Monte Carlo simulation of MPPC photosensors for the T2K experiment

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Fabrice Retiere, Thomas Linder, Scott Oser, TRIUMF
Antonin Vacheret, Imperial College London
Martin Haigh, University of Warwick

Introduction

- A lot of experimental data is now available for MPPC devices.

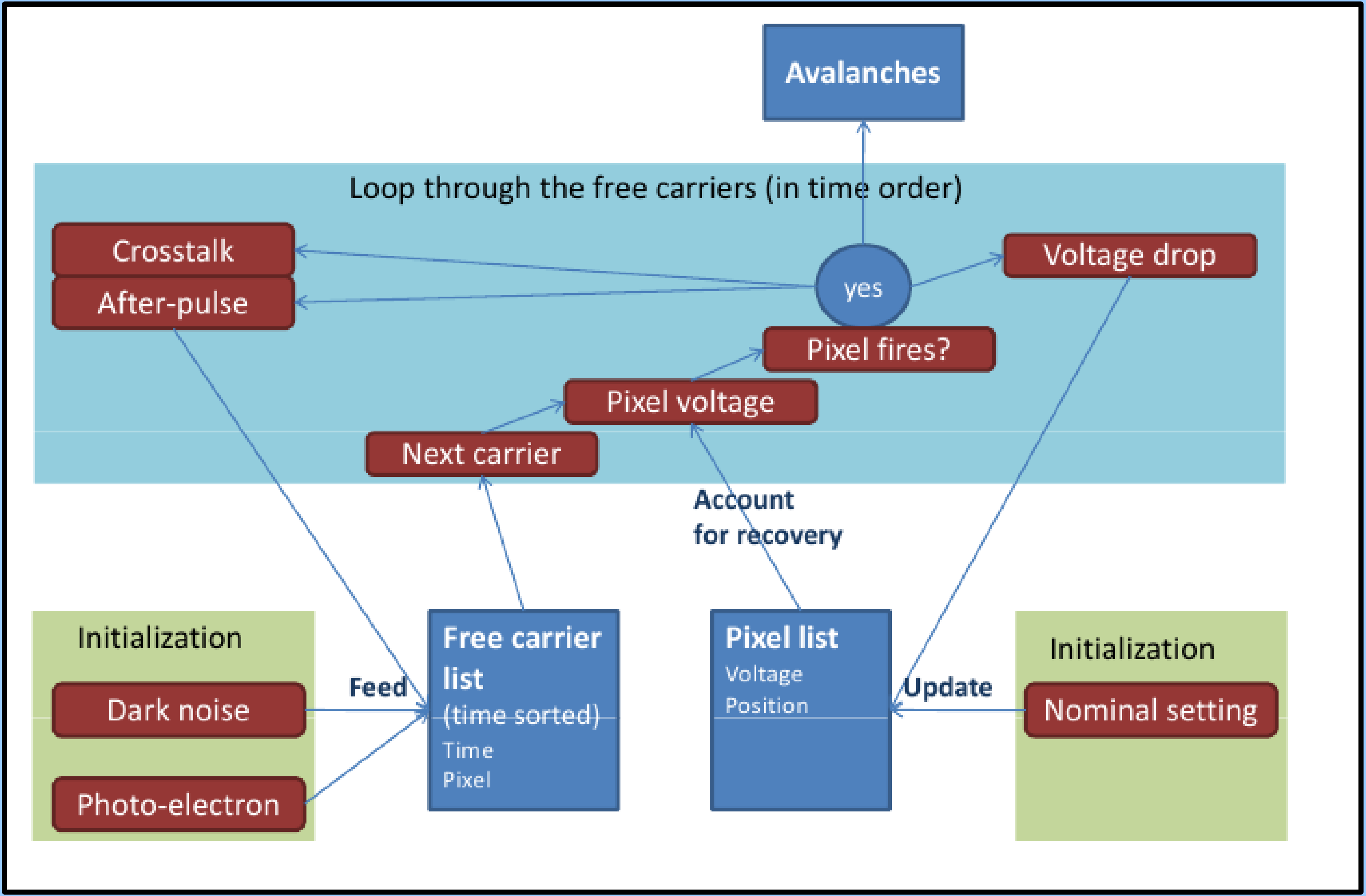
- Very useful to build a complete model to describe MPPC behaviour:
  - Test the models used to describe individual device features.
  - Use in a detector simulation chain.
  - Extrapolate test-bench results.

- T2K/ND280 photosensor group now has a mature MPPC Monte-Carlo:
  - C++ object code. Standalone version depends on only the GSL libraries.
  - Finite 2D array of pixels => saturation effects.
  - Dark noise, crosstalk (CT) and afterpulsing (AP).
  - Voltage recovery.
  - Gain smearing.
  - Parameters set as quadratic functions of $V_{bias} – V_{bd}$.

Simulation Framework

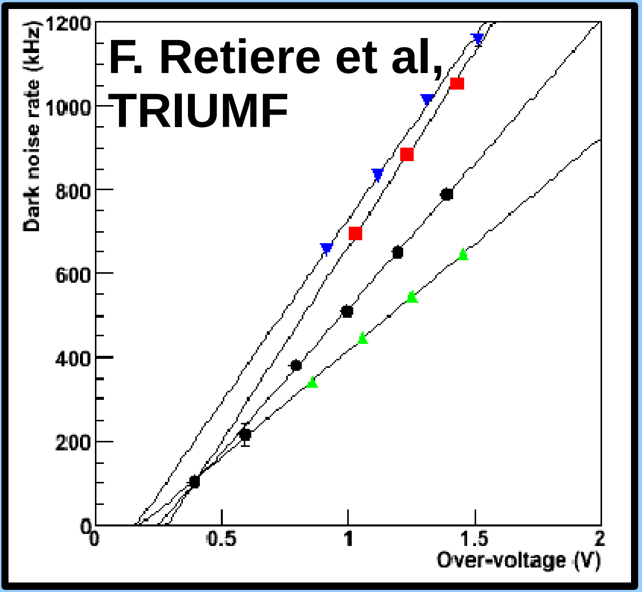
- Based on a time-ordered list of “free carriers” (T. Linder/S. Oser, TRIUMF).
  - Create initial list consisting of real incident photons and thermal carriers.
  - Step through the list in time order. Decide whether the carrier generates an avalanche, and if so add it to an output list.
  - If AP/CT are generated from an avalanche, add the AP/CT to the list of carriers and process them later, in time order.
- Stepping through the list in time order allows cascades of CT/AP to be dealt with naturally.
- Easy to incorporate voltage recovery:
  - recalculate pixel voltages before dealing with each carrier;
  - only need to store the previous voltage values and the time elapsed since the last carrier.

Simulation Framework

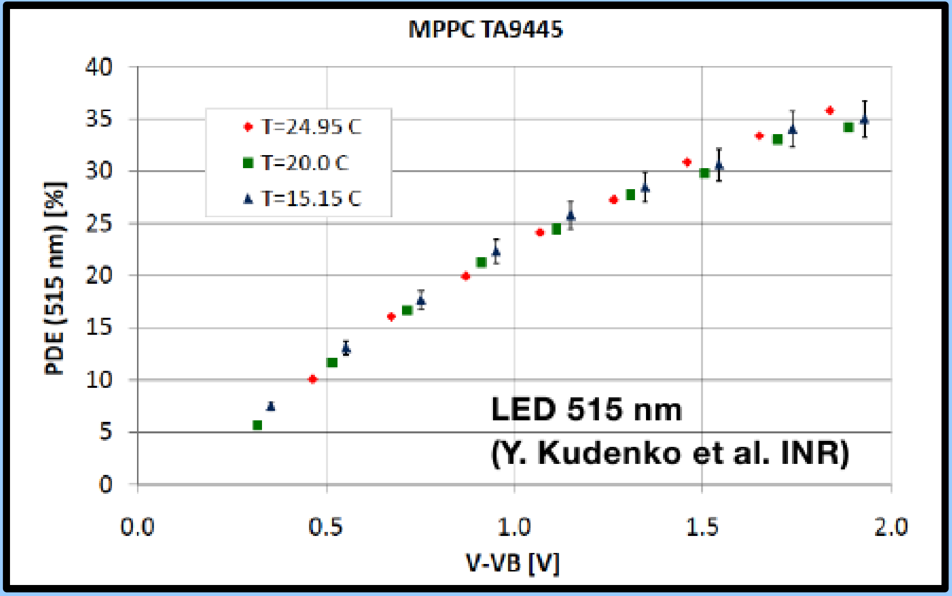


Dark noise and PDE

- Dark count rate (DCR) linear in overvoltage.
  - Carriers generated at initialization using correct dark rate for applied bias voltage.
  - Account for recovery effects – carrier only fires pixel with probability DCR(V_{pixel})/DCR($V_{applied}$).
- Exponential dependence of DCR on temperature. In simulation but need more data to tune it.



- PDE modelled as linear in overvoltage.
  - Detailed measurements at INR, Sheffield suggest PDE saturates.
  - Simulation will be modified to account for this, but it already fits low-light data well for a range of gains (see later).
  - Dependence on wavelength not yet implemented (not very important for ND280 Y11 light).
  - See D. Orme's talk for detail on PDE measurements.



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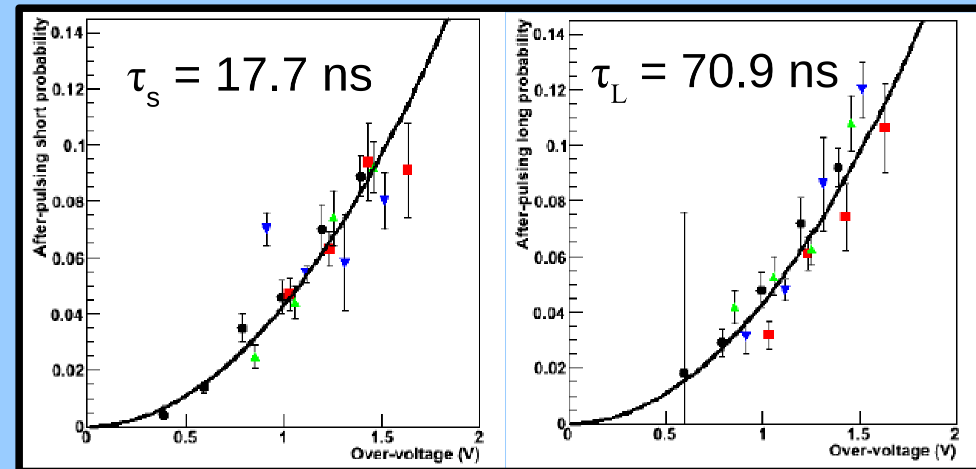
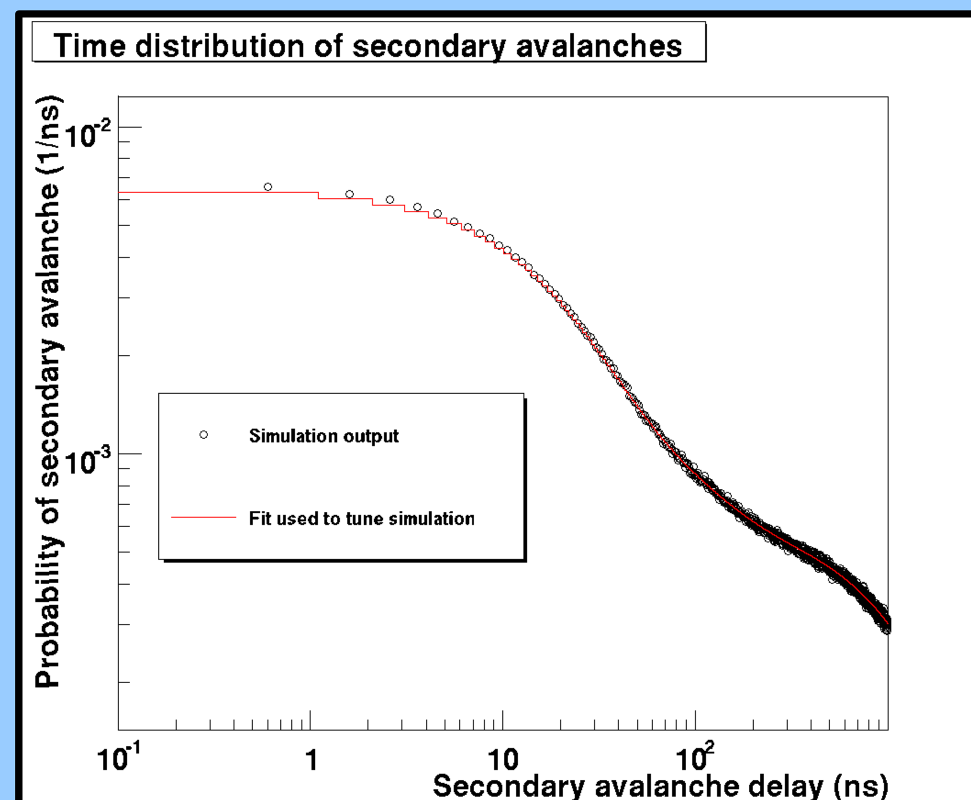
Afterpulsing

- Based on TRIUMF data – time distribution of delay between trigger and subsequent pulse.
- Data fitted well with a double exponential time distribution for AP.
  - Use same distribution in simulation.

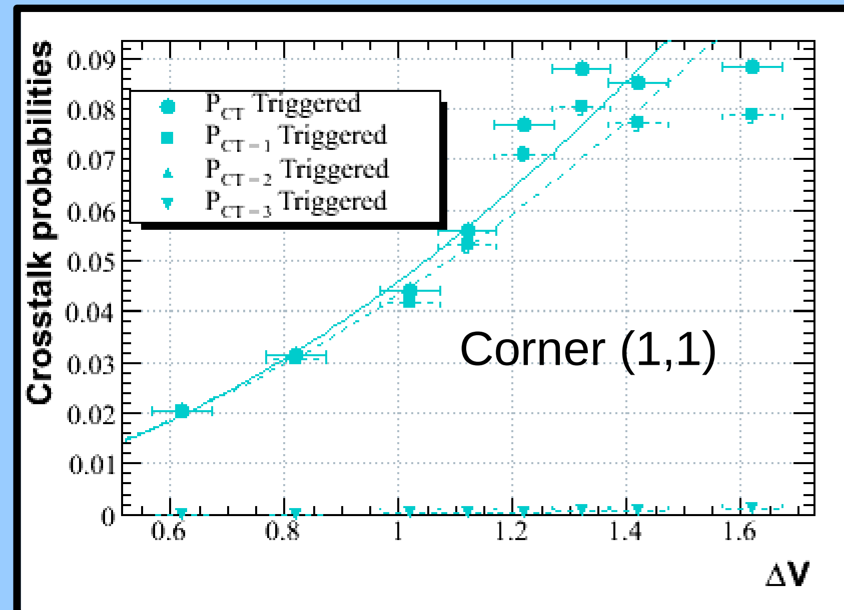


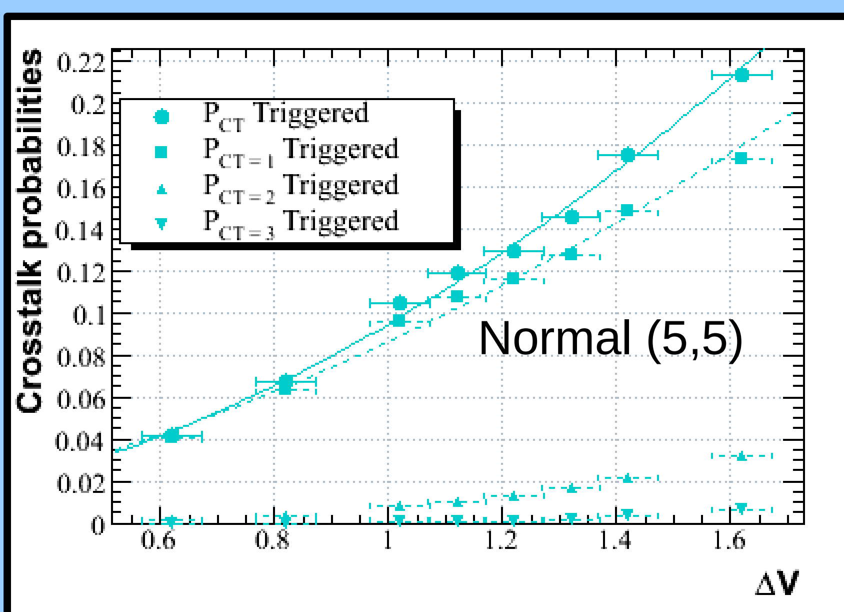
- Validate by doing the same delay analysis for simulation results.
  - Good agreement between simulation and the input fit used to tune it.

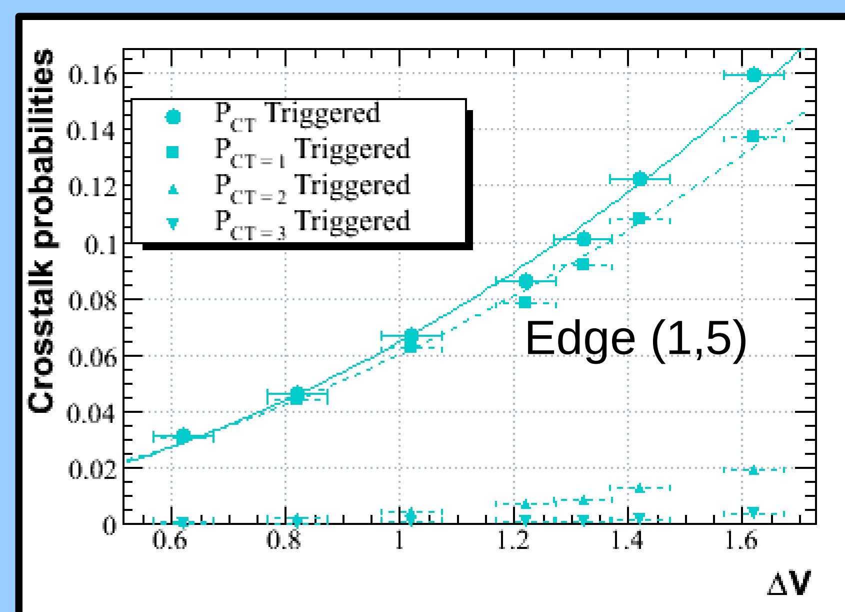


Crosstalk

- 1,2,3 CT probabilities measured for different pixels at ICL.
  - Lower for edge and corner as they have fewer neighbours.
- Data doesn't uniquely define a microscopic model .
  - Choose something with a few parameters and tune to data.

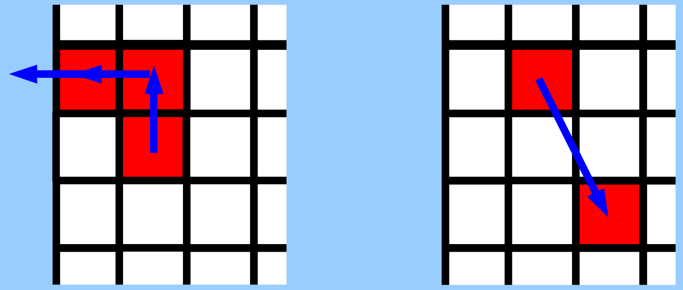






Crosstalk model

- Relatively simple model:
  - Each pulse can only cause one crosstalk, but a crosstalk can cause further crosstalk - “cascade-only”.
  - Total $P_{CT} = aV+bV^2$ (V is overvoltage of primary pixel).
  - Crosstalk pixel selected randomly; each candidate weighted by $e^{-r/Range}$, where r is distance from primary.
  - Only consider 5x5 grid centred on primary, for speed.
  - If candidate is off edge of device, get no CT.



CT cascade ends if Rand>P_{CT} or the cascade goes off the edge.

Tuning to data

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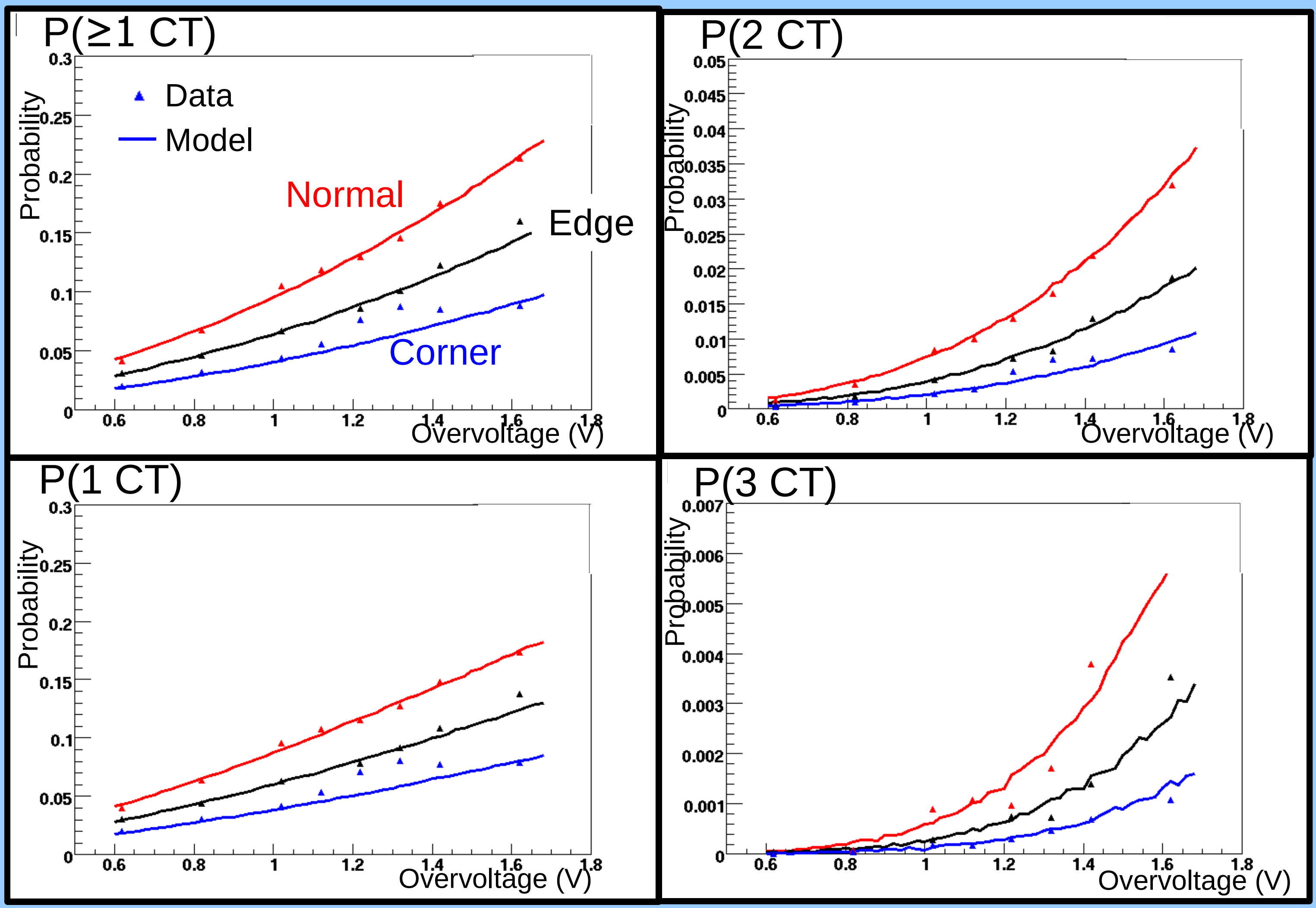
- Data for total CT on pixel (5,5) used to fix total CT probability.
- Model fits quite well to data for all pixels, with Range=0.4 pixels.
  - Data for corner pixel appears to saturate. Not clear how to model this but not very important for bulk MPPC behaviour since it only affects a small number of pixels.



Recovery

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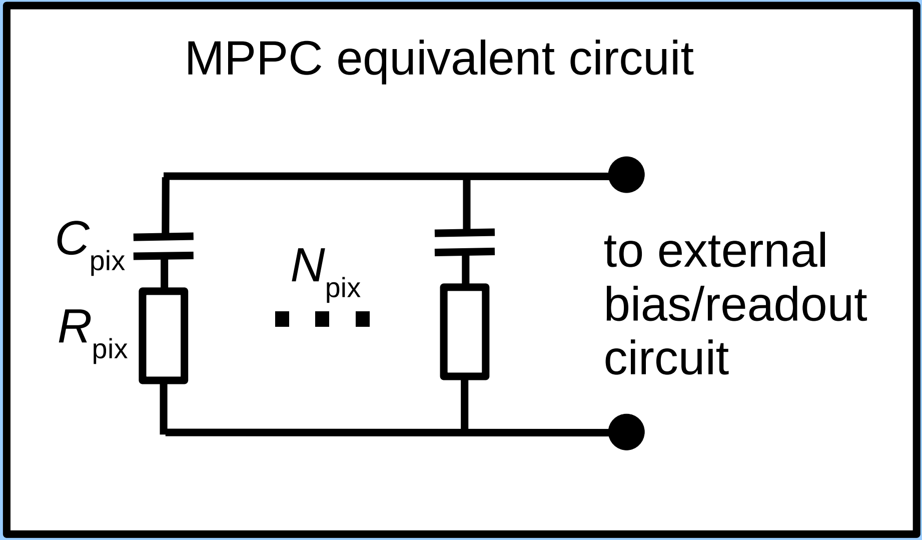
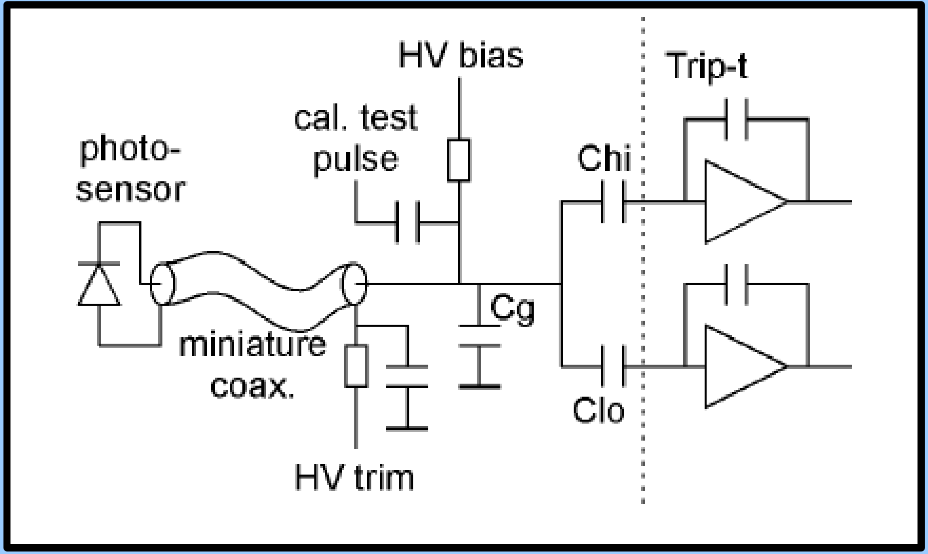
- Pixel recovery time is finite since charge flow limited by quenching resistor.
  - Model a pixel as an RC series circuit.
  - Capacitor discharges when pixel fires.
  - R = 150 kΩ, C = 90 fF => intrinsic pixel recovery time $\tau_S = RC$ = 13.5ns. Pixels will recover exponentially with decay constant τ_S if the MPPC is connected to a voltage source.

- Actual recovery behaviour depends on details of readout circuit.
  - Simulation defines abstract interface to recovery model so a class describing the relevant readout circuit can be "plugged in".



TFB Electronics

- Several subdetectors in the ND280 near detector use the Trip-T Front-end Board (TFB) for readout.
  - Uses the Trip-t ASIC developed for the D0 experiment.
  - MPPC bias voltage on a common line for all channels. Gains controlled by a trim voltage on “ground” pin of each MPPC.
  - MPPC charge split capacitively into high/low gain channels.
  - Readout cycle follows ND280 beam structure – 23 x 540 ns integration “timeslices” with 50 ns reset time in between.



TFB Electronics

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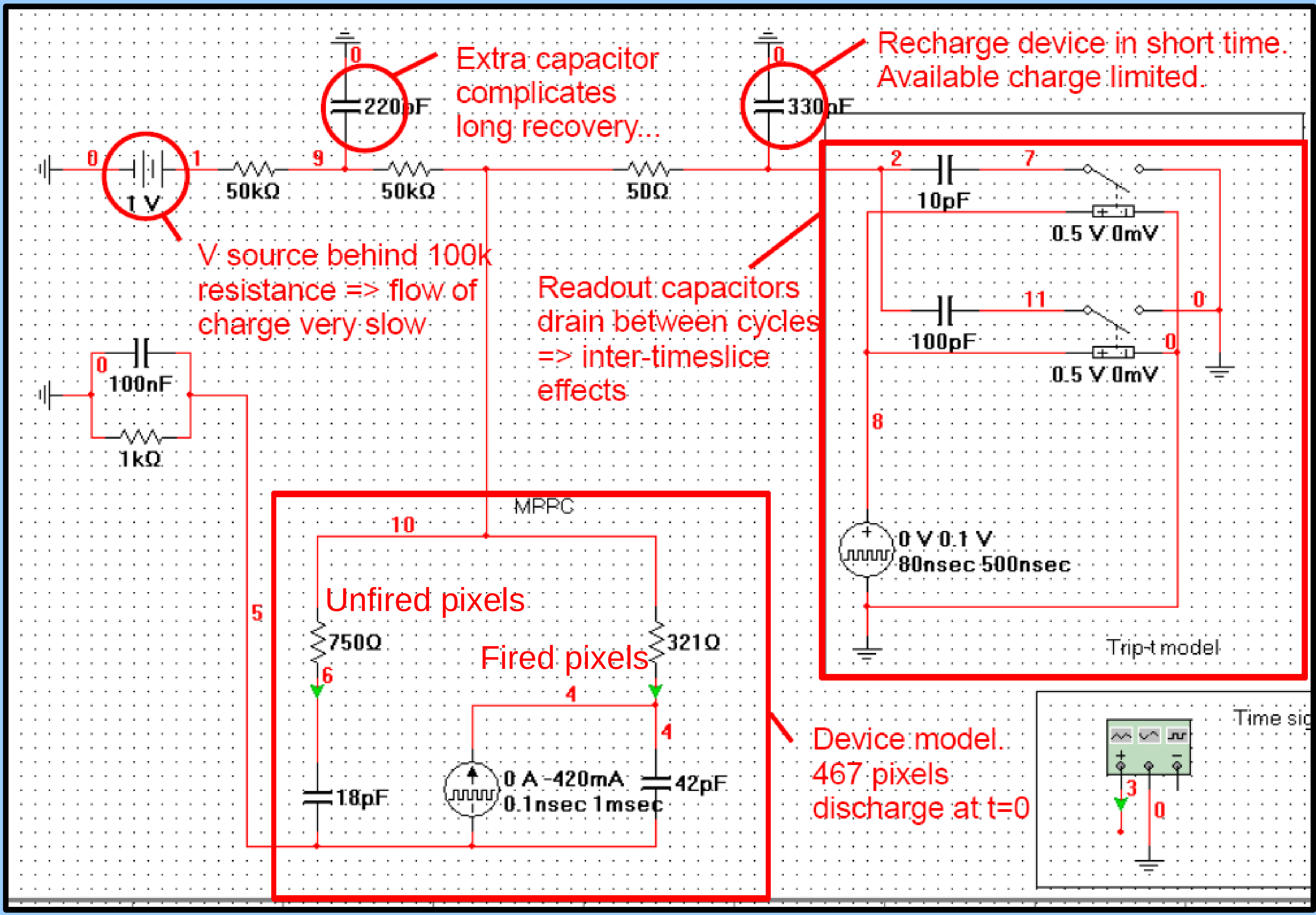
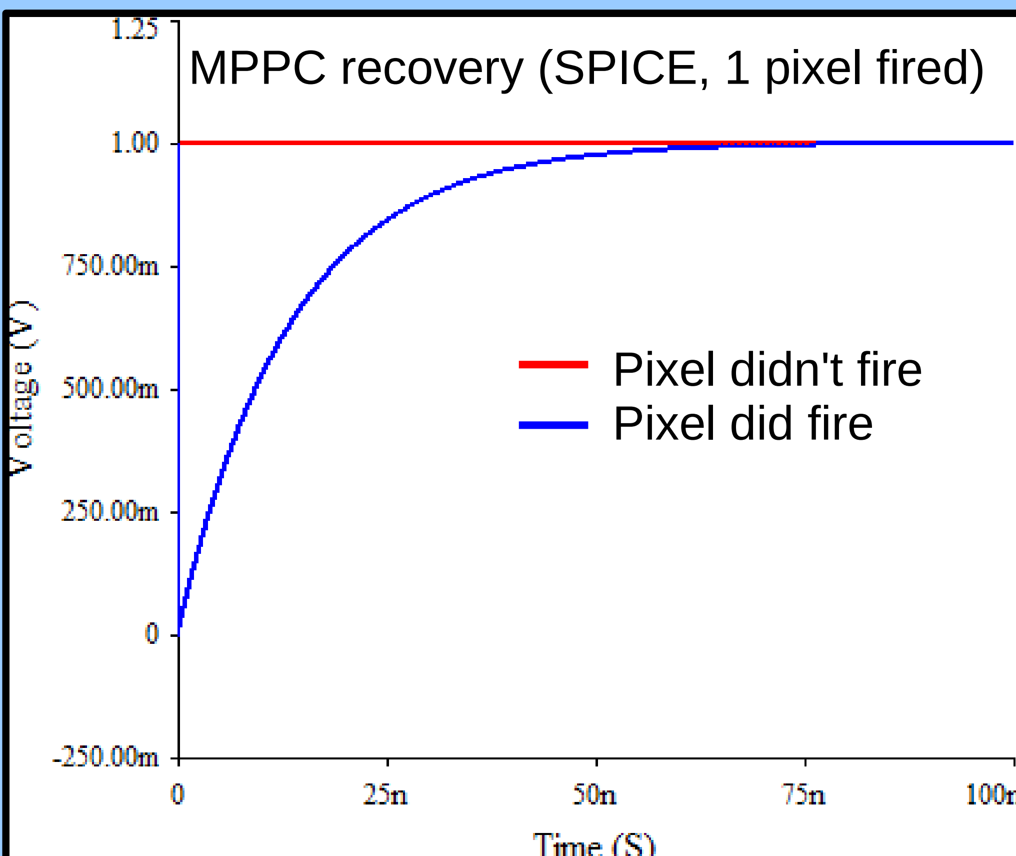
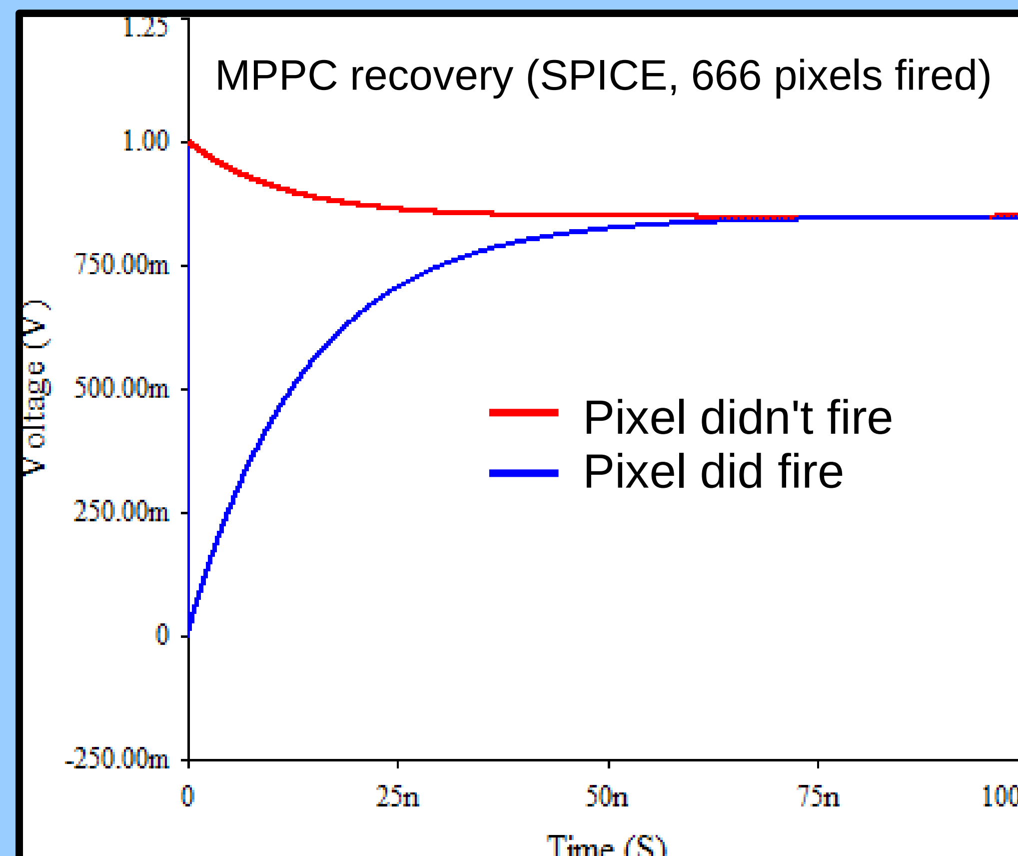
- Developed a SPICE model including MPPC and its interface to the TFB.
  - Suppose we discharge some of the pixels, all at *t*=0. Then the MPPC is equivalent to two RC series circuits, corresponding to the unfired and the fired pixels.



Recovery: SPICE short-time prediction

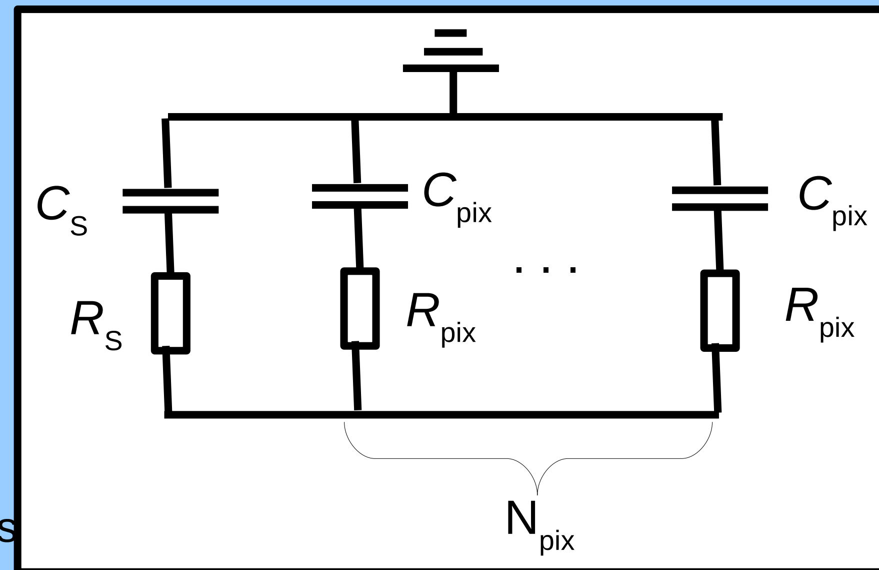
- Recovery for fired pixels close to exponential with intrinsic time constant τ_S.
  - Pixels don't fully recover (for short times) if signal is large. Unfired pixels also drained.
  - Looks fairly simple => try and model short-time behaviour analytically.





Recovery: Local Capacitor Model

- Ignore bias source and just consider local capacitor C_S.
  - Fairly simple equivalent circuit.
  - Analytic solution for pixel voltages $V_i(t)$ is a single exponential to leading order.
  - Time constant τ_1 same as intrinsic recovery time.
  - Equalization of voltage between pixels and C_S =>unfired pixels are drained slightly for large signals



Initial voltage

Final voltage

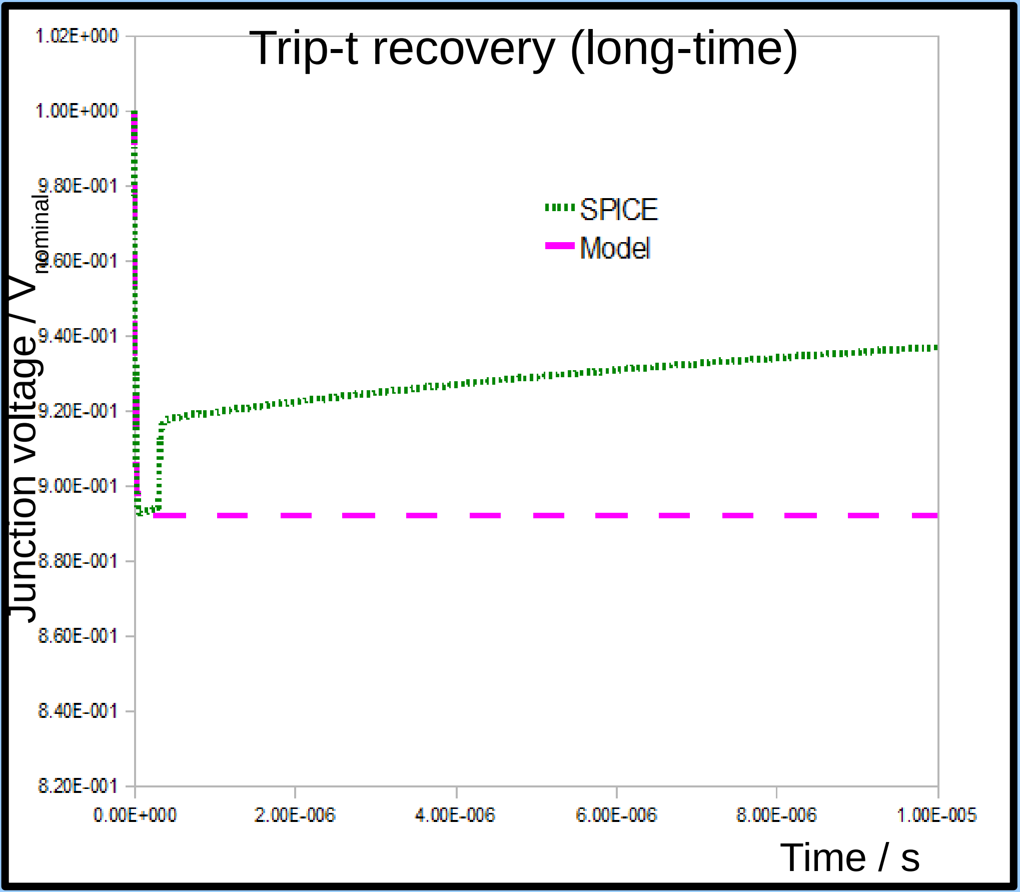
Small since $\tau_1 \approx \tau_2$

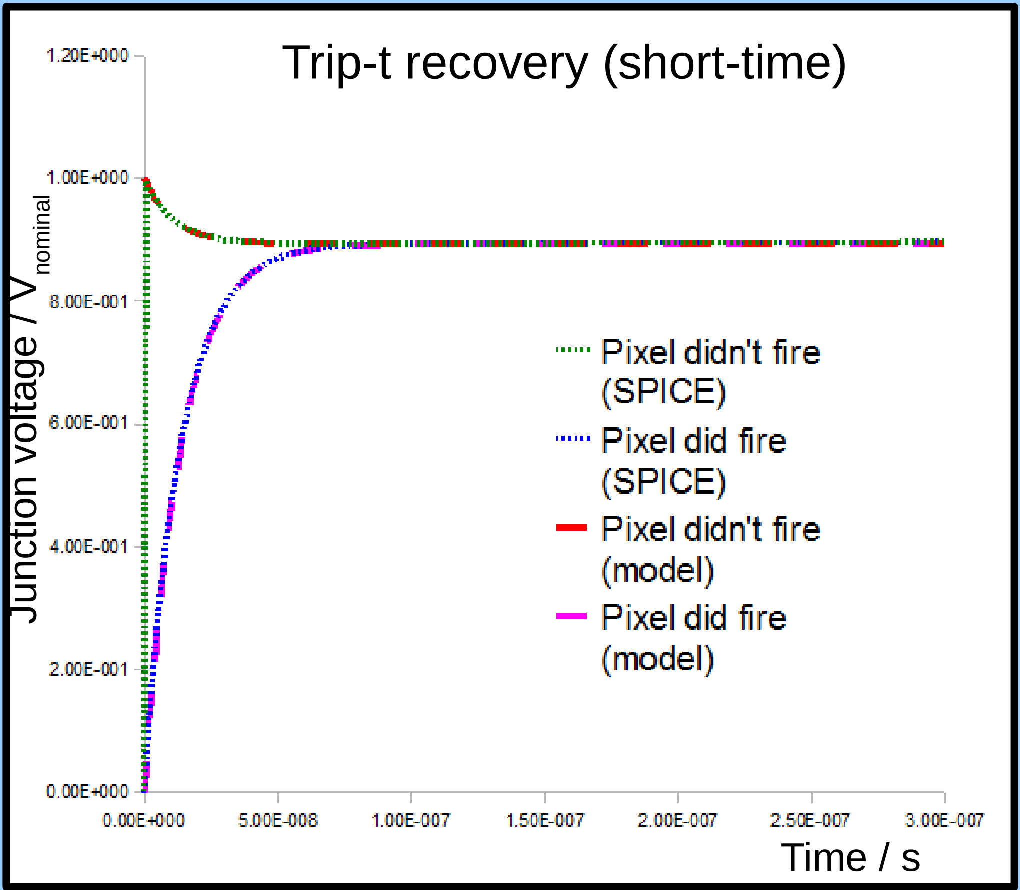
$$V_i(t)=V_i(0)e^{-t/\tau_1}+\left(V_S(0)-\frac{A\tau_2}{C_S}\right)\left(1-e^{-t/\tau_1}\right)+\frac{A(\tau_2/C_S-R_S)}{1-\tau_1/\tau_2}\left(e^{-t/\tau_2}-e^{-t/\tau_1}\right)$$

$$\tau_1=R_{pix}C_{pix},\quad \tau_2=\frac{R_{pix}/N_{pix}+R_S}{1/C_S+1/C_{pix}N_{pix}},\quad A=\frac{V_S(0)-\sum V_i(0)/N_{pix}}{R_{pix}/N_{pix}+R_S}$$

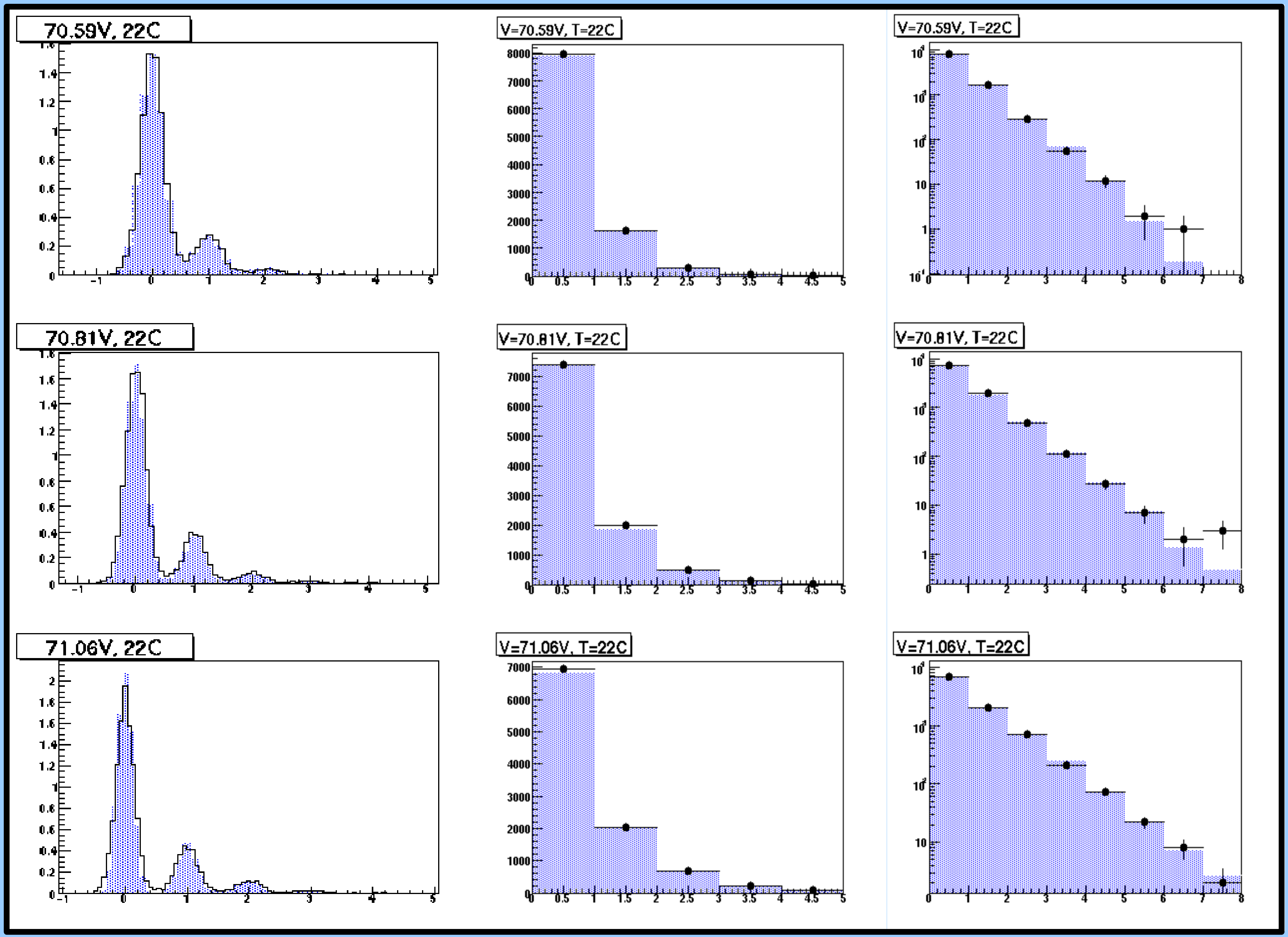
Recovery: Local Capacitor Model

- Local capacitor model reproduces short-time SPICE result very well (for ~1 TFB cycle).
- Long-time results not so important for analysis.
- Inter-timeslice effects are also present and not included in the model.
- Local capacitor model simple enough to put into MC.

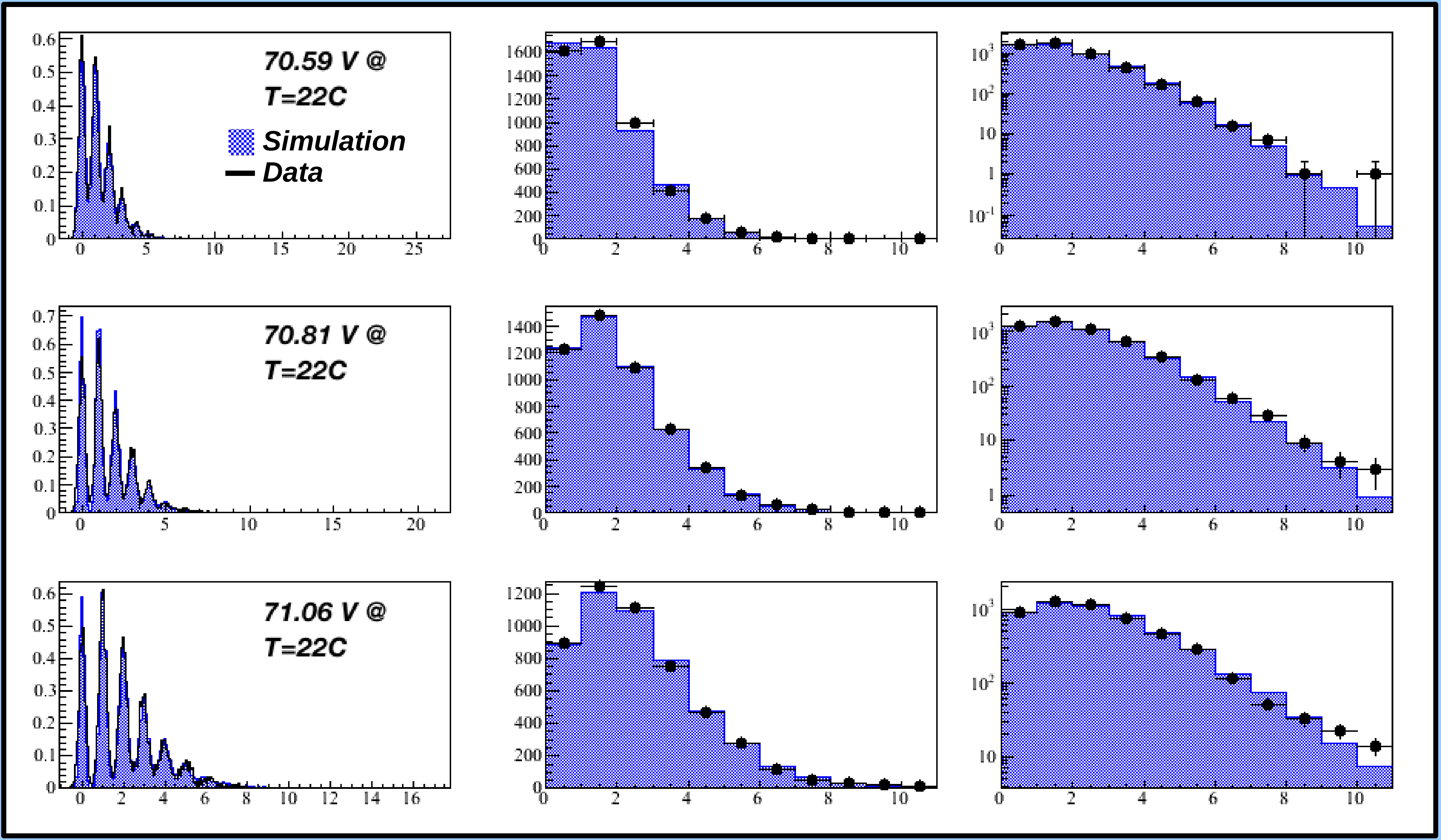




Comparison to data – dark noise

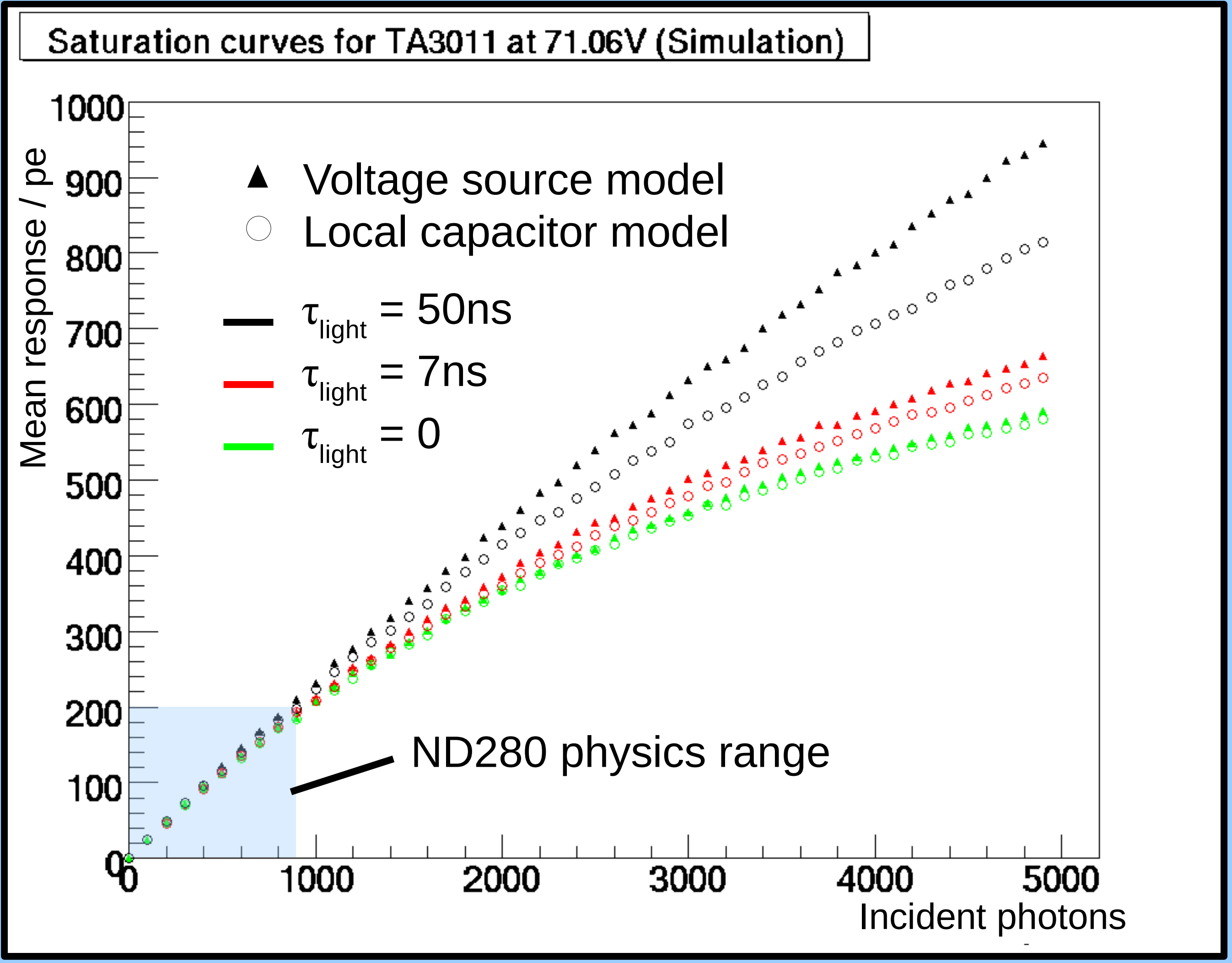


Comparison to data – low light



Saturation

- Use simulation to predict response to high level illumination.
- Decay time of Y11 fibre used in ND280 is 7ns – same timescale as sensor recovery. =>saturation will depend on details of recovery model.
- Compare TFB model with recovery from voltage source (pixels recover independently with timescale τ_S = 13.5 ns).



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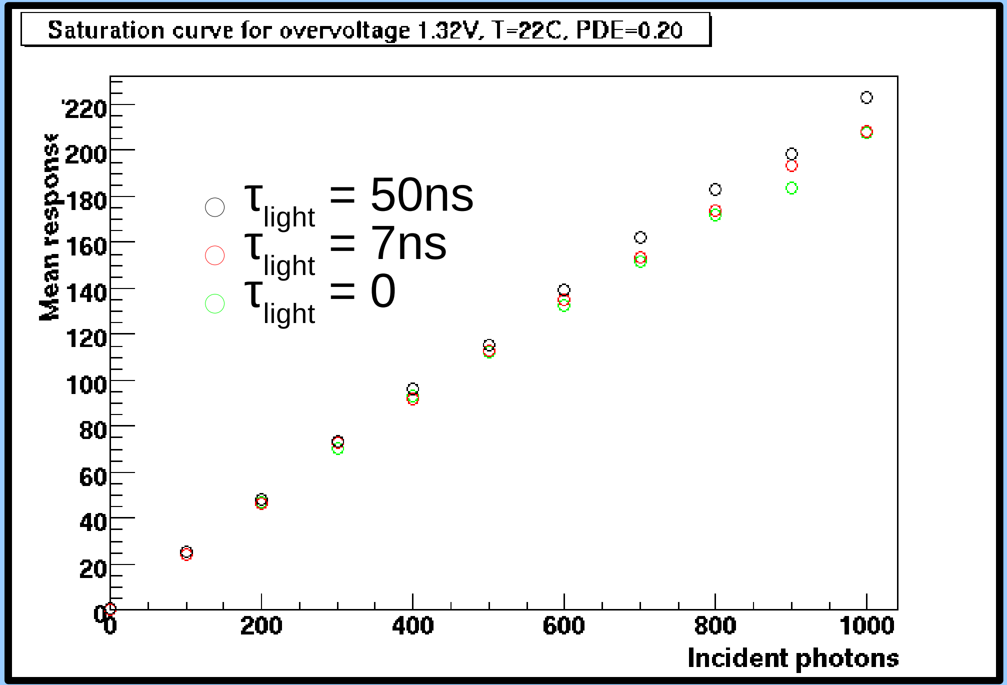
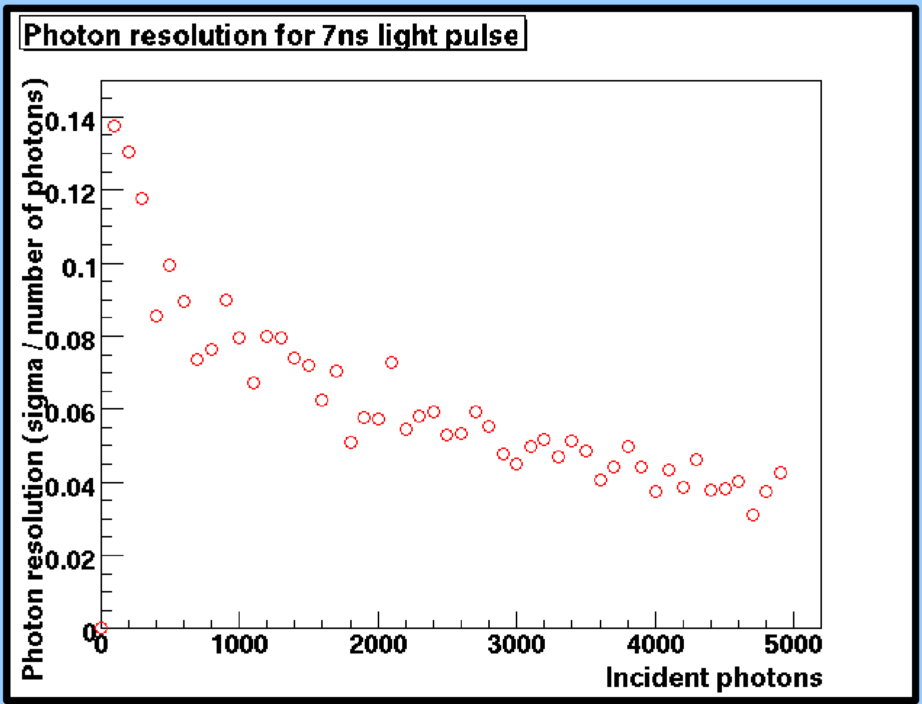
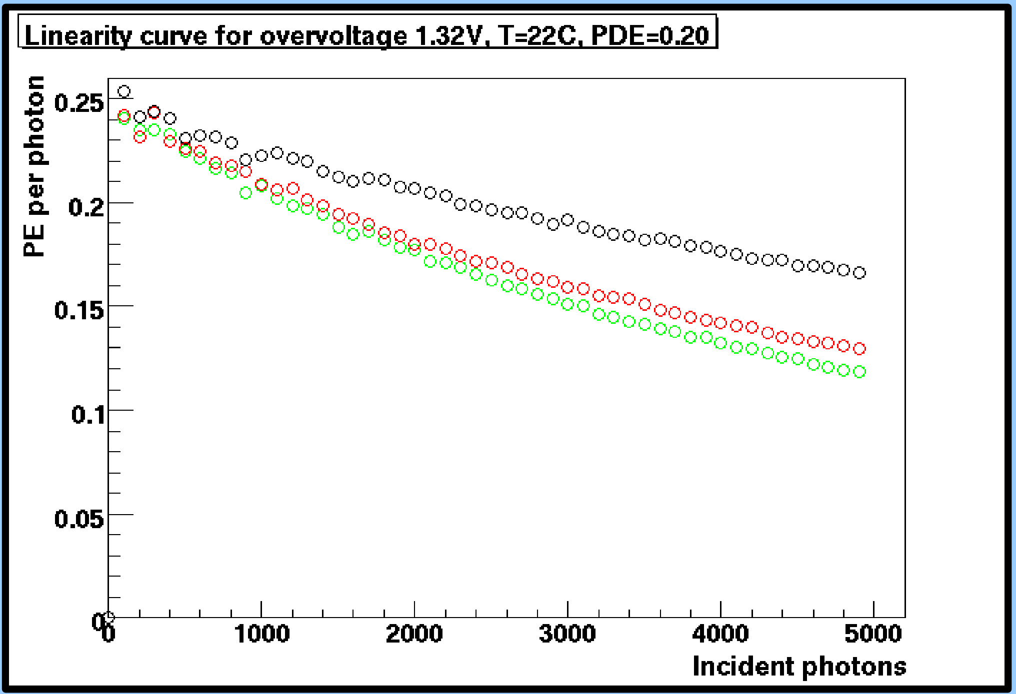
Saturation

- MPPC response is fairly linear over ND280 physics range.
- Linearity curve depends quite strongly on the time distribution of incoming light.



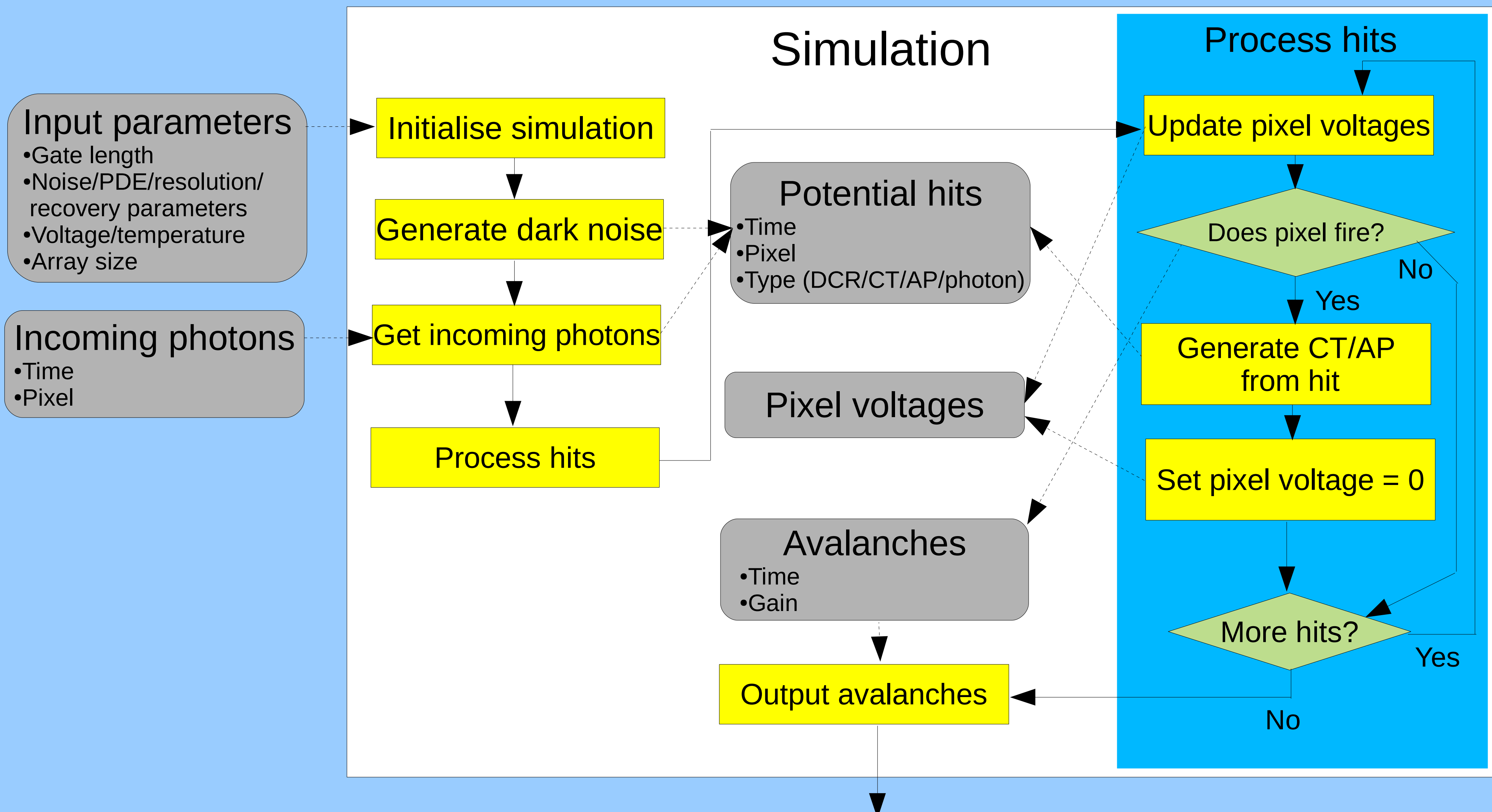




Conclusion

- The T2K/ND280 collaboration have developed a simulation containing all MPPC features.
- Models for individual features based on characterisation measurements.
- MPPC behaviour well-validated for low-light data.
- Recovery of pixel voltage for the ND280 TFB electronics has been studied and implemented in simulation.
- Saturation response looks sensible but must be compared to real data.
- There is room to make some elements a little more sophisticated, but simulation is basically complete.

Simulation Framework



Afterpulsing

- Measured using a waveform analysis study.
  - Measure time between a trigger pulse and next pulse.
  - Distribution fitted assuming AP time distribution is a double exponential $P(t)=Ae^{t/\tau_S}+Be^{t/\tau_L}$.
  - Probabilities scale as overvoltage^2. Time constants independent of voltage.

F. Retiere et al, TRIUMF