Delayed avalanche in SiPMs and especially MPPCs

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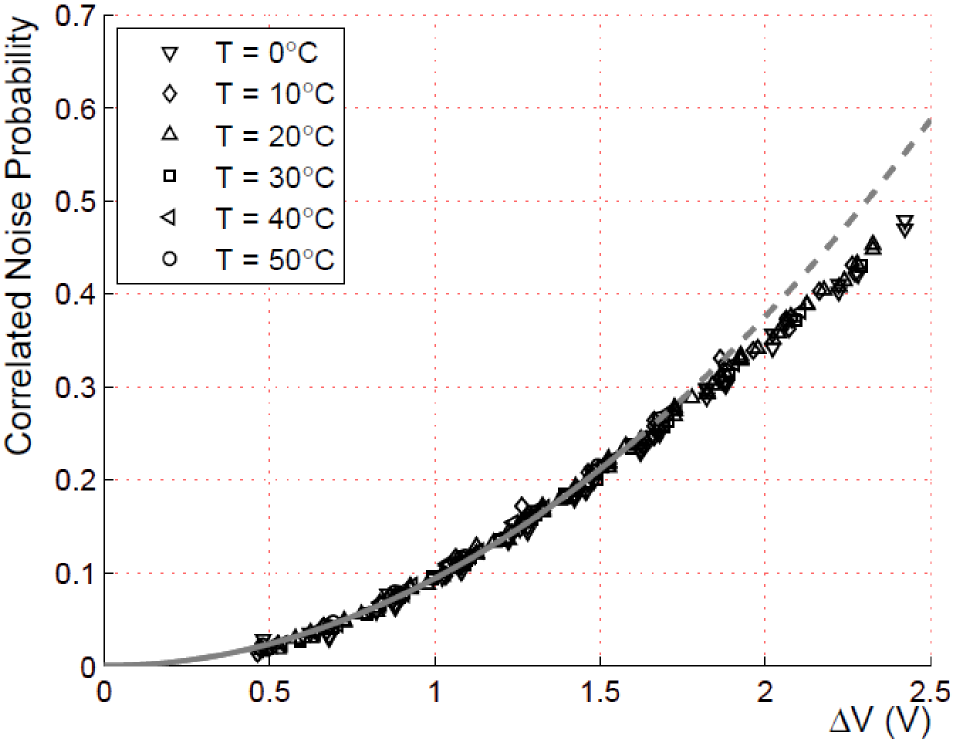
With help from Y. Iwai (Hamamatsu)

TRIUMF

Motivation



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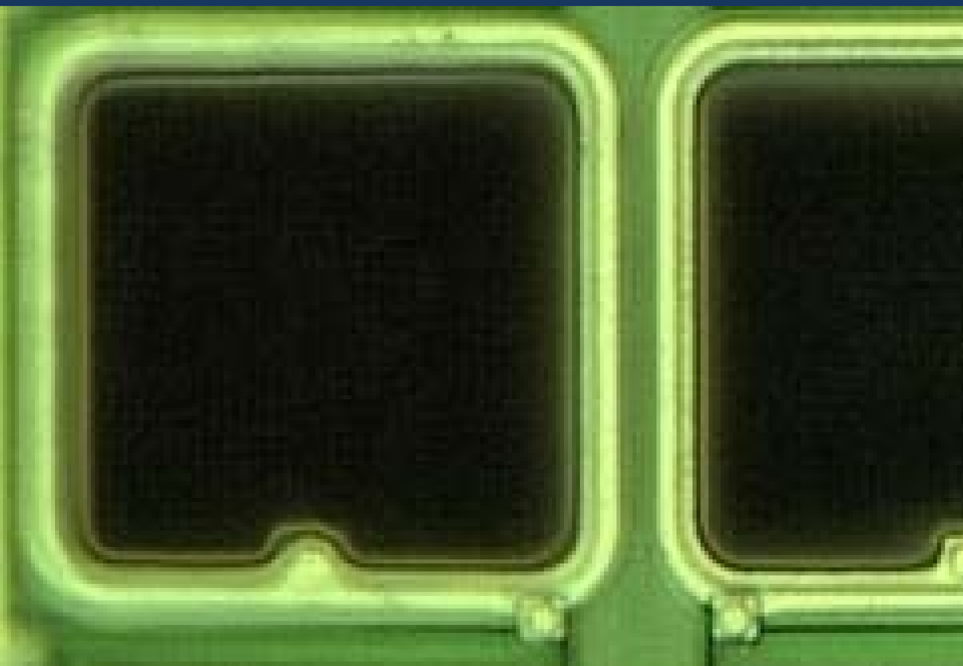
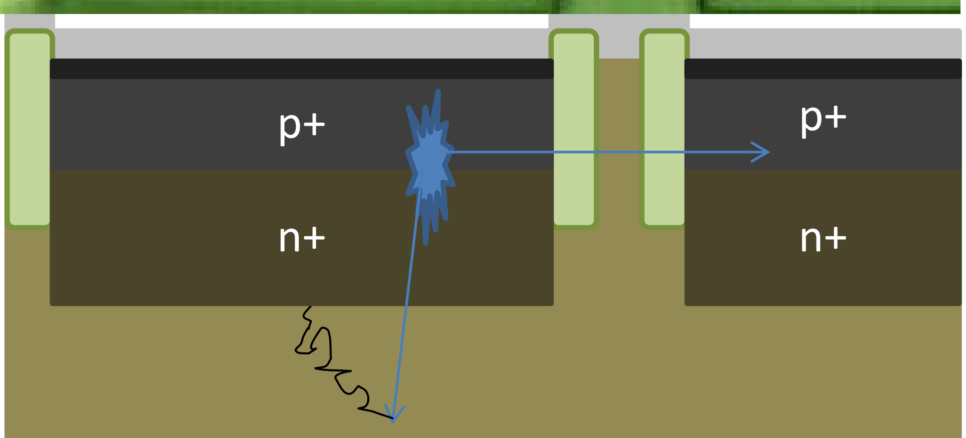
NIM A656 (2011) 69-83

- Correlated noise
  - Cross-talk
  - After-pulsing
- Limit the MPPC over-voltage reach
  - Large dark noise pulses
    - Big concern for experiment with low PE count
  - Large excess noise factor = worse energy resolution
- Dark noise is not the main concern except for timing

Cross-talk and after-pulse

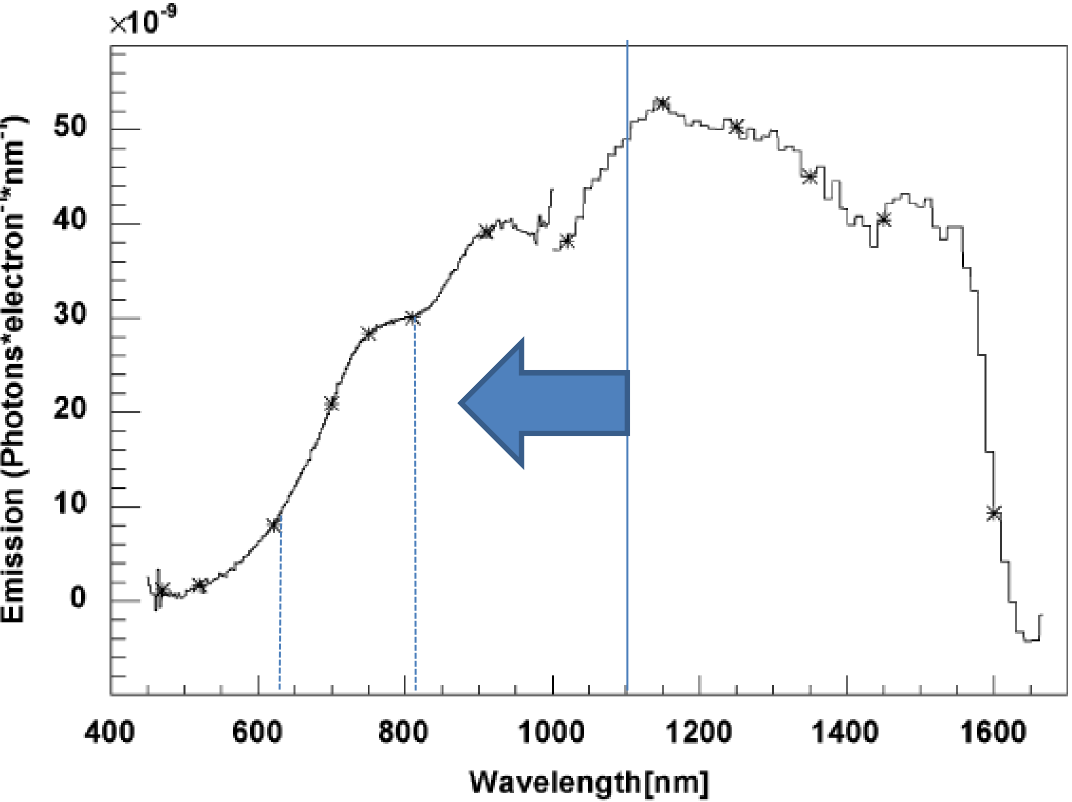




- Cross-talk
  - Prompt = by definition
  - Origin: photons produced in the avalanche absorbed in neighboring high field region
- After-pulse
  - Delayed = by definition
  - “Usual” origin: carrier produced in the avalanche trapped on impurities
  - Alternative origin: photons absorbed in bulk
    - Delay due to diffusion
    - Lets test this hypothesis

Use external light source

Spectrum of photons emitted in MPPC avalanches



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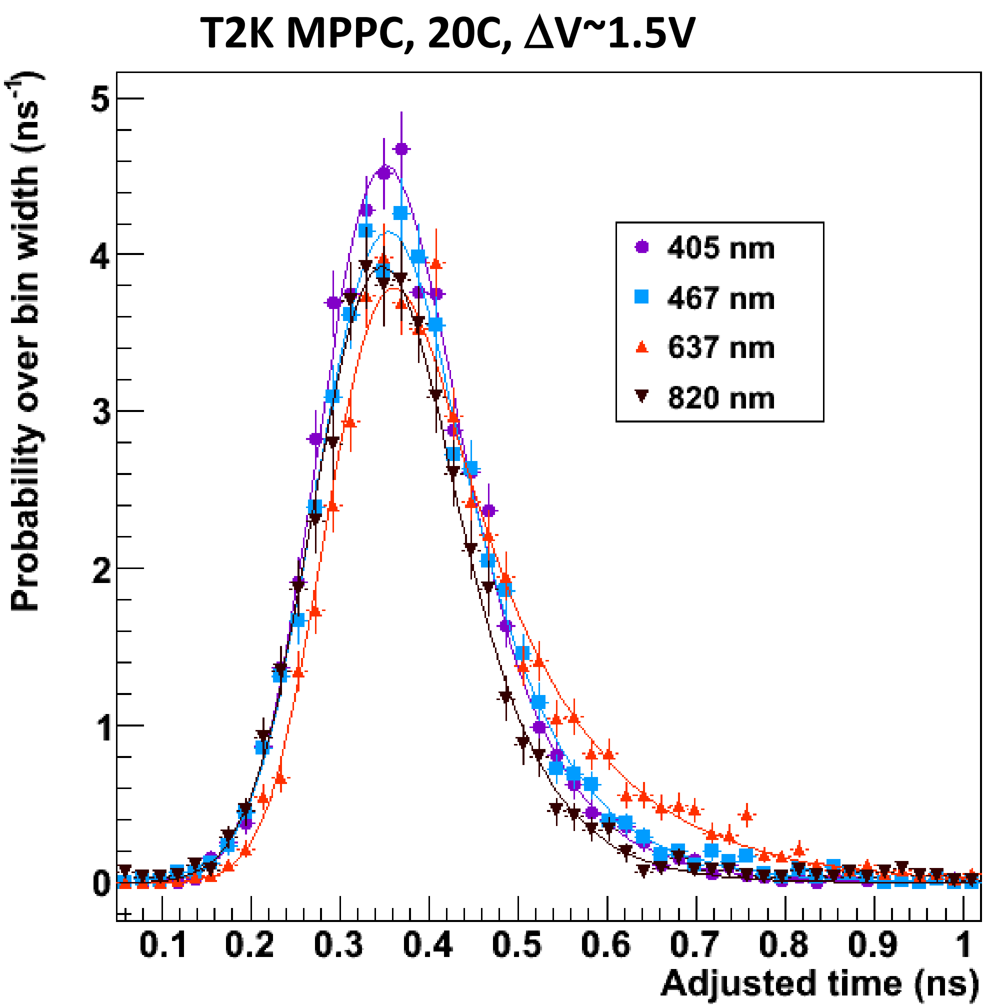
- Setup
  - Light sources: 404, 437, 637, 820nm
    - Pulse width and jitter <80ps
    - 820nm lent to us by Hamamatsu thanks to Y. Iwai
  - MPPC (or other SiPM)
  - High speed amplifier
  - Oscilloscope to record waveforms
  - Temperature controlled chamber

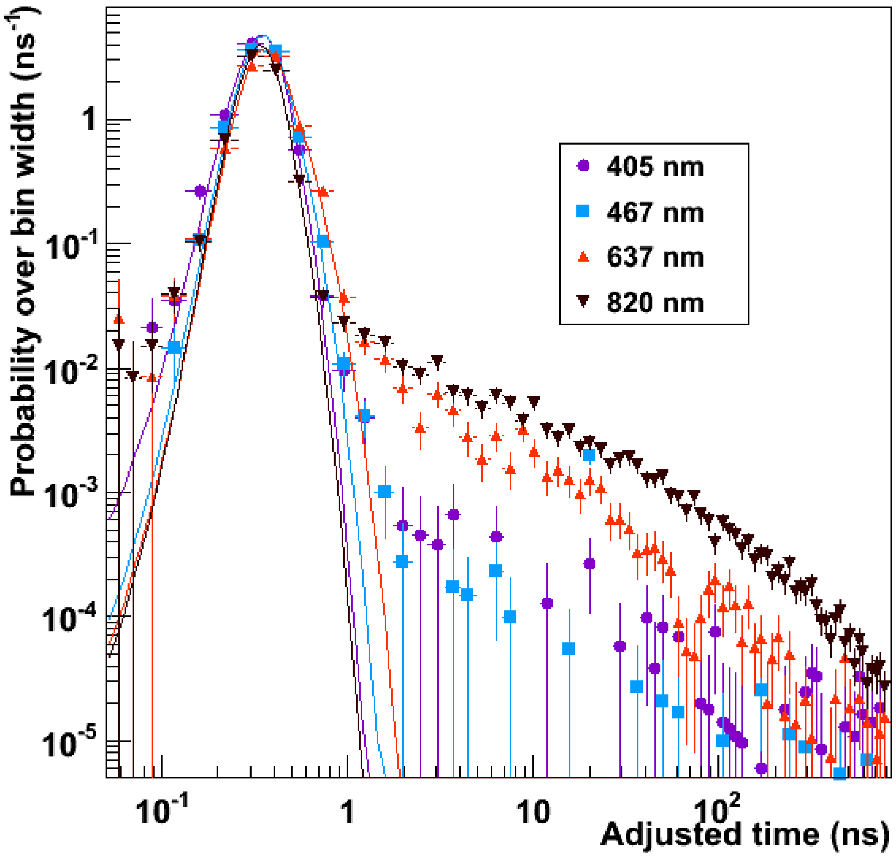
Analysis method



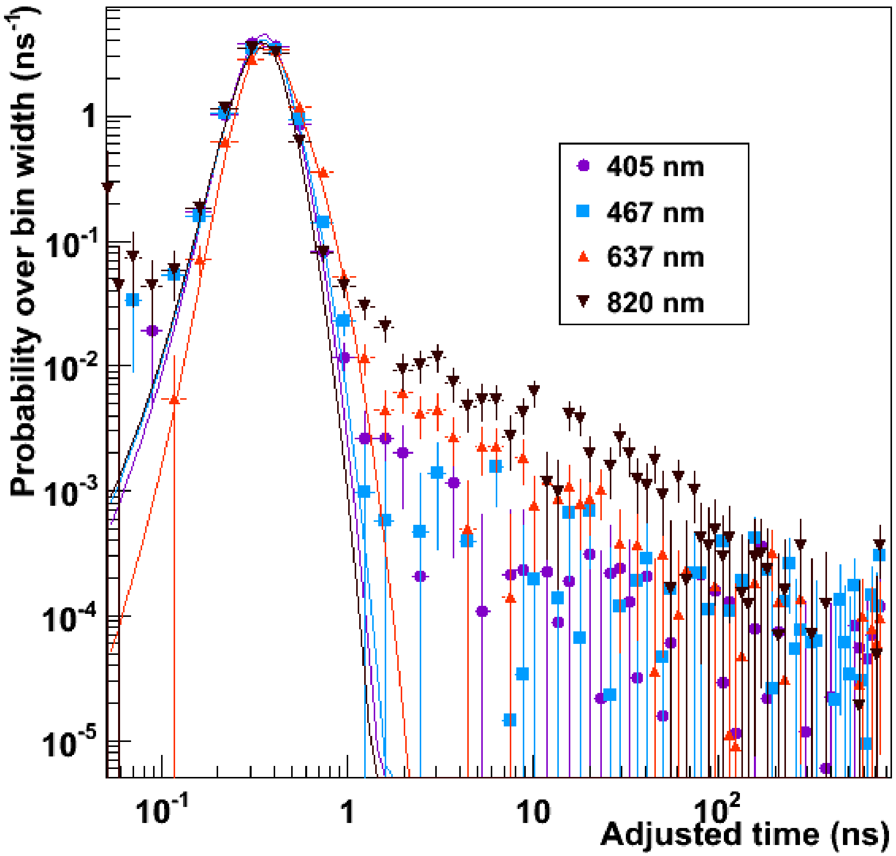
- Look for pulses within a 1us window
- Accept only events with 1 pulse to avoid after-pulse
  - Set the light level to maximize efficiency
- Subtract out the noise contribution
  - Measure prior to light pulse
- Normalize distribution to one
- Fit prompt peak by the convolution of an Gaussian and exponential

Look beyond the prompt pulse
Evidence for delayed avalanches

T2K MPPC, -60C, ΔV~1.5V

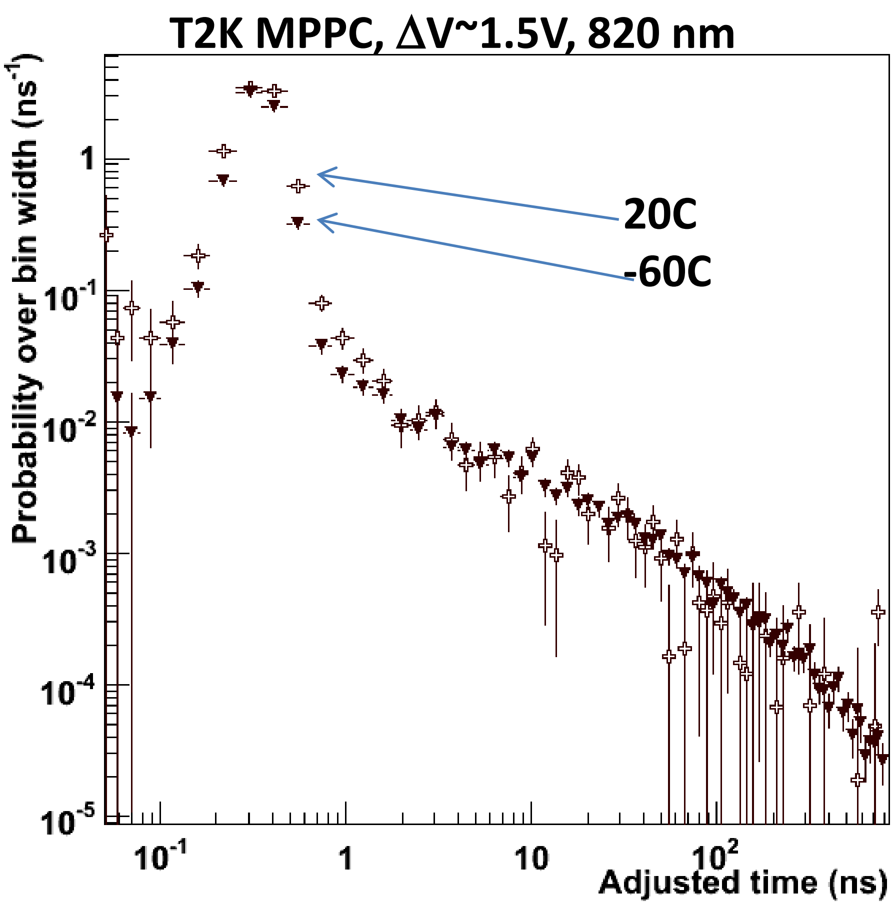


T2K MPPC, 20C, ΔV~1.5V



Time of the prompt peak set to 0.3 ns to show well on the logX plot

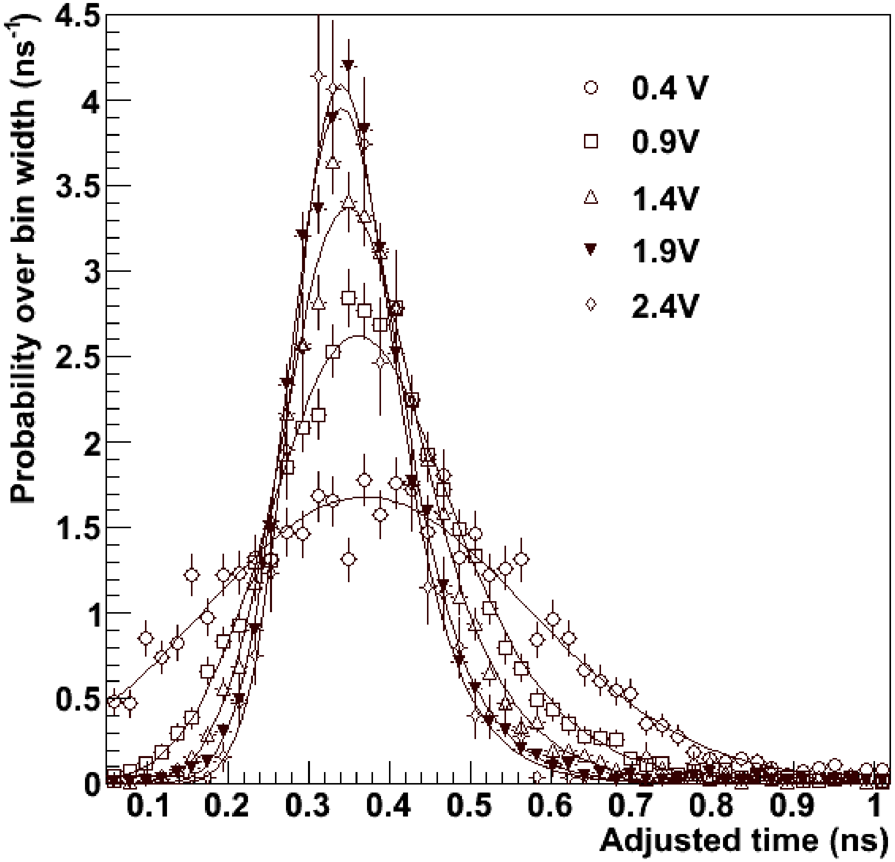
Dark noise is an issue at 20C

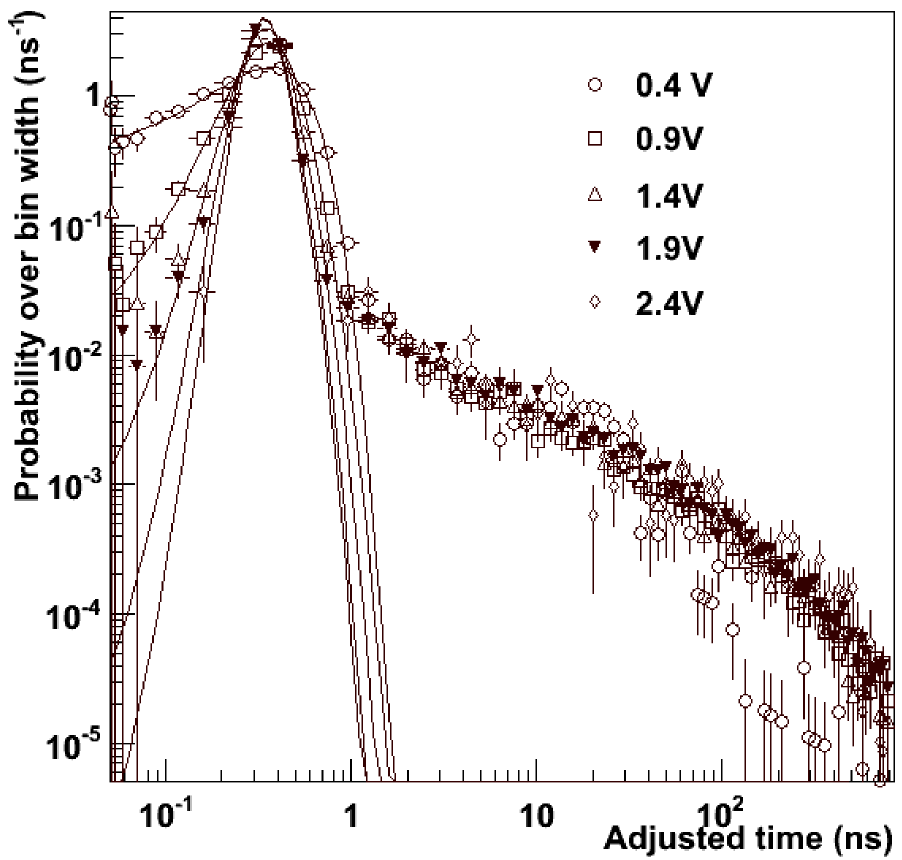


- Large correction in the tail. Limit the statistical accuracy
- Prompt peak a bit wider at 20C
- Tail does not seem to change
  - Expected because the coefficient of diffusion vary weakly with temperature

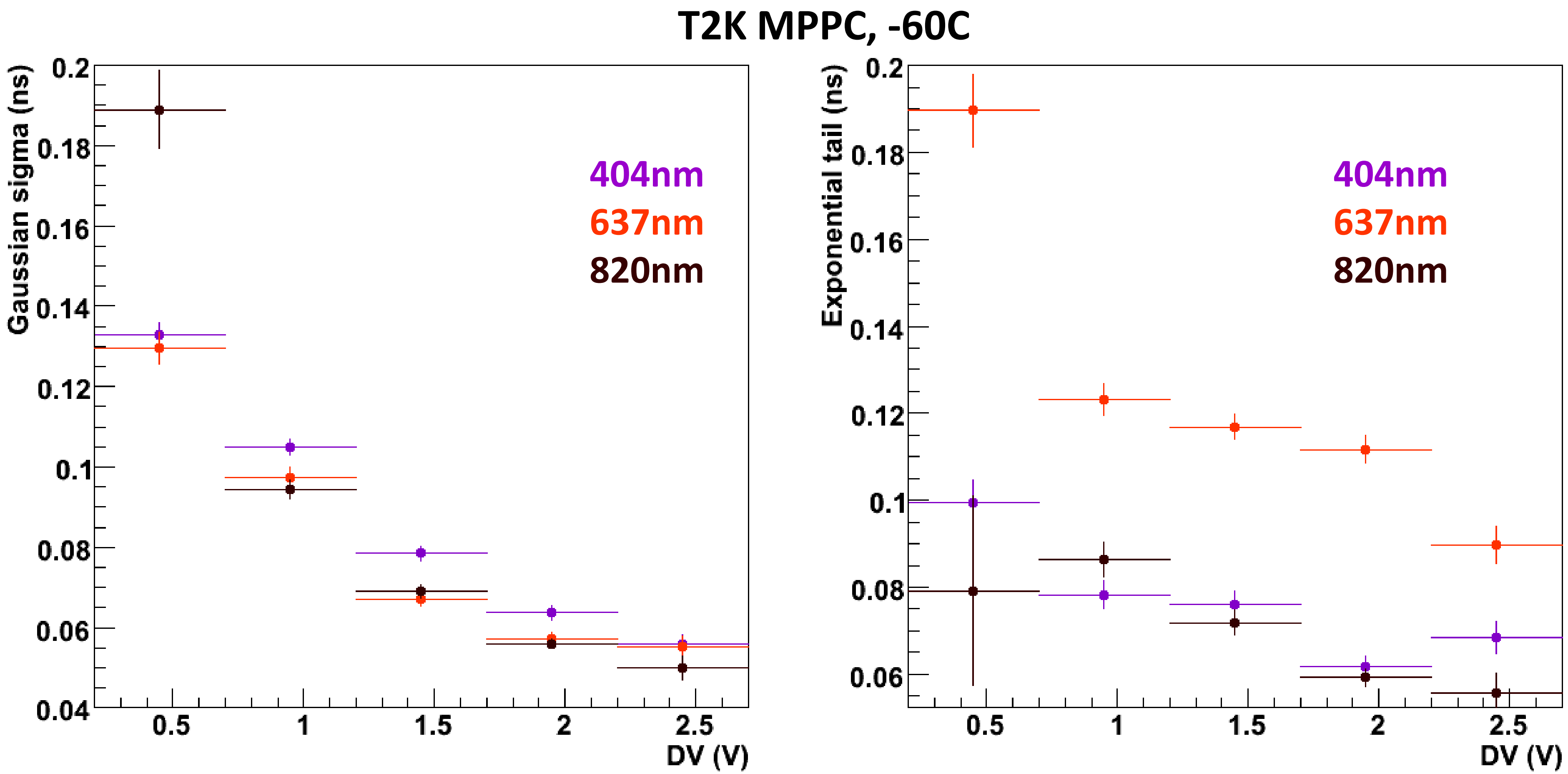
Over-voltage dependence

T2K MPPC, 820 nm, -60C





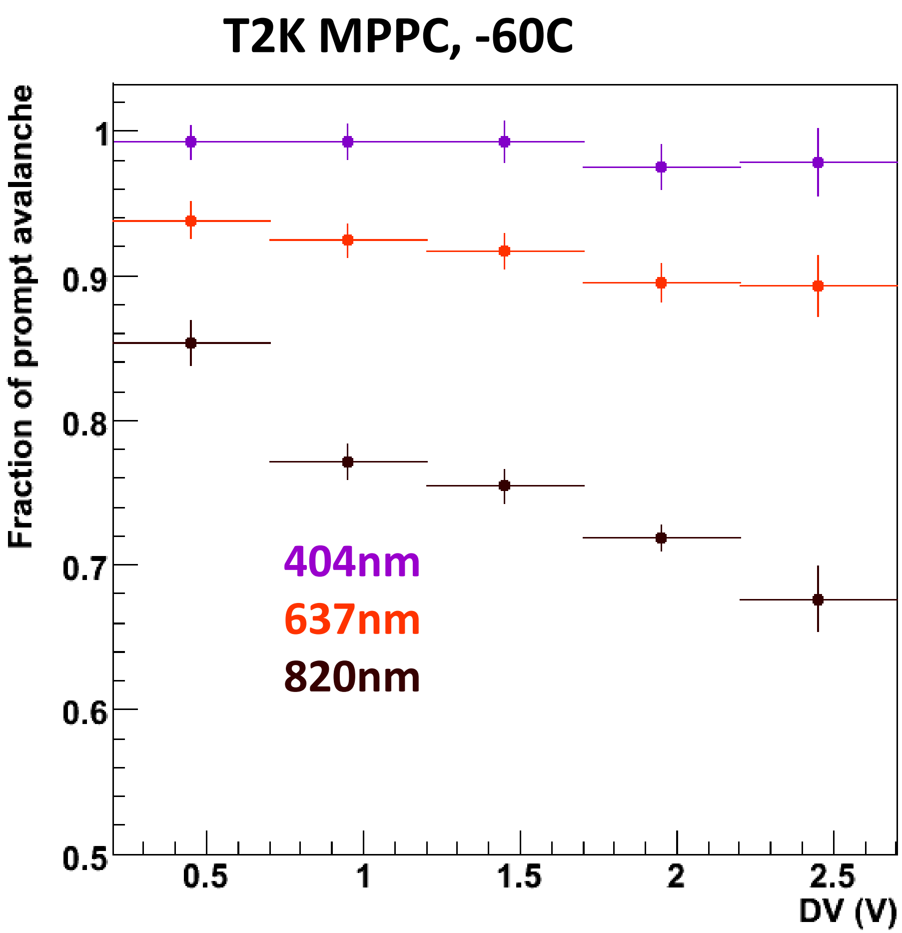
Prompt pulse shape change vs over-voltage



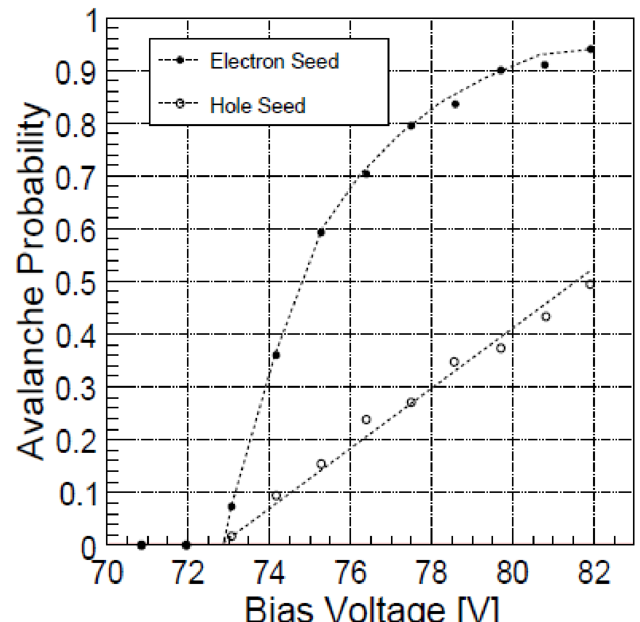
Wider pulse at 637nm, most likely due to the laser

FWHM timing resolution is a combination of Gaussian sigma and exponential tail

Fraction of prompt light decreases with increasing over-voltage



- Late light is 100% due to holes
  - Increased hole contribution with DV



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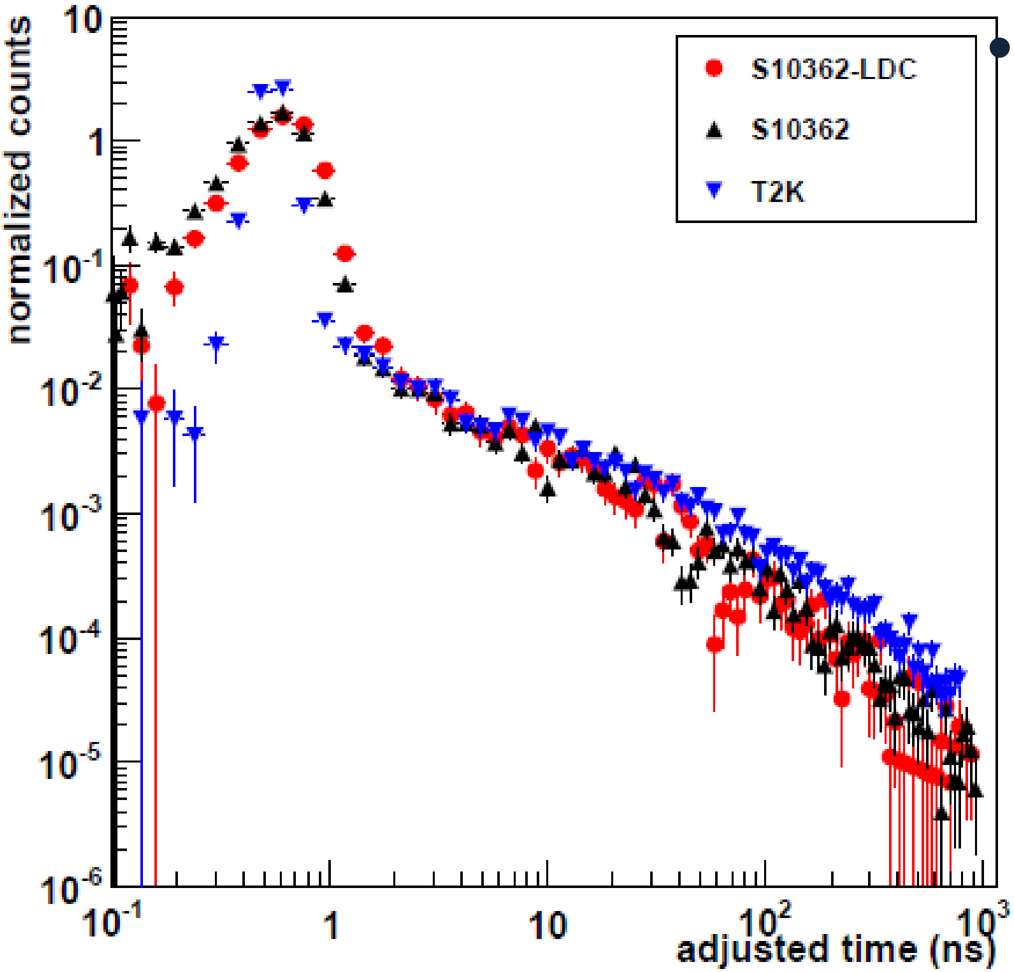
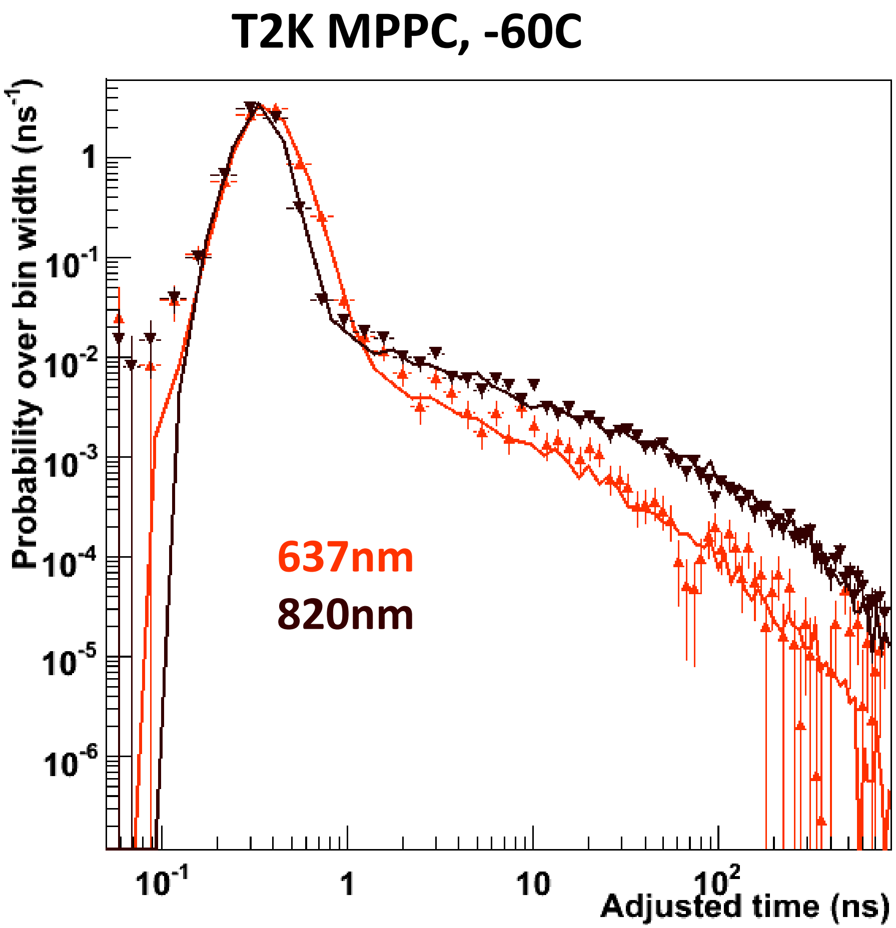
Late light and dark noise rate



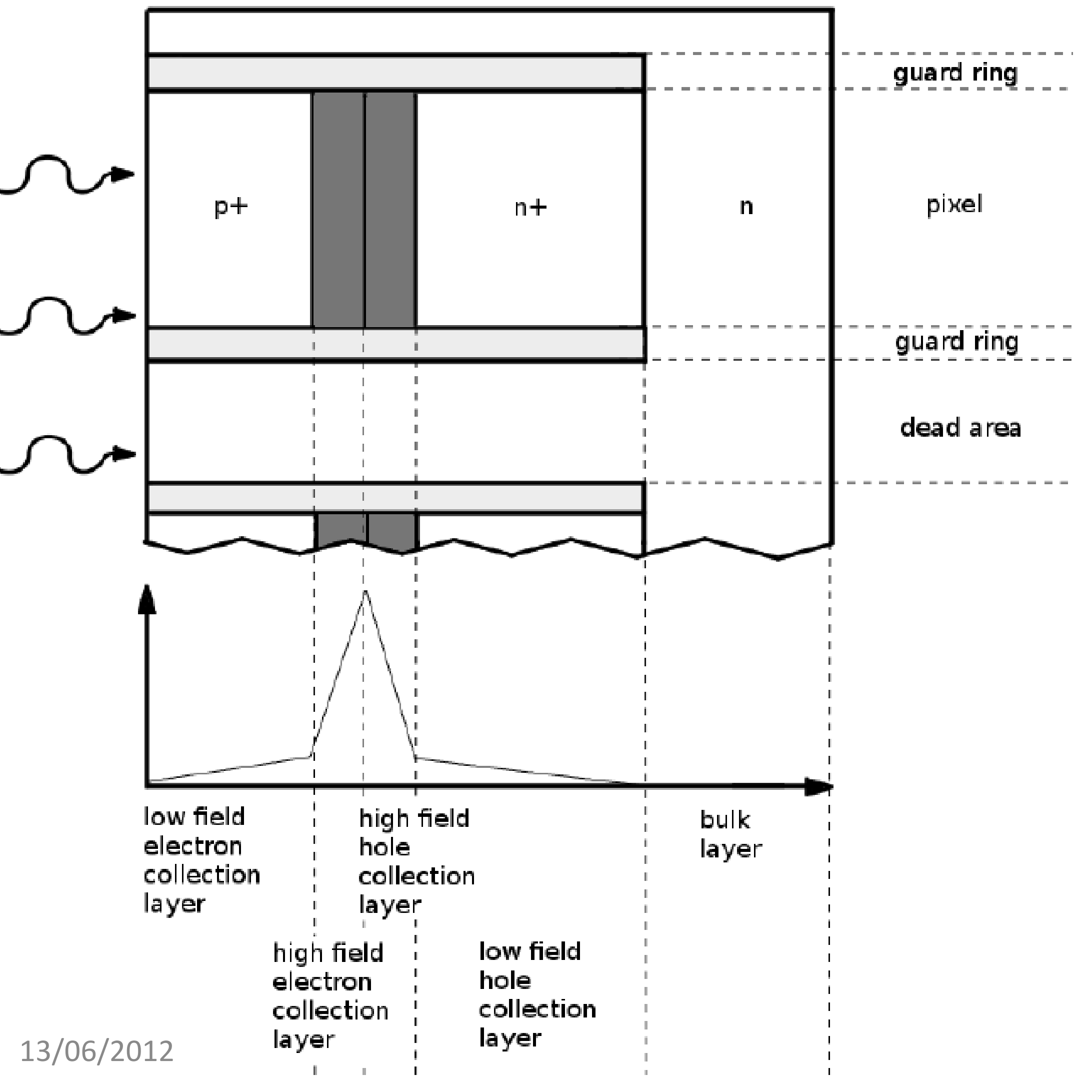
- Two version of the $1x1mm^2$ MPPC
  - LDC device has ½ the dark noise rate
  - Expected to see a change in hole lifetime. Not seen!

Simple simulation



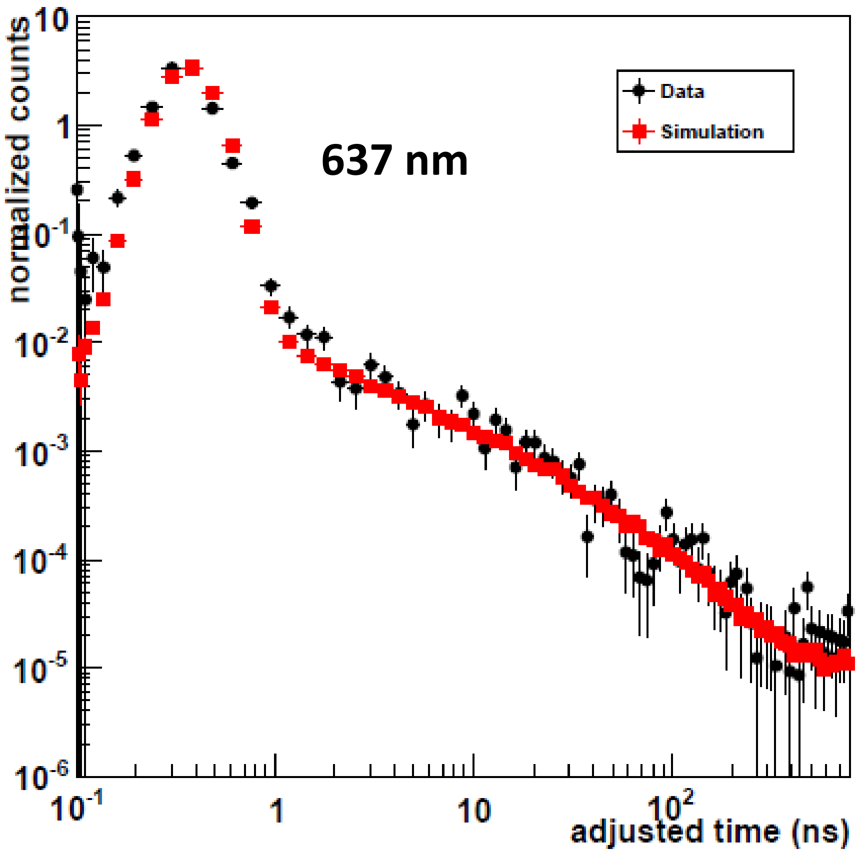
- High field region
  - 2.5 μm deep e- avalanche region (0.8 probability)
  - 2.5 μm deep hole avalanche region (0.2 probability)
  - Use measured prompt distribution (not modeled)
- Zero field region
  - 5 μm – 300 μm
  - Random walk with D = 1.2 $\mu m^2/ns$
- Hole life time = 300 ns
  - Adjusted

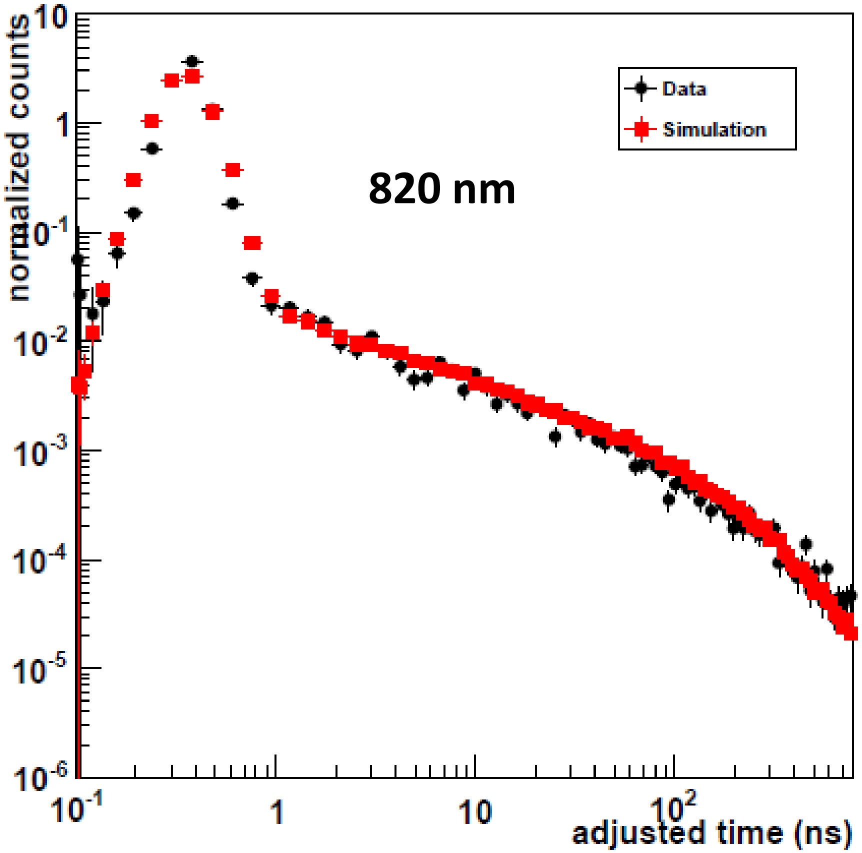
More complete simulations



- 3D model
  - Diffusion in 3D
  - Dead space between the diode
- Low field and high field regions
  - Necessary to reproduce tails
- Free parameter
  - Hole life time
  - Size of the low and high field regions

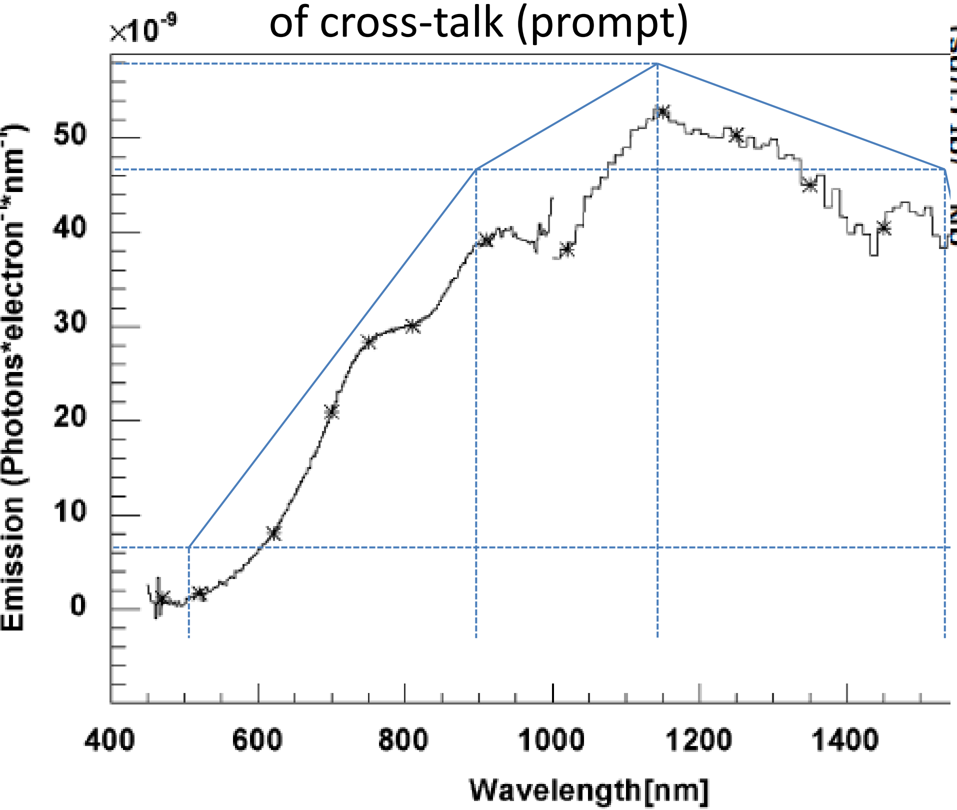
More complete simulations





Inferring contribution due to the photons produced in the avalanche

Rescale photon flux by a factor of 2 to get right amount of cross-talk (prompt)



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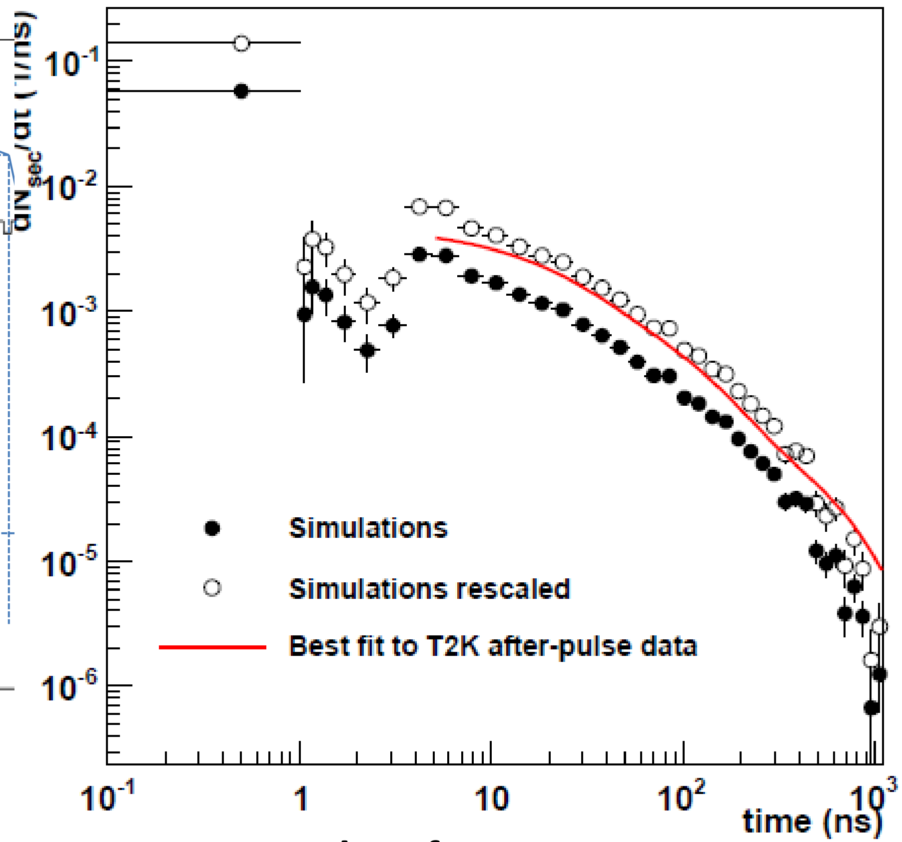
Use complete simulations changing the light source: internal and broad spectrum



T2K data from:
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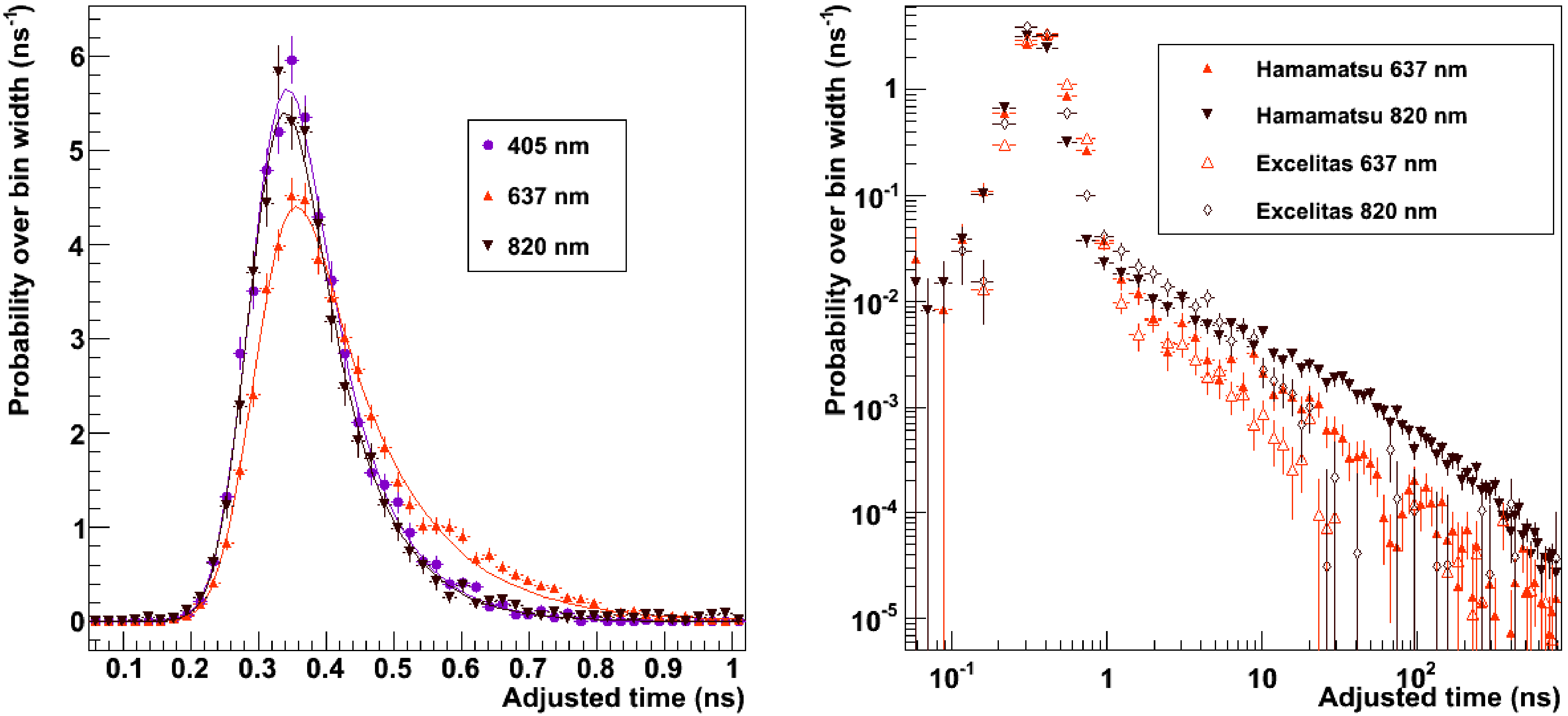
Same analysis for Excelitas devices



Prompt peak a bit narrower (better single photon timing resolution)
Fewer delayed avalanches

Summary

- Delayed avalanches clearly visible at 637 and 820 nm
  - Late avalanche probability increase with ΔV
  - Timing distribution mostly unaffected by ΔV
  - Weak dependence with temperature
  - More late avalanches for Hamamatsu than Excelitas
- Phenomena consistent with holes created in the bulk diffusing back to junction
  - Simulations can reproduce the data
  - Several free parameters because junction structure is unknown
- Phenomena can explain after-pulsing
  - Required x2 photon flux however

Outlook

- Blocking "avalanche" photons expected to improve MPPC performance
  - Blocking n++ layer
  - TSV (i.e. Deep trenches)
- Simulations
  - Wealth of data to constrain SiPM response
  - But little time...
    - Anybody interested in collaborating?
- Timing resolution: exponential tail issue
  - Worsen the single photon timing resolution by 20-40%
  - Were does it come from?
    - Low field region?
    - Slower pixels?
  - Depth dependence can be studied with different wavelength
  - Position dependence required a focused, fast light source