# Phase-2 CMS ECAL APD Spike Rejection Studies Using 2021 and 2025 Test Beam Data

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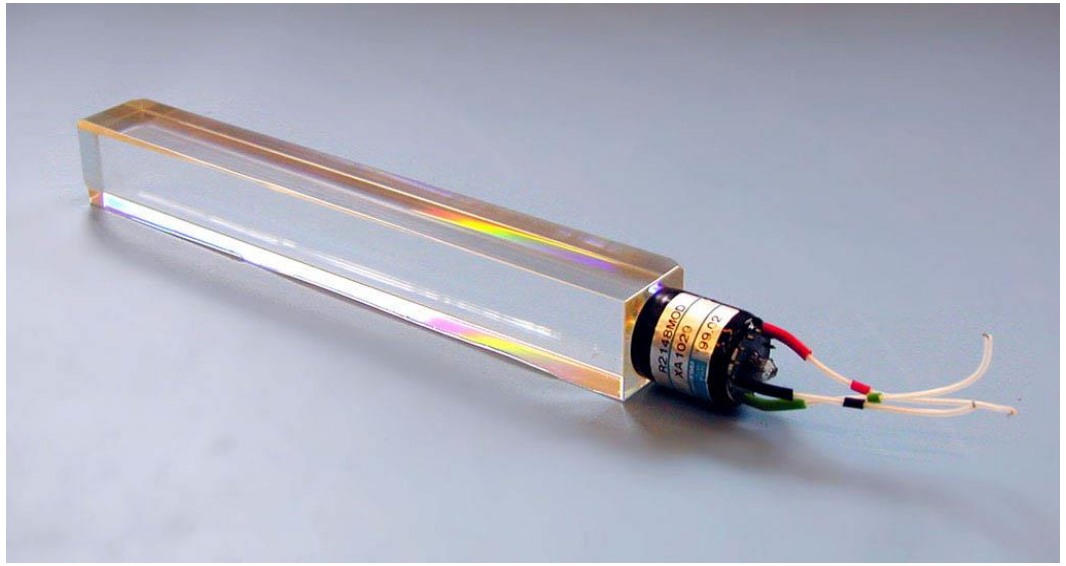
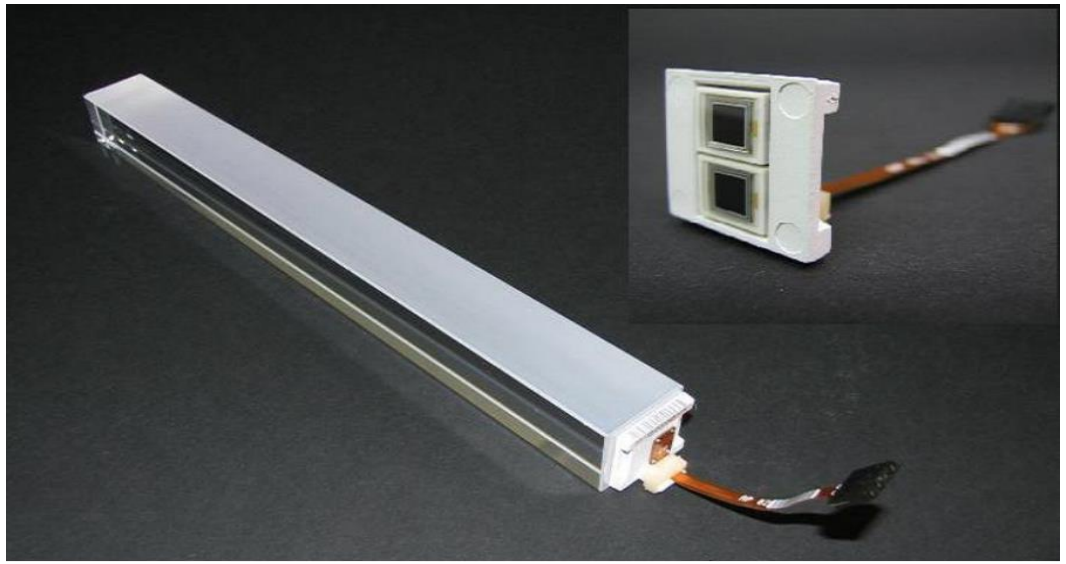
# Phase 2 Upgrade and ECAL spikes

# Overview of Phase 2 ECAL Upgrade

- **<u>ECAL (current):</u>**
  - Measures $e^-/\gamma$ **energies**
  - **~76k $PbWO_4$ crystals** (barrel + endcaps), read out by **APDs/VPTs**
  - **Wide dynamic range:** 50 MeV–2 TeV
- **<u>Upgrade</u>**:
  - $PbWO_4$ **crystals + APDs** in EB **remain**
  - **Endcaps replaced** by HGCAL
  - **Upgraded readout electronics**: new L1T requirements: **100kHz → 750kHz, 4µs →12.5µs**, higher PU
- **<u>Target</u>**: Maintain Phase 1 performance despite aging



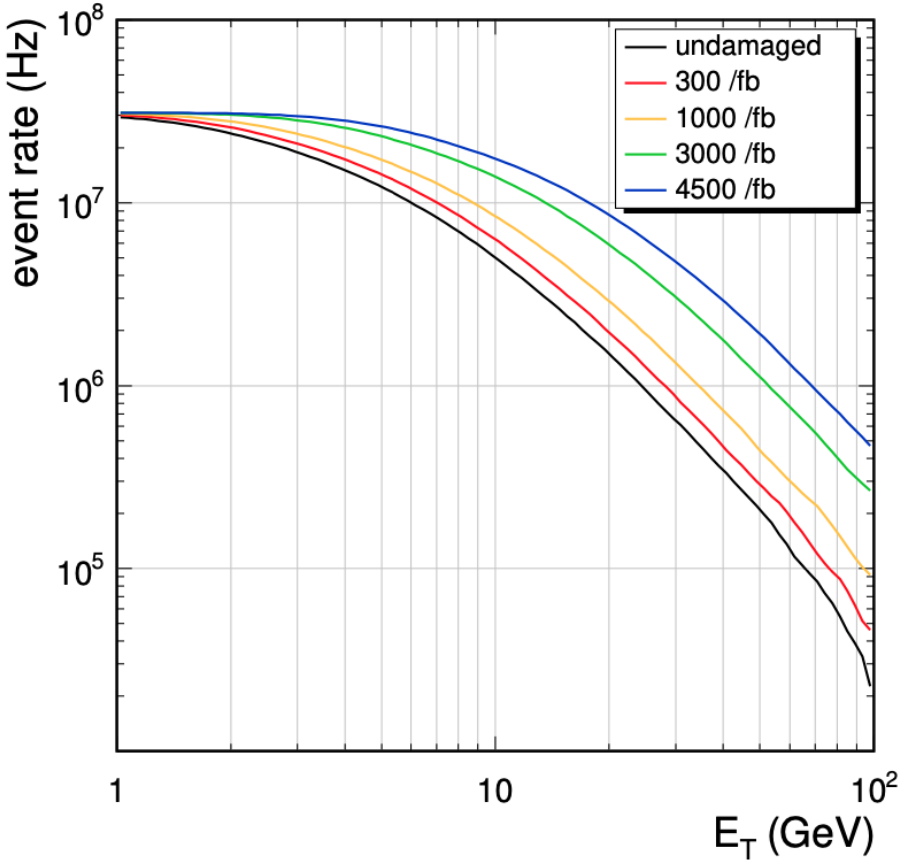


# ECAL spikes

- **Spikes** – large apparent **energy deposits within the APDs**, result of **direct ionisation** of APD material (**usually isolated to a single crystal**) by a highly ionizing particle, during LHC collisions

- **Often satisfy the conditions for triggering** electrons and photons in CMS
- **Above 10 GeV ECAL hits are dominated by spikes**

- **<u>If untreated, spike rate would saturate the L1T bandwidth of 750 kHz</u>** (> 1MHz at 20 GeV)
- To reduce the rate of spikes to a negligible level (< 1 kHz above 20 GeV) **<u>require spike rejection efficiency >99.9%</u>**




Expected rate of events with ⟨PU⟩ = 200 for Phase-2 with ECAL energy deposits above specific $E_T$ thresholds after 300, 1000, 3000, and 4500 $fb^{-1}$ with no spike mitigation. [1]

# This talk

- **Study performance** of proposed **Phase-2 spike killing algorithms with final ECAL Phase-2 electronics**
- Use **test beam data to provide samples of electrons and spikes** (the latter from direct ionization of the APDs with a pion beam)
- **Understand how well spike killing algorithms perform** both in isolation and together
- **Find optimised thresholds** for the algorithms to obtain the desired spike killing performance
- Caveat: **test beam environment is different** (more challenging) to what is expected in CMS - the spikes and EM signals always occur in the same region of the detector (defined by the pion beam spot). The final performance will be evaluated using MC simulations of the full detector, tuned with inputs (pulse shapes) derived from test beam data.

# Test Beam setup

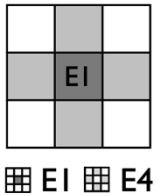
# Test Beam Setup (2025, SPS H4)

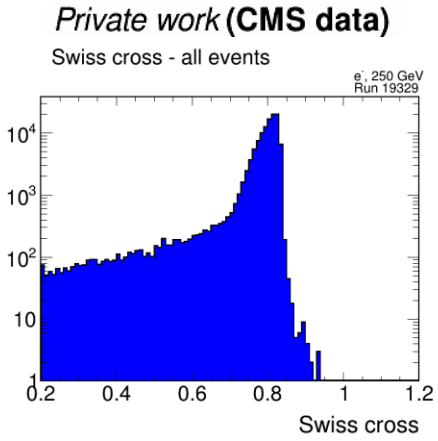
- **Setup:** full supermodule ($^1/_{36}$ of ECAL barrel) with 400 channels equipped with Phase-2 electronics, 5×5 crystal matrix readout
- **Beam:** e/π, 25–300 GeV, ΔE/p ≈ 0.5% (very pure)
- **Instrumentation:**
- Hodoscopes → position (σ ≈ 150 μm)
- MCPs → timing (σ ≈ 15 ps)
- **Readout Electronics:** Phase-2 electronics, Final FE + VFE chain (CATIA + LiTE-DTU)
- **Goal:** validate full Phase-2 system performance

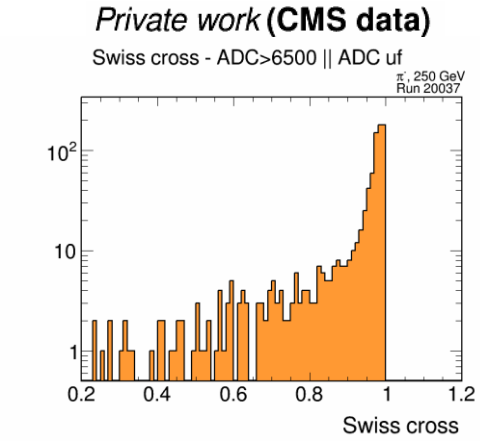

# Spike-killing algorithms

# Algorithms overview:

- **Swiss Cross** (topology) - based on **ratio between energy** in **central** crystal and **sum of energies in the 4 adjacent** crystals
- **Given by**: $D_{swiss} = 1 - \frac{E_4}{E_1}$,
- **less than ~0.9 for EM signals, approaches 1 for spikes**



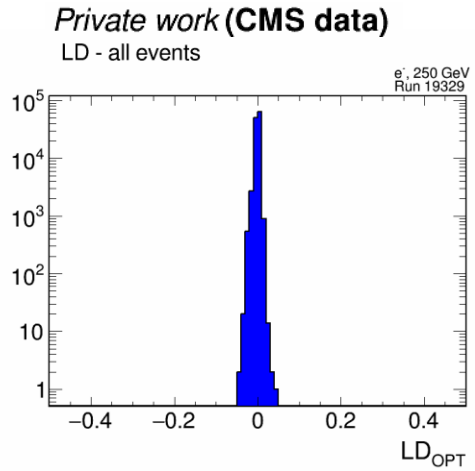

- **LD** (linear discriminant) - exploits different pulse shapes of spikes and EM signals
- **Formula**: $LD = R_+ - \sum_{i=0}^{3} p_i \times R_-^i$ , where:

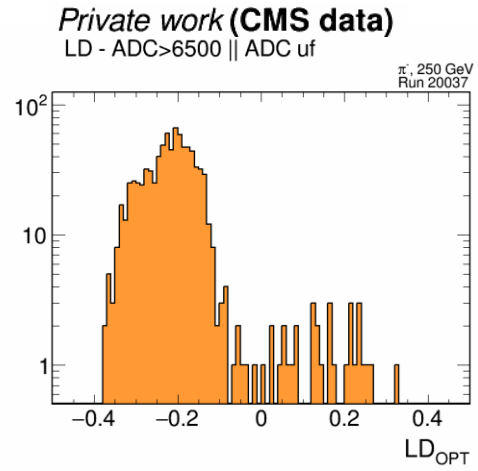
$$R_- = \frac{a_{i-1}}{a_i} \quad , \quad R_+ = \frac{a_{i+1}}{a_i}$$

and $\mathbf{a_i}$ – sample centred on the **maximum**,

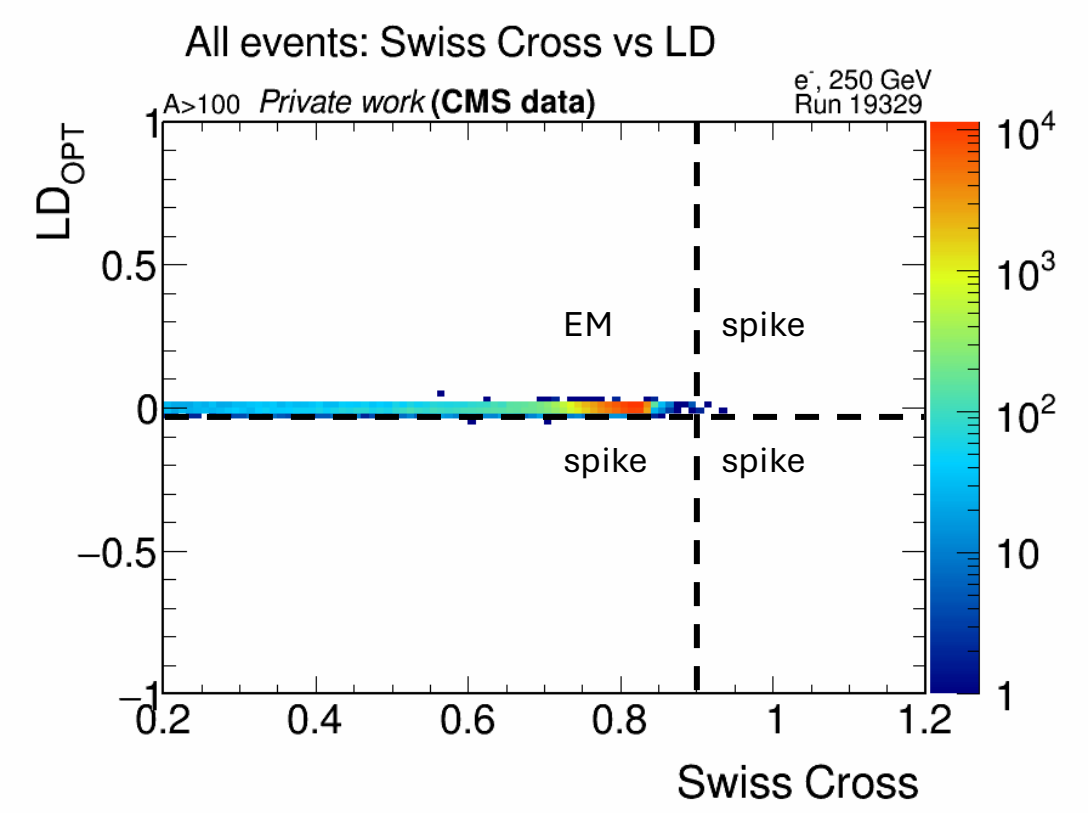
$\mathbf{p_i}$ – **weights** retuned for this TB data

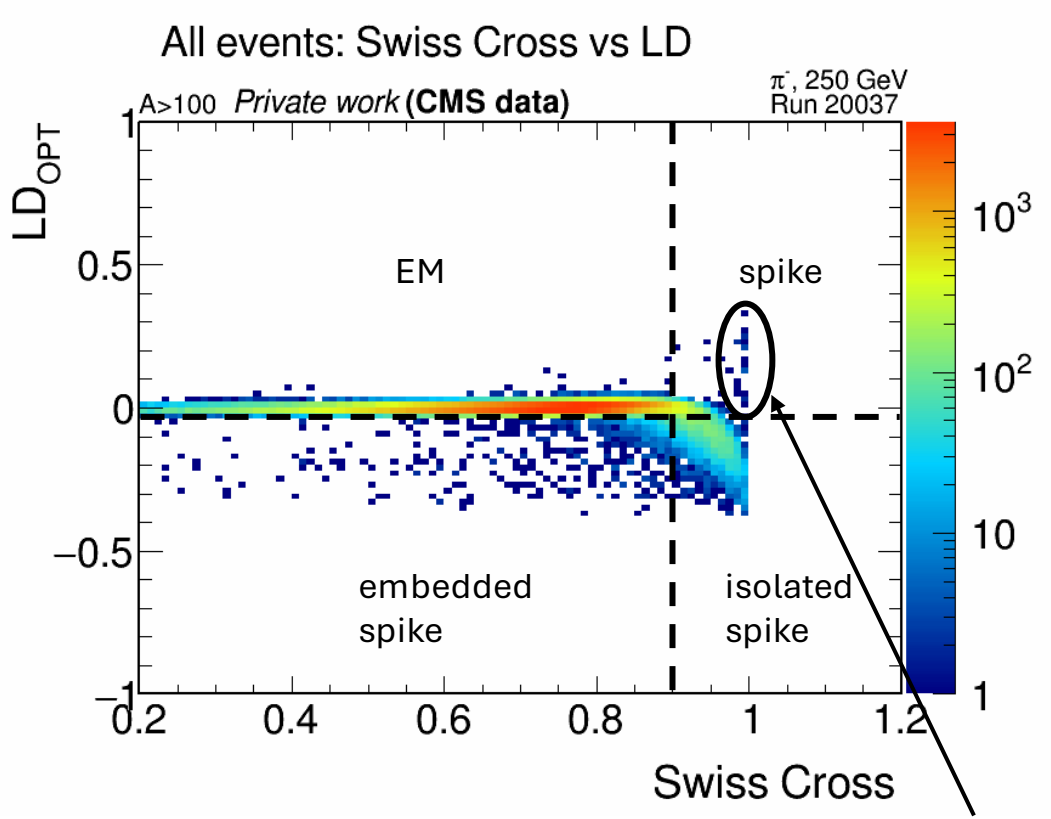
- **For signal LD~0, for spikes LD<0**



# Swiss Cross vs LD




Broad “flat-top” events saturating the ADC, also seen in 2021 TB

**EM and various spike-like regions are marked by the lines**
threshold cut values are not optimised here

# Method

# Efficiency Definition & Optimisation Strategy

**Event Selection & Metrics:**

- **Quality Cuts:**
  - **Spike selection:**
    - Reconstructed 5x5 **energy > beam energy**
    - Signal pulse has an **underflow** after the peak - characteristics of spikes

- **Efficiency definitions:**
  - **Signal eff.** $(e^{-}) = \frac{\text{events - mistagged spike candidates}}{\text{events}}$
  - **SK eff.** $(\pi) = \frac{\text{tagged spikes}}{\text{all spikes}}$

- **Target performance:**
  - **≥ 99.9% spike-tagging efficiency**
  - **≤ 2 % signal loss**

## Method & Optimisatioon

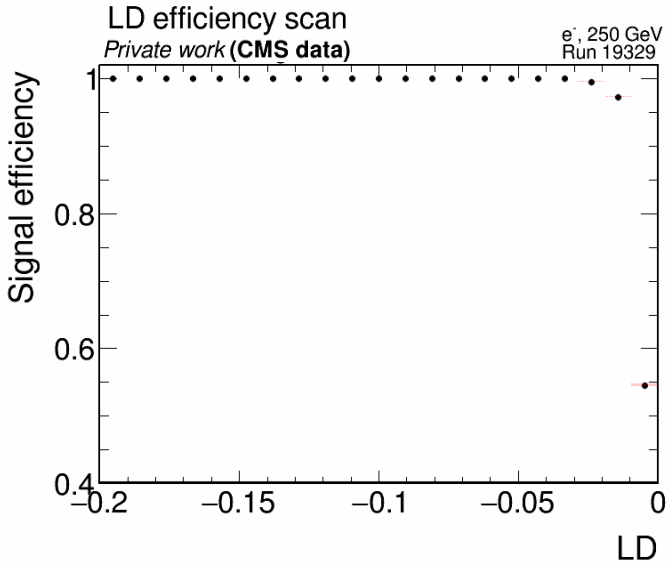
- **1D parameter scan** :
  - Scan parameters:
    - **SC** ∈ [0.7, 0.99]
    - **LD** ∈ [−0.3, 0]
  - Study performance of each algorithm in the given parameter range

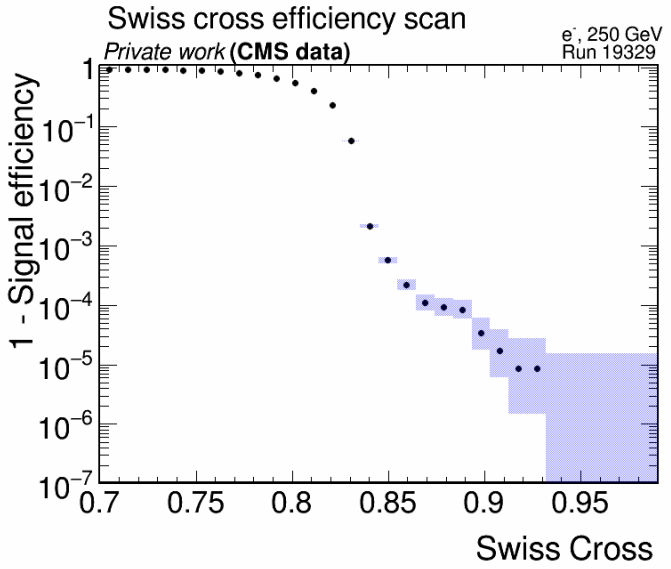
- **2D parameter scan :**
  - Parameters**:**
    - SC ∈ [0.8, 0.95], LD ∈ [−0.2, 0]
    - Use **OR logic**
  - Select combined thresholds to optimise signal and spike efficiency

***Test beam limitation:*** spike & EM shower are more concentrated → reduced performance of Swiss Cross vs real CMS conditions

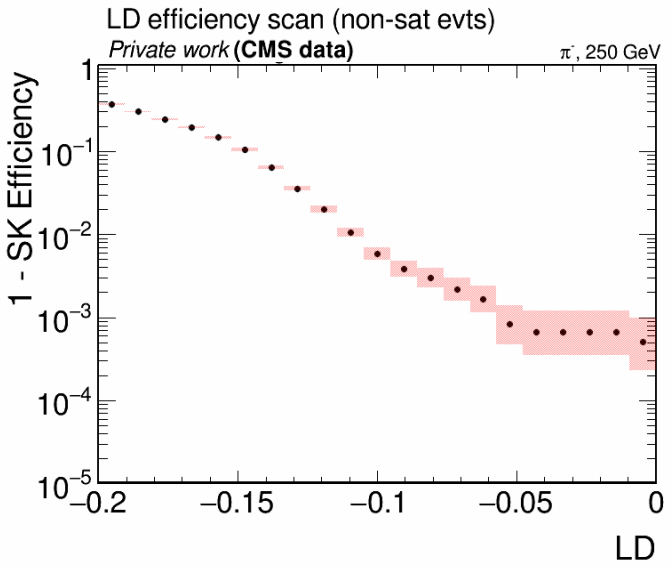
# Performance of Spike-Killing Algorithms

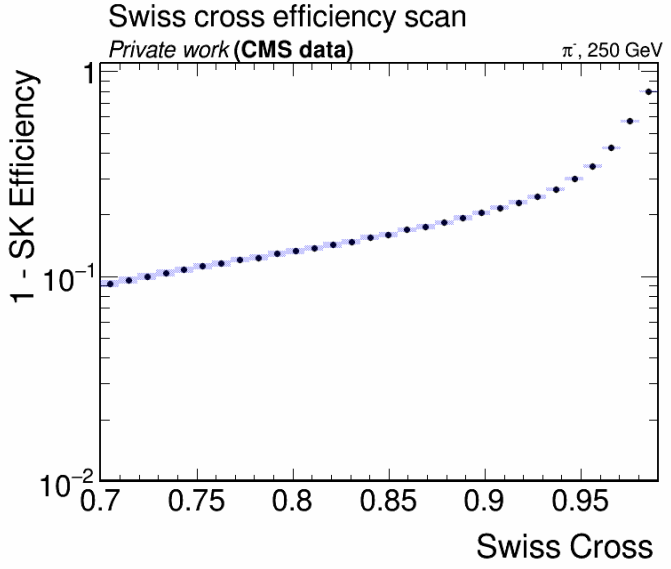
**Electron**




**Pion**




- **LD:**
  - **Acceptable signal loss** for LD < ~−0.03
  - Spike rejection **limited to 95%** by presence of **saturated events** (effective energy >1.5 TeV) (back up)
  - **If these are removed, efficiency reaches desired 99.9% level**
- **Swiss Cross:**
  - **Acceptable signal loss** for SC > ~0.84
  - **Spike rejection limited** (~90%) because spikes are not normally isolated in the test beam data
  - **Not affected by saturated signals**

→ **Neither algorithm alone meets SK requirements**

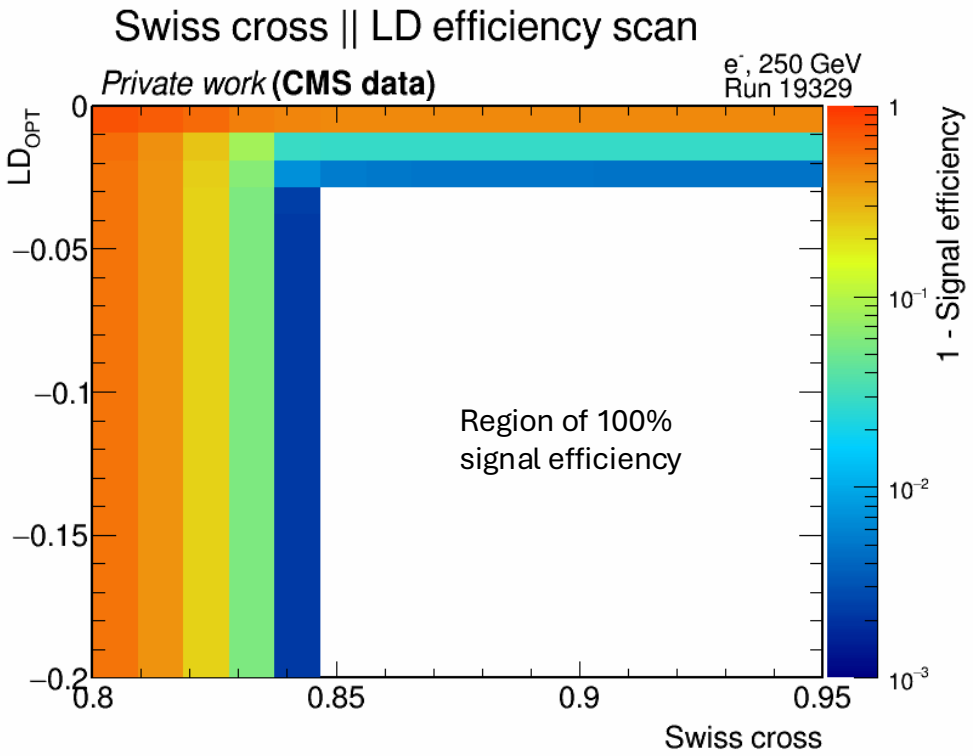
## Key takeaway

- **Combination of SC + LD is required** to obtain desired performance in test beam data
- **Saturated events limit performance in test beam**
- **Saturation in CMS is rare, but possible** -> will use MC to assess

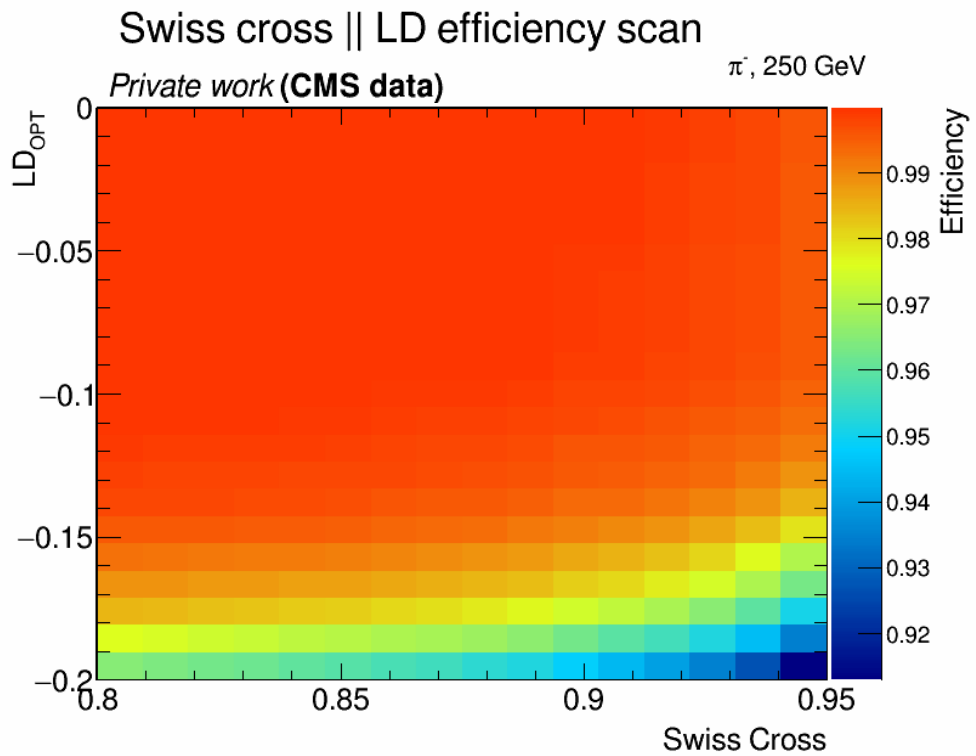
Plots shown: **non-saturated events for LD** (more representative); **SC unaffected**

# 2D Optimisation

**Electron**

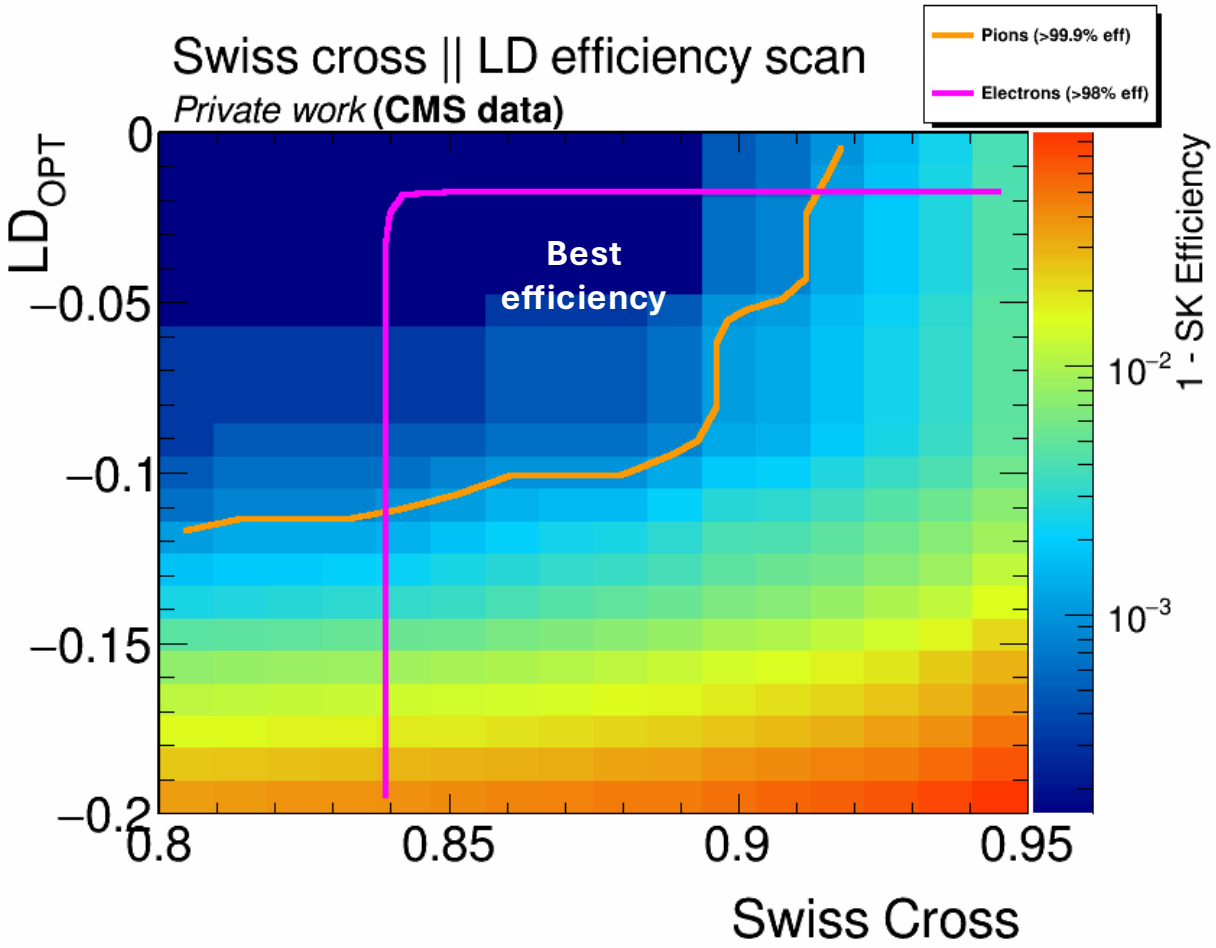



**Pion**

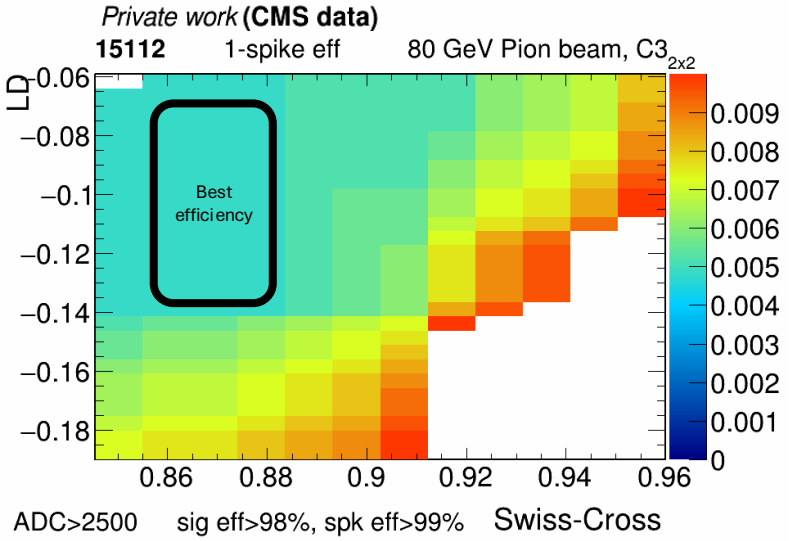



- **Simultaneous optimisation of Swiss Cross and LD**
- **Required SK threshold of >99.9% reached in the large section of the pion plot**
- **Signal efficiency of >98% also can be reached within that region**
  - **→ <u>Conclusion: the optimised OR combination shows the best SK performance without sacrificing the signal efficiency</u>**

# 2D Optimisation summary




From 2021 TB:




- The **contour plot on the left,** shows the overlap of the required efficiency regions:
  - **The magenta contour shows the signal efficiency >98% calculated from the e- sample**
  - **The orange contour shows the spike-killing efficiency of >99.9% for the pions**
- **<u>The region between these two curves fulfils the recommended efficiency criteria</u>**

- The <u>optimal Swiss Cross</u> values are <u>in-line with</u> findings from a 2021 test beam run (top plot); the <u>optimal LD</u> values shifted to a <u>less-negative</u> region <u>due to a change in pulse shapes</u> in comparison with 2021

# Conclusions & next steps

- Spike killing efficiency measured in ECAL test beam data - best performance obtained using combination **LD OR SC → both algorithms are needed**
- **Spike killing efficiency >99.9%** and **signal efficiency >98%** can be simultaneously obtained by optimising the cuts

- Improve by using **additional tagging criteria** to access more spike-candidate events
- **Future TB** aims to investigate **lower energy spikes**
- **Check and validate performance in simulation at 200PU** using existing spike simulation and updated pulse shapes measured from 2025 test beam

# Thank you for your attention

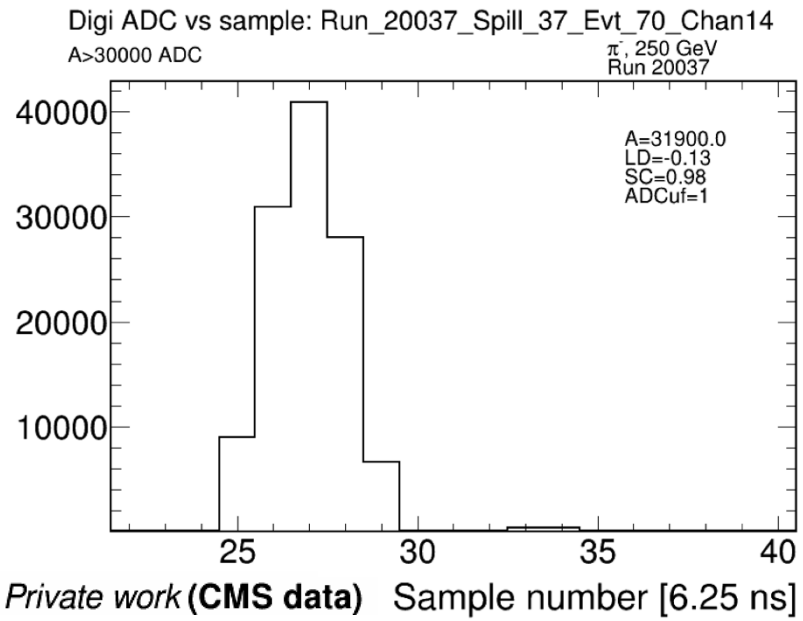
# Bibliography

[1] The CMS Collaboration. The Phase-2 Upgrade of the CMS Barrel Calorimeters. Technical report, CERN, Geneva, 2017.

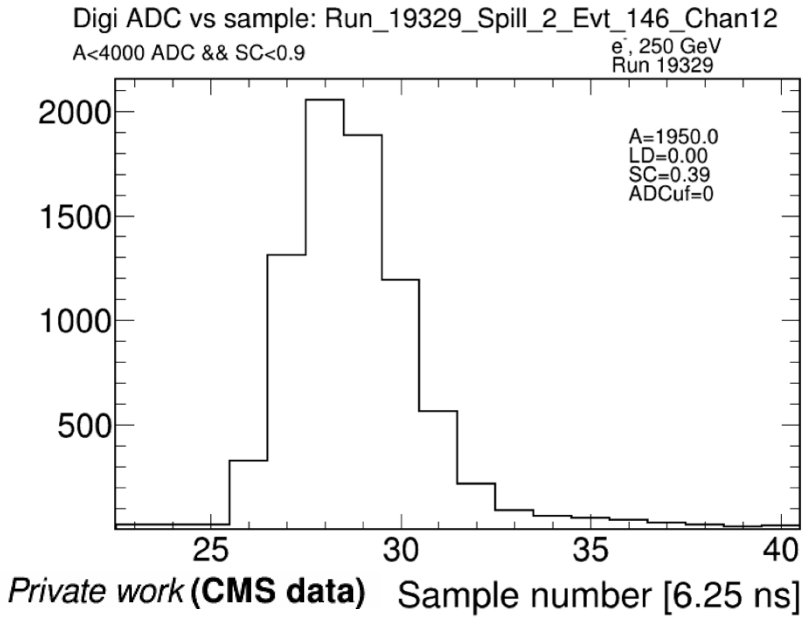
# Back up

# Pulse shapes

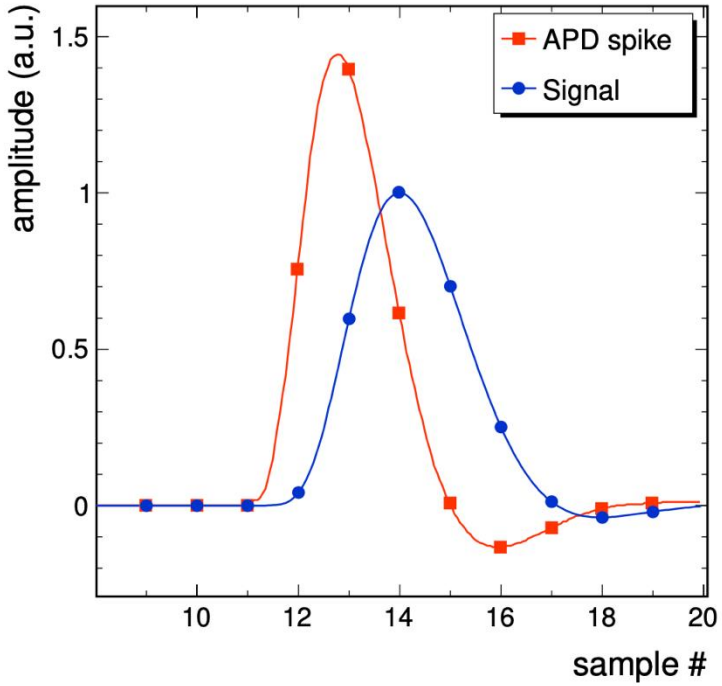
## Spike pulse




## EM pulse




## TDR result




Pulse shapes from APD spike and scintillation signals. The amplitude samples from digitization with 160 MHz sampling frequency are shown as dots. [1]

# LD efficiency scan – all events

**Pion – all events**