Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Simulated Photo-nuclear Kaon Production Analysis for LDMX

Chloe Greenstein
Fermilab New Perspectives

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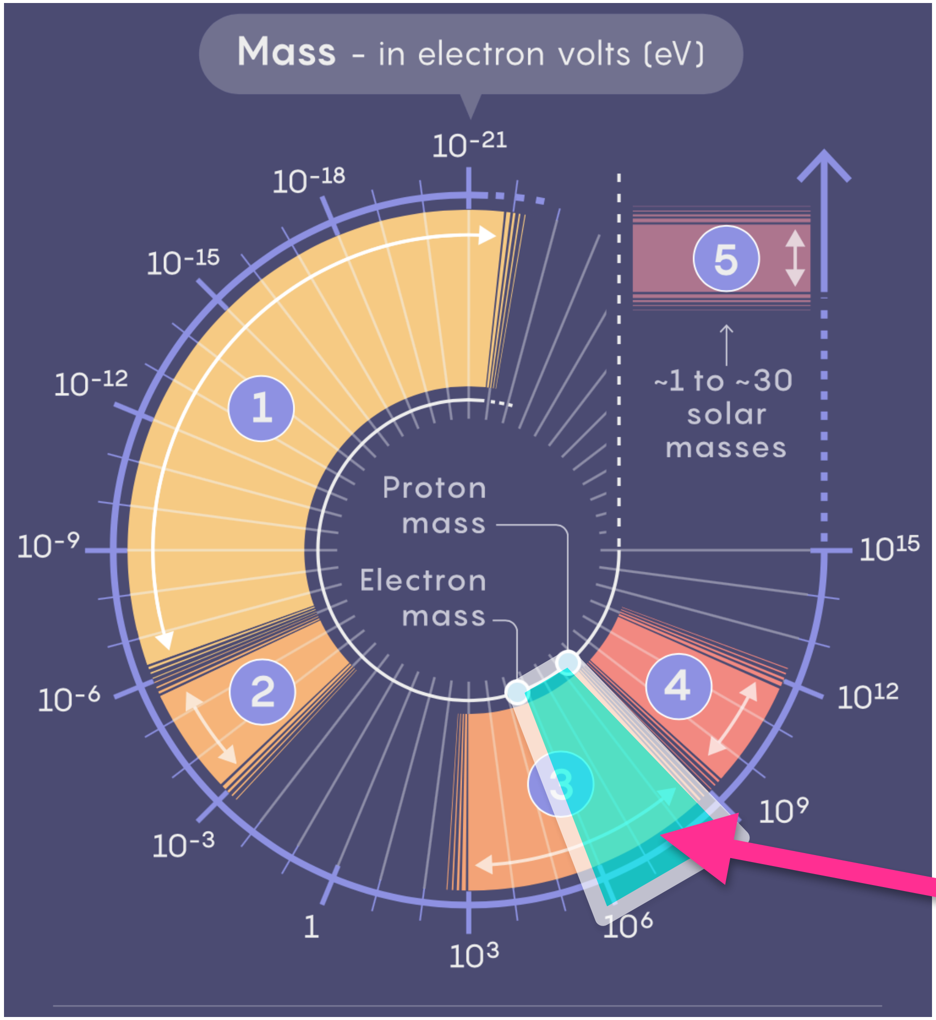
The Search for Light Dark Matter



Infographic illustrating the spectrum of energy possibilities being tested for DM and the associated experiments. (Wood 2020)

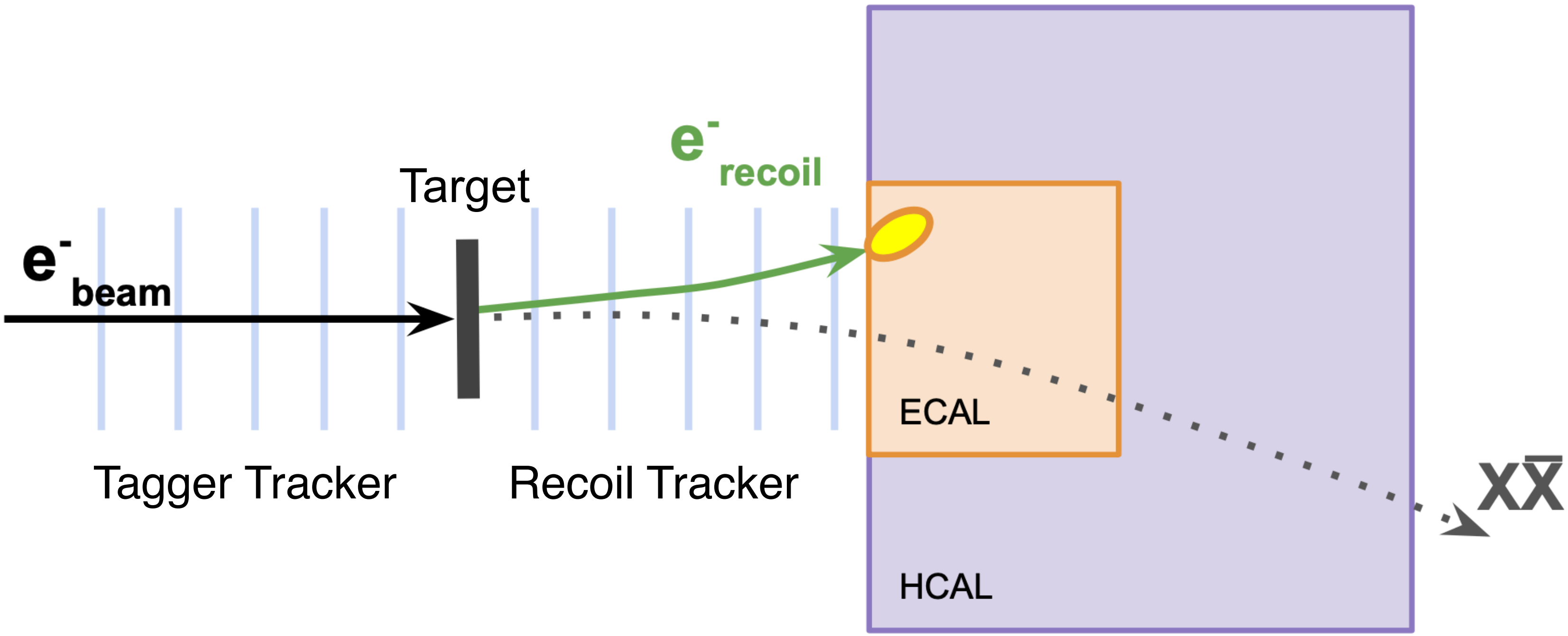
What does "light DM" mean: Sub-GeV

- Assumes DM particles to act similarly SM particles
- Determined by observations of current universe and required parameters of early universe

Range for this study

Light Dark Matter eXperiment (LDMX)

Proposed accelerator experiment: electron beam incident on nuclear target

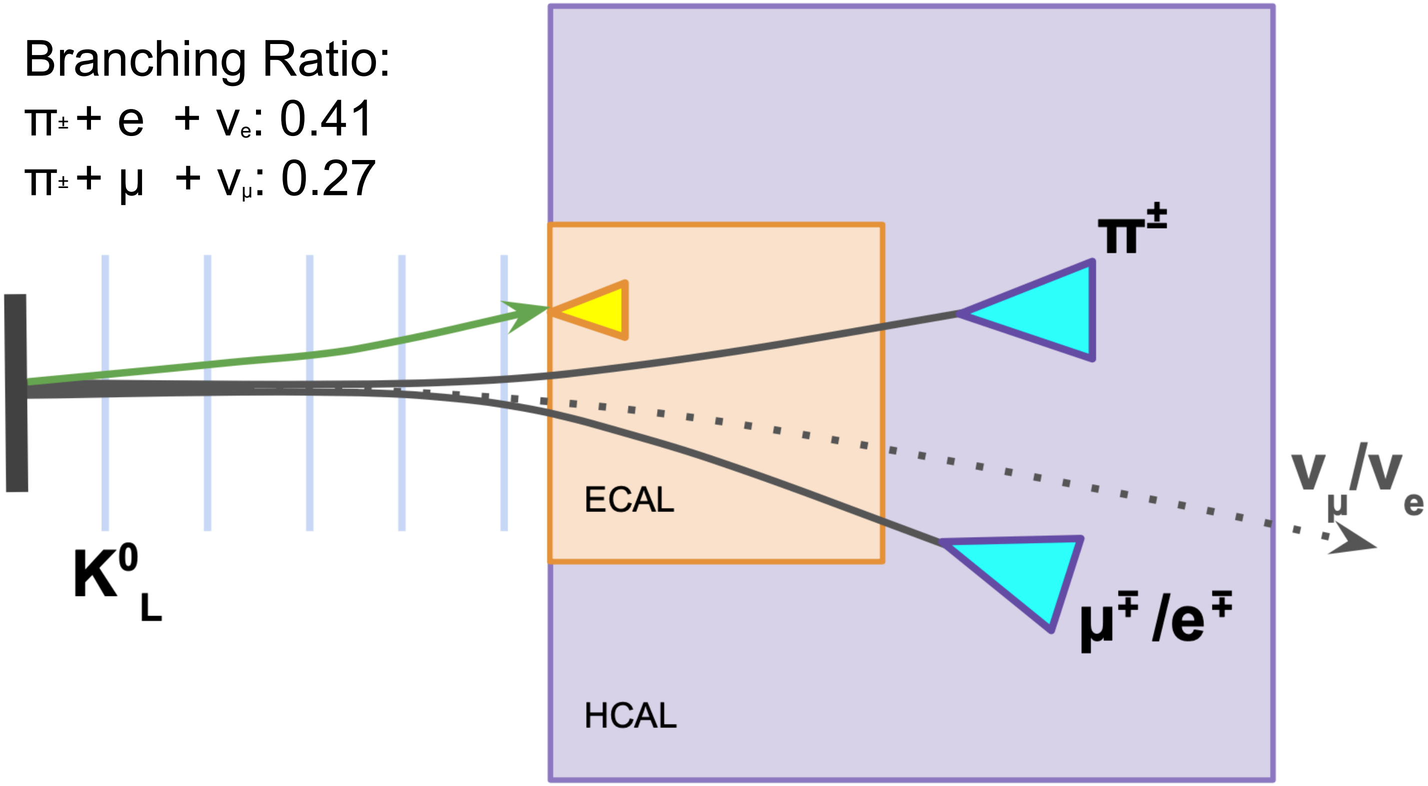


Outline of the LDMX experiment shows the electron beam passing through a tagging tracker, impacting a tungsten target, the recoil tracker, the electromagnetic calorimeter, and the hadron calorimeter.

K-long semi-visible decay

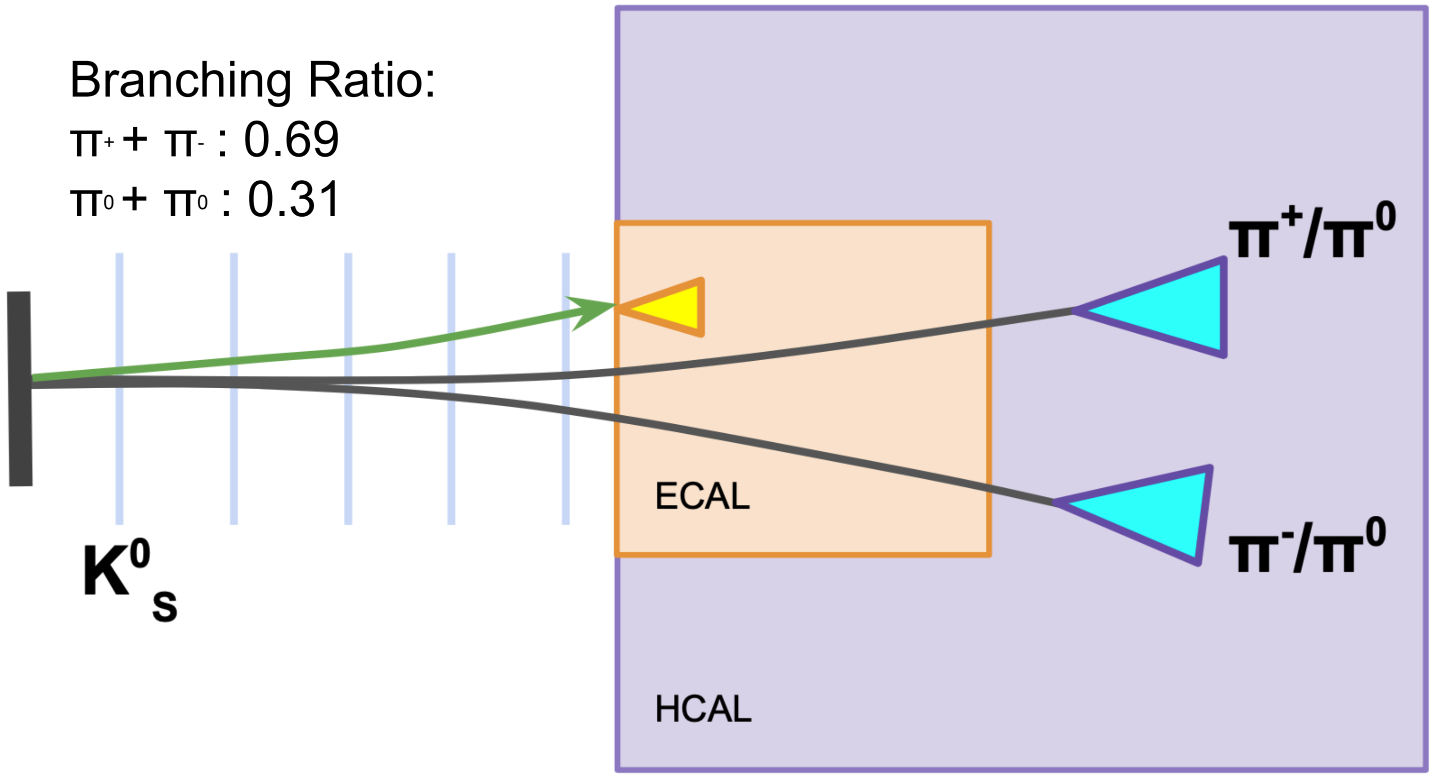
Hard production to model

Can not detect neutrino background, needs to be accounted for elsewhere



Conceptual drawing of the LDMX experiment, showing the path of the products of K-long decay from a fixed-target, through the recoil tracker, the electromagnetic calorimeter, and hadron calorimeter.

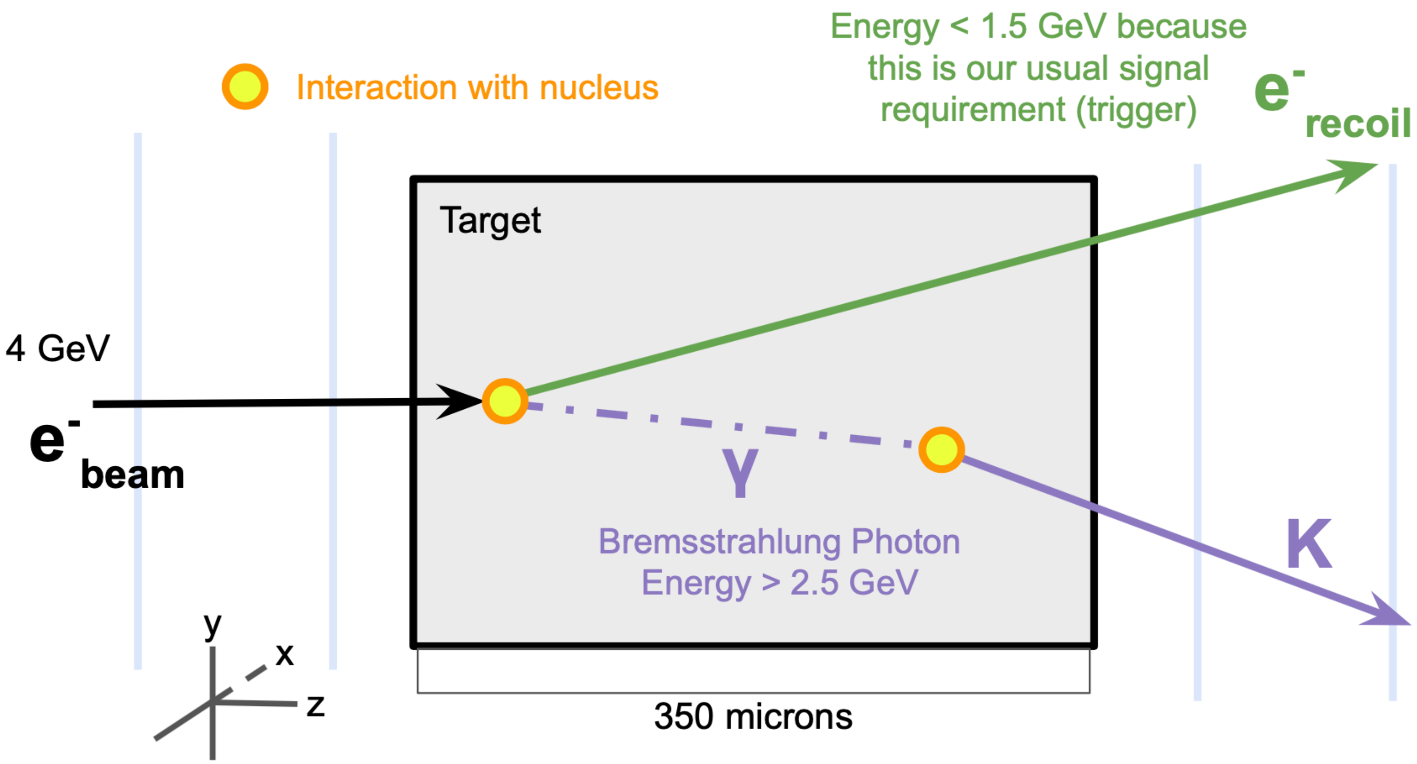
K-short visible decay



Conceptual drawing of the LDMX experiment, showing the path of the products of K-short decay from a fixed-target, through the recoil tracker, the electromagnetic calorimeter, and hadron calorimeter.

Simulation Generated Photo-nuclear Interactions

Simulated events (everything that I will show is at generator level - not making many assumptions of the detector)

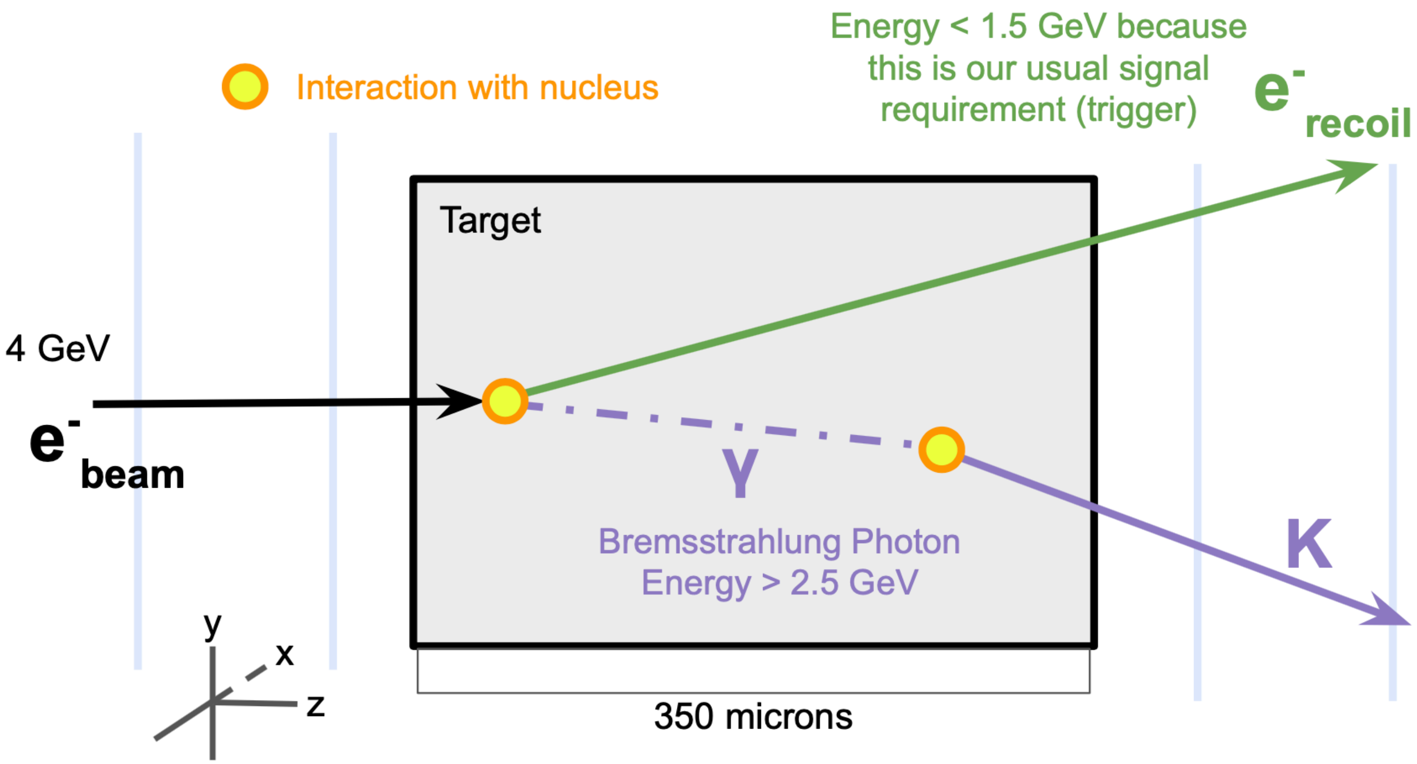


Outline of the LDMX experiment shows the electron beam passing through a tagging tracker, impacting a tungsten target, the recoil tracker. The paths of the recoil electron and Bremsstrahlung photon are labeled with their simulation requirements.

Simulation Generated Photo-nuclear Interactions

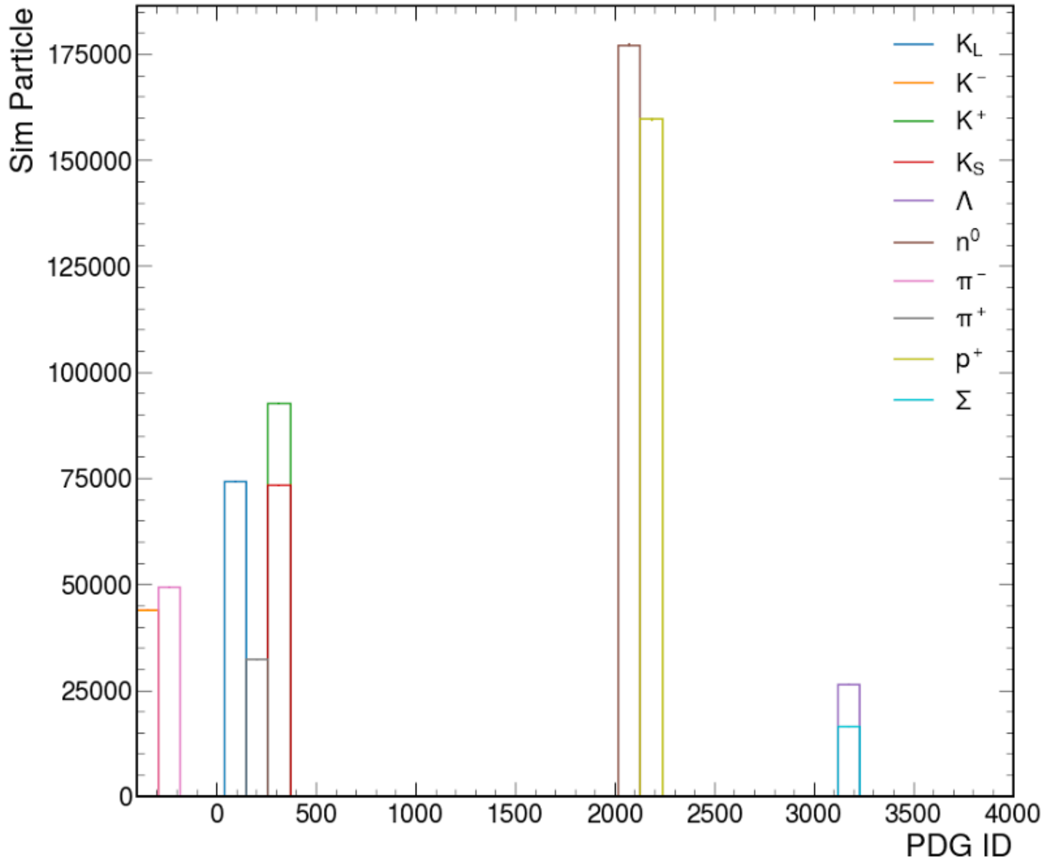
Kaon rate: 1 Truth K_S per 50,000 Events Generated

Kaon rate with biased cross section: 1 Truth K_S per 48 Events Generated



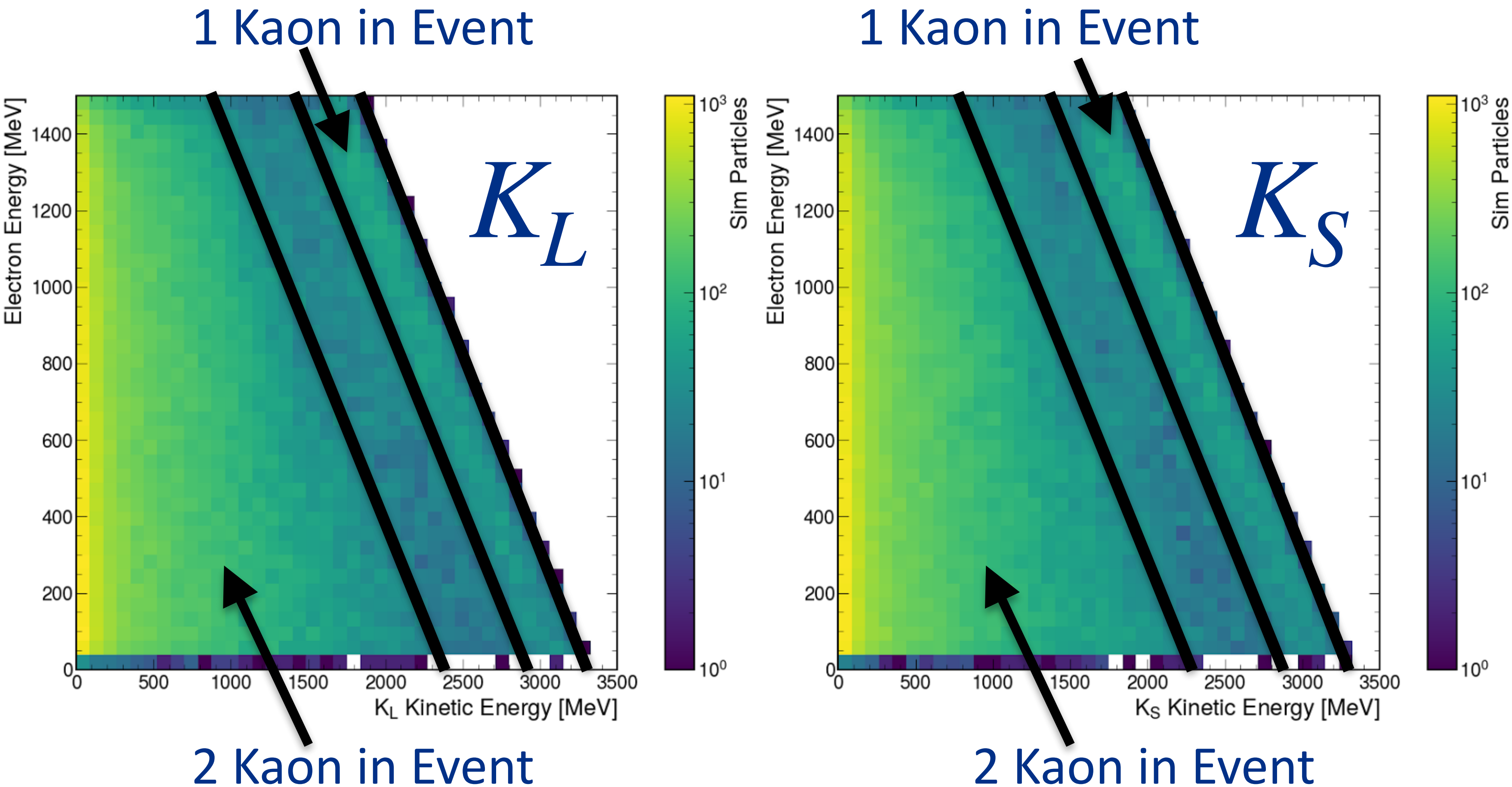
Outline of the LDMX experiment shows the electron beam passing through a tagging tracker, impacting a tungsten target, the recoil tracker. The paths of the recoil electron and Bremsstrahlung photon are labeled with their simulation requirements.

Particles produced in PN interaction



Histogram representing the PDG ID (Monte Carlo Numbering Scheme) of particles generated in the PN generator. This plot includes particles with the top two highest kinetic energies per event. The plot indicates charged kaons, neutral kaons, lambda, neutrons, charged pions, protons, and sigma.

Truth Kaon Kinetic Energy vs. Recoil Electron Energy



2D histogram representing the kinetic energy of truth K-long (left) and truth K-short (right) vs. recoil electron energy.

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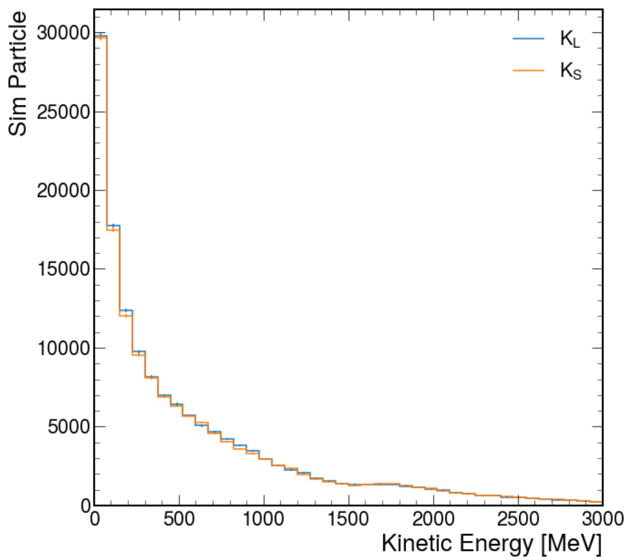
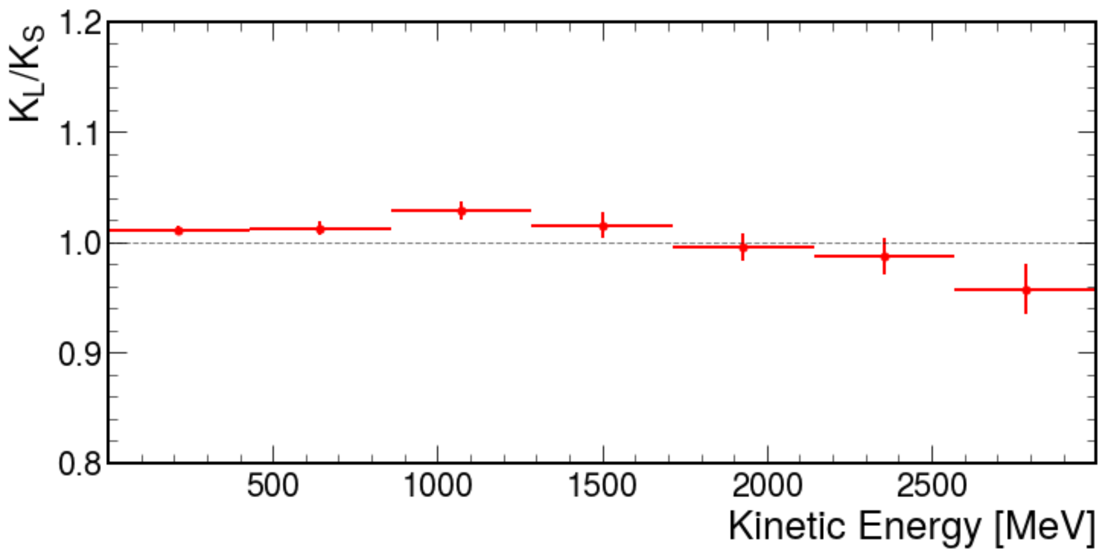
Truth Kaon Ratio In Generated PN Events



The kinetic energy of all truth K-long and truth K-short.



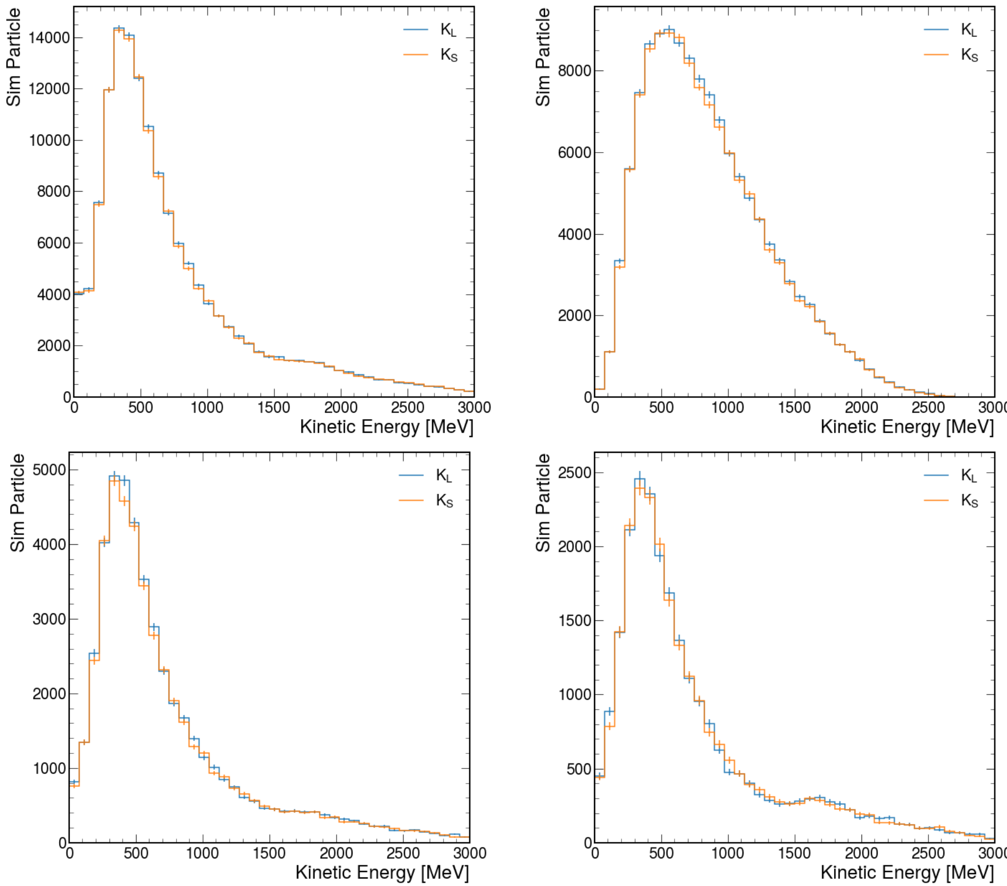
The ratio of all truth K-long to all truth K-short separated by kinetic energy range.

Truth Kaon Ratio In Different Cases of Events

Looking only at 2 most energetic particles per event and what particles are produced in association with the Kaons:

Truth K^0
N_{kaon}= 1

Truth K^0
N_{kaon}= 2



Truth K^0
N_{kaon}= 1
N_{Lambda}= 1

Truth K^0
N_{kaon}= 1
N_{Sigma}= 1

Kinetic Energy of truth K-long and truth K-short. The event cases are listed to the side.

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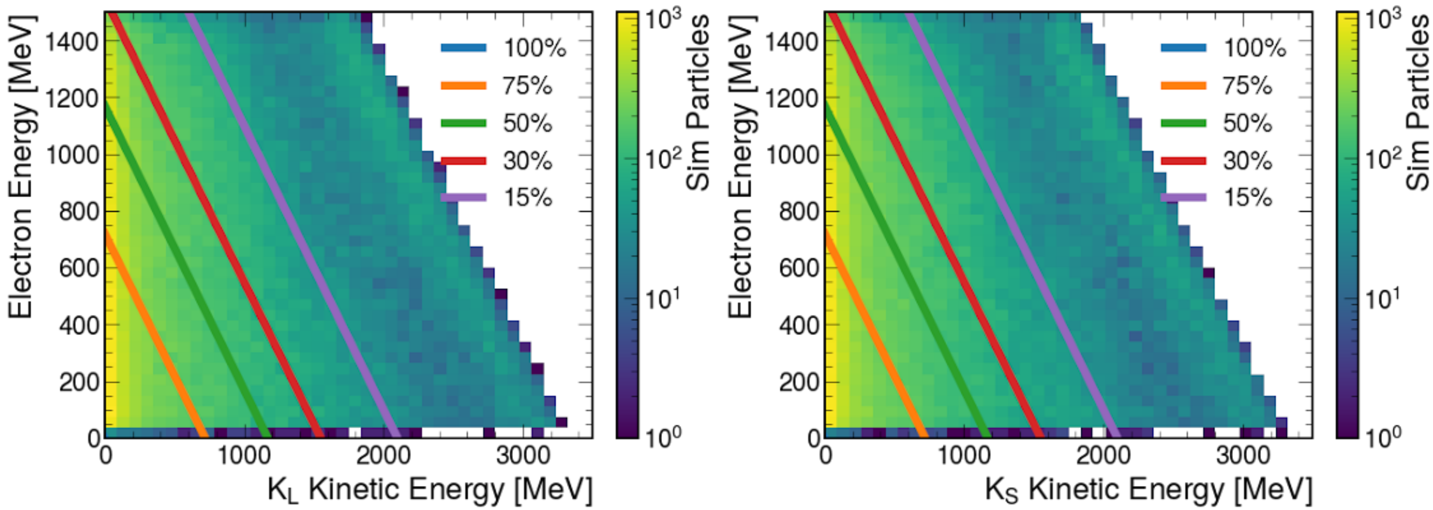
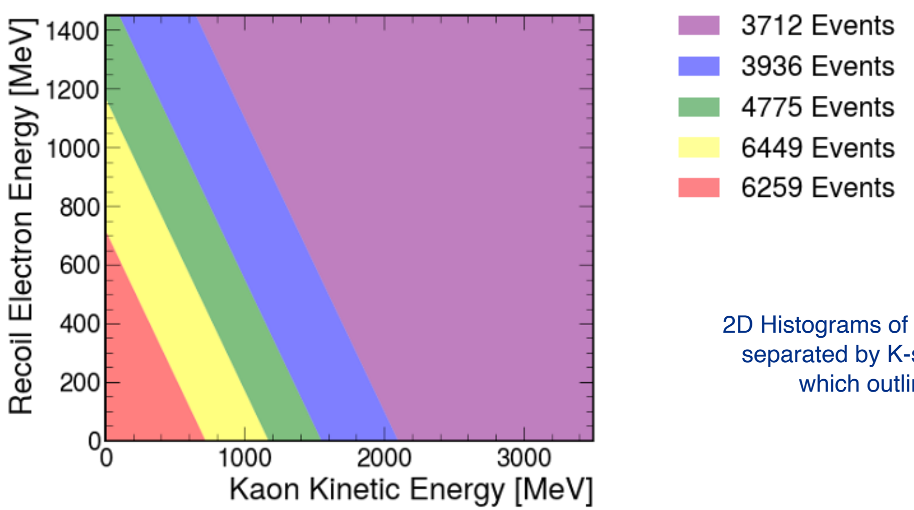
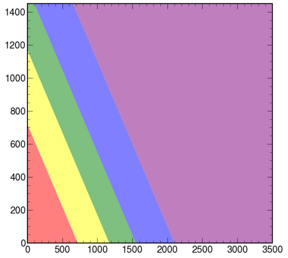
KE vs. Electron E plot Separated by Percentile





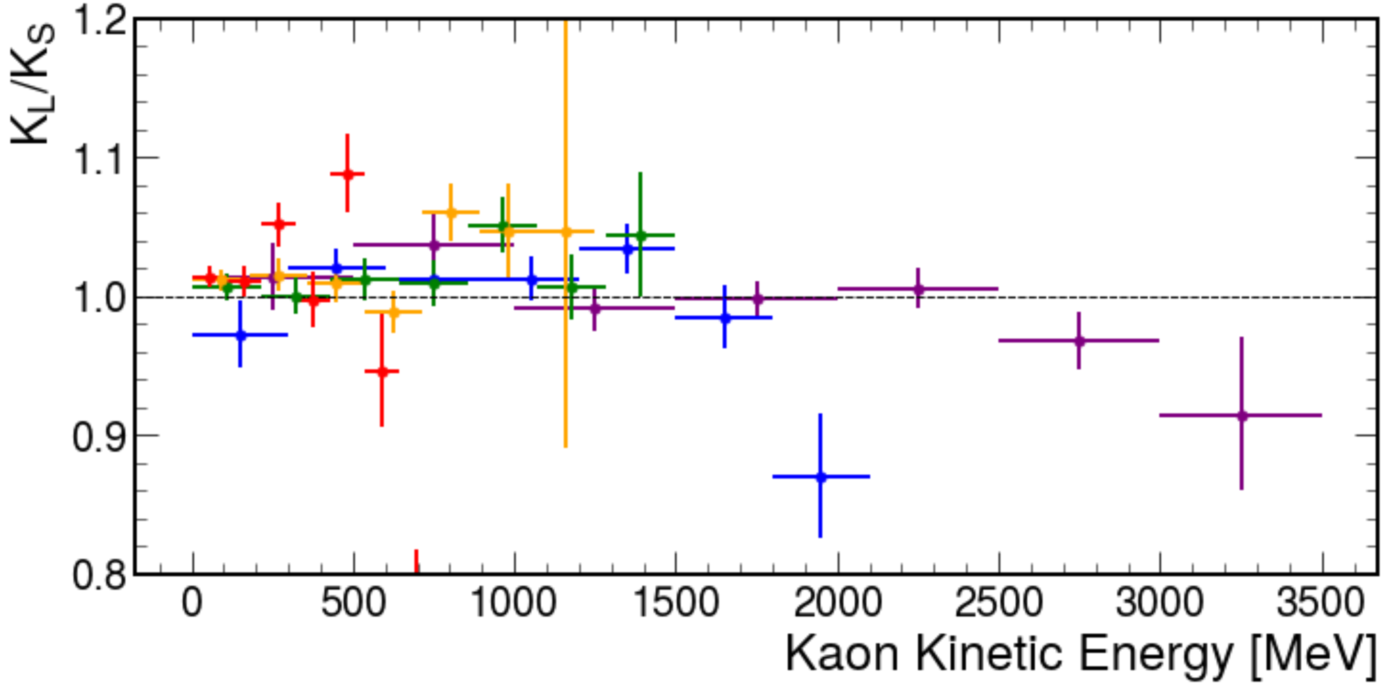
2D Histograms of the Kinetic Energy of Kaons and Electron Energy separated by K-short and K-long. The lines represent percentile which outline percentile selections in the bottom plot.

Truth Kaon KE Ratio by Percentile



These ratios show that at in all kinematic regions,

truth K-long to K-short ratio stays around 1:1



The ratio of truth K-long to truth K-short separated by kinetic energy range. This plot includes all of the energy percentiles overlapped: purple as top 15% (top left), blue as top 15%-30% (top right), green as top 30%-50% (middle left), yellow as top 50%-75% (middle right), and red as top 75%-100% (bottom left).

Smearing Truth px, py, and pz of Pions for K-short Reconstruction

Reconstructed K-short from truth kin always match truth K-short in simulation

Smearing observables accounts for detector sensitivity/uncertainty

Px [MeV]	Uncertainty
0<px<100	3.00 MeV
100<px<500	3.20 MeV
500<px<1000	3.40 MeV
1000<px<1300	3.50 MeV
1300<px	3.85 MeV

Py [MeV]	Uncertainty
0<py<100	3.75 MeV
100<py<350	3.80 MeV
350<py<500	4.20 MeV
500<py<1000	4.80 MeV
1000<py<1200	4.98 MeV
1200<py<2000	3.85 MeV
200<py	5.50 MeV

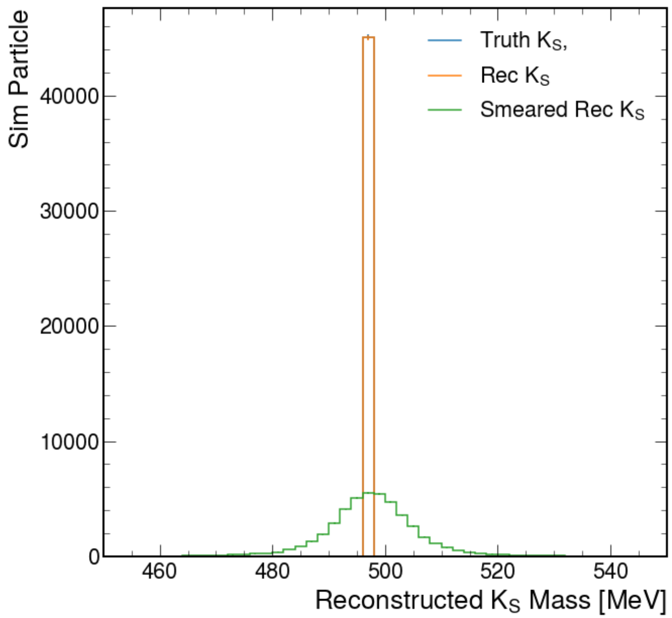
Pz [MeV]	Uncertainty
0<pz<50	4.04%
50<pz<100	4.10%
100<pz<250	4.15%
250<pz<500	4.20%
500<pz<1000	4.35%
1000<pz<2000	4.77%
2000<pz<3000	5.23%
3000<pz<4000	5.73%
4000<pz	6.00%

Tables outlining the piecewise functions of uncertainty for momentum in the x, y, and z direction in MeV and percentage.

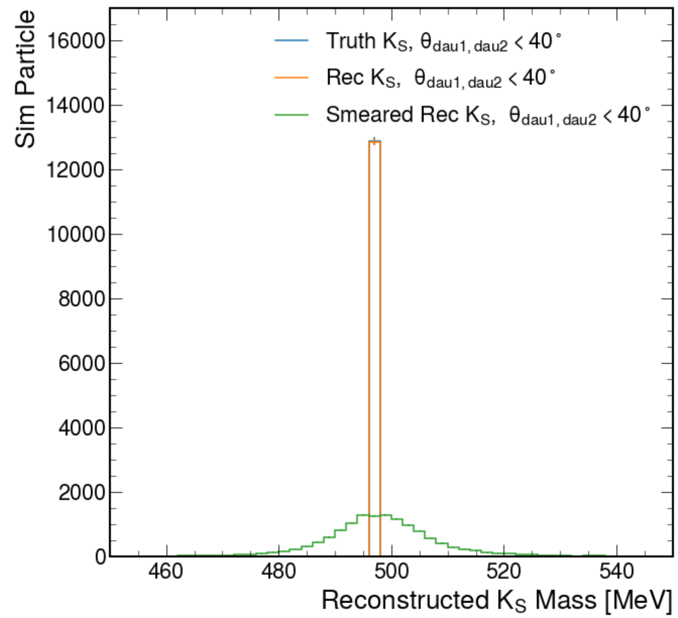
PN Events, Reconstructing Mass With Smearing Without and With Theta Cut

Reconstruction is done by creating the Lorentz vector for the daughters and summing their energy to recreate the mom particle

Smearing has mass resolution +/- 20 MeV

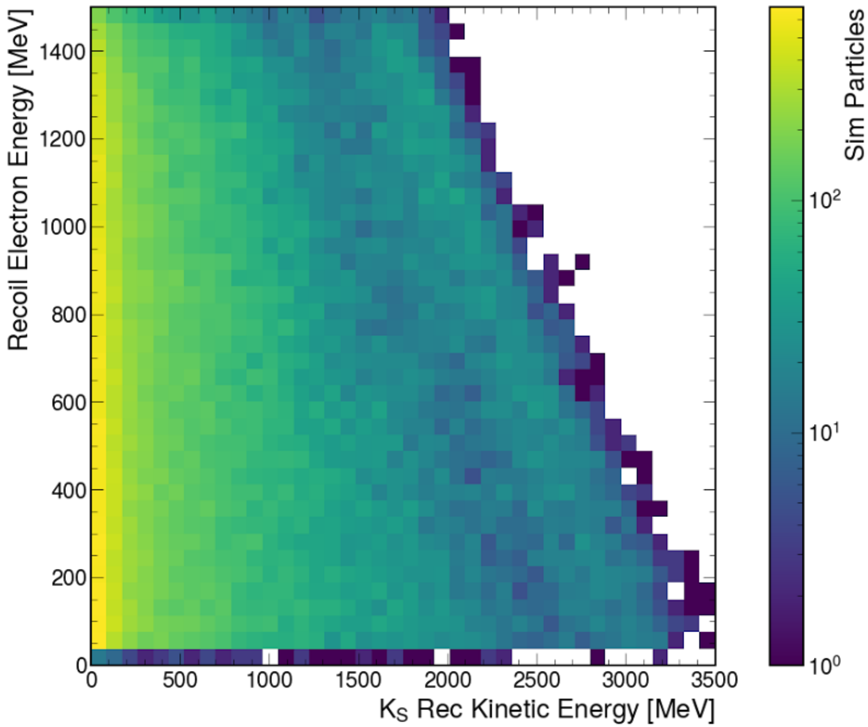


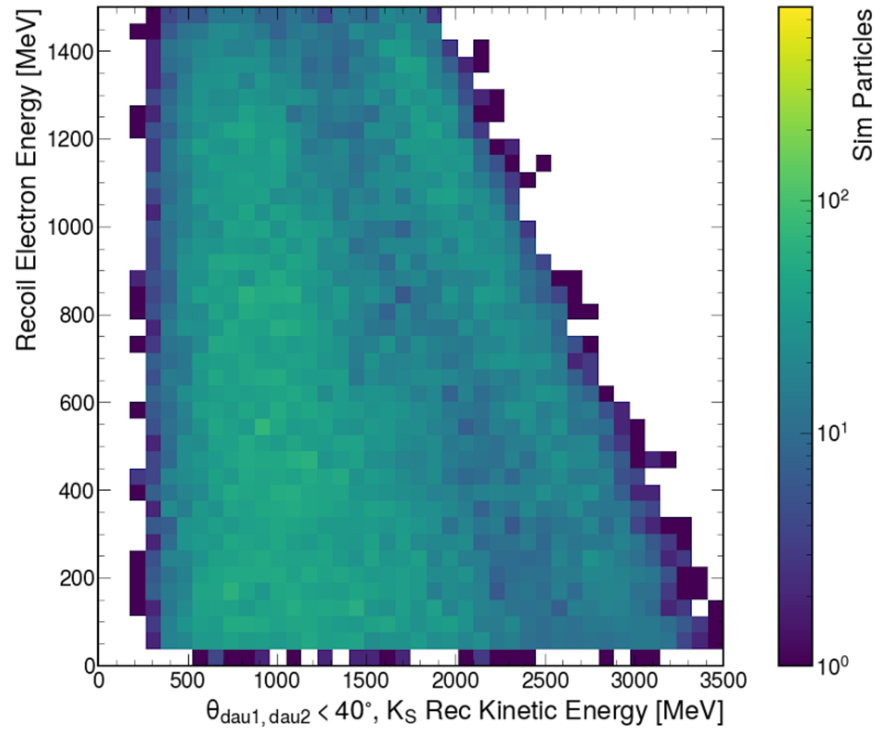
Truth K-short, Reconstructed K-short, and Smeared Reconstructed K-short Mass



Truth K-short, Reconstructed K-short, and Smeared Reconstructed K-short Mass where daughters have theta <40 degrees.

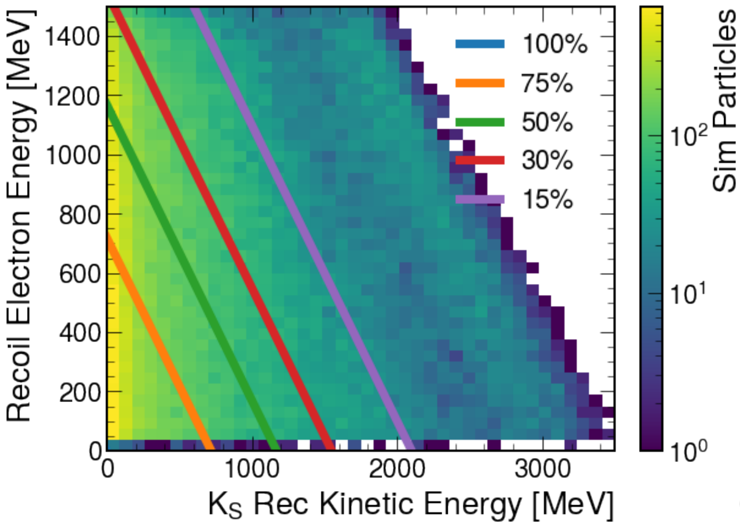
Reconstructed Kaon Kinetic Energy vs. Recoil Electron Energy

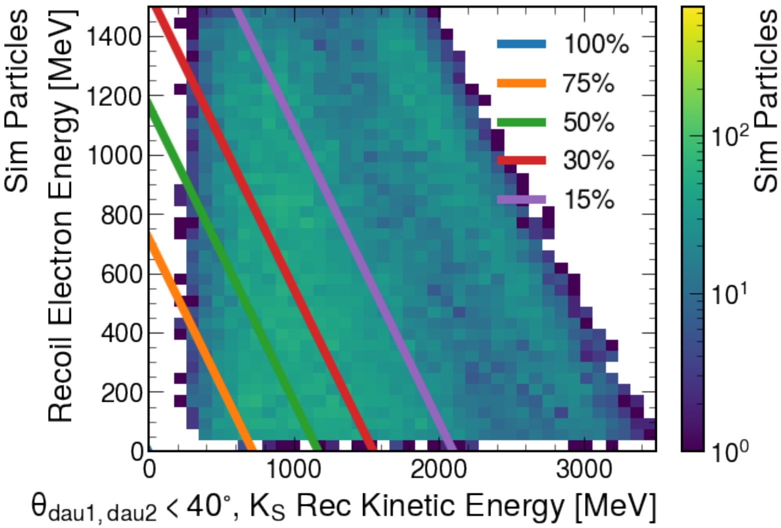


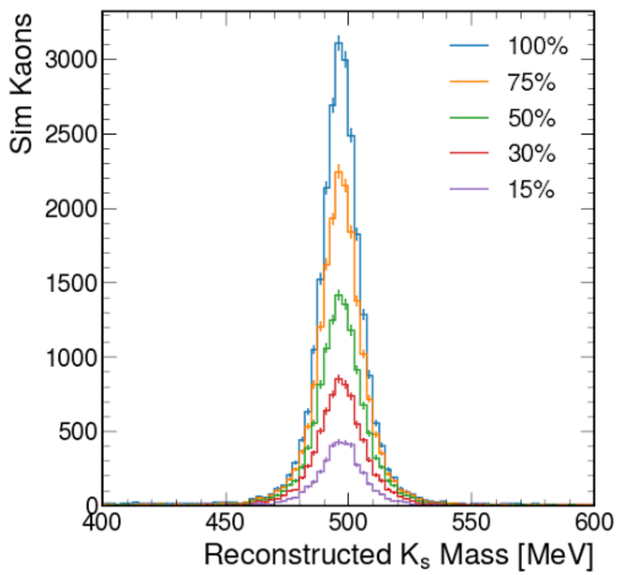


2D Histogram representing the kinetic energy of Reconstructed Kaons vs recoil electron energy. From left to right, these plots account for K-short reconstructed from all pion daughters and K-short reconstructed from daughters that fall within theta < 40 degrees.

KE vs. Electron E plot Separated by Percentile

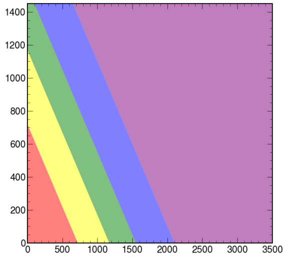






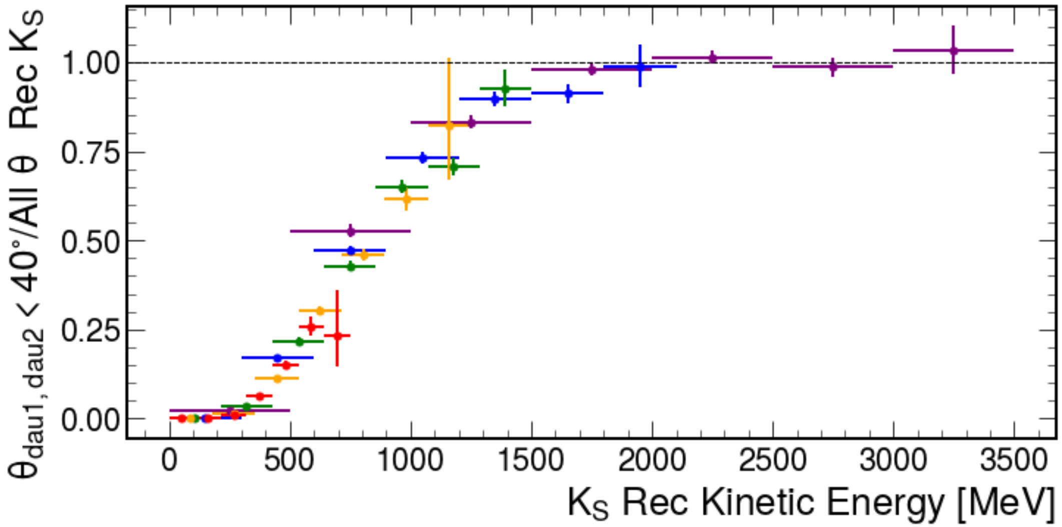
2D Histograms of the Kinetic Energy of Kaons and Electron Energy separated by Reconstructed K-from all daughters (top left) and Reconstructed K-short with daughters in the theta acceptance of 40 degrees (top right). The lines represent percentile. (Bottom) The mass of the reconstructed K-short with daughters in the theta acceptance separated by percentiles.

Reconstructed Kaon KE Ratio by Percentile



The theta acceptance requirement removes few K-short with higher energy: good for veto

Less optimistic for reconstructing low energy K-short (less likely to detect daughters)



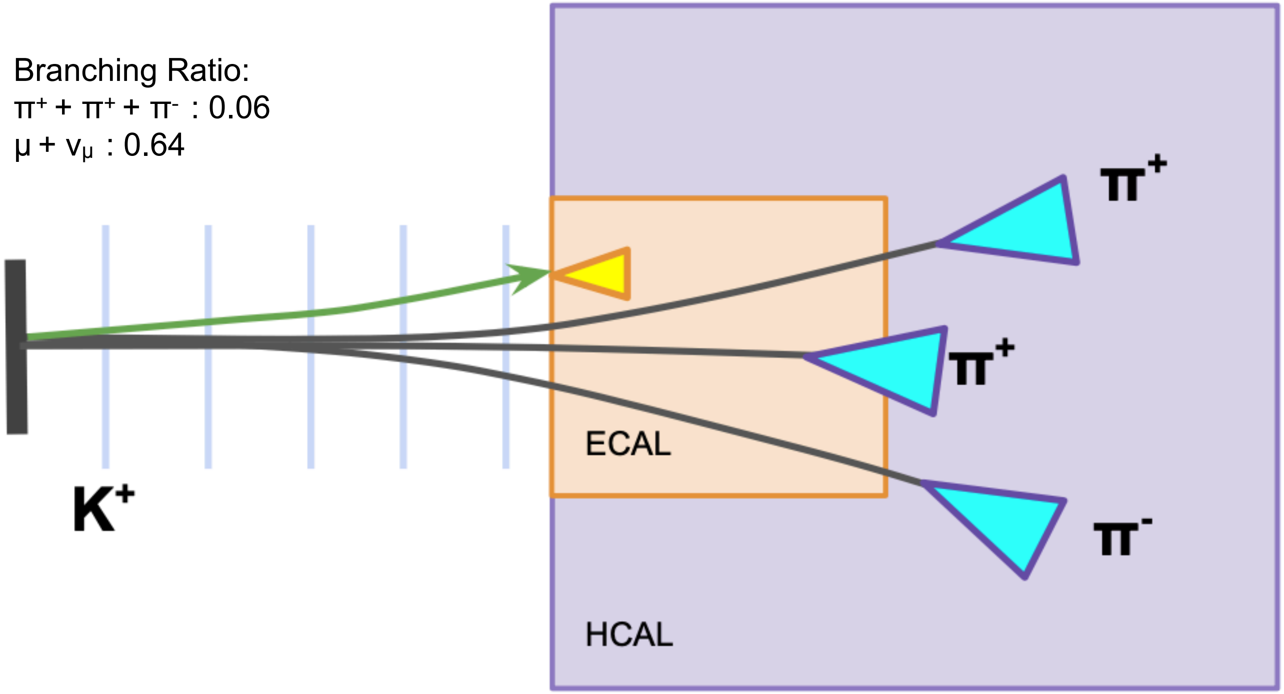
The ratio of reconstructed K-short from all daughters to reconstructed K-short from daughters with theta acceptance of 40 degrees. This plot includes all of the energy percentiles overlapped: purple as top 15% (top left), blue as top 15%-30% (top right), green as top 30%-50% (middle left), yellow as top 50%-75% (middle right), and red as top 75%-100% (bottom left).

Moving forward: Can we reconstruct K^+?

Can predict K_L from K_S, but K^+ rate differs by unknown rate within factor of 3

Attempt to reconstruct K^+ from pi decay, but small branching ratio

Should explore Kaon time of flight or energy loss through the detector



Conceptual drawing of the LDMX experiment, showing the path of the products of K-plus decay from a fixed-target, through the recoil tracker, the electromagnetic calorimeter, and hadron calorimeter.

Takeaways

- What is the rate that we expect of producing Ks?
  - With 1e16 EOT (electrons on target - expected LDMX luminosity):
  - Expect 1.7e-5 photo-nuclear background events, 1 in 50000 will have a Ks
  - This gives a total of **~3.4e6 K_S**

- K_S can be used to predict K_L (in all kinematic regions)
  - We can reconstruct K_S from charged pion decays (assuming we can reconstruct pions 40 degrees away from the beam-line z)
  - This provides a handle to estimate the neutrino background from K_L decay

References

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Acknowledgements

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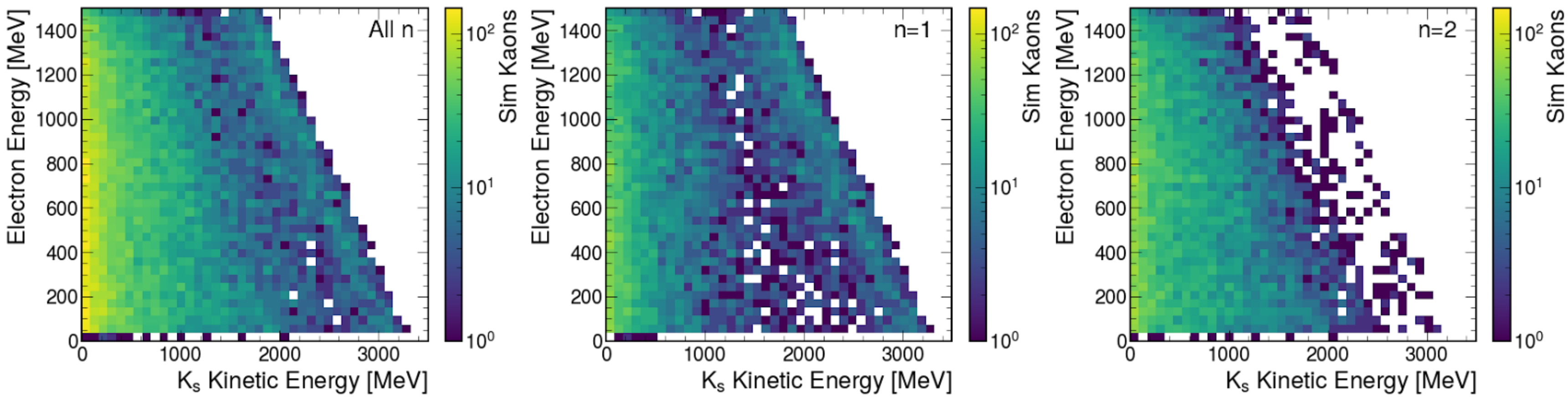
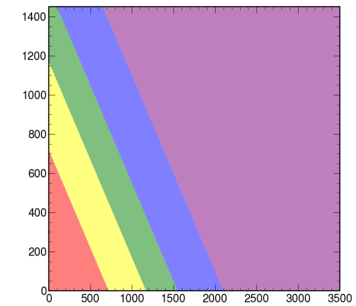
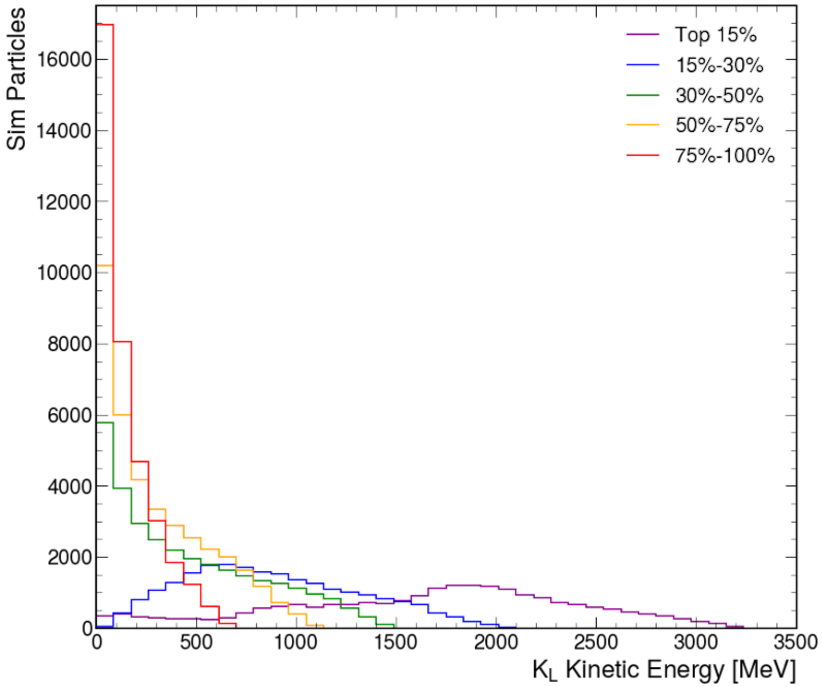
Backup Slide: Truth Kaon Kinetic Energy vs. Recoil Electron Energy

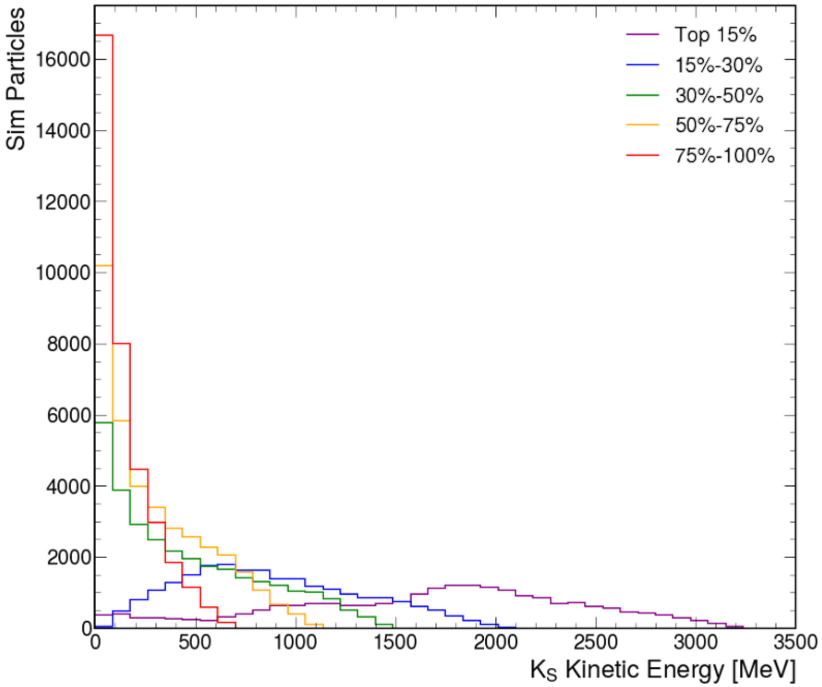


2D histogram representing the kinetic energy of all truth K-short (left), truth K-short produced with no other kaons (middle), and K-short produced with one other kaon (right) vs. recoil electron energy.

Backup Slide: Truth Kaon KE by Percentile

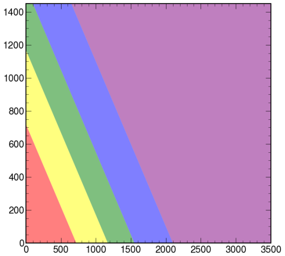




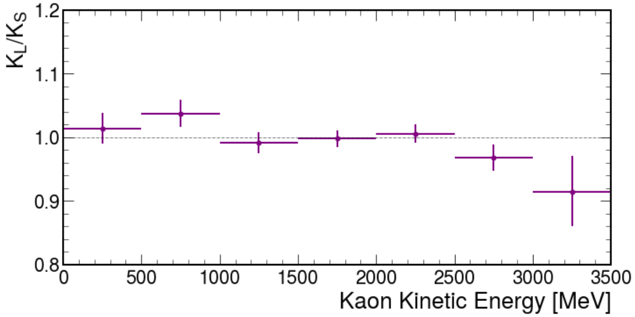


Kinetic Energy of K-long (left) and K-short (right) separated by percentile range.

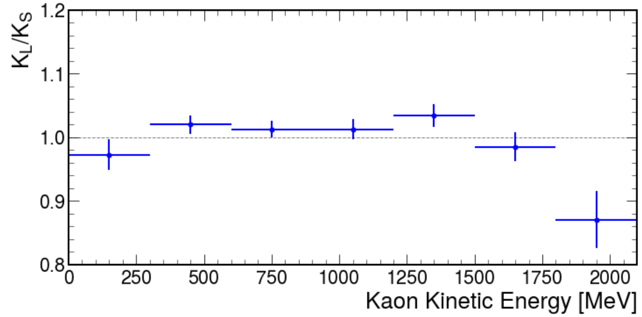
Backup Slide: Truth Kaon KE Ratio by Percentile



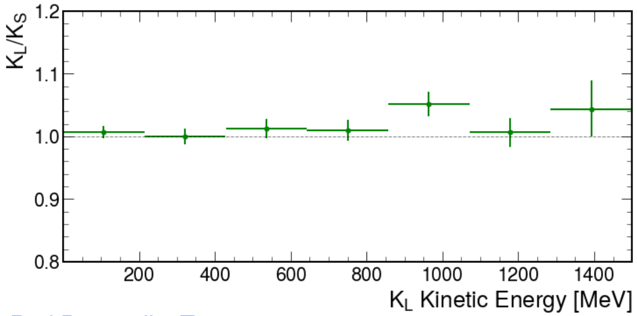
Purple Percentile: Top 15%



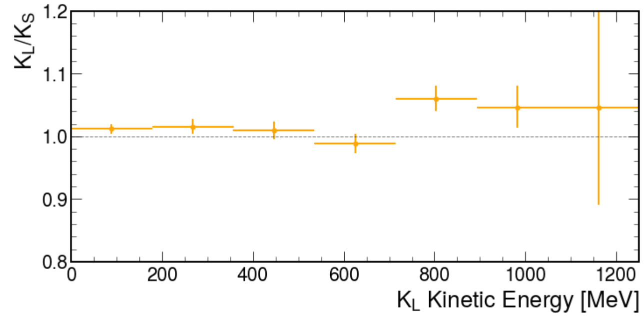
Blue Percentile: Top 15-30%



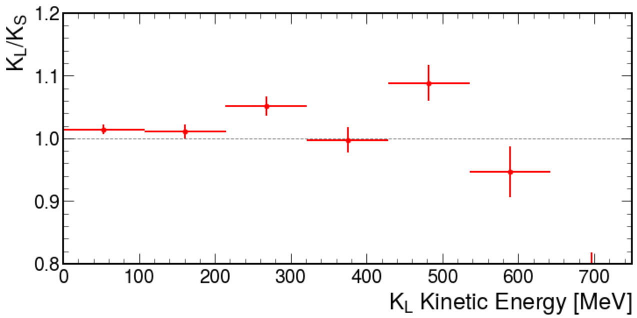
Green Percentile: Top 30-50%



Yellow Percentile: Top 50-75%

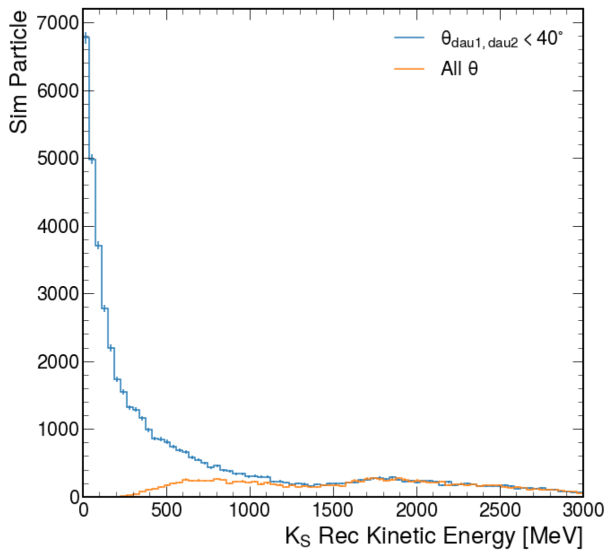


Red Percentile: Top 75-100%

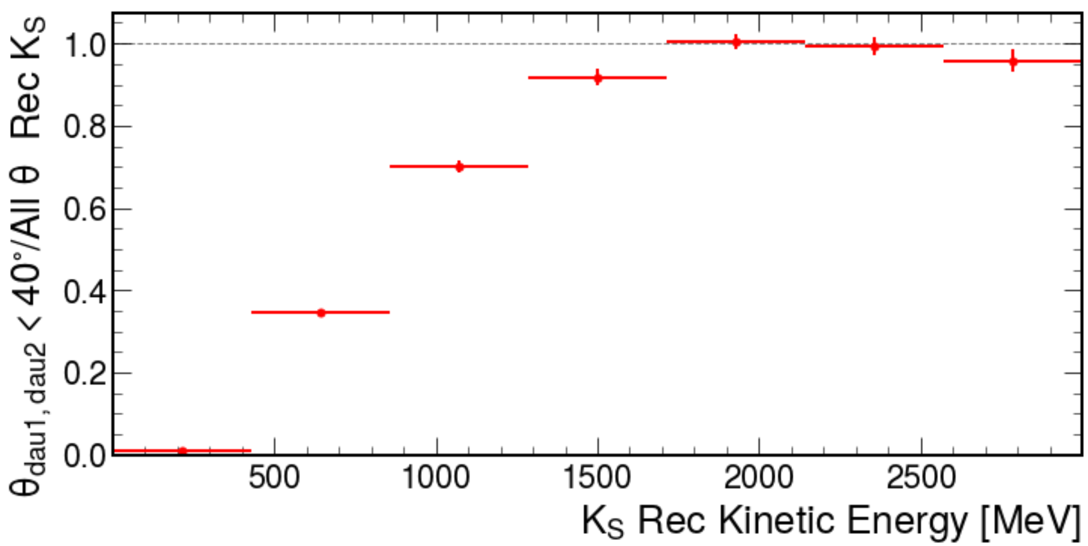


The ratio of truth K-long to truth K-short separated by kinetic energy range. The plots each represent an energy percentile: purple as top 15% (top left), blue as top 15%-30% (top right), green as top 30%-50% (middle left), yellow as top 50%-75% (middle right), and red as top 75%-100% (bottom left).

Backup Slide: Reconstructed Kaon Ratio

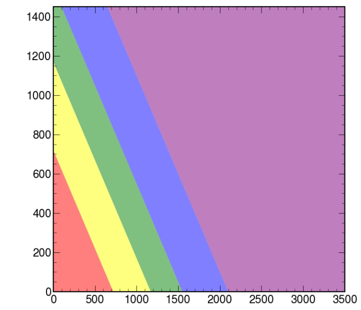


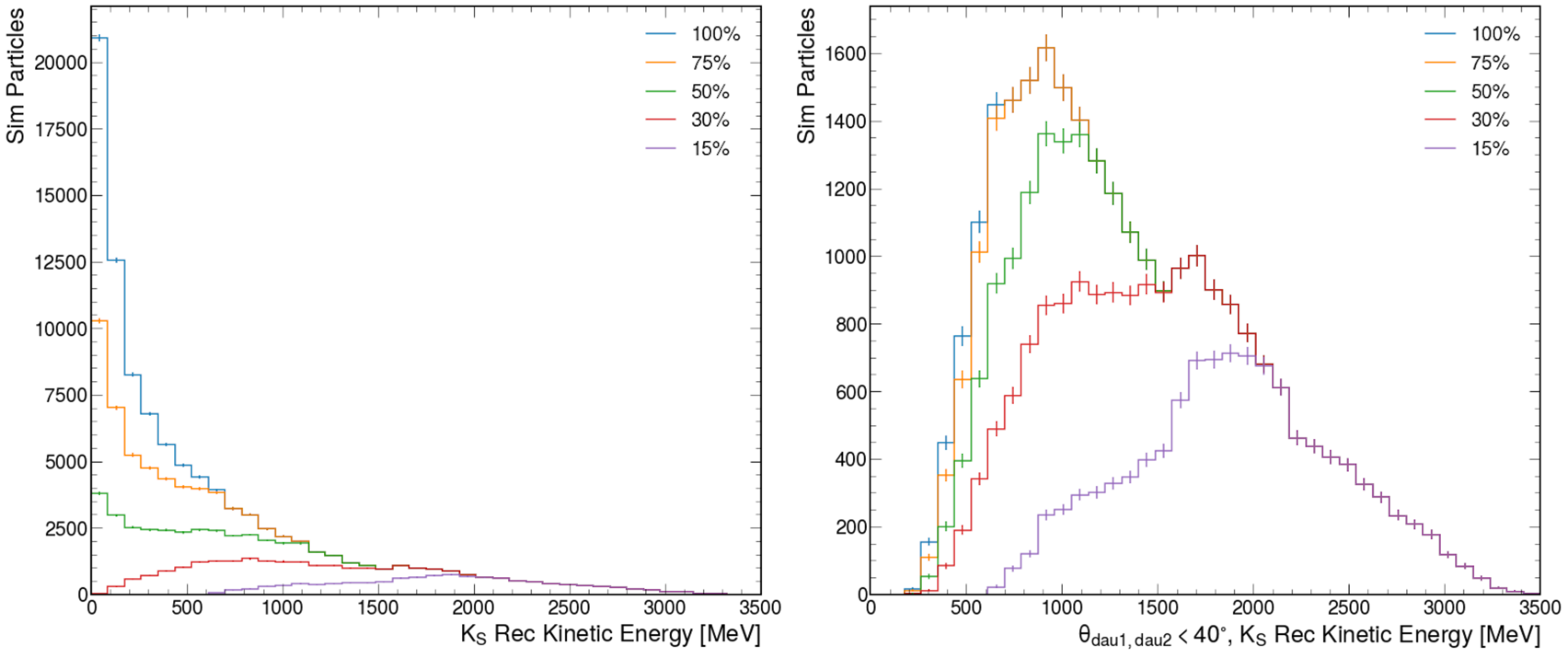
The Kinetic energy of reconstructed K-short from all daughters compared to daughters where both fall within theta acceptance of 40 degrees.



Ratio of K-short reconstructed from daughters with theta acceptance of 40 degrees to K-short from all daughters.

Backup Slide: Reconstructed Kaon KE by Percentile





Kinetic Energy of reconstructed K-short from all daughters and reconstructed K-short from daughters within the 40 degree acceptance separated by percentile range.

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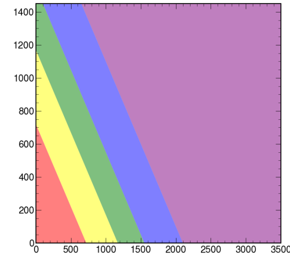
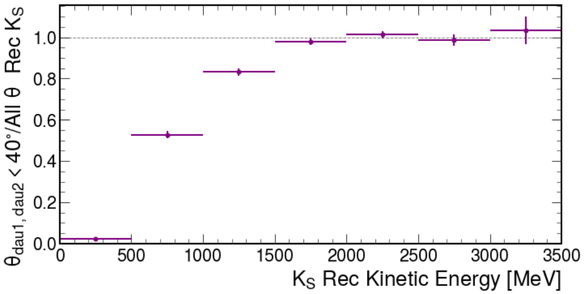
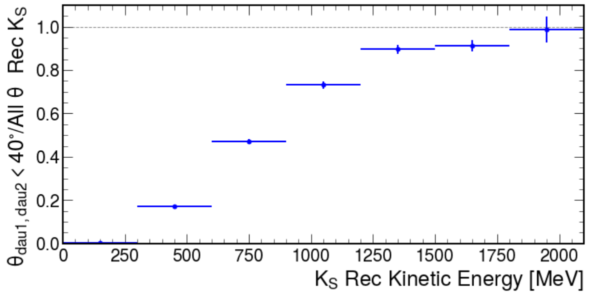
Backup Slide: Reconstructed Kaon KE Ratio by Percentile



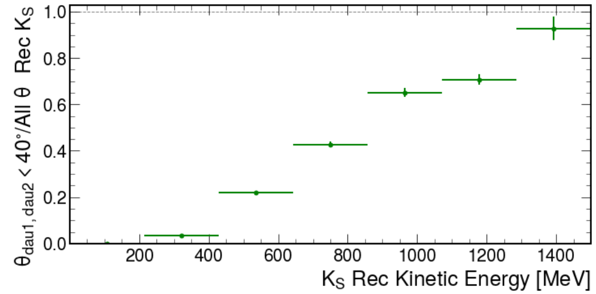
Purple Percentile: Top 15%



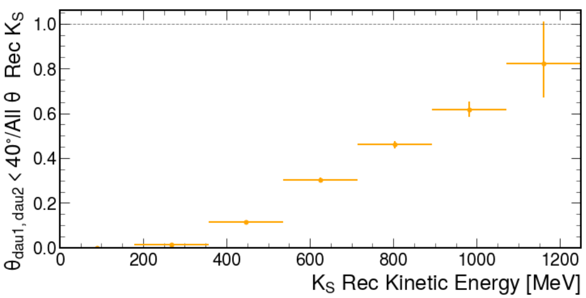
Blue Percentile: Top 15%-30%



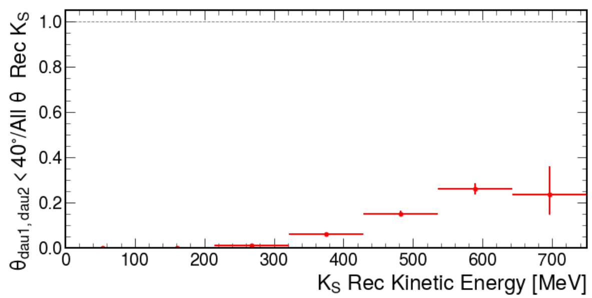
Green Percentile: Top 30%-50%



Yellow Percentile: Top 50%-75%



Yellow Percentile: Top 50%-75%



The ratio of reconstructed K-short from all daughters to reconstructed K-short from daughters with theta acceptance of 40 degrees. The plots each represent an energy percentile: purple as top 15% (top left), blue as top 15%-30% (top right), green as top 30%-50% (middle left), yellow as top 50%-75% (middle right), and red as top 75%-100% (bottom left).

Backup Slide: Reconstructing K-long from K-short

Using the branching ratio (BR) and the ratios found earlier, K-long can be predicted with the equations:

$$K_S = \frac{K_S(\pi^+\pi^-)}{BR_{\pi^+\pi^-}}$$

$$K_L = \frac{K_L}{K_S} * \frac{K_S(\pi^+\pi^- : measured)}{BR_{\pi^+\pi^-}}$$

$$K_S(\pi^+\pi^- : measured) = K_S(\pi^+\pi^- : truth) * Acceptance(\theta_{\pi^+\pi^-} < 40°)$$

$$K_L = \frac{K_L}{K_S} * K_S(\pi^+\pi^- : truth) * \frac{Acceptance(\theta_{\pi^+\pi^-})}{BR_{\pi^+\pi^-}}$$