New method of out-of-time energy subtraction for the CMS hadronic calorimeter

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on behalf of the CMS collaboration

CALOR
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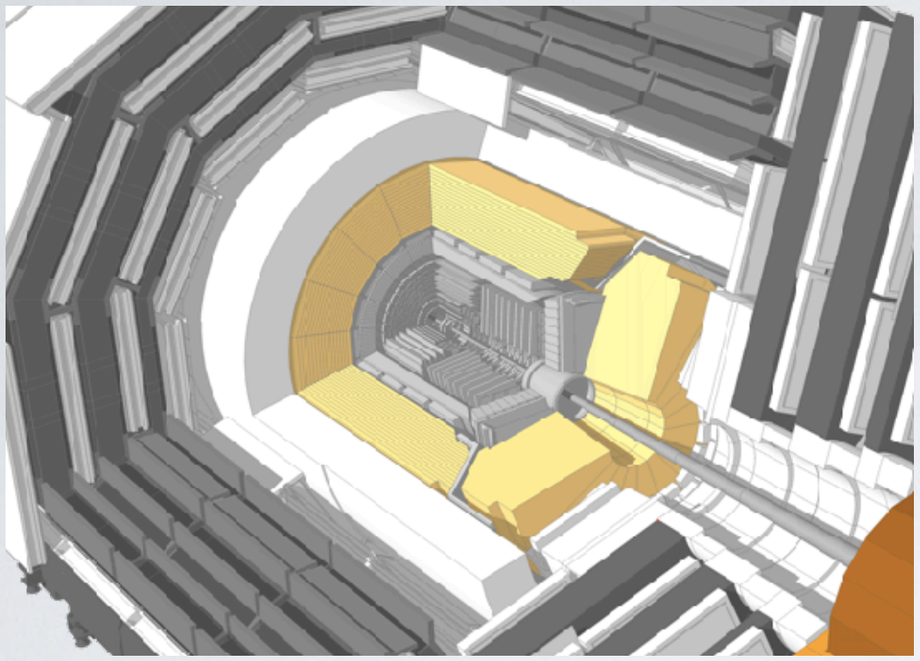
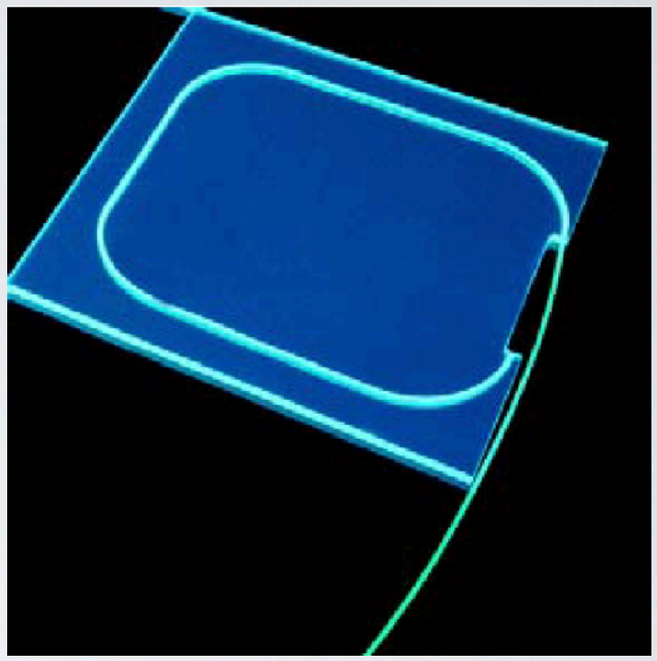
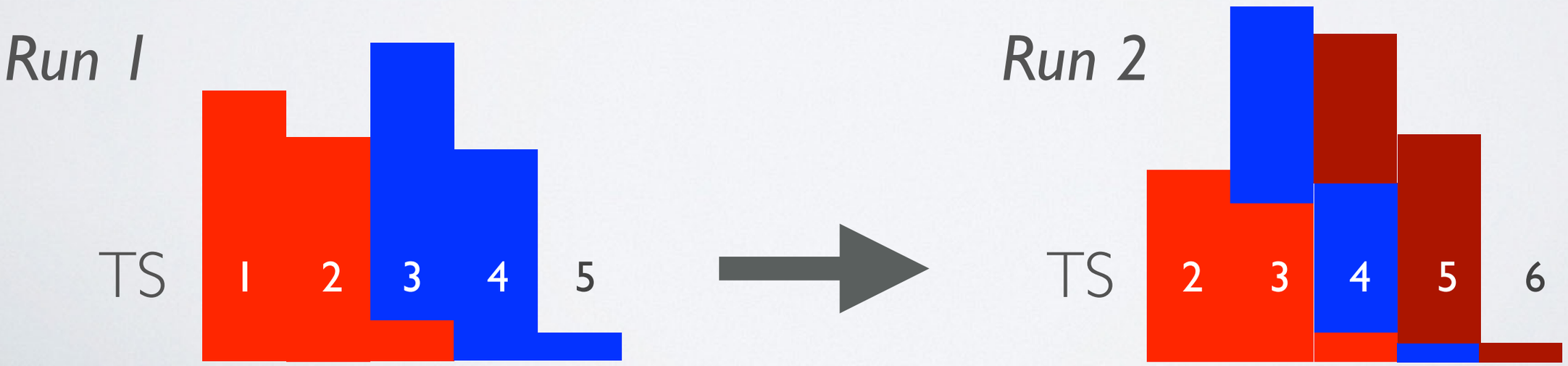
Hadronic Barrel and Endcap Calorimeters



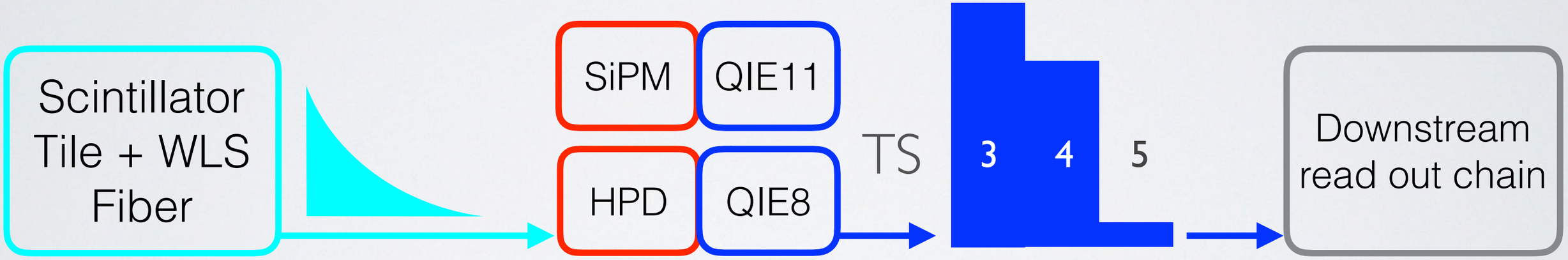


- LHC Run 2 (2015-2018) bunch spacing is 25 ns
- HB/HE response is 65% contained in 25 ns, and 90% contained in 50 ns
  - Dominated by plastic scintillator + WLS fiber response time



HB/HE readout chain

- Plastic scintillator + WLS fiber
- Optical readout by silicon photomultipliers (upgraded HE) or hybrid photodiodes
- Signal integrated and digitized at 40 MHz by QIE11 (upgraded HE) or QIE8
  - Introduces significant pulse shaping, including "time slew"



- Store 8 time slices (25 ns each) with bunch crossing of interest in 4th time slice
- Local reconstruction goal: work backwards from digitized QIE8/11 output to in-time energy deposit

Pulse shape measurements

- Pulse shape with HPD readout measured in test beams in 2004-2006 [*]
  - Does not accurately reproduce in situ pulses

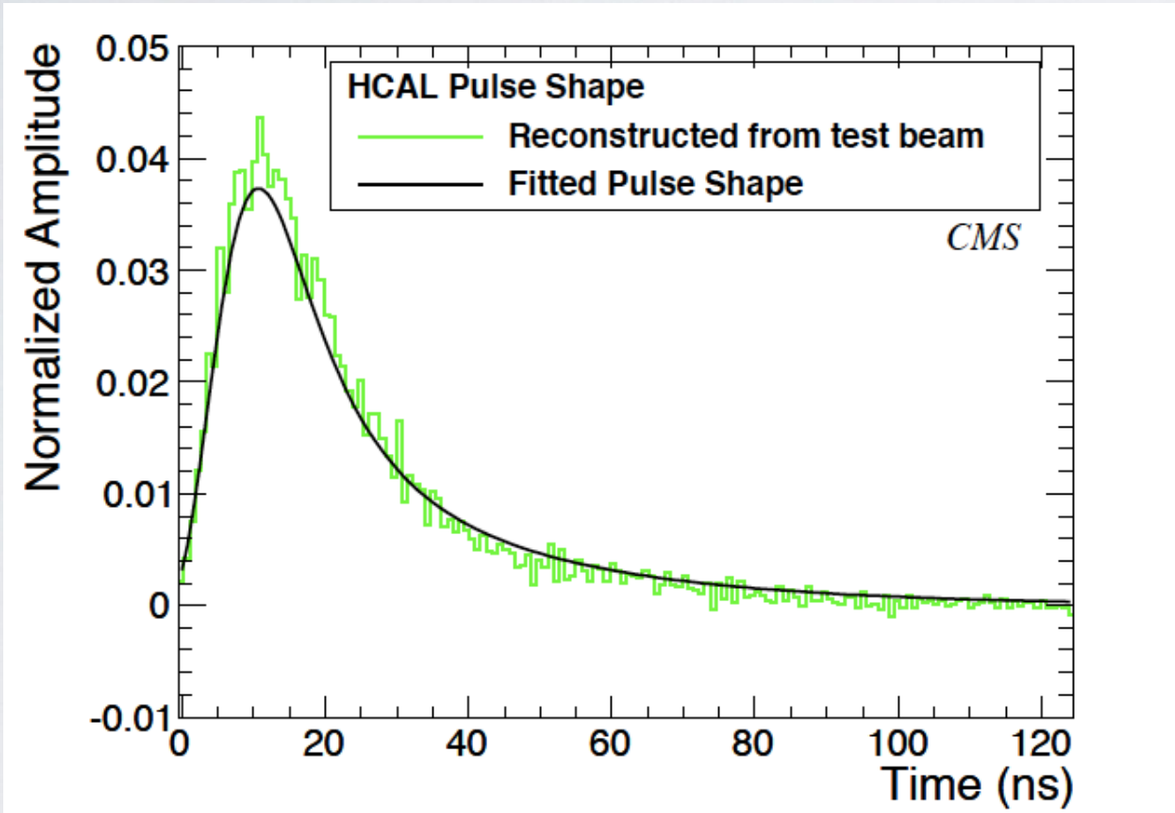


Figure 5: Average pulse shape reconstructed for the HCAL from H2 beam test data using 300 GeV pions.

- **New! QIE11 time-to-digital converter (TDC)** allows for in situ pulse measurements with Phase 1 readout
  - 500 ps resolution on rising edge

- First in situ measurement from 2017 HE pilot wedge HEP17

- Today: updated measurement from fully upgraded HE in 2018 data

[*] https://doi.org/10.1088/1748-0221/5/03/T03013

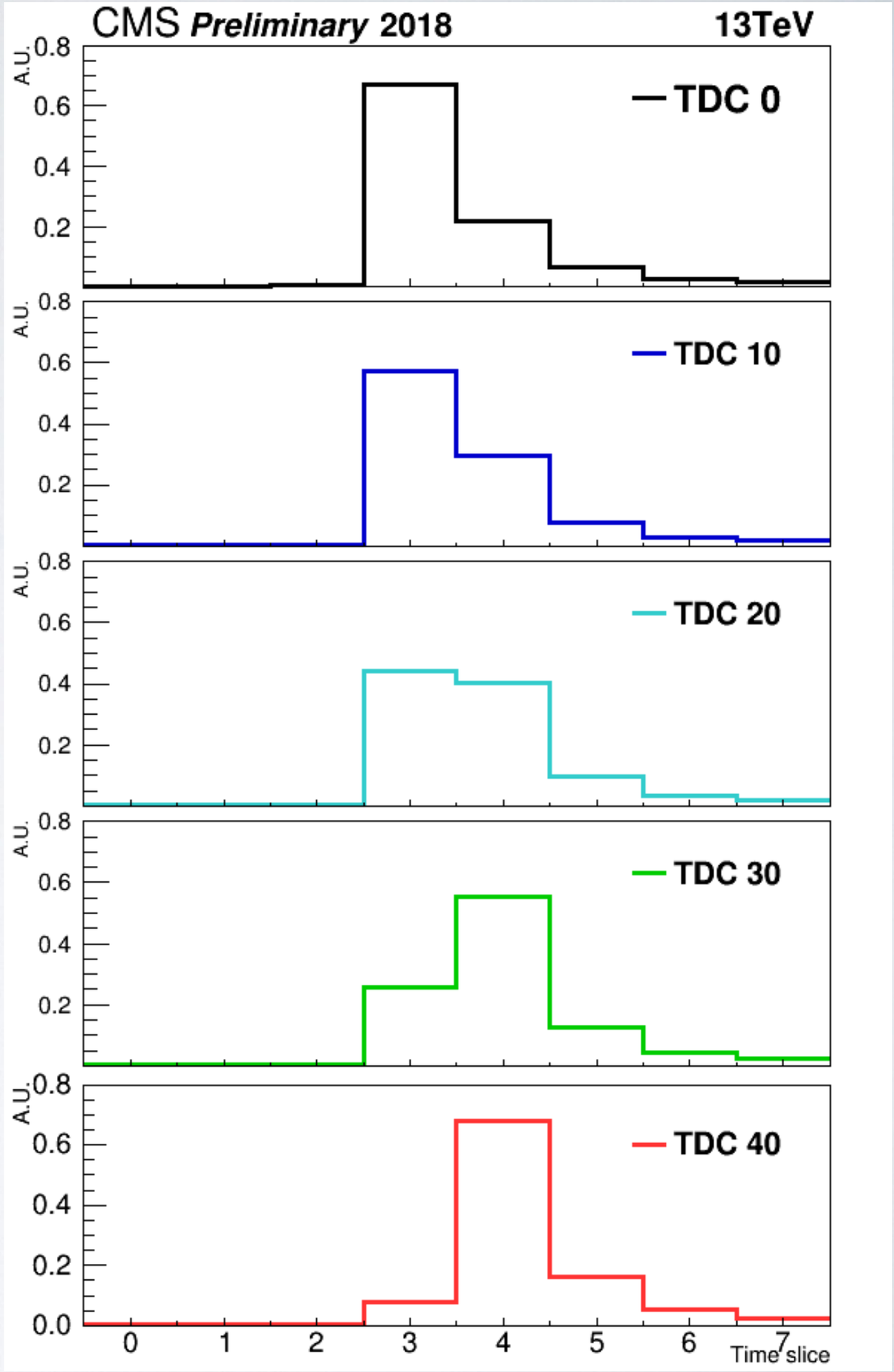
On-detector phase scan

- During LHC commissioning phase, delivers lone bunch collisions (3+ μs spacing)

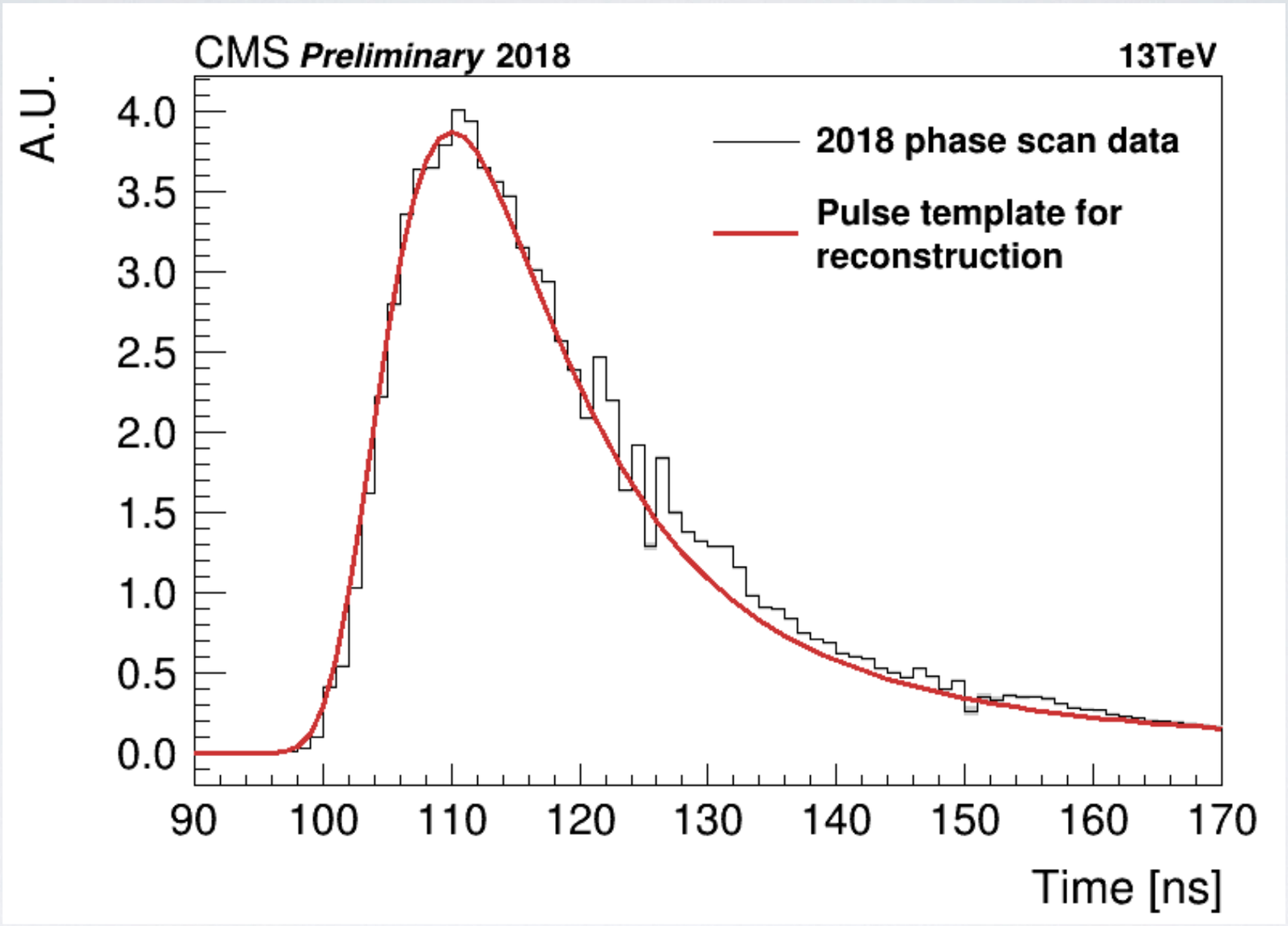
- Scan QIE offset for 25 ns integration window with respect to external clock in 1 ns steps
  - In normal operations, QIE phases set to align channels

- Select hits with total charge in 8 TS greater than 30 pC

- Bin according to TDC value, and compute average pulse shape



2018 HE SiPM pulse shape measurement

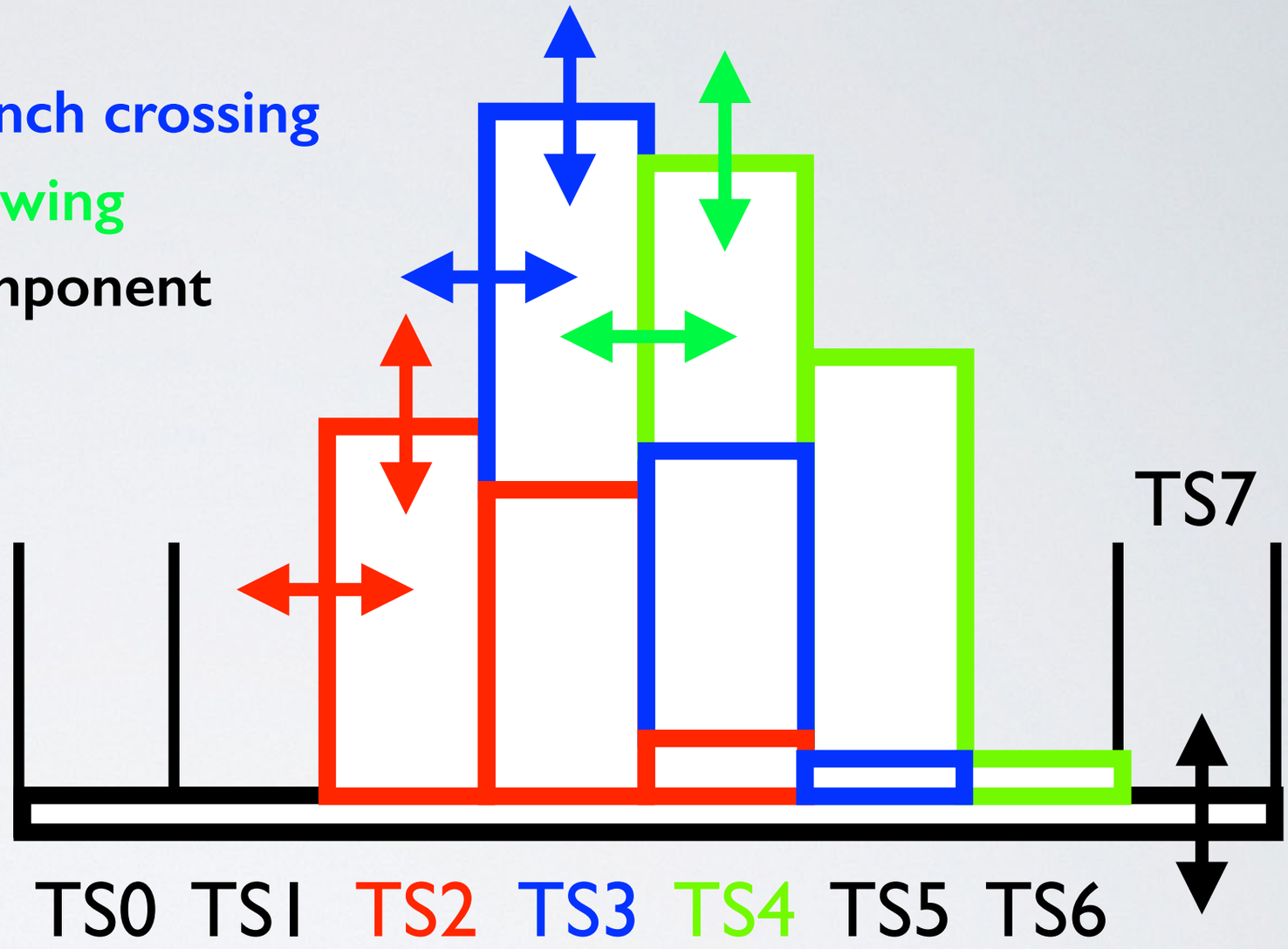


- Overlaid pulse template is Landau fitted to 2017 phase scan

- In situ pulse shape measurement with the full readout chain: scintillator tiles, Y11 wavelength-shifting fibers, SiPM optical readout, and QIE11 integration and digitization.

HB/HE out-of-time pileup mitigation

- Fit for up to three pulses in **bunch crossing of interest**, **previous**, and **following** crossings and **flat baseline component**
  - Using non-negative least squares optimization algorithm



- Write template fit as

$$\chi^2 = \underbrace{\left(\sum A_i \mathbf{p}_i - \mathbf{TS}\right)^{\mathrm{T}}}_{\text{Residual term}} \underbrace{\left(\boldsymbol{\Sigma}_{\mathbf{d}} + \sum A_i^2 \boldsymbol{\Sigma}_{\mathbf{p_i}}\right)^{-1}}_{\text{Covariance matrix}} \underbrace{\left(\sum A_i \mathbf{p}_i - \mathbf{TS}\right)}_{\text{Residual term}}$$

Pulse shape template fit

$$\chi^2 = \left(\sum A_i \mathbf{p}_i - \mathbf{TS}\right)^{\mathrm{T}} \left(\mathbf{\Sigma_d} + \sum A_i^2 \mathbf{\Sigma_{p_i}}\right)^{-1} \left(\sum A_i \mathbf{p}_i - \mathbf{TS}\right)$$

Residual term — Covariance matrix — Residual term

- A_i : fitted pulse amplitudes
- p_i : energy-dependent pulse shape templates
- TS : observed data

- **Σ_d : dark noise term, including**
  - electronic noise
  - ADC granularity
  - photo-statistics
  - dark current (SiPM-only)

- **Σ_{pi} : pulse shape uncertainty…**

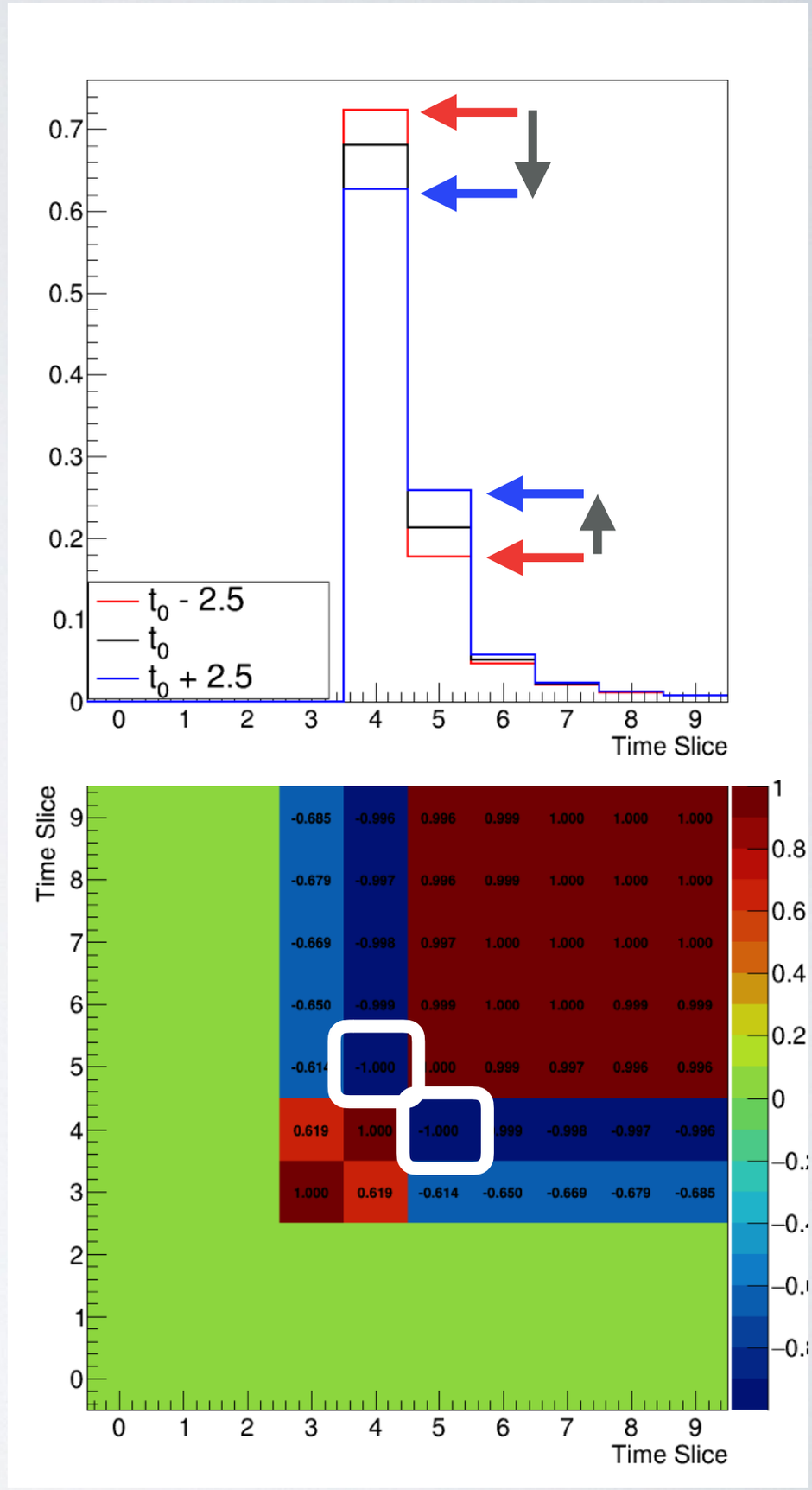
Signal model

$$\left(\boldsymbol{\Sigma_d} + \sum A_i^2 \boldsymbol{\Sigma_{p_i}}\right) \left(\sum A_i \mathbf{p}_i - \mathbf{TS}\right)$$

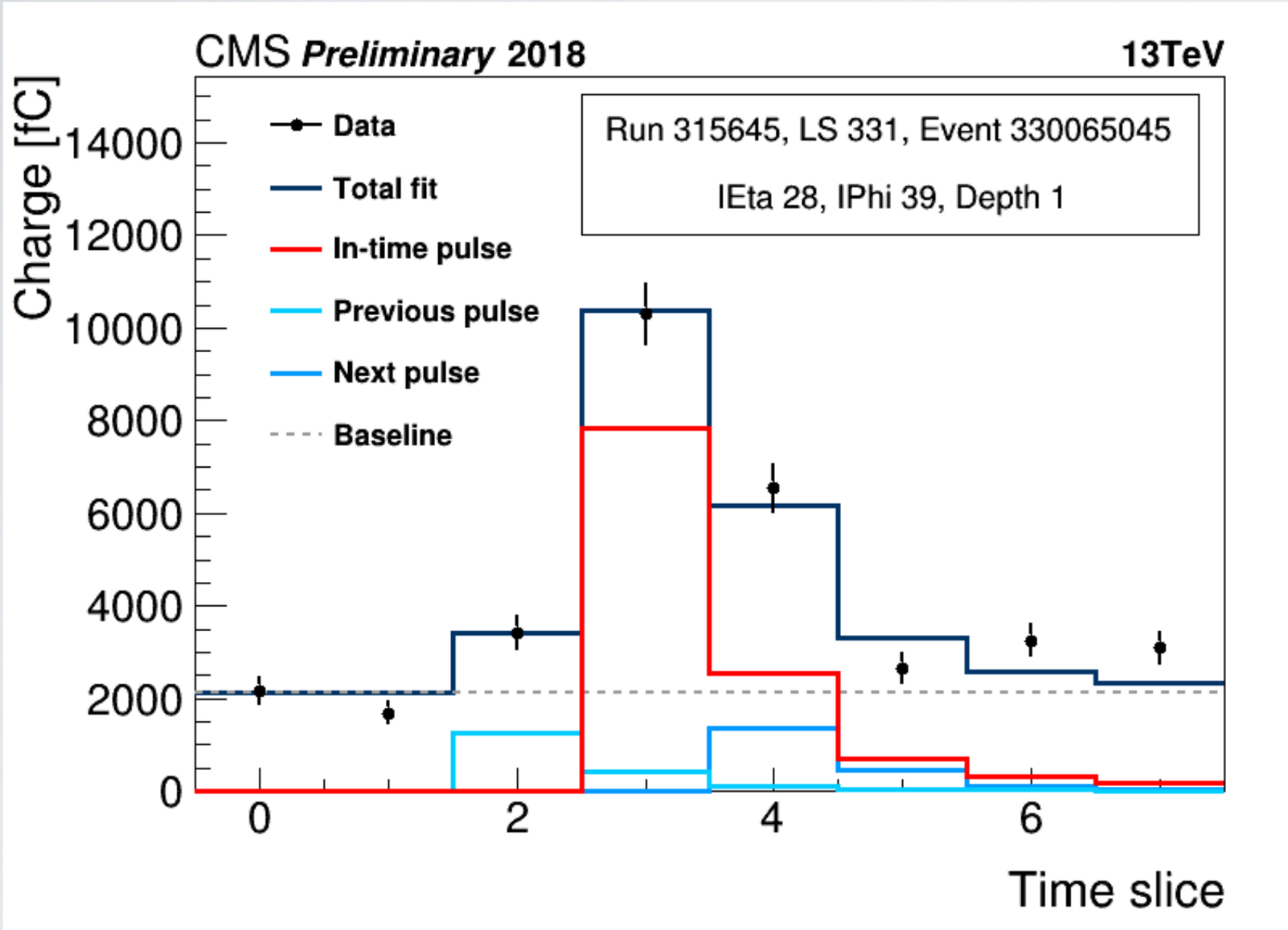
- Nominal pulse shape templates (including time slew model) and uncertainties are modeled as variable arrival time

- Build covariance matrix by shifting the template forward and backwards in time by 1σ variation
  - 2.5 ns for SiPM, 5.0 ns for HPD

- Covariance matrix encodes relative behavior of pulse shape as it is shifted



Example of single channel reconstruction in 2018 HE



- **Data uncertainties** include electronic noise, photo-statistical, and ADC granularity components

- **The red distribution is the in-time pulse (goes to downstream event reconstruction)**

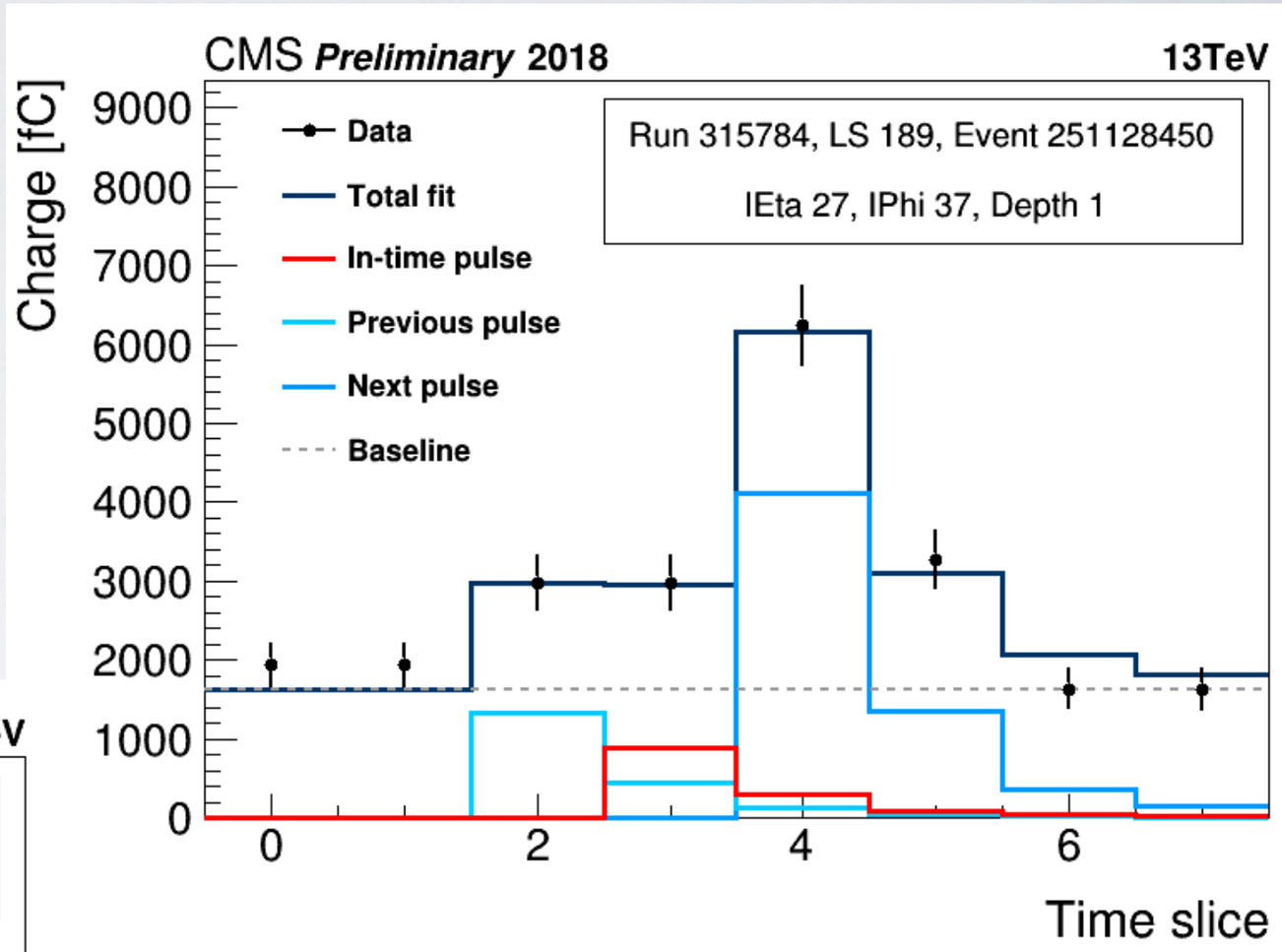
- **Light blue distributions are fitted out-of-time pulses**

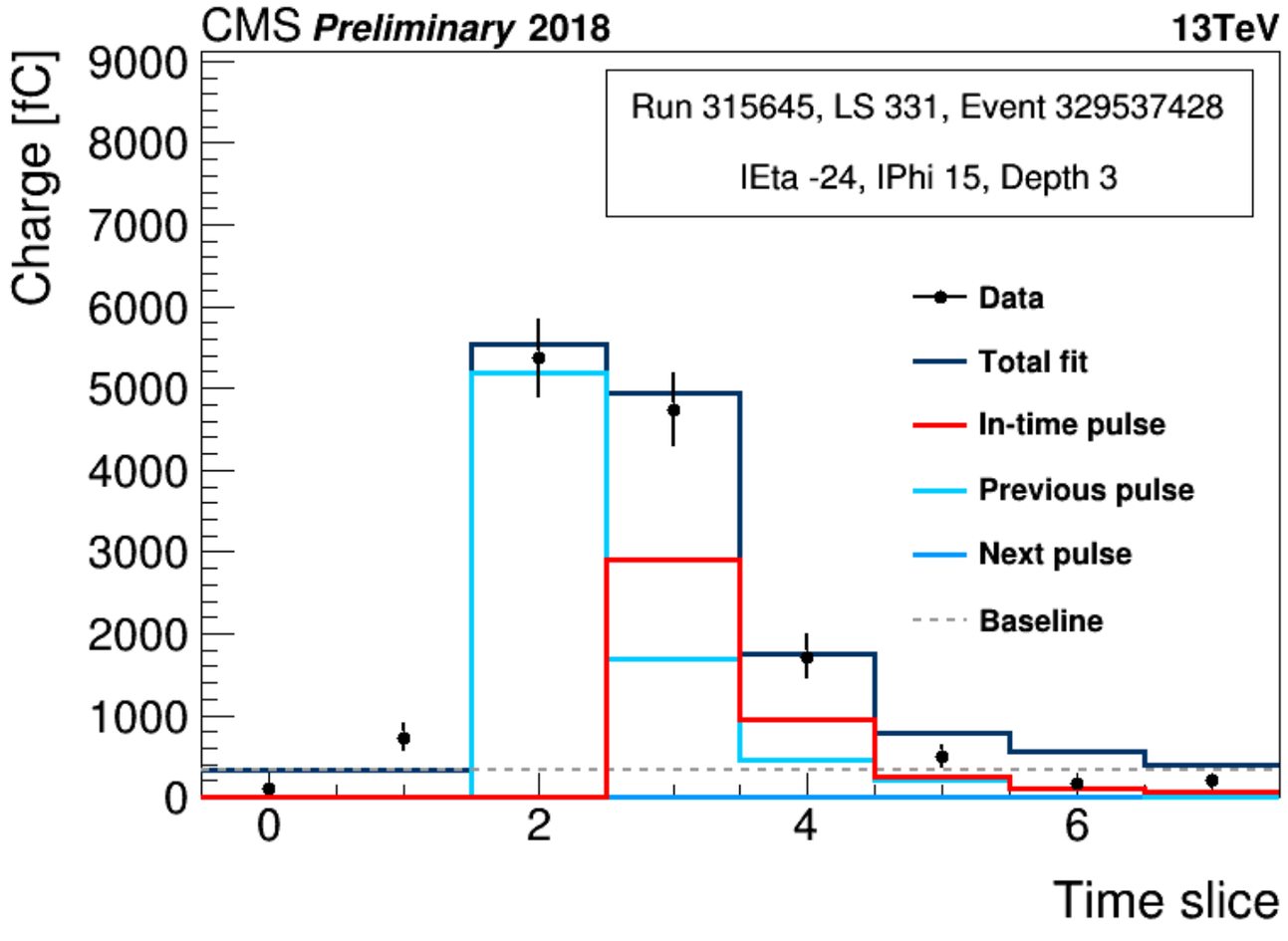
- Grey dashed line is the fitted baseline value

- **Dark blue distribution is total fit, including all four components**

Examples of single channel reconstruction in 2018 HE

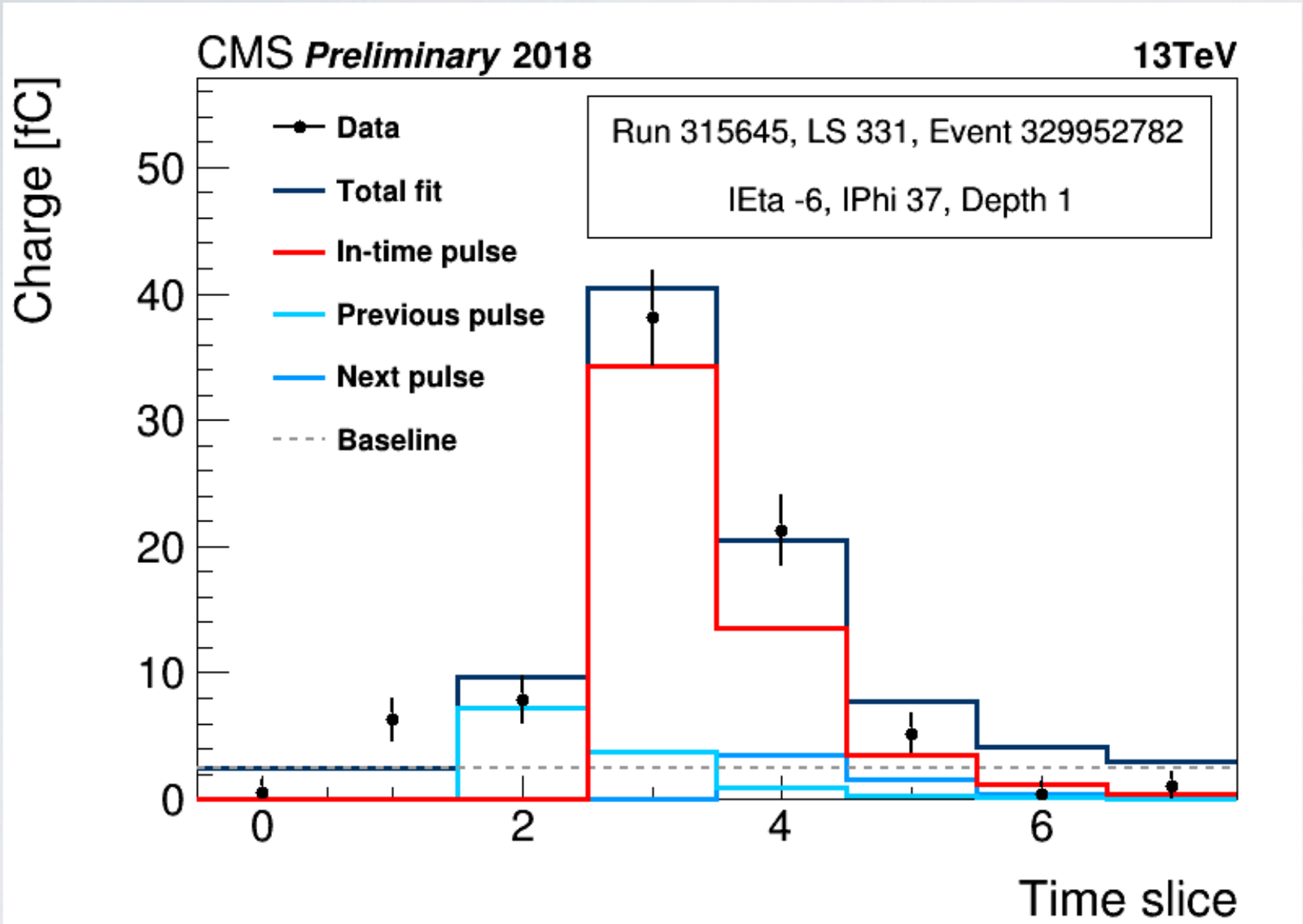
- Also get reasonable results for pulses in next or previous collisions





- **The red distribution is the in-time pulse (goes to downstream event reconstruction)**

Example of single channel reconstruction in 2018 HB

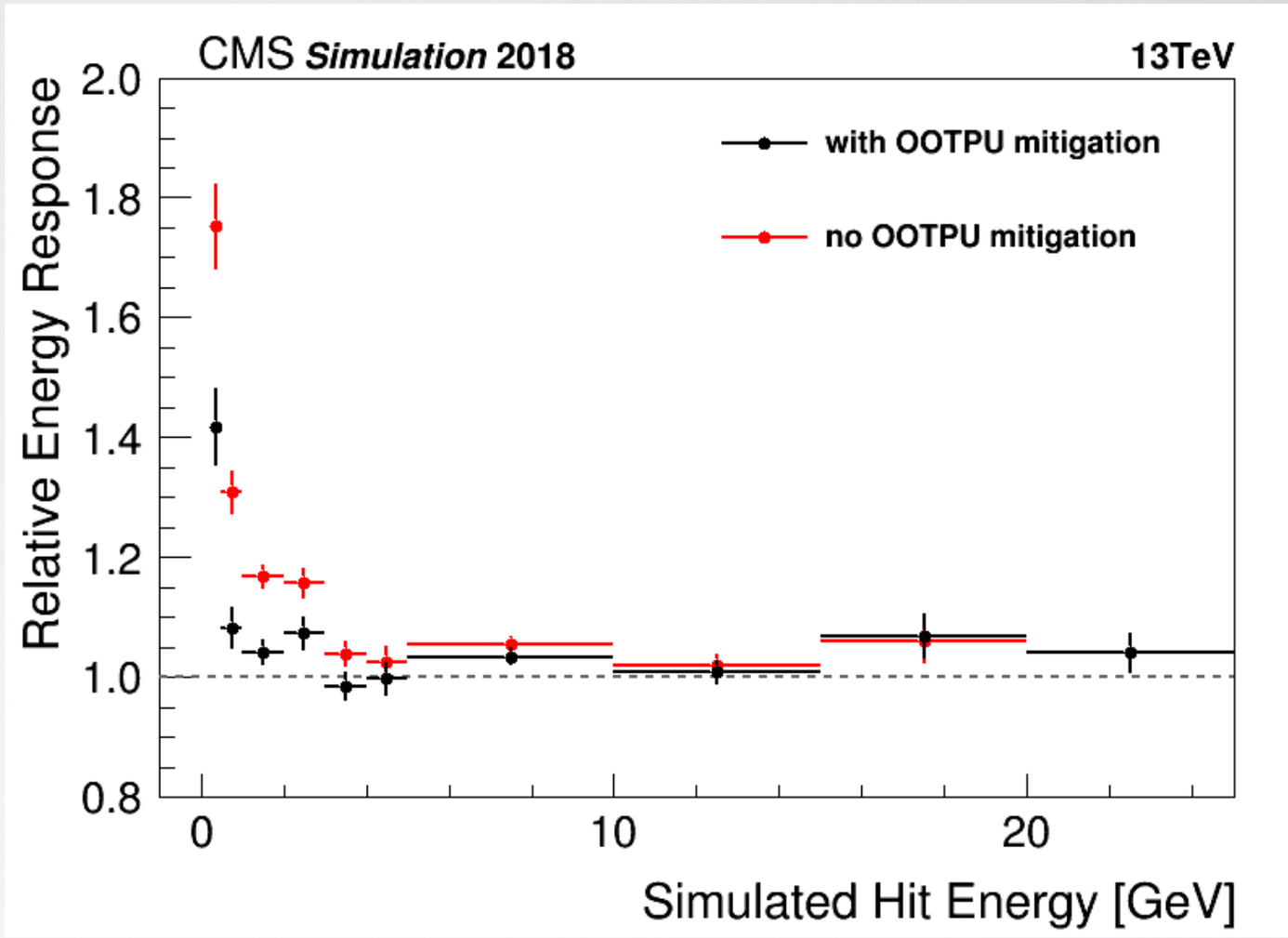


- **The red distribution is the in-time pulse (goes to downstream event reconstruction)**

- *Difference in charge scale because of differences in photo-detection efficiency and amplification*

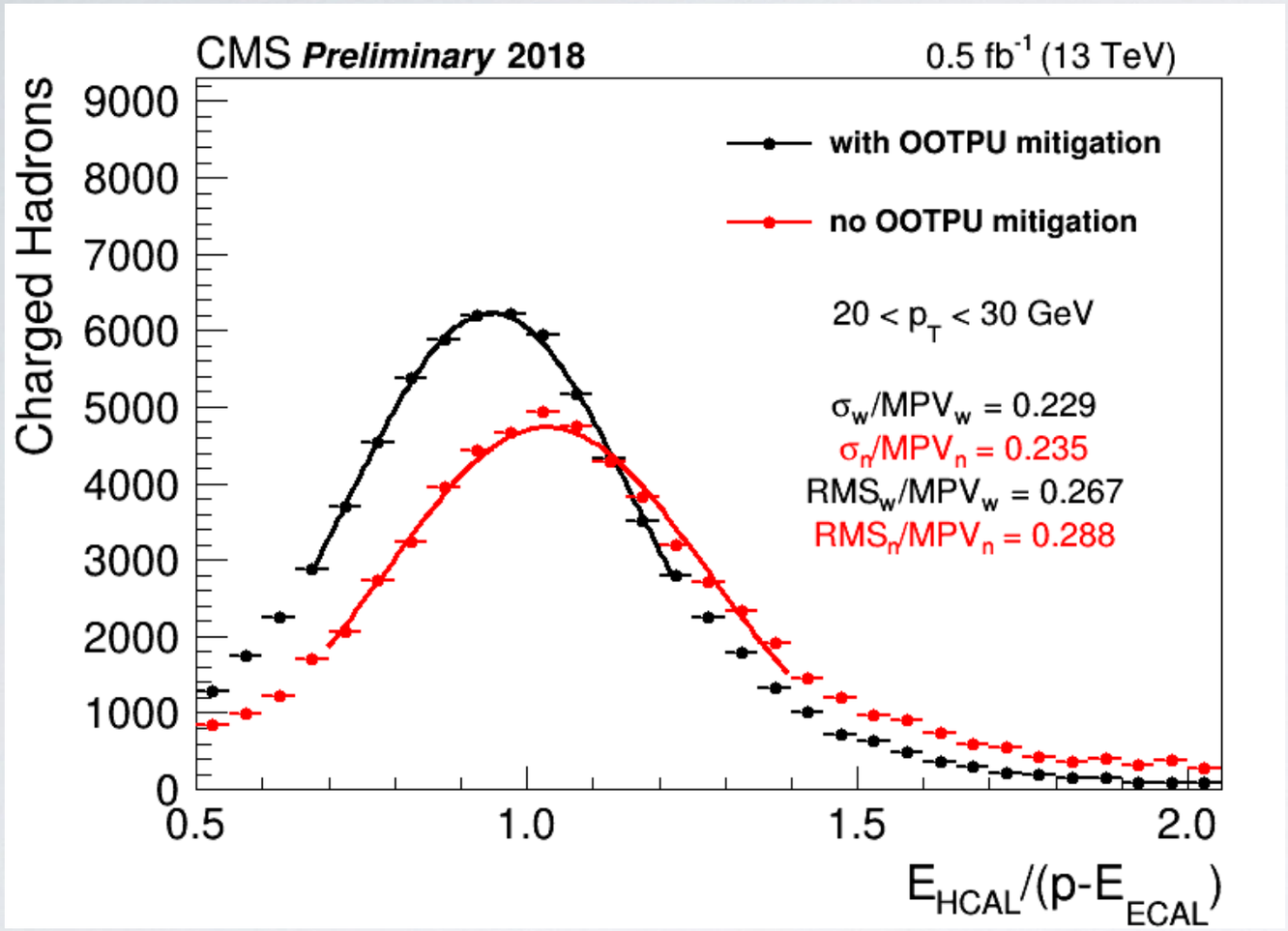
Relative energy response (Simulation)

- Single pion simulation, flat in energy between 50 and 100 GeV, in two conditions
  - 50 PU@25 ns bunch spacing
  - No PU
- **Relative energy response** is response (reconstructed hit energy over simulated hit energy) in the 50 PU@25 ns scenario divided by the no PU response



- Higher relative energy response indicates higher pileup contamination
- OOTPU mitigation gives up to 25% reduction in pileup contamination for lowest simulated energy bin (200 MeV to 500 MeV) — important regime for isolation calculations

Charged hadron resolution

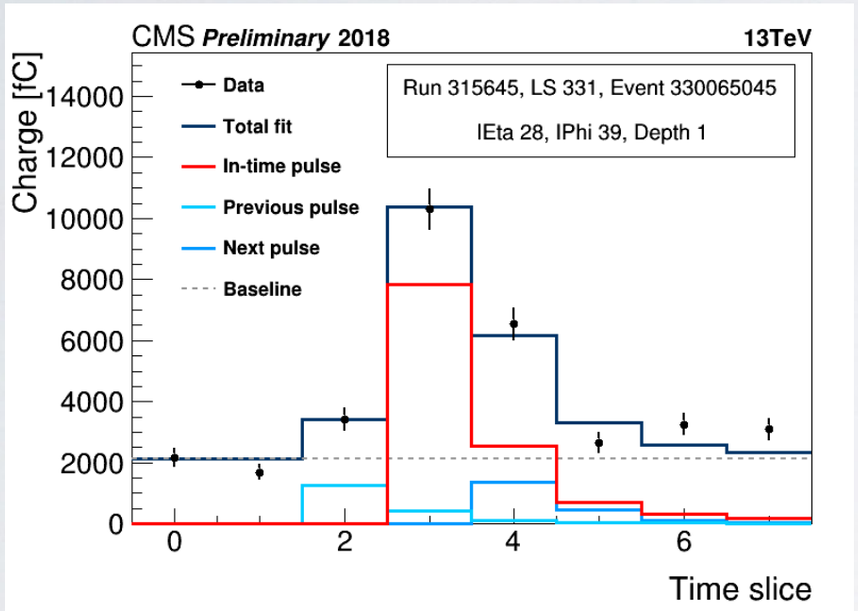


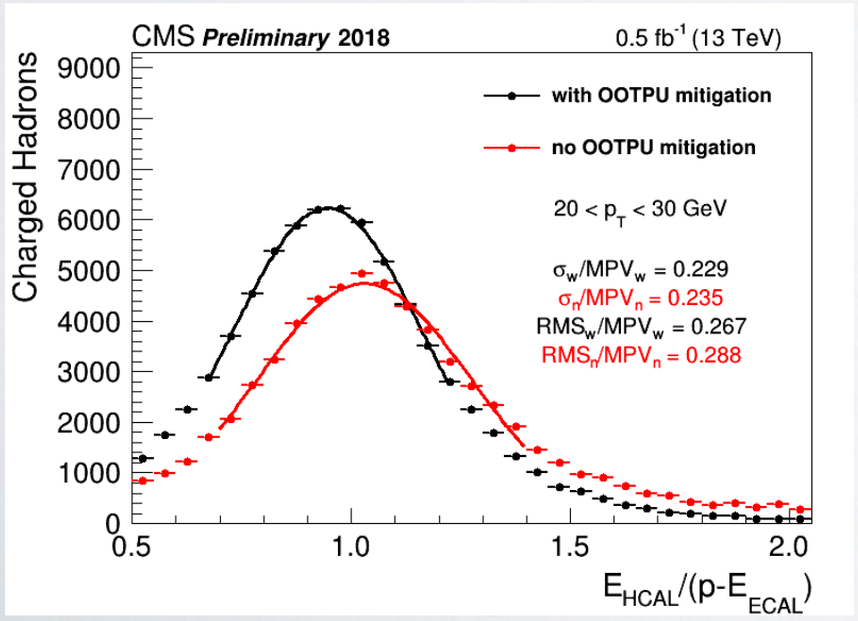
- Relative response of HCAL energy to track momentum for isolated charged pion candidates with track momentum between 20 and 30 GeV
- Black (red) points and fitted gaussian are with (without) out-of-time pileup subtraction
- *RMS values are calculated for plotted range only*

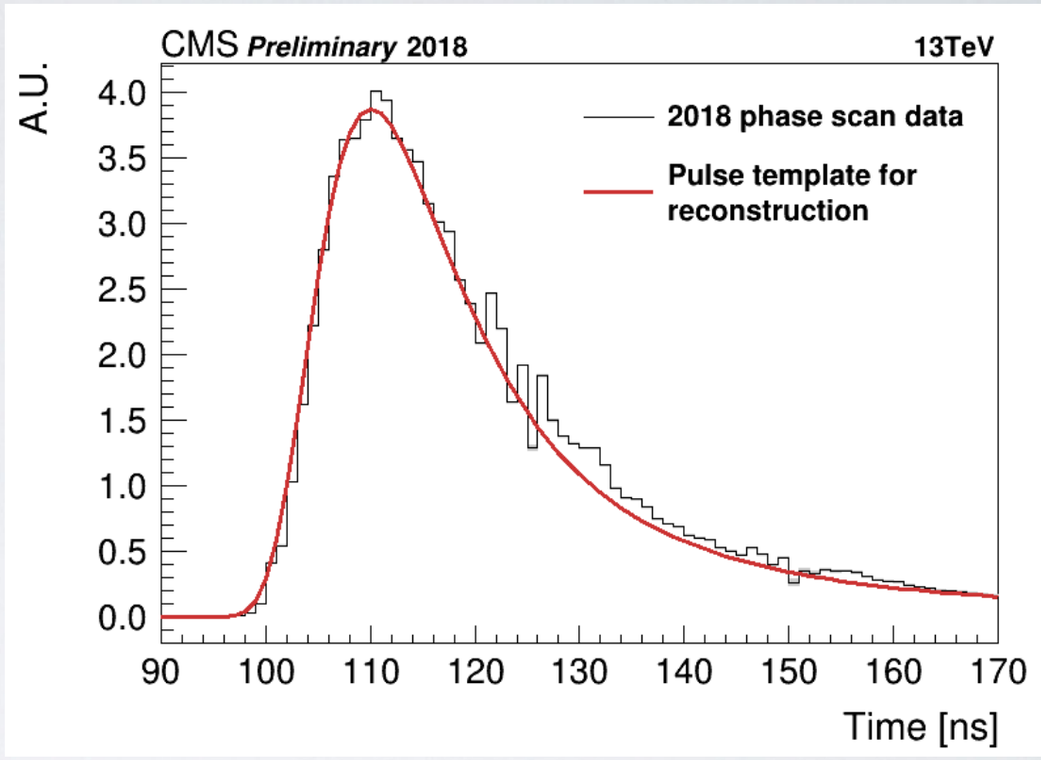
- Same events are used in each distributions, but no OOTPU scenario has long tail with E/p ratio above 2.0 due to pileup contributions
- **Out-of-time pileup mitigation improves hadronic energy resolution**

Summary

- In situ pulse shape measurement for upgraded CMS hadronic endcap instrumented with SiPM+QIE11 readout







- Out-of-time pileup mitigation algorithm for 2018 CMS endcap and barrel hadronic calorimeters

- Preliminary results from 2018 data demonstrating improved hadronic energy response and resolution