Experimental result on measuring the Migdal effect with neutron-induced nuclear recoils at the keV level in liquid xenon

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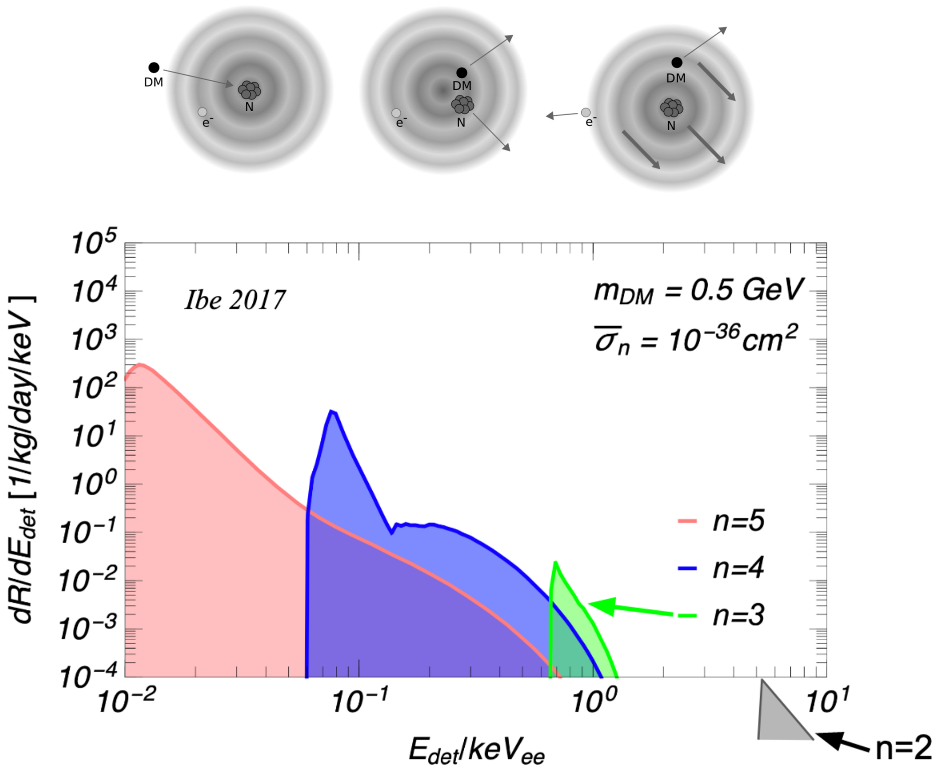
Migdal effect and dark matter searches

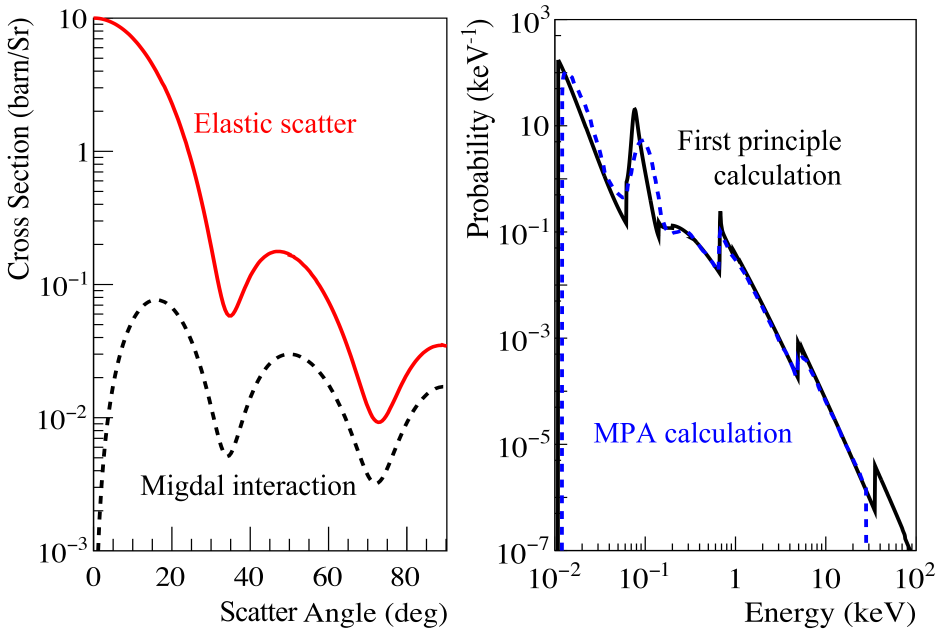
- Interactions between a neutral particle and a nucleus may result in atomic excitation or ionization
- First studied by Migdal and further developed by Ibe and other authors
- Migdal atomic relaxation can lead to keV electron recoil (ER) energy for sub-keV nuclear recoils (NRs)
- Potential enhancement of low-mass dark matter sensitivity has been explored
  - LUX, ***PRL 122 131301 (2019)***
  - XENON1T, ***PRL 123, 241803 (2019), PRD.106.022001 (2022)***
  - DarkSide50, *arXiv:2207.11967*
  - EDELWEISS, ***PRD 106, 062004 (2022)***
  - CDEX-1B, ***PRL 123.161301 (2019)***
  - SuperCDMS, *arXiv: 2203.02594*
  - and more …
- This effect has not been definitively verified



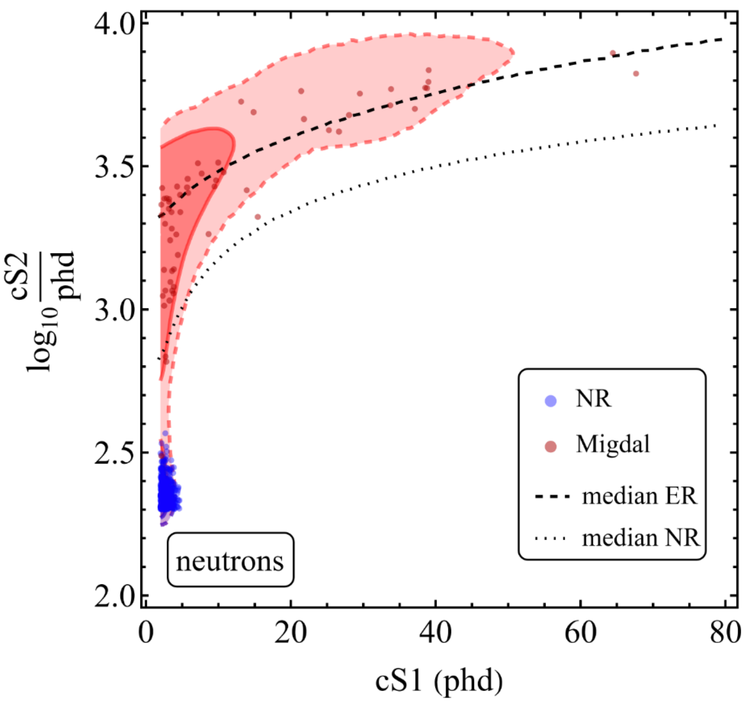
Observable energy for Migdal interactions induced by 0.5 GeV dark matter in liquid xenon, *Ibe, et al, JHEP, 03 (2018), 194*

Neutron-induced Migdal interactions in xenon

- Neutrons could induce Migdal interactions in LXe
- Migdal signals accompanying low-energy NRs can be well separated from pure NRs to be directly observed
- Migdal cross section is proportional to that of elastic scatters with an additional $E_n(1-\cos\boldsymbol{\theta})$ dependence



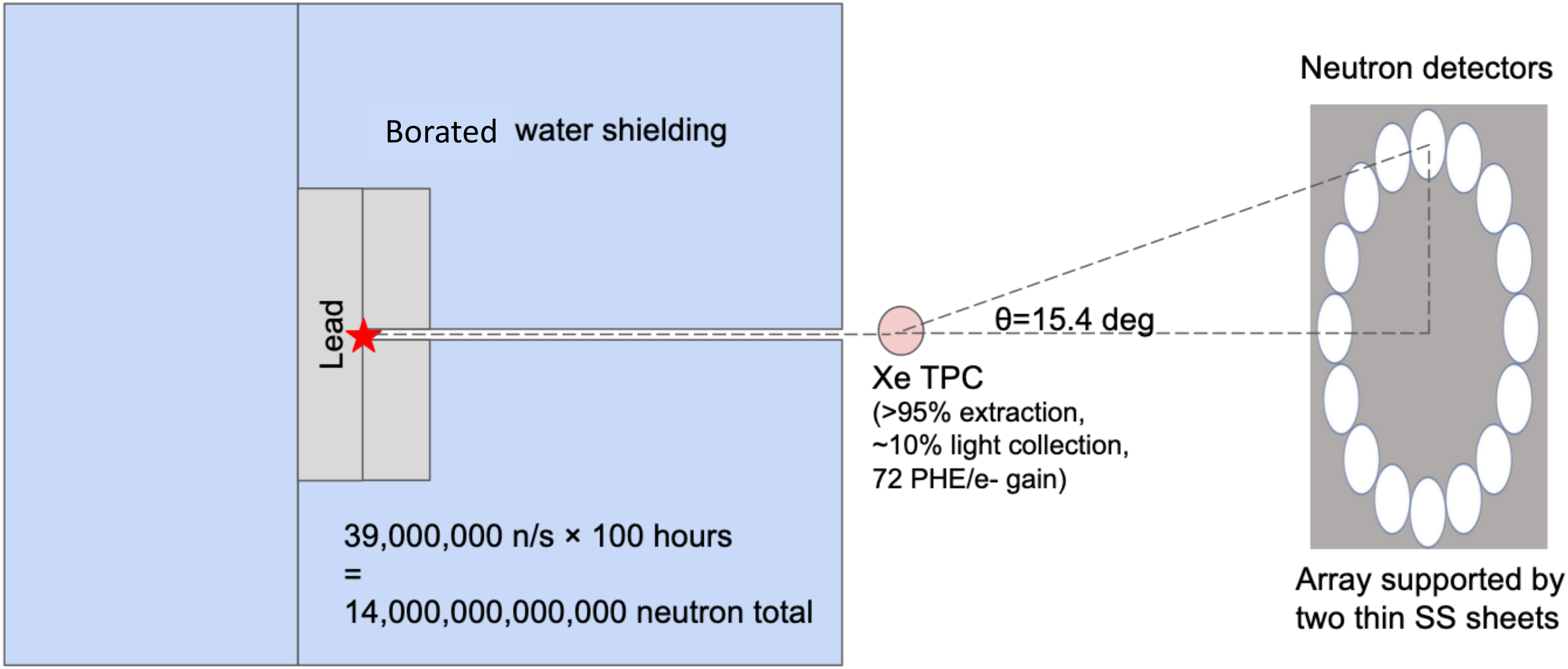
Calculated cross section (left figure, dashed line) and energy spectrum (right figure, two methods tested) for Migdal interactions of 14MeV neutron with xenon



Simulated LXe response to Migdal interactions produced by 17keV neutrons, *Bell et al, PRD 105, 096015 (2022)*

Measuring Migdal with 14.1MeV neutrons

- **High energy neutrons (14.1 MeV):** enhance Migdal cross section, reduce neutron multiscatter (NMS) background
- **Tag scattered neutrons:** obtain precise Migdal interaction time, reduce background
- **Quasi-mono-energetic NR:** reduce uncertainties in signal rate calculation, background modeling from nuclear cross section, and signal detection efficiency
- **Low scatter angle:** reduce NR energy, separate Migdal events from pure NRs

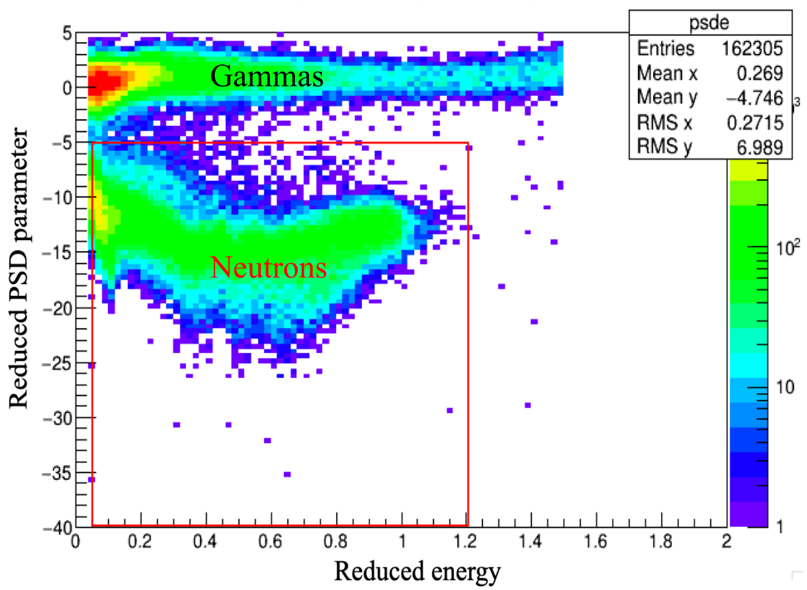


Experimental setup at LLNL

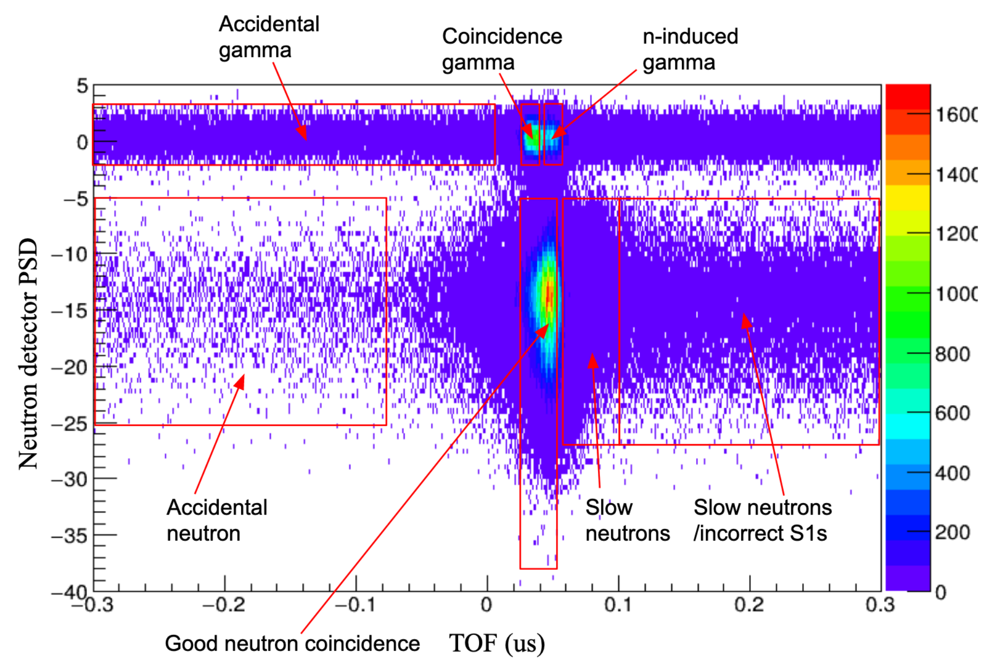
Migdal search event selection

Analysis cuts select neutron coincidence events to search for candidate Migdal interactions

- Single scatter (SS) in xenon TPC, with conservative S1 and S2 pulse quality cuts
- Definitive neutron detection in liquid scintillator (LS) detector array
- Precise time of flight (TOF) delay between Xenon TPC signal and LS detector signal



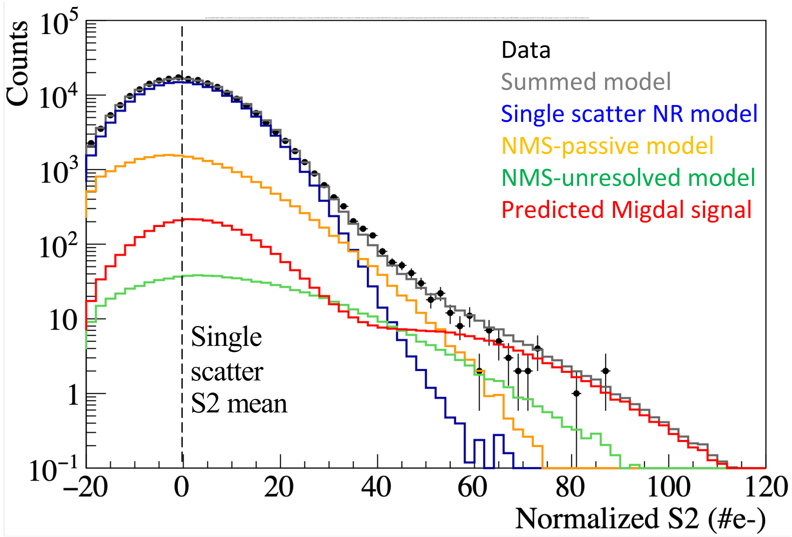
A typical distribution of the Pulse Shape Discrimination (PSD) parameter and reduced energy in a neutron detector. Gammas are normalized to have a PSD value of ~0 and neutrons have negative PSD values



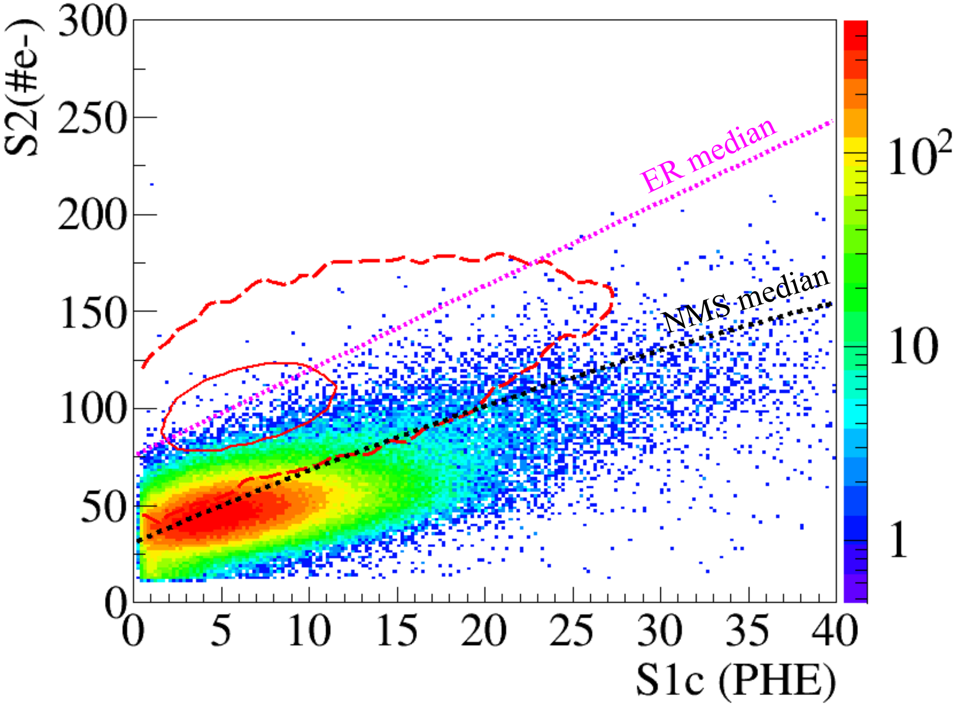
An illustration of neutron PSD vs Time of flight (TOF) for one coincidence neutron detector

M-shell (0.5—3keV) Migdal search

- Sufficient ER energy to be separated from NRs
- S1 and S2 distributions modelled with NEST (tuned to SS)
- Neutron multi-scatter (NMS) is modeled using tuned NEST and validated with z-resolved NMS data
- ER background is negligible
- 2D likelihood fit favors a lower Migdal signal rate in the M-shell signal region than what we calculated
- Final statistical significance under evaluation



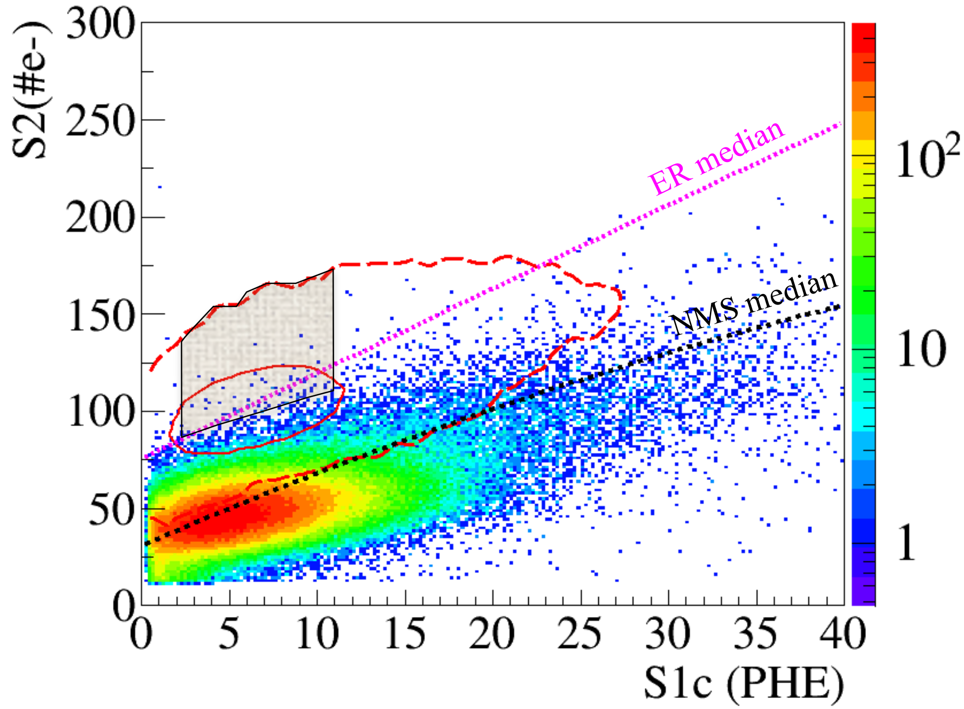
Normalized S2 distribution of data and models for range 3<S1<11 PHD



S1-S2 distribution of data used for M-shell Migdal analysis. Red lines illustrate the 50% (solid) and 90% (dashed) of M-shell signal contours; magenta line indicates the median ER distribution and black line shows the median NMS background.

M-shell (0.5—3keV) Migdal search – simple check

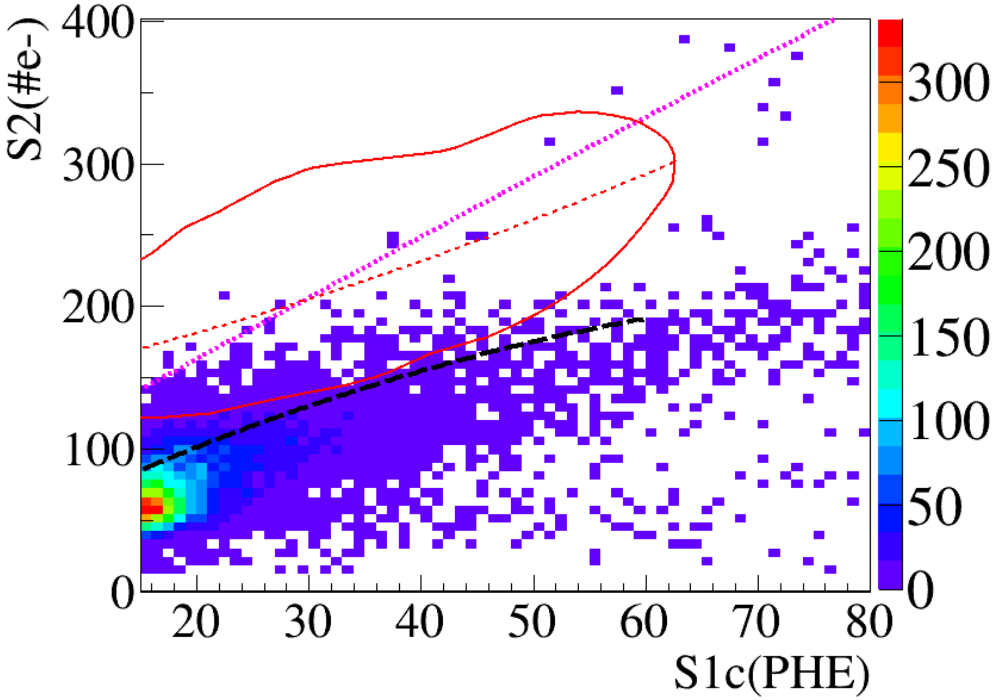
- 280k events have S1>3PHE (reduce accidentals)
  - 235k single scatter NR events
  - 38k multiscatter in passive materials
  - ~2—4k unresolved NMS in xenon TPC
- ~4000 Migdal interactions expected in this region
  - ~200 events with ER energy depositions of 0.5—3 keV (M-shell)
  - Up to 20 extra photons may be produced
  - ~50—100 electrons may be added
- Conservative cut and count to illustrate sensitivity
  - ROI: above M-shell signal median and below 90% contour, 3<S1<11
  - 39–60 signals expected
  - 21+/-5 background expected from neutron multi-scatters (NMS), and 13+/-3 background events from neutron passive scatters in passive materials
  - 45 events observed in total
  - Cut and count sensitivity will increase if we move lower S2 bound up (more complex systematics)



S1-S2 distribution of data used for M-shell Migdal analysis. Red lines illustrate the 50% (solid) and 90% (dashed) of M-shell signal contours; magenta line indicates the median ER distribution and black line shows the median NMS background.

L-shell (3—30keV) Migdal search

- L-shell Migdal signals have higher energy (3—30keV) so they could be better separated from the pure NR background events
- Large S1s are easy to identify
  - Fewer cuts, increased statistics: ~400k NR total
  - ~10 L-shell signals expected
  - More stringent TOF cut used to reject accidental background
- Cut and count to illustrate signal to background ratio in this energy regime
  - ROI: above Migdal signal median and below 85% signal contour
  - 3–4.7 signals expected
  - 3.4+/-2 NMS background expected and 5.2+/-2 ER background expected
  - 7 events observed in total
  - Full systematic uncertainties being studied



S1-S2 distribution of data used for L-shell Migdal analysis. Red lines illustrate the median (dotted) and 85% contour (solid) of L-shell signals; magenta line indicates the median ER distribution and black line shows the median NMS background.

Implications of experimental result

We do not seem to observe events at the predicted rate in our expected signal region

- Theoretical uncertainty in Migdal rate calculation needs further evaluation
  - up to 35% discrepancy is observed when testing different calculation methods
  - More theoretical studies to understand the origin of these differences
- Our experimental condition is different from that expected for a low-mass dark matter search
  - Co-existence of NR and ER with comparable ionization cloud size may enhance recombination, and cause Migdal signals to move toward background region
  - Low-mass dark matter searches would have negligible NR component so they won't be as impacted by this phenomenon
  - Lower energy NR-based Migdal searches (ideally with subthreshold NR components) can mitigate this effect and mimic a dark matter search scenario more closely
  - More experimental efforts are being planned

Summary and outlook

- The Migdal effect can substantially improve the sensitivity of existing experiments to low-mass dark matter interactions
- Tagged scatters of neutrons with liquid xenon is a promising approach to search for the Migdal effect directly
- We carried out a direct search for the Migdal effect in liquid xenon using 14.1MeV neutrons and demonstrated a Migdal signal to background ratio of ~>1
- Preliminary analysis of experimental data suggests that we do not observe events at the predicted rate in our expected signal region
- More theoretical work is being conducted and the analysis is being finalized – publication to be released soon
- Additional experimental efforts are being planned to mitigate possible biases that may have existed in this experiment

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