Contents

Progress Report: Optimization of dpol_breakup Experiment Configuration

Date: November 26, 2025
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Subject: Progress on Simulation Framework and Configuration Optimization

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1. Objective

The primary goal is to determine the optimal experimental configuration for the `dpol_breakup` experiment by evaluating detection efficiency and reconstruction accuracy under various setups.

Key Questions: - What is the optimal target position for different magnetic field strengths? - How does the beam deflection angle affect detection efficiency? - What is the achievable momentum resolution with the current PDC setup? - How can we improve reconstruction speed and accuracy?

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2. System Architecture & Data Flow

We have established a complete simulation and analysis framework with the following pipeline:

```
+---------------------+
|   QMD Raw Data      |  (~2x10^6 events per configuration)
|   (d+Pb, d+Sn, etc.)|
+----------+----------+
           |
           | Apply physical cuts, sampling
           v
+---------------------+
|   Geant4 Input      |  (~3x10^4 sampled events)
|   (ROOT/Macros)     |
+----------+----------+
           |
```

```
          | Configure geometry, magnetic field
          v
+--------------------+
| Geant4 Simulation  |  (~120 events/s)
| (Hit trees, EdepTree)|
+----------+---------+
          |
          | Extract hit positions and energies
          v
+--------------------+
| PDC Reconstruction |  (~0.05-1 events/s)
| (Track fitting)    |
+--------------------+
```

Components: - **Scripts**: Developed for QMD data transformation, cutting, sampling, and reconstruction analysis - **Visualization**: Support for both 3D event display and batch processing - **Status**: Core framework operational and ready for optimization testing

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3. Performance Benchmarks

Current Performance:

- **Geant4 Simulation**: ~120 events/s
- **PDC Reconstruction**: ~0.05 - 1 events/s (using TMinuit to reconstruct proton momentum)
  - *Note*: The reconstruction speed is currently a bottleneck and is a primary focus for optimization
  - *Issue*: Performance is poor for some events, showing systematic momentum bias

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4. Detailed Progress

4.1. QMD Data Processing

Challenge: The raw data volume is excessive (approx. 2×10^6 events per target/gamma configuration).

Action: Applied physical cuts to focus on the region of interest and reduce data volume.

Applied Cuts:

- **Momentum Cuts**: |p__y,p - p__y,n| < 150 MeV/c and (p__x,p + p__x,n) < 200 MeV/c
- **Angular Cuts**: |pi - |phi_rotation|| < 0.2 rad
- **Result**: Data volume reduced to ~3 x 10^4 events, significantly improving processing feasibility

Selection Stage	Conditions / Code Logic	Event Count	Remarks
No Cut on P	- Single target- One special gamma	2×10^6	Initial large dataset
Cut on P(Impact Parameter Selection)	`abs(pyp_orig - pyn_orig) < 150(vec_sum_orig[0]**2 + vec_sum_orig[1]**2) > 2500(pxp + pxn) < 200`	5×10^5	Cuts based on momentum and position to select impact parameter

Selection Stage	Conditions / Code Logic	Event Count	Remarks
Further Cut on Angle	`(np.pi - abs(phi_for_rotation)) < 0.2`	3×10^4	Final selection based on angular distribution

Next Step: Implement systematic data sampling with stratified sampling to ensure uniform coverage of the phase space.

4.2. Geant4 Simulation

Objective: Evaluate detection efficiency across various experimental configurations.

Current Configuration:

- Target position: Configured based on a 5 degree beam deflection in a 1.2 T magnetic field
- Magnetic field strength: 1.2 T
- Detector geometry: PDC1, PDC2, NEBULA array
- Beam energy: 190 MeV/nucleon (deuteron)

Simulation Results:

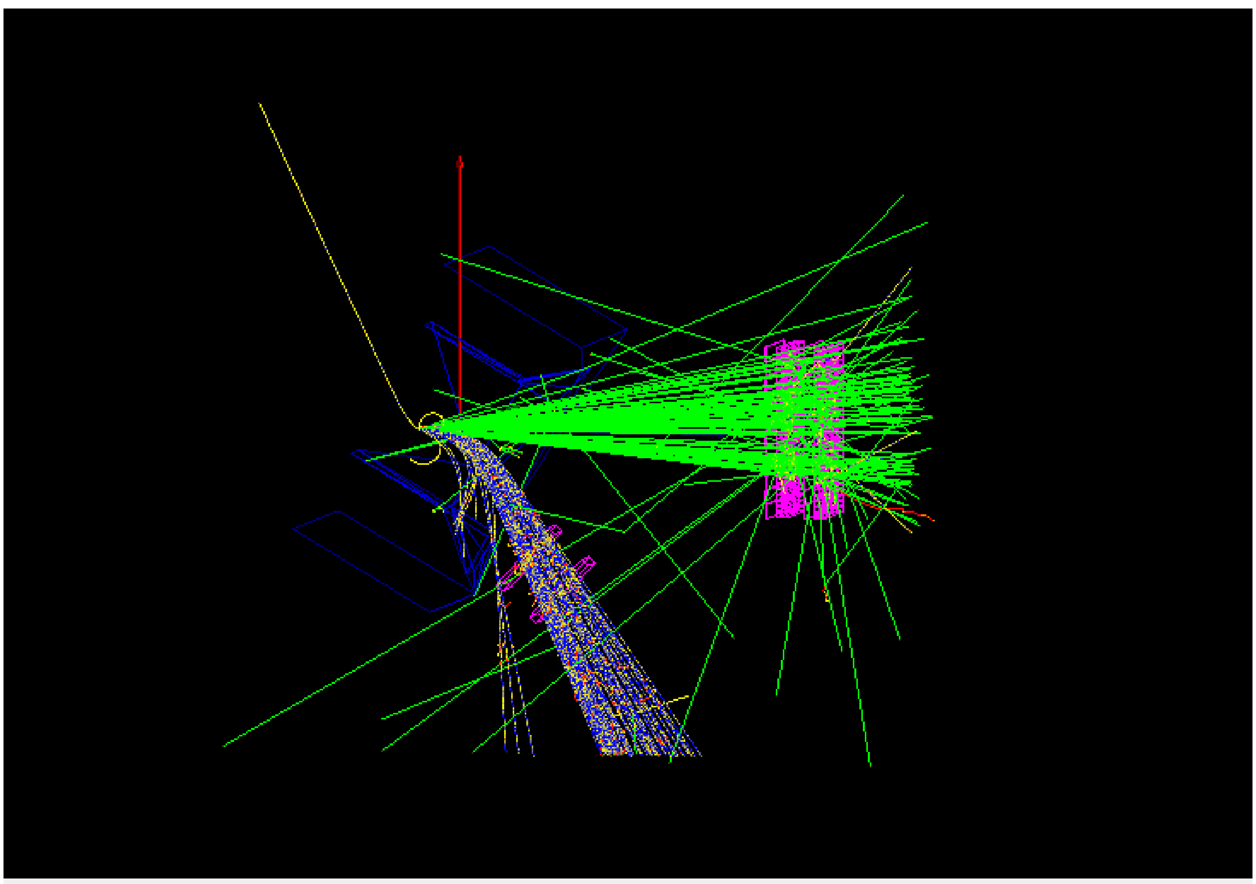


Figure 1: Visualization of accumulated 5000 simulated events showing particle trajectories in the detector system.

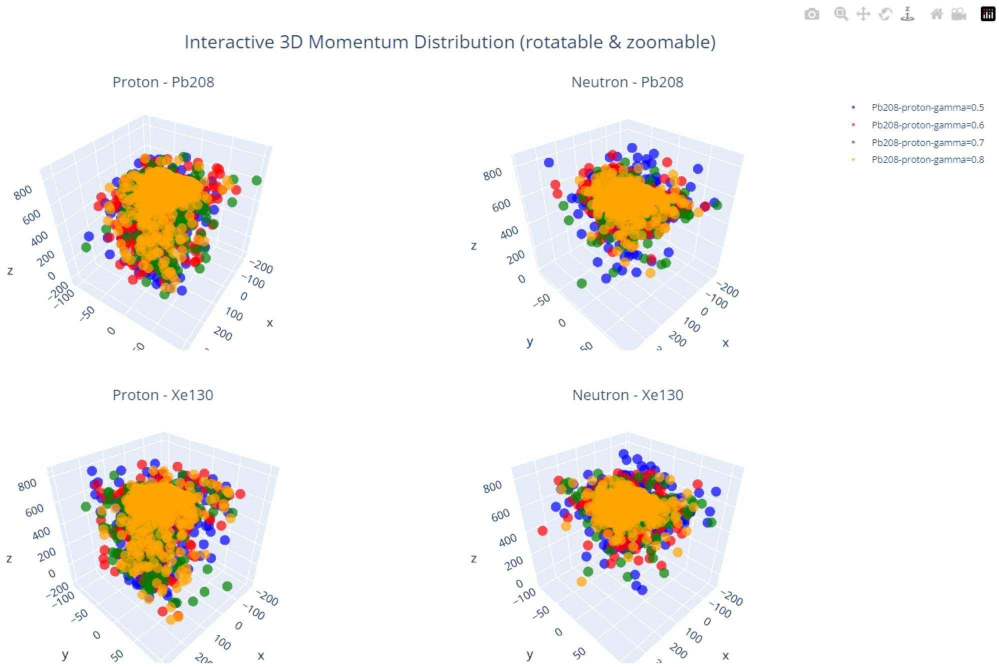


Figure 1: QMD Data Flow

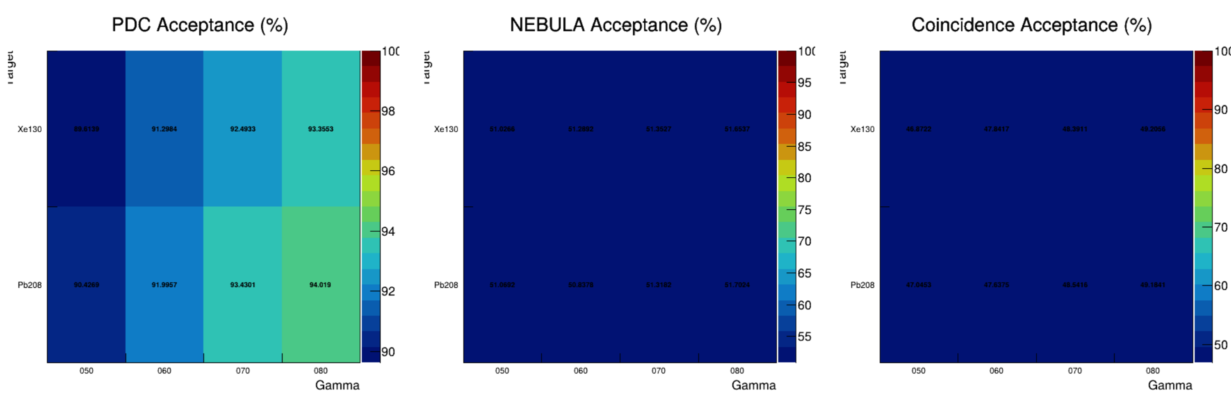
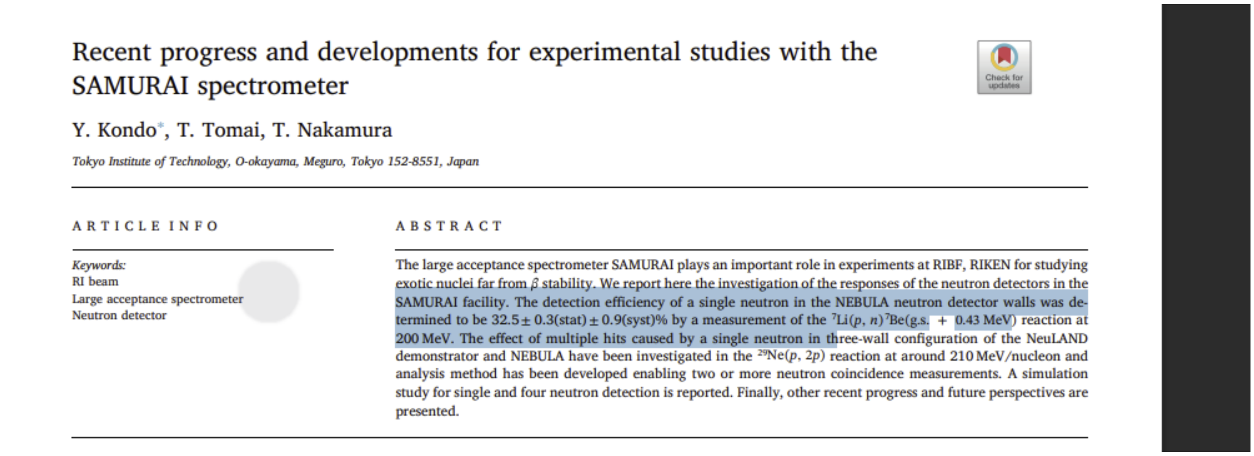


Figure 2: Detection efficiency (an event is counted as detected if it records any energy deposit in the Geant4 tree). Configuration: beam rotated by 5° in a 1.2 T magnetic field. Deuteron initial coordinates fixed at x' = b(impact parameter), y' = 0, z' = 0 (z is not randomized).

Comparison with Reference Data:



Recent progress and developments for experimental studies with the SAMURAI spectrometer

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ABSTRACT

The large acceptance spectrometer SAMURAI plays an important role in experiments at RIBF, RIKEN for studying exotic nuclei far from β stability. We report here the investigation of the responses of the neutron detectors in the SAMURAI facility. The detection efficiency of a single neutron in the NEBULA neutron detector walls was determined to be 32.5 ± 0.3(stat) $\pm$ 0.9(syst)% by a measurement of the ^{7}Li$(p,n)^{7}$Be(g.s. + 0.43 MeV) reaction at 200 MeV. The effect of multiple hits caused by a single neutron in three-wall configuration of the NeuLAND demonstrator and NEBULA have been investigated in the ^{29}Ne$(p,2p)$ reaction at around 210 MeV/nucleon and analysis method has been developed enabling two or more neutron coincidence measurements. A simulation study for single and four neutron detection is reported. Finally, other recent progress and future perspectives are presented.

Figure 3: Detection efficiency from reference paper for comparison.

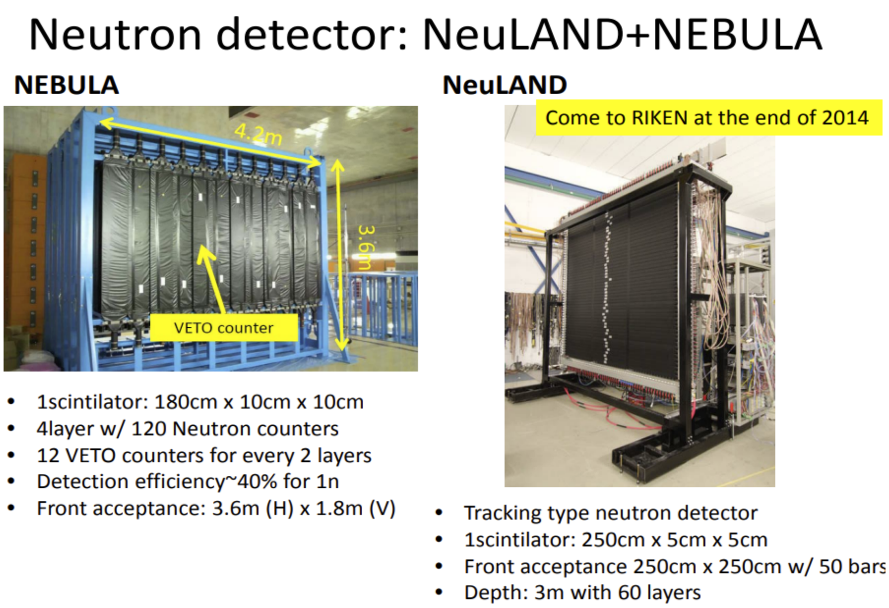

Figure 4: Experimental setup diagram from previous presentation slides.

Planned Parameter Scan:

Generate multiple candidate macros with varying:

- Magnetic field values: 0.8 T, 1.0 T, 1.2 T,??
- Target positions: Aligned with optimal PDC acceptance regions
- Beam deflection angles: 0 deg (outside magnet), 5 deg,

4.3. PDC Analysis & Reconstruction

Reconstruction Methodology:

Since the PDC primarily determines the particle **direction**, the reconstruction algorithm optimizes the **momentum magnitude** by minimizing the distance between the back-propagated track and the known target position.

Algorithms Implemented:

1. **Grid Search**: Robust global search but computationally expensive
2. **Gradient Descent**: Fast but sensitive to local minima and noise
3. **TMinuit (ROOT)**: Currently the primary method (using MIGRAD/SIMPLEX algorithms)

Current Issues:

1. **Reconstruction Quality**: While many events are reconstructed correctly, a subset shows poor results
2. **Momentum Bias**: Analysis of momentum residuals (Delta p = p_reco - p_true) reveals a **double-peak structure**:
   - Peak 1: Around 0 MeV/c (correct reconstruction)
   - Peak 2: Around -200 MeV/c (systematic underestimation)
3. **Speed Bottleneck**: Reconstruction takes 1-20 seconds per event

Optimization Focus:

- Tuning the Runge-Kutta (RK) stepping for charged particle motion in the magnetic field to balance precision and speed
- Refining TMinuit convergence criteria to avoid local minima
- Implementing better initial momentum guess based on PDC direction

Reconstruction Results:

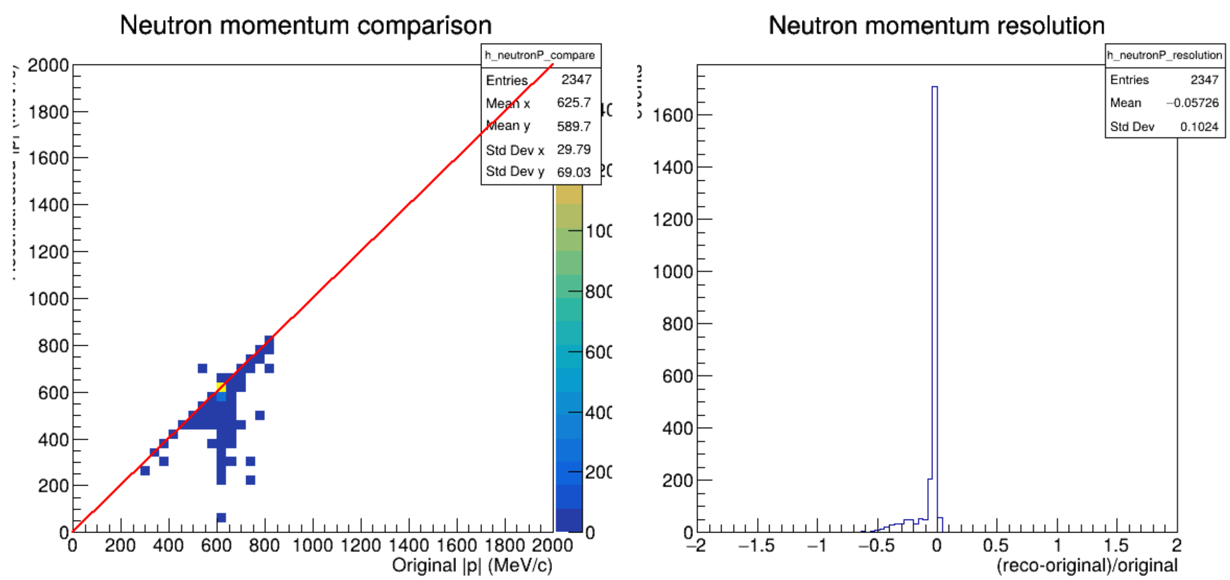

Figure 5: Comparison between reconstructed neutron momentum and input momentum from QMD data.

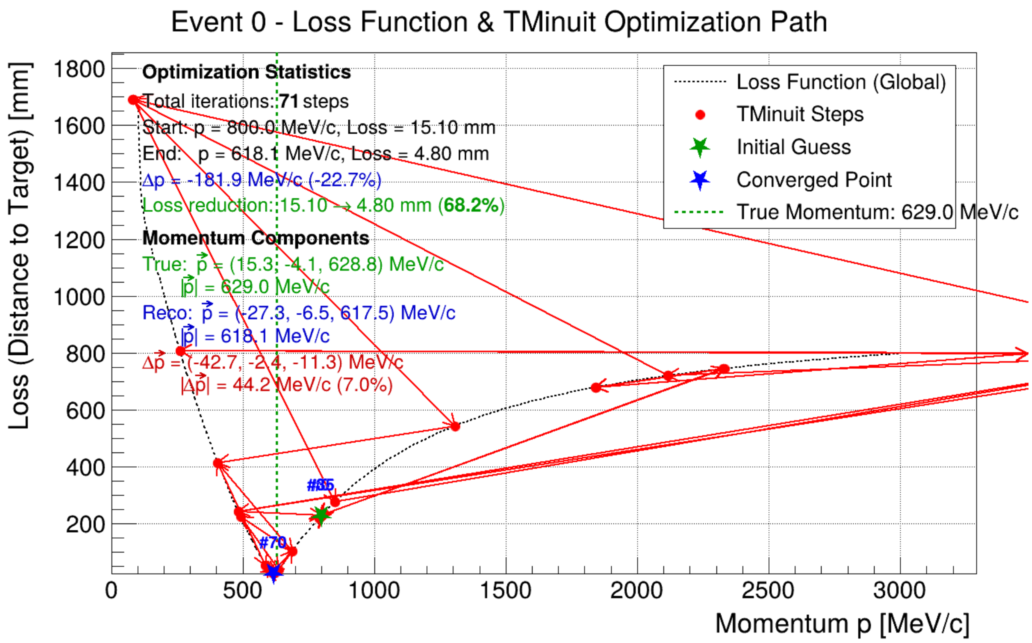

Figure 6: TMinuit optimization step-by-step debugging visualization showing convergence behavior and iteration details.

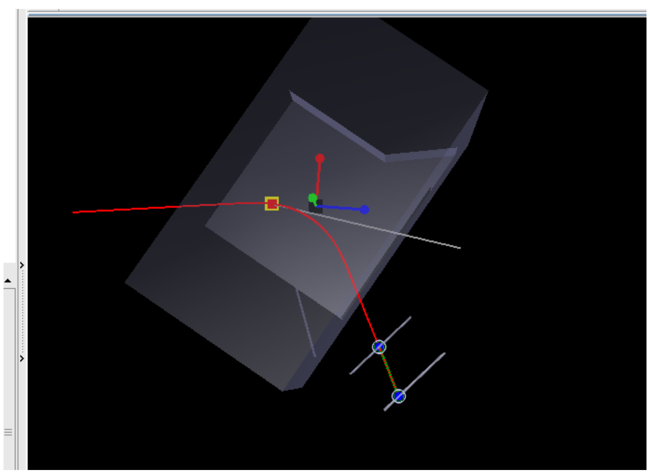

Figure 7: 3D event display showing particle trajectories, PDC hit positions, and detector geometry.

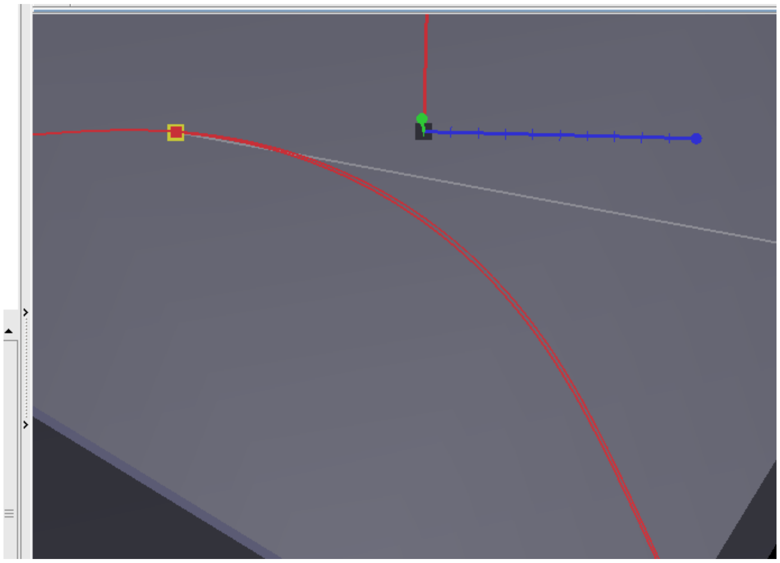

Figure 8: Zoomed view of the event display focusing on the target region and track back-propagation.

Example Reconstruction Output:

```
Input: proton, |p| = 629.0 MeV/c
Initial momentum guess: 800 MeV/c

MIGRAD failed with error code: 4
Trying SIMPLEX algorithm...

TMinuit optimization completed:
  Best momentum: 618.13 ± 2849.91 MeV/c
  Final distance: 4.79785 mm
  Convergence status: 1 (3=converged)
  EDM (estimated distance to minimum): 2.84217e-14
```

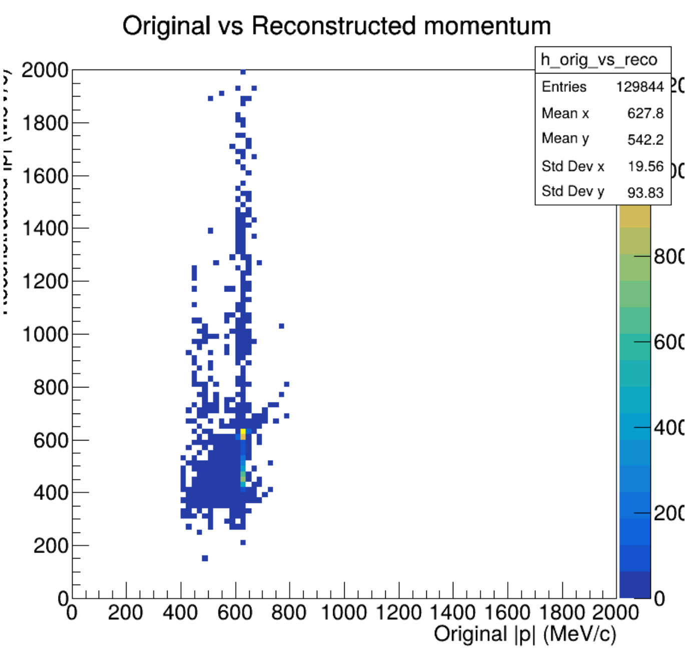

Figure 9: 2D histogram showing correlation between true and reconstructed momentum values.

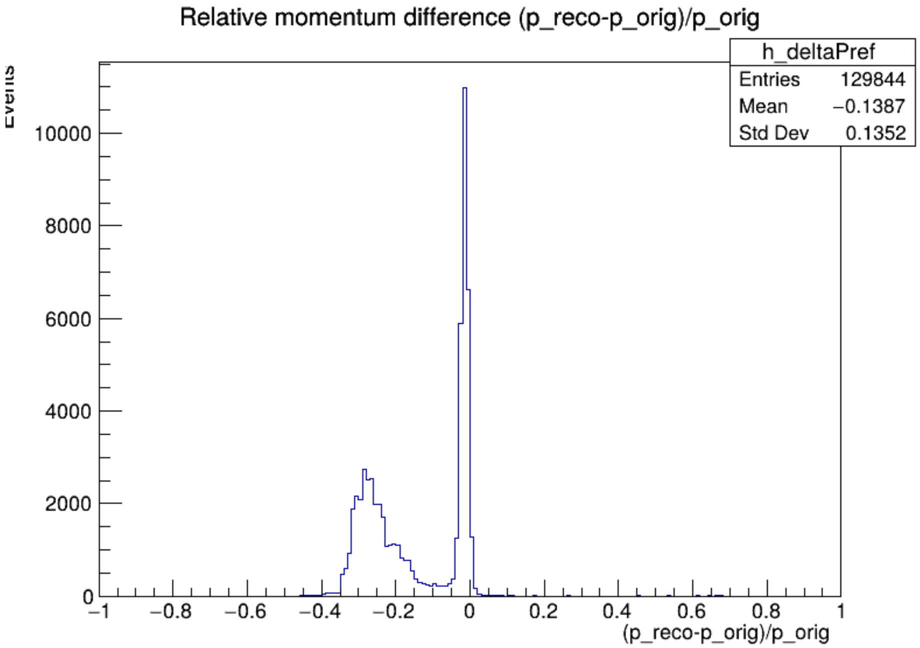

Figure 10: Distribution of momentum residuals (Delta p = p_reco - p_true) showing the characteristic double-peak structure.

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5. Optimization Strategy

To address the low reconstruction speed (currently ~0.1-1 Hz) and accuracy issues, the following strategies are being implemented:

1. **Algorithm Optimization**: Adjusting the track calculation step size and magnetic field integration precision
2. **Batch Processing**: Implementing memory-efficient batch analysis by discarding unnecessary track objects during I/O
3. **Parallel Computing**: Enabling multi-threading to process multiple events simultaneously
4. **I/O Optimization**: Using asynchronous logging to prevent I/O blocking
5. **Smart Initial Guess**: Using PDC direction and typical momentum range to improve TMinuit convergence
6. **Adaptive Step Size**: Implementing adaptive RK step size based on magnetic field strength and curvature

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6. Next Steps (Priority Tasks)

High Priority:

1. **Data Generation**: Complete QMD data sampling and generate final ROOT files for Geant4 input
2. **Performance Tuning**: Continue optimizing the Geant4 simulation and reconstruction code for speed
3. **Configuration Study**: Systematically test different target positions corresponding to various magnetic fields and beam deflection angles

Medium Priority:

1. **Physics Analysis**: Investigate isovector effects in deuteron simulations
2. **Systematic Studies**: Evaluate systematic uncertainties in momentum reconstruction

3. **Validation**: Compare simulation results with experimental data (if available)

Low Priority:

1. **Documentation**: Complete technical documentation for all analysis tools
2. **Code Cleanup**: Refactor and optimize codebase for maintainability

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7. Technical Implementation Details

7.1. QMD Data Sampling

Current Status: Implementation in progress

Planned Approach:

- Stratified sampling based on momentum and angular distributions
- Ensure uniform coverage of physics-relevant phase space
- Target: 30,000 events per configuration (reduced from 2,000,000)
- Format: ROOT files compatible with Geant4 primary generator

Tools:

- `scripts/qmd_analysis/`: QMD data processing scripts
- Output format: BeamSimData ROOT objects

7.2. Geant4 Simulation

Implementation Status: Fully operational

Key Components:

- **Geometry**: SAMURAI spectrometer setup with PDC chambers and NEBULA
- **Physics Lists**: QGSP_BIC_HP for hadron interactions
- **Magnetic Field**: Uniform field map (configurable strength)
- **Primary Generator**: Reading from QMD-derived ROOT files
- **Output**: Hit positions, energy deposits, particle IDs

Configuration Files:

- `configs/simulation/geometry/`: Detector geometry definitions
- `configs/simulation/physics/`: Physics list configurations
- Magnetic field maps: *(excluded from Git, stored locally)*

7.3. PDC Analysis & Reconstruction

Core Algorithm: Track back-propagation with momentum optimization

7.3.1. PDC Hit Reconstruction

The PDC analysis reconstructs particle hit positions from two drift chambers using a **Center-of-Mass (CoM) weighted energy deposition** method.

Reference: `libs/pdcanalysis/src/PDCSimAna.cc:177-202`

Process:

1. Process U and V layer hits independently

2. Apply Gaussian position smearing for detector resolution (sigma ~ 200 micrometers)
3. Reconstruct 3D positions at PDC1 and PDC2
4. Transform coordinates accounting for spectrometer rotation angle

Key Classes:

- `PDCSimAna`: Main analysis class (`libs/pdcanalysis/include/PDCSimAna.hh:22-61`)
- Hit position formula: Center-of-mass weighted by energy deposition

7.3.2. Runge-Kutta Integration (Core Physics Engine)

The trajectory calculation uses **4th-order Runge-Kutta integration** for solving particle motion in magnetic fields.

Reference: `libs/pdcanalysis/src/ParticleTrajectory.cc:159-206`

Physics Implementation:

```
// Relativistic kinematics
E = sqrt(p² + m²)

// Lorentz force equation
dp/dt = q(v × B)

// Integration parameters
Step size: typically 1.0 mm
Physics constant: 89.87551787 (for unit conversion)
```

Code References:

- RK4 implementation: `ParticleTrajectory.cc:159-206`
- Magnetic field integration: `ParticleTrajectory.cc:120-157`
- Unit conversion constant (line 141): 89.87551787

Performance Considerations:

- Trade-off between step size and accuracy
- Smaller steps → higher accuracy but slower computation
- Current step: 1 mm (can be optimized to 2-5 mm for speed)

7.3.3. Momentum Optimization with TMinuit

Approach: Minimize distance between back-propagated track and target position

Objective Function:

```
chi^2 = sqrt((x_track - x_target)^2 + (y_track - y_target)^2 + (z_track - z_target)^2)
```

Algorithm Sequence:

1. Use PDC1 and PDC2 hits to determine particle direction
2. Make initial momentum guess (typically 600-1000 MeV/c)
3. Run TMinuit MIGRAD algorithm
4. If MIGRAD fails (error code 4), fall back to SIMPLEX
5. Extract best-fit momentum and uncertainty

Challenges:

- Local minima in chi^2 landscape
- Large uncertainty estimates (indicating convergence issues)
- Systematic bias for certain momentum ranges

7.3.4. NEBULA Neutron Reconstruction

For neutral particles (neutrons), a completely different approach is used.

Reference: `libs/nebula/src/NEBULAReconstructor.cc:203-271`

Methodology:

1. **Time-of-Flight (TOF)** based reconstruction (no magnetic field effect)
2. Energy-weighted position clustering
3. Time window clustering (default: 10 ns)
4. Energy threshold filtering (default: 1 MeV)

Physics Formulas:

```
Beta calculation: beta = (flight_distance / flight_time) / c
Lorentz factor: gamma = 1 / sqrt(1 - beta^2)
Kinetic energy: KE = (gamma - 1) x m_neutron
Momentum: p = gamma x m_neutron x beta x c
```

Key Parameters:

- Time window: 10 ns (clustering threshold)
- Energy threshold: 1 MeV (noise rejection)
- Position resolution: ~5 cm (limited by bar size)

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8. Summary

Achievements:

- [x] Complete simulation framework operational (QMD -> Geant4 -> Reconstruction)
- [x] Multiple reconstruction algorithms implemented and tested
- [x] Identified key bottlenecks: reconstruction speed and systematic momentum bias
- [x] Established baseline performance benchmarks

Current Challenges:

- [!] Reconstruction speed: 0.05-1 Hz (target: >10 Hz)
- [!] Momentum bias: Double-peak structure in residuals
- [!] Large statistical samples needed for configuration optimization

Next Milestones:

1. Complete QMD sampling and generate production-scale input files
2. Optimize reconstruction algorithms to achieve >10 Hz performance
3. Run systematic configuration scans (magnetic field, target position)
4. Validate against experimental data and published results

Contact:

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- Repository: Dpol_smsimulator

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