CALOR 2024
第２０回 素粒子・原子核物理学
カロリメータ検出器国際会議
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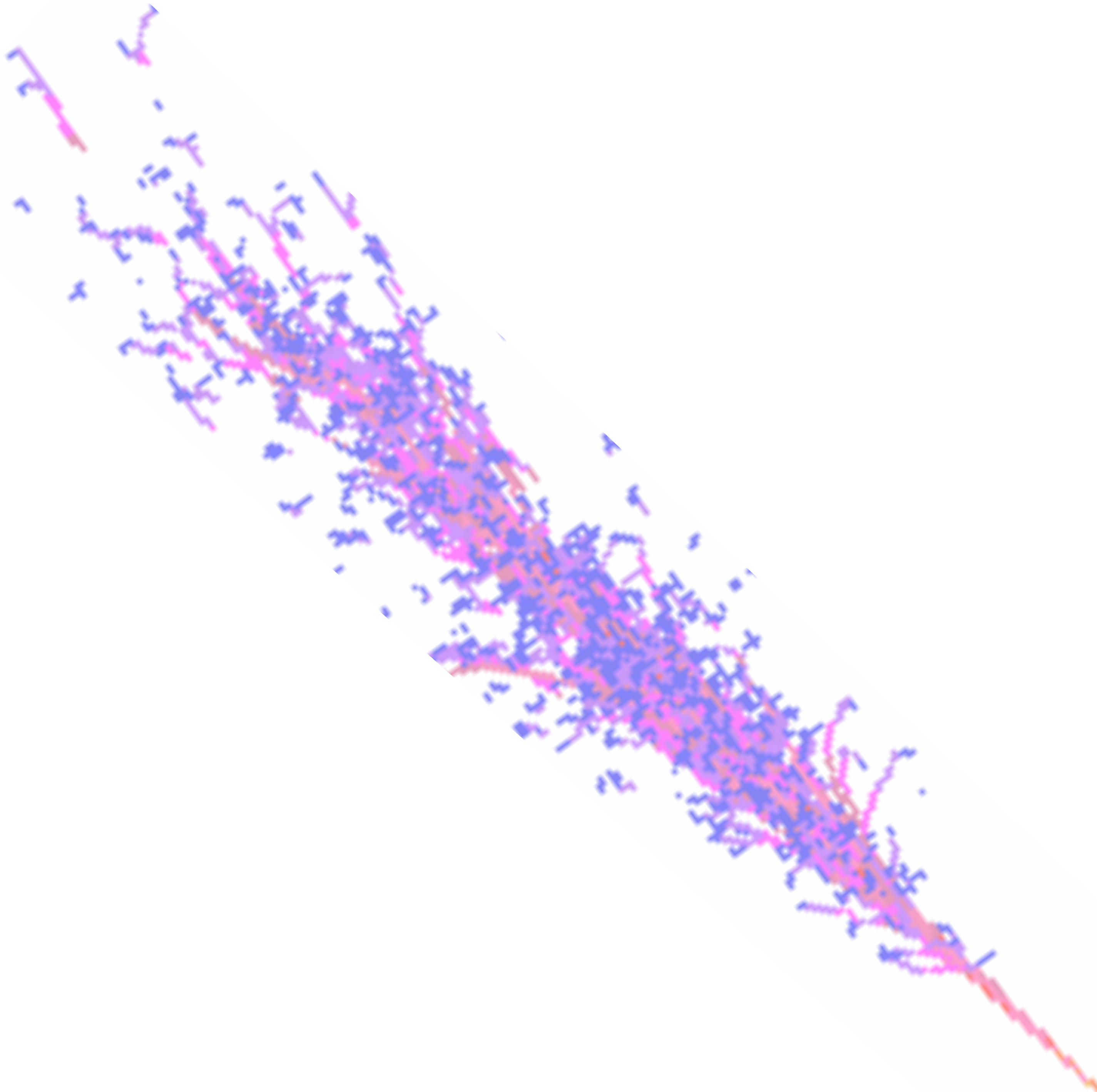
CMS ECAL: Meeting the trigger performance challenges of Run 3

CALOR 2024 | Tsukuba, Japan | 20 May 2024

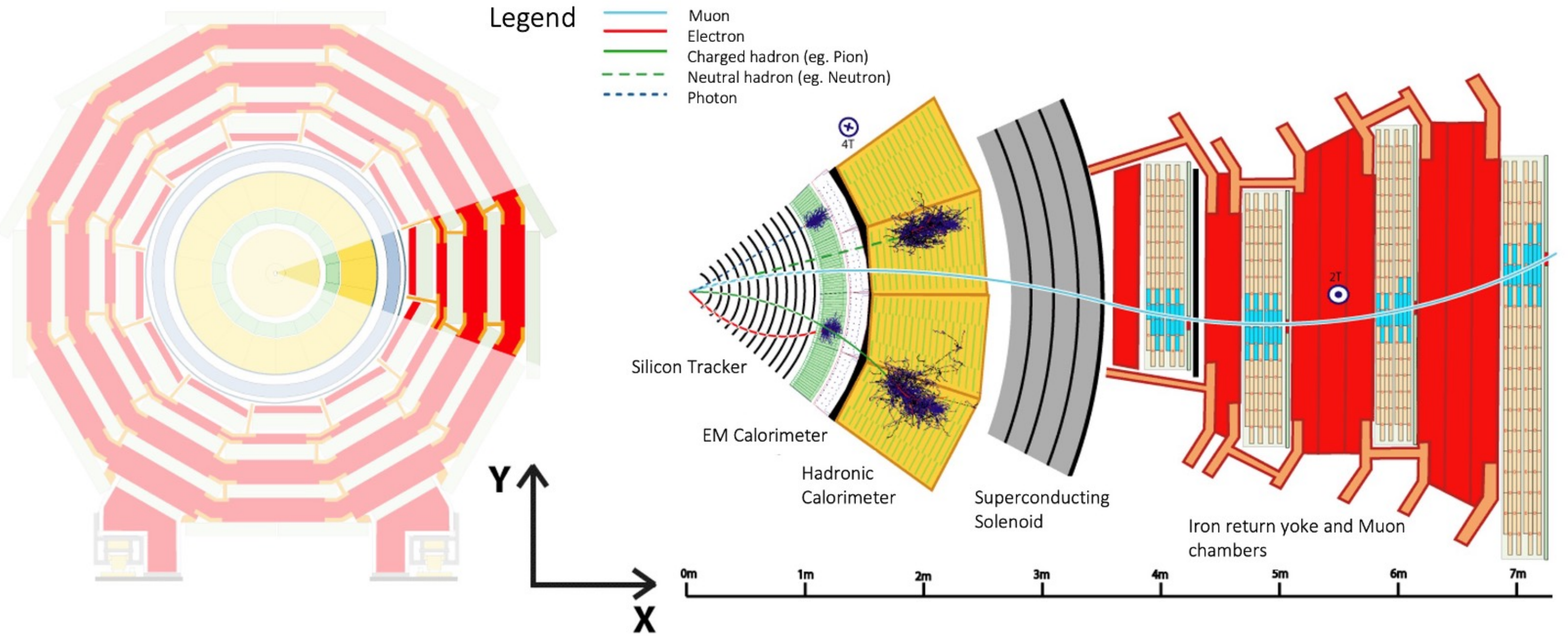
John Dervan (Northeastern University)
On behalf of the CMS Collaboration

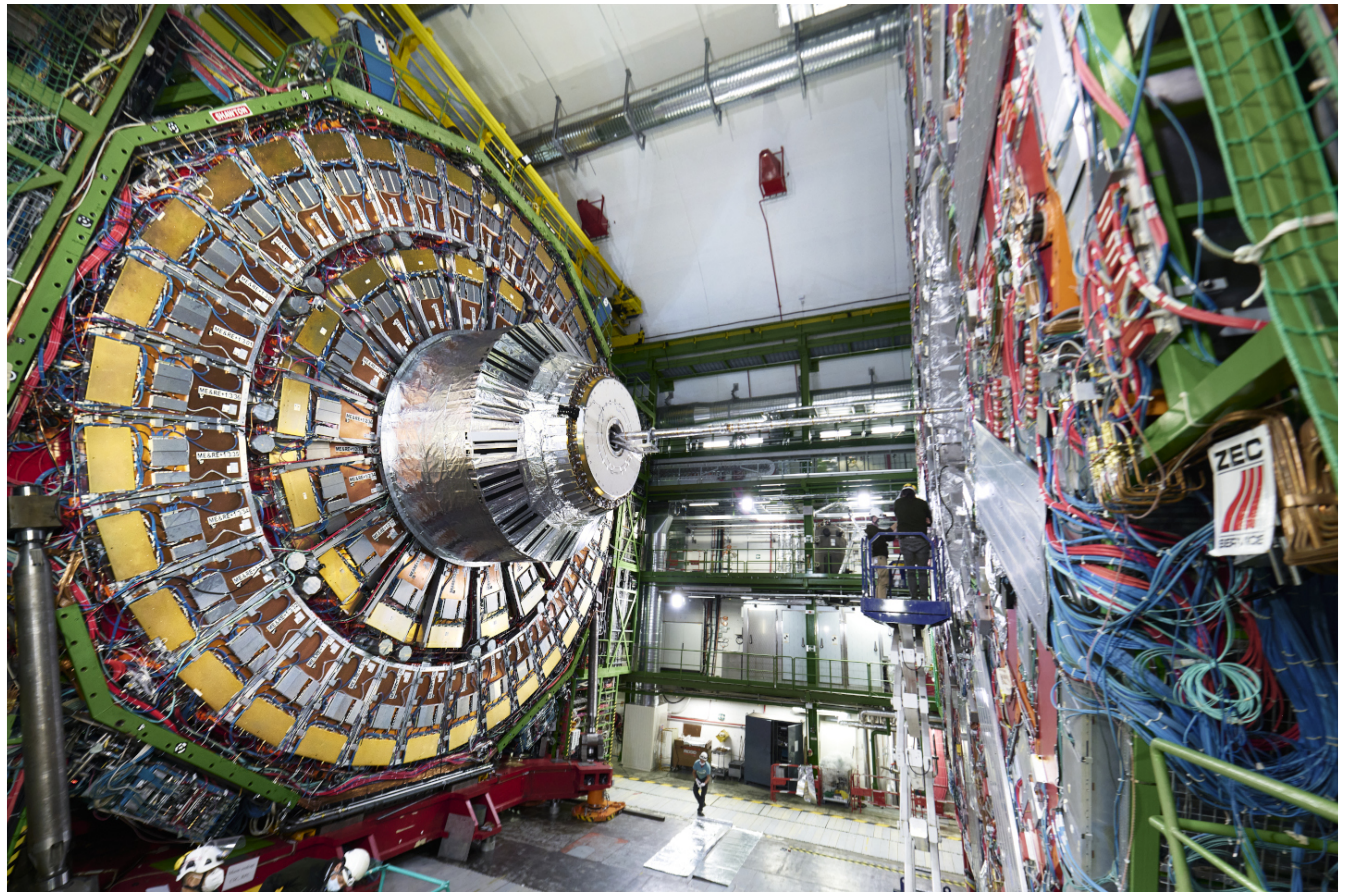


Compact Muon Solenoid

*The **Compact Muon Solenoid (CMS)** detector is a general-purpose detector at the **Large Hadron Collider***

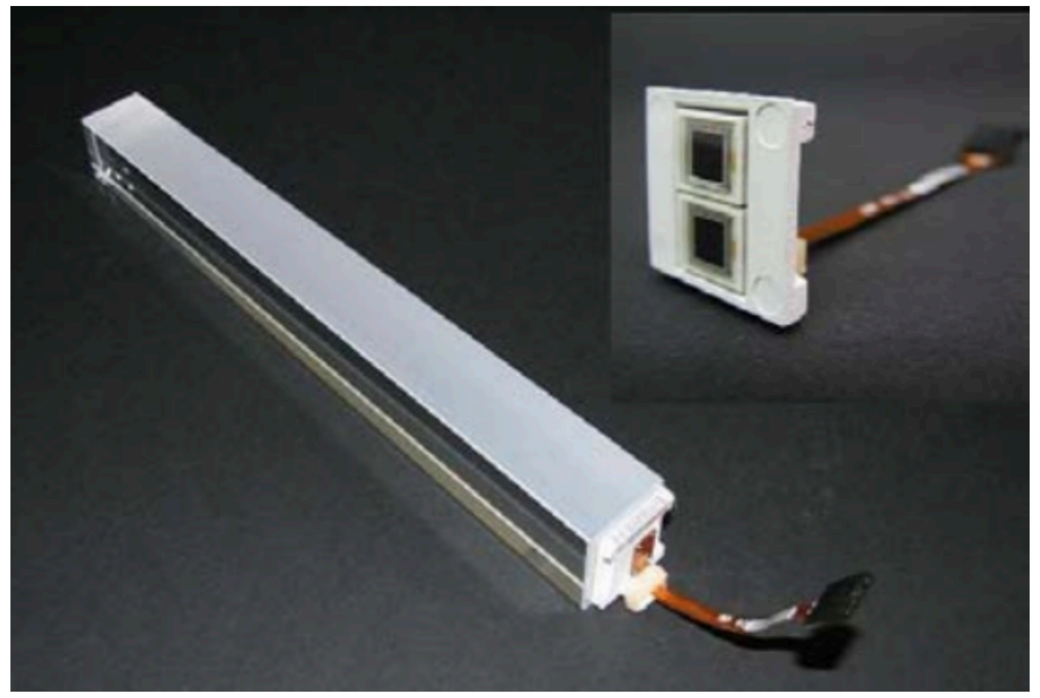
- Physics program combines **precision measurements** with searches for **new physics** (SUSY, dark matter, extra dimensions, etc.)
- Combines input from **multiple sub-detectors** to identify and measure the **momenta/energies** of objects like electrons, photons, muons, taus, jets, and missing E_T (MET)



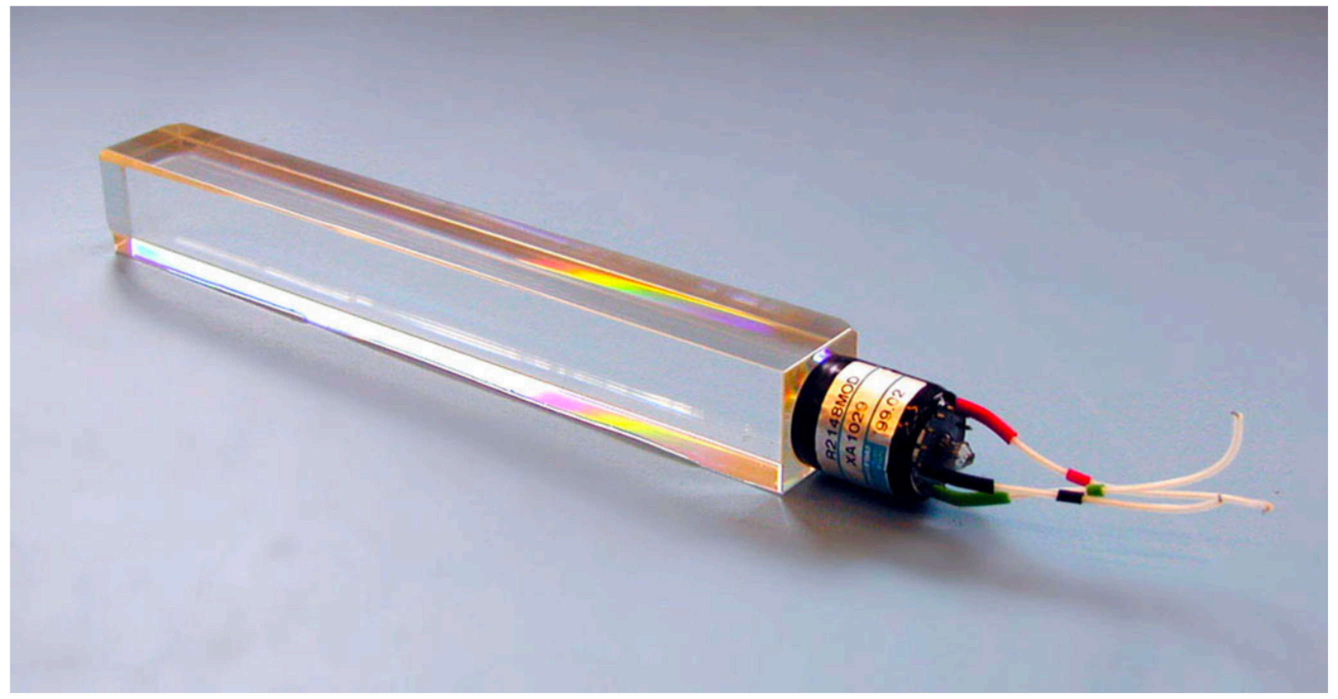


A crash course in the CMS ECAL

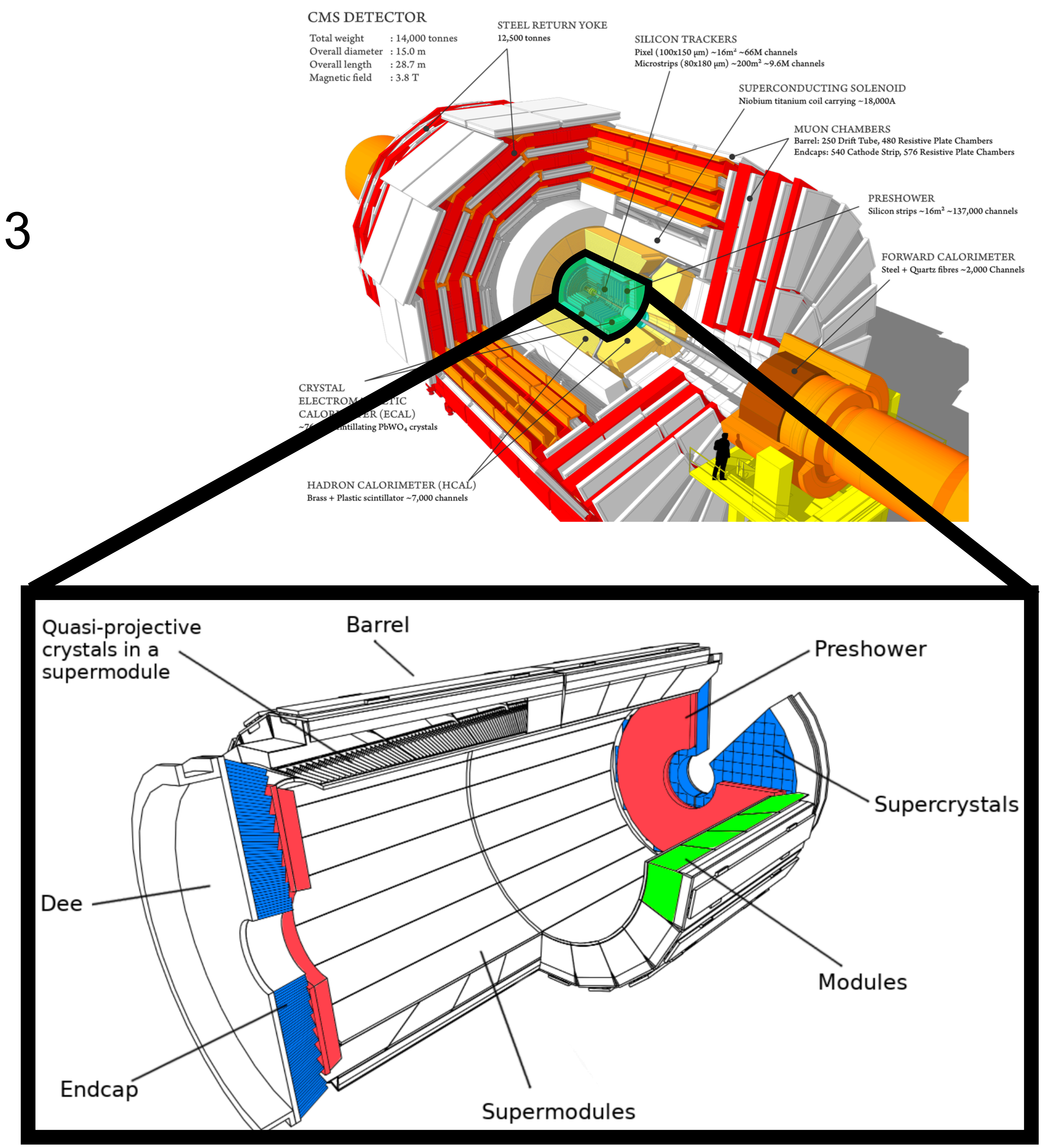
- **Homogenous crystal calorimeter** measuring **electron & photon** energies + EM fractions of jets, taus, and energy sums
- ECAL: **75,848 $PbWO_4$ crystals** provide hermetic coverage to $|\eta| < 3$
    - **Barrel** (EB): 61,200 crystals → APDs ($|\eta| < 1.479$)
    - **Endcap** (EE): 7324 ×2 crystals → VPT ($1.479 \leq |\eta| < 3$)
    - **Preshower** (ES): auxiliary silicon-based detector for π_0 decays
- Target intrinsic resolution: 0.5% for high-energy electrons/photons



EB crystal with avalanche photodiode (APD)



EE crystal with vacuum phototriode (VPT)

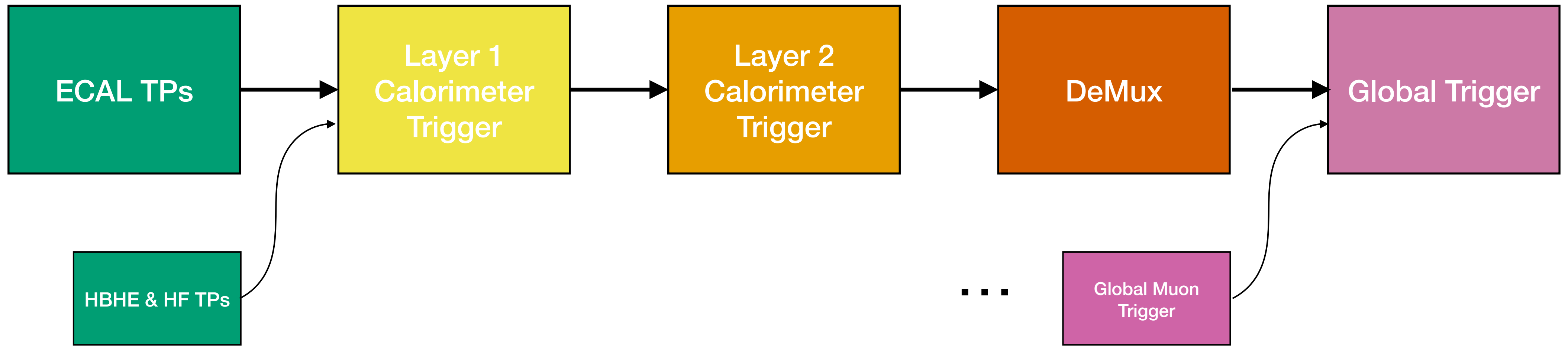


Triggering at CMS

The CMS trigger system optimizes physics of interest given bandwidth constraints

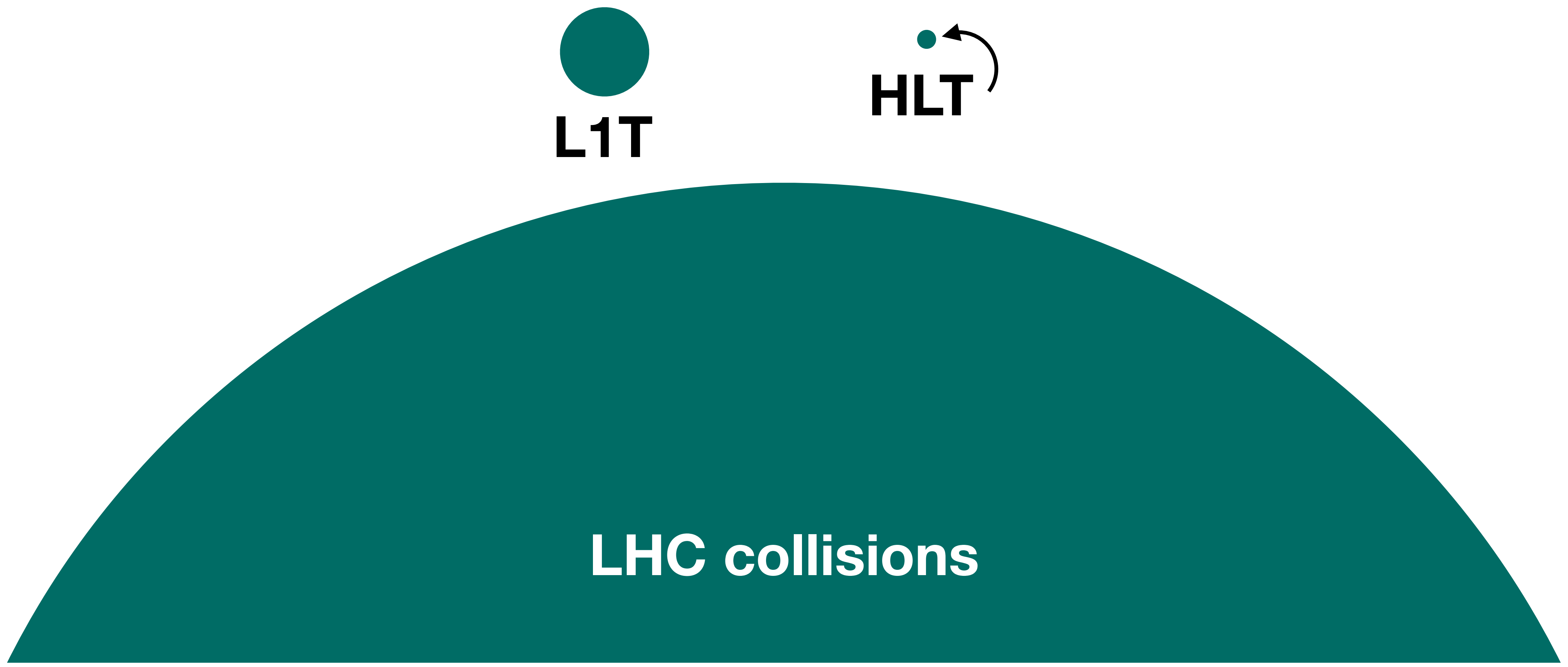
Level-1 Trigger (L1)

- Hardware-level algorithms on custom electronics
- Fixed latency of **3.8μs**
- Information from **calorimeters (ECAL/HCAL)** and **muon system** fed to global trigger
- Reduces 40MHz LHC collision rate to ~**110kHz**


ECAL TPs
Layer 1 Calorimeter Trigger
Layer 2 Calorimeter Trigger
DeMux
Global Trigger
HBHE & HF TPs
…
Global Muon Trigger

High-Level Trigger (HLT)

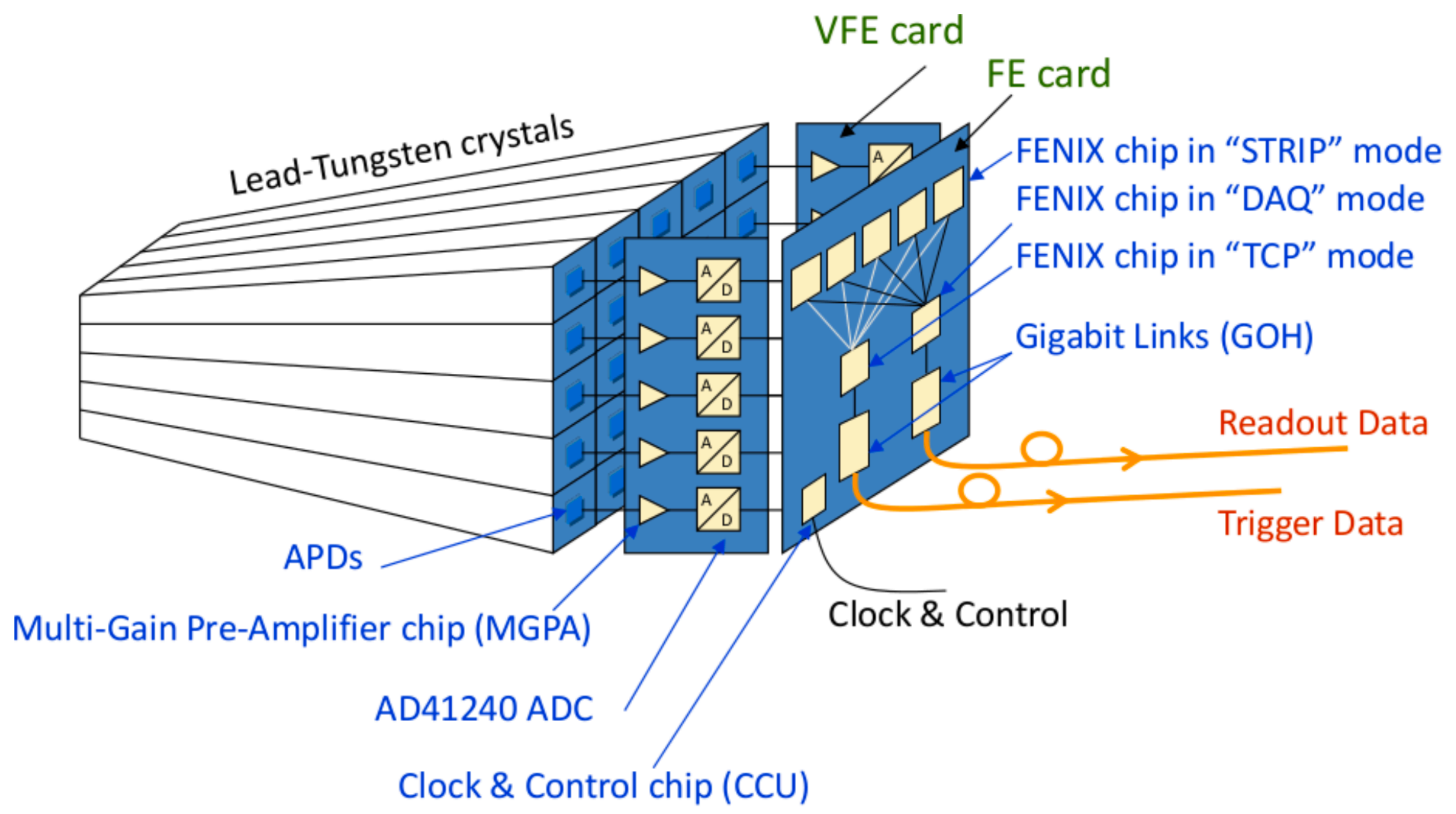
- High-level physics algorithms on event filter farm
- Processing time of **90ms/event**
- Reduces L1 event rate down to **5kHz**
- Includes tracking/vertexing information



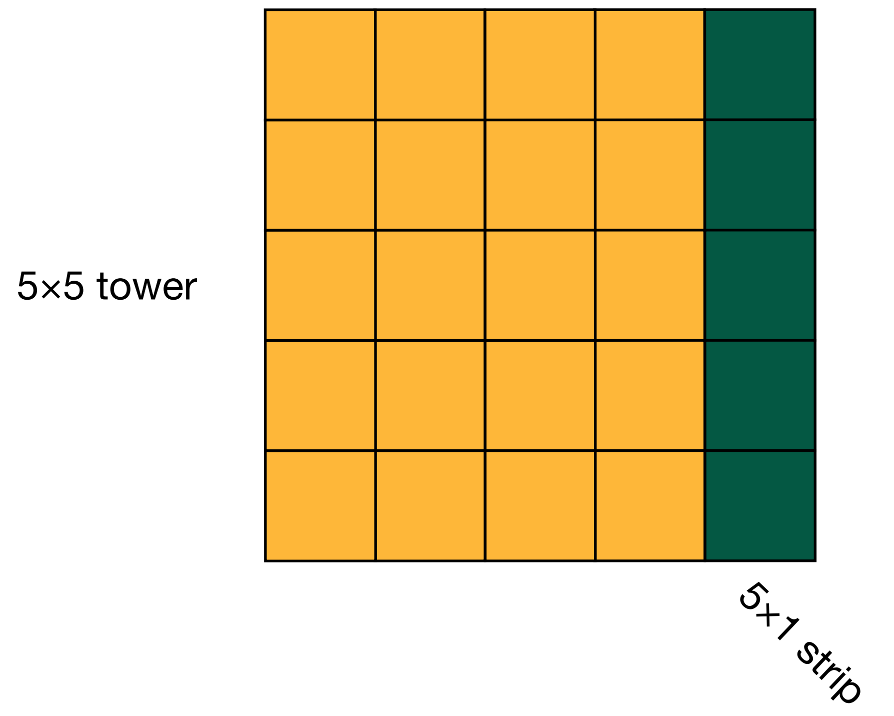
(to scale)

ECAL trigger: an overview

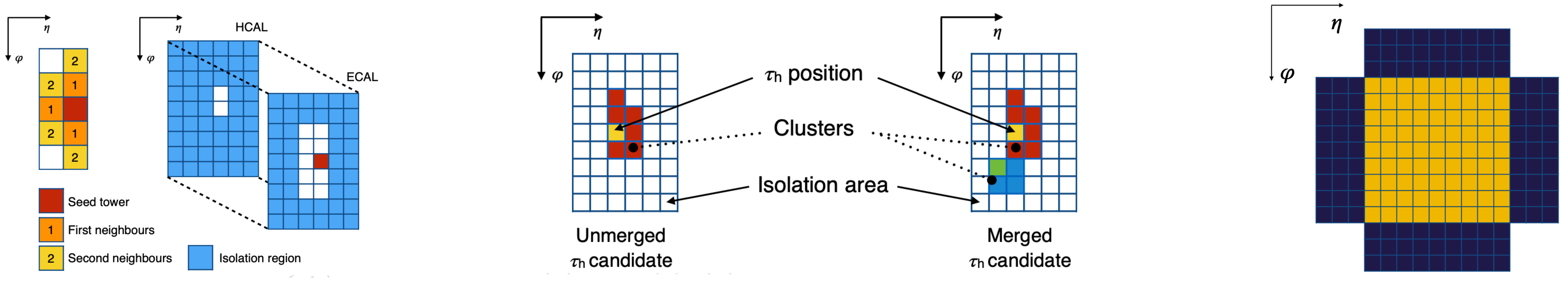
- ECAL sums energies in neighboring crystals (trigger towers) and sends **trigger primitives** (**TPs**) to L1 trigger to form L1 electron/photon (e/γ) and jet candidates
- TPs include
  - Transverse energy (E_T) value (per-strip/pseudostrip of 5 crystals)
  - Up to 2 feature bits to characterize inter-crystal energy spread (EB)
  - LHC bunch-crossing assignment



Goal: keep rates stable, thresholds low, and efficiency high



ECAL trigger tower (EB); EE towers are between 5–25 crystals (1–5 strips)



EG clustering/iso region

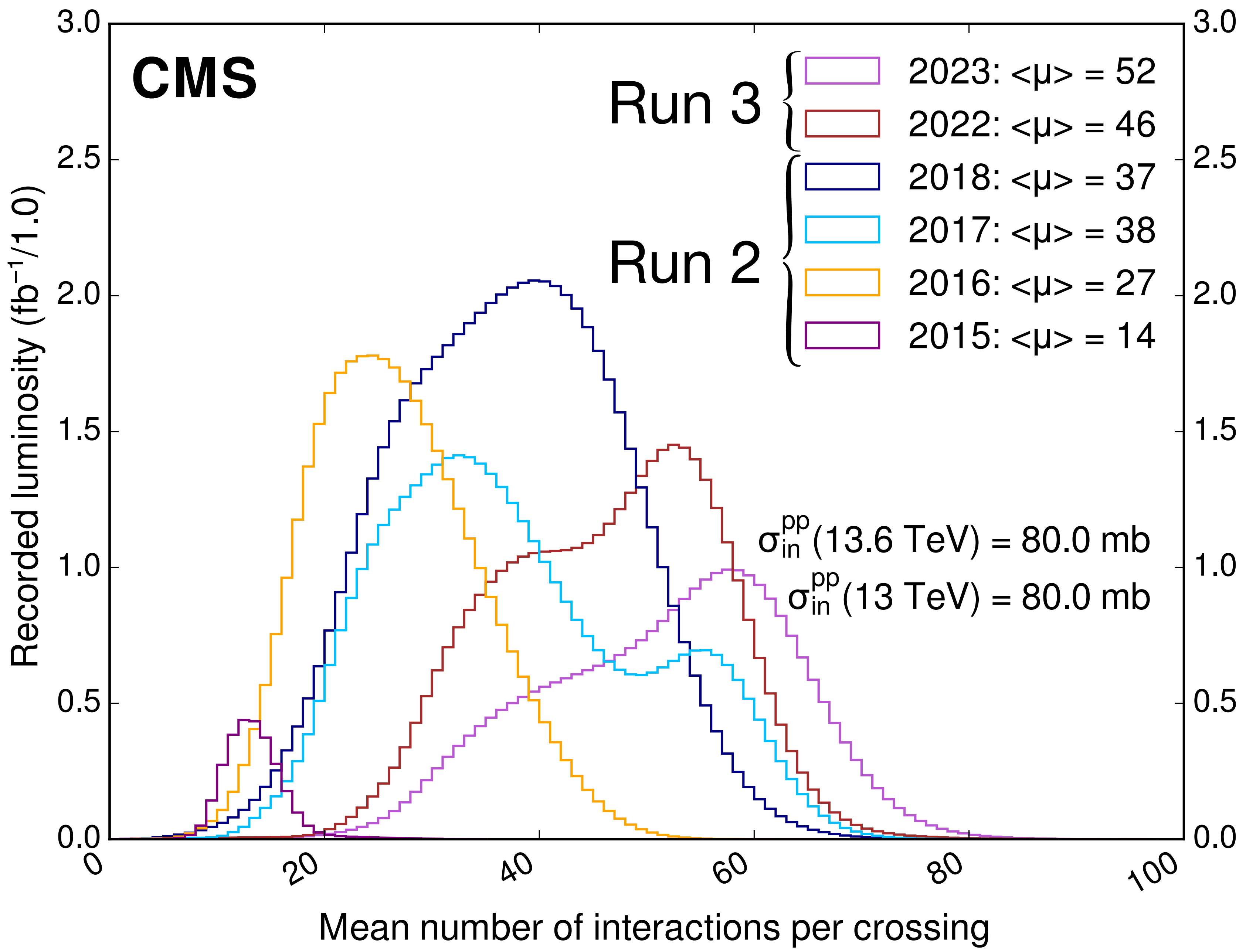
Hadronic tau clustering/iso region

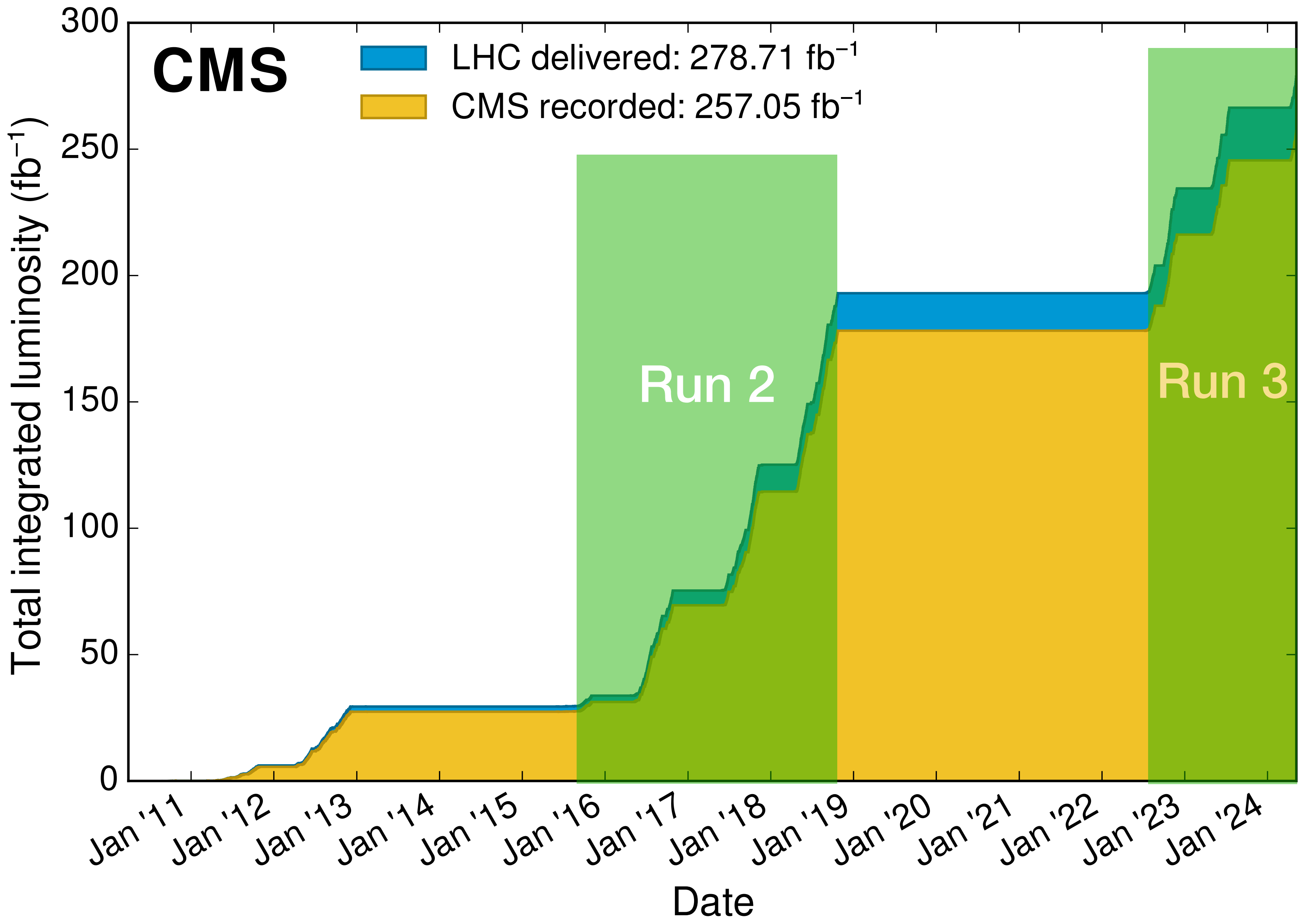
Jet 9×9 sliding window

ECAL L1 object clustering

The catch: luminosity

As the delivered luminosity increases, ECAL must maintain good trigger performance





- Run 3 pileup is substantially higher than Run 2
- Total expected for Run 3: 260fb^{-1}

The catch: luminosity

As the delivered luminosity increases, ECAL must maintain good trigger performance

Crystal transparency loss

Direct APD signals

The catch: luminosity

As the delivered luminosity increases, ECAL must maintain good trigger performance

Crystal transparency loss

- $PbWO_4$ crystals have short X_0, small R_M, fast scintillation time
- Irradiation leads to formation of **color centers** due to oxygen vacancies + lattice impurities
- Two types of radiation damage:
    - Electromagnetic damage: **dose rate** dependent, partially recoverable via **annealing** at room temperature
    - Hadron damage: **dose**-dependent, non-recoverable

Direct APD signals

The catch: luminosity

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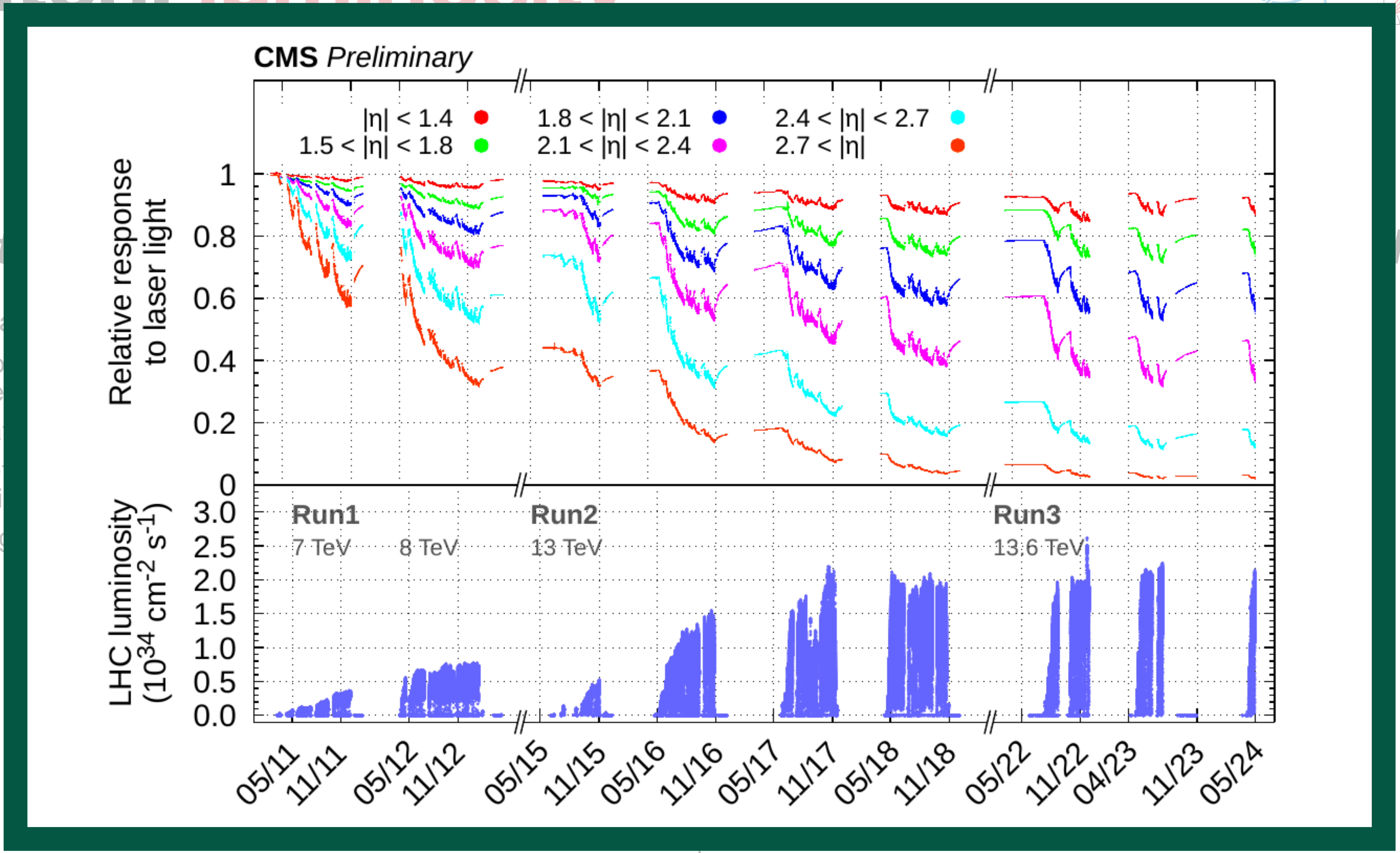

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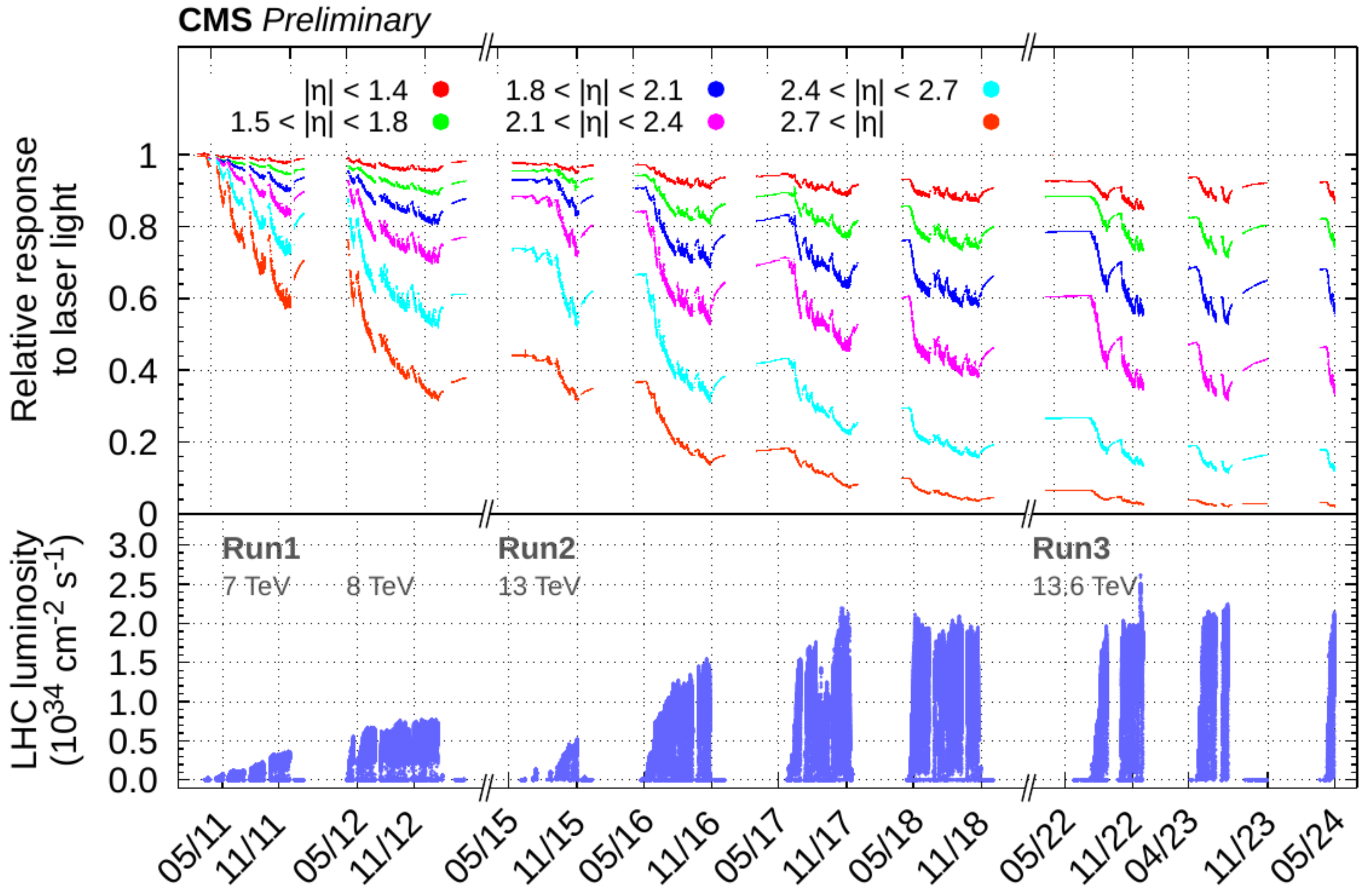
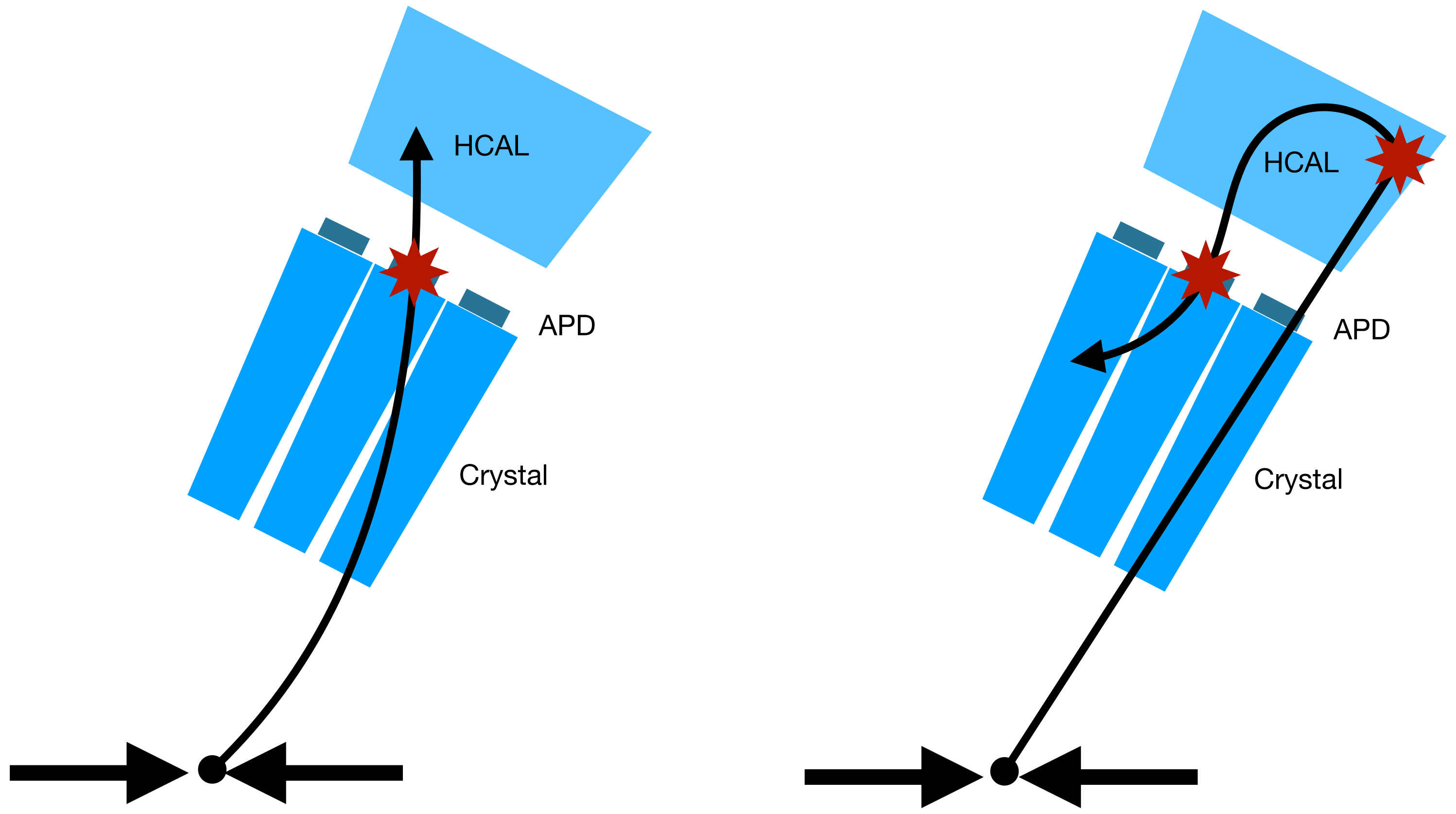


Direct APD signals

- Large apparent energy pulses ("**spikes**") are induced by direct hadronic ionization of APDs



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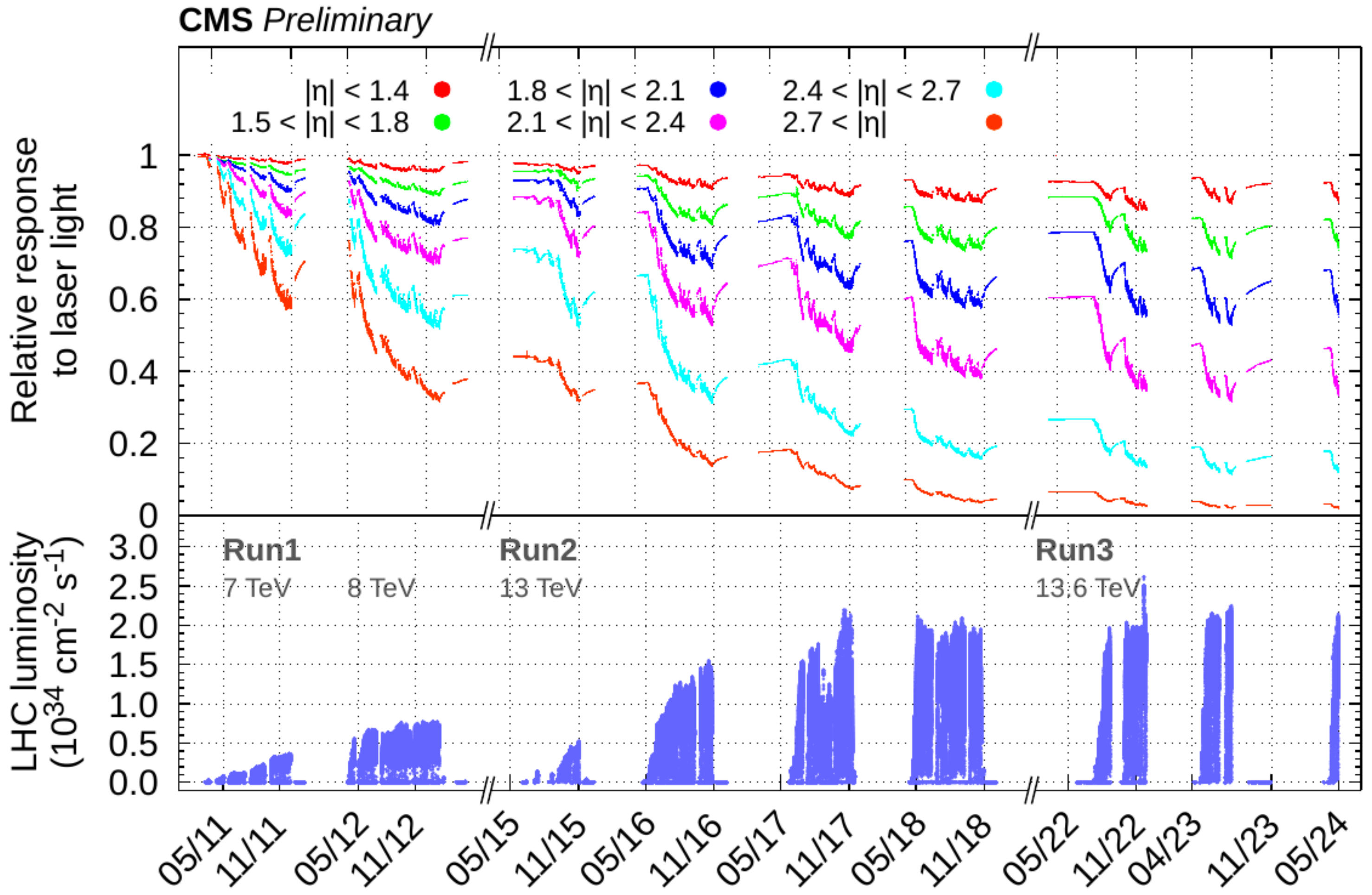

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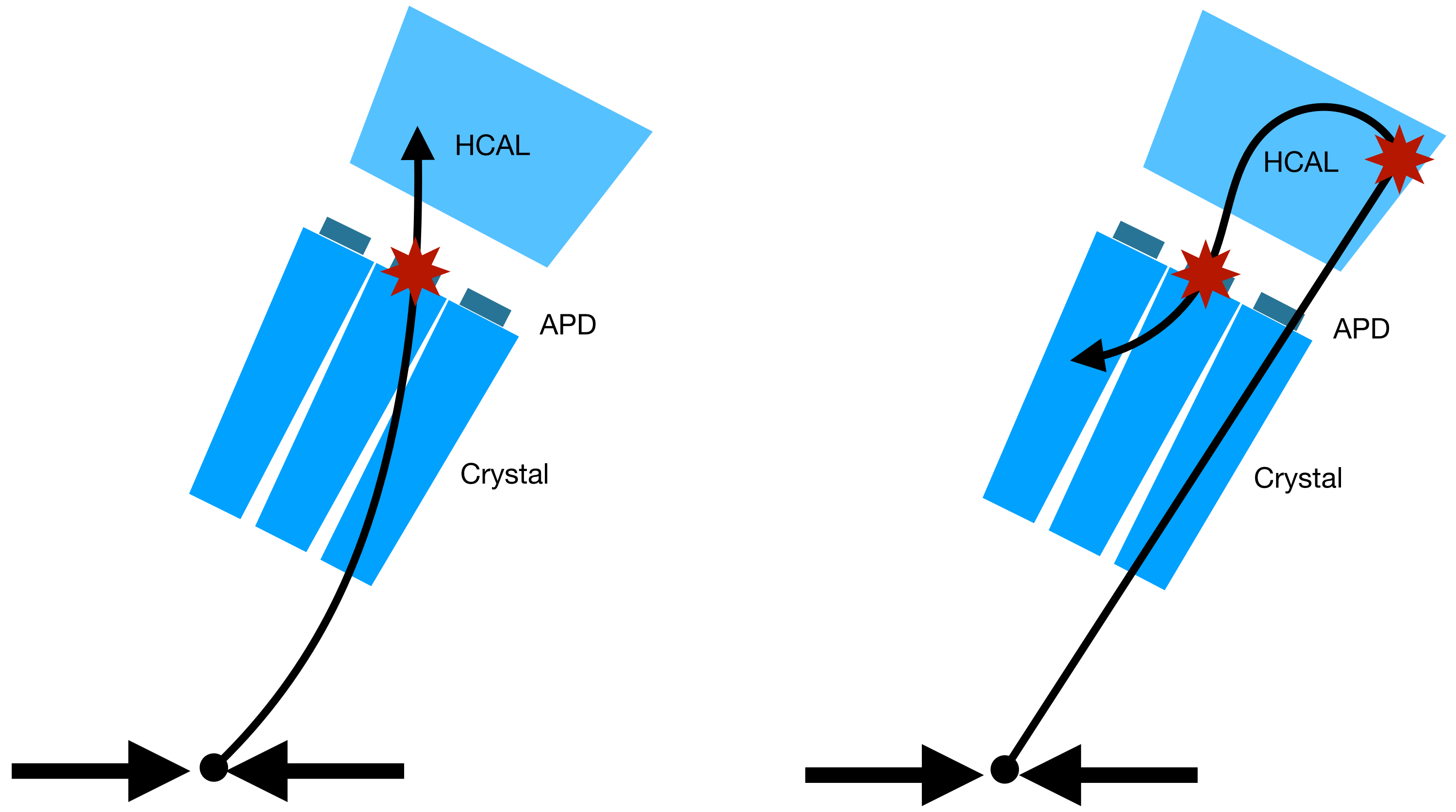

- Unmitigated, spikes would saturate the trigger bandwidth at L1
  - Risk introducing significant biases in electron, photon, jet, and MET energy reco
- Spikes become more prevalent with higher instantaneous luminosity/pileup

The catch: luminosity

As the delivered luminosity increases, ECAL must maintain good trigger performance

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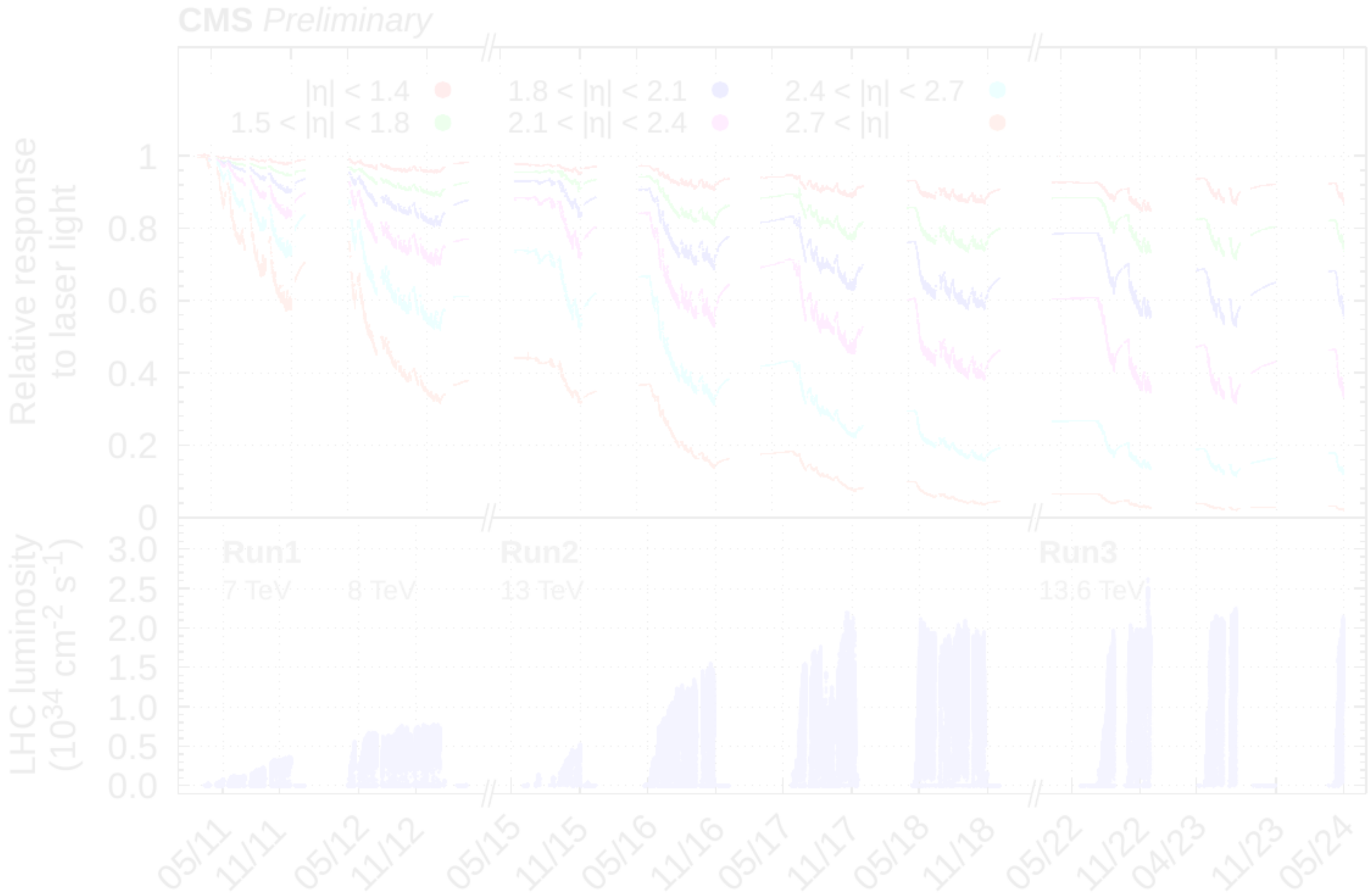
Approach:

- Better tracking of response changes at L1 and HLT

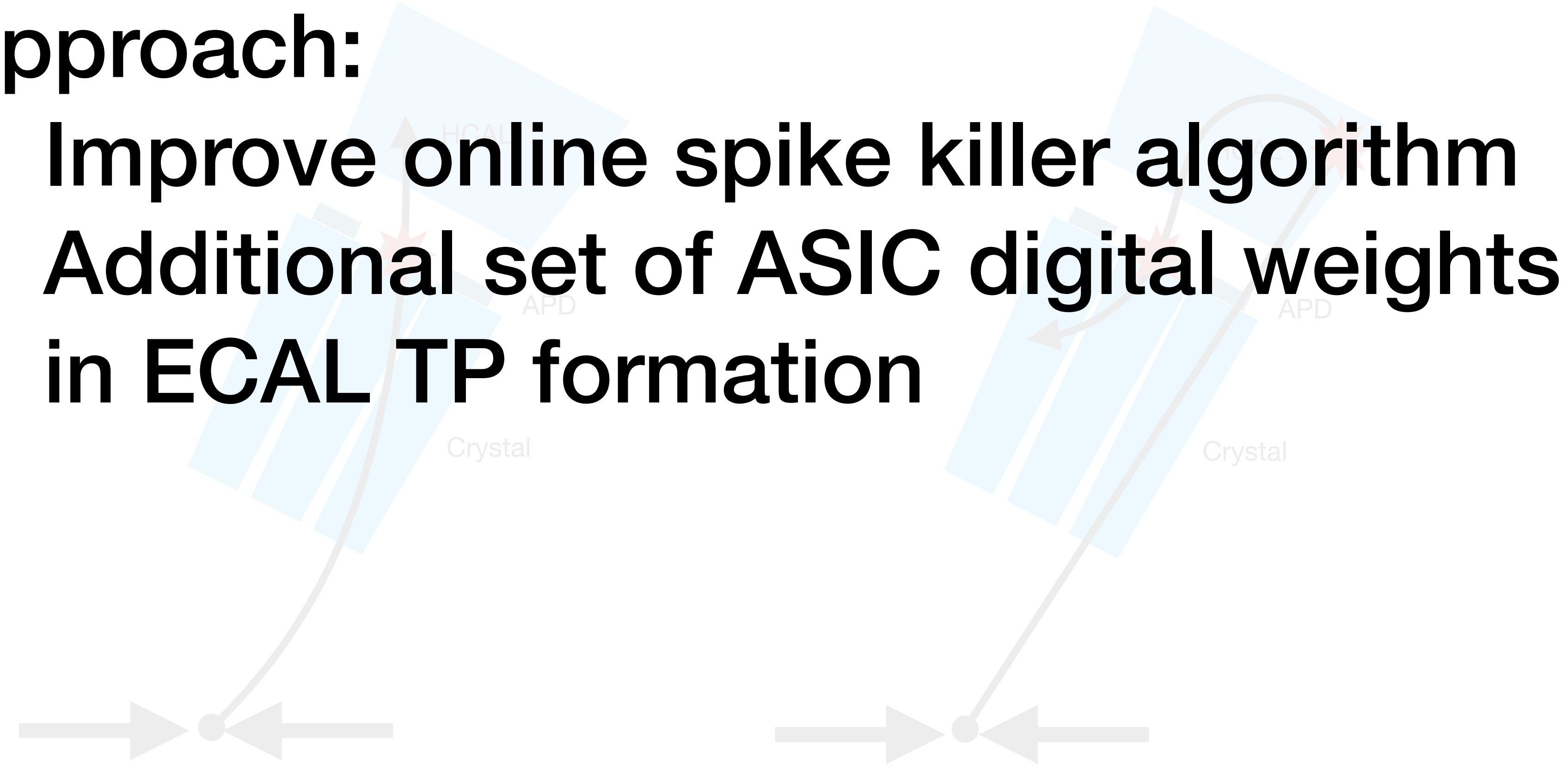


Direct APD signals

- Large apparent energy pulses ("**spikes**") are induced by direct hadronic ionization of APDs

Approach:

- Improve online spike killer algorithm
- Additional set of ASIC digital weights in ECAL TP formation



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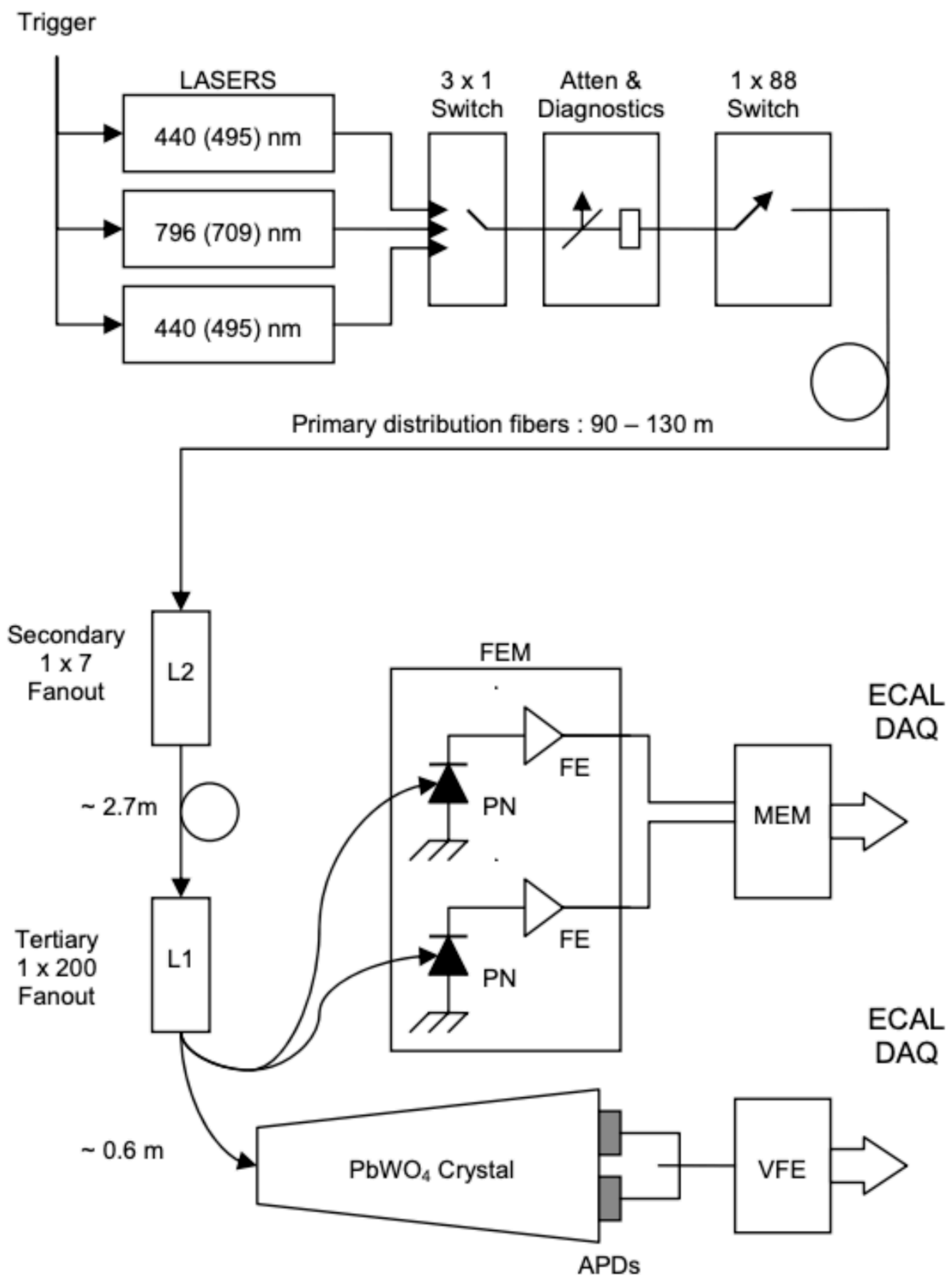
Measuring crystal transparency

- ECAL has a **dedicated laser system** which fires at each crystal once per 40-min cycle during collisions
- Transparency measurements processed → give corrections to stabilize per-channel response over time
  - Lower amplitude → larger correction
- Corrections validated and inserted into **offline database** → used for prompt reco within 48h
- At L1/HLT, transparency corrections are updated during each LHC interfill
- See talk by M. Tornago for further information

LHC Run	1	2	
Year(s)	2012	2015–16	2017–18
Corrections Method	• Once per week • η ring granularity • EE only	• Once per week • Per-crystal granularity • EE+EB	• Twice per week • Per-crystal granularity • EE+EB



Changes for Run 3

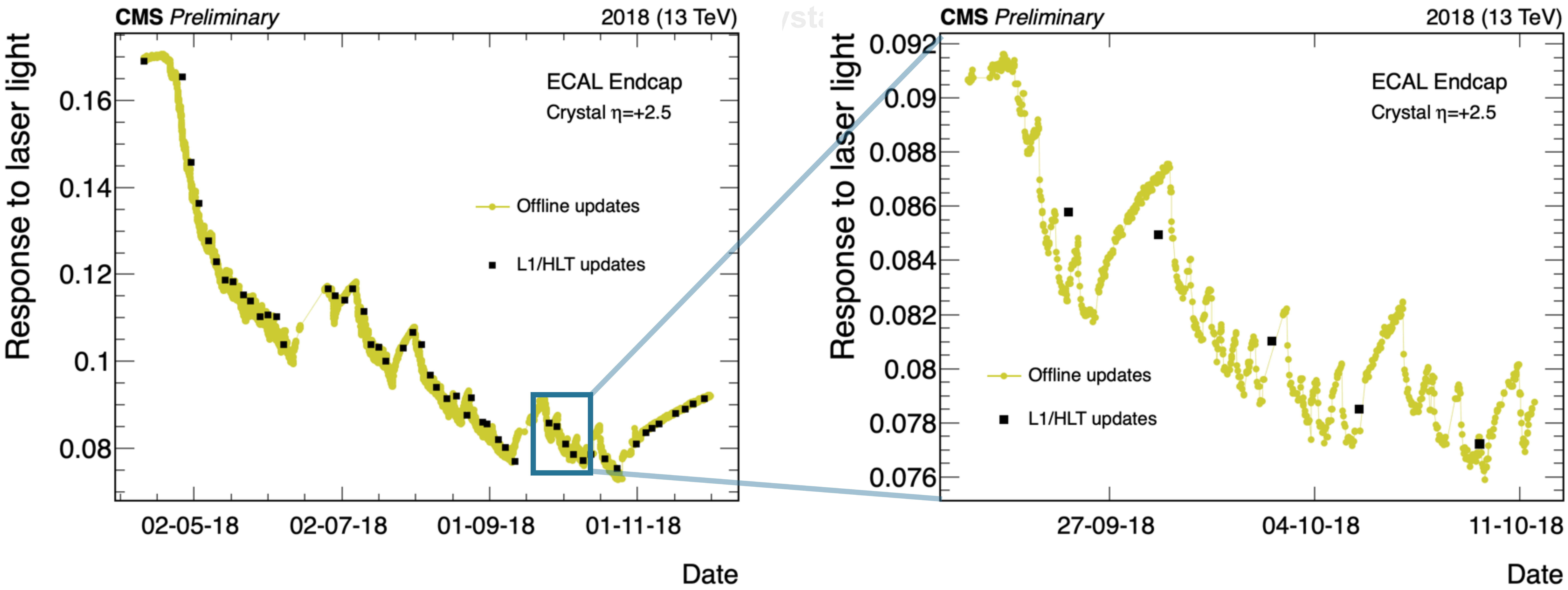
- Method updated ahead of Run 3 to implement **per-crystal**, **once-per-LHC-fill** laser transparency updates across **EE & EB**

Changes for Run 3

Twice per week…

Full-year run

Three-week period



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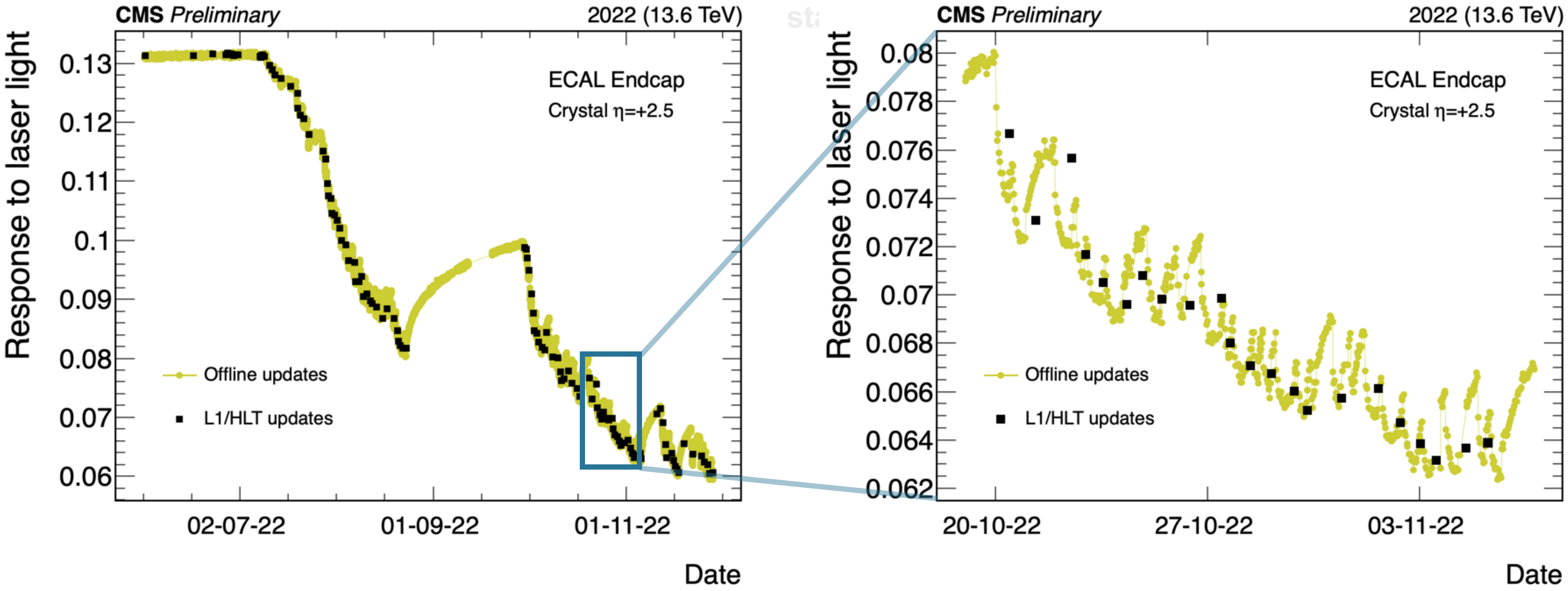
Changes for Run 3

…vs *once per fill*


Full-year run

Three-week period

Once-per-fill updates capture more granularity in crystal transparency changes compared to twice-per-week

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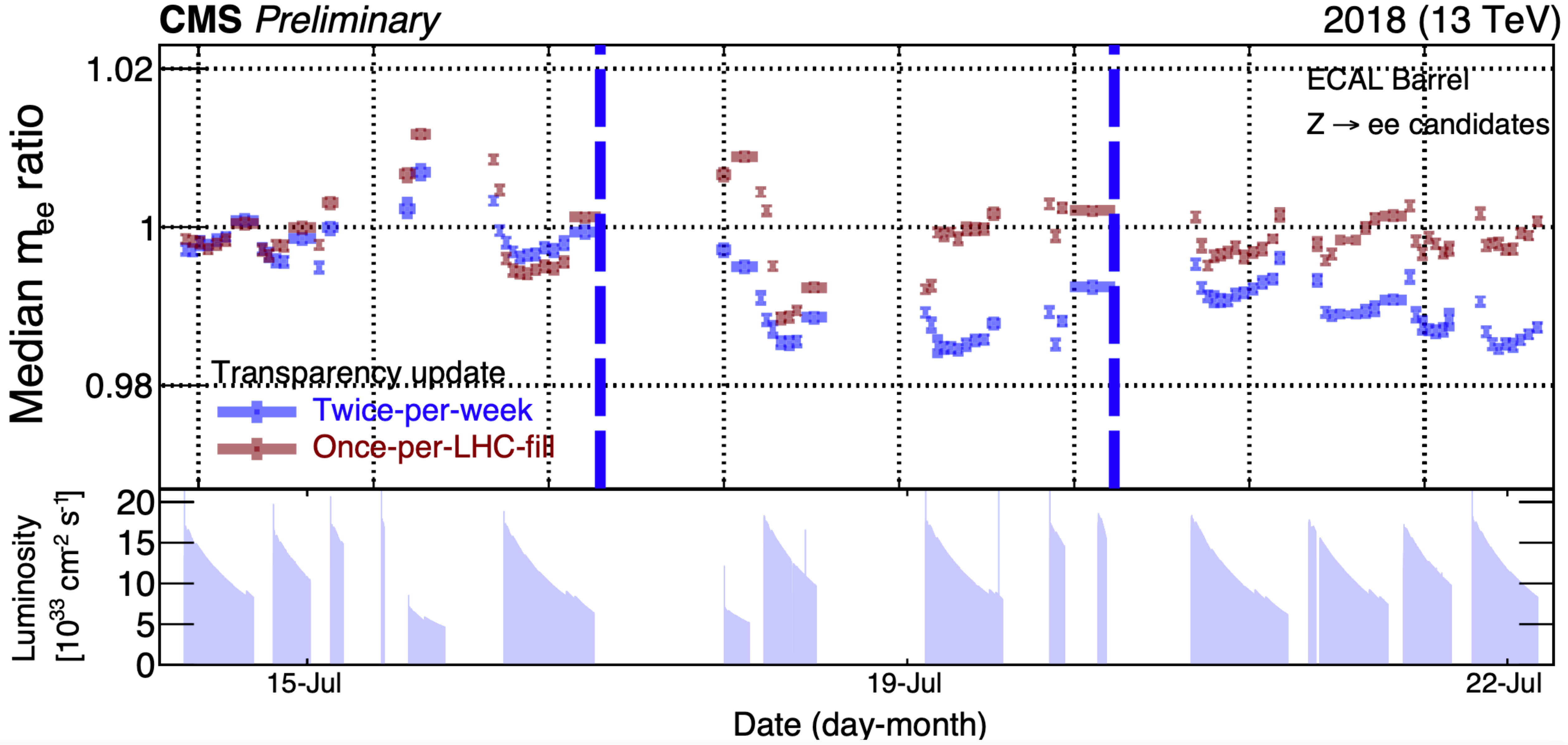
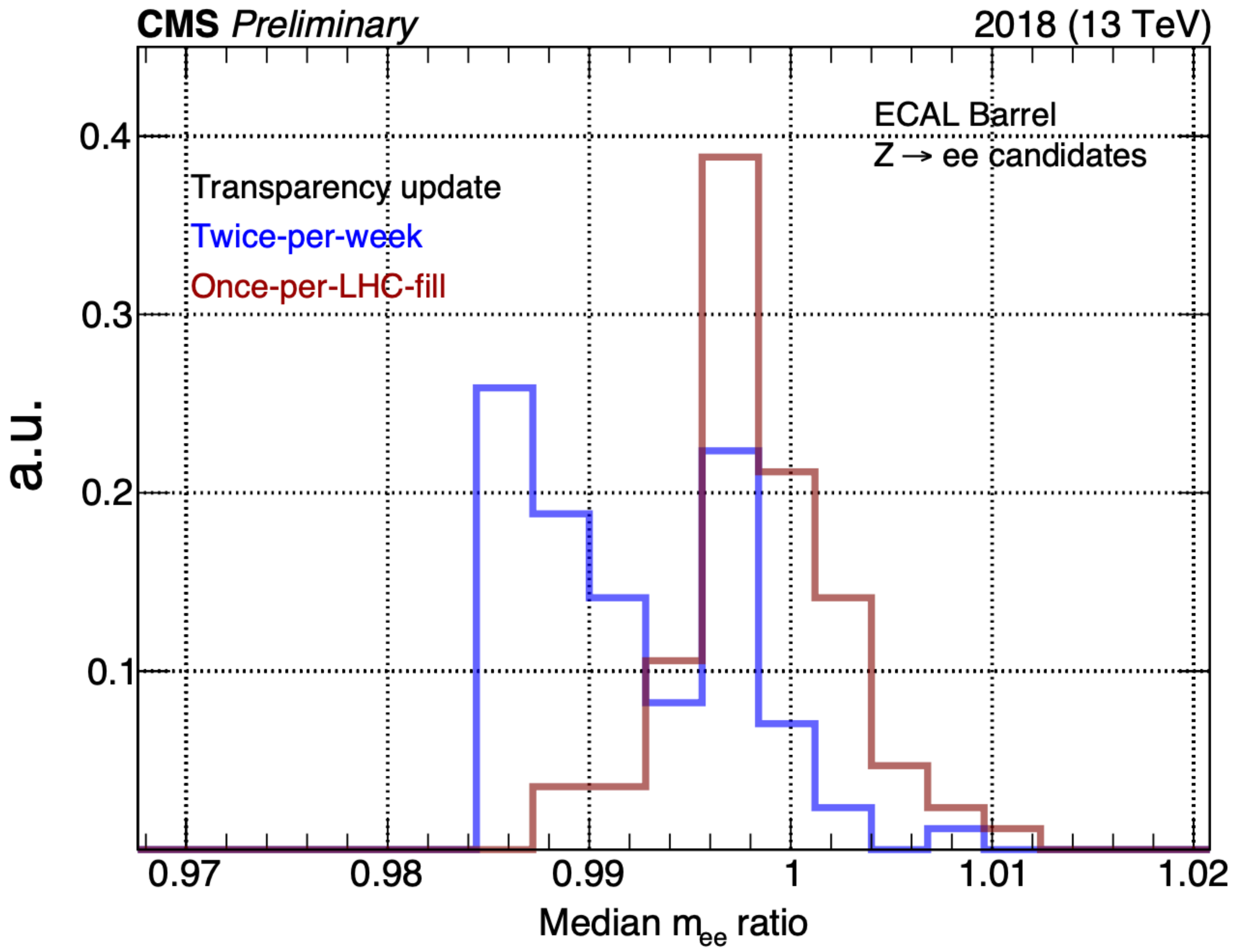
Changes for Run 3

- Method updated ahead of Run 3 to implement **per-crystal**, **once-per-LHC-fill** laser transparency updates across **EE & EB**
- $Z \rightarrow ee$ mass ratio compared to full offline results → once-per-fill scheme results in **more stable energy scale**





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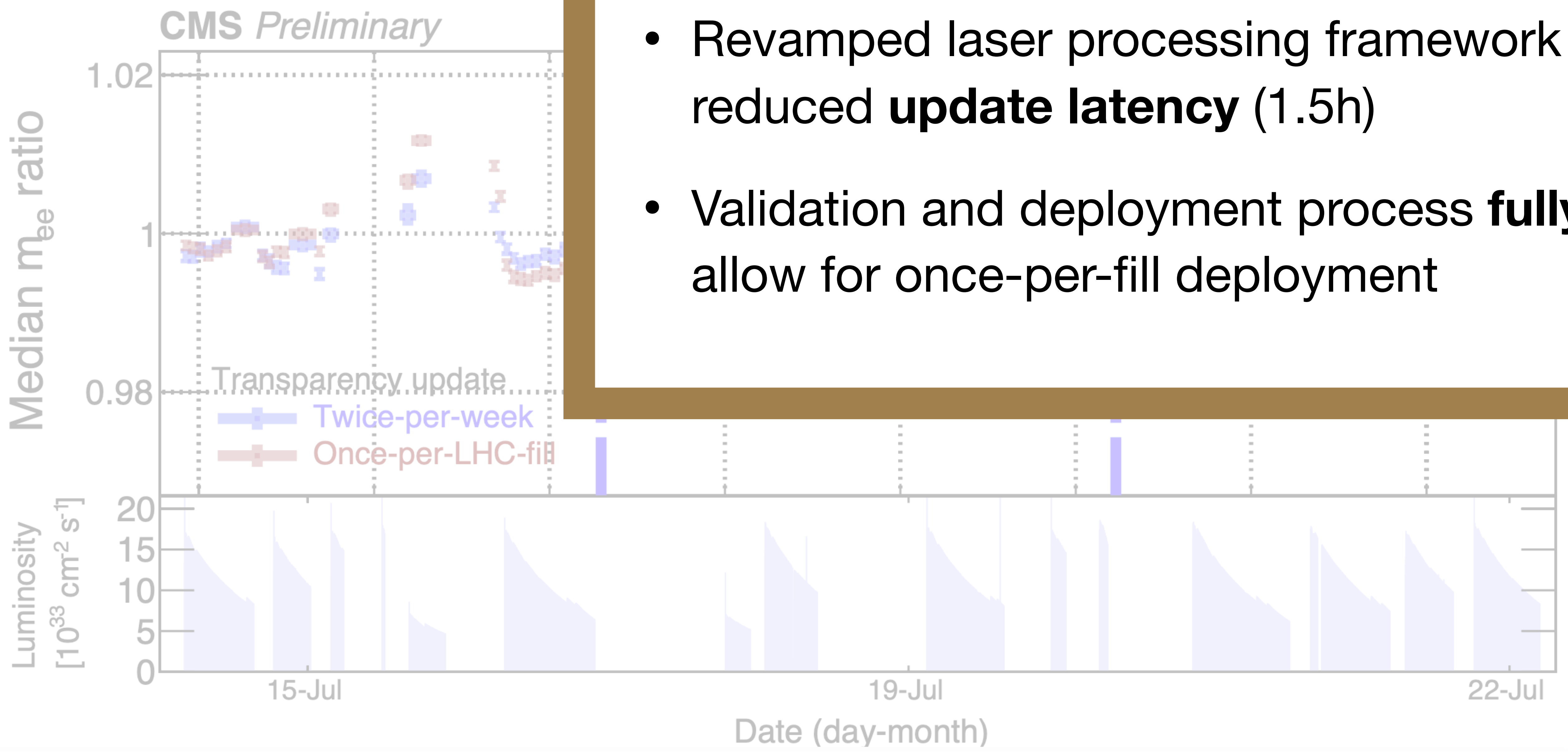
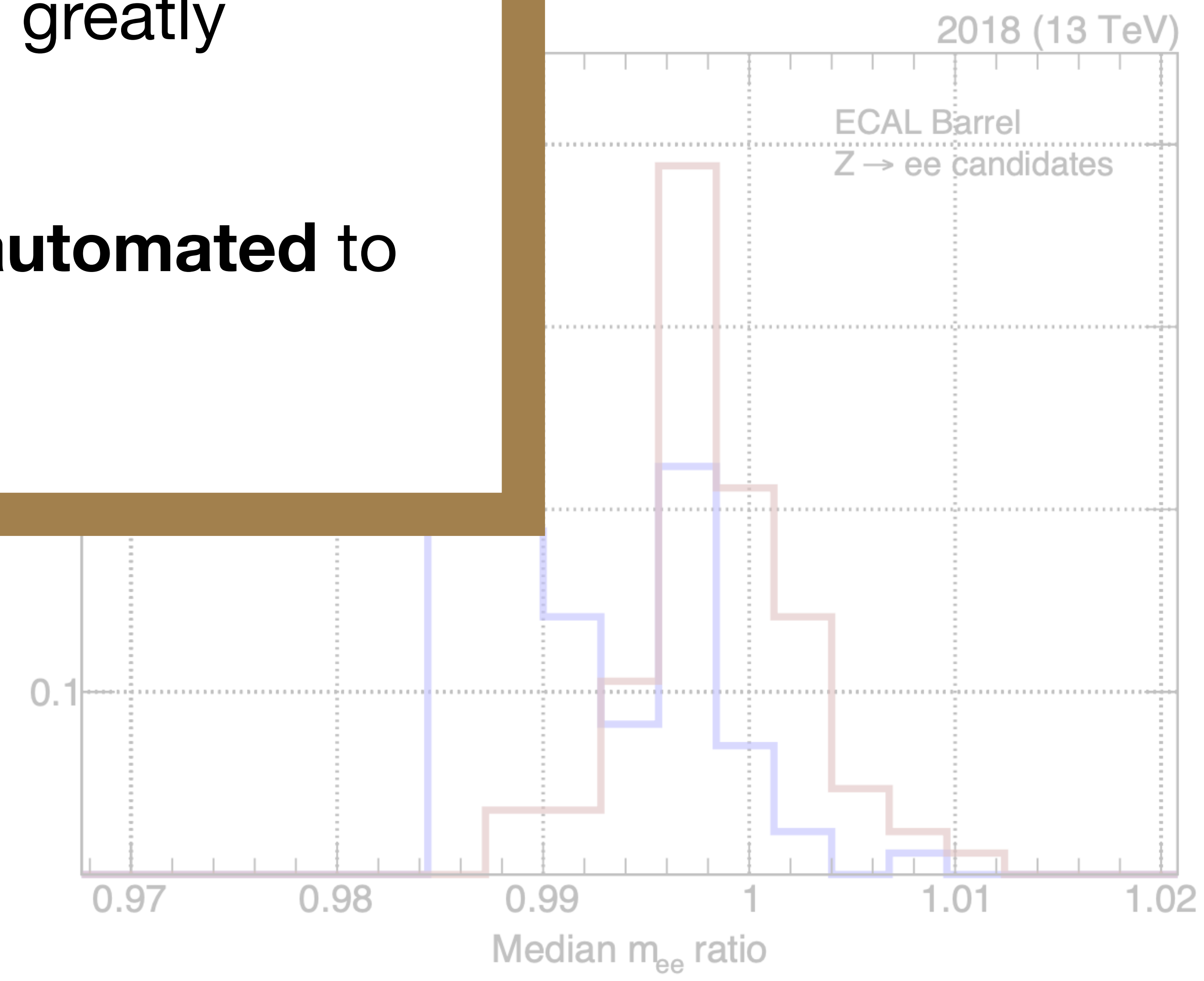
How is this accomplished?

- Revamped laser processing framework → greatly reduced **update latency** (1.5h)
- Validation and deployment process **fully automated** to allow for once-per-fill deployment



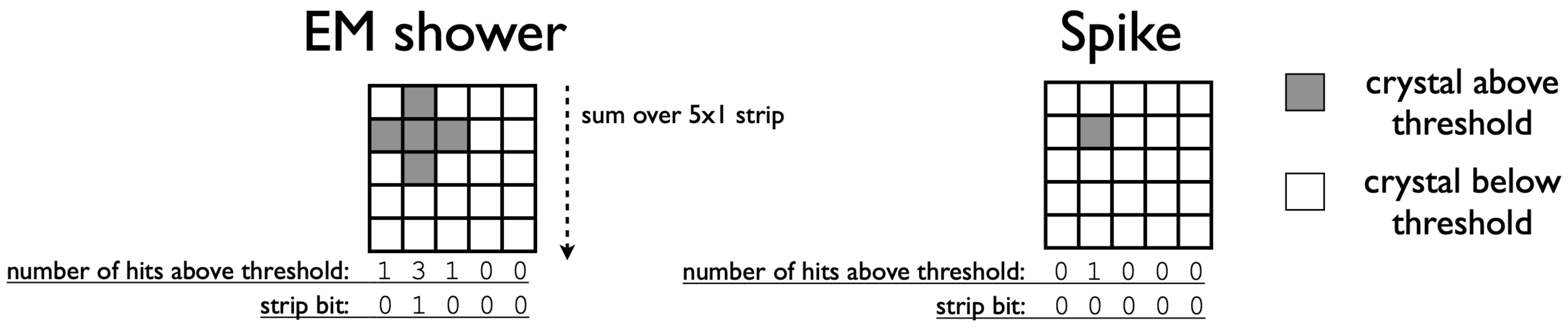


Spikes and the art of rejecting them

ECAL uses a combination of **online** and **offline** spike killing to reduce the impact of spikes

Online

- **Strip Fine Grain Veto Bit (sFGVB)** exploits the spike deposit shape in a single TT

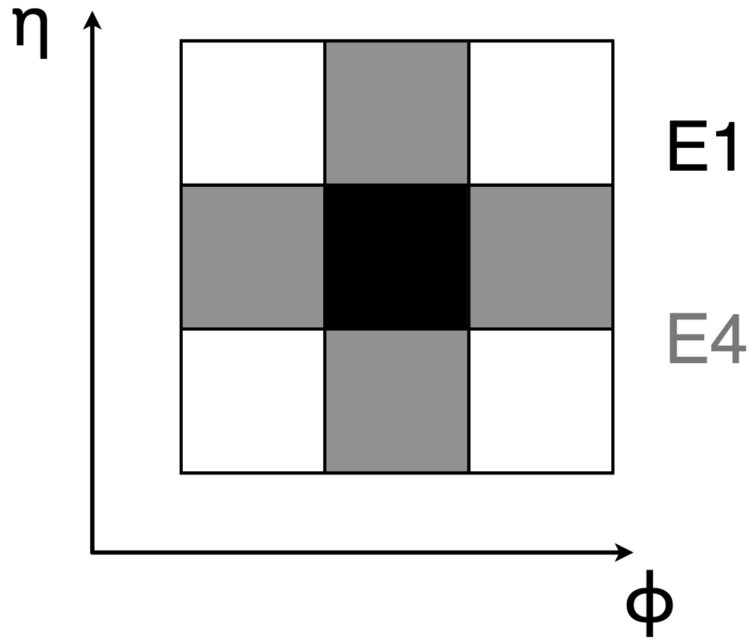


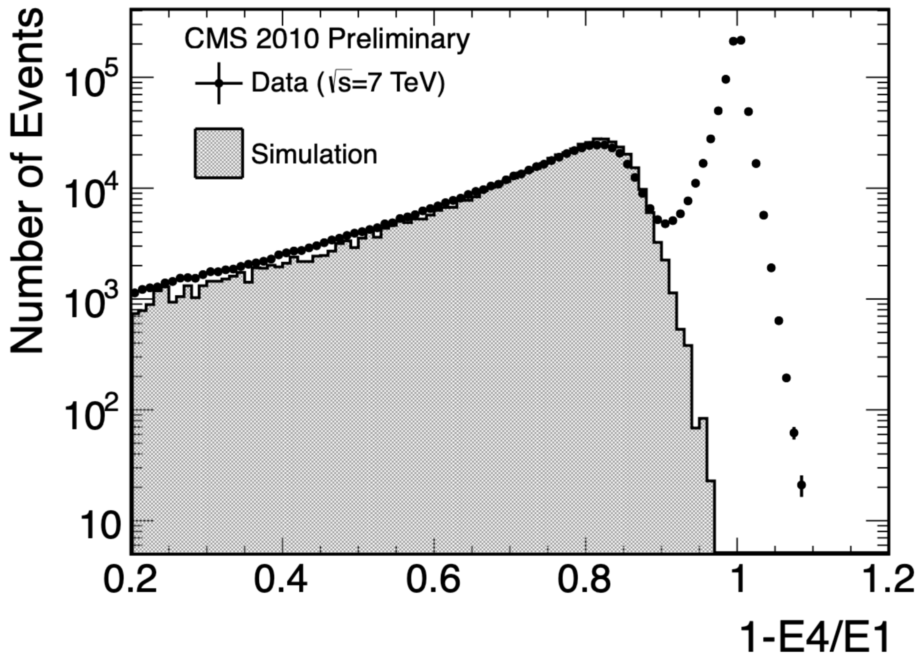
sFGVB result: **1** (shower-like) sFGVB result: **0** (spike-like)

- If E_T^{tow} > killing threshold AND sFGVB == 0 → no trigger
- sFGVB rejects >95% of spikes above 8GeV with minimal impact on electron trigger efficiency

Offline

- Use “Swiss cross” variable: $SC = 1 - \frac{E_4}{E_1}$





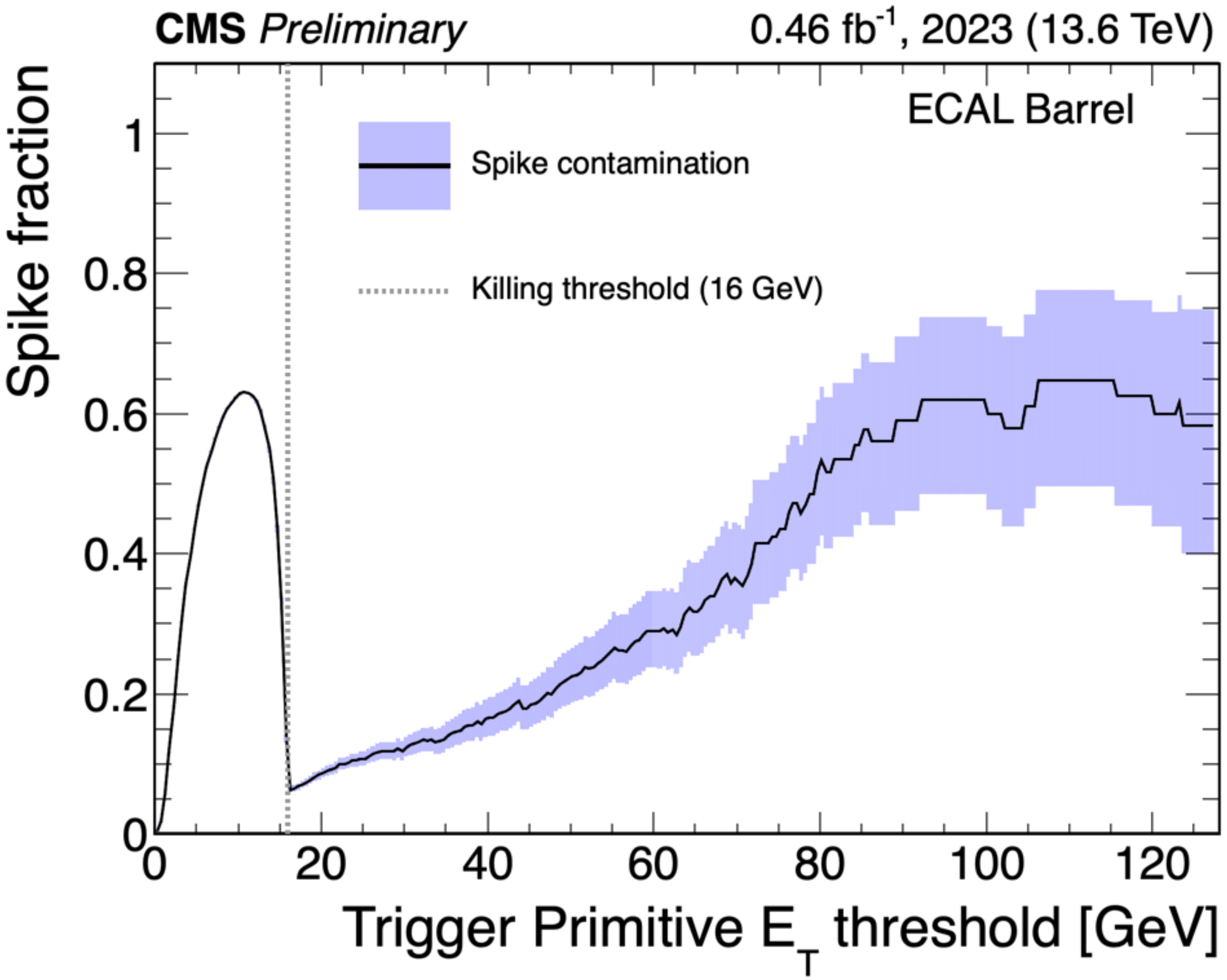
- SC exploits anomalous energy sharing between crystals in spikes
- Cut of SC > 0.95 → 99% spike rejection above 10 GeV, minimal impact on EM shower selection efficiency

See proceedings from CALOR 2012

Spikes and the art of rejecting them

- Spike killer implemented since 2011
- Requires retuning with changing luminosity conditions
- Retuned during LHC long shutdown 2 (LS2) ahead of Run 3 to cope with higher PU and expected photodetector noise
    - 16 GeV killing threshold → 12% contamination at 30 GeV
    - Lower energy spikes not removed at L1

*What if we could **reduce low-energy spikes** by targeting ones that are **out-of-time**…*
*and what if we could do it **online**?*



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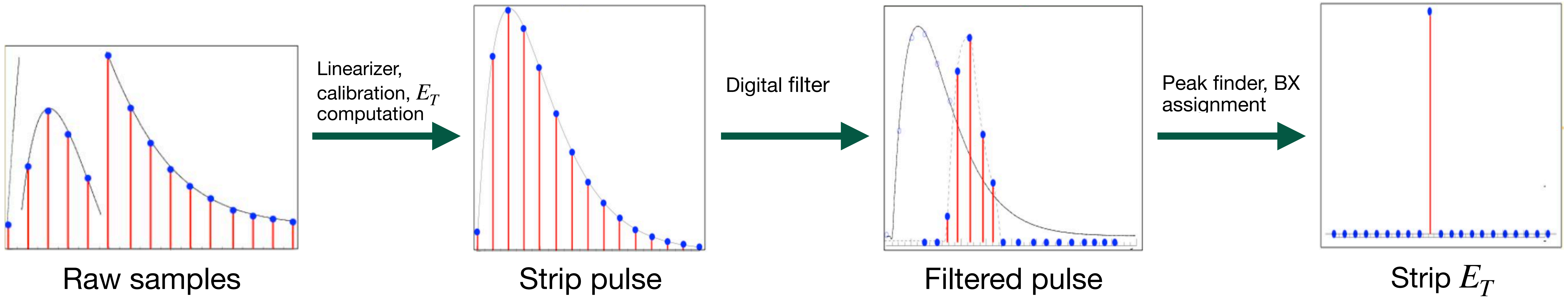
ECAL TPs: a deeper dive

- Trigger primitives from ECAL consist of quality bits + **measurement of E_T**
- On-detector ASICs perform amplitude reco using digital filter (“weights”) on digitized pulse



Linearizer, calibration, E_T computation

Digital filter

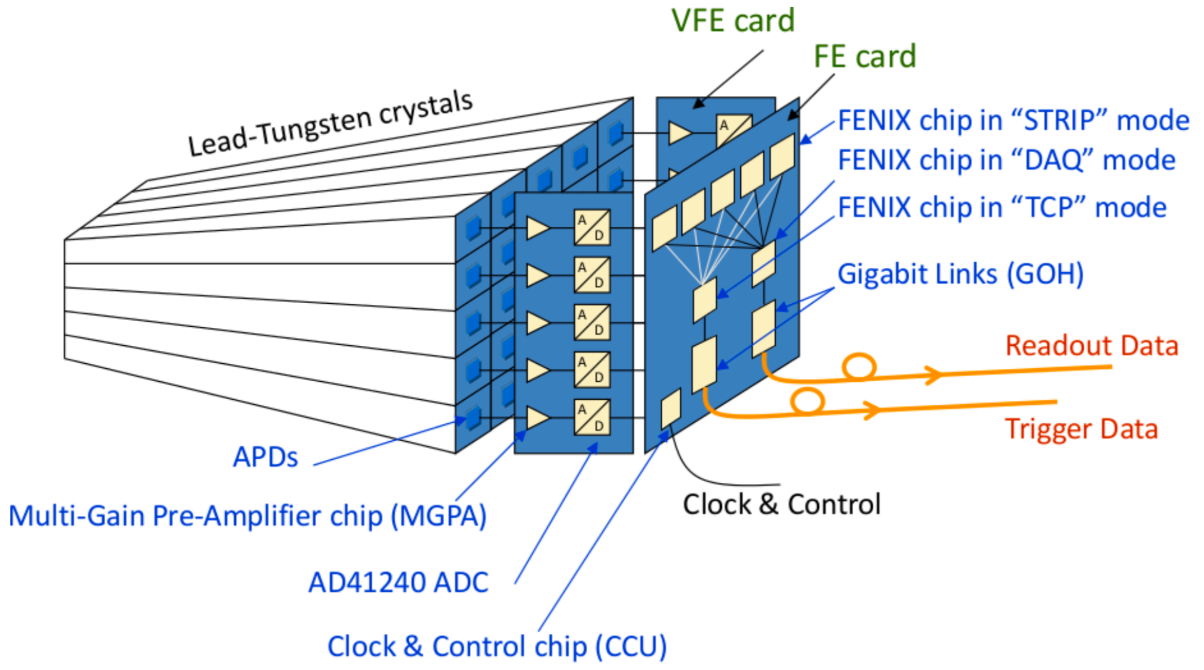
Peak finder, BX assignment

Raw samples

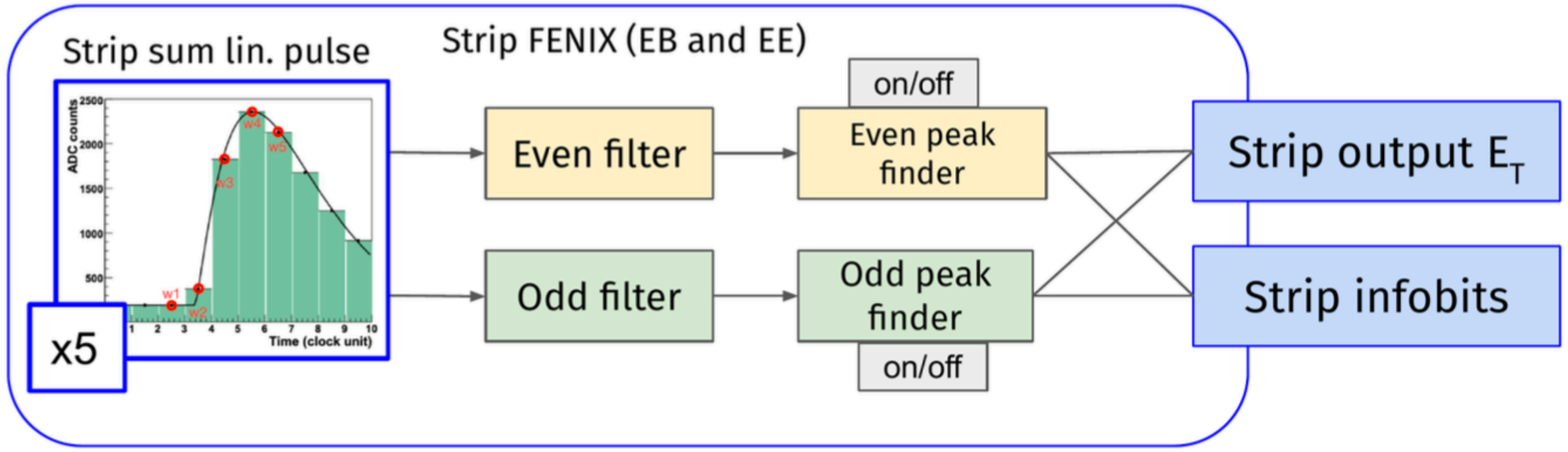
Strip pulse

Filtered pulse

Strip E_T



- These (“EVEN”) weights are fully configurable: can be derived for a given waveform
- Following Run 2, **second set** (“ODD”) of tunable then-unused weights in ECAL ASICs was explored as an **out-of-time tagger**



Strip sum lin. pulse

Strip FENIX (EB and EE)

Even filter

on/off

Even peak finder

Strip output E_T

Odd filter

Odd peak finder

on/off

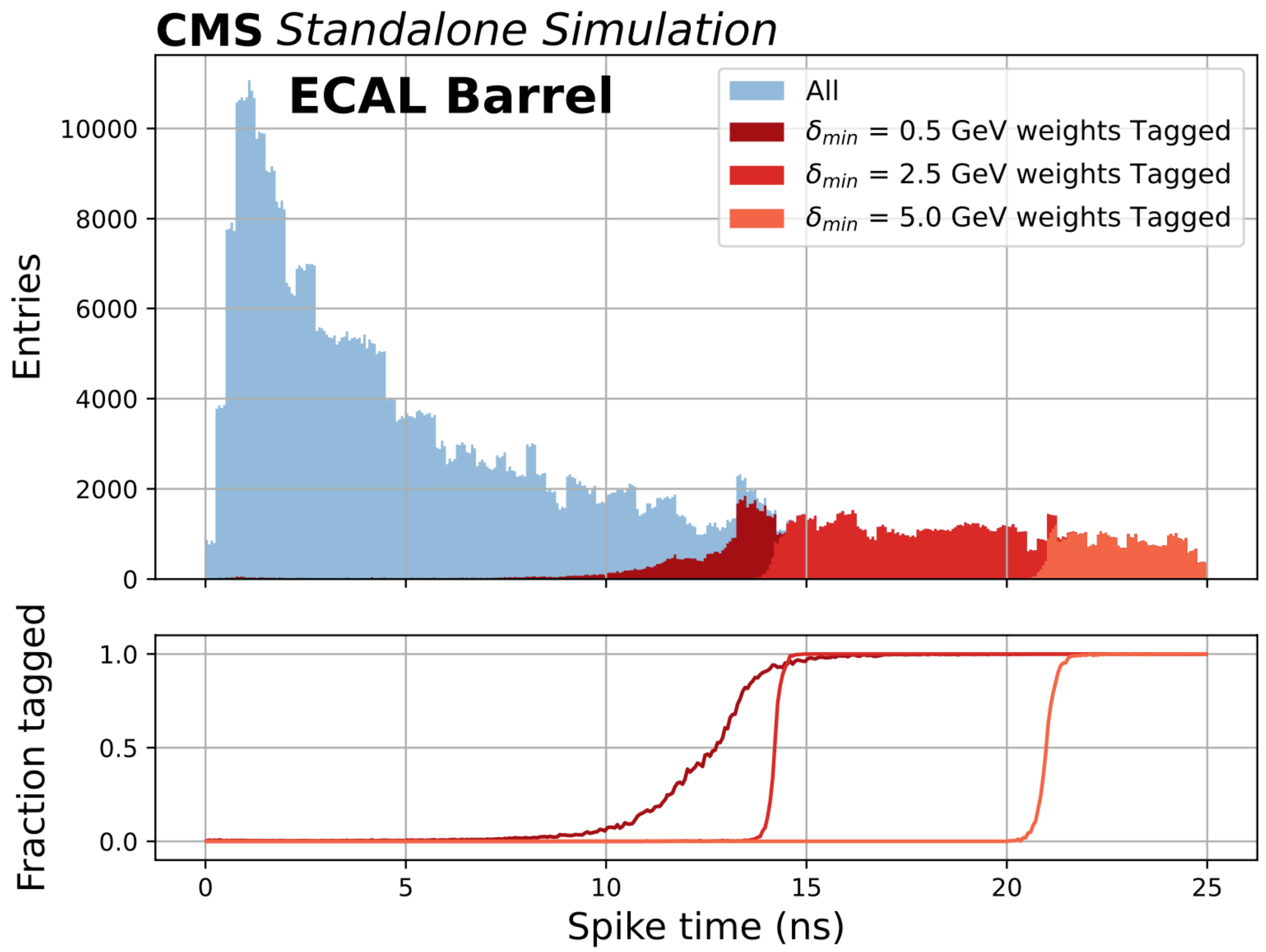
Strip infobits

x5

The **double weights** mechanism

Derivation

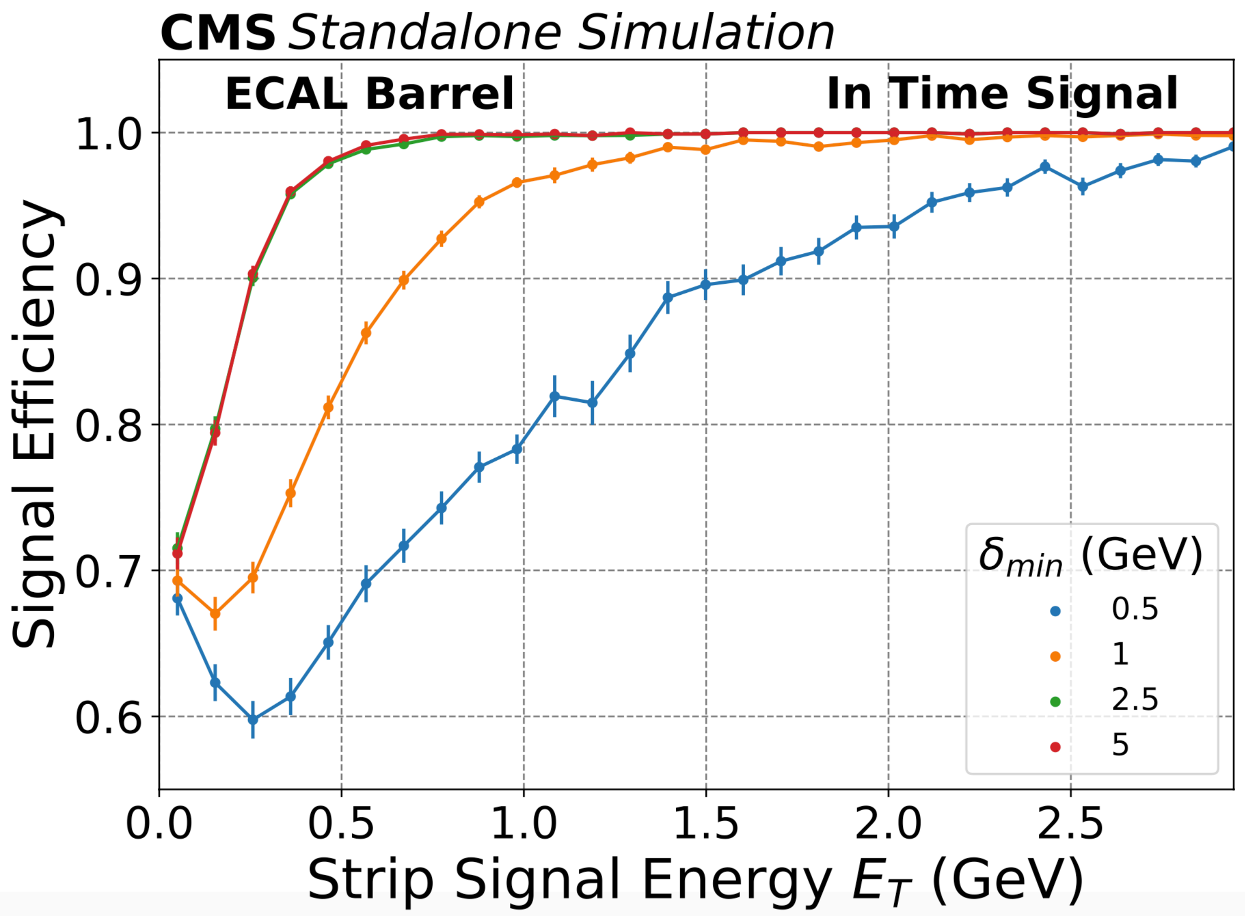
- Presently, the weights have been optimized to target **late (+10ns) spikes**
- ODD weights candidate values computed via numerical optimization with loss function
  - Explored favoring signal retention, spike efficiency
  - Computed for several working points of $\delta_{min} = E_T^{ODD} - E_T^{EVEN}$
  - Plots shown here use δ_{min} of 2.5 GeV



Usage

- The **double weights** mechanism relies on duplicating the EVEN weights data path and comparing the weighted sums of strip digitized pulses
  - If $E_T^{ODD} - E_T^{EVEN} \geq \delta_{min} \rightarrow$ tag
  - If $E_T^{ODD} - E_T^{EVEN} < \delta_{min} \rightarrow$ do nothing

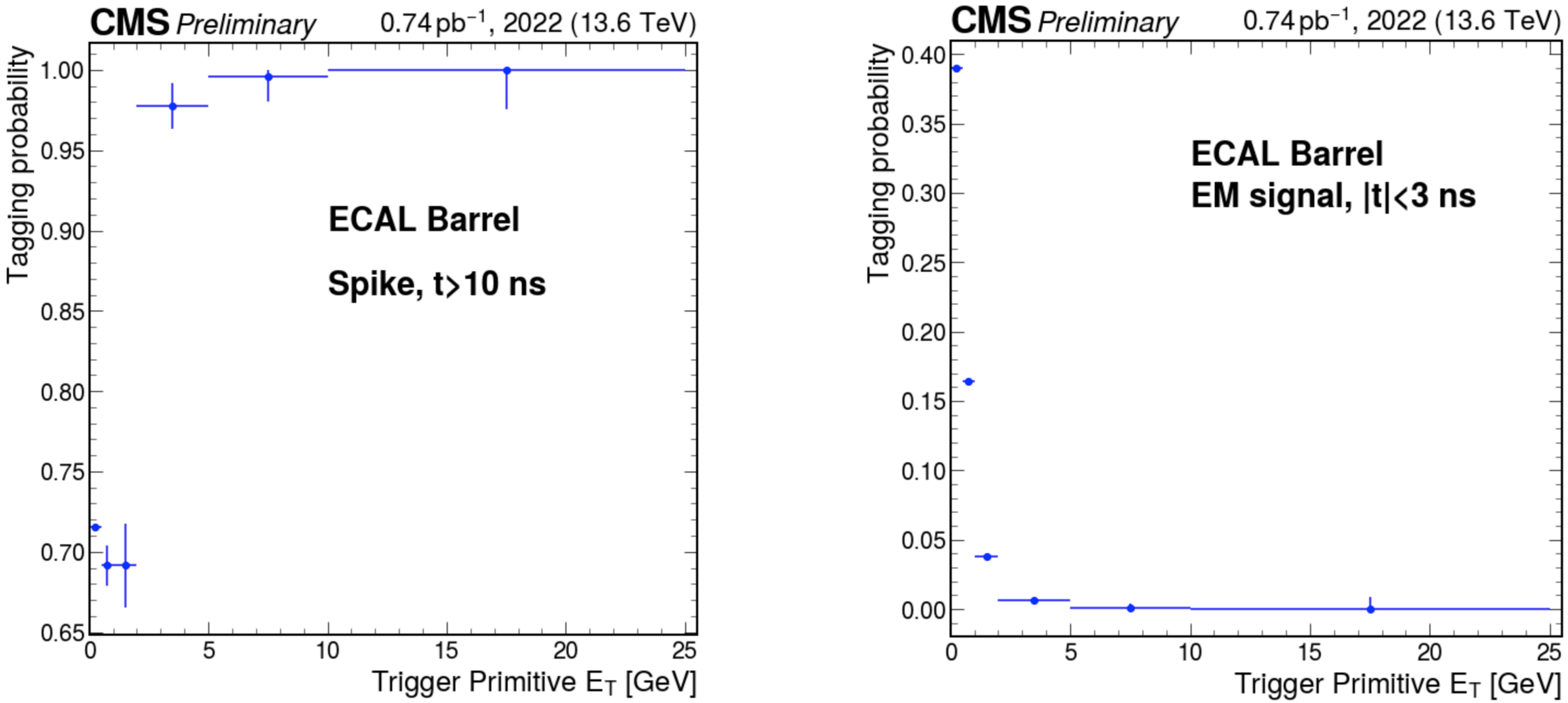
where $$E_T = \sum_{i=1,\ldots,5} S_i \times w_i$$



δ_{min} (GeV)	Signal efficiency (%)	Spike rejection (%)
0.5	78.2	77.6
2.5	95.6	62.5
5.0	95.7	19.2

How do the double weights **perform**?

- Double weights flag **more than 99%** of out-of-time spikes above $E_T \geq$ 5GeV while mis-tagging **less than 1%** of real EM signals above $E_T \geq$ 2GeV



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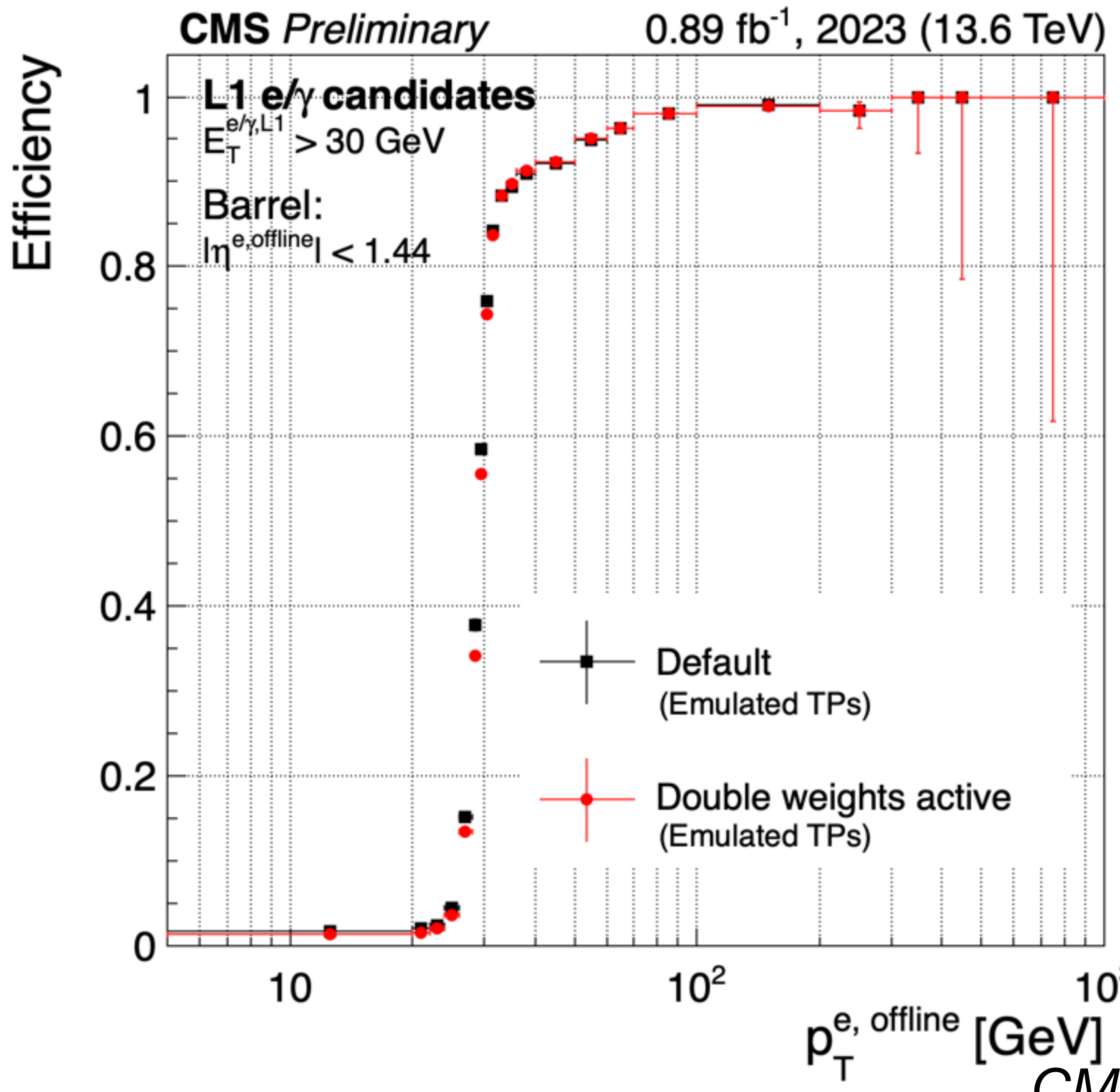
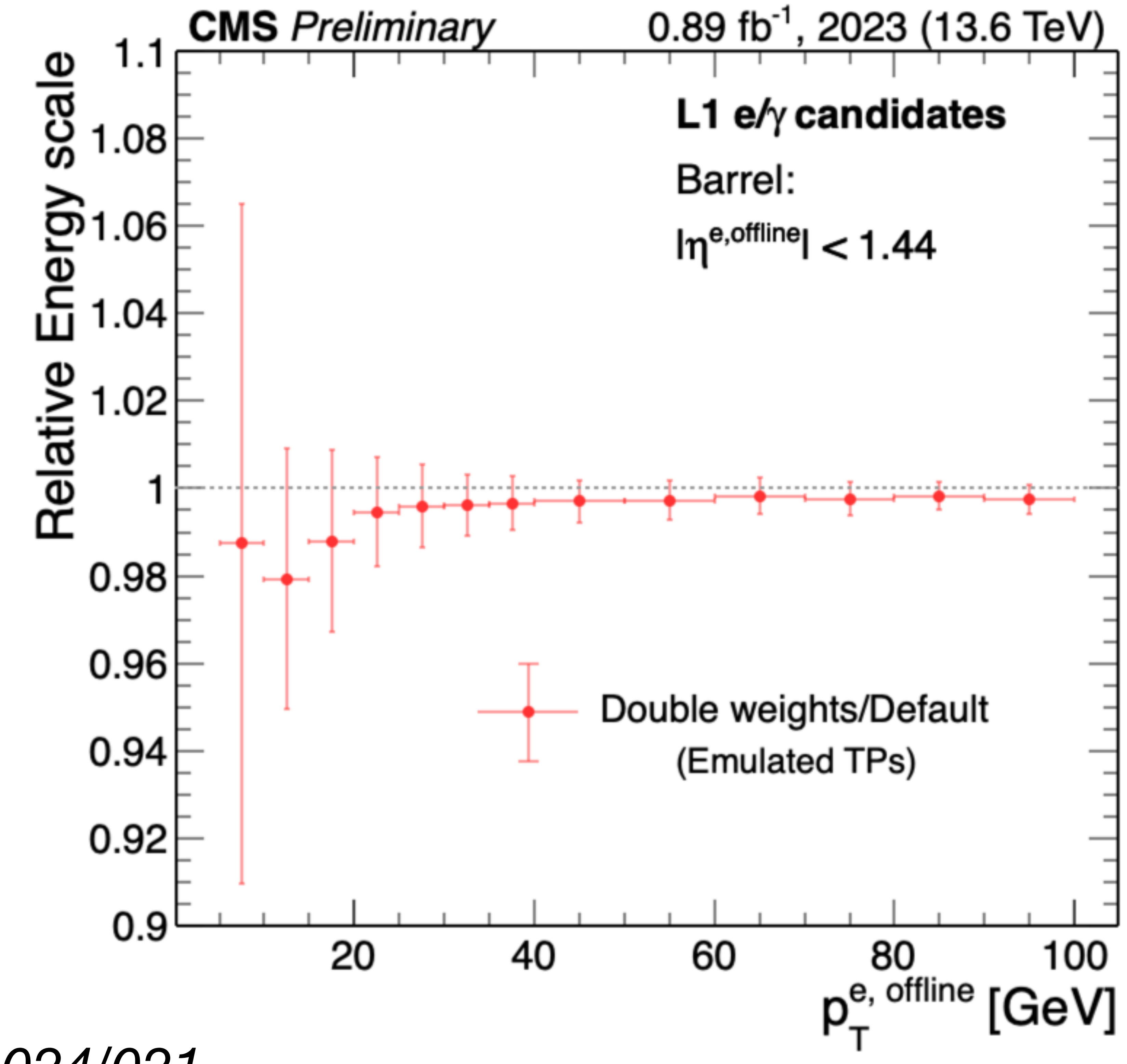
- Electron/photon **triggering efficiency** and **L1 energy scale** are not significantly impacted by double weights





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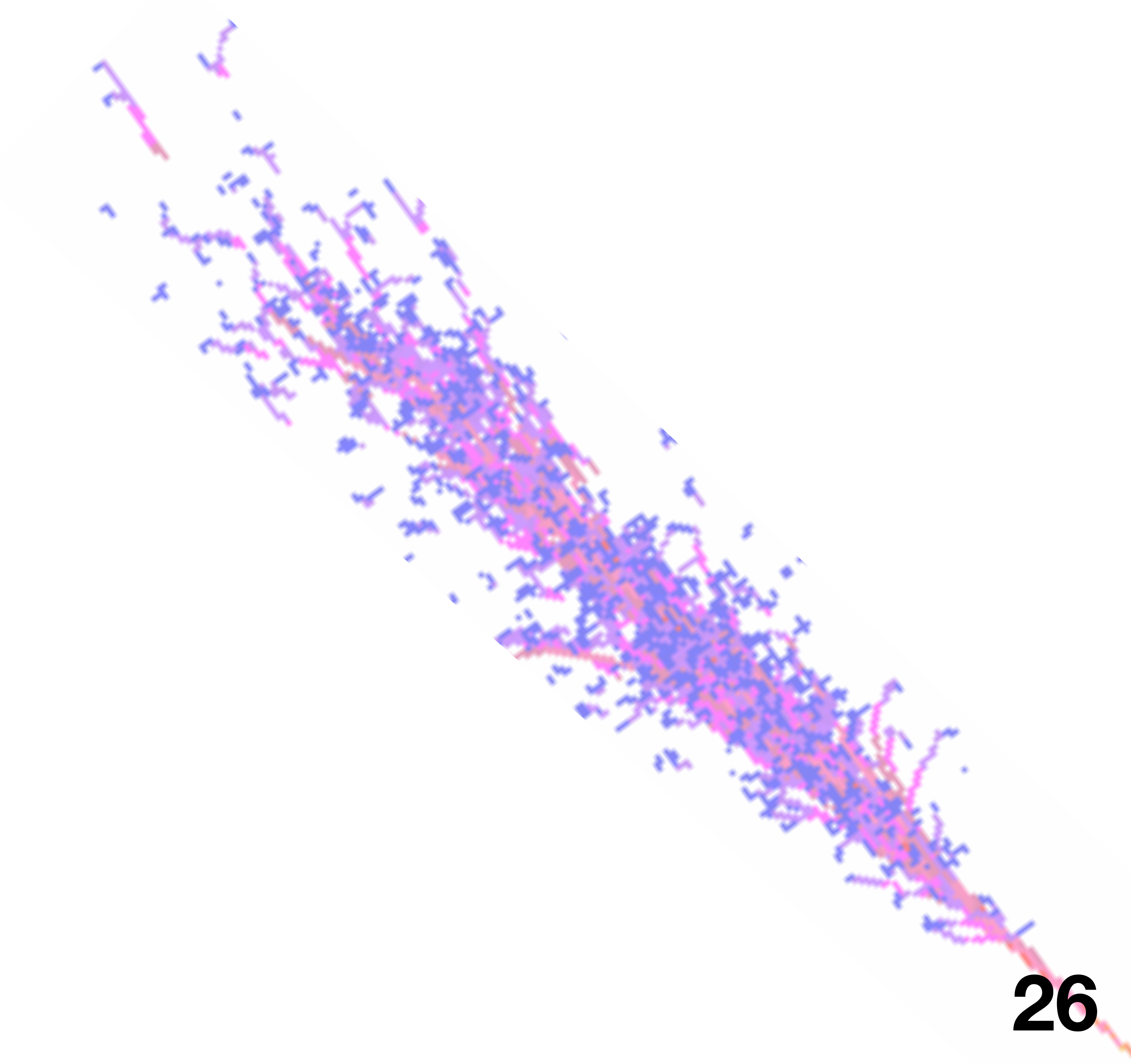
Conclusions: meeting the challenges of Run 3

- The CMS ECAL plays a central role in the functionality and performance of the **CMS trigger system** at L1 and HLT
- In Run 3, the **increased instantaneous luminosity** compared to earlier years poses a challenge to maintaining good trigger performance
  - The impacts of **crystal transparency loss** and **direct APD pulses** in EB become more severe with increasing luminosity
- These are addressed in Run 3 with:
  - A revamped transparency **validation and deployment** system allowing for **per-fill updates** at per-crystal granularity
  - A retuned **online spike killer**
- Moreover, a new functionality in the strip FENIX ASIC is being explored to **mitigate late spikes at L1**
  - The double weights mechanism appears to benefit spike killing without significant impact on signal efficiency or energy scale but require some final investigation and quantification of improvement before deciding whether to implement online

Thank you!



Backup

Double weights numerical optimization

- Sets of ODD weights, $\{W_{2,i}\}$, obtained from gradient descent with the following loss function

$$L = (\lambda_{sig} \times L_{sigEff}) + (\lambda_{spk} \times L_{spkRej}) + (\lambda_{Norm} \times W2LN) + W2LL$$

$$L_{sigEff} = \begin{cases} (A_{W_2,d_1} - A_{W_1,d_1}) \geq \delta_{min} : & (A_{W_2,d_1} - A_{W_1,d_1}) \\ (A_{W_2,d_1} - A_{W_1,d_1}) < \delta_{min} : & 0 \end{cases}$$

$$L_{spkRej} = \begin{cases} (A_{W_1,d_2} - A_{W_2,d_2}) \geq \delta_{min} : & (A_{W_2,d_1} - A_{W_1,d_1}) \\ (A_{W_1,d_2} - A_{W_2,d_2}) < \delta_{min} : & 0 \end{cases}$$

$$W2LN = \sum_{i=1}^{5} |W_{2,i}|$$

$$W2LL = \begin{cases} W2LN < 1 : & 0 \\ W2LN \geq 1 : & W2LN \times (-100) \end{cases}$$

$$A_{W_x,d_x} = \sum_{i=1}^{5} W_{x,i} \times d_{x,i}$$

$W_{x,i}$: EVEN ($x = 1$) and ODD ($x = 2$) weights

$d_{x,i}$: signal ($x = 1$) and spike ($x = 2$) digis

- Tunable λ parameters
  - λ_{sig}, λ_{spk} : prioritize signal efficiency or spike rejection (1.5, 0.5 chosen)
  - λ_{Norm} : control weight magnitude. Larger value → prioritize small weights

Impact of once-per-fill updates at HLT