Correcting Signal Saturation in DEAP-3600

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WNPPC
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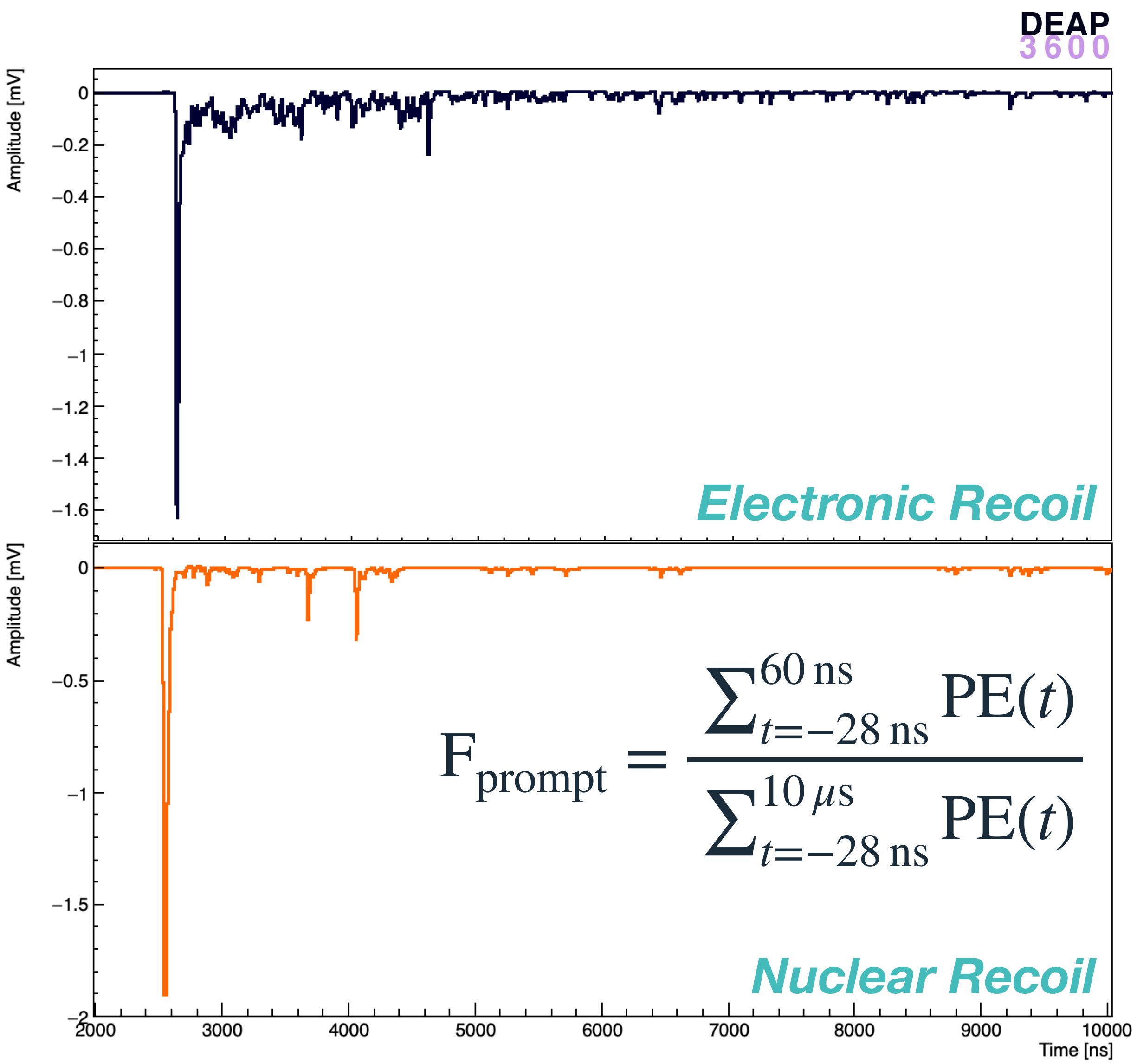
TRIUMF

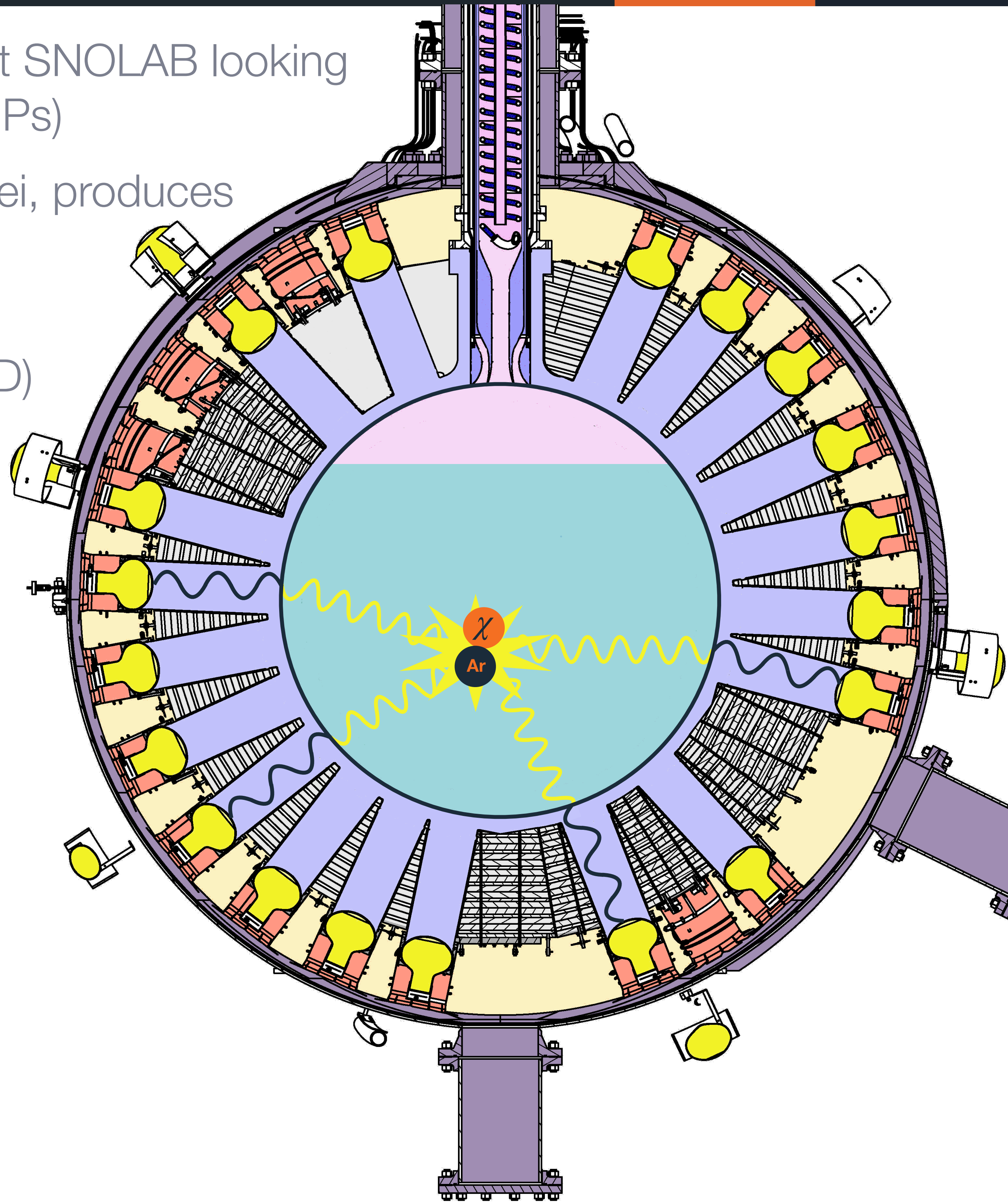
Contents

DEAP-3600

- Tonne scale, LAr-based dark matter search at SNOLAB looking for Weakly Interacting Massive Particles (WIMPs)
- Dark matter elastically scatters off argon nuclei, produces scintillation
- Particle identification via photo-electron (PE) counting and pulse-shape discrimination (PSD)



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



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DEAP-3600

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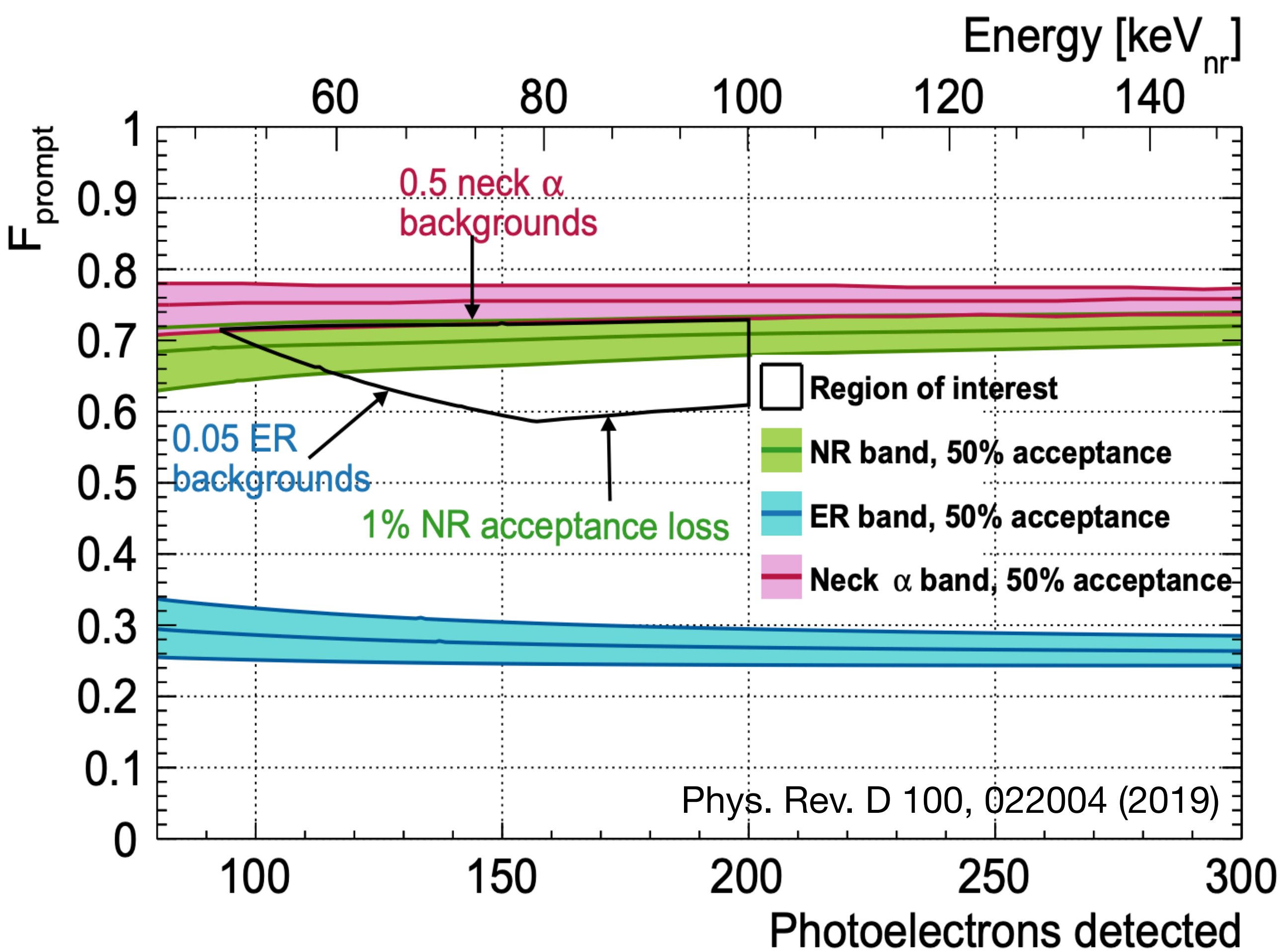
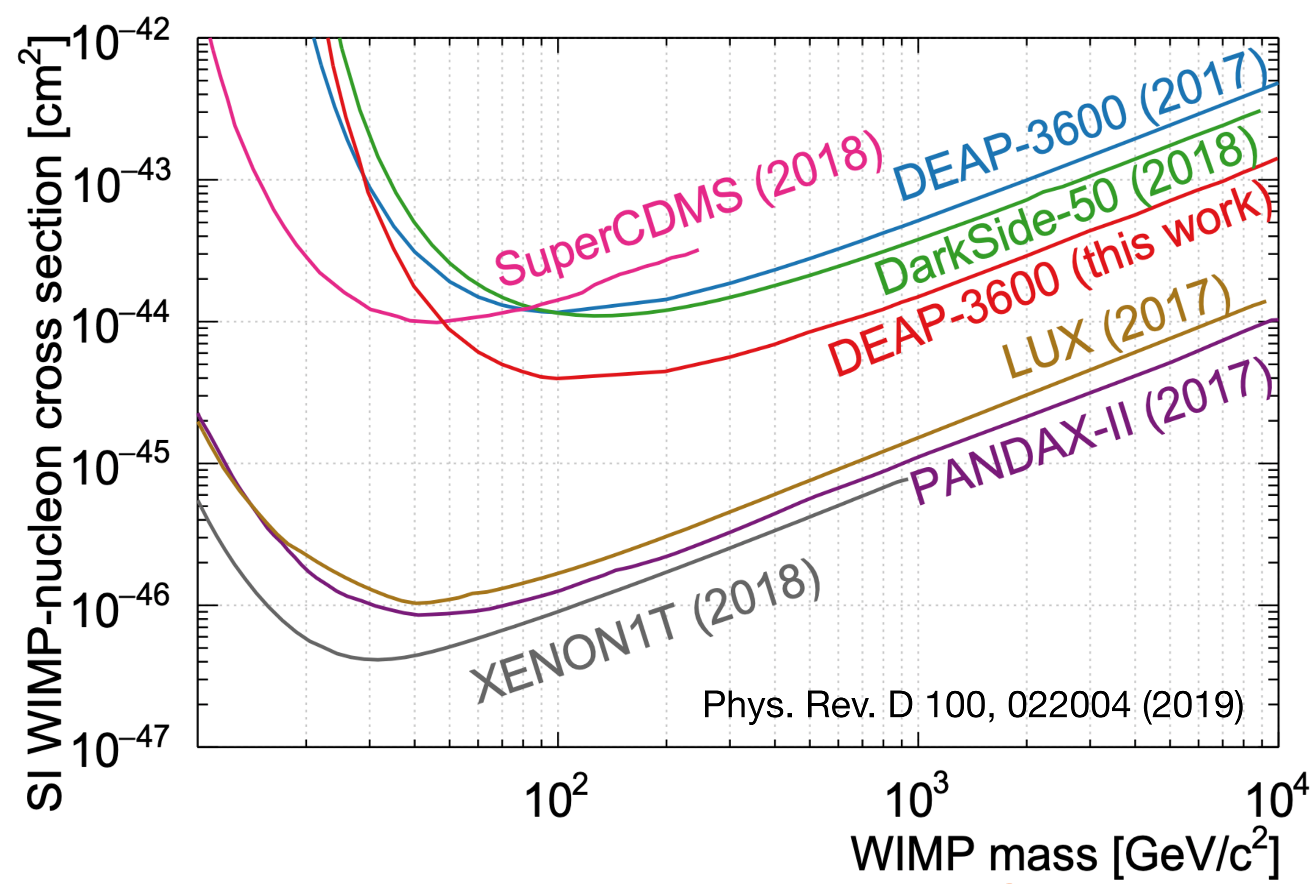


- Region of Interest (ROI) defined to balance background leakage with nuclear recoil (NR) acceptance losses
- No less than 1% acceptance loss at lower F_{prompt} bound and 30% at upper bound

- DEAP's limit of spin-independent WIMP-nucleon cross-section at 758 tonne-days exposure is:
  - 3.9×10^{-45} cm^2 for 100 GeV/c^2 WIMP mass
  - 3.5×10^{-44} cm^2 for 1 TeV/c^2 WIMP mass



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Since the 231-Day Publication

- Major updates in analysis software: blinding scheme has been implemented and machine learning used to discriminate against neck alphas
- Published on electromagnetic backgrounds and ^{42}K activity in the detector—accepted to Phys. Rev. D on October 30, 2019: **Phys. Rev. D 100, 072009 (2019)**
- Paper describing liquid-argon scintillation pulse shapes submitted to EPJ C. **(arXiv:2001.09855)**

On the Horizon

- Dark matter parameter estimation using multi-variate analysis and profile likelihood ratio techniques
- Investigation of exotic dark matter candidates. (MIMPs, 5.5 MeV solar axions, etc…)

Signal Saturation

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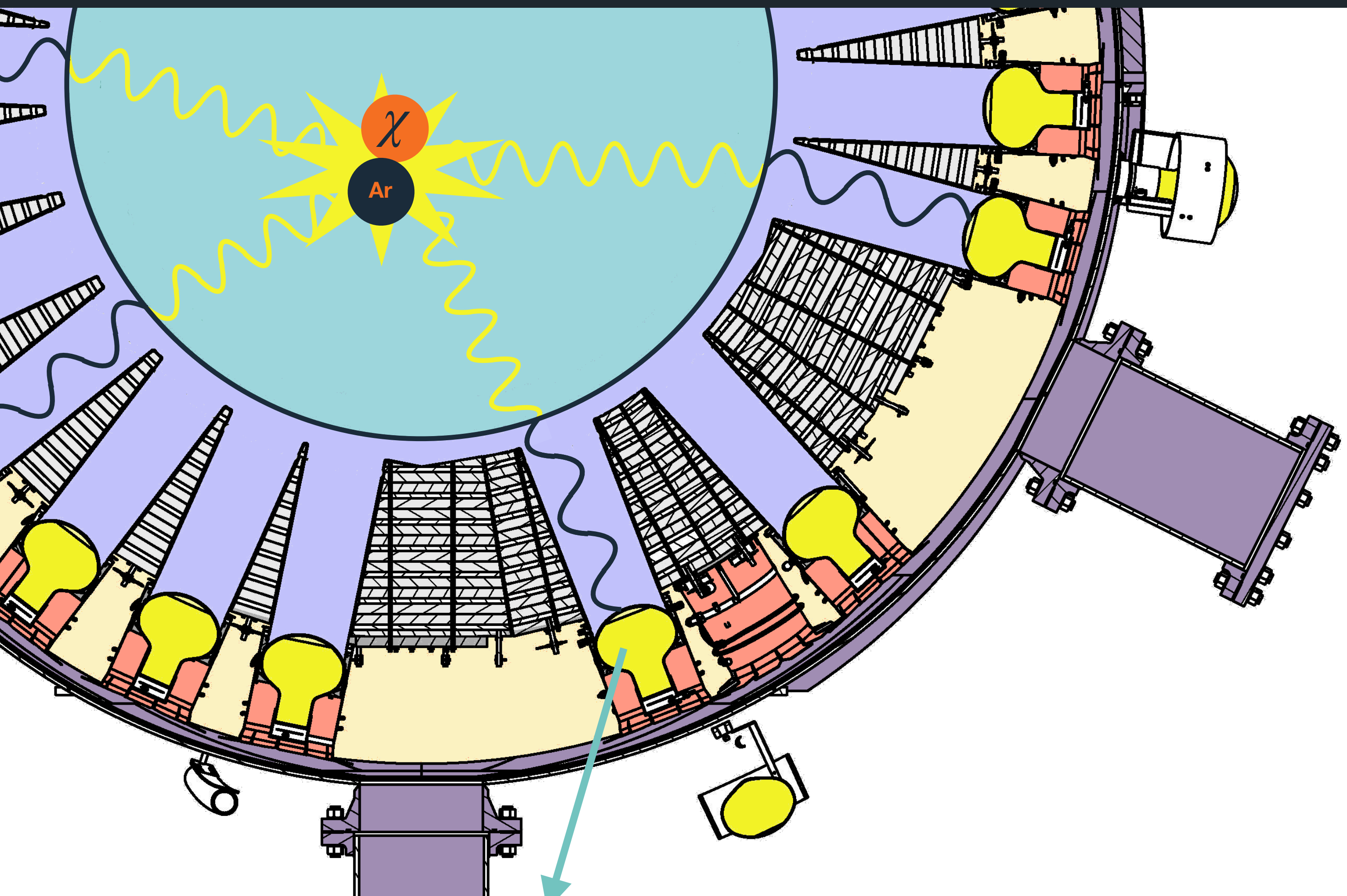
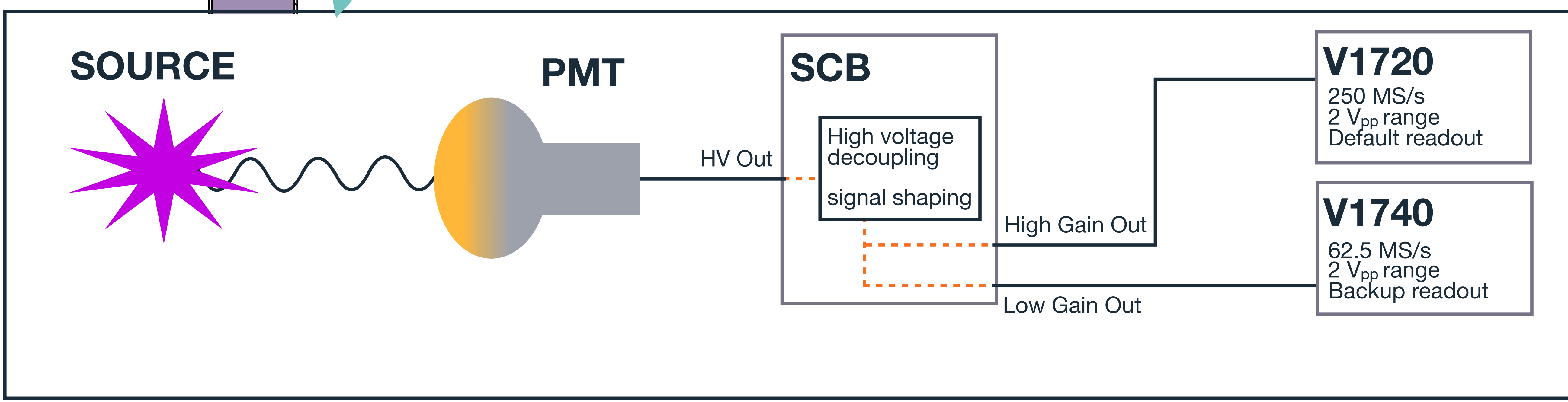


- DAQ infrastructure consists of three stages:
  1. **Photomultiplier Tubes (PMTs)**
  2. **Signal Conditioning Boards (SCBs)**
  3. **Digitizers (CAEN V1720/V1740 modules)**



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Signal Saturation

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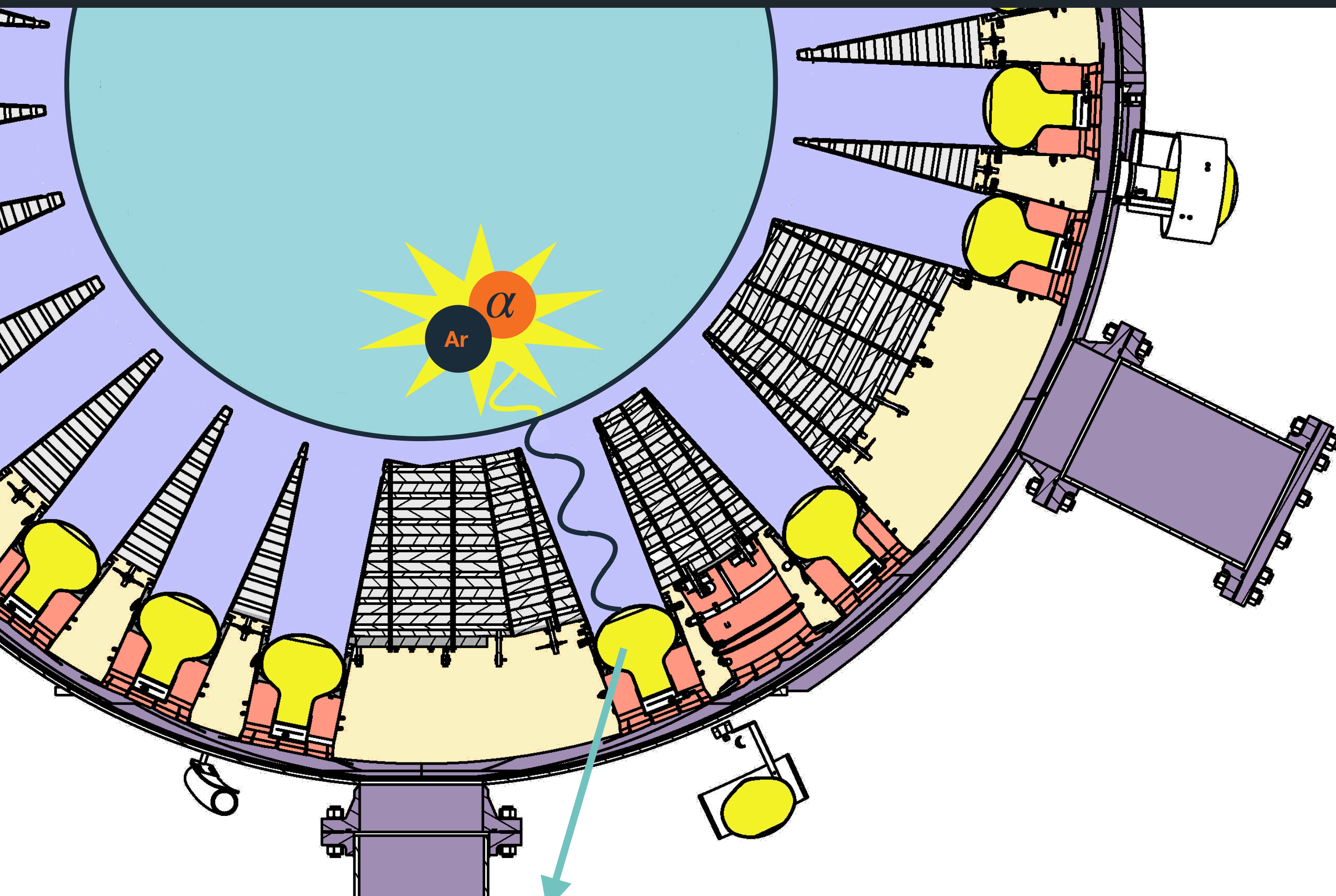
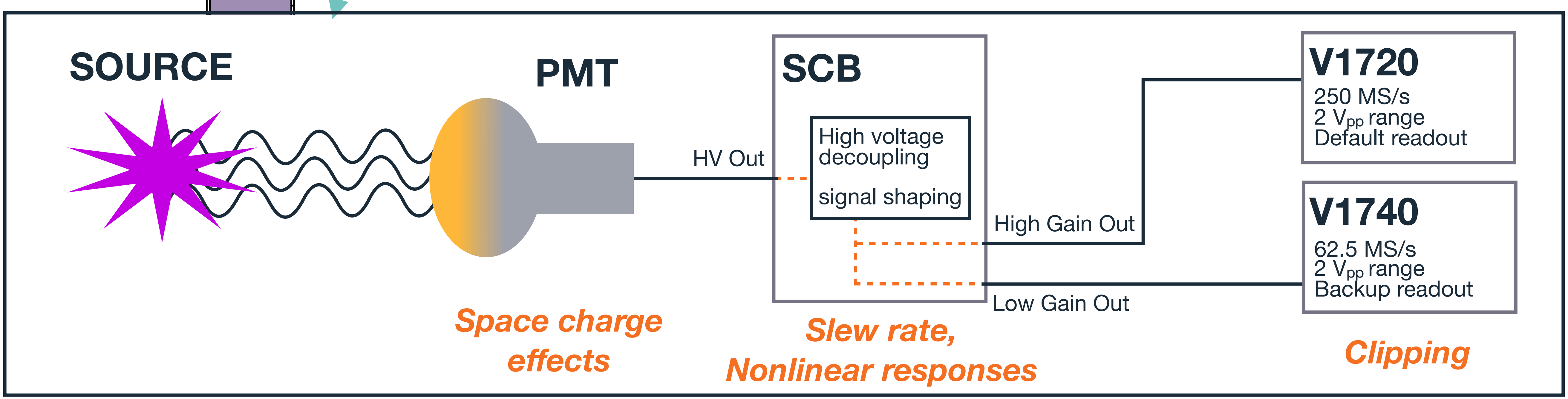


- Excessive light can push hardware into nonlinear or saturated regimes
- Any high energy or alpha related analyses are heavily affected
- Note: potential WIMP events are unaffected by saturation effects



Signal Saturation

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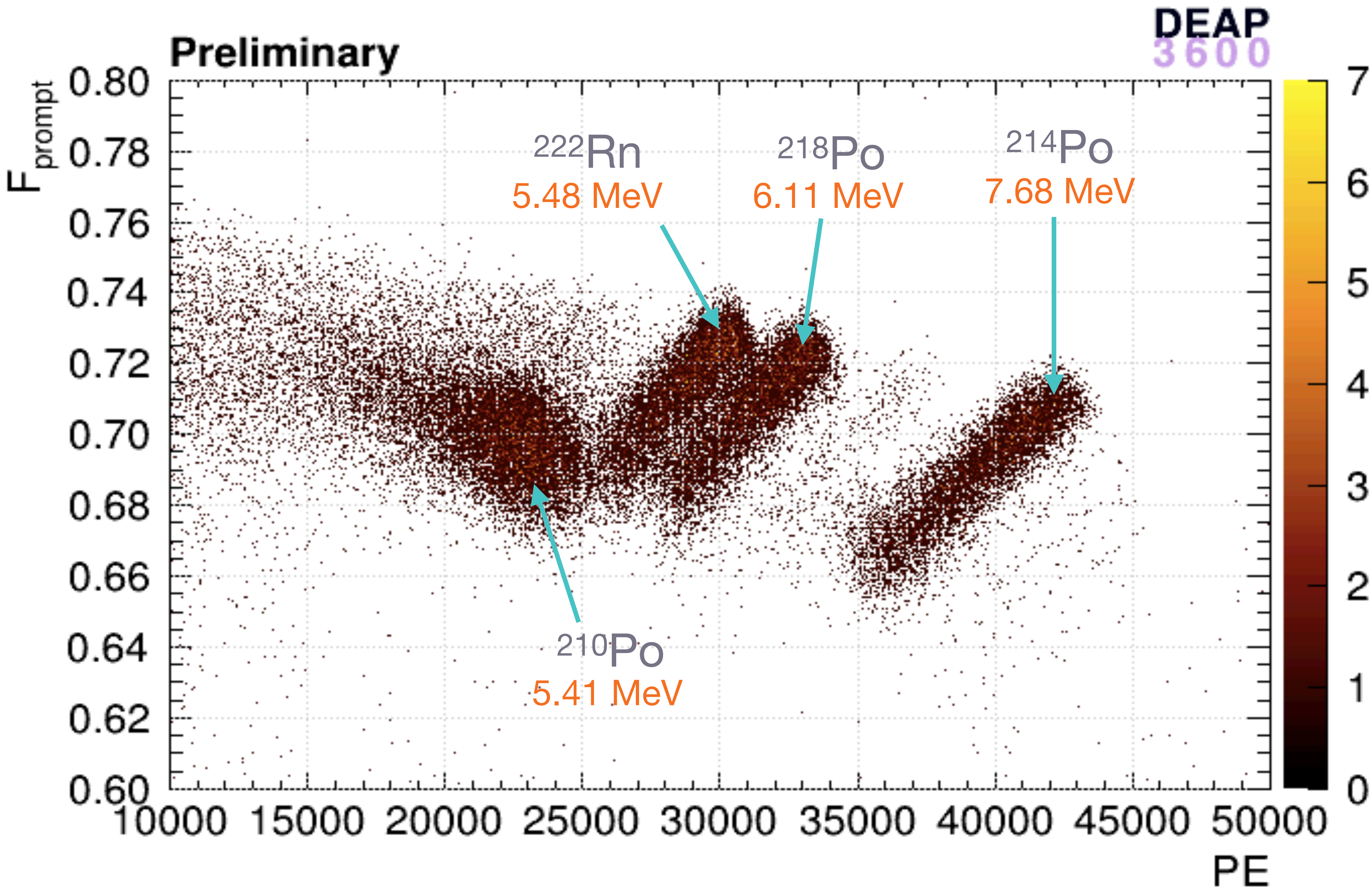
High Energy Surface and Bulk Alphas: Charge vs F_{prompt}



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Correction Method

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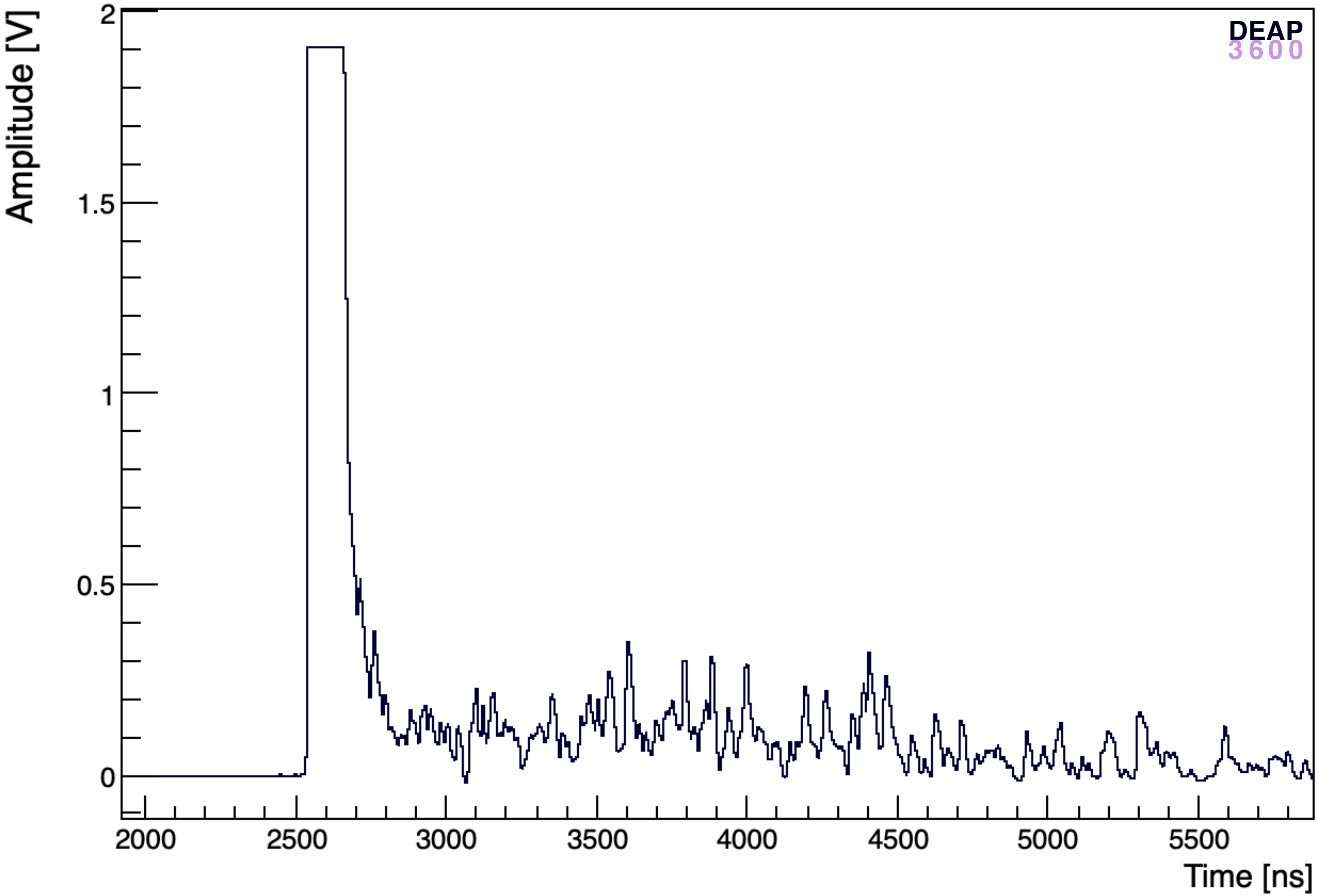

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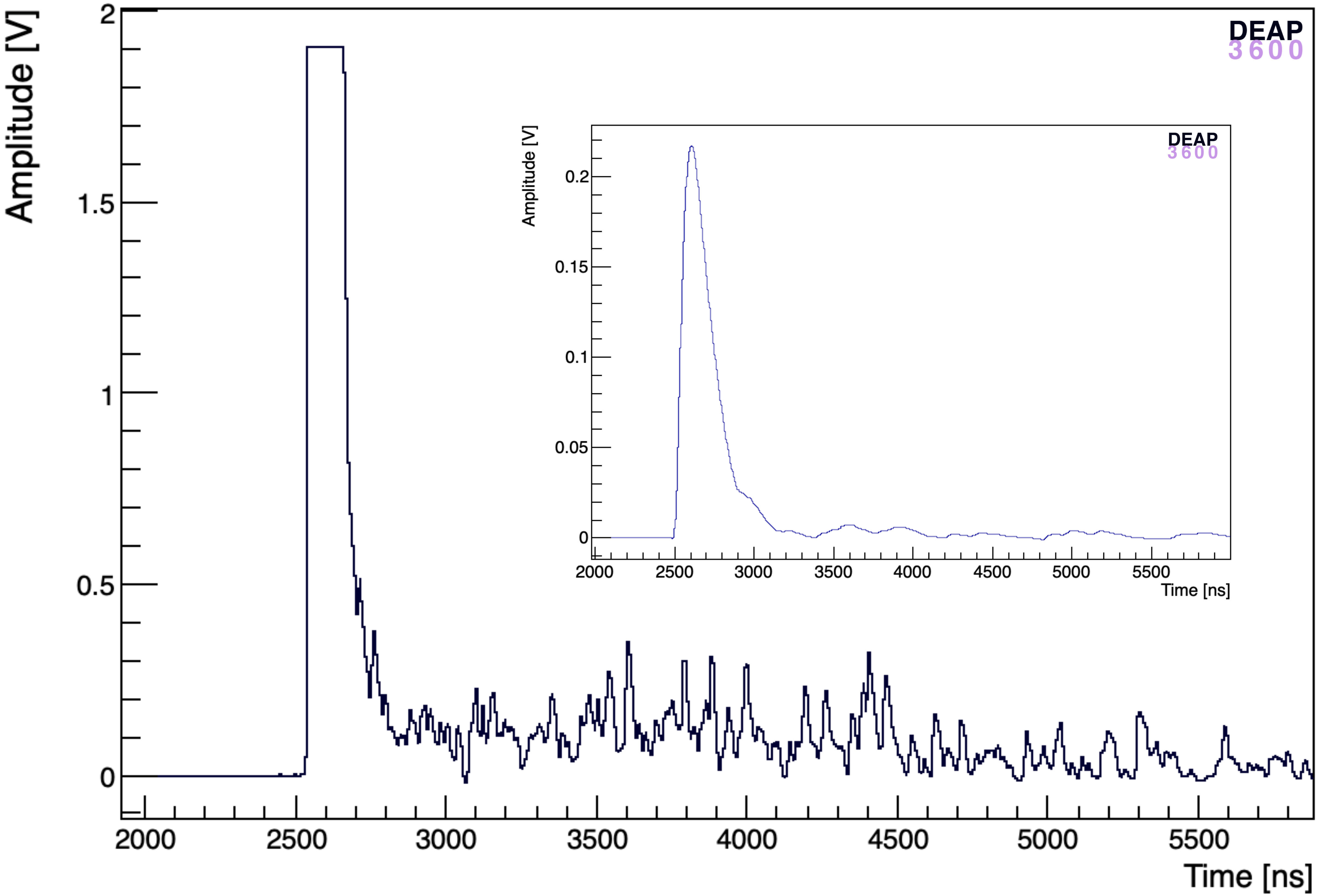
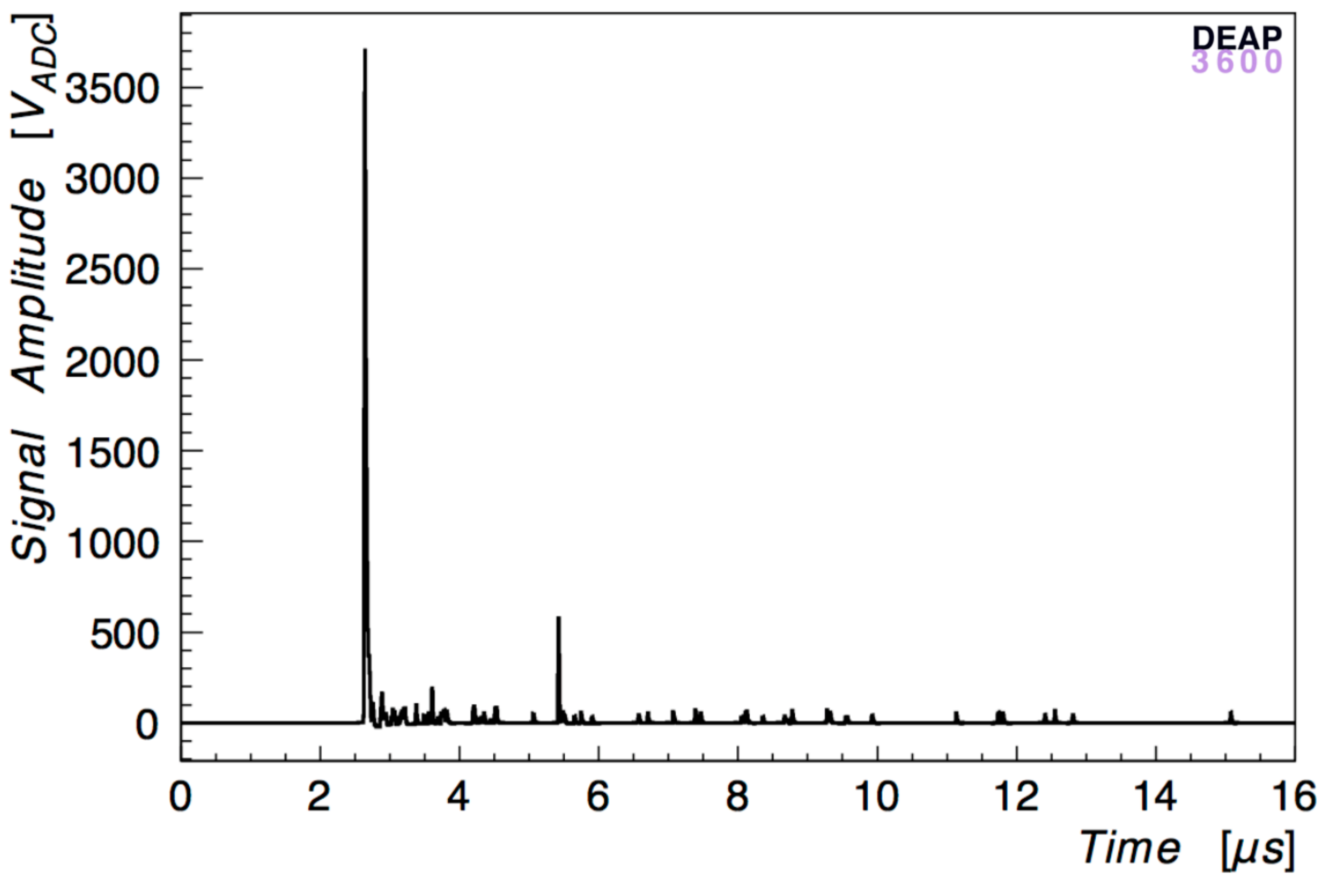
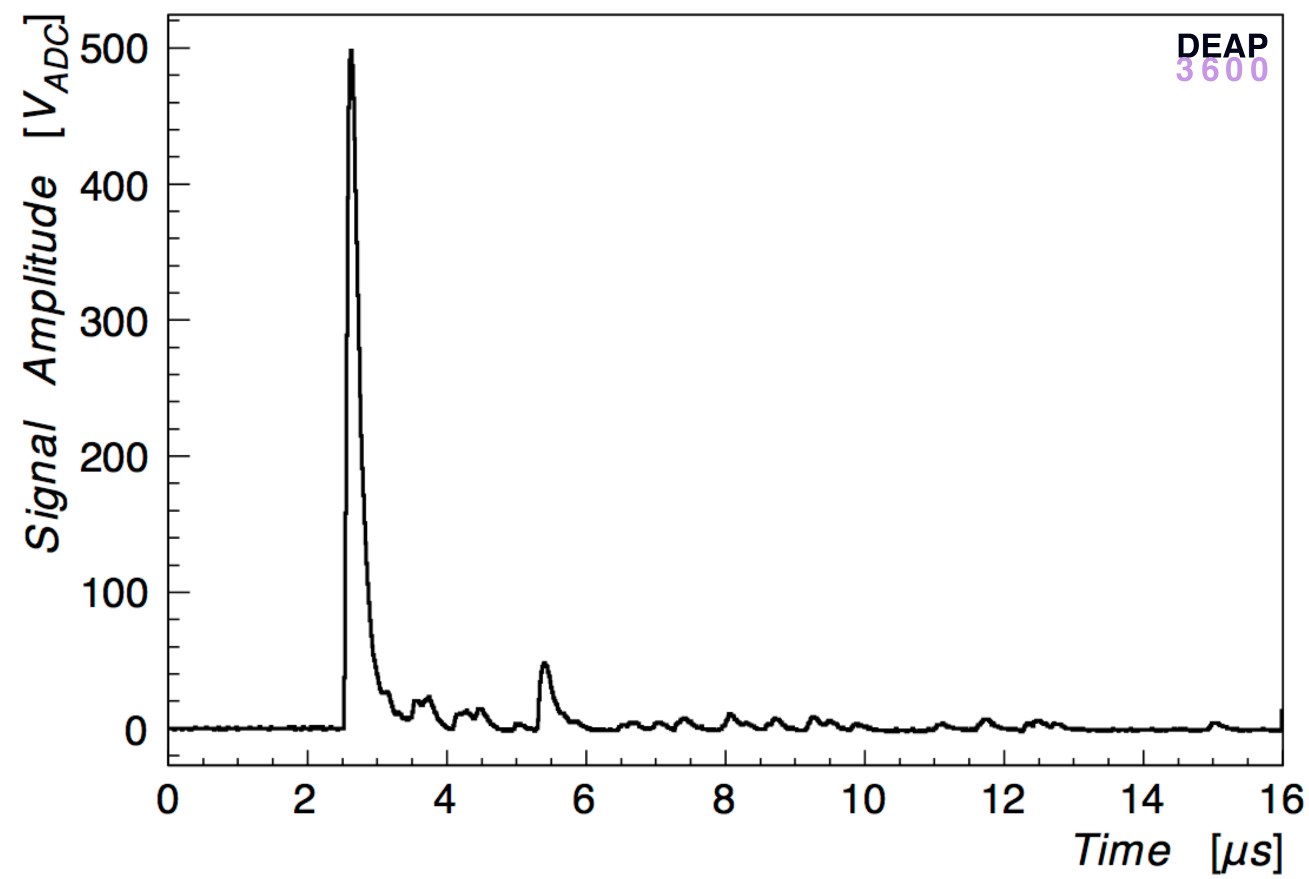


Correction Method

Alpha Raw High Gain Waveform



Alpha Raw Low Gain Waveform



- Low gain channel has broader pulses from more extensive SCB shaping than high gain channel
- Can we reconstruct high gain channel with low gain channel waveform?

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Correction Method

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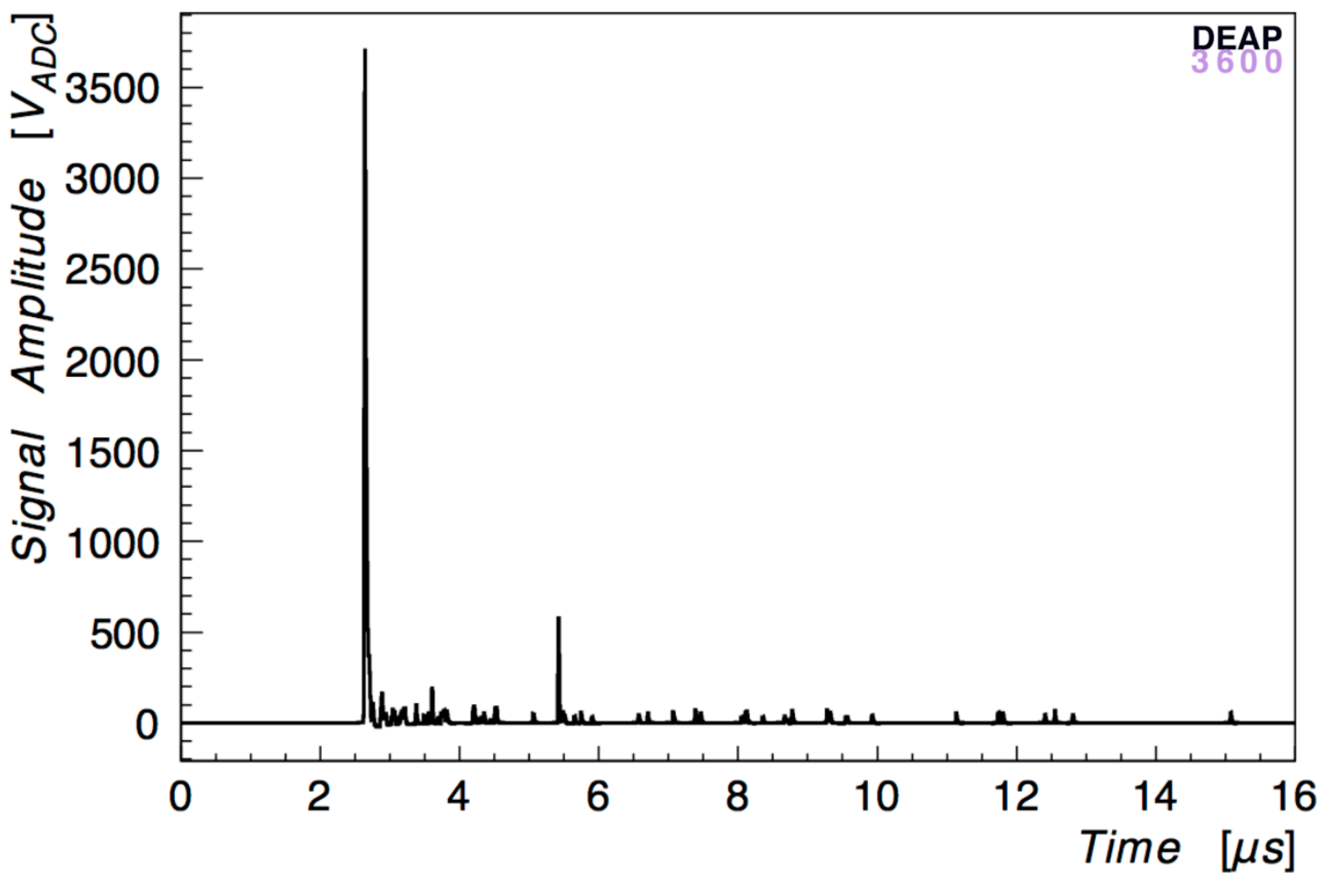
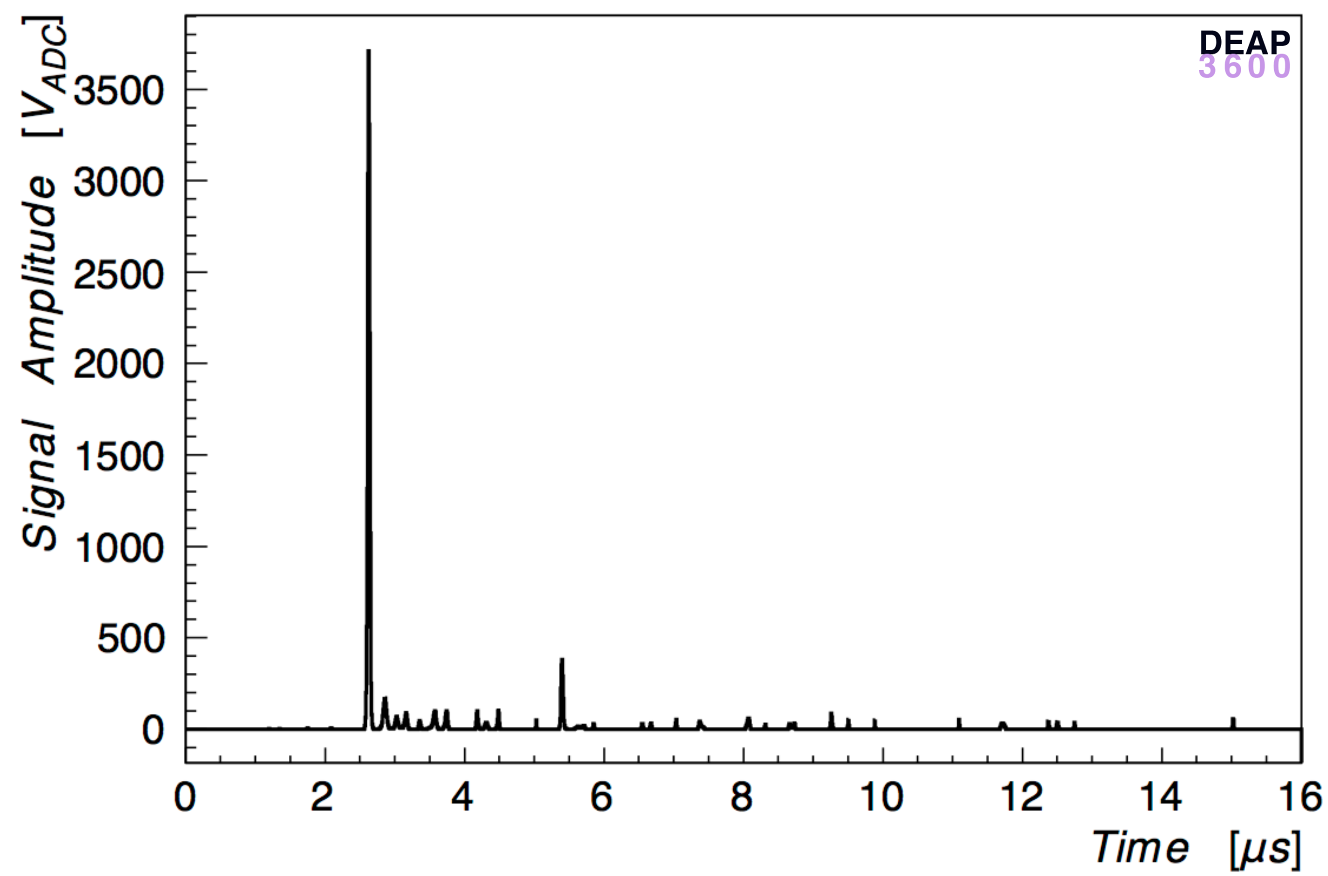
Alpha Raw High Gain Waveform



Alpha Processed Low Gain Waveform



- Deconvolution of the low gain channel waveforms greatly increases time resolution, allowing for complete reconstruction of clipped high gain channel pulses
- Reconstruction method validated with unclipped pulses, shows strong linear correlation in pulse charge

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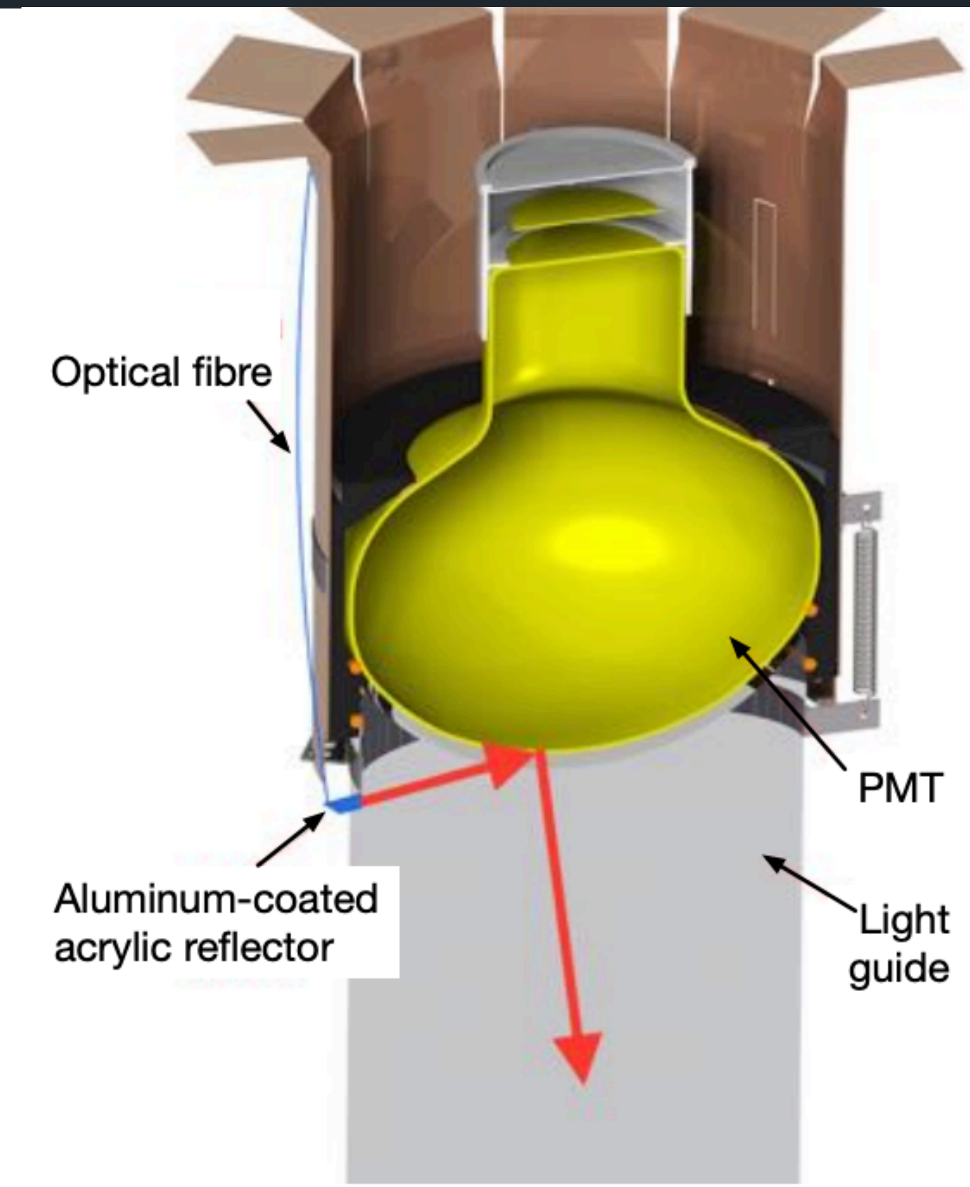
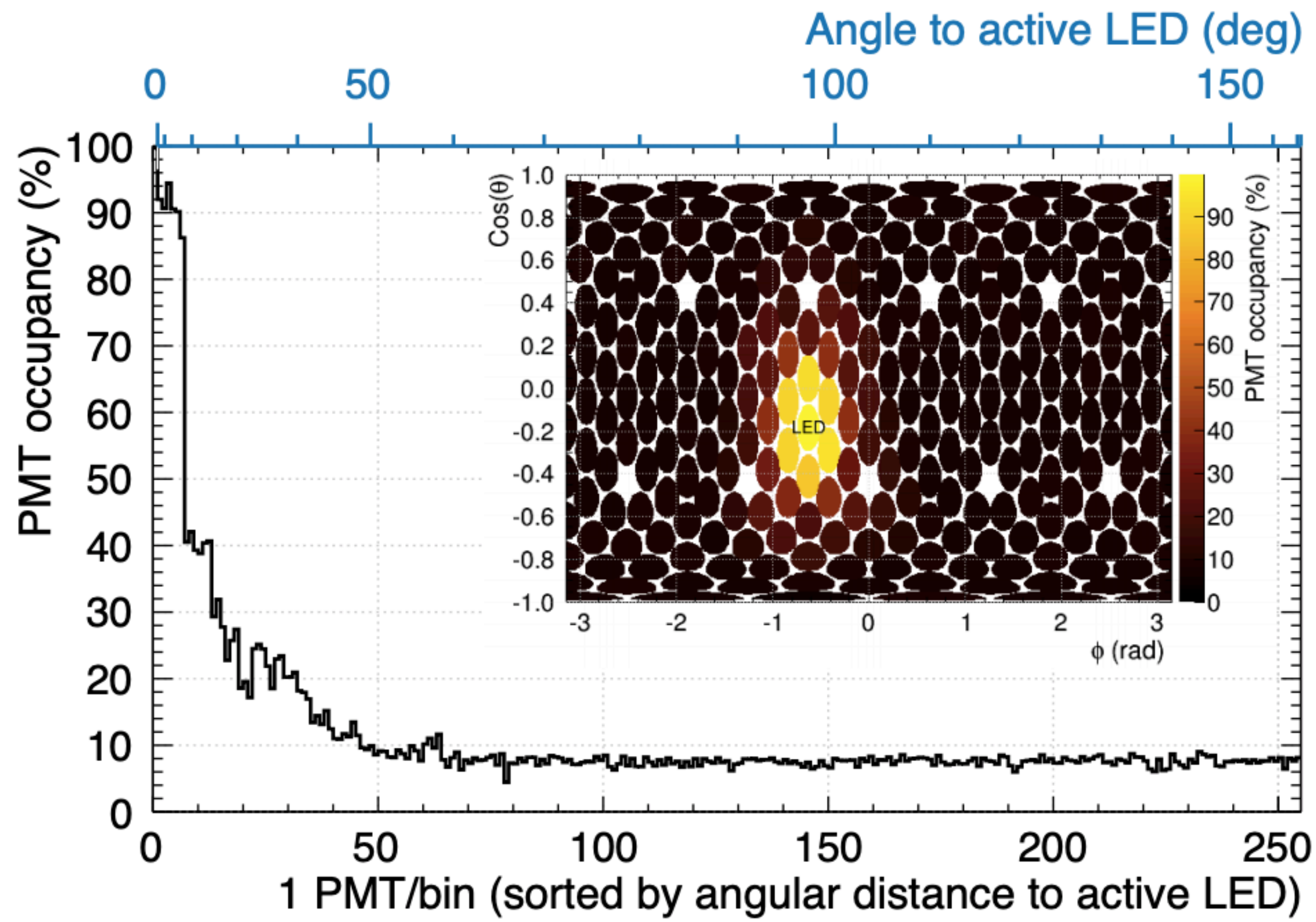
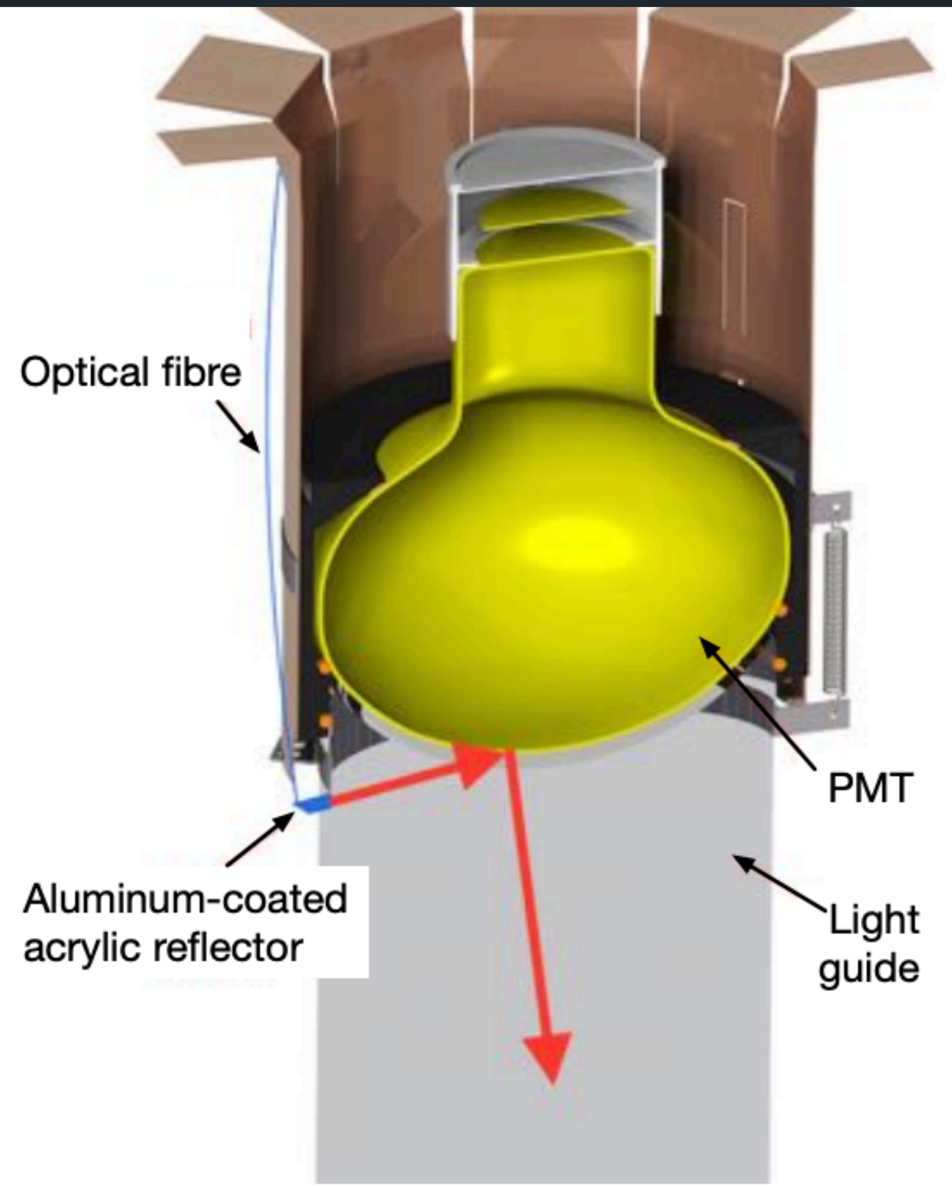
Correction Method

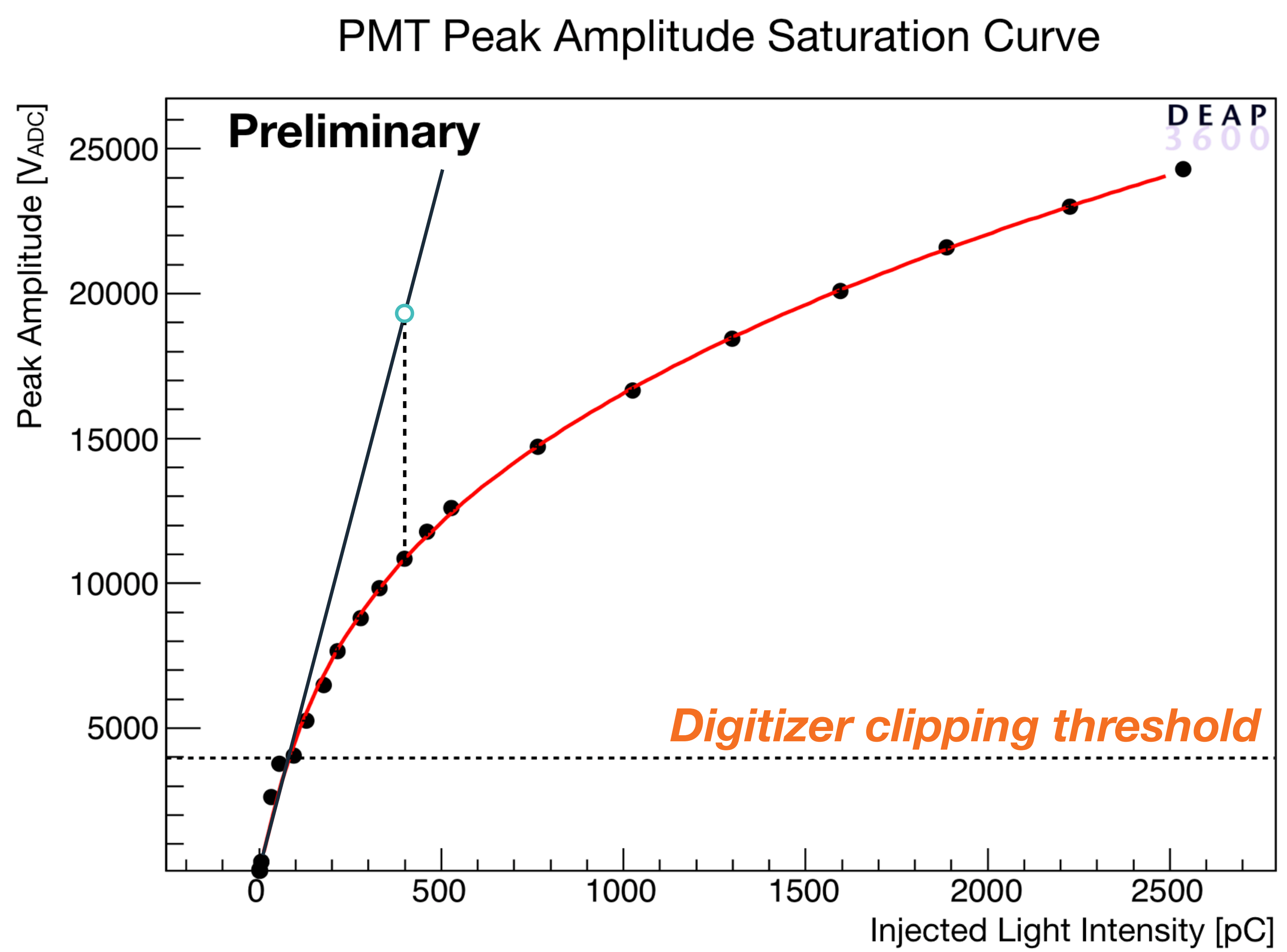




- Measure PMT saturation in-situ using LED light injection system
- Illuminated PMT is saturated while the furthest PMT responses remain linear
- Compare measured charge in illuminated PMT to integrated charge in 200 furthest PMTs

Correction Method





- Measure PMT saturation in-situ using LED light injection system
- Illuminated PMT is saturated while the furthest PMT responses remain linear
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PMT Saturation

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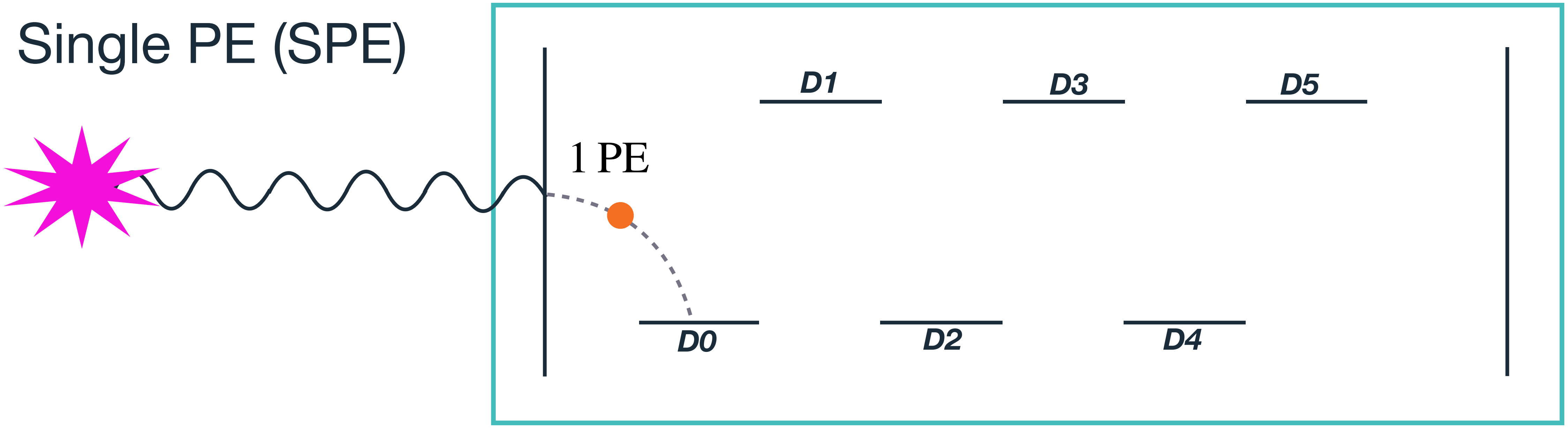
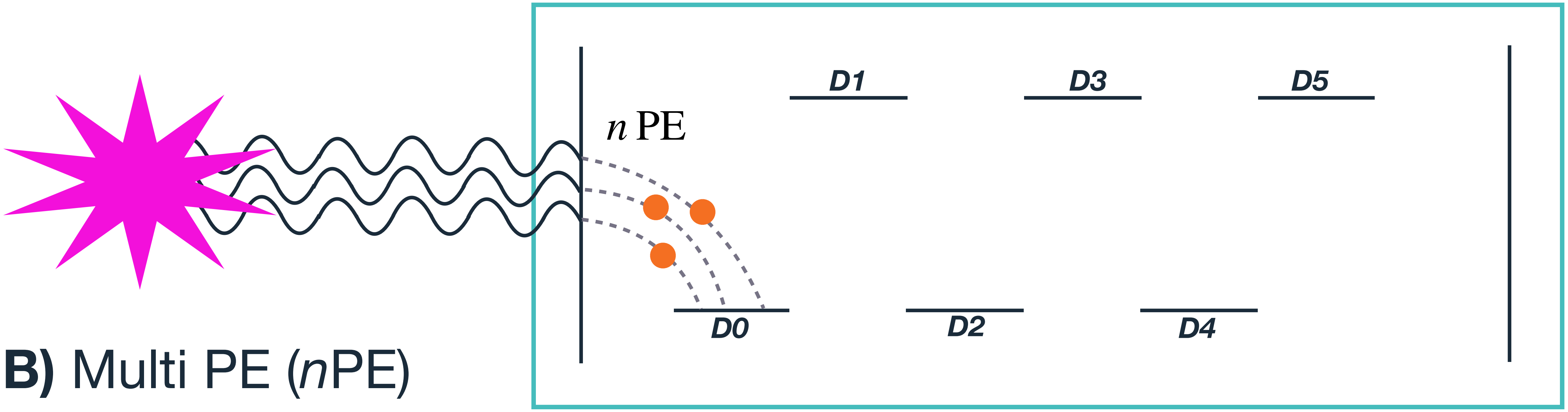
A) Single PE (SPE)



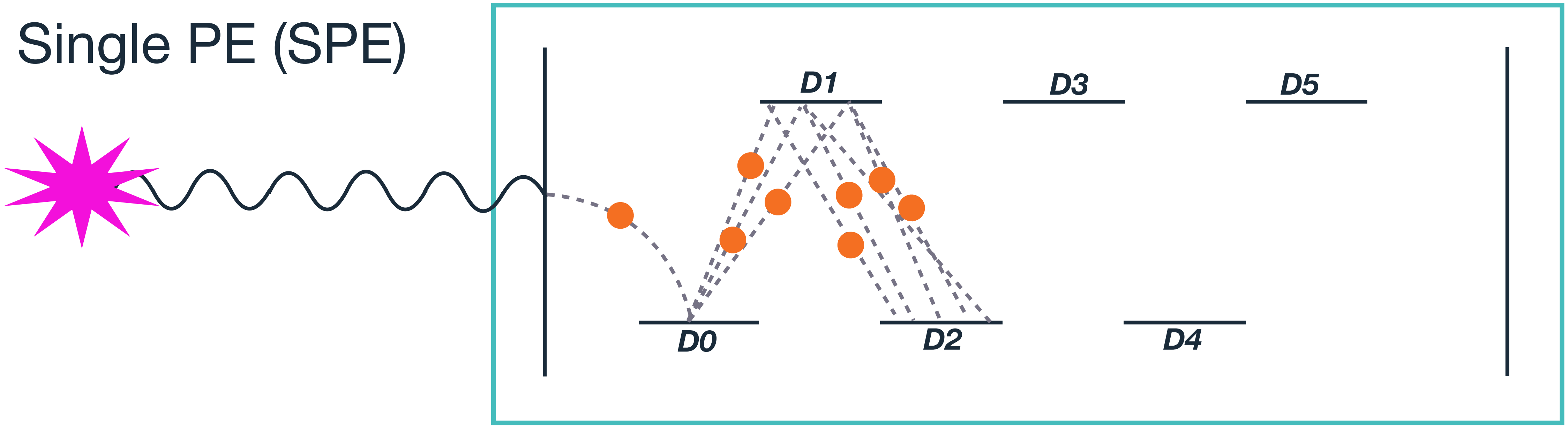
We expect output of case (B) to be *n* times that of case (A)



B) Multi PE (*n*PE)

PMT Saturation

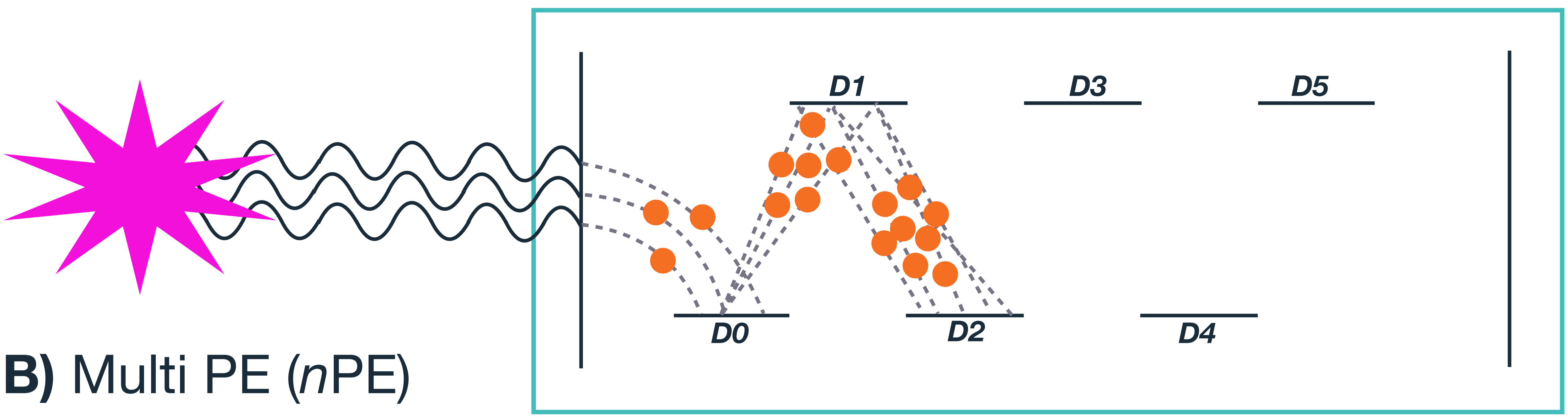
A) Single PE (SPE)



Initially charge growth in both cases is exponential

$$V_{01}^{SPE} = V_{01}^{nPE}$$

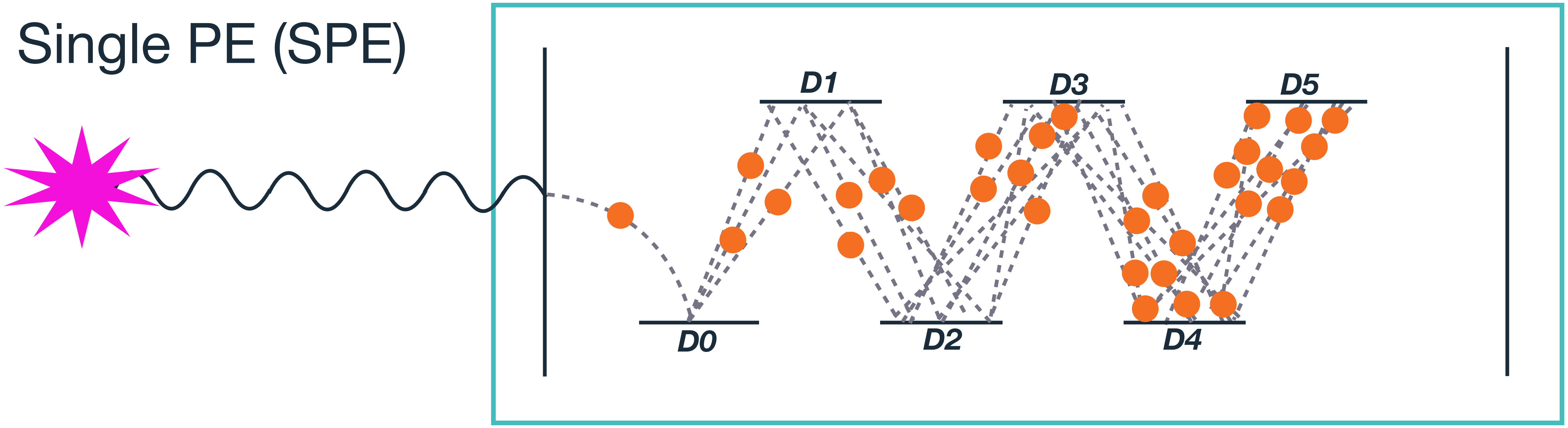
$$V_{12}^{SPE} \approx V_{12}^{nPE}$$



B) Multi PE (*n*PE)

PMT Saturation

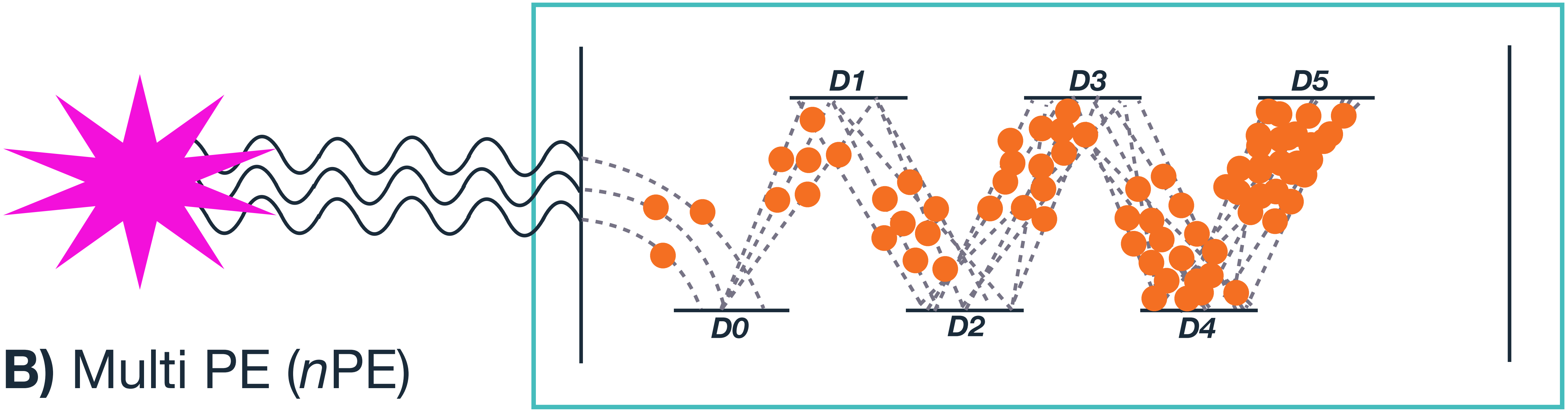
A) Single PE (SPE)



Electron cloud in case (B) screens trailing ones; lowers gain in last dynodes

$$V_{34}^{SPE} < V_{34}^{nPE}$$

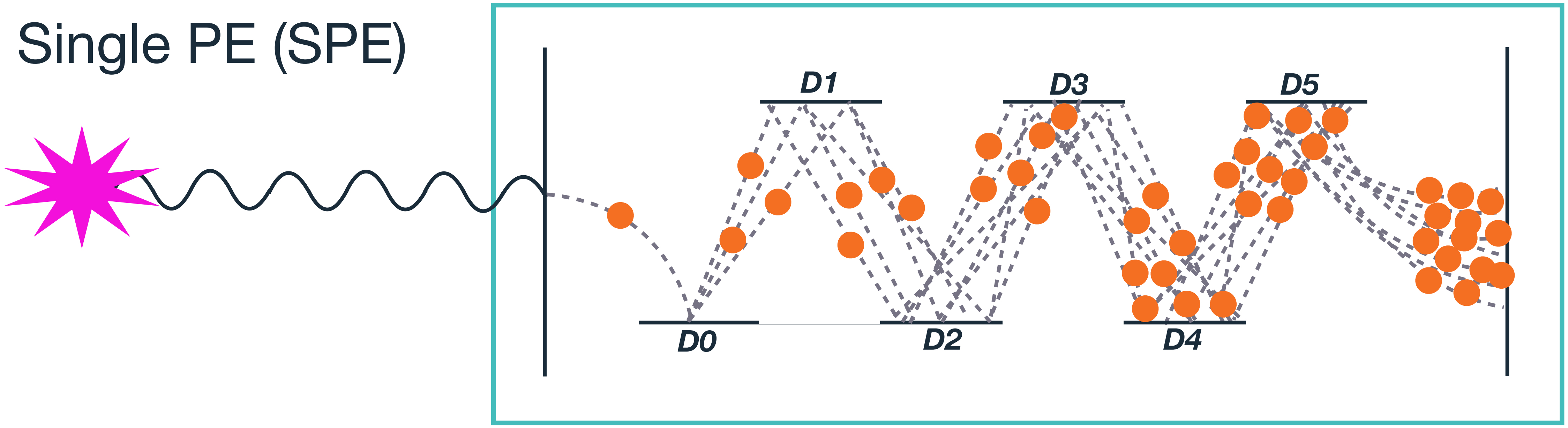
$$V_{45}^{SPE} \ll V_{45}^{nPE}$$



B) Multi PE (*n*PE)

PMT Saturation

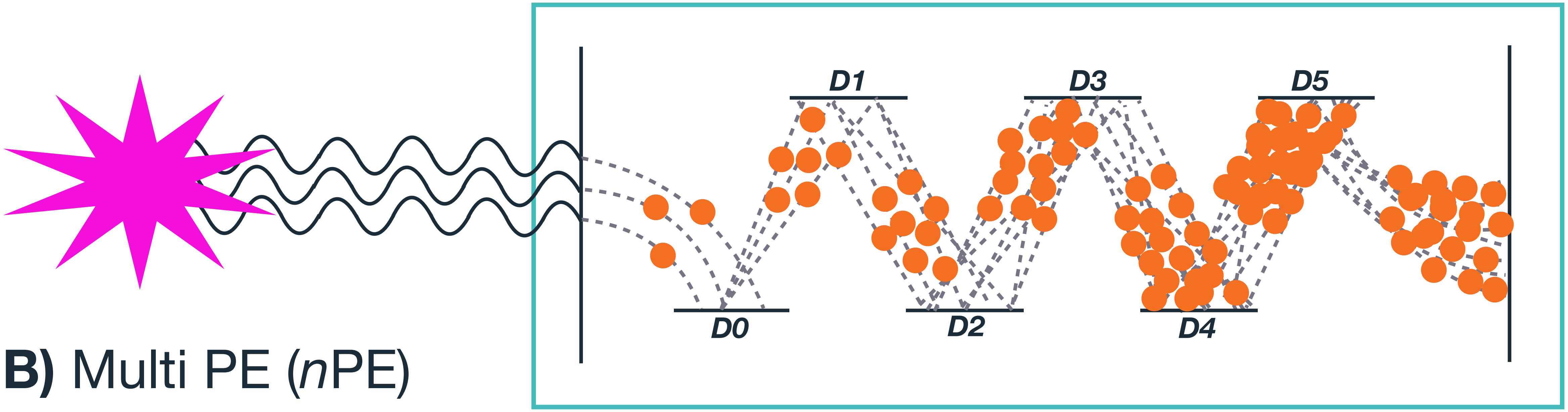
A) Single PE (SPE)



Q_A

This results in nonlinear relationship between cases (A) and (B)

$Q_B < nQ_A$

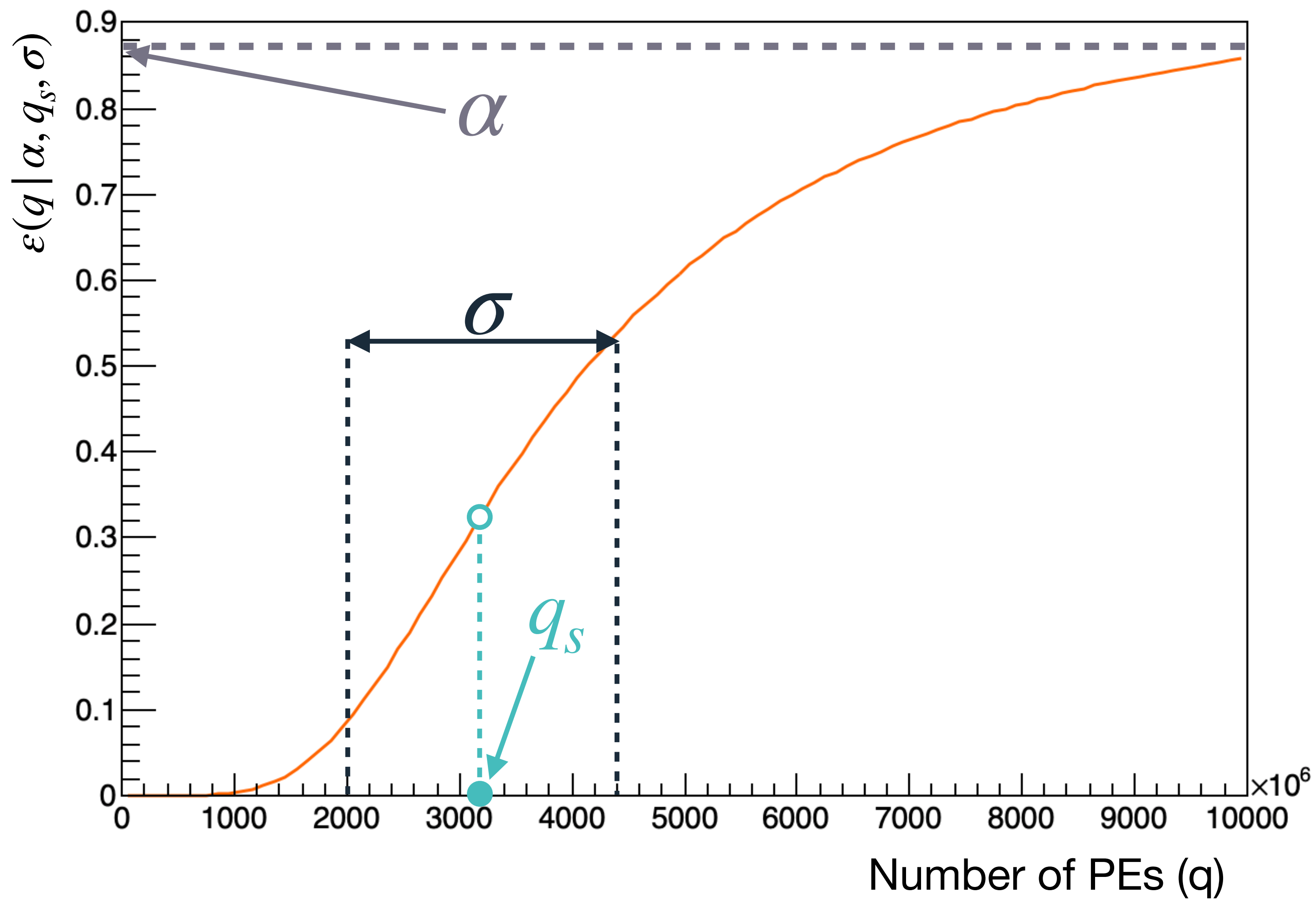


Q_B

B) Multi PE (*n*PE)

PMT Saturation

- This physical process informs the PMT saturation model used in the correction scheme
- Integrate charge as it accumulates from dynode to dynode in the PMT while reducing the gain as space charge effects increase



$$\mathcal{Q} = q_0 + \sum_{i=1}^{10} q_i \quad \left\{ \begin{aligned} q_{i+1} &= q_i + \Delta q \\ \Delta q &= \mathrm{G}\left(1 - \varepsilon\right) q_i \\ \varepsilon &\equiv \varepsilon(q_i \,|\, \alpha, q_s, \sigma) \end{aligned} \right.$$

Performance

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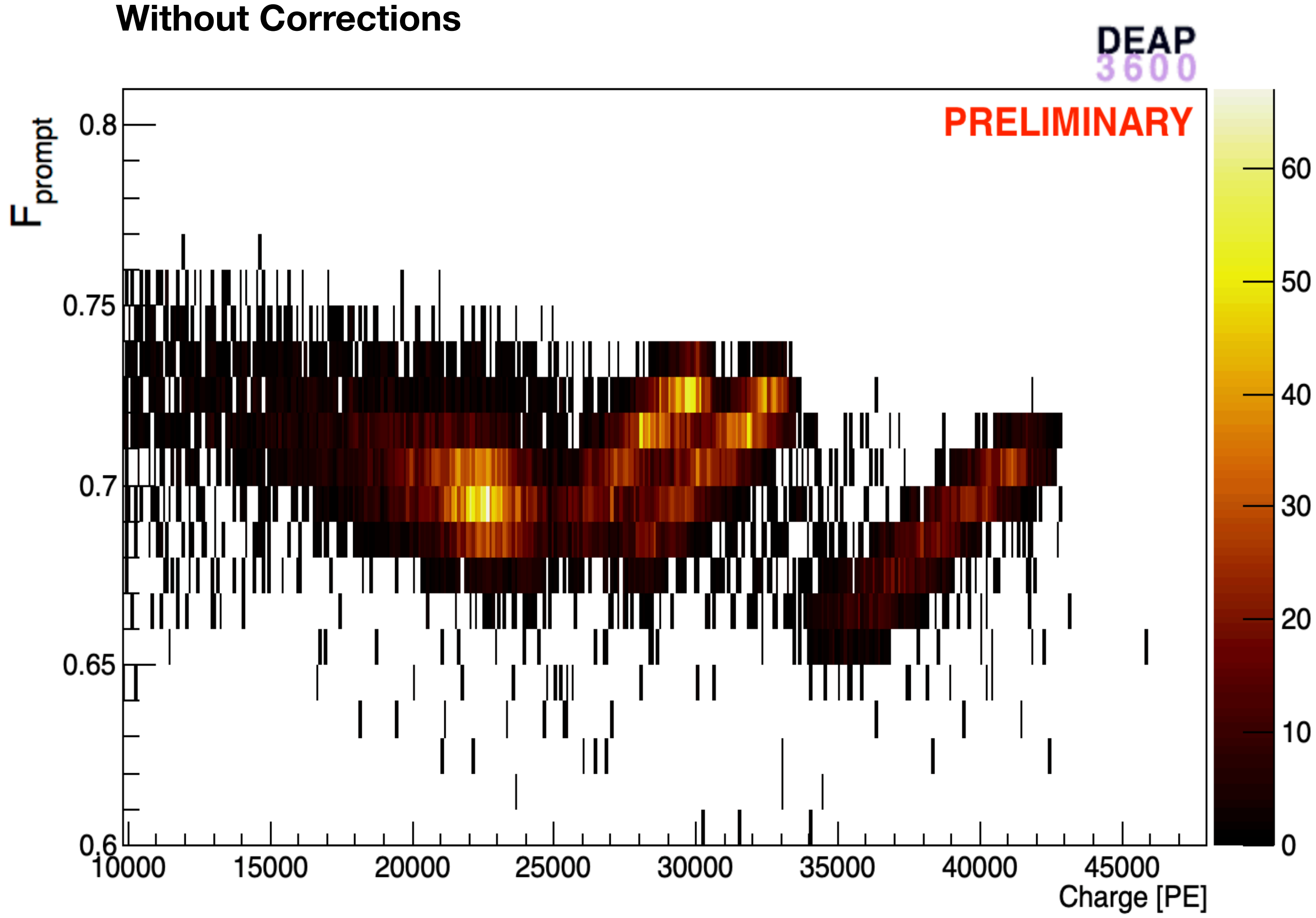
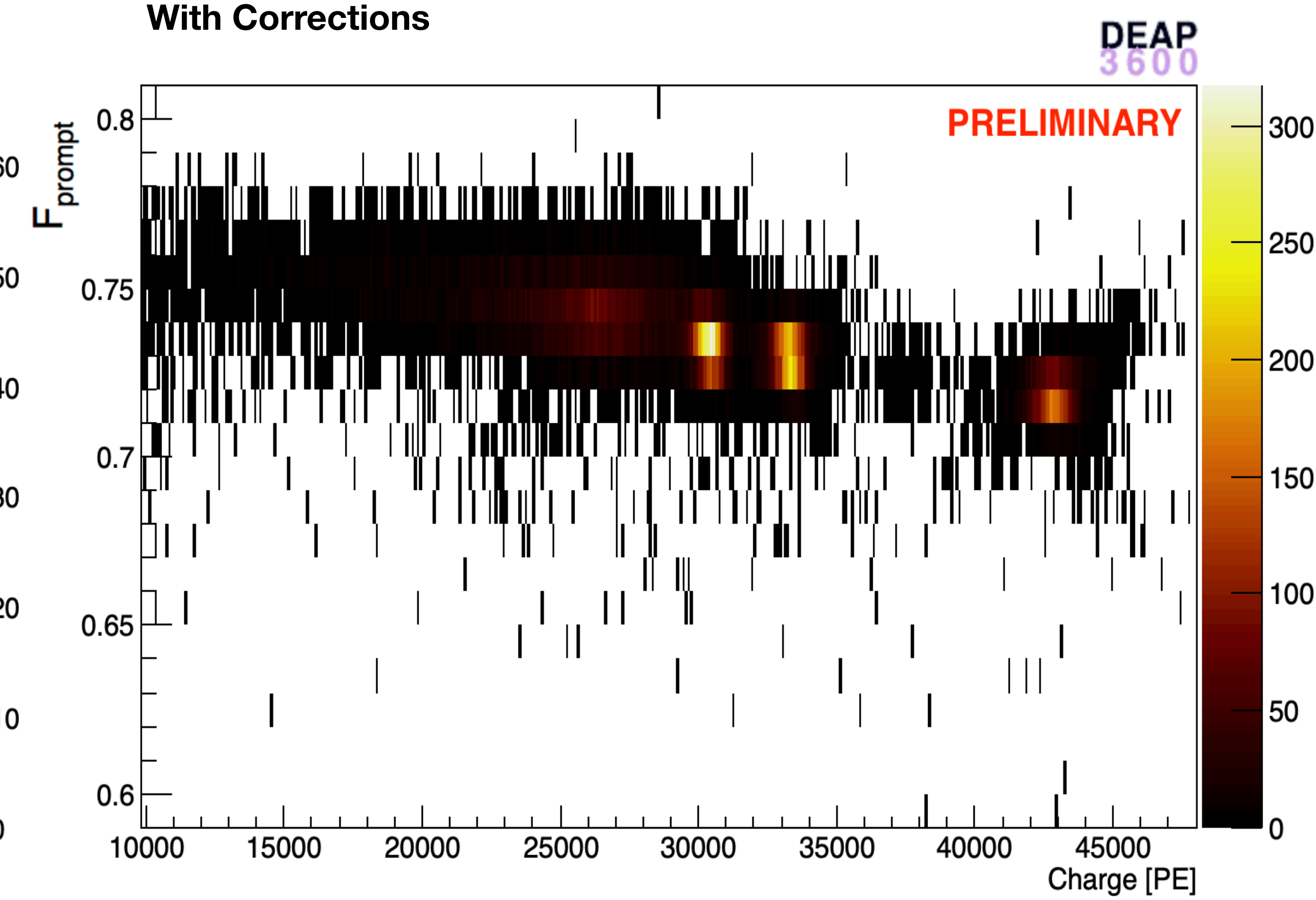
High Energy Surface and Bulk Alphas: Charge vs F_{prompt}
Without Corrections



High Energy Surface and Bulk Alphas: Charge vs F_{prompt}
With Corrections



- Digitizer clipping and PMT nonlinearity corrections eliminate the effects seen in the alphas originating from LAr bulk
- Results in accurate estimation of deposited energy from alphas in LAr

Conclusions

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Importance of having corrected data

- High energy analyses are prohibitively difficult without having corrected data
- Having corrected data will generally help improve energy and position reconstruction over wider energy range

What can we look at now?

- Alpha scintillation physics in LAr can now be more closely analyzed (e.g. quenching effects)
- Improved characterization of surface backgrounds for future analysis using profile likelihood ratio and multi-variate analyses