SHANGHAI JIAO TONG UNIVERSITY
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PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

Study of signal response of low energy nuclear recoil in PandaX

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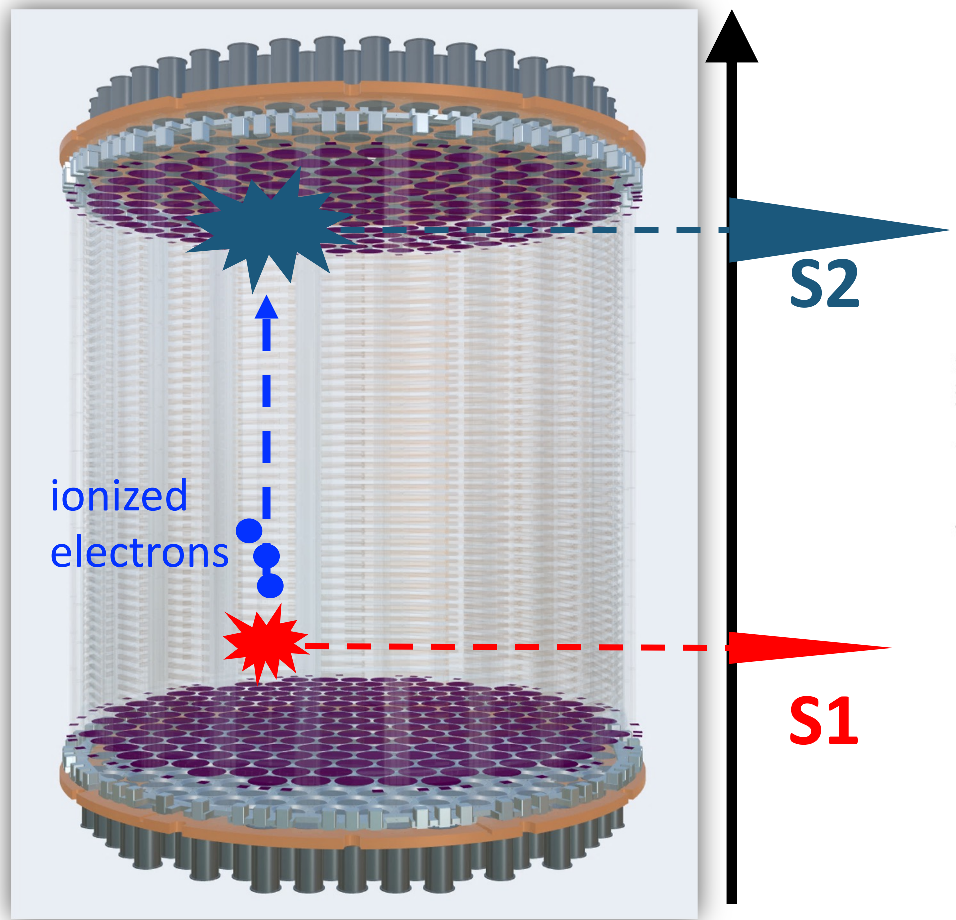
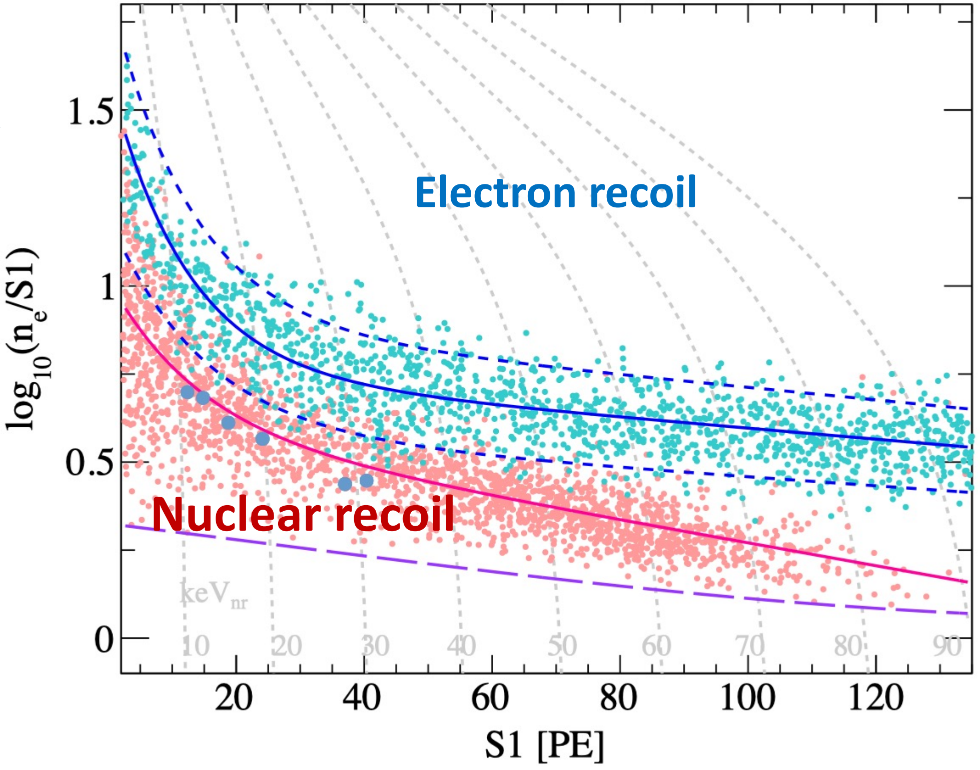
LIDINE 2025

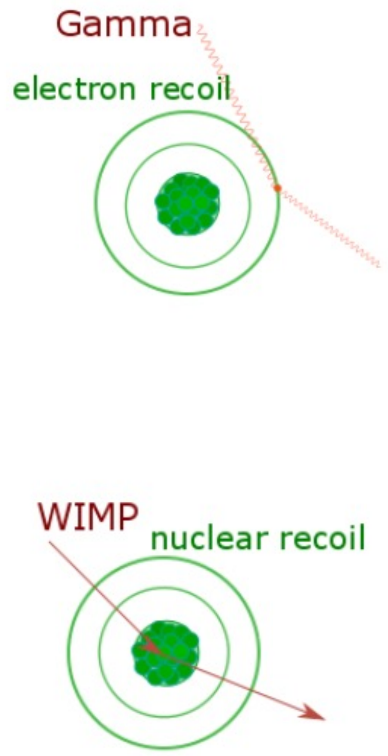
LIGHT DETECTION IN NOBLE ELEMENTS

PandaX: Dual-phase xenon TPC

- **Paired scintillation (S1) and ionization (S2) signals**
  - Precise energy measurement and 3-D position reconstruction
  - Discrimination of nuclear recoil (NR) and electron recoil (ER) signals

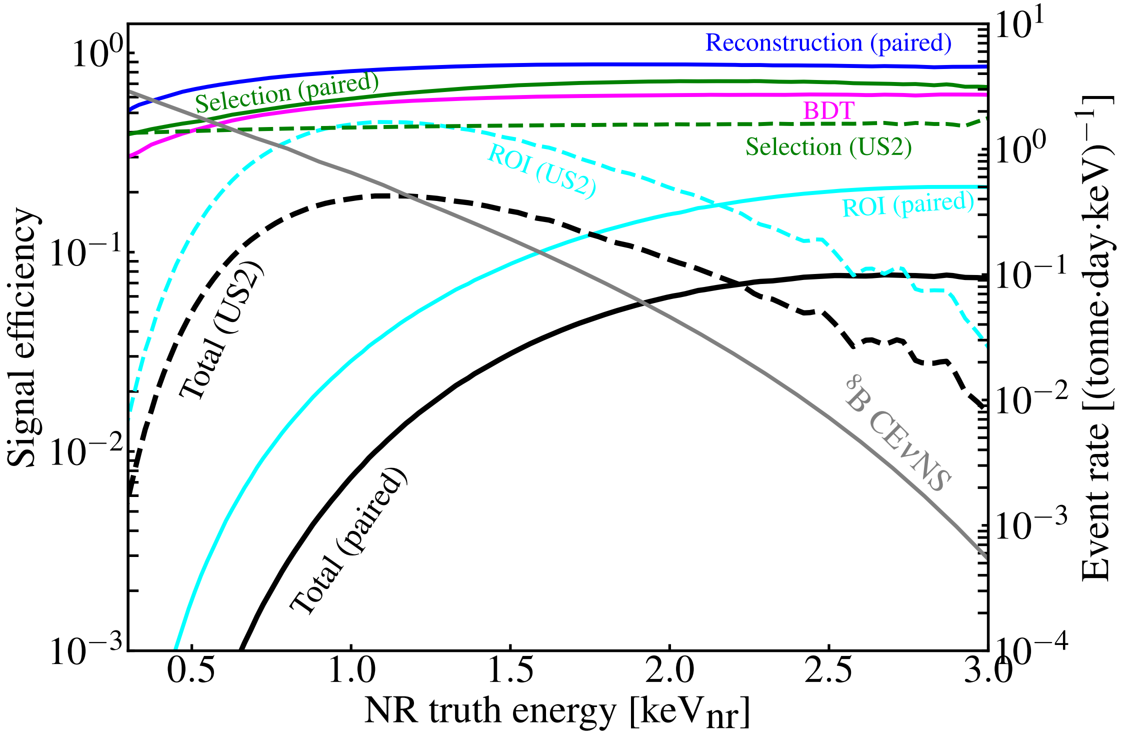


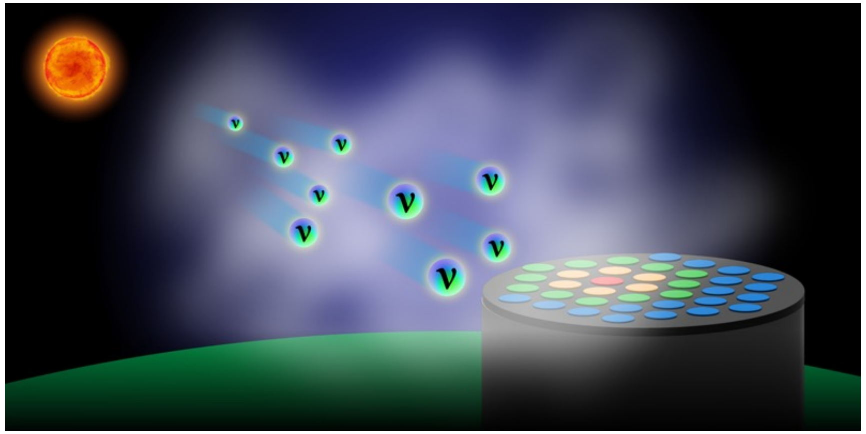


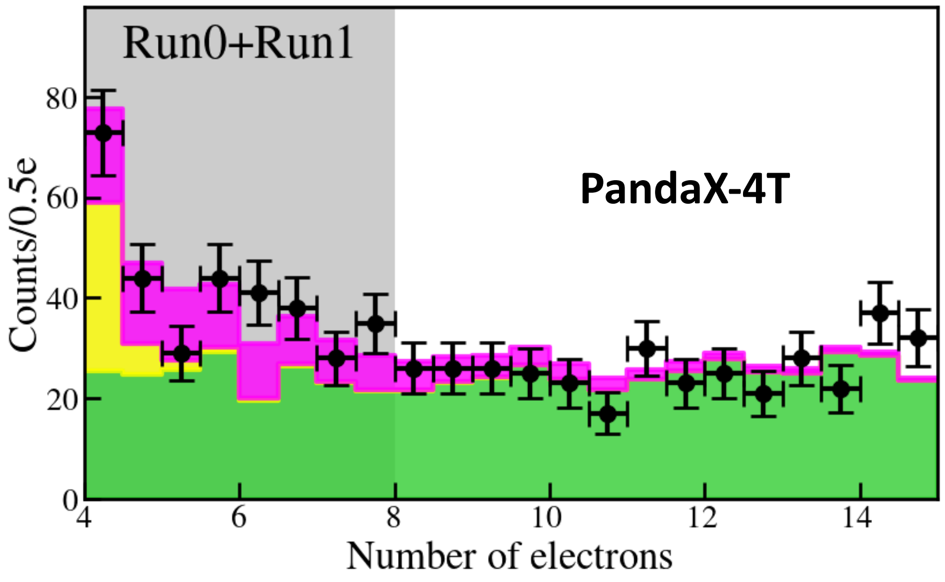


Solar ^{8}B neutrino CEvNS signal

- **Low threshold detection: NR threshold ~3keV –> ~0.3keV**
  - low threshold paired ROI
  - **Ionization S2-only ROI**

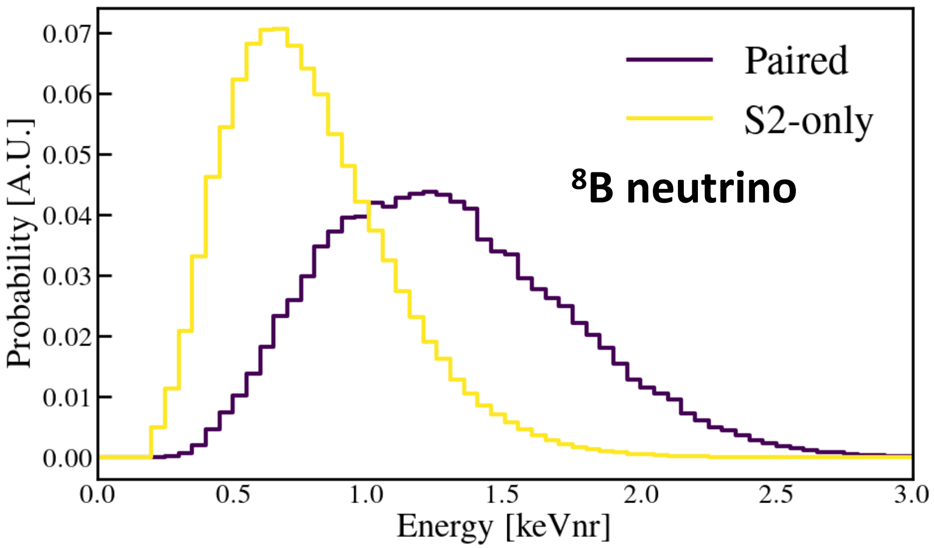


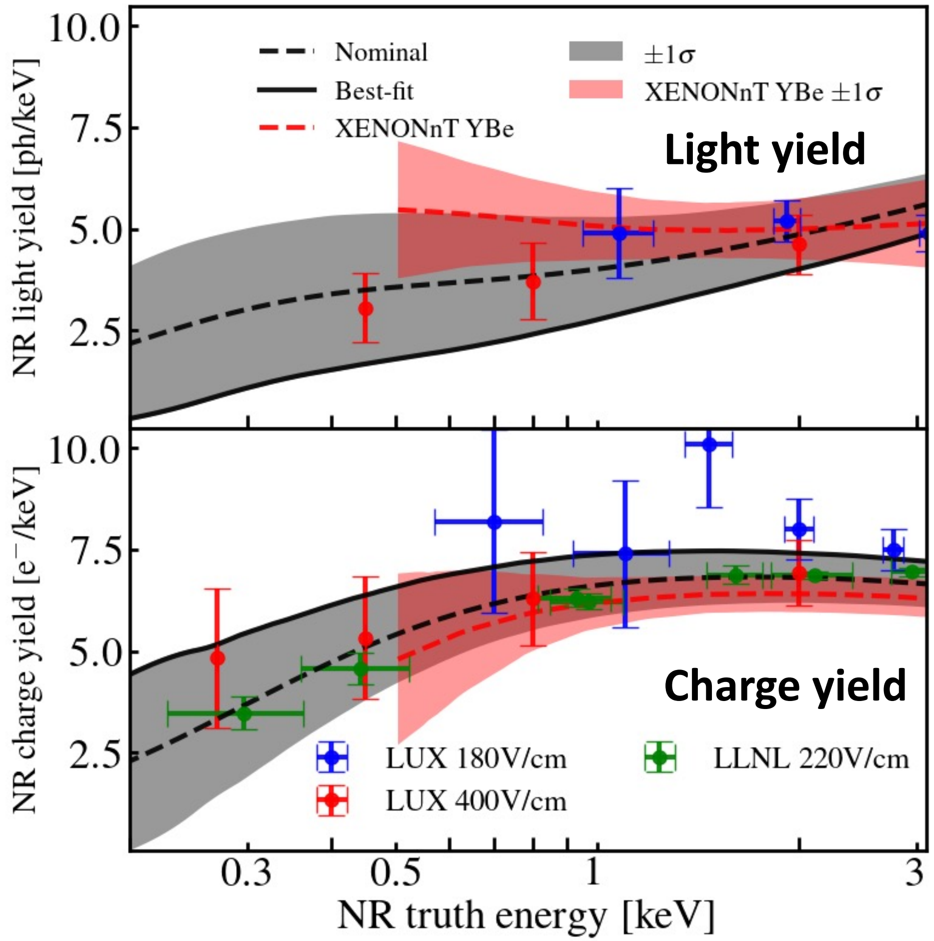




Low Energy NR LY/CY

- **Low energy NR response in xenon**
  - relying on global measurement (NEST)
  - combined fit on paired and S2-only with LY/CY variation anti-correlated
  - Best-fit tends to have higher charge-yield
- **Better to measure it directly from our detector**





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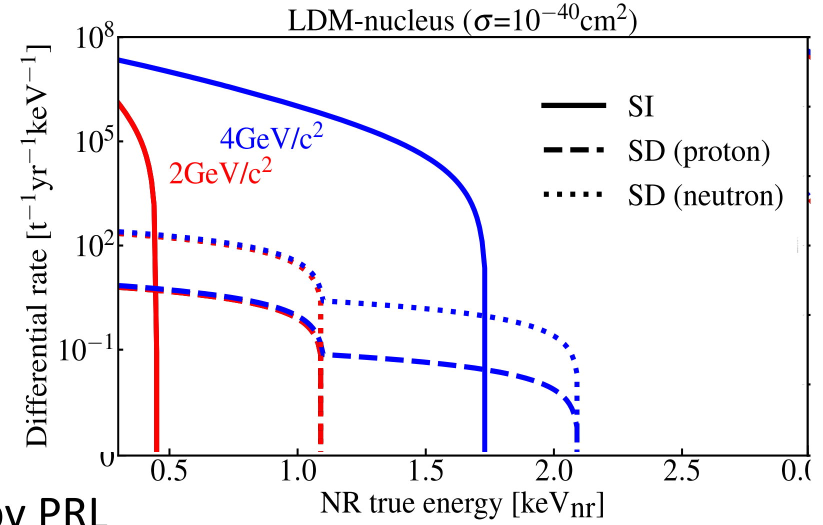
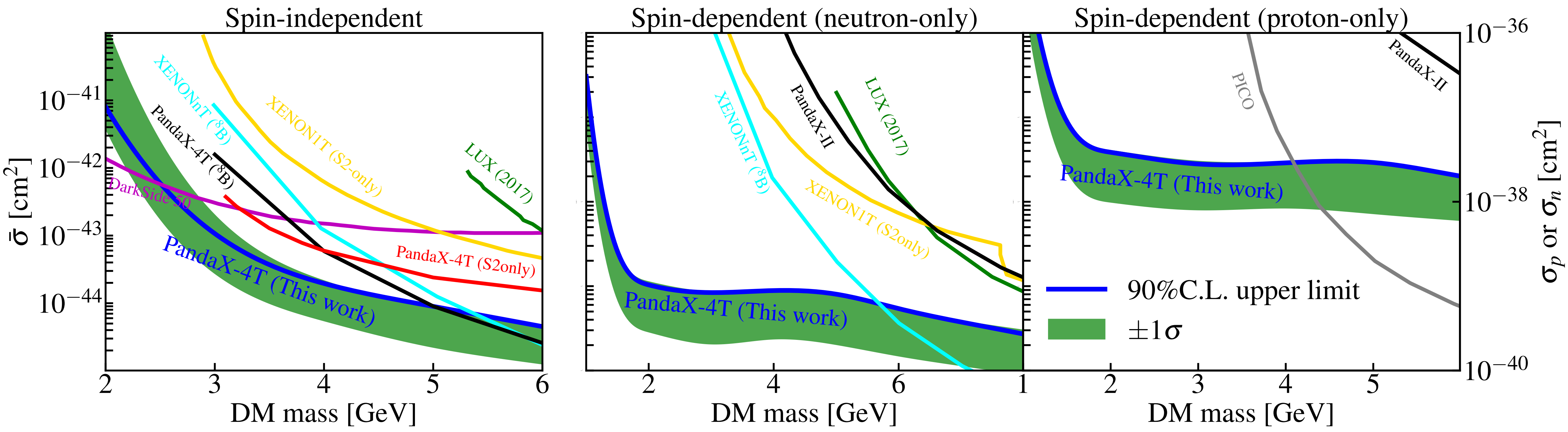
Low mass dark matter

- **Sensitivity to low mass dark matter**
  - Different energy spectra w.r.t neutrino CEvNS
  - Extend to ~2GeV WIMP mass
- **Challenge: low energy NR response**

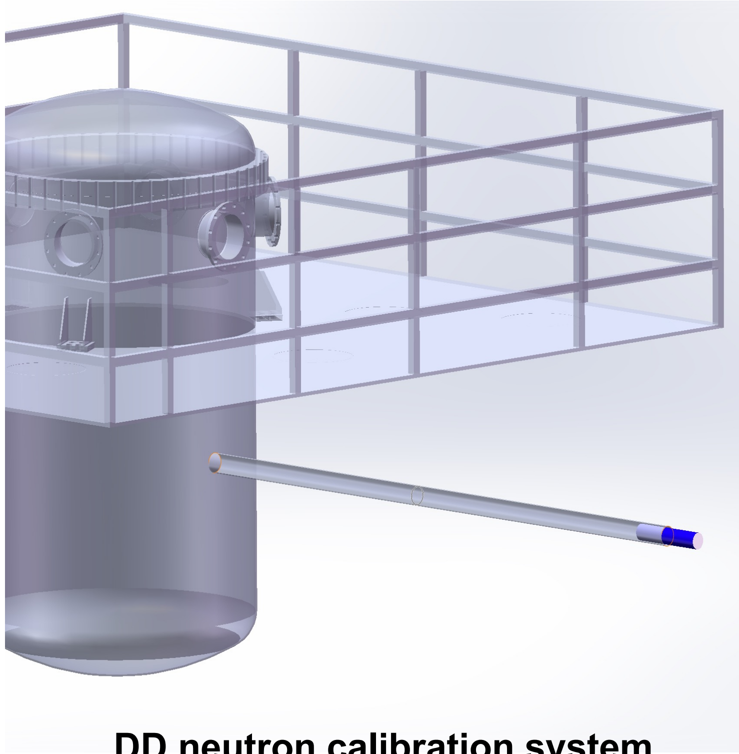


arXiv:2507.11930, accepted by PRL

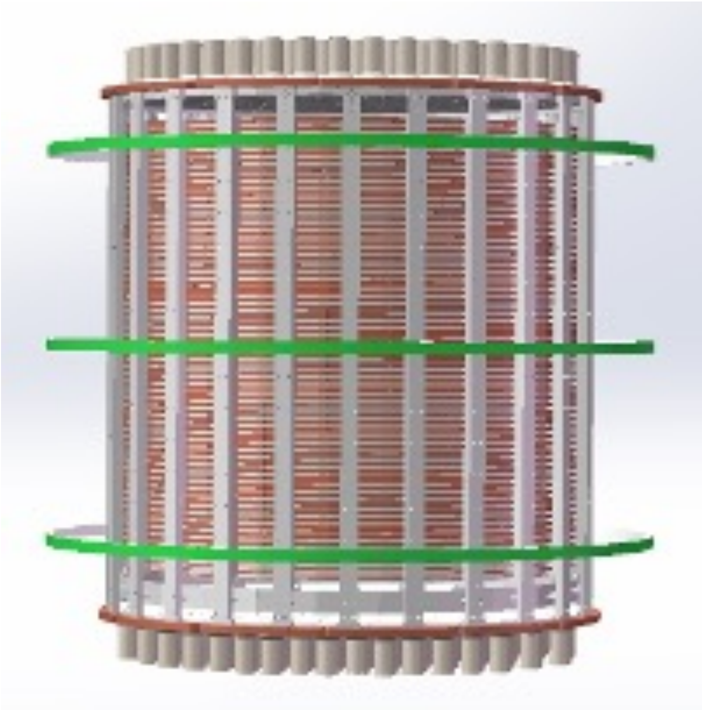


Neutron calibration

- **Mono-energetic 2.45 MeV neutrons generated from DD nuclear collision outside of the 900m^3 water shielding**
- **Am-Be neutrons between inner vessel and outer vessel**



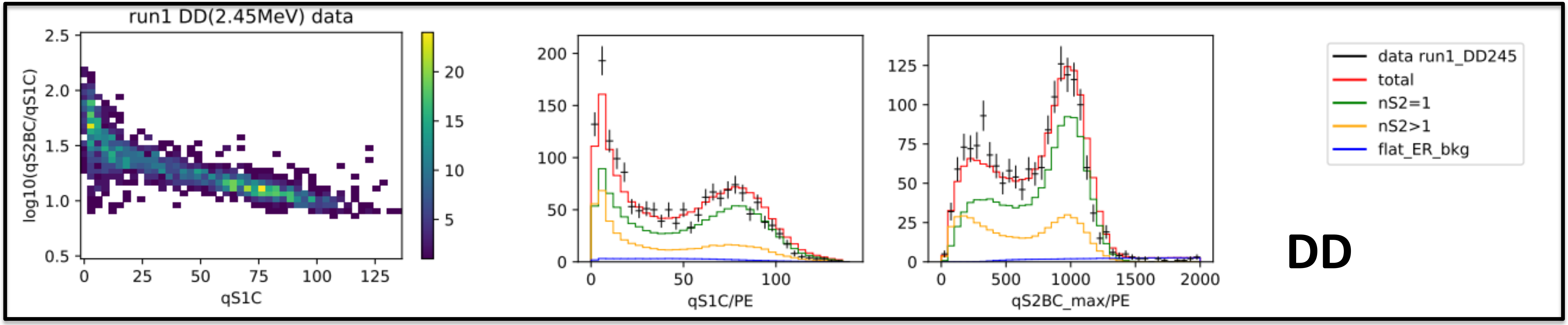
DD neutron calibration system

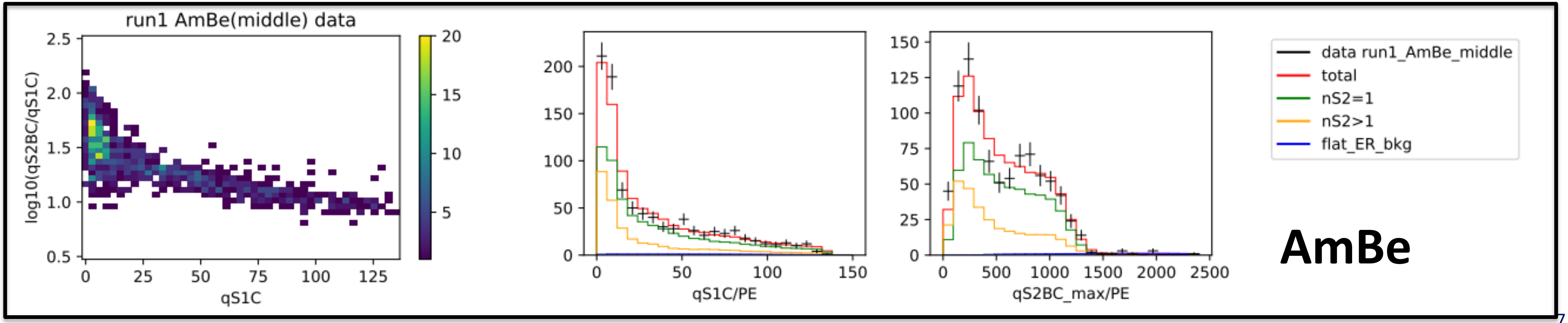


AmBe neutron calibration loops

Fitting Calibration Data

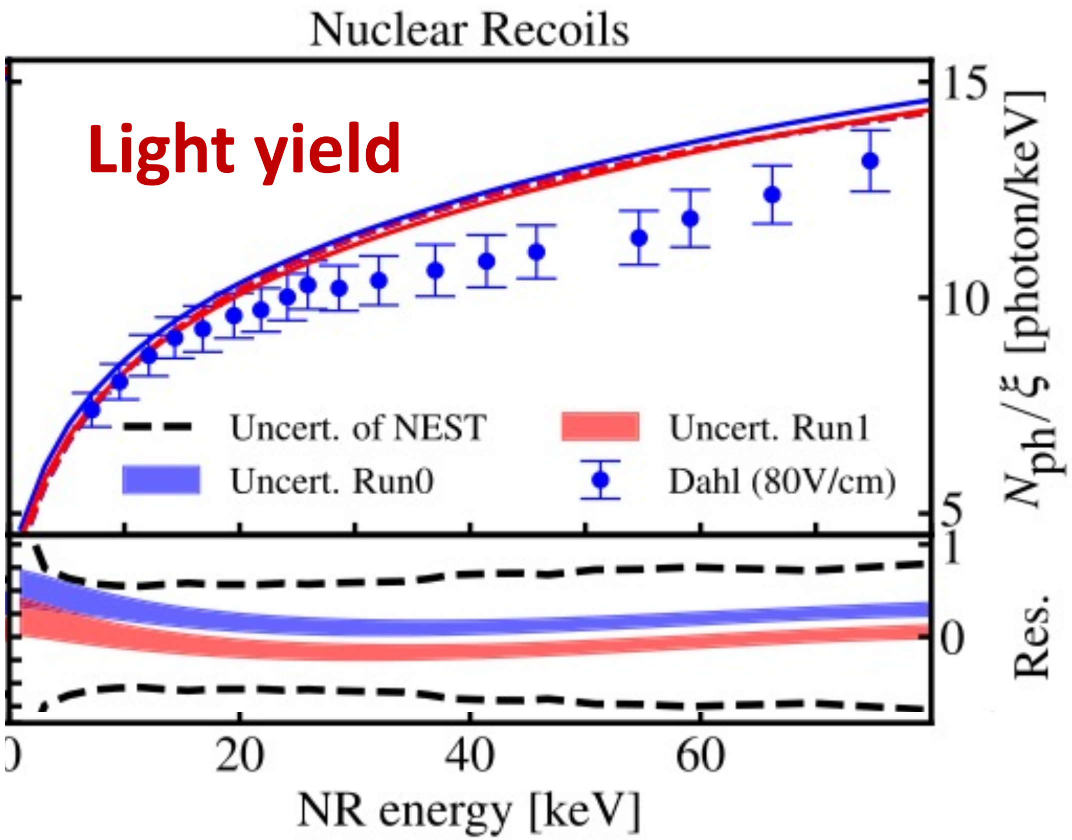
- **Select single-scattering events,**

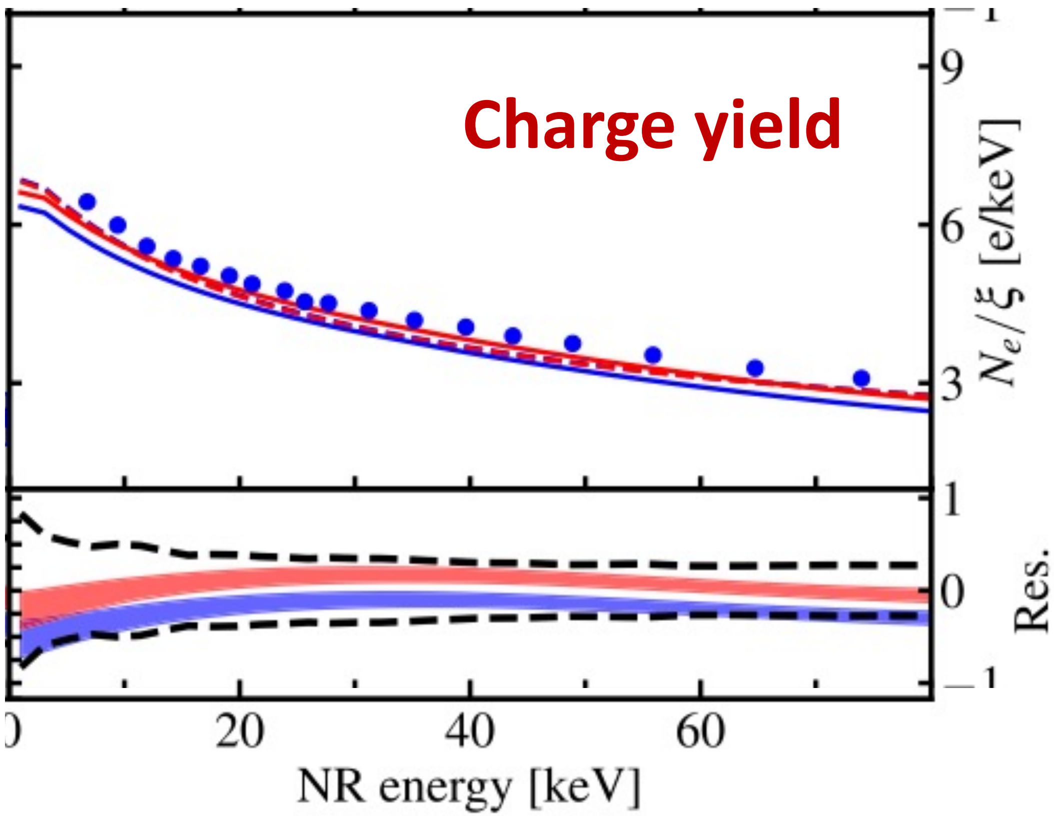




NR LY/CY

- **NR response obtained for energy above a few keVs**

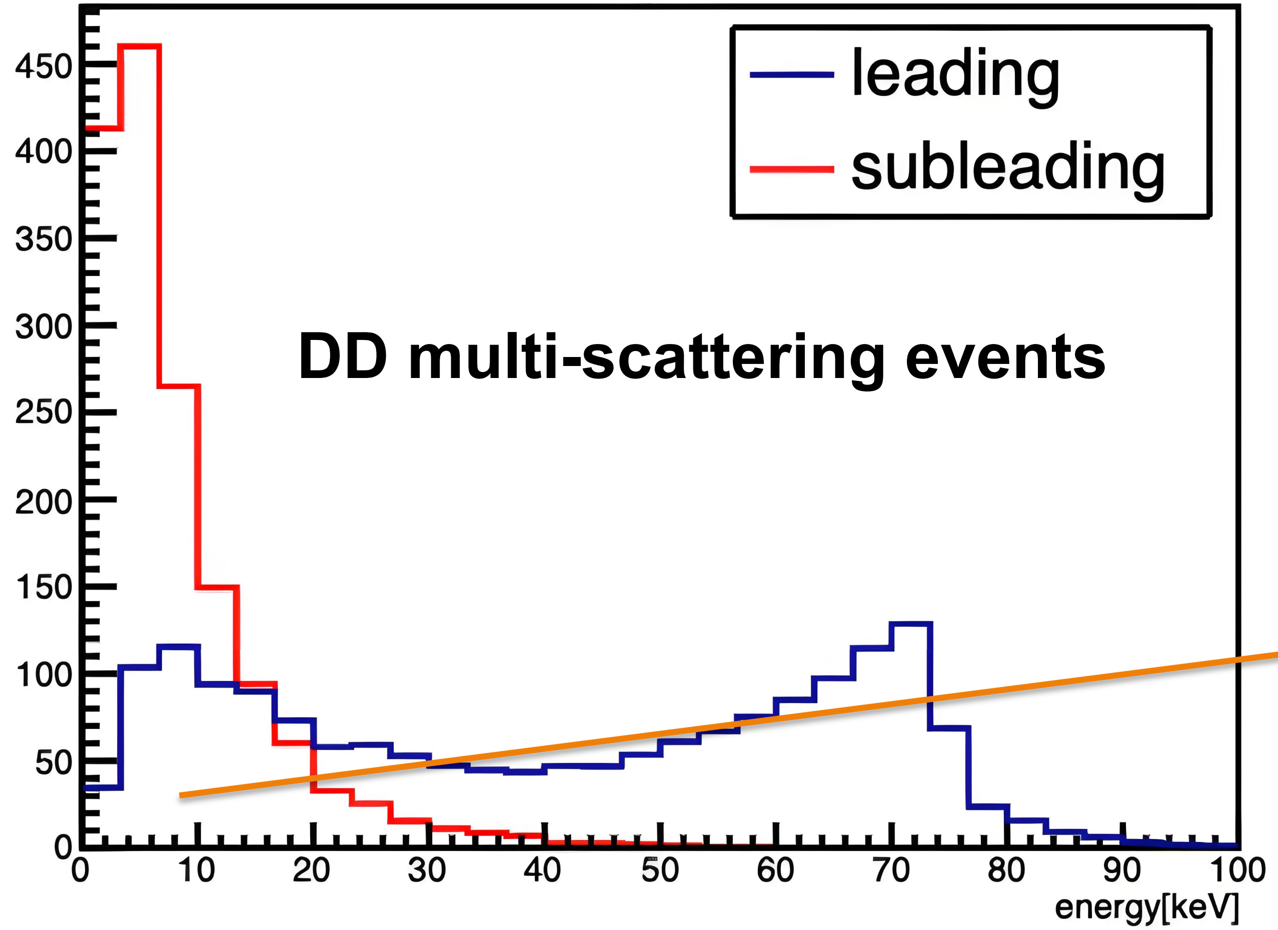


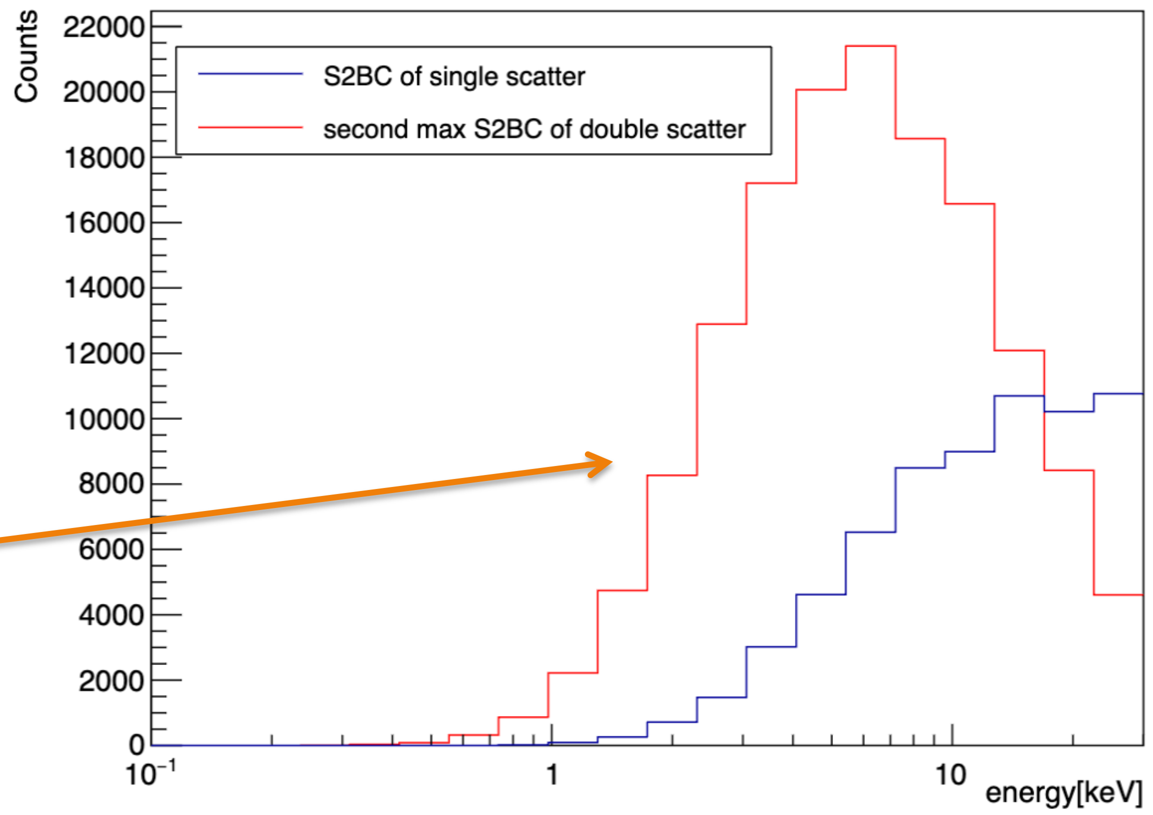


Phys. Rev. D 110 (2024), 023029

Lower energy NR signals

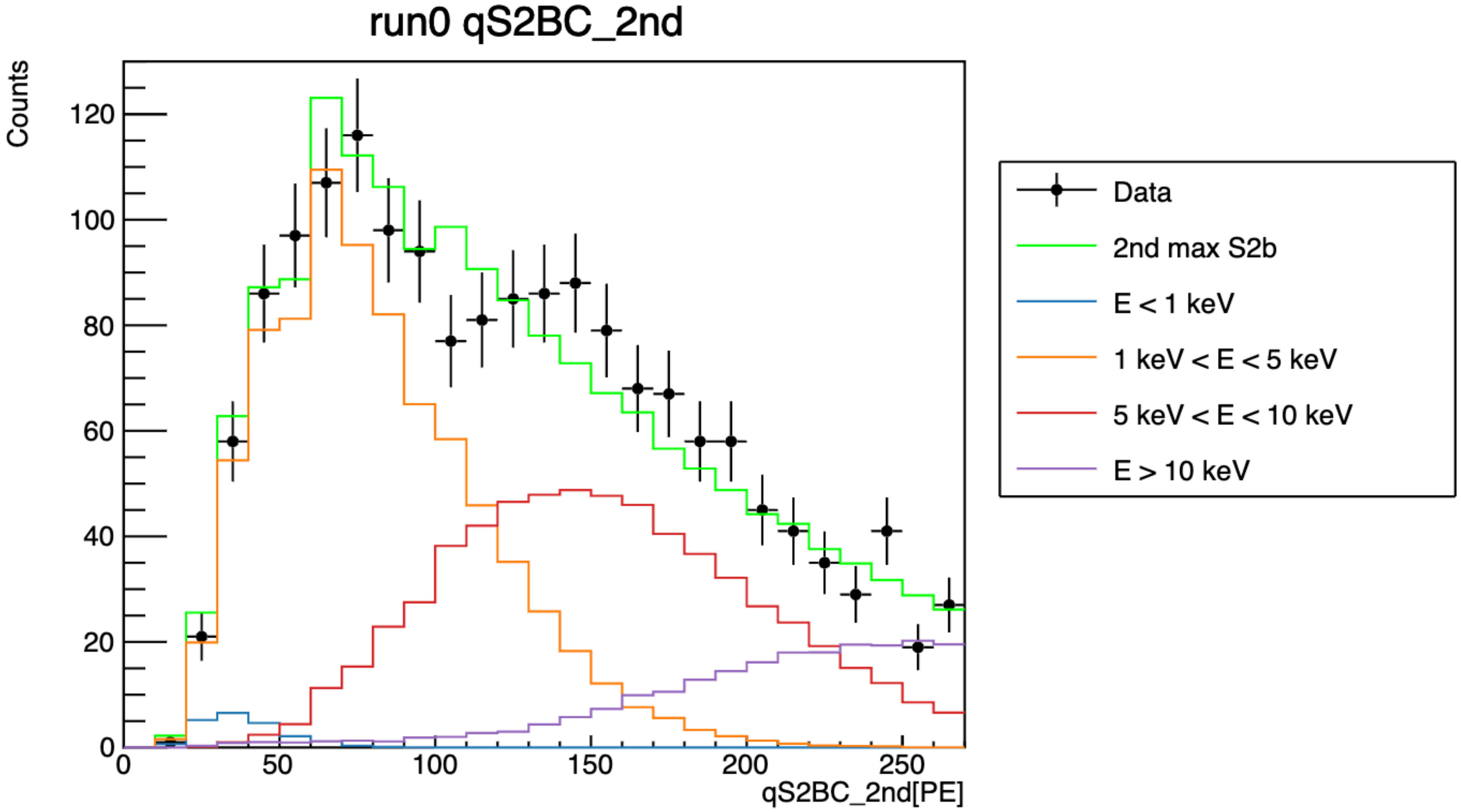
- **Mutli-scattering in neutron events**
- **Subleading S2 is a good source of NR signals below a few keVs**





Subleading S2 in DD double-scattering

- **Fitting for lower energy NR Charge Yield from double-scattering DD events**



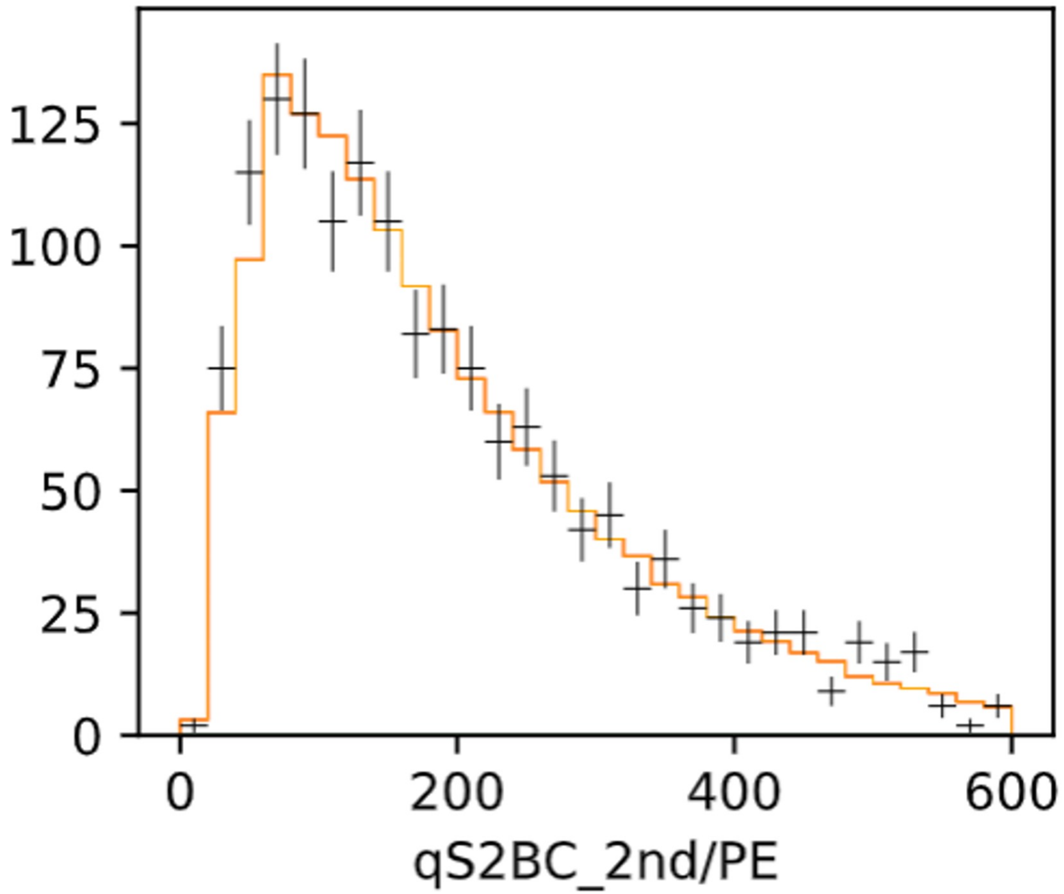
Signal Response Model in NEST2.0

- **In NEST model, charge yield and light yield is given by:**
  - $N_q' = \alpha E^{\beta}$
  - $Q_y'(E,\epsilon,\rho) = \frac{1}{\varsigma(\epsilon,\rho)(E+\varepsilon)^p}(1 - \frac{1}{1+(E/\zeta)^{\eta}})$, $\varsigma\ (\epsilon,\rho) = \gamma\epsilon^{\delta}(\frac{\rho}{\rho_0})^{\nu}$
  - $L_y'' = \frac{N_q'}{E} - Q_y'$
  - $L_y' = \frac{N_{ph}}{E}$, $N_{ph} = L_y'' E(1 - \frac{1}{1+(E/\theta)^{\iota}})$
- **N_i and N_{ex} is given by Q_y' and L_y', and Fano factor for NR is also considered:**
  - $N_{ex} = G[\langle N_{ex}\rangle, \sigma_{ex}]$, $\sigma_{ex} = \sqrt{F_{ex}\langle N_{ex}\rangle}$
  - $N_i = G[\langle N_i\rangle, \sigma_i]$, $\sigma_i = \sqrt{F_i\langle N_i\rangle}$
- **And parameters ξ and ω for fluctuations of recombination fraction are adjusted in Signal Model.**

Parameter	NEST v2
α	$11.0^{+2.0}_{-0.5}$
β	$1.10^{+0.05}_{-0.05}$
γ	$0.0480^{+0.0021}_{-0.0021}$
ϵ	$12.6^{+3.4}_{-2.9}$
ζ	$0.3^{+0.1}_{-0.1}$
η	2^{+1}_{-1}
θ	$0.30^{+0.05}_{-0.05}$
ι	$2.0^{+0.5}_{-0.5}$
F_{ex}	0.4
F_i	0.4
ξ	0.59
ω	0.19

Fit Result

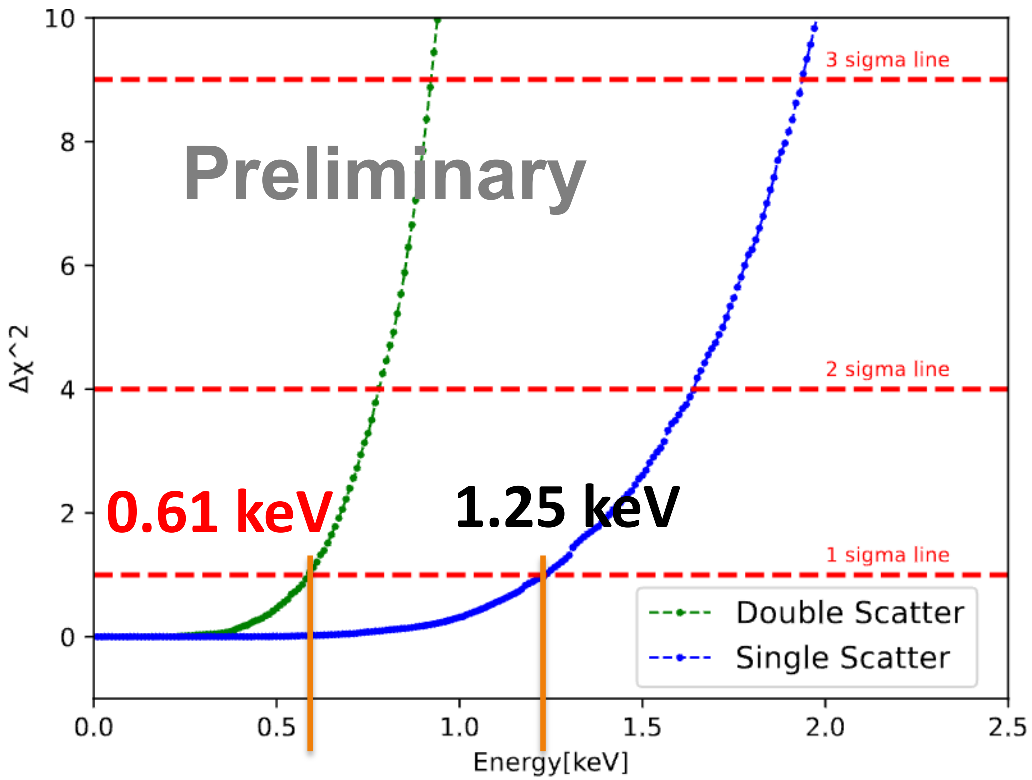
- **1D fitting of subleading S2 is used to tune the charge yield parameters of low energy region.**

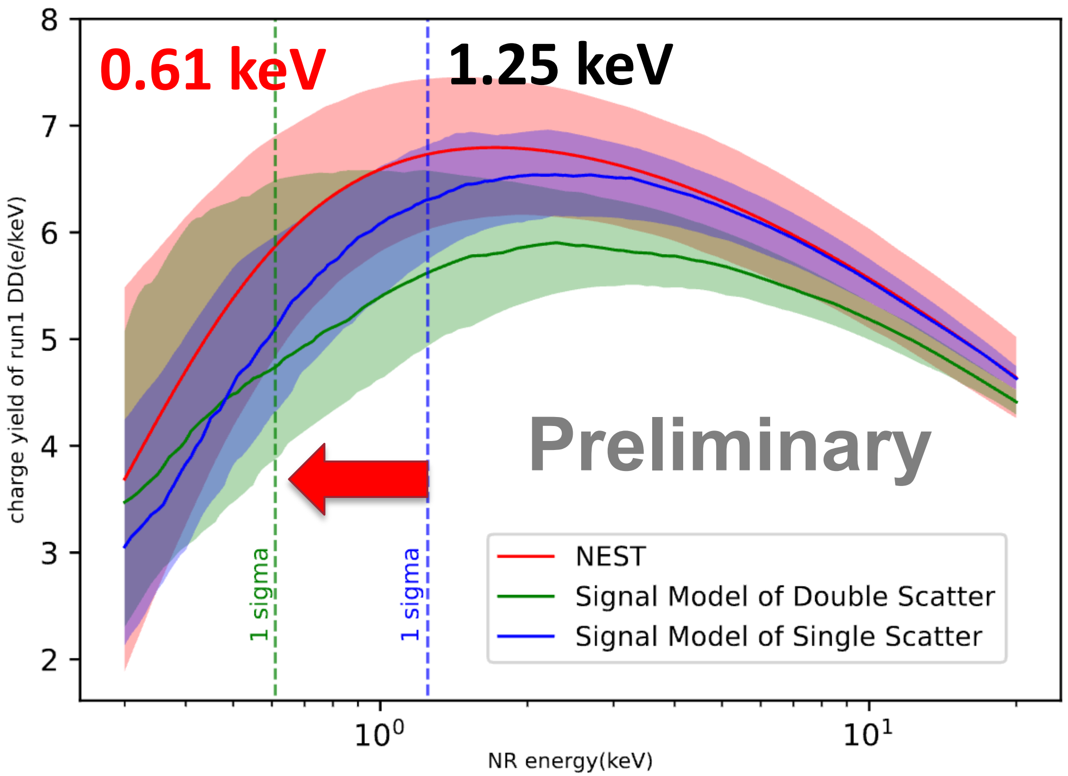


Parameter	NEST v2	Run1 subleading
α	$11.0^{+2.0}_{-0.5}$	$12.0^{+1.7}_{-1.1}$
β	$1.10^{+0.05}_{-0.05}$	$1.10^{+0.06}_{-0.04}$
γ	$0.0480^{+0.0021}_{-0.0021}$	$0.0482^{+0.0014}_{-0.0018}$
ϵ	$12.6^{+3.4}_{-2.9}$	$14.7^{+3.1}_{-3.0}$
ζ	$0.3^{+0.1}_{-0.1}$	$0.3^{+0.2}_{-0.1}$
η	2^{+1}_{-1}	2^{+2}_{-1}
θ	$0.30^{+0.05}_{-0.05}$	$0.30^{+0.06}_{-0.06}$
ι	$2.0^{+0.5}_{-0.5}$	$2.2^{+0.7}_{-0.7}$
F_{ex}	0.4	$0.5^{+0.4}_{-0.4}$
F_i	0.4	$0.4^{+0.4}_{-0.3}$
ξ	0.59	$0.53^{+0.28}_{-0.36}$
ω	0.19	$0.21^{+0.52}_{-0.18}$

Low Energy NR Charge Yield

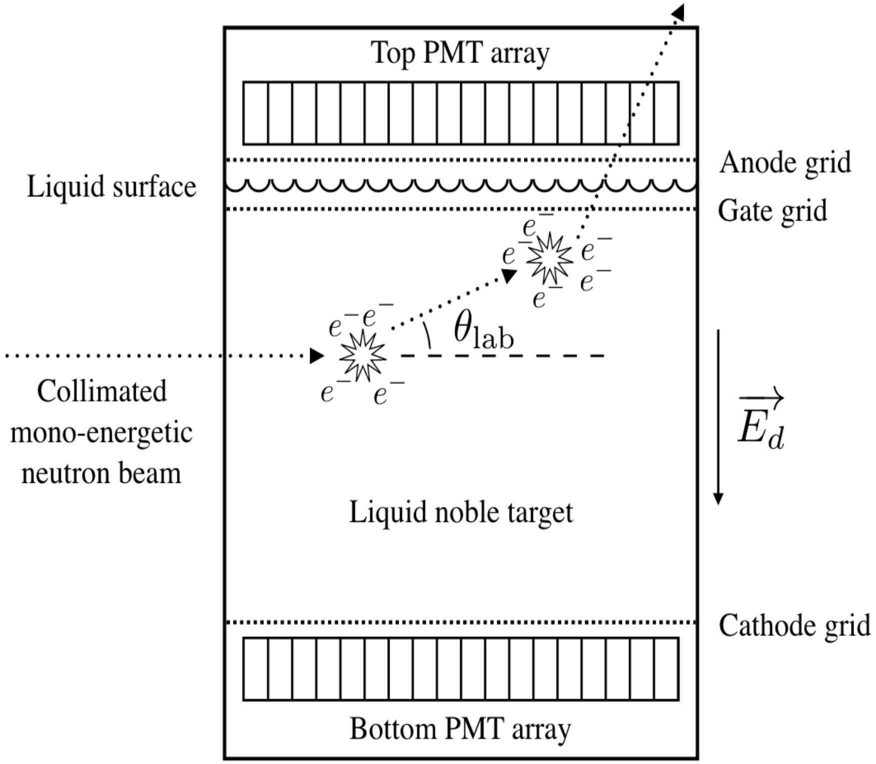
- **Reliability evaluation by cutting off the corresponding yield below a certain energy from the best fit yield measurement and calculating the $\Delta\chi^2 = \chi^2(E_{thr}) - \chi^2(0)$**
  - $\chi^2 = \sum_{i=1}^{N} \frac{(O_i - E_i)^2}{E_i}$, O_i and E_i are the observed and simulated counts per bin.





NR energy full reconstruction

- **Energy reconstruction from scattering angle**
- **To validate the fitted NR charge yield**
  - Work-in-progress



double scatter events

⇩

3D position (x, y, z)

⇩

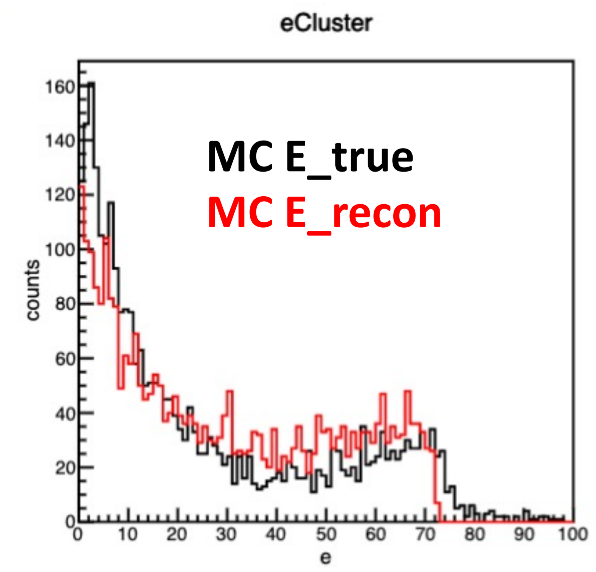
scattering angle(θ_{CM})

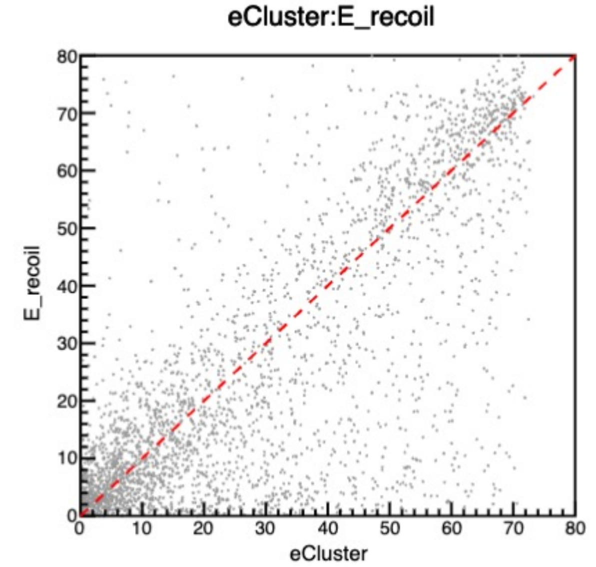
⇩

nuclear recoil energy(E_{nr})

⇩

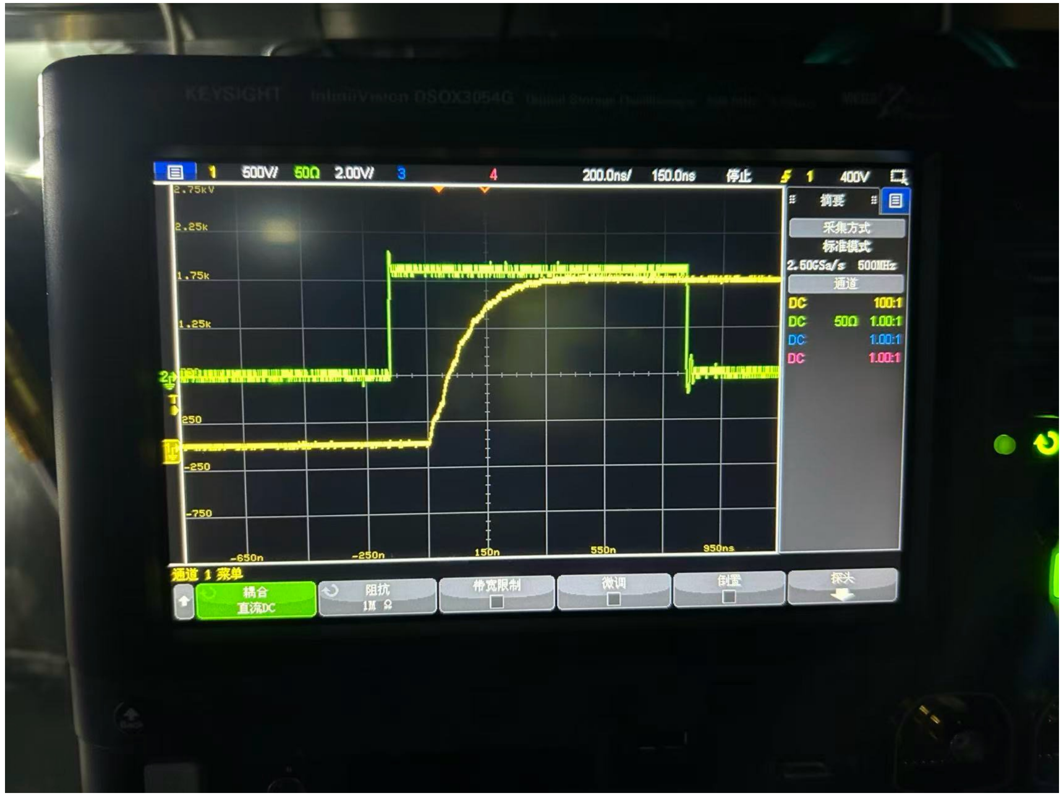
NR charge yield (Q_y)

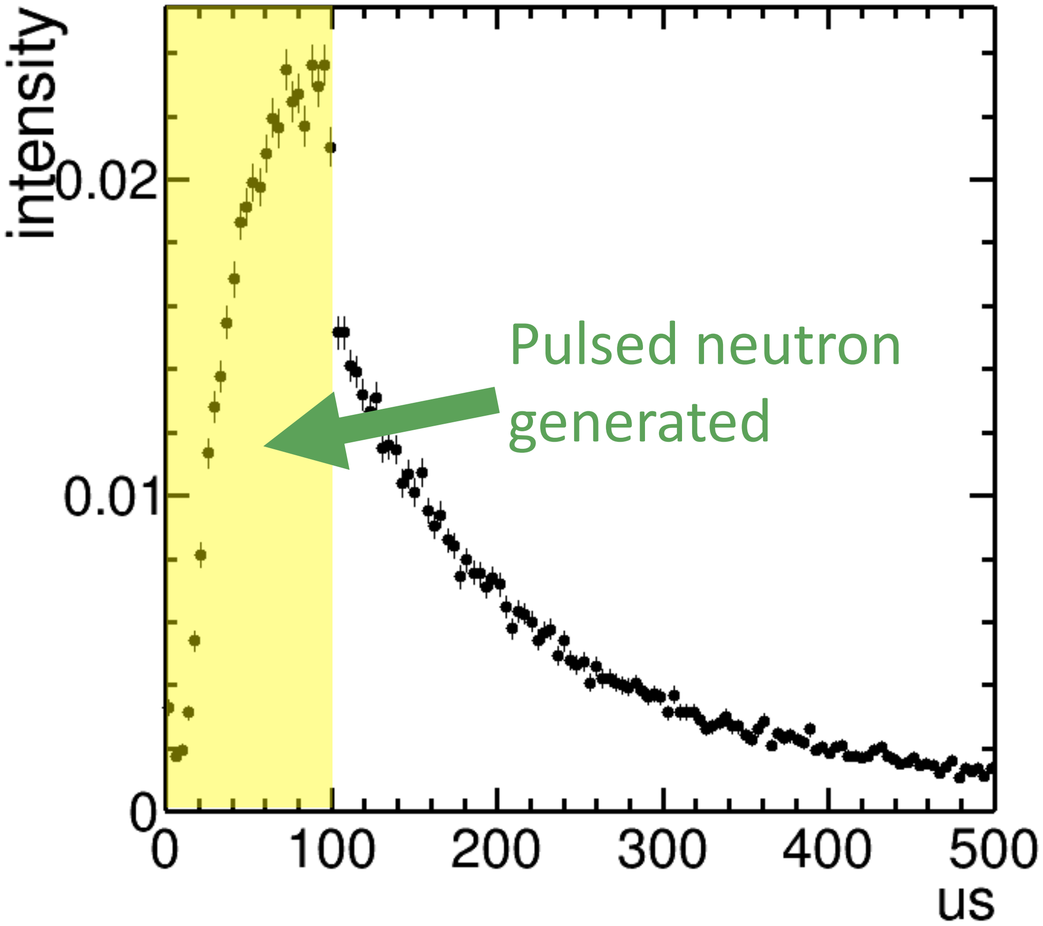




Pulsed DD calibration

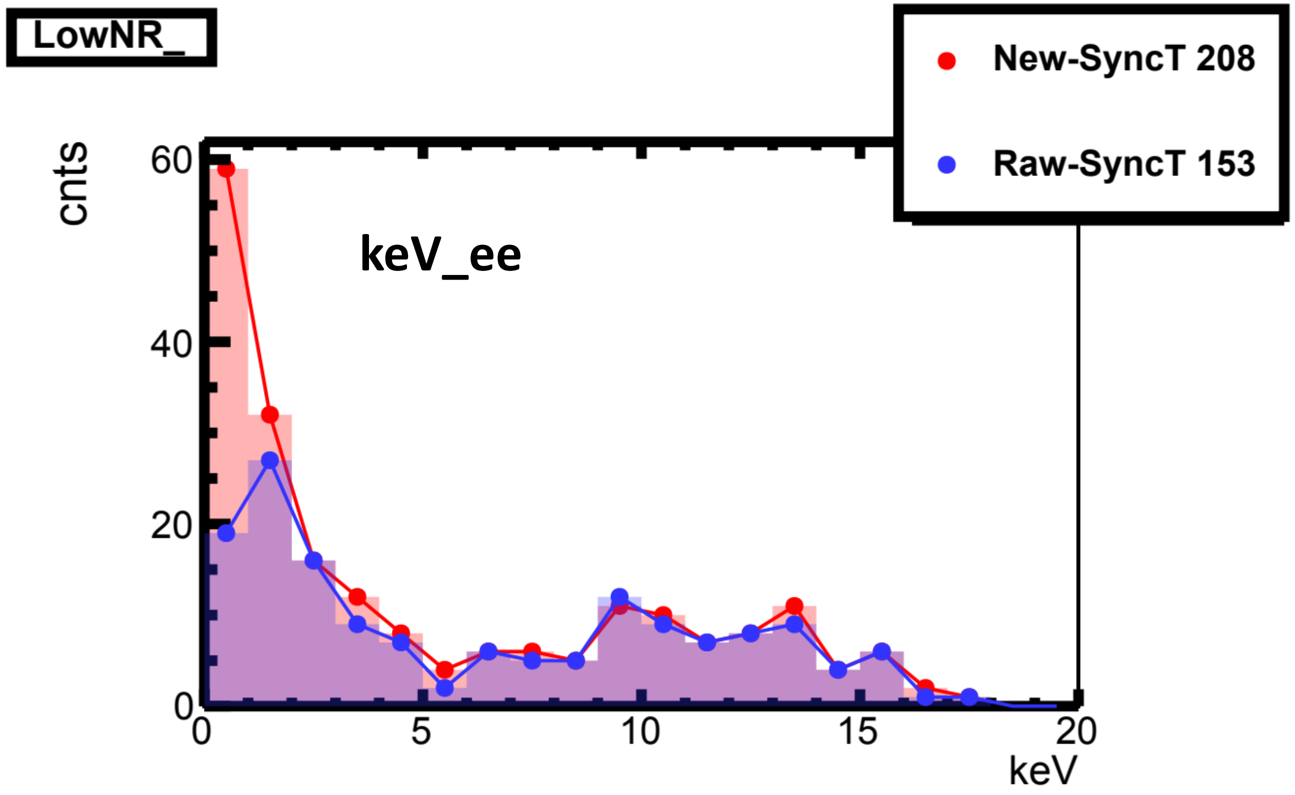
- **100us ionization HV pulse achieved**
- **Synchronization signal recorded in PandaX-4T**

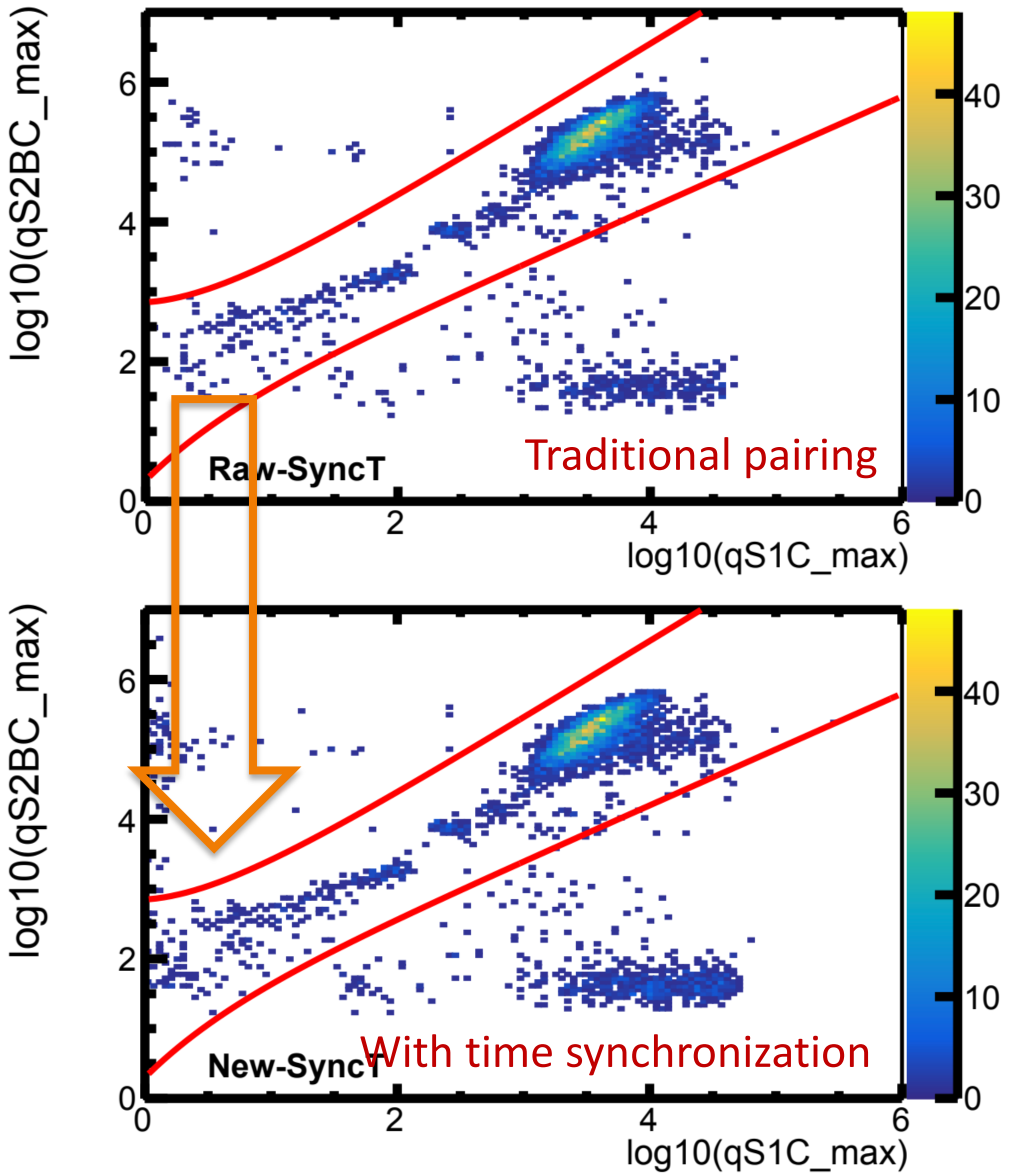




Pulsed DD calibration

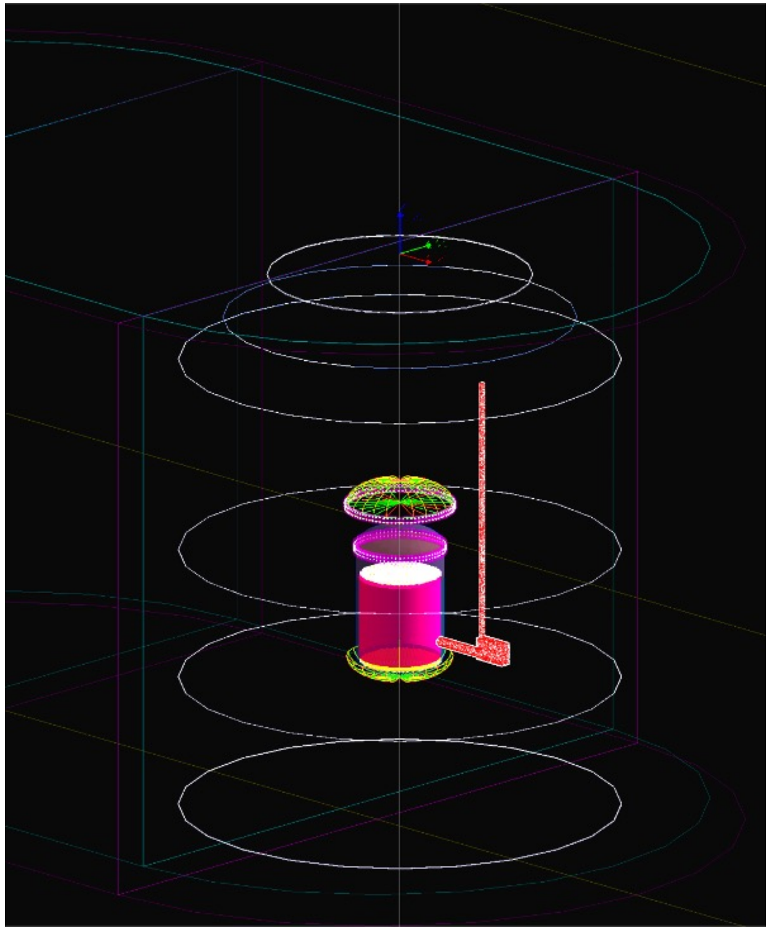
- **With DD time synchronization, able to recover some low energy NR events**

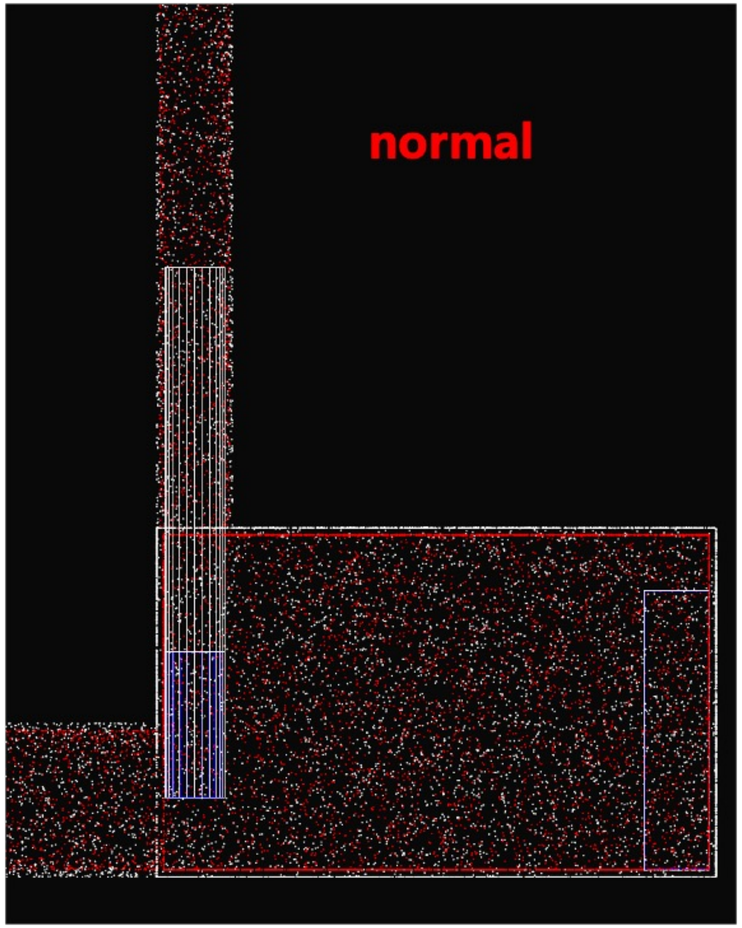


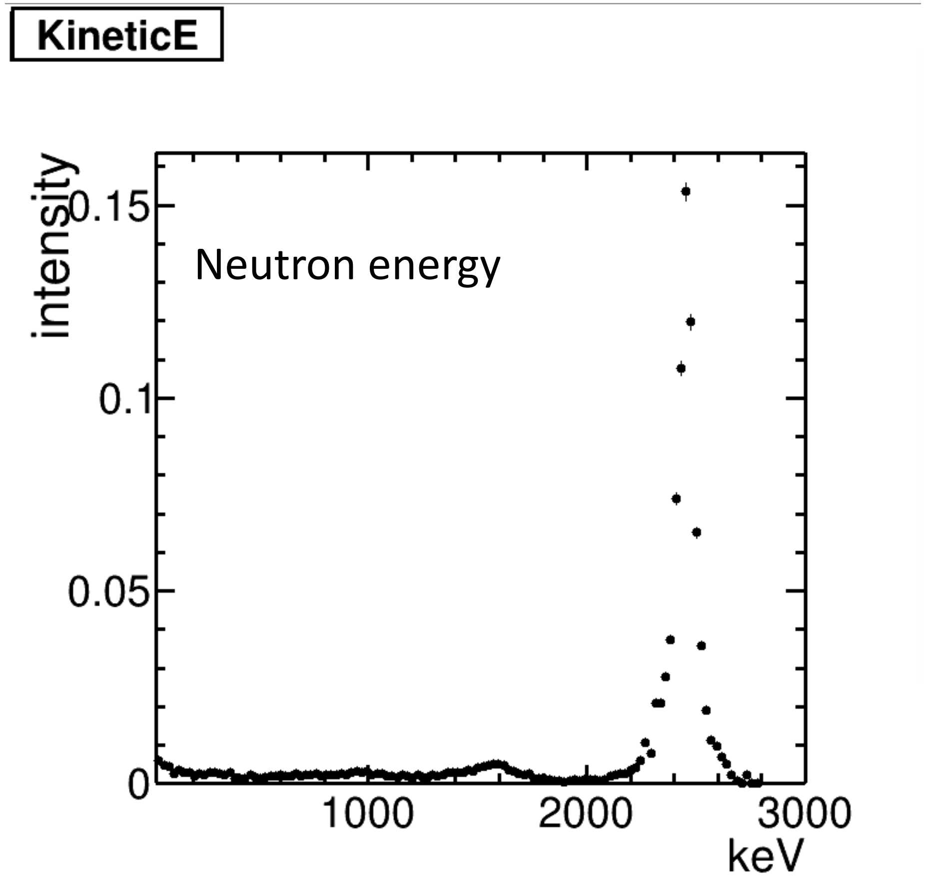


New DD Calibration System

- **Designing new DD calibration system for next stage PandaX-xT**

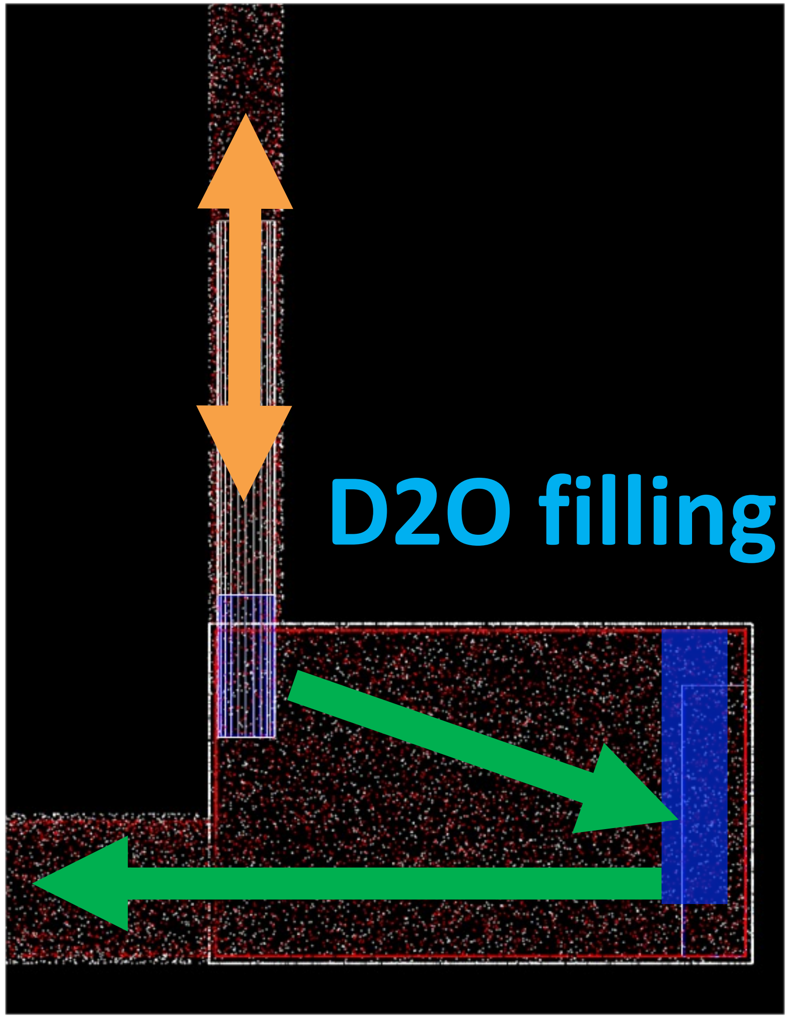


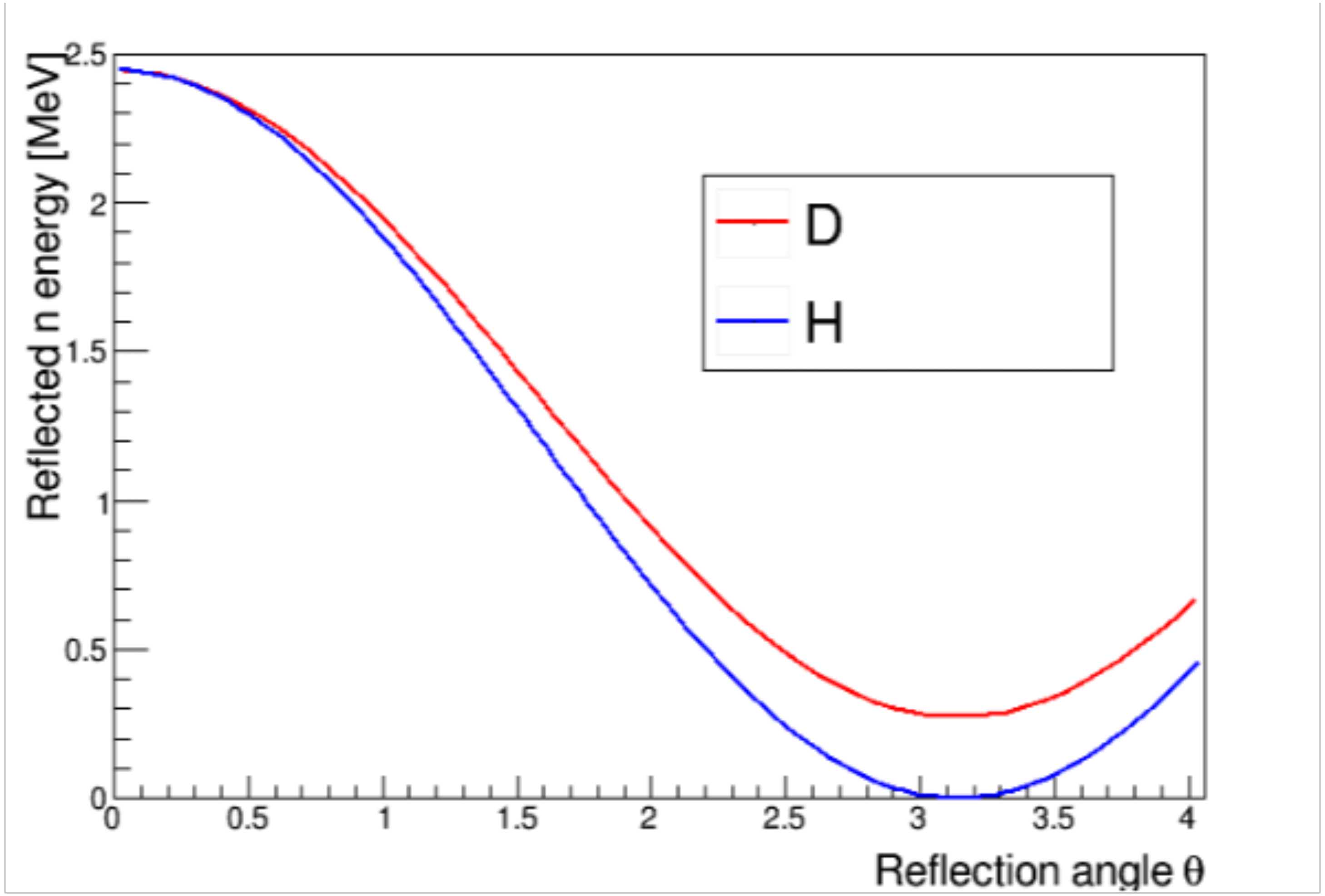




New DD Calibration System

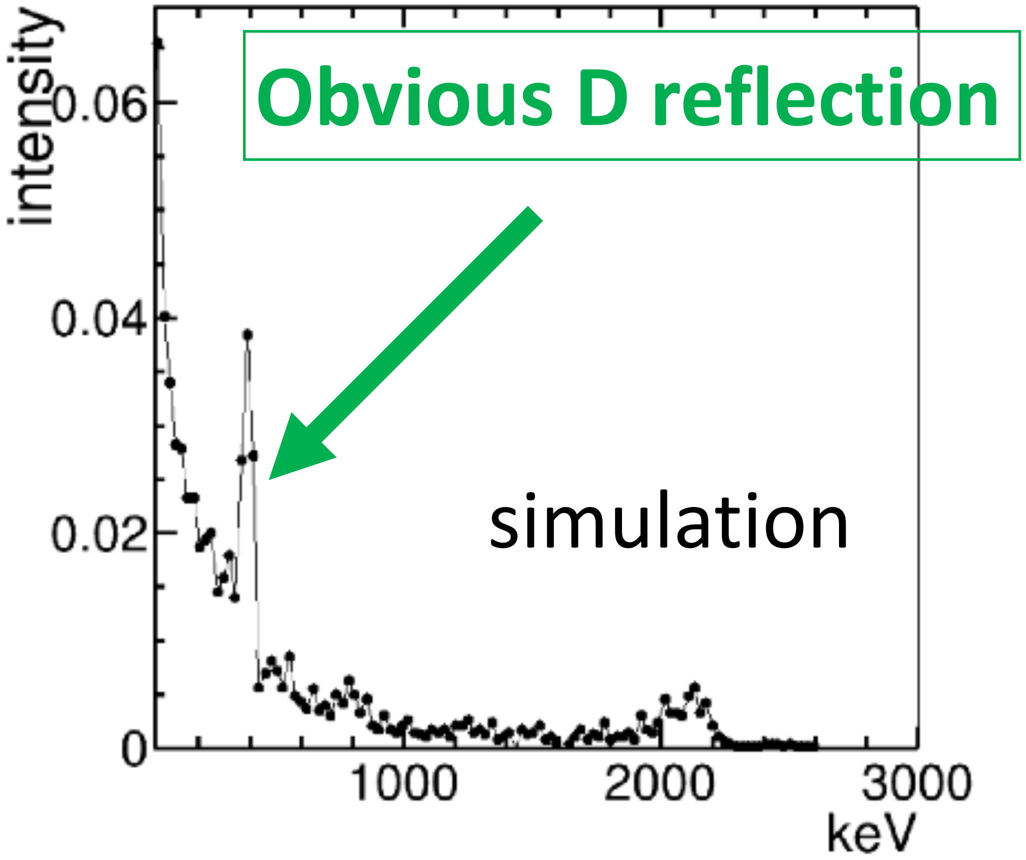
- **Neutron + D_2O scattering**

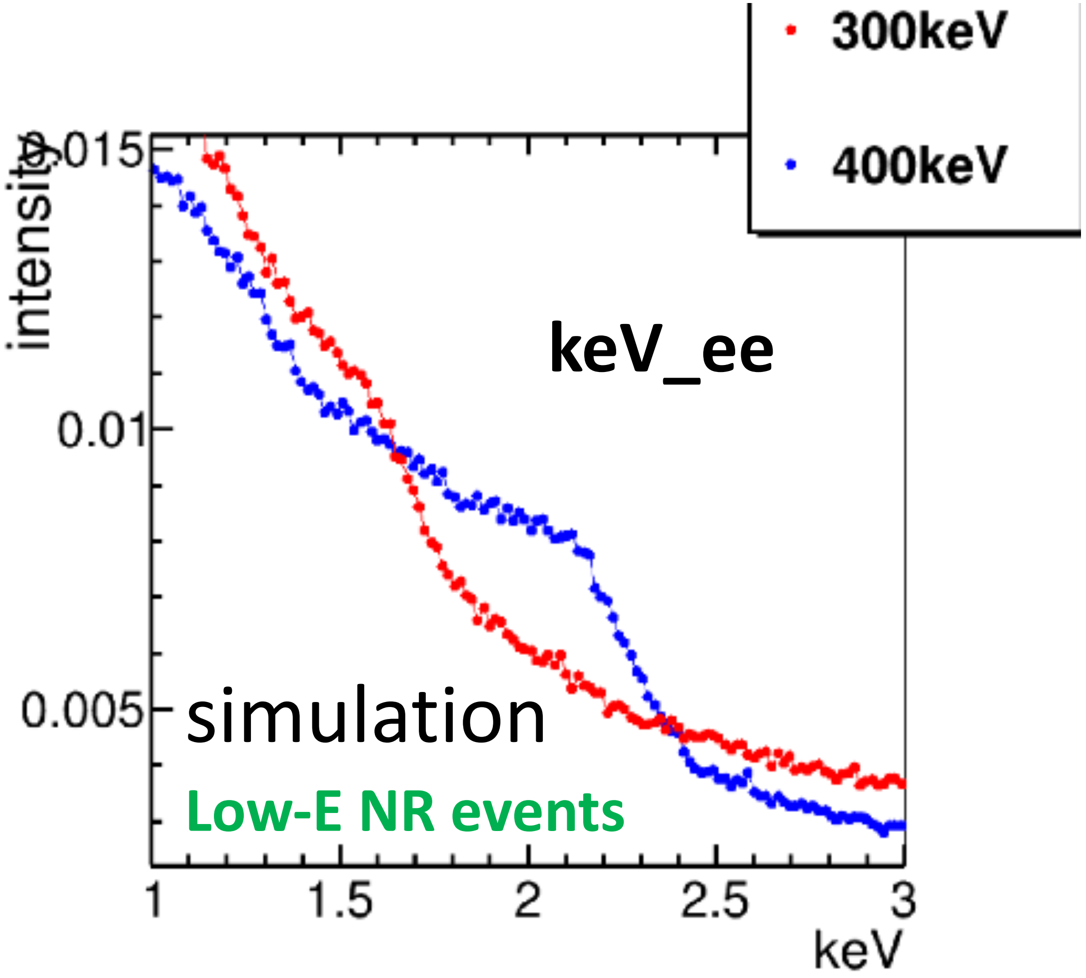




New DD Calibration System

- **With an angle of -42.9 degrees, expect to have 400keV neutrons**
- **Providing a large sample of low-E NR calibration**





Summary

- **Low energy NR calibration plays a cruciel rule in searchs of low mass dark matter or low energy neutrinos**
- **Exploring multiple sources to calibrate the low-E NR signal response**
  - Multiple scattering neutron events
  - Pulsed DD calibration
  - New design of DD system