Progress Report: Optimization of dpol_breakup Experiment Configuration

Simulation Framework and Configuration Study

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SAMURAI Collaboration

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Outline

Research Objectives

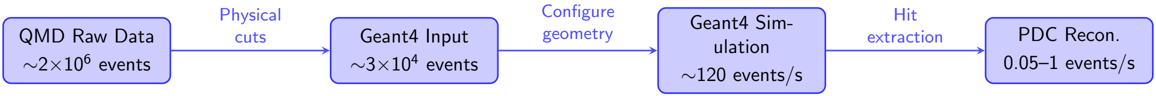
Primary Goal

Determine the optimal experimental configuration for the `dpol_breakup` experiment by evaluating detection efficiency and reconstruction accuracy.

Key Questions:

1. What is the optimal target position for different magnetic field strengths?
2. How does the beam deflection angle affect detection efficiency?
3. What momentum resolution can we achieve with the current PDC setup?
4. How can we improve reconstruction speed and accuracy?

Complete Simulation Framework



Framework Components

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

Current Bottleneck

PDC reconstruction speed: 0.05-1 events/s (target: $>$10 events/s)

Performance Status

Current Performance:

- Geant4 Simulation: $\sim$120 events/s
- PDC Reconstruction: 0.05-1 events/s
- Issues: Systematic momentum bias

Target Performance:

- Reconstruction: $>$10 events/s
- Momentum resolution: ??
- Detection efficiency: ?? (for config target position)

Performance Challenges

- Speed bottleneck in track fitting
- TMinuit convergence issues
- Systematic bias for certain momentum ranges

Data Processing Strategy

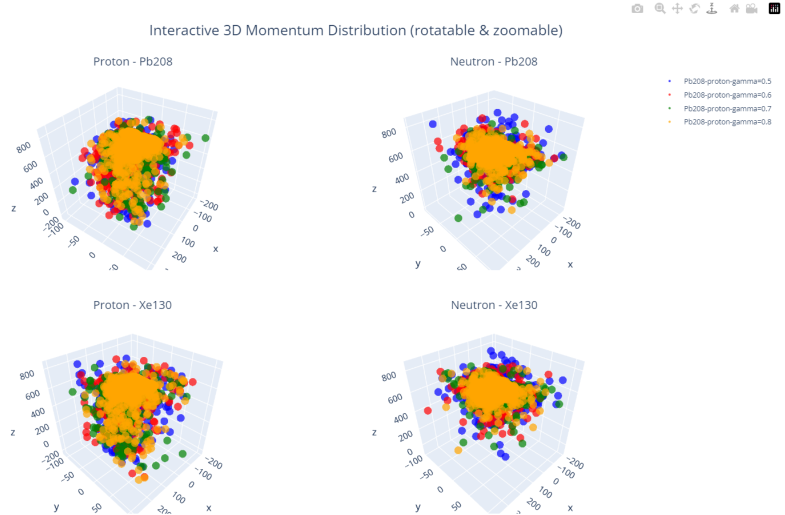
Challenge: Massive data volume ($\sim 2\times10^6$ events per configuration)

Solution: Apply physical cuts to focus on region of interest

Selection Stage	Conditions	Event Count
No Cut	-	2×10^6
Momentum Cut	$\lvert p_{y,p} - p_{y,n} \rvert < 150$ MeV/c	5×10^5
	$(p_{x,p} + p_{x,n}) < 200$ MeV/c	
Angular Cut	$\lvert \pi - \lvert \phi_{rot} \rvert \rvert < 0.2$ rad	3×10^4

Result: 98.5% data reduction while preserving physics of interest

QMD Data Flow



Current Configuration

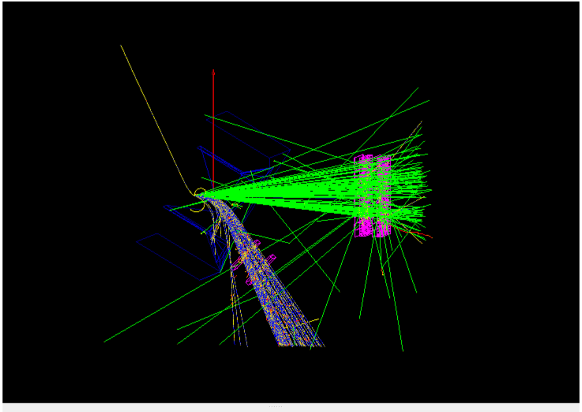
- **Target position:** Based on 5° beam deflection in 1.2 T field
- **Magnetic field:** 1.2 Tesla
- **Detector geometry:** PDC1, PDC2, NEBULA array

Planned Parameter Scan:

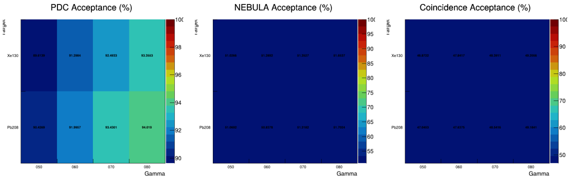
- Magnetic field: 1.2, 1.4, 1.6 Tesla (for pdc acceptance and resolution)
- Beam deflection angles: 0 (outside chamber), 5 degrees(inside), other angles
- Target positions: related to B and beam angle.
- PDC position (related to above all)

Simulation Visualization

5deg 1.2T Configuration

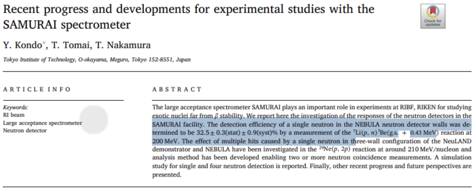


5000 accumulated events



Detection efficiency

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.

Reference from paper

Neutron detector: NeuLAND+NEBULA

NEBULA

- 1scintilator: 180cm x 10cm x 10cm
- 4layer w/ 120 Neutron counters
- 12 VETO counters for every 2 layers
- Detection efficiency~40% for 1n
- Front acceptance: 3.6m (H) x 1.8m (V)

NeuLAND

Come to RIKEN at the end of 2014

- Tracking type neutron detector
- 1scintilator: 250cm x 5cm x 5cm
- Front acceptance 250cm x 250cm w/ 50 bars
- Depth: 3m with 60 layers

Experimental setup

Conclusion: Our results are consistent with published references

Reconstruction Methodology

Principle: PDC determines particle *direction*; optimize *momentum magnitude* by minimizing distance to target

Implemented Algorithms:

1. **Grid Search**
   - \+ Robust, finds global minimum
   - – Computationally expensive
2. **Gradient Descent**
   - – slow convergence (now situation)
   - – Sensitive to local minima and noise (in this no local minima)
3. **TMinuit (ROOT)** $\leftarrow$ Current primary method
   - Uses MIGRAD/SIMPLEX algorithms
   - Fallback strategy if MIGRAD fails

Current Challenges

Issue 1: Reconstruction Quality

Inconsistent performance - subset shows poor results

Issue 2: Momentum Bias

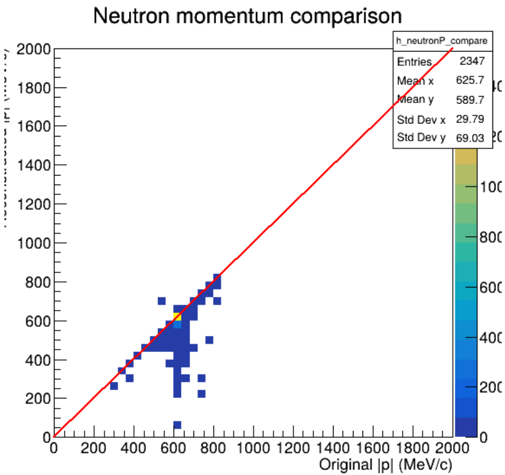
Double-peak structure in residuals ($\Delta p = p_{reco} - p_{true}$):

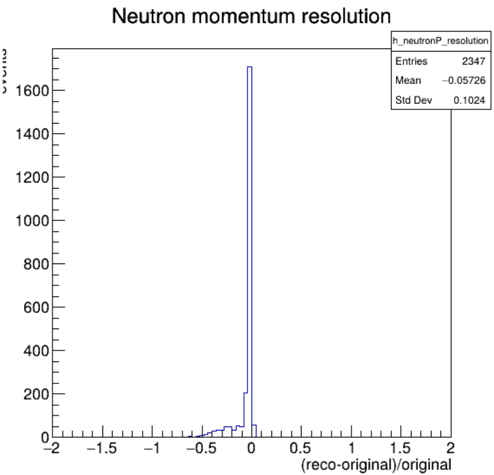
- Peak 1: ∼0 MeV/c (correct reconstruction)
- Peak 2: ∼-200 MeV/c (systematic underestimation)

Issue 3: Speed Bottleneck

Reconstruction: 1-20 seconds per event (too slow for production)

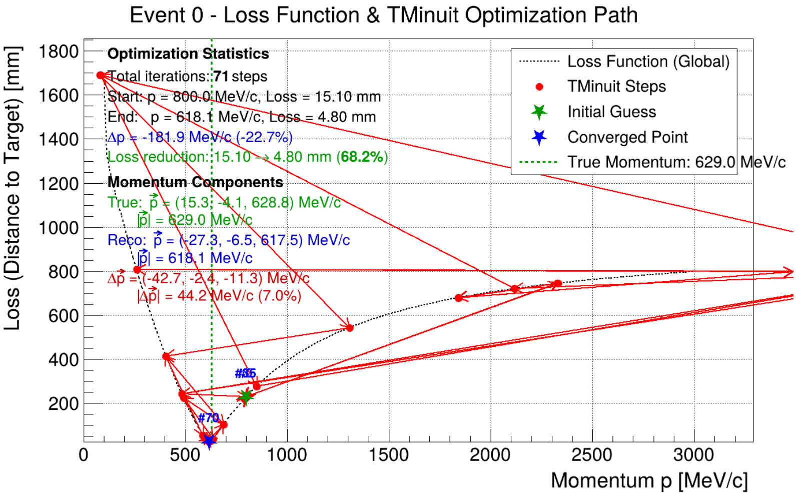
Reconstruction Results (1/3)





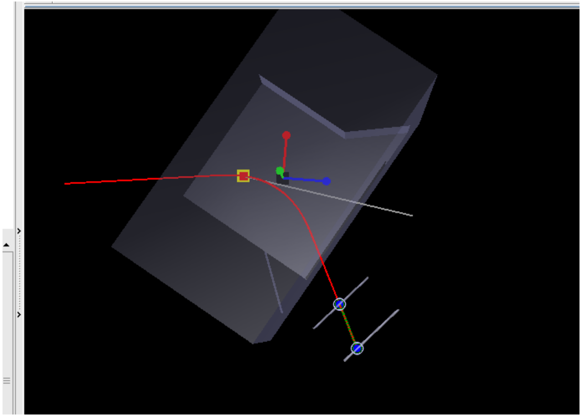
Neutron momentum: Reco vs Input

Reconstruction Results (2/3)

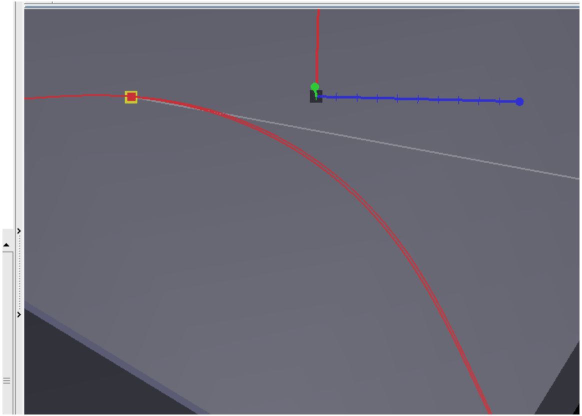


TMinuit optimization steps

Reconstruction Results (3/3)



3D event display



Zoomed view – track back-propagation

Example Case: Convergence Issues

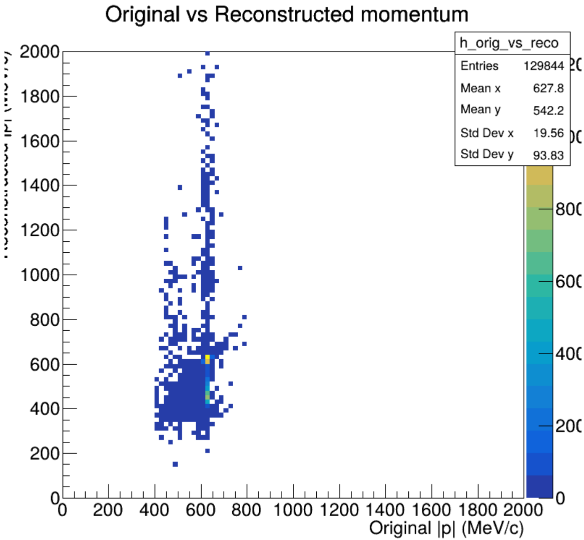
Input: Proton, $|p| = 629.0$ MeV/c

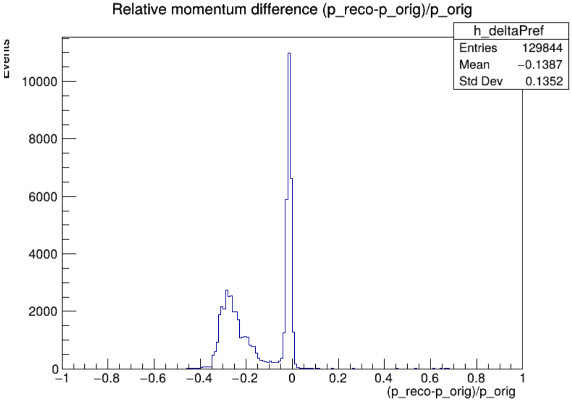
```
Initial momentum guess: 800 MeV/c

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

TMinuit optimization completed:
  Best momentum: 618.13 +/- 2849.91 MeV/c  ← Huge uncertainty!Final distance:  4.79785 mmConvergence status:  1
      (3=converged)EDM (estimated distance to minimum):  2.84217e-14
```

Analysis:

- Result (618 MeV/c) close to true value (629 MeV/c)
- But uncertainty ($\pm$2850 MeV/c) indicates convergence problems
- Likely stuck in local minimum, not global minimum

Momentum Correlation & Residuals





Residual distribution - double peak

Core Algorithms

1. PDC Hit Reconstruction

- Center-of-mass weighted energy deposition method
- Process U and V layers independently
- Gaussian smearing: $\sigma \approx 0.5$ mm
- Transform coordinates for spectrometer rotation

2. Runge-Kutta Integration (4th order)

- Solve particle motion in magnetic fields
- Relativistic kinematics: $E = \sqrt{p^2 + m^2}$
- Lorentz force: $\frac{dp}{dt} = q(v \times B)$
- Step size: 1 mm (trade-off: accuracy vs speed)

3. TMinuit Objective Function

$$\chi^2 = \sqrt{(x_{track} - x_{target})^2 + (y_{track} - y_{target})^2 + (z_{track} - z_{target})^2} \quad (1)$$

4. NEBULA Neutron Reconstruction

- Time-of-Flight (TOF) based - no magnetic field effect
- Energy-weighted position clustering
- Time window: 10 ns
- Energy threshold: 1 MeV

Physics formulas:

$$\beta = \frac{d_{flight}/t_{flight}}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$KE = (\gamma - 1) \times m_n, \quad p = \gamma m_n \beta c$$

Six-Point Optimization Plan

1. **Algorithm Optimization**
   - Adjust Runge-Kutta step size (1 mm $\rightarrow$ 2-5 mm)
   - Tune magnetic field integration precision
2. **Batch Processing**
   - Memory-efficient analysis
   - Discard unnecessary track objects during I/O
3. **Parallel Computing**
   - Multi-threading for simultaneous event processing
4. **I/O Optimization**
   - Asynchronous logging to prevent blocking
5. **Smart Initial Guess**
   - Use PDC direction and typical momentum range
   - Improve TMinuit convergence
6. **Adaptive Step Size**
   - RK step depends on B-field strength and curvature

Priority Tasks

High Priority

1. Complete QMD data sampling $\rightarrow$ Generate ROOT files for Geant4
2. Optimize simulation & reconstruction code for speed
3. Systematic configuration study (B-field, target, beam angle)

Medium Priority

1. Investigate isovector effects in deuteron simulations
2. Evaluate systematic uncertainties
3. Validate against experimental data

Low Priority

1. Complete technical documentation
2. Code refactoring for maintainability

Summary

Achievements:

- ✓ Complete simulation framework
- ✓ Multiple reconstruction algorithms
- ✓ Identified bottlenecks
- ✓ Baseline benchmarks

Current Challenges:

- ! Speed: 0.05-1 Hz $\rightarrow$ need $>$10 Hz
- ! Momentum bias (double-peak)
- ! Large statistics needed

Key Milestones

1. Complete QMD sampling for production-scale input
2. Optimize reconstruction to 10 Hz
3. Run systematic configuration scans
4. Validate against experimental data

Thank You

Thank you for your attention!

Questions & Discussion

Contact:
Tian (tbt23@mails.tsinghua.edu.cn)
Repository: github.com/tianbaiting/Dpol_smsimulator
Branch: restructure-cmake

Backup: Additional Technical Details

Available for further discussion:

- Detailed Runge-Kutta implementation
- TMinuit configuration parameters
- Memory profiling results
- Parallelization strategies
- Code structure and API documentation