Migdal Search in the LUX-ZEPLIN Dark Matter Experiment

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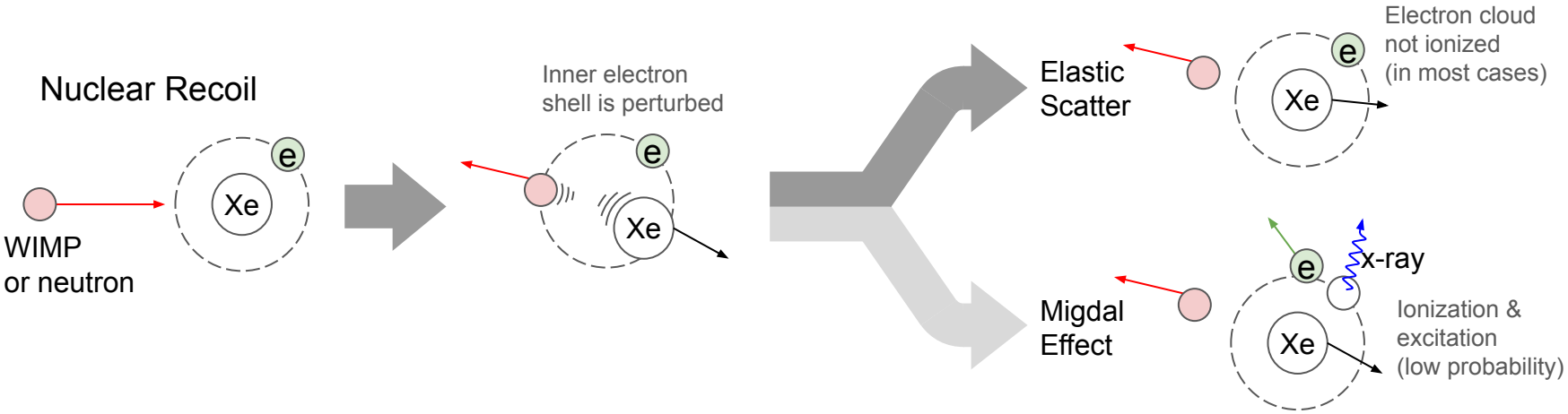
On behalf of the LZ Collaboration

UCLA Dark Matter 2023
03/31/2023

BROWN

Migdal Effect and Dark Matter Search

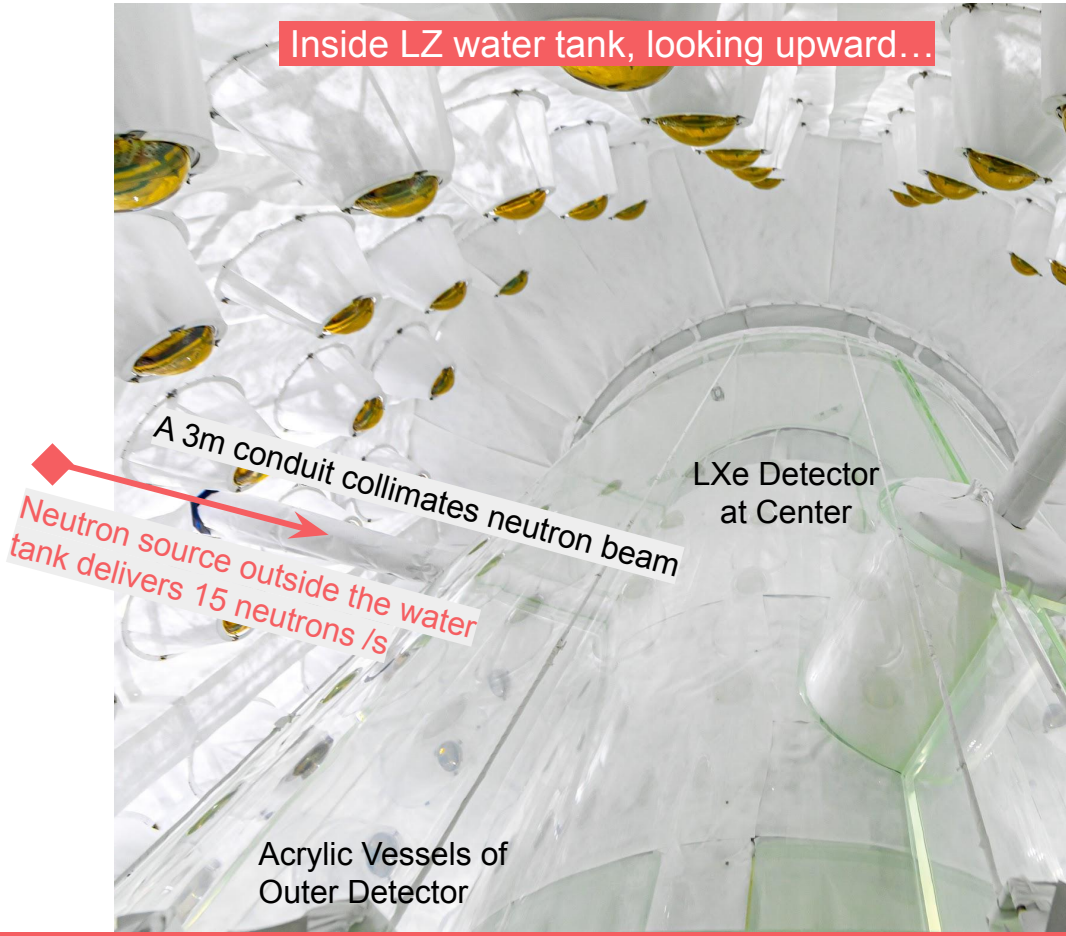


- Migdal Effect: In the recoil of nucleus, electron cloud falls behind resulting in possible ionization and excitation
- Increase sensitivities to sub-GeV/c^2 dark matter
  - Deposited energy from inelastic Migdal events is higher than conventional elastic nuclear recoil
  - e^- and γ make more detectable excitations

DD Neutron as a Source of Nuclear Recoil (NR)

- DD Migdal run
  - Deliver 15M of 2.45 MeV monoenergetic neutrons into LXe TPC
  - Collected 36k single scattered NR >20 keVnr after data quality cuts
  - Adelphi Technologies' DD109 Neutron Generator is used to produce 2.45 MeV monoenergetic neutrons.

- Gamma background from DD generator is low, so very low fraction of electron recoil (ER) events in LXe
  - Residual Bremsstrahlung gammas shielded by 6 mm Pb surrounding the main chamber
  - Further suppressed by selecting events coincident with neutron pulses (at 150 Hz with the width of 50 us per pulse)
  - Akerib et al. arXiv:1608.05381, Verbus et al. Nucl. Instrum. Methods A851, 68, Huang DOI:10.26300/zvs6-fx07

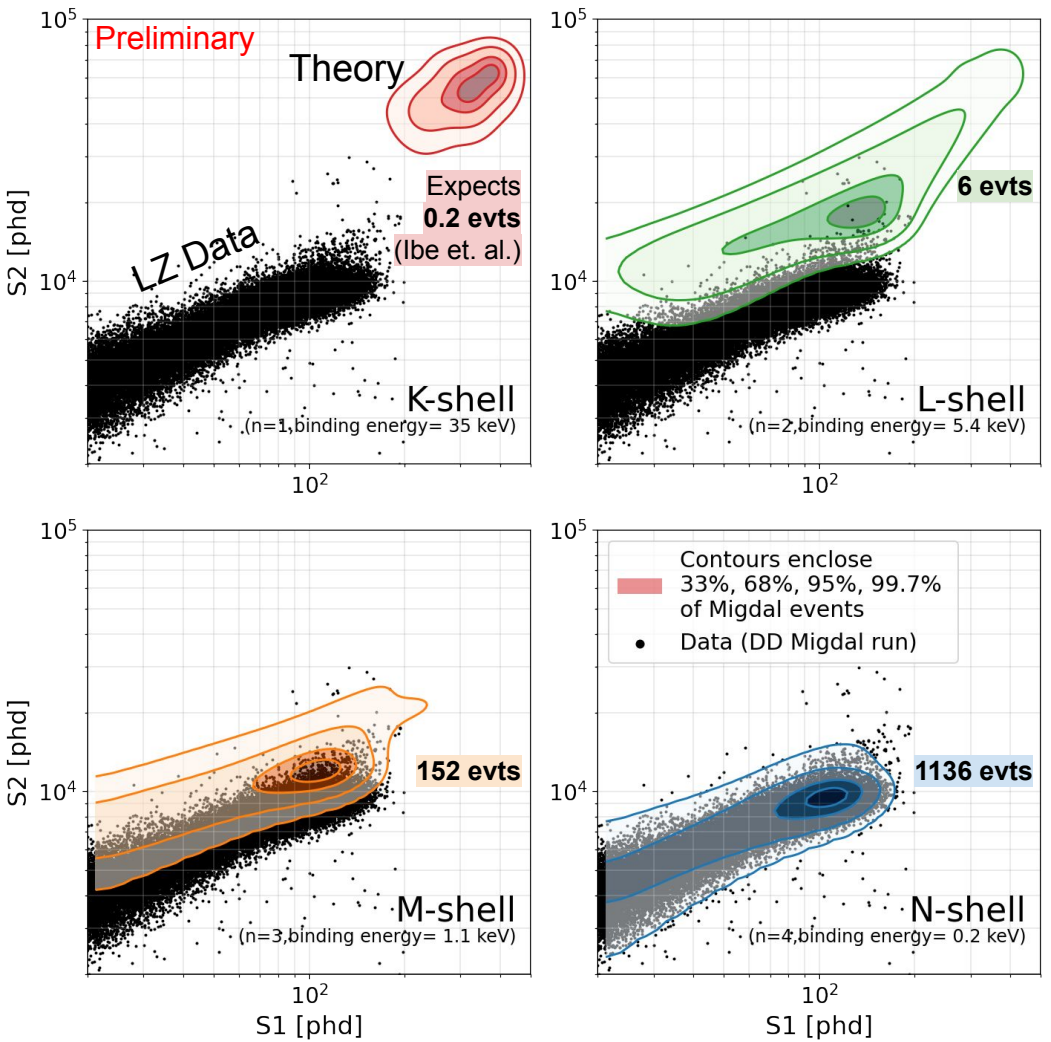


Migdal Signal Calculation

- Migdal rate and deposited energy are predicted based on Ibe et al.
  - Calculated Number of Migdal Events for 36k SS above threshold (E_{Recoil}>20 keVnr) is shown in the plots (JHEP03(2018)194)
  - Cox et al. (Phys. Rev. D 107, 035032) reported 1.2x higher rate due to multiple ionization in Xe

Our analysis focuses on:

- L-shell Migdal
  - Expect 6 events, with +5 keVee
- M-shell Migdal
  - Expect 152 events, with +1 keVee
- Other shells are …
  - K shell Migdal is too few
  - N shell Migdal is too similar to NR

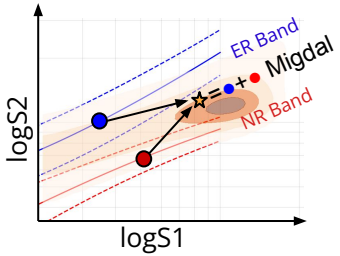


The Migdal Effect and Relevant Backgrounds (1/2)

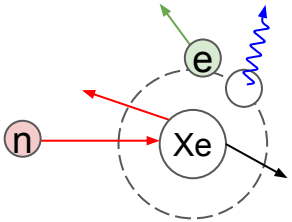
Neutron
Electron
Photon
Xe

SIGNAL

Migdal : Signal



ER component boosts the signal above the NR band.



MFP of e- or x-ray from L or M shell Migdal is <<1 mm close to NR site
→ single S2 (SS)

BACKGROUND

MSU : bkg for M-shell migdal

Multiple Scatter Unresolved in position

IE+CSU : bkg for L-shell migdal

Inelastic and Compton Scattering Unresolved in position

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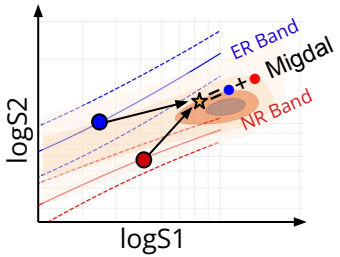

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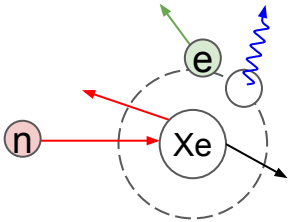

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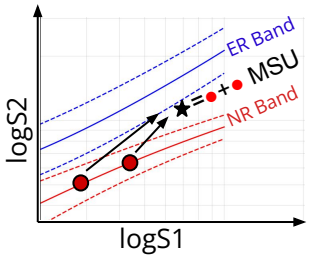

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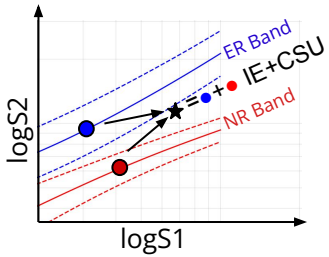

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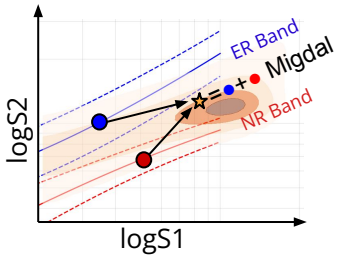

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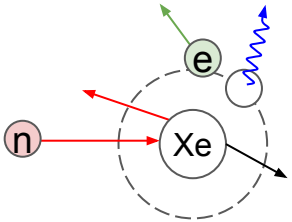

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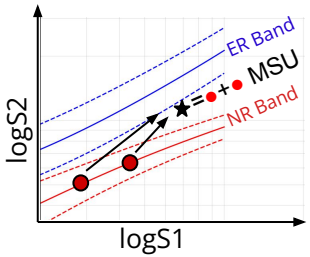

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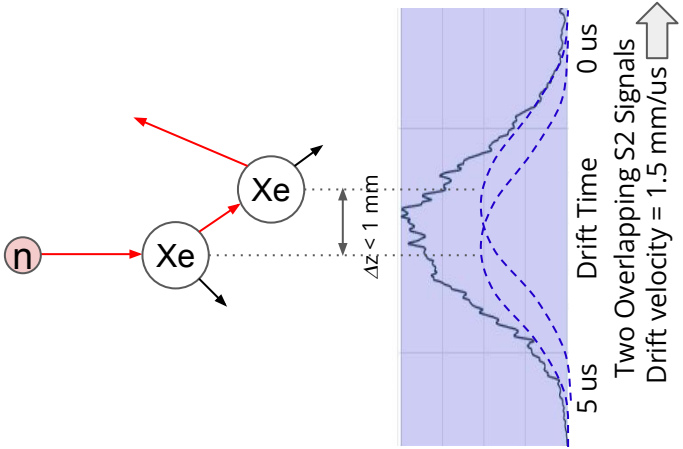

IE+CSU : bkg for L-shell migdal

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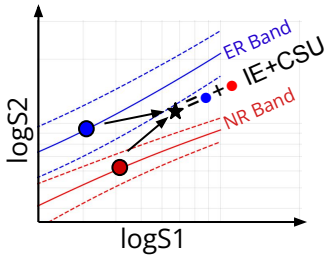

Event can appear above NR band if **ER and NR** vertices are added but **unresolved**

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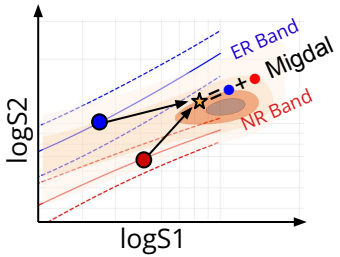

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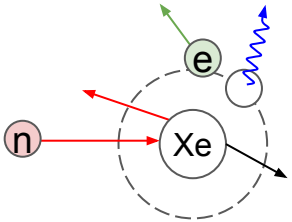

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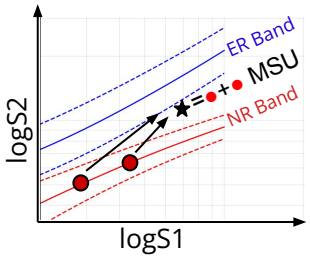

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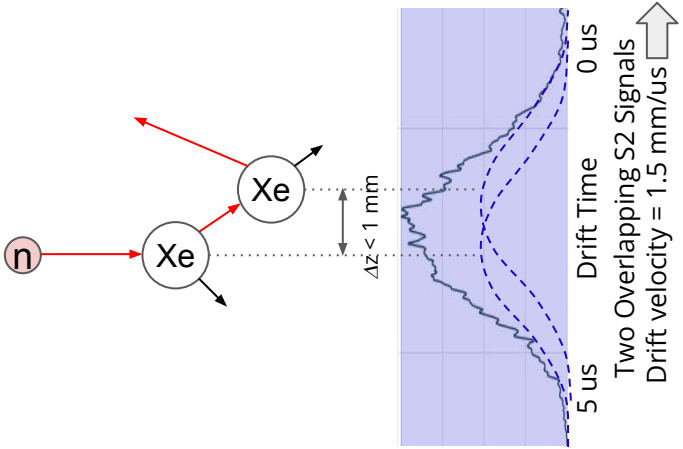

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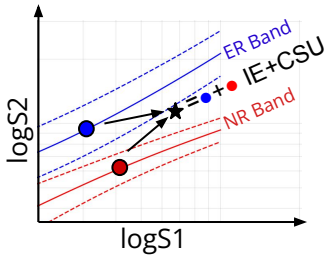
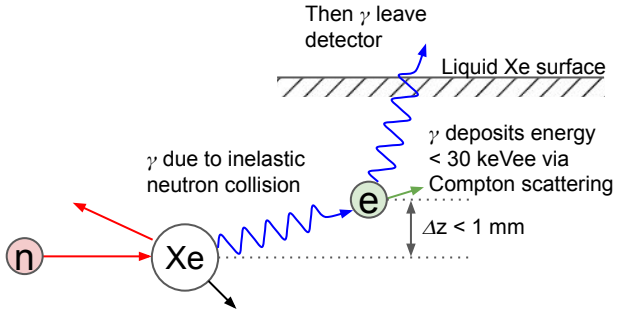


Event can appear above NR band if **ER and NR** vertices are added but **unresolved**



* e- or γ from typical IE scatter deposits energy greater than Migdal signal, or deposits multiple times.

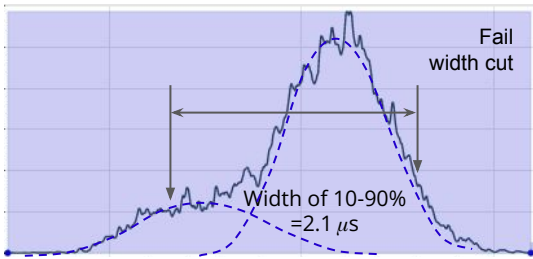
Relevant Backgrounds (2/2)

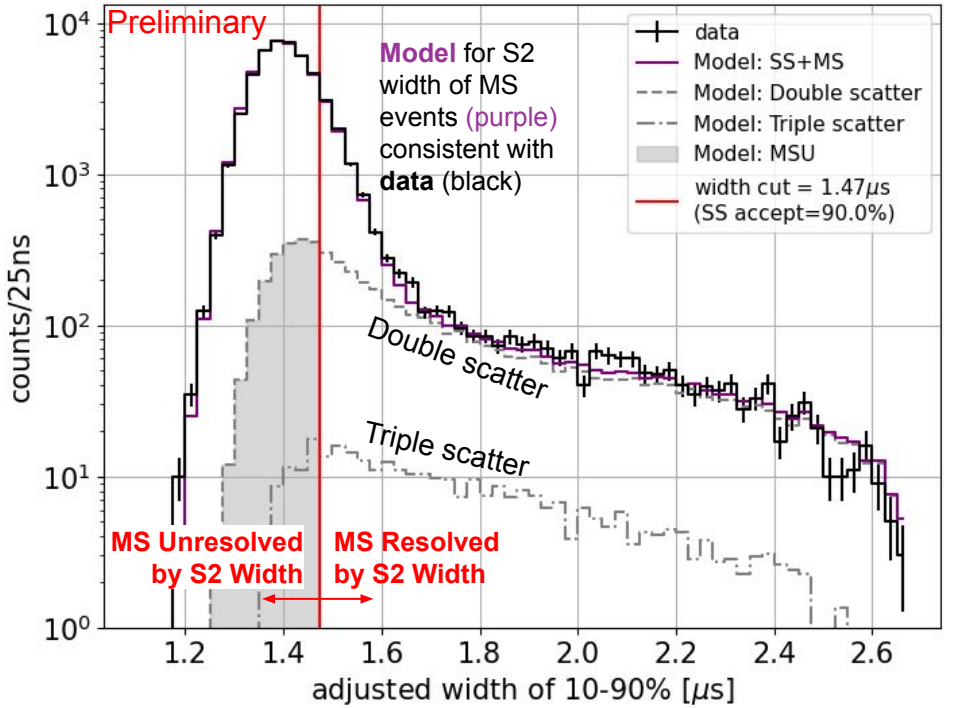
- Measured S2 width of multiple scatter backgrounds is greater than that for SS at the same position
  → use S2 pulse width cut

- MSU (Multiple Scatter Unresolved in position)
  - Model for S2 width distribution of MS events is based on GEANT4-BACCARAT
  - After applying S2 width cut, MSU/SS is **[4.56 ± 0.04(stat) ± 0.12(sys)]%**
  - Agreement in MS event rate between model and data in an isolated MS region outside SS + Migdal region

- IE+CSU (InElastic and Compton Scattering Unresolved in position)
  - Model is based on GEANT4-BACCARAT, ENDF/B-VIII.0, Table of Isotopes (Firestone, Shirley, 8th ed.)
  - Ratio of predicted number of IE+CSU to SS in data is **[6.9e-3 ± 0.5e-3(sys.)]%**

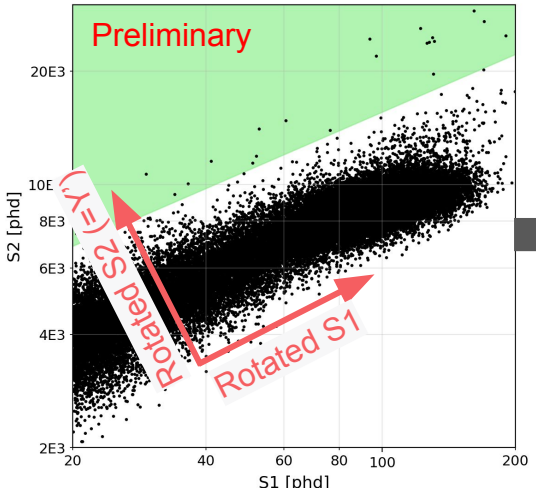
- Other backgrounds considered are subdominant **(Total ~0.1 events)**
  - Including ER-band SS, Inelastic 40 keVee leakage, and accidental S1+S2 coincidences
  - Also similar NR+ER processes (see Araújo et al. arXiv:2207.08284)



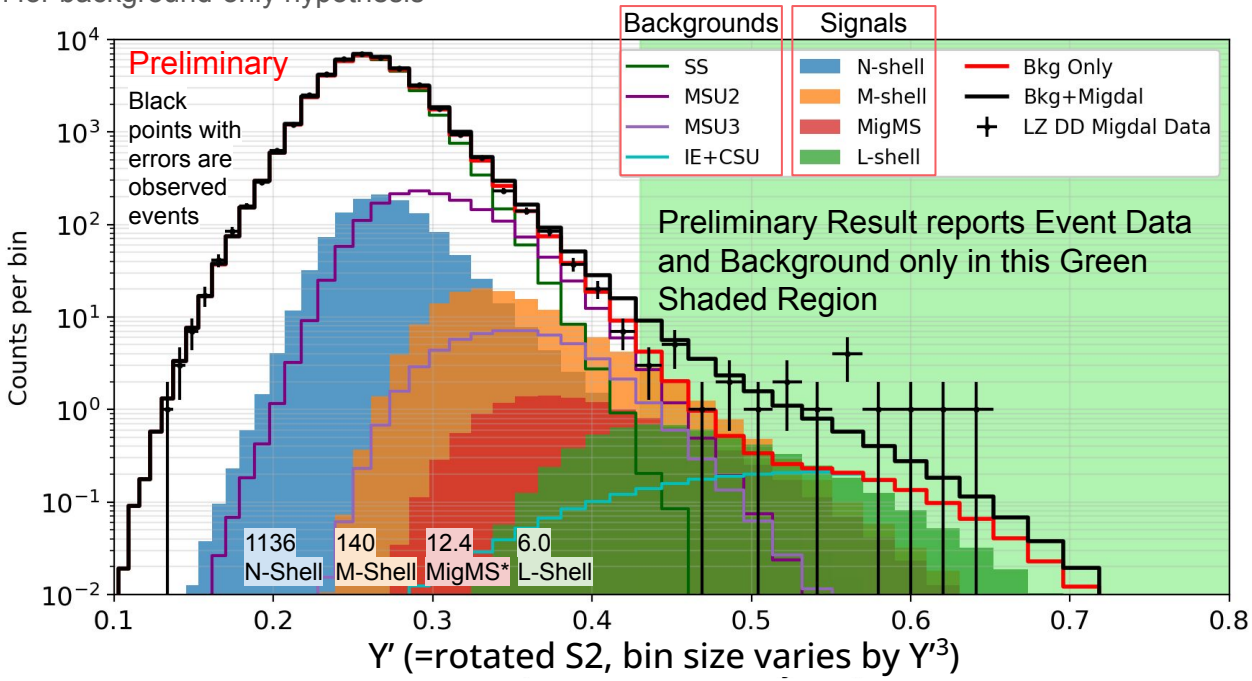


Model With Expected Migdal Signal

- Fit data (dominated by NR SS event main body) with Ly, Qy yield model
- Model generates S1,S2 PDFs of all signal and background components, weighted by predicted event rate.
  - Use expected signal rates from Ibe Migdal calculations
- Simple analyses uses a rotation in S1,S2 distribution to emphasize vertical separation between expected signal region and SS population. Separation in shown in the “rotated S2” parameter (denoted Y’)
- Using the models, select Y’ range after Signal/Bkg > 1 (⇔ Y’ > 0.42, shaded green region)
- Use High S/B range as test region for background-only hypothesis



*** MigMS** Multiple scattering (unresolved spacially) of Migdal + conventional NR vertex events is also included in final analysis.

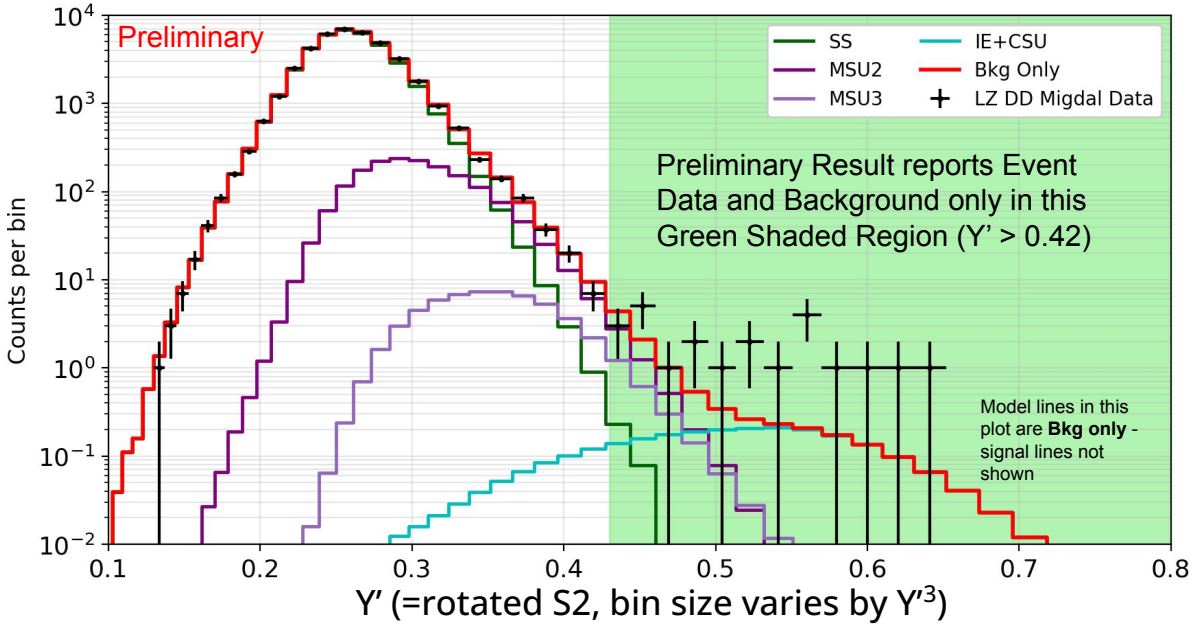


Preliminary Result: Background-Only Comparison

In Background-only model:

- Count total background events in Y' > 0.42
- Determine significance of excess in model over data
  - Systematic uncertainties of background components incorporated in full calculation via poisson pdf:
    $P(n \geq N_{obs} | \mu_{pred} * (1+k))$, $k = (\text{sys. unc.})/\mu_{pred}$

Observe a 3.4 σ excess in data in Y' in region of high S/B



Source		Number of events in Y' > 0.42
Observed Data Events		**23**
BG Model Prediction	SS	0.3 +/- 0.1 (sys.)
	MSU2	4.9 +/- 0.1 (sys.)
	MSU3	2.4 +/- 0.1 (sys.)
	IE+CSU	2.0 +/- 0.2 (sys.)
Total BG Model Predicted		**9.6 +/- 0.5 (sys.)**
Significance versus BG-only Model Poiss(n≥23|μ=9.6+0.5)		**3.4 σ**

Conclusion

- Direct search of L and M-shell Migdal effect is performed for LZ experiment using 15M neutrons into LXe TPC at 2.45 MeV
- Compare results with expected Migdal signals in S1-S2 space calculated based on Ibe et al. and Cox et al.
  - Sensitive to Migdal Events with Nuclear Recoils in energy 10-74 keVnr
  - Cox predicts rates ~1.2x those of Ibe
- In preliminary high-S2 region analysis, observing 23 events on a background 9.6±0.5(sys)
  - Observed excess consistent with Migdal signal predicted by Ibe and Cox
  - The background models are well-constrained and are dominated by:
    - Unresolved Neutron Multiple Scattering (MSU) being consistent with simulations and well constrained by data (MSU-only region)
    - Inelastic Nuclear Recoil + local Compton Scattering of Emitted Gamma-Ray (IE+CSU) highly suppressed/evaluated with simulation and calculation.
  - All other backgrounds are subdominant
- Profile Likelihood Ratio (PLR) analysis using more observables that contains an expected 6 L-shell and 152 M-shell (if Ibe et al., 1.2x higher if Cox et al.) is being finalized

Thank you!

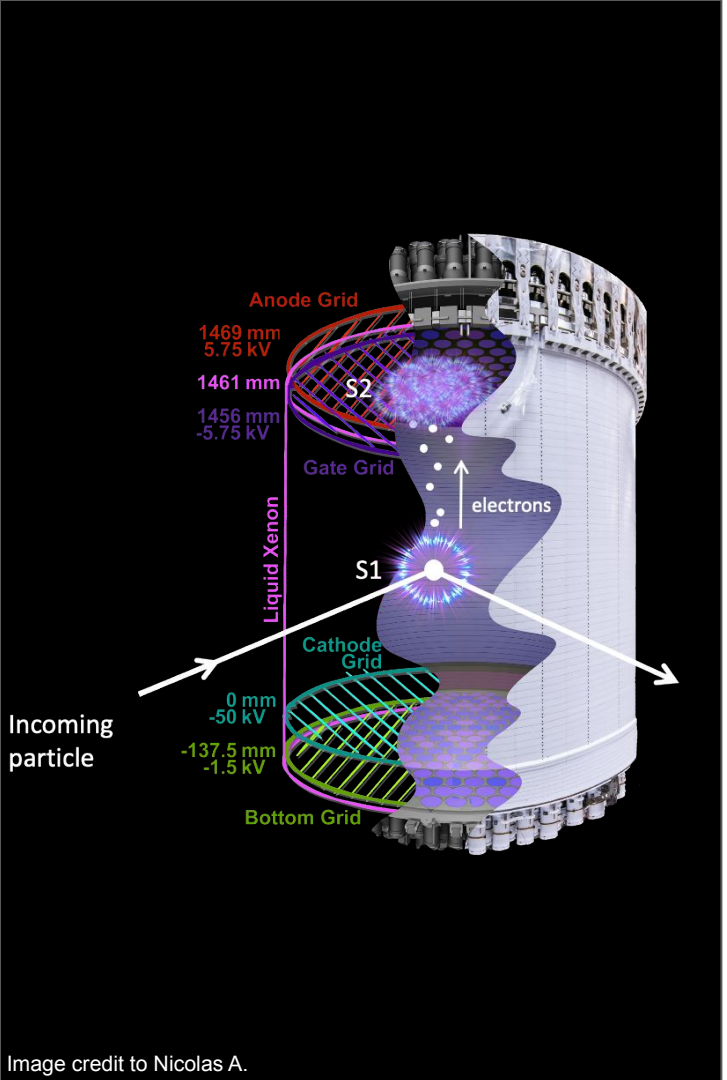


Image credit to Nicolas A.

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Thanks to our sponsors and 36 participating institutions!

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South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
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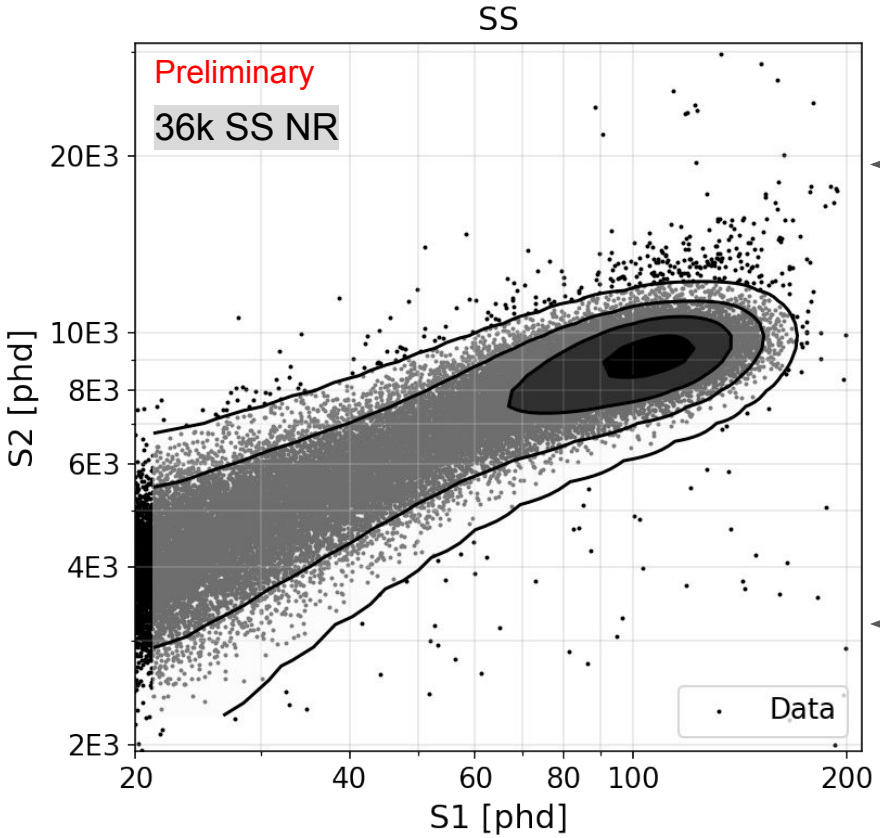
Backup

Single Scatter (SS) NR in S1-S2 Space

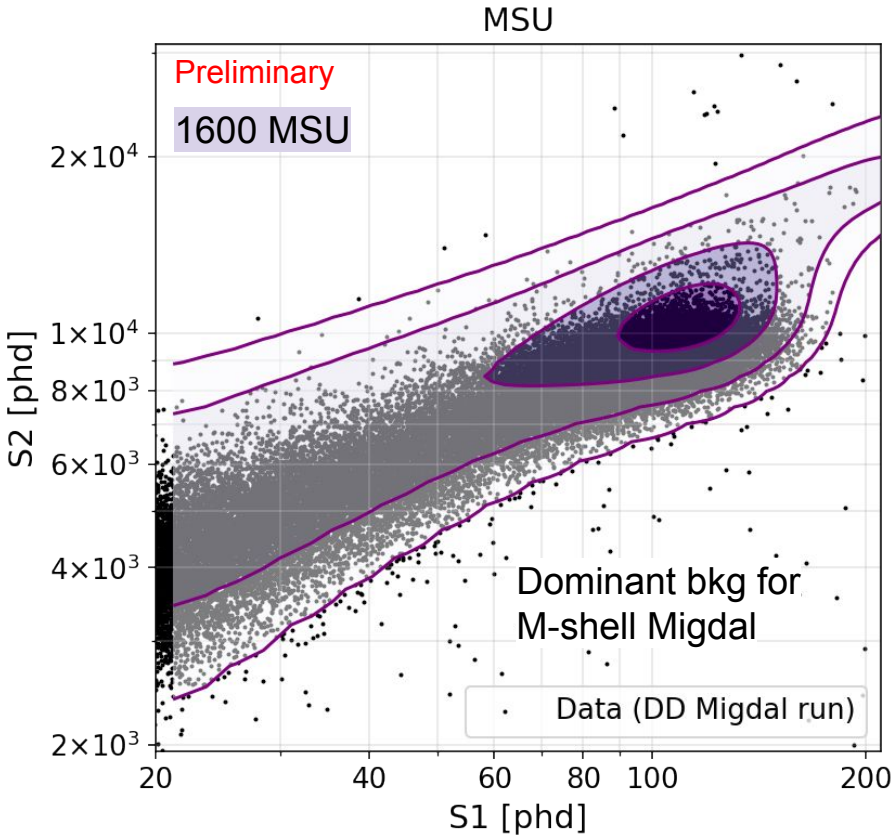
* Contours enclose 33%, 68%, 95%, 99.7% of SS

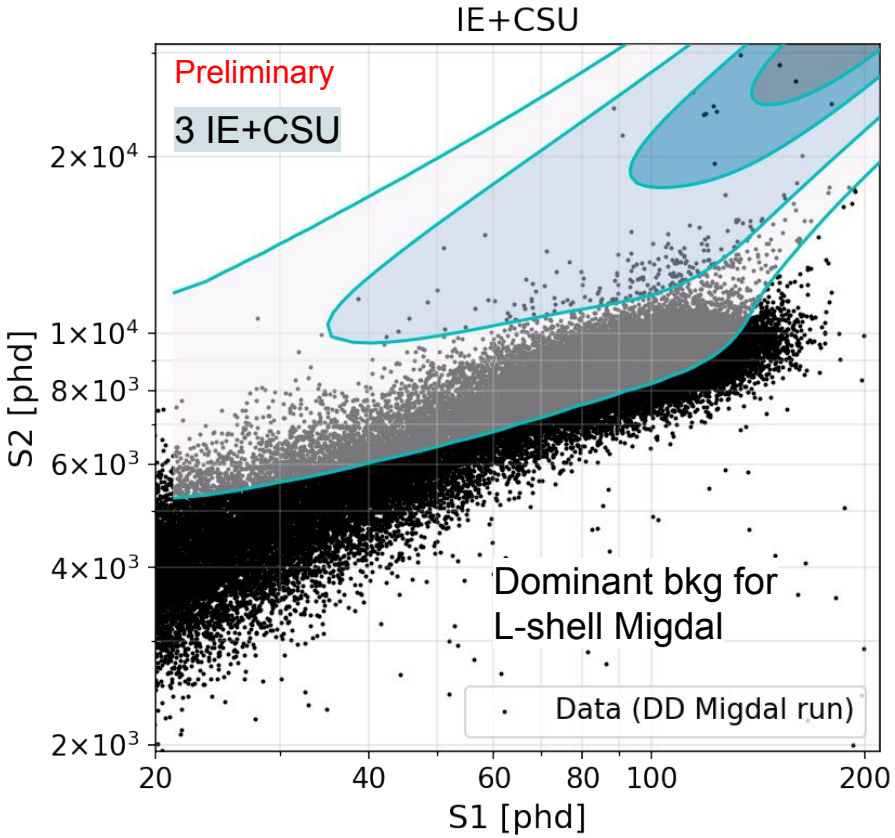


Signal region is above the SS

Events below SS has resulted in an increase of S1 signal due to neutron-X (no second S2). Events are dominated by neutrons interacting in Gaseous Xe generating additional S1 signal. This phenomenon only generates events on the lower side of the band.

Relevant Backgrounds in S1-S2 Space

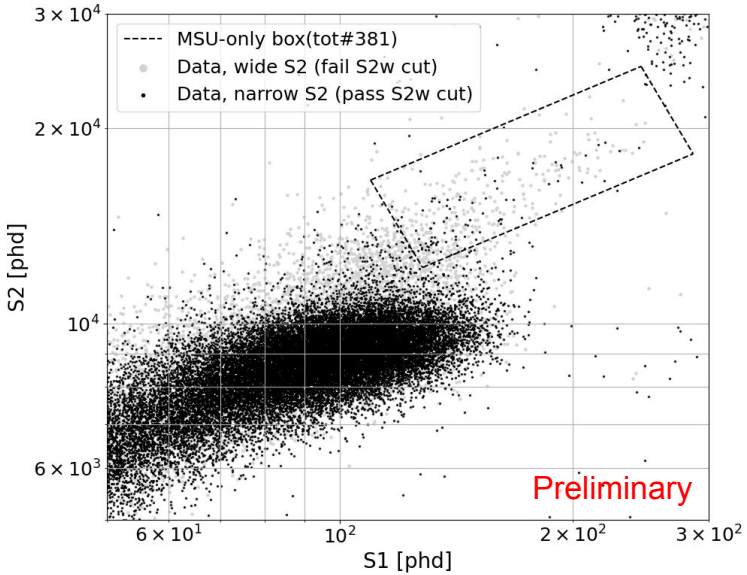


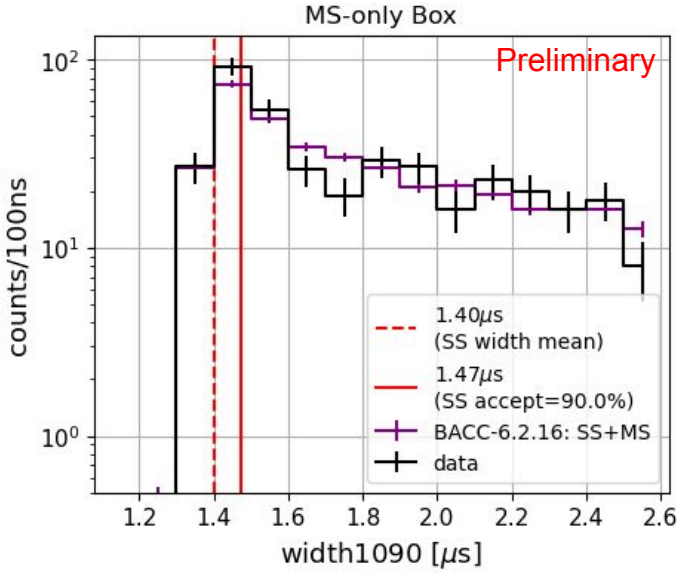


* Contours enclose 33%, 68%, 95%, 99.7% of Bkg events

MSU-only Region

- MSU/SS ratio can be confirmed directly with the observation of isolated Multiscatter events that appear above Single Scatter Region (black dotted box)
  - Contaminated by Migdal events is <1% of total observed in the box so acts as excellent control of MS event prediction
- Agreement in absolute MS event number between Simulation and Experiment.
  - Observed Data: 375±19, GEANT4 Simulation Model: 364±7

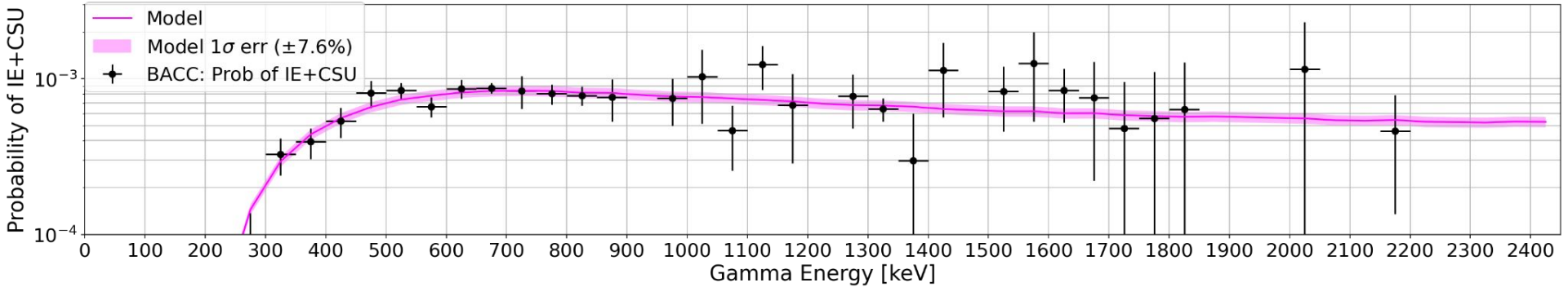




Background Model - IE+CSU

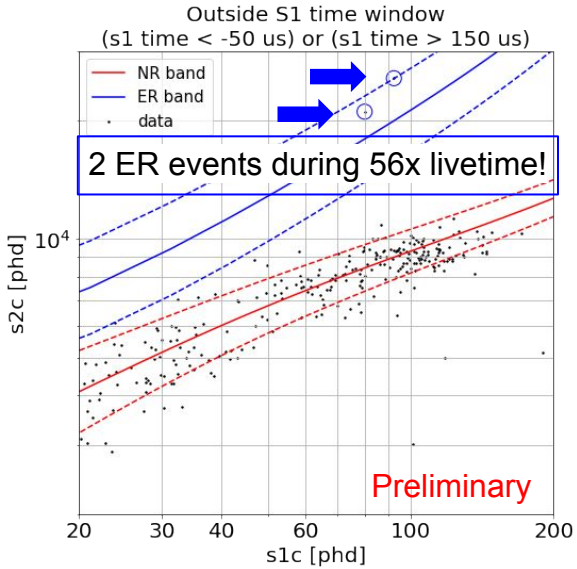
InElastic scattering of neutrons + **C**ompton **S**cattering **U**nresolved in position

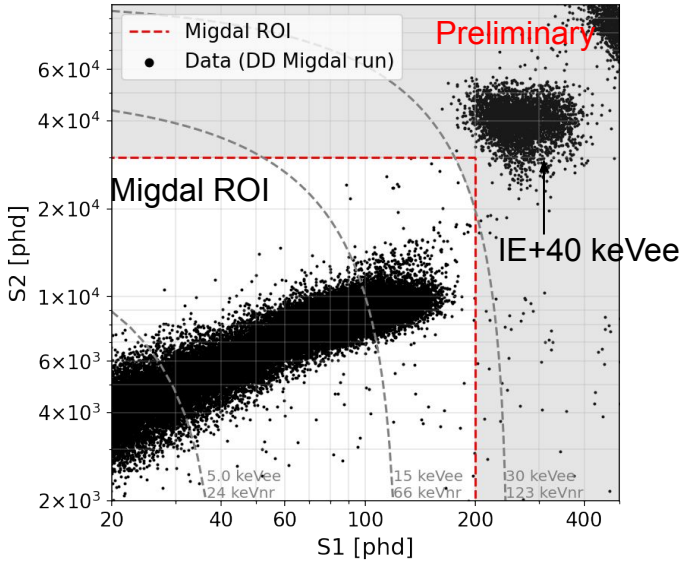
- **Predicted # of Background Events in Data based on Simulations for IE+CSU : 2.6±0.2(sys.)**
- For such an event to be a background for Migdal a gamma from IE should satisfy:
  - CS close to IE site to be recognized as single S2
  - Not interact until it leave TPC (distance > 3cm)
  - Deposit < 30 keVee to appear in Migdal ROI
  - Be emitted alone
- Our model is based on BACCARAT(GEANT4), ENDF/B-VIII.0, Table of Isotopes (Firestone, Shirley, 8th ed.)
  - BACCARAT is used to model the single CS probability at a given separation from NR as a function of gamma energy and position
  - Cross section for a given Xe excited states by IE is from ENDF/B
    - Our study shows that IE xsec is not well implemented in BACCARAT. We observed (0.5-3.0)x ENDF/B
  - Probability of decay to ground state for a given Xe level is from ToI (8th).



Other Backgrounds Are Subdominant (Total 0.1 Events)

- ER suppressed by narrow S1 time window for neutron source & conduit profile cut in LXe [left plot]
  - Neutron pulse window is 50 μs while time between neutron pulses is 6.7 ms
  - The neutron source is collimated by conduit profile so interactions region is 2% of fiducial volume
  - The total number of ER background is 0.03 +/- 0.02, determined by rate of ER events outside neutron pulsing window
- IE+40 keV (129Xe) event population is well isolated from Migdal S1, S2 ROI [right plot]
  - The total number of 40 keVee within ROI is 0.079 +/- 0.004
- Other unresolved NR+ER processes considered for LZ DD measurement in LXe and found to be subdominant
  - See discussion of possible additional processes in [Araújo et al. arXiv:2207.08284]





Other Backgrounds (ER and IE 40 keVee)

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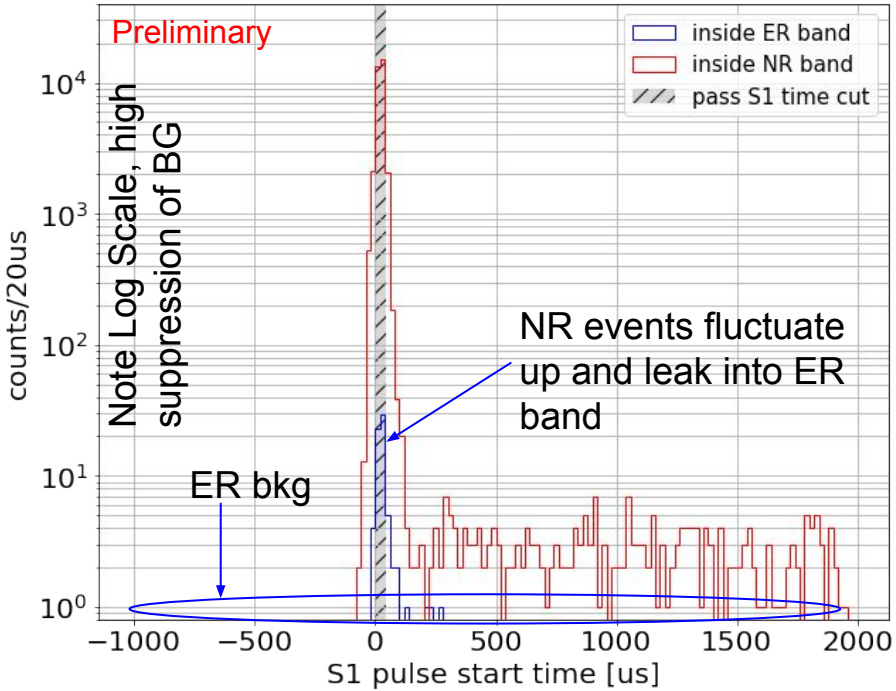
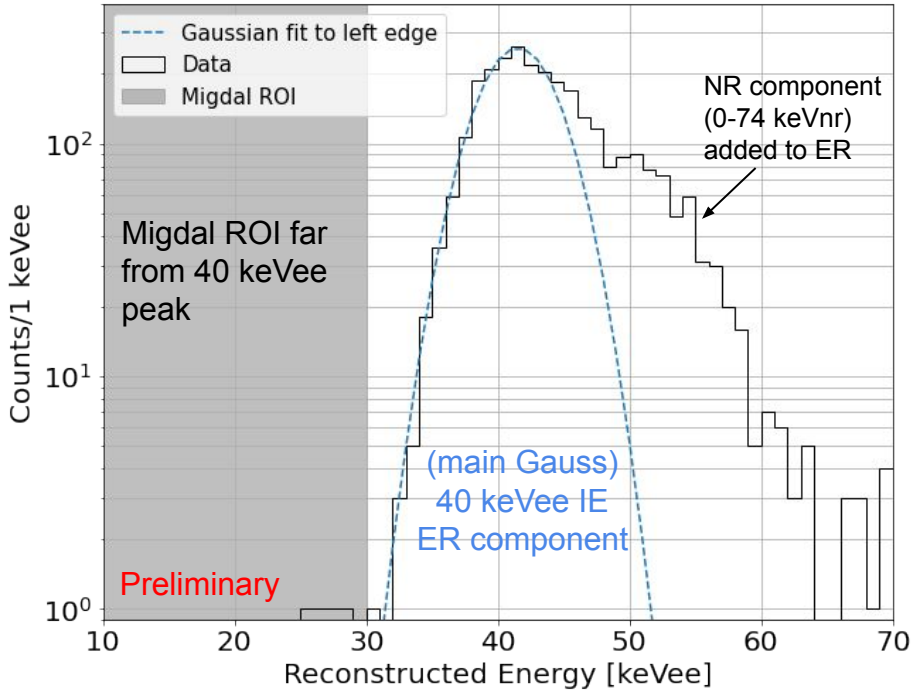
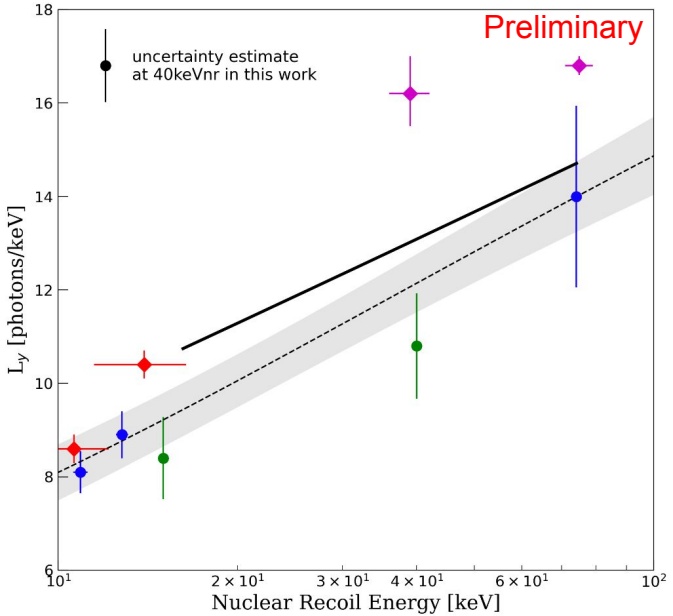


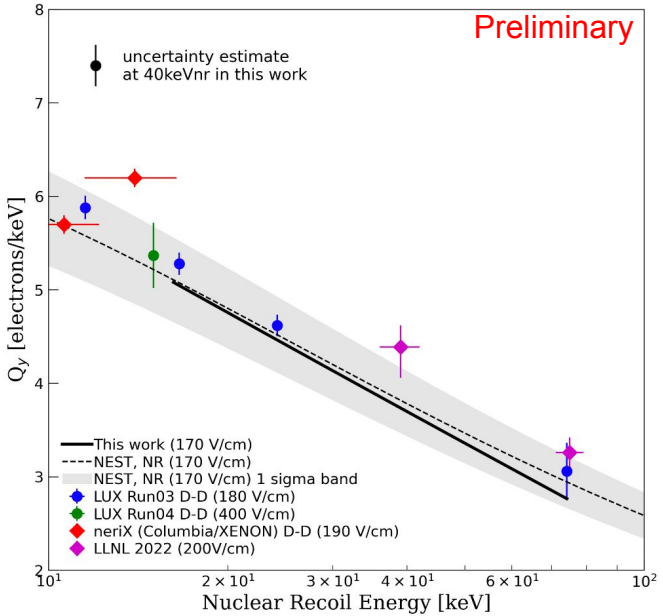
Total number of 40 keVee IE is 0.079 +/- 0.004



S1 and S2 Nuclear Recoil Photon Yield Models Fit to Data

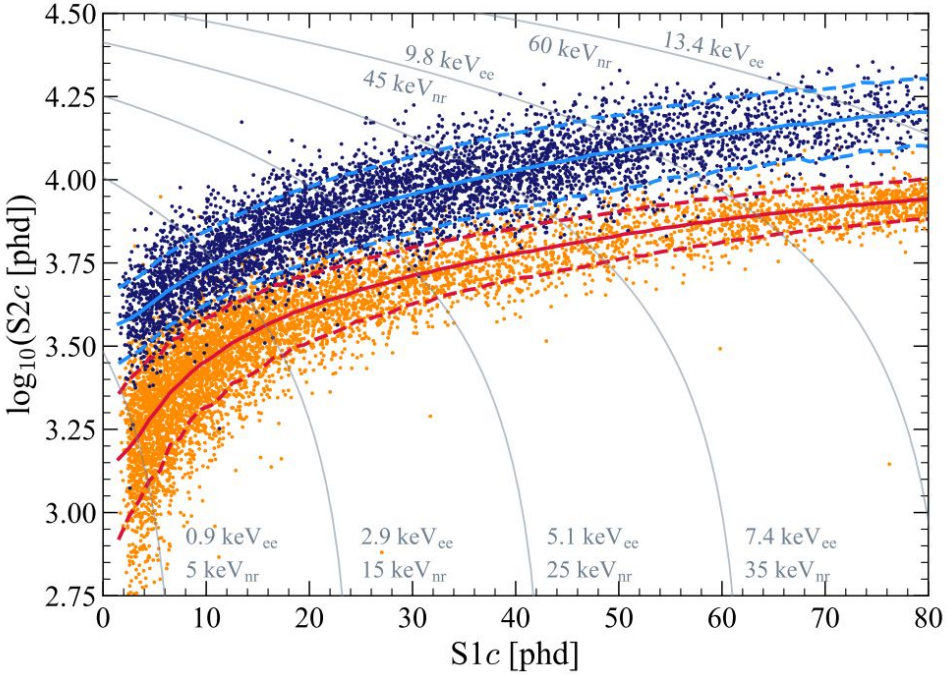
- Fit data (dominated by NR SS event main body) with Ly, Qy yield model
  - Recoil energy spectrum from GEANT4+BACCARAT simulation of neutron source and LZ
  - Sum of light and charge signals obey Lindhard-like power law
  - Energy-dependent yield found from the fit to S1 S2 data agrees well with other measurement (see plot)
  - S1 var/mean = 1.2 consistent with NEST model
  - S1 S2 anticorrelation independent of E_nr



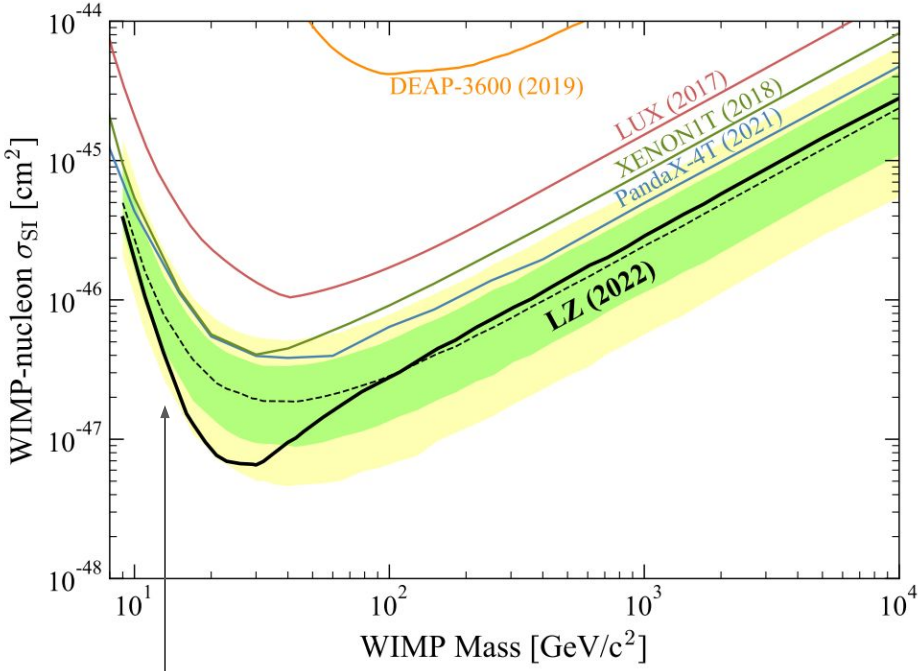


M. Szydagis et al. arXiv:2211.10726 (also thanks for the python code for plotting), Pershing et al. Phys. Rev. D 106, 052013 (2022)

Direct Dark Matter Search (LUX-ZEPLIN Experiment)



Electron recoils make ~5x larger S1 and S2 than nuclear recoils



Less sensitive to low mass WIMP because of detector threshold
→ can be improved with Migdal effect!

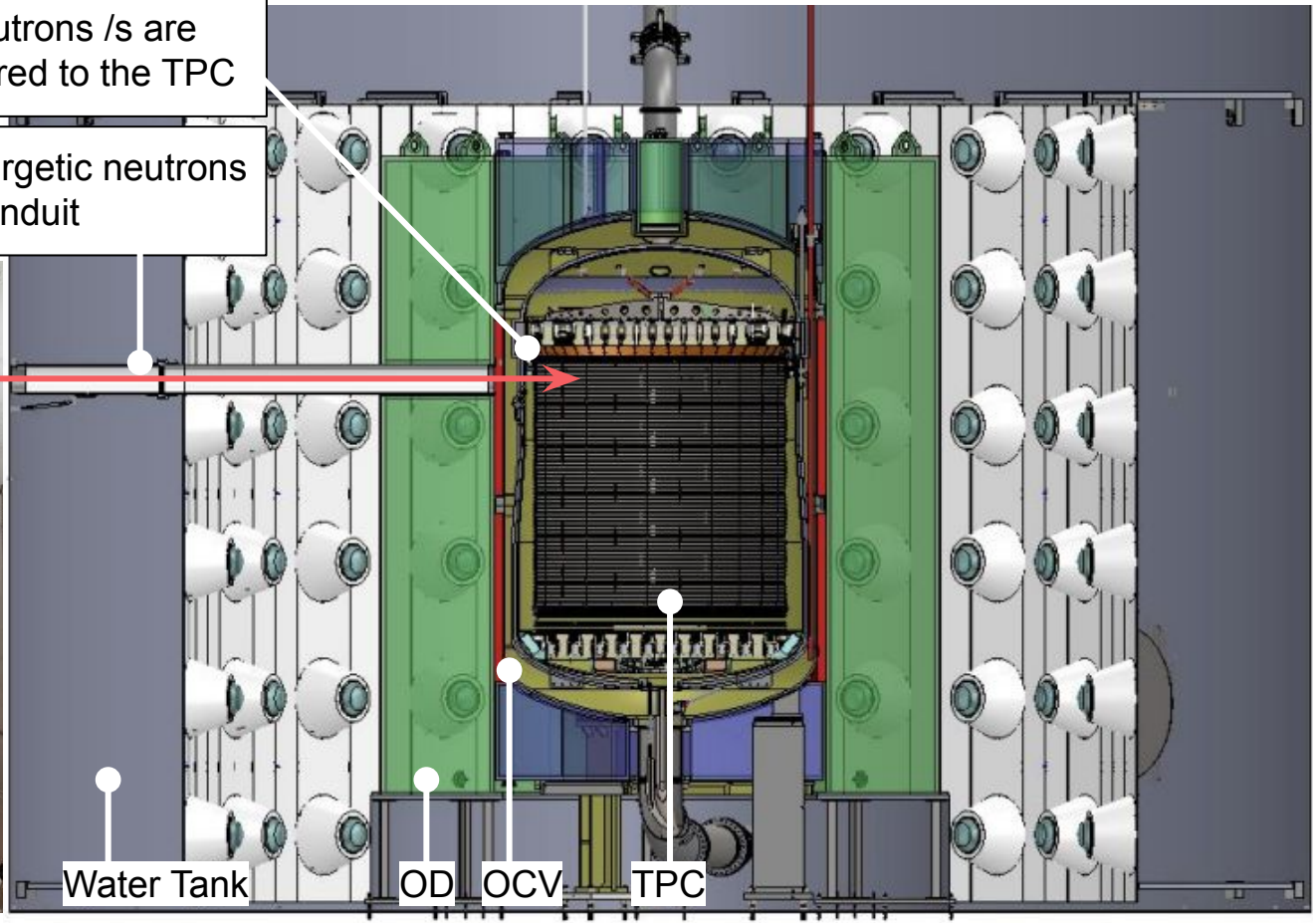
arXiv:2207.03764 (2022)

DD Neutron Generator Deployment

Akerib et al. arXiv:1608.05381
Verbus et al. Nucl. Instrum. Methods A851, 68
Verbus DOI:10.7301/Z01G0JQ7
Huang DOI:10.26300/zvs6-fx07

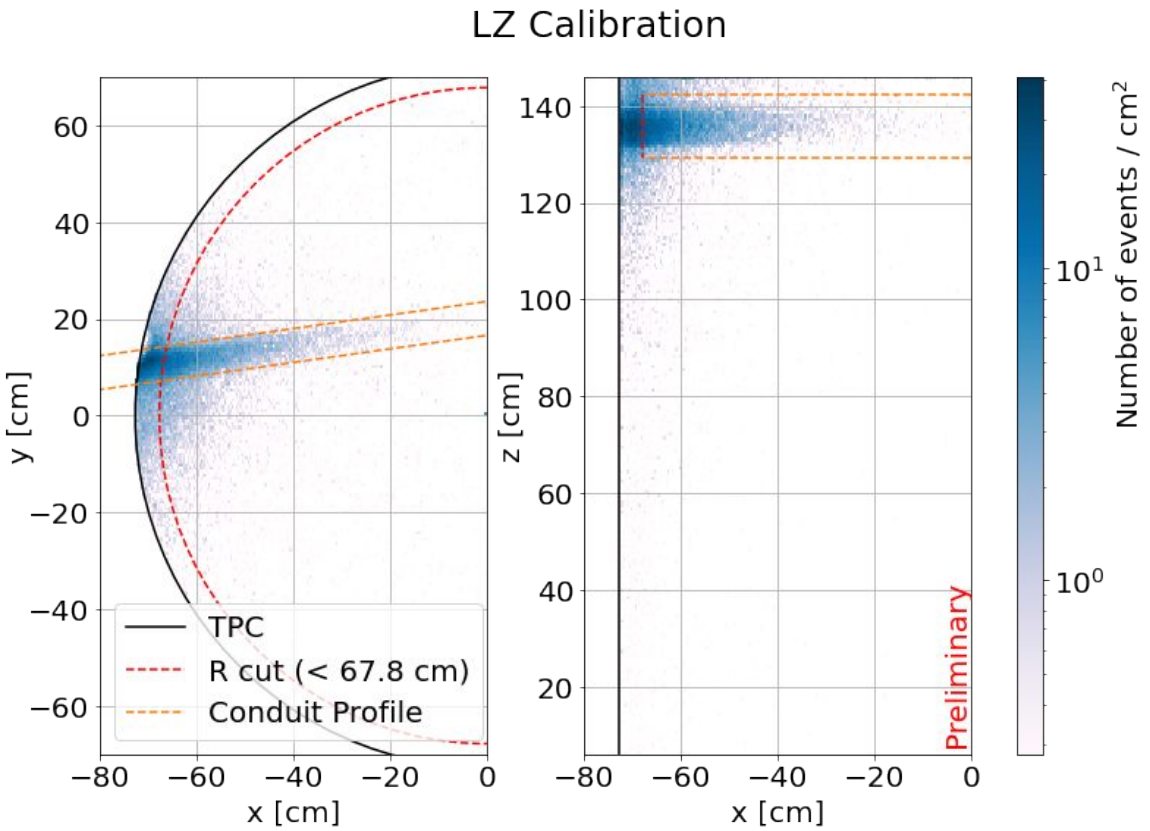
15 neutrons /s are delivered to the TPC

2.45 MeV monoenergetic neutrons sent down a 3 m conduit



Collimated Neutron Beam: Conduit Profile Cut

- DD neutron generator produces 2.45 MeV monoenergetic neutrons.
- Neutrons are sent down a 3 m conduit to make a collimated neutron beam into TPC
- Conduit profile cuts are used to select pure 2.45 MeV neutrons that didn't have interaction before entering LXe and thus didn't lose energy.
- Narrow conduit constraints z position and reduces systematic uncertainties.



Time Projection Chamber