Recent results from g4sbs

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The Super BigBite Spectrometer (SBS) in Hall A

- E12-07-109: Proton form factor ratio $G_{Ep}/G_{Mp}$ using polarization transfer
- E12-09-016 and E12-09-019: Neutron magnetic form factor $G_{Mn}$ and neutron form factor ratio $G_{En}/G_{Mn}$
  - SBS is a novel magnetic spectrometer based on time-tested “detectors behind a dipole magnet” approach
  - Detects forward-going, high-energy particles with medium solid angle acceptance and large momentum bite at highest achievable luminosities of CEBAF
  - Physics program: nucleon EMFFs and SIDIS, 180 beam-days approved in Hall A
  - Conditionally approved: Pion structure function via tagged DIS, 27 days Hall A

- GEN + GMN: 50 + 25 beam-days in Hall A
- SSA in SIDIS: 64 beam-days in Hall A
- GEP: 45 beam-days in Hall A
- SSA in SIDIS: 64 beam-days in Hall A
- E12-09-018: Transverse target SSA in SIDIS

UCONN
Jefferson Lab
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SBS Collaboration Meeting 2016
GEANT4 MC Requirements for SBS Experiments

- Detector background rates/occupancies:
  - Inform shielding design
    - Reduce detector background rates from sources other than target
    - Calculate radiation budgets
    - Design shielding of SBS electronics
  - Inform DAQ/trigger requirements/design
  - Inform/test reconstruction software development

- SBS/BigBite magnetic field maps:
  - Characterize SBS optics/spin transport
  - Optimize SBS acceptance for the different experiments

- Detector performance:
  - Characterize position/time/energy resolution of detectors

- New proposal development:
  - Realistic and accurate acceptance and rate calculations (and detector resolution)
  - Flexible interface to physics event generators
**g4sbs**: GEANT4 MC for SBS experiments

- Source code available in a github repository owned and managed by JLab: [https://github.com/JeffersonLab/g4sbs](https://github.com/JeffersonLab/g4sbs)
  - Write access to the repository is managed by Ole Hansen.
  - Multiple branches exist, but most recent development has taken place in the *uconn_dev* branch, periodically merged into the (more stable, but out-of-date) *master* branch.

- External libraries required:
  - ROOT: version 5 only for now—ROOT 6 compatibility is in the works
  - GEANT4: version 10.0 or later for recent code versions (for latest version with spin tracking, requires version 10.1 or later!)

- *g4sbs* documentation page (developed and maintained by UConn group):
    - Existing: how-tos for installation and execution, documentation of g4sbs-specific commands, where to download field maps, etc.
    - Forthcoming: documentation of output ROOT tree structure, self-contained, working example scripts for running the simulation, example ROOT macros for data analysis
Existing Geometries—GEP

- Detectors:
  - ECAL, HCAL, CDet, GEMs (front tracker and polarimeter GEMs), CH$_2$ analyzer
- SBS magnet:
  - Iron yoke w/cutout, coils, front and rear field clamps, pole shims to reach higher field integral
- Target:
  - LH$_2$ cell, vacuum chamber+snout
- Beamline:
  - Downstream beam pipe, flanges, magnetic shielding, corrector dipoles, lead shielding

An elastic $ep$ event in g4sbs illustrating full detector response
Existing Geometries—SIDIS

A SIDIS $^3$He(e,e'$\pi^+$)X event in g4sbs

- Detectors: HCAL, RICH, SBS GEMs, BigBite (GEMs, GRINCH, Shower+Preshower)
- SBS magnet: Iron yoke w/cutout, coils
- 60-cm $^3$He gas target, glass cell
- BigBite magnet
- Beamline: “standard” downstream beam pipe
- Missing: target chamber details, shielding and collimation, downstream beamline shielding, target magnetic shielding, etc.
Existing Geometries—GEN+GMN

A quasi-elastic $^3$He(e,e’n)X event in g4sbs

- Detectors: HCAL, BigBite (GEMs, GRINCH, Shower+Preshower)
- SBS magnet: Iron yoke w/cutout, coils
- 60-cm $^3$He gas target, glass cell
- BigBite magnet
- Beamline: “standard” downstream beam pipe
- Missing: target chamber details, shielding and collimation, downstream beamline shielding, target magnetic shielding, etc.
Targets

- Currently available target options (driven by SBS physics program):
  - Gas targets:
    - Hydrogen
    - $^3\text{He}$
    - (fictional) free neutron
  - Liquid hydrogen/deuterium

- To be added:
  - Solid targets
  - Optics/dummy targets
  - Empty target
  - Polarized NH$_3$
  - Others?
Magnetic Field

• “Standard” BigBite field map available
• SBS TOSCA maps have been calculated for most configurations
  • Only GEP 12 GeV\(^2\) map has been extensively simulated so far using g4sbs
  • SBS field map is not independent of SBS angle/distance from target, because of beamline active and passive magnetic shielding elements
• Uniform SBS magnetic field in dipole gap available as an approximation when detailed TOSCA map is not available or when speed is more important than precision.
• Spin tracking available using SBS TOSCA map—soon to be added for uniform field.
“Built-in” event generators in g4sbs

• Elastic ep or quasi-elastic (e,e’p), (e,e’n):
  • Rosenbluth cross section weight computed using Kelly parametrization of nucleon FFs.

• Inclusive inelastic ep, en, ed:
  • Christy-Bosted parametrization of inclusive inelastic structure functions
  • Final-state nucleon generated assuming πN final state

• Inclusive DIS:
  • Final-state electron using CTEQ6 PDFs.

• ”Beam:” throw beam electrons at target from upstream (w optional ”rastering”, currently no option for position/angle offset)

• SIDIS:
  • N(e,e’h)X, with h = π+/π-/π0/K+/K-/p/pbar
  • Leading-order cross section with CTEQ6 PDFs and DSS2007 q→h fragmentation functions

• Wiser: inclusive pion production

• “Gun”: generic particle gun (any valid GEANT4 particle).
  Generate flat in angle and momentum within user-defined limits
• PYTHIA6.4 interface written to study “minimum bias” events at high energies (W > 2 GeV), mainly to analyze trigger rates.
• Uses built-in ROOT/Pythia6 generator “TPythia6”
  • Requires ROOT build with Pythia6 add-on enabled
  • Pythia6 ROOT add-on is not a requirement for g4sbs, only for stand-alone event generator!
• Standalone ROOT-based PYTHIA6 event generator produces ROOT tree containing events and primary particles
• g4sbs reads events from a ROOT file in a standard format and generates primary particles to propagate through experiment layout
  • Using “gamma/e-” option simulates ”all” physics with photon-nucleon invariant mass W > 2 GeV (includes photoproduction)
• Standard ROOT format (LUND-based) easily extensible to other event generators.
New: GEP Trigger analysis with "L2" logic

- Signal in HCAL logic group with max signal for elastic ep events, with different cuts on FPP event topology (top left)
- Top right: HCAL trigger efficiency vs. threshold for different event topologies
- Bottom right: Dependence of efficiency on FPP scattering angle in FPP1 (2)
Correlated ECAL-HCAL trigger efficiency

For events with a “good” scattering in FPP1 (left) and events with a “good” scattering in FPP2.
Implement ep angular correlations in the coincidence trigger, by listing for each HCAL trigger sum all ECAL trigger sums exceeding 0.1% of the total event rate.
New: GEP Trigger rates with “L2” HCAL logic

- Top left: ECAL trigger rate vs threshold
- Top right: HCAL L2 trigger rate vs threshold (based on global OR of all possible 4x4 sums of HCAL signals)
- Bottom left: real coincidence rate (PYTHIA6 events) vs ECAL/HCAL thresholds.
- TO DO: analysis of accidentals (not trivial for correlated coincidence trigger with many logic combinations)
• Effect of reversing front-back orientation of all GEMS, for GEP 12 GeV$^2$ configuration:
  • $\sim20\%$ increase for FT layer 1 hit rates, smaller increases for subsequent FT layers
  • Negligible changes in FPP1/FPP2 hit rates
BigBite and SBS optics from GEANT4

- Charged particles are traced through magnetic field layout of BigBite/SBS in GEANT4 using classical 4th-order Runge-Kutta numerical integration of the equation of motion.
- Charged-particles deposit energy in GEMs, making “hits”—GEM “hits” are then smeared by a Gaussian with a σ of 70 µm, representing the coordinate resolution of GEMs, and a straight-line track is fitted.
- In MC, we know the track parameters at the target and at the “focal plane” (GEM location).
- We expand the reverse transport matrix in a power series in the measured track parameters:

\[
(x'_{tgt}, y'_{tgt}, y_{tgt}, 1/p) = \sum_{i+j+k+l+m \leq 6} C^{ijklm}_{x', y', y, 1/p, x', y', y, x'_{tgt}, y'_{tgt}, y_{tgt}, 1/p, x'_{tgt}, y'_{tgt}, y_{tgt}}
\]

- Track parameters at the target are \textit{linear} functions of the expansion coefficients
  - Use standard linear algebra libraries, e.g., Singular Value Decomposition (SVD), to fit the coefficients, avoid pitfalls of nonlinear fitting/numerical minimization/Minuit
- \textbf{Why fit }1/p\textbf{ instead of }p\textbf{ or the traditional }\delta = 100 \times (p/p_0 - 1)\textbf{ in the expansion?}
  - SBS/BigBite are large-acceptance spectrometers—range of “delta” can equal or exceed ±100%, it is no longer a good expansion variable.
  - SBS/BigBite are non-focusing, dipole spectrometers\textbf{→}an expansion in }1/p\textbf{ converges very quickly— }x_{fp}, x'_{fp}\textbf{ are almost linear in }1/p\textbf{ for dipole magnets}
SBS and BigBite Optics/Resolution from g4sbs—Old results

SBS angle, vertex and momentum resolution for 1.4-Tesla uniform field, $\sigma_p/p \sim 0.5\%$ (average for 2-10 GeV pions)

BigBite angle, vertex and momentum resolution for ”map_696A.dat”, $\sigma_p/p \sim 1.1\%$
Optics and Spin Transport Studies for GEP, $Q^2 = 12 \, \text{GeV}^2$

Track vertical bend angle vs. momentum

SBS angular and vertex acceptance for GEP highest $Q^2$

- GEANT4 simulation for optics and spin transport:
  - Use “particle gun” generator with limits chosen wide enough to populate full acceptance of SBS (use 40 cm target)
  - Proton momenta generated in the range of 5-9 GeV (corresponding to highest $Q^2$ of GEP)
  - Generate 10,000 protons in three different starting spin orientations in the fixed TRANSPORT coordinate system:
    - Pure “X” (vertically down)
    - Pure “Y” (horizontal, toward small angle)
    - Pure “Z” (along SBS central ray)
  - Fit reconstruction coefficients and spin transport matrix elements
SBS optics fitting from GEANT4

- SBS angle, vertex and momentum resolution for 5-9 GeV protons
- \( \sigma(x_{\text{ptar}}) \sim 0.3 \) mrad
- \( \sigma(y_{\text{ptar}}) \sim 0.6 \) mrad
- \( \sigma(y_{\text{tar}}) \sim 1.5 \) mm
- \( \sigma(p)/p \sim 0.66\%
- Improvement of the fit not significant beyond about 4\(^{\text{th}}\)-order expansion of reconstruction coefficients
Spin transport properties of SBS in GEP

- Spin precession in a magnetic field is governed by the Thomas-BMT equation.
- For an almost pure dipole field, as in SBS, the proton spin precesses relative to its trajectory by an angle: $\chi = \gamma \kappa_p \theta_{bend}$
- Precession angle is almost constant within useful acceptance of SBS for elastic ep events (cancellation between momentum dependence of gamma and thetabend).

\[
\frac{dS}{dt} = \frac{e}{m \gamma} S \times \left[ \frac{g}{2} B_\parallel + \left( 1 + \gamma \left( \frac{g}{2} - 1 \right) \right) B_\perp \right]
\]

BMT equation for protons
Spin fit results (5th-order)

- Fit deviations from the ideal dipole approximation up to 5th-order (still some room for improvement)
- Fit individual matrix elements directly
- Don’t enforce any event-by-event unitary constraints on the 3x3 rotation matrix.
- Determinant results very close to 1 in most events anyway.
- TO DO: Add sieve slit to MC, analyze systematics of spin transport calculation.
• Longitudinal segmentation of C16 lead-glass to implement depth-dependent radiation-induced darkening
C16/ECAL Thermal Annealing Simulation

- GEANT4 dose rate calculation, comparison between GEP 12 GeV\(^2\) case (left), C16 prototype test in Hall A (middle), and ratio C16/GEP (right)
C16 Signal Reduction after calibration of model

- C16, rad. damage OFF
- C16 rad. damage ON

$4 \times 4$ summed $N_{\text{phe}}$, max not in edge block
C16 Individual block spectra

- Left: Simulated number of photoelectrons in C16 blocks, elastic events
- Right: Actual data from prototype (assumption of identical spectra in “undamaged” state, validated by GEANT4, used to simplify gain matching)

Figure 16. Energy spectra for individual blocks for runs 764 and 772. Run 764 was before the C16 was moved to 10 degrees to induce a large radiation dose on the C16 while the oven was on. The data from run 764 is the black histogram and the gain coefficients of set 755A were used. Run 772 was taken when the C16 had been moved back to 31 degrees after the large dose of radiation. The red histogram is data from run 772 analyzed using the gain coefficients from run 755A. All blocks show a small energy spectrum for run 772 when using gain coefficients 755A indicating the blocks suffered some radiation damage that was not compensated by the oven. The green histogram is data from run 772 analyzed using gain coefficients which will give the same energy spectra as in run 764 (gain coefficient set 772B). The ratio of 772B/764 is a measure of the radiation damage.
Projected ECAL Performance

- Left: ECAL photoelectron yield vs. energy deposition, undamaged case
- Right: ECAL photoelectron yield vs. energy deposition, thermal equilibrium state in GEP 12 GeV² point
- Average ratio equilibrium/undamaged = (96.3 +/- 0.2) %
- More details in final report to DOE (see Mark's final report to DOE (requires login))
Documentation Update

- Documentation remains in Hall A Wiki for now:
- Up-to-date as of now; recent additions include documentation of ROOT output file and tree structure
Other ongoing projects

• RTPC simulation for TDIS (Rachel Montgomery, Glasgow)
• GEn recoil with charge-exchange polarimetry (John Annand, Glasgow)
• Optimization of GMn acceptance
• Radiation budget calculations (Dasuni Adikaram)
Near-term plans for Monte Carlo

• Geometries needed:
  • Sieve slit
  • Details of beamline/targets for experiments/configurations other than GEP, 12 GeV²

• Full digitization of detectors:
  • More detailed GEM description, with parametrized strip response, clusters, etc.
  • Generate pseudo-data: full signal chain from energy deposition to parametrized voltage vs. time, ADC/TDC values
  • Develop and benchmark reconstruction algorithms
  • Highest priority next few months: analysis of GEM tracking

• Trigger simulations for BigBite w/GRINCH

• Re-do experiment figure-of-merit projections, prepare for Jeopardy/PAC reapproval process

• Optimize detector layout for SIDIS

• Simulation/results document/white paper