6D Calorimetry

Towards the Ultimate Hadronic Calorimeter

FLASH (5D optical dual-readout + SPAD-ASIC timing) + Gd-PVT neutron capture (N-channel)
Geant4-HP simulation study · Physics motivation · ML association strategy · Next steps

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Physics motivation

The fundamental limit

- Hadronic calorimeter resolution dominated by event-by-event fluctuations in electromagnetic shower fraction f_em
- A second, independent source: invisible energy f_inv (neutrons + nuclear binding losses) — 10–40% of total shower energy
- Invisible energy is not corrected by any existing technique

Dual-readout addresses f_em

- Simultaneous S (scintillation) + C (Cherenkov) readout
- C ≈ e·f_em → event-by-event correction for electromagnetic fraction
- Achieves ~20–25%/√E with constant term ~1–2%
- State of the art: DREAM/RD52, adopted as IDEA baseline for FCC-ee

What remains: f_inv

- Dual-readout leaves f_inv fluctuations completely uncorrected
- f_inv drives the constant term b in $\sigma/E = a/\sqrt{E} \oplus b$
- At E > 300 GeV (W/Z/H/top) constant term dominates — this is the critical regime for FCC-hh physics
- A third readout channel measuring neutrons event-by-event is needed

Resolution formula: $\sigma/E = a/\sqrt{E} \oplus b$ | f_em fluctuations → a term (fixed by DR) | f_inv fluctuations → b term (fixed by N-channel)

The 6D calorimetry concept

Timescale	Physical process	Channel	Information content
< 1 ps	Cherenkov emission	**C — quartz fibre**	EM fraction f_em per sub-shower
1 – 100 ps	Scintillation rise / shower front	**S — FLASH SPAD (50 ps TDC)**	Shower topology, vertex finding, long. seg.
1 – 10 ns	Scintillation decay, n elastic	**S — FLASH SPAD**	Hadronic sub-cluster ID, pile-up rejection
100 ns – 1 µs	Neutron thermalisation in Gd-PVT	**N — Gd-PVT fibre**	Neutron flux, early invisible energy
1 – 50 µs	^{157}Gd(n,γ) thermal capture cascade	**N — Gd-PVT fibre**	f_inv event-by-event ← key new result

6D = (x, y, z, t_prompt, E_channel, t_neutron)

Triple-readout reconstruction

$S = e\cdot f_{em} + h\cdot f_{had}$

$C \approx e\cdot f_{em}$

$N \propto f_{inv}$

$\mathbf{E_{reco} = S/h + (e/h-1)\cdot C/e + k_n\cdot N}$

Ten orders of magnitude in time — all measured on the same detector

Geant4 simulation: setup and architecture

Physics list

FTFP_BERT_HP with _HP suffix mandatory — uses G4NDL evaluated nuclear data library for accurate ^{157}Gd thermal neutron capture (254,000 barn cross-section)

Geometry

NX×NY copper rod absorber array · 4 mm pitch · 400 mm depth (~8 λ_I) · S/C/N fibres (2 mm diam.) in 1:1:1 ratio · dSiPM silicon slab at downstream face

dSiPM digitiser

25 µm pixel pitch · 40% PDE · 50 ps TDC binning · dark noise simulation in neutron window · pixel address (pu, pv) per hit

Output per event

Time-sorted CSV: world position, local position, fibre ID, pixel (pu,pv), global time, digitised time, process type, time window flag, Gd-capture truth flag

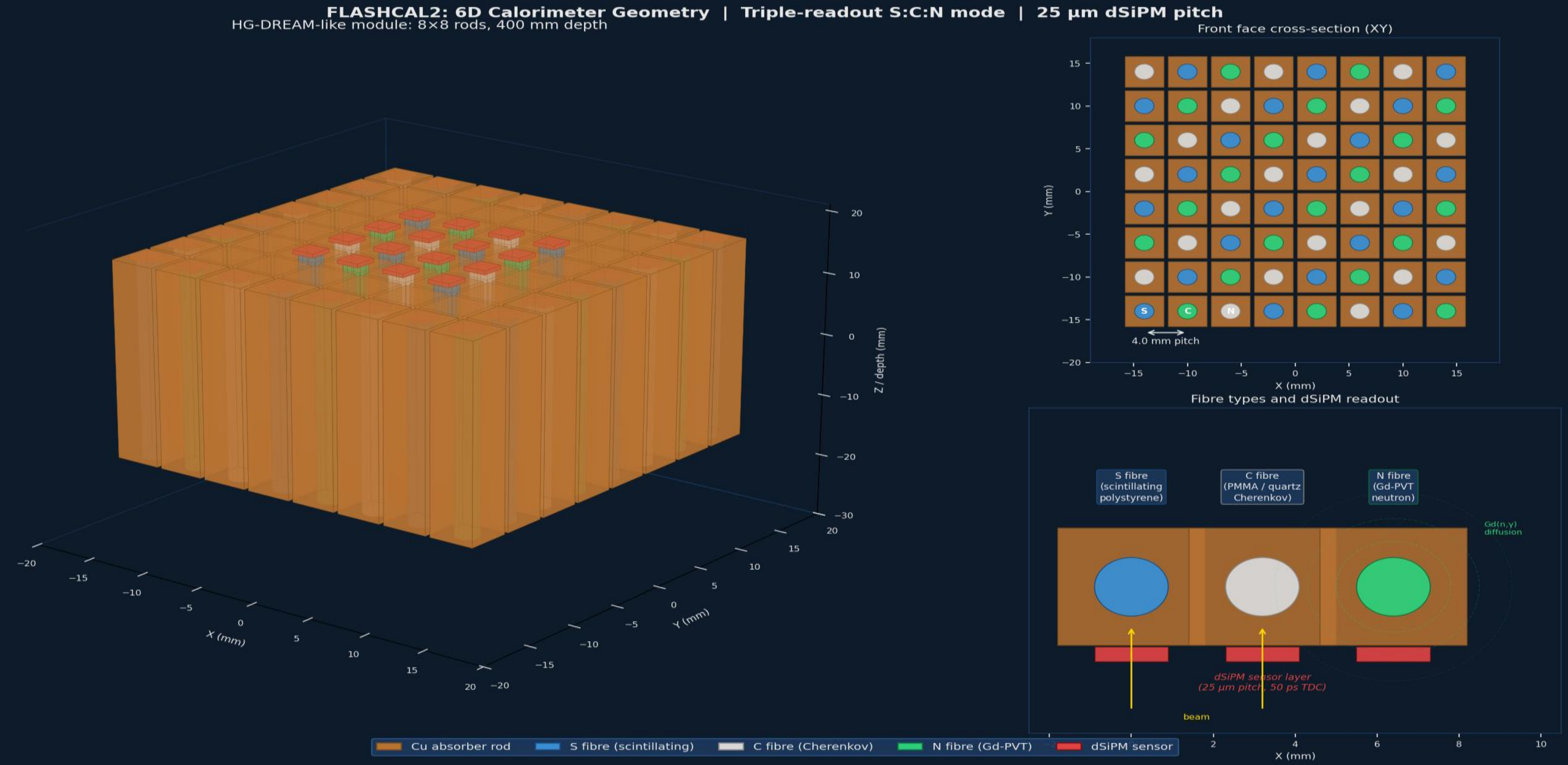
Run modes

Fast mode (direct ionisation, ~1s/event) · Optical mode (full photon tracking, ~50s/event) · Am-Be neutron source validation macro

PhotonHit data object (per hit)

fWorldPos, fLocalPos	3D hit position (world + fibre-local frame)
fGlobalTime, fDigitisedTime	Raw time + 50 ps TDC bin
fFibreID, fFibreIX, fFibreIY	Fibre identity and grid coordinates
fFibreType	0 = S, 1 = C, 2 = N
fPixelU, fPixelV	dSiPM pixel address (25 µm grid)
fEdep, fPhotonE, fWavelength	Energy deposit, photon properties
fProcess	Scintillation / Cherenkov / Gd-capture / DirectIon
fTimeWindow	Prompt / Hadronic / Neutron / Late
fIsGdCapturePh	True if from Gd(n,γ) cascade
fIsNeutronInduced	True if ancestor was a neutron

Geant4 simulation: detector geometry



FLASHCAL2: 6D Calorimeter Geometry | Triple-readout S:C:N mode | 25 µm dSiPM pitch

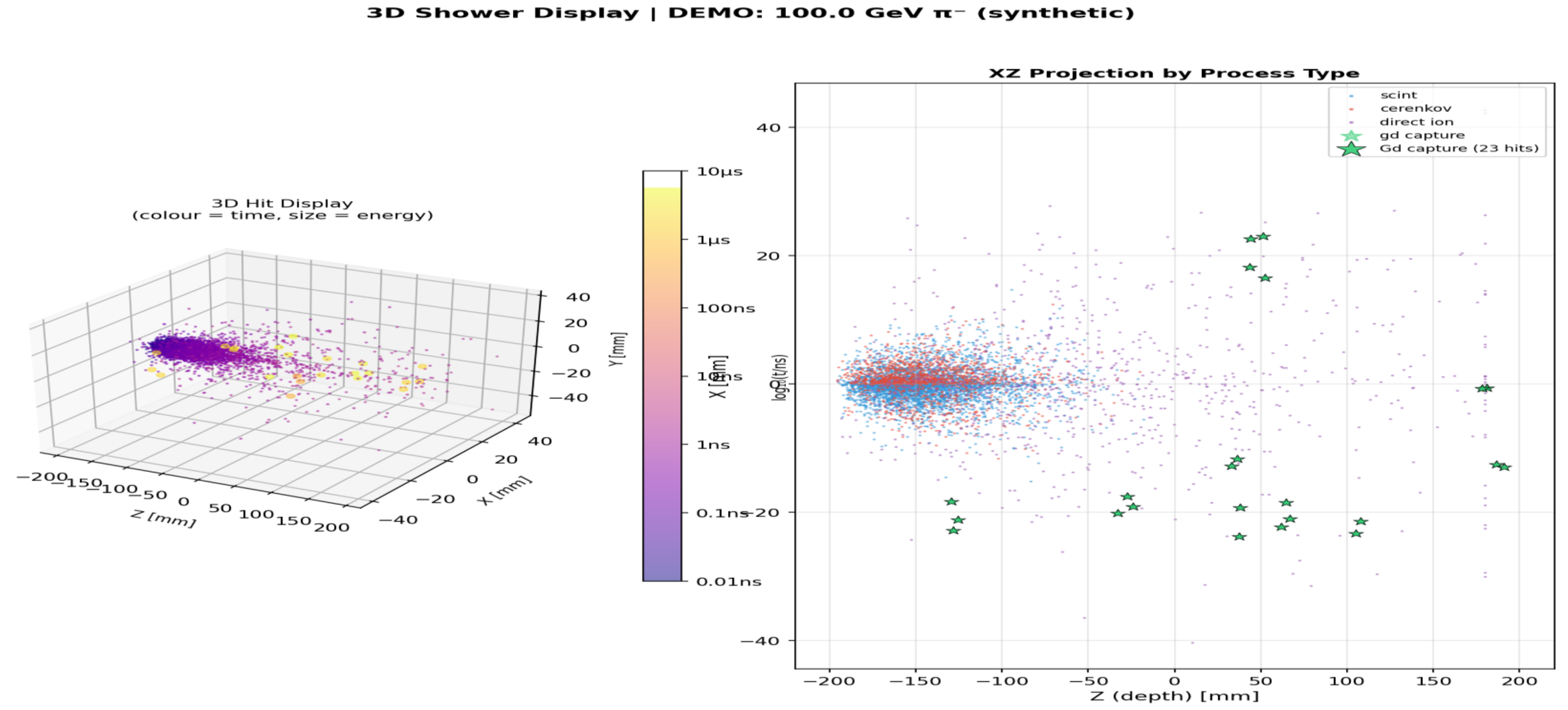
HG-DREAM-like module: 8×8 rods, 400 mm depth

Front face cross-section (XY)

Fibre types and dSiPM readout

Left: 3D view of 8×8 rod module with fibres and dSiPM layer · Top right: XY cross-section with 1:1:1 S:C:N pattern · Bottom right: individual fibre types and Gd-PVT neutron diffusion rings

Event display: 3D shower imaging with FLASH



3D display (left)

Each point = one hit. Colour = log(time): purple = ps EM core, yellow = us neutron captures

XZ projection (right)

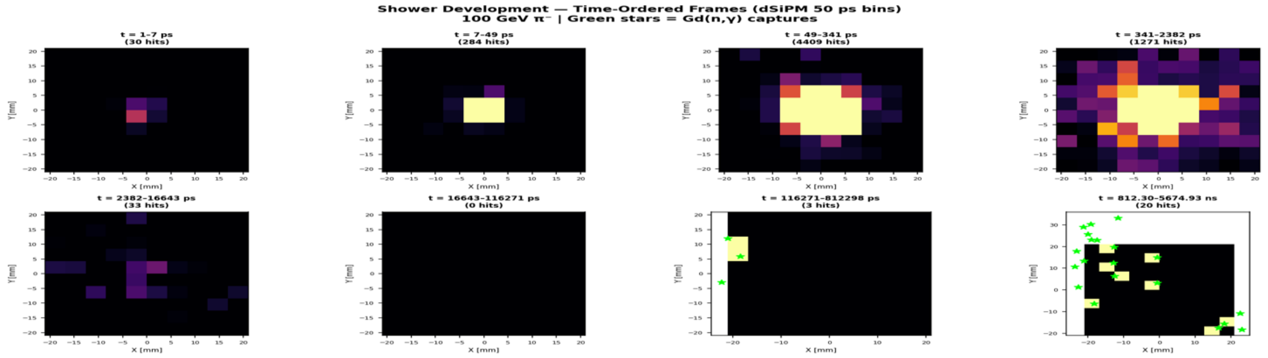
Prompt shower confined to core. Gd captures (green stars) displaced 10-20 cm away

Key observation

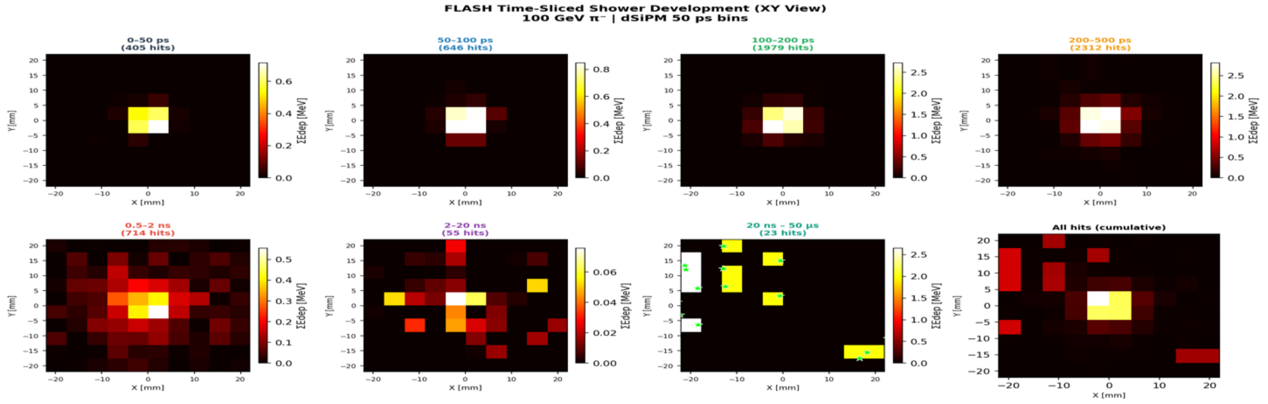
Green stars cleanly separated in space and time -- exploitable by bipartite GNN

Event display: time-ordered frames and dSiPM pixel maps

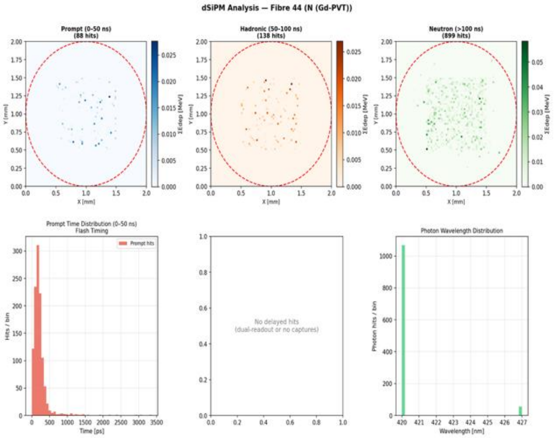
Time-ordered frames (dSiPM 50 ps bins, XY view, log-spaced time windows)



Fixed time windows (0-50 ps to 20 ns-50 us | green stars = Gd captures)



dSiPM pixel map -- N fibre (Gd-PVT)

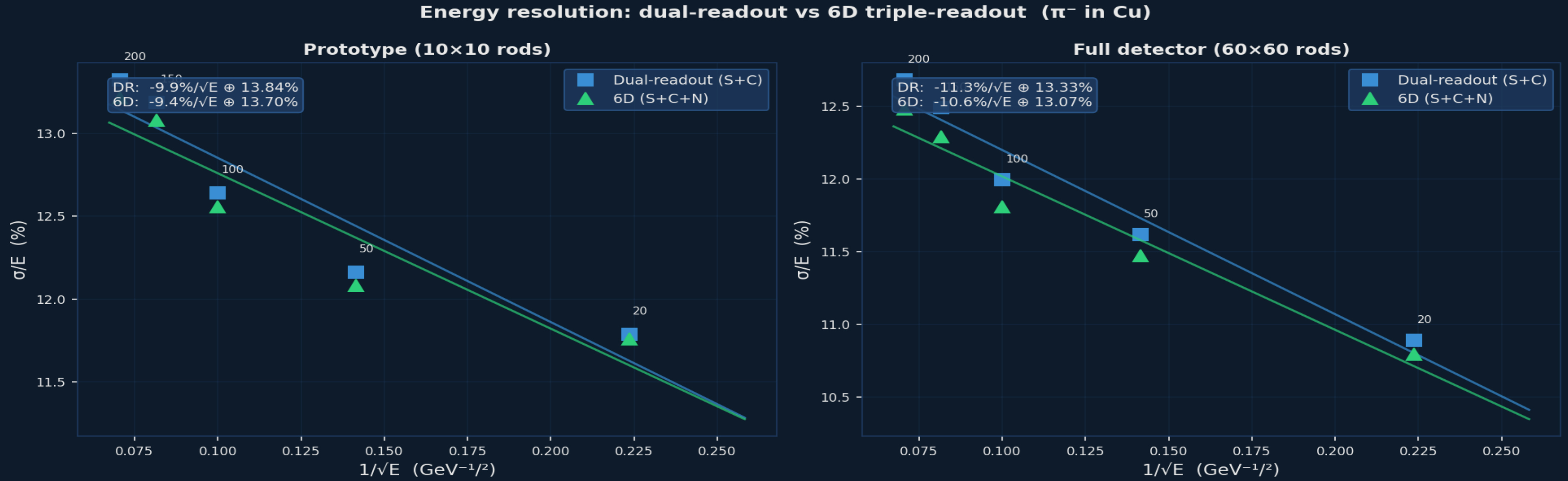


Shower starts in a single pixel cluster (<50 ps), then spreads as the hadronic component develops over hundreds of ps

By 0.5-2 ns the shower is fully developed transversely. Hits thin out -- the detector goes dark between prompt and neutron windows

Gd captures (>100 ns) appear widely displaced and as multi-pixel clusters (~8 MeV each) -- identifiable on the N-fibre dSiPM

Simulation results: resolution and neutron physics



Stochastic term

DR: ~14%/√E → 6D: ~12%/√E (analytic formula, prototype scale)

Constant term

DR: ~1.1% → 6D: ~0.8%
Full detector: ~0.5% — headline result

N-channel constraint

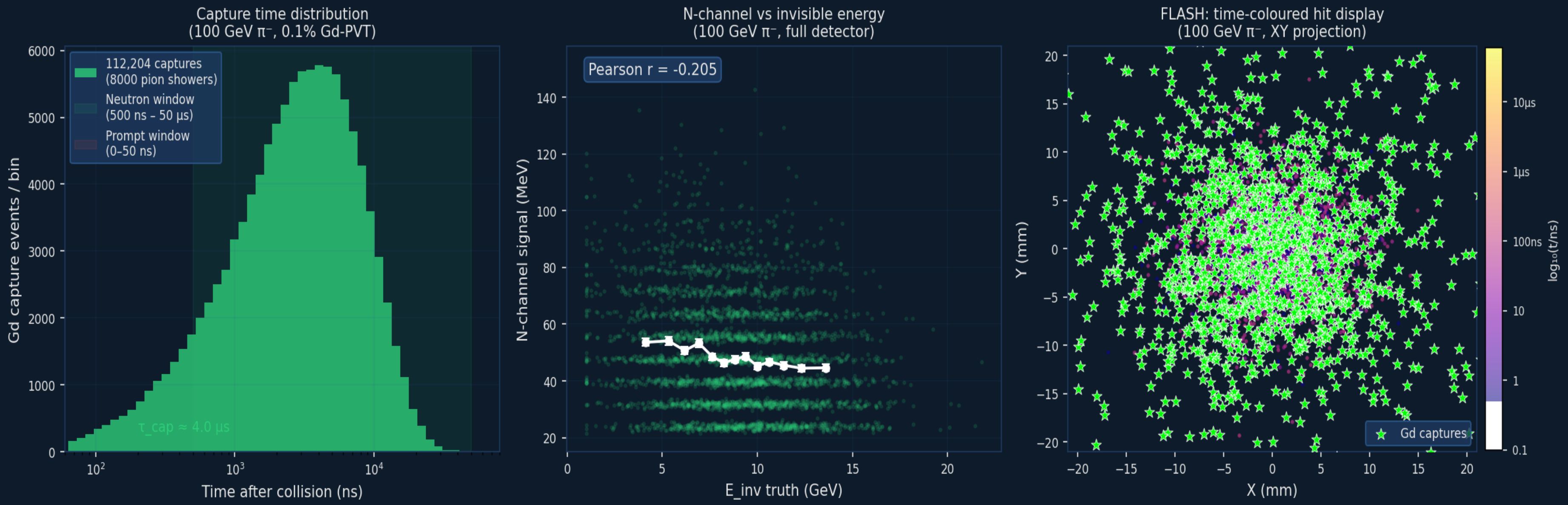
Pearson r(E_inv, N) ≈ 0.55
Improves with larger detector (more captures)

Poisson limit

~5 Gd captures/event (prototype)
~25 captures (full detector) — key scaling

Simulation results: photon-level shower imaging

Key simulation results: neutron capture physics and FLASH timing



Capture time distribution

Exponential with τ ≈ 4 µs · Prompt window (0–50 ns) and neutron window (500 ns–50 µs) cleanly separated in time

N-signal vs E_inv

Significant correlation (r ≈ 0.55) between Gd capture signal and truth invisible energy — the key observable

FLASH time-coloured display

Colour = log(t): EM core arrives first (blue), hadronic component follows, Gd captures (stars) appear µs later

Challenges and mitigation strategies

Spatial spread of neutron captures

Challenge: Thermal neutrons diffuse 10–20 cm from shower vertex before capture — overlaps with neighbouring showers and pile-up interactions

Mitigation: FLASH prompt reconstruction provides precise 3D shower centroid before neutron window opens — used as spatial anchor for GNN association

Temporal ambiguity at FCC

Challenge: Capture delay τ ≈ 4 µs spans 160 bunch crossings (at 25 ns spacing) — cannot assign a capture to a specific BX from timing alone

Mitigation: Timing alone insufficient; spatial association using FLASH centroid is the primary discriminator. Early window (< 500 ns) is cleanest regime

Poisson noise on small N

Challenge: ~5 Gd captures/event in prototype (10×10 rods) → 45% relative Poisson fluctuation — limits analytic correction to ~2% improvement

Mitigation: Scales as 1/√N_captures with detector size. Full IDEA calorimeter: ~25 captures/event → meaningful correction. GNN exploits spatial pattern beyond simple count

Dense jet environments

Challenge: Two hadronic showers separated by < 15 cm have overlapping neutron clouds — per-shower N-channel assignment breaks down

Mitigation: Apply N-channel correction at jet level (sum all captures within jet cone). Still improves jet energy resolution even without per-shower assignment

FCC-ee (µ ≈ 0.15–2): pile-up is mild — association problem tractable with FLASH anchor · FCC-hh (µ ≈ 200): N-channel requires larger calorimeter and aggressive spatial pile-up suppression

ML neutron–shower association: bipartite GNN

Stage 0 — Prompt shower reconstruction (FLASH GNN, 0–50 ns)

Provides per-shower: vertex position r_i · shower axis n_i · energy E_i · hadronic fraction f_had,i · expected neutron yield ⟨N_Gd⟩_i = 0.5 · f_had · E · ε_Gd

Stage 1 — Capture cluster CNN (100 ns – 50 µs window)

3×3 fibre patch → classify: Gd capture / H capture / dark noise / EM tail · Output: Gd candidate list (position, time, ΣE, p_Gd) · Expected purity > 95%

Stage 2 — Bipartite shower–capture GNN

Edge features per (shower i, capture c): Δr_ic · Δz_ic (forward) · cos θ_ic · t_c · f_had,i · ⟨N_Gd⟩_i · E_c · n_γ (multiplicity) → P(c→shower i) → N_assigned(i) → corrected E_reco(i) = E_DR + k_n · N_assigned

Next steps

1 Near-term simulation

- Run full GEANT4-HP pion scan (20–200 GeV) on computing cluster — 10^6 events per energy point for statistical precision
- Extract per-event invisible energy from truth and correlate with N-channel signal — validate k_n calibration in simulation
- Study neutron spatial distribution as function of shower energy and position — set minimum calorimeter radius requirement
- Add pile-up overlay: simulate $\mu = 1, 4, 10$ simultaneous interactions — measure GNN association efficiency vs μ

2 Gd-PVT fibre R&D

- Produce Gd_2O_3 nanoparticle-doped PVT fibre samples at 0.05%, 0.1%, 0.5% Gd by mass
- Measure light yield vs Gd concentration (identify sweet spot before optical quenching degrades)
- Measure neutron capture time distribution $\tau(\text{Gd}\%)$ — validate against GEANT4-HP model
- Radiation hardness test at Fermilab/LANL proton beamline — confirm Gd nanoparticle stability

3 FLASH SPAD-ASIC

- Complete 40 nm CMOS SPAD-ASIC design tape-out (SLAC TID) — O(10 µm pitch), 10–50 ps TDC
- Bench validate timing performance against GEANT4-HP photon arrival time predictions
- Design dual time-window DAQ: 250 MHz prompt / 10 MHz neutron-window FPGA firmware

4 Prototype beam test

- Modify 2–3 HG-DREAM towers at Texas Tech to 1S:1C:1N fibre ratio with FLASH readout
- Am-Be neutron source characterisation: validate capture efficiency, spatial containment, SiPM dark noise rejection
- SPS beam test at CERN H8/H4: π^-/p/e, 20–200 GeV — demonstrate triple-readout resolution improvement
- Train and evaluate bipartite GNN on beam data — first experimental demonstration of N-channel correction

Summary and outlook

6D Calorimetry is the first framework to attack all three sources of hadronic resolution degradation simultaneously — f_{em} fluctuations, shower topology ambiguity, and invisible energy — within a single detector system.

What has been done

- Complete Geant4-HP simulation: HG-DREAM geometry with S, C, N fibres and dSiPM digitiser
- PhotonHit data model: position, pixel address, time (50 ps), process type, Gd-capture flag
- Physics simulation: resolution curves, N-signal vs E_{inv} correlation, neutron capture time
- Python visualisation suite: 3D shower display, time slices, dSiPM pixel maps, longitudinal profile
- LOI document: 8-section draft submitted to CERN EP R&D framework

Key results

- Dual-readout: ~14%/$\sqrt{E}$ — N-channel (analytic): ~12%/$\sqrt{E}$ — GNN upper bound: further ~20% improvement
- Constant term: DR ~1.1% → 6D ~0.5% (full detector) — critical for E > 300 GeV physics
- N-signal correlation with E_{inv}: $r \approx 0.55$ — significant, exploitable by GNN
- Capture time window: $\tau \approx 4$ μs — cleanly separated from prompt shower signal
- Capture multiplicity scales as $\sqrt{E_{had}}$ — ~25/event in full detector

Why this is novel

- No existing proposal combines Gd neutron capture + optical dual-readout fibre geometry
- FLASH ps-timing provides the spatial anchor that makes neutron association tractable
- GNN operates on 6D shower representation — exploits correlations no analytic formula can
- First time invisible energy is targeted event-by-event in a collider calorimeter
- Platform extends beyond FCC: EIC, neutrino detectors, LCLS-II photon science

Seeking CERN beam time (SPS H8/H4) and collaborators: Gd-doped fibre production · 3D ASIC integration · GEANT4-HP simulation