First application of CsI(Tl) pulse shape discrimination at an e^+e^- collider to improve particle identification at the Belle II experiment

PhD completed at the University of Victoria under supervision of Dr. J. M. Roney

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

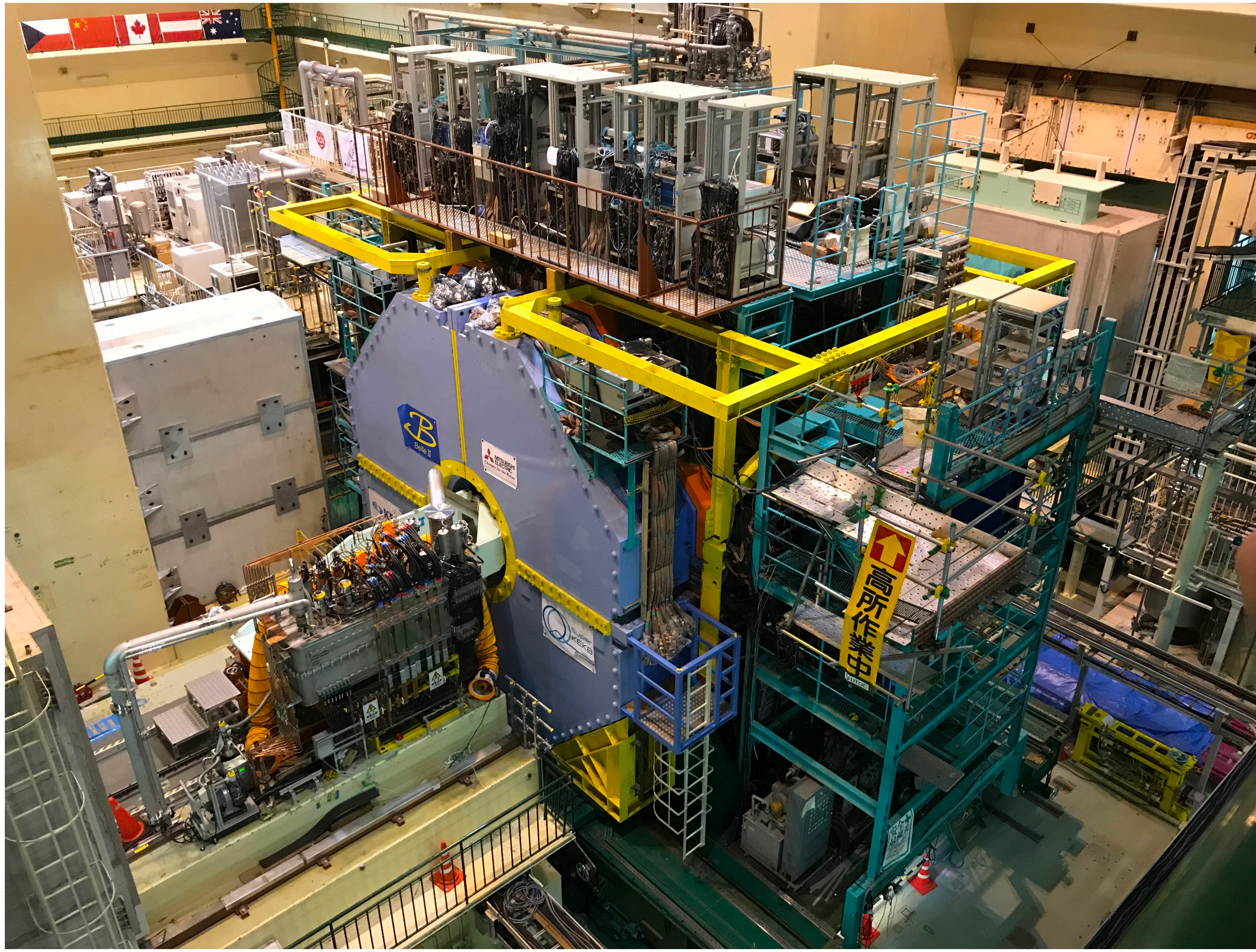
University of Victoria

Belle II

DESY.

The Belle II Experiment

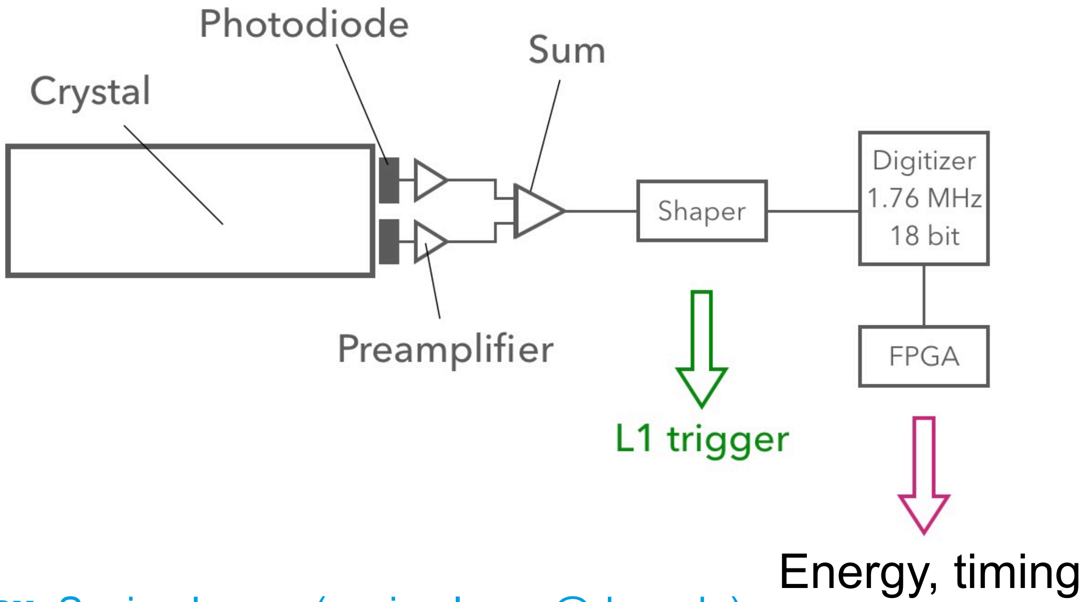
- New B-Factory Experiment at the SuperKEKB asymmetric e^+e^- collider in Japan.
  - ➡ $\sqrt{s} = 10.58$ GeV ($\Upsilon(4S)$ resonance)
  - ➡ Aims to integrate 50 ab^{-1}
- Exploring the luminosity frontier for new physics:
  - ✓ Precision flavour sector measurements
  - ✓ Searches for rare/forbidden processes
  - ✓ Dark sector searches

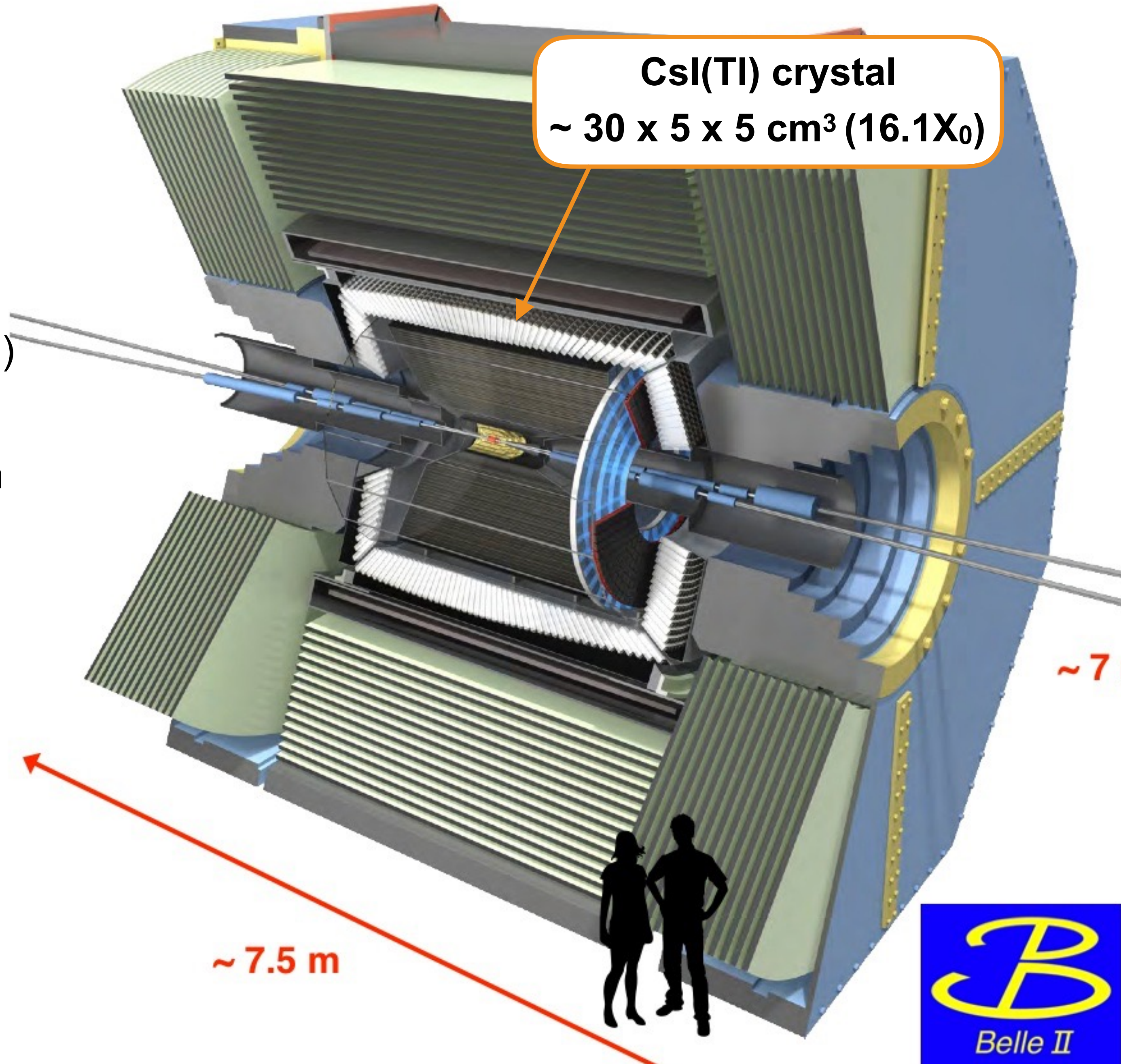


- **First e^+e^- collider to implement CsI(Tl) pulse shape discrimination (PSD) as new method to improve particle identification (this talk!).**

Belle II Electromagnetic Calorimeter

- Constructed from 8736 CsI(Tl) scintillator crystals.
- Performs:
  - ✓ Event triggering
  - ✓ Photon, π^0, η, K_L^0 reconstruction
  - ✓ Charged and neutral Particle IDentification (PID)
- Crystal readout electronics upgraded to allow for **waveform digitization** and online FPGA waveform analysis.



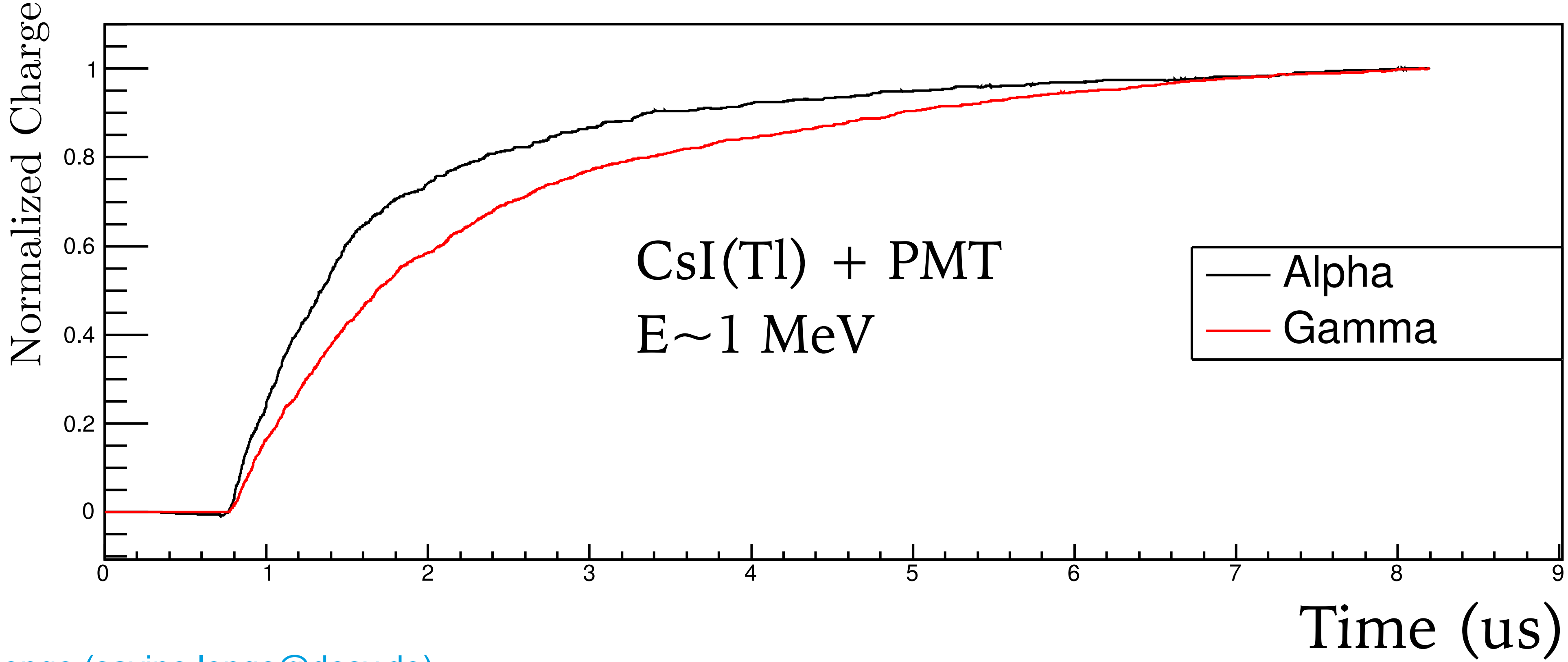


CsI(Tl) Pulse Shape Discrimination

- CsI(Tl) scintillation crystals known to have capability for pulse shape discrimination (PSD).

  ➡Energy deposits from protons and alpha particles have faster scintillation time relative to electrons.

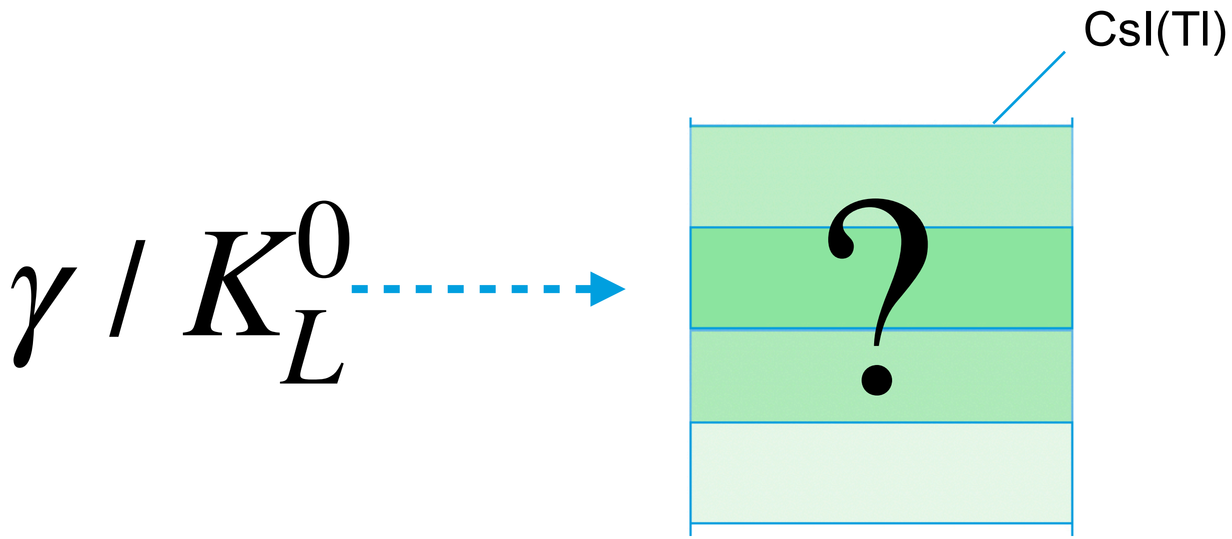
- Particle identification with PSD well-established at low energies (<10 MeV).



Neutral Particle Identification at B Factories

- K_L^0 vs photon identification challenging and crucial to numerous Belle II analyses:
  - ➡ K_L^0-ID for precision measurement of $\sin(2\phi_1)$ with $B \to J/\psi K_L^0$
  - ➡ K_L^0-veto for $|V_{ub}|$
  - ➡ Hadronic split-off identification, E_{extra}
- Previous B Factories relied on spacial distribution of cluster energy to separate photons and neutral hadrons however performance was limited.

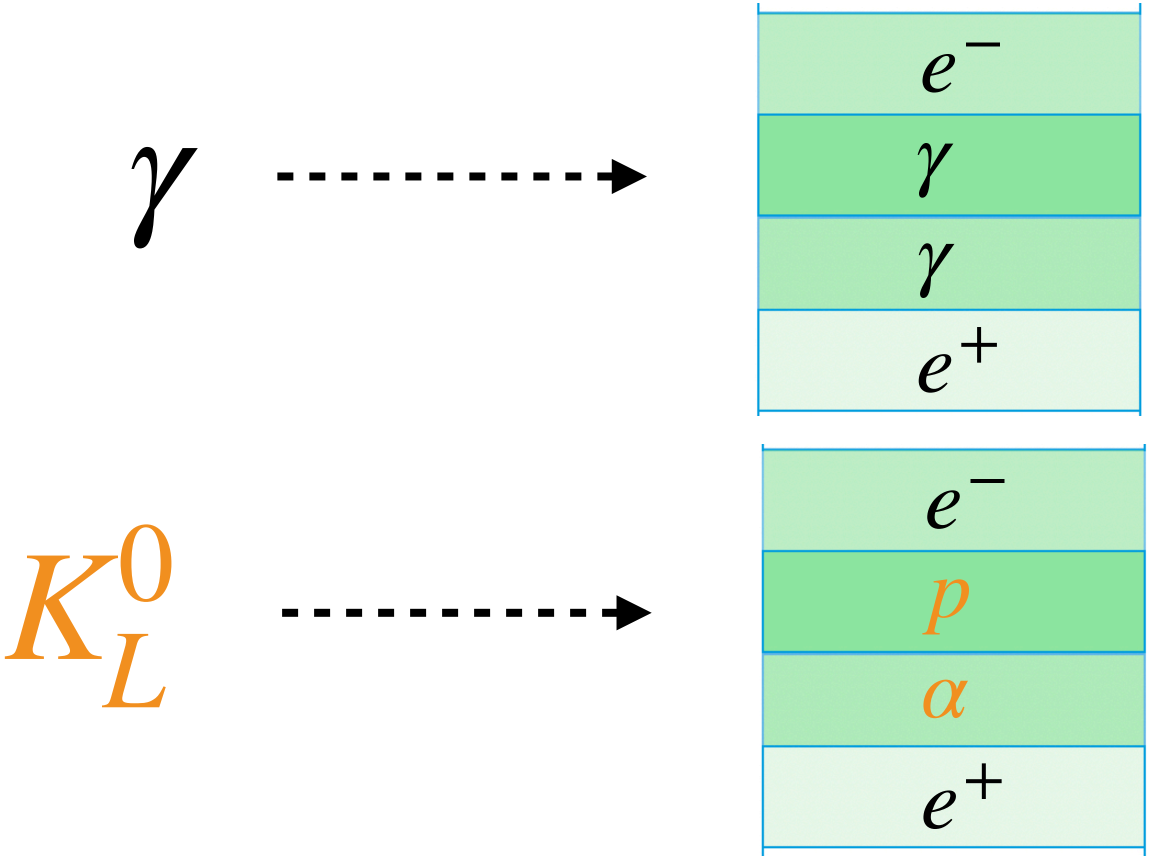
Measurement	B_{CP} Mode	# of B_{tag}	Purity (%)
BaBar [15]	$J/\psi K_S^0(\pi^+\pi^-)$	5426	96
	$J/\psi K_S^0(\pi^0\pi^0)$	1324	87
	$\psi(2S)K_S^0$	861	87
	$\chi_{c1}K_S^0$	385	88
	$J/\psi K_L^0$	5813	56
Belle [16]	$J/\psi K_S^0$	12649	97
	$\psi(2S)(l^+l^-)K_S^0$	904	92
	$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$	1067	90
	$\chi_{c1}K_S^0$	940	86
	$J/\psi K_L^0$	10040	63

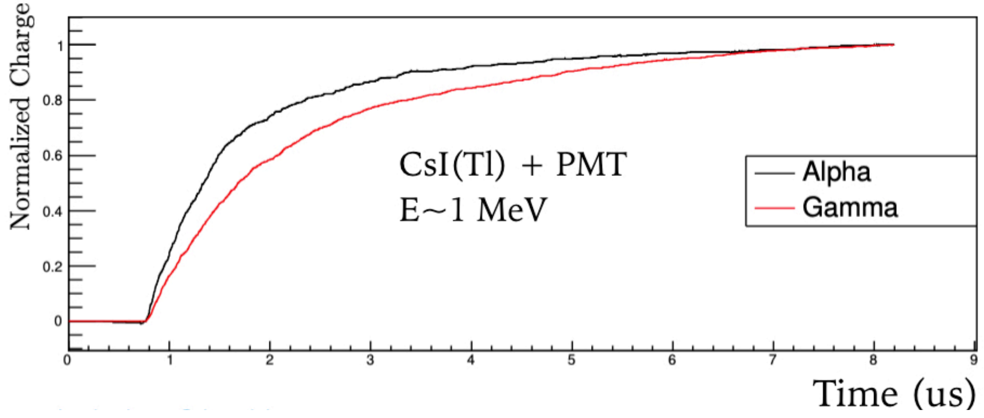


[15] B. Aubert et al. (BaBar Collaboration) Phys. Rev. D 79, 072009 (2009) arXiv: 0902.1708
[16] I. Adachi et al. (The Belle Collaboration) Phys. Rev. Lett. 108, 171802 (2012) arXiv: 1201.4643

PSD to improve particle identification at B Factories

- Secondary particles in electromagnetic vs. hadronic showers are very different.
- Expect secondary protons/alphas in hadronic showers to produce variety of scintillation pulse shapes.
  - ➡ Distinguish electromagnetic vs. hadronic showers using scintillation pulse shapes of cluster crystals.

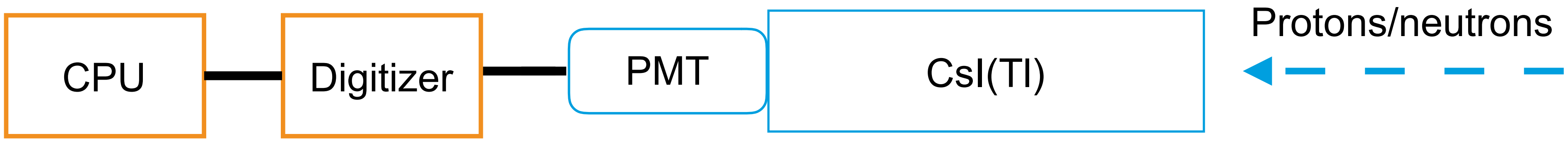


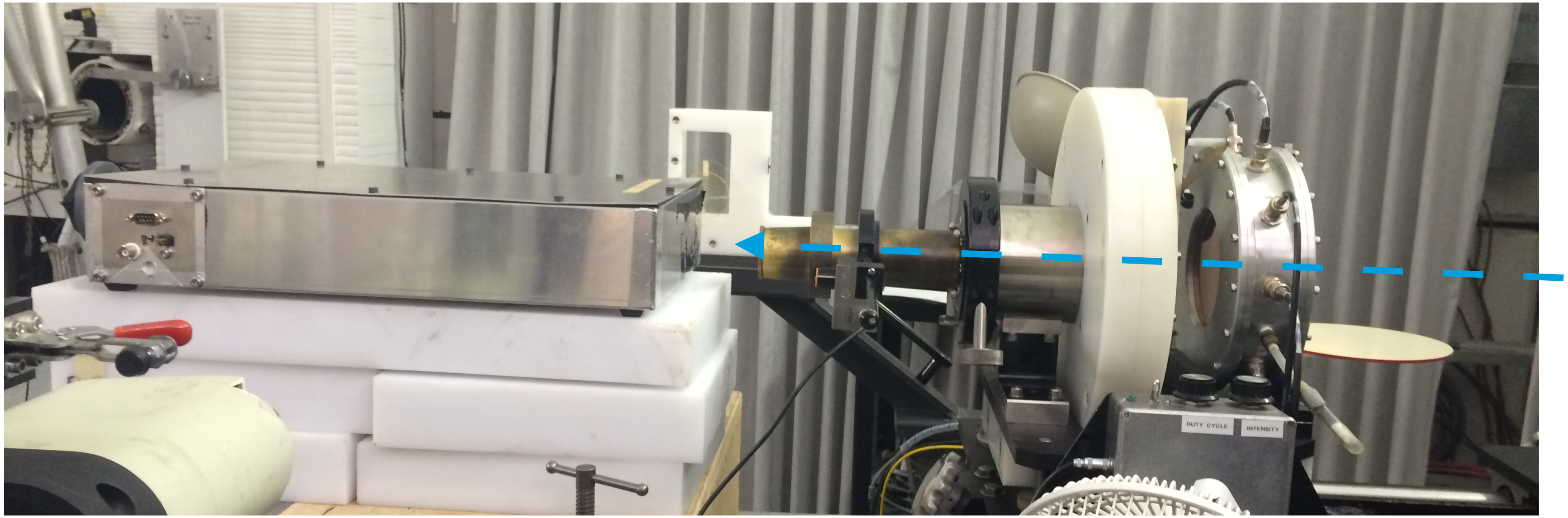


Testbeam at TRIUMF

- Testbeam completed at TRIUMF Proton/Neutron Irradiation Facility.
- CsI(Tl) scintillation pulses from energy deposits by fast neutron and protons.

➡PMT output directly digitized (no shaping).

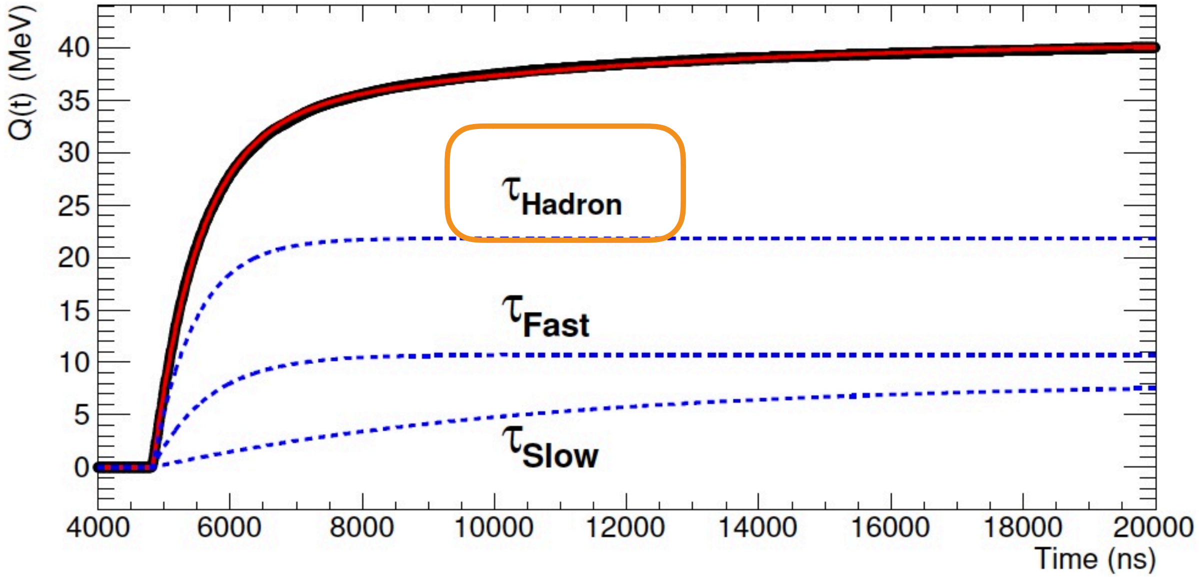




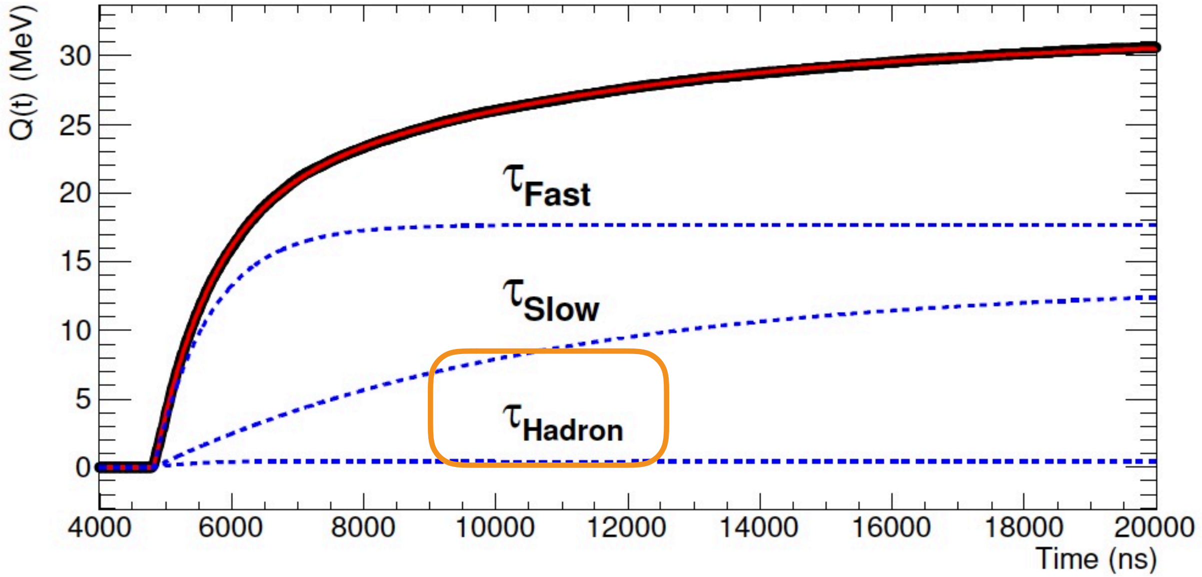
Hadron Scintillation Component

- Analysis of TRIUMF waveforms demonstrated the variety of scintillation pulse shapes can be modelled by adding a third ***"hadron scintillation component"*** with time constant of 630 ± 10 ns.
  - ➡Hadron scintillation component only emitted by high dE/dx energy deposits.
  - ➡No hadron component in muon/photon scintillation emission.

Alpha particle from neutron scatter



Cosmic muon



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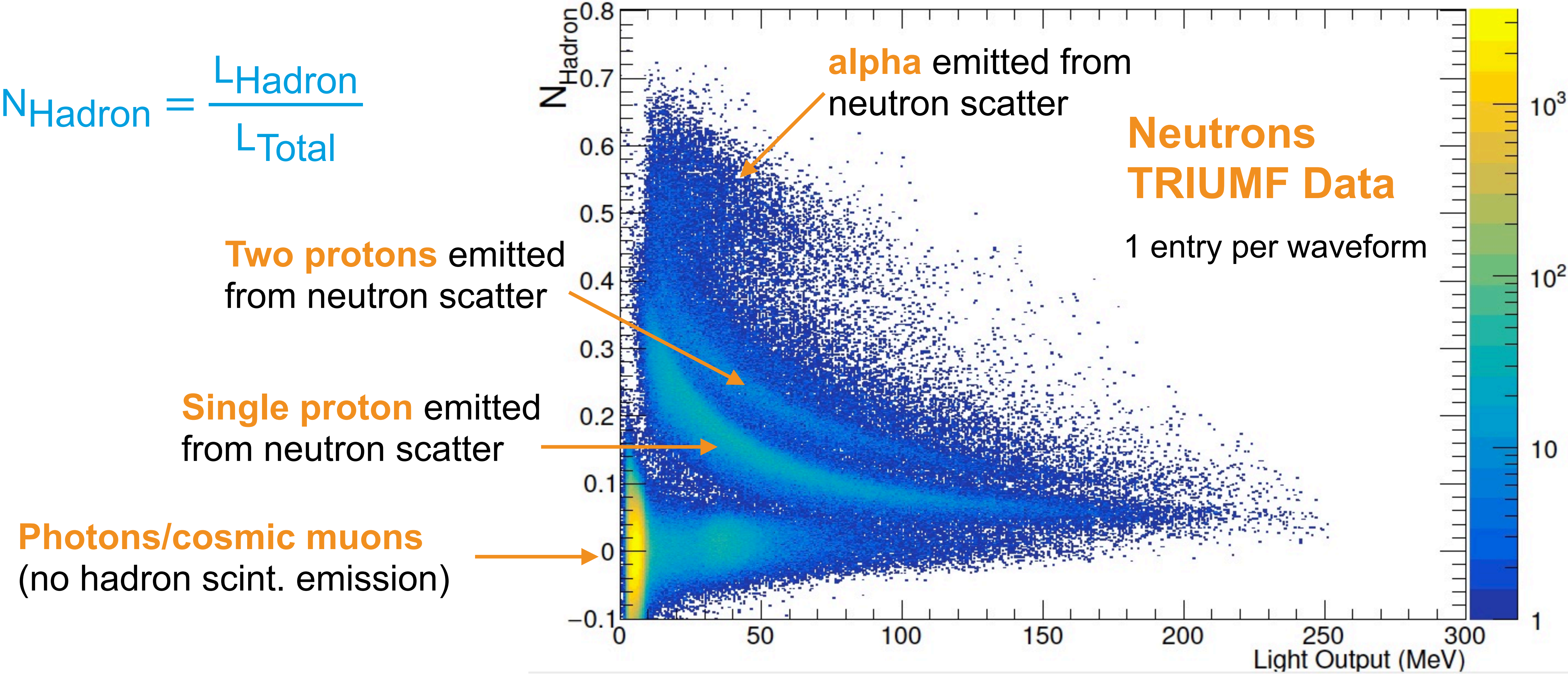
Pulse Shapes from TRIUMF Neutron Data

- Pulse shape characterized by ***Hadron Intensity*** **(N_{Hadron})** defined as the fraction of scintillation emission in hadron scintillation component.

$$N_{Hadron} = \frac{L_{Hadron}}{L_{Total}}$$



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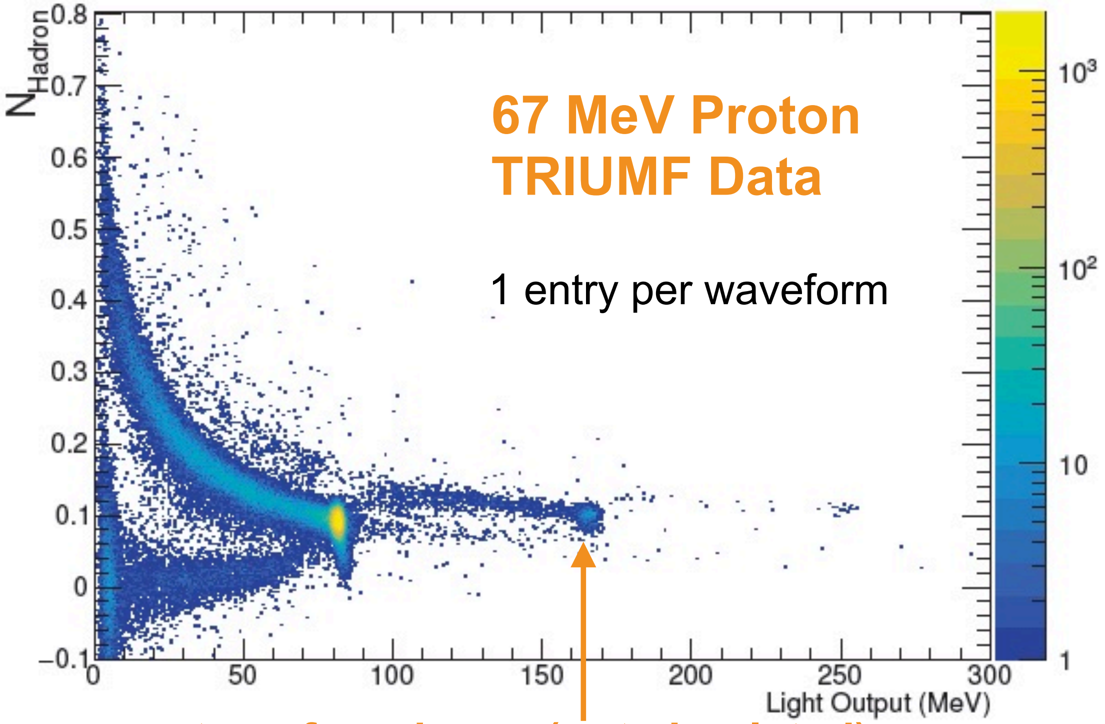
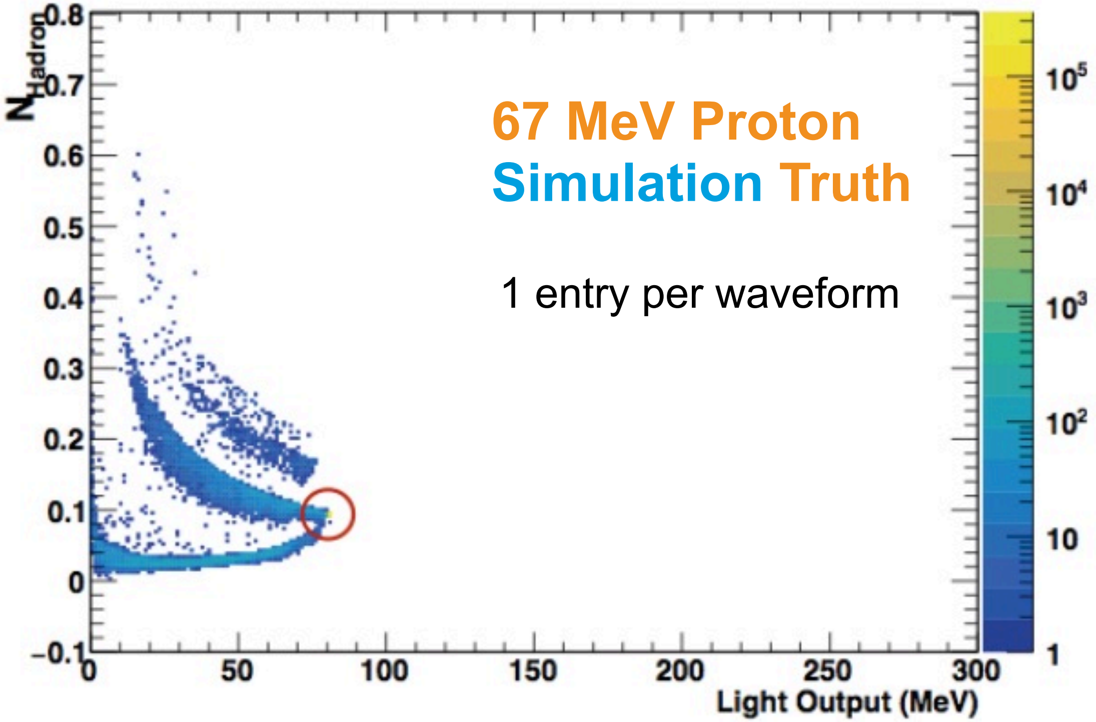
Simulating Pulse Shape Discrimination

- CsI(Tl) scintillation response to highly ionizing particles not simulated by default GEANT4.
- Model formulated to compute hadron scintillation component light output from particle dE/dx.
  - ➡ Model incorporated into GEANT4.
  - ➡ Simulated pulse shapes computed from instantaneous dE/dx of secondary particles produced by GEANT4.



Two primary protons from beam (not simulated)



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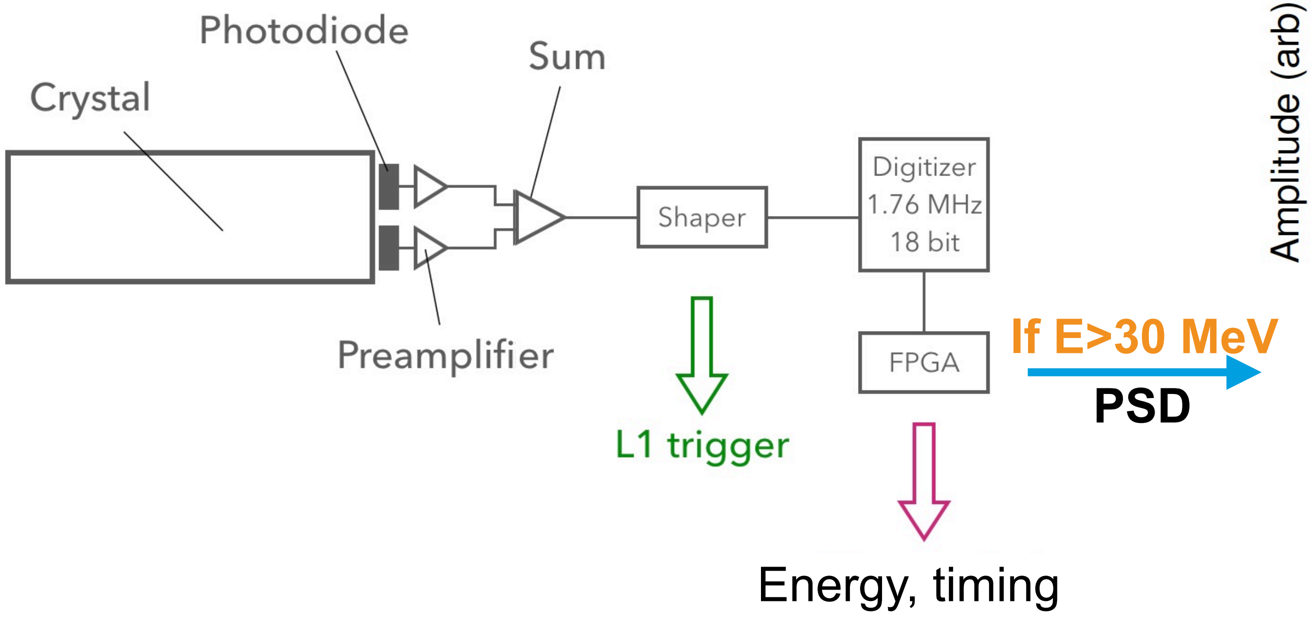
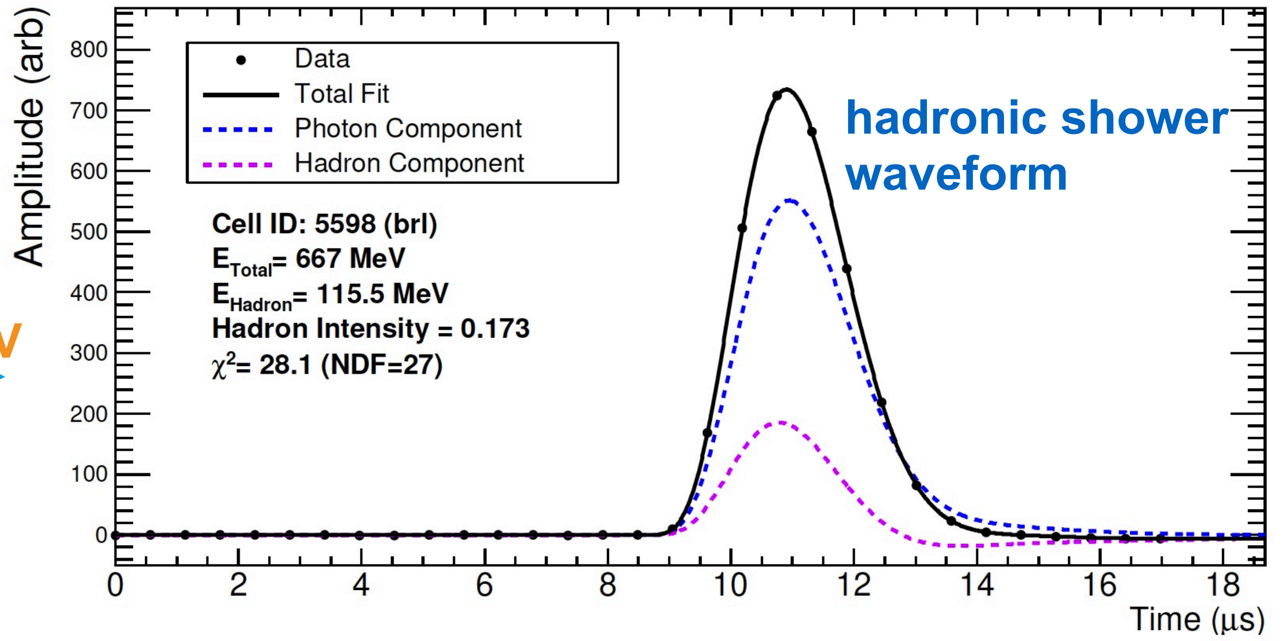
CsI(TI) Pulse Shape Discrimination at Belle II

- Calorimeter electronics firmware modified to allow for recording of digitized waveforms.
  - ➡If crystal energy exceeds 30 MeV, digitized waveform is saved offline.
- Waveform characterization techniques and simulation methods developed in TRIUMF study applied at Belle II.
  - ➡Measure hadron intensity via multi-template fit.



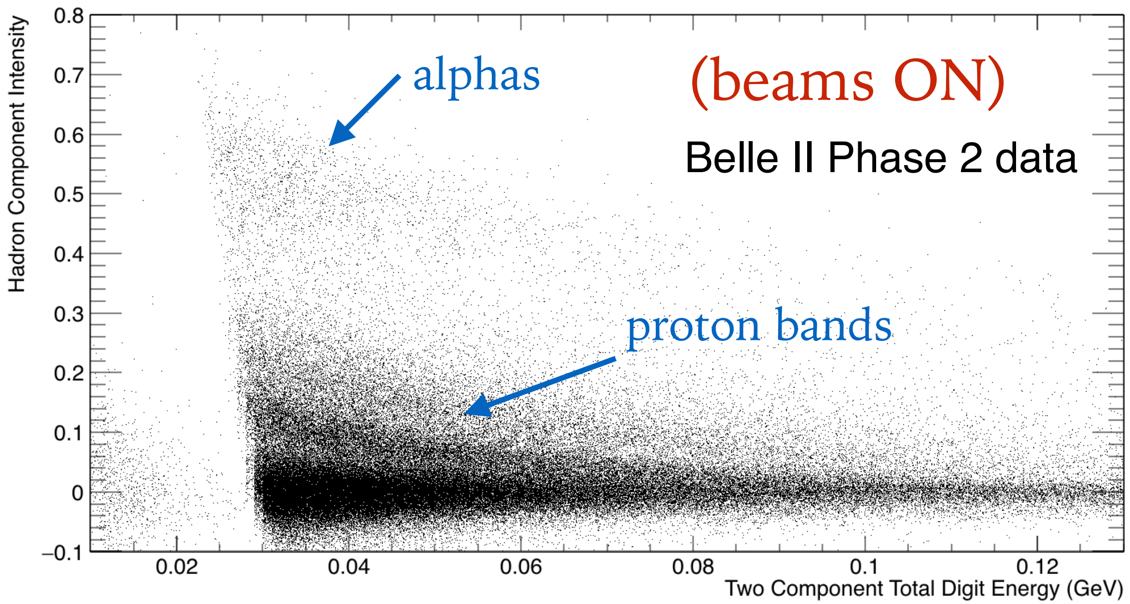
Example Belle II waveform:

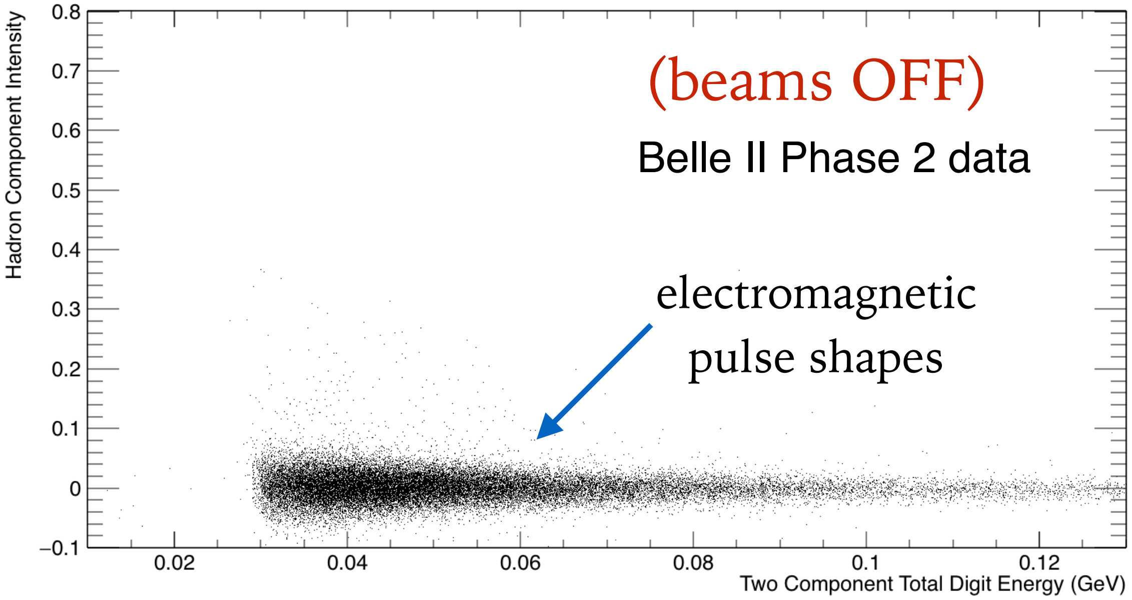


First SuperKEKB Beams = First Hadrons at Belle II!

- On long-awaited first day SuperKEKB beams circulated, hadronic interactions from fast neutron background observed in Belle II data using PSD!
  - ➡Only Belle II data available previously was cosmic muons where hadrons were very sparse.
- Belle II commissioning run in 2018 integrated 0.5 fb^{-1} of collision data.
- Control samples of $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p/\bar{p}, \gamma$ and K_L^0 selected for detailed studies of PSD.

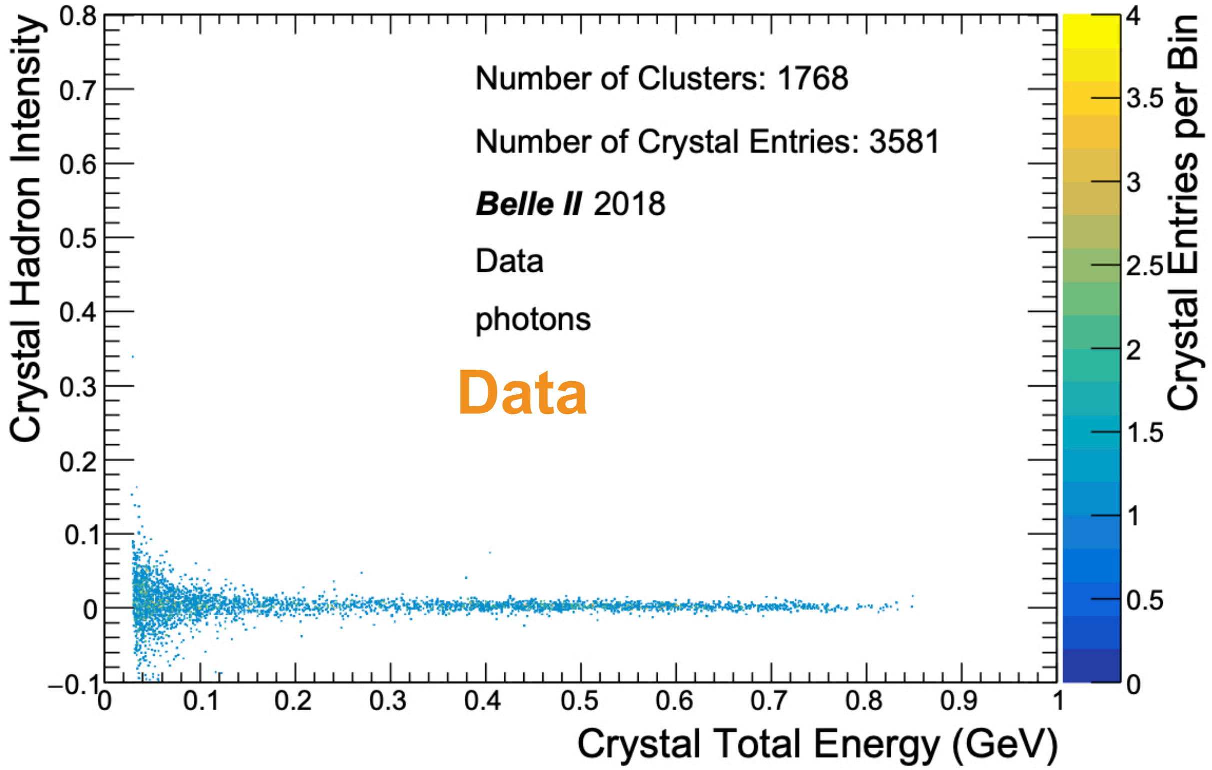
First hadrons observed at Belle II with PSD:

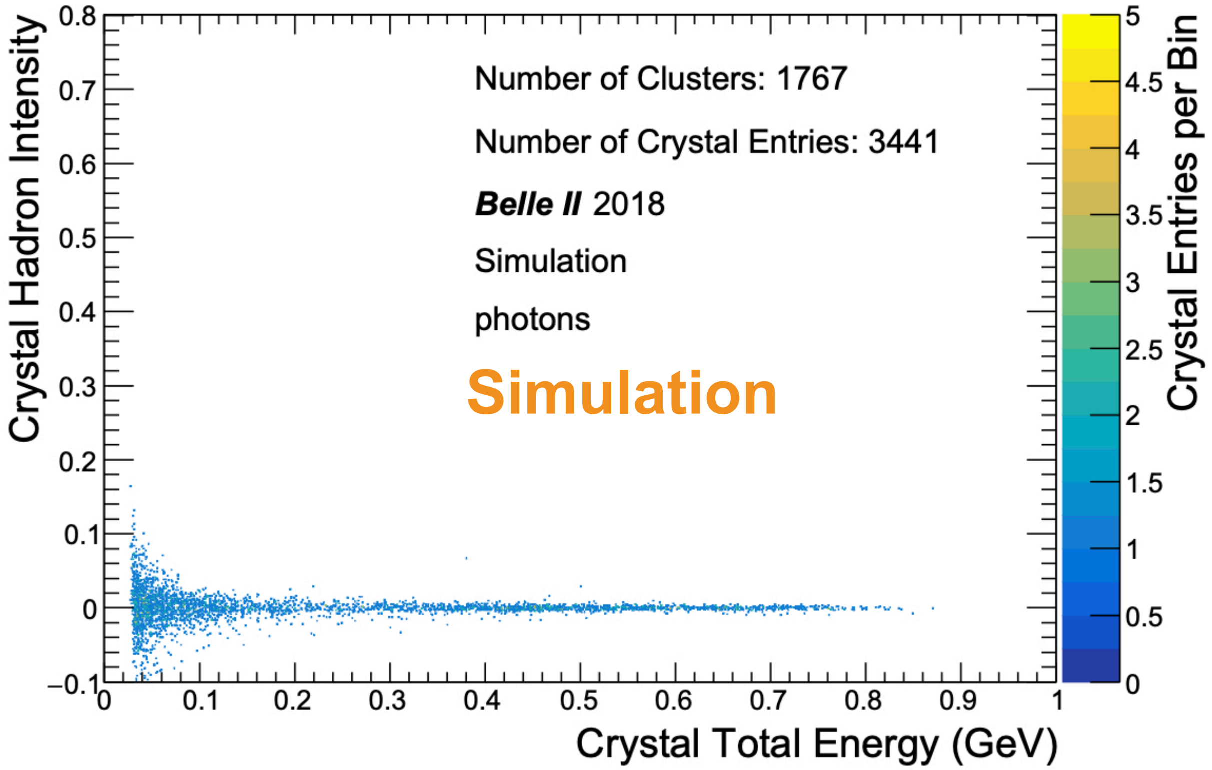




Photon Pulse Shapes at Belle II

- Photon control sample selected from: $e^+e^- \to \mu^+\mu^-\gamma$.
- No highly ionizing particles in electromagnetic showers.
    - ➡Expect pulse shapes to have hadron intensity of zero.





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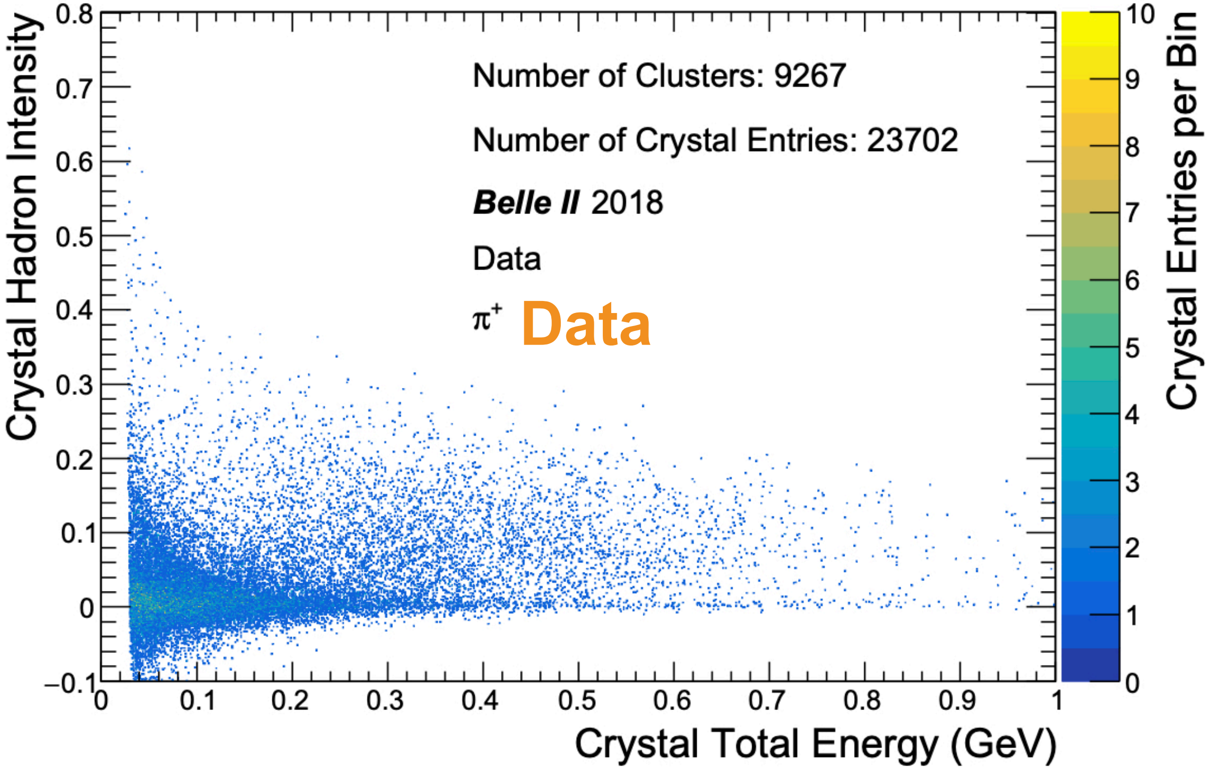
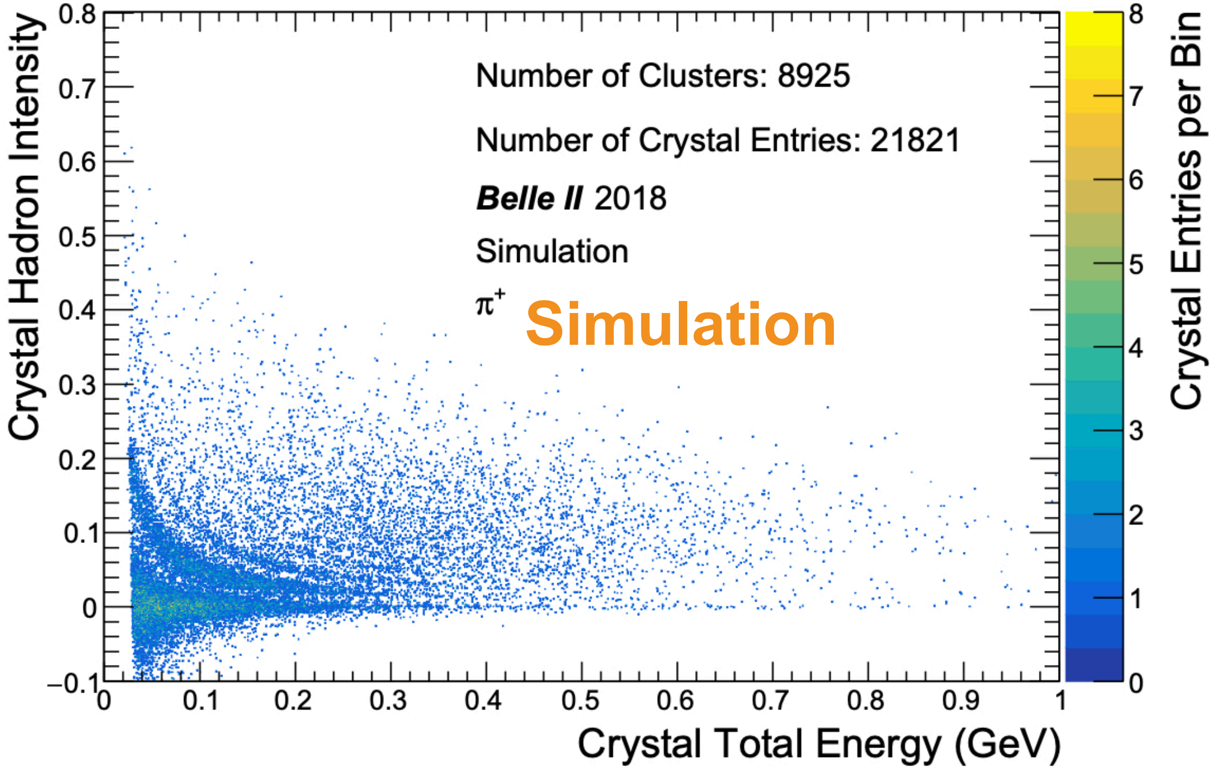
Charged Pion Hadronic Shower Pulse Shapes

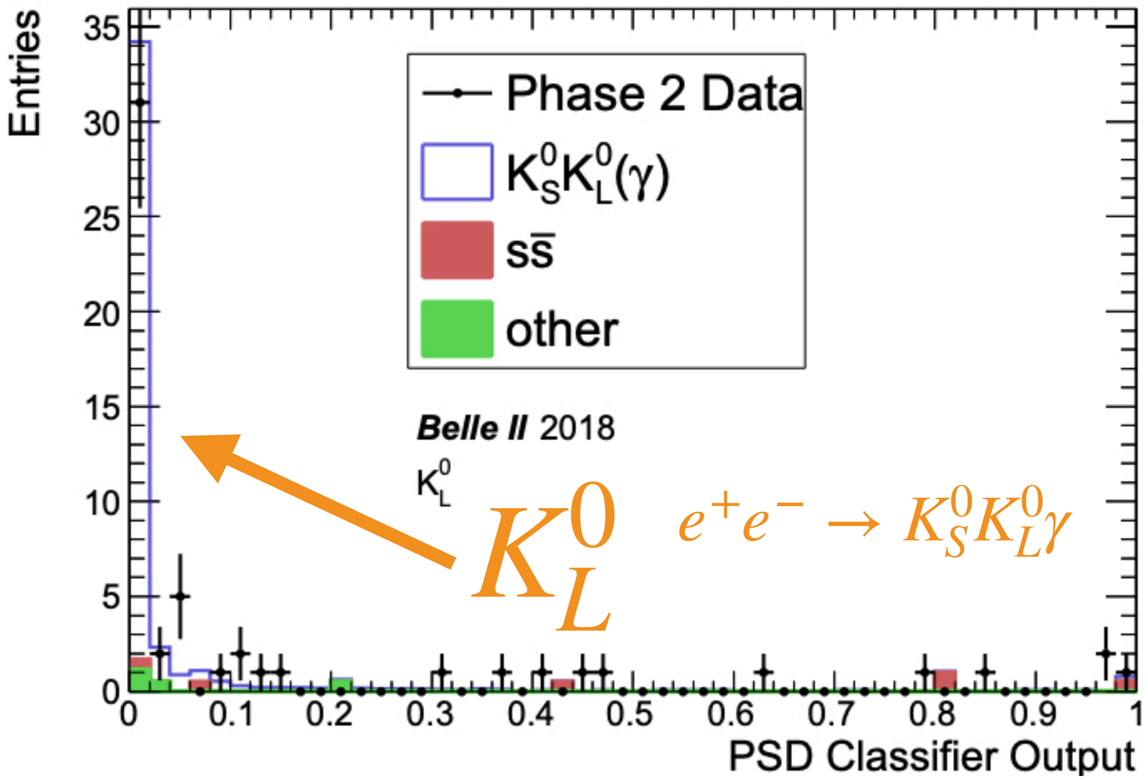
- Charged pion control sample selected with: $K_S^0 \to \pi^+\pi^-$.
- Pion hadronic showers produce highly ionizing secondaries (protons, alphas etc.) leading to variety of pulse shapes.
- Main features of pulse shape distributions observed in data are reproduced by pulse shape simulations.

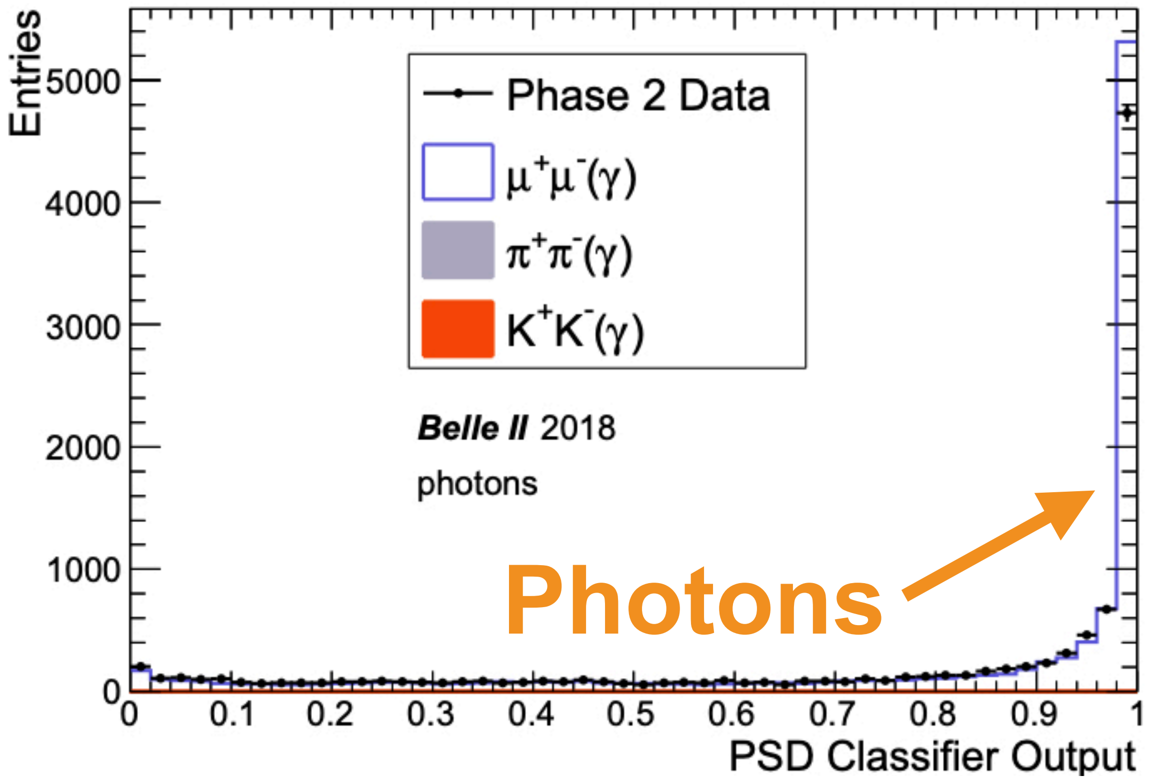




PSD for Neutral PID at Belle II

- Boosted Decision Tree classifier trained on simulation to use crystal PSD information to identify hadronic vs. electromagnetic showers.
- Classifier tested on photon and K_L^0 control samples selected from Belle II data.
- Significant degree of separation achieved by PSD-based classifier.





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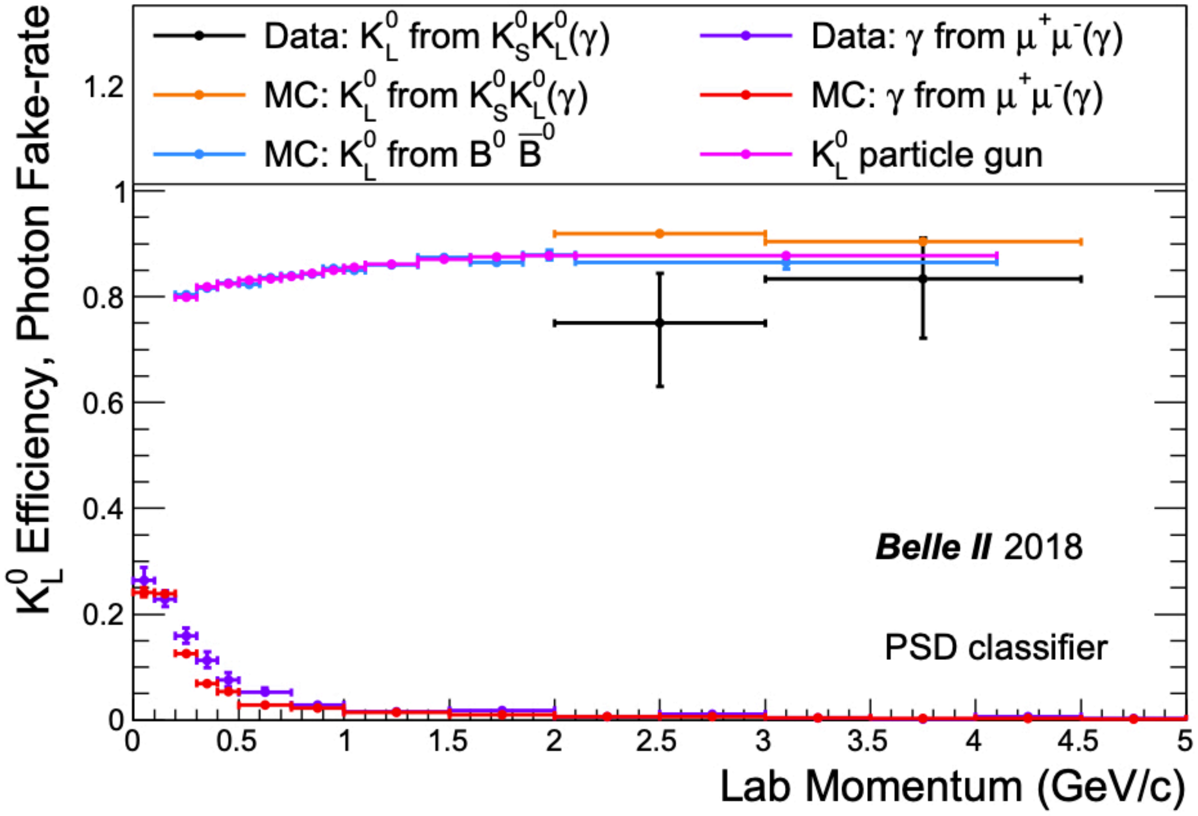
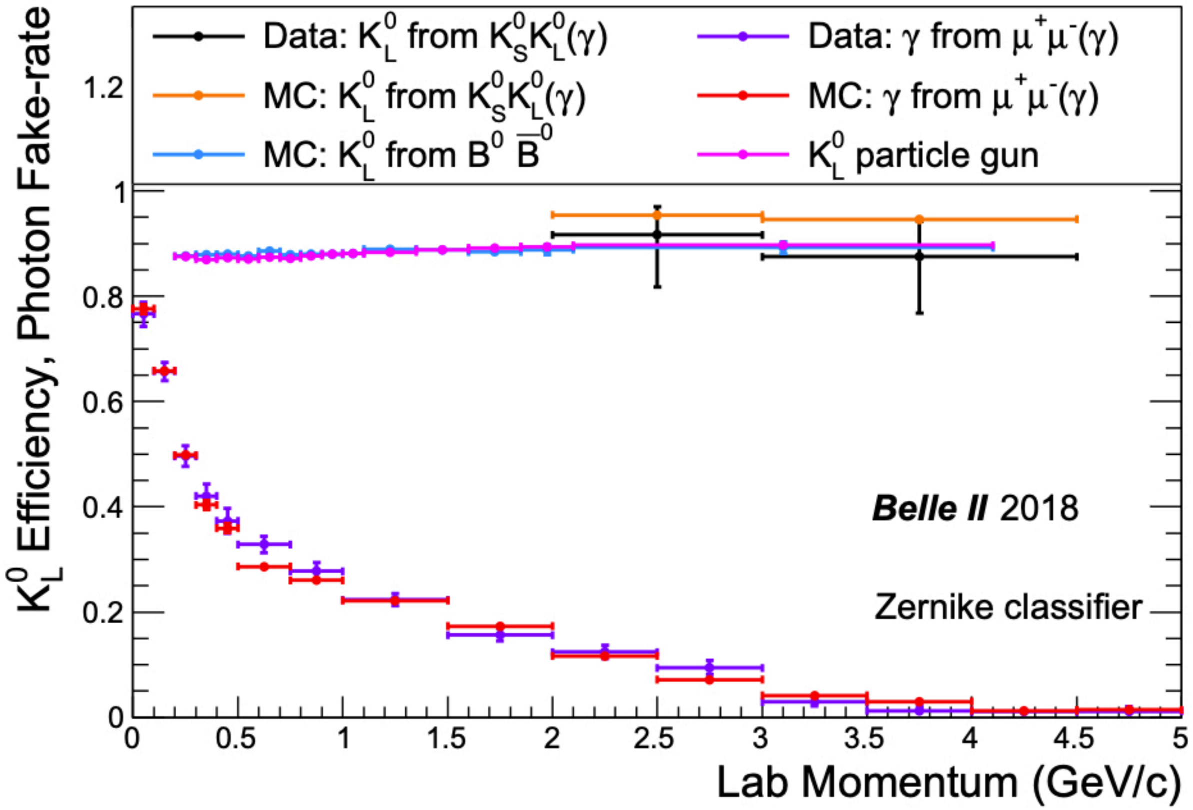
Performance Comparison to Shower-shapes

- Performance of PSD-based classifier compared to independent state-of-the-art shower-shape approach to K_L^0-ID.
- At same K_L^0 efficiency, PSD significantly improves the photon-as-hadron fake-rate at all photons energies relative to Zernike (shower-shape) classifier.





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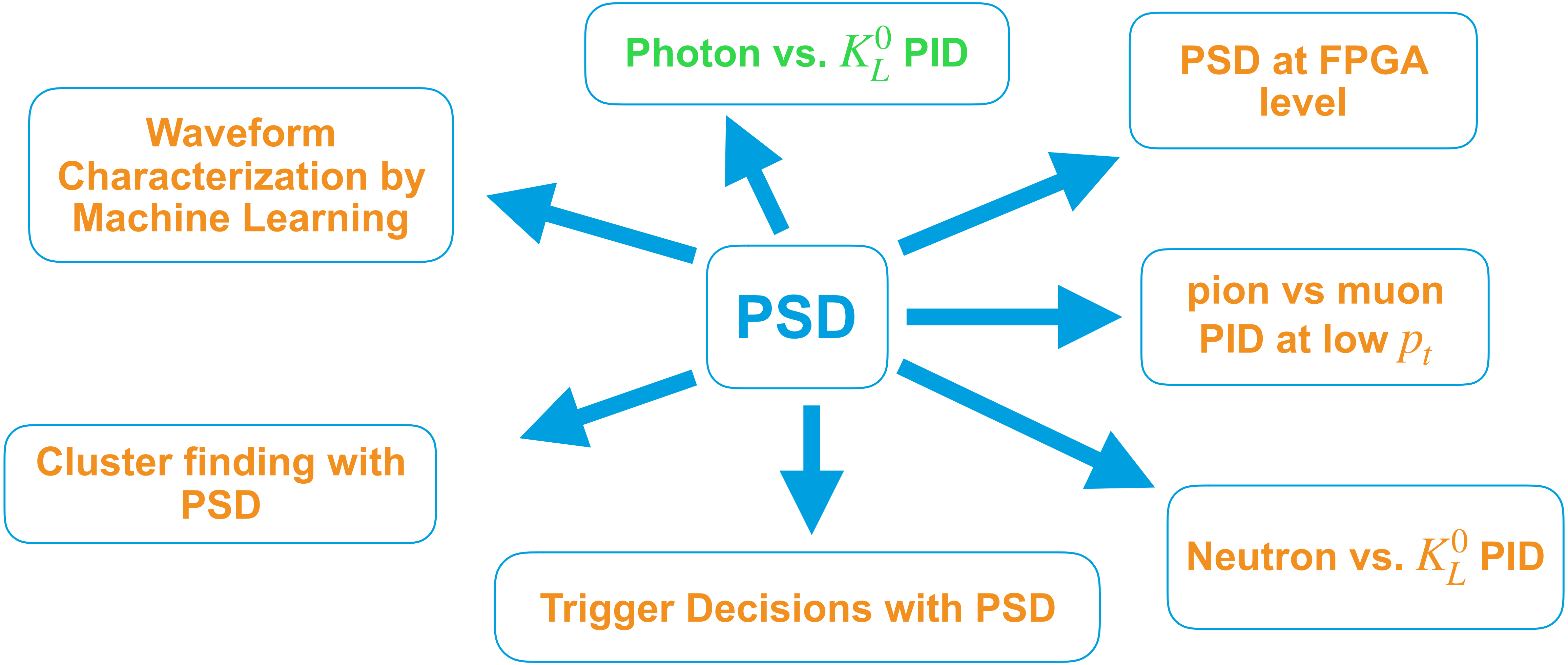
New Directions for PSD at Belle II

- New PSD dimension of calorimeter information has led to several studies exploring potential for PSD to improve other areas of calorimeter performance.



Summary

- Pulse shape discrimination with CsI(Tl) studied as a new method to improve particle identification at high energy e^+e^- colliders.
- Analysis of TRIUMF testbeam data developed new method to characterize CsI(Tl) scintillation pulse shapes.
- Simulation methods for PSD formulated and incorporated in GEANT4 framework.
- PSD has brought significant improvements in K_L^0 vs. Photon separation at Belle II.

➡Link to thesis

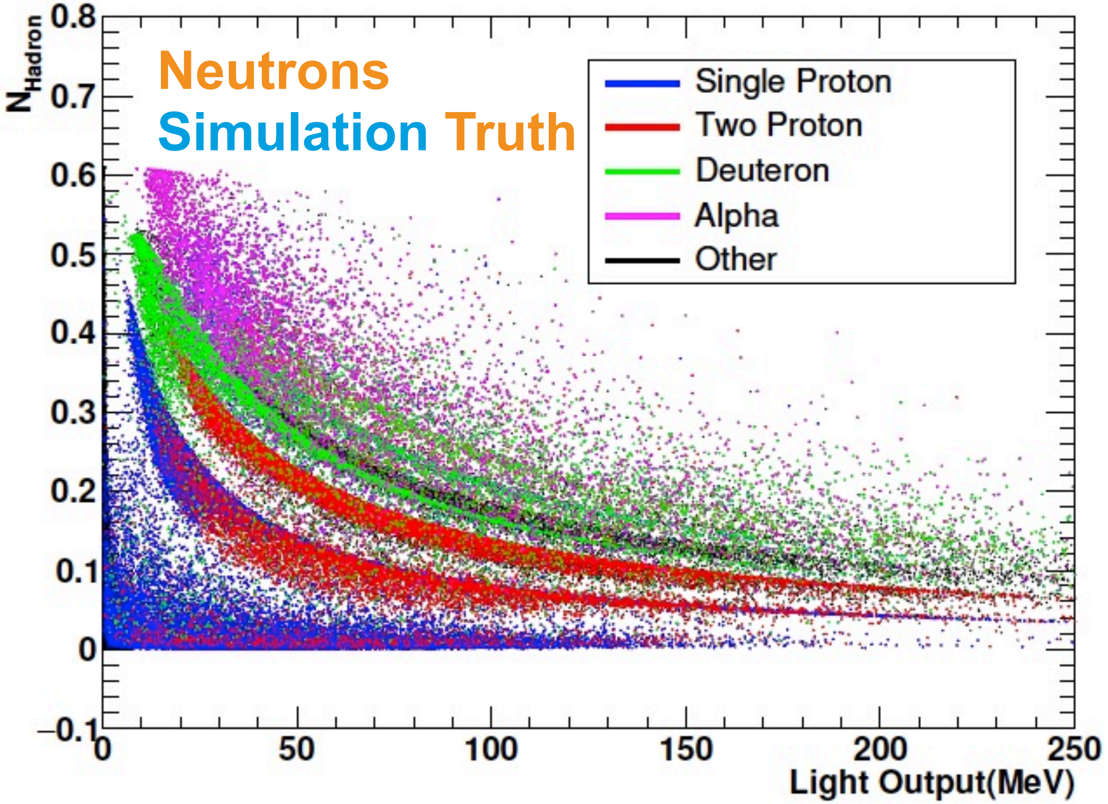
➡TRIUMF testbeam: S. Longo and J. M. Roney 2018 JINST 13 P03018 arXiv:1801.07774

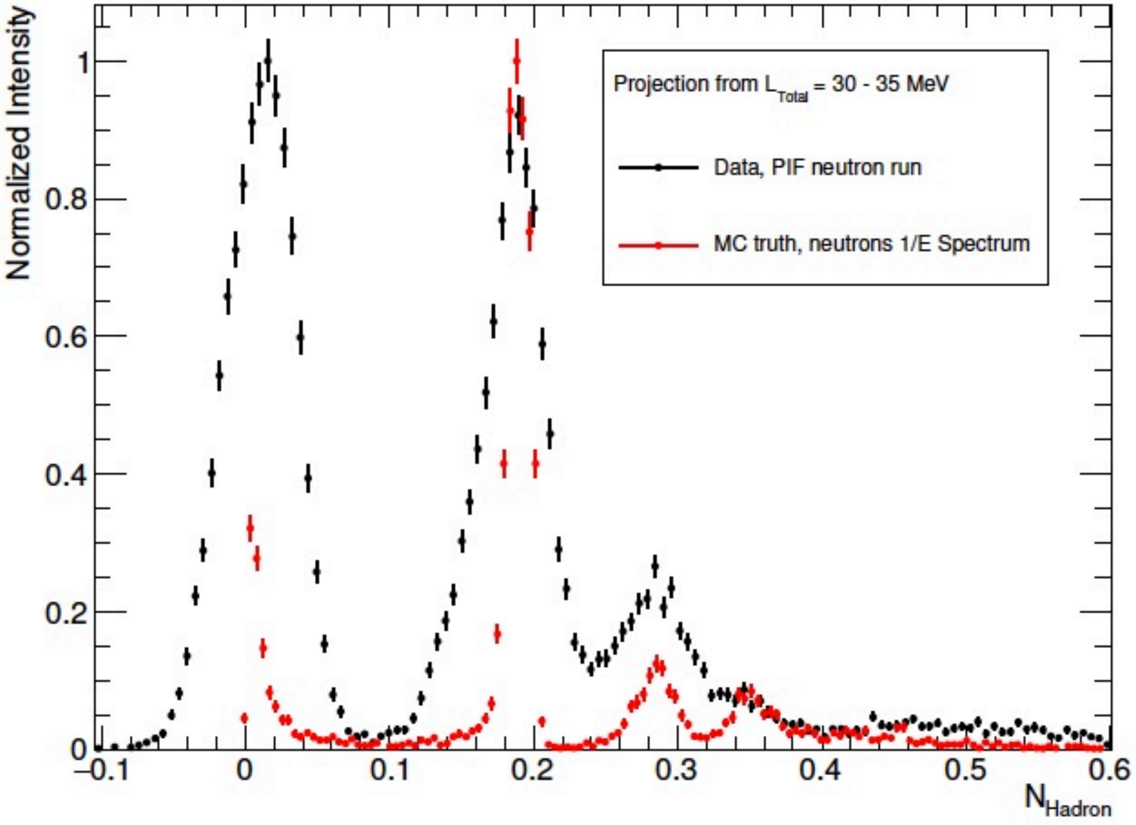
➡PSD at Belle II: S. Longo et al. Nucl. Instrum. Meth. A 982 (2020) 164562 arXiv: 2007.09642

Extra slides

Simulation Validation - Neutrons

- Features observed in neutron data are reproduced by PSD simulations.
  ➡MC truth verifies origin of bands.





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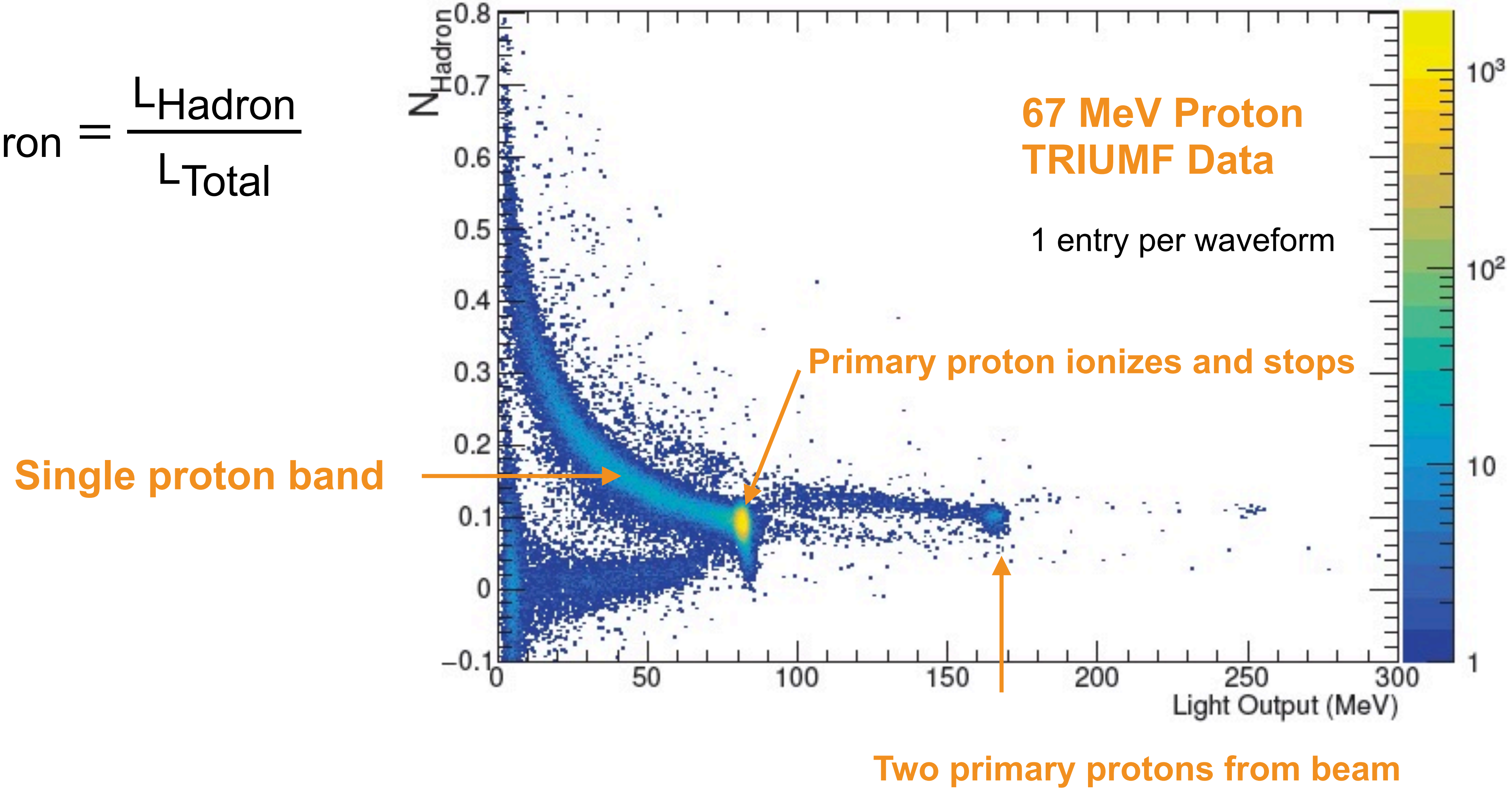
Pulse Shapes from TRIUMF Proton Data

- PSD spectrum depends on the interactions of the primary particle.
- Most protons ionize then stop in crystal, resulting with waveform on “single proton band”.

$$N_{Hadron} = \frac{L_{Hadron}}{L_{Total}}$$



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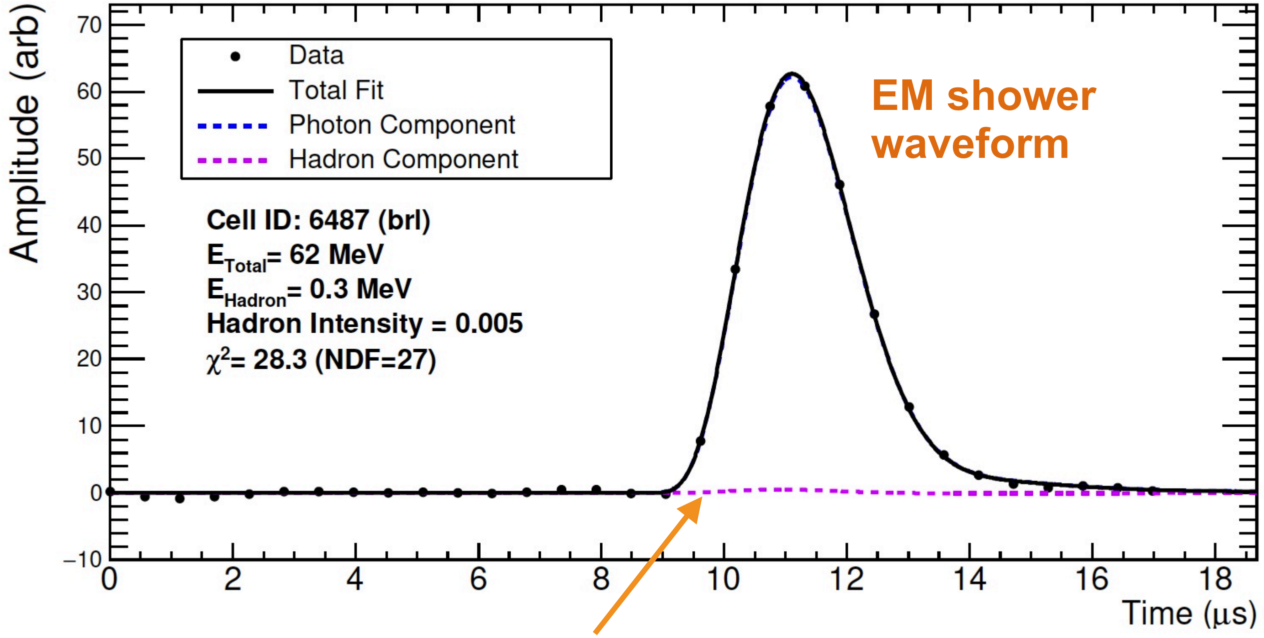
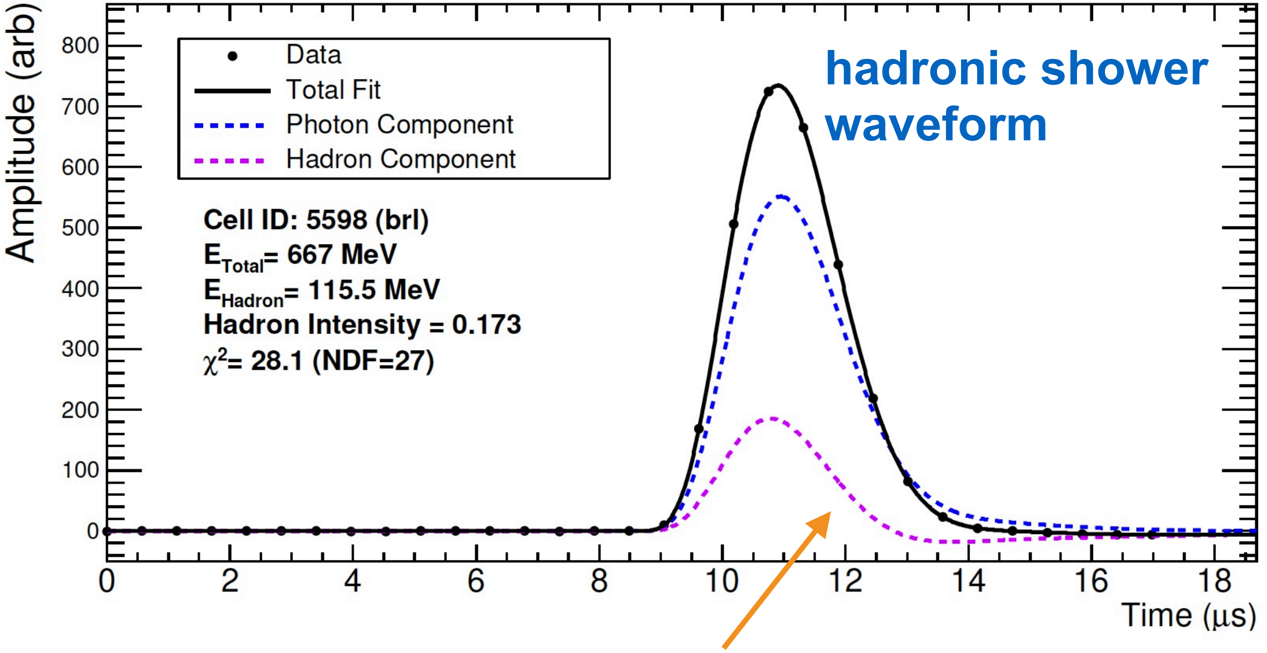
Belle II Waveform Characterization

- Waveform characterization techniques developed in TRIUMF study applied to Belle II.
  - ➡Mesure hadron intensity via multi-template fit.
- Photon and Hadron templates calibrated for each calorimeter crystal (8736 total).
- Belle II hadron template computed by convolving impulse response of Belle II signal chain with hadron shape measured in TRIUMF study.



EM shower: Hadron component of scintillation emission is negligible.



Hadronic shower: Hadron component of scintillation emission present.