Recombination in liquid xenon using the Large Underground Xenon (LUX) Experiment

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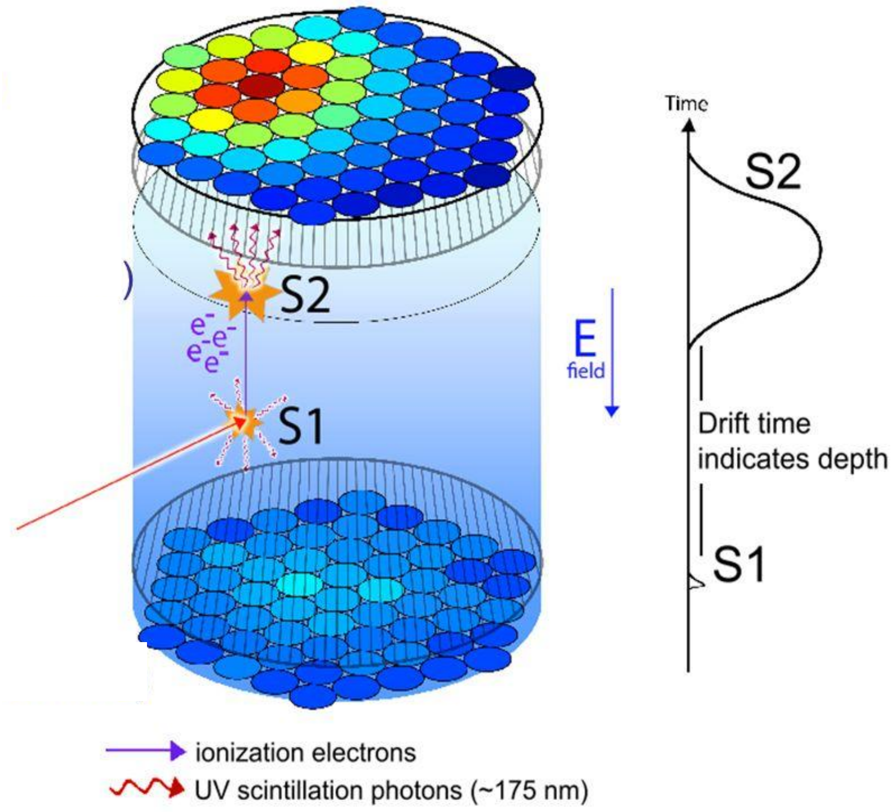
NorCal HEP-EXchange

With: The LUX Collaboration

The Large Underground Xenon Experiment (LUX)



- Two-phase xenon time projection chamber
- Particle recoils produce primary scintillation light (S1), ionized electrons, and heat
- Charge drifts through electric field, extracted into gas phase region, produce secondary scintillation light (S2)
- S1 and S2 detected by photomultiplier tubes (PMTs)
- Time between S1/S2 gives z-position of event; pattern of S2 on PMTs gives x/y-position

LUX 2014-16 Run

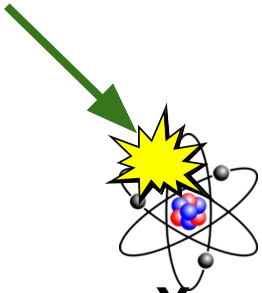
- Data-taking from September 2014 - August 2016

- WIMP Search includes 332 live-days of data, fiducial volume of ≈ 100 kg

- LUX has launched many calibration campaigns, in order to measure our detector response to nuclear and electronic recoils.
    - Examples for Electron Recoils (ER): ^{83m}Kr, CH_3T, ^{14}C, ^{131m}Xe

- Varying drift field in the detector, due to charges getting caught on the Teflon walls
    - Recently published paper with an in-depth description of how we modeled the electric field: *JINST* **12** P11022

Energy Partitioning in Xenon



Xe

$N_{excitons}$ Xe_2^* → $n_{photons} = N_{excitons} + r\, N_{ions}$

$= (N_{ex}/N_i + r)\, N_i$

Fraction *r* recombine

N_{ions} Xe^+/e^- → $n_{electrons} = (1 - r)\, N_{ions}$

Heat (negligible in electron recoils, larger fraction in nuclear recoils)

Energy Partitioning in Xenon

- Can calculate the energy of a recoil from the S1 and S2 signals:

Photon work function:
W = (13.7 ± 0.2) eV/quanta

$$E = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right) = W\left(n_{ph} + n_e\right)$$

S1 gain:
g_1 ≈ 0.1 photoelectrons/photon

S2 gain:
g_2 ≈ 20 photoelectrons/electron

Energy Partitioning in Xenon

- Define mean light and charge yields using the Gaussian means of the S1 and S2 distributions:

$$L_y = \frac{\langle n_{ph} \rangle}{E} \qquad Q_y = \frac{\langle n_e \rangle}{E}$$

- Can calculate recombination probability, as well. We take $N_{ex} / N_i = 0.2$ to be constant with energy, consistent with measurements

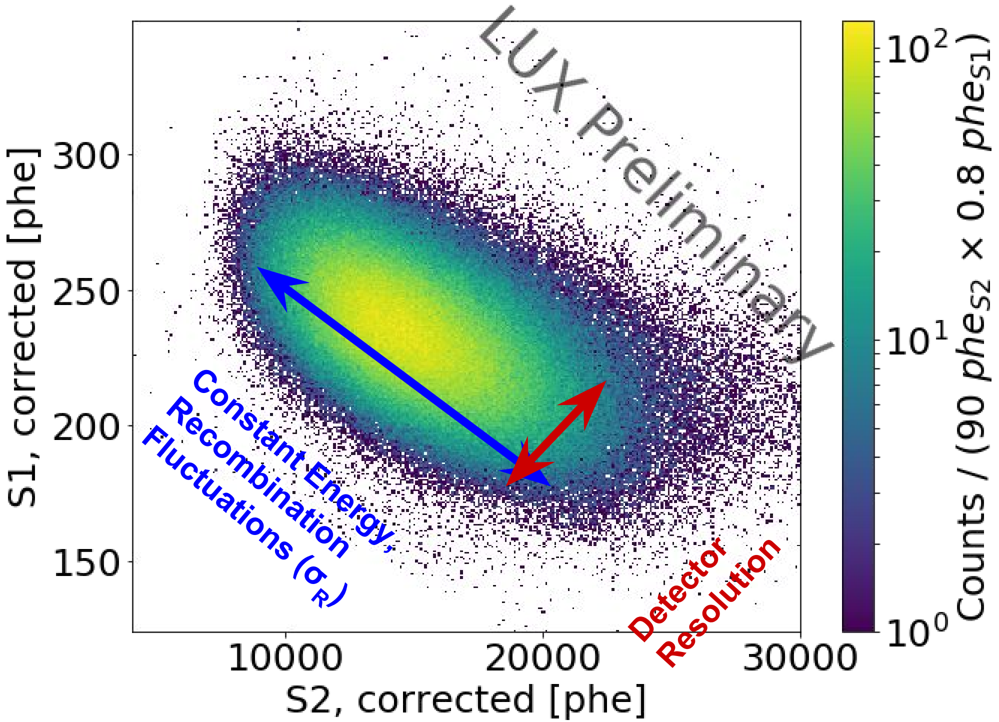
$$\langle r \rangle = \frac{\langle n_{ph} \rangle / \langle n_e \rangle - N_{ex}/N_i}{\langle n_{ph} \rangle / \langle n_e \rangle + 1}$$

- Recombination is a statistical process, so there are fluctuations in how many light/charge quanta are produced. Measure the size of these fluctuations by finding the total width and subtracting detector resolution effects:

$$\sigma_r^2 = \frac{1}{2}\left[\left(\frac{\sigma_{S1}}{g_1}\right)^2 + \left(\frac{\sigma_{S2}}{g_2}\right)^2 - \left(\frac{\sigma_E}{W}\right)^2\right]$$

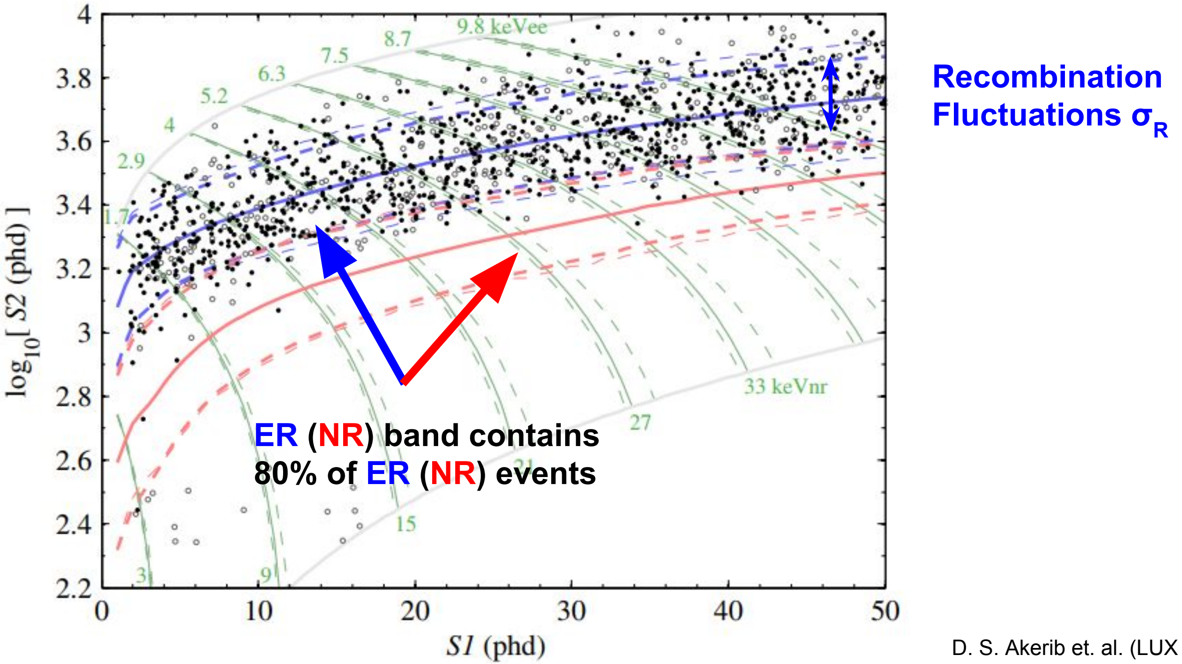
Recombination

- Recombination fluctuations cause S1 + S2 signals to smear out
  - Below: ^{83m}Kr calibration data (two-step 41.55 keV recoil) from 2014-09



Recombination

- Charge-to-light ratio is different for electron recoils vs. nuclear recoils → discriminate
  - At right: "bands" of ER and NR events; fluctuations give the ER band its width
- Goal: Measure recombination and light/charge yields as a function of E-field



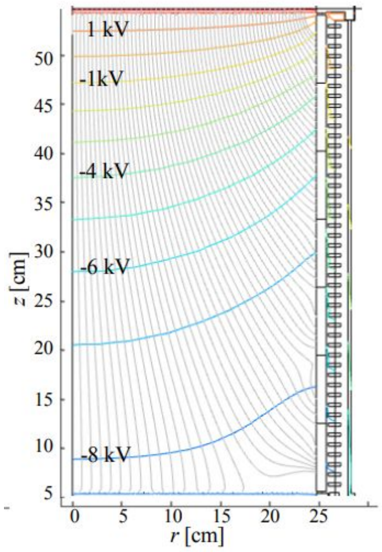
D. S. Akerib et. al. (LUX Collaboration)
PRL **118**, 021303 (2017)

Electric field variation in LUX

- In the 2014-16 run of LUX, we had a non-uniform drift field in the liquid phase
- Field lines are not parallel, so S2-based position reconstruction is incorrect
- We constructed a model of the LUX electric field, represented by “maps”:

    Real space → S2-space

    3D position (real/S2) → E-field value



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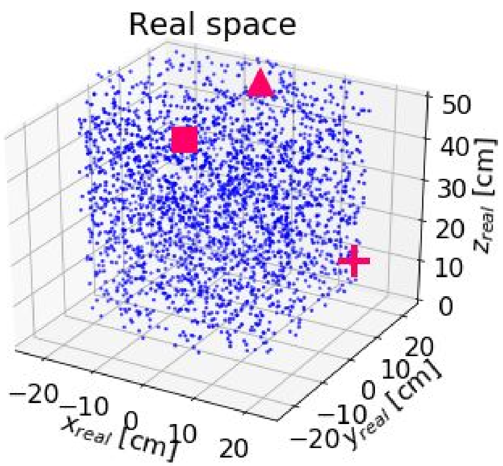
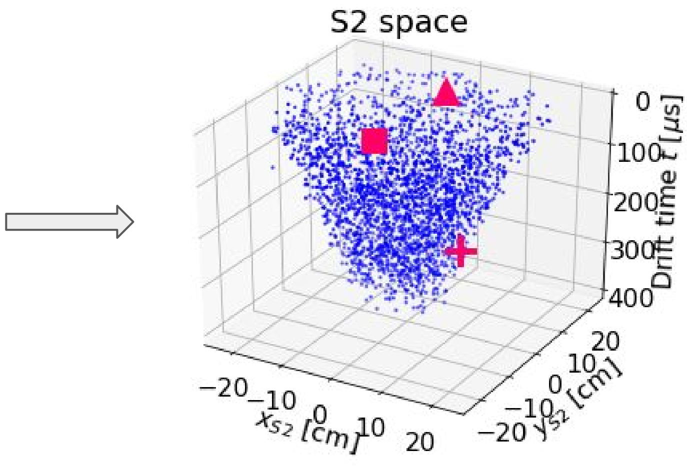


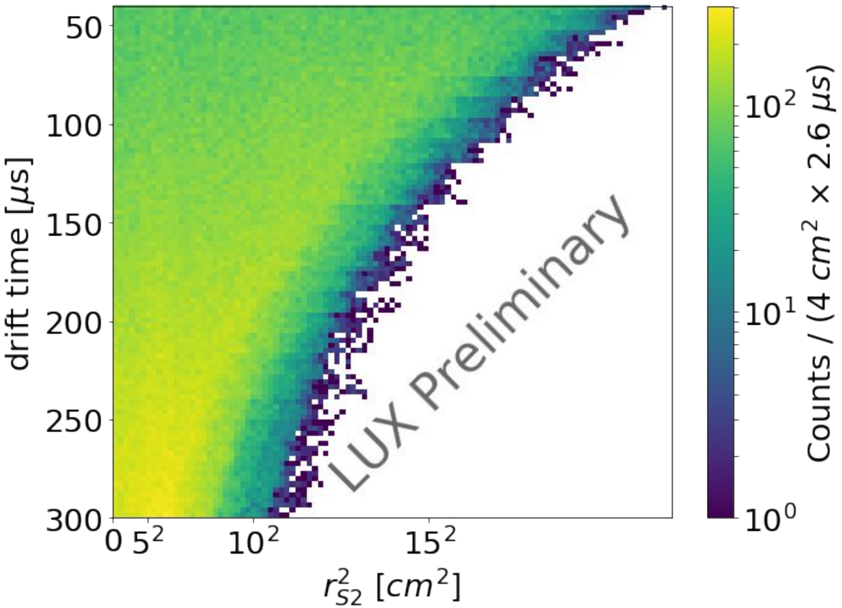


Random points uniformly distributed in real space

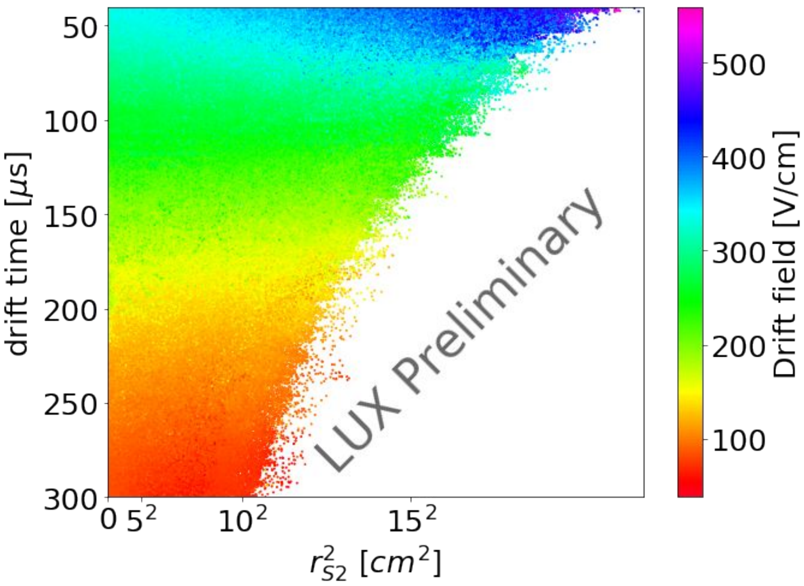
Electric field variation in LUX

- ^{83m}Kr is an excellent calibration source to study E-field, injected ~weekly
  - Decays via two conversion electrons, giving a 32.1 + 9.4 = 41.5 keV recoil
  - Half-life of 1.8 hours, so it mixes uniformly within the detector volume (on a timescale of a few minutes) before decaying

^{83m}Kr data from Sep 2014

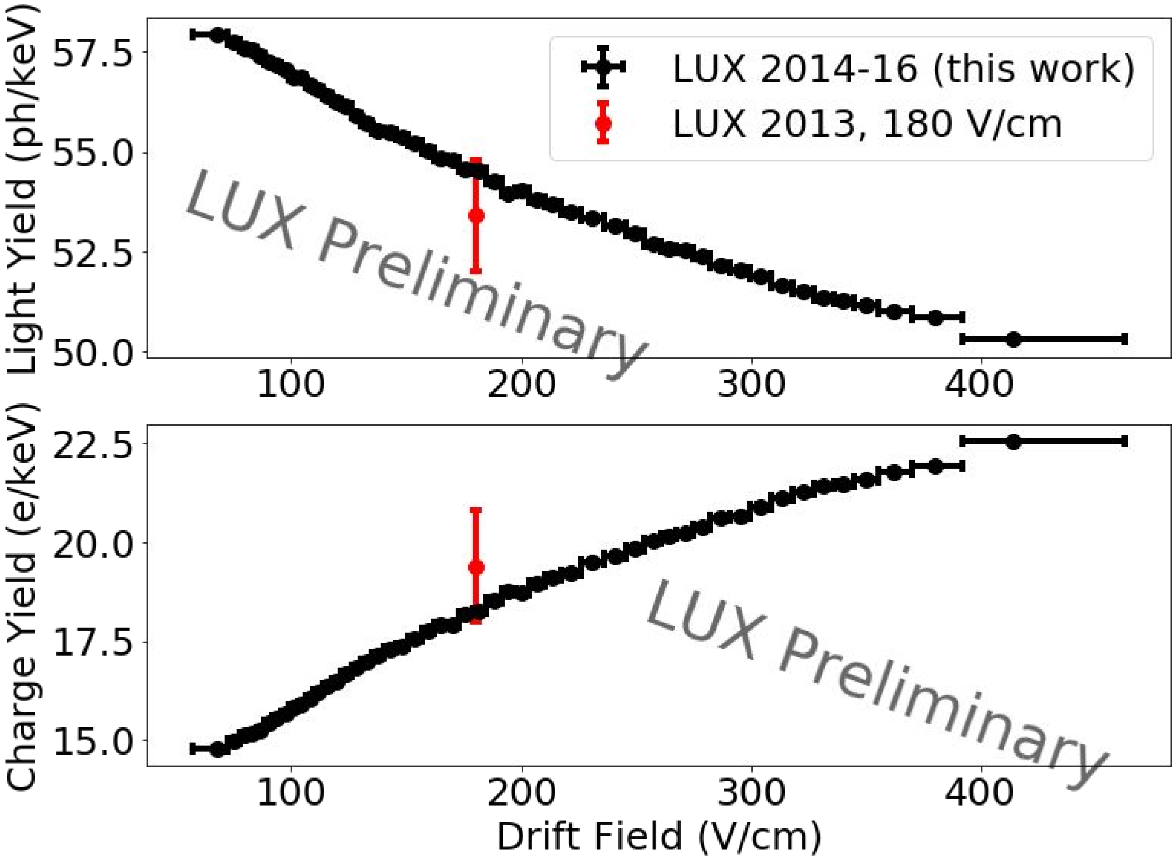


Field value interpolated from model, based on x_{S2}, y_{S2}, drift time



Yields

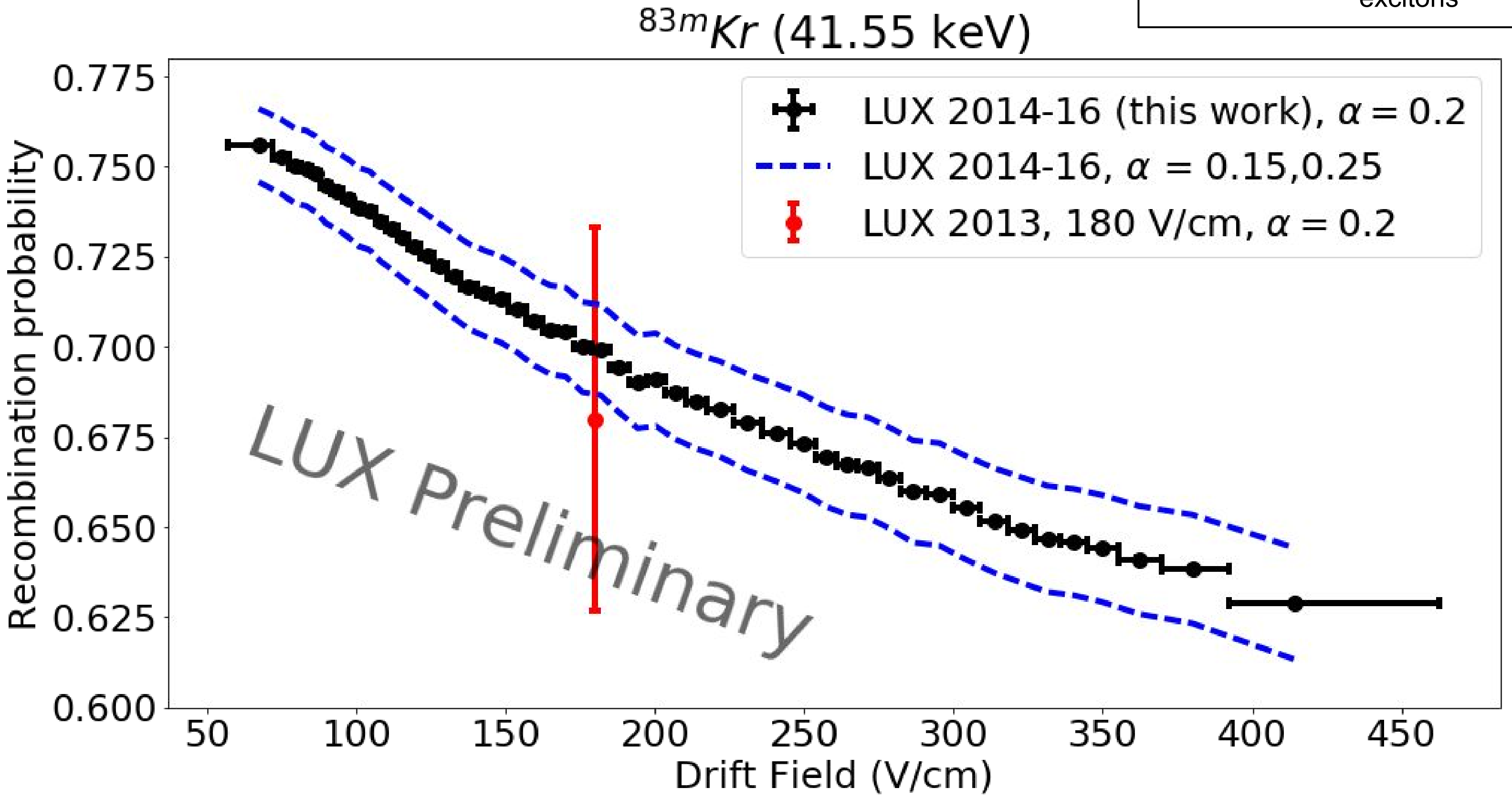
- Separate ^{83m}Kr data into bins based on E-field magnitude at each event location
- Within each bin, measure mean S1 and S2 → get light and charge yields, recombination probability, and recombination fluctuations
- At right: measured yields. Calculated separately; naturally add to 73 quanta/keV at all fields



Recombination Probability

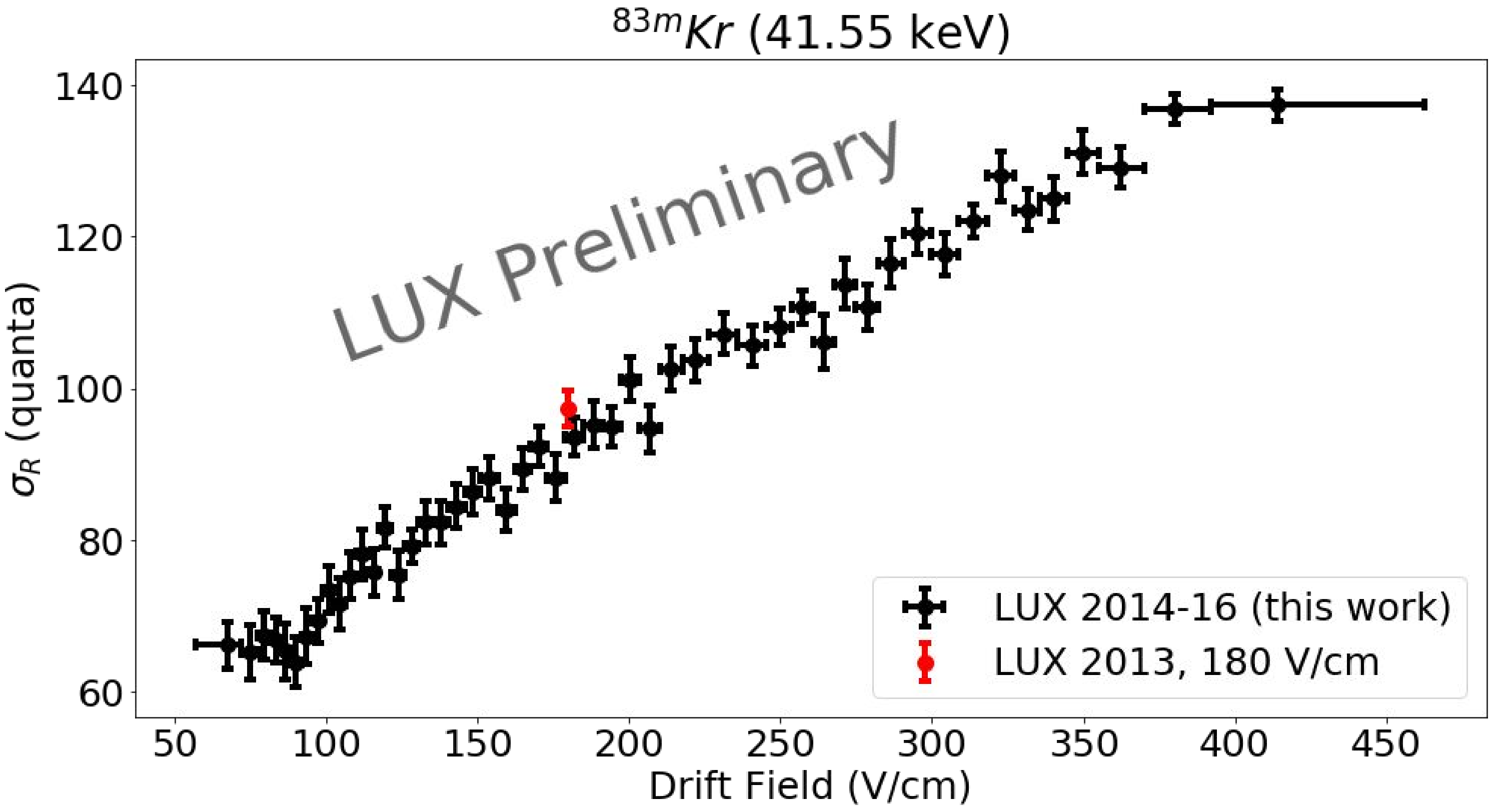
$$\langle r \rangle = \frac{\langle n_{ph} \rangle / \langle n_e \rangle - N_{ex}/N_i}{\langle n_{ph} \rangle / \langle n_e \rangle + 1}$$

$\alpha \equiv N_{excitons} / N_{ions}$



Recombination Fluctuations

$$\sigma_r^2 = \frac{1}{2}\left[\left(\frac{\sigma_{S1}}{g_1}\right)^2 + \left(\frac{\sigma_{S2}}{g_2}\right)^2 - \left(\frac{\sigma_E}{W}\right)^2\right]$$



Summary + future work

- Energy partitioning in xenon is important for understanding xenon microphysics, calibrating our detector, and ER/NR discrimination
- LUX can be used to measure yields and recombination parameters as a function of electric drift field
- Future work:
    - Use ^{131m}Xe data for the same purpose. It is higher energy (163.9 keV), so we should be able to see the behavior of these quantities as $r \rightarrow 0.5$
    - More careful study of systematic uncertainties
- Bigger picture: Understanding xenon physics at different fields can inform future liquid xenon experiments