

Web3D 2026

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Doha, Qatar

HGCalVis: Web-Based Importance-Ordered Visualization of CERN's HGCal Particle Showers

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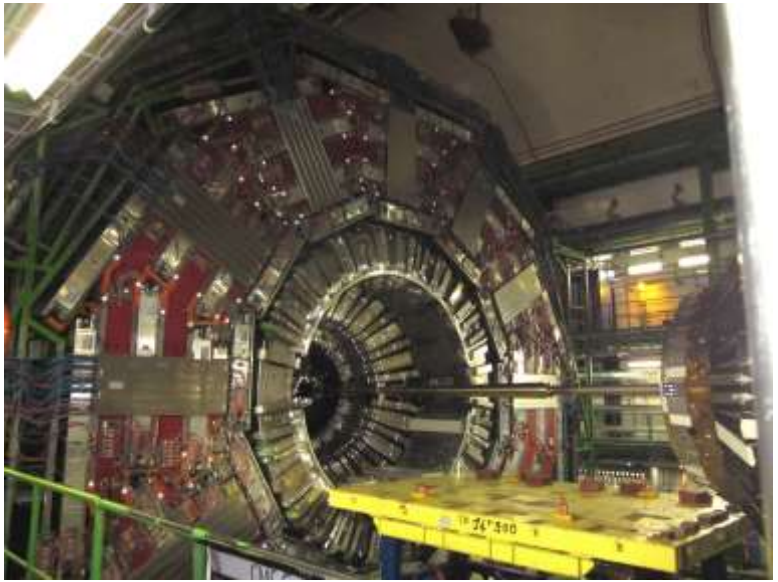
Web3D 2026 · Doha, Qatar · Paper Session 3: Digital Twins and Scientific Visualization



CERN

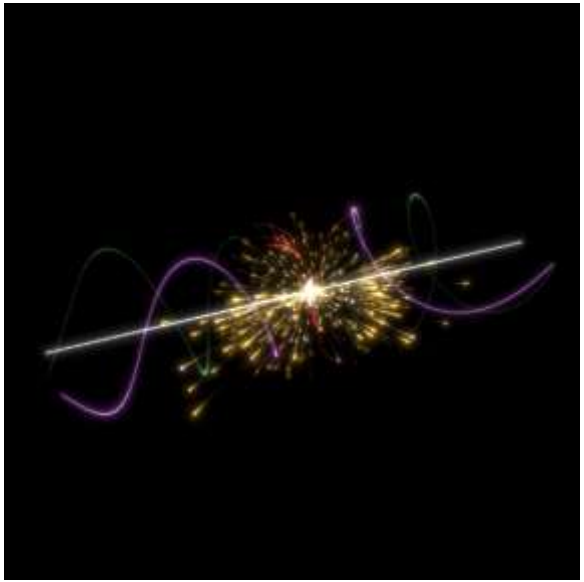
Accelerator, detectors

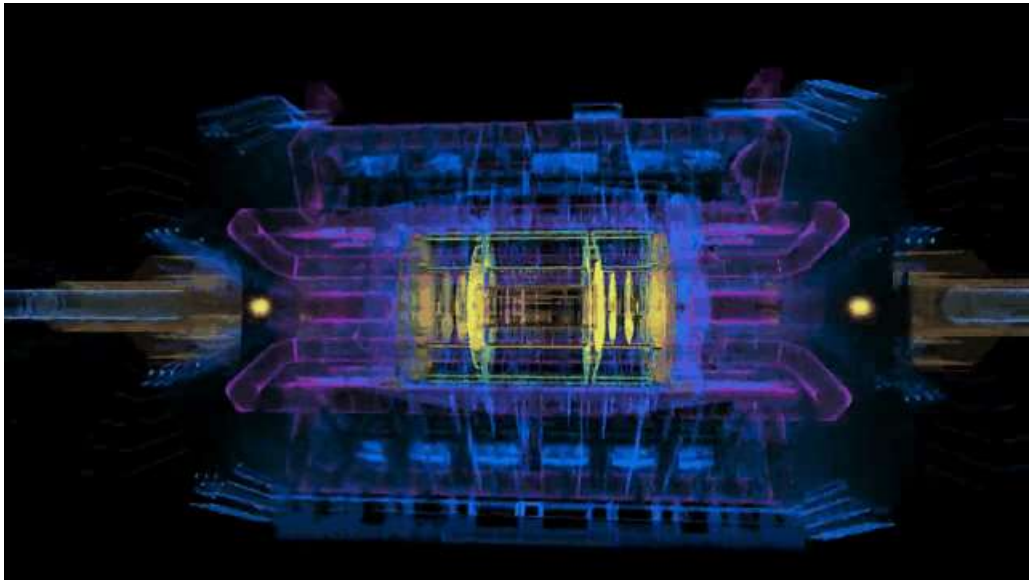




Particle Collisions

Particle collision and particle showers





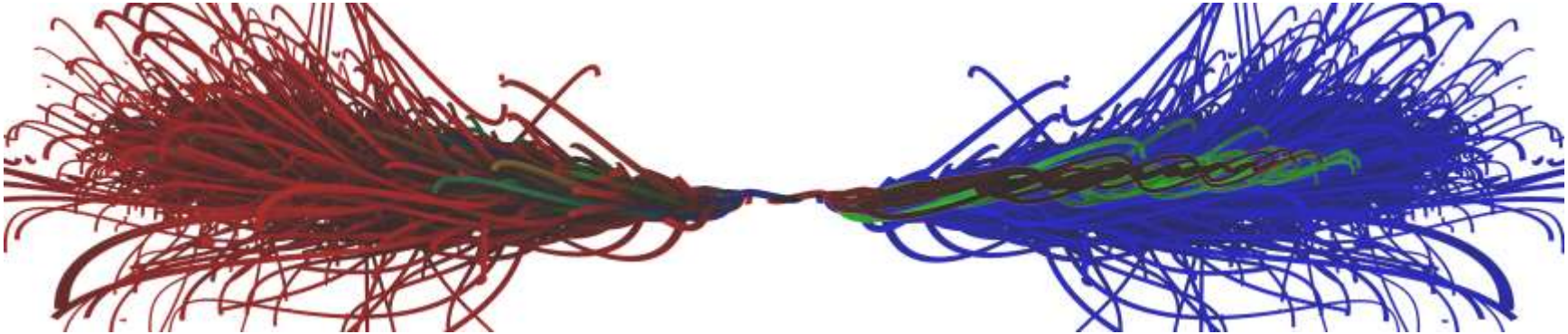
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Where are the highest-energy tracks?

A simulated electromagnetic shower, rendered in two ways

Cylinder shading + SSAO

Importance-Ordered Rendering (IOR)



The few high-energy (blue) tracks are buried in the red core

High-energy tracks stay on top of the low-energy context

Default coloring: normalized starting energy

0 (lowest) 0.5 1 (highest)

IOR clusters

High energy Medium energy Low energy

New CERN detector validated with simulated showers

LHC UPGRADE · FROM ~2029

Collider upgrade

≈10× more collisions
CMS calorimeter to be replaced

NEW DETECTOR

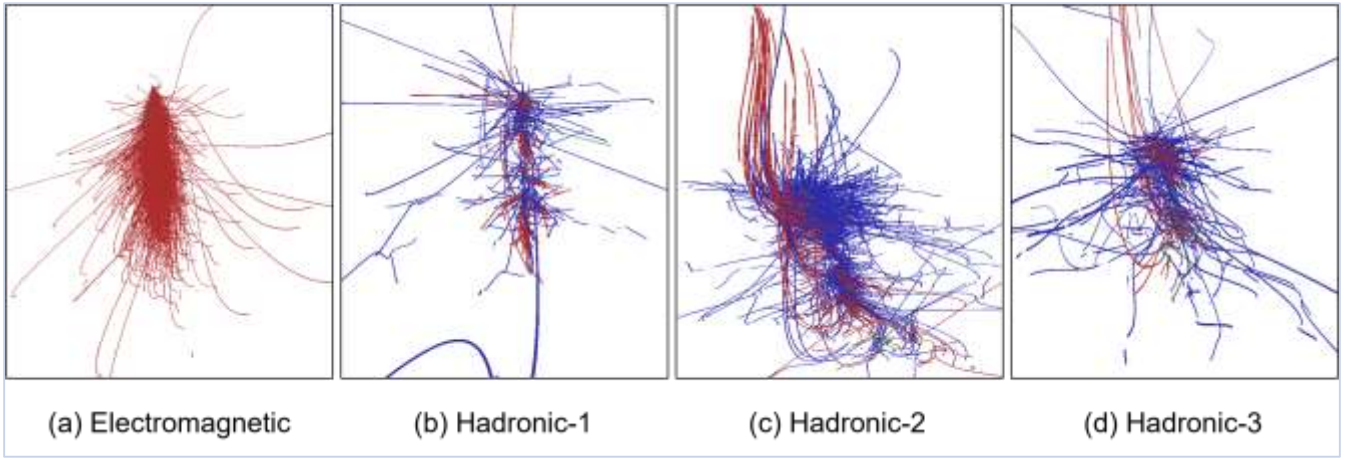
CMS New detector

≈6 million sensors

VALIDATED BY SIMULATION

Simulated showers

One event = 2k–23k trajectories packed into ≈1 m³



The four production datasets (1,983–22,604 tracks). The few high-energy tracks that matter are buried among low-energy secondaries.

From analysis questions to design requirements

Analysis questions

From a year of weekly meetings with CERN physicists and developers

- **Q1** What does the high-energy “spine” of the shower look like?
- **Q2** How deep does the shower penetrate, and how does that depend on the particle type?
- **Q3** Which descendants of a parent track carry most of the energy?
- **Q4** Are there outliers: unusually long tracks, energy in unexpected regions?
- **Q5** Did the reconstruction software wrongly merge tracks from different parents?

Design requirements

- **R1** **Browser-only,** no installation
- **R2** **≥ 30 FPS** on consumer hardware, up to 23k tracks
- **R3** **Important tracks always visible**, with context
- **R4** **Filtering** by energy, particle type, time, and sub-tree
- **R5** **Hierarchy navigation**, linked to the 3D view
- **R6** **Replaceable importance metric** (energy by default)

Later evaluated by study tasks → T1 depth cues: Q2, Q4 · T2 IOR: Q1 · T3 schematic view: Q3, Q5



Why a browser, and why WebGL 2.0?

Why a browser?

- CMS Classic Viewer is **a desktop application**: *heavy to install, hard to share*
- CERN is moving its viewers to the **browser**
- **Thousands of collaborators in 50+ countries;** a browser client is shared by URL (**R1**)

Why WebGL 2.0?

- **Stable** and runs everywhere
- **Used by CERN**'s web viewers
- **WebGPU** was still stabilizing

What it constraints

AVAILABLE
multiple render targets · texture sampling · blending

MISSING
atomics · storage buffers · compute shaders · programmable blending

LITERATURE METHODS CAN'T BE PORTED
per-pixel lists (A-buffer), order-independent transparency, opacity optimization

→ **Goal: solve occlusion with multi-pass rasterization only**



Dense-line methods don’t port to WebGL



Transparency / OIT

A-buffer, depth peeling, per-pixel linked lists; opacity optimization

NOT AVAILABLE

No atomics
No storage buffers or
No large per-pixel state



Clustering & density control

Line-cluster hierarchies

POOR FIT

Offline preprocessing



Illustrative & importance-driven

Depth-dependent halos, LineAO; importance-driven volume rendering

CLOSEST

IOR is an object-space, line-based analogue

Existing particle-shower viewers: Not web-based. None address occlusion at this scale.

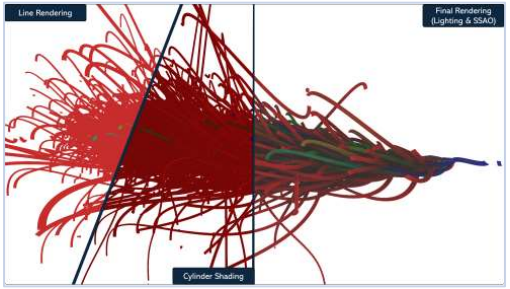
Our solution Outline

Rendering

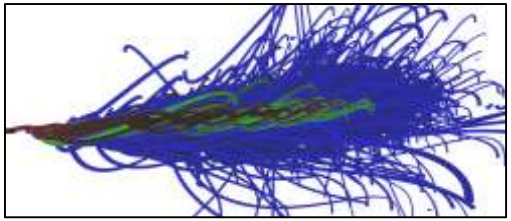
Schematic View

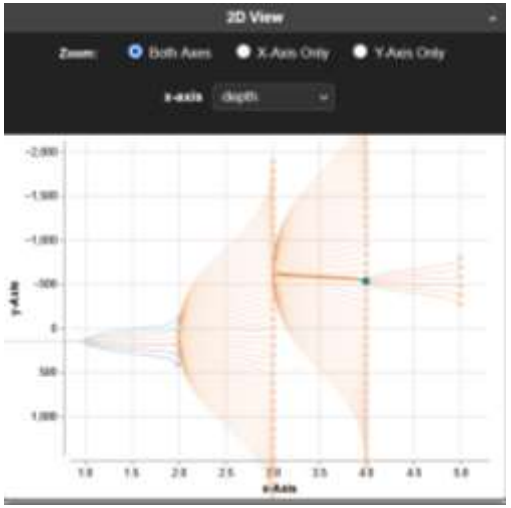
User Study

Shading



IOR



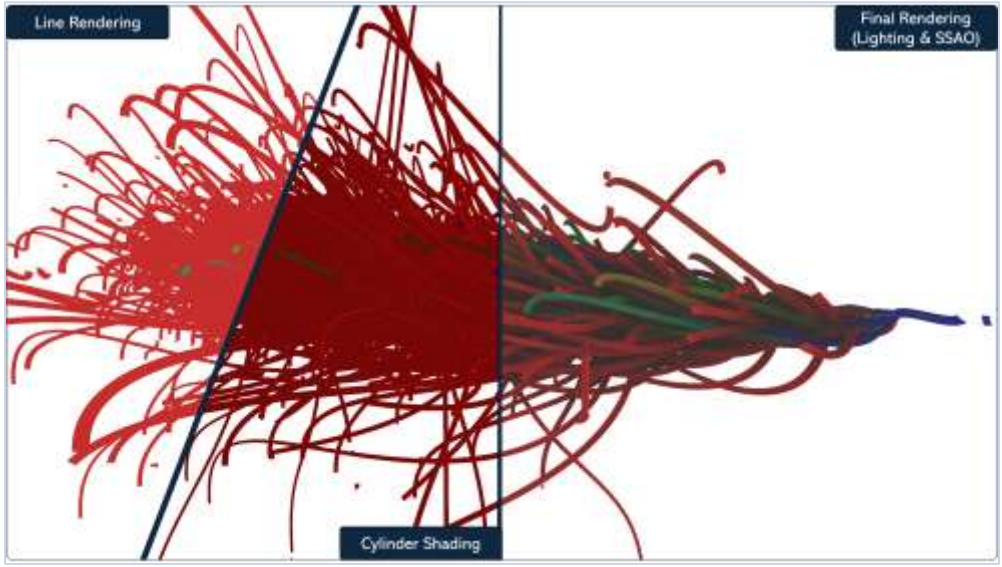




Perceptually Enhanced Rendering



Depth and motion cues



Plain lines → cylinder shading → lighting + SSAO

Cylinder-shaded lines
Fragment shader rotates its normal *($n' = n \cos\theta + b \sin\theta$)*

Screen-space ambient occlusion
Better depth perception

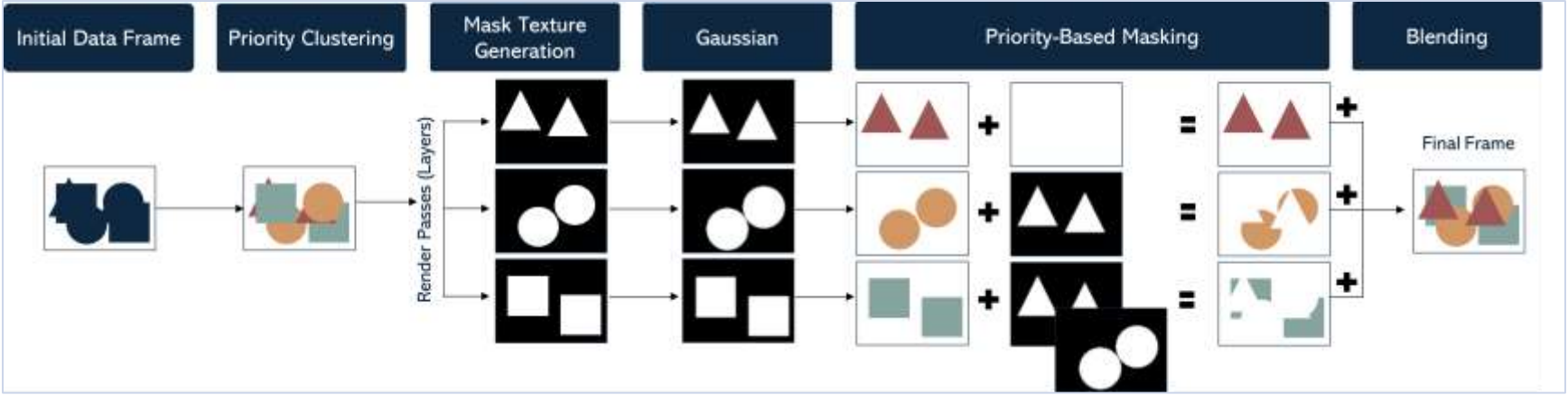
Dashed-line animation
Convey the direction of travel

Time-based animation
Reveals how the shower develops

Importance-Ordered Rendering (IOR)

R3 · R6

Idea: high-energy tracks are always drawn on top; low-energy tracks remain as soft context.



1 Cluster

Split tracks into k energy clusters (k = 3: low, medium, high); boundaries are user-adjustable

2 Render per cluster

Each cluster gets its own G-buffer: position, normal, depth, shaded color, and a presence mask

3 Blur the masks

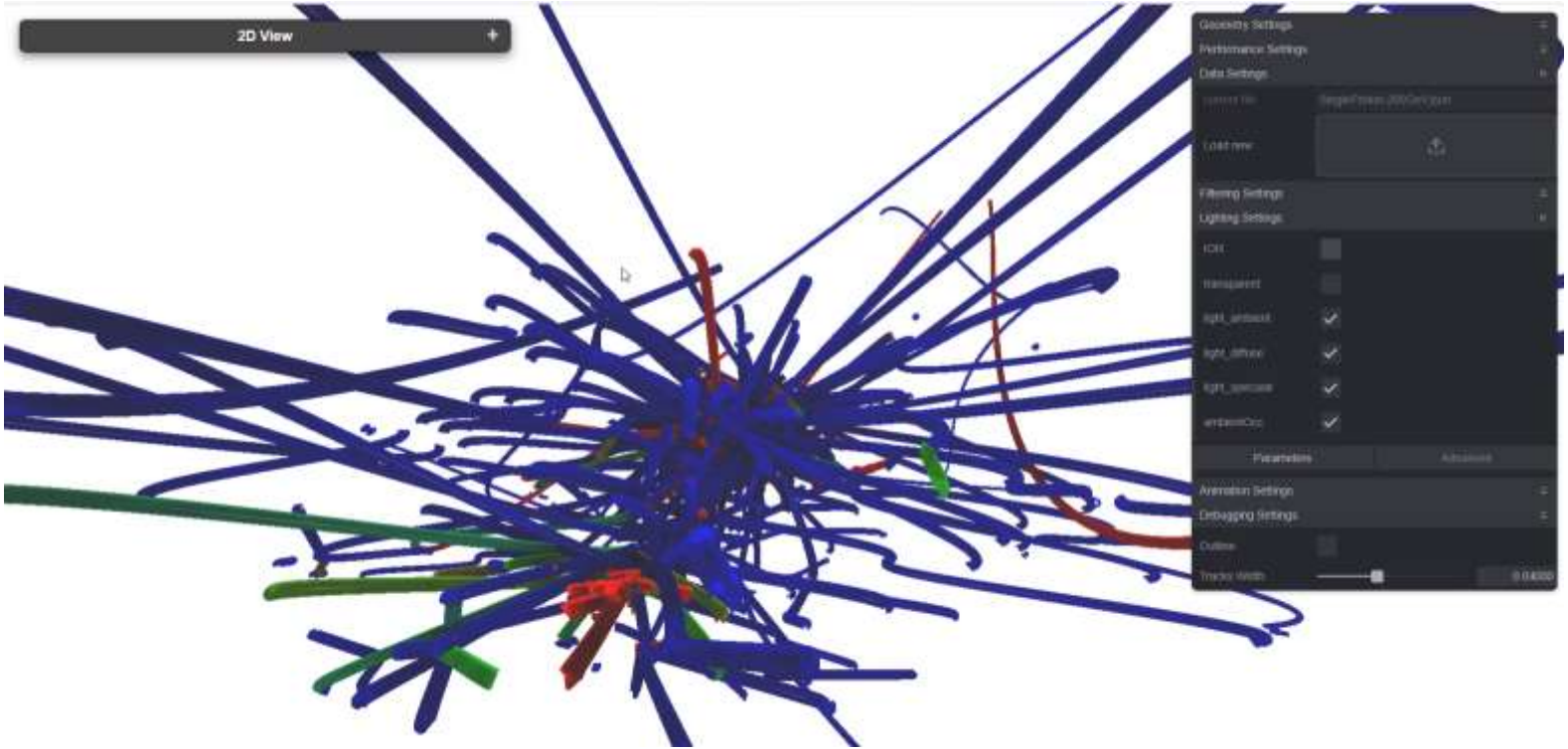
A separable two-pass Gaussian turns each mask into a soft halo

4 Composite

From low to high, each cluster is dimmed wherever a more important cluster is present.

IOR in action

R3



Demo: a proton shower (1,983 tracks), orbiting with IOR off, then on

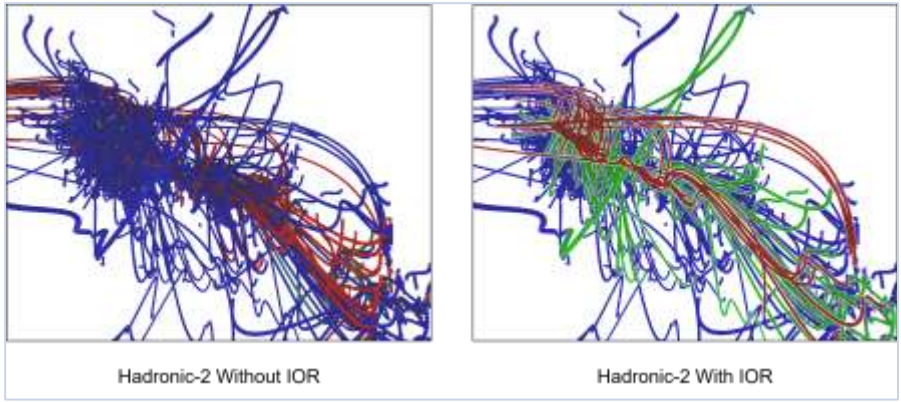
IOR stays within WebGL 2.0

R1

Only what WebGL 2.0 exposes

- Multiple render targets, texture sampling, and blending;
- Gaussian blur => two fragment-shader passes
- Compositing => dedicated fragment shader

Densest dataset · 22,604 tracks

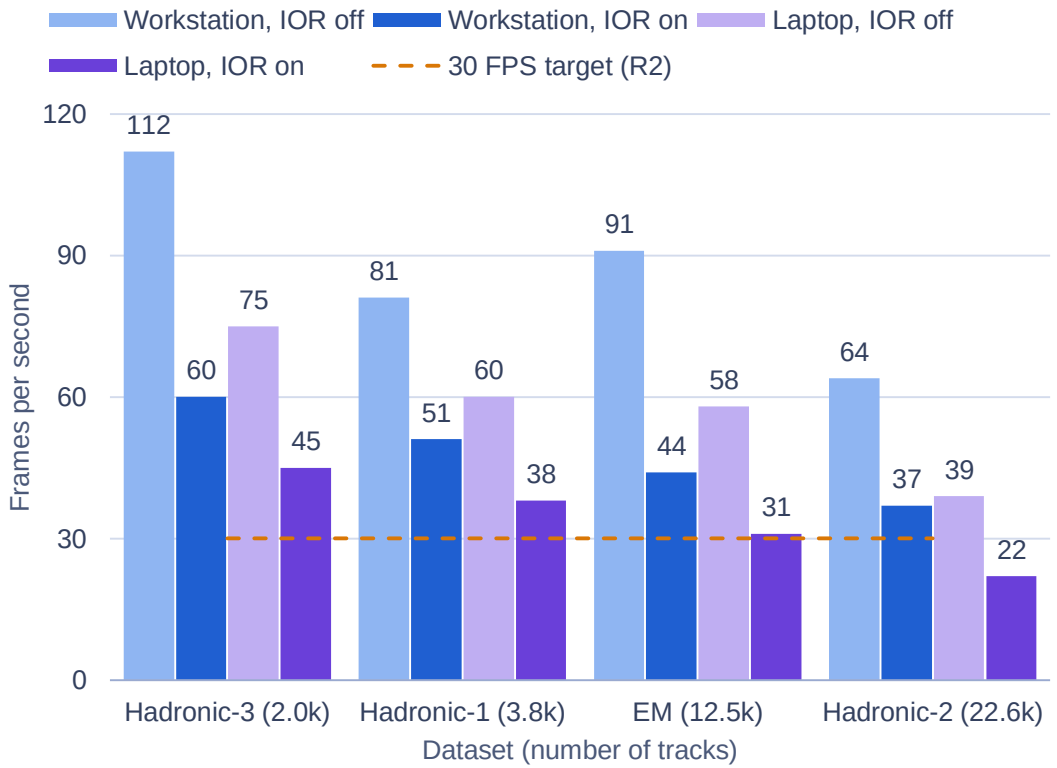


Without IOR **With IOR**

All data lives in regular 2D textures, so IOR runs on any WebGL 2.0 implementation.

Interactive on a workstation, usable on a laptop

R2



- **Workstation** (RTX 3050**):**
  With IOR: ≥ 37 FPS on every dataset
- **Laptop** (Intel Iris Xe, integrated):
  With IOR: 22 FPS on the largest dataset.
  Without IOR: > 30 FPS
- **IOR roughly halves FPS.** Its cost grows with viewport size, not track count

1920×1080 · Chrome 129 · Windows 11 · 100 segments per curve · median FPS over 5 s of orbiting · IOR: 3 clusters, Gaussian r = 2, σ = 1

Schematic View



Linked 3D and schematic views

R4 · R5

1 Schematic tree

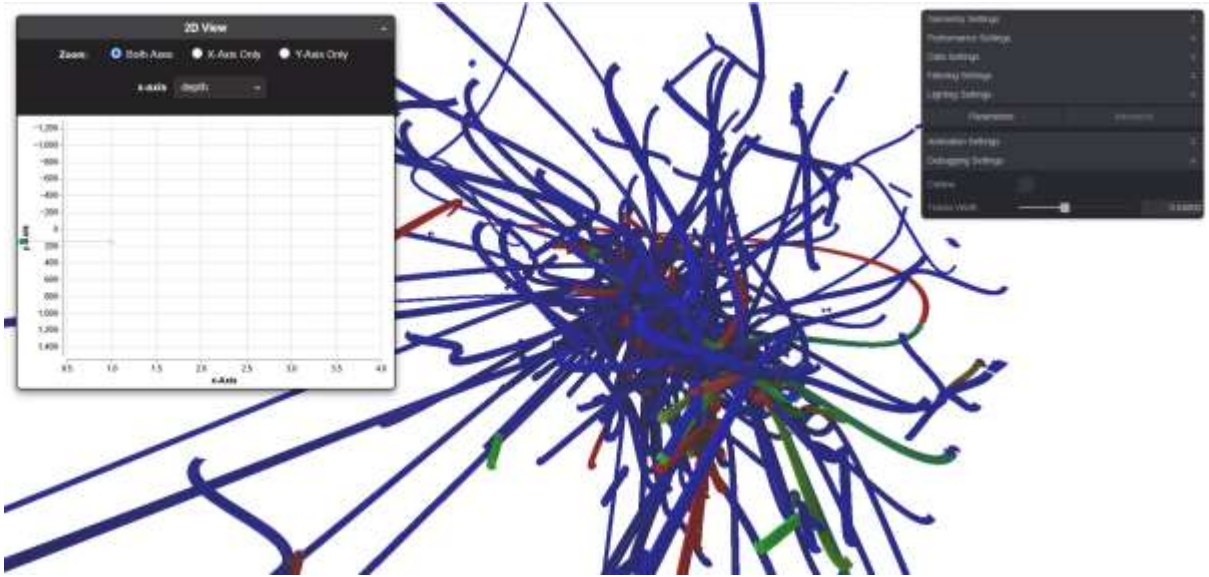
Each node is a trajectory, placed by creation time or depth z

2 Linked selection

Clicking a node restricts the 3D view to its sub-tree

3 Multi-attribute filtering

Particle ID, energy, and time ranges combine with the sub-tree filter



Demo: filtering and the linked schematic view

User Study



Preliminary user study: one task per feature

19 **participants**

11 engineers/computer scientists, 6 physicists or physics students, 2 other technical participants

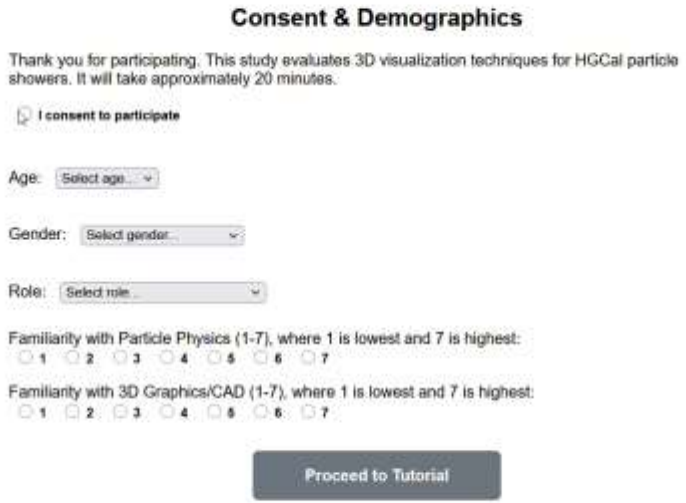
- Within-subjects, remote, in the browser
- 7 trials; condition order counterbalanced
- Accuracy vs. pre-computed ground truth, plus completion time
- 3 Likert items + 1 open question

Task	Prompt	Conditions
T1 · Depth cues	*"Of the two highlighted trajectories, which one is closer to the camera?"*	off / on
T2 · IOR	*"Click on the highest-energy trajectory in this shower."*	no cue / color only / IOR
T3 · Schematic view + filtering	*"Find all direct daughter trajectories of the highlighted parent track."*	off / on

T2's color-only condition separates the energy color map from importance-ordered compositing.

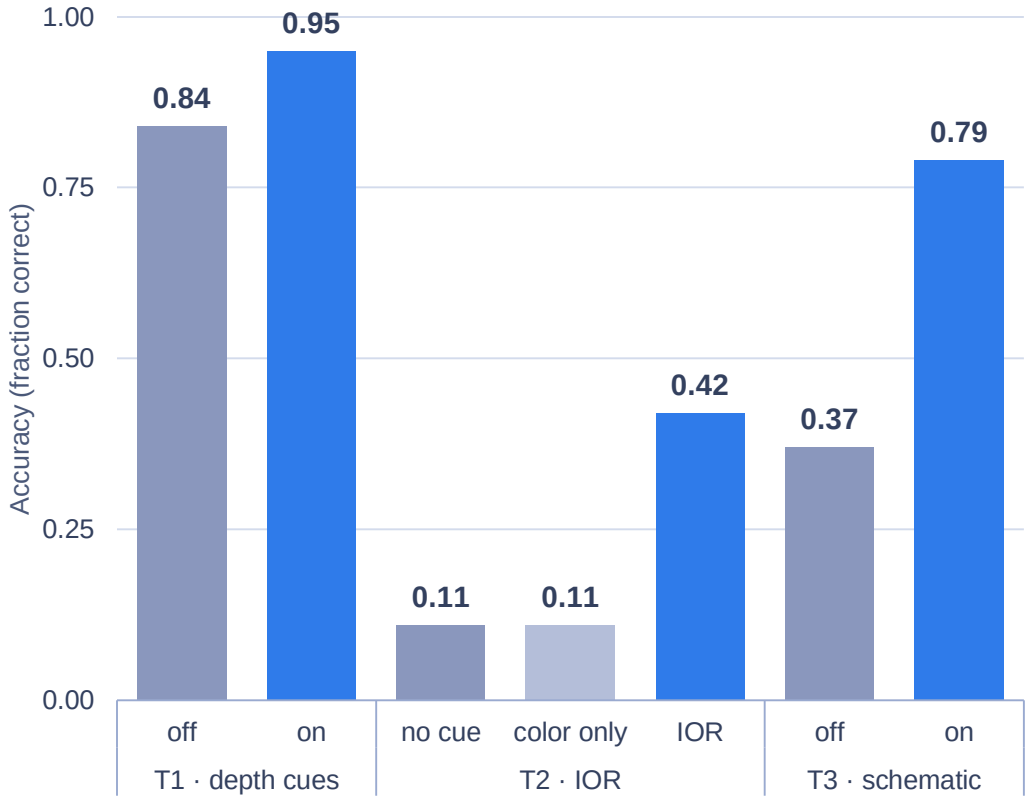


User study walkthrough



T1 depth cues (off / on) → T2 highest-energy track (no cue / color only / IOR) → T3 daughter tracks (schematic view off / on)

IOR and the schematic view improve accuracy



T2 · IOR

11% → 42%

McNemar p = 0.03 · color alone stayed at 11%

T3 · SCHEMATIC VIEW

37% → 79%

p < 0.01 · median time 27 → 50 s

T1 · DEPTH CUES

7.7 s → 6.9 s

median time, Wilcoxon p = 0.01 · accuracy near ceiling

N = 19 per condition. T3 accuracy = exact recovery of the daughter set. Full statistics in the supplementary material.

Subjective ratings and expert use cases

5.8 / 7
IOR helped me identify the high-energy tracks

5.1 / 7
Shading + SSAO made the spatial layout easier to read

4.9 / 7
The schematic view and filtering helped me navigate

“For the first time I can see the spine of the shower without running a separate analysis script.”

— simulation lead at CERN (paraphrased)

Detector design validation
Schematic view ordered by z + IOR was the most-used pair of features

Debugging the reconstruction software
Pick a parent in the tree; the 3D view shows only its descendants

Outreach
Showers shown to visitors by sharing a URL



Limitations and next steps

Limitations

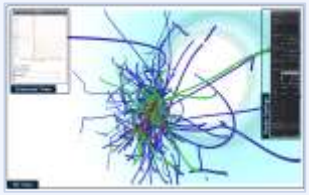
- IOR is a heuristic: Approximated depth between clusters
- Tablets and phones are untested
- Study is preliminary (N = 19; T2 accuracy still 0.42)

Next steps

- Port to WebGPU
- Overlay reconstructed tracksters to expose reconstruction failures
- glTF extension carrying per-track importance, particle type, and energy
- Integrate into CERN's web event viewer
- Run a larger study



Conclusions



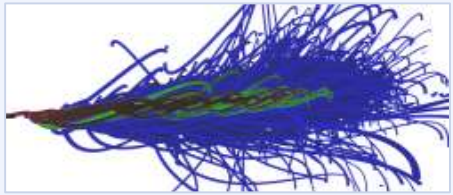
1 **A zero-install viewer for dense particle showers**

Runs in any browser; ≥ 37 FPS with up to 22.6k tracks



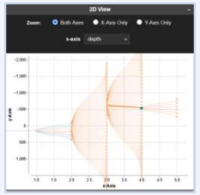
2 **Depth cues make spatial judgments faster**

Median response time 7.7 s → 6.9 s ($p = 0.01$)



3 **IOR keeps the most important tracks visible**

Accuracy 11% → 42% ($p = 0.03$); color alone: 11%



4 **The linked schematic view makes the hierarchy navigable**

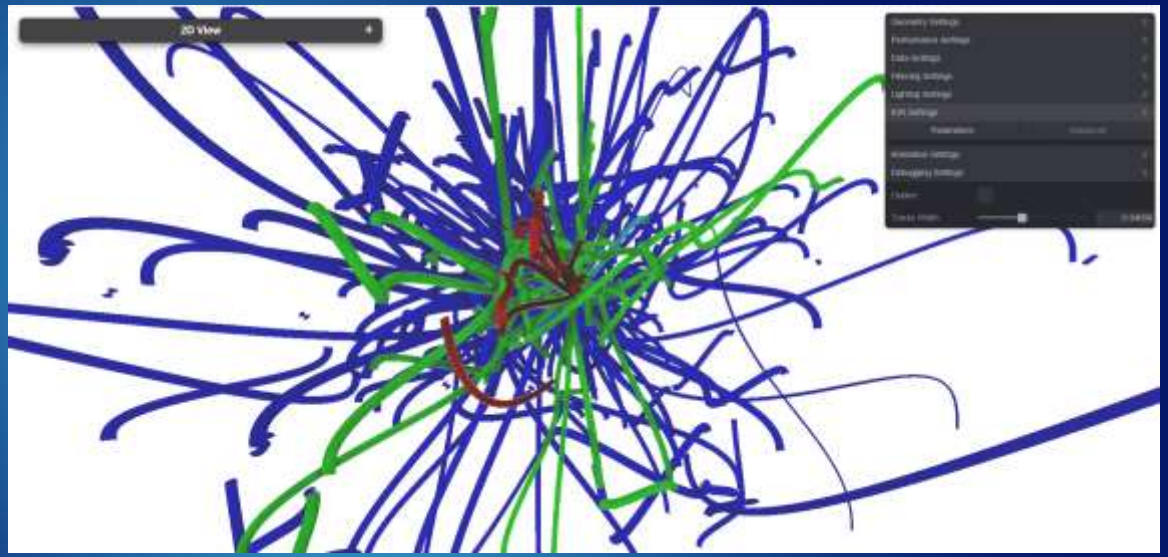
Complete daughter sets found 37% → 79% ($p < 0.01$)

Preliminary study, N = 19 · CERN experts use HGCalVis for detector design validation and reconstruction debugging

Thank You!

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Live demo: HGCalVis running in the browser







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