

## Design of a high-speed and low-noise preamplifier for SiPM

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### Abstract

In the R&D for upgrading the KL0 and  $\mu$  detector (KLM) in Belle II experiment using scintillator and silicon photomultiplier (SiPM), we design a compact preamplifier with high speed and low-noise. The preamplifier has a good gain stability, a baseline noise level of  $\sigma = 0.3$  mV, a good time resolution that can achieve  $< 20$  ps, and can be applied comprehensively to SiPMs. To reduce the pile-up in using a large size SiPM or an array of SiPMs, which is due to the large capacitance and high dark count rate, we adopt pole-zero-cancellation which reduce both the rise time and the fall time of a SiPM signal. The combinations of the preamplifier and several kinds of SiPMs show time resolutions better than 50 ps for most of the cases; when the number of detected photons is larger than 60, a time resolution of about 25 ps can be achieved

### Full Text

#### Preamble

#### Design and Performance of a High-Speed and Low-Noise Preamplifier for SiPM

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In the context of research and development for upgrading the  $K^0_L$  and muon detectors in the Belle II experiment using scintillators and silicon photomultipliers (SiPMs), we have designed a compact high-speed and low-noise preamplifier. The preamplifier demonstrates excellent gain stability, a bandwidth of 426 MHz, a baseline noise level of  $\sigma = 0.6$  mV, a dynamic range of up to 170 mV for input signal amplitude, and a time resolution of 20 ps. It can be widely applied to various SiPMs. By adopting pole-zero cancellation in the preamplifier, both the rise and fall times of SiPM signals are reduced, which significantly improves time resolution and mitigates pile-up when using large-area SiPMs or SiPM arrays. Various combinations of the preamplifier with several types of SiPMs achieved time resolutions better than 50 ps in most cases; when the number of detected photons exceeded 60, a time resolution of approximately 25 ps was attained.

**Keywords:** Silicon photomultiplier, High-speed amplifier, Low noise, High time resolution

## Introduction

Scintillation-based detector technology has been employed in experiments for over a century, from Rutherford's use of ZnS to contemporary applications. This technology continues to advance rapidly, particularly with the development of various inorganic scintillators such as BGO, PWO, and LYSO, alongside novel silicon-based photon detectors [?, ?]. Scintillation detection with photomultipliers is now comprehensively utilized in particle and nuclear physics experiments.

The Belle II experiment [?, ?], a super B-factory that began its physics run in 2019, employs diverse photon detection technologies including time-of-propagation counters and aerogel ring-imaging Cherenkov detectors for charged particle identification, an electromagnetic calorimeter for high-energy photon detection, and the  $K^0_L$  and muon detector (KLM) for  $K^0_L$  and muon identification [?]. The KLM detector modules in the endcaps and the two innermost barrel layers are based on extruded scintillators coupled to wavelength-shifting fibers and silicon photomultipliers (SiPMs), representing a significant upgrade from the resistive plate chambers (RPCs) used in the original Belle KLM. While this new technology has demonstrated good performance, the remaining 13 barrel layers still rely on legacy RPCs from Belle. As indicated in the Snowmass Whitepaper [?], Belle II is considering a complete KLM upgrade to scintillator modules, which would involve approximately 38,000 readout channels.

By leveraging the excellent timing properties of scintillators and SiPMs, it becomes possible to measure the time-of-flight of neutral hadrons such as  $K^0_L$  and neutrons. This capability is critical for improving  $K^0_L$  identification and, furthermore, for measuring the momentum of  $K^0_L$  or neutrons. Meanwhile, a scheme employing SiPMs and plastic scintillation systems for muon detectors or hadron calorimeters is also anticipated for the proposed Circular Electron Positron Collider (CEPC), a Higgs factory [?, ?]. The SiPM is a novel photode-

detector composed of parallel avalanche diodes operating in Geiger mode, offering several advantages including compact size, low operating voltage ( $V_{op}$ ), excellent time resolution, and immunity to magnetic field interference. SiPMs are commonly used in scientific research, medical diagnostics, and biochemical detection [?]. The rise time ( $\tau_{rise}$ ) of SiPM signals is only a few hundred picoseconds, enabling exceptional timing performance with an optimized front-end readout. However, SiPM signals are inherently small and require front-end amplification, with timing performance primarily constrained by the amplifier's bandwidth and noise level. This front-end readout is called a preamplifier. Furthermore, as the photosensitive area of the SiPM increases, its dark count rate rises significantly, posing challenges for preamplifier design. In practice, detectors in particle and nuclear physics experiments often require hundreds or thousands of front-end readout channels to be placed in a small space, necessitating low-cost, compact preamplifiers suitable for multi-channel integration. While certain commercial preamplifiers for SiPM are available [?], they typically have large volumes, complex circuits, and difficulty meeting the requirements of high time resolution and high integration density for large-scale detectors.

Considering the R&D needs for the KLM upgrade in Belle II and the muon detector in CEPC, we have designed a compact preamplifier that operates with various SiPMs. This preamplifier offers advantages of fast rise time, low noise, low cost, and simple circuit topology. In this study, we present the design and performance of this preamplifier, followed by the time resolution results obtained from combinations of the preamplifier with different types of SiPMs.

## II. Design of the Preamplifier

Figure 1 Figure 1: see original paper shows the circuit diagram of a SiPM equivalent model [?], where  $C_d$ ,  $R_d$ , and  $R_q$  represent the capacitance of the reverse-biased diode, the diode resistance, and the quenching resistor resistance, respectively;  $C_q$  is the parasitic capacitance of  $R_q$ , and  $R_s$  is the load resistance of the SiPM. When the SiPM operates at  $V_{op}$ , its gain is related to  $Q = (C_d + C_q)(V_{op} - V_{br})$ , where  $V_{br}$  is the breakdown voltage. For a SiPM containing  $N_{pixel}$  pixels, the total capacitance is  $C_{tot} = N_{pixel} \cdot (C_d + C_q)$ . Figure 1(b) demonstrates an LTspice simulation [?] using parameters for the S13360-6025PE [?], showing a typical SiPM signal with a fast rise time  $\tau_{rise} = R_d(C_d + C_q)$  and a slow fall time  $\tau_{fall}$  that can be described as:

$$i_d(t) = (C_q + C_d)(C_q/\tau_{fast} - C_d/\tau_{slow})$$

where  $\tau_{fast} = R_s C_{tot}$  and  $\tau_{slow} = R_q(C_d + C_q)$  are the fast and slow components of  $\tau_{fall}$ , respectively. When multiple SiPMs are combined in parallel for a large total photosensitive area, both  $\tau_{rise}$  and  $\tau_{fall}$  increase [?]. A large  $\tau_{rise}$  is detrimental to good time resolution, while a large  $\tau_{fall}$  typically causes signal pile-up and increases detector dead time. This is particularly problematic for ultra-high

luminosity experiments such as Belle II, which was designed for a luminosity of  $0.8 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ . To reduce the long  $\tau_{\text{fall}}$ , we employ pole-zero cancellation (PZC) in the preamplifier, which also reduces  $\tau_{\text{rise}}$ .

Considering the requirements for large bandwidth and low noise, we selected the LMH6629 operational amplifier chip from Texas Instruments [?] for the preamplifier design. This chip features a voltage slew rate of 1600 V/ $\mu\text{s}$ , an input voltage noise of 0.69 nV/ $\sqrt{\text{Hz}}$ , and a -3 dB bandwidth of 900 MHz at a stable gain of +10 V/V, making it suitable for the extremely fast  $\tau_{\text{rise}}$  of SiPM signals.

Figure 2 Figure 2: see original paper shows the principle diagram of the preamplifier circuit, which adopts negative feedback to improve the  $\tau_{\text{rise}}$  of the output signal and gain stability. For multi-channel applications in experiments, we designed a power supply board for 8-channel parallel preamplifiers, as shown in Fig. 2(c). The preamplifier units plug directly into the power supply board and connect to SiPM readout boards via RF cables. This design can accommodate different readout board sizes and various SiPM types, enhancing the preamplifier's versatility.

### A. Bandwidth and Noise

The effect of electronic noise on systematic timing performance is estimated by [?]:

$$\sigma_{\text{noise}} / (dV/dt)$$

where  $\sigma_{\text{noise}}$  is the baseline noise level and  $dV/dt$  is the voltage slope of the signal's rising edge. To achieve  $\tau_{\text{rise}} = 1 \text{ ns}$ , the amplifier bandwidth ( $f_{\text{BW}}$ ) should be approximately  $f_{\text{BW}} = 0.35/\tau_{\text{rise}} = 350 \text{ MHz}$ .

Thus, we set the amplifier gain to 26 dB with  $R_f = 1 \text{ k}\Omega$  and  $R_g = 50 \Omega$  for negative feedback, as shown in Fig. 2(a). According to the LMH6629 datasheet [?], we calculated the preamplifier bandwidth to be 428 MHz. With a standard load resistance  $R_s = 50 \Omega$ , the preamplifier provides a current gain of 1050 V/A for current signals output from the SiPM.

The equivalent noise at the preamplifier input can be calculated according to Ref. [?] as:

$$e_{\text{ni}} = \sqrt{[e_n^2 + (i_n R_s)^2 + 4kTR_s + [i_n(R_f||R_g)]^2 + 4kT(R_f||R_g)]}$$

where  $e_n$  and  $i_n$  are the intrinsic input voltage and current noise, respectively;  $k$  and  $T$  are the Boltzmann constant and temperature. The LMH6629 is an ultra-low noise operational amplifier with  $e_n = 0.69 \text{ nV}/\sqrt{\text{Hz}}$  and  $i_n = 2.6 \text{ pA}/\sqrt{\text{Hz}}$ . We calculated the equivalent input noise to be  $e_{\text{ni}} = 1.41 \text{ nV}/\sqrt{\text{Hz}}$ . By integrating  $e_{\text{ni}}$  over the bandwidth, the preamplifier baseline noise level is  $\sigma_{\text{noise}} = 587 \mu\text{V}$ .

An LTspice simulation [?] yielded a -3 dB bandwidth of 417 MHz and noise level of  $\sigma_{\text{noise}} = 517 \mu\text{V}$ , consistent with calculations. We also measured the frequency characteristics using an N5222B network analyzer from 10 MHz to 1 GHz, obtaining a -3 dB bandwidth of 426 MHz for small signals (200 mVpp) and 240 MHz for large signals (2 Vpp).

To suppress power supply noise and improve amplifier reliability, we designed a four-layer PCB with all components placed close to the LMH6629 to minimize connection lengths. We also employed ultra-high PSRR, ultra-low noise regulators—the LT3045 positive regulator and LT3094 negative regulator—to reduce power supply ripple, as shown in the inset of Fig. 2(b).

## B. PZC to Reduce Pile-up

According to Eq. (1), the fast component of the falling edge  $\tau_{\text{fast}}\{\text{fall}\}$  is primarily determined by the load resistance  $R_s$ . For certain high-gain, large-area SiPMs such as the Hamamatsu MPPC S13360-6025PE [?], the terminal capacitance  $C_{\text{tot}}$  is 1280 pF. With  $R_s = 50 \Omega$ ,  $\tau_{\text{fast}}\{\text{fall}\}$  is approximately 64 ns, making the total  $\tau_{\text{fall}}$  significantly longer and potentially causing pile-up in SiPM-based detectors.

Implementing PZC in the preamplifier circuit effectively reduces  $\tau_{\text{fall}}$  and avoids signal pile-up by attenuating low-frequency components in the output signal. PZC also reduces  $\tau_{\text{rise}}$ , which is beneficial for improving time resolution according to Eq. (2). Figure 3 Figure 3: see original paper shows the PZC implementation in the preamplifier. The PZC transfer function in the frequency domain is:

$$V_{\text{out}}(s) = (s + \tau_{\text{f}}^{-1}) / (s + \tau_{\text{1}}^{-1}) \cdot (s + \tau_{\text{2}}^{-1}) / (s + \tau_{\text{f}}^{-1}) \cdot V_{\text{max}}$$

where  $V_{\text{max}}$  is the maximum output signal amplitude,  $\tau_{\text{f}} = R_{\text{q}} C_{\text{d}}$ ,  $\tau_{\text{1}} = R_{\text{1}} C_{\text{1}}$ , and  $\tau_{\text{2}} = R_{\text{1}} R_{\text{2}} C_{\text{1}} / (R_{\text{1}} + R_{\text{2}})$ . Signal cancellation occurs when  $\tau_{\text{1}} = \tau_{\text{f}}$ , changing the output signal decay time to  $\tau_{\text{2}}$  ( $\tau_{\text{2}} < \tau_{\text{1}}$ ).

LTspice simulations show that the output impedance after the PZC network is no longer a constant  $50 \Omega$  and the signal amplitude is reduced. To compensate for gain loss and ensure  $50 \Omega$  output impedance, we use a two-stage amplifier after the PZC, as shown in Fig. 3(a). To demonstrate PZC's effect on signal shape, we used a DT5810B [?] to simulate SiPM signals with  $\tau_{\text{rise}} = 3 \text{ ns}$  and  $\tau_{\text{fall}} = 50 \text{ ns}$ , inputting them to the designed preamplifiers. A Tektronix MDO3024 oscilloscope captured the input and output waveforms, as shown in Fig. 3(b). Output signals without PZC have nearly the same  $\tau_{\text{rise}}$  and  $\tau_{\text{fall}}$  as the input signals. Signals after PZC (without the two-stage amplifier) show  $\tau_{\text{rise}} = 1.2 \text{ ns}$  and  $\tau_{\text{fall}} = 20 \text{ ns}$ —significant improvement, though with reduced amplitude. Signals from the preamplifier with the two-stage amplifier after PZC maintain the improved  $\tau_{\text{rise}}$  and  $\tau_{\text{fall}}$  while showing significantly larger amplitudes. The  $\tau_{\text{rise}}$  improvement is crucial for good time resolution,

and a short  $\tau_{\text{fall}}$  is important for avoiding pile-up in detector operation.

Another test studied PZC's effect on pile-up. We used a picosecond-level laser MDL-PS-450 [?] as the light source, tuning its frequency from 0.8 MHz to the maximum 20 MHz. Photons from the laser were detected by two SiPMs connected in parallel to preamplifiers with and without PZC. Figure 3(c) shows the oscilloscope signals. The  $\tau_{\text{fall}}$  from the preamplifier without PZC is approximately 200 ns, with pile-up appearing at laser frequencies around 2 MHz. With PZC implemented,  $\tau_{\text{fall}}$  reduces to approximately 5 ns, with no pile-up even at 20 MHz laser frequency. This test demonstrates that PZC significantly reduces pile-up in high-rate environments.

### III. Performance of the Preamplifier

To apply this preamplifier in experiments such as the potential upgraded KLM in Belle II, we characterized its performance including gain stability, output signal dynamics, noise level, and single photoelectron signal measurement. Based on these results, we then studied the time resolution of combined preamplifier-SiPM systems.

#### A. Linearity Between Input and Output Signals

With  $R_f = 1 \text{ k}\Omega$  and  $R_g = 50 \text{ }\Omega$  as shown in Fig. 2, we calculated the preamplifier gain to be +21 V/V. We used a DT5810B [?] to generate SiPM-like pulses with  $\tau_{\text{rise}} = 1 \text{ ns}$  and  $\tau_{\text{fall}} = 50 \text{ ns}$ , with amplitudes from 2 mV to 80 mV as input signals. A Tektronix MSO58 oscilloscope measured the output signals to study linearity. The tests yielded an ideal, stable Gaussian gain distribution. Fitting with a Gaussian function gave a mean of 21 and  $\sigma = 0.087 \pm 0.002$ , demonstrating excellent gain stability. To study the dynamic range, input signal amplitudes were extended from 80 mV to 200 mV. A good linear relationship was observed between input and output signals across a wide dynamic range. When the preamplifier supply voltage ( $V_{\text{bias}}$ ) increased from 2.5 V to 3.9 V, the maximum input signal amplitude maintaining linear gain increased from 90 mV to 170 mV, with corresponding output amplitudes from 0.9 V to 1.7 V. The gain of 10 in these tests is due to the 50  $\Omega$  impedance of the oscilloscope, which was set to full bandwidth (2 GHz) and 50  $\Omega$  input impedance.

#### B. Noise Level of the Baseline

According to Eq. (2), time resolution depends heavily on the output signal noise level, which is determined primarily by the preamplifier baseline and SiPM noise. An MSO58 oscilloscope with 2 GHz sampling rate measured the baseline over a 3000 ns interval, with amplitudes projected onto a one-dimensional histogram. The distribution was fit with a Gaussian function, with  $\sigma$  representing the baseline noise level. The preamplifier baseline noise measured without SiPM was  $\sigma$

= 302  $\mu\text{V}$ . With the oscilloscope's 50  $\Omega$  input impedance, the actual preamplifier noise level is  $\sigma_{\text{noise}} = 604 \mu\text{V}$ , consistent with calculations and simulations.

We also measured baseline noise levels for preamplifiers coupled to different SiPM types from NDL (Beijing) [?, ?] and Hamamatsu [?, ?], as listed in Table 1. These noise levels include SiPM contributions and must be accounted for in time resolution calculations per Eq. (2). As noted, the noise levels in Table 1 are half the actual values due to the oscilloscope's 50  $\Omega$  input impedance. Generally, baseline noise increases with terminal capacitance and  $N_{\text{pixel}}$ . For large SiPMs,  $N_{\text{pixel}}$  can reach  $10^4$  levels with dark count rates in the MHz range, resulting in relatively high baseline noise.

### C. Measurement of a Single Photoelectron

A typical SiPM measurement is the single photoelectron peak spectrum, which characterizes SiPM performance. From the gain and resolution of a single photoelectron, we can estimate the number of photoelectrons (or fired SiPM pixels) based on signal pulse height. We measured single photoelectron signals by combining SiPMs with the preamplifier as a basis for further measurements, such as time resolution versus photoelectron number.

Initial measurements were performed with S13360-1325CS, S13360-1350CS, and S13360-1375CS, which share a 1.3 mm  $\times$  1.3 mm photosensitive area but have different pixel sizes of 25  $\mu\text{m}$ , 50  $\mu\text{m}$ , and 75  $\mu\text{m}$  [?], respectively, as listed in Table 1. Figure 4 Figure 4: see original paper shows the single photoelectron pulse shapes, with  $\tau_{\text{rise}} < 1 \text{ ns}$  and amplitudes  $> 10 \text{ mV}$ . However, the 1.3 mm  $\times$  1.3 mm photosensitive area is often too small for efficient photon collection in detectors. Our R&D for the KLM upgrade concluded that large SiPMs or multiple SiPM combinations are needed for good time resolution, such as the 13360-6025PE from Hamamatsu [?] with a 6.0 mm  $\times$  6.0 mm photosensitive area. Figure 4(b) shows a typical single photoelectron signal from 13360-6025PE and the average of many signals captured by an oscilloscope, yielding  $\tau_{\text{rise}} \approx 3 \text{ ns}$ —larger than small SiPMs due to the 13360-6025PE's large capacitance. For a small-gain amplifier, we achieved  $\tau_{\text{rise}} \approx 2 \text{ ns}$  in our tests. All tests were conducted under weak light conditions. We also established an LTspice SiPM circuit model for 13360-6025PE and simulated single photoelectron signals with the preamplifier or an ideal amplifier. Simulation and measured pulse results showed excellent agreement, as shown in Fig. 4(b).

## IV. Time Resolution Achieved from the Combination of the Preamplifier and SiPM

Time resolution is one of the most important characteristics of certain detectors. For scintillation detectors using SiPMs as photosensors, time resolution is determined by the scintillator material, SiPM, and front-end readout with the preamplifier.

To determine the preamplifier's time resolution, we used a DT5810B to generate pulse signals with different amplitudes, inputting them into two parallel preamplifiers. A Tektronix MSO58 oscilloscope digitized and saved output waveforms, with arrival times determined via constant-fraction discrimination (CFD) in off-line analysis. From the time difference distribution between the two parallel preamplifiers, we obtained the standard deviation  $\sigma$  and considered  $\sigma/\sqrt{2}$  as the time resolution of a single preamplifier. Figure 5 [Figure 5: see original paper] shows time resolution versus input signal amplitude. With  $\tau_{\text{rise}} = 2$  ns set for the DT5810B, the preamplifier achieved approximately 20 ps time resolution for input signals  $> 20$  mV, and 30–50 ps for small signals of 5–10 mV. Figure 5(a) shows that time resolution degrades as  $\tau_{\text{rise}}$  increases. As discussed in Section II B, PZC can reduce  $\tau_{\text{rise}}$ , which is highly beneficial for time resolution. We set  $\tau_{\text{rise}} = 7.5$  ns and compared preamplifiers with and without PZC. Figure 5(b) shows their time resolutions versus input amplitude. Despite output amplitude reduction from PZC, the improved  $\tau_{\text{rise}}$  yielded better time resolution. For example, with 20 mV input signals, time resolution improved from 50 ps to 25 ps with PZC implementation.

We combined our preamplifier with SiPMs to determine photon detection time resolution. Using a picosecond-pulsed laser MDL-PS-450 [?] as the light source, the test setup and results are shown in Fig. 6 [Figure 6: see original paper]. Two SiPMs detected laser photons and were connected to two preamplifiers, as shown in Fig. 6(a). We measured signal amplitude and arrival time for both channels, determining time resolution from their time difference distribution. Time resolution depends strongly on the number of detected photons. Based on measured signal amplitude and single photoelectron amplitude from Section III C, we estimated the number of photons detected (or fired pixels). Studies with small SiPMs (EQR10-11-1010 from NDL and S13360-1350 from Hamamatsu) showed similar performance, as shown in Fig. 6(b). With approximately five detected photons, time resolutions were 40–50 ps, improving to approximately 25 ps when photon numbers exceeded 40. Studies with large SiPMs (EQR15-11-6060 from NDL and S14160-6050 from Hamamatsu [?], both 6.0 mm  $\times$  6.0 mm) showed similar performance with  $>60$  photons, achieving time resolutions better than 25 ps, as shown in Fig. 6(b). With low photon numbers, S14160-6050 outperformed EQR15-11-6060 due to its significantly lower dark count rate and higher gain.

## V. Comparison with Some Commercial Preamplifiers

We compared our preamplifier with commercial SiPM preamplifiers including the Hamamatsu C12332-02 [?], NDL AMP-20-2 [?], and Cremat CR-Z-SiPM [?].

1. Commercial preamplifiers are one- or two-channel devices measuring approximately 5 cm, 10 cm, or 15 cm in size, whereas our 8-channel array shown in Fig. 2(b) is only about 10 cm long. Based on the schematic in Fig. 2(a), we can further improve the design for significantly higher

integration when implementing hundreds or thousands of SiPM channels in large detectors.

2. According to datasheets, C12332-02 has 200 MHz bandwidth at -20 V/V gain, and AMP-20-2 has 350 MHz bandwidth at -10 V/V gain. Testing demonstrates our preamplifier achieves approximately 426 MHz bandwidth. The CR-Z-SiPM is a charge-sensitive preamplifier unsuitable for fast signal amplification.
3. Our preamplifier offers superior noise performance, with a measured baseline noise level of approximately 0.6 mV—nearly 80% lower than that of AMP-20-2.
4. Figure 5 demonstrates our preamplifier’s excellent time resolution.
5. The Hamamatsu C12332-02 uses OPA846 as its core amplifier, while our LMH6629-based design shows better performance in bandwidth, slew rate, and noise level.
6. Our preamplifier cost per channel is approximately two orders of magnitude lower than commercial products.

Note that this preamplifier design aims to enable implementation of tens of thousands of SiPM channels in sub-detectors for the potential Belle II upgrade or CEPC experiment, requiring excellent performance. Therefore, we focused on simple design, high integration, high time resolution, large bandwidth, large dynamic range, low noise, and low cost.

## VI. Summary

Motivated by R&D for the Belle II KLM upgrade and CEPC muon detector, we designed a compact, high-speed, low-noise preamplifier for SiPMs. The preamplifier achieves 426 MHz bandwidth, 0.6 mV baseline noise level, <1 mV total noise with various SiPMs, large dynamic range (up to 170 mV input), and very fast  $\tau_{\text{rise}}$  for excellent time resolution. *PZC proves highly effective for improving both  $\tau_{\text{rise}}$  and  $\tau_{\text{fall}}$  of SiPM signals, significantly enhancing time resolution and reducing pile-up with large SiPMs or arrays. The preamplifier alone achieves better than 20 ps time resolution. Combined with various SiPMs, time resolutions better than 50 ps are demonstrated; with large photon numbers, 25 ps resolution is achieved. This preamplifier’s excellent performance will facilitate Belle II KLM upgrades for measuring neutral hadron hit times ( $K^0_L$  or neutrons) based on hadronic clusters in the detector.*

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