HEP Journal Club 02/22/2022

Jeff Schueler

Application of recoil-imaging time projection chambers to directional neutron background measurements in the SuperKEKB accelerator tunnel

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Overview

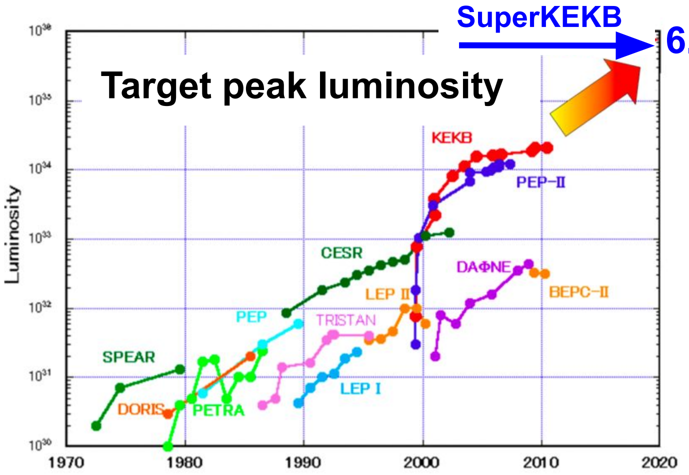
1. (Neutron) backgrounds at SuperKEKB (Ch. 1)
2. Phase 3 BEAST TPC system (Ch. 2)
3. Particle ID (Ch. 4)

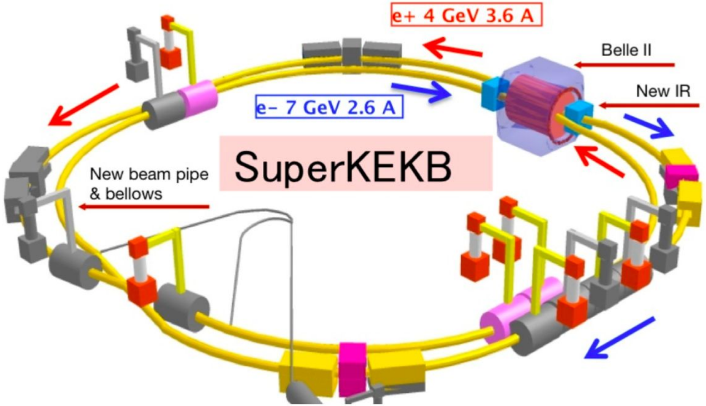
4. Neutron background modeling in the SuperKEKB tunnel (Ch. 5)
5. Background composition results (Ch. 6.1)
6. Energy spectra (Ch. 6.2)
7. Angular and directional analysis (Ch. 6.3)
8. Extrapolations, impact, and current related work (Ch 6.4, 7)

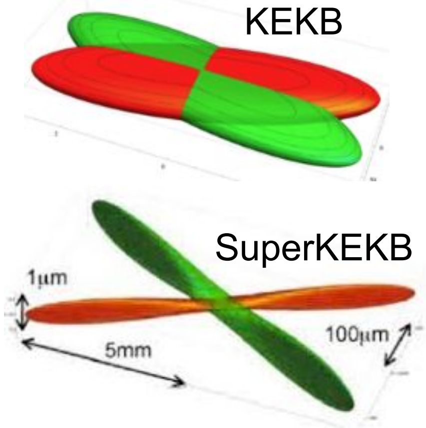
Goals of this paper: Survey the neutron backgrounds in the tunnel regions surrounding Belle II, assess how well we model backgrounds in this region (data vs MC comparisons), and determine if additional background remediation measures are needed to protect Belle II from fast neutron backgrounds originating outside of Belle II

SuperKEKB

- e^+e^- circular collider providing collisions for the Belle II B-factory experiment since March 2018
- Holds the current world record luminosity (3.1 x 10^{34} $cm^{-2}s^{-1}$ as of June 2021)
- Target peak luminosity is a factor ~20-30 larger than the current world record



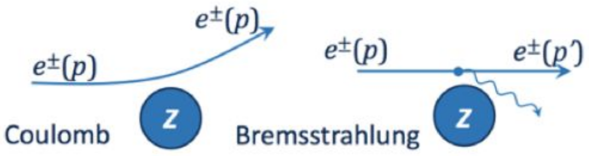




High luminosity comes at the cost of elevated beam-induced backgrounds, which must be mitigated to ensure stable operation of Belle II

Single beam neutron background sources in SuperKEKB tunnel

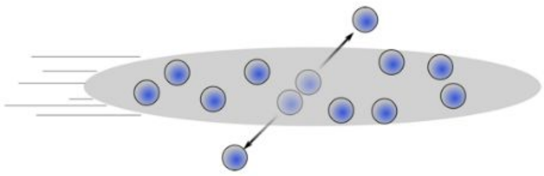
Beam-gas



Coulomb scattering and Bremsstrahlung from beam particles interacting with gas atoms in the beam pipe

$$\propto IPZ_e^2$$

Touschek



Intra-bunch scattering

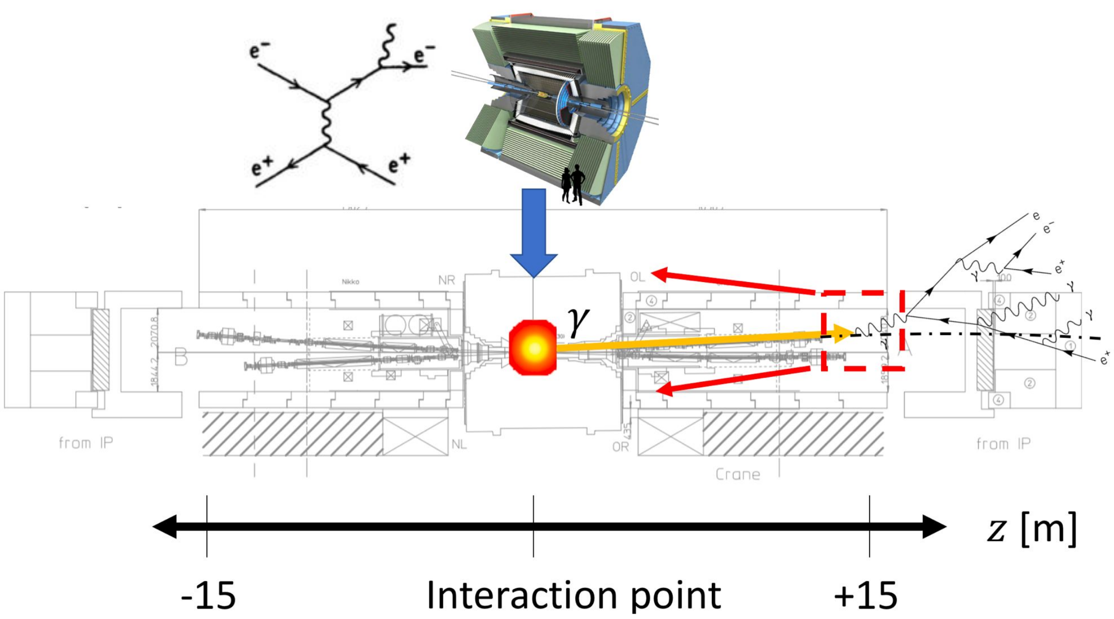
$$\propto \frac{I_b}{\sigma_x \sigma_y \sigma_z} \times I_b n_b$$

Neutron backgrounds are pernicious:

- Electrically neutral -> highly penetrating
  - Lose energy primarily through elastic scattering off of atomic nuclei
- Difficult to simulate
- Degrade detector performance if not well shielded

Beam-induced backgrounds: Background particles generated from SuperKEKB accelerator operation. Beam-induced backgrounds are *not* necessarily the same as physics backgrounds.

Collision-based neutron backgrounds and radiative Bhabha hotspots



- During collisions, high energy photons from radiative Bhabha (RBB) events travel straight through the beam pipe and collide with the walls of the beampipes
- These collisions form localized RBB hotspots that generate copious amounts of neutrons via the giant dipole resonance
- The rate of RBB photons generating these neutron hotspots should be proportional to the collision rate and thus luminosity
- SuperKEKB is the world’s highest luminosity collider, so neutron backgrounds from RBB hotspots are expected to be significant

Prior to this paper, RBB hotspots had never been directly surveyed. A chief goal of this paper was to instrument and survey neutron backgrounds near these hotspots.

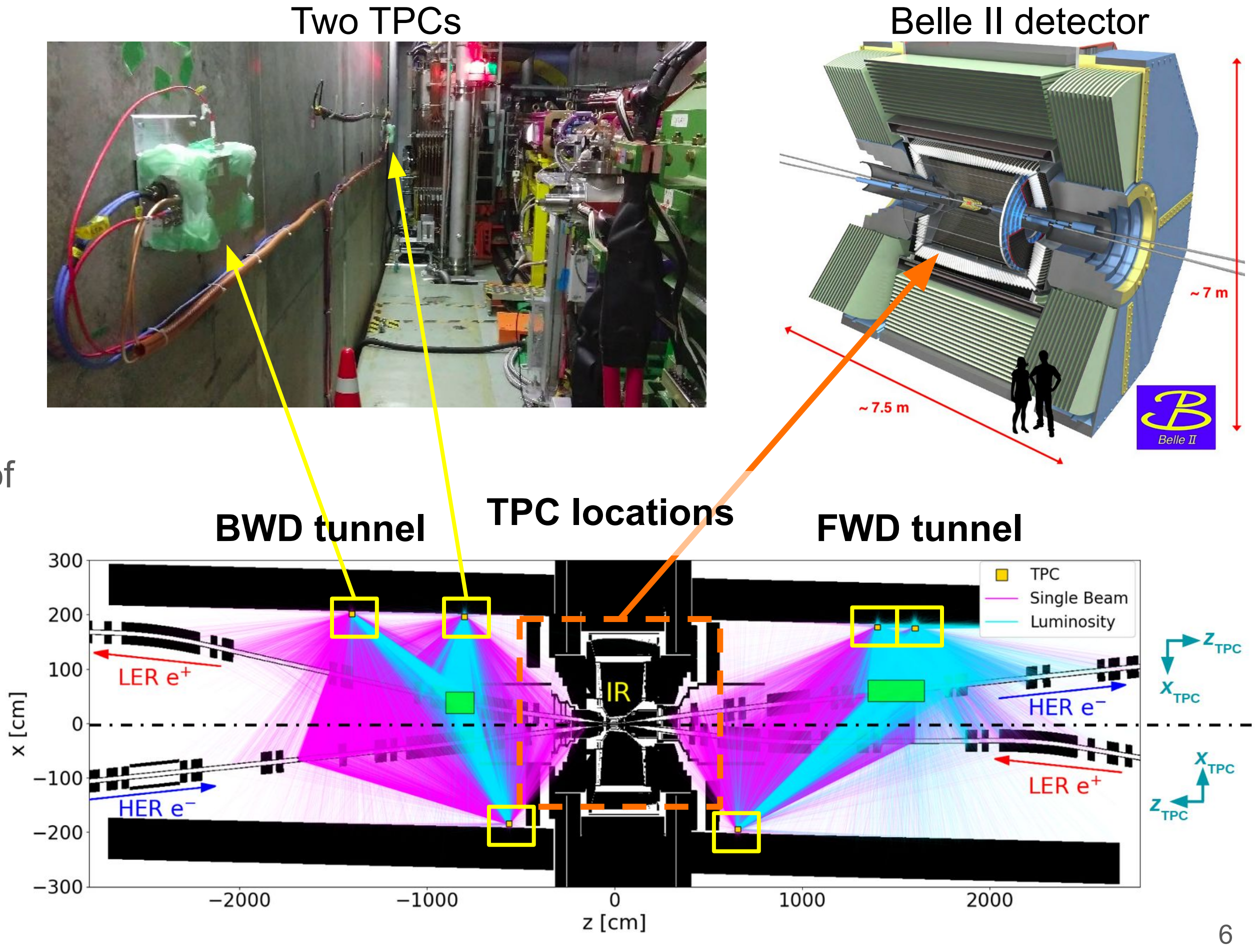
The TPC system

TPC system: 6 gaseous “recoil-imaging” TPCs that measure neutrons from nuclear recoils

Capable of measuring nuclear recoil:

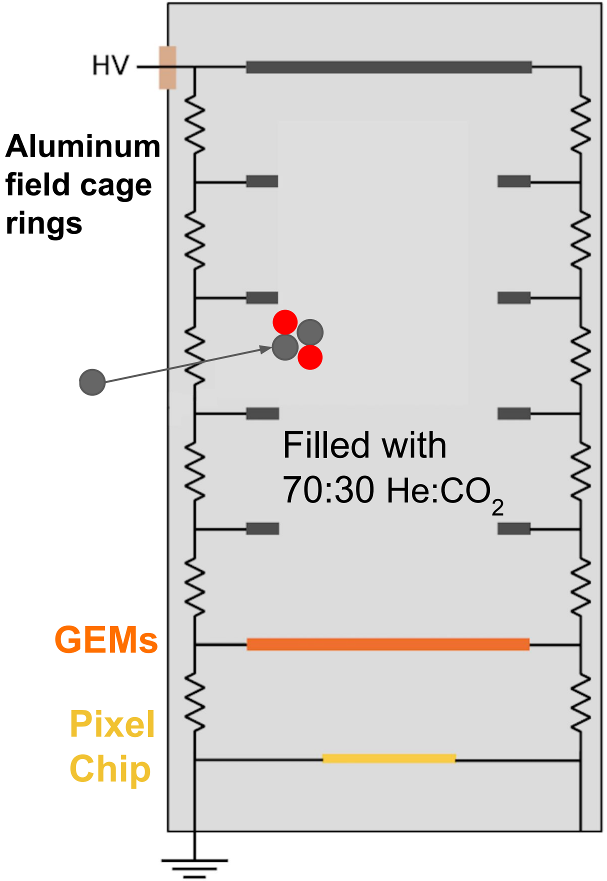
- Rates
- Energy Spectra
- Angular Distributions
- Recoil “sense” (vector direction of tracks)

Goal of TPC system: *Measure* neutron backgrounds in the tunnel region surrounding Belle II

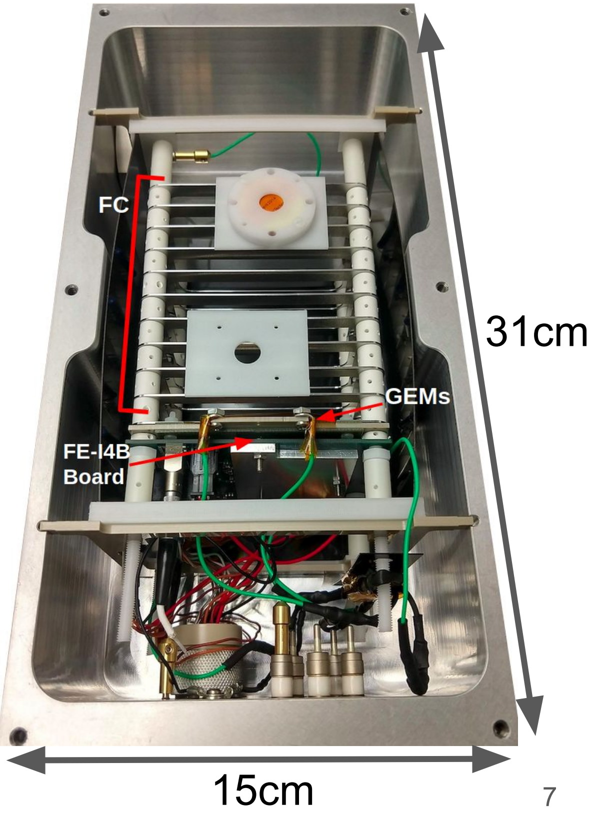


Detection Principle: BEAST TPCs detect neutrons from nuclear recoils

Neutron enters the TPC and scatters off of the nucleus of a gas atom



Actual Vessel



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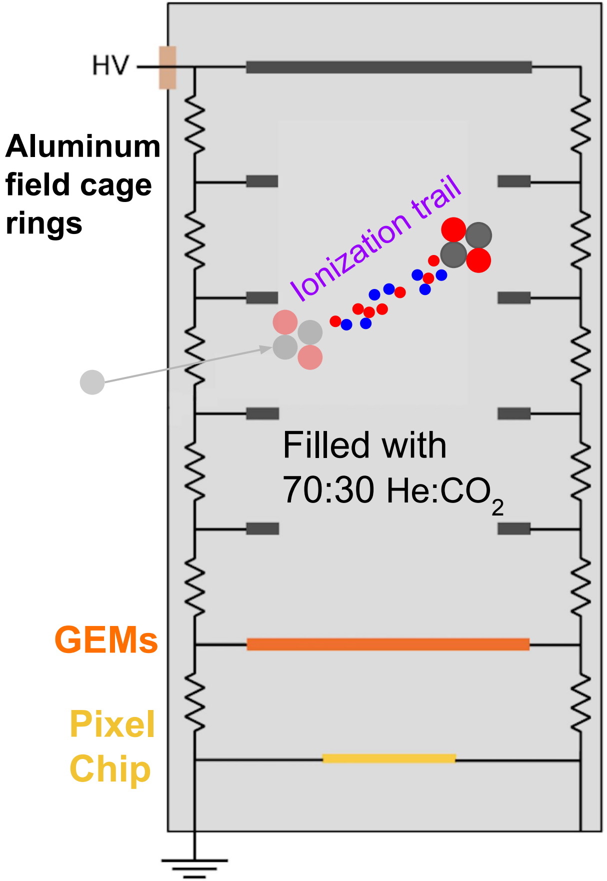
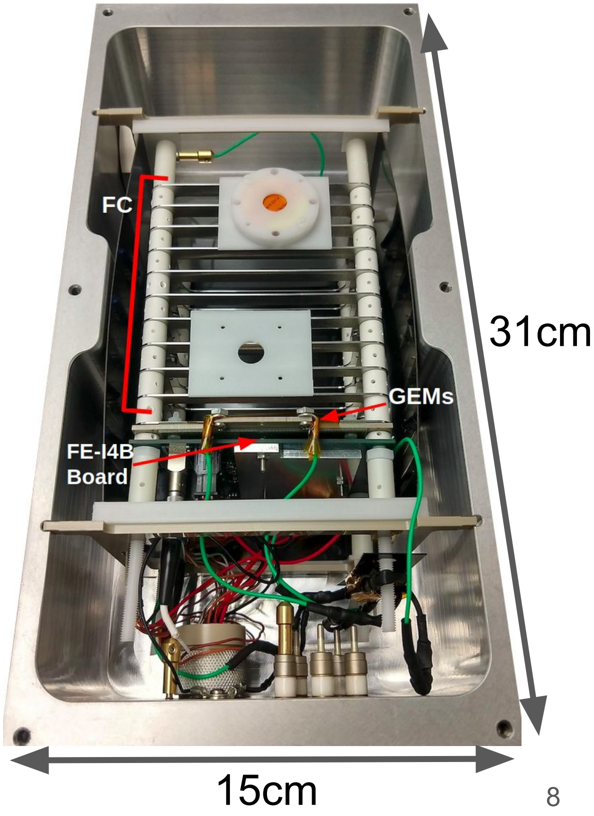
Gas nucleus recoils and ionizes other gas atoms in its path, forming an *ionization trail*



Actual Vessel



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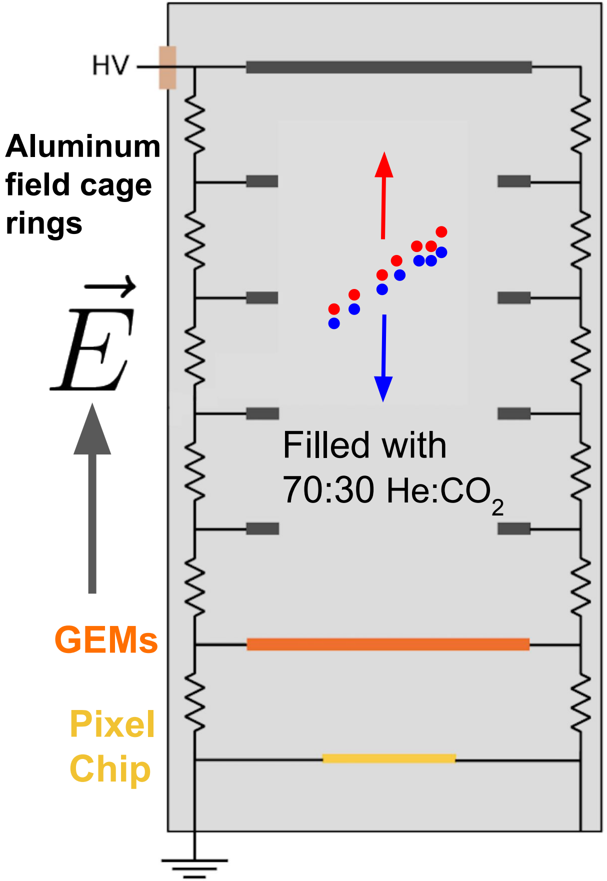
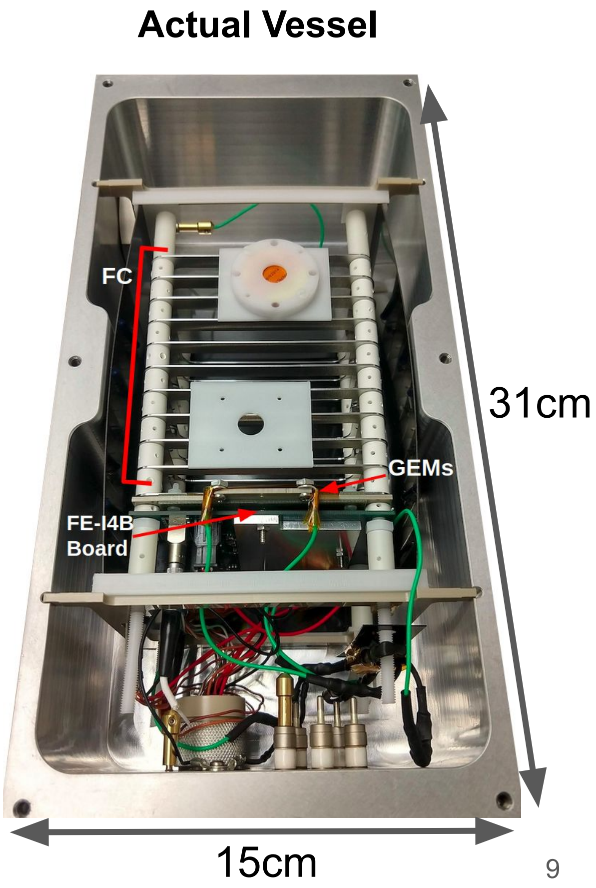
Uniform electric field separates charge: Electrons drift against the field toward the double gas electron multiplier (GEM) layer





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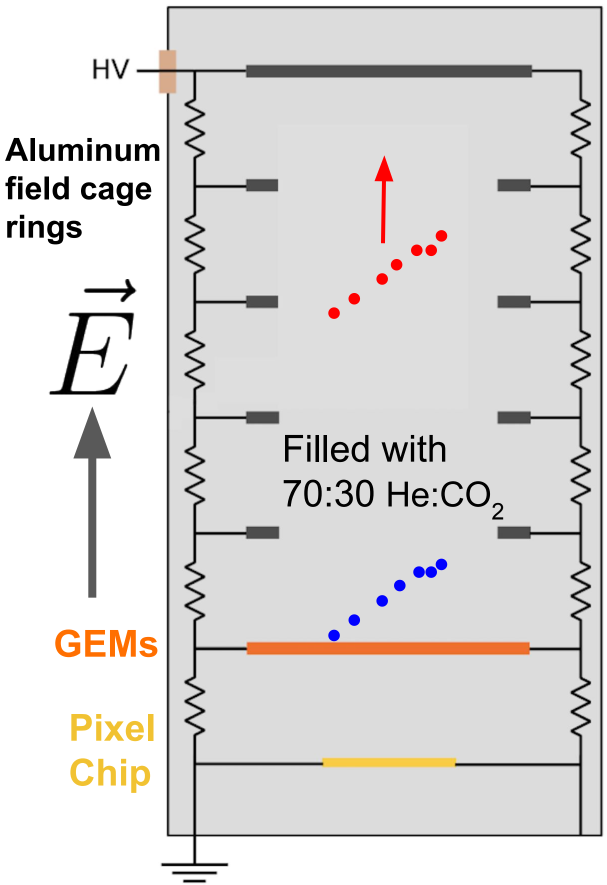
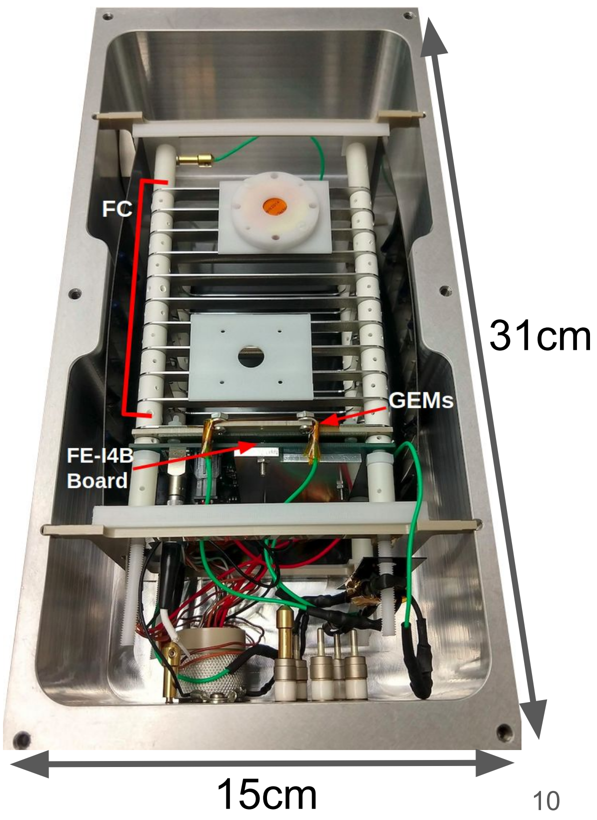
Electrons drift at constant speed



Actual Vessel



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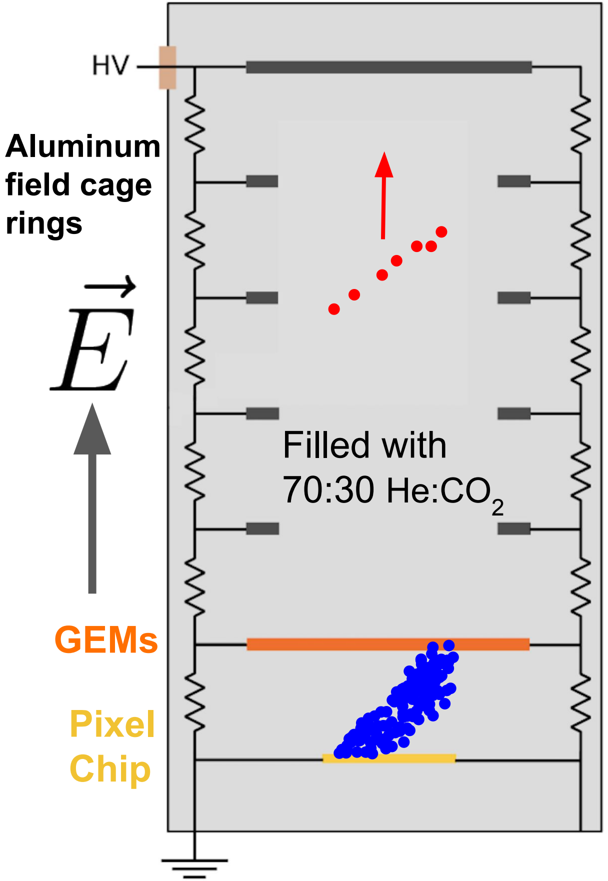
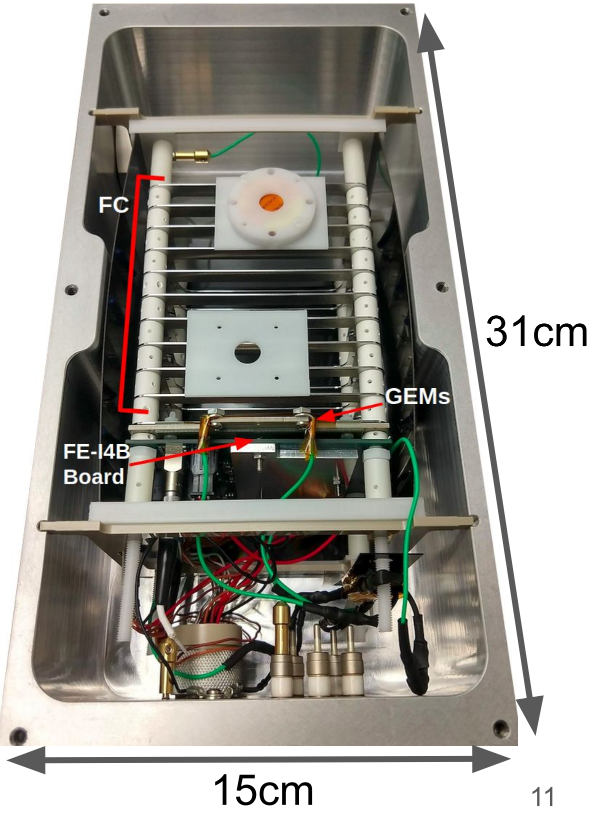
Electrons drift at constant speed

Charge is avalanche multiplied by ~30-40 through each GEM and collected by an **ATLAS FE-I4B pixel ASIC**



Actual Vessel



Recoil-imaging TPCs reconstruct events in 3D

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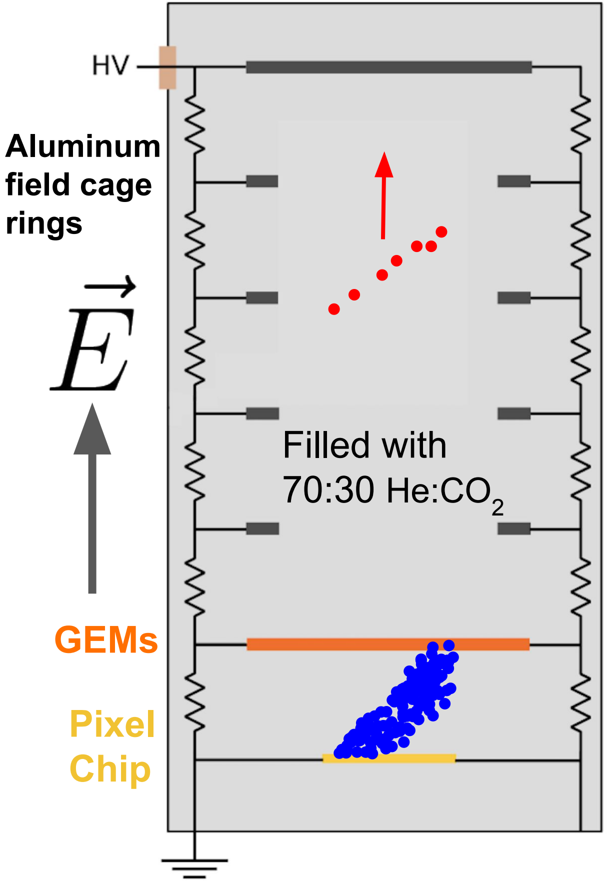
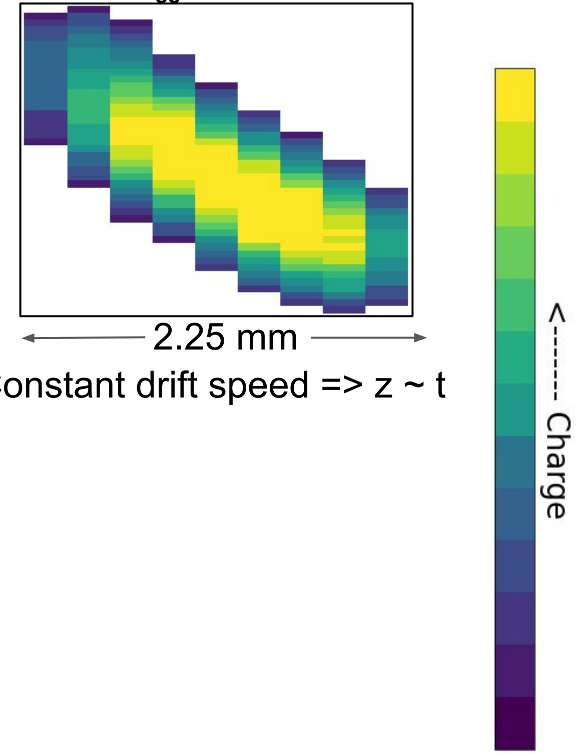


210 keV$_{ee}$ track on chip



-Constant drift speed => z ~ t

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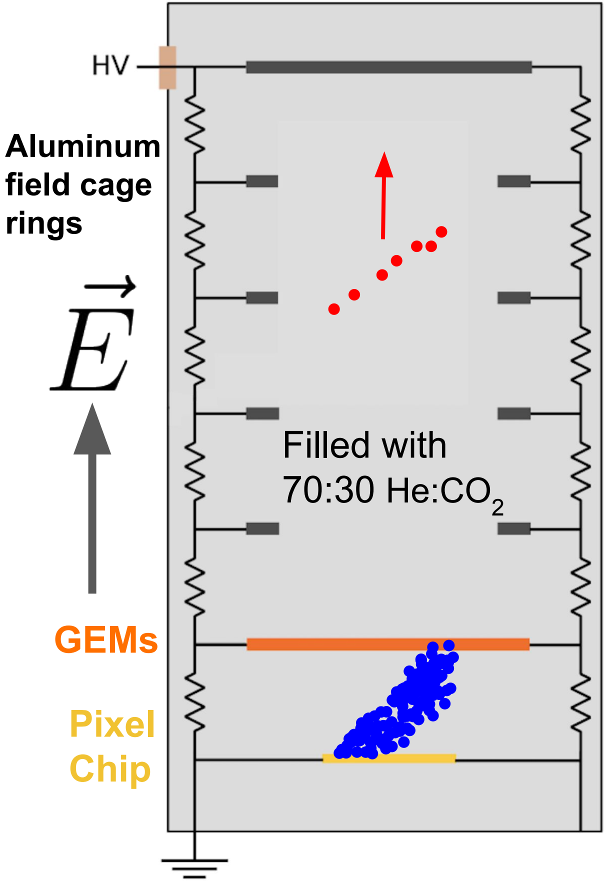
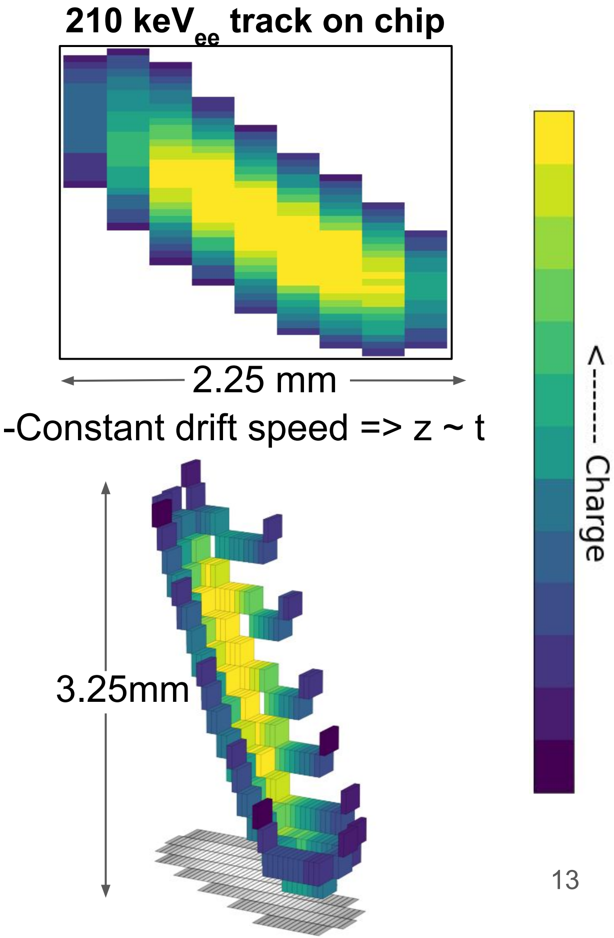
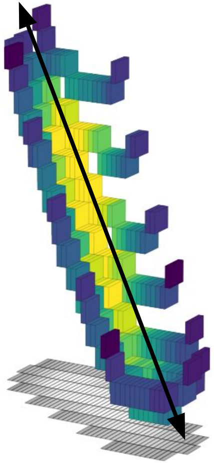
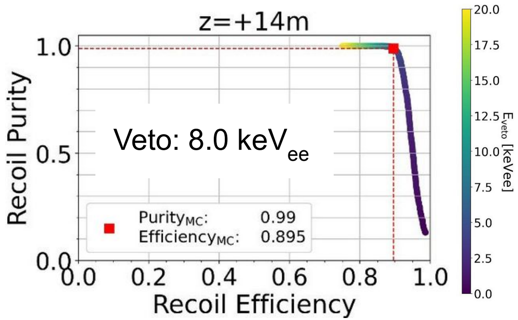


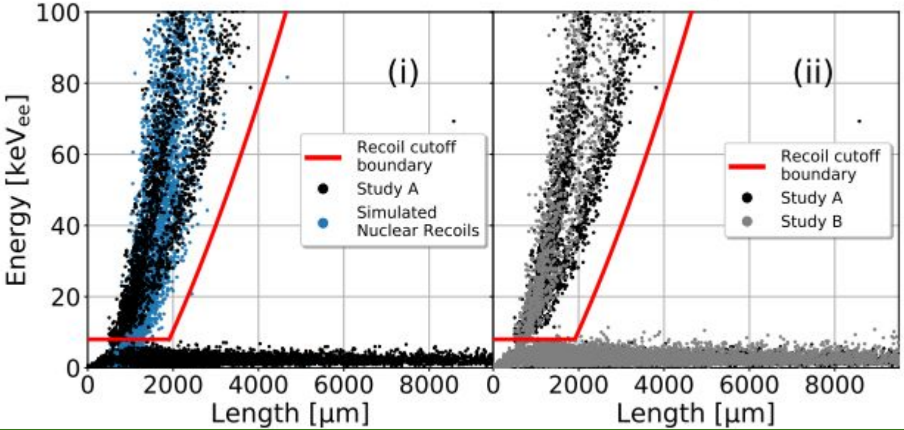


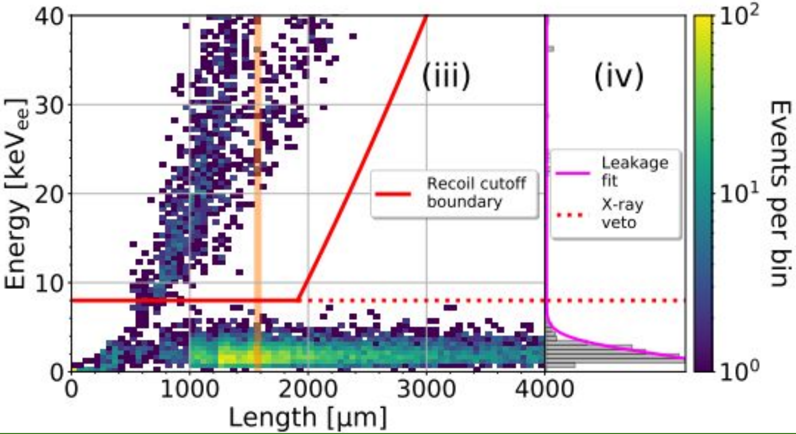
Selecting events

- **Pages 6-9** detail our full calibration and signal selection criteria
- The key takeaway is below:



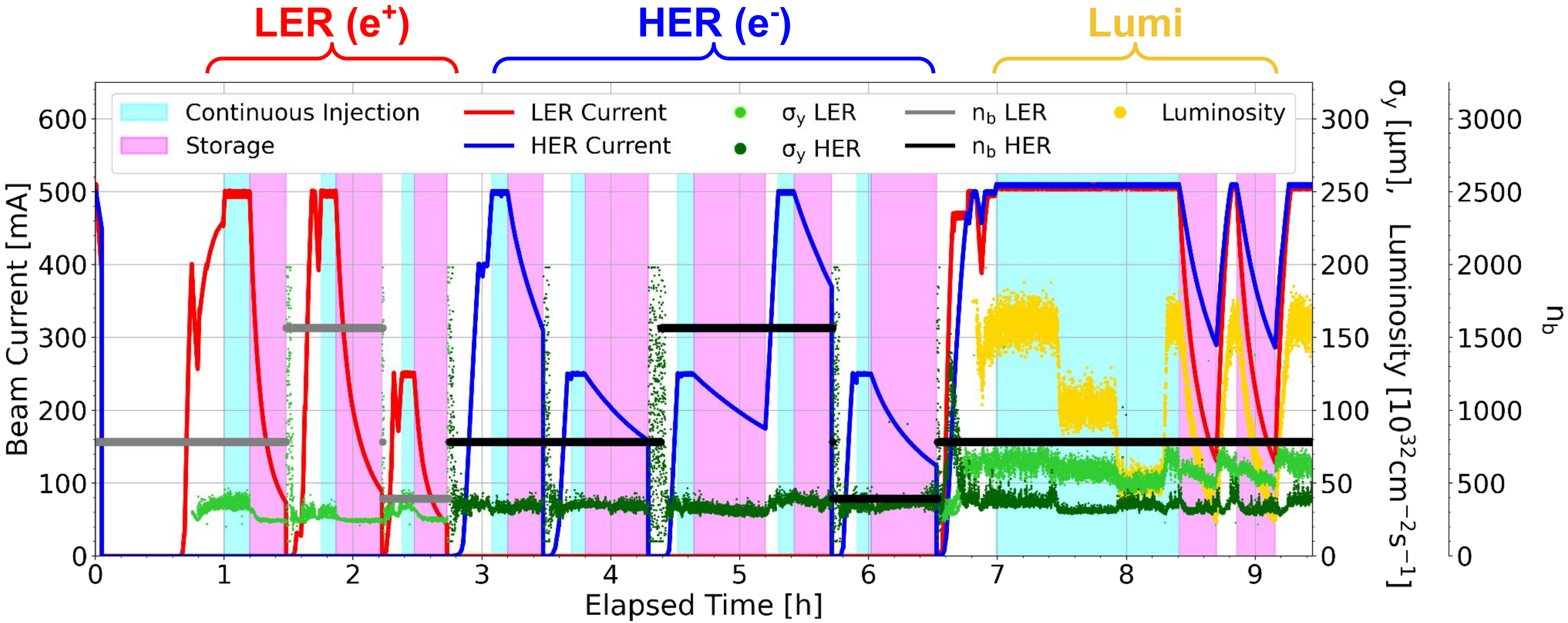






Energy and 3D track length are enough to select a nearly background free (>99% recoil purity) sample of neutron-induced nuclear recoils for our studies

Background studies (Figure 8, page 10)

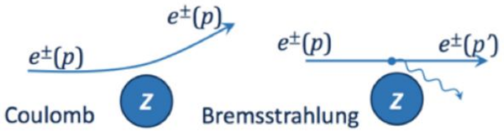


- Two dedicated beam background studies analyzed in this work
  - **Study A: Took place on May 9th 2020 and is the primary focus of this paper**
  - Study B: Took place on June 16th 2021 and is used to provide a systematic for collision background measurements
- We focus only on the magenta shaded “beam storage” regions, as injection periods create an additional background component that can be more difficult to model

Modeling neutron backgrounds during storage periods

1. Beam-gas (equation 12, page 10):

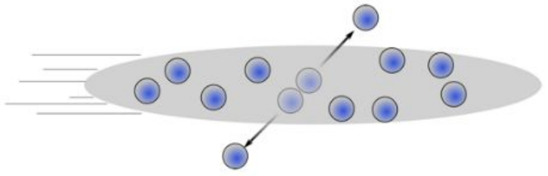
$$R_{bg,i} = \boxed{B_{0i}} \cdot I_i P_{meas,i} - \boxed{B_{1i}} \cdot I_i \quad i = \mathrm{LER},\ \mathrm{HER}$$



Empirical sensitivity parameters that together encode contributions to neutron backgrounds

2. Touschek (page 11):

$$R_T = \boxed{T} \cdot \frac{I_b^2 n_b}{\sigma_x \sigma_y \sigma_z} \qquad I_b = \frac{I}{n_b}$$



$$R_{T,i} = \boxed{T_i} \cdot \frac{I_i^2}{\sigma_{yi}^{\boxed{\alpha_i}} \sigma_{zi} n_{bi}} \quad i = \mathrm{LER},\ \mathrm{HER}$$

Empirical correction factor to correct for both "beam-blowup" effect + enhanced Touschek rates from upstream collimators that affect tunnel measurements

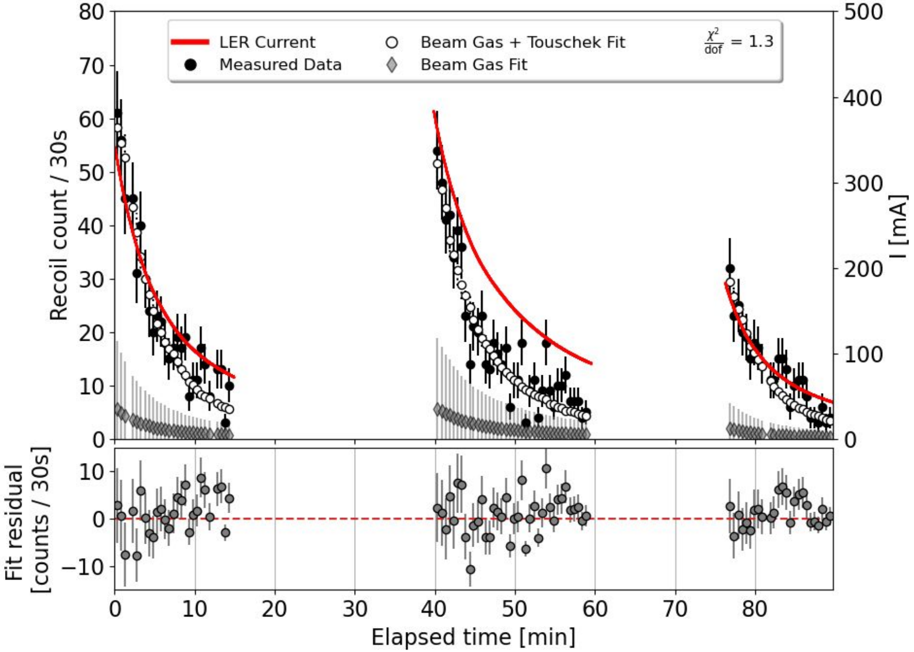
3. Single beam combined model:

$$\boxed{\begin{aligned} R_{\mathrm{SB,i}} &= R_{bg,i} + R_{T,i} \\ &= B_{0i} \cdot I_i P_{meas,i} - B_{1i} \cdot I_i + T_i \cdot \frac{I_i^2}{\sigma_{yi}^{\alpha_i} \sigma_{zi} n_{bi}} \quad i = \mathrm{LER},\ \mathrm{HER} \end{aligned}}$$

Single beam fit example (Figure 9, page 12)

$$R_{\mathrm{SB,i}} = B_{0i} \cdot I_i P_{meas,i} - B_{1i} \cdot I_i + T_i \cdot \frac{I_i^2}{\sigma_{yi}^{\alpha_i} \sigma_{zi} n_{bi}} \quad i = \mathrm{LER, HER}$$

$\alpha_{LER} = 2.4$
$\alpha_{HER} = 1.0$



Single beam LER background model fit to a FWD TPC with $B_{0,LER}$,$B_{1,LER}$, and T_{LER} determined by fit to measured parameters.

Modeling collision backgrounds (page 11)

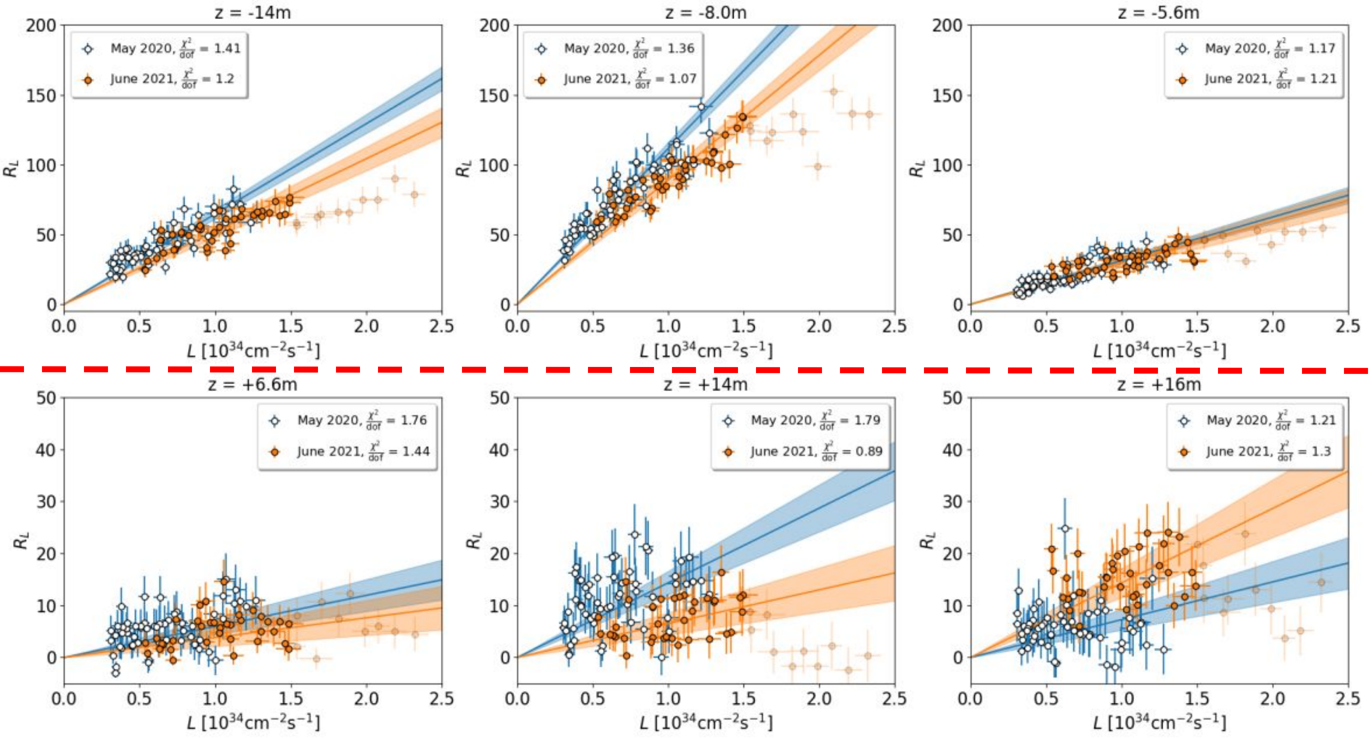
Total rate:

$$R = \overbrace{R_{\mathrm{SB,LER}} + R_{\mathrm{SB,HER}}}^{\text{Single beam}} + \overbrace{R_L}^{\text{Luminosity}}$$

Luminosity (collision) rate:

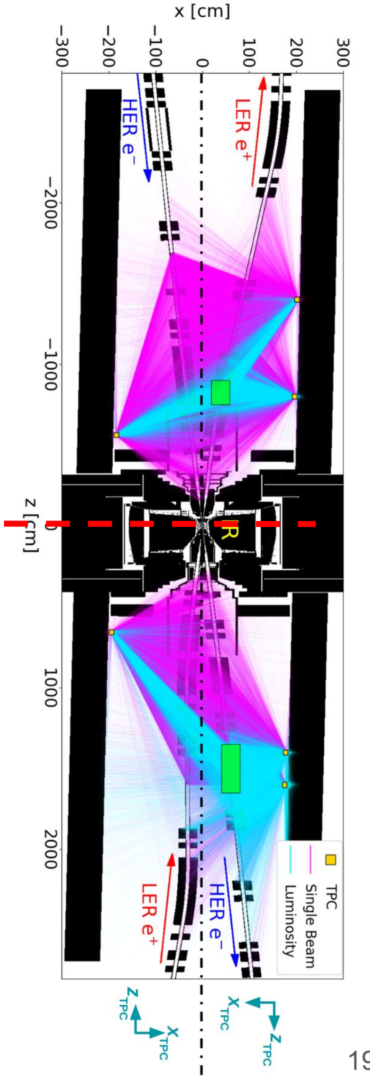
$$\boxed{R_L = R - \left(\sum_{i=\mathrm{LER,HER}} B_{0i} I_i P_{meas,i} - B_{1i} I_i + T_i \frac{I_i^2}{\sigma_{yi}^{\alpha_i} \sigma_{zi} n_{bi}} \right) = m_L L}$$

Collision background fits (Figure 10, page 13)



BWD

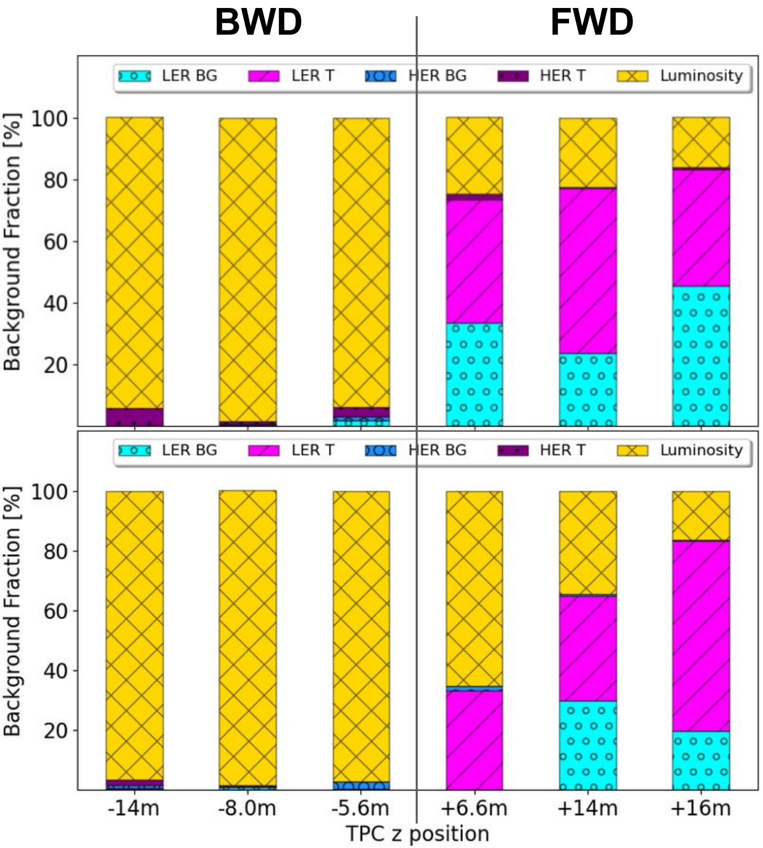
FWD



$$R_L = R - \left(\sum_{i=\mathrm{LER,HER}} B_{0i} I_i P_{meas,i} - B_{1i} I_i + T_i \frac{I_i^2}{\sigma_{yi}^{\alpha_i} \sigma_{zi} n_{bi}} \right) = m_L L$$

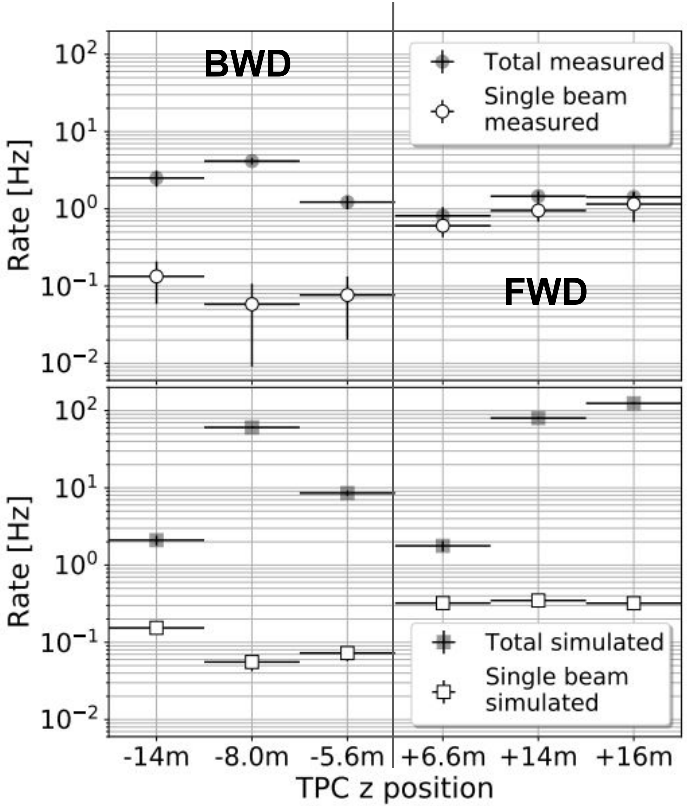
Background composition (Table 5 and Figs 11 and 12)

Study	Ring	(β^*_x, β^*_y) [mm,mm]	I [mA]	P [nPa]	(σ_y, σ_z) [μm, mm]	n_b	L [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]
A	LER	(80,1)	510	30	(60, 5.9)	783	1.1
	HER	(60,1)	510	14	(35, 6.4)	783	
B	LER	(80,1)	730	35	(65, 5.8)	1174	2.5
	HER	(60,1)	650	14	(35, 6.2)	1174	



Study A

Study B

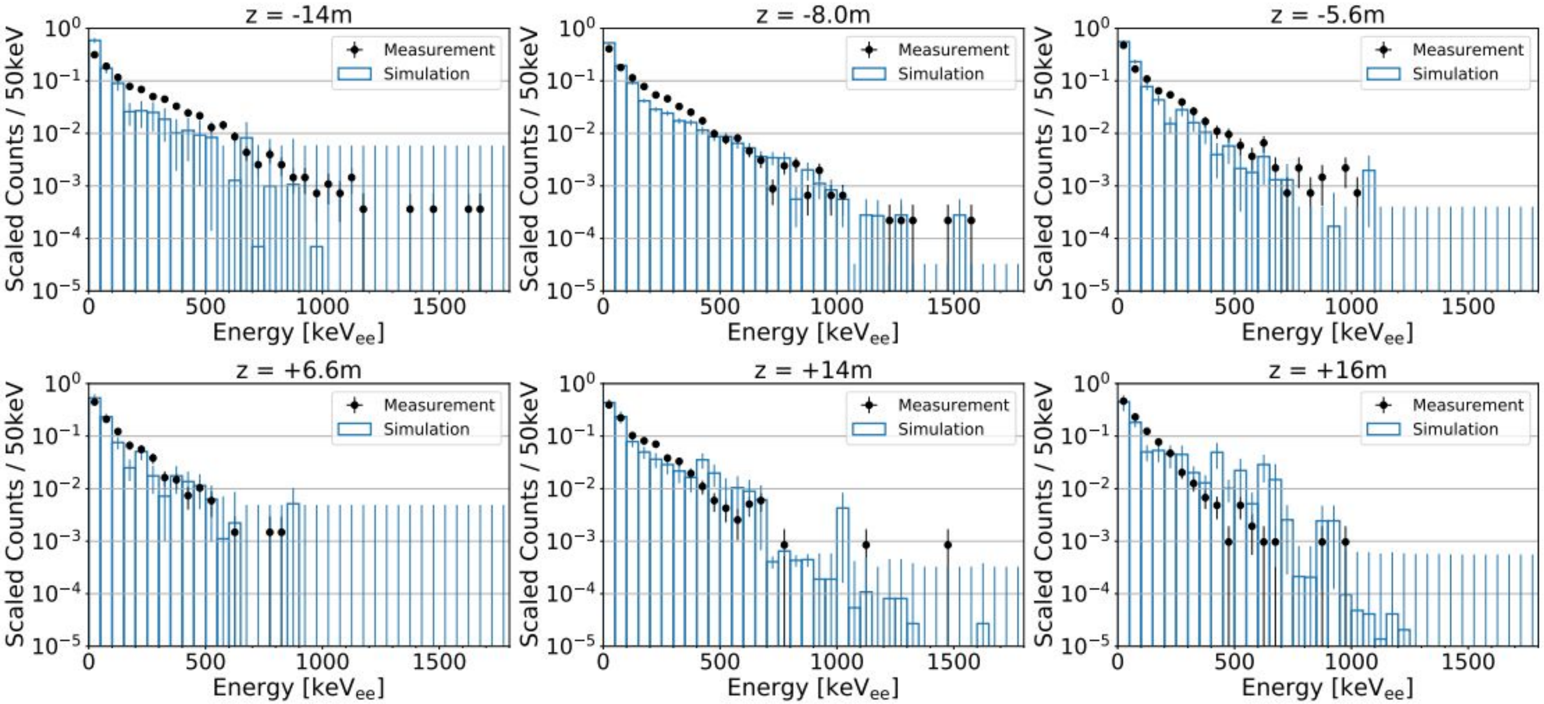


Data/MC rates (page 13)

TPC z[m]	LER Beam Gas	HER Beam Gas	LER Touschek	HER Touschek	Collisions: $L_{\text{Study A}}$ $[^{+(\text{sys.})}_{-(\text{sys.})} \pm (\text{stat.})]$	Collisions: $L_{\text{Study B}}$ $[^{+(\text{sys.})}_{-(\text{sys.})} \pm (\text{stat.})]$	$\text{Total}_{\text{Study A}}$
-14	1.82 ± 5.2	0	N/A	0.89 ± 0.5	$1.20^{+0.03}_{-0.13} \pm 0.20$	$1.02^{+0.00}_{-0.43} \pm 0.20$	1.20 ± 0.22
-8.0	9.52 ± 17	$39.3 \pm 65.$	N/A	0.57 ± 0.6	$0.07^{+0.00}_{-0.00} \pm 0.01$	$0.05^{+0.00}_{-0.02} \pm 0.00$	0.07 ± 0.01
-5.6	22.9 ± 31	$16.1 \pm 24.$	N/A	0.54 ± 0.5	$0.14^{+0.00}_{-0.03} \pm 0.02$	$0.13^{+0.00}_{-0.05} \pm 0.02$	0.14 ± 0.03
+6.6	$186. \pm 80$	0	0.98 ± 0.4	4.61 ± 8.0	$0.15^{+0.13}_{-0.15} \pm 0.07$	$0.10^{+0.00}_{-0.10} \pm 0.04$	0.44 ± 0.11
+14	$471. \pm 240$	47.8 ± 140	1.92 ± 0.5	N/A	$(7^{+3}_{-5} \pm 2) \times 10^{-3}$	$(3^{+0.6}_{-3} \pm 1) \times 10^{-3}$	0.02 ± 0.00
+16	$480. \pm 260$	0	1.61 ± 0.5	N/A	$(2^{+3}_{-2} \pm 1) \times 10^{-3}$	$(4^{+0.0}_{-4} \pm 1) \times 10^{-3}$	0.01 ± 0.00

In the BWD tunnel, luminosity-induced (collision) neutron rates overwhelmingly dominate and are overestimated in simulation in z = -8.0m and z = -5.6m. Touschek rates are modeled very well in MC and simulated beam-gas rates are greatly underestimated in FWD tunnel.

Energy spectra (figure 13, page 15)



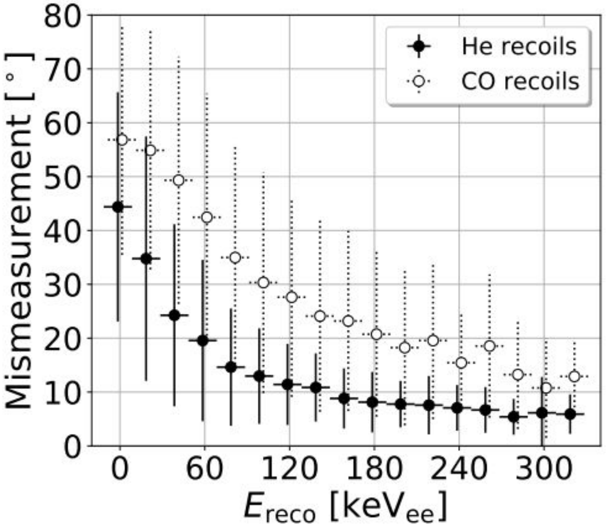
Exponentially decaying spectra with slopes in reasonable agreement. Vast majority of measured recoils are below 500 keV$_{ee}$.

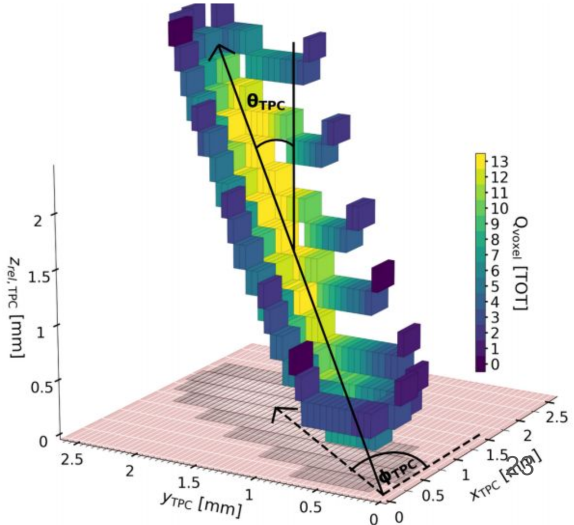
Simulated angular resolution (Fig. 14, pg. 16)

- We aim to compare the angular distributions of recoil tracks between measurement and simulation

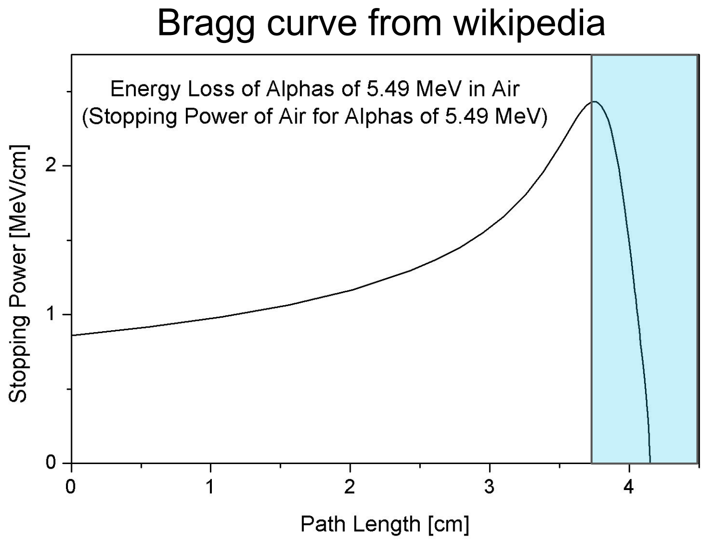
- Before doing this, we need to select recoils where our angular resolution is good enough that we can assign track directions relatively unambiguously

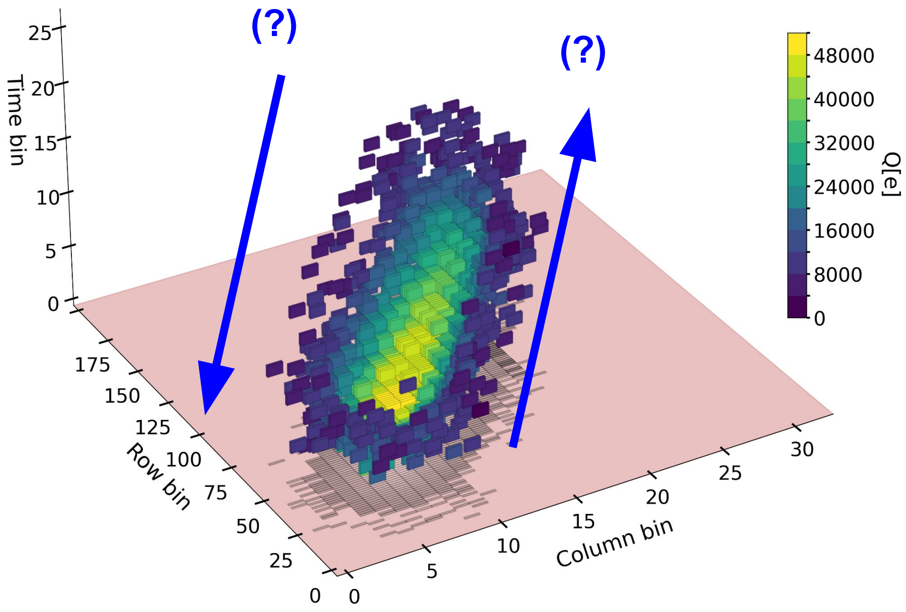
By comparing the average difference in axial inclination angle θ between our identified principal axis and the true simulated direction of tracks, **we decide to only include He recoils with energies > 40 keV$_{ee}$ for our angular analysis**





Directional Head-tail assignment

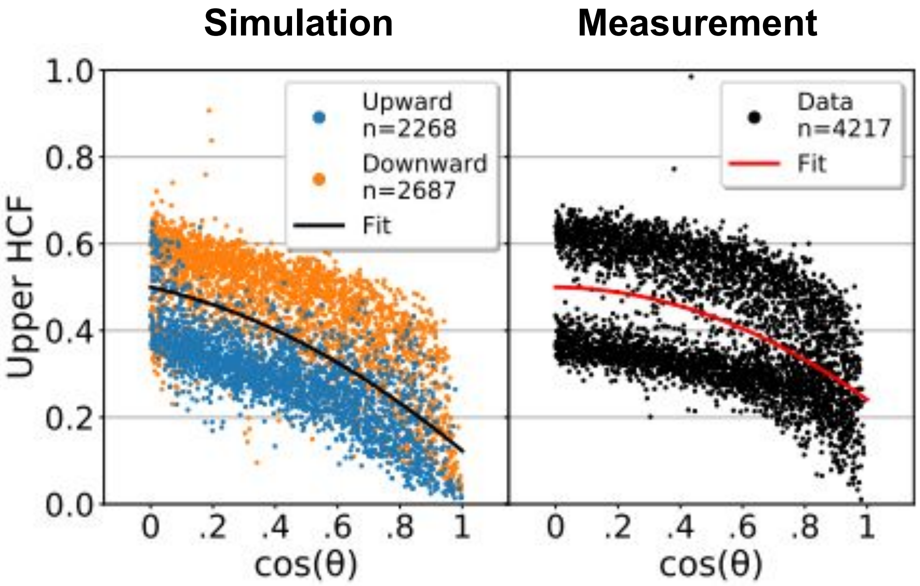


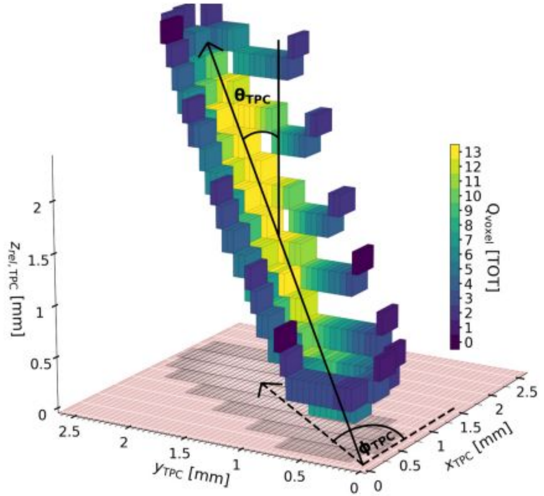


- TPC recoils are in the blue shaded region, “beyond the bragg peak”, meaning a recoil event is expected to produce less ionization the further it travels
- We can thus infer the *vector* “head” direction of the track to be the side of the track with less charge

- Charge integration effects bias the measured charge asymmetry away from the charge asymmetry of the primary track
- This effect is most pronounced in highly inclined tracks

Correcting head-tail assignment (Figure 15, pg. 16)



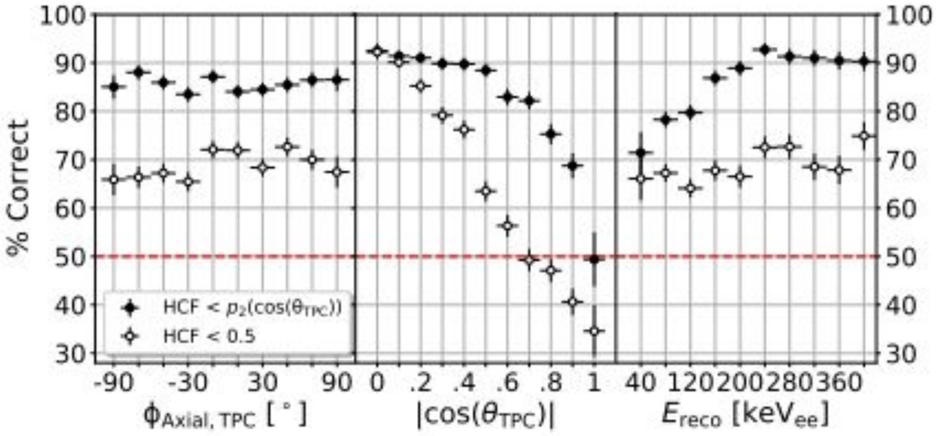


1. Make the *a priori* assignment that the track points upward in *z*
   a. Restricts cos(θ) > 0
2. Split the track in half along the midpoint of its principal axis and count the charge on either half

Baseline method: If the Upper head charge fraction (Upper HCF) is > 0.5, flip the direction of the track

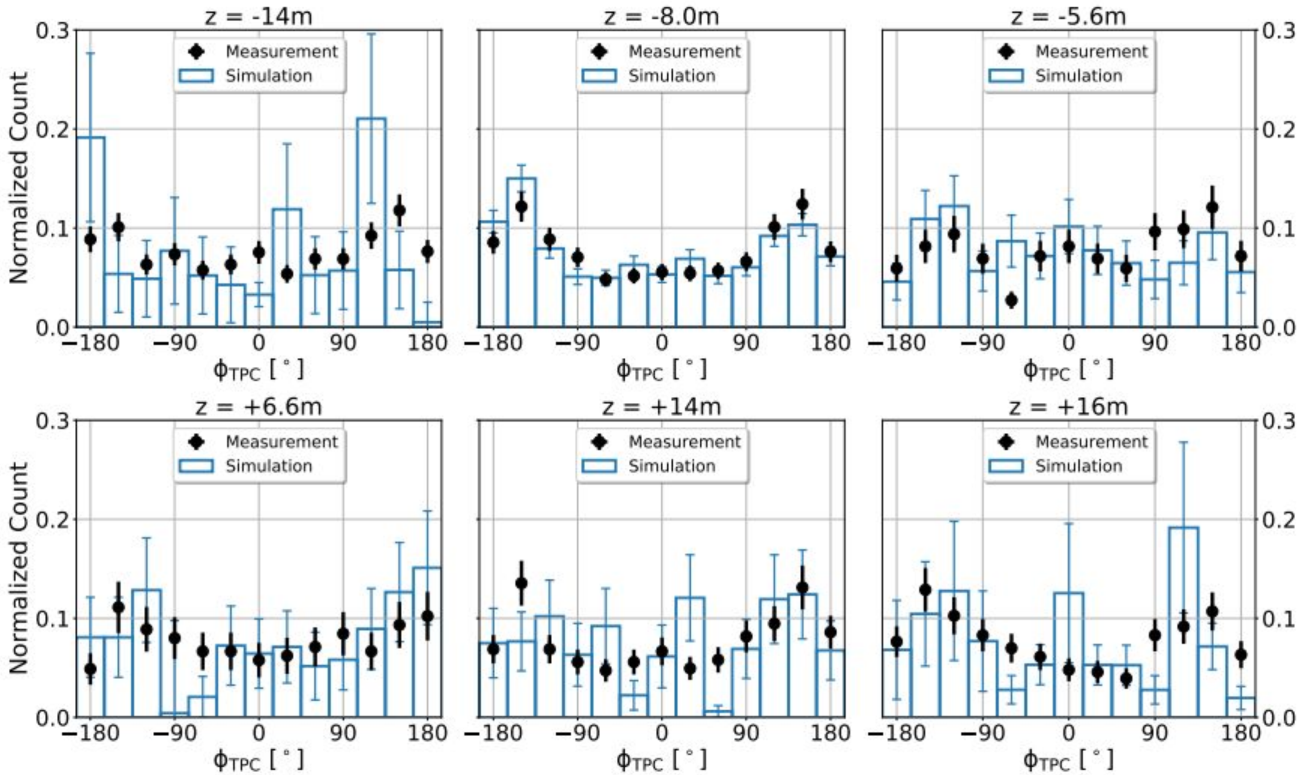
“Axial correction” method: Define a selection boundary by fitting a 2nd degree polynomial to Upper HCF vs cos(θ). If Upper HCF > fit boundary, flip the direction of the track

Simulated vector directional assignment results (Fig 16, pg 17)



Axial correction method yields a large improvement over the baseline method. Selecting only tracks pointing back towards the beam-pipe gives us a 91% head-tail selection efficiency compared to 72% for the baseline method

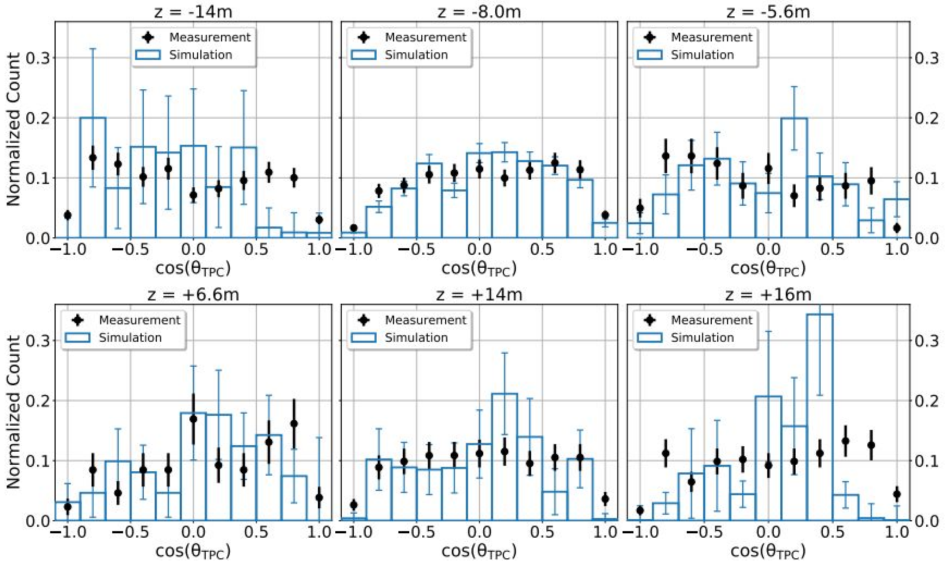
ϕ distribution after vector directional assignment (Fig. 18 and Table 7)



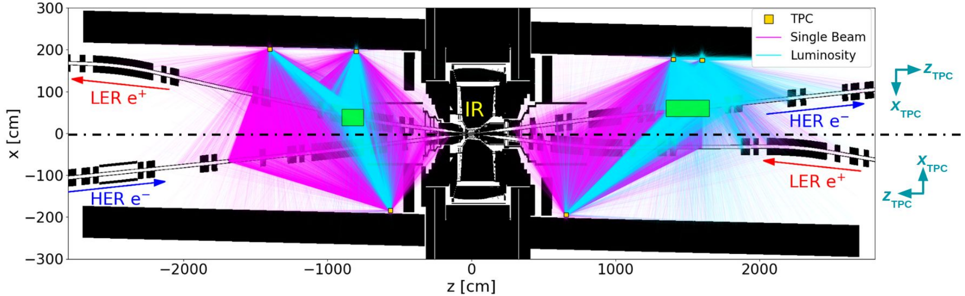
- $|\phi|$ > 90° points back to the beampipe
- χ^2 hypothesis test suggests good agreement in ϕ disribution for the three TPCs closest to Belle II

TPC	p_ϕ	$p_{\cos\theta}$
$z = -14$ m	0.02	0.10
$z = -8.0$ m	0.54	0.06
$z = -5.6$ m	0.40	0.08
$z = +6.6$ m	0.87	0.83
$z = +14$ m	0.02	0.26
$z = +16$ m	0.05	0

cos(θ) distribution after vector directional assignment (Fig. 19 and table 7)



- Distributions are of events coming from the beam pipe ($|\phi| > 90°$)
- 91% head-tail efficiency in MC for this sample
- Nearly all measured rates in BWD tunnel are RBB backgrounds
- cos(θ) relative agreement between data and MC in the BWD tunnel suggests we are measuring the BWD hotspot



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Extrapolations for outer KLM endcap at $L = 6.0 \times 10^{35} cm^{-2}s^{-1}$

Provided by KLM expert

TPC	Luminosity data/MC	Scaled TPC 1 MeV Equivalent Flux [10^8/cm^2/year]	Raw EKLM Flux [10^8/cm^2/year]	Scaled EKLM 1 MeV Equivalent Flux [10^8/cm^2/year]
$z = -14$ m	$1.20^{+0.03}_{-0.13} \pm 0.20^*$	1070 ± 210		
$z = -8.0$ m	$0.07^{+0.00}_{-0.00} \pm 0.01$	616 ± 58	3.6	4.4
$z = -5.6$ m	$0.14^{+0.00}_{-0.03} \pm 0.02$	345 ± 64		
$z = +6.6$ m	$0.15^{+0.13}_{-0.15} \pm 0.07^*$	104 ± 45		
$z = +14$ m	$(7^{+3}_{-5} \pm 2) \times 10^{-3}$	72 ± 18	141	21
$z = +16$ m	$(4^{+0}_{-4} \pm 1) \times 10^{-3}$	73 ± 12		

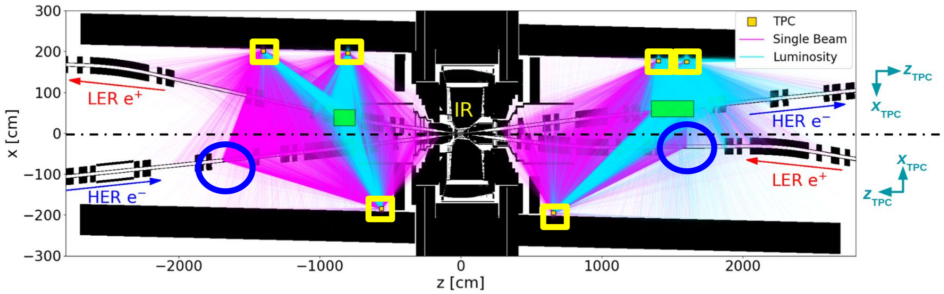
- TPCs are subject to much higher neutron fluxes from RBB hotspots than what flies back to the KLM
- Scaling the raw EKLM flux by the largest TPC data/MC ratio yields annual neutron fluxes far below the $O(10^{11})$/cm^2/year tolerance of the most neutron sensitive Belle II detectors

Belle II detectors are safe from RBB neutron hotspots in the tunnels

Summary

- Performed the first survey of neutron backgrounds in the tunnel region surrounding Belle II
- Luminosity backgrounds overwhelmingly dominate in the BWD tunnel in both measurement and simulation
- data/MC suggests Touschek production mechanism is modeled well
- Energy spectra are consistent between measurement and simulation suggesting that the material description in the tunnel region
- Consistency between modeled and measured angular distributions suggest all except the TPC at z = +16m are sensitive to a RBB hotspot in measurement but simulation overestimates the neutron flux from these hotspots, especially in the FWD tunnel
- Belle II detectors are safe from RBB hotspot
  - MC predicts up to 95% of neutrons generated in the tunnel to come from these hotspots -> Given that these hotspots are highly localized, it may be worth shielding them

Current status and impacts of this work



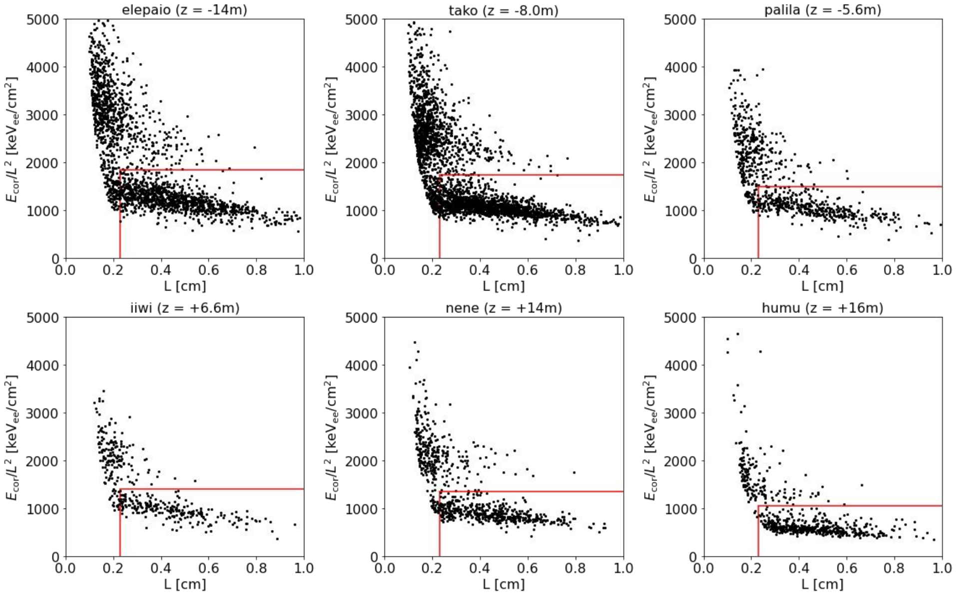
- TPCs are still recording data and will do so at least until Summer 2022
- Neutron radiation taskforce was created and neutron shielding has been placed near the simulated RBB hotspot locations
- The data/MC Touschek agreement in the TPCs established that there are large Touschek neutron backgrounds downstream of the circled collimators
  - Motivated beam optics adjustments that led to a ~40% reduction in backgrounds
- Improved TPC background rejection and introduced a new procedure that improved directional performance of the TPCs
- The introduction of the “axial” correction method for head-tail assignment inspired a project I’m currently working on that further improves head-tail assignment for directional dark matter applications

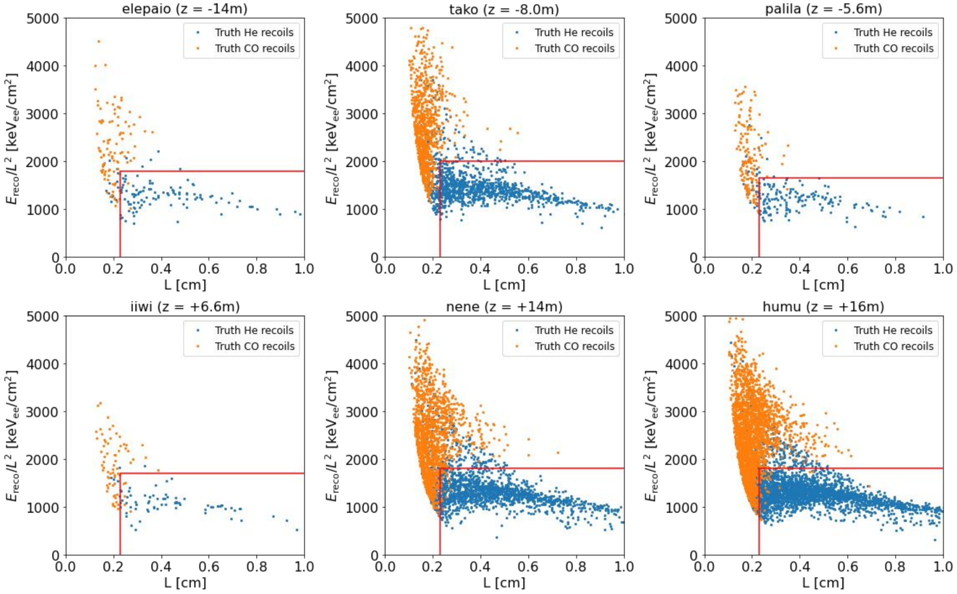
Status of paper submission: Reviewer comments received. Recommended for publication after a few minor revisions.

Backup

Selecting He recoils for angular analysis

Measurement





Simulation