the preamplifier is then sent to the SA and TA. The SA output after giving the input of preamplifier pulse is shown (c). The shaping time is kept at 2μs. The pulse form TA helps in understanding the estimation of rise time and versus energy plot which helps in separation bulk and surface events. These SA and TA pulses were digitized with 200 MHz and 60 MHz flash analog-to-digital converters.