Purity Monitoring for ProtoDUNE-SP

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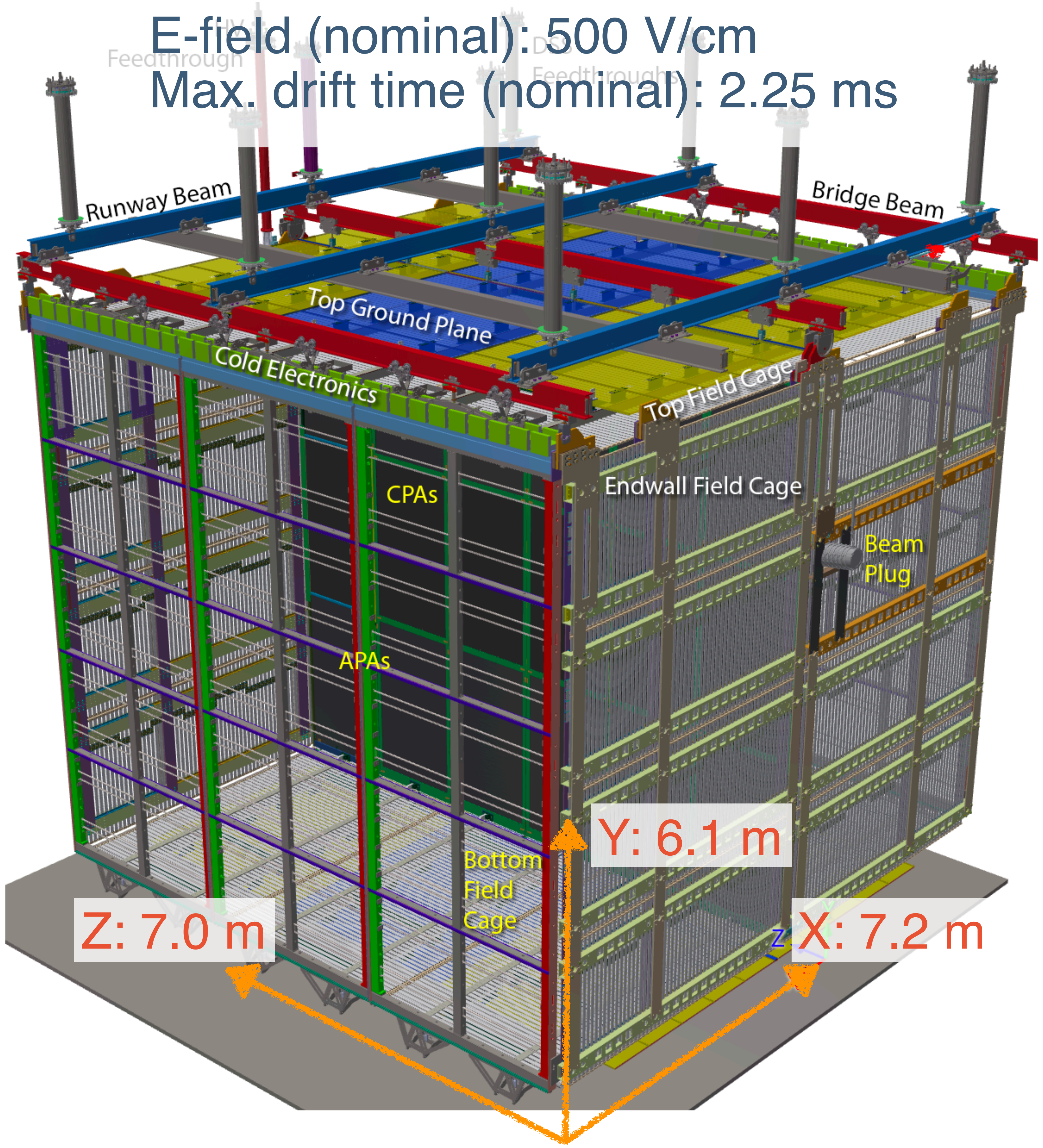
DUNE and ProtoDUNE-SP

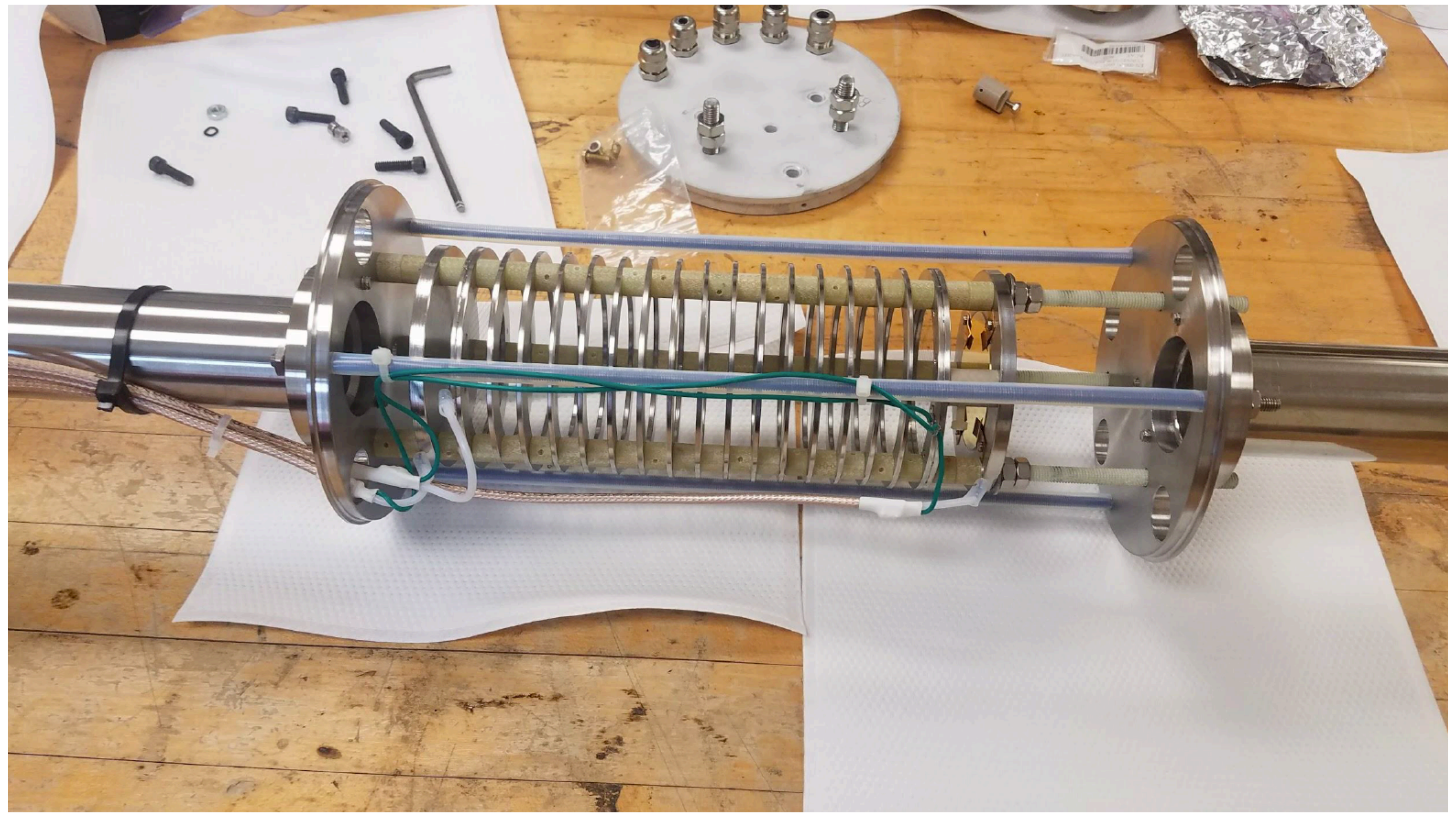
- DUNE is a next-generation long-baseline neutrino oscillation experiment based on liquid argon TPC (LArTPC) technology.
- ProtoDUNE-SP is the single-phase prototype of DUNE at CERN, which finished its 2-year Phase-I running in July 2020.
- LAr impurities (e.g. O_2, H_2O) capture the ionized electrons, therefore lower and bias the measured charge.
- A large value of the drift electron lifetime corresponds to higher liquid argon purity.

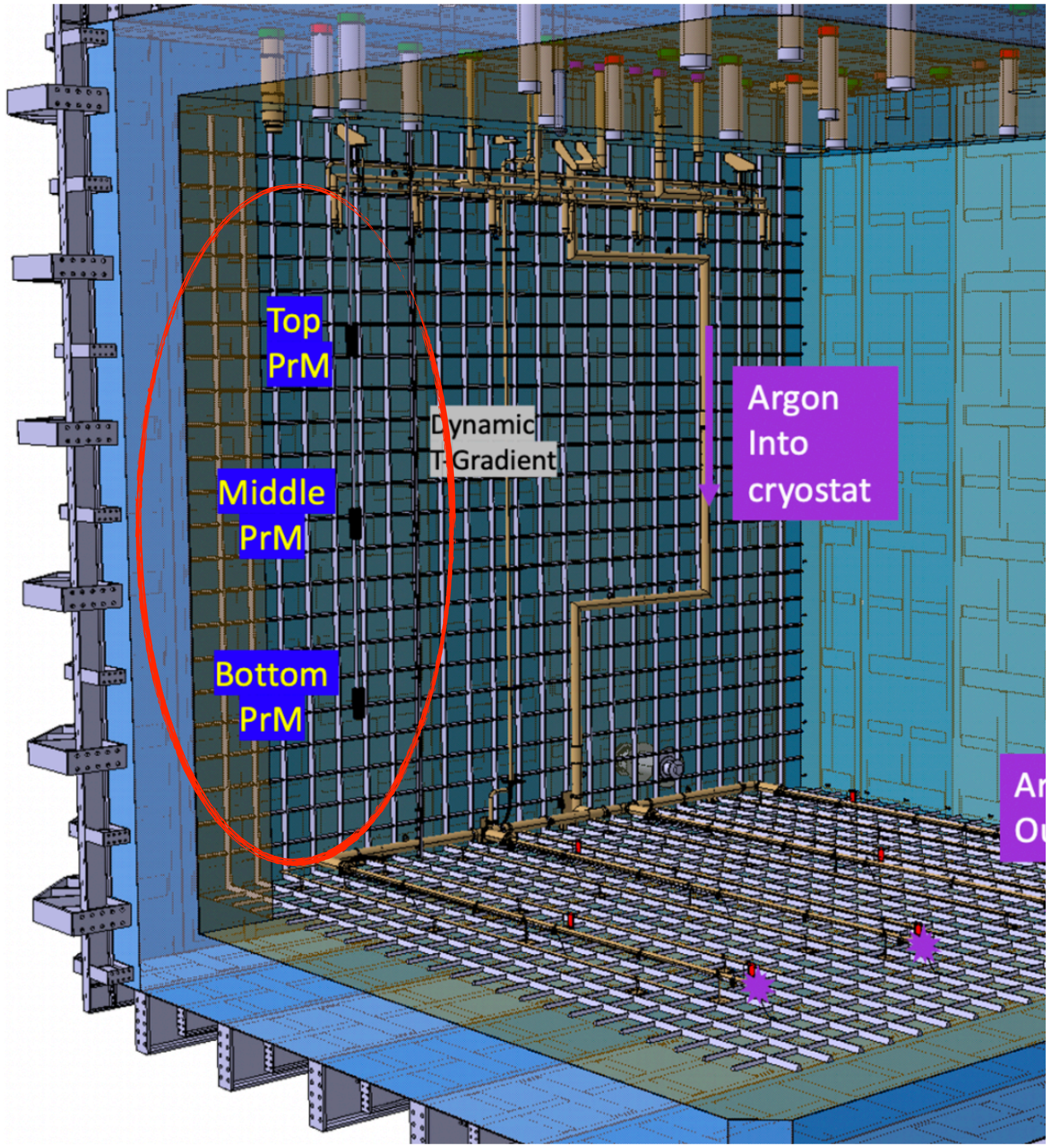


Schematic of ProtoDUNE-SP

Purity monitor

- A miniature TPC to measure the lifetime of drift electrons.
- ProtoDUNE-SP-I has 3 PrMs located inside the cryostat, outside the field cage, with the same length 25 cm.





Principle of the purity monitor

- It actively generates electrons by shinning light on the photocathode.
- The attenuation of the charge from the cathode to the anode gives the lifetime of drift electrons in the liquid.
  - Small statistical error: many flashes per measurement
  - Small space charge effect: small active volume

Charge measured at the anode/cathode

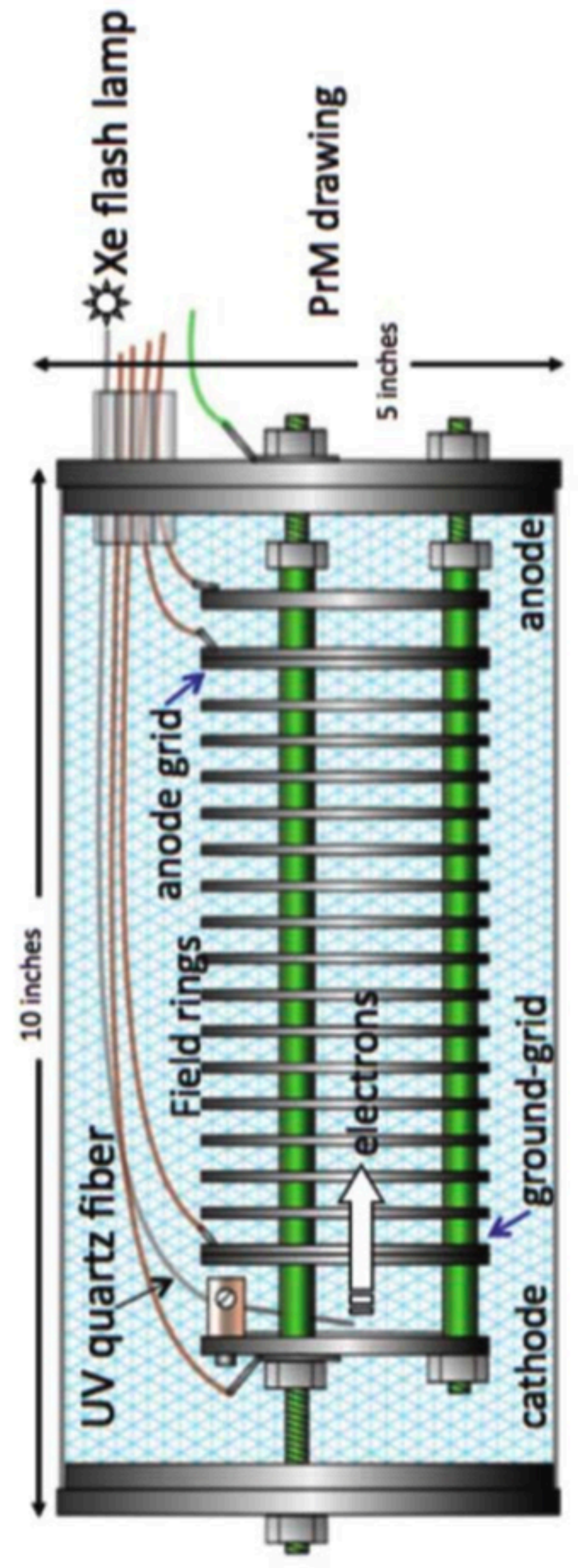
Drift time of electrons between the anode and the cathode

$$Q_A/Q_C = e^{-t_{\mathrm{drift}}/\tau}$$

Lifetime of the drifting electrons → gives the concentration of impurities

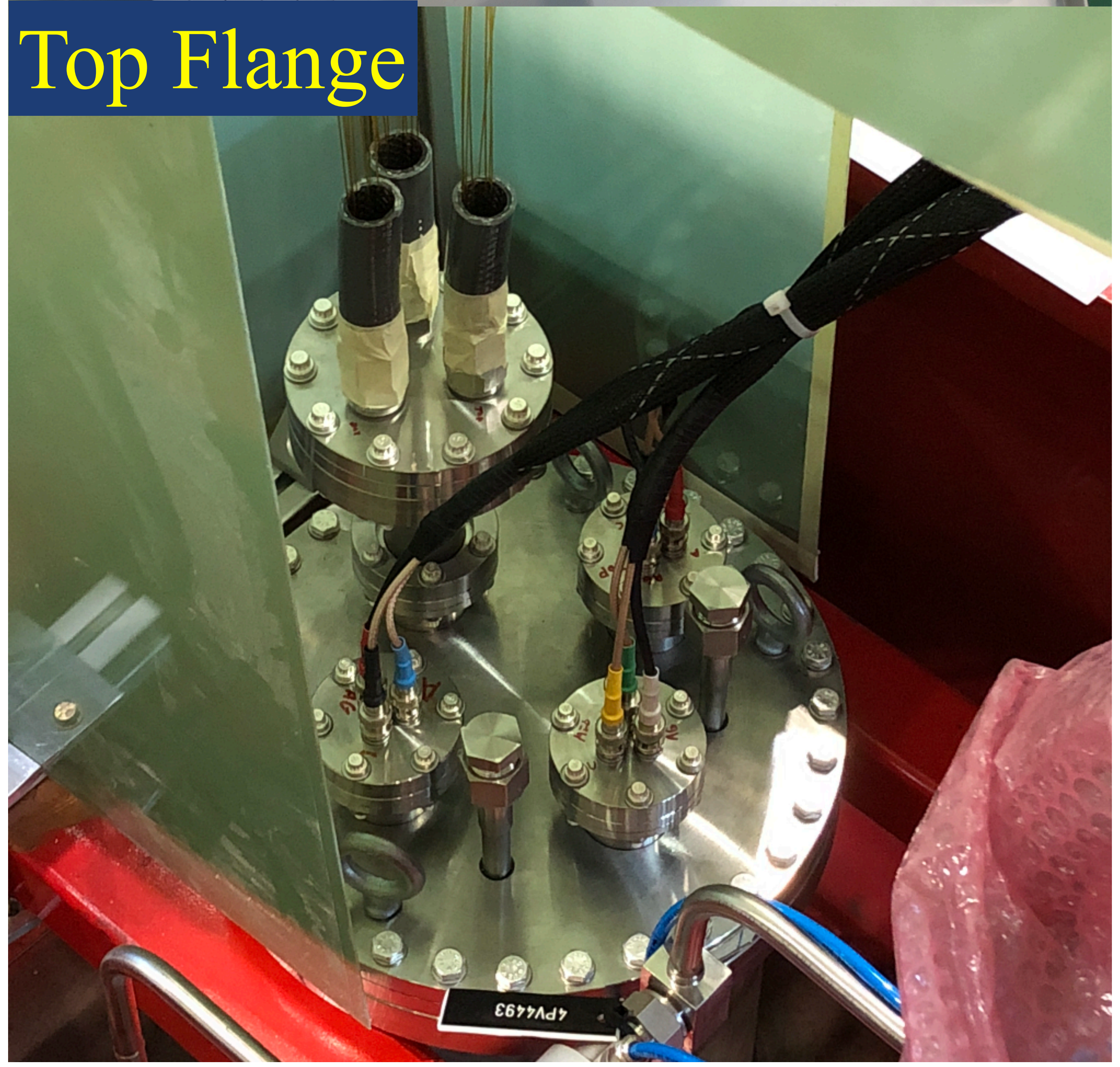
Components of the purity monitor

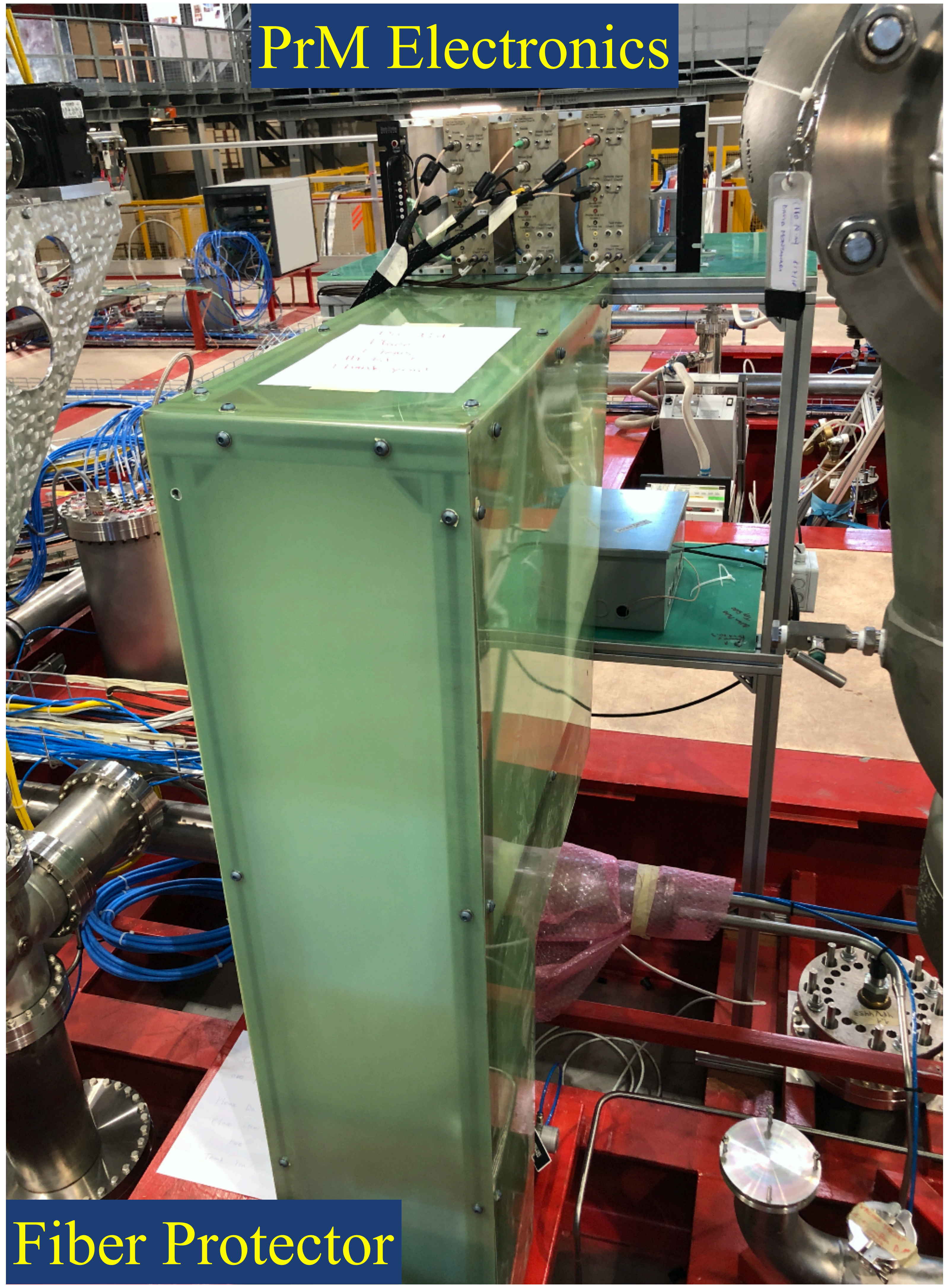
- Xe flash lamp light source
- Al-Ti-Au photocathode for drift electron generation
- Cathode/anode grids for charge screening at readout
  - Transparency/Inefficiency: determined by the geometry of the grids and E-fields settings
- Accelerator rings (Field rings) for field-shaping to give an uniform electric field in the drift volume



M. Adamowski et al., JINST 9, P07005 (2014).

Assembly in ProtoDUNE-SP



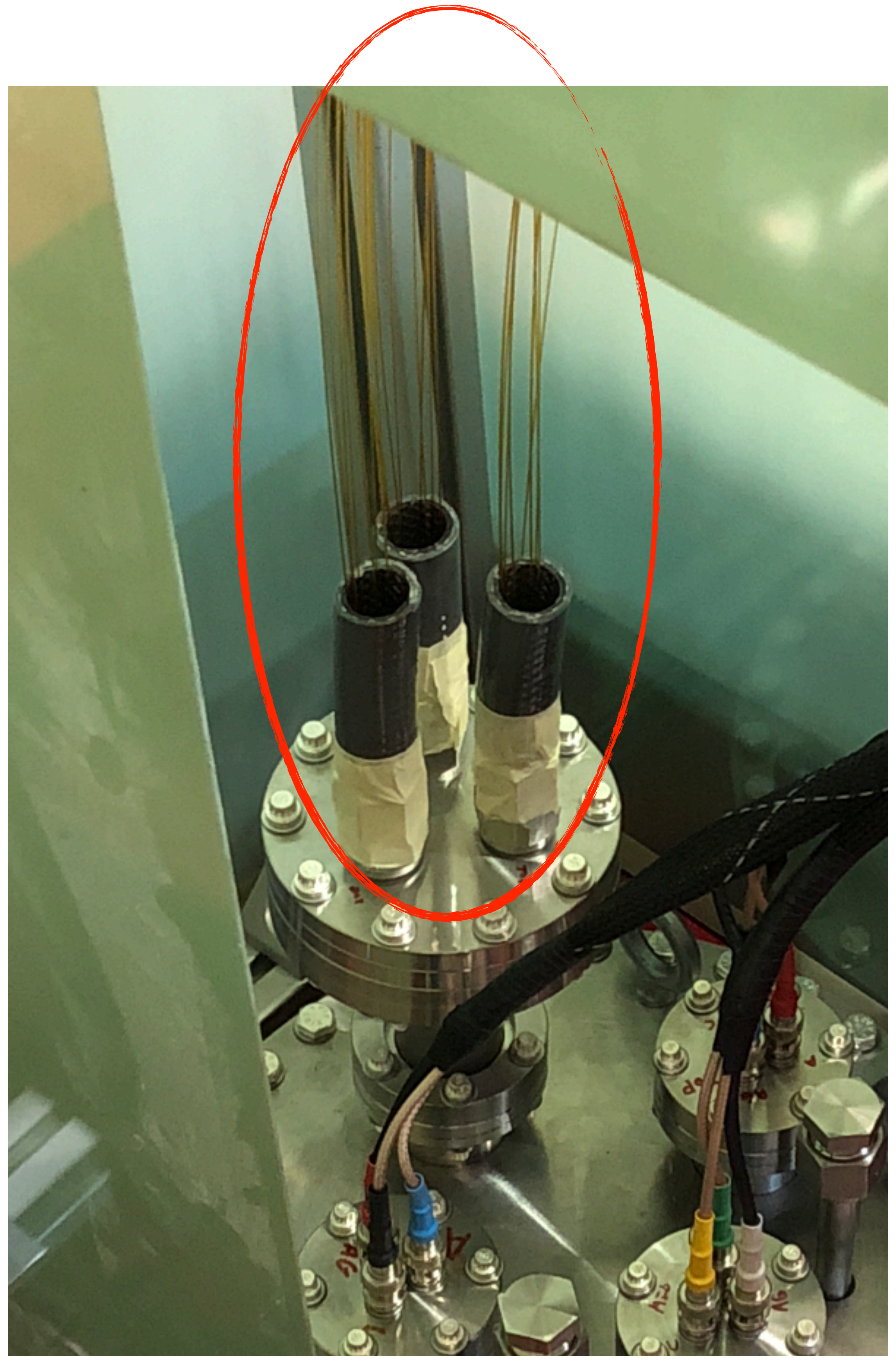


Purity monitors in ProtoDUNE-SP-I

Highlights in ProtoDUNE-SP-I

- Low signal strength has limited the precision and measuring ranges of PrMs in previous LArTPC experiments.
  - Using 8 fibers (8-channel feedthrough, Conax Technologies BSWS) instead of one. The signal is 6 times larger.
- Ran PrMs at large Cathode/Anode HV ratios (50/250 V, 50/500 V). Longer drift time so as to lower Q_A/Q_C during ProtoDUNE-SP-I running.

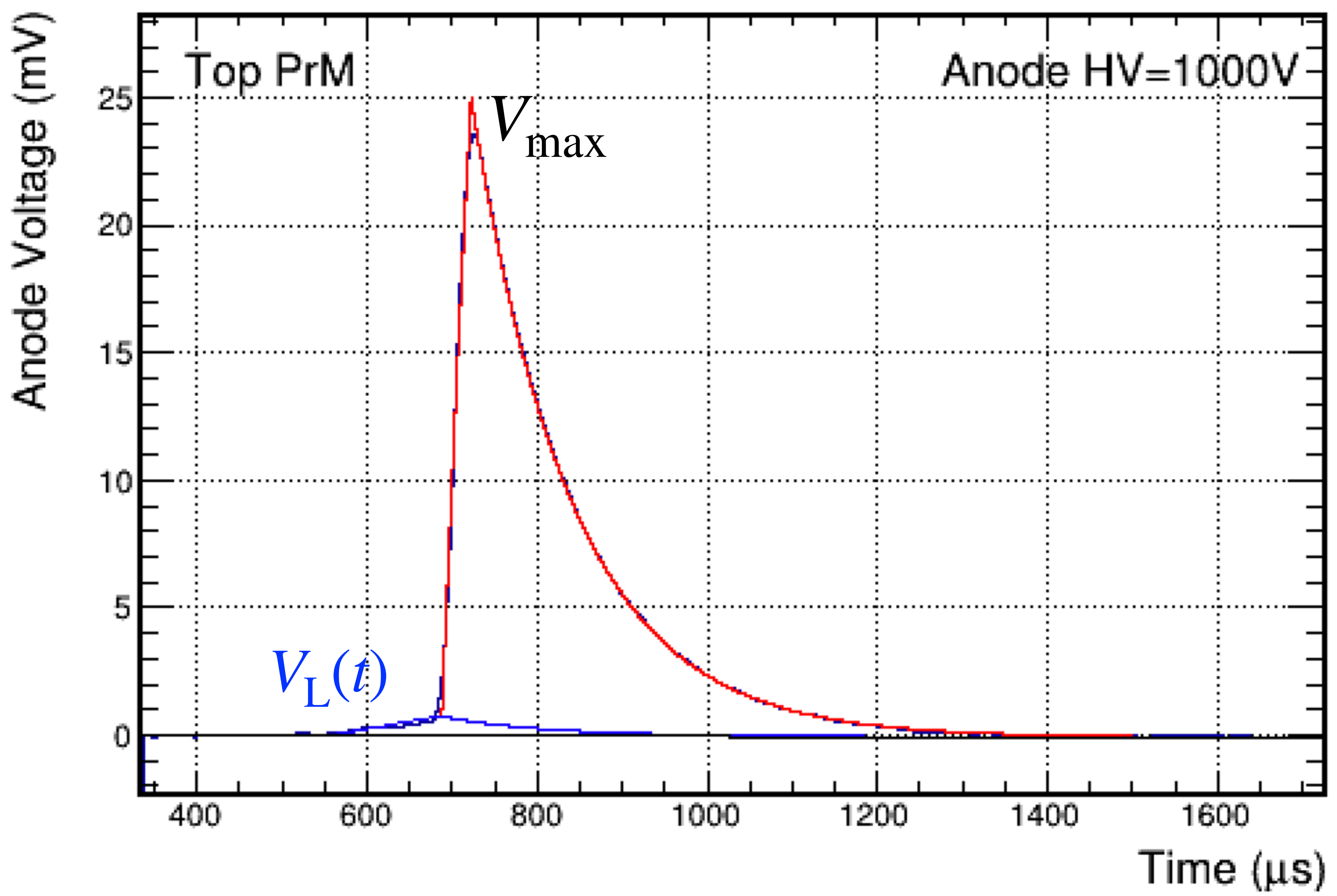
$$Q_A/Q_C = e^{-t_{\rm drift}/\tau} \rightarrow \tau = -\frac{t_{\rm drift}}{\ln(Q_A/Q_C)}.$$



Fit to precisely measure the charge

- An integration RC circuit was used in the readout to measure the charge.
- A waveform model was established.
- Parameterize induced current.
- Free parameters: t_{rise}, t_{start}, $V_0 = Q/C$.

✓ Good agreement to the waveform data.



t = Time - t_{start}

Output voltage at rising edge: $t \leq t_{\mathrm{rise}}$

$$V(t) = V_0 \frac{1 - \exp\left(-t/\mathrm{RC}\right)}{t/\mathrm{RC}}$$

Observed maximum voltage V_{max}

$$V_{\mathrm{max}} = V(t_{\mathrm{rise}}) = V_0 \frac{1 - \exp\left(-t_{\mathrm{rise}}/\mathrm{RC}\right)}{t_{\mathrm{rise}}/\mathrm{RC}}$$

Output voltage at falling edge: $t > t_{\mathrm{rise}}$

$$V(t) = V_{\mathrm{max}} \exp\left(-\frac{t - t_{\mathrm{rise}}}{\mathrm{RC}}\right)$$

$V_{\mathrm{L}}(t)$: Extra voltage caused by induced current:

Anode: $V_{\mathrm{L}}(t) = at \ (t < 0)$, $V_{\mathrm{L}}(t) = V_{\mathrm{L}0} \exp(-\frac{t - t_{\mathrm{rise}}}{\mathrm{RC}}) \ (t > 0)$. Cathode: $V_{\mathrm{L}}(t) = 0$

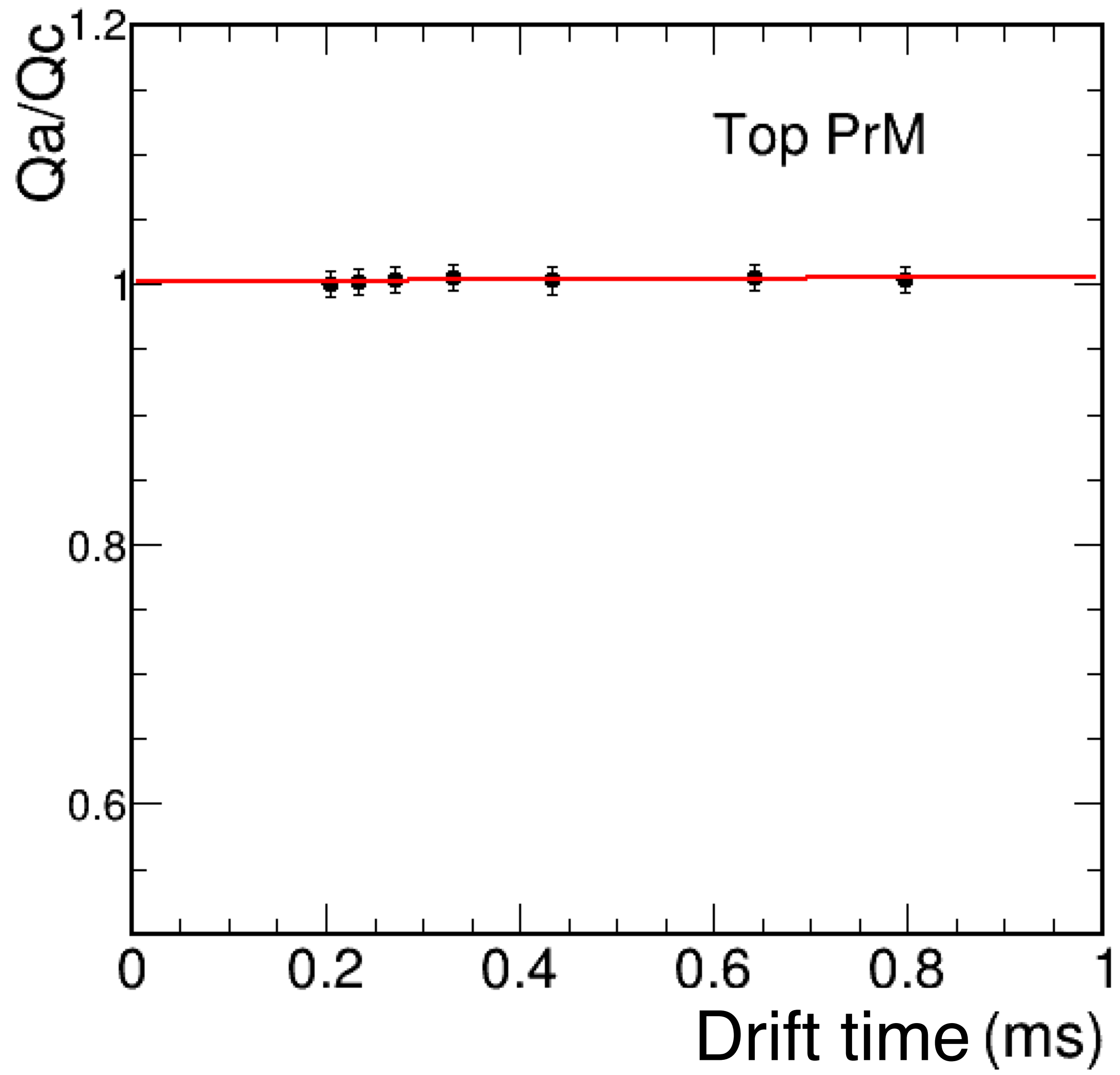
Electron lifetime measurement by PrM

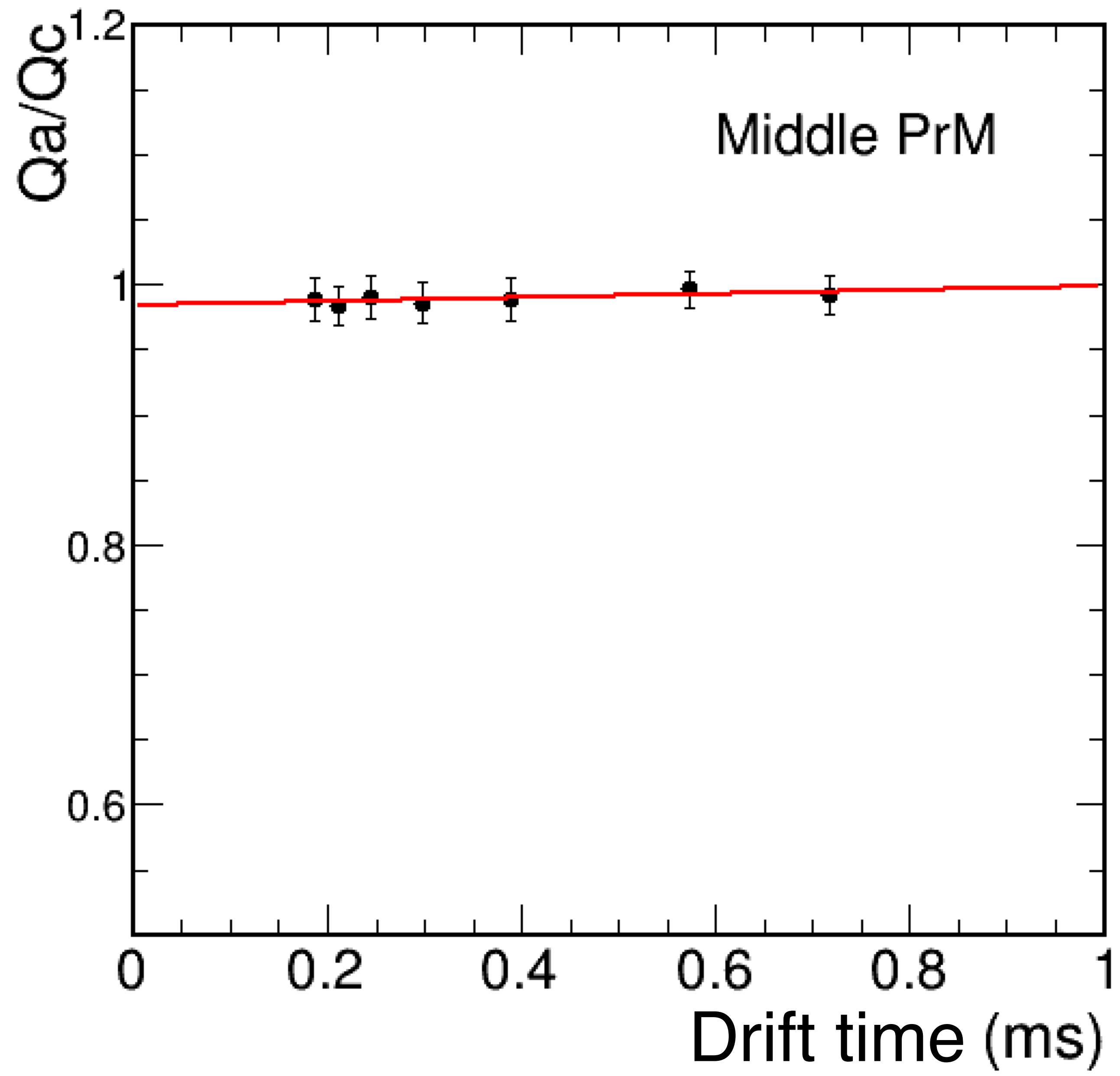
- Large Cathode/Anode HV ratio resulted in NOT 100% transparency of the cathode grid.
- Transparency correction is necessary to take account for the loss of Q_A.
  - Taking data at a calibration point (high purity) with full-transparency E-field (small Cathode/Anode HV ratio: 1:20) at 7 different voltages: 40/800 V, 50/1000 V, 75/1500 V, 100/2000 V, 125/2500 V, 150/3000 V, 175/3500 V. Drift time ranges from 0.2 - 0.8 ms.
  - Q_A/Q_C v.s. drift time can be obtained, and then calculated $\left(Q_A/Q_C\right)_{\text{expected}}$ at large HV ratio (drift time 1.2/2.3 ms).
- The transparency correction factor can be determined as

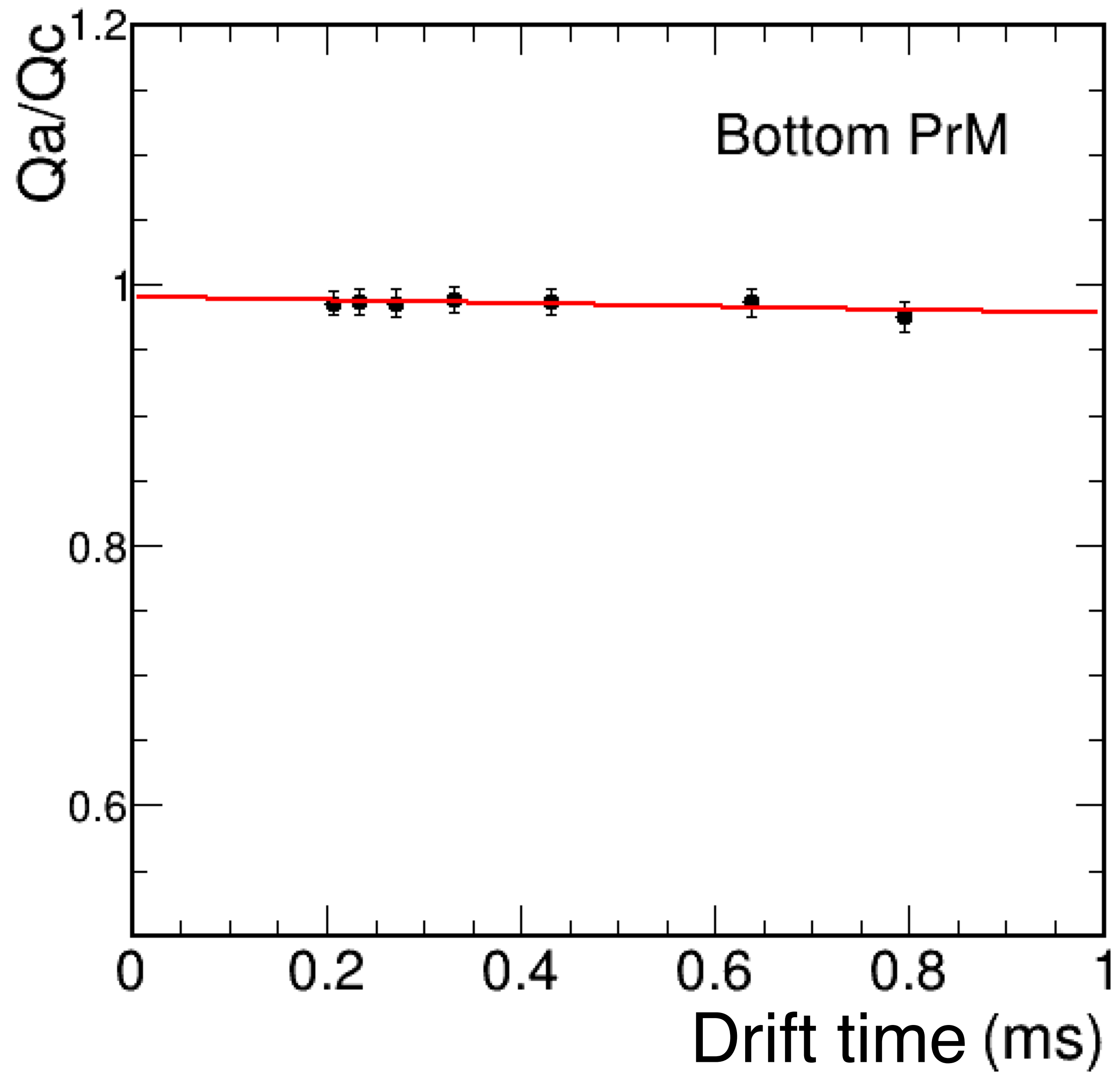
$$f_{\text{trans}} = \frac{\left(Q_A/Q_C\right)_{\text{expected}}}{\left(Q_A/Q_C\right)_{\text{observed}}}.$$

Transparency correction to the lifetime measurement

- Fit to the full-transparency data at 7 cathode/anode HVs and 3 PrMs.
  - Calculate $\left(Q_A/Q_C\right)_{\text{expected}}$ at large HV ratio (50/250) V and (50/500) V.
- Uncertainties include statistical fluctuations, baseline of the waveform, RC constants, and grid inefficiencies.
  - ~1% (excluding transparency correction) for each HV point of top and bottom PrMs.

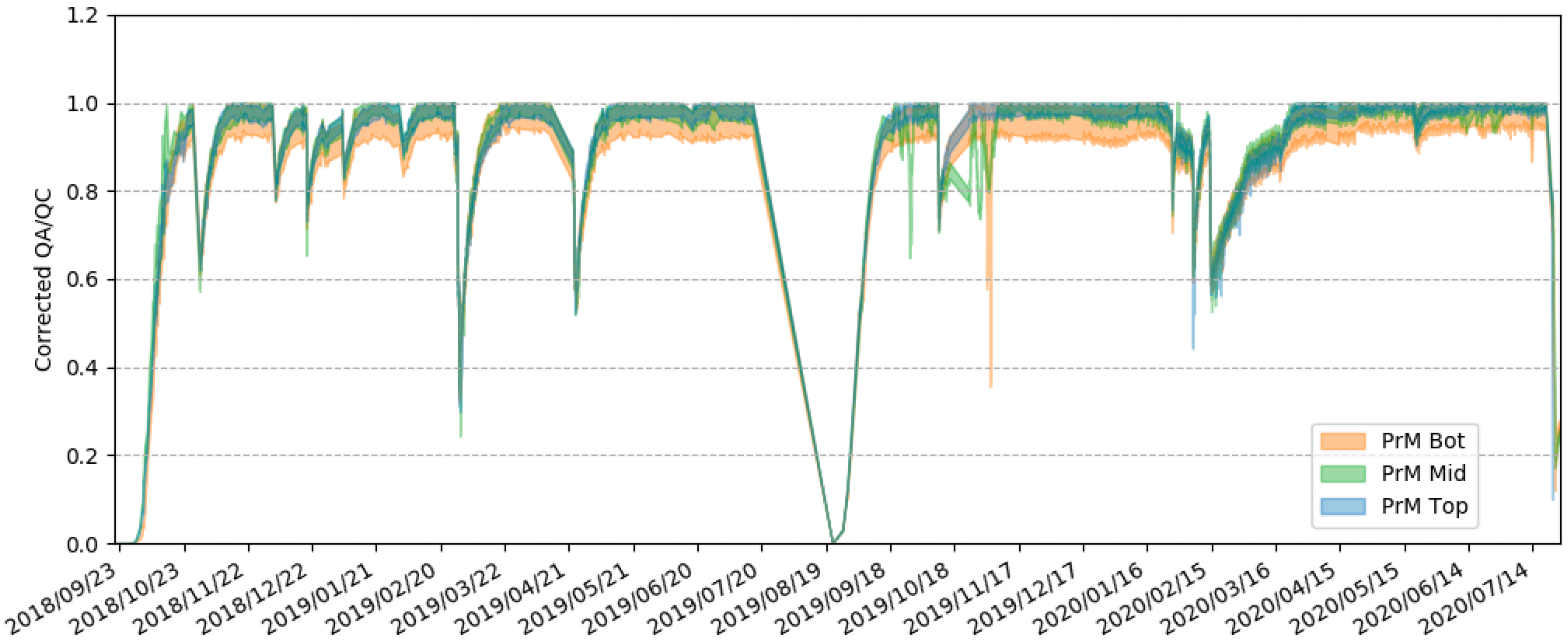




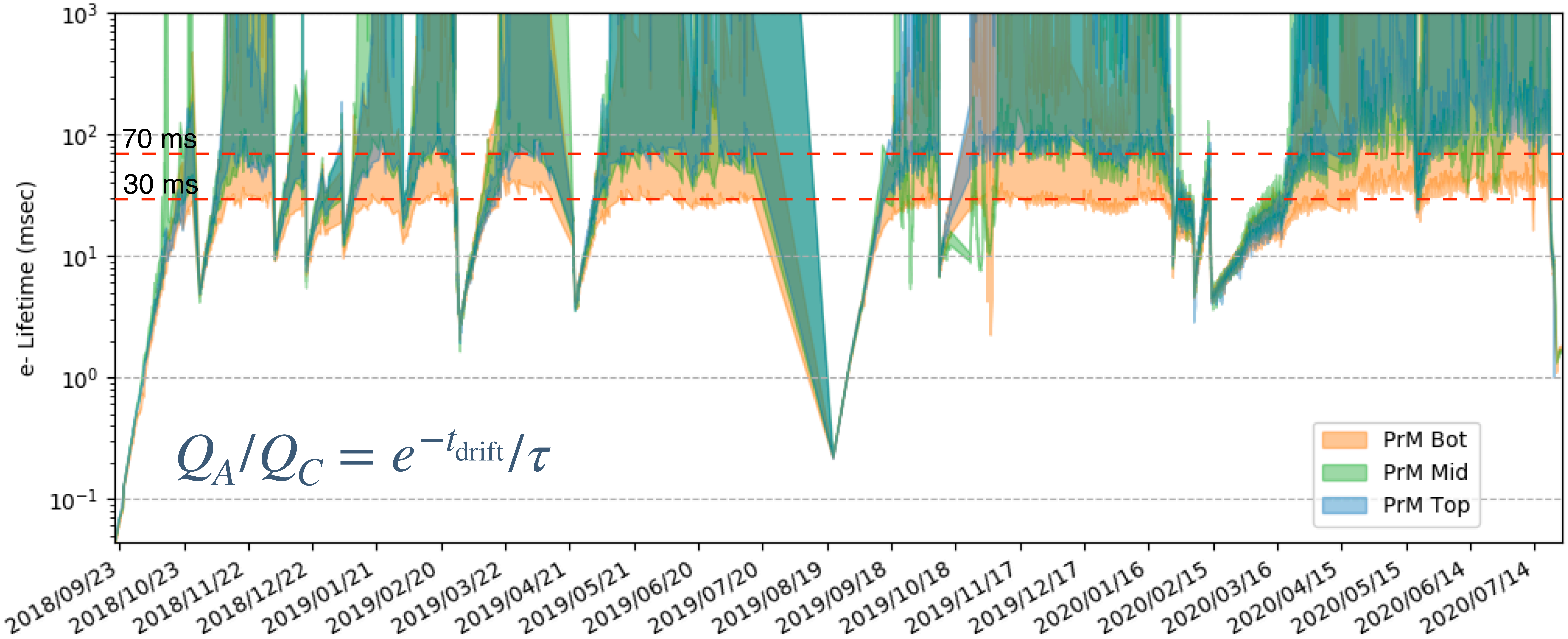


Q_A/Q_C for 2.3 ms drift time

- Transparency correction factor measured at the calibration point was used to correct Q_A/Q_C and lifetime values over the ProtoDUNE-SP Phase-I running period.
    - Stat.+Syst. uncertainty with transparency correction: Top PrM 1.9%, Middle PrM 2.2%, Bottom PrM 3.9%.



Drift electron lifetime from purity monitors



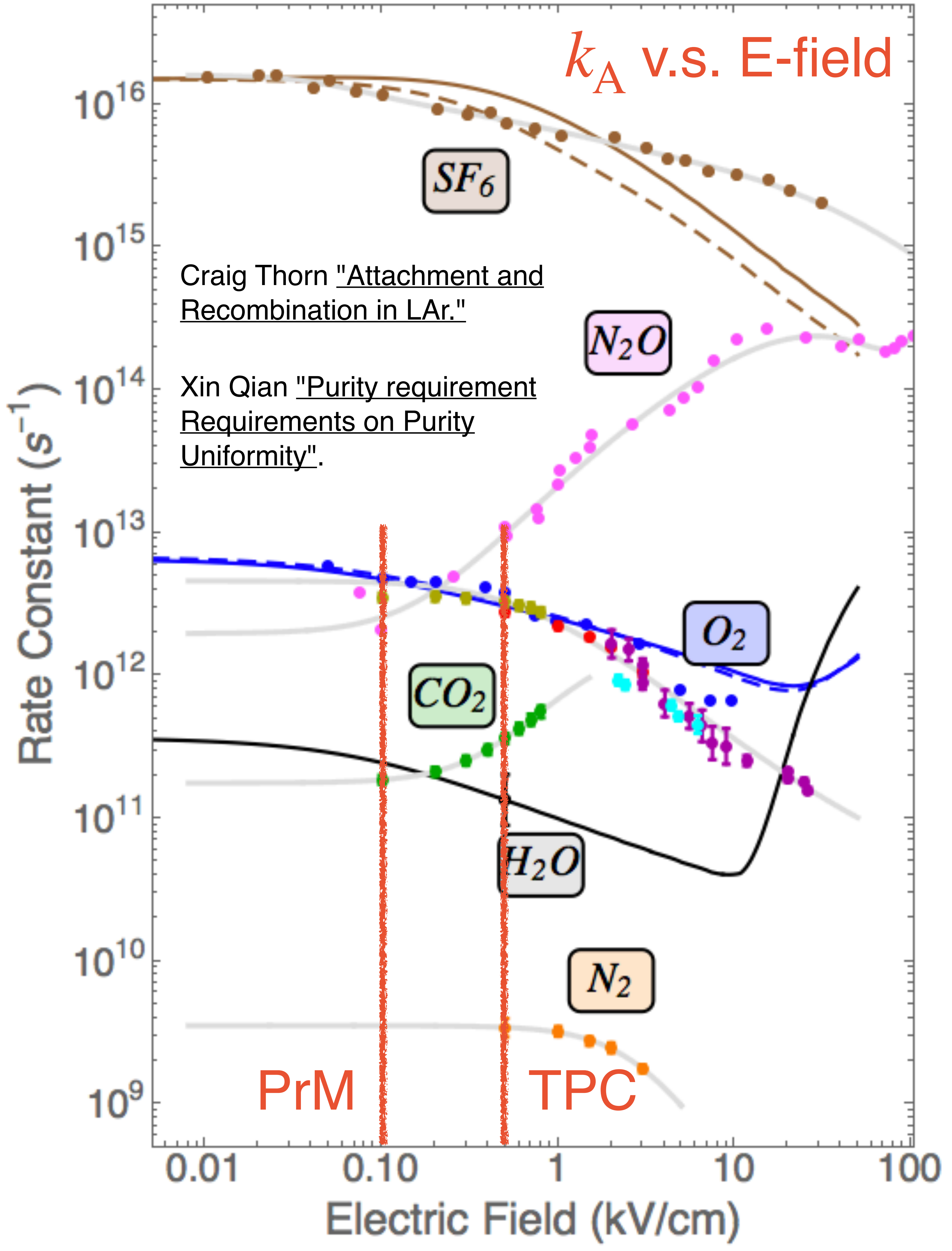
- Validated with cosmic ray tagger data.
- High LAr purity and electron lifetime (> 30 ms) achieved at ProtoDUNE-SP.
- Key component of LArTPC calibration - corrects charge loss caused by LAr impurities.

Apply PrM results to LArTPC calibration

- Electron lifetime $\tau = 1/(k_A \cdot n_s)$
  - k_A: electron attachment rate, n_s: impurity concentration.
  - k_A is a function of the E-field. Purity monitors run at 10-100 V/cm and TPC runs at ~500 V/cm.
  - Electron lifetime at TPC E-field (τ_{TPC}) can be determined from electron lifetime at PrM E-field (τ_{PrM}) with an attachment rate correction:

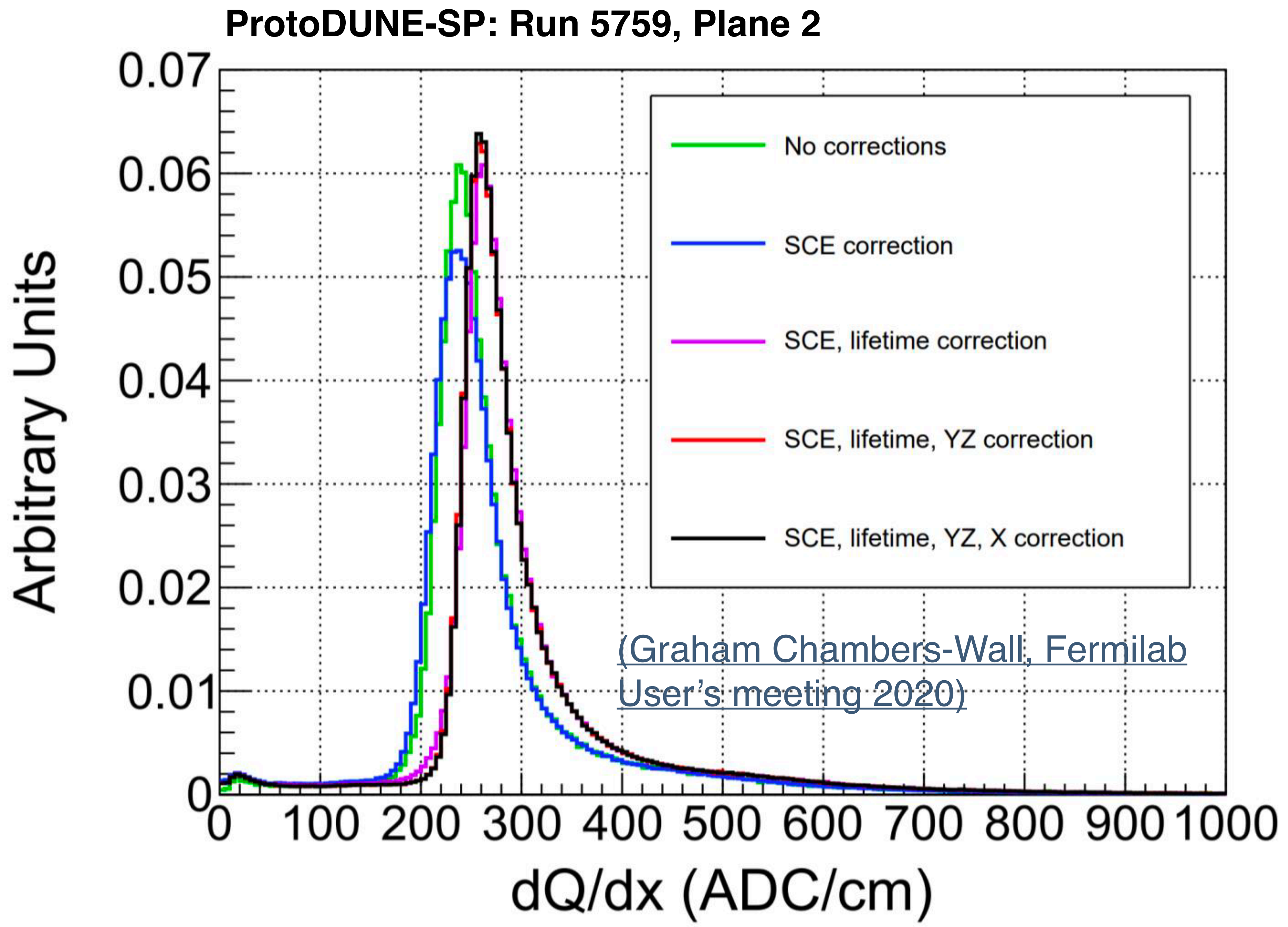
$$\tau_{TPC} = \tau_{PrM} \cdot k_A(V_{PrM})/k_A(V_{TPC}).$$

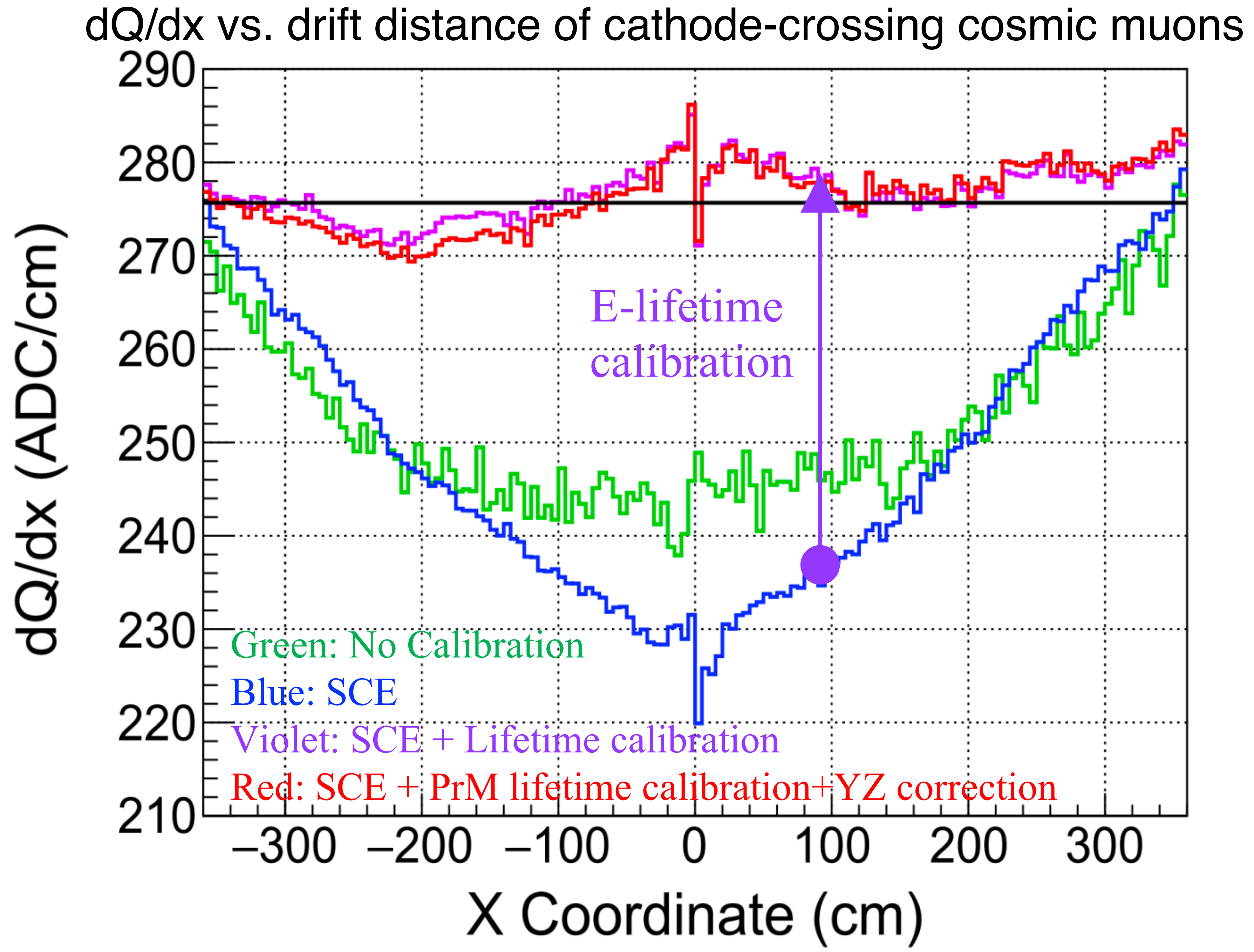
- $k_A(V_{PrM})/k_A(V_{TPC}) \approx 1.3$ obtained from a parameterization fit to the O_2 data.
- Shape of k_A v.s. E-field for H_2O is similar to O_2 in the range (0.01-1) kV/cm.



Calibration scheme of ProtoDUNE-SP

- Electron lifetime calibrated with purity monitors.
- Space charge effect corrected with cosmic rays.
- Position calibration based on cosmic rays.
- Absolute energy calibration: stopping muons in cosmic rays.
- Other calibration methods under development: Ar39, neutron source, laser, radioactive source.





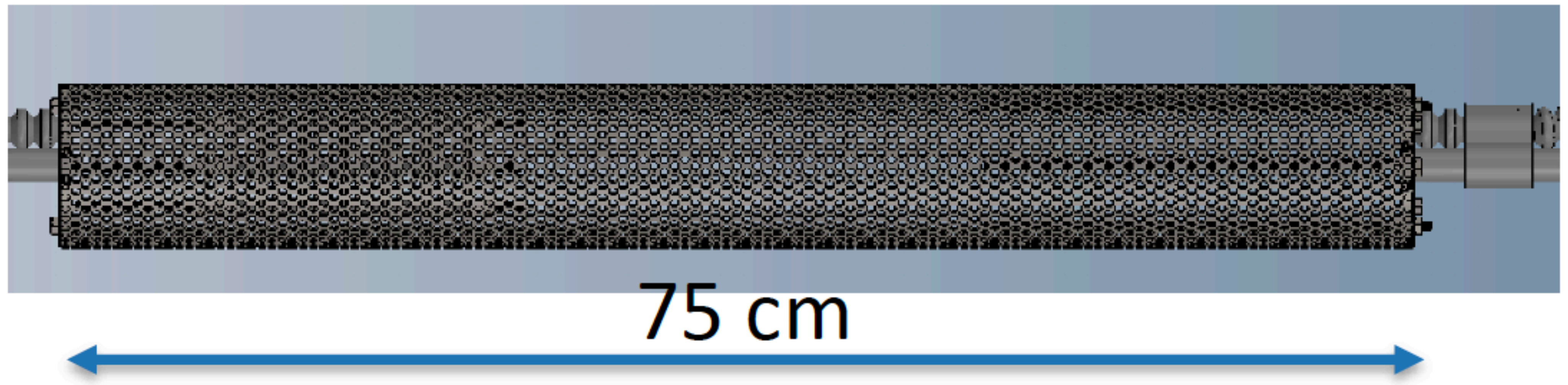
- Charge resolution improved
- Charge attenuation and non-uniformity on TPC signal are corrected

Design of purity monitors for ProtoDUNE-SP-II

Proposed purity monitor for ProtoDUNE-SP-II

- DUNE is preparing ProtoDUNE-SP Phase-2 run, expected to start in late 2022.
- A long purity monitor was proposed to substitute for the middle PrM, to reduce the syst. uncertainty introduced by transparency correction.
  - Enough drift time: 2.3 ms
  - Full-transparency of the grid
- The distribution of the electric field was studied by simulation.
- The inefficiency and transparency of grids were calculated for different configurations.

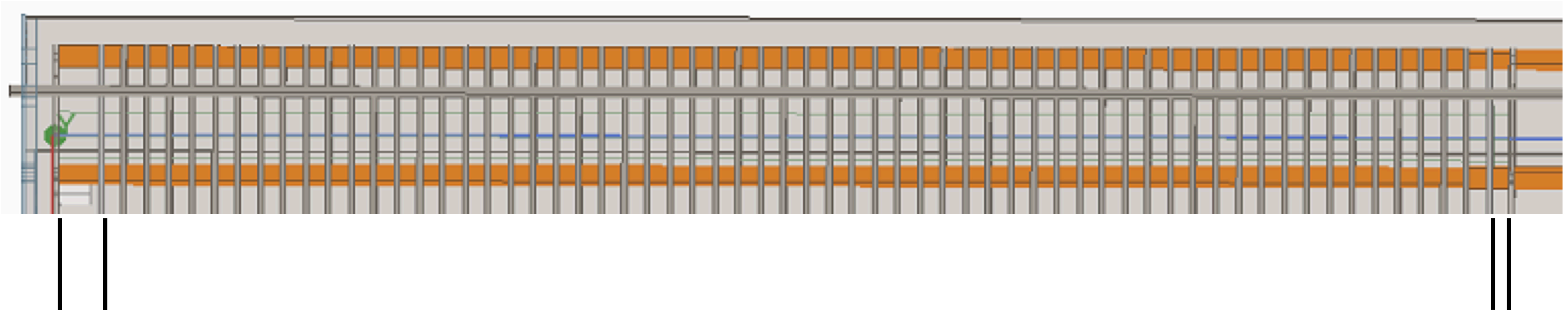
Long PrM for ProtoDUNE-SP-2 and DUNE



Total length 75 cm
Electron drift distance 64 cm
Drift time = 2.3 ms @ 100% grid transparency

Simulation of the electric field

- To study the uniformity of the electric field, we used ANSYS Maxwell3D to simulate the distribution of electric field given the geometry and voltage settings of the PrM.



E1=~25 V/cm

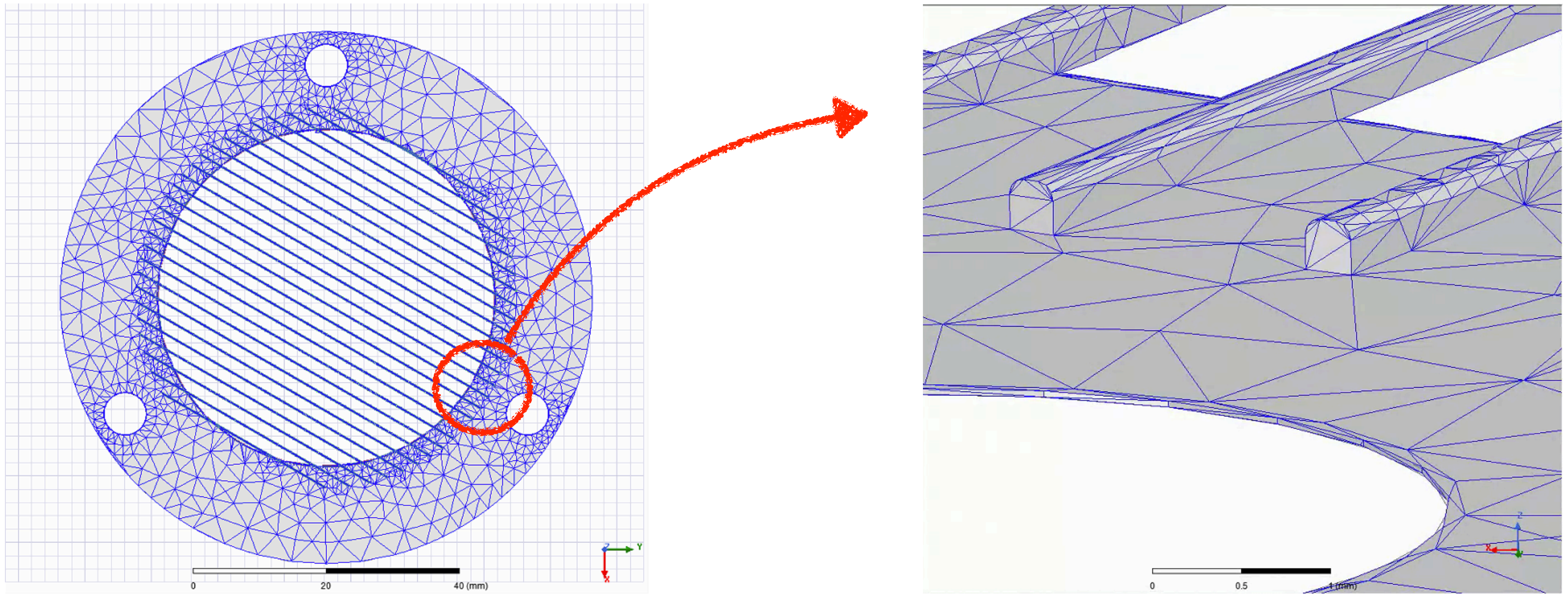
E2=~62 V/cm

E3=~200 V/cm

An example of configuration of the Grid:

r (wire radius): 150 um

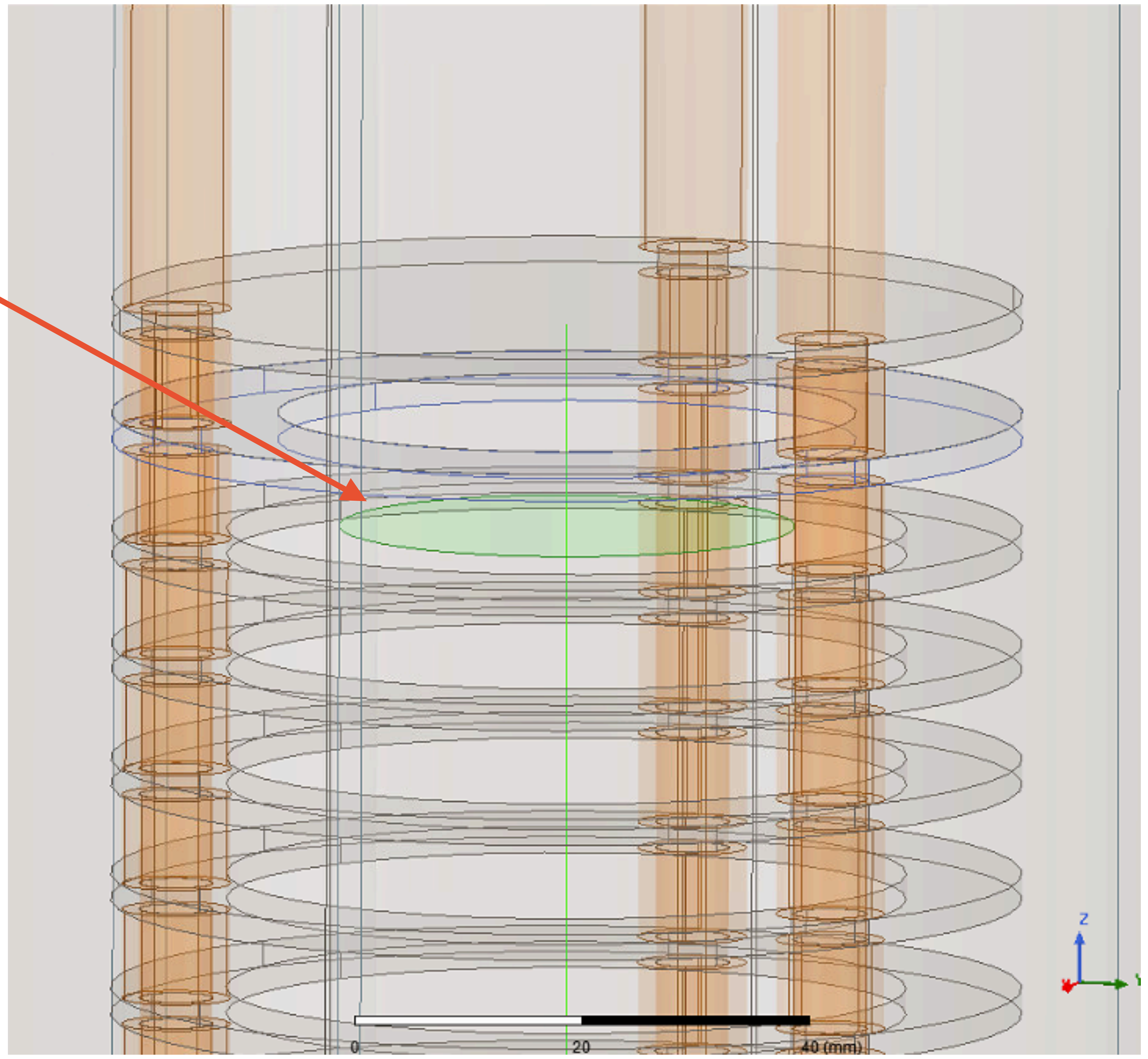
d (distance between wires): 2 mm



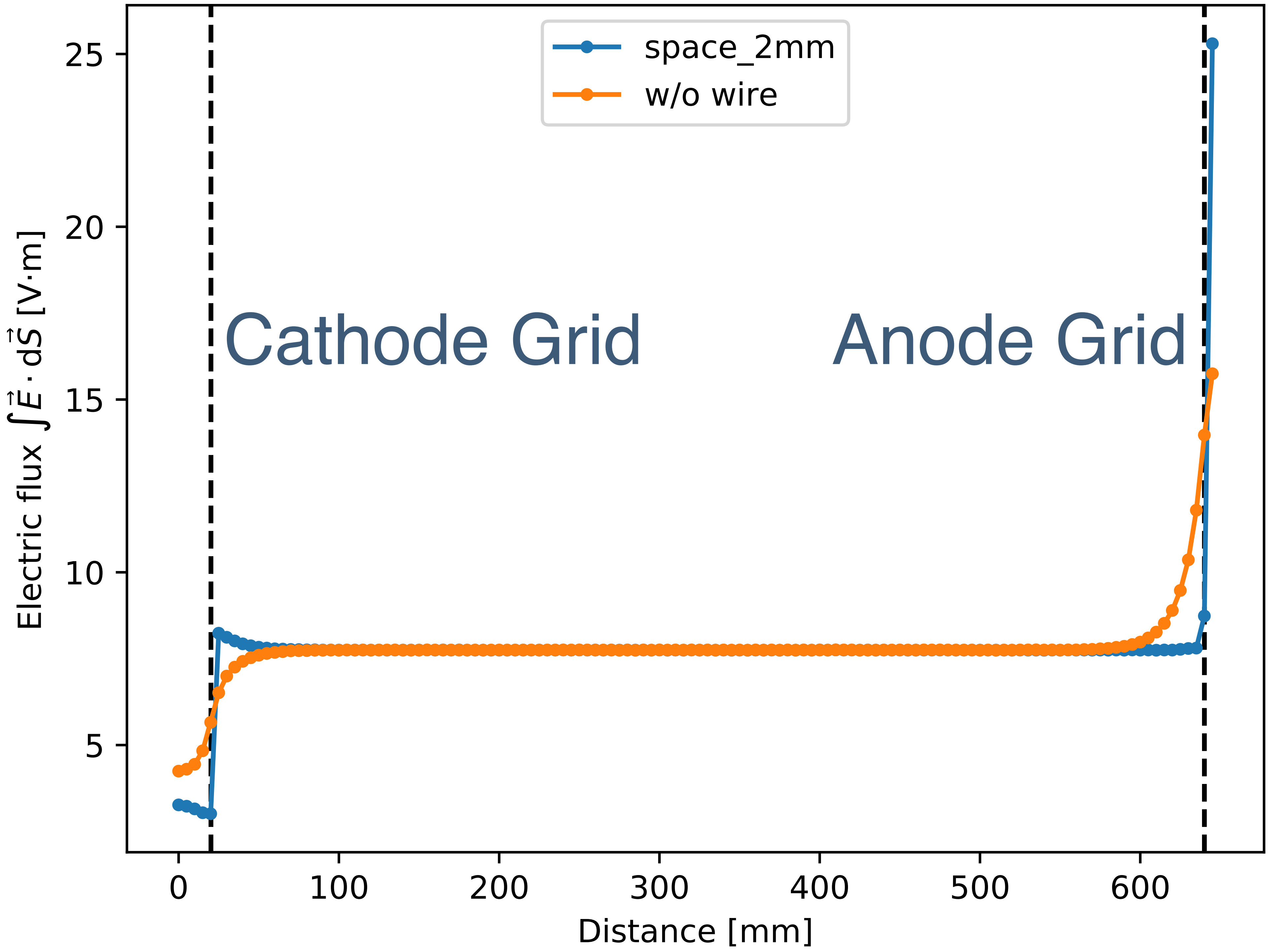
Simulation of the electric field

- The electric flux $\int \vec{E} \cdot \mathrm{d}\vec{S}$ in the drift volume along the drift path was calculated from the simulation results.
- The electric field is uniform distributed in the most of the drift region as expected, but has slight distortion near the Grid.

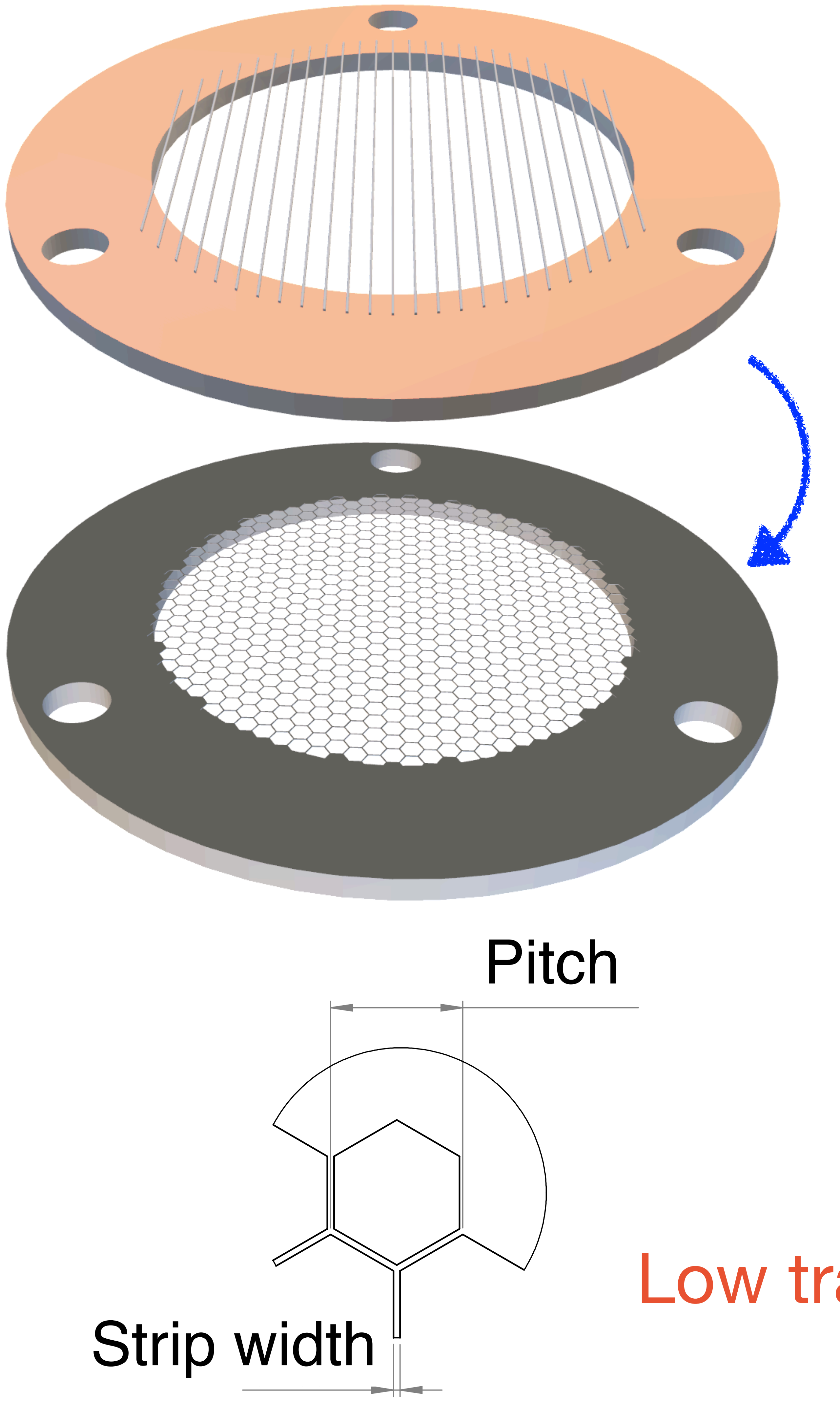
$\mathrm{d}\vec{S}$



$\int \vec{E} \cdot \mathrm{d}\vec{S}$



Grid geometry: Hexagonal mesh



- Hexagonal mesh is easier to solder and manufacture.
- Transparency (Tc/Ta) and inefficiency (Ec/Ea) of cathode/anode grids were calculated with different configurations of pitch size and strip width. (*O. Bunemann et al, Canad. J. Res. 27a (1949) 191.*)

Tc/Ta/Ec/Ea	**Pitch**						
Strip width (um)	**1 mm**	**1.5 mm**	**1.8 mm**	**2.0 mm**	**4.0 mm**	**5.0 mm**	**8.0 mm**
32	100%/100%/ 0.00796/0.0204	100%/100%/ 0.0147/0.0377	100%/100%/ 0.0192/0.0491	100%/100%/ 0.0222/0.057	100%/100%/ 0.0571/0.146	100%/100%/ 0.0765/0.196	100%/100%/ 0.139/0.357
50	100%/100%/ 0.00593/0.0152	100%/100%/ 0.0117/0.0299	100%/100%/ 0.0155/0.0397	100%/100%/ 0.0182/0.0466	100%/100%/ 0.049/0.125	100%/100%/ 0.0663/0.17	100%/100%/ 0.123/0.316
63.5	100%/100%/ 0.00484/0.0124	100%/100%/ 0.01/0.0257	100%/100%/ 0.0135/0.0347	100%/100%/ 0.016/0.041	100%/100%/ 0.0446/0.114	100%/100%/ 0.0609/0.156	100%/100%/ 0.115/0.293
100	94.1%/99.6%/ 0.00277/0.0071	100%/100%/ 0.00693/0.0178	100%/100%/ 0.00981/0.0251	100%/100%/ 0.0119/0.0304	100%/100%/ 0.0364/0.0931	100%/100%/ 0.0505/0.129	100%/100%/ 0.098/0.251
200		79.4%/86.6%/ 0.00219/0.0056	89.6%/96[illegible] 0.004[illegible]/0.[illegible]	[illegible]	[illegible]	[illegible]%/ [illegible]089	100%/100%/ 0.0727/0.186
500				[illegible]	[illegible]	[illegible]6%/ [illegible]355	100%/100%/ 0.0393/0.101

High inefficiency

Low transparency

Manufactured and plan to test them in the lab

UCIRVINE DUNE

Summary and Prospect

- The offline fit method works well for the charge (Q_A/Q_C) measurement.
- Achieve 1% Q_A/Q_C uncertainty at the calibration point (drift time $\leq$ 0.8 ms).
  - Uncertainty is 1.9% for the top purity monitor after transparency correction for low transparency runs over ProtoDUNE-SP-I period.
- Electron lifetime measured by PrMs are applied to the calibration scheme.
- Longer PrM was proposed for ProtoDUNE-SP-II. The simulation shows good uniformity of E-field in the most of the drift region.
- Several grids with different configurations are manufactured and will be test in the lab.

Stay tuned!

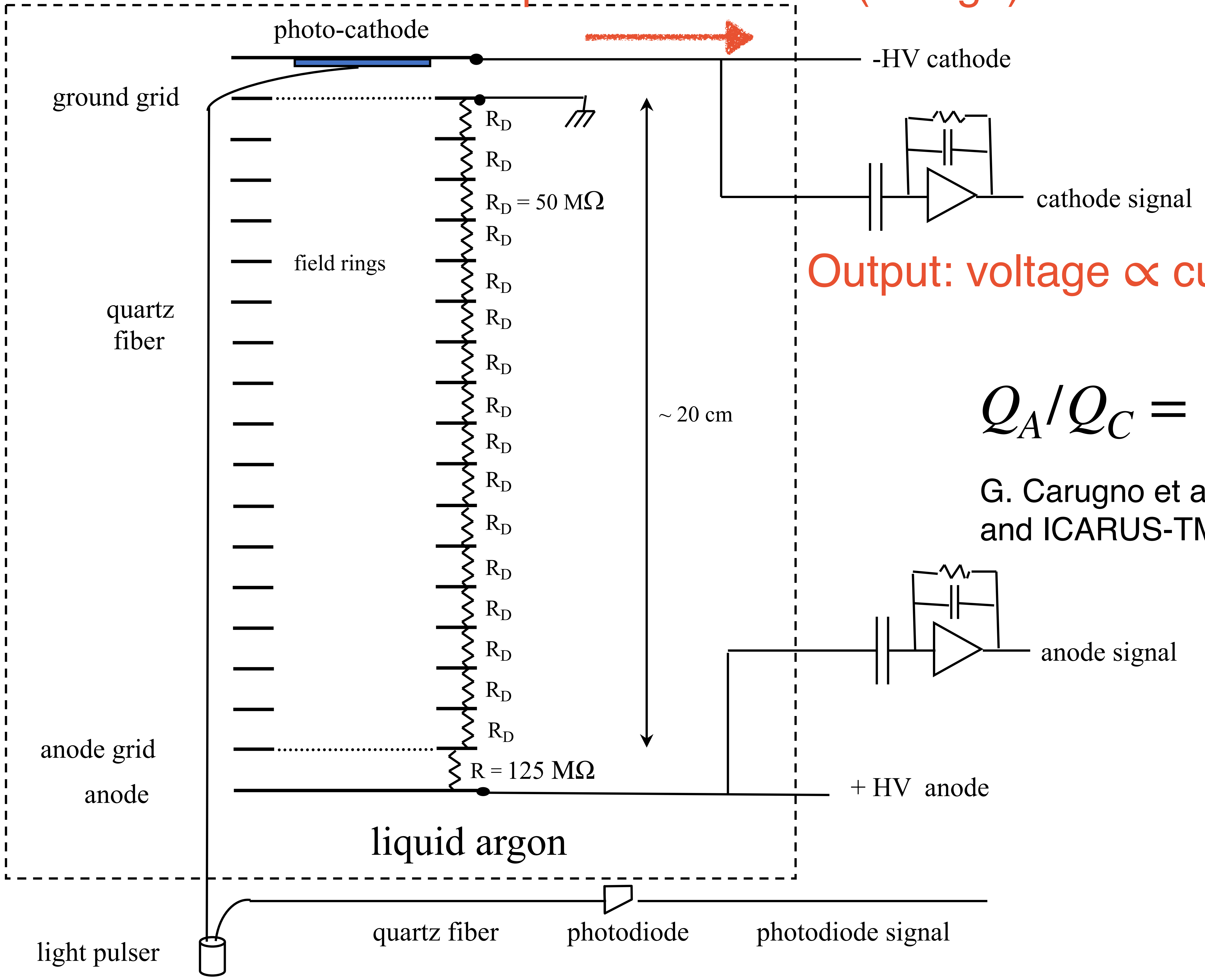
Backup

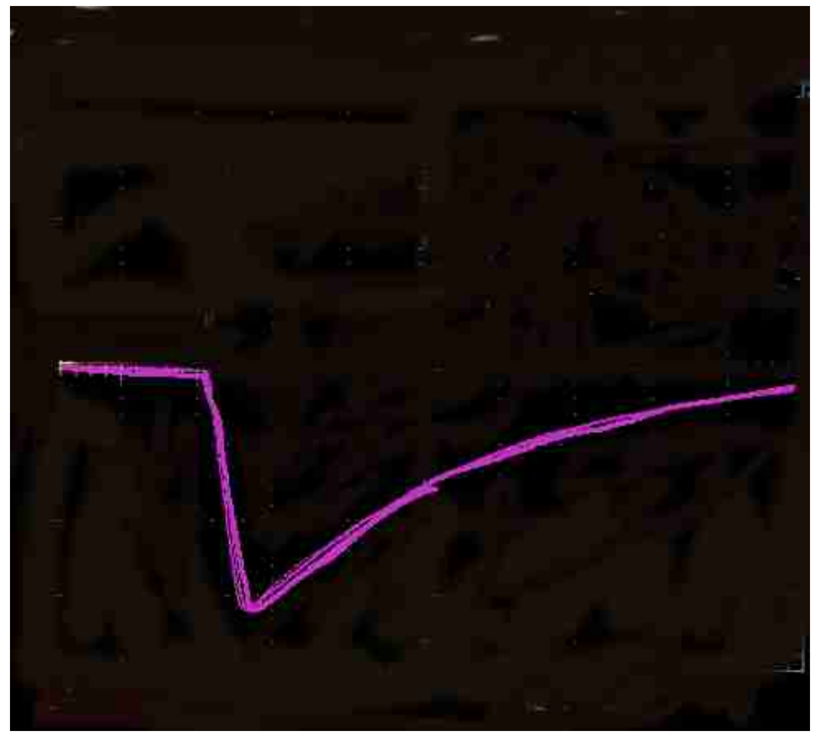
Diagram of the Purity Monitor

Readout electronics

- Use an integration RC circuit, voltage ∝ charge
- Do not use pure current amplifiers (voltage ∝ current) for signal/background issues
- Need to convert observed voltage into charge on cathode and anode

Input: current vs. t (charge)

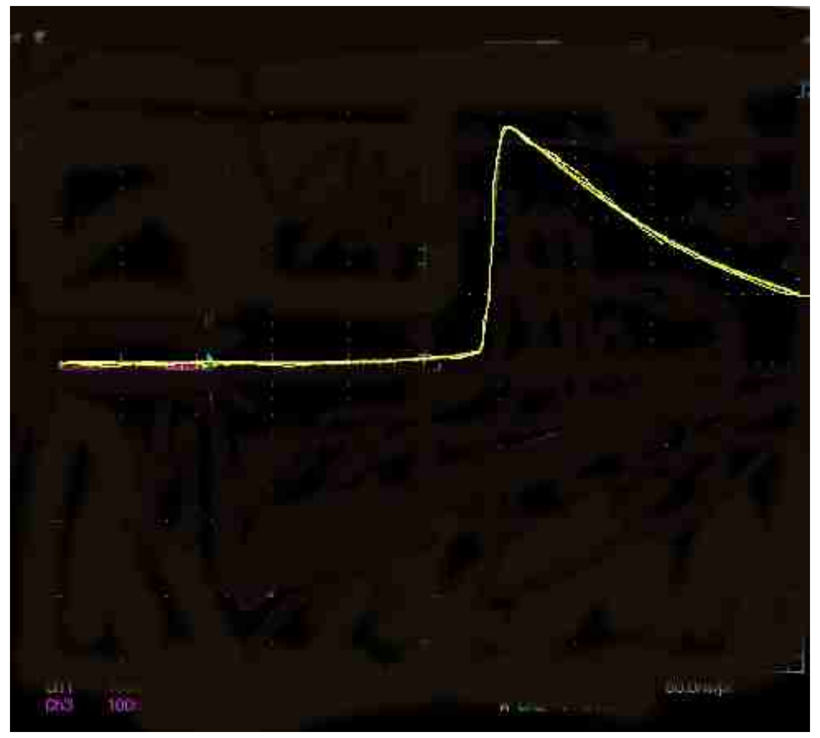




Output: voltage ∝ current vs t

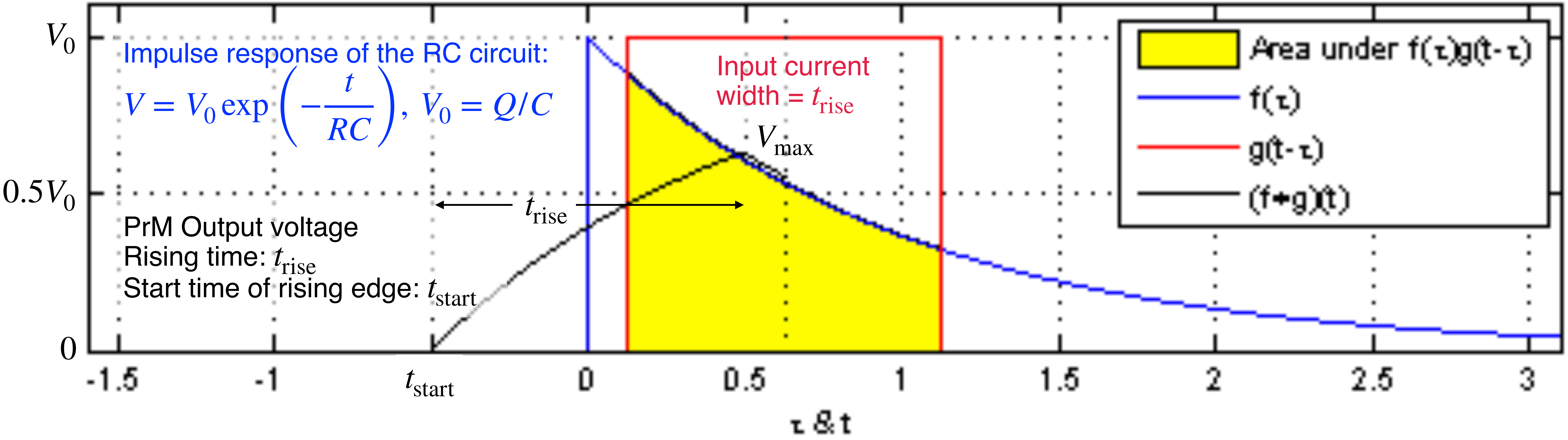
$$Q_A/Q_C = e^{-t_{\text{drift}}/\tau}$$

G. Carugno et al., NIM A292 (1990) and ICARUS-TM/02-14



Waveform of PrM Signals

Output voltage = Impulse response of the circuit $\otimes$ Input current



t = Time - t_{start}

Output voltage at rising edge: $t \le t_{rise}$

$$V(t) = V_0 \frac{1 - \exp\left(-t/RC\right)}{t/RC}$$

Observed maximum voltage V_{max}

$$V_{max} = V(t_{rise}) = V_0 \frac{1 - \exp\left(-t_{rise}/RC\right)}{t_{rise}/RC}$$

Output voltage at falling edge: $t > t_{rise}$

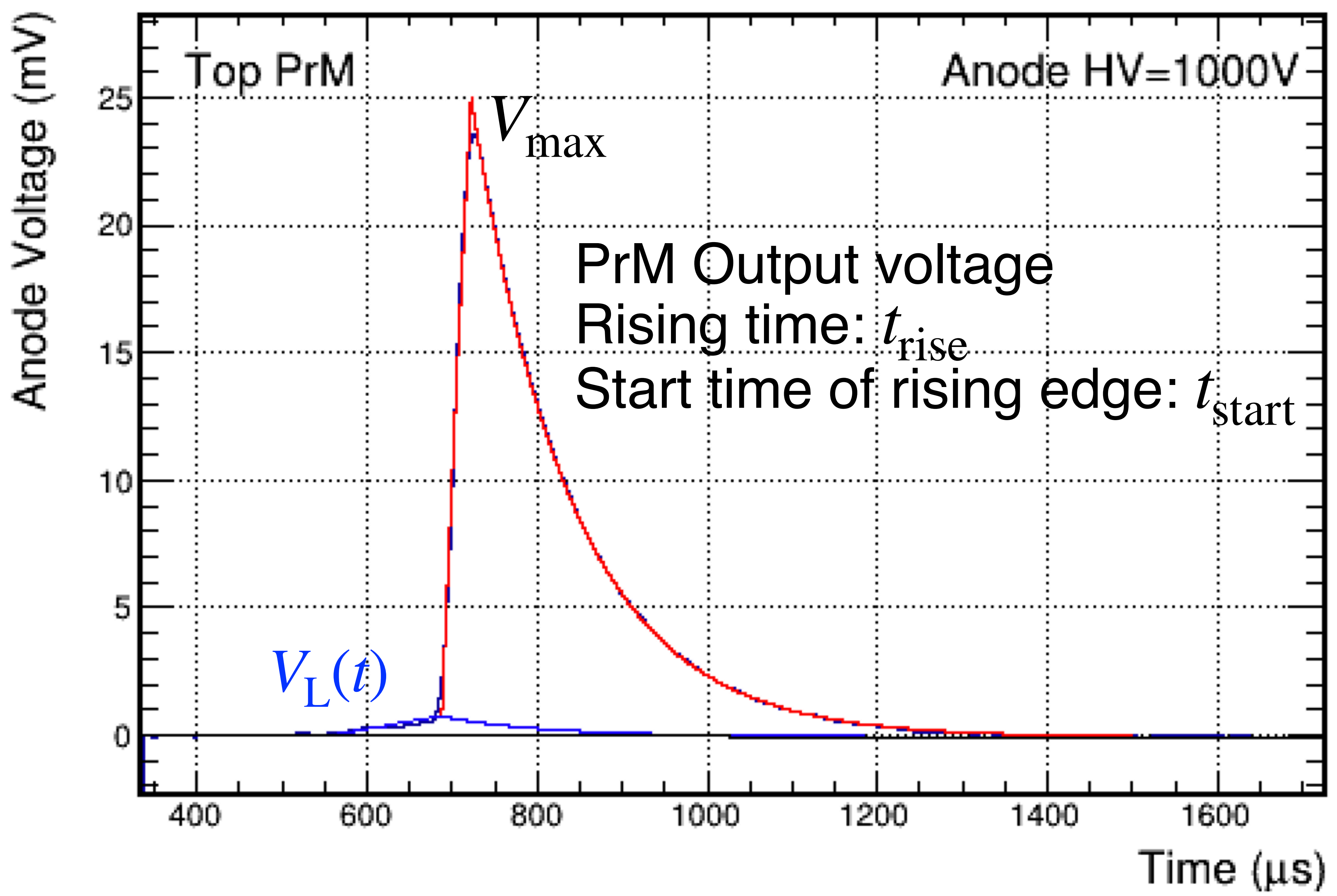
$$V(t) = V_{max} \exp\left(-\frac{t - t_{rise}}{RC}\right)$$

$V_0 = Q/C$ is the measurement of charge on the cathode and anode of the purity monitor

Fit to precisely measure the charge

- A waveform model was established.
- Parameterize induced current.
- Free parameters: t_{rise}, t_{start}, $V_0 = Q/C$.
- Fix RC to average values measured at different HVs
- Free linear baseline function

✓ Good agreement to the waveform data.



t = Time - t_{start}

Output voltage at rising edge: $t \le t_{\text{rise}}$

$$V(t) = V_0 \frac{1 - \exp(-t/\text{RC})}{t/\text{RC}}$$

Observed maximum voltage V_{max}

$$V_{\text{max}} = V(t_{\text{rise}}) = V_0 \frac{1 - \exp\left(-t_{\text{rise}}/\text{RC}\right)}{t_{\text{rise}}/\text{RC}}$$

Output voltage at falling edge: $t > t_{\text{rise}}$

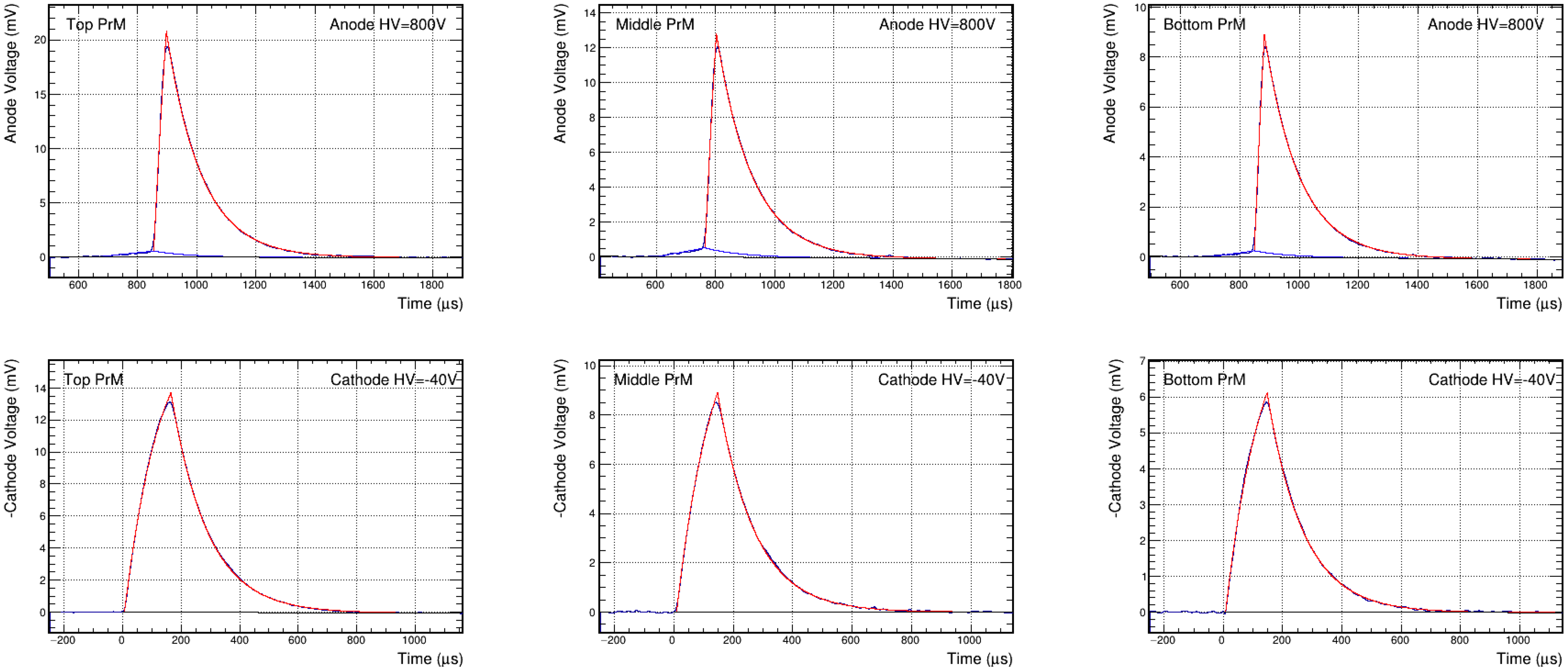
$$V(t) = V_{\text{max}} \exp\left(-\frac{t - t_{\text{rise}}}{\text{RC}}\right)$$

$V_L(t)$: Extra voltage caused by induced current:

Anode: $V_L(t) = at \ (t < 0)$, $V_L(t) = V_{L0} \exp(-\frac{t - t_{\text{rise}}}{\text{RC}}) \ (t > 0)$. Cathode: $V_L(t) = 0$.

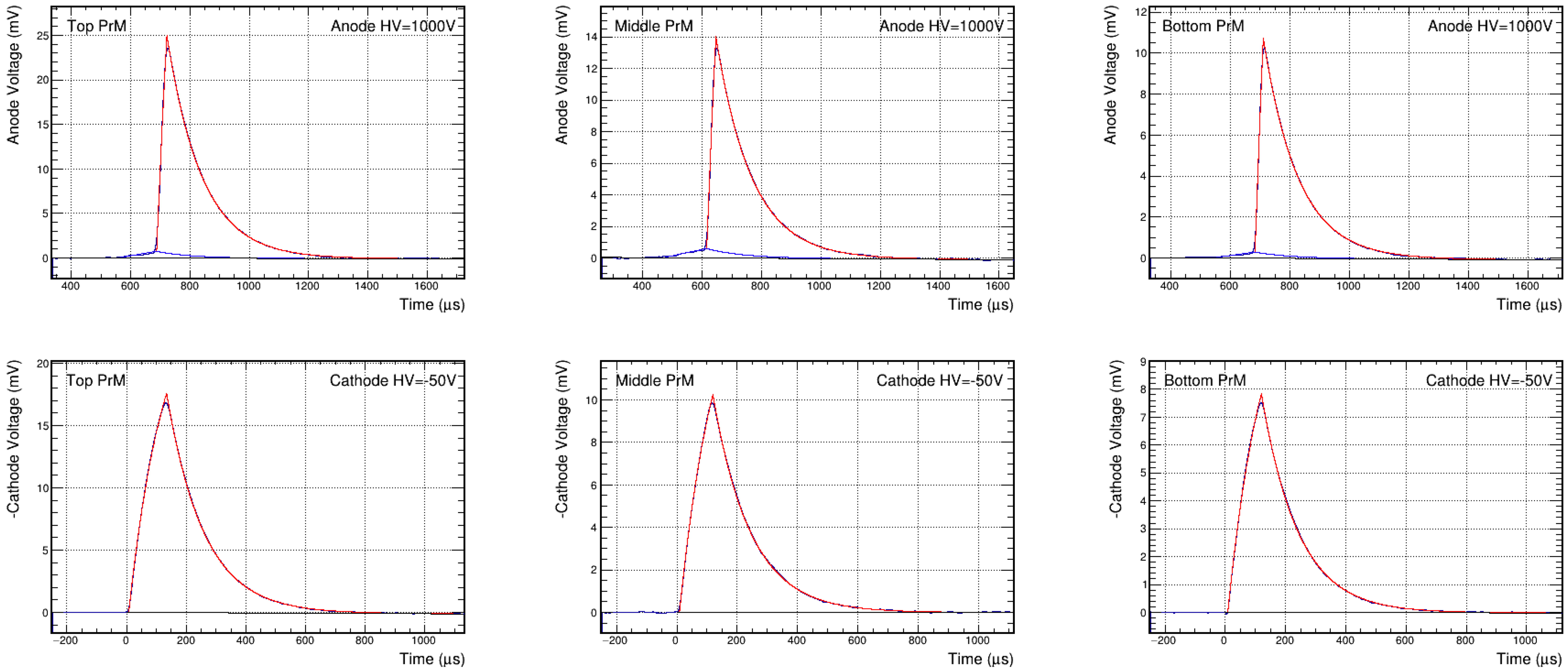
Fitting at different HVs

Cathode/Anode HV = -40 V/800 V



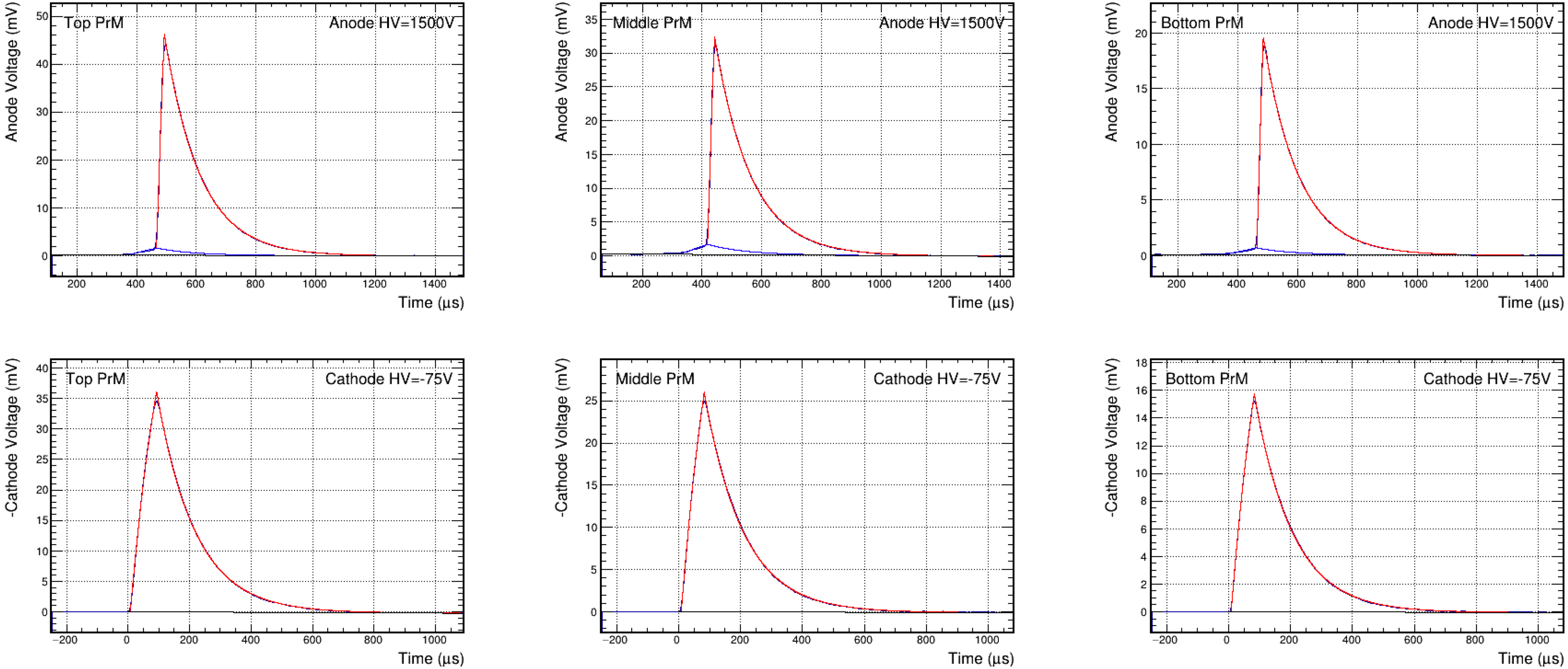
Fitting at different HVs

Cathode/Anode HV = -50 V/1000 V



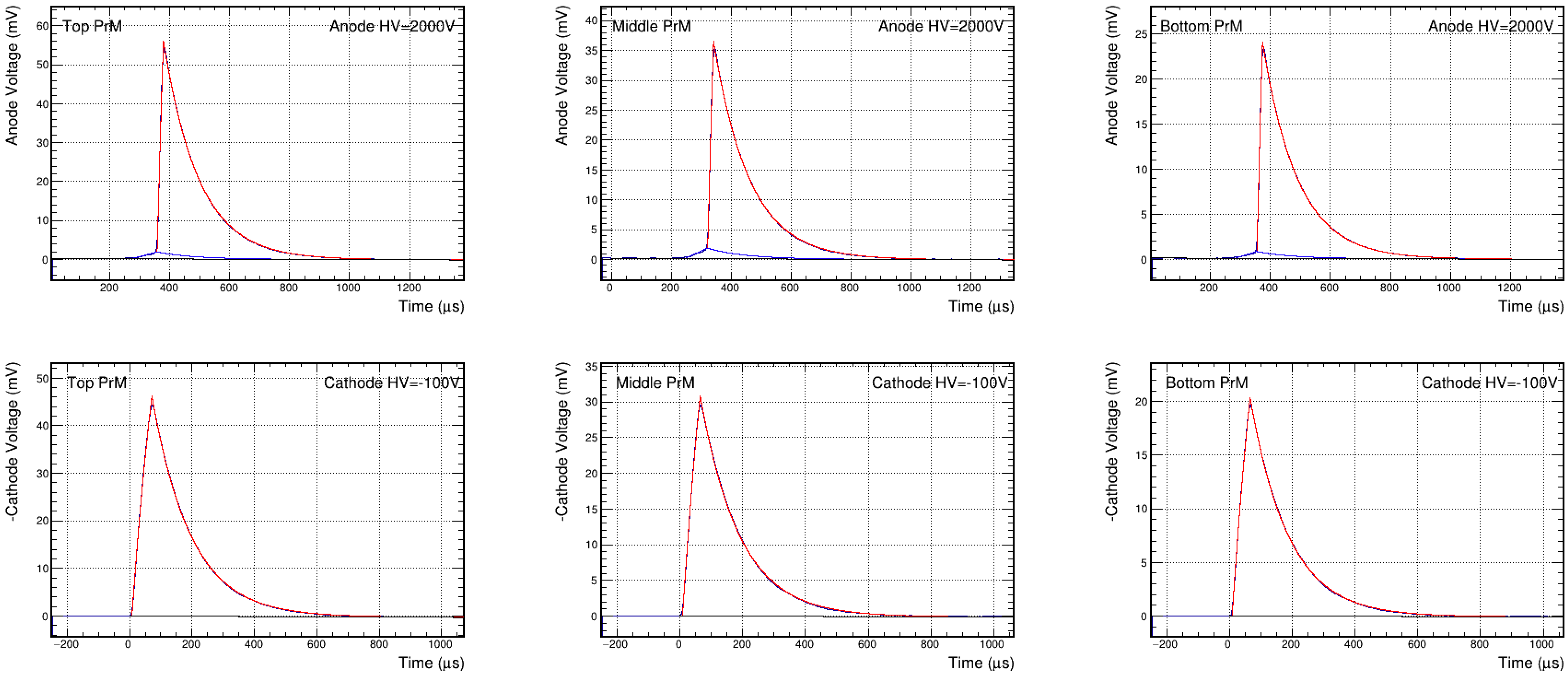
Fitting at different HVs

Cathode/Anode HV = -75 V/1500 V



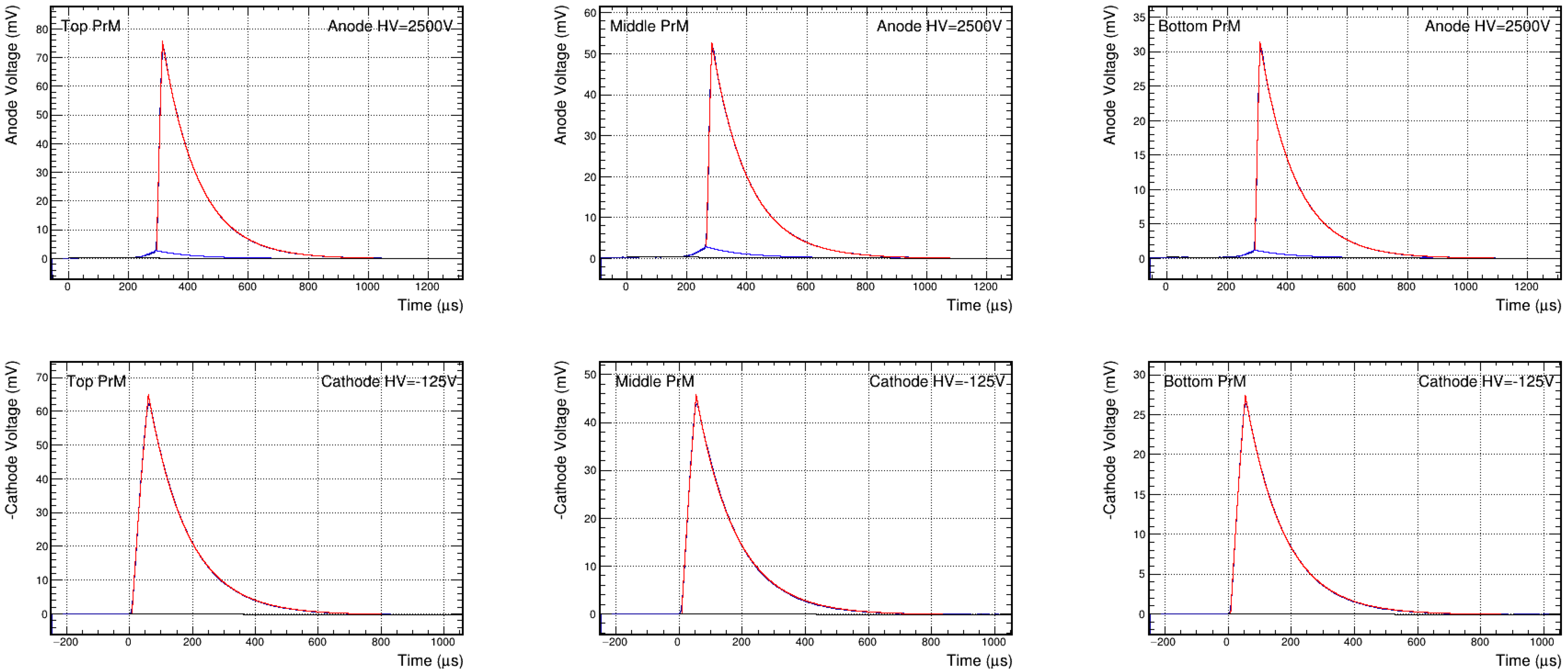
Fitting at different HVs

Cathode/Anode HV = -100 V/2000 V



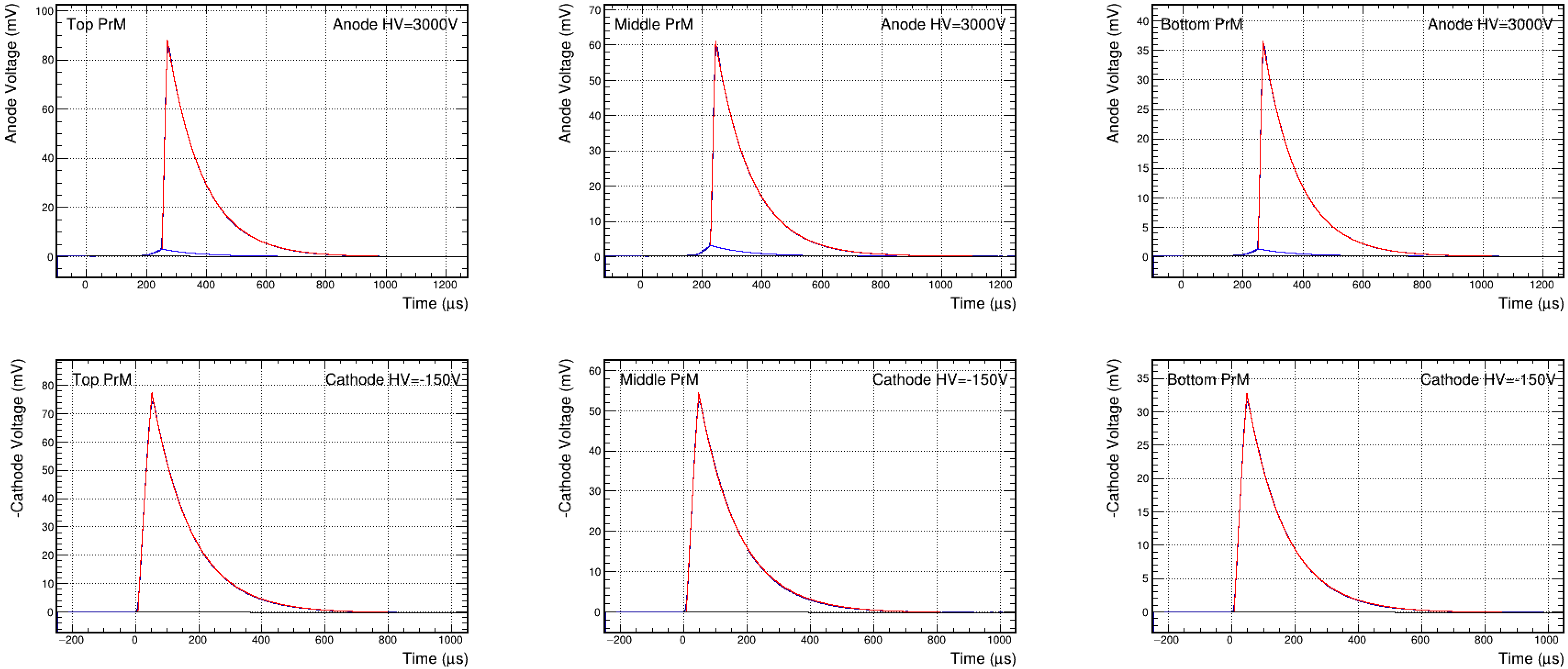
Fitting at different HVs

Cathode/Anode HV = -125 V/2500 V



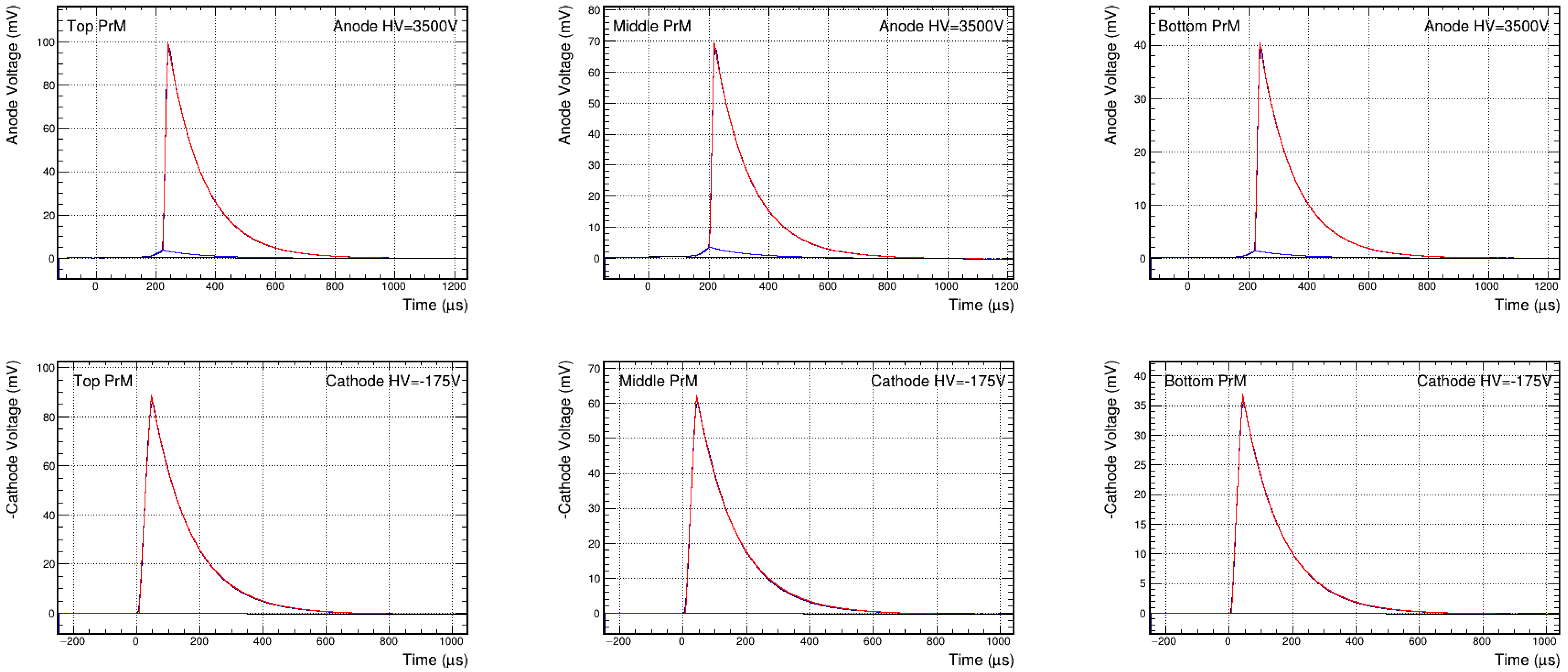
Fitting at different HVs

Cathode/Anode HV = -150 V/3000 V



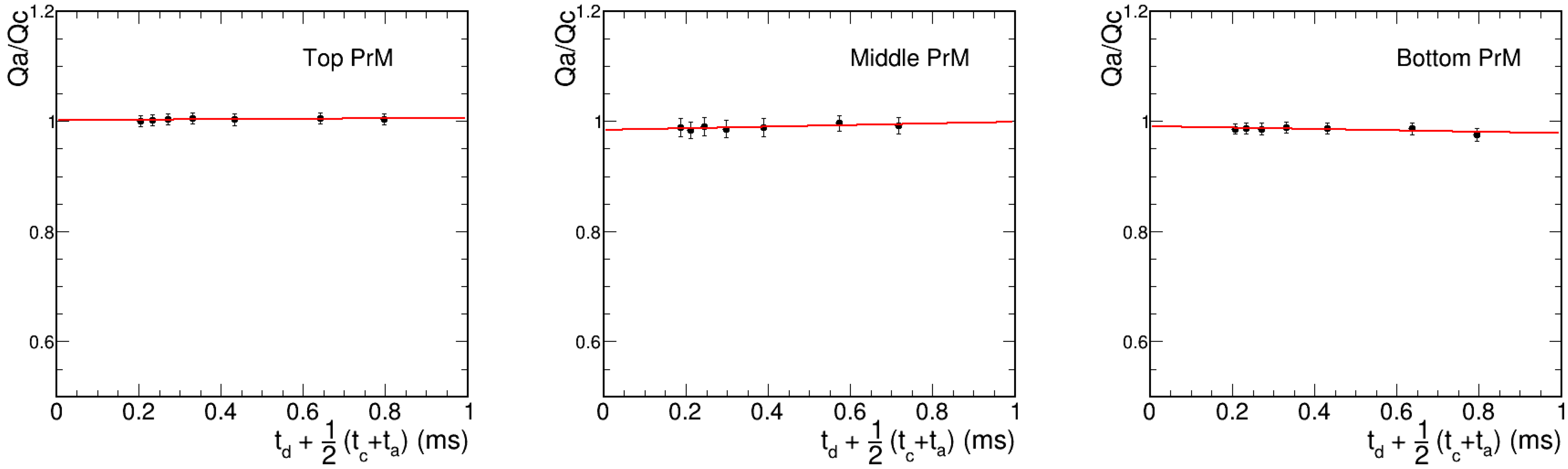
Fitting at different HVs

Cathode/Anode HV = -175 V/3500 V

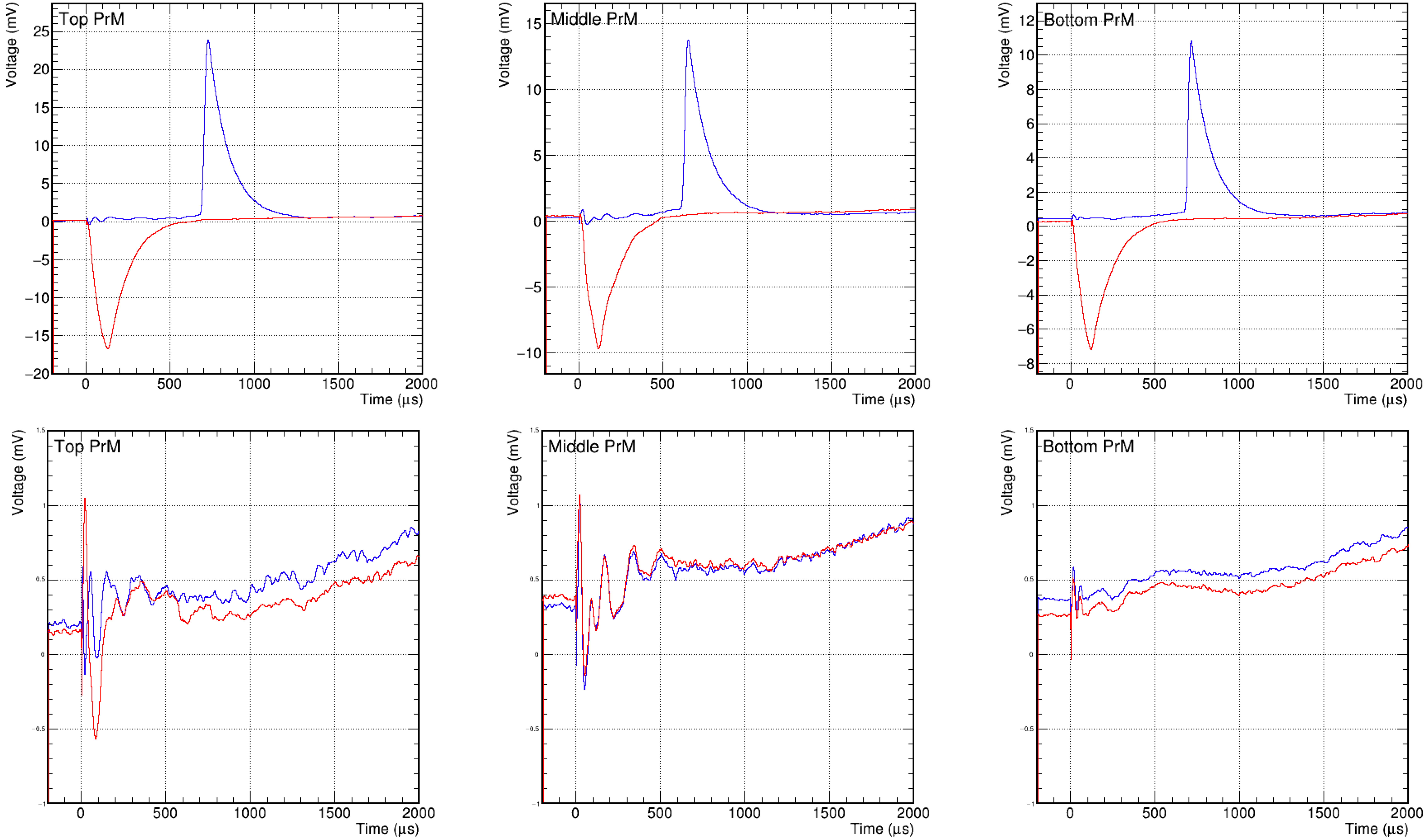


Lifetime measurement for transparency correction

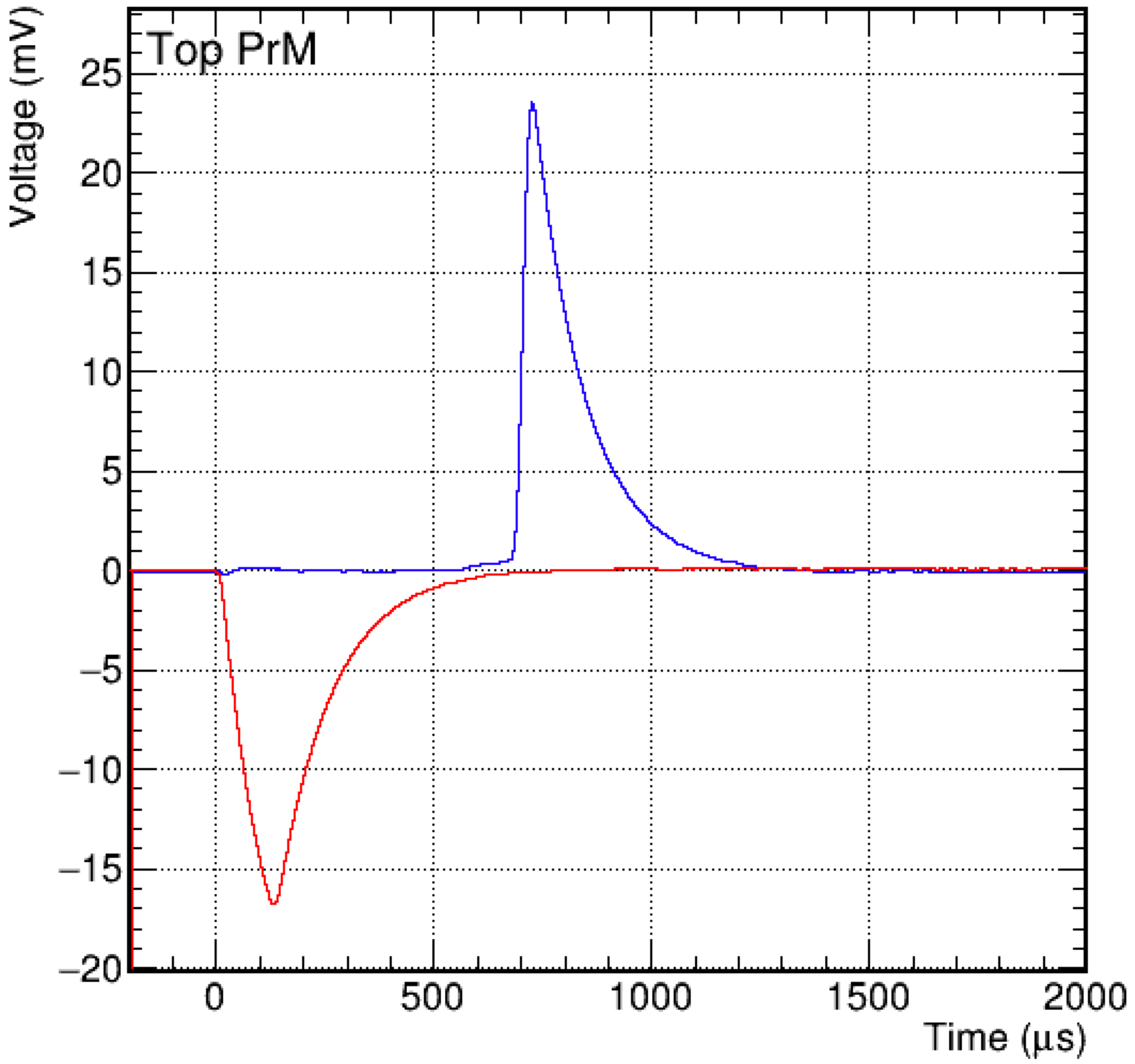
- Fit to full transparency data (2020/Jan/11) at different cathode/anode HVs to obtain the lifetime at high purity.
  - Calculate $(Q_A/Q_C)_{\text{expected}}$ at 50/250 V and 50/500 V.
- The measurement uncertainties include statistical and time-dependent fluctuations, uncertainties in the baseline of the purity monitor signal waveform, cathode and anode RC constants, and uncertainties in the grid shielding inefficiencies.
  - Other uncertainties such as signal rise time, electron drift time are found to be small.
- The uncertainty of Q_A/Q_C (excluding transparency correction) is ~1% for each HV point in the top and bottom PrMs.
- Float Q_A/Q_C at drift time = 0 ms (GainCor) in the fit so results not affected by cathode/anode gain difference and electron loss on grids.

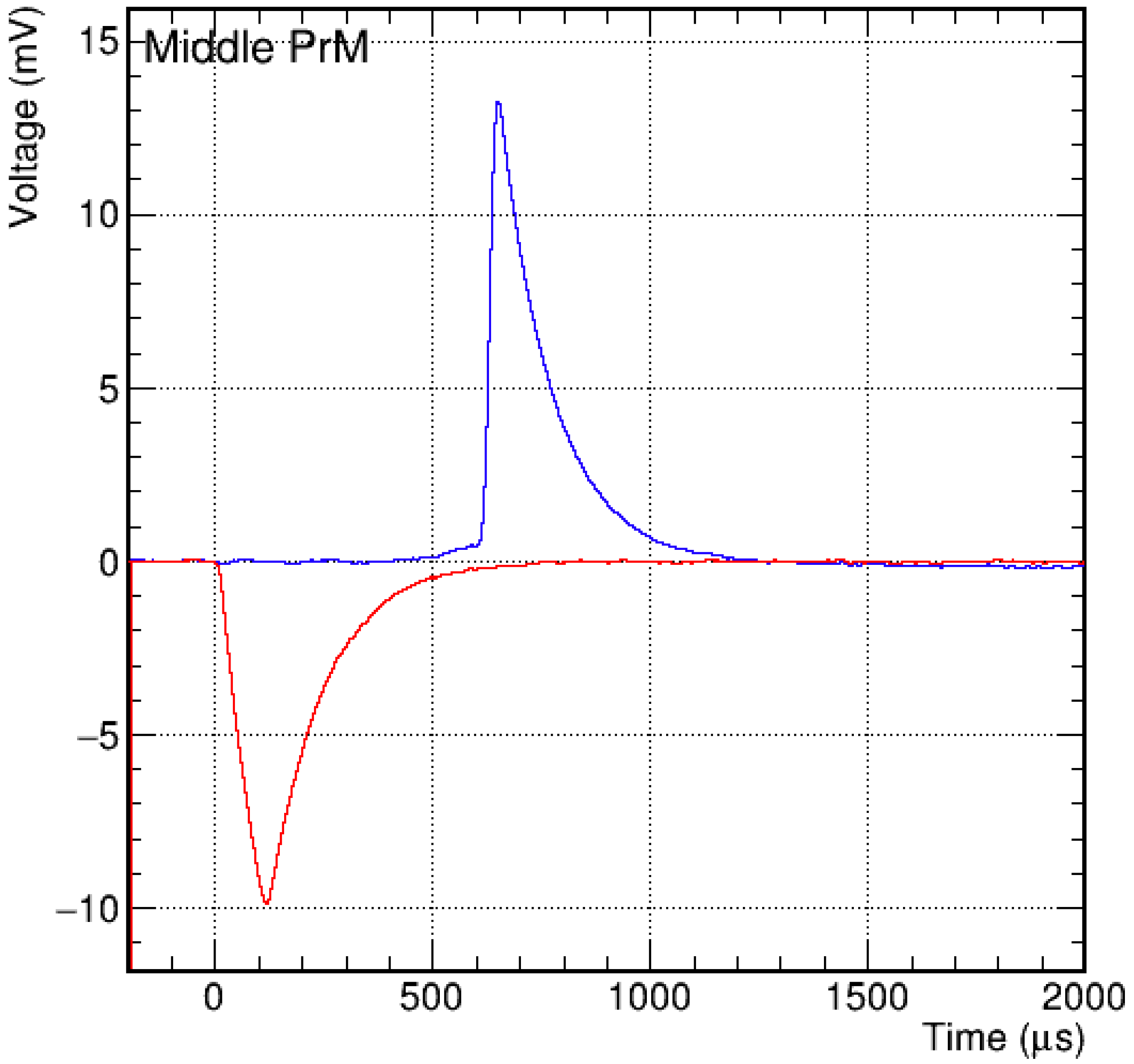


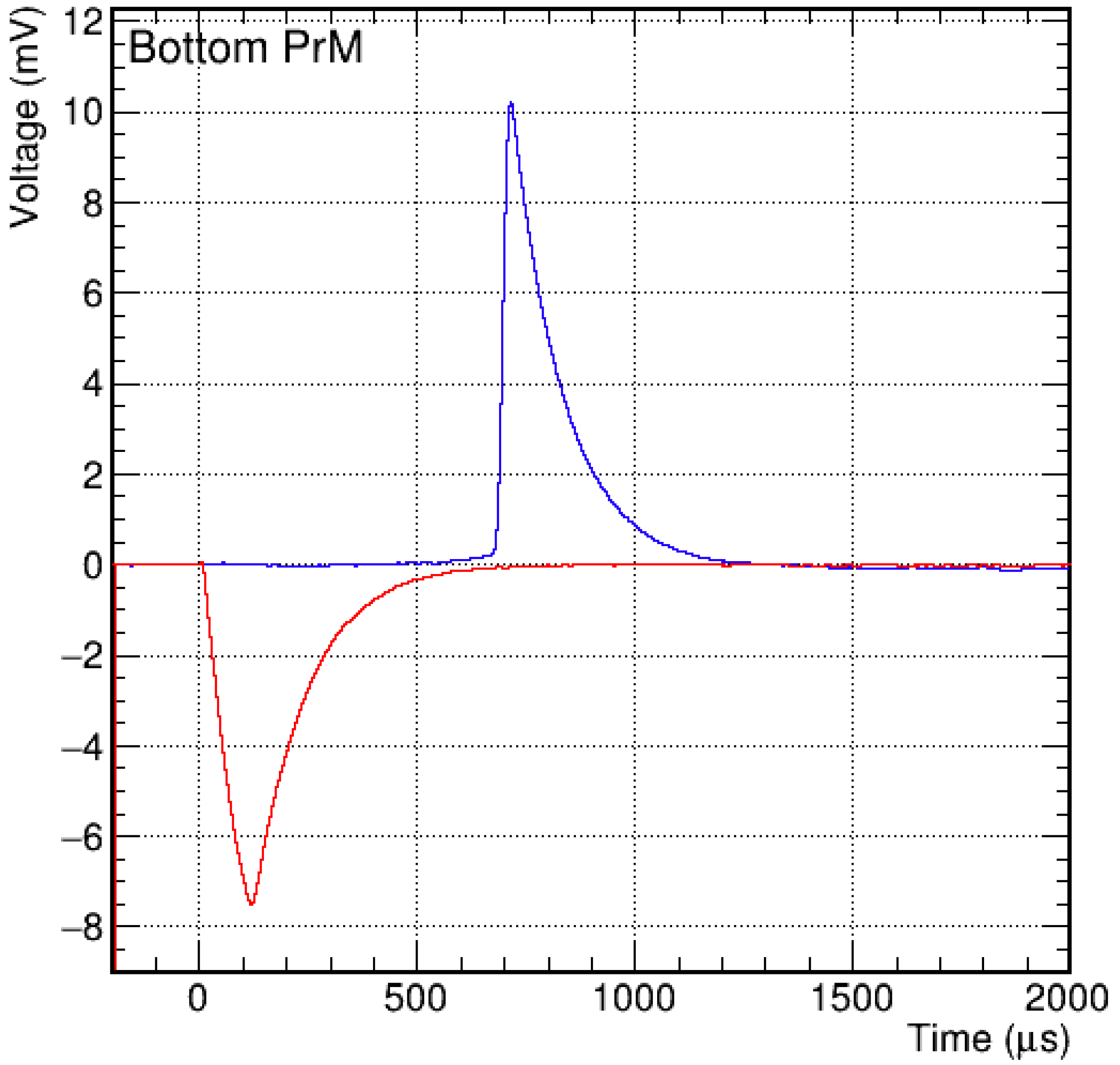
Baseline subtraction



Baseline subtraction







Apply PrM results to LArTPC calibration

How to apply PrM results to the calibration for LArTPCs? Attachment rate correction is needed.

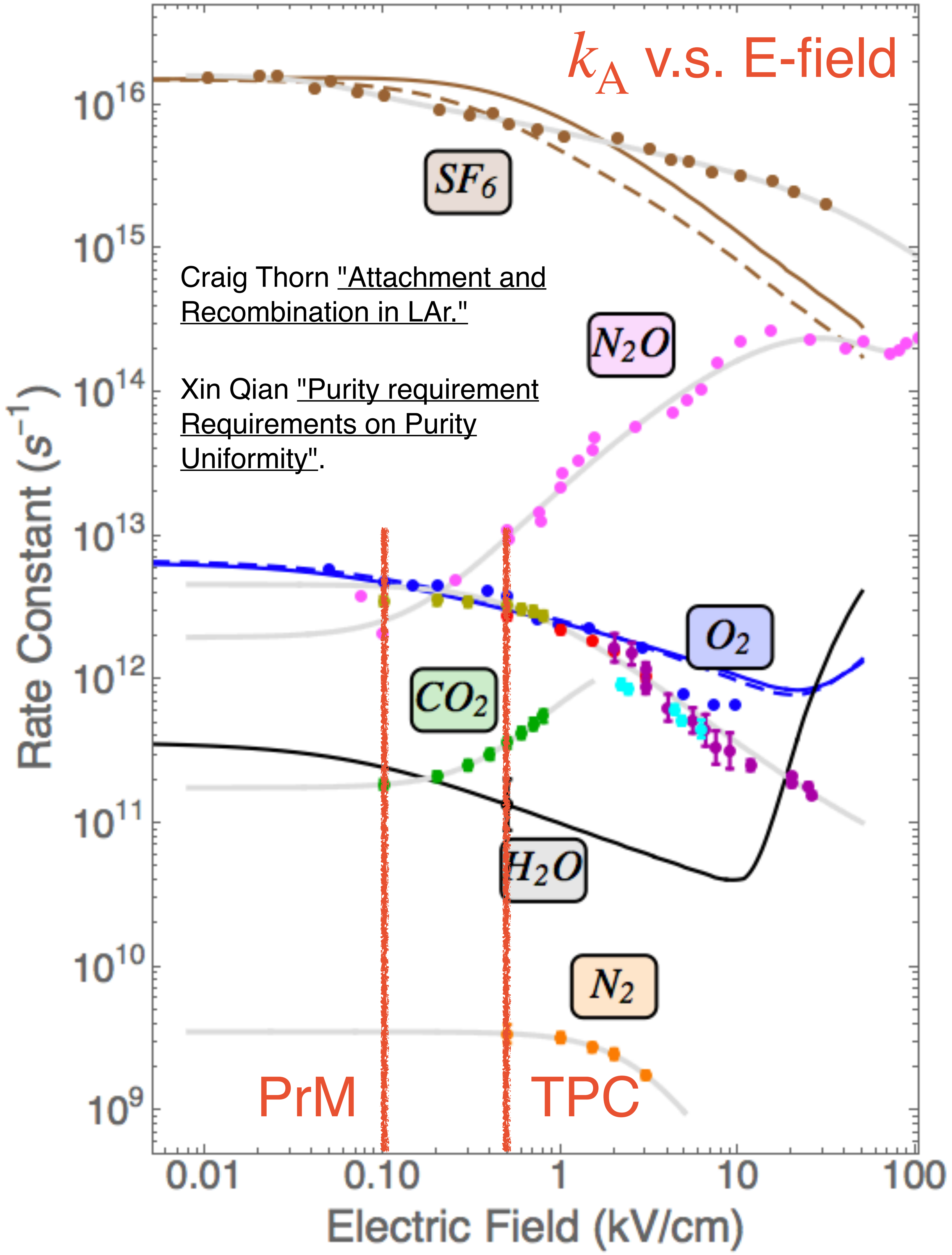
- Electron lifetime $\tau = 1/(k_A \cdot n_s)$
  - For a certain type of LAr impurity (O_2, H_2O etc): k_A is the electron attachment rate, n_s is the impurity concentration
- k_A is a function of the E-field. Purity monitors run at 10-100 V/cm and TPC runs at ~500 V/cm.
- Electron lifetime at TPC E-field (τ_{TPC}) can be determined from electron lifetime at PrM E-field (τ_{PrM}) with an attachment rate correction:

$$\tau_{TPC} = \tau_{PrM} \cdot k_A(V_{PrM})/k_A(V_{TPC}).$$

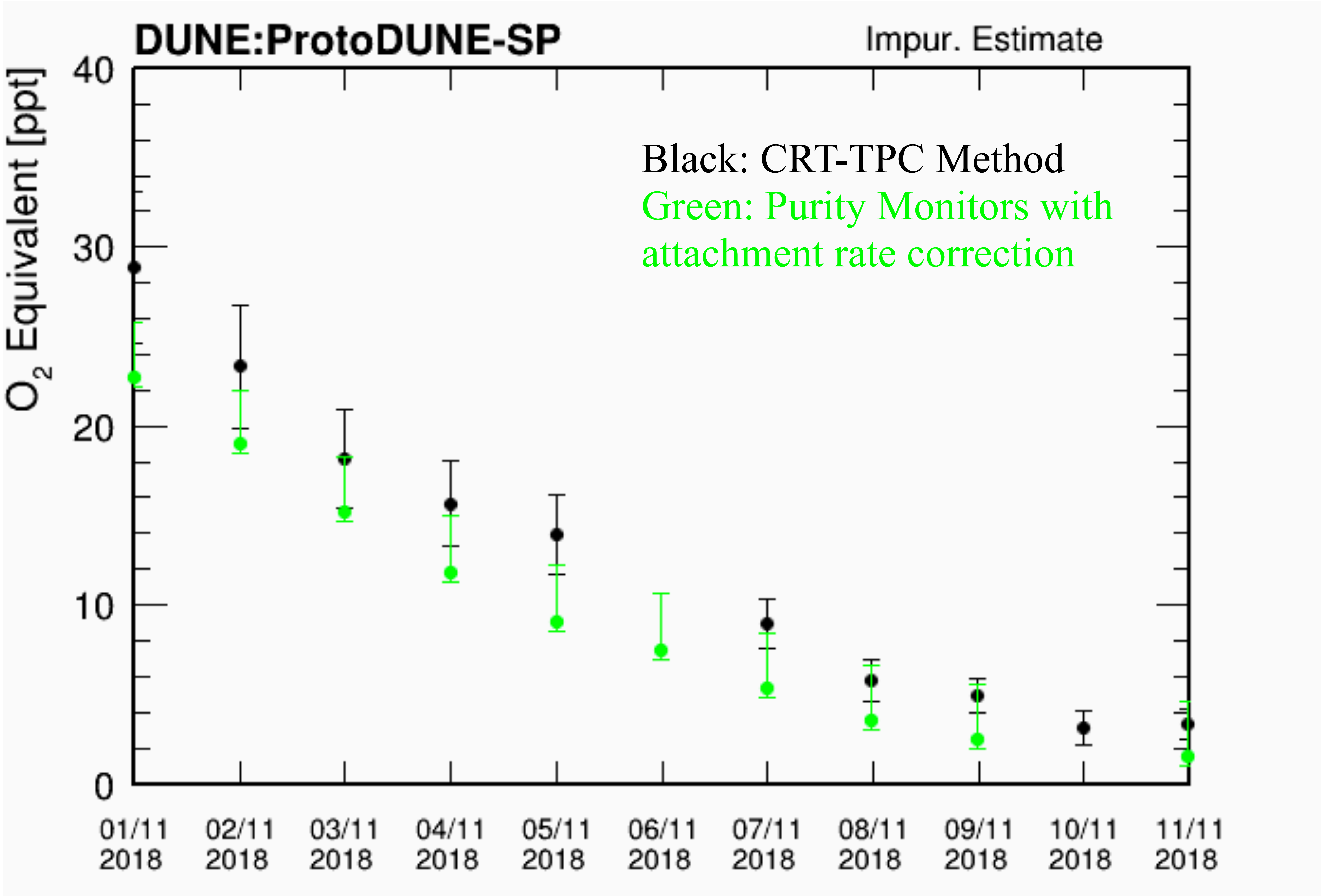
- $k_A(V_{PrM})/k_A(V_{TPC}) \approx 1.3$ obtained from

$$k_A = \frac{\frac{a_1}{b_1} + a_1 E + a_2 E^2 + a_3 E^3 + a_4 E^4}{1 + b_1 E + b_2 E^2 + b_3 E^3 + b_4 E^4}.$$

  - Parameterization from Craig Thorn's document 'Attachment and Recombination in LAr'.
- Though absolute attachment rates could be very different between O_2 and H_2O, shapes of the k_A v.s. E-field curve for H_2O is expected to be similar to O_2 in the E-field range 0.01-1 kV/cm.



Purity monitor and CRT/TPC electron lifetime



- The impurity measured by purity monitors and TPC/CRT are in good agreement.
- Provided PrM lifetime to ProtoDUNE-SP analysis group for run-by-run lifetime calibration.