LUX-ZEPLIN (LZ) Projected Sensitivity to New Physics via Low-Energy Electron Recoils[1]

Winnie Wang, for the LZ collaboration

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Acknowledgements

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UMASS AMHERST

Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Detector specifications

Overall Design Specs

- LZ is primarily a WIMP dark matter experiment
  - TPC containing 7 tonne active volume liquid Xe
  - Gd liquid scintillator, skin region veto – ER physics
  - Outer detector for detection of neutrons, gamma rays
- Located ~5000 feet underground in Lead, SD
- ~200 person collaboration

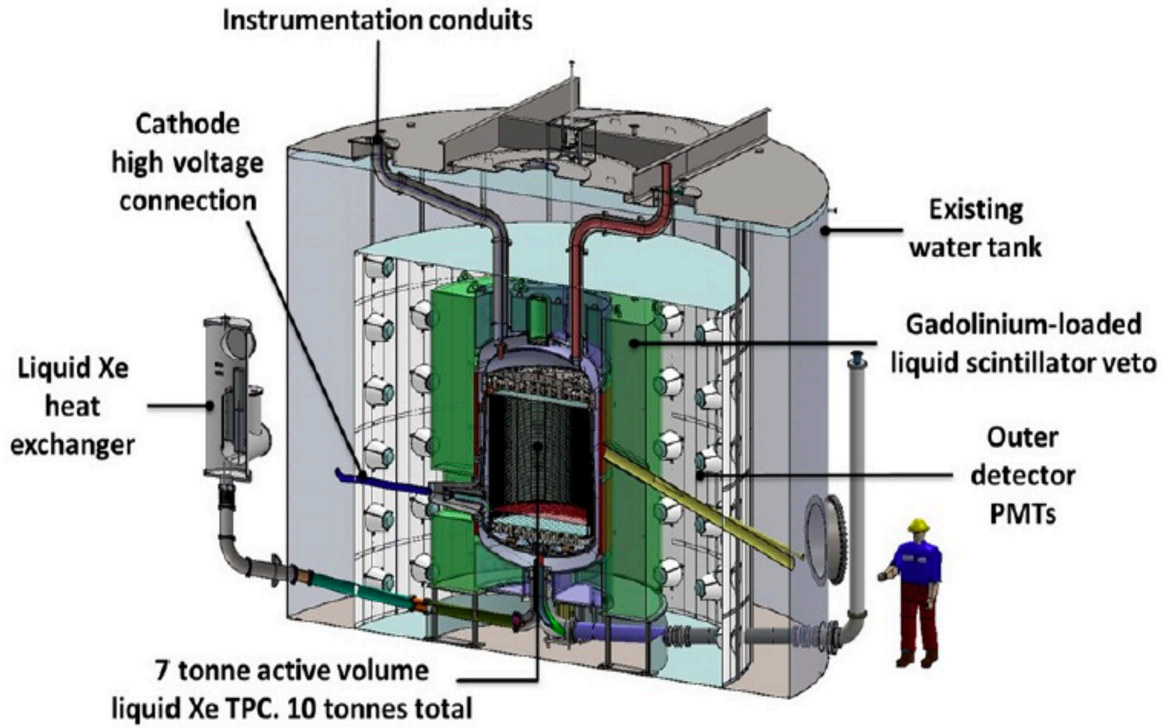


*Figure from reference [2]

LZ’s background (after vetoing)

- LXe self-shielding reduces backgrounds
  - Threshold within ~1keV regime
  - All signals are from electron recoil (ER)

- Fiducial mass: 5.6 tonnes (within black-dashed line)

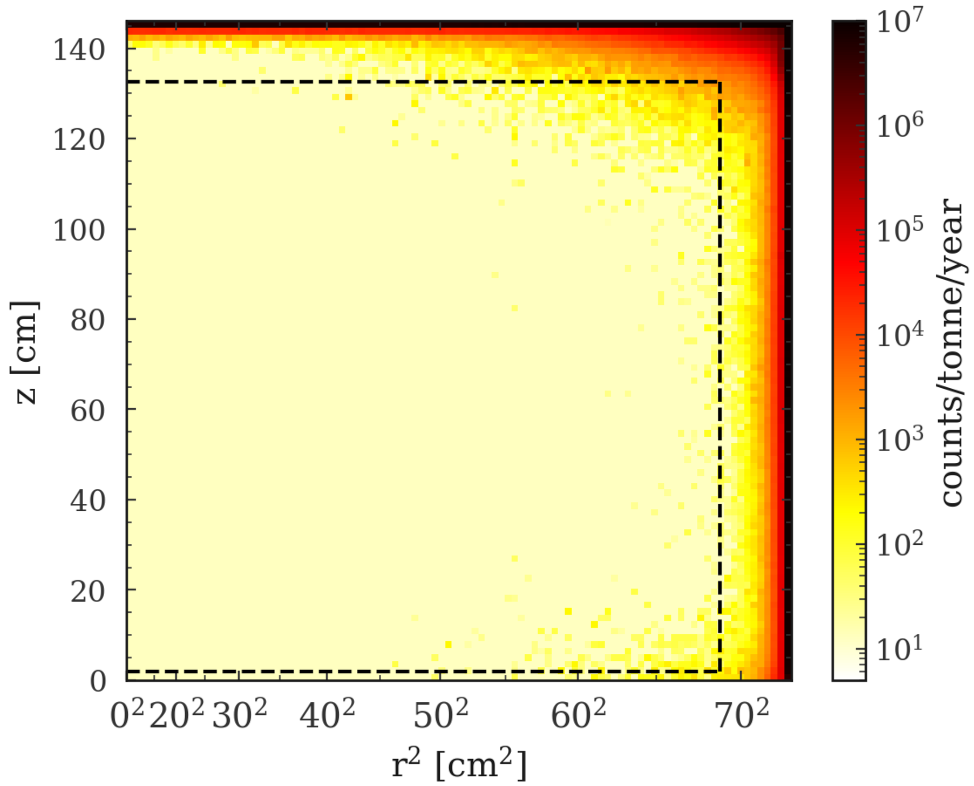


*Figure from reference [1]

LZ's background components

- Most ER backgrounds are contributed by Rn-222, solar neutrinos
  - Xe136 vvββ background becomes dominant at ~40 keV
  - Nuclear recoil negligible
  - ER region: 0-100 keV

- Showing the fluxes as seen by the detector, not including experimental effects

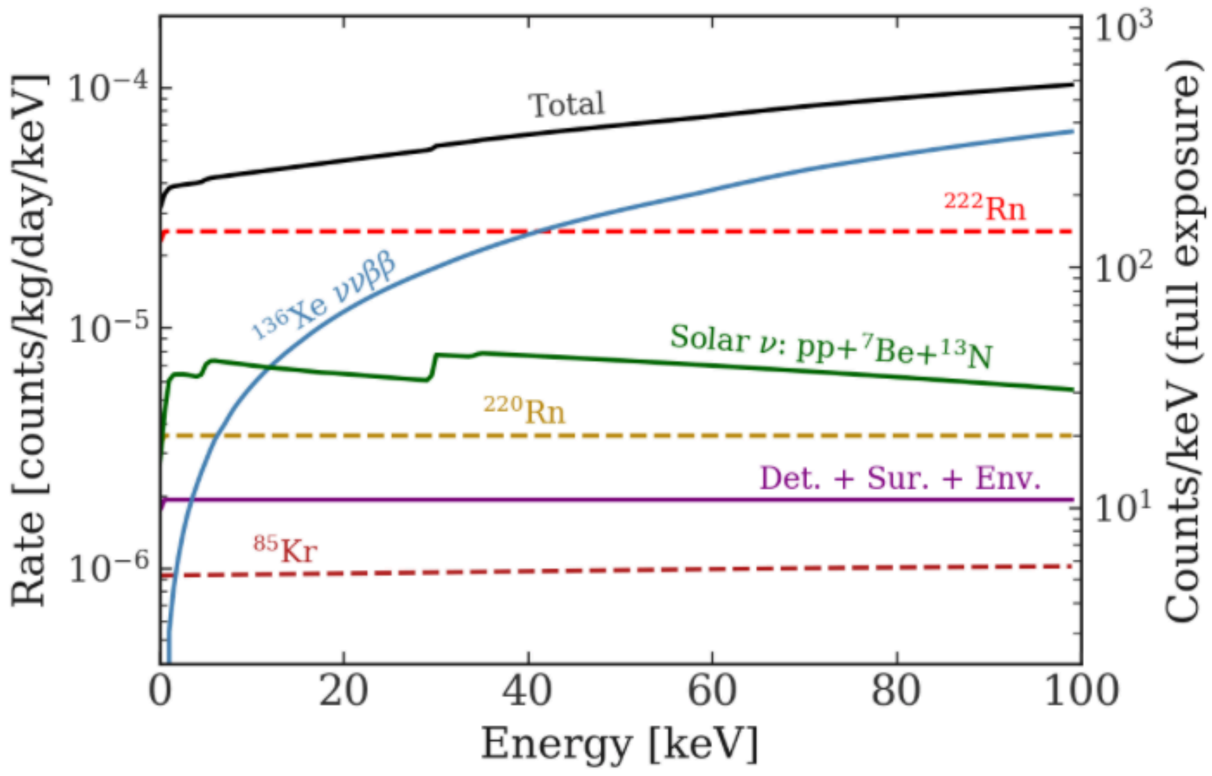


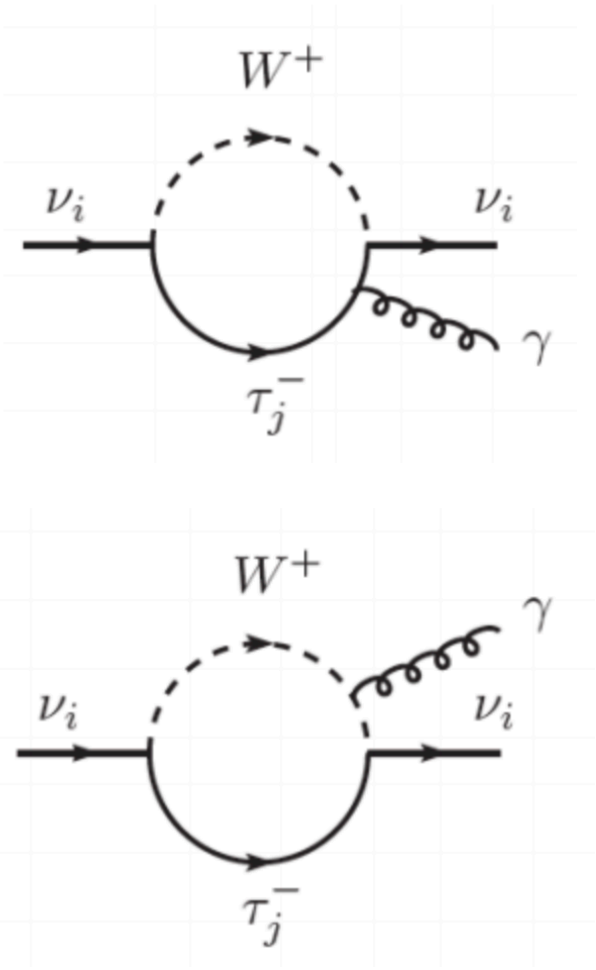
*Figure from reference [1]

Low Energy ER Physics

Evaluated models

Neutrino EM properties

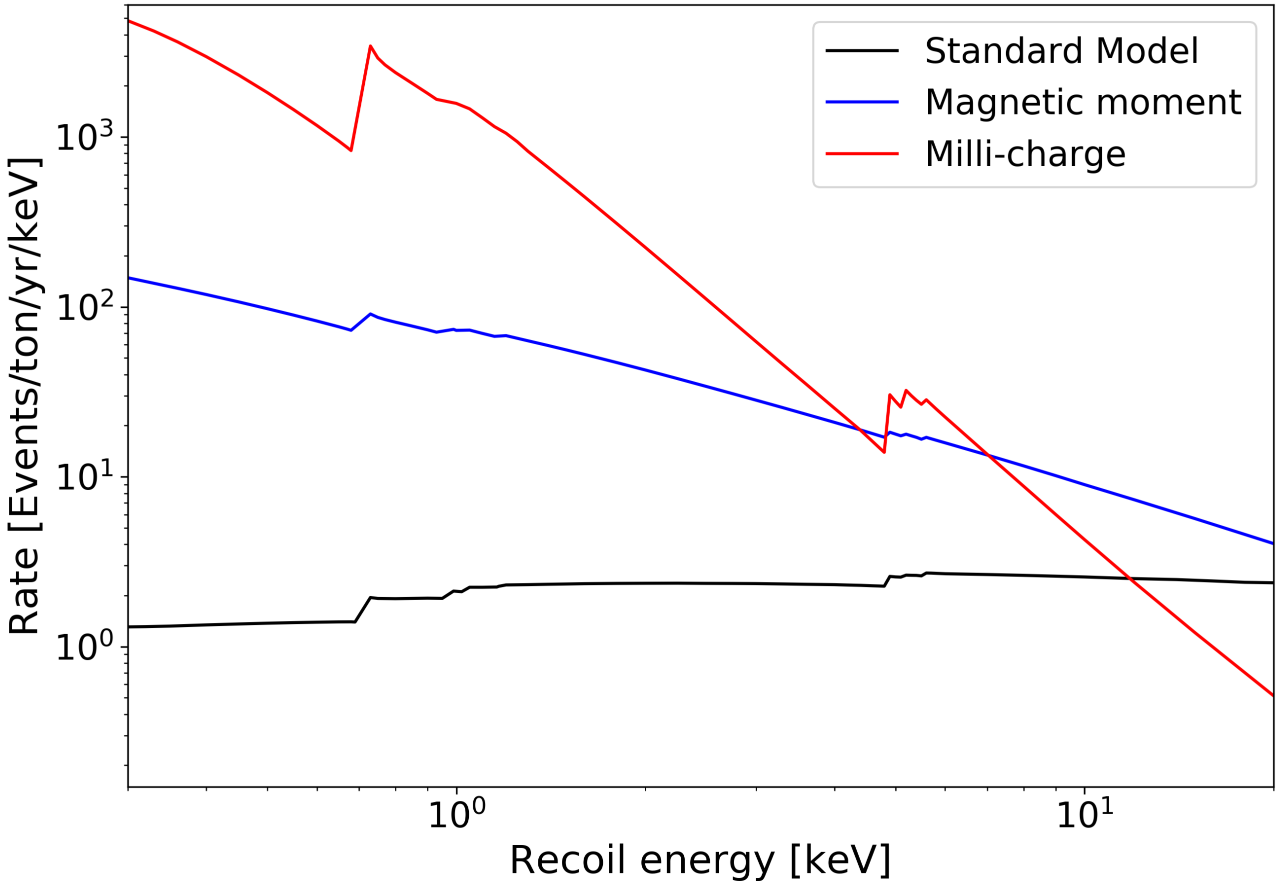
- Discovery of neutrino oscillations implies that neutrinos have non-zero mass; non-zero E&M properties
- Extensions in neutrino BSM models predict enhancement to strength of neutrino EM interactions
  - Neutrino-electron scattering
- We consider sensitivities to magnetic moment or effective milli-charge only
  - Limits on properties placed from solar neutrinos



*Figures from reference [3]

Analysis: Bound Xe electrons

- At low energies, electron binding energies become relevant
- Using results Hsieh et al., using relativistic calculations from [4]
  - Rates are calculated assuming leading limits on q_ν and μ_ν

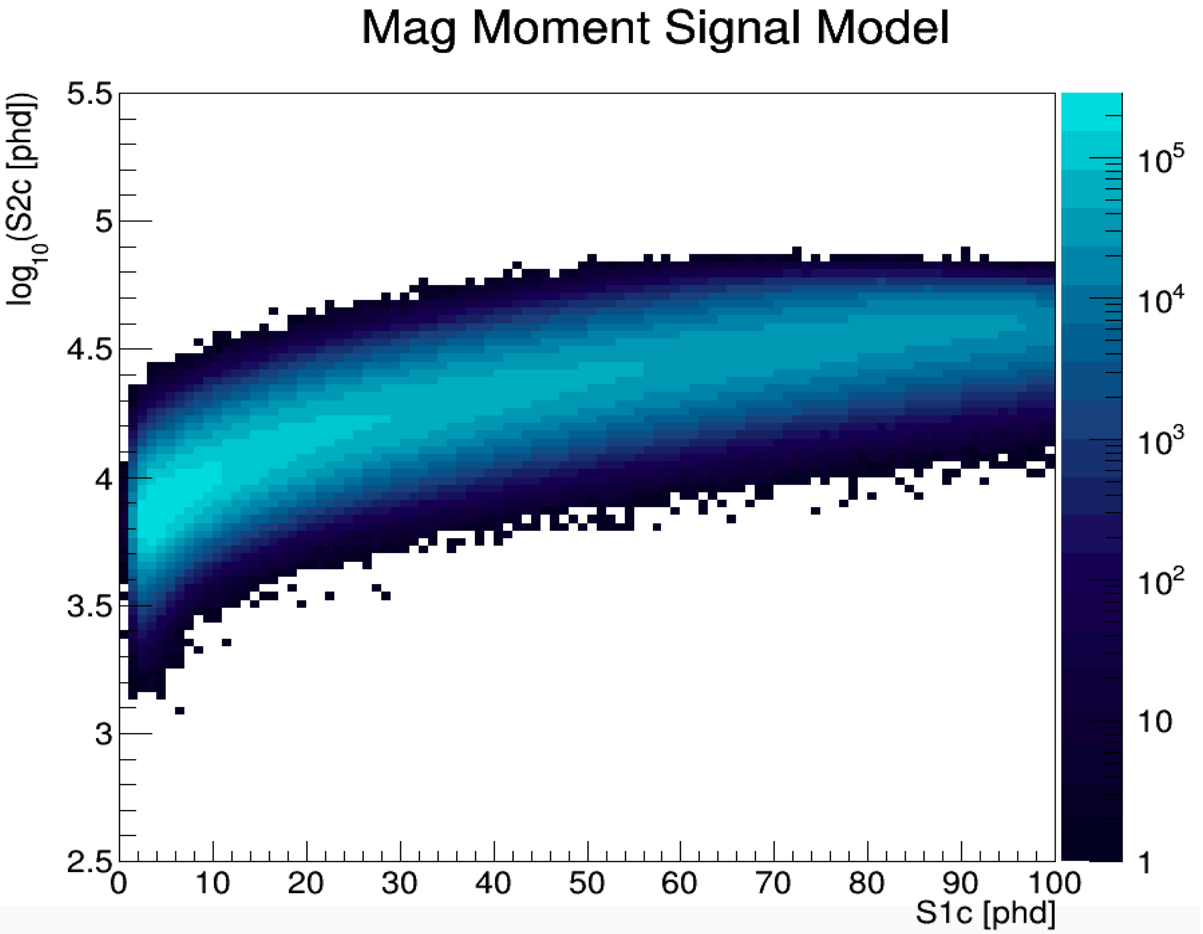


*Figures from reference [4]

Analysis: Reconstruction; threshold

- We reconstruct energies using NEST to obtain histogram of scintillation (S1) and electron (S2) signal counts
  - 3 PMT coincidence threshold on S1

- Then reconstruct energy based on histogram

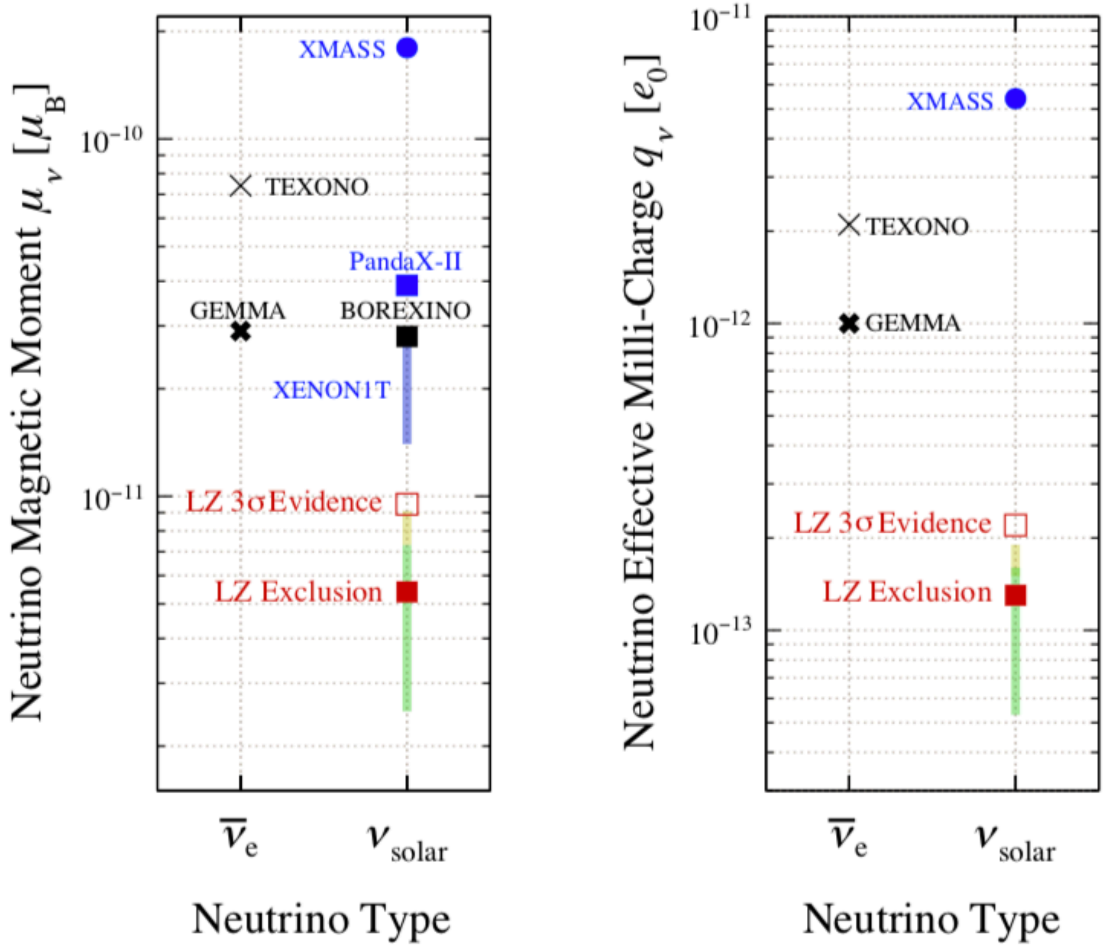


Statistical Analysis model

- Model assumes a 5.6 tonne x 1000 days exposure
  - Exposure is assumed over ~4 years
- We use a frequentist test; profile likelihood ratio method
- Background rate uncertainties are included as nuisance parameters
- We project double-sided 90% CL upper exclusion limits
  - (we also considered 3σ evidence sensitivities)

Sensitivity study results

- Exclusion sensitivity limits of the proposed neutrino magnetic moment, effective milli-charge (90% CL):
  - $\mu_\nu = 5.1 \times 10^{-12}\ \mu_B$, corresponds to ~110 signal counts (~7x improvement over Borexino[5])
  - $q_\nu = 1.05 \times 10^{-13}\ e_0$, corresponds to ~27 signal counts (~10x improvement over GEMMA[6])

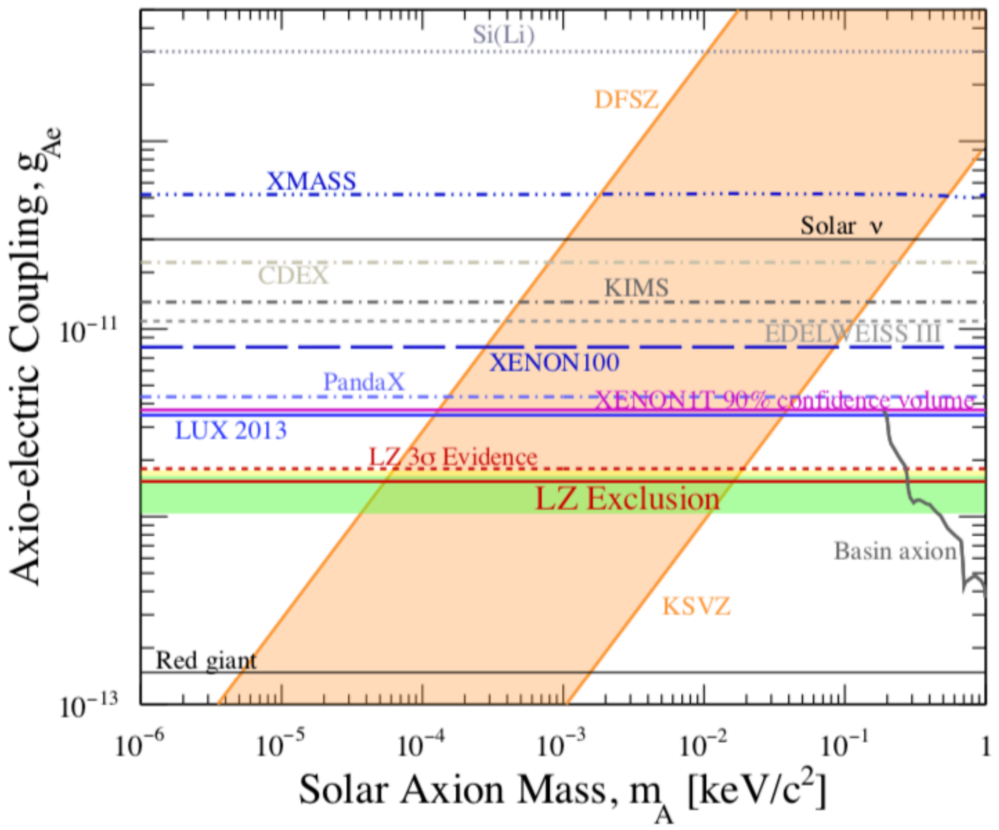


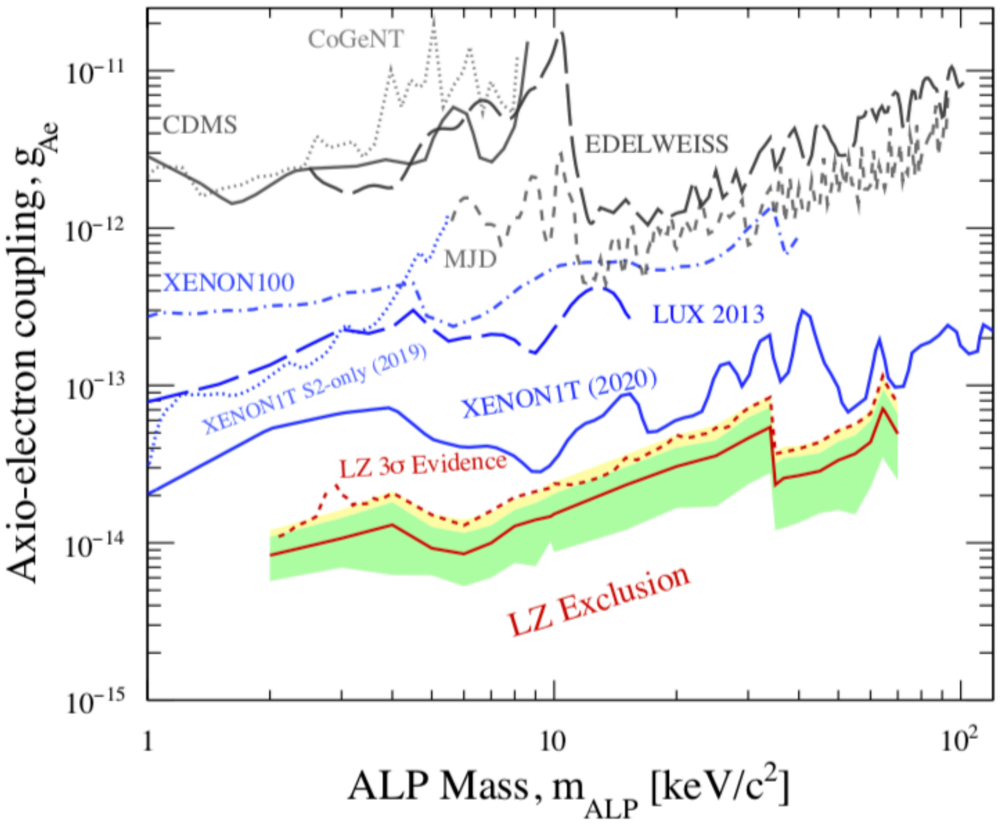
*Figures from reference [1]

Other physics models

- Solar axions
  - Potential candidates that solve the strong CP problem
- Axion-like particles
  - Nambo-Goldstone-like bosons; galactic dark matter candidate
- Hidden/dark photons
  - Hypothetical gauge boson that doesn't interact with Standard Model particles; cold dark matter candidate
- Mirror Dark Matter
  - Isomorphic particles of hidden sector
- Leptophillic EFT:
  - Dark matter coupling to leptons measured by axial-vector cross section

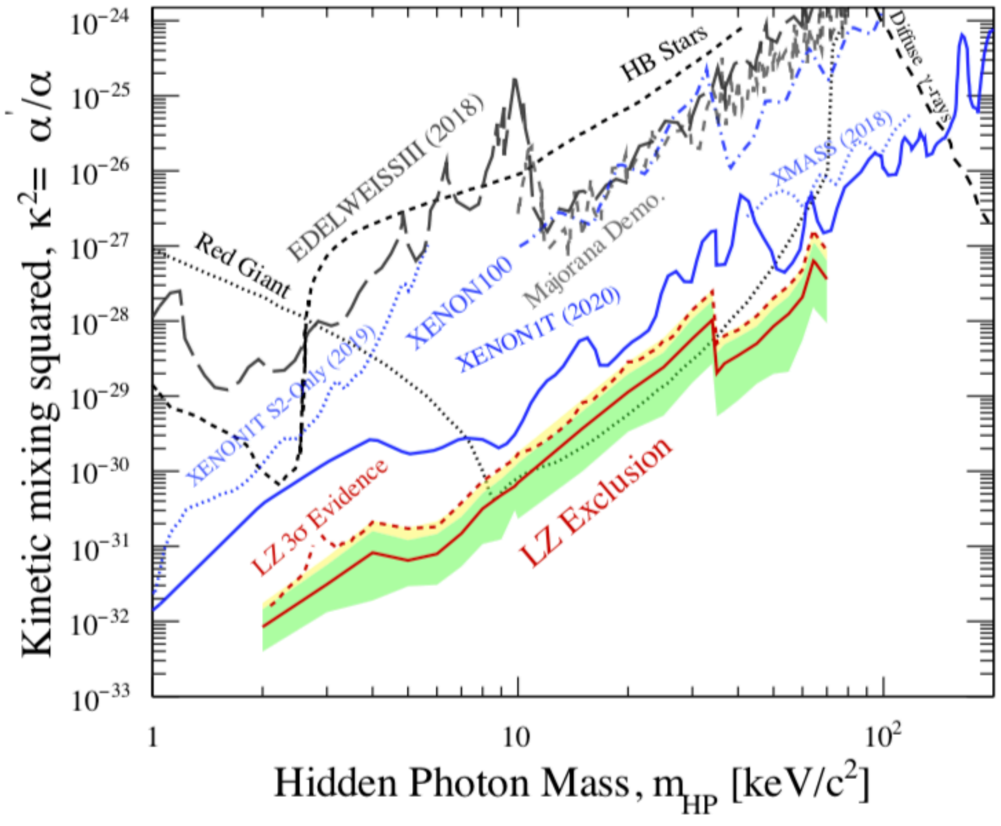
Results: Axions, Axion-like Particles

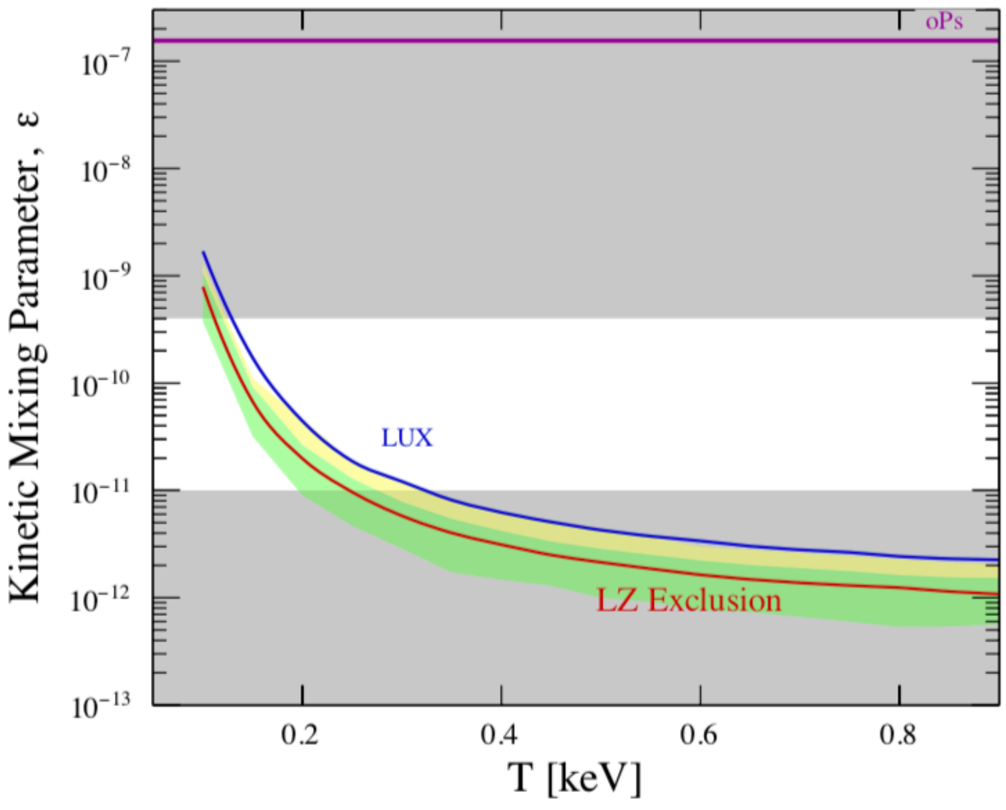




*Figures from reference [1]

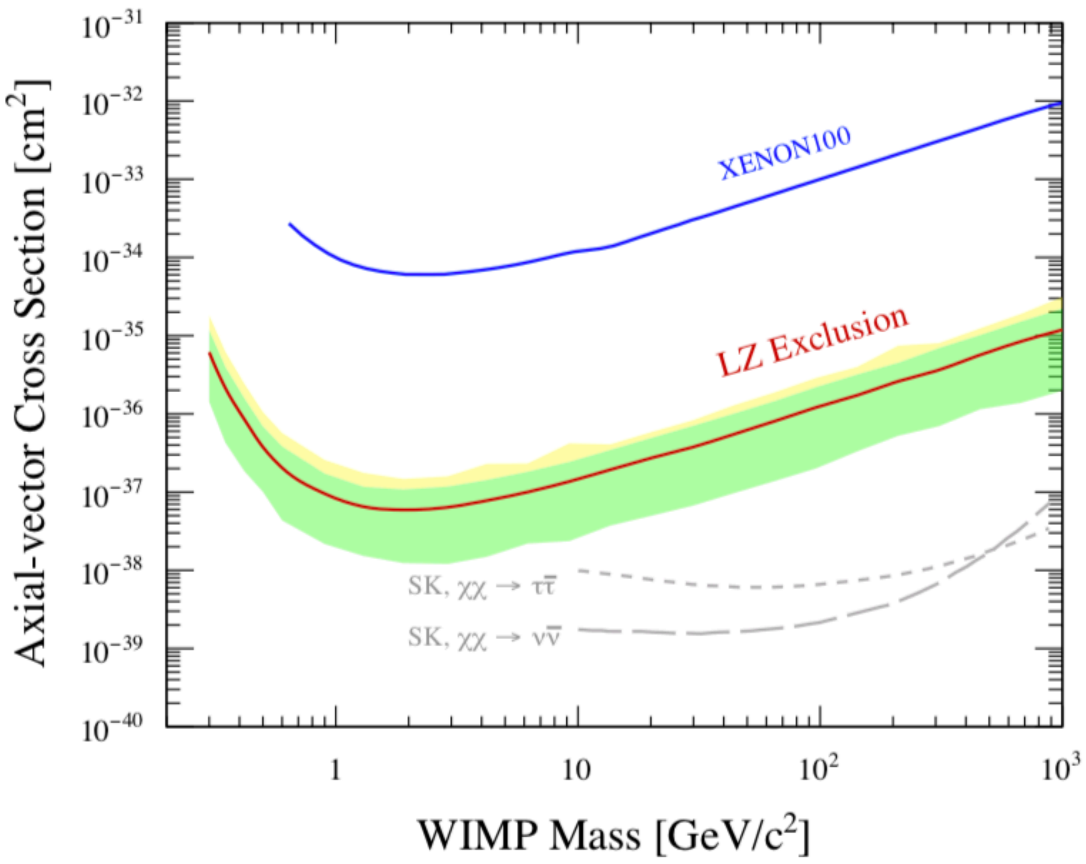
Results: Hidden photon, MDM





*Figures from reference [1]

Results: Leptophillic EFT



*Figures from reference [1]

Conclusion

- LZ expects world-leading sensitivities to these ER physics:
  - Effective neutrino magnetic moment, milli-charge
  - Solar axions, axion-like particles
  - Hidden/dark photons
  - Mirror dark matter
  - Leptophillic EFT

- Recent publication describes sensitivities of a 1000d run
  - arXiv: 2102.11740
- LZ is looking forward to starting science operations soon!

Extra slides

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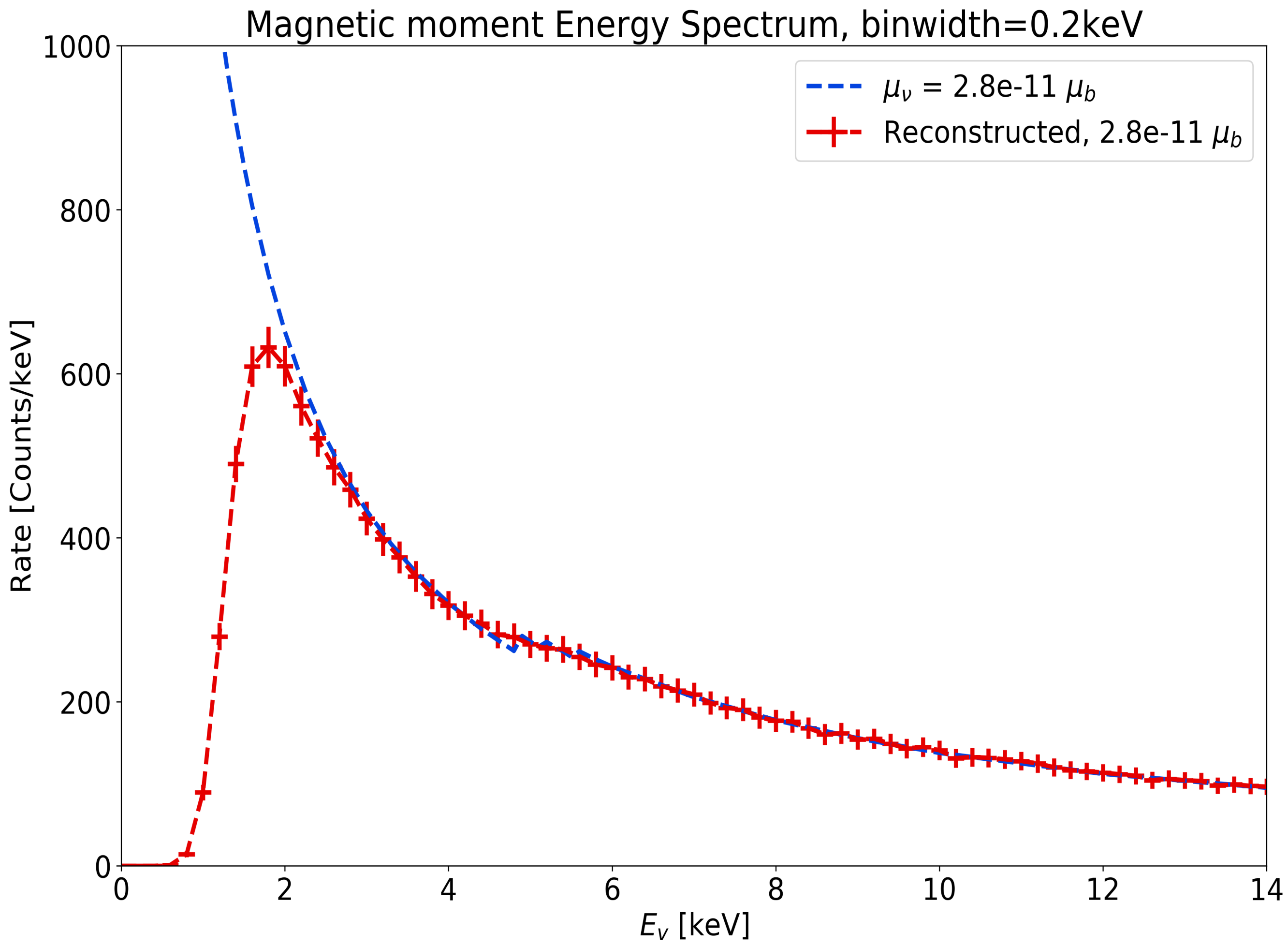
References

1. ”Projected sensitivities of the LUX-ZEPLIN (LZ) experiment to new physics via low-energy electron recoils” https://arxiv.org/abs/2102.11740
2. “LUX-ZEPLIN Technical Design Report”, https://arxiv.org/abs/1703.09144
3. “Large Neutrino Magnetic Dipole Moments in MSSM Extensions”, https://arxiv.org/abs/1312.2505
4. ”Discovery potential of multi-ton xenon detectors in neutrino electromagnetic properties” https://arxiv.org/abs/1903.06085
5. “Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data”, https://arxiv.org/abs/1707.09355
6. “New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment”, https://arxiv.org/abs/1411.2279

Neutrino EM form factor

$$\left(\frac{d\sigma_{\nu,e}}{dT_e}\right) \simeq \left(\frac{d\sigma_{\nu,e}}{dT_e}\right)_{\rm weak} + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_{\rm B}}\right)^2 + \frac{2\pi\alpha}{m_e}\left(\frac{1}{T_e^2}\right)q_\nu^2,$$

Analysis: Reconstruction; threshold



Other physics models (cont.)

- (See Fig. 4, or extra slides for figures)
- Solar axions
  - Axio-electric coupling: g_{Ae} ~= 1.1 x 10^{-11} (10^{-6} keV < m_A < 1 keV)
- Axion-like particles
  - Axio-electron coupling: g_{Ae} ~= (1-5) x 10^{-14} (1 keV < m_A < 100 keV)
- Hidden/dark photons
  - 1 x 10^{-32} < κ^2 < 1 x 10^{-26} (HP mass 2 GeV < m_{HP} < 100 GeV)
- Mirror Dark Matter
  - 1 x 10^{-12} < ε < 2 x 10^{-8} (~0.1 keV < E < 1 keV)
- Leptophillic EFT:
  - Axial-vector cross section: ~ 10^{-38} < x-section < 10^{-35} (1 < m_{WIMP} < 10^3 GeV)

Statistical Analysis model (cont.)

$$L(\sigma, \boldsymbol{\nu}|\mathfrak{D}) = \left[\underbrace{\mathrm{Pois}(n_0|\mu)}_{\text{Extended term}} * \underbrace{\prod_{e=1}^{n_0} \frac{1}{\mu}\left(\mu_s(\sigma) f_s(\boldsymbol{x_e}|m_{\mathrm{WIMP}}) + \sum_{b=1}^{N_b} \mu_b f_b(\boldsymbol{x_e}|\boldsymbol{\nu})\right)}_{\text{Event probability model}}\right]$$

$$* \underbrace{\prod_{p=1}^{N_p} f_p(\boldsymbol{g_p}|\nu_p)}_{\text{Constraint term}}$$

Extended term

Event probability model

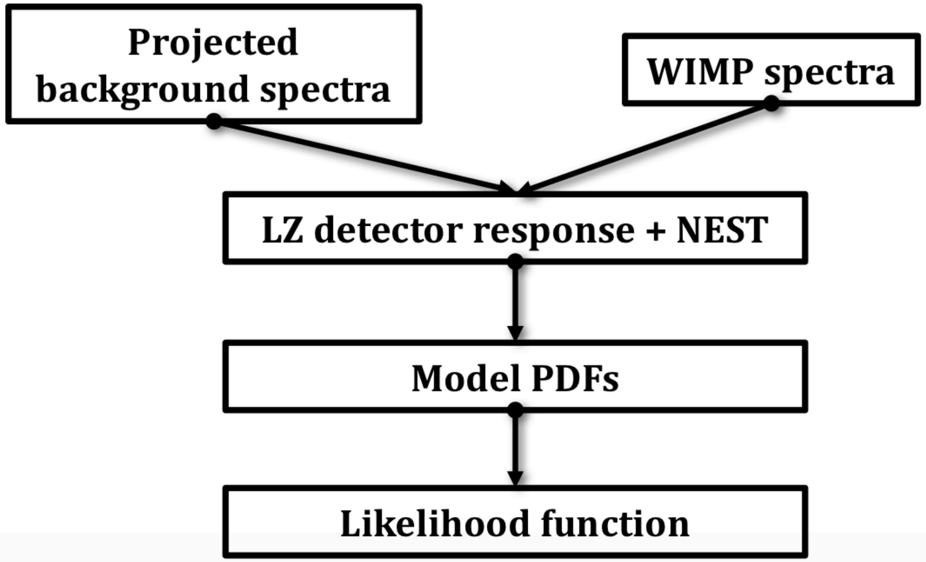
Constraint term

- Observables: $\boldsymbol{x} = \{S1, S2\}$
- Parameter of interest: $\sigma_{\mathrm{WIMP}-N}$
- Nuisance parameters:

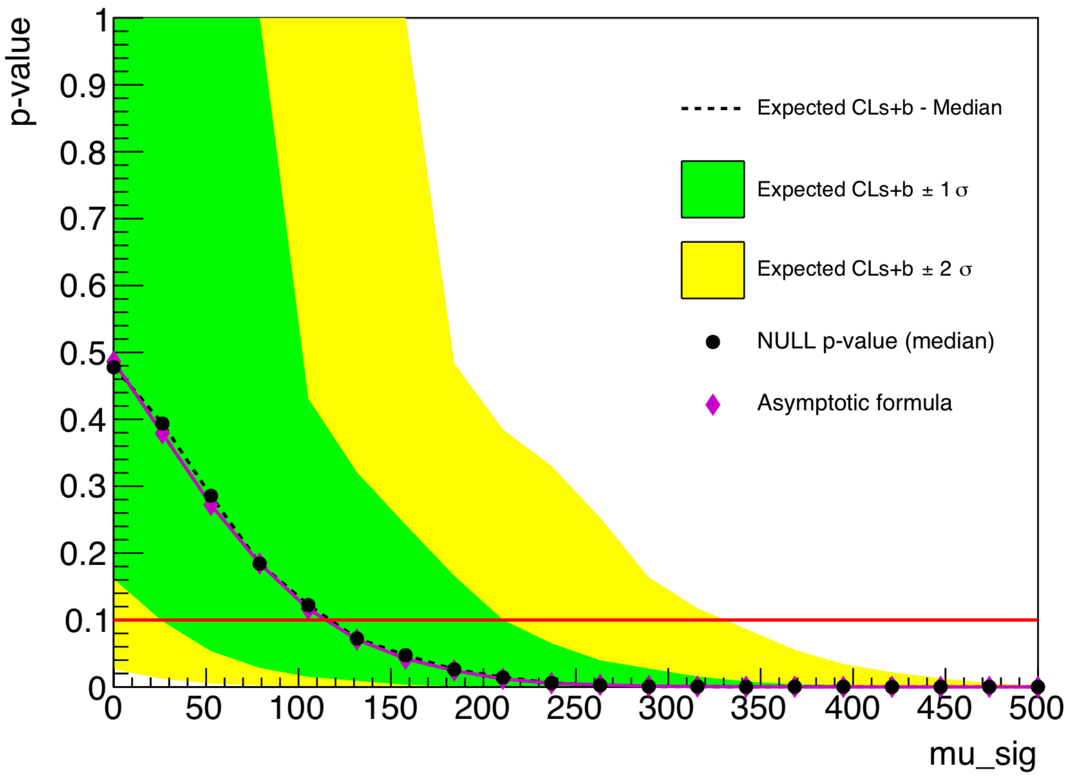
$$\boldsymbol{\nu} = \{\mu_b\}_{b=1}^{b=N_b}$$

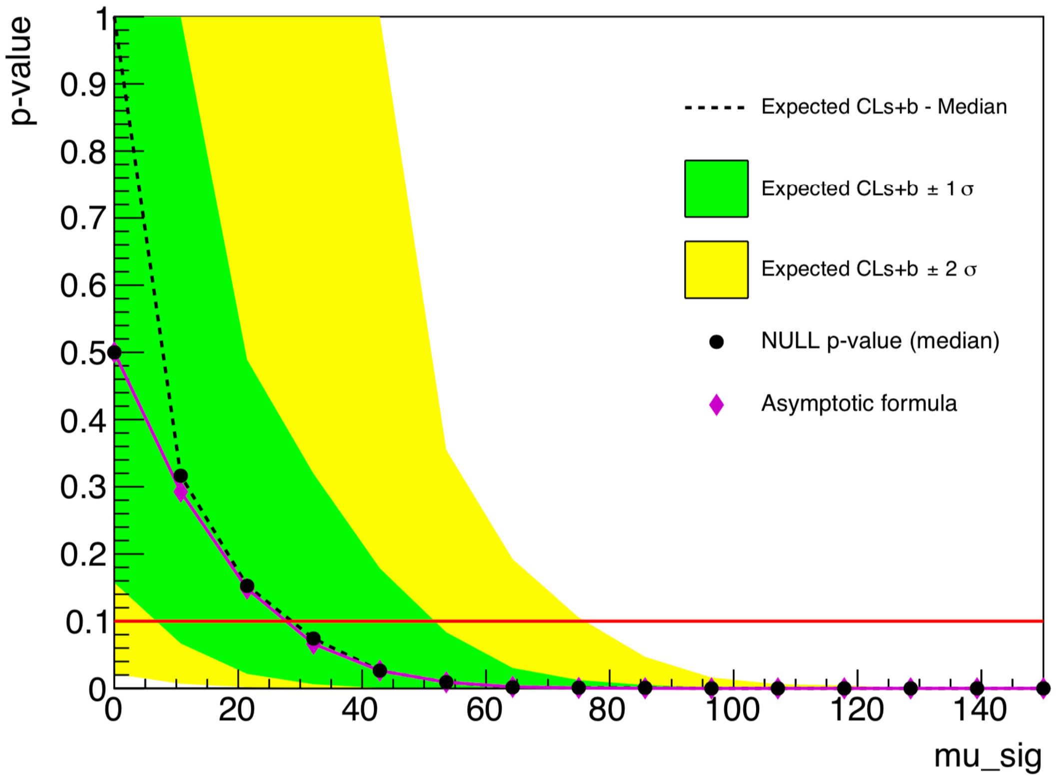
- Global observables:

$$\mathbf{g} = \{a_b\}_{b=1}^{b=N_b}$$



Neutrino EM PLR Results





Results

- Exclusion limits of the proposed neutrino magnetic moment and effective milli-charge
  - μ_v
    - $+1\sigma$ value: $\mu_v \sim= 7.2 \times 10^{-11}\ \mu_B$, which corresponds to ~220 signal counts
    - -1σ value: $\mu_v \sim= 2.6 \times 10^{-11}\ \mu_B$, which corresponds to ~20 signal counts
  - q_v
    - $+1\sigma$ value: $q_v \sim= 1.08 \times 10^{-12}\ e_0$, which corresponds to ~52 signal counts
    - -1σ value: $q_v \sim= 5.7 \times 10^{-14}\ e_0$, which corresponds to ~7 signal counts