

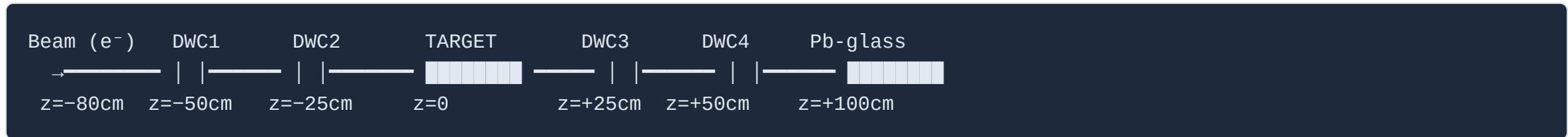
Technical Deep Dive

What the code actually does — for project owners

7 source files · 2 CI pipelines · 3 analysis scripts · 11 materials

Geant4 — Detector Geometry

Layout along Z-axis (beam direction):



Component	Material	Size	Purpose
DWCs ($\times 4$)	Ar/CO ₂ 80/20 gas (10 mm gap)	$10 \times 10 \text{ cm}^2$	Measure particle direction before/after target
Target	Configurable via macro	$10 \times 10 \text{ cm}^2$, variable thickness	Material under study
Calorimeter	PbO lead glass	$15 \times 15 \times 30 \text{ cm}^3$	Energy measurement (optional extension)
World	Air	$3 \times 3 \times 3 \text{ m}^3$	Contains all volumes

Key: One binary runs all 22 configurations. Macro commands `/beamscan/target/material` and `/beamscan/target/thickness` reconfigure the target between runs — no recompilation needed.

Geant4 — Physics List & Per-Event Data

Physics List: FTFP_BERT + option4

FTFP_BERT: Fritiof + Bertini cascade

- Handles hadronic interactions (p , π , n)
- Nuclear elastic + inelastic scattering
- *This is why G4 gives 12% more than Highland*

EM option4: most accurate MCS model

- G4UrbanMscModel for electrons
- G4WentzelVIModel for hadrons
- Step limiter ensures small steps in

What happens per event

1. **ParticleGun** fires e^- at $z = -80$ cm
2. Particle traverses DWC1 → DWC2
(*SteppingAction records first hit per plane*)
3. Particle enters **TARGET** → MCS happens
4. Particle exits → DWC3 → DWC4
5. Particle hits Calorimeter → energy deposited
6. **EventAction** computes all angles + momenta

Geant4 — The 9-Column Ntuple

Column	Unit	How computed	Used for
theta3D_mrad	mrad	<code>acos(inDir . outDir)</code>	Full 3D scattering angle
thetaX_mrad	mrad	<code>atan2</code> difference in x-z plane	Primary classification observable
thetaY_mrad	mrad	<code>atan2</code> difference in y-z plane	Cross-check / 2D analysis
pIn_GeV	GeV	Momentum at DWC2 (before target)	Beam energy verification
pOut_GeV	GeV	Momentum at DWC3 (after target)	Energy loss measurement
deltaP_MeV	MeV	$p_{\text{In}} - p_{\text{Out}}$	dE/dx spectroscopy
xTarget_mm	mm	Interpolated x position at target plane	Beam profile
yTarget_mm	mm	Interpolated y position at target plane	Beam profile
caloEdep_MeV	MeV	Total energy deposited in lead glass	Particle ID (future)

9 columns per event — enough for MCS classification AND momentum-loss spectroscopy. Students can mine this data for multiple physics analyses beyond the primary classification.

Geant4 — Multi-Threading & Output Format

MT-Mode Architecture

Geant4 11.3.2 auto-detects CPU cores.

GitHub Actions runner: **4 cores → 4 threads.**

Each thread writes its own CSV file:

```
events_nt_beamscan_t0.csv  
events_nt_beamscan_t1.csv  
events_nt_beamscan_t2.csv  
events_nt_beamscan_t3.csv
```

`ActionInitialization.cc` creates per-thread copies of `RunAction` + `EventAction` + `SteppingAction`.

WCSV Format (not standard CSV!)

Geant4 writes `#class`

`tools::wcsv::ntuple` headers with metadata, **not a plain CSV.**

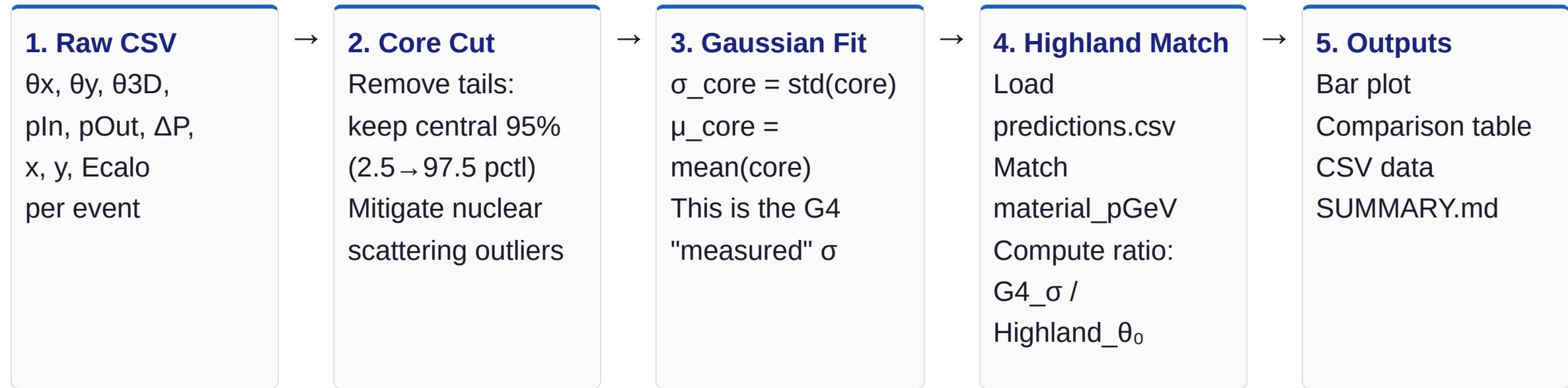
Our parser (`analyze_geant4.py`) handles:

- `#separator` line → detects delimiter
- `#column` lines → extracts column names
- Data lines → splits and zips into dicts

Why this matters:

`pandas.read_csv()` fails on Geant4

Analysis Pipeline — From Raw Events to Classification



Why the Core Cut Matters

MCS produces a **Gaussian core + non-Gaussian tails**. The tails come from: (a) nuclear elastic scattering (large single kicks), (b) nuclear inelastic events (secondaries), (c) delta rays. Highland predicts only the Gaussian core, so we cut the tails for a fair comparison.

Highland Calculator — The Analytic Engine

The Formula (PDG 2024)

$$\theta_0 = \frac{13.6 \text{ MeV}}{p\beta c} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \frac{x}{X_0} \right]$$

`compute_predictions()` does:

1. Look up X_0, ρ from MATERIALS_DB
2. Or accept student-provided X_0/ρ in YAML (*custom materials!*)
3. Compute θ_0 via Highland formula
4. Estimate
 $dE/dx \approx 2 \text{ MeV}/(\text{g/cm}^2) \times \rho \times x$
5. Store result: $\theta_0, dE, X_0, \rho, p, \text{thickness}$
6. For all material pairs:

Output Files

`predictions.csv` — 11 materials × 2 momenta = 22 rows
Columns: name, g4name, category, X_0 , ρ , thickness, p , θ_0 , dE

`distributions.png` — Gaussian curves overlaid for all materials

`classification.png` — 2D plot: $\theta_0(3 \text{ GeV})$ vs $\theta_0(6 \text{ GeV})$ with 1/p line and cluster annotations

`SUMMARY.md` — Table + pair separations + N_events

CI/CD — Two Pipelines, Two Purposes

⚡ Highland CI (~30 sec)

Triggers: PR touching `requests/* .yaml`, push to main, or manual dispatch

Steps:

1. Checkout repo
2. `pip install pyyaml jsonschema matplotlib`
3. Validate YAML against JSON schema
4. Run `highland_calculator.py`
5. Upload `predictions/` as artifact
6. If PR: **post comment with plots +**

⚛️ Geant4 CI (~20 min)

Triggers: manual dispatch only (*too expensive for every PR*)

Steps:

1. Checkout repo
2. Install Miniforge (conda)
3. `conda install geant4` (11.3.2) + cmake, gcc, matplotlib, scipy
4. `cmake + make beamscan`
5. `generate_macros.py` → 22 `.mac` files
6. `run_all.sh` → runs all 22 simulations

Macro Generation & Scattering Computation

generate_macros.py

Reads student YAML → writes one `.mac` per material × momentum:

```
# Auto-generated: PE_3.0GeV_10.0mm.mac
/run/initialize
/gun/particle e-
/gun/energy 3.0 GeV
/beamscan/target/material G4_POLYETHYLENE
/beamscan/target/thickness 10.0 mm
/beamscan/output/filename \
    geant4_output/PE_3.0GeV_10.0mm/events
/run/beamOn 2000
```

Plus `run_all.sh`:

```
for f in macros_auto/*.mac; do
```

The Scattering Angle Computation

`SteppingAction` records first hit per DWC → position + momentum at each plane.

`EventAction::EndOfEventAction` computes:

```
inDir  = (pos[DWC2] - pos[DWC1]).unit()
outDir = (pos[DWC4] - pos[DWC3]).unit()

θ_3D = acos(inDir · outDir)
θ_x  = atan2(out.x, out.z) - atan2(in.x, in.z)
θ_y  = atan2(out.y, out.z) - atan2(in.y, in.z)
```

Only events hitting **all 4 DWCs** are kept
(natural acceptance cut).

Bugs Found & Fixed — Engineering Story

Severity	Bug	Root Cause	Fix
CRITICAL	X ₀ Values Wrong (4 materials)	PVC, CaCO ₃ , Al ₂ O ₃ , Fe ₂ O ₃ had X ₀ in g/cm ² instead of cm. Highland overpredicted PVC (physically impossible).	Recomputed using Tsai formula + PDG cross-checks
HIGH	PET/PE Substring Collision	"PE" in "PET_3.0GeV" → True in Python. Highland matching grabbed PE's value for PET.	m.startswith(material + "_") instead of in
MEDIUM	Workflow Push Race Condition	20-min Geant4 run + concurrent push → rejected.	git pull --rebase before git push
REJECTED	ChatGPT Review — 8 Regressions	Reviewed old snapshot. Deleted ActionInitialization (breaks MT), removed wcsv parser, reverted to hardcoded filenames, used wrong PE X ₀ .	All changes rejected after analysis

● Every bug has a commit, a rationale, and a verification. This is engineering discipline that BL4S reviewers will notice — it shows the team understands what their code does.

Request Schema — What Students Can Configure

Full YAML Structure

```
author: "Name"          # required
description: "Research Q" # required
materials:
  - name: PE           # display name
    geant4_name: G4_POLYETHYLENE
    thickness_mm: 10     # 1-100 mm
    # Optional: override for custom materials
    X0_cm: 47.9
    rho: 0.94
beam:
  particle: e-        # e-, e+, pi+, pi-
  momenta_GeV: [3.0, 6.0] # list
  num_events: 10000   # per configuration
```

Validated by `schemas/request.schema.json`
(Draft 2020-12).

Named Examples in Repo

Valentina —

`valentina_pvc_detection.yaml`

PVC vs PE → recycling QC

Tomás — `tomas_thickness_study.yaml`

PE at 5, 10, 20 mm → test $\sqrt(x/X_0)$ scaling

Lucía — `lucia_heritage_study.yaml`

SiO_2 , CaCO_3 , Al_2O_3 , Fe_2O_3 → heritage materials

Sofía —

`sofia_custom_material_example.yaml`

Student provides own X_0 and ρ → custom

End-to-End

Student types

→ gets publication-ready physics plots back in

 YAML →  PR →  CI →  Plots →  Merge →  Geant4 →  Website

¡La física fundamental es para todos!