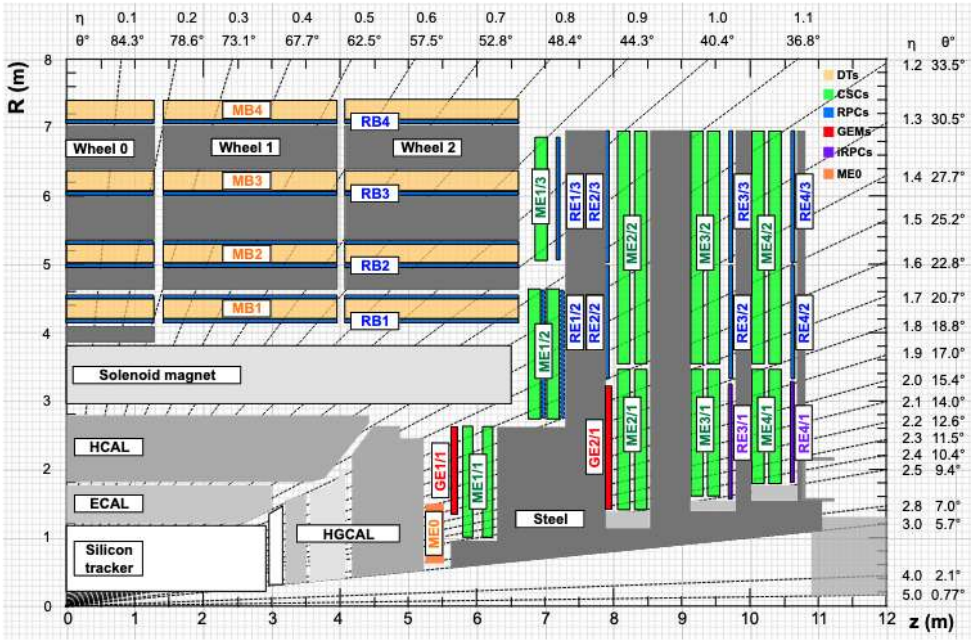
Cosmic-Ray Study on HSCP Search Capability with the iRPC Prototype Readout System

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On behalf of CMS collaboration

Outline

1. CMS RPC/iRPC upgrade and HSCP
2. CMSSW Simulation Studies for HSCP
3. CERN 904 lab cosmic ray experiment setup and data analysis
4. Data-Driven Toy MC in CERN 904 lab and CMS Endcap condition
5. Summary

CMS Phase-2 upgrade of Endcap RPC system



	RPC	iRPC
HPL thickness (mm)	2	1.4
Number of gas gaps	2	2
Gas gap thickness (mm)	2	1.4
Space resolution in η (cm)	20 - 28	1.5
Space resolution in ϕ (cm)	0.8 - 1.9	0.3 - 0.6
Intrinsic timing resolution (ns)	1.5	0.5

Ref1:A. Samalan et al., "Upgrade of the CMS resistive plate chambers for the high luminosity LHC," JINST 17 (2022) C01011.
Ref2:B. Boghrati, CMS RPC Link System, DRD1 Collaboration Meeting (2024)
Ref3: A. Cabrera et al., "Novel ideas for CMS L1 trigger in HL-LHC using RPC ultimate timing performance," Nucl. Instrum. Meth. A 1077 (2025) 170477.

Upgrade of Link System to improve timing resolution for existing RPC (|η| < 1.9) Station1-4, ring2-3

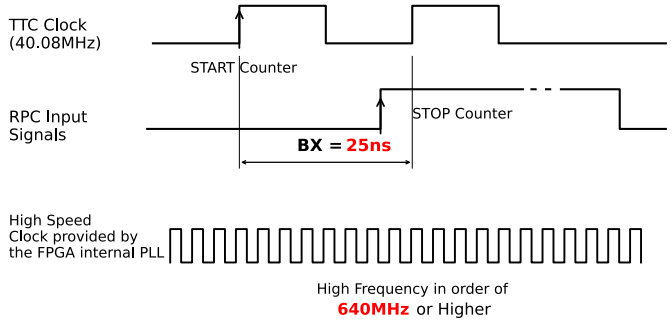


Fig. TTC clock in the new link system.

RPC: The upgraded RPC Link System provides sub-BX timing information:
bunch crossing (BX)-level: 25 ns → subBX: 25/16 = 1.56 ns
The corresponding quantization uncertainty is reduced: 7.2 ns → 0.45 ns
Total timing resolution: $\boldsymbol{\sigma_t \sim 1.57ns}$

Extend the RPC coverage up to |η| = 2.4 to increase redundancy in high eta region in stations 3 and 4

iRPC: intrinsic timing resolution--0.5ns
Double-ended readout+Smaller strip pitch
→ better spatial resolution
Total timing resolution: $\boldsymbol{\sigma_t \sim 0.5 - 0.6ns}$

After the Phase-2 upgrade , RPC/iRPC system provide finer time information for Endcap Muon Track Finder (EMTF) Trigger Primitives (TP) and offline analysis

Muon like HSCPs characteristic and its search strategy

- Heavy stable charged particles(HSCPs) are massive, long-lived charged particles.
- Some HSCPs can traverse muon system, but arrive late compared to prompt muons.
- RPC and iRPC provide time-of-flight information for β reconstruction (β=v/c).
  - Improved timing resolution → better β resolution

	Selection criteria			
	p_T (GeV/c)	$I_{as}^{(l)}$	$1/\beta$	Mass (GeV/c^2)
Tracker-only	>70	>0.4	–	>0 >100 >200 >300 >400
Tracker+TOF	>70	>0.125	>1.225	>0 >100 >200 >300
Muon-only	>230	–	>1.40	–
$\|Q\| > 1e$	–	>0.500	>1.200	–
$\|Q\| < 1e$	>125	>0.275	–	–

REF:CMS Collaboration, "Search for heavy long-lived charged particles in ppcollisions at $\sqrt{s} = 7$TeV," **JHEP 08 (2013) 122.**

The search for HSCPs is an important target in HL-LHC, with its slow speed, it requires timing information, trigger, and readout capabilities to preserve and identify delayed signals.

Monte Carlo strategy for HSCP studies

Main properties to study with CMSSW Phase-2 simulation

1. Inter-layer hit delays
   →layer-dependent trigger stretching for endcap RPC
2. Latest RPC arrival time compared to prompt muon
   →DAQ readout-window requirement for endcap RPC
3. time-of-flight information
   →reconstruct RPC/iRPC $1/\beta$
   RPC: four existing endcap stations; iRPC: RE3/1 and RE4/1(endcap iRPC station3 and 4,ring1).

CMSSW Phase-2 long lived scalar tau (stau, $\tilde{\tau}$) sample

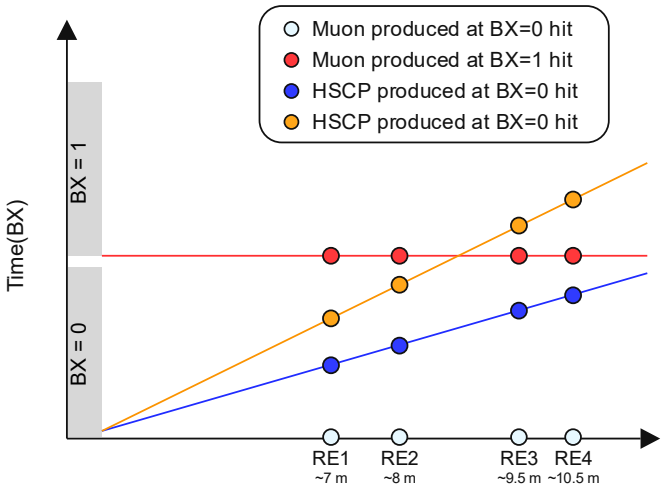
- $\tilde{\tau}$(PDG ID 1000015), $m_{\tilde{\tau}} = 500\ \mathrm{GeV}$
- Generator:FlatRandomPtGunProducer*
- $0.1 < \beta_{\mathrm{gen}} < 1.0$
- $1.2 <| \eta |< 2.4$
- Phase-2 RPC/iRPC geometry
- Only particles propagating toward the **positive-z endcap** are used

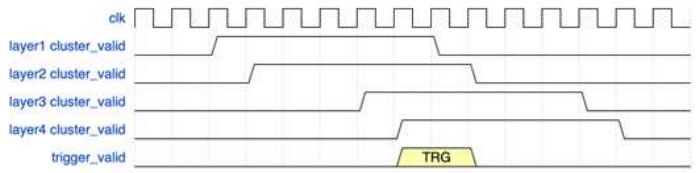
How to generate Trigger signal

- HSCPs travel slower than prompt muons, so hits in different RPC layers can be spread over multiple BXs

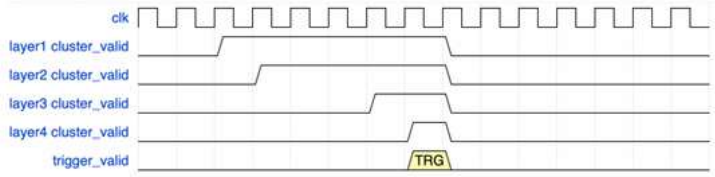
How long must each layer's RPC hit information be held to overlap with the delayed hit?

Layer-dependent timing windows maintain slow-particle efficiency while reducing accidental coincidences and unnecessary hold time.

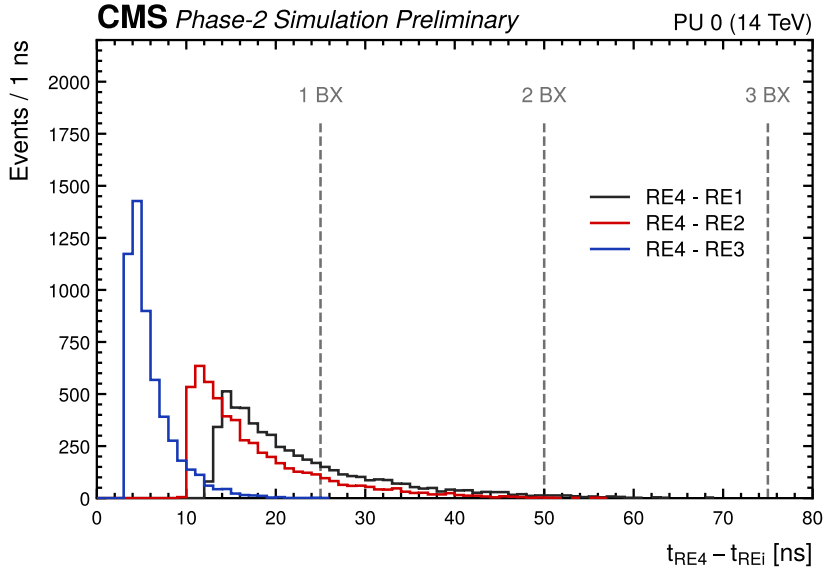




Unified stretching



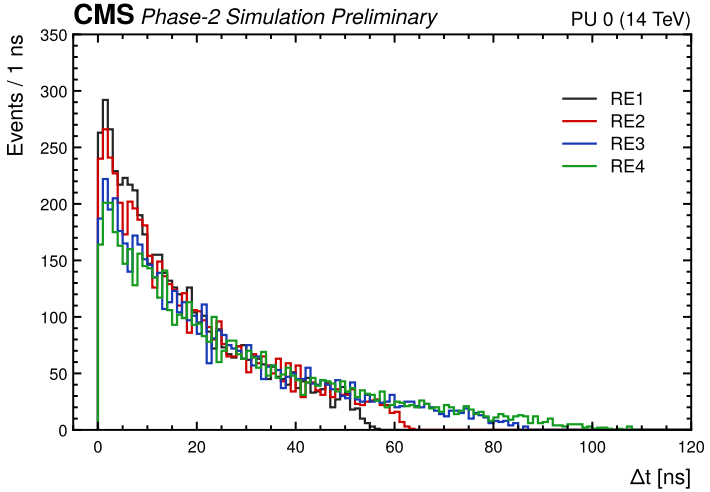
Layer-dependent stretching



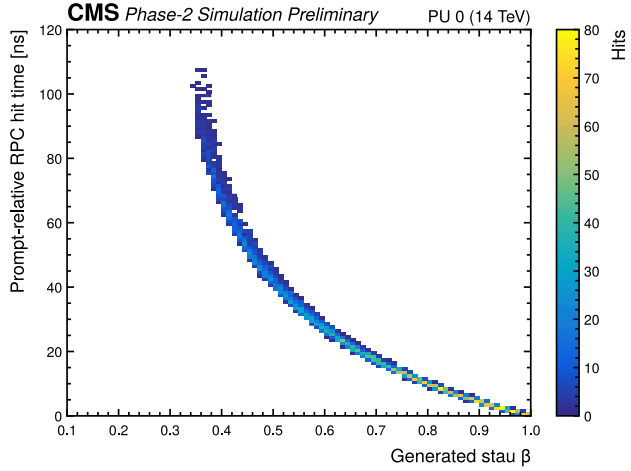
- Timing requirement from CMSSW :
  - 3/3/1/1 BX covers approximately 99.9% of four-station HSCP events.
- Recommended layer-dependent trigger holding window:
  - 4/3/2/1 BX for RPC RE1/RE2/RE3/RE4, including timing and BX-boundary margin.

DAQ Window and buffer depth design

- HSCPs travel more slowly and reach the same RPC detector position later than prompt muons. Without extending the readout window, delayed HSCP hits may fall outside the window.
- We use long lived stau sample to evaluate the delay and design the DAQ window.



HSCP hits arrive later than the prompt muon reference; the longest-path outer station gives the largest delay tail.



The delay increases rapidly at low β.

+3 BX → 95.67%
+4 BX → 99.81%
+5 BX → 100% in current sample

For complete HSCP event read out

DAQ readout window: minimum **5 BX** wider than the design for **prompt muon**

Simulation of RPC/iRPC for Offline HSCP Speed Reconstruction

- Generated long-lived stau samples use Phase-2 geometry in the endcap region.
- Obtain hit information from 4 stations of RPC and two stations of iRPC.
- Reconstruct β with hit information.

Reconstruction process

$$\frac{1}{\beta_i} = 1 + \frac{c\Delta t_i}{L_i}$$

$$w_i = \left(\frac{L_i}{c\sigma_{t,i}}\right)^2$$

$$\left\langle \frac{1}{\beta} \right\rangle = \frac{\sum_i w_i\,(1/\beta_i)}{\sum_i w_i}$$

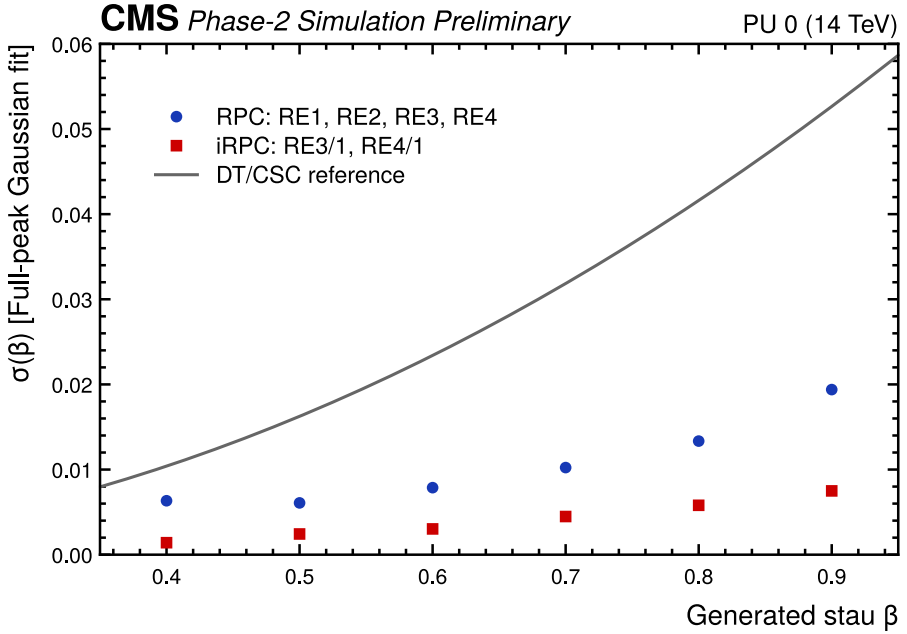
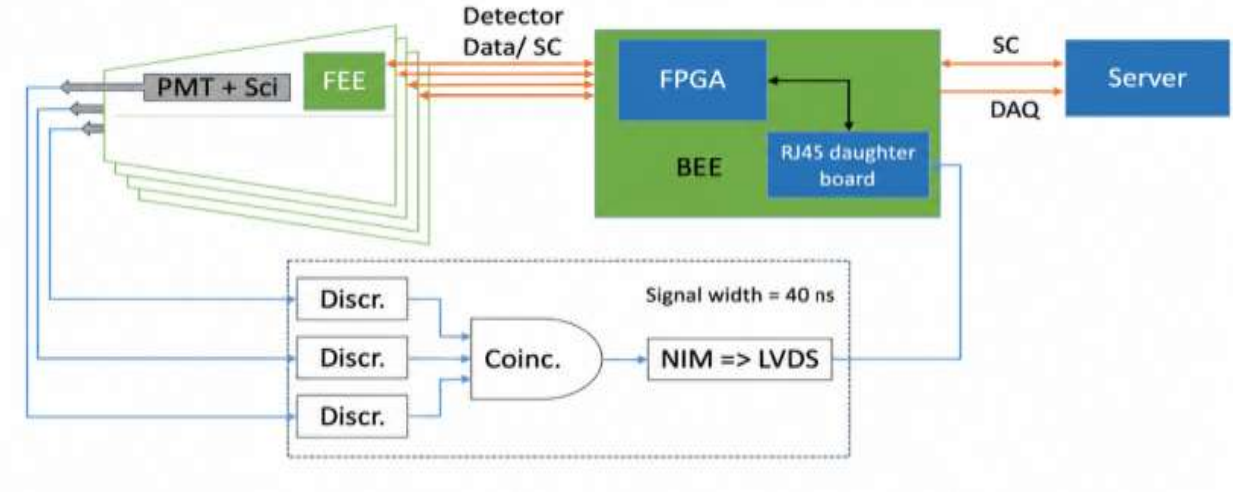


Fig . Performance of RPC&iRPC β reconstruction

- The grey curve : DT/CSC Run-2 reference **benchmark** of β resolution in HSCP velocity reconstruction, σ(1/β)=0.065* converted to σ(β).
- Both studied endcap RPC and iRPC configurations **remain below the benchmark** over the evaluated velocity range

- Upgraded RPC/iRPC timing has the potential to satisfy the offline HSCP β reconstruction requirement

Experiment Setup in 904 for validation



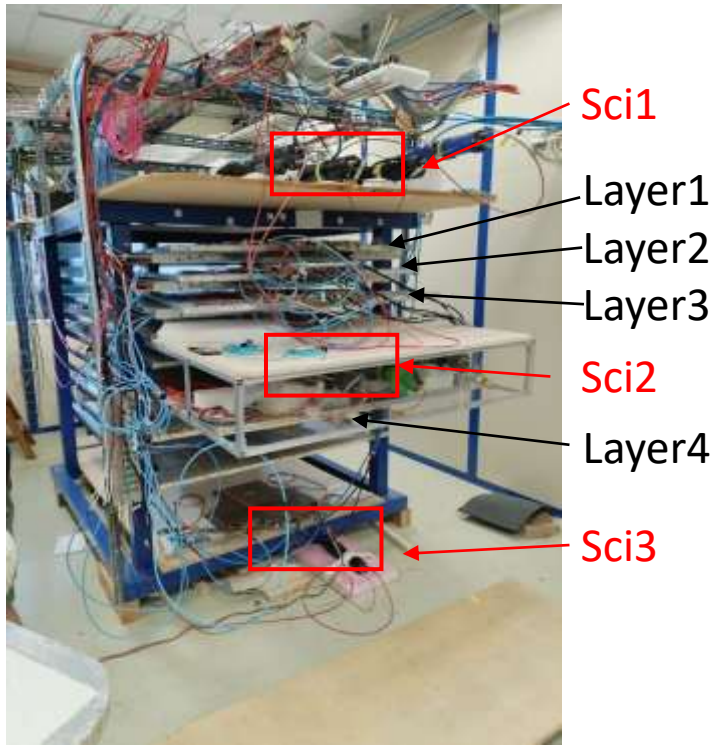


Fig. Physical setup of the four-links iRPC system for reliability testing

- Trigger: Triple-coincidence using three layers of plastic scintillators (Sci).
  - Sci 1 AND Sci 2 AND Sci 3
  - Sci 1 (above Layer 1): Two large scintillators in OR logic;
  - Sci 2 (below Layer 3): Two large scintillators in OR logic;
  - Sci 3 (below Layer 4): One **small** single scintillator.
- Distance between 4 layer :11 cm、 11 cm、 117 cm
  - The large Layer 3–Layer 4 separation increases the measurable time-of-flight difference
- All four links use optical fibers of **the same length** to minimize link-dependent propagation delays and preserve timing consistency.

Frontend Electronics Calibration for Reliable time Measurement

- Before time measuring, channel-dependent electronics effects must be removed or controlled.
- **Goal: establish a solid baseline for time measurements**.

- Frontend Electronics (FEE) Calibration
  - **TDC Time Alignment**
    - Remove channel-dependent timing offsets.
  - **Threshold Calibration**
    - Equalize channel response and suppress noise.
  - **Check-Sort-Push readout**
- Working Voltage Confirmation
  - Ensure stable operation on the efficiency plateau

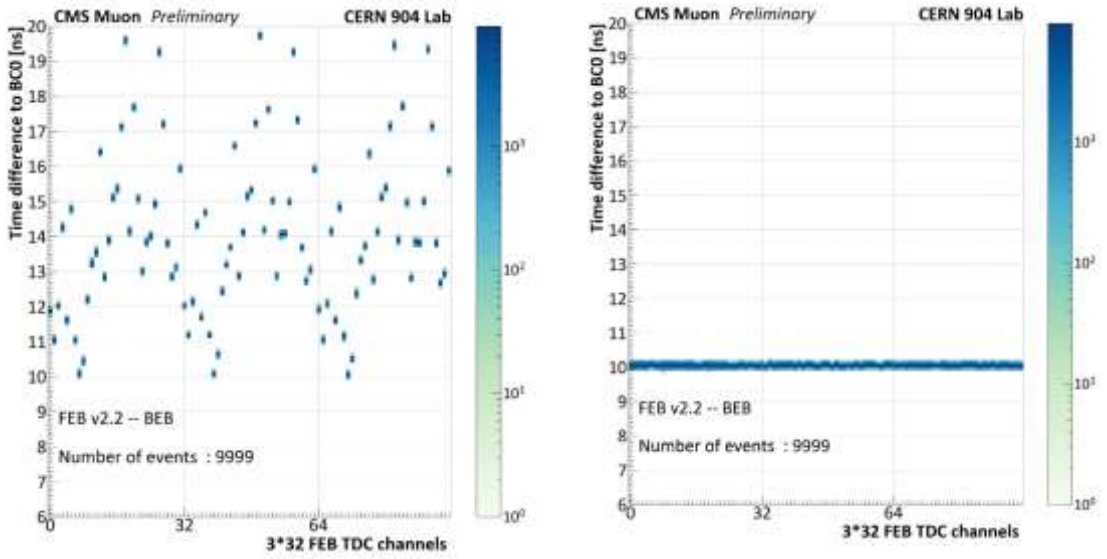


Fig.Timestamp distributions before and after TDC alignment

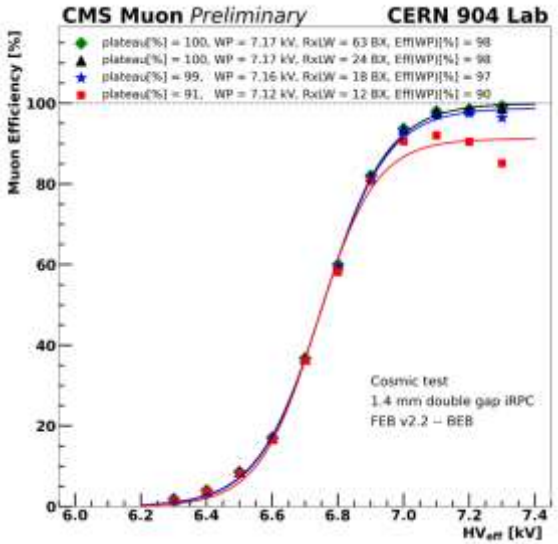
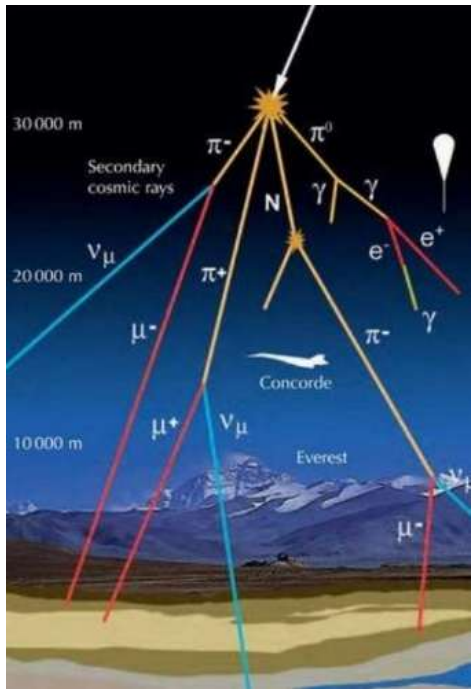
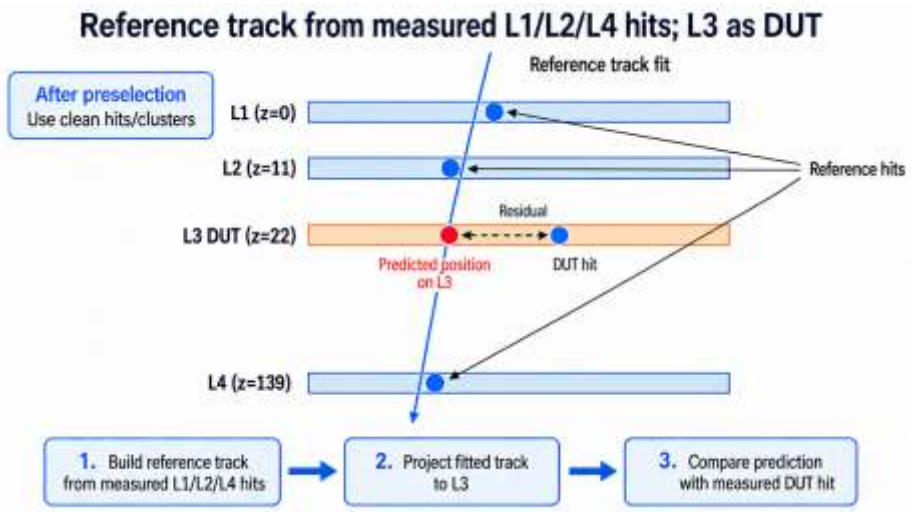


Fig.HV Efficiency Scan

Data taking and analysis process

- Cosmic ray muon at ground level:
  - are relativistic ($\beta \approx 1$) , so they provide a natural reference for timing validation.
  - penetrating and approximately straight at this scale





RAW TDC data

1. Local reconstruction
   Hit preselection → Clustering

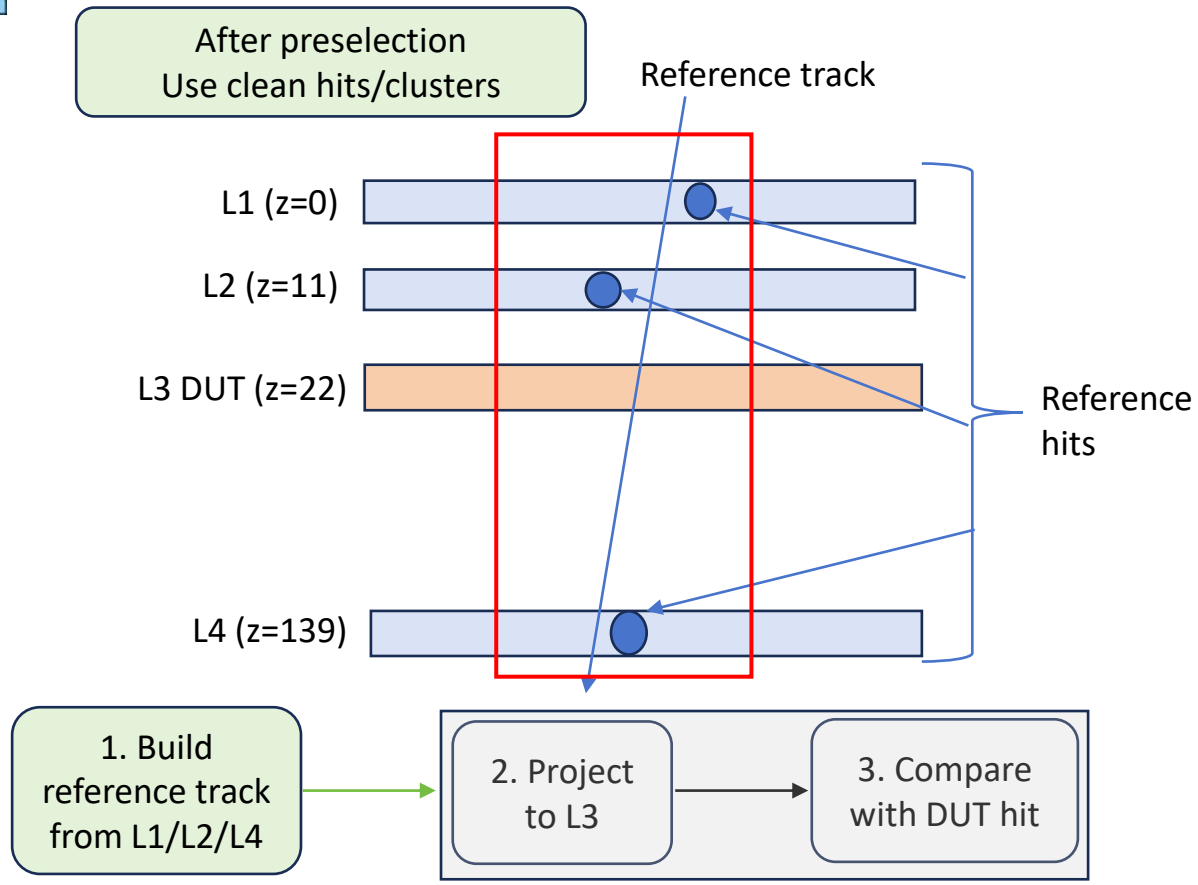
2. L1/L2/L4 reference-track reconstruction
   Candidate formation →
   spatial–timing ranking →
   shared-cluster ambiguity resolution

3. Independent L3 Device Under Test(DUT) confirmation
   Track extrapolation →
   L3 association →
   spatial and timing consistency

Clean four-layer muon sample

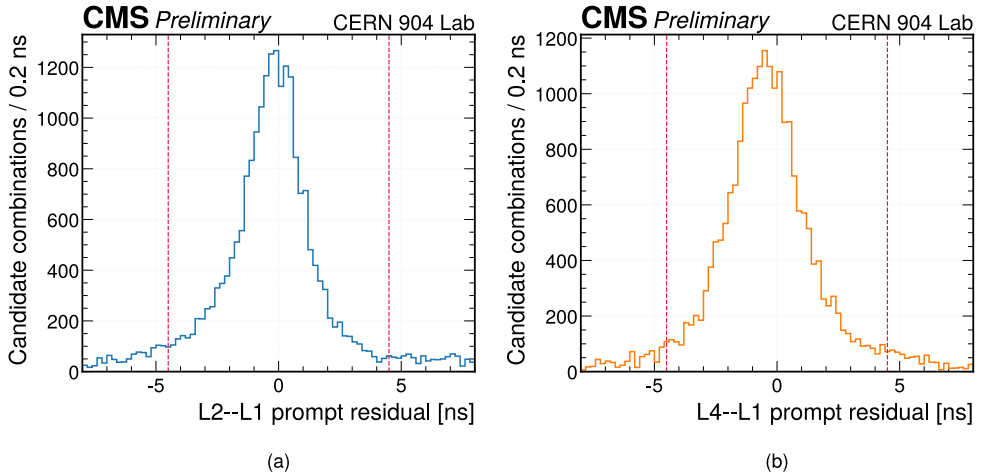
*more detailed procedure is in backup

Building the L1/L2/L4 reference track



Process to **build L1/2/4 reference track**

- Form all L1–L2–L4 cluster combinations

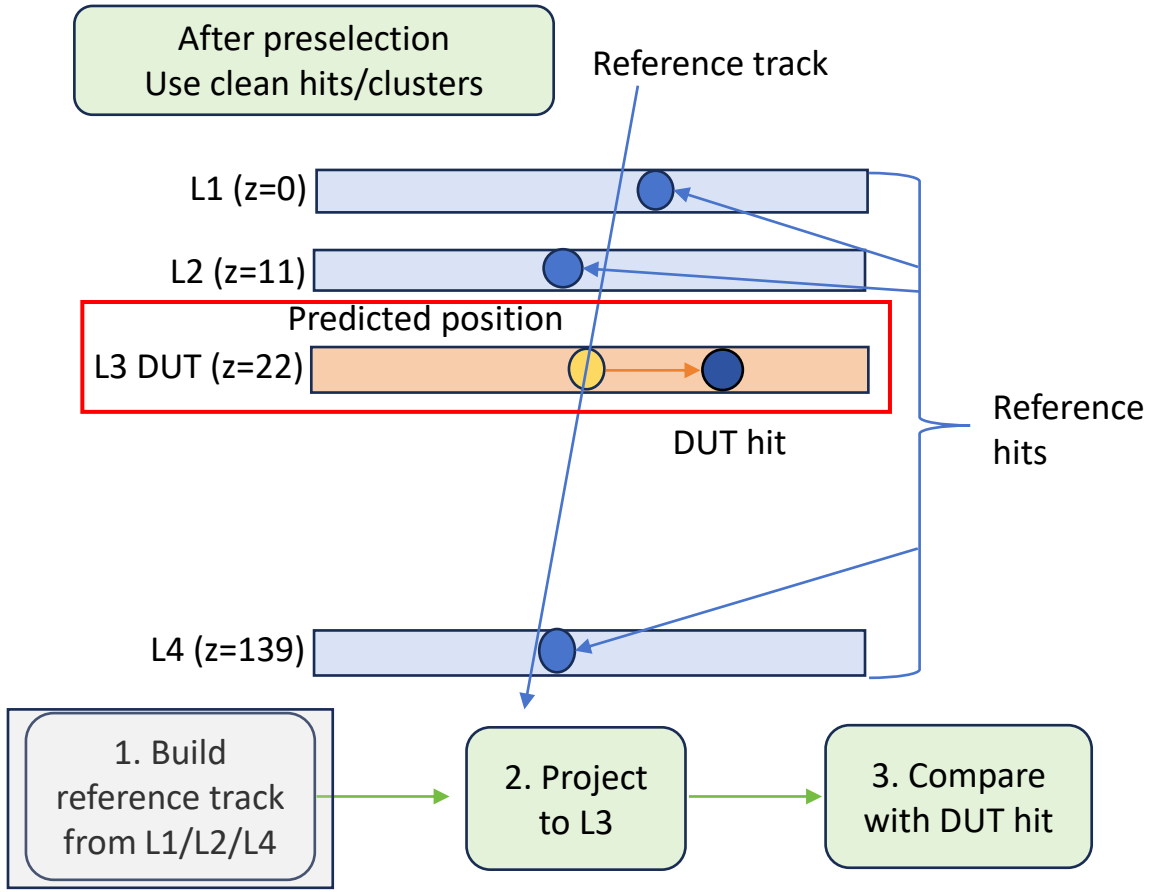


- Apply broad prompt timing gates:
  $| \Delta t_{21} |, \ | \Delta t_{41} | < 4.5$ ns.
- Rank candidates with spatial χ^2 + timing χ^2.
- select the minimum-score candidate

- L3 information is not used when selecting the reference track.

- The best L1/L2/L4 combination defines an independent reference track.
- Its projection provides the predicted cluster position and time on L3.

Reference-track extrapolation and L3 DUT matching



- **L3 DUT matching**
  1. Calculate the predicted position and time at L3.
  2. Obtain all the cluster on L3.
  3. Associate the closest spatially compatible L3 cluster.
  4. Calculate the spatial and timing residuals.

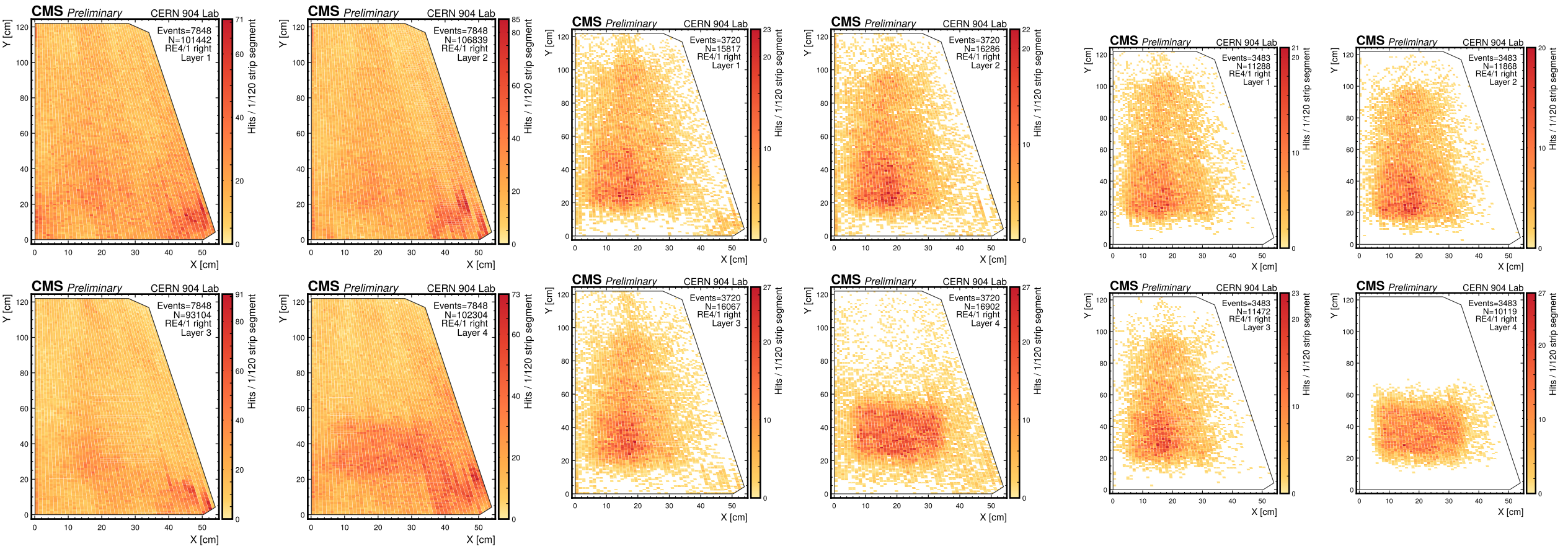
- Normalized spatial-matching variable R:

$$R = \sqrt{\left(\frac{x_3^{\mathrm{meas}} - x_3^{\mathrm{pred}}}{\sigma_x}\right)^2 + \left(\frac{y_3^{\mathrm{meas}} - y_3^{\mathrm{pred}}}{\sigma_y}\right)^2}$$

- **Selection threshold:**
  R<3 , $|\Delta t_3|$<2 ns

Since L3 is not used in the reference-track reconstruction, the L3 residuals provide an independent DUT performance measurement.

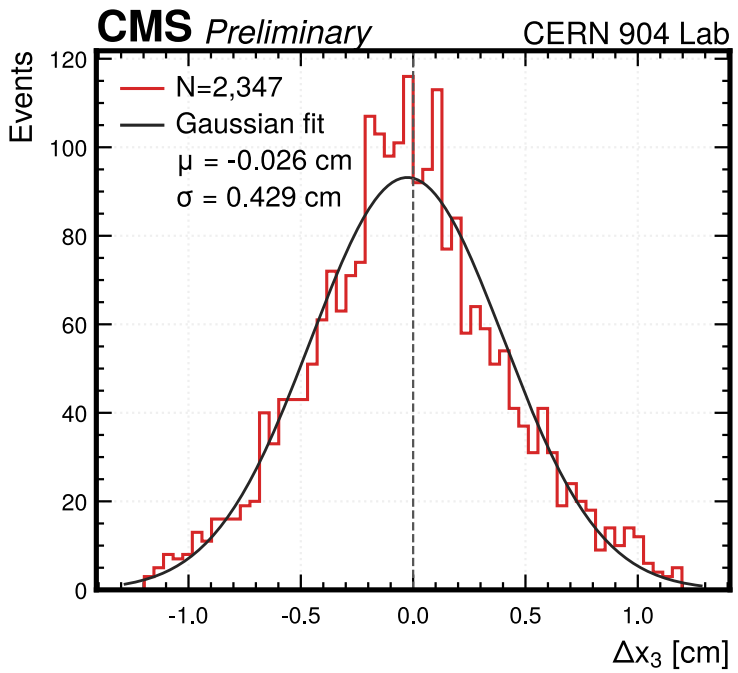
Hit map along with selection process

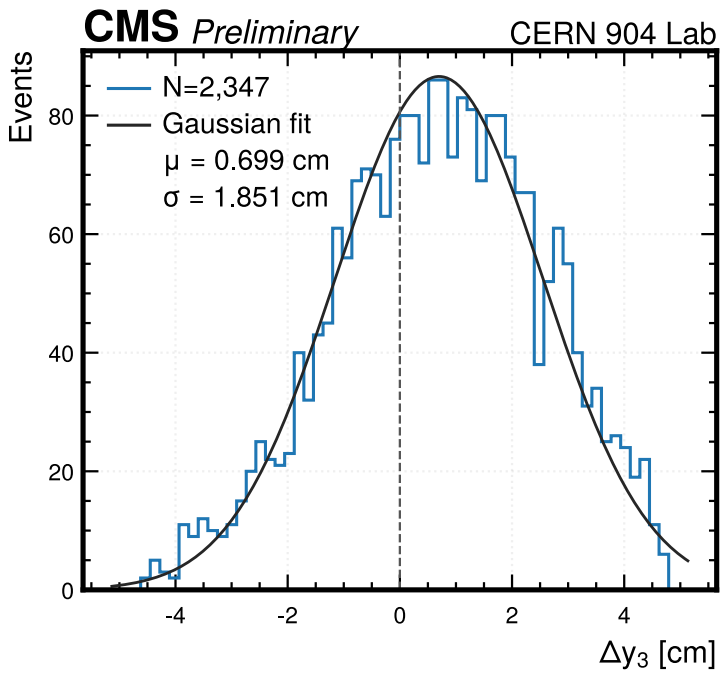


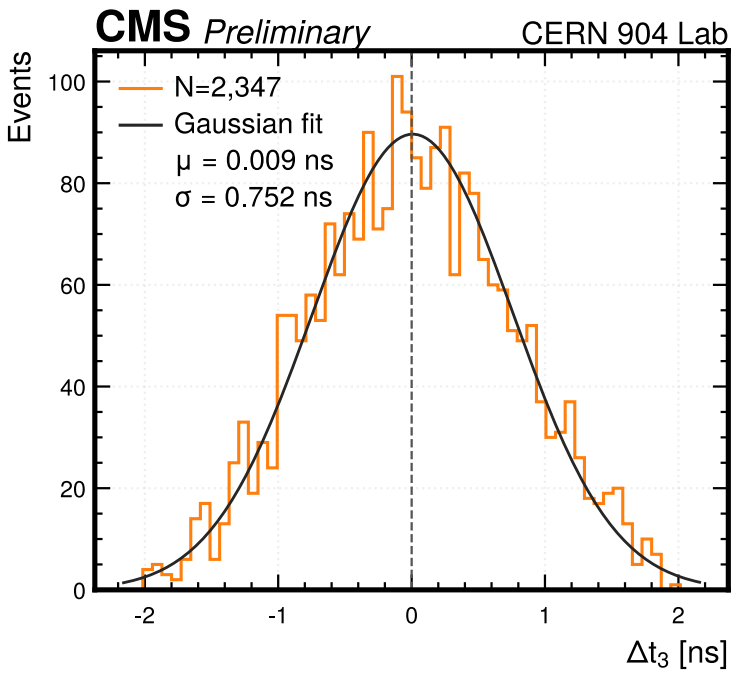
Raw hits → After hit preselection → Good tracks candidates

As the selection proceeds, noise and incompatible hits are strongly suppressed, while the scintillator-defined trigger acceptance area becomes progressively visible,retaining clean cosmic-muon tracks.

Measured DUT performance in the CERN 904 Lab







Measured residual width

$\sigma_{x,\mathrm{meas}} = 0.429\,cm$

$\sigma_{y,\mathrm{meas}} = 1.851\,\mathrm{cm}$

$\sigma_{t,\mathrm{meas}} = 0.752\mathrm{ns}$

$$\sigma_{(DUT)} = \frac{\sigma_{(meas)}}{\sqrt{(1+k)}}$$

$$k = \frac{\left(\sum_{(i=1)}^{N} z_i^2\right)}{\left(N\sum_{(i=1)}^{N} z_i^2 - \left(\sum_{(i=1)}^{N} z_i\right)^2\right)} = 0.399$$

Unbiased L3 result

$\sigma_{x,DUT} = 0.363\,cm$

$\sigma_{y,\mathrm{DUT}} = 1.564\,\mathrm{cm}$

$\sigma_{t,\mathrm{DUT}} = 0.637\mathrm{ns}$

$\sigma_{x,\mathrm{typical}} \approx 0.3 - 0.6\mathrm{cm}$

$\sigma_{y,\mathrm{typical}} \approx 1.5 - 2\mathrm{cm}$

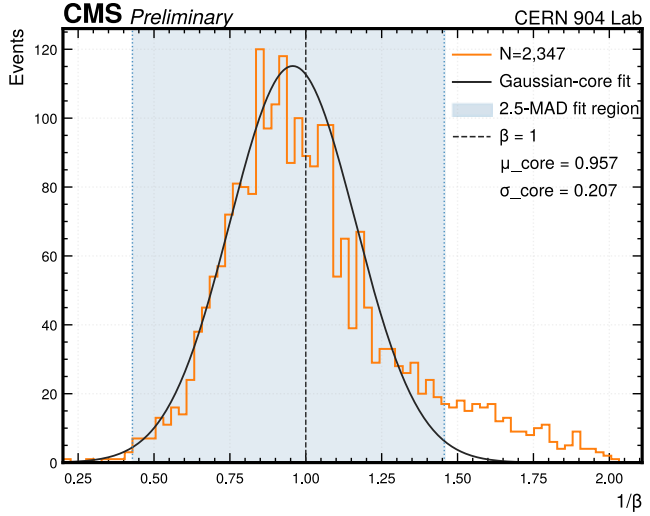
$\sigma_{\mathrm{t,typical}} \approx 0.5 - 0.7\mathrm{ns}$

- These measured detector resolutions are subsequently used in the Toy MC.

CERN 904-Lab 1/β Reconstruction and Toy-MC Validation

Validation:

- Compare Toy MC β distribution with real data β distribution
- Consistent → validated response model

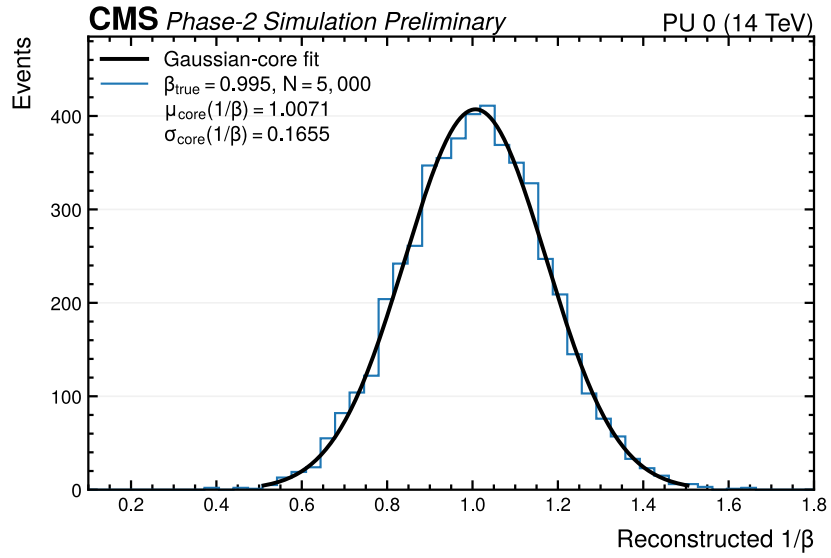


Data analysis result

$\mu_{904\text{data}}\left(\frac{1}{\beta}\right) = 0.957$

$\sigma_{904\text{data}}\left(\frac{1}{\beta}\right) = 0.207$

- Toy MC:Measured x/y/timing response + cosmic-angle distribution + 904-Lab geometry



Toy MC result

$\mu_{904\text{mc}}\left(\frac{1}{\beta}\right) = 1.007$

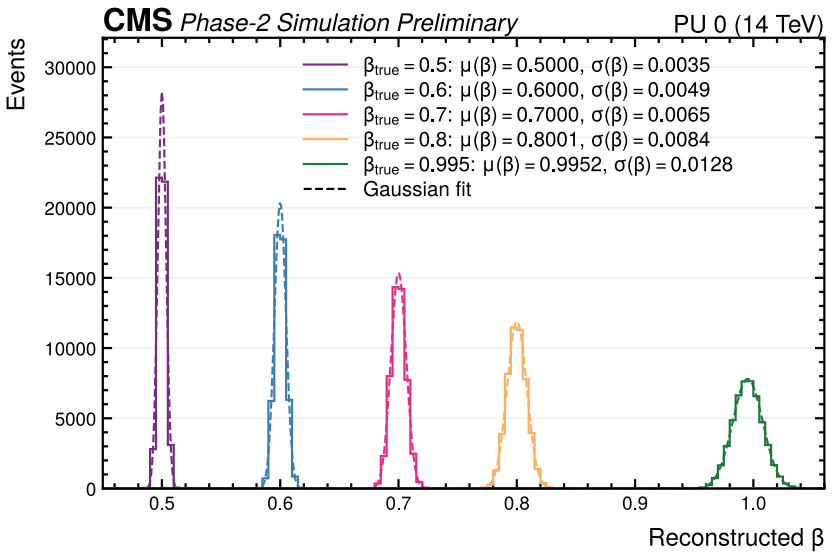
$\sigma_{904\text{mc}}\left(\frac{1}{\beta}\right) = 0.166$

- The validated 904-Lab response model can be used for the CMS endcap long-distance projection.

CMS Endcap Projection of 1/β Resolution

- Data-driven detector resolutions are projected to the CMS Phase-2 endcap geometry.

$$\sigma_t, \sigma_x, \sigma_y \xrightarrow{\text{MC simulation}} \sigma(1/\beta)$$

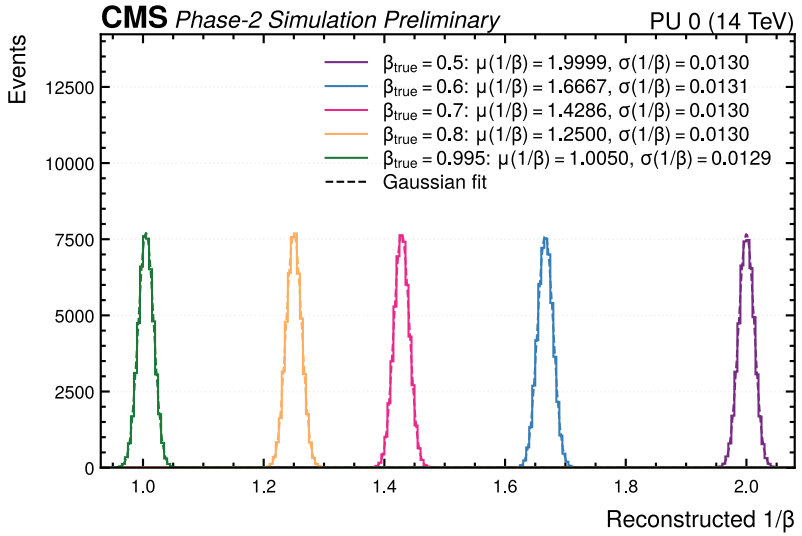


Simulation inputs

$$z_{\mathrm{RE3/1}} = 975.65\ \mathrm{cm}$$

$$z_{\mathrm{RE4/1}} = 1065.75\ \mathrm{cm}$$

$x + y + t$ detector-response smearing



- Projected performance in long distance :
  $\boldsymbol{\sigma(1/\beta)_{CMS}}$ **= 0.013 < 0.065**

- **With the CMS endcap geometry, the projected $\sigma(1/\beta)$ is below the DT/CSC benchmark of 0.065 and is consistent with the CMSSW HSCP simulation , can meet with the HSCP offline β reconstruction requirement.**

Summary

- Phase-2 RPC/iRPC provides finer timing capability
- CMSSW Simulation Studies made on Trigger and DAQ window for HSCP search
- CERN 904 Lab validation made by a 4 layer iRPC setup
- Detector-response projection made with a Toy MC for iRPC Endcap

The study connects the measured iRPC prototype response to the expected CMS-scale time-of-flight performance, supporting the use of upgraded iRPC timing for slow-particle velocity reconstruction in Phase-2 CMS.

- **Thanks for listening !**

Back up

References

1. **[Slide 3 , References]** A. Samalan et al., "Upgrade of the CMS resistive plate chambers for the high luminosity LHC," *JINST* **17** (2022) C01011, doi:10.1088/1748-0221/17/01/C01011.

2. **[Slide 3 , References]** B. Boghrati, "CMS RPC Link System," *2nd DRD1 Collaboration Meeting & Topical Workshop on Electronics for Gaseous Detectors*, CERN, 19 June 2024.

3. **[Slide 3 , References]** A. Cabrera et al., "Novel ideas for CMS L1 trigger in HL-LHC using RPC ultimate timing performance," *Nucl. Instrum. Meth. A* **1077** (2025) 170477, doi:10.1016/j.nima.2025.170477.

4. **[Slide 3 , References]** CMS Collaboration, "The Phase-2 Upgrade of the CMS Muon Detectors," CERN-LHCC-2017-012, CMS-TDR-016 (2017).

5. **[Slide 4 , References]** CMS Collaboration, "Searches for long-lived charged particles in pp collisions at $\sqrt{s} = 7$TeV," *JHEP* **07** (2013) 122, arXiv:1305.0491.

6. **[Slide 5 , References]** CMS Software Guide, *Particle Guns*; CMS CMSSW, IOMC/ParticleGuns/FlatRandomPtGunProducer

7. **[Slide 8 , References]** CMS Collaboration, "Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$TeV," *Phys. Rev. D* **94** (2016) 112004, arXiv:1609.08382.

8. **[Slide 11, References]** T. Hebbeker and C. Timmermans, "A compilation of high energy atmospheric muon data at sea level," Astropart. Phys. 18 (2002) 107–127, doi:10.1016/S0927-6505(01)00180-3.

9. **[Slide 15, References]** S. Dong et al., "Performance study of the JadePix-3 telescope from a beam test," *Nucl. Instrum. Meth. A* **1065** (2024) 169551, doi:10.1016/j.nima.2024.169551.

Backup——Cut flow

Nominal production: run1576 • L3 DUT • cluster time-span < 3 ns • no L1/L2/L4 RMS hard cut

Stage	Yield	Definition / purpose
Raw decoded records	7,848 events 1,120,883 hits	Per-strip HR/LR calibrated hit records and physical-strip geometry
HR/LR match + geometry	7,848 events 403,689 hits	Valid two-ended hit and inside-strip acceptance
Trigger-time preselection	7,837 events 399,321 hits	$0 \le LR - L1T - 25\ ns \le 250\ ns$
Occupancy guard	3,720 events 65,072 hits	Reference layers L1/L2/L4: hits/event [1,15] ; L3 is kept blind
Accepted clusters	3,720 events 25,219 clusters	Cluster $\Delta t < 3$ ns; along-strip span < 9 cm; one supported gap;L4 fiducial cut x[5,45],y[15,60]
Candidate combinations	3,533 events 16,630 candidates	L1 anchors × L2/L4 clusters; $\lvert\Delta t_{21}\rvert$, $\lvert\Delta t_{41}\rvert < 4.5$ ns
Best candidate + shared cluster	3,533 events 3,758 reference tracks	Minimum combined space+timing score; shared-cluster duplicates removed; RMS diagnostic only
L3 broad association	3,483 events 3,707 tracks	Extrapolate to L3; assign nearest cluster before the final quality cuts
Final L3 sample	2,328 events 2,347 track	$R < 3$ and $\lvert\Delta t_3\rvert < 2$ ns

Backup——Data-driven Toy Monte Carlo strategy

Data-driven Toy MC

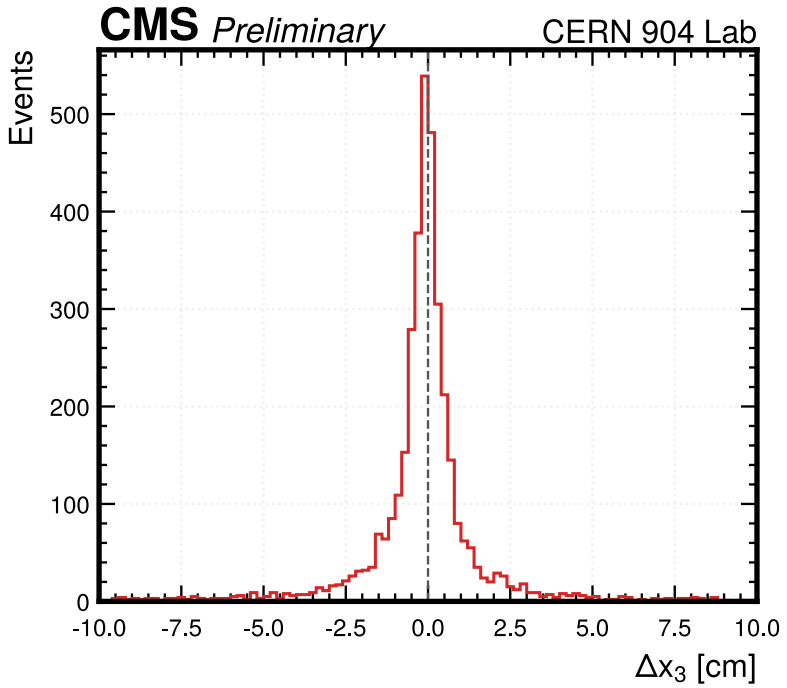
Main missions

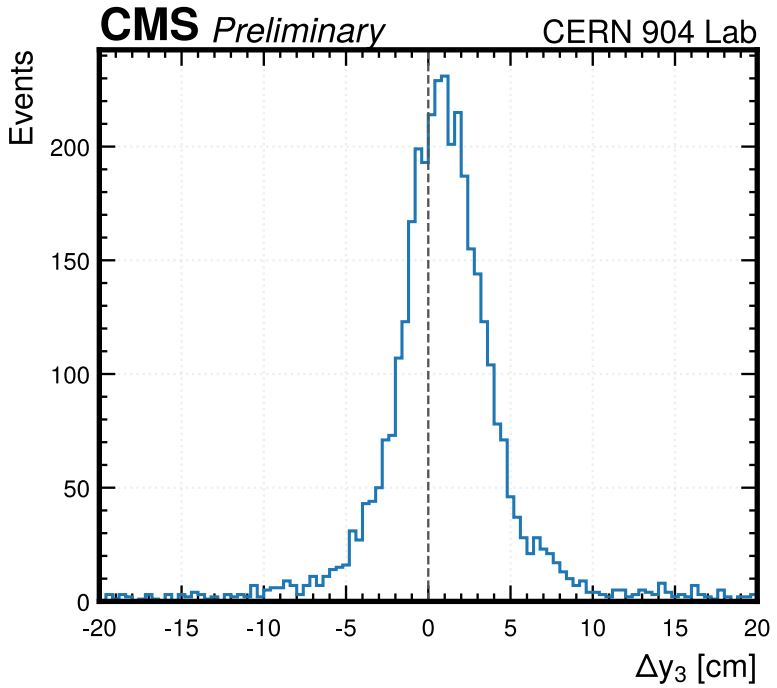
- Validate the $1/\beta$ reconstruction in the 904-Lab geometry.
- Propagate the same response to the CMS endcap geometry

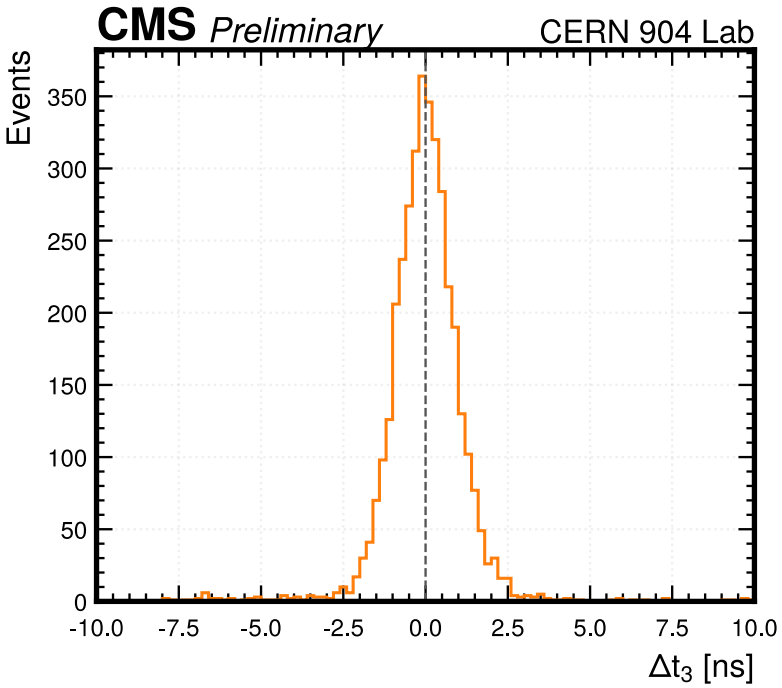
Simulation inputs

- measured $x/y/t$ resolutions in the CERN 904 data
- cosmic angular distribution from CERN 904 data
- CERN 904 geometry and CMS endcap geometry
- same $1/\beta$ reconstruction process
- In CMS endcap Toy MC ,assume Collision t_0 known ,and use the long distance from IP to the detector

Back up——L3 associated original track quality







These plots show the L3 spatial and timing residuals after the broad L3 association in the four-layer CERN 904 iRPC telescope. In this setup, L1, L2, L3, and L4 denote the four physical detector layers arranged from top to bottom, each consisting of an RE4/1 iRPC chamber. The vertical separations between consecutive layers are 11 cm, 11 cm, and 117 cm, respectively. L1, L2, and L4 are used to reconstruct the reference track, while L3 is treated as an independent device under test (DUT).

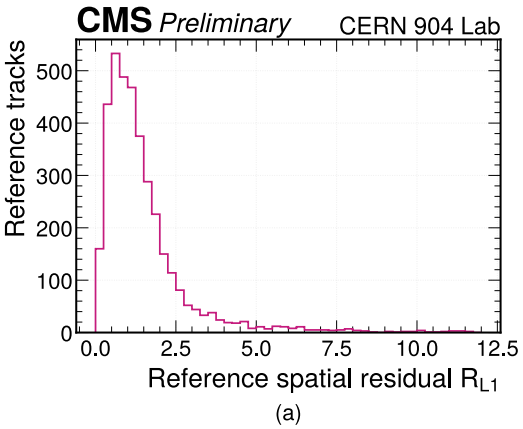
The L3 position and arrival time are predicted using the independent reference track reconstructed from L1, L2, and L4, and are compared with the associated L3 cluster. **The left, middle, and right panels show the across-strip spatial residual Δx_3, the along-strip spatial residual Δy_3, and the timing residual Δt_3 , respectively.**

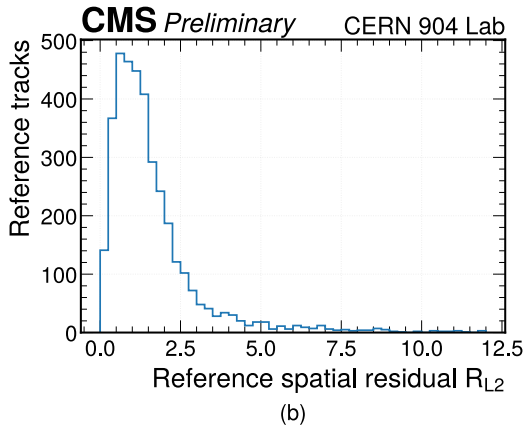
The residuals are defined as: $\Delta x_3 = x_3^{\mathrm{meas}} - x_3^{\mathrm{pred}}, \Delta y_3 = y_3^{\mathrm{meas}} - y_3^{\mathrm{pred}}, \Delta t_3 = t_3^{\mathrm{meas}} - t_3^{\mathrm{pred}}$.

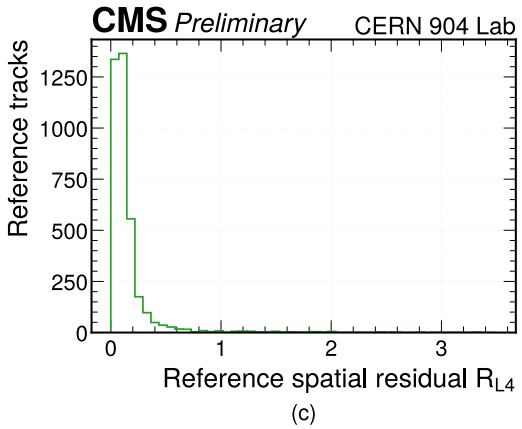
The along-strip residual is broader than the across-strip residual because the along-strip position is reconstructed from the double-ended timing difference and has a poorer spatial resolution.

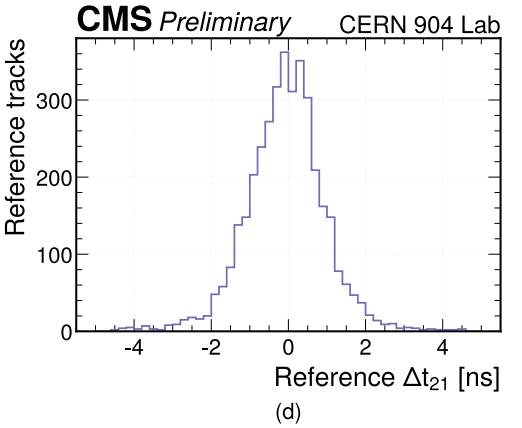
The remaining tails mainly come from incorrect L3-cluster associations, accidental hits. Therefore, the final requirements should be applied to obtain a cleaner Device under test(DUT) sample.

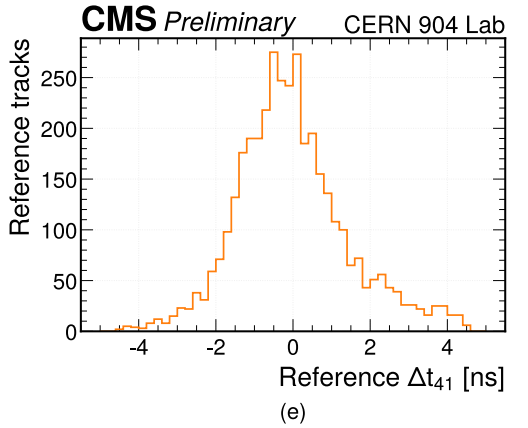
Back up——L1/2/4 reference track quality

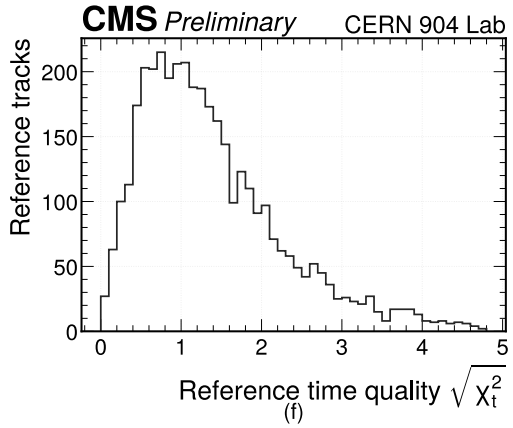












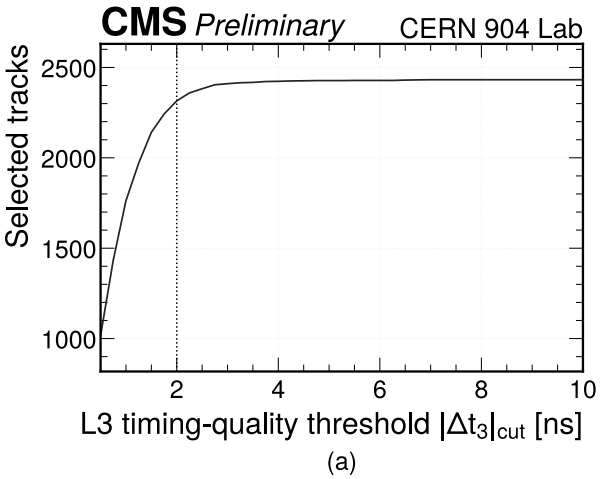
Spatial and timing quality distributions of the selected L1–L2–L4 reference tracks in the four-layer CERN 904 iRPC telescope. In this setup, L1, L2, L3, and L4 denote the four physical detector layers arranged from top to bottom, each consisting of an RE4/1 iRPC chamber. L1, L2, and L4 are used to reconstruct the reference track, while L3 is treated as an independent device under test (DUT). **The upper-left, upper-middle, and upper-right panels** show the spatial residuals of the L1, L2, and L4 clusters relative to the fitted straight reference track. Spatial residual R is

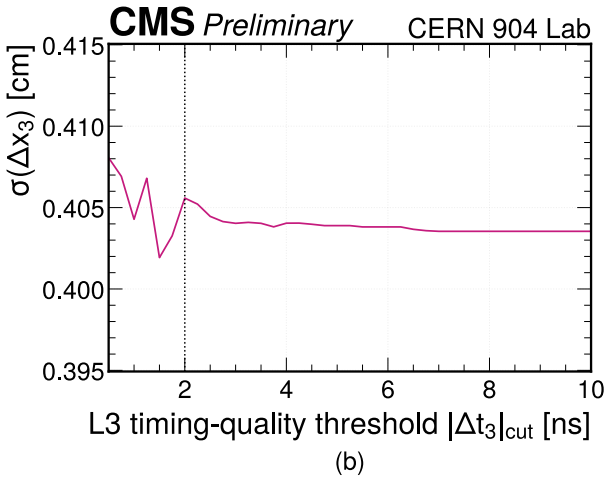
$$R^2 = \chi^2_{(space)} = \sum_{(i\in N)} \left[\frac{\left(x_i - x_i^{(fit)}\right)^2}{\sigma_x^2} + \frac{\left(y_i - y_i^{(fit)}\right)^2}{\sigma_y^2} \right]$$

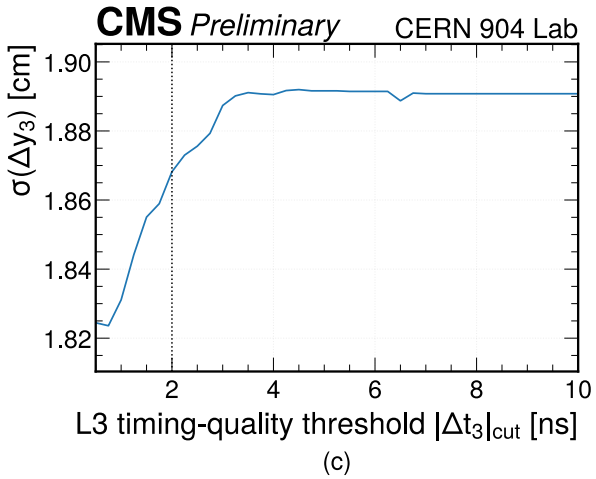
The lower-left and lower-middle panels show the L2–L1 and L4–L1 cluster-time residuals, and **the lower-right** panel shows the combined reference-track timing-quality $\sqrt{\chi^2_{(time)}}$, which is defined as: $\chi^2_{(time)} = \left(\frac{\Delta t_{(21)}}{\sigma_{(21)}}\right)^2 + \left(\frac{\Delta t_{(41)}}{\sigma_{(41)}}\right)^2$

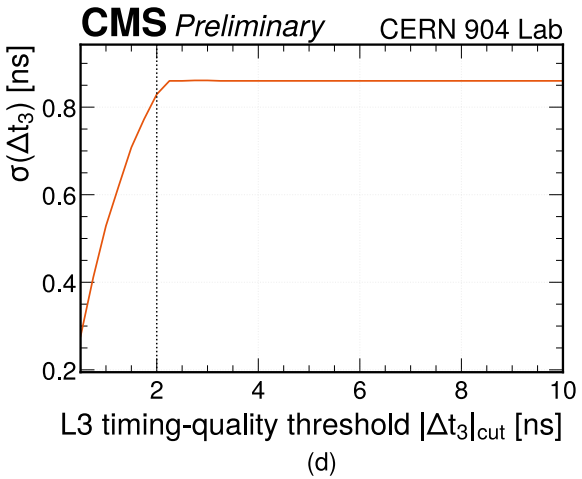
The concentration of the selected candidates at small spatial residuals and near-zero timing residuals demonstrates that the ranking procedure suppresses incompatible cluster combinations and provides a reliable extrapolation to L3 DUT.

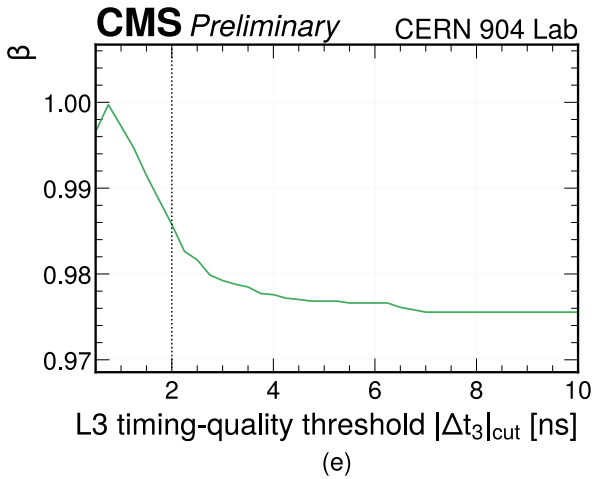
Back up——Optimization of timing consistency in L3

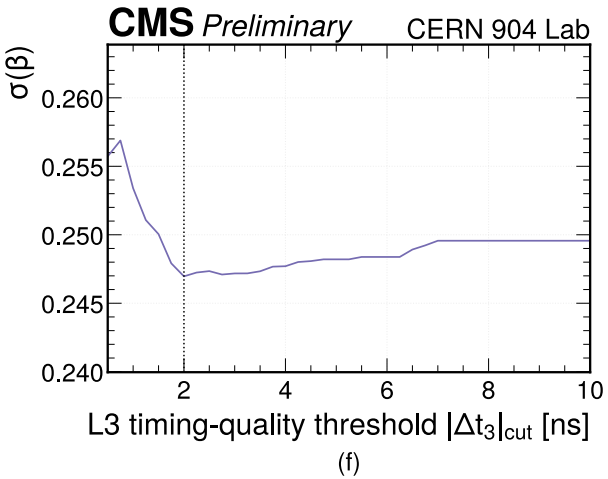












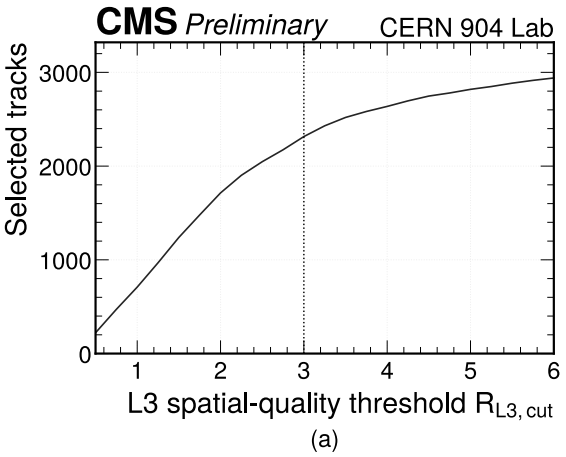
These plots show the dependence of the selected sample and reconstructed observables on the L3 timing-consistency threshold $|\Delta t_3|$ cut in the four-layer CERN 904 iRPC telescope. The L3 timing residual is defined as the difference between the measured and predicted L3 time, $\Delta t_3 = t_3^{\mathrm{meas}} - t_3^{\mathrm{pred}}$.

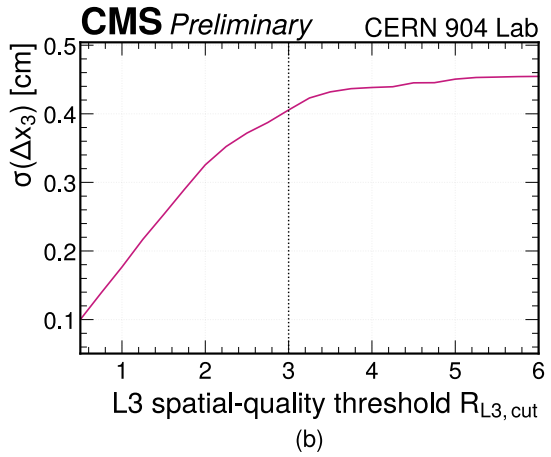
In this setup, L1, L2, L3, and L4 denote the four physical detector layers arranged from top to bottom, each consisting of an RE4/1 iRPC chamber. For each L1–L2–L4 reference track, the expected L3 time is predicted after accounting for the reference-track timing relation and calibrated layer offsets. **From upper left to lower right**, the panels show the retained events, the across-strip residual width, the along-strip residual width, the timing residual width, the mean reconstructed β and the width of the reconstructed β distribution.

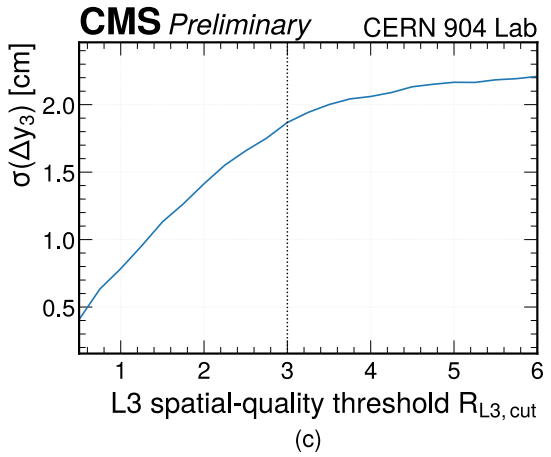
Requirement of $|\Delta t_3| < 2$ ns is selected near the onset of the stability region, where the event yield is already close to saturation and the residual widths vary slowly. The reconstructed-β mean and width are shown only as stability diagnostics and are not used directly to define the selection.

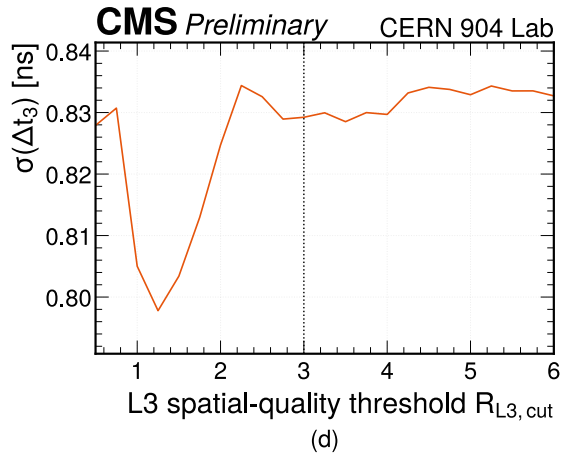
This requiring can reject hits like accidental L3 associations, noise hits, and events with abnormal timing.

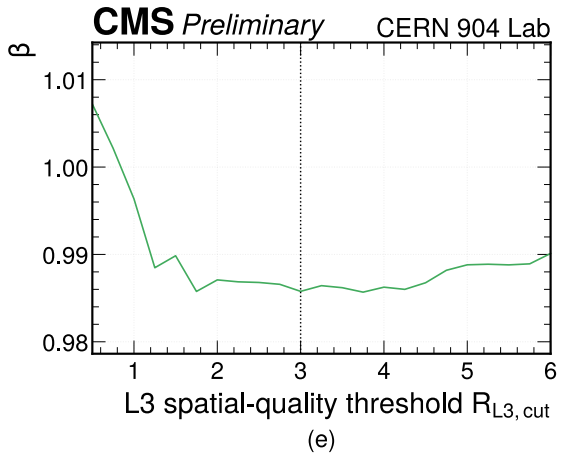
Back up——Optimization of spatial consistency in L3

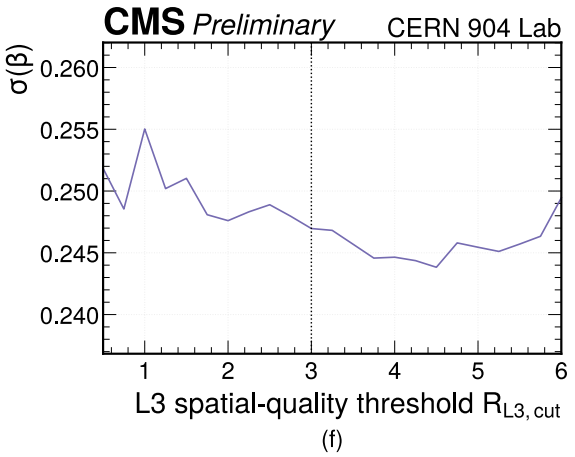












These plots show the dependence of the selected sample and reconstructed observables on the L3 spatial-consistency threshold $R_{\mathrm{L3,cut}}$.
Spatial residual $R_{\mathrm{L3,cut}}$ is

$$\mathrm{R}^2_{\mathrm{L3,cut}} = \chi^2_{(space)} = \sum_{(i\in \mathrm{N})} \left[\frac{\left(x_i - x_i^{(fit)}\right)^2}{\sigma_{\mathrm{x}}^2} + \frac{\left(y_i - y_i^{(fit)}\right)^2}{\sigma_{\mathrm{y}}^2} \right]$$

L1, L2, L3, and L4 denote the four physical detector layers arranged from top to bottom, each consisting of an RE4/1 iRPC chamber. A reference track is reconstructed from the L1, L2, and L4 clusters, assuming a straight trajectory through the telescope. This track predicts the expected L3 position. The spatial matching variable R quantifies the normalized distance between the predicted L3 position and the measured L3 cluster position.

From upper left to lower right, the panels show retained events, across-strip residual width, along-strip residual width, timing residual width, mean reconstructed β, and width of reconstructed β as functions of $R_{\mathrm{L3,cut}}$.

As the spatial threshold is loosened, more L3 associations are accepted and the spatial residual distributions naturally become broader. Around R=3, the increase in event yield begins to slow while most of the central, spatially compatible population is retained. Therefore,R<3 is chosen as the spatial-matching requirement. The reconstructed-β observables are shown only as stability diagnostics and are not used directly to optimize the cut.

Back up——CMSSW local version MC workflow

Simulation setup

- **CMSSW:** `CMSSW_14_1_0_pre3`
- `Use private SimMuon/RecolMuon/EMTFTools`
- **Architecture:** `el8_amd64_gcc12`
- **Detector configuration:** Phase-2 RPC/iRPC development geometry
- **Particle:** long-lived stau, PDG ID 1000015

`G4 generate PSimHit`

Geant4 produces `PSimHit` objects containing the particle time of flight, local hit coordinates and detector identifiers.

iRPC digitization

1.A position-dependent cluster size is sampled, and the original hit is spread over neighboring strips.

2.The Geant4 arrival time is converted into a prompt-reference-subtracted delay.

3.A common intrinsic timing fluctuation is applied:

$$t_0 = t_{\mathrm{G4}} + \delta t_{\mathrm{intrinsic}}, \delta t_{\mathrm{intrinsic}} \sim \mathcal{N}(0, 500\ \mathrm{ps}).$$

4.The along-strip position is smeared:

$$y_{\mathrm{smear}} = y_{\mathrm{SimHit}} + \delta y.$$

5.The smeared y is used to generate double-ended times:

$$t_{\mathrm{LR}} = t_0 + \frac{L/2 + y_{\mathrm{smear}}}{v_{\mathrm{signal}}} + \delta t_{\mathrm{LR}},$$
$$t_{\mathrm{HR}} = t_0 + \frac{L/2 - y_{\mathrm{smear}}}{v_{\mathrm{signal}}} + \delta t_{\mathrm{HR}}.$$

6.Each endpoint receives independent electronics jitter and independent TDC quantization.

7.The time and along-strip position are reconstructed as

$$t_{\mathrm{reco}} = \frac{t_{\mathrm{LR}} + t_{\mathrm{HR}}}{2} - \frac{L_{\mathrm{strip}}}{2v_{\mathrm{signal}}},$$
$$y_{\mathrm{reco}} = \frac{v_{\mathrm{signal}}}{2}(t_{\mathrm{LR}} - t_{\mathrm{HR}}).$$

The current signal propagation speed is $v_{\mathrm{signal}} = 0.66c$.

Back up——CMSSW local version MC workflow

Timing reference and BX assignment

The digitizer stores a prompt-reference-subtracted timing quantity rather than the full absolute Geant4 TOF. This enables delay-based reconstruction:

$$\frac{1}{\beta} \simeq 1 + \frac{c\, t_{\mathrm{delay}}}{L}.$$

•RPC: 25 ns BX plus 1.5625 ns sub-BX;

•iRPC: approximately 2.5 ns coarse time plus 9.77 ps fine TDC bins.

Offline speed reconstruction

$$\frac{1}{\beta_{\mathrm{reco}}} = 1 + \frac{c(t_{\mathrm{rec}} - t_{\mathrm{offset}})}{L_{\mathrm{geom}}}, L_{\mathrm{geom}} = \sqrt{r_{\mathrm{hit}}^2 + z_{\mathrm{hit}}^2}.$$

•RPC performance is evaluated with four stations;

•iRPC performance is evaluated with two stations, RE3/1 and RE4/1;

•measurements are combined in $1/\beta$ space.

The present reconstruction uses the straight IP-to-hit path. The current ntuple does not store the cumulative Geant4 trajectory length; a truth-assisted “effective path” is therefore only a proxy, not a measured Geant4 path length.

Back up--formula

- Rank candidates with spatial χ^2 + timing χ^2.

$$\chi^2_{(candidate)} = \chi^2_{(space)} + \chi^2_{(time)}$$

$$\chi^2_{(space)} = \sum_{(i\in\{1,2,4\})} \left[\frac{\left(x_i - x_i^{(fit)}\right)^2}{\sigma^2_{(x,i)}} + \frac{\left(y_i - y_i^{(fit)}\right)^2}{\sigma^2_{(y,i)}} \right]$$

$$\chi^2_{(time)} = \left(\frac{\Delta t_{(21)}}{\sigma_{(21)}}\right)^2 + \left(\frac{\Delta t_{(41)}}{\sigma_{(41)}}\right)^2$$

- Dut resolution

$$\sigma^2_{(meas)} = \sigma^2_{(DUT)} + \sigma^2_{(tel)}$$

$$k = \frac{\left(\sum_{(i=1)}^{N} z_i^2\right)}{\left(N\sum_{(i=1)}^{N} z_i^2 - \left(\sum_{(i=1)}^{N} z_i\right)^2\right)}$$

$$\sigma_{(DUT)} = \frac{\sigma_{(meas)}}{\sqrt{(1+k)}}$$