A Novel Approach to Calorimeter-based Particle Identification at the Belle II Experiment using Scintillator Pulse Shape Discrimination

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The Belle II Experiment

- B-Factory experiment located at the asymmetric SuperKEKB e^+e^- collider in Japan.
- Aims to collect 50 ab^{-1} dataset by operating at world record luminosities.
- Belle II will search for new physics in the flavour sector of the Standard Model.
- This talk discusses **Pulse Shape Discrimination (PSD)** which is a **new particle ID technique using the CsI(Tl) scintillator crystals in the Belle II calorimeter.**

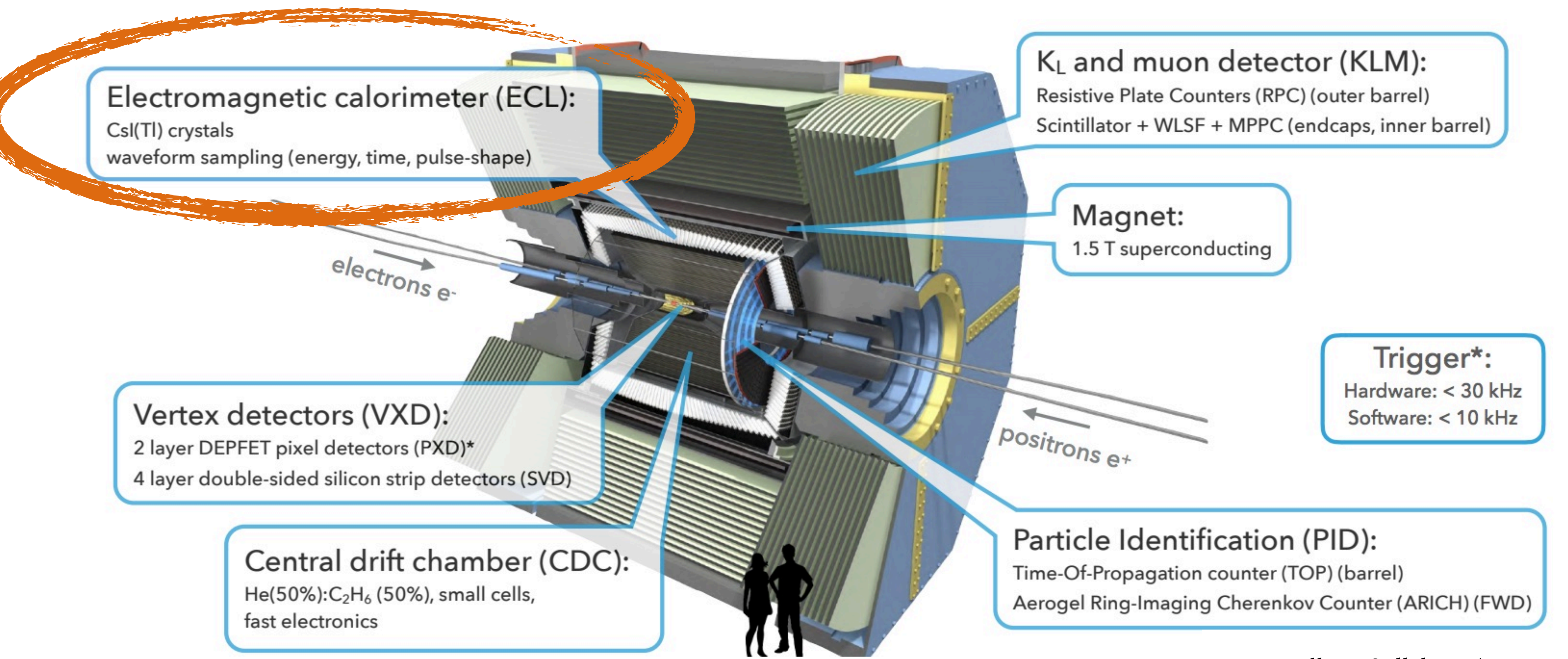
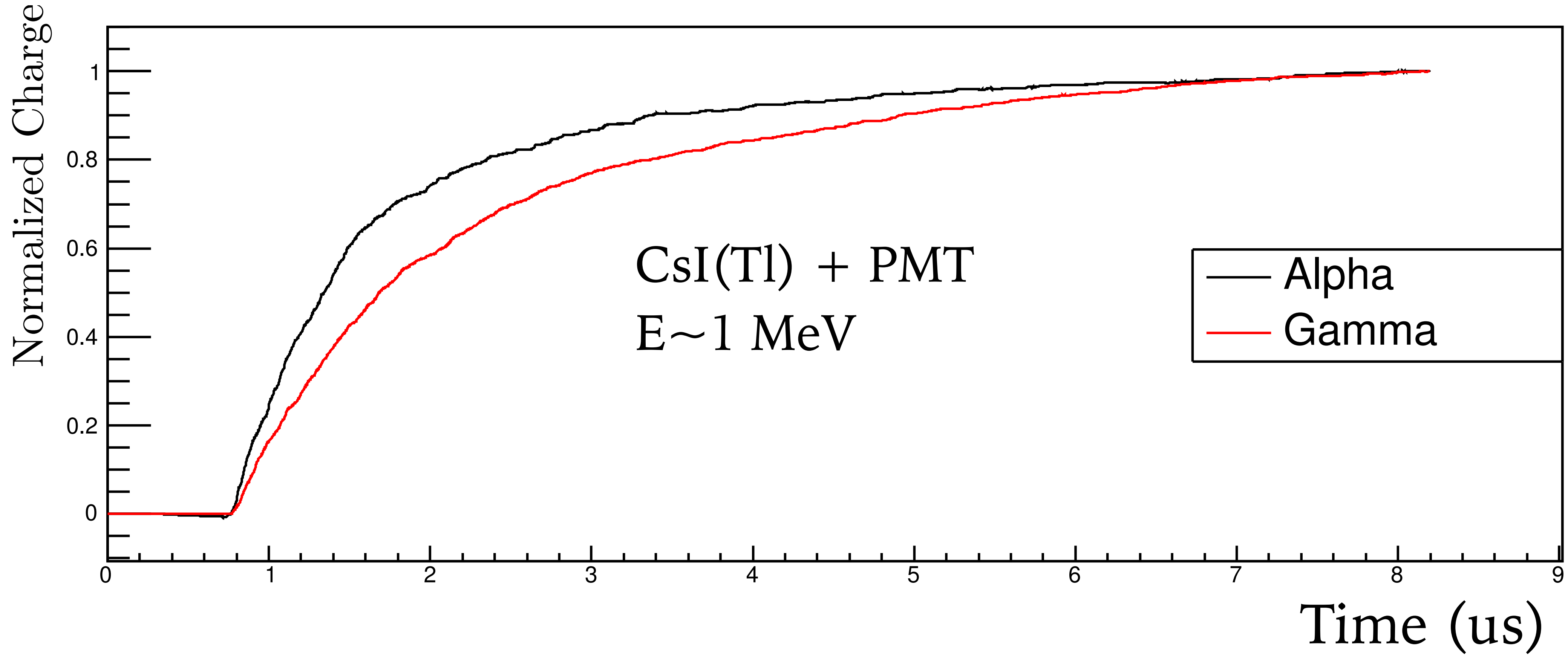


Image: Belle II Collaboration, T. Ferber

CsI(Tl) Pulse Shape Discrimination

- When a particle deposits energy in a CsI(Tl) crystal a scintillation pulse is emitted.
- **The shape the scintillation pulse depends on the ionization dE/d*x* of the particle depositing energy in the crystal.**
- Below shows CsI(Tl) pulse comparison for low energy photon and alpha particles.

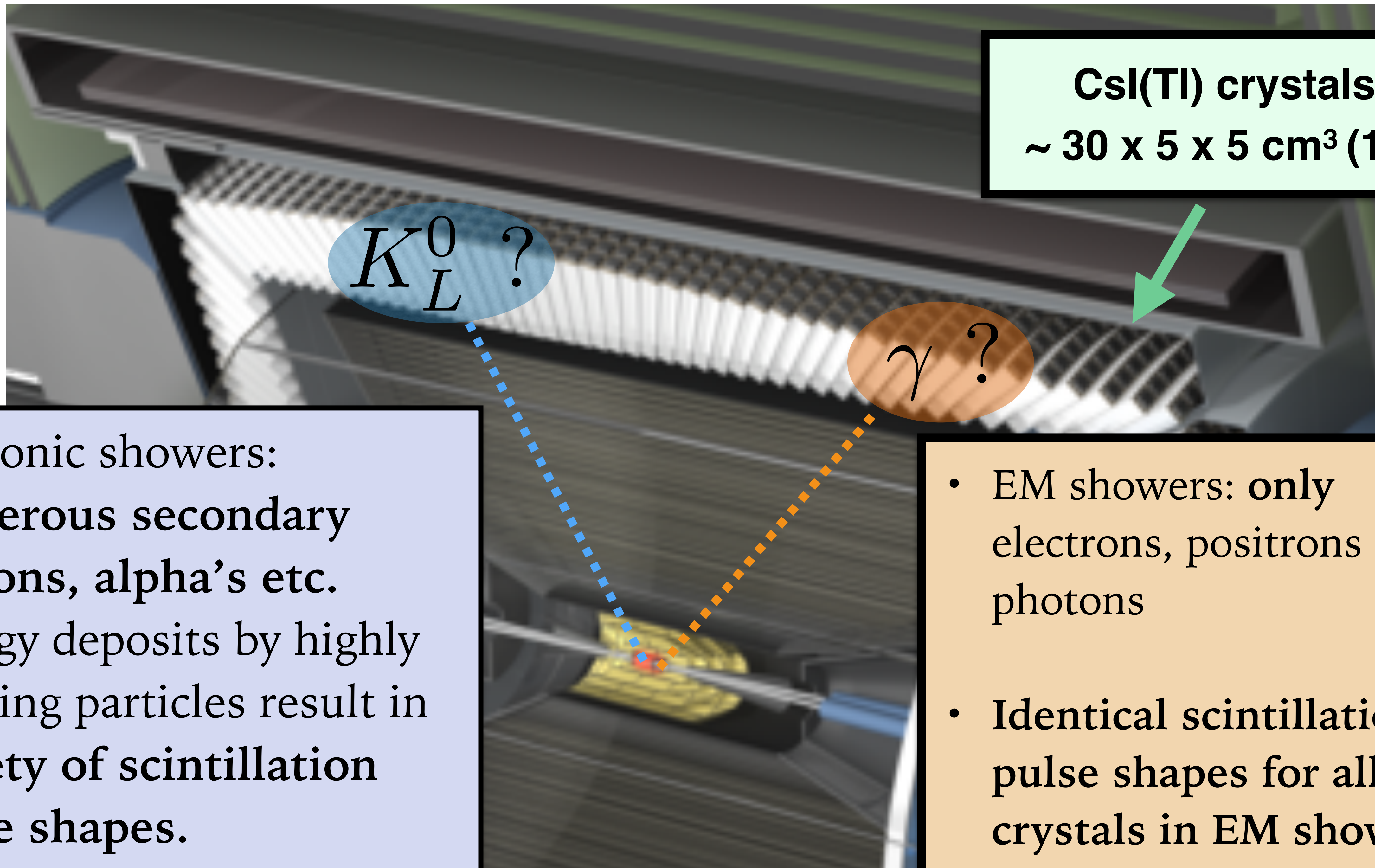


- From the pulse shape the **secondary particles that deposit energy in a calorimeter crystal can be identified!**

Primary Application: Neutral Hadron vs Photon ID

- K_L^0 and photon detector signature can be very similar - no track in drift chamber and energy cluster in calorimeter.

- **Secondary particles** in EM vs. hadronic showers however are **very different:**



- Hadronic showers: **numerous secondary protons, alpha's etc.**
- Energy deposits by highly ionizing particles result in **variety of scintillation pulse shapes.**

- EM showers: **only** electrons, positrons and photons

- **Identical scintillation pulse shapes for all crystals in EM showers**

Some Examples of PSD Impact on Belle II Physics

- **PSD** provides a method to **definitively classify calorimeter clusters as electromagnetic or hadronic shower's.**

- **PSD was not applied at Belle or BaBar** (bandwidth limited). With introduction at Belle II, there are numerous applications for improvements in Belle II physics measurements.

- Measurements of $\sin 2\beta / \sin 2\phi_1$ using $B^0 \to J/\psi K_L^0$ golden mode.
  - **Belle/BaBar purity of 50-60%** due to difficulty of separating kaon-long from photons in calorimeter. ($K_S^0 \to \pi^+\pi^-$ mode purity was 96-97%). [1,2]

- Measurement of CKM element $|V_{ub}|$ with $B \to X_u l \nu_l$ decays.
  - Belle/BaBar limited by background from CKM favoured $B \to X_c l \nu_l$ where X_c decays to a K_L^0. **Very few analyses applied kaon-long veto.**

- E_{extra} - used in analyses with missing energy.
  - With PSD E_{extra} can be divided into hadronic and EM showers.

[1] B. Aubert et al., BaBar Collaboration, *Measurement of Time-Dependent CP Asymmetry in $B^0 \to c\bar{c}K^{(*)0}$ Decays*, Phys. Rev. **D79** (2009) 072009.

[2] I. Adachi et al., Belle Collaboration, *Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays*, Phys. Rev. Lett. **108** (2012) 171802.

Pulse Shape Discrimination at Belle II

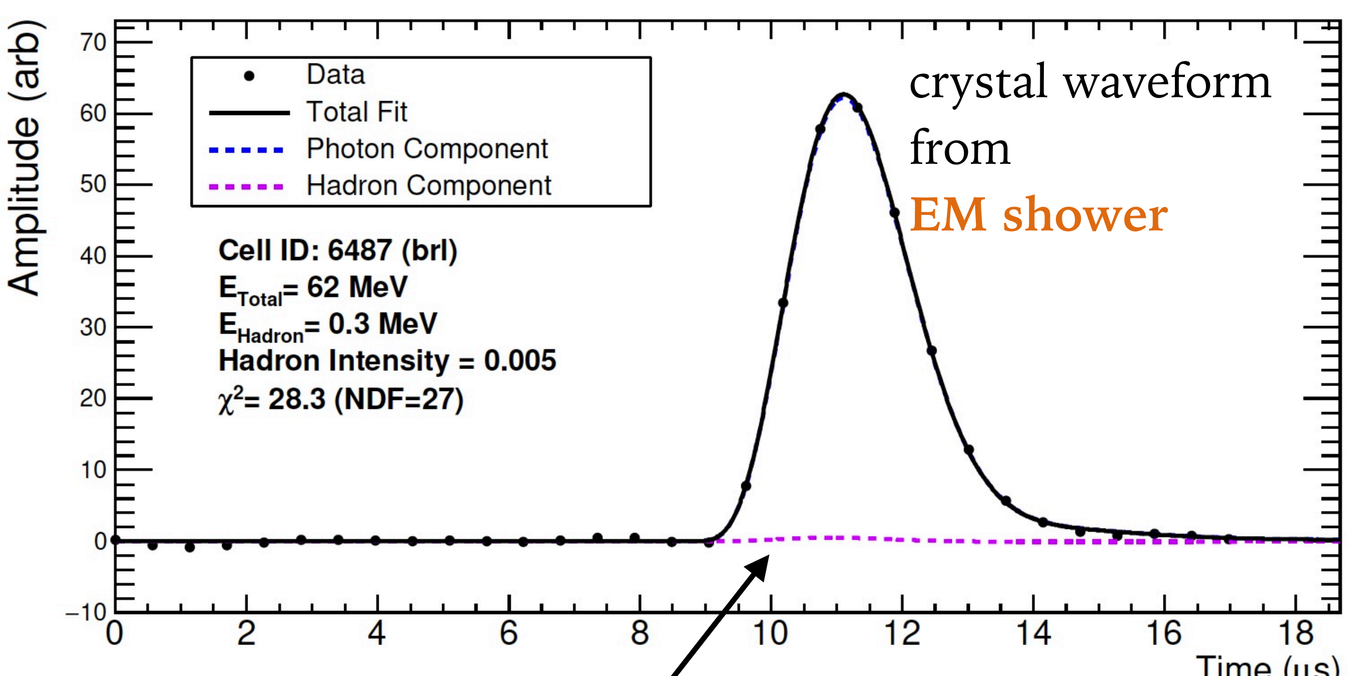
- **Belle II applied CsI(Tl) Pulse Shape Discrimination for the first time during data-taking in summer 2018!**

- **If calorimeter crystal energy exceeds 30 MeV,** digitized (18-bit ADC @1.7 MHz) CsI(Tl) waveform is recored for **offline pulse shape analysis through template fits**.

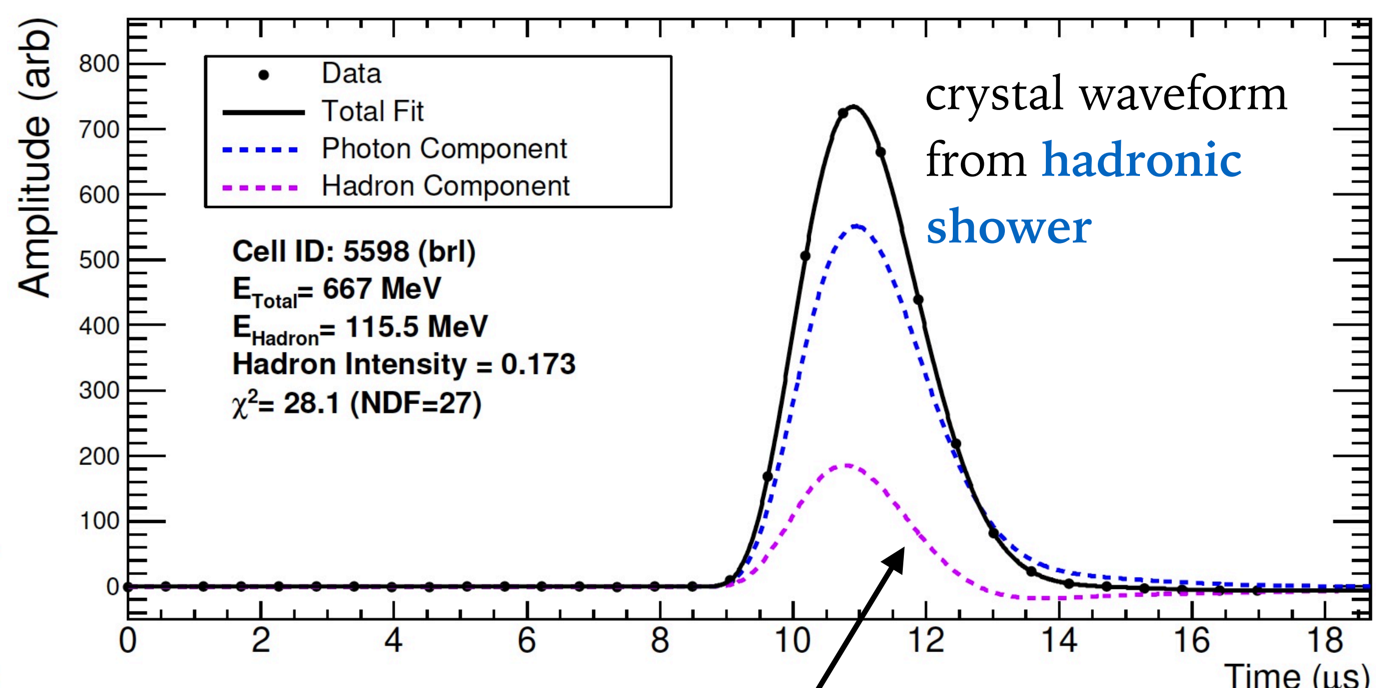
- From testbeam [3]: CsI(Tl) scintillation emission can be divided into two types:

"**Photon Component**": Scintillation produced by **EM showers and low dE/dx particles (MIPs)**.

"**Hadron Component**": Scintillation **only** produced by **highly ionizing particles (protons, alphas)**.



EM showers: Hadron scintillation component emission is negligible.



Hadronic shower: Hadron scintillation component emission is produced.

[3] S. Longo and J. M. Roney 2018 JINST 13 P03018 https://doi.org/10.1088/1748-0221/13/03/P03018. arXiv:1801.07774

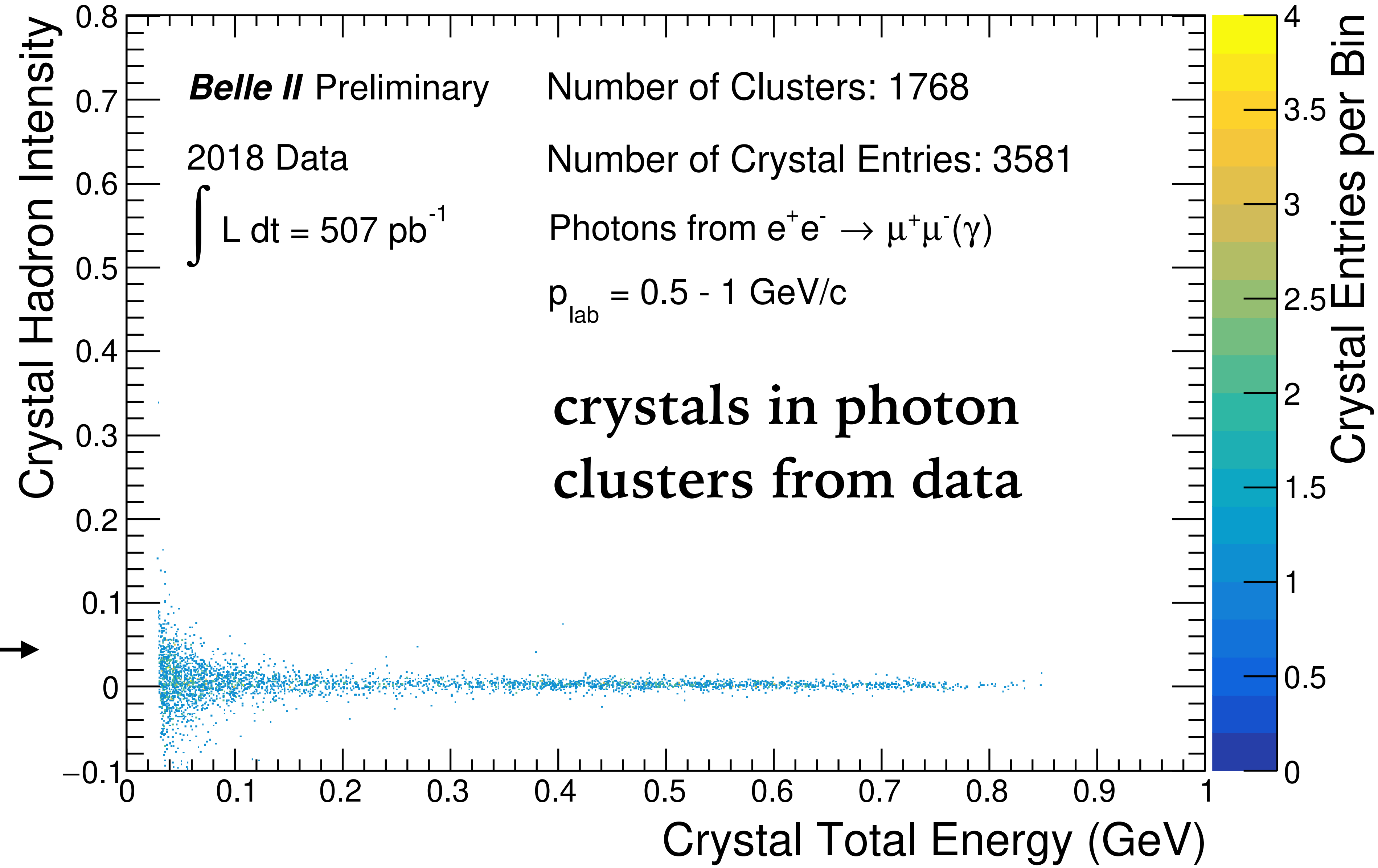
Crystal Pulse Shapes in EM Showers

- **Crystal Hadron Intensity vs Crystal Energy** plot below shows pulse shapes of crystals in a control sample of **photons** selected from Belle II 2018 data

$$\text{Crystal Hadron Intensity} = \frac{\text{hadron scintillation component emission}}{\text{total scintillation emission (photon+hadron component)}}$$

- EM Showers: only electrons, photons and positions - **expect no hadron scintillation component emission.**

- Crystals in **photon clusters** have **negligible hadron intensity** because no highly ionizing particles are present. (limited by noise)



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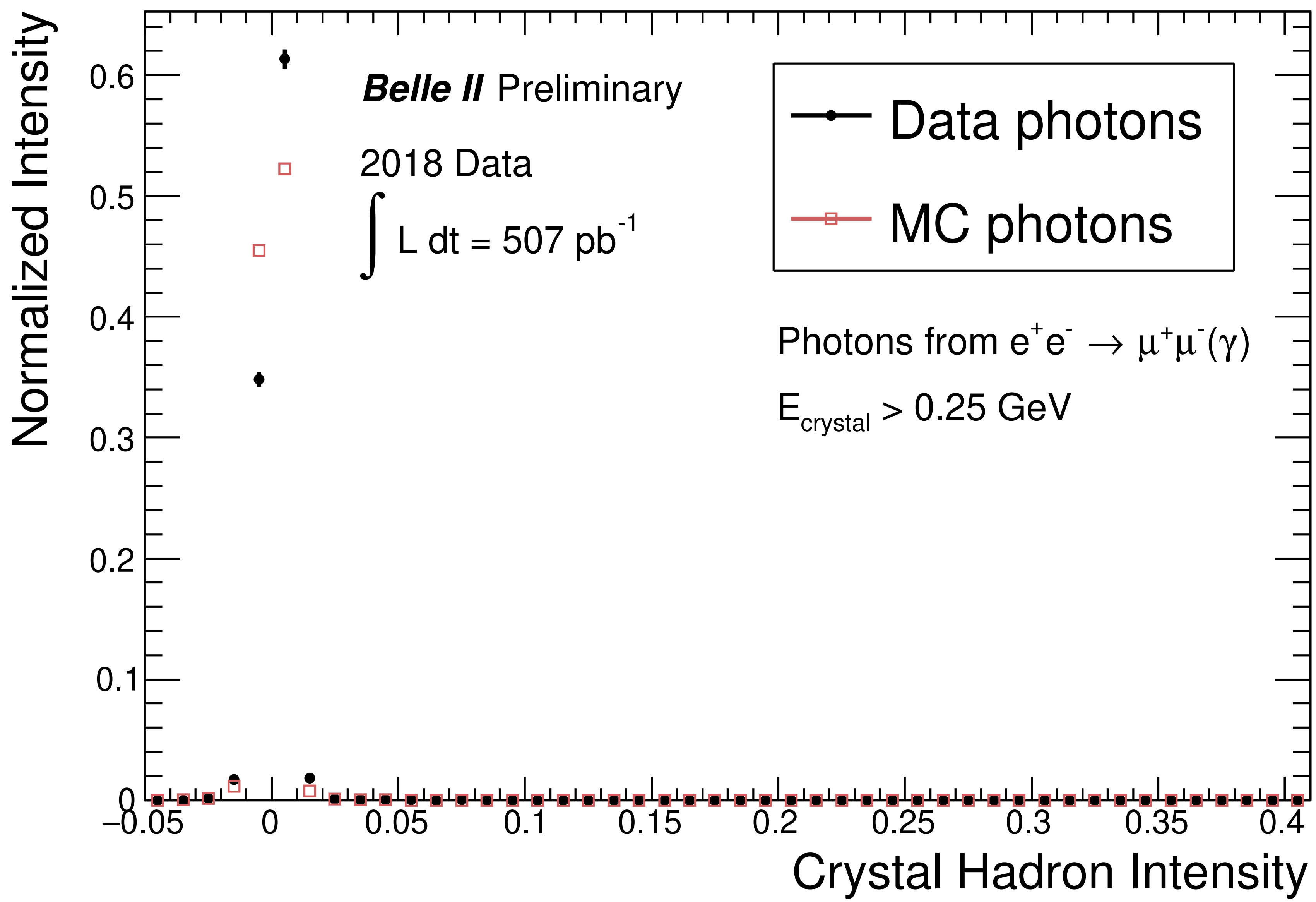
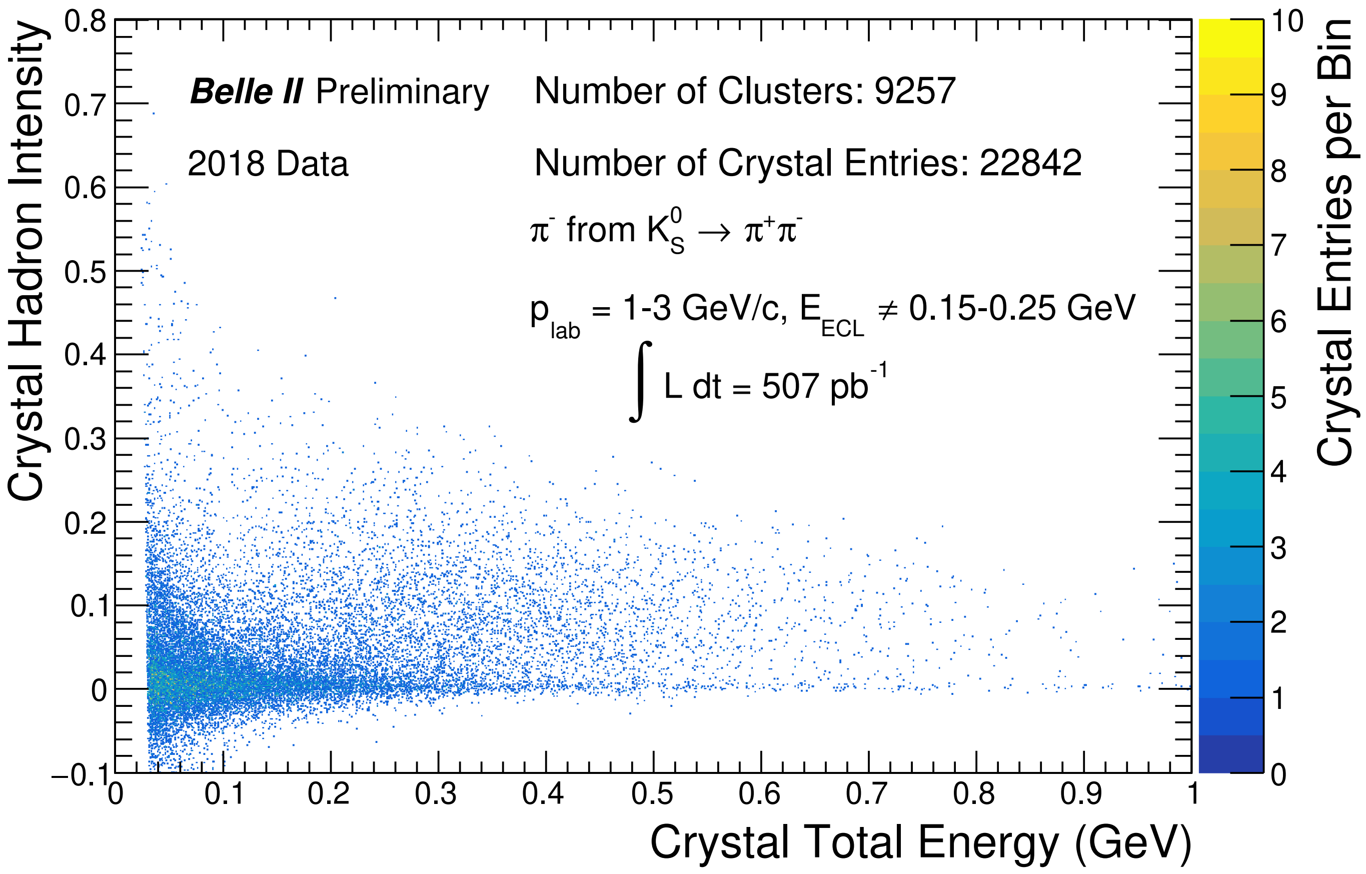


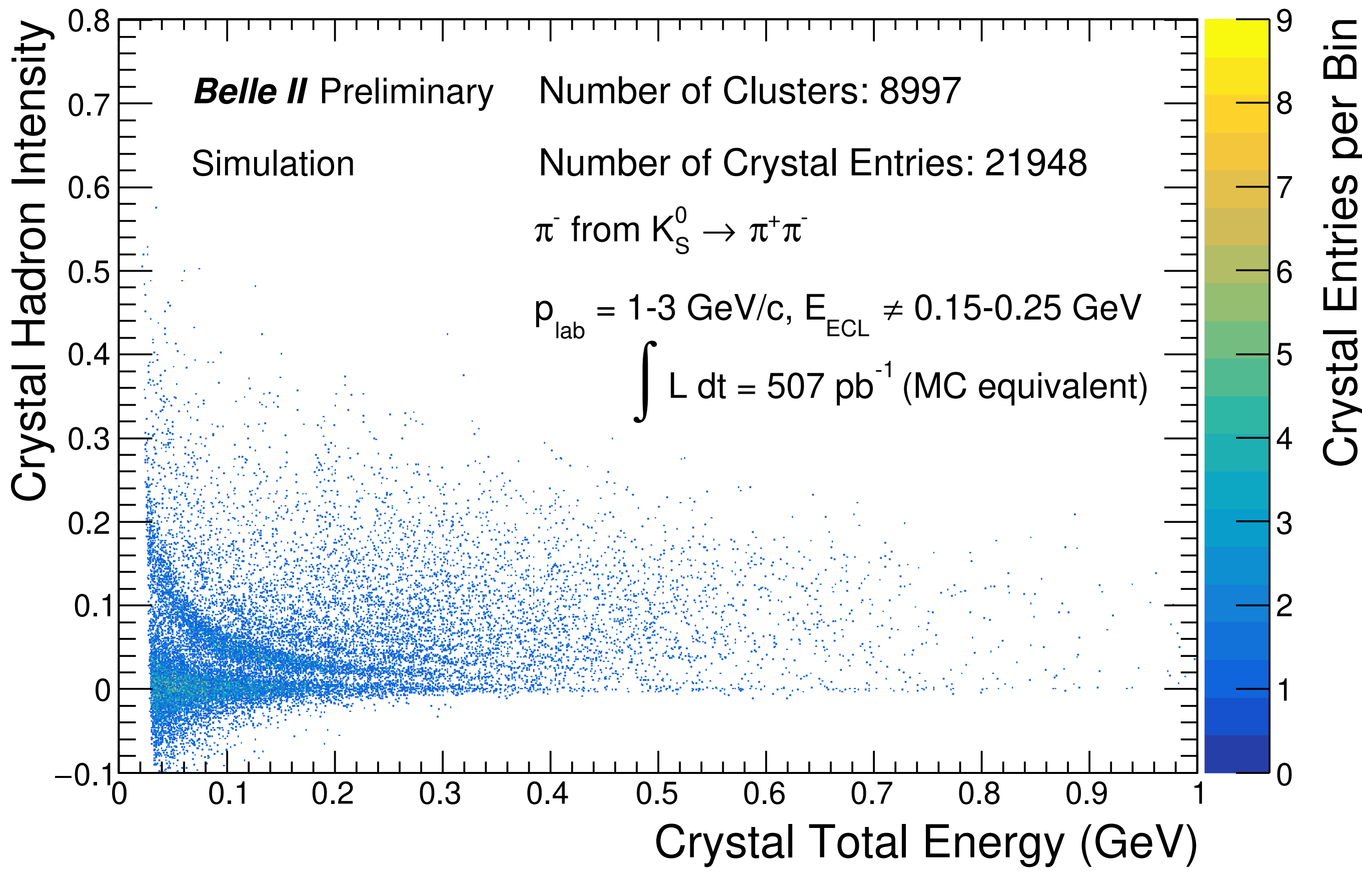
Crystal Pulse Shapes in Pion Hadronic Showers

- **Hadronic shower:** numerous **highly ionizing particles (protons, alpha particles etc)** are produced. Crystal can have a significant fraction of scintillation emission in **hadron scintillation component.**

- Band structures in **Crystal Hadron Intensity vs Crystal Energy** distributions arise from multiples of secondary protons stopping in a crystal volume.

- Simulation of ionization dependent CsI(Tl) pulse shape achieved by methods developed in ref [3].

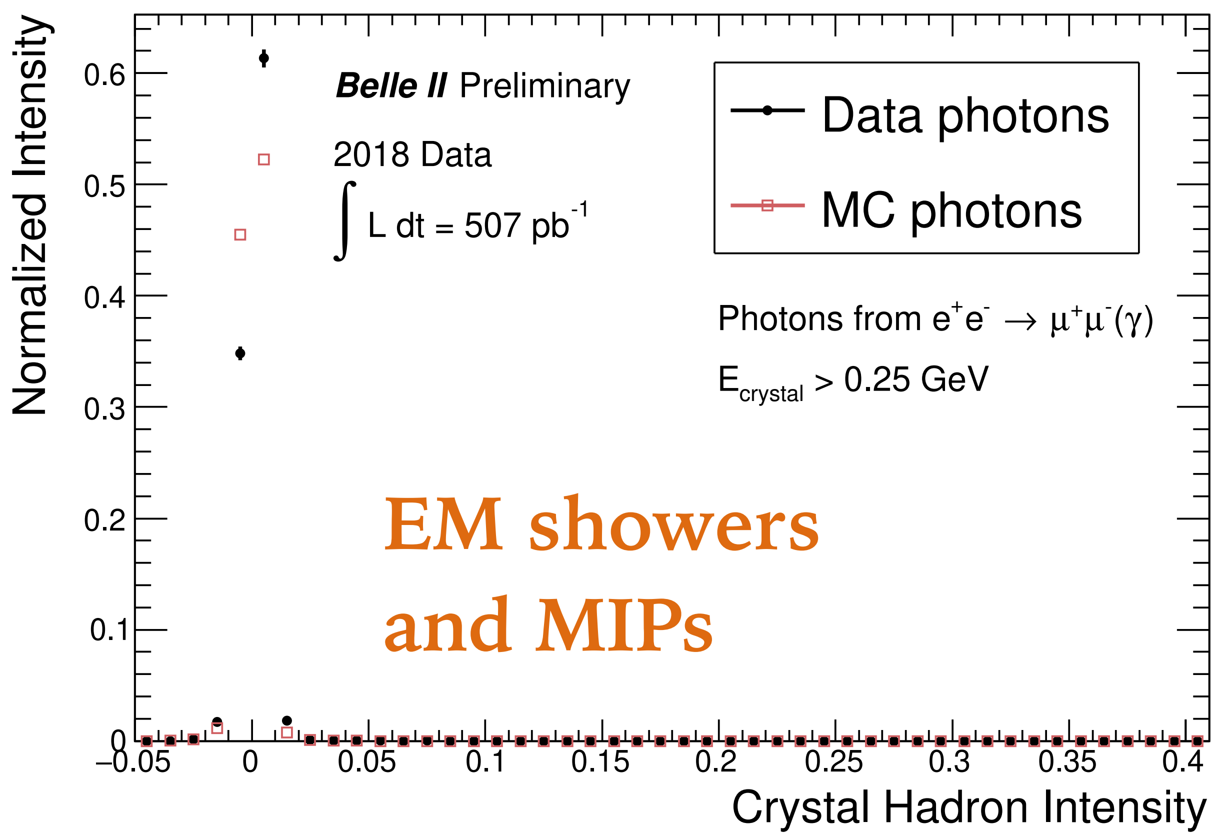


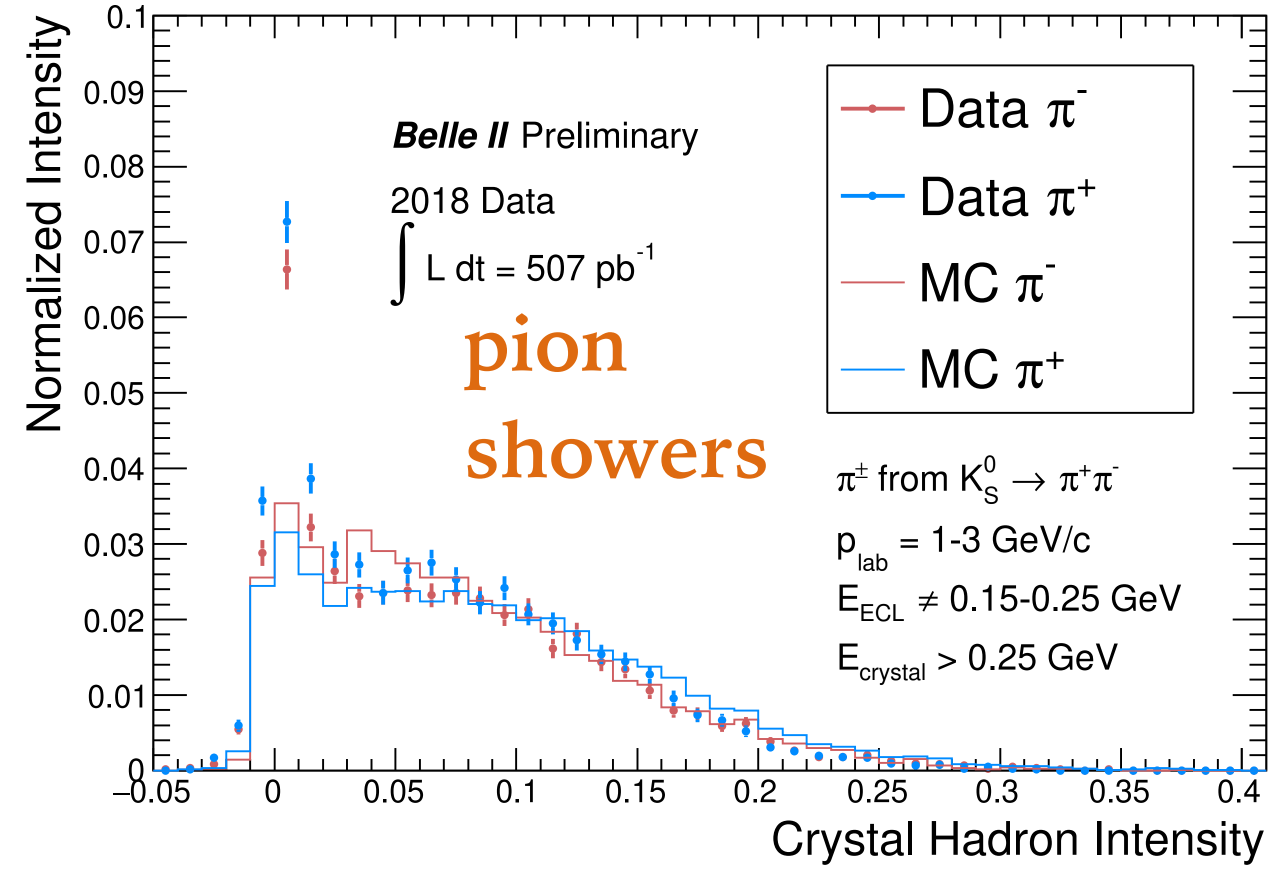


[3] S. Longo and J. M. Roney 2018 JINST 13 P03018 https://doi.org/10.1088/1748-0221/13/03/P03018. arXiv:1801.07774

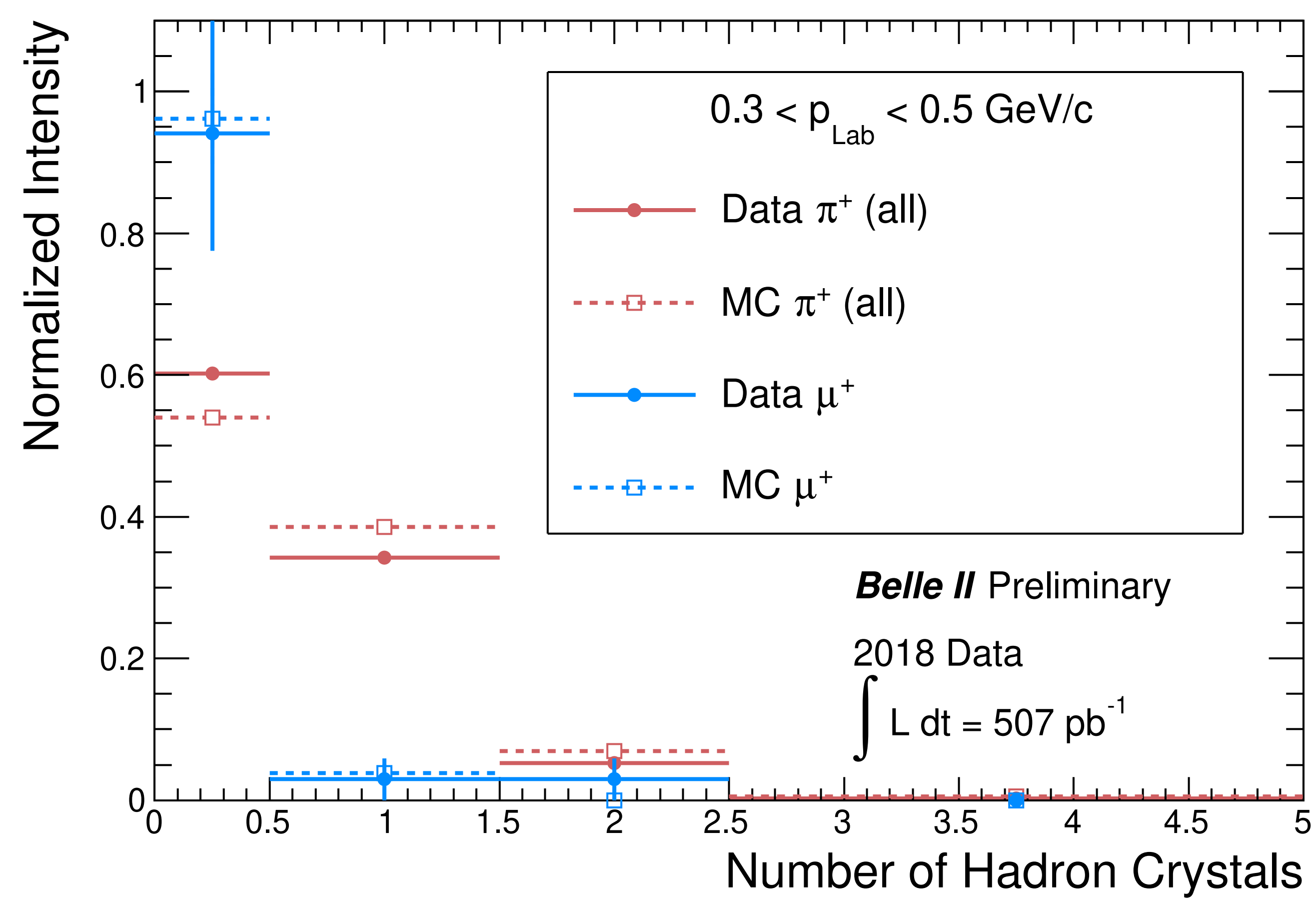
*MC does not simulate crystal-by-crystal variations in scintillation response - results in improved resolution to data.

Charged Particle ID with Pulse Shape Discrimination





- PSD has application for improving areas of **electron vs muon vs pion ID.**
- Eg: Electron EM shower vs pion hadronic shower - E/p can by similar but pulse shapes of crystals are very different.
- Eg: Low momentum muon vs pion, PSD can detect hadrons produced by pion nuclear interactions.

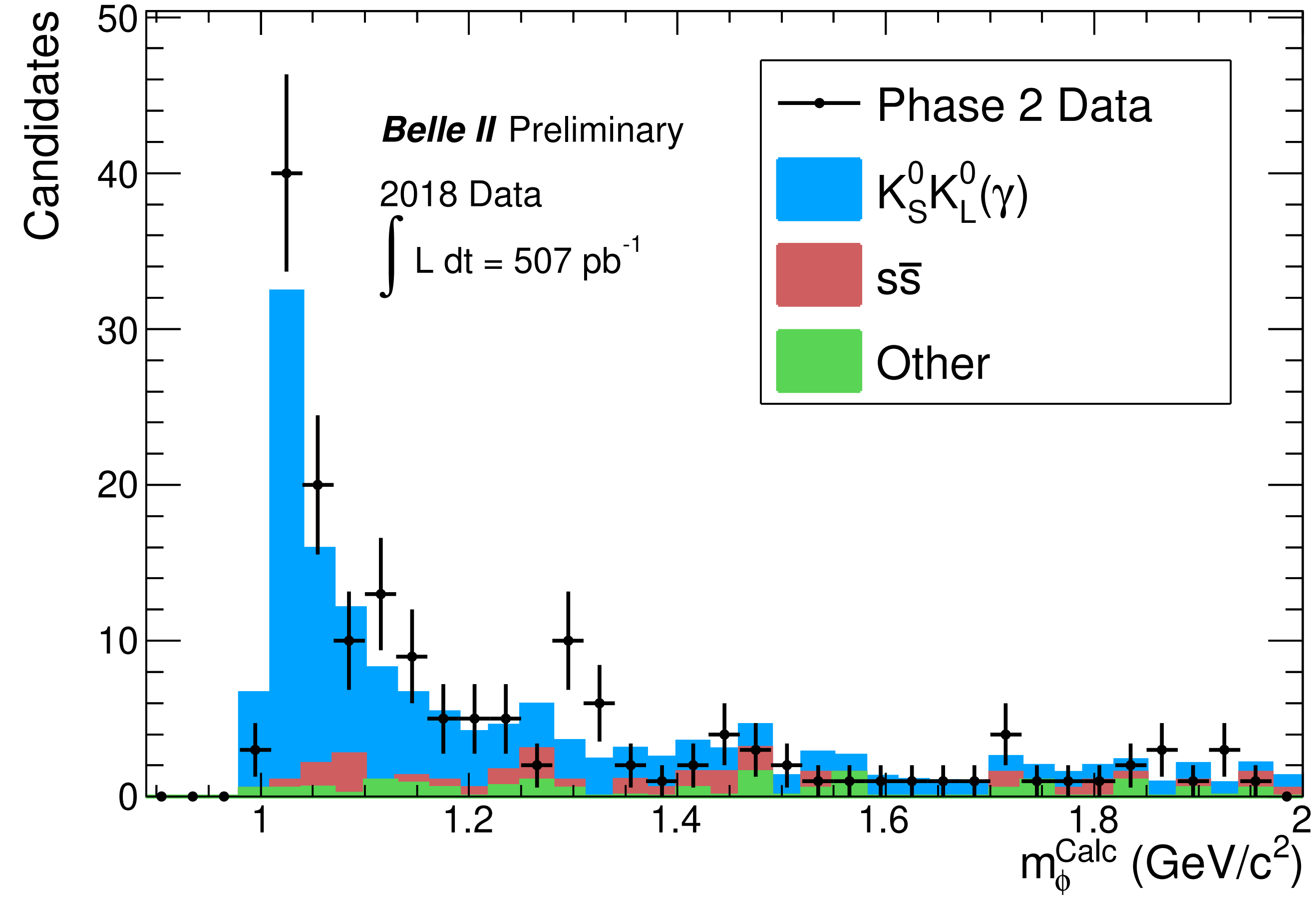


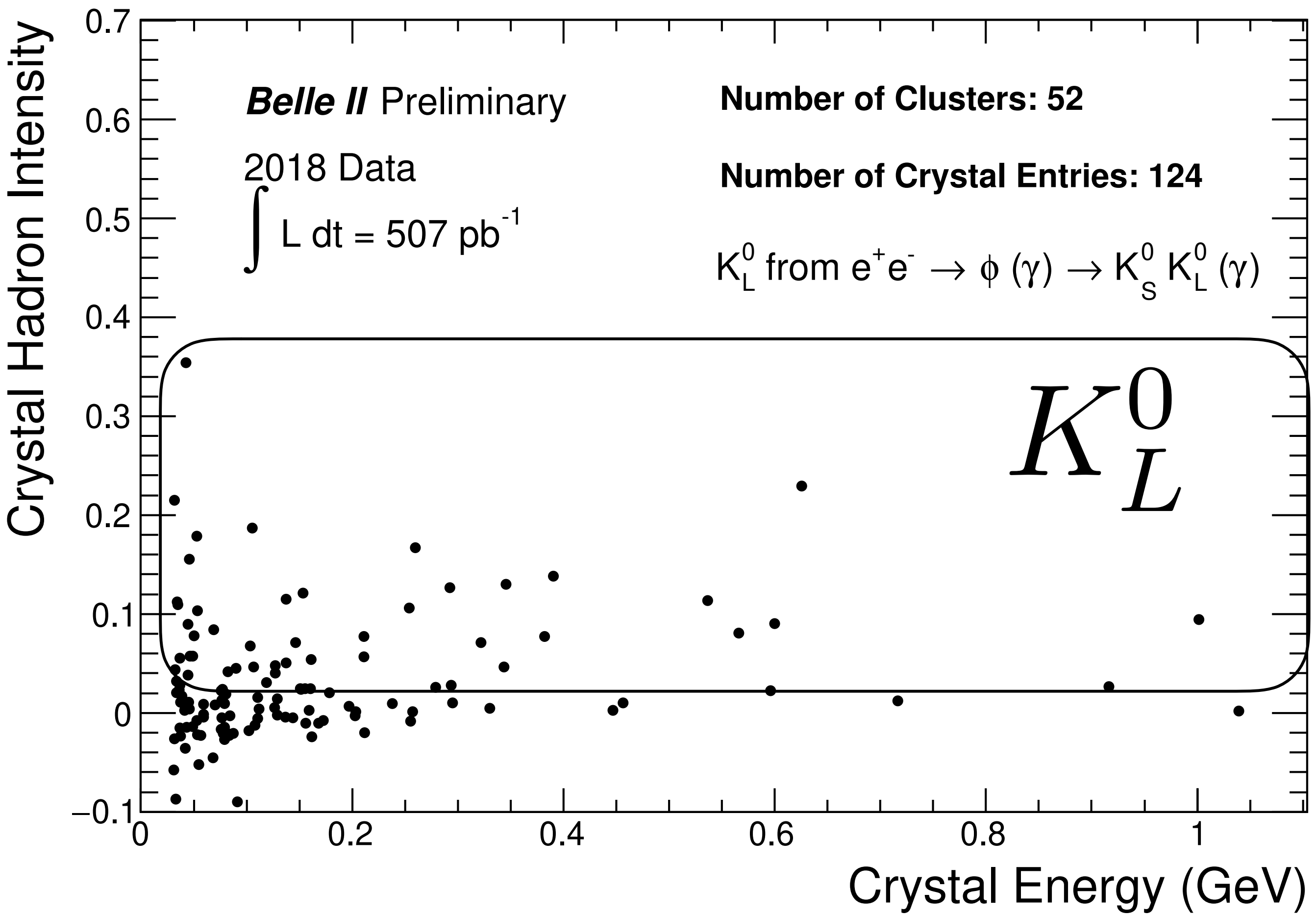
Kaon-long Control Sample from Data

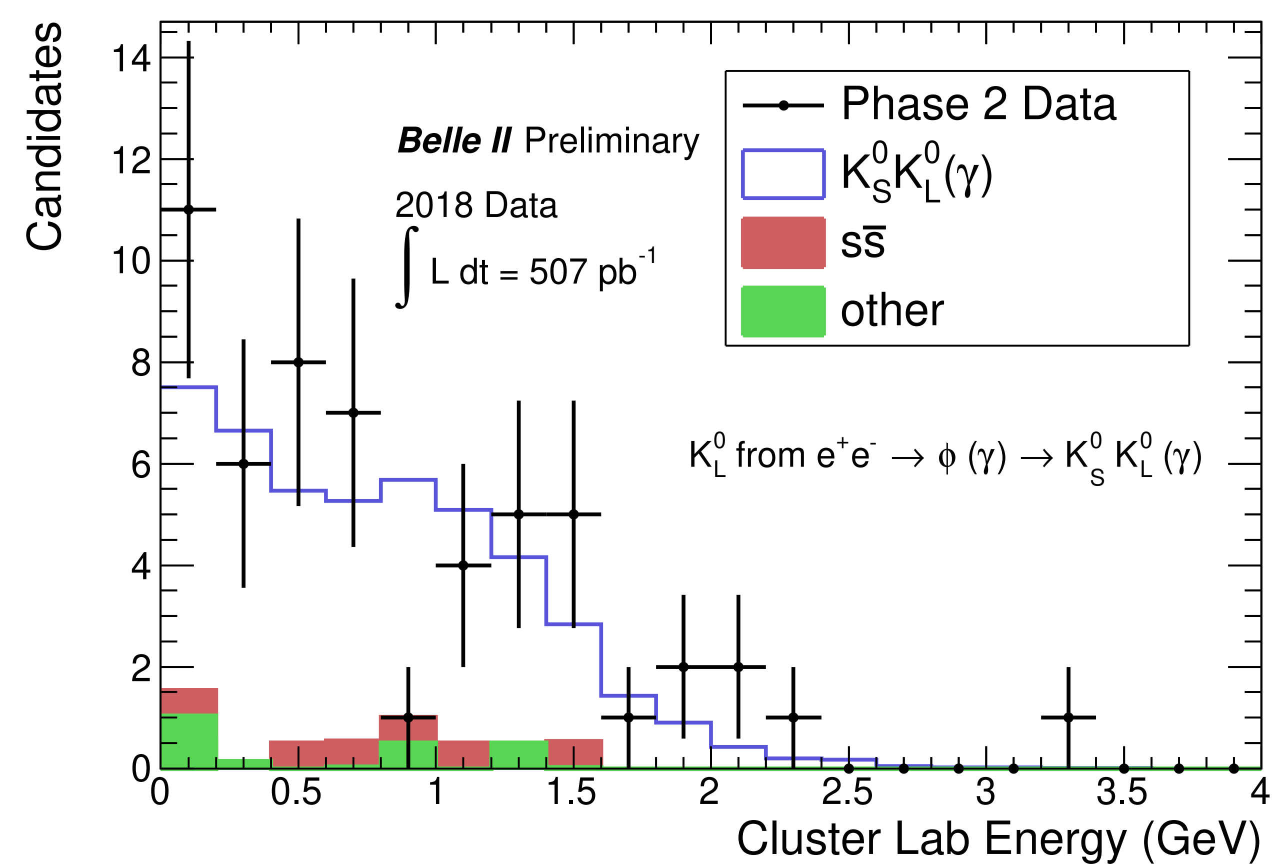
- K_L^0 kinematically selected from:

$$e^+e^- \to \phi\gamma_{ISR} \to K_S^0\ K_L^0\ \gamma_{ISR}$$

- Momentum ranges from 2-5 GeV/c.
- Cluster energies typically below 1.5 GeV due to hadronic shower energy losses.
- **Even in small sample, numerous crystals with hadron-like pulse shapes (circled) are present.**





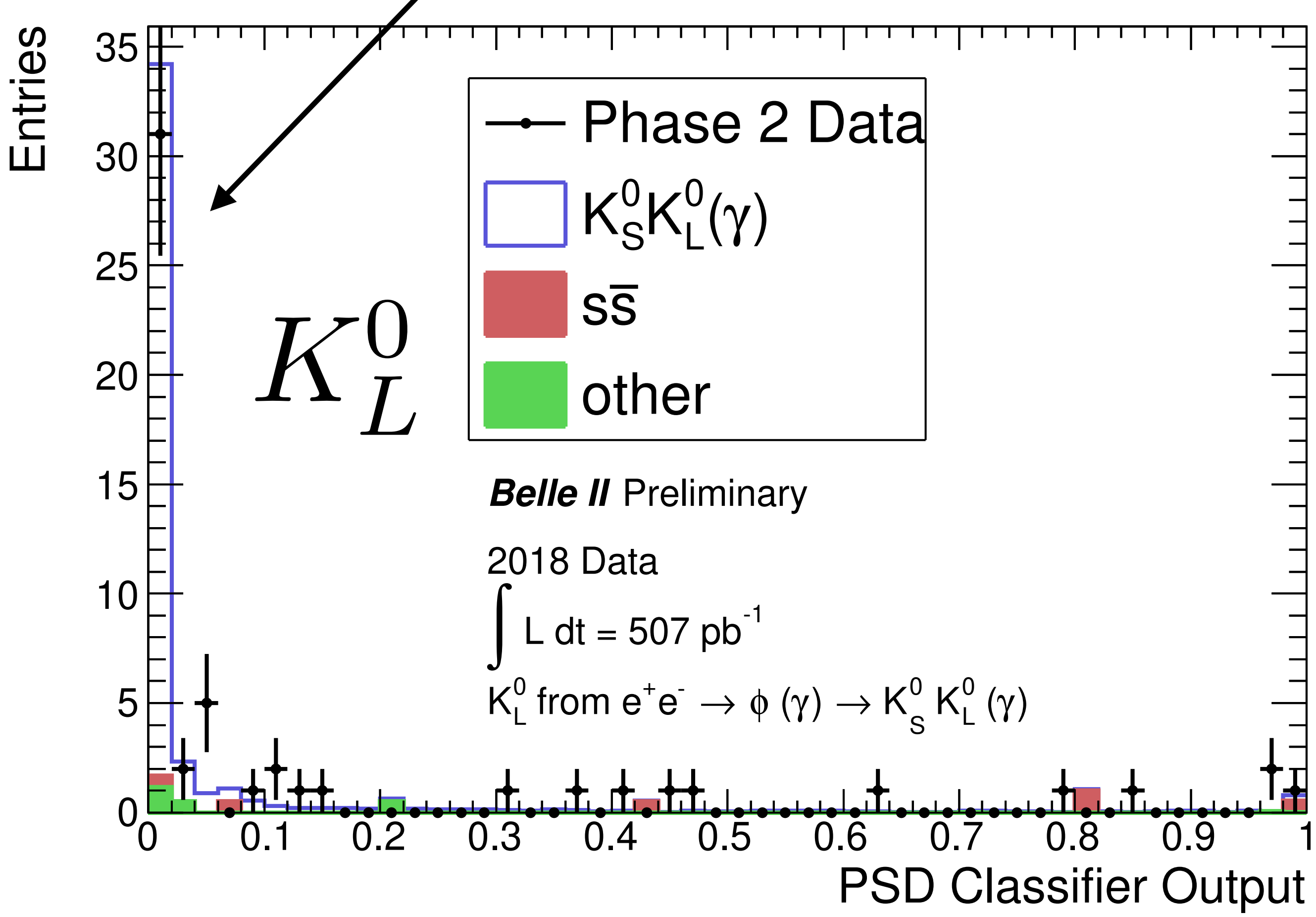


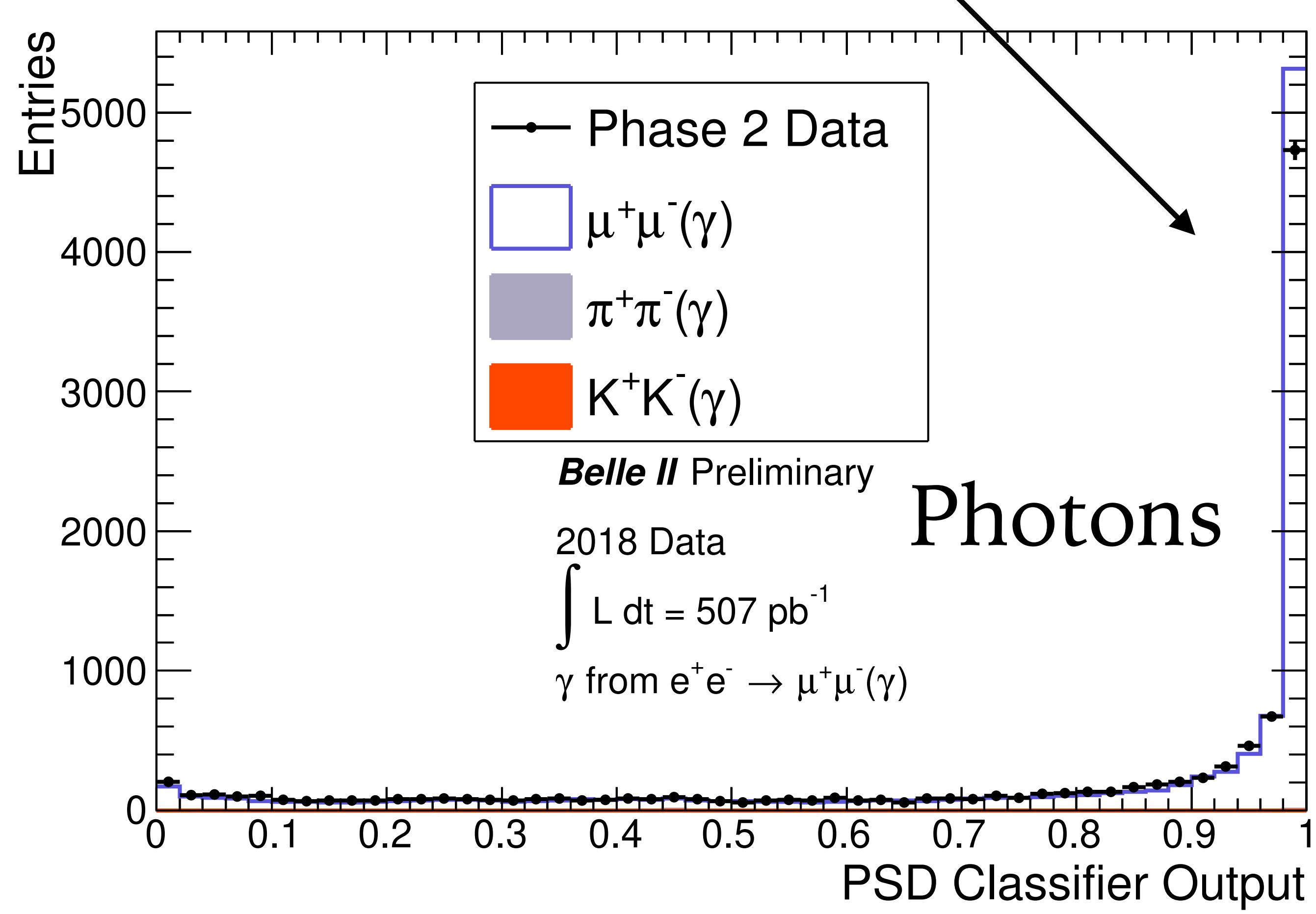
Multivariate Classifier for Kaon-long vs Photon Identification

- Classifier inputs: **crystal energy, crystal hadron intensity (pulse shape), crystal location in cluster**. Limited to only crystals with waveforms recorded and waveform fit with good χ^2.
- Trained with particle-gun MC samples of photons, kaon-long and anti-neutrons.
- **Performance evaluated with control samples of photons and kaon-longs selected from Belle II data.**

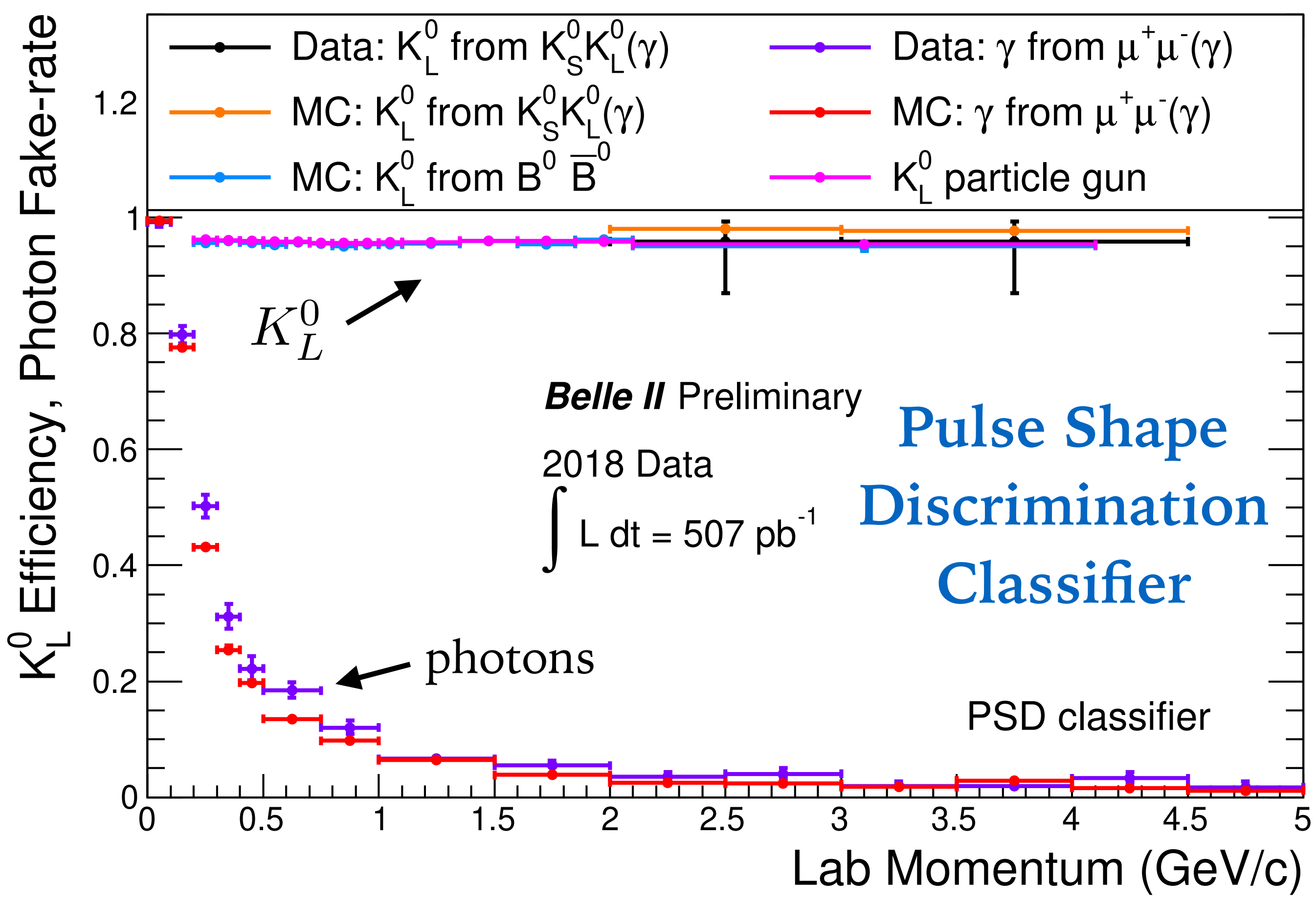
K_L^0 **peaking near 0 (hadron-like)**

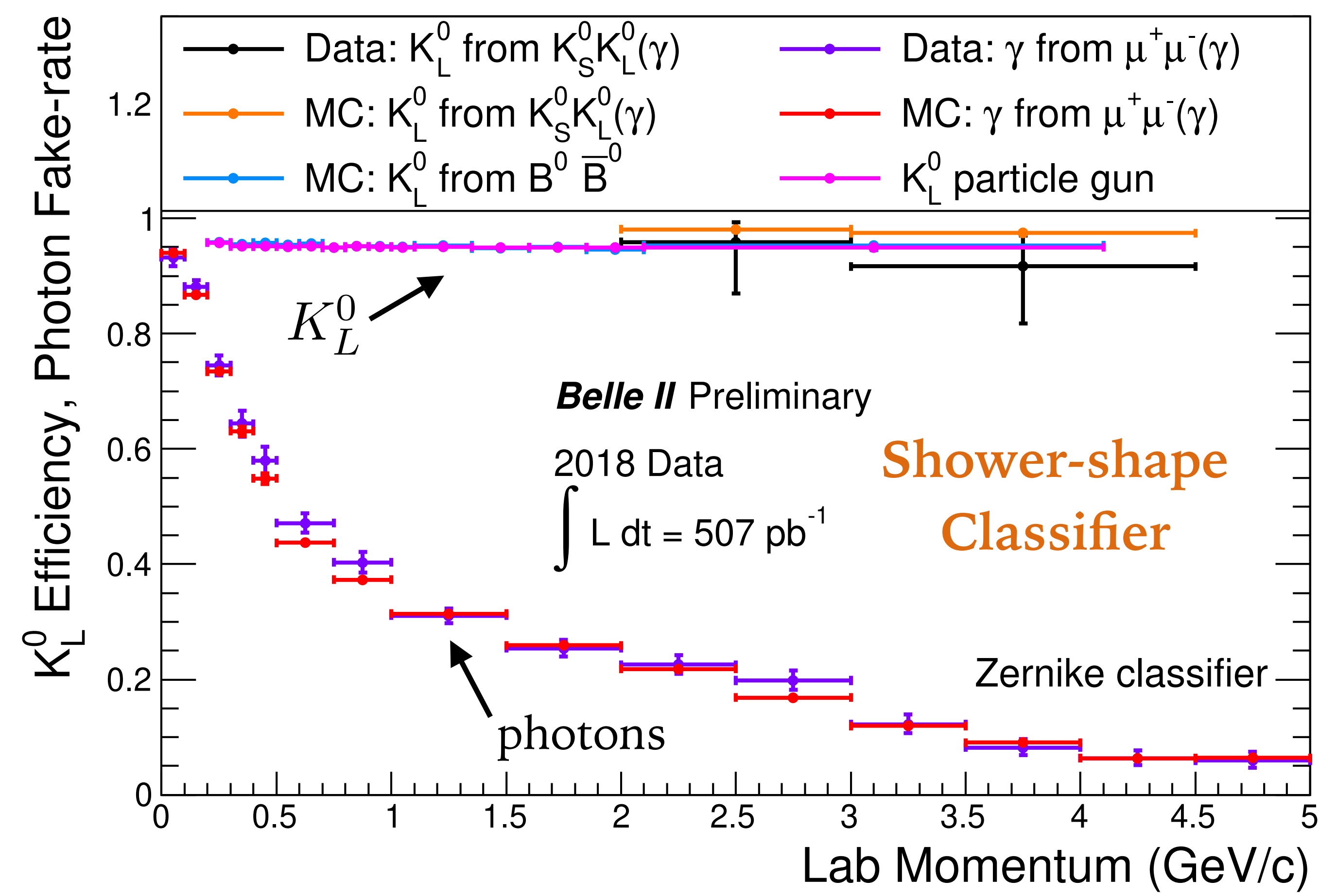
Photons peaking near 1 (EM-like)





PSD Performance Compared to Shower-Shapes





- Compare with shower-shape based (Zernike) classifier developed in ref [4].
- Classifier cuts set individually to achieve 95% kaon-long efficiency in particle gun. **Comparison is with the *photon as hadron* fake-rate.**
- ***Photon as hadron*** **fake-rate of PSD classifier is less than half of shower-shape based classifier at most momenta.**

[4] A. Hershenhorn et al., *ECL shower shape variables based on Zernike moments*, BELLE2-NOTE-TE-2017-001.

Conclusions

- **During first collision data-taking run in summer 2018, Belle II was the first e^+e^- collider to implement CsI(Tl) pulse shape discrimination for improving particle identification.**

- Pulse shape discrimination has potential to improve many Belle II analysis due to unique information provided.

- Improvements in kaon-long and photon identification through the application of pulse shape discrimination were demonstrated.

- **Pulse shape discrimination offers a new and independent approach to improving particle identification at high energy physics experiments.**

- **Pulse shape discrimination is not limited to CsI(Tl).** Calorimeter designs for future colliders should consider optimizing for energy resolution, timing resolution, radiation hardness ***and pulse shape discrimination capabilities.***

The End

Thanks!