Alpha Quenching Factor in Liquid Argon

Susnata Seth, Mark Boulay
(on behalf of the DEAP Collaboration)

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DEAP 3600 Carleton University Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Outlines

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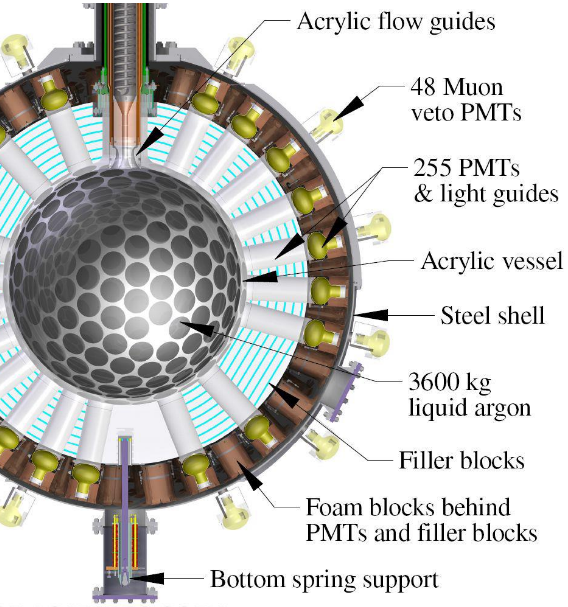
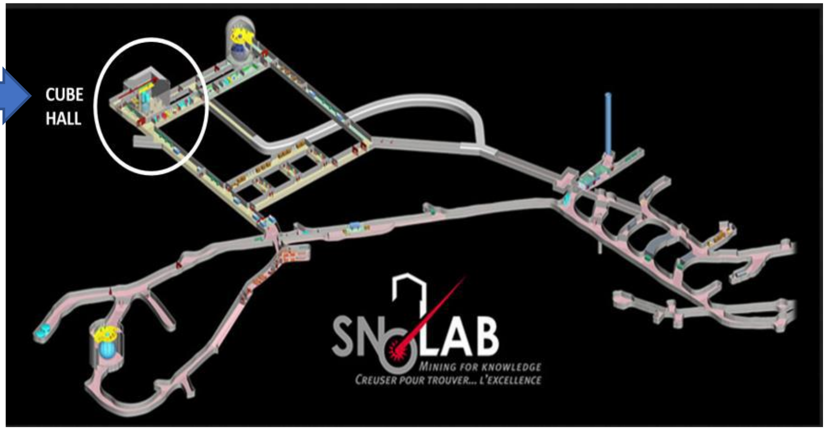
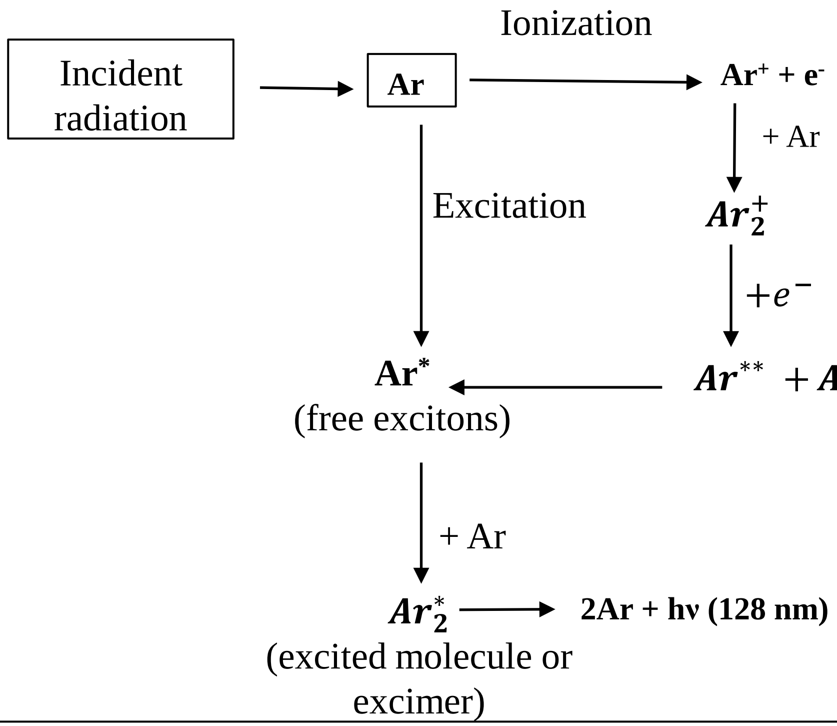
- Objectives
- Relative measurement of alpha quenching factor
- Analysis Procedure and Results
- Summary and Outlook

Introduction: DEAP-3600 Experiment







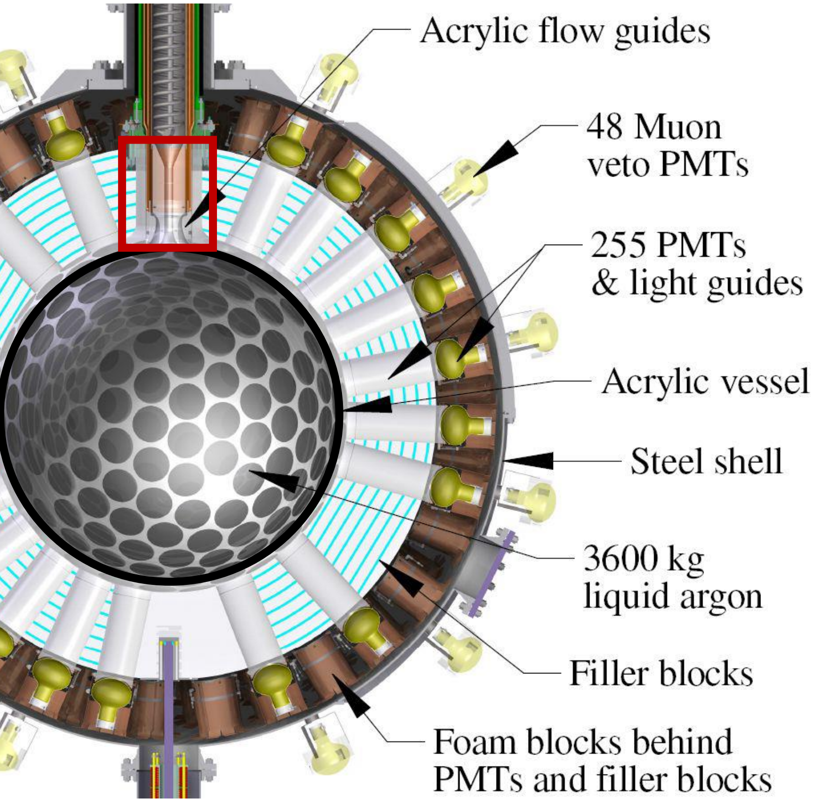
- The DEAP-3600 (**D**ark matter **E**xperiment using **A**rgon **P**ulseshape discrimination) experiment is located approximately 2 km underground at SNOLAB underground facility in Sudbury, Canada.
- Liquid argon (LAr) is used as the target material -- acquires scintillation light signal.
- **Scintillation time profile provides discrimination** between nuclear recoil and electron-recoil events ---nuclear recoil event produces more light in prompt time window.
- Data was collected from November, 2016 – March, 2020, now undergoing hardware upgrades.
  - Analyses of three years data set are in progress to improve the background model and to have the improved limit on WIMP-nucleon spin-independent cross section.
- Expected to fill the detector and start collecting data near end of 2023.

*[**Refs:** P.-A. Amaudruz et al., Astroparticle Physics 108 (2019) 1–23 , R. Ajaj et al., Physical Review D 100, 022004 (2019)]*

Overview : Quenching Factor

- A portion of deposited energy by incident particle within a scintillating material (e.g. liquid argon) leads to light generation. This effect is known as “quenching”.
- Quenching depends on incident particle’s type and energy.
- $\boldsymbol{Quenching\ Factor = \frac{Measured\ Energy}{Deposited\ Energy} = \frac{Detectected\ Photoelectrons}{Light\ Yield \times Deposited\ Energy}}$
- Light yield relates the energy deposited in the detector to the number of detected photoelectrons (PEs).
    - It can be measured from the calibration of energy response of detector using gammas/electrons.

Importance of Alpha Quenching Factor



- Alpha particles are one of the intrinsic backgrounds.
  - ❑Originates from alpha–decays from short- and long-lived radon (^{222}Rn) progeny.
- Position of alpha contamination within detector:
  - ❑in the LAr bulk (full energy deposition – easy to identify)
  - ❑on the inner surface of acrylic vessel (efficient position reconstruction & selection of fiducial volume)
  - ❑on the surfaces of acrylic neck flowguides
  - ❑on or embedded within dust particulates

Challenging backgrounds: need better understanding of energy deposition.

- Measurement of alpha quenching factor plays significant role in estimation of deposited energy.
  - ❑Development of a well understood background model.
  - ❑Identification and mitigation of alpha background events.

Objectives: Analysis Method

- Absolute uncertainty of alpha quenching factor is not known for the DEAP-3600 experimental data.

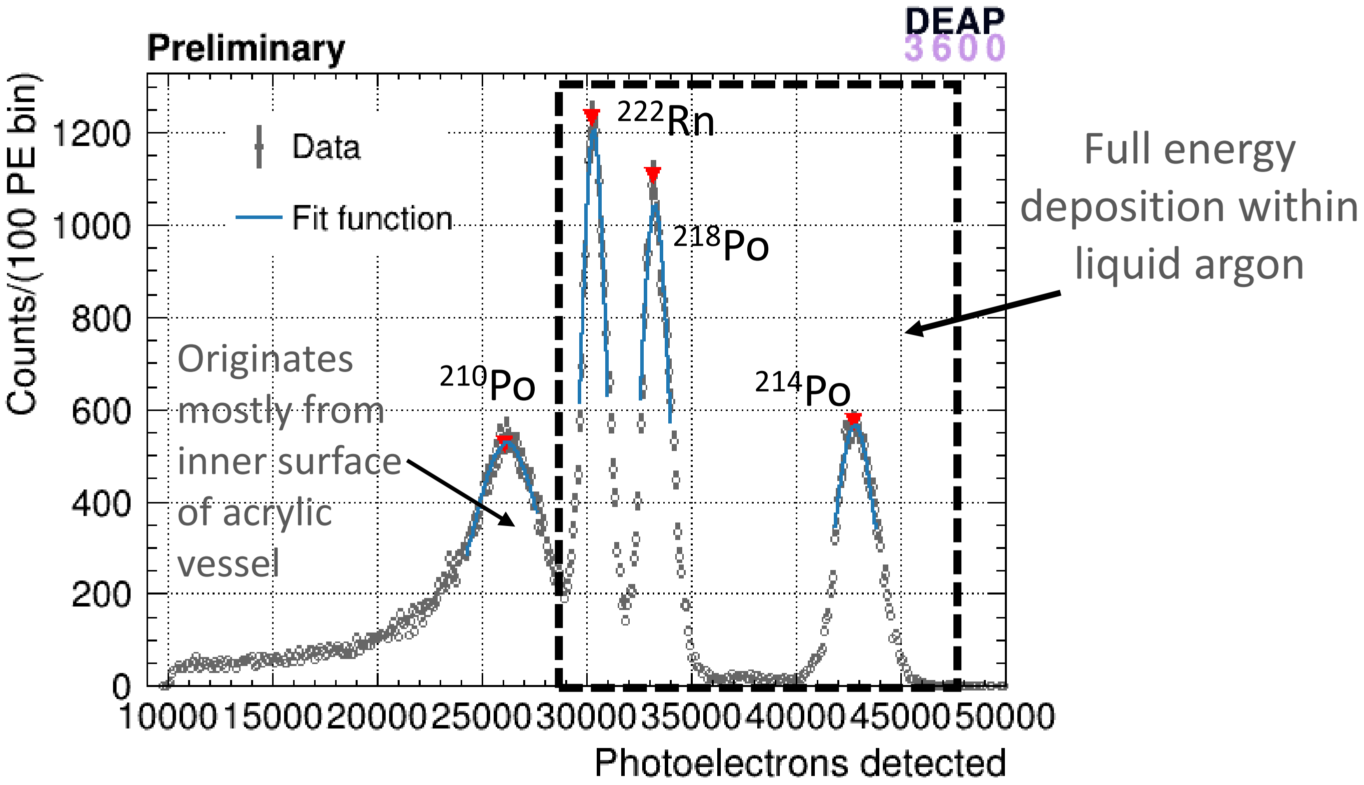
- Present approach is to make the relative measurement of alpha quenching factor at high energy (∼MeV).

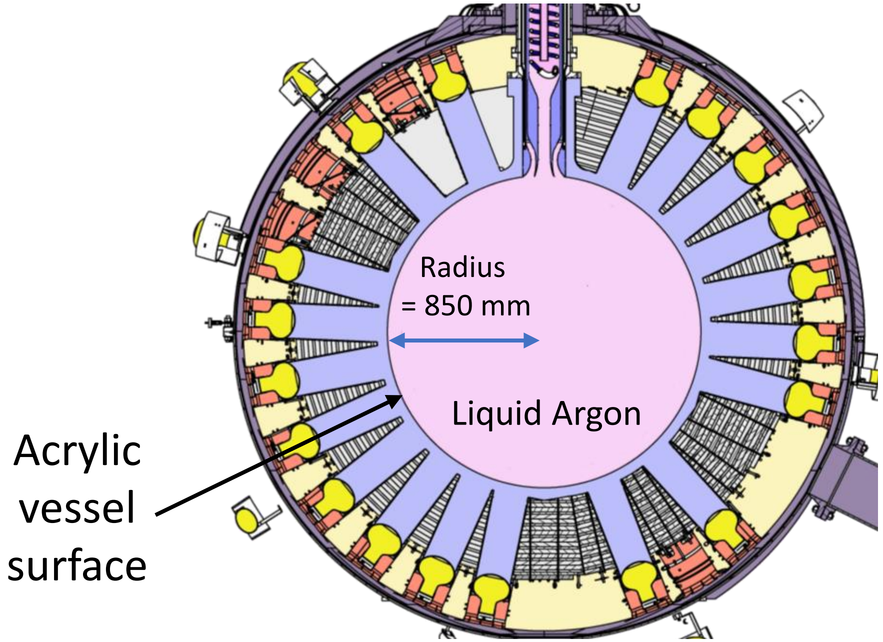
- Exploring the shape of the quenching factor vs energy curve considering relative uncertainties in quenching factor at high energy.

- Probing the uncertainty of extrapolating the quenching factor to the low-energy region (∼ few tens to few hundreds keV).

Measurement of Alpha Quenching Factor

Alpha Induced Events





Three years (November, 2016 – March, 2020) open dataset of DEAP-3600 experiment is used . (Data has been blinded 80% since January, 2018)

^{238}U Chain Decay Modes

Parent Nuclei	Daughter Nuclei	Half-life, $t^{1/2}$	Q-value [MeV]	Decay Mode [MeV]
^{222}Rn	^{218}Po	3.823 d	5.590	α[5.489]
^{218}Po	^{214}Pb	3.10 min.	6.114	α[6.002]
^{214}Pb	^{214}Bi	26.8 d	1.024	β[1.024]
^{214}Bi	^{214}Po	19.9 min	3.272	β[3.272]
^{214}Po	^{210}Pb	164.3 μs	7.833	α[7.686]
^{210}Pb	^{210}Po	22.3 yr	0.0635	β[0.0635]
^{210}Po	^{206}Pb	138.376 d	5.407	α[5.304]

Relative Measurement of Quenching Factor

- DEAP-3600 detector is calibrated at low energy (keV to 1.3 MeV) region whereas alphas have energies comparatively at higher region (approx. 5-8 MeV).

- Non-linearity in the measurement of light yield can lead to incorrect evaluation of quenching factor.

- **Step I : Estimation of relative light yield using :**

  - **Alpha quenching factor for ^{210}Po isotope = $Q_{210_{Po}}^{Doke\ et\ al.}$ = 0.71 $\pm$ 0.028 . [*Ref: T. Doke et al. NIMA 269 (1988) 291*]**

  - Photoelectron (PE) value for alphas from ^{222}Rn in DEAP-3600 data.

  - $Q_{222_{Rn}}^{Calib}$ = **0.71 $\pm$ 0.028**

  - $PE_{222_{Rn}} = Q_{222_{Rn}}^{Calib} \times E_{222_{Rn}} \times LY_{Relative}$

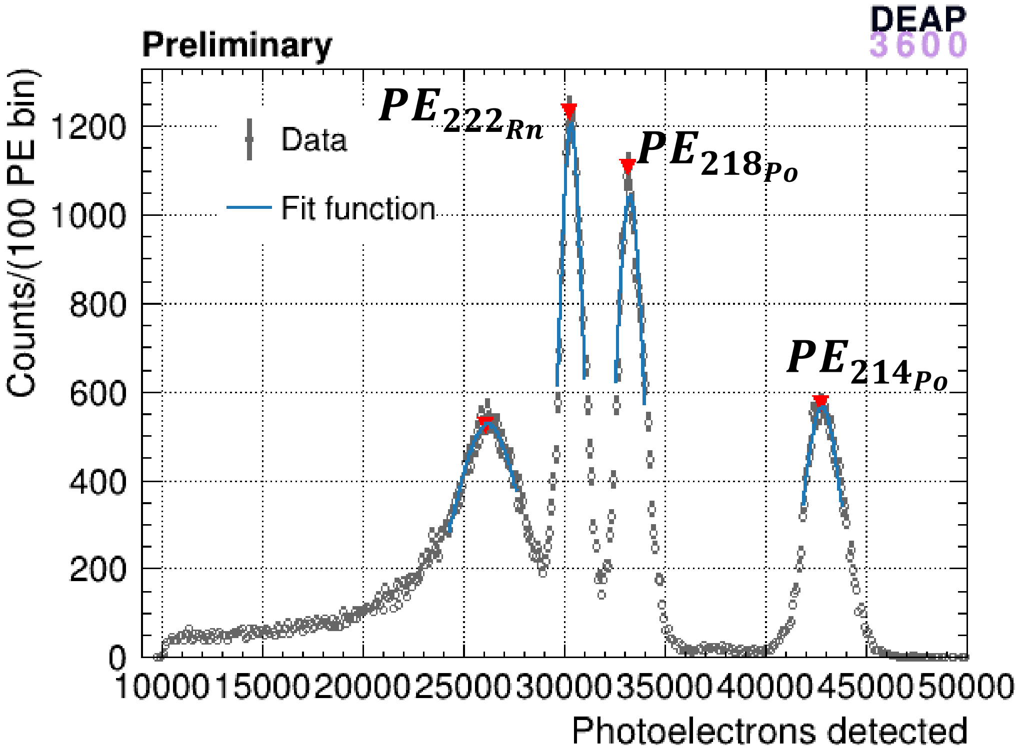
[Assumption: Negligible difference in quenching factor of alphas originated from ^{210}Po and ^{222}Rn isotopes because energies of alphas are nearly same (5.304 MeV and 5.489 MeV respectively).]

Relative Measurement of Quenching Factor

- **Step II : Calculation of quenching factor**

  - $Q_{^{218}Po} = \frac{PE_{^{218}Po}}{E_{^{218}Po} \times LY_{Relative}} = \frac{PE_{^{218}Po}}{PE_{^{222}Rn}} \times \frac{E_{^{222}Rn}}{E_{^{218}Po}} \times Q^{Calib}_{^{222}Rn}$
  - $Q_{^{214}Po} = \frac{PE_{^{214}Po}}{E_{^{214}Po} \times LY_{Relative}} = \frac{PE_{^{214}Po}}{PE_{^{222}Rn}} \times \frac{E_{^{222}Rn}}{E_{^{214}Po}} \times Q^{calib}_{^{222}Rn}$

Ratio of PE can be obtained from DEAP-3600 data



Using ratios of peak energies makes the analysis insensitive to the absolute energy calibration at high energy in DEAP-3600 experiment.

Peaks are fitted by Gaussian distribution -- mean of Gaussian distribution is taken as the Photoelectron (PE) peak position.

Uncertainties in Quenching Factor

Isotope	Alpha Energy in MeV	$\frac{PE_{isotope}}{PE_{222_{Rn}}}$	Uncertainty in $\frac{PE_{isotope}}{PE_{222_{Rn}}}$	Quenching Factor	Relative Uncertainty in Quenching Factor	Uncertainty in Quenching Factor	Comments
^{210}Po	5.305	-	-	0.710	-	0.028	*Ref : T. Doke et al., NIMA 269 (1988) 291*
^{222}Rn	5.489	-	-	0.710	-	0.028	***Calibration data*** *[QF is assumed to be same as* ^{210}Po *data]*
^{218}Po	6.002	1.096	0.002	0.712	0.001	0.028	From relative measurement
^{214}Po	7.686	1.410	0.006	0.715	0.003	0.028	From relative measurement

Development of Energy Dependent Quenching Factor Curve

Quenching Factor Model

Birks' Law

- Local concentration of quenching agent (damage molecule) at any point on the track is proportional to stopping power of incident particle.
- Describes measured light per unit length (dL/dr) as a function of the electronic energy loss per length (dE/dr).

$$\frac{dL}{dr} = \frac{A\frac{dE}{dr}}{1+kB\frac{dE}{dr}} \Longrightarrow \frac{dL}{dE} = \frac{A}{1+kB\,\frac{dE}{dr}}$$

A, kB are treated as fitted constants and can be estimated from experimental data.

- **Quenching factor :**

$$QF_{Birks}(E) = \frac{1}{N_{step}}\sum\frac{dL}{dE} = \frac{1}{N_{step}}\sum_{i=1}^{N_{step}}\frac{A}{1+kB\left(\frac{dE}{dr}\right)_i}$$

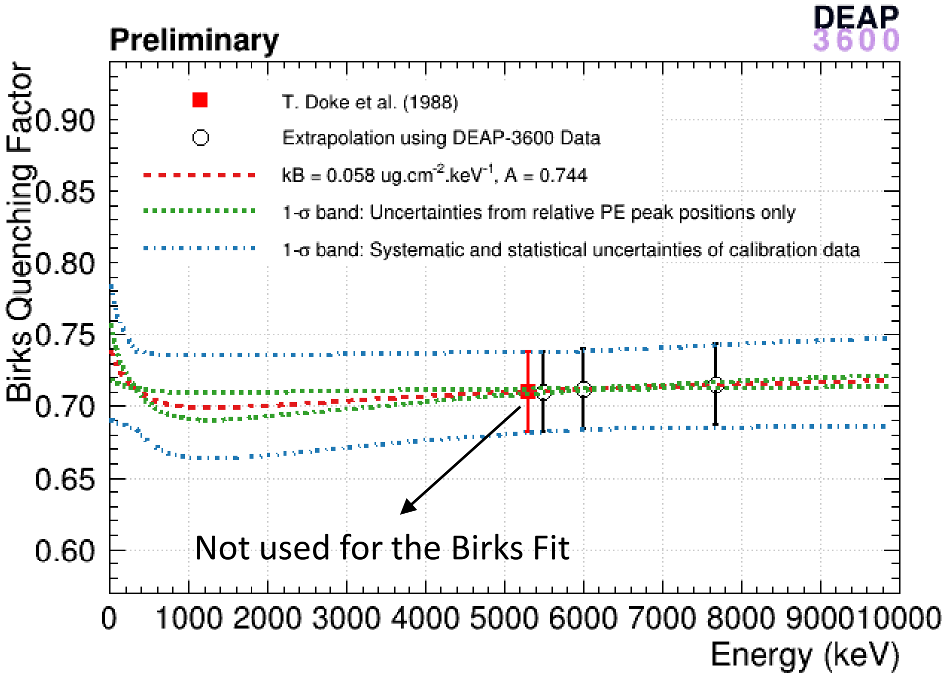
Lindhard's Approach

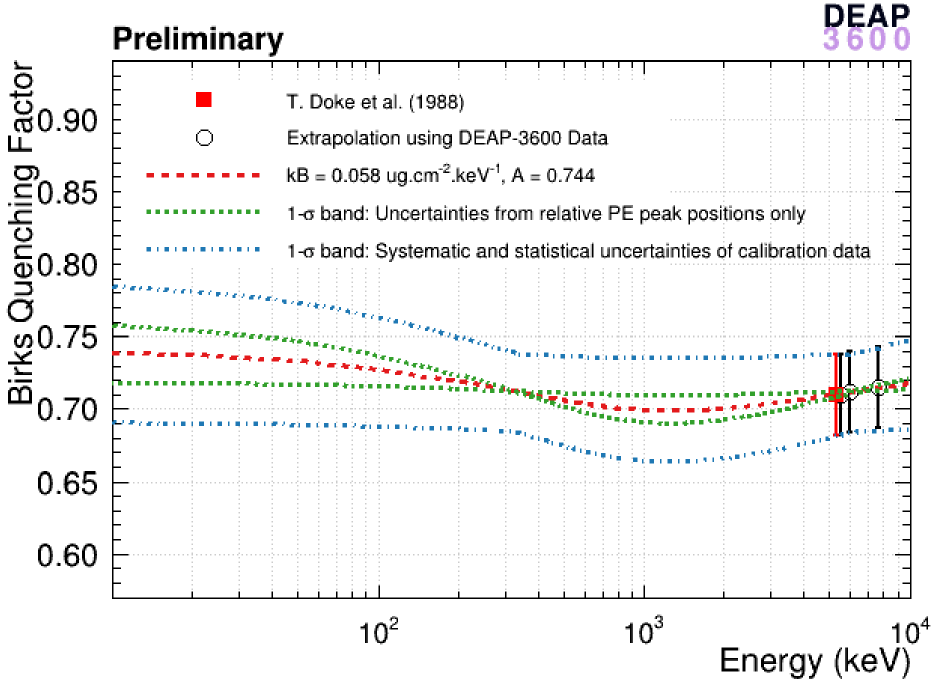
- Total energy loss by an incident particle within a substance can be divided into two parts :
  - ❑ Produces electronic excitation or ionization (electronic collision).
  - ❑ Produces translational motion of whole atom, excluding internal excitation of the atom (nuclear collision).
- **Energy lost in ionization** plays significant role in producing scintillation light.
- **Quenching factor :**

$$QF_{Lindhard}(E) = \frac{E_{dep,electronic}}{E_{dep,electronic} + E_{dep,nuclear}}$$

[Refs: J. B. Birks, Proc. Phys. Soc. A 64 (1951) 874 , J . Lindhard et al., Mat. Fys. Medd. Dan . Vid. Selsk . 33, no . 10 (1963)]

Birks Quenching Factor



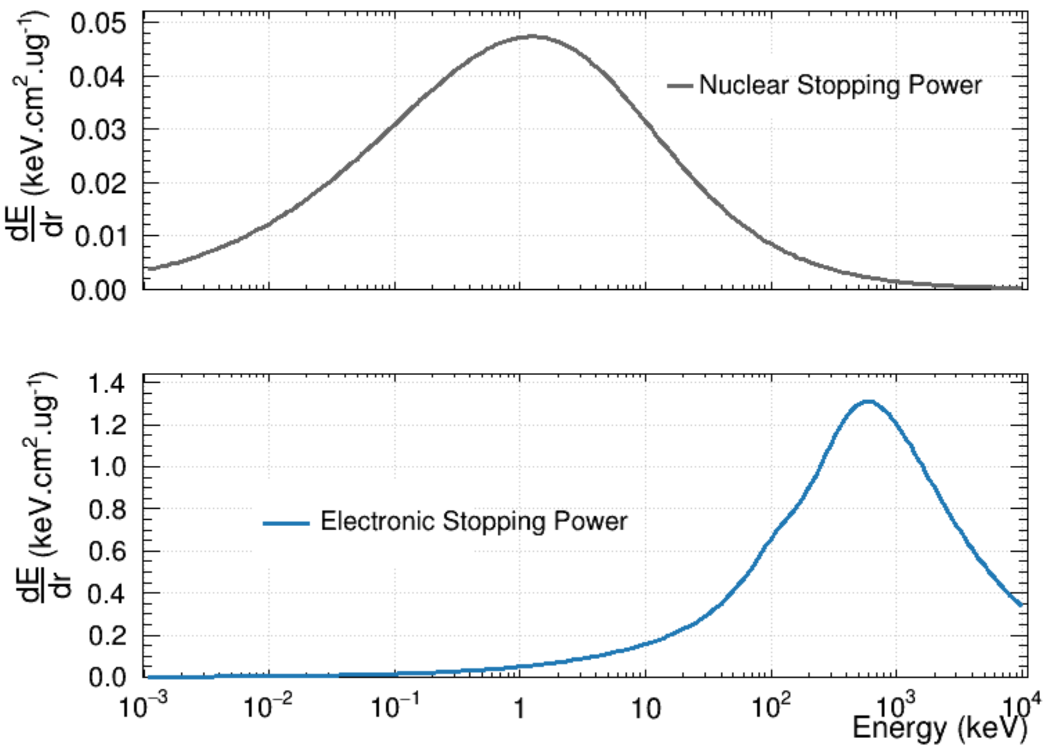


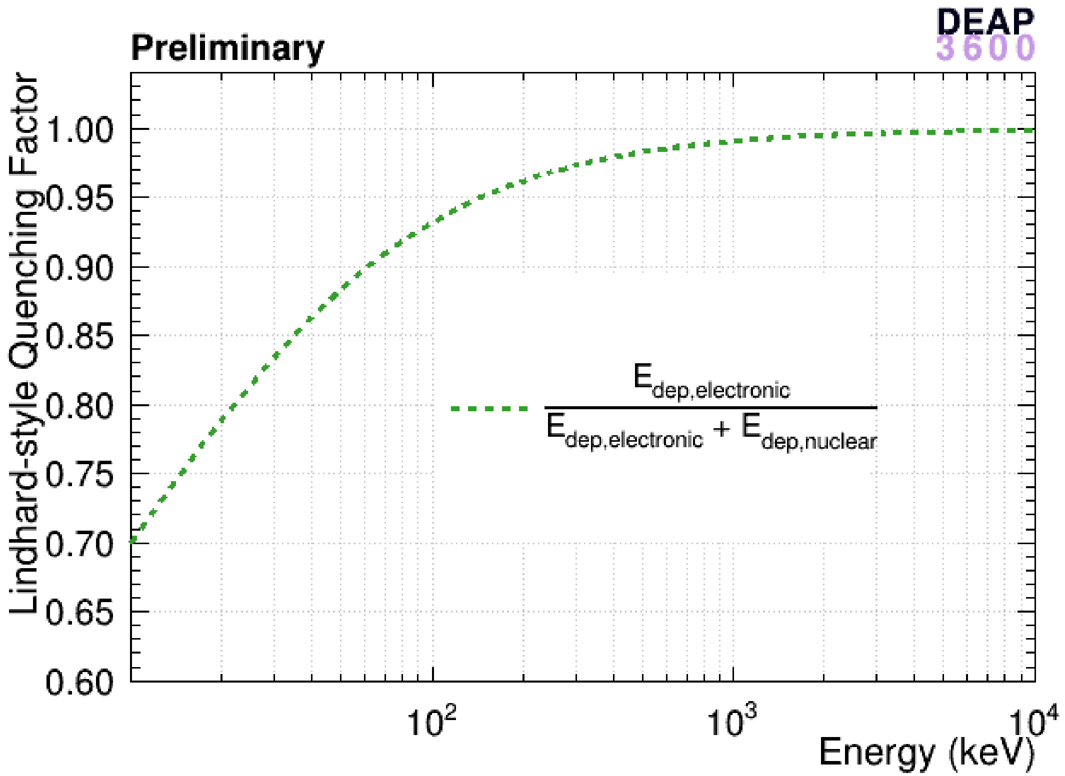
- 1-sigma contour is drawn in (kB, A) parameter space.
- **Shape of the 1-sigma band (green curve) depends on relative uncertainties of the DEAP-3600 data.**
- At MeV energy, the relative uncertainty in quenching factor is quite small (0.2 - 0.4 %) ⇒ leads to constraint the energy dependence of quenching factor well ⇒ nearly flat.
- The asymmetric shape of uncertainty band comes from the worst (kB, A) fit which is consistent with the data points at the 1 sigma level.

- 1-σ upper and lower bands (green curve) are multiplied by $R_1 = \frac{Q_{max}^{Calib}}{Q_{max}^{222Rn}}$ and $R_2 = \frac{Q_{min}^{Calib}}{Q_{min}^{222Rn}}$, respectively. **[$Q_{min}^{222Rn}$ and Q_{max}^{222Rn} are extracted from green curve]**
- **Shape (blue curve) is determined by 1-σ error band** using **relative uncertainties** and consider absolute uncertainty of calibration data.
- Provides maximum and minimum values of quenching factor for each energy.

Lindhard-style Quenching Factor

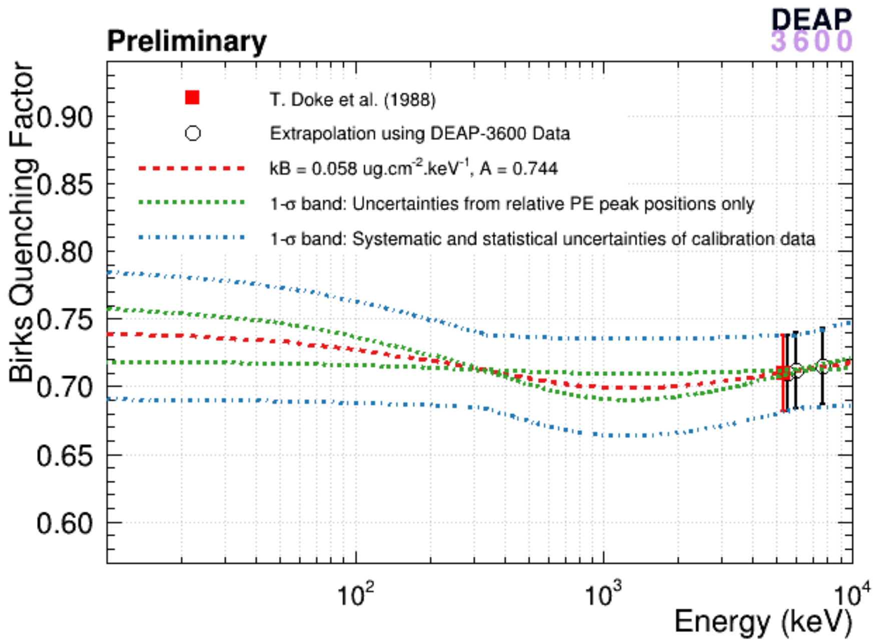
SRIM-2013 (The Stopping and Range of Ions in Matter)



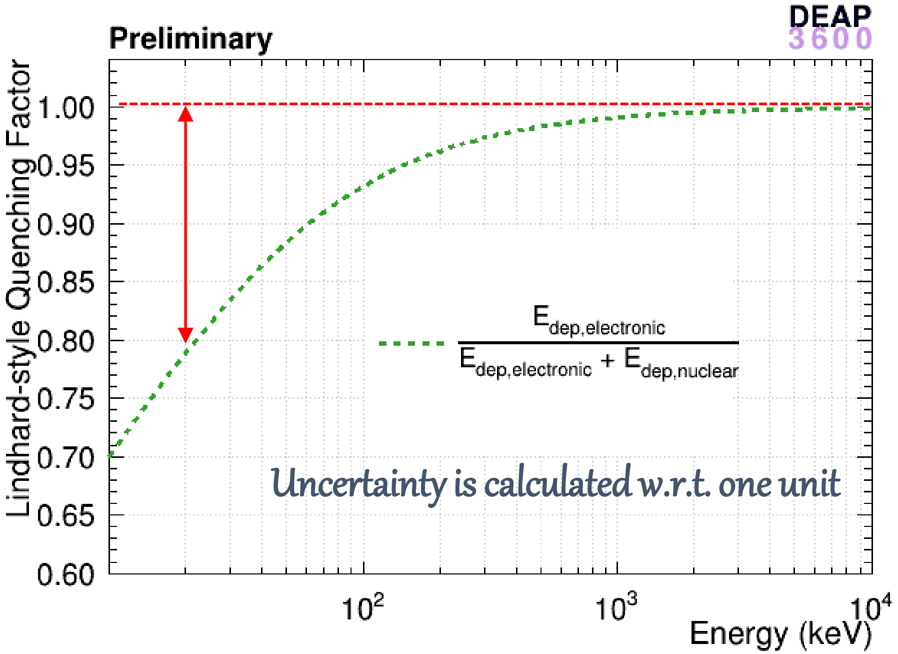


Lindhard-style Quenching Factor for 10 keV - 10 MeV using SRIM stopping power curves.

Quenching Factor Curve from Relative Measurement



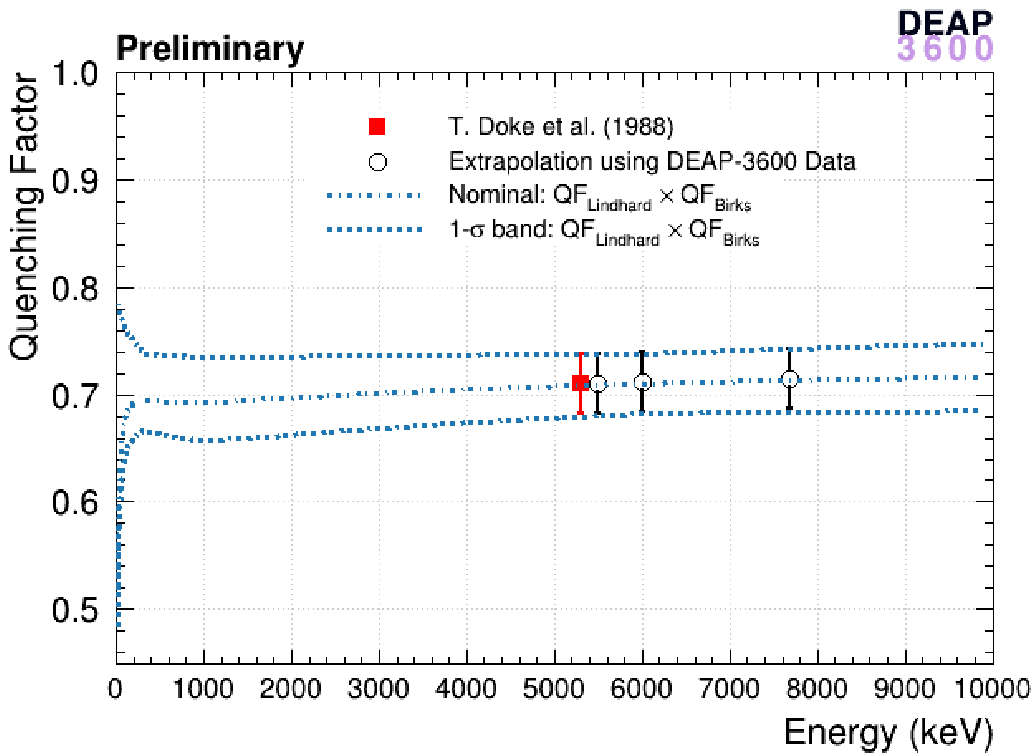
- **Method is adopted** from **D.-M.** Mei et al. approach [Ref: Astroparticle Physics 30 (2008) 12] which was used for nuclear recoils of few tens to few hundred keV:
  - ❑ Quenching Factor = Lindhard-style Quenching Factor × Birks' Quenching Factor.
  - ❑ Birks' Quenching Factor is dominant at higher energy region, whereas Lindhard-style quenching plays important role in lower energy region.

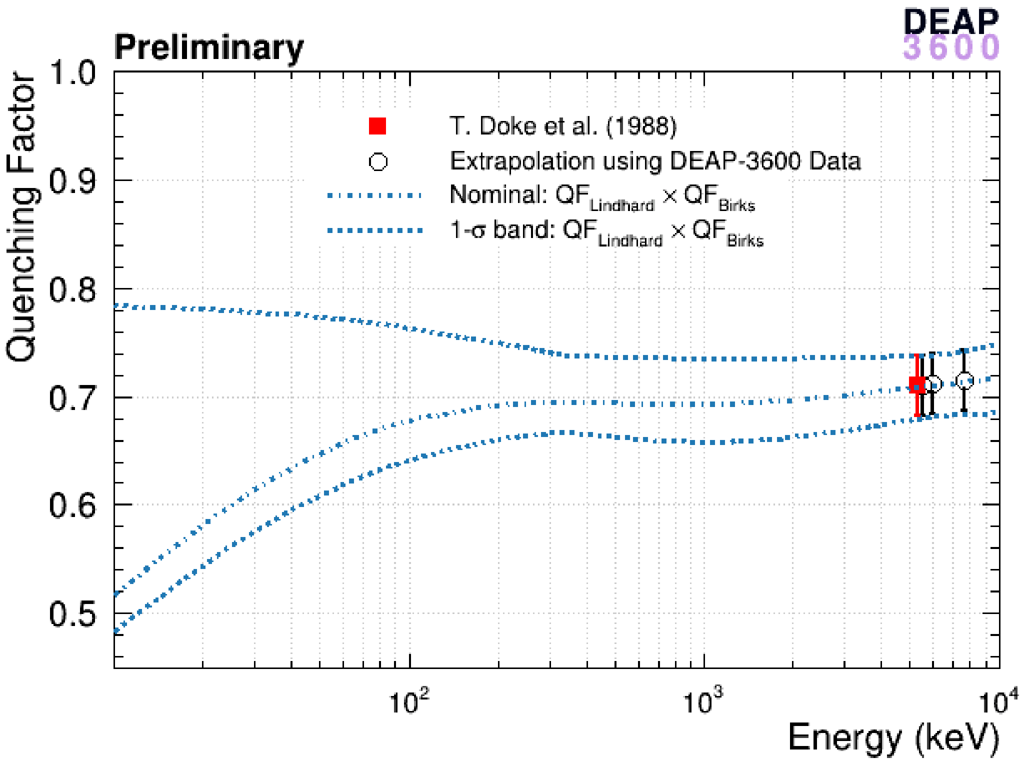


In (30 – 600) keV energy region,

- **Electronic stopping power is dominant for alphas** whereas in case of ^{40}Ar nuclear recoil, electronic and nuclear stopping power are comparable.
- For alphas, greater than 80% of total energy loss is due to electronic collision whereas nuclear recoils this is about (30 – 70)%.

Energy Dependent Alpha Quenching Factor in Liquid Argon





- Shape of the 1-σ error band for quenching factor can be validated by the measurement of quenching factor.
- Measurements of alpha quenching factors for **few hundreds of keV – few MeV region** using Argon-1 (a modular single phase liquid argon cryostat) at Carleton University are underway.

Summary and Outlook

- Relative measurement of alpha quenching factor is performed considering T. Doke et al.'s alpha quenching data for ^{210}Po as calibration data.

- We can well-constrain the energy dependence of quenching factor by using relative uncertainties.

- 1-sigma uncertainty bands for energy dependent quenching factor curve are developed which will be validated by experimental results.

- Direct measurement of alpha quenching at Carleton University in a small argon detector is underway.

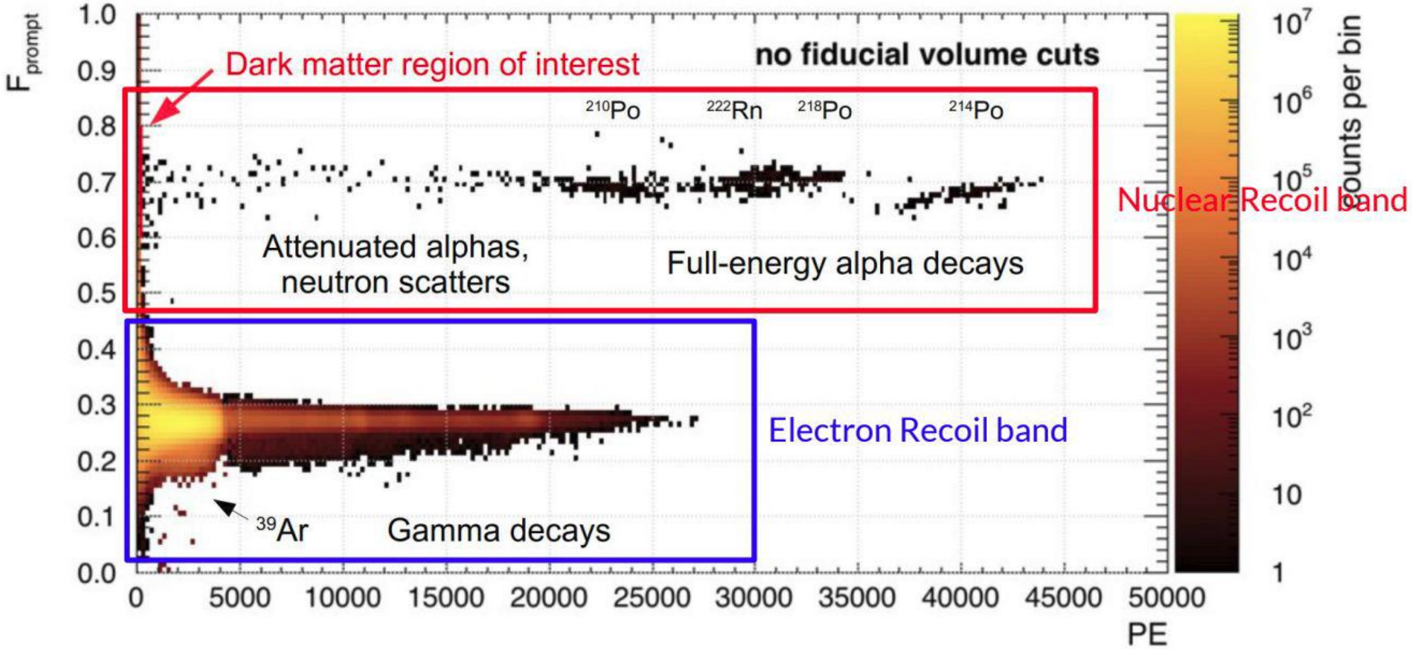
Thank you for your kind attention

Extra Slides

Activity of alpha –decays within liquid argon

Component	Activity
^{222}Rn LAr	(0.153 ± 0.005) µBq/kg
^{218}Po LAr	(0.159 ± 0.005) µBq/kg
^{214}Po LAr	(0.153 ± 0.005) µBq/kg

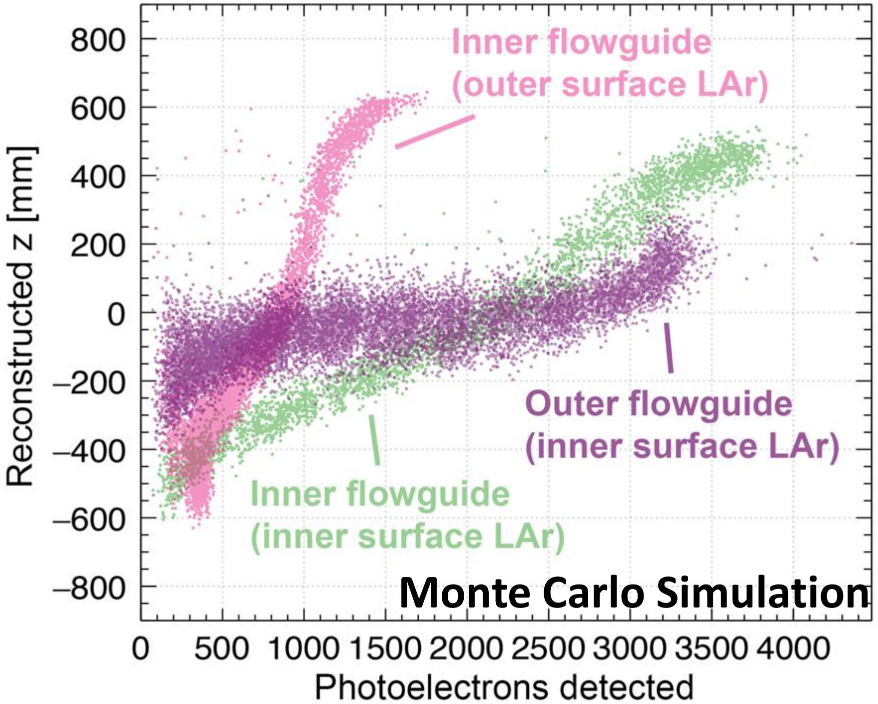
Phys. Rev. D 100, 022004 (2019)



$$F_{prompt} = \frac{\sum_{t=-28\,ns}^{60\,ns} PE(t)}{\sum_{t=-28\,ns}^{10\,\mu s} PE(t)}$$

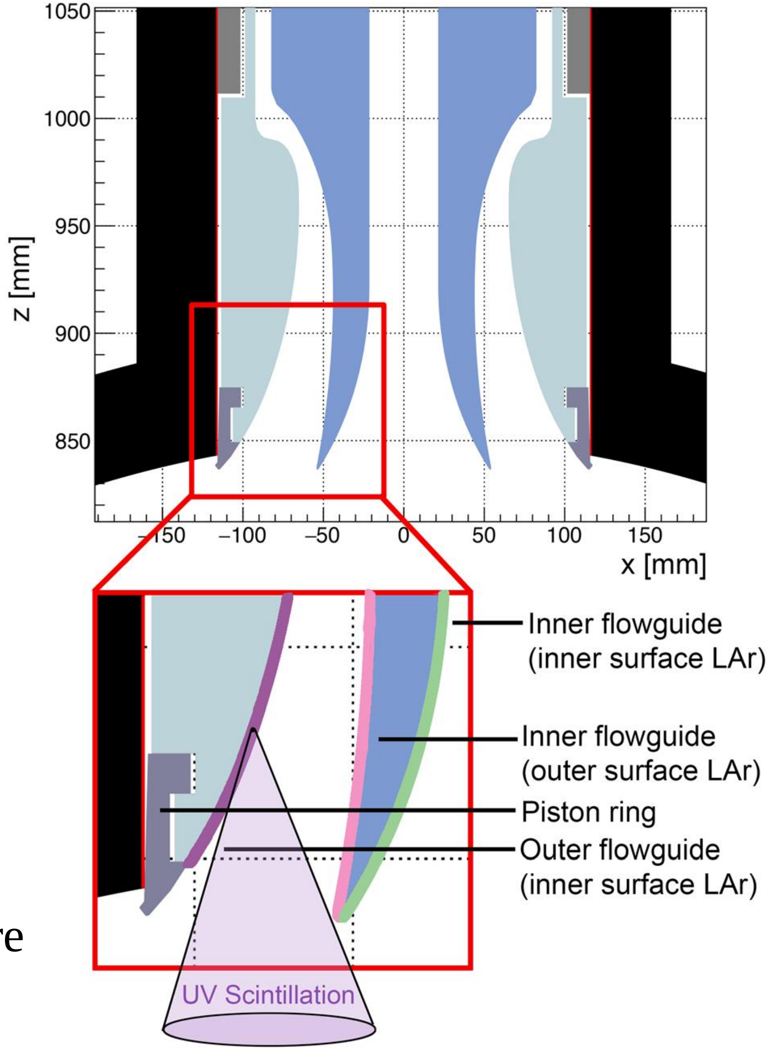
Neck Alpha Backgrounds

- Originated from ^{210}Po α-decays on the acrylic surfaces of flowguides located at the neck of the detector.
- Produces significant backgrounds at low energy due to **shadowed/degraded** alpha decays.
- Position of shadowed alpha-decay events tends to reconstruct within fiducial volume.



Optical model :

- Assumes the surfaces of flowguides are coated with a thin liquid argon layer.
- Results in an F_{prompt} distribution consistent with data.



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Dust Alpha Backgrounds

- ^{238}U and ^{232}Th decay chain present on dust particulates can be the source of alphas.
- Dust particles shadow the scintillation light and degrade energy of the alpha particles.
- Different dust sizes are simulated and the size distribution is modelled by a power law.