Online and offline analysis software and Monte Carlo simulations

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SBS Collaboration Meeting and GMN Hall Readiness Review

2/17/2021

UCONN

Purpose

- Event reconstruction software processes the raw data from the experiment into physics information—particle four-vectors, interaction vertices, and PID assignments
- Provide real-time monitoring of low-level detector information for calibrations and data quality assurance
- Reduce the raw data to a more human-readable and easily digestible form (ROOT Trees, histograms) for subsequent high-level physics analysis
- More so than in past experiments in Hall A, SBS reconstruction software, with the much greater data rate and volume to be generated by these experiments, needs focus on performance/speed/efficiency in terms of both raw data I/O and event reconstruction algorithms.

Existing SBS Software

- SBS online/offline analysis software is based on Podd, the standard C++/ROOT-based Hall A analysis framework, and uses the ROOT-based "OnlineGUI" for online monitoring plots for shift workers, etc.
- Existing repositories:
  - **SBS-offline**: (principal authors: S. Riordan, A. Puckett, E. Fuchey, J.-O. Hansen, J. C. Cornejo) https://github.com/JeffersonLab/SBS-Offline Main software repository of SBS-specific libraries, source codes, database files and replay scripts. Includes raw data decoders for all currently planned SBS DAQ modules and basic skeleton classes for all major SBS subsystems, within Podd/analyzer framework. **Already in use for commissioning of HCAL, BigBite calorimeters, timing hodoscope, others.**
  - **Libsbsdig**: (principal author Eric Fuchey) https://github.com/JeffersonLab/libsbsdig Main library for digitization of simulation output; translates *g4sbs* output (hit time, position, energy deposit) into simulated raw detector signals ("pseudo-data"), populates "hit" data structures used by reconstruction (ADC, TDC, crate, slot, channel, etc); purpose is to test and develop reconstruction algorithms on simulated events using identical algorithms to those used for real data: **Crucial for high-rate tracking studies done so far**
  - **G4sbs**: (principal authors Andrew Puckett, Seamus Riordan, Eric Fuchey, many contributors) https://github.com/JeffersonLab/g4sbs GEANT4-based simulation of all of the SBS experiments. Documentation at https://hallaweb.jlab.org/wiki/index.php/Documentation_of_g4sbs
  - **SBSGEM_standalone**: (principal author A. Puckett, contributions from Weizhi Xiong, Sean Jeffas, others) https://github.com/ajpuckett/SBSGEM_standalone standalone GEM reconstruction code, takes decoded raw data (after common-mode/pedestal subtraction and zero suppression), does clustering, tracking, and alignment. Presently the main tracking code in use for GEM commissioning.

SBS software working group

- Mailing list: https://mailman.jlab.org/mailman/listinfo/Sbs_software
- Standing weekly meeting; currently Fridays at 1:00 PM
- SBS Software Coordinator: Andrew Puckett
- Core software working group members/participants:
  - JLab: J.-O. Hansen, A. Camsonne, M. Jones, S. Barcus, D. Flay, H. S.-Vance, B. Wojtsekhowski
  - CMU: J.-C. Cornejo, B. Quinn
  - Glasgow: R. Montgomery, D. Hamilton, R. Marinaro
  - Syracuse: W. Xiong
  - UConn: A. Puckett, E. Fuchey, P. Datta, S. Seeds
  - Hampton U: M. Kohl, T. Gautam, others
  - Northern Michigan U: W. Tireman
  - Significant contributions from UVA, W&M, Stony Brook, others

G4sbs: SBS Monte Carlo Simulation

- *G4sbs* is a success story within the overall SBS software effort: mature and well-developed
- Many users and contributors from inside and outside the core collaboration; **successful use in new proposal development and approval, assisting in detector design, and even used extensively in reanalysis of Hall A GEN-I data (E02-013).**
- Self-contained GEANT4 application with self-documenting ROOT output including version control
- Github version control and code maintenance
- CMake-based build system works "out of the box" on most Linux and Mac OS systems
- Minimal external dependencies (only ROOT, GEANT4, and python required), and planning to keep it that way!
- Thorough (albeit slightly outdated) documentation, maintained by the UConn group
- Flexible geometry configuration/event generation machinery
- Straightforward addition of new detectors/geometries with standardized ROOT outputs using pre-defined "sensitive detector" types that can handle most common use cases without modification.
- STL vectorization of array-valued output ROOT Tree branches—completely dynamically sized arrays, easier AND faster to read back with far less "memory waste" during analysis.
- Built-in event generators for main processes/targets of interest for SBS program
- Flexible interface to generic external event generators—separate event generation from detector simulation, re-use same "minimum-bias" events in many detector configurations.
- Anyone with reasonable C++/GEANT4/ROOT proficiency can contribute (and many have!)

SBS Software High-level Milestones and Timeline, as of Feb. 2021

High-level milestone	Estimated completion status as of today	Expected readiness date	Estimated expert manpower to complete (FTE-weeks)	Main experts/responsible persons
Raw data decoders for all subsystems in all relevant configurations	85%	April	2-3	JLab/Hall A/SBS DAQ team, O. Hansen, subsystem leads
Low-level histograms and data quality checks for online monitoring	70%	April	2-3	Subsystem leads, A. Puckett, Paul King
Implementation of production analysis framework in Podd/SBS-offline (critical path)	**40%**	**May**	**6-8**	**A. Puckett, O. Hansen, E. Fuchey, J. C. Cornejo**
Complete simulated experiment analysis for GMN/GEN-RP/WAPP--validation of reconstruction framework at high rate	70%	April	4-6	A. Puckett, E. Fuchey, W. Xiong
Event displays	65%	April	1-2	Subsystem leads, Sean Jeffas, A. Puckett, E. Fuchey
Calibration scripts and detailed commissioning plans with beam, dependencies	40%	June	2-4	Subsystem leads, A. Puckett
Online Monitoring Plots for shifters: OnlineGUI/Panguin/etc.	25%	July	1-2	Paul King, A. Puckett, others
Decode maps for all subsystems	80%	May	1-2	Subsystem leads, DAQ experts (Mark Jones?)
“Production” databases for all subsystems with beam (geometry/calibration constants/etc)	50%	June	2-3	Subsystem leads, A. Puckett, E. Fuchey, J. C. Cornejo, Mark Jones

Notes on Software Milestones and Design Philosophy, I

- The critical-path items for software readiness for beam are:
  - Collecting existing decoders/databases and reconstruction codes under the common umbrella of Podd/SBS-offline, with necessary attention to speed and efficiency of data processing
  - Implementing the "spectrometer-level" reconstruction algorithms that require the various detectors to share information with each other in a coherent way (without coupling them too tightly to maintain analysis flexibility)
- In SBS, the required event-reconstruction approach is at odds with the high-level design and "standard algorithm" of Podd.
- In traditional Podd, the primacy of tracking detectors within "spectrometers" is a ubiquitous assumption, with tracking detectors being processed first before passing track information along to the processing of other non-tracking detectors (PID, calorimeters, scintillators, Cherenkov, etc), which are then used to refine tracks, which are then used to refine calorimetry/PID/timing info…
  - Such an approach is well-suited to an HRS-type environment with relatively clean events/low background rates
- **In SBS, the spectrometer-level event reconstruction algorithm will generally proceed in the opposite order: reconstruction will start with high-energy clusters in total-absorption calorimeters, used to constrain search regions for tracking.**
- Each SBS experiment has somewhat specialized requirements on the processing order of detectors, but the reconstruction of BigBite will always follow the same basic approach.
- Our path of least resistance is probably to abandon the use of Podd's "THaSpectrometer" class altogether, and write specialized "apparatus" classes inheriting the more flexible "THaApparatus", whose reconstruction methods will process the detector information in the specific order required by the specialized requirements of the experiment in question—this will require some duplication of existing "THaSpectrometer" functionality in order to implement the specialized reconstruction codes needed

Notes on Software Milestones and Design Philosophy, II

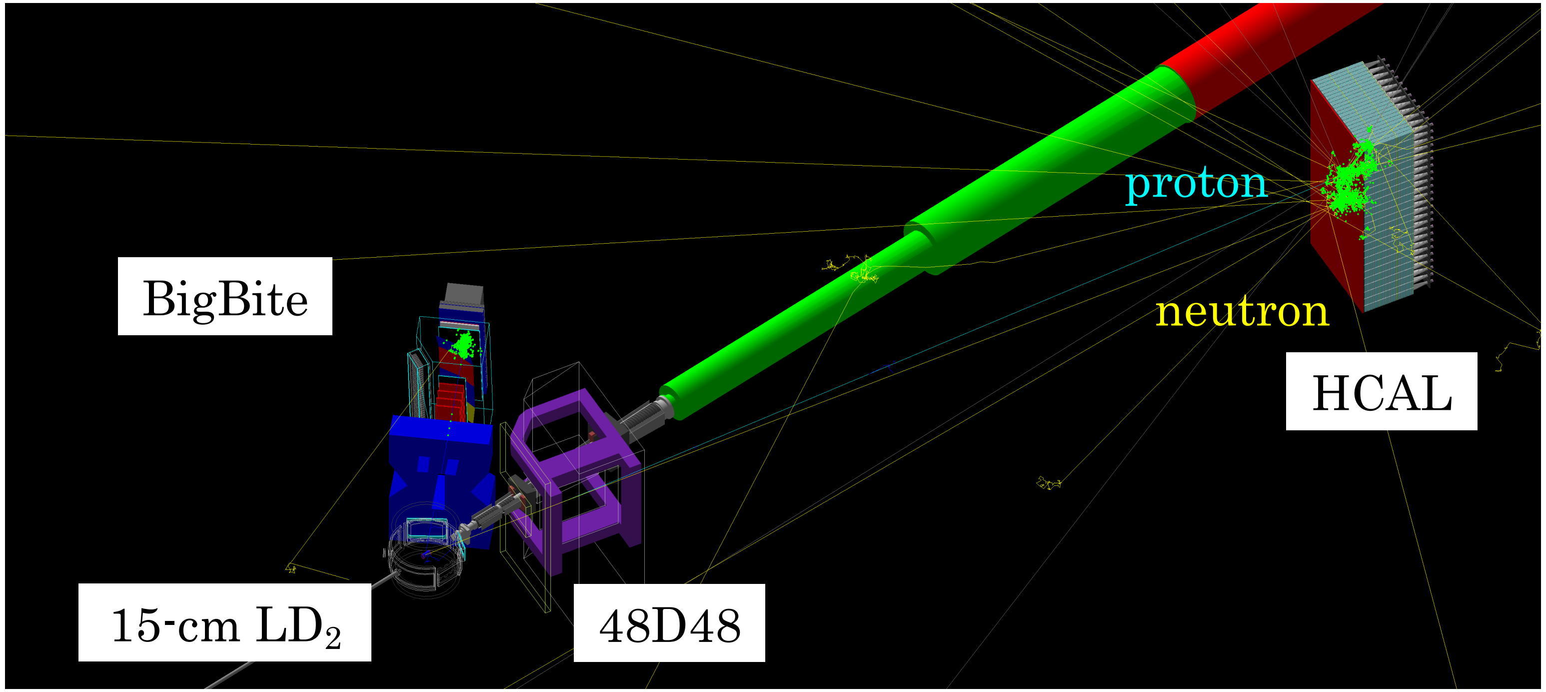
- We cannot abandon efforts on simulation and the development of the simulation-reconstruction interface, as they are still presently our best and only way to validate high-rate reconstruction algorithms prior to beam commissioning
- Cosmic data and event displays are useful for low-level checkout and calibrations, alignments, and sanity checks, but event displays in particular will be of somewhat limited utility in the Hall A high-rate environment, particularly for the GEMs, and cosmic data do not tell us anything meaningful about the expected performance of our algorithms at high rate.
- Much of what we develop prior to the move to Hall A will need to be redone in Hall A (decode maps, geometry databases, calibrations and calibration constants, etc).
- We are collecting necessary information about each subsystem, calibration and commissioning plans with beam, and subsystem interdependencies for such plans, in the SBS reconstruction software white paper (work in progress):
    - Read-only link here (to contribute, contact Andrew Puckett)

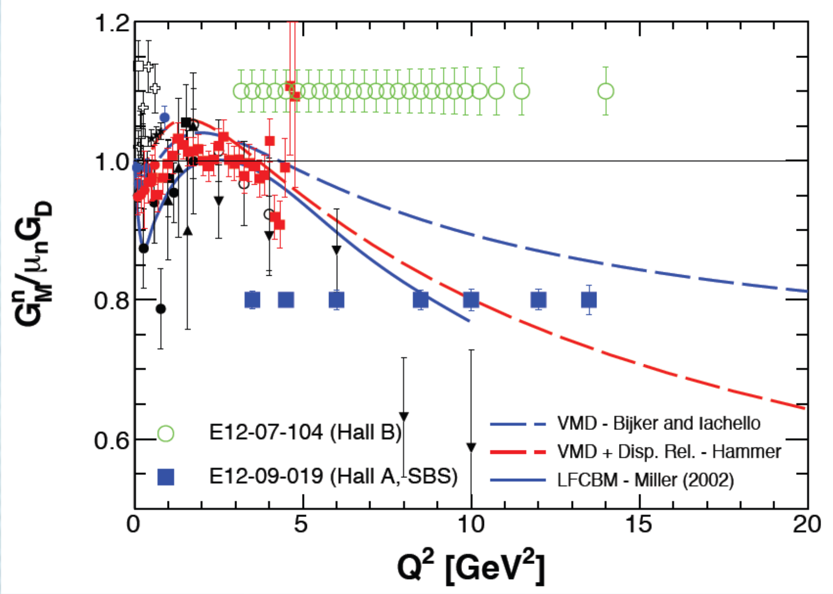
SBS software workforce through GMN run group

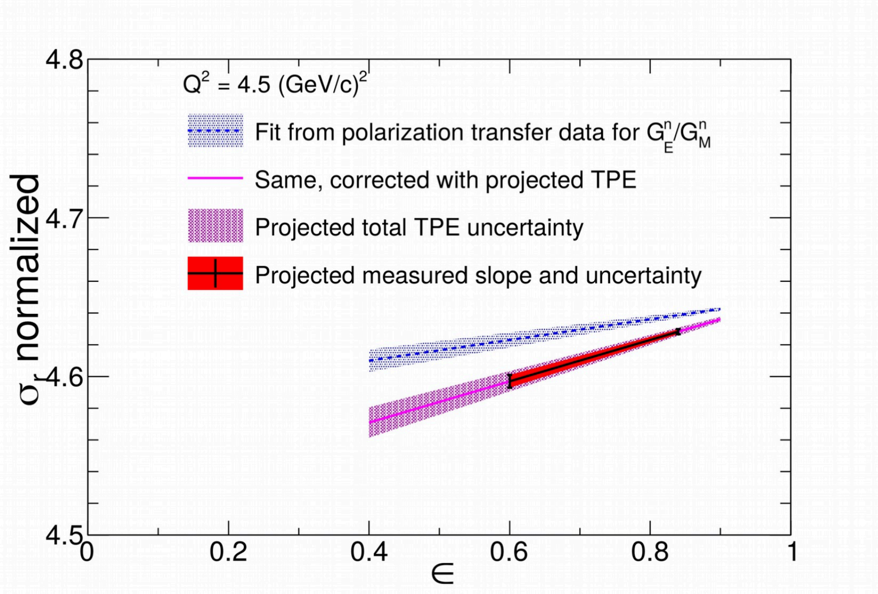
Institution	Personnel	Projects	Dedicated software manpower commitment through calendar 2021
UConn	A. Puckett (PI), E. Fuchey (PD), P. Datta and S. Seeds (Ph.D. students)	SBS-offline, g4sbs, GEM tracking, all software for all detectors	0.7 FTE Faculty, 0.8 FTE PD, ~0.5 FTE Ph.D.-level grad. students
JLab	H. S.-Vance, D. Flay, O. Hansen, M. K. Jones, S. Barcus, A. Camsonne	Optics, Hall A software infrastructure (Podd), simulations, HCAL, decoding, DAQ, etc.	~0.75 FTE lab staff: 0.5 (Hansen) + ~0.25 (all others combined, estimated) + ~0.25 FTE PD (Barcus)
CMU	J.-C. Cornejo	HCAL, SBS-offline, g4sbs, others	~0.4 FTE PD average
Syracuse	W. Xiong	GEP tracking (relevant to GMN BigBite and GEN-RP analysis)	0.4 FTE PD
Ohio U	P. King	Online monitoring plots	??
UVA group	See GEM group presentations	GEM tracking and monitoring plots	??
Glasgow	R. Montgomery, D. Hamilton, R. Marinaro, G. Penman	BB timing hodoscope, CDET, GEN-RP analysis, simulations	0.2 FTE Faculty, 0.4 FTE PD, 1.2 FTE Ph.D. student
Stony Brook	J. Bernauer + PD + student(s)	TDIS simulations, event generators, radiative corrections	??
INFN, W&M, Northern Michigan, CNU, Hampton, UMass, others			

- There are other groups/names left out among regular software meeting participants, and subsystem leads will contribute additional efforts and information. This table includes only those who responded to my request for manpower commitments

GMN in *g4sbs*





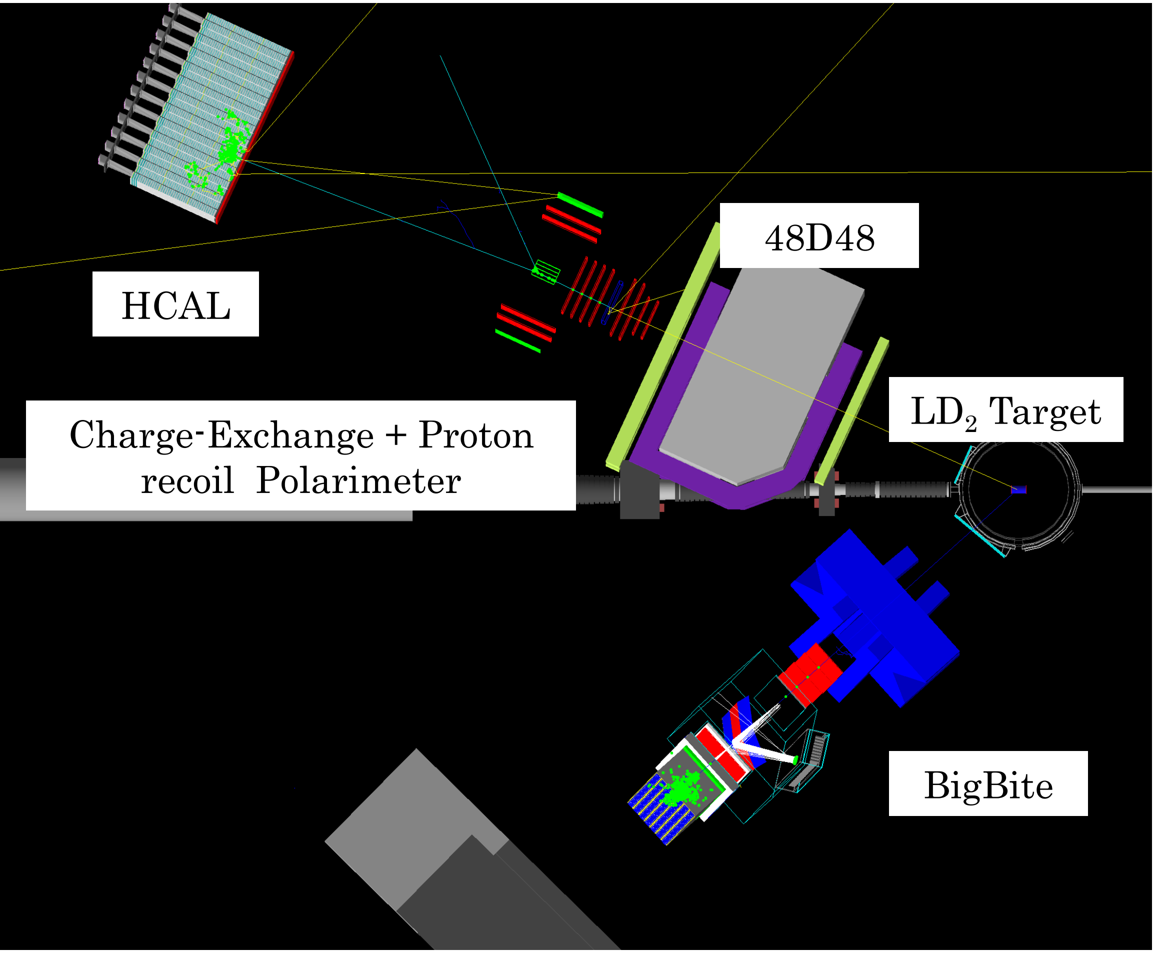


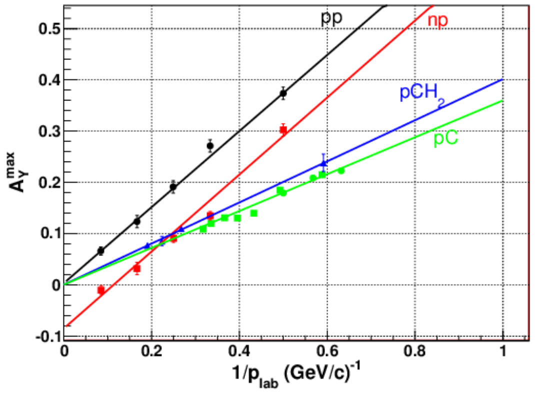
- E12-09-019 will measure neutron magnetic form factor G_M^n to 13.5 GeV^2 using the "ratio" method on deuterium.
- E12-20-010, a recently approved "add-on" measurement, will determine the Rosenbluth slope in elastic *en* scattering for the first time at $Q^2 = 4.5\ GeV^2$
- Uses hadron calorimeter for efficient nucleon detection; magnetic deflection for charge ID
- BigBite detects electron, defines $\vec{q}$ vector, vertex for selection of quasi-elastic

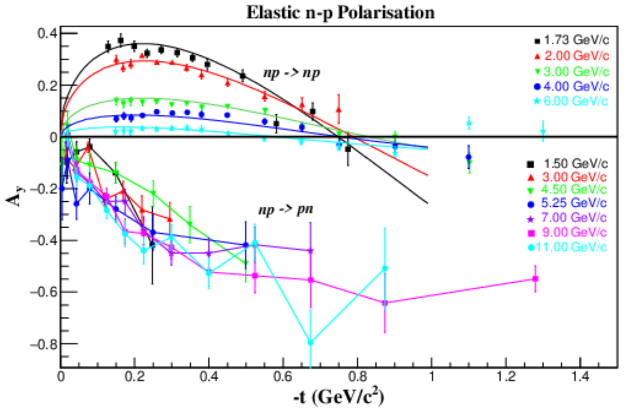
GMN analysis detector/software specifications

- BigBite spectrometer—reconstruct full kinematics of scattered electron:
  - Momentum reconstruction: $\frac{\sigma_p}{p} \approx 1 - 1.5\%$
  - Angular resolution: $\sigma \approx 1 - 2\, mrad$ (in-plane and out-of-plane)
  - Vertex resolution: $\sigma_z \leq 1\, cm$ ($\sigma_{y_{tgt}} \approx 2\, mm$)
  - Predict $\vec{q}$ direction and neutron position at HCAL from Q.E. kinematics
  - Suppress charged pions using preshower calorimeter plus GRINCH
  - Straight-line tracks in field free regions → simple and reliable data analysis!
- Hadron Calorimeter HCAL—reconstruct neutron kinematics; nucleon charge ID:
  - Time resolution $\sigma_t \approx 0.5 - 1\, ns$
  - Angular resolution ~2 mrad
  - Energy resolution (for hadrons): ~25% at $p_N \cong 3 - 7\, GeV$
  - Reconstruct missing parallel and perp. momenta, reject protons and inelastics

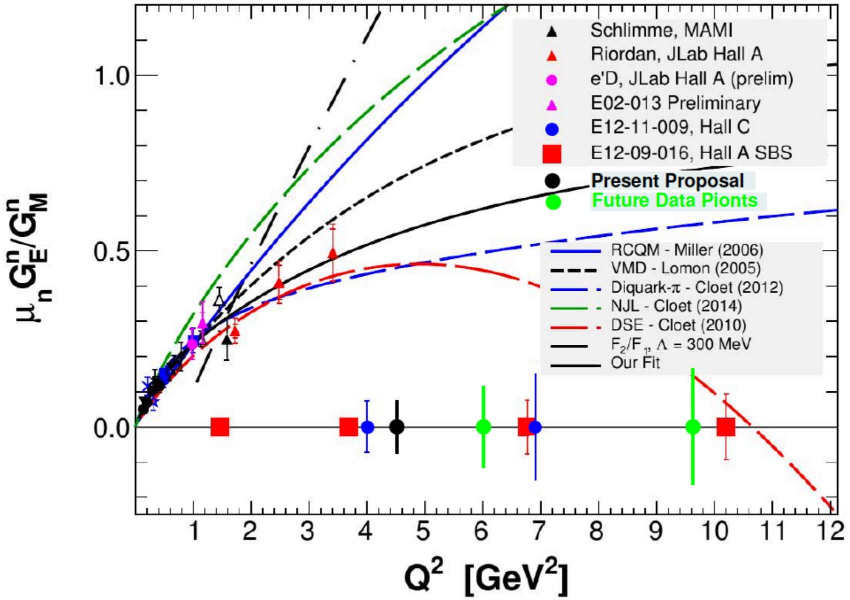
GEN-RP in *g4sbs*







Analyzing powers for np, pp, pA scattering vs. initial momentum (left) and vs. transferred momentum (right)

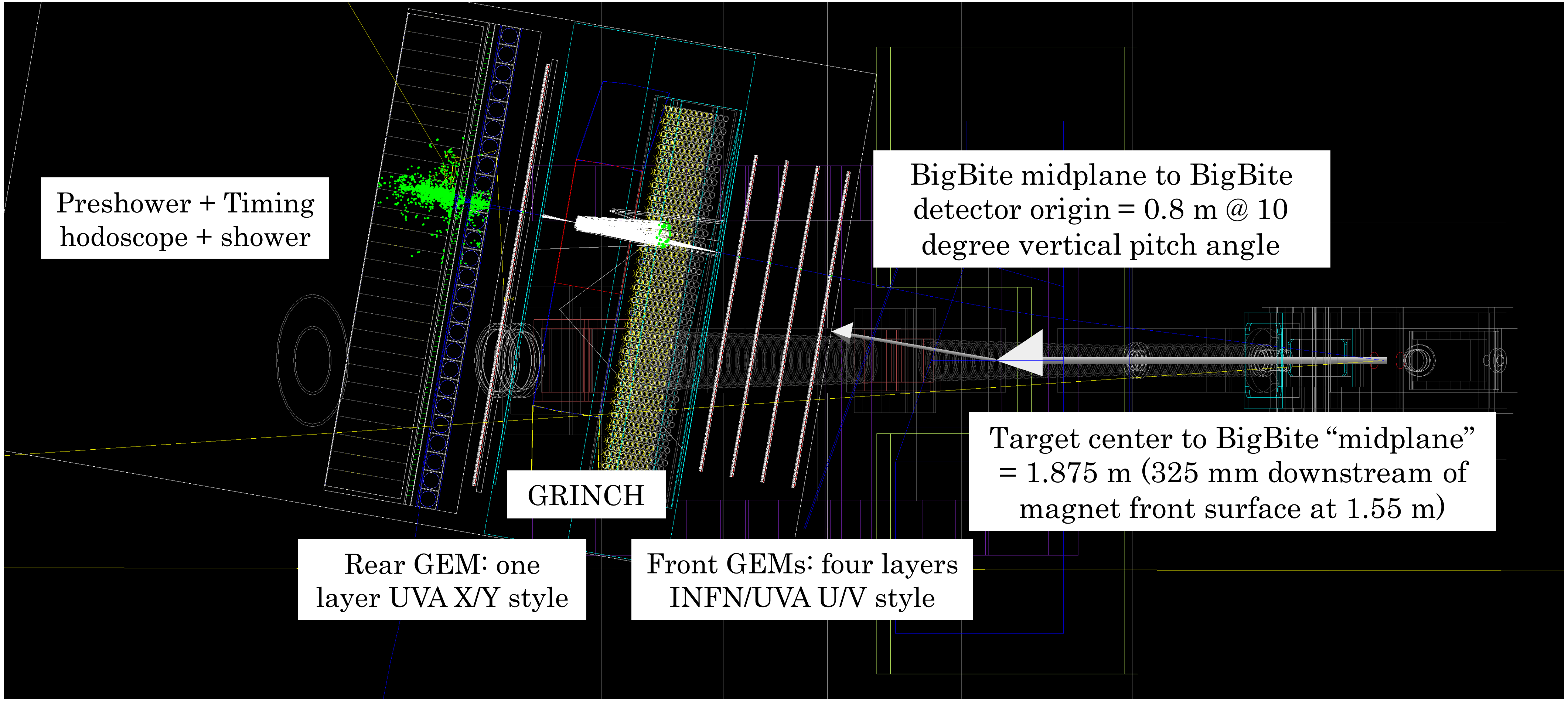


- E12-17-004 layout (above) and projected results (right):
  - First use of charge-exchange polarimetry in a FF experiment
- E12-20-008 approved as add-on to measure K_{LL} for $\gamma n \rightarrow \pi^- p$

GEN-RP analysis detector/software requirements

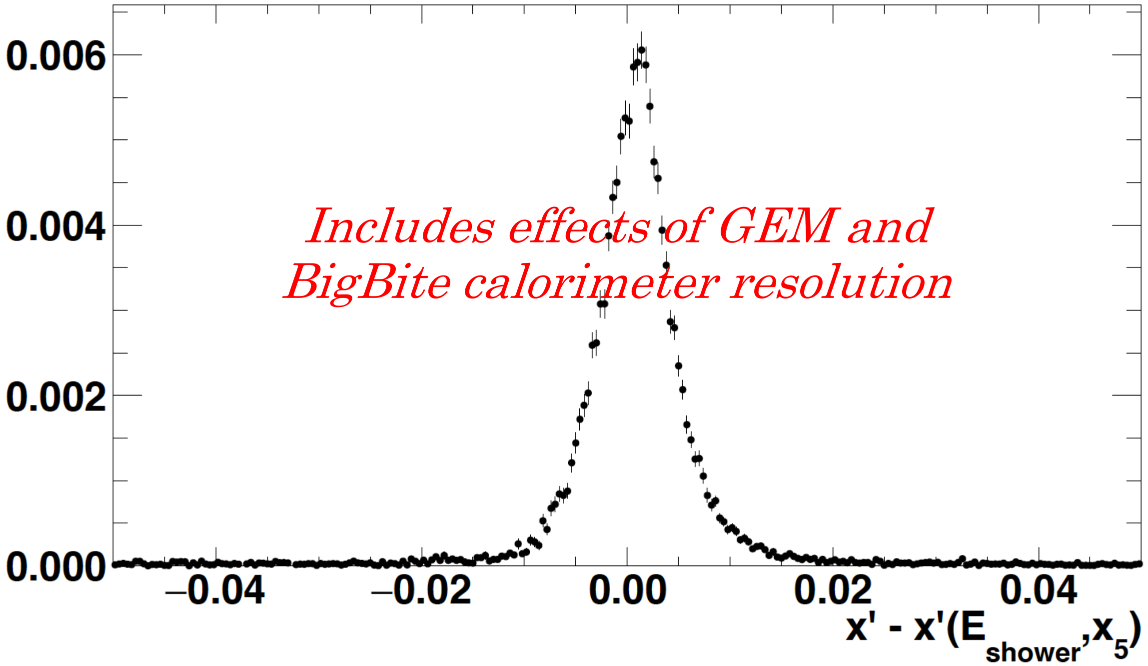
- Electron arm requirements same as GMN and all other neutron FF experiments
- Hadron arm additional requirements:
  - HCAL in trigger—coincidence with BigBite calorimeter (not software per se)
  - HCAL clustering—use high-energy cluster to constrain the tracking in rear GEMs of charge-exchange polarimeter and reconstruct angles for "active analyzer" events
  - **Front GEMs as charge veto for proton rejection**—GEN-RP says they do not require full track reconstruction in front GEMs nor reconstruction of charged tracks back to the target, but WAPP requires this, so we will develop anyway
  - **Front GEM tracking and SBS optics calibration for WAPP—SBS sieve slit not guaranteed in time for GMN run group—need LH2 elastic to calibrate!**
  - **Rear GEM tracking—**track forward protons produced in charge-exchange reactions by quasi-elastically scattered neutrons incident on steel analyzer
  - Reconstruct large-angle recoil protons in side GEMs and scintillators

BigBite event reconstruction algorithm, I

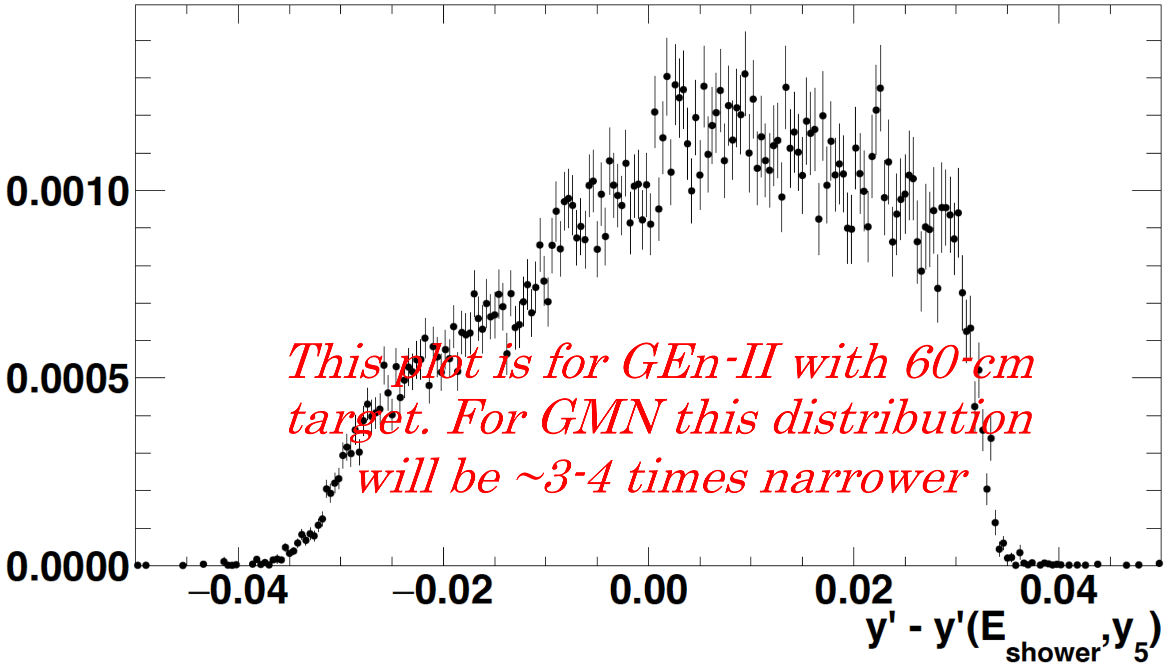


- BigBite event reconstruction starts from a high-energy cluster in the shower/preshower and a nearby hit in the 5th GEM layer (which has significantly lower occupancy than front GEM layers)
- Calorimeter energy reconstruction and precise 5th GEM layer position, together with first-order BigBite optics, give tight constraint on track search region in front GEMs

BigBite reconstruction algorithm, II: generic approach to fast tracking @high rate



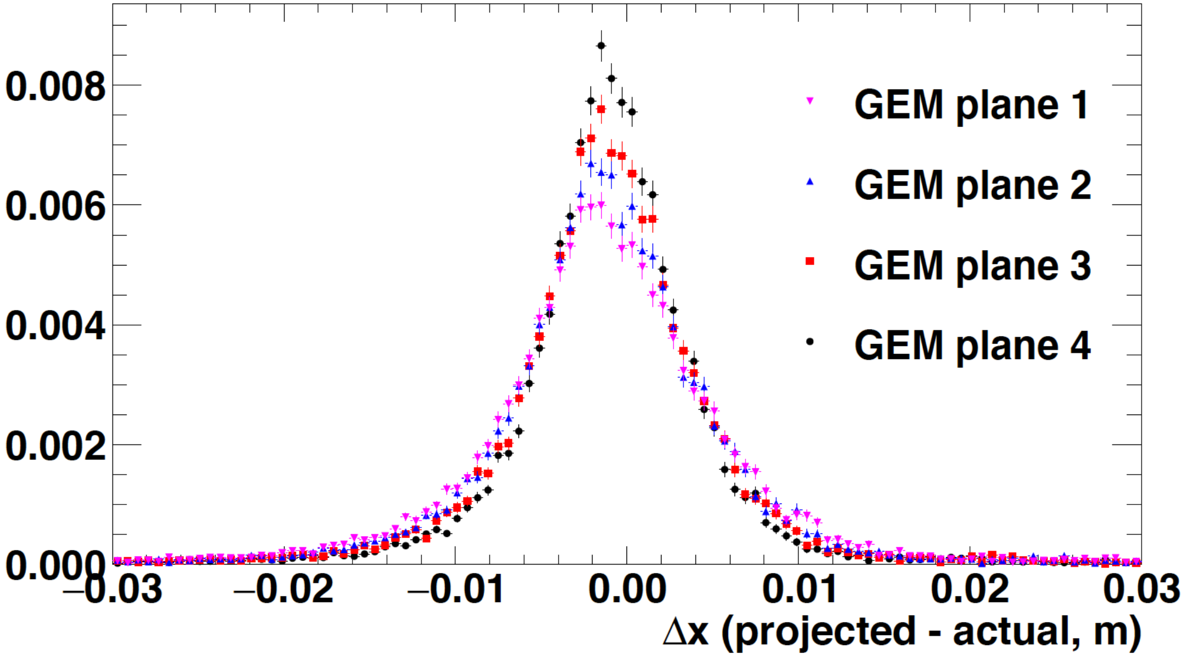
Dispersive direction track slope constraint

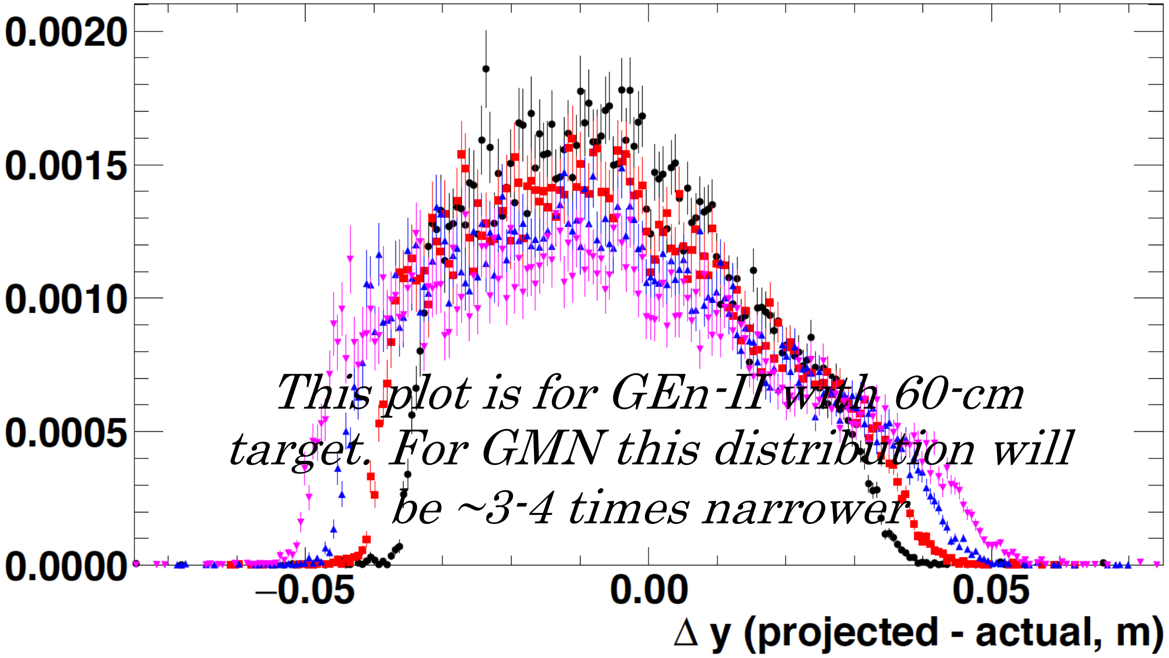


Non-dispersive direction track slope constraint

- Position and energy of calorimeter cluster define ~100 cm^2 search region for hits in 5th GEM layer (~5% of GEM module active area). 5th GEM layer has low occupancy→few background hits expected in search region
- Use calorimeter energy (resolution $\frac{\sigma_E}{E} \approx \frac{7.5\%}{\sqrt{E\ (GeV)}}$) and precise hit coordinate at 5th GEM layer with 1st-order optics of BigBite to predict track slopes along dispersive (X) and non-dispersive (Y) directions.
- This procedure defines the track slope in dispersive (non-dispersive) direction to within $\Delta x'(\Delta y') = \pm 10\ (\pm 15)\ mrad$, where the extra width along Y is due to the target extent.

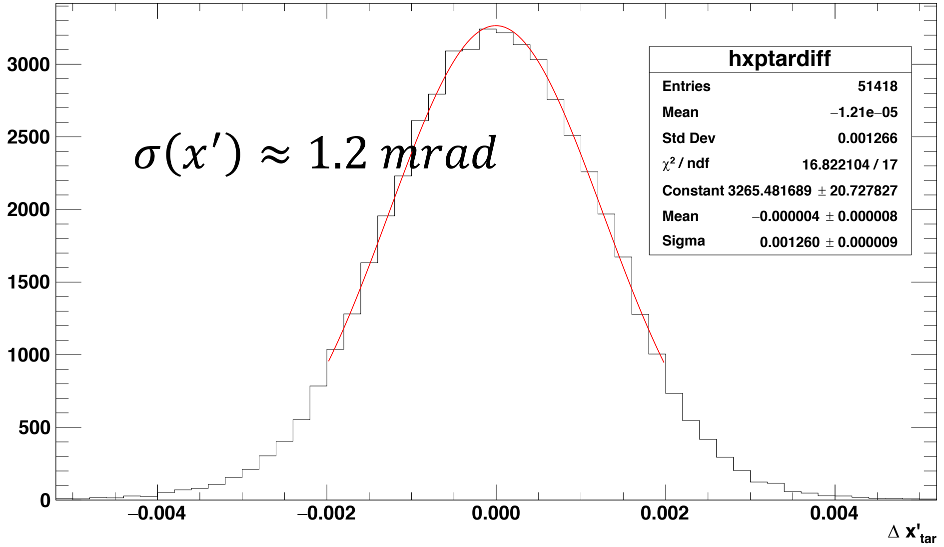
BigBite reconstruction algorithm, III

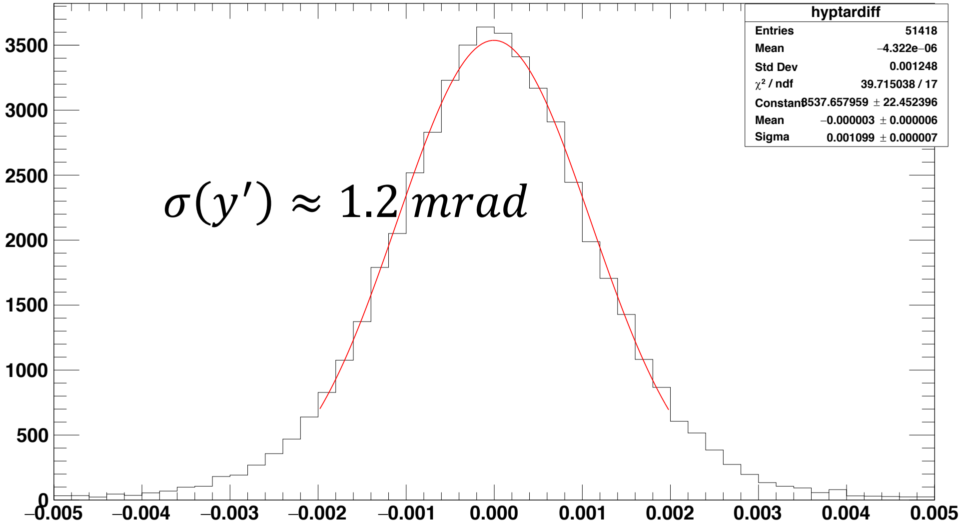


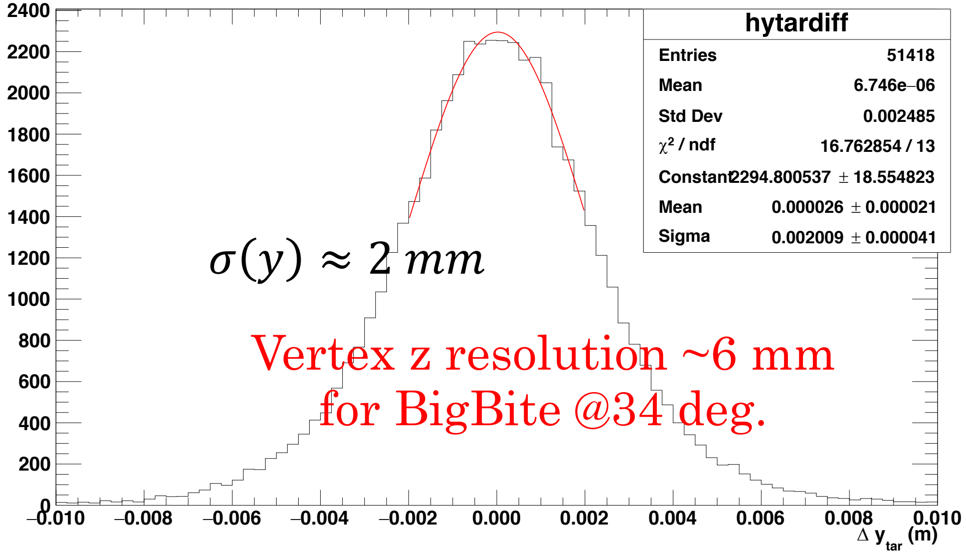


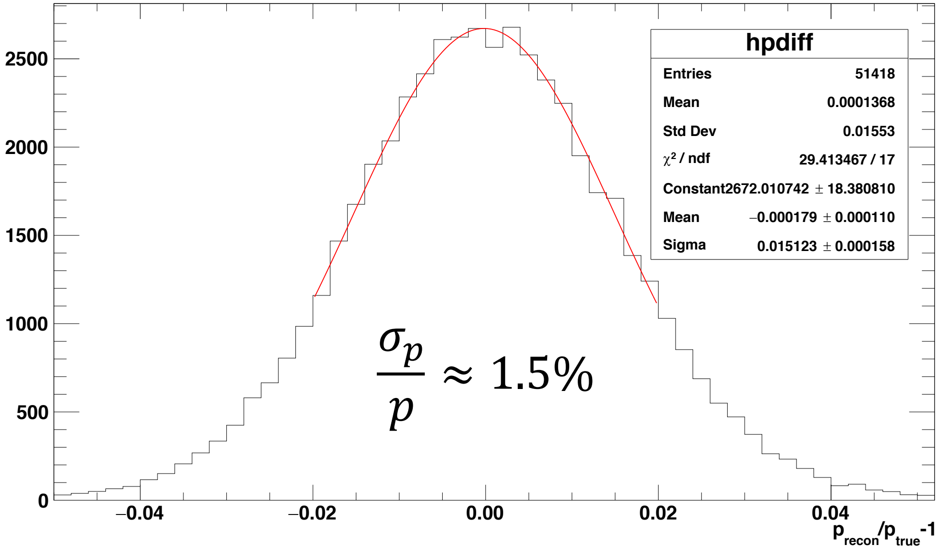
- Track slope constraints from previous slide allow us to define a small search region for tracking at each GEM layer by projecting the "track seed" from calorimeter/rear GEM to each GEM plane:
  - For the X (dispersive) direction, we can use ±20 mm at all four layers
  - For the Y (non-dispersive) direction, the search region size varies from about ±60 *mm* at the first (front) layer to ±40 mm at the fourth (rear) layer (for GEn with 60-cm target). For GMN/GEN-RP/nTPE/WAPP we can most likely use ± 30 *mm* at all four front GEM layers
- **This reduces the track search region to about 1.2% of the active area of a GEM module in the worst case.**
- Within the search region, we expect, on average, about 1.2 background hits/module/event* in GMN → forgiving combinatorics = fast tracking! *--true hits, this does not include fake hits from incorrect X/Y combinations

BigBite Resolution ($p_e \approx 2-5\ GeV$)

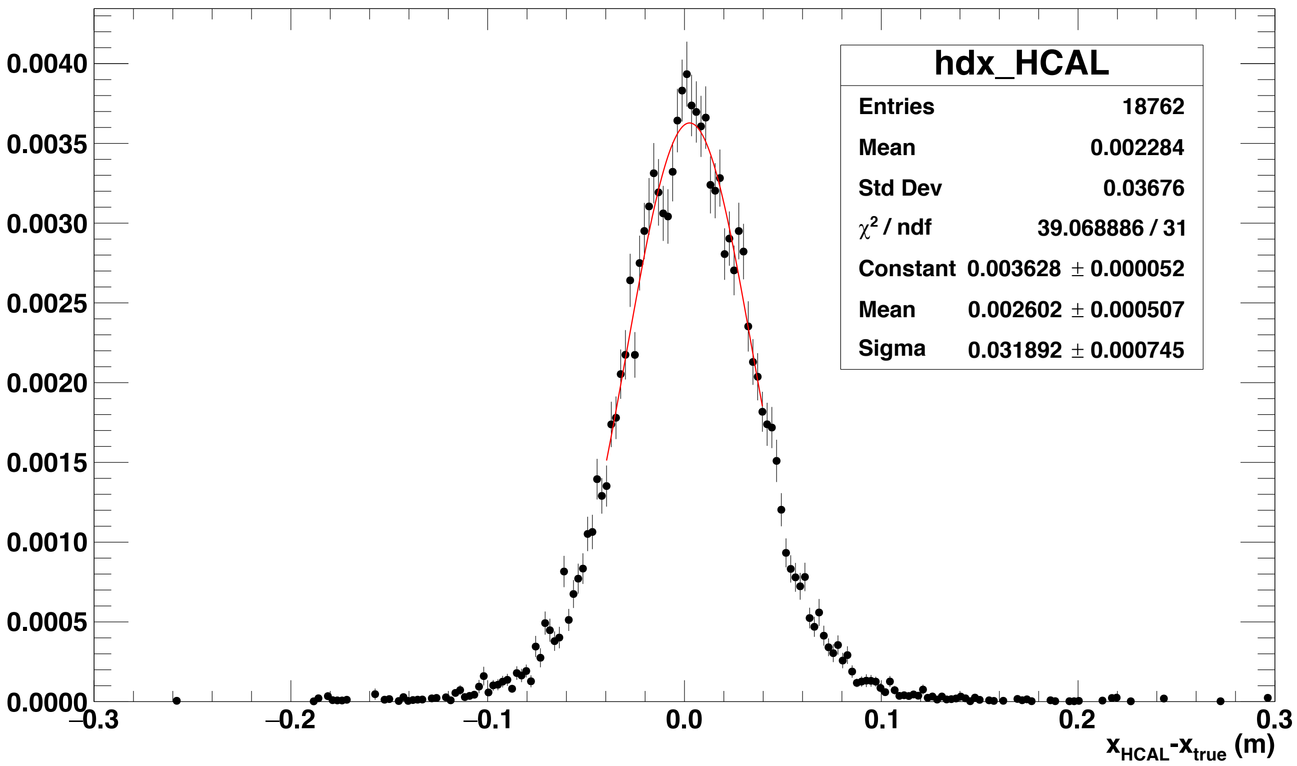




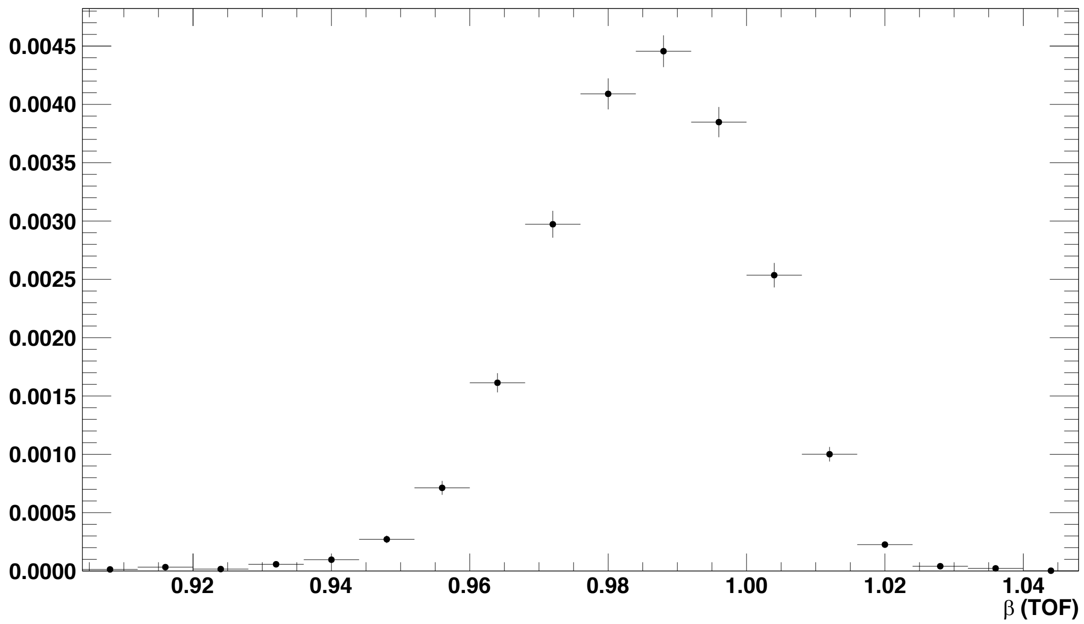




HCAL Resolution



- HCAL coordinate resolution for high-energy nucleons ~3 cm.
- At a distance of 17 m from target, the angular resolution is ~2 mrad → this is the most powerful constraint to reject inelastics at the highest Q^2
- Energy resolution $\frac{\sigma_E}{E} \approx 25\%$ provides *modest* discrimination between elastic/inelastic
- For GMN/GEN-RP/nTPE/WAPP w/LD2 target, angle resolution provides sufficient rejection of inelastic events; TOF resolution less critical



- At $Q^2 = 10.2\ GeV^2$, we have $p_n \approx 6.3 \frac{GeV}{c}, \beta \approx 0.99$.
- As $\beta \to 1$, the nucleon momentum from TOF is smeared out asymmetrically, momentum resolution blows up.
- Under such conditions, the *angular* resolution of HCAL provides the best constraint for selecting elastics/rejecting inelastics—TOF resolution has limited discriminating power at these velocities
- Full optical photon simulations of HCAL indicate time-over-threshold/signal duration can help with γ/n discrimination

SBS GEM reconstruction code (standalone version)

- GEM reconstruction (and alignment) code w/clustering, alignment, and track-finding, stored and maintained in github repository: https://github.com/ajpuckett/SBSGEM_standalone
- Major contributions to fast track-finding algorithm from Weizhi Xiong (Syracuse U. postdoc and first author of PRAD Nature paper) and Sean Jeffas (event displays)
- This (primarily) UConn-developed code is already being used to analyze decoded GEM data from a wide variety of experiments:
  - INFN cosmic data, 2018-present: 4 layers of 3 GEM modules each, 40x50 cm^2 per module area
  - UVA GEMs, beam test in Hall A, 2016, 5 layers one module each, 50x60 cm^2
  - UVA EEL clean room data, 2019-present, 4 and 5-layers data with four modules each, 16-20 modules total
  - GEMs in HRSs during PREX/CREX
  - Simulated, digitized high-rate data in SBS GEP and other experiments

README.md

SBSGEM_standalone

Standalone ROOT macros for analysis of GEM data.

Requirements: Working ROOT installation; decoded GEM data in standard ROOT Tree format.

GEM_reconstruct.C: main clustering/hit reconstruction/tracking code; developed for analysis of GEM data from INFN cosmic ray test stand. Takes decoded GEM data as input (strips fired by module and six ADC samples from APV25), reconstructs 2D hits, finds straight-line tracks, produces diagnostic histograms and ROOT Tree.

GEM_reconstruct_HallAtest.C: same as GEM_reconstruct.C, but specialized for analysis of Hall A GEM test data from 2016. Uses additional information from the calorimeter that was part of the test; computes simple sum of calorimeter ADC values.

GEM_reconstruct_standalone_consolidated.C: consolidated version with capability to analyze three different data formats: Hall A GEM test 2016, INFN cosmic stand, UVA EEL cosmic stand. THIS IS THE VERSION THAT WILL BE DEVELOPED AND SUPPORTED GOING FORWARD!

GEM_align.C: Alignment code; takes the output of GEM_reconstruct.C as input, determines best set of translational (x0, y0, z0) and rotational (alpha_x, alpha_y, alpha_z) "yaw, pitch, roll" offests to minimize chi-squared of straight line tracks.

Usage example:

root [0] .L GEM_reconstruct.C+ root [1] GEM_reconstruct("../HitData/GEMfixNov18 /Hit_run3805_*.root","configINFN.txt","temp.root");

General usage: GEM_reconstruct(infilename, configfilename, outfilename);

Here infilename gives the absolute or relative path name from the working directory to the decoded GEM data file in ROOT Tree format.

configfilename gives the name of the text configuration file, which defines the geometry and all relevant parameters for the clustering, hit reconstruction, and tracking.

outfilename is the desired name of the output ROOT file.

Similarly, for the alignment code:

root [0] .L GEM_align.C+ root [1] GEM_align(inputfilename, configfilename, outputfilename);

where inputfilename is the name of a root file that is the output of GEM_reconstruct containing the relevant reconstructed hit and track information, configfilename is the text configuration file, and outputfilename is the name of a text output file containing the new alignment parameters for each module. The output of GEM_align can be directly copied and pasted into the configuration file for GEM_reconstruct to repeat the tracking with the new alignment parameters.

Example configuration files are:

configINFN.txt: Example configuration file for INFN GEM four layer cosmic test data from Nov. 2018 configHallAtest.txt: Example configuration file for five layer UVA GEM Hall A beam test data from 2016. configalign.txt: Example alignment configuration file for INFN four-layer cosmic test data. configalignHallAtest.txt: Example alignment configuration file for five-layer UVA GEM Hall A beam test data 2016.

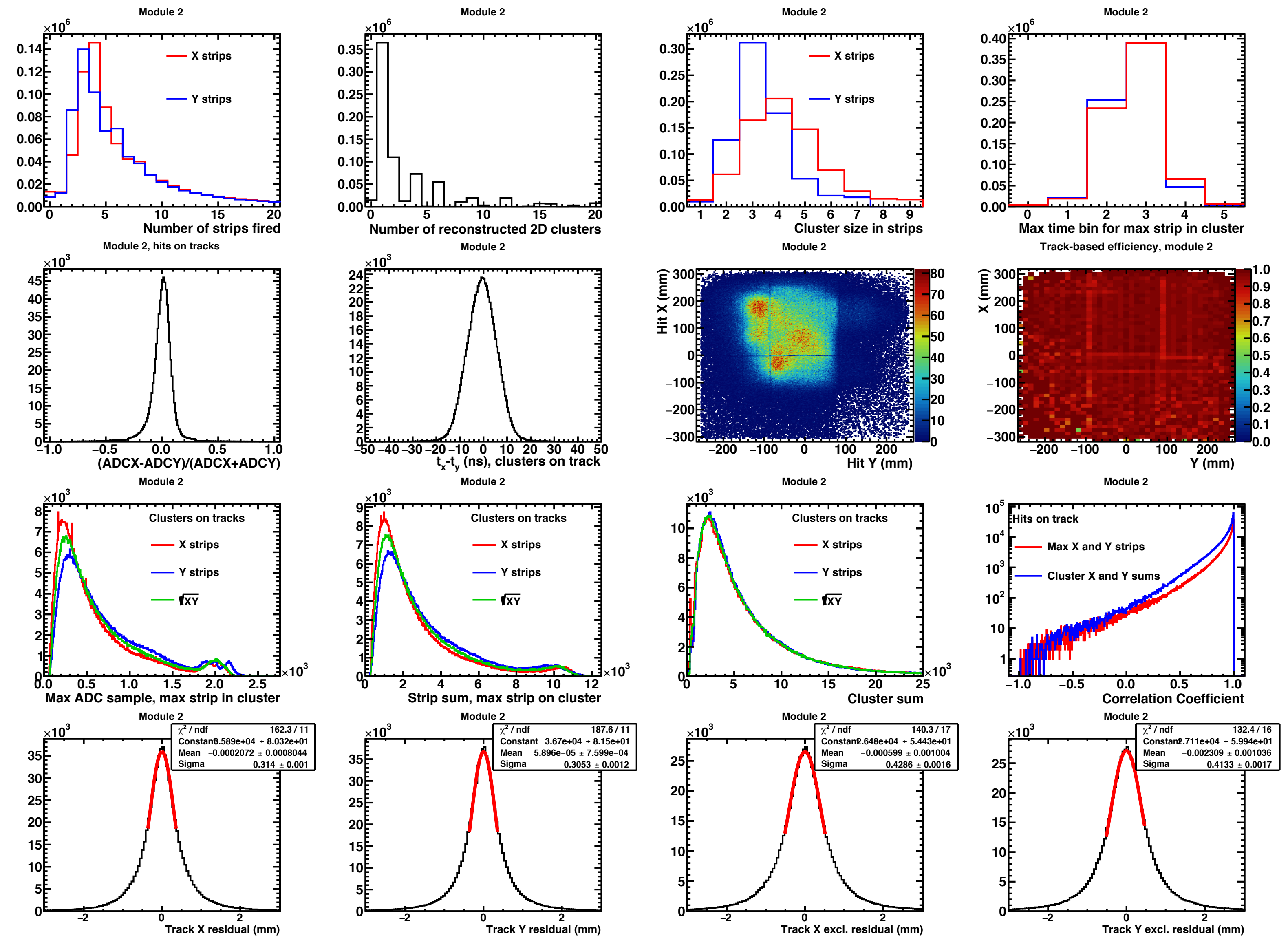
I have also added two utility macros:

plot_GEMrun_summary.C plot_GEMrun_summary_HallA.C

which can be used to generate a PDF file with a nice "standard" group of summary plots of the analysis.

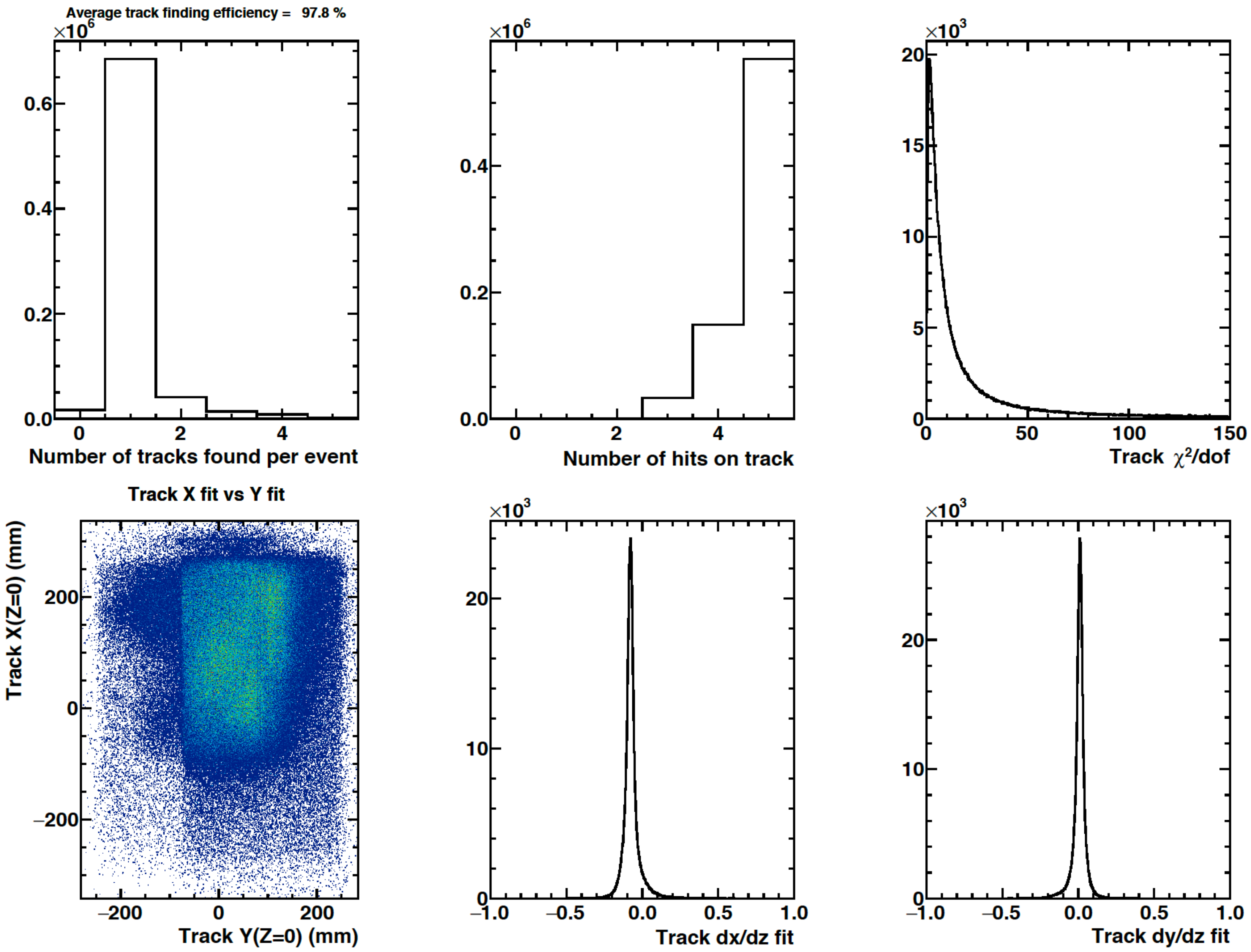
Detailed documentation of configuration parameters is forthcoming. In the mean time, read the source code.

Per-Module Diagnostic Plots, example (Hall A beam test, 2016):



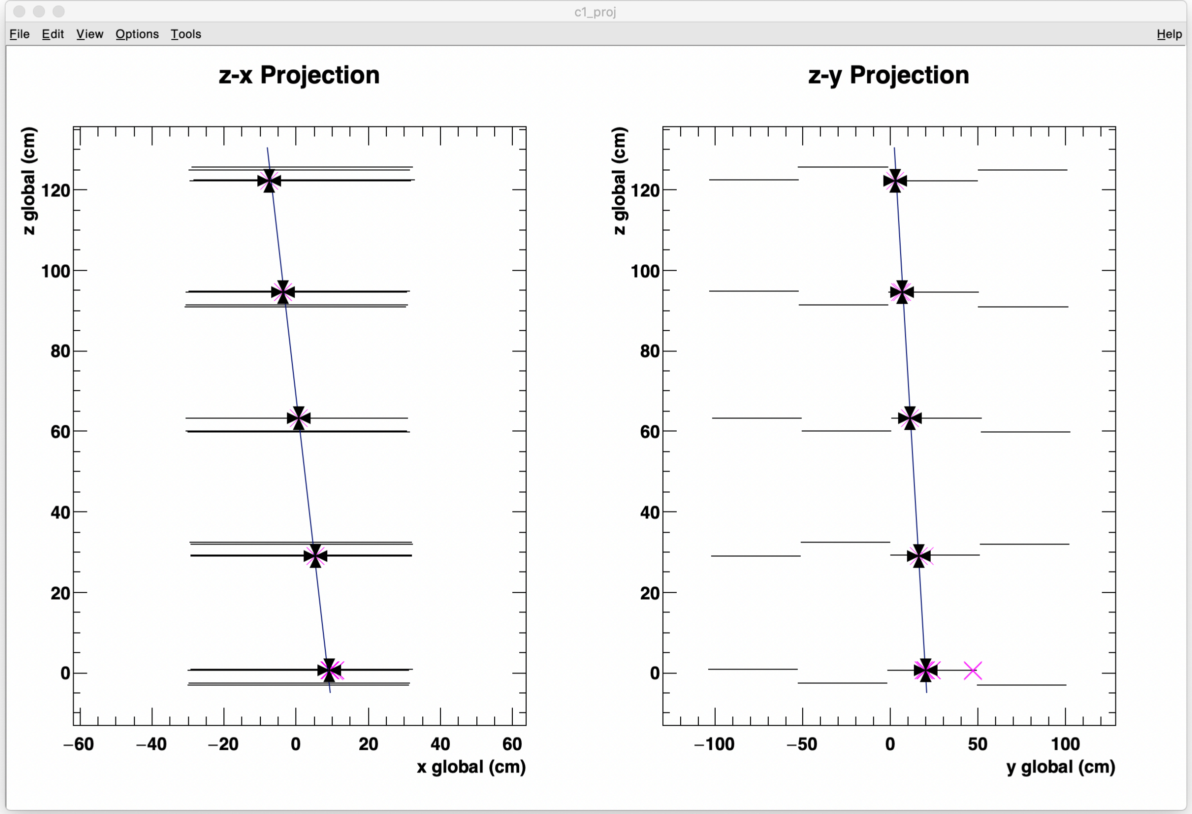
- "Standardized" set of diagnostic plots
- Top row: strip and cluster multiplicities, max time sample distribution (trigger latency check)
- 2nd row: XY ADC and time correlation, module hit map and track-based efficiency
- 3rd row: ADC distributions–max sample on max strip, max strip sum, cluster sum
- 4th row: tracking residuals in X/Y—"inclusive" (include all hits on fitted track) and "exclusive" (exclude hit in question from fitted track)

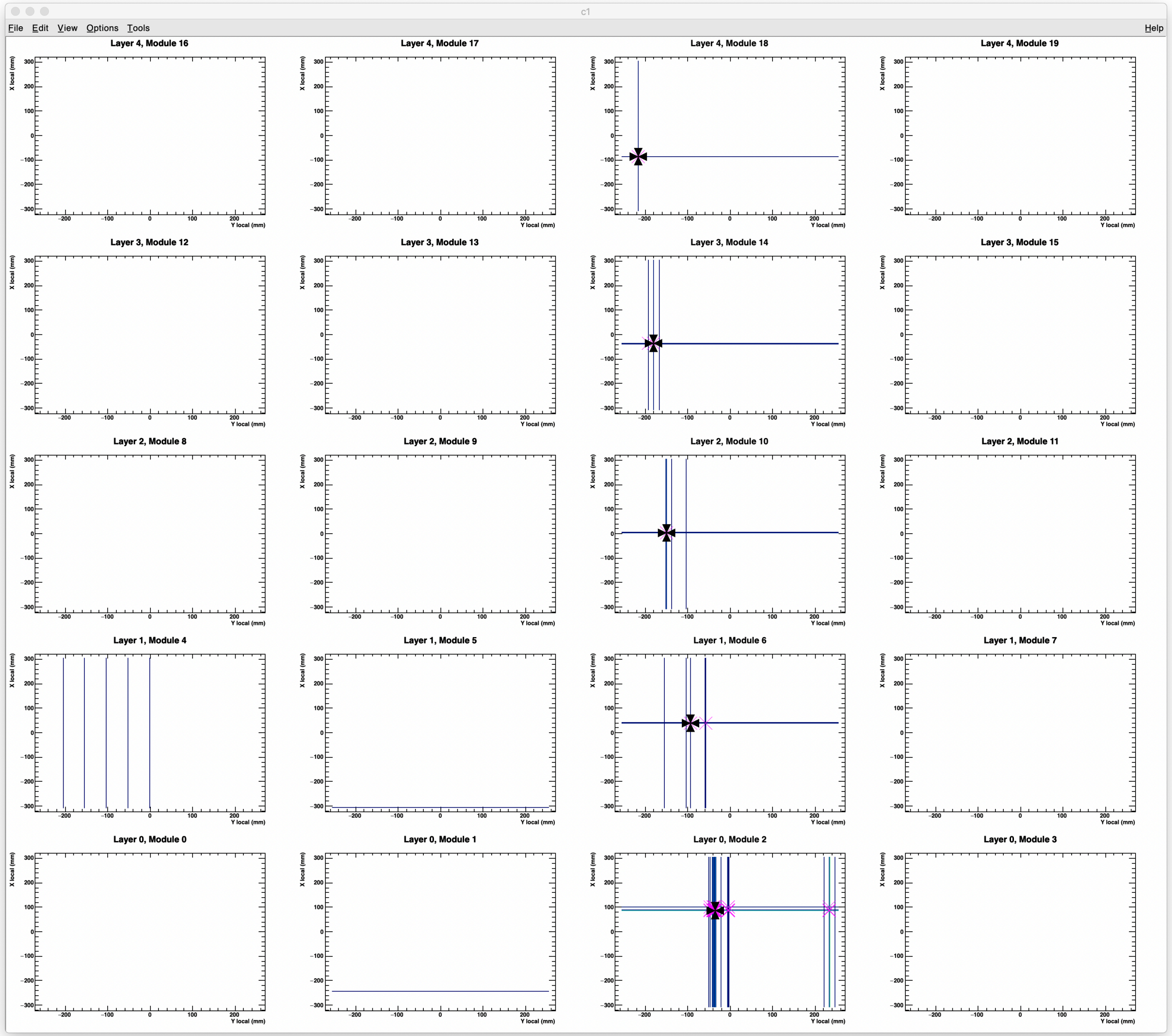
Tracking results: 2016 Hall A test



- 5-layer tracking efficiency ≥ 95% based on events with two good scintillator TDC hits and calorimeter FADC sum > 5,000 ADC channels
- Tracking-finding efficiency for events with at least one 2D cluster in at least 3/5 modules is 97.8%
- Efficiency results based on track reduced $\chi^2 \leq 300$, which corresponds to maximum single tracking residual of ~5 mm for tracks with all 5 layers fired.

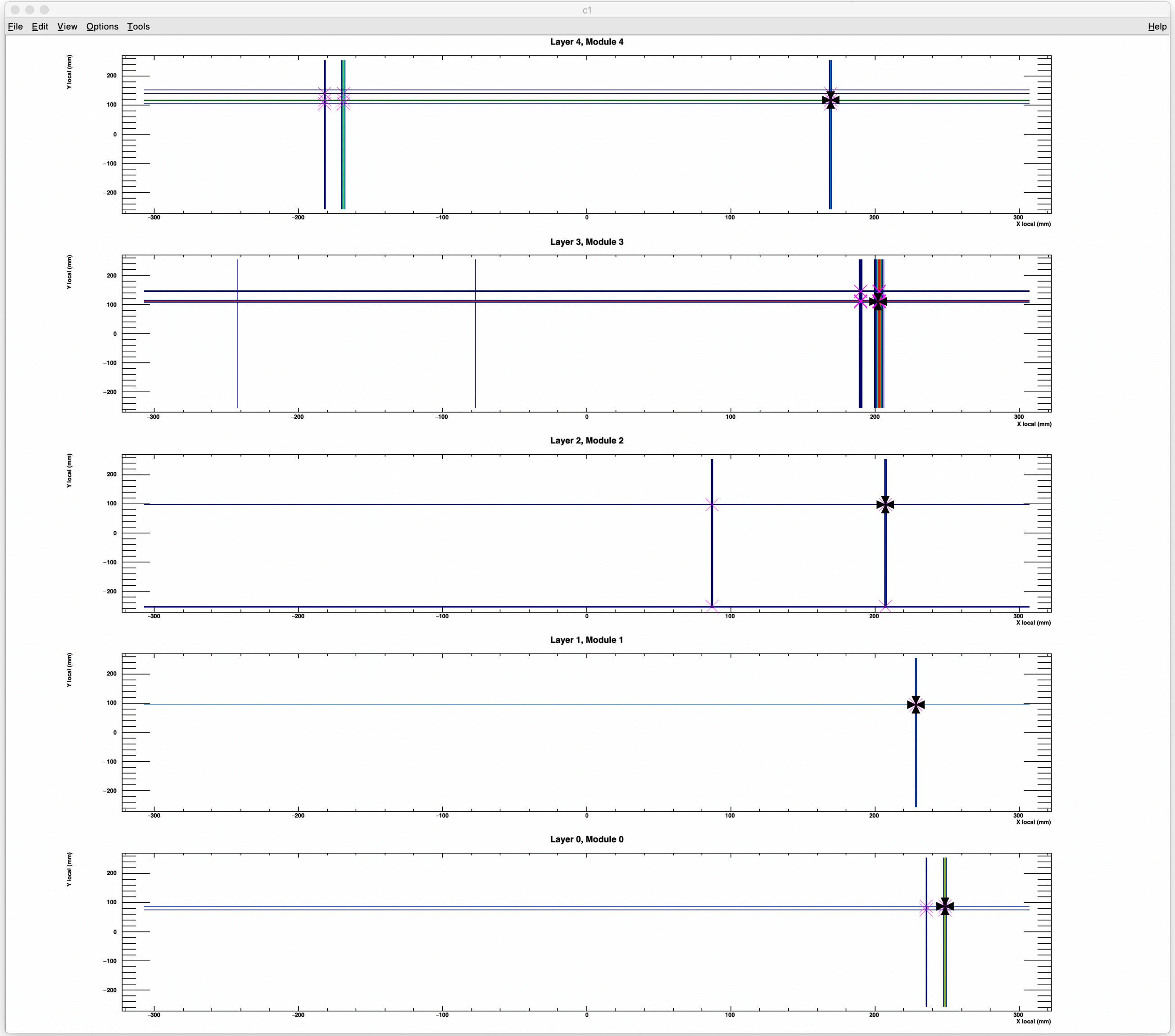
GEM Event Display—cosmics

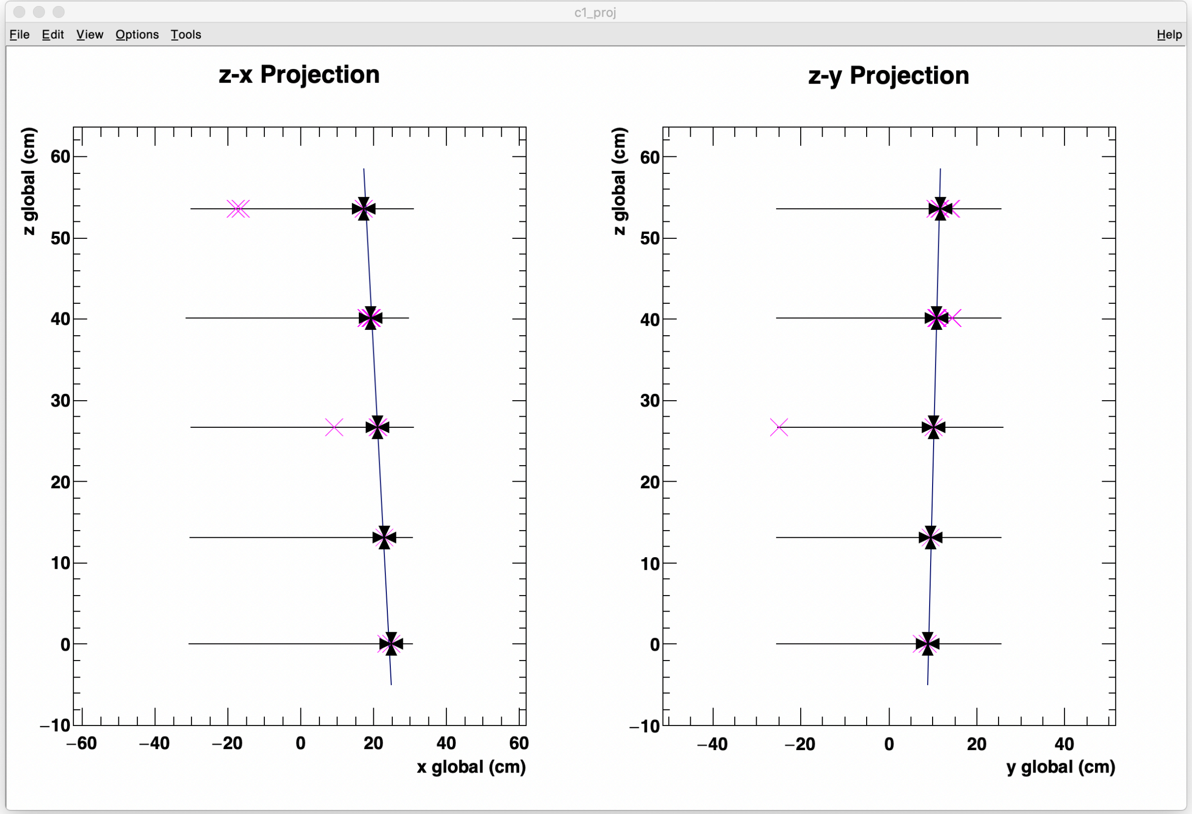




- XZ and YZ projection displays by Sean Jeffas (UVA Ph.D. student)—See talk tomorrow!
- XY display by module (by Andrew Puckett)
- Very useful in debugging tracking/alignment

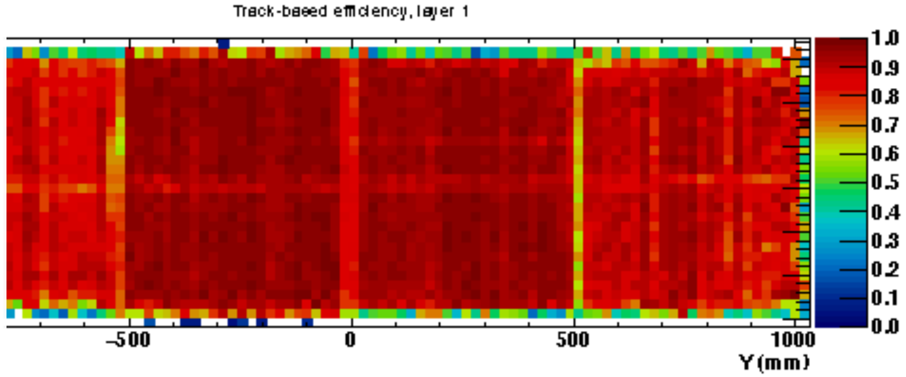
GEM event display—Hall A beam test data (2016)

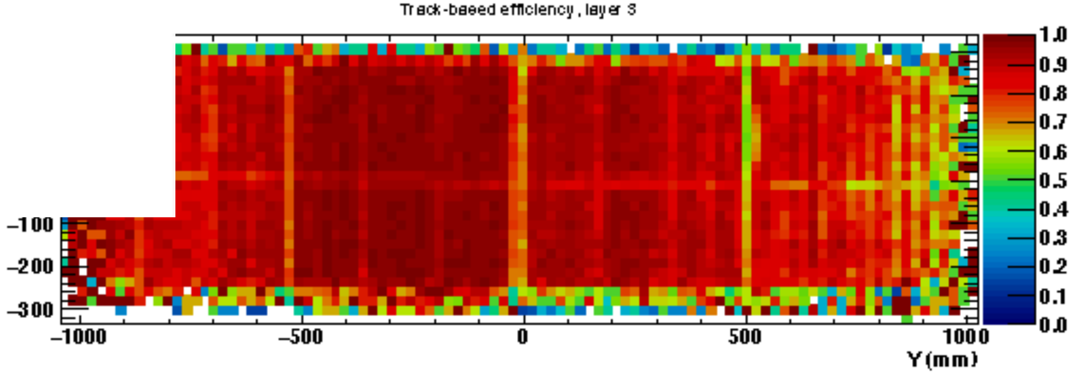


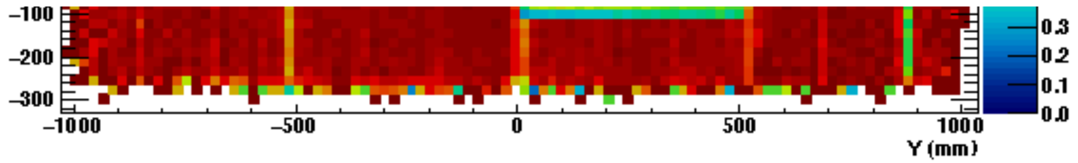


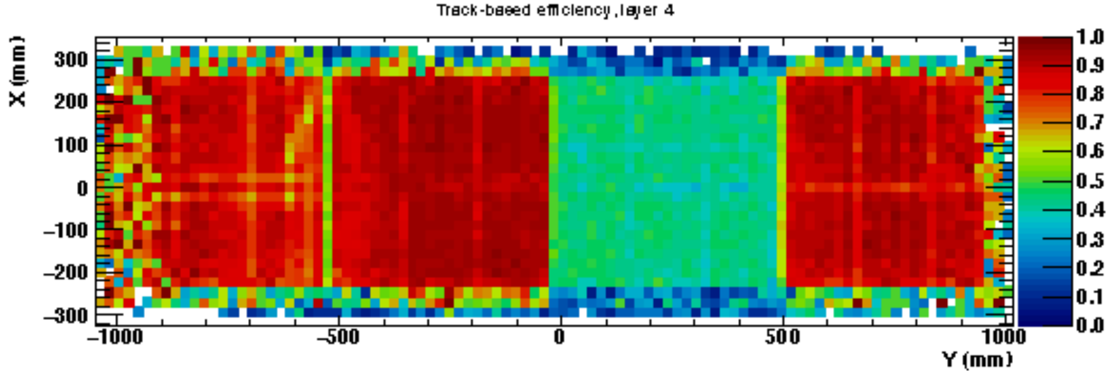
- Event display works "out of the box" with arbitrary layout/geometry
- I had not looked at the latest display with Hall A data before a few minutes ago… seems to work perfectly

un 2811, Jan. 2021)







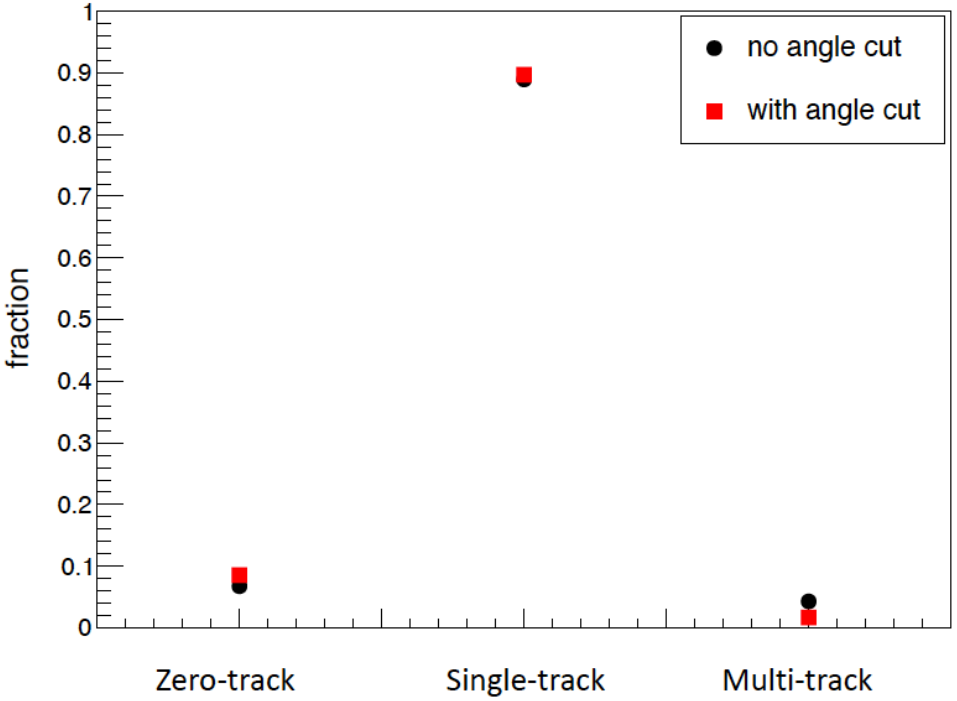


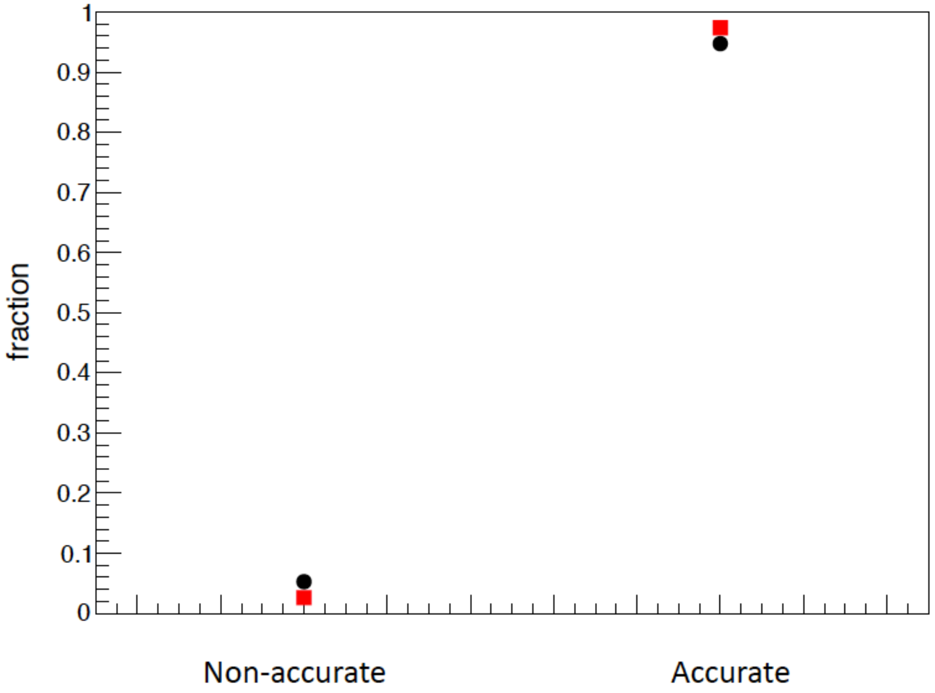
- Known issues in this run include an HV trip.
- Spurious effects near module edges 0in efficiency calculation eliminated with less-biased efficiency calculation

Simulated high-rate tracking (SBS GEP experiment)

Angular cuts using constraint points

- Tracking efficiency with and without the angular cut, at 20% bg of GEP case
- After additional cut for multi-track events
- Accuracy only for single-track case





~90% track reconstruction efficiency and ~97% "accuracy" already achieved at 20% of full GEP luminosity (equivalent to ~100% of expected background/occupancy for GMN run group)

Fast Track-finding Algorithm (Weizhi Xiong)

Performance and results

Single track efficiency [%]

	0% bg	10% bg	20% bg	50% bg
Old	97.2	93.4	89.6	75.3
new	97.0	92.3	88.5	73.4

Single track accuracy [%]

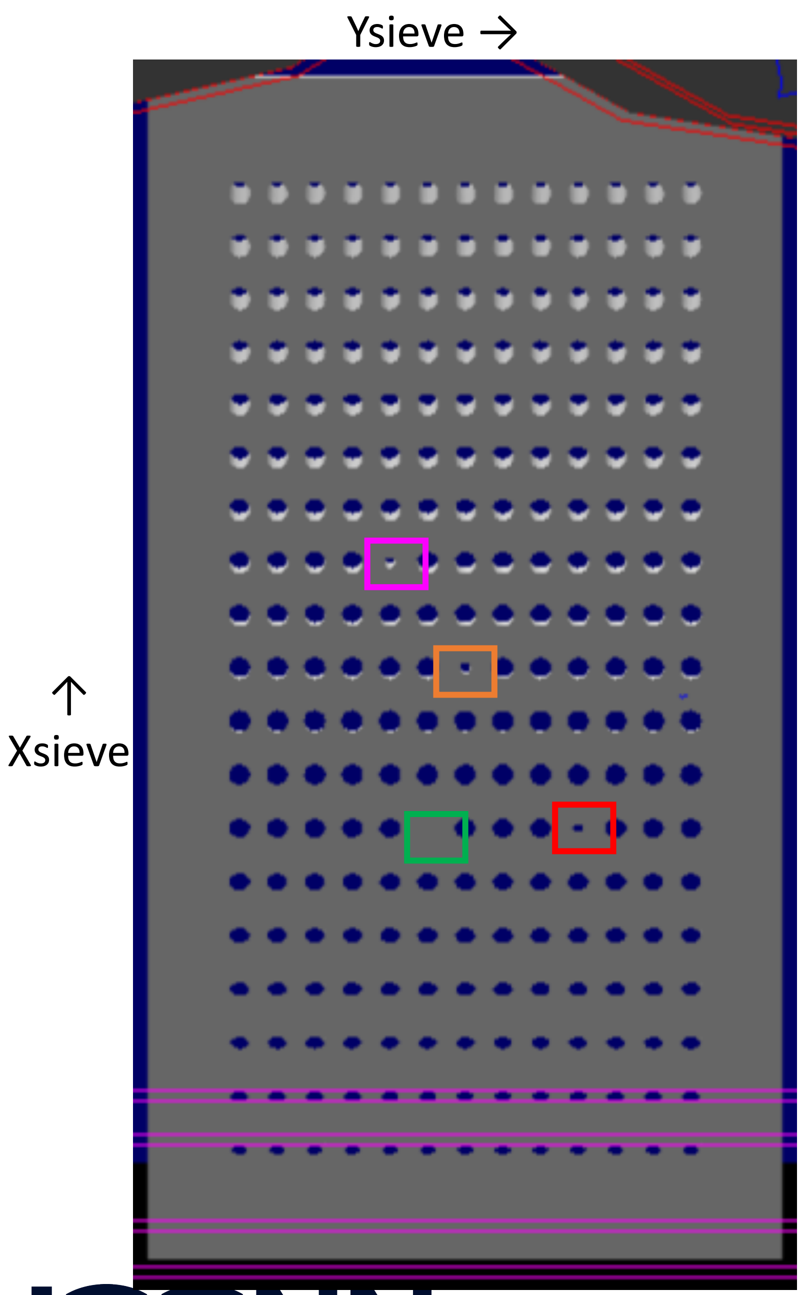
	0% bg	10% bg	20% bg	50% bg
Old	99.7	99.0	98.3	87.7
new	99.6	98.9	97.6	88.3

Time per event [ms]

	0% bg	10% bg	20% bg	50% bg
Old	0.05	2.6	73.6	40000 to 60000
new	0.06	0.1	0.2	0.6

- Compared to “brute force” track-finding used successfully at low occupancy (cosmics, Hall A beam test), preliminary new ”grid search” algorithm improves speed by ~10^5 at high occupancy without significant loss of track-finding efficiency or accuracy

Optics/Sieve



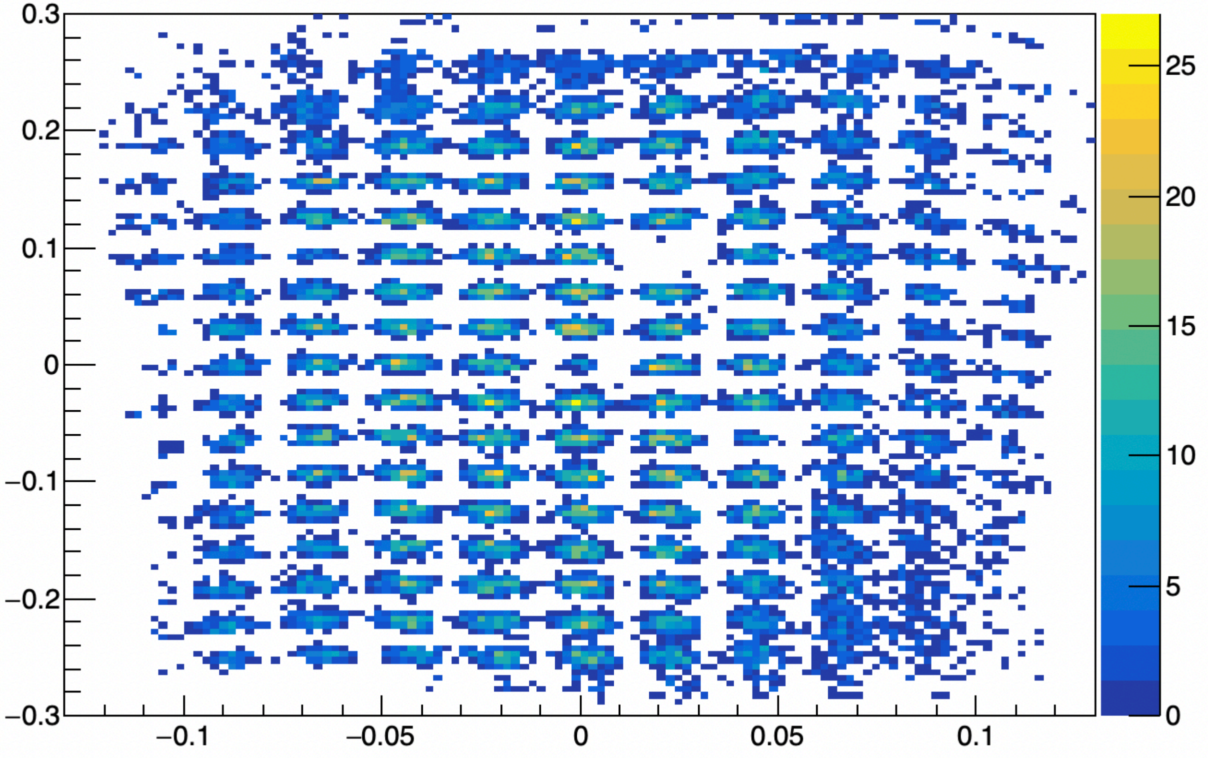
New sieve design:

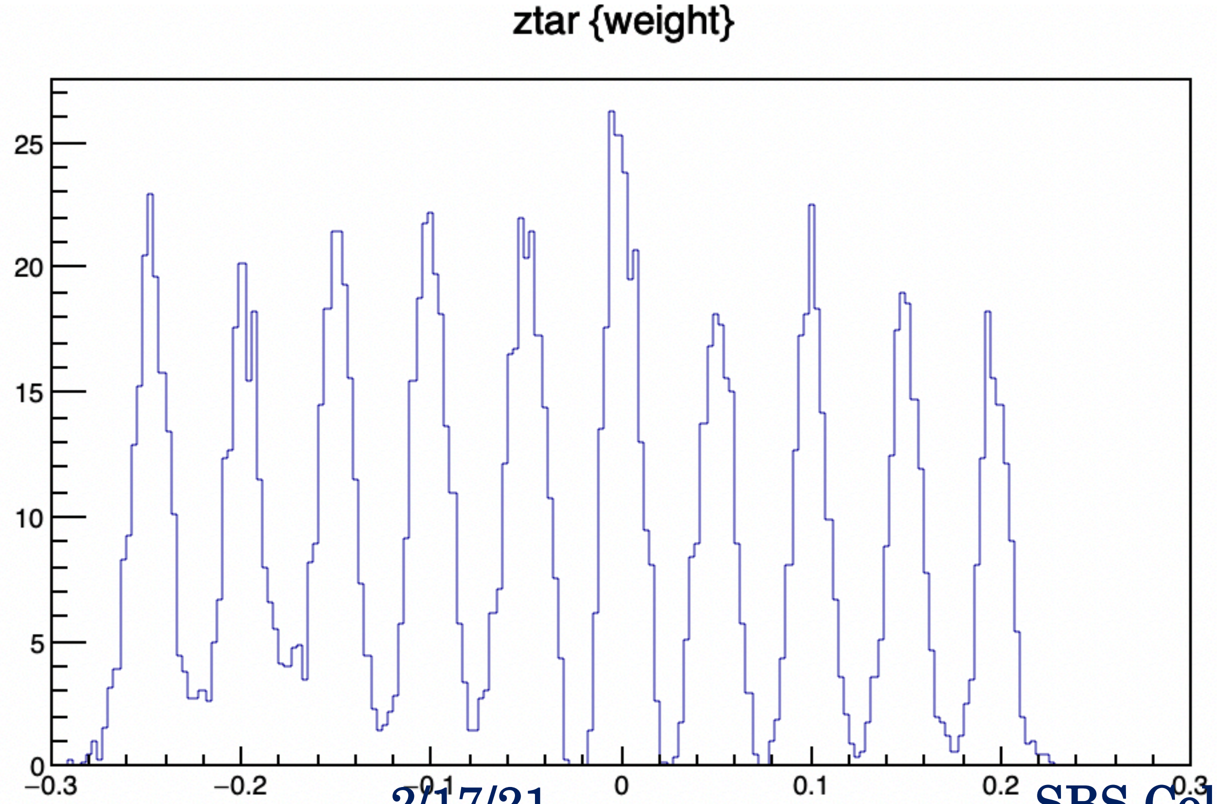
- 0.5” diameter holes
- Holes are spaced (on front of plate) by 1.25” in xsieve and 7/8” in ysieve
  - Holes are angled in xsieve (see below)
  - no angling of holes in ysieve
- gridding 13x19 (ysieve x xsieve)
- Red, orange, and pink squares (at left) are for half diameter holes
- The green box at left is missing a hole entirely
- The orange box shows the central hole

Angles in xsieve:

- Angled to a point at 1.372m from the front face of the sieve
- Θ=atan(xSieve/1.372m)

- Sieve and zTarget shown after all event selection cuts
- Q2=3.5, BB at 1.8m, 32.5 deg





Cuts:

1. Initial cuts:
   - 1 track
   - 5 hits
   - |Xfp| < 0.55
   - X^2/dof <= 30

2. Sieve hole selection cuts on xpfp vs xfp and ypfp vs yfp

BigBite Sieve Slit Summary

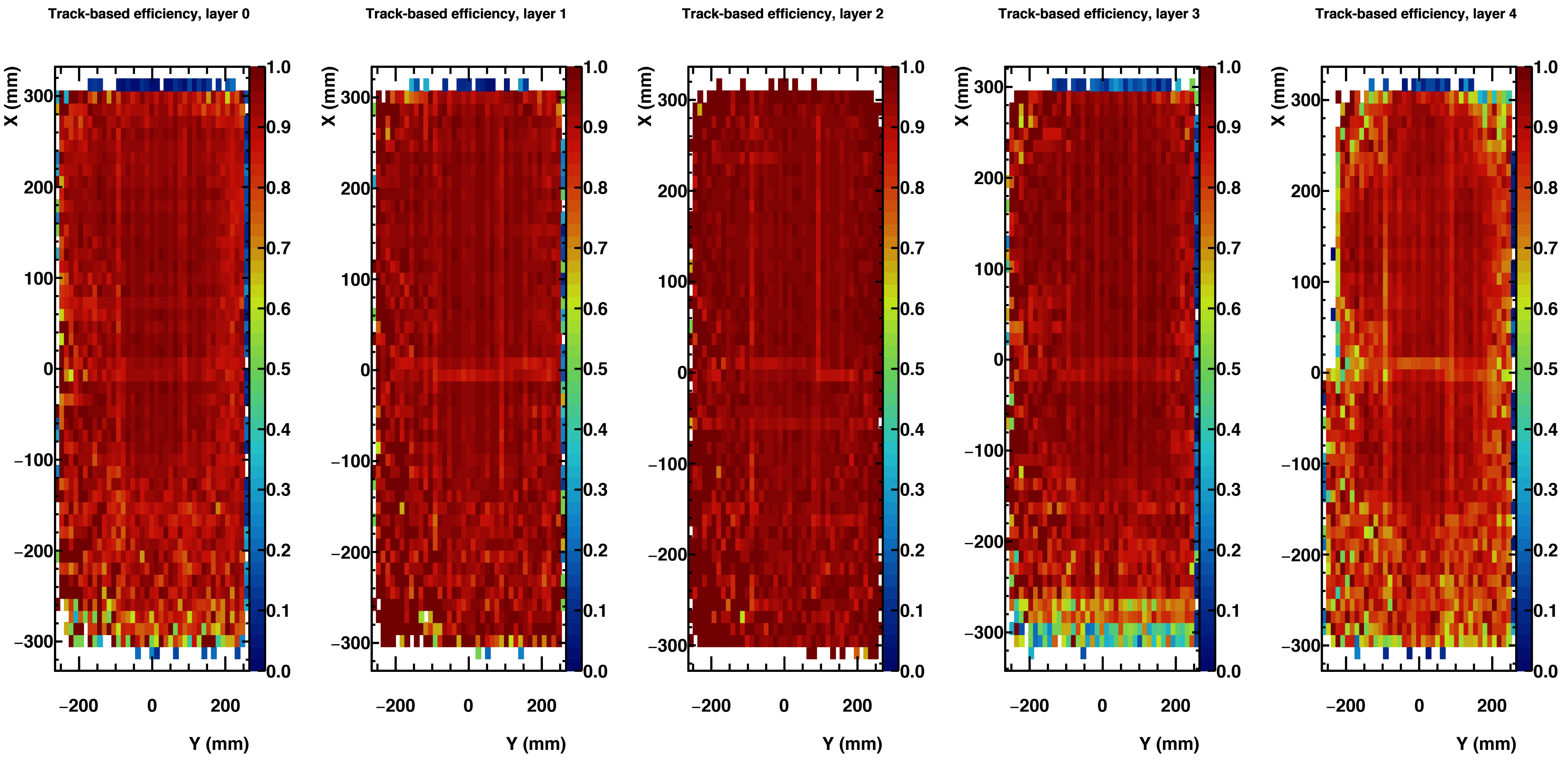
- Desired BigBite sieve design/geometry finalized back in December
- Holly put the geometry into CAD
- Bogdan, Holly, Andrew, Mark met last week to discuss manufacturing tolerances to meet SBS program requirements
- Final specifications sent to Robin on Feb. 9, 2021

Summary and Conclusions

- Software effort faces some challenges (expert manpower spread a little thin) but is on track for readiness well before beam.
- We need more input from subsystem leads and (at least occasional) representation and reporting of certain subsystems at our software meeting
- Performance of the event reconstruction algorithms needed for GMN/GEN-RP/nTPE/WAPP is already tested and demonstrated to be sufficient up to about 200-300% of the expected worst-case background level in the experiment, in terms of both speed and accuracy/resolution.
- Strong core software working group led by UConn with good support from JLab/Hall A and many outstanding contributions from collaborating institutions.
- Questions?

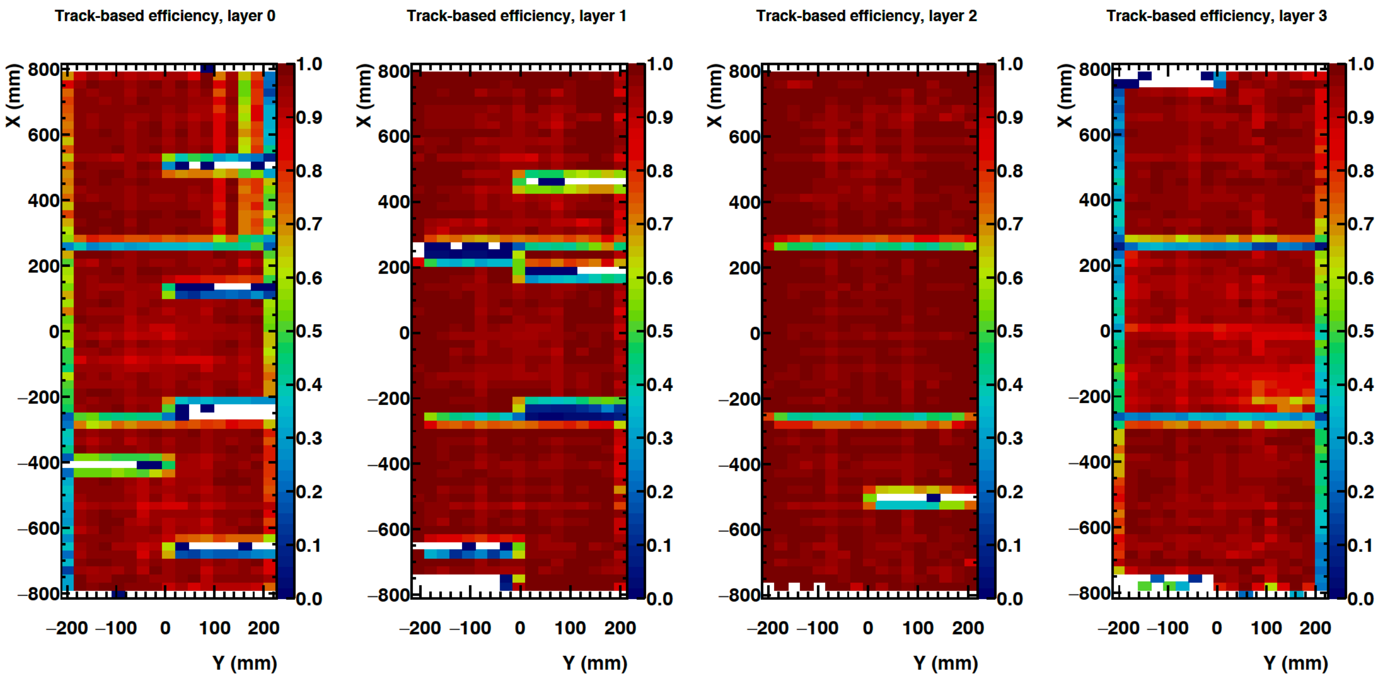
Backup Slides

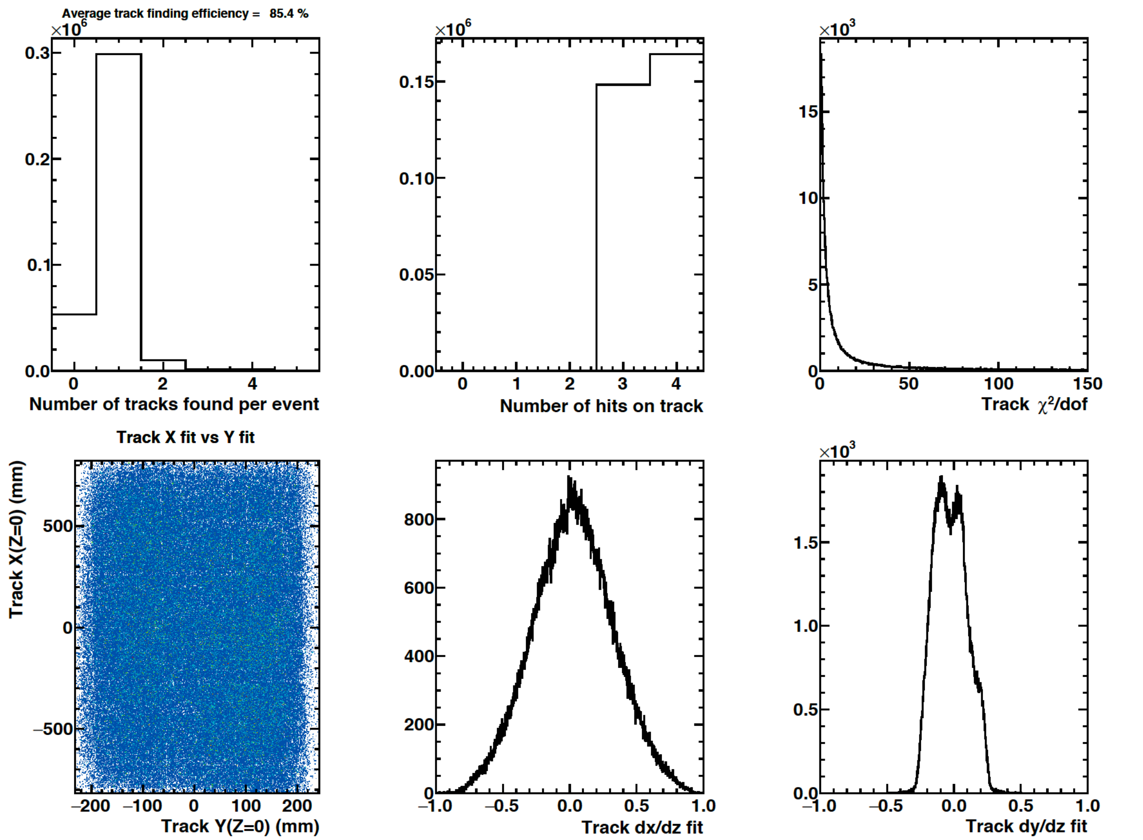
Hall A Test, 2016: Local, Track-Based Efficiency

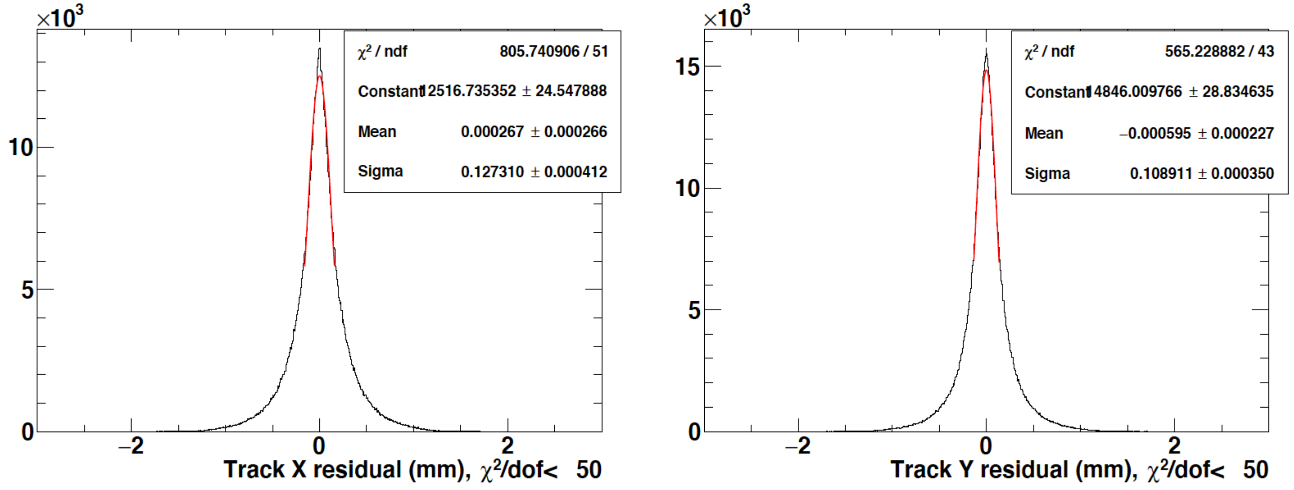


Track-based efficiency is defined as the probability that a hit occurred on a module within some maximum distance from the projection of a track fitted to all the other modules

Tracking Results: INFN GEM performance (Cosmic Run 3805, 2018)

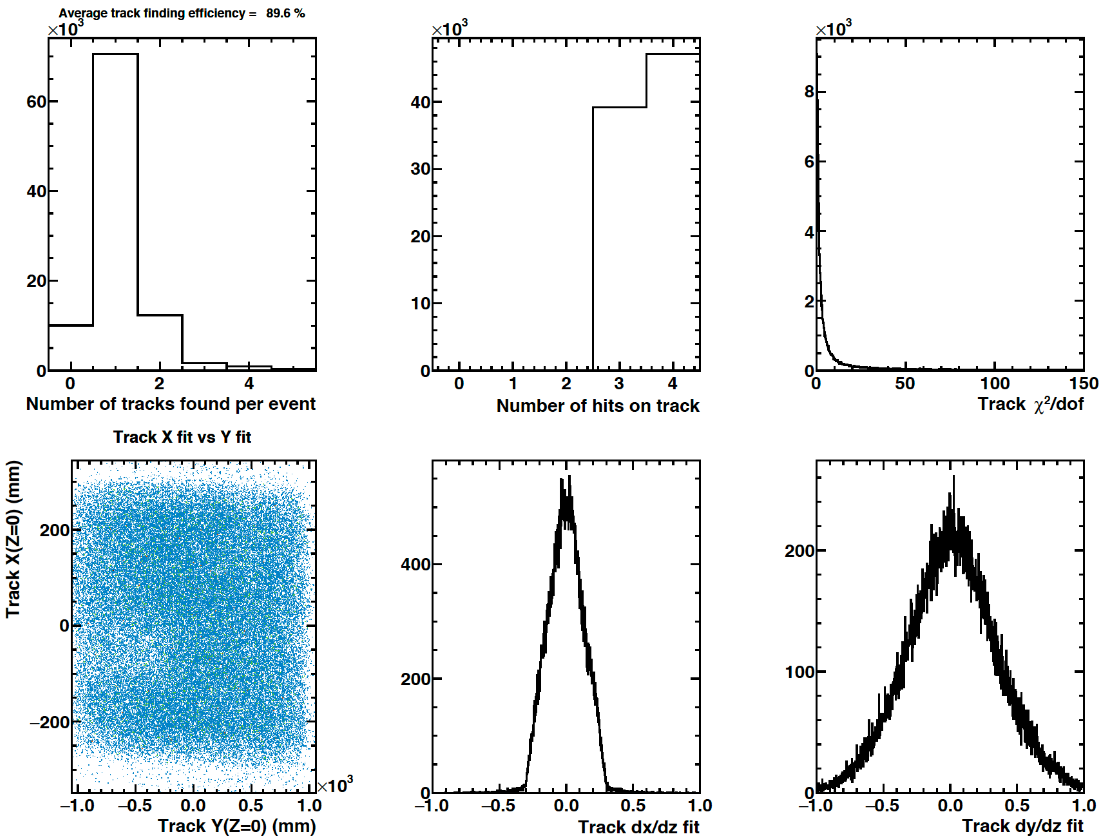


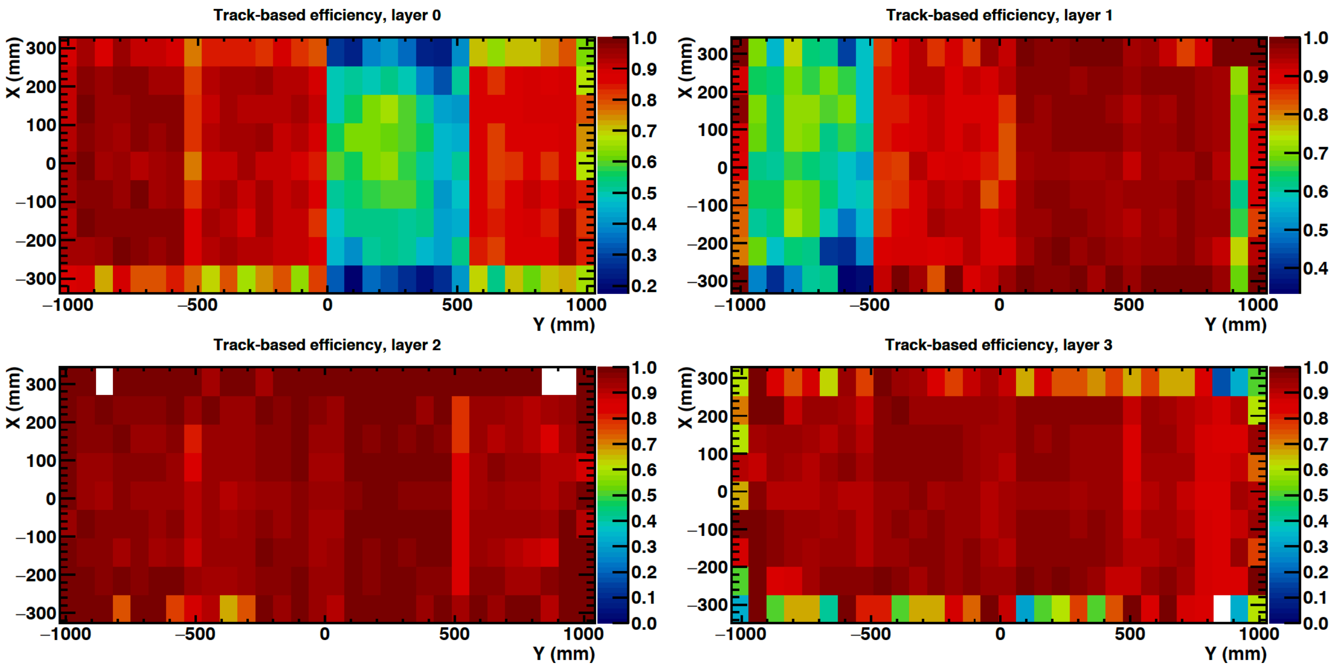


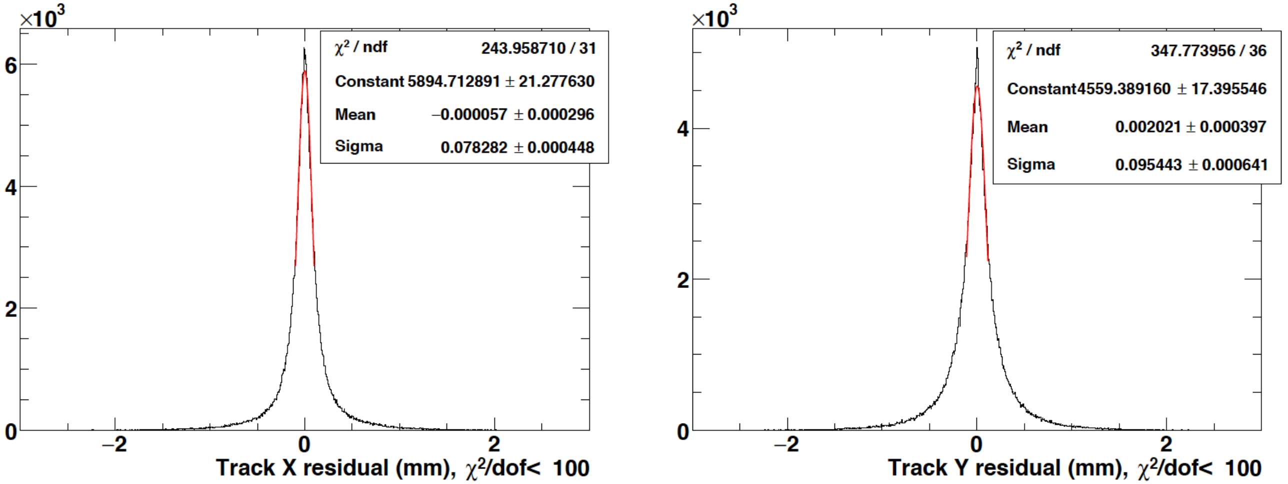


- Local efficiencies typically above 95%
- Spatial resolution from tracking residuals ~110-130 micron
- 4-layer track-finding efficiency of 85% (not corrected for effects of dead areas)
- Optimal arrangement of layers and selection of best modules will increase efficiency

UVA GEM 4-layer performance w/cosmic rays 2020 (pre-COVID)



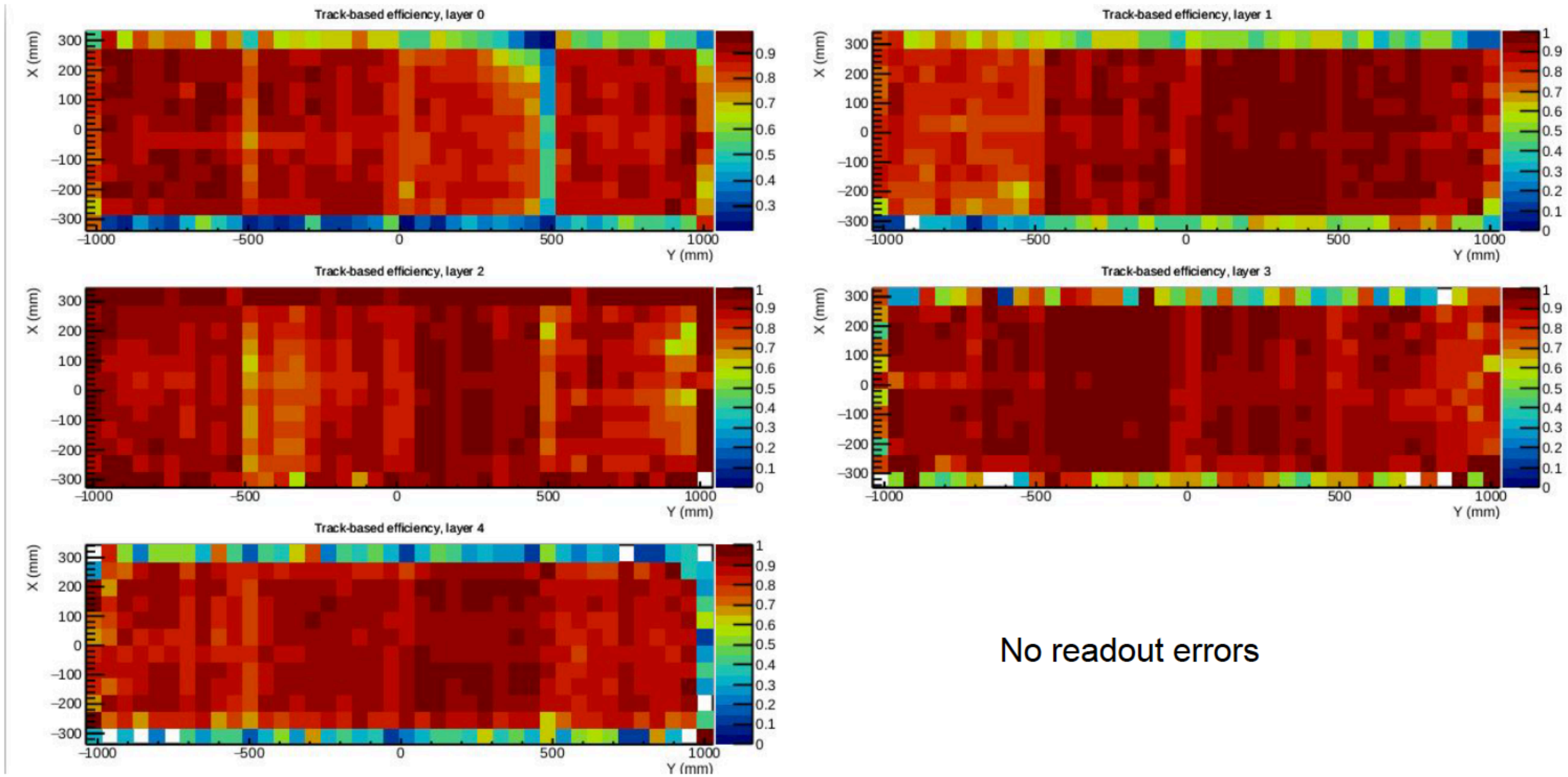




- Except for two modules with known lower gain at operating HV, all modules 95% efficient
- ~90% overall 4-layer track-finding efficiency
- Spatial resolution ~78 (95) microns in X (Y)
- Results obtained before optimization of trigger latency, and correcting noise/grounding issues

UVA GEM 5-layer tests (Oct. 2020)

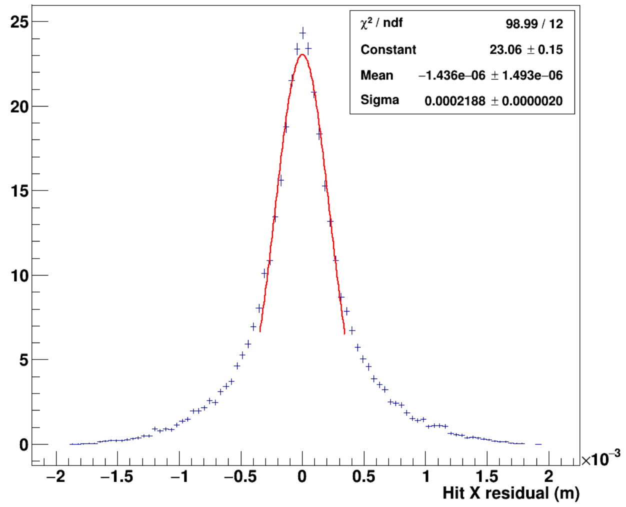
4050 V equivalent no configuring APVs

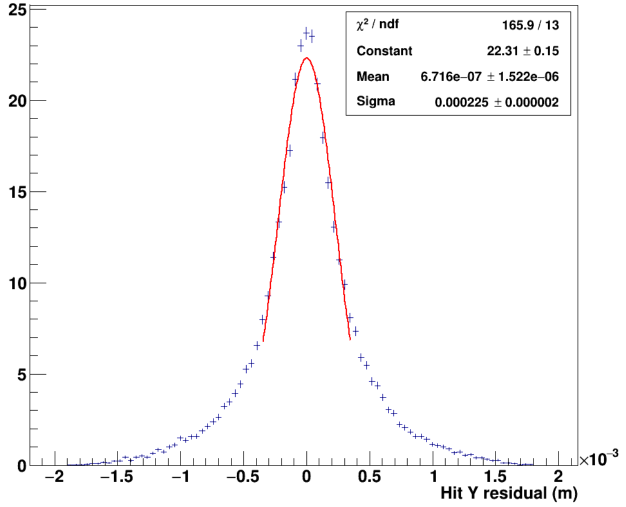


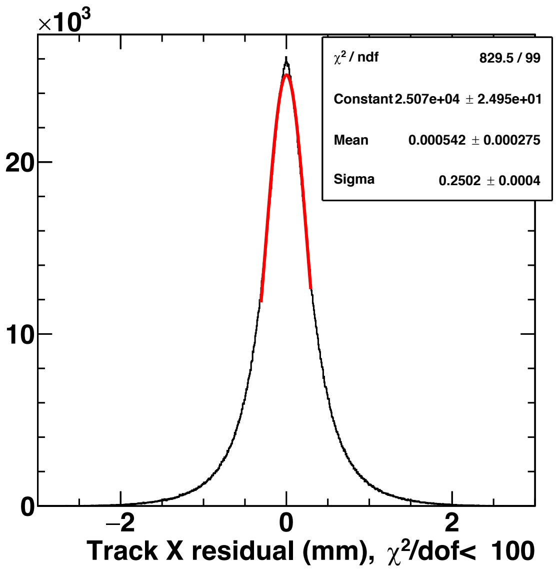
No readout errors

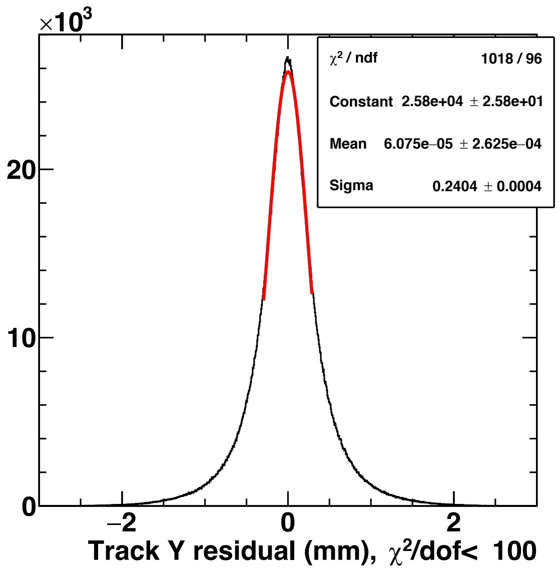
GEM reconstruction software in use for rapid analysis of cosmic ray UVA GEM commissioning data: currently underway with 5 layers/20 modules

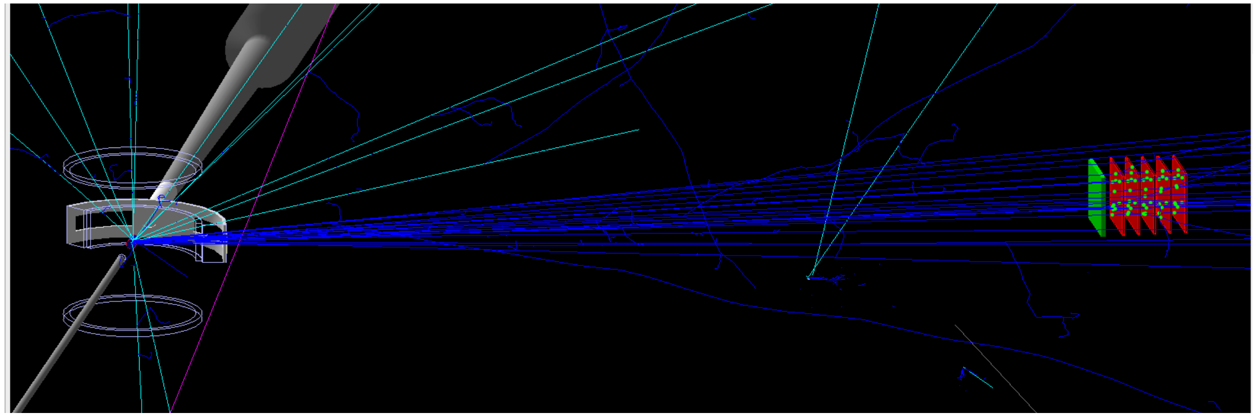
Hall A Test, 2016: Spatial Resolution



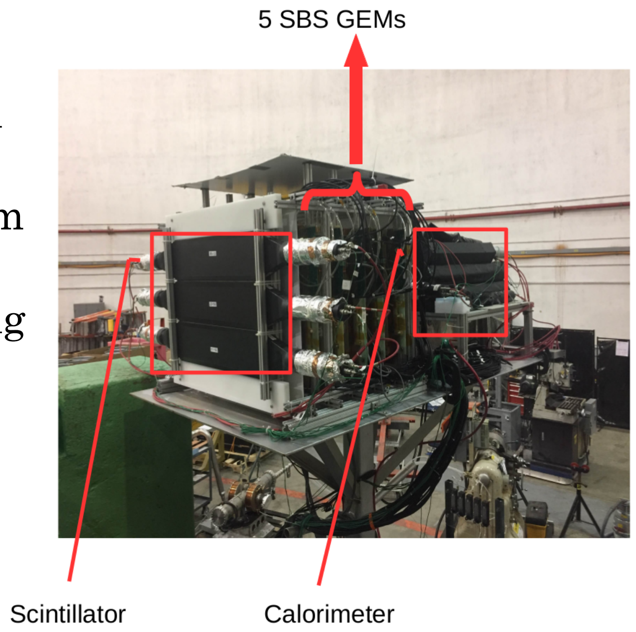








- 5-layer UVA GEM test carried out during Hall A DVCS in 2016
- 6.4 GeV @5 uA on 15-cm LH_2 target
- ~1-2% occupancy during test

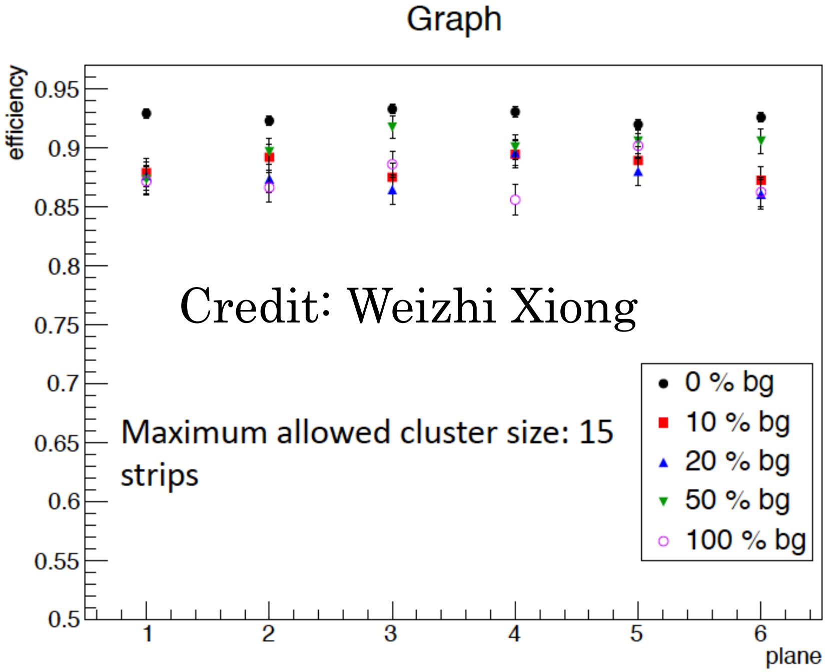


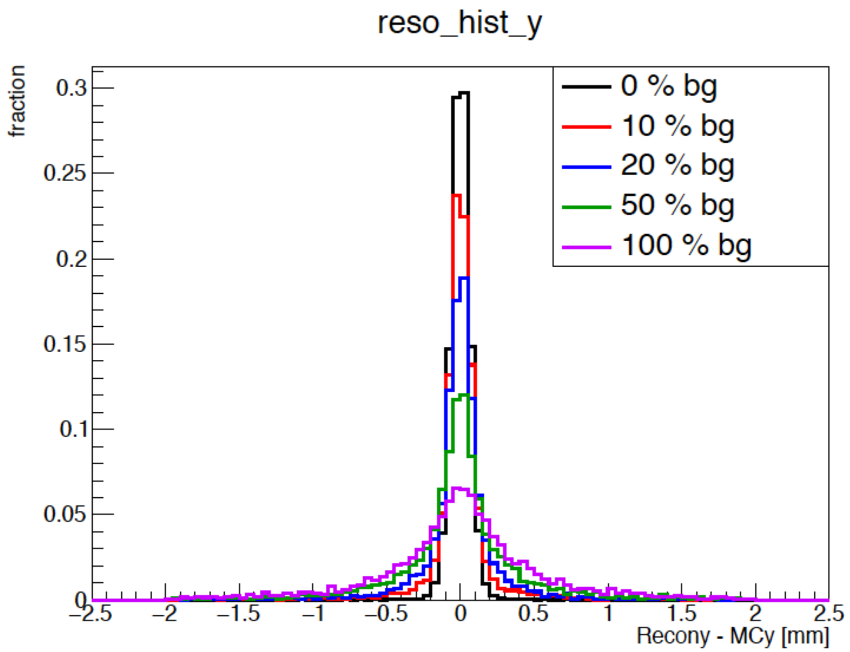
- Comparing real (top left) and simulated (top right) tracking residuals using equivalent definitions shows that the spatial resolution during this test was dominated by multiple scattering.
- Most of the tracks through the GEMs were electrons with energies ~150-1100 MeV.

Simulated high-rate tracking (SBS GEP experiment)

GEM efficiency and resolution

- GEM efficiency and resolution with the current algorithm
- GEM is counted as efficient if there is a reconstructed hit within +/- 5 strips (2mm) around the MC hit
- GEM resolution: the difference between the MC hit and its closest reconstructed hit within the +/- 5 strips range



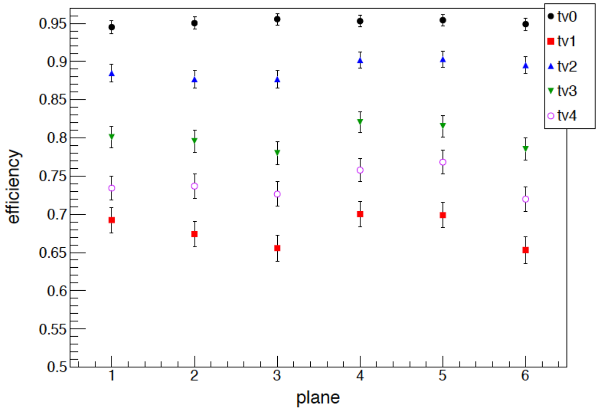


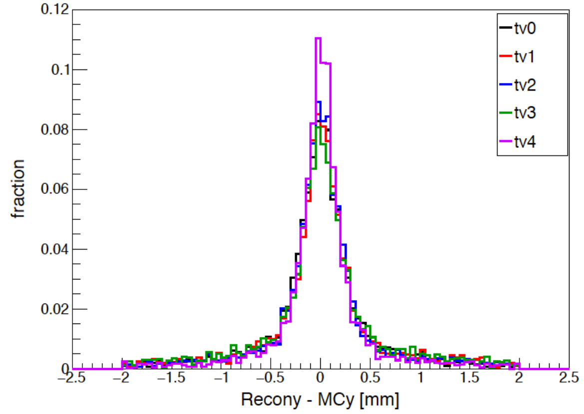
Results on GEM efficiency/resolution vs. background level with an early version of clustering algorithm

Simulated high-rate tracking (SBS GEP experiment)

Compare different time cuts

- All with 100% GEP background





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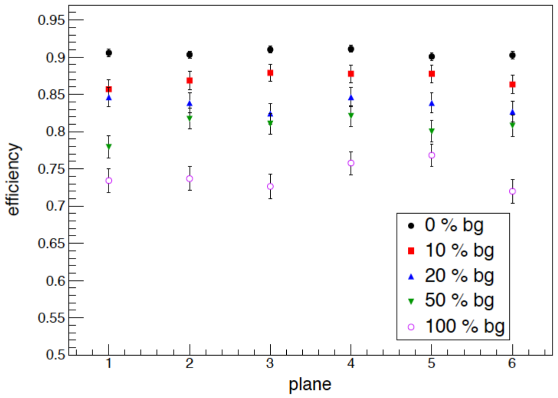
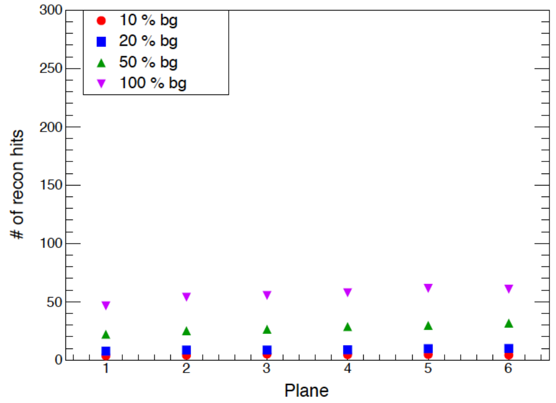
Effect of timing cut (tv4)

- cut the ratio of the first 3 samples: r1 = s1/s3, r2=s2/s3, accept if r1 < 1.3, r2 < 1.1 and r1 < r2 (the cuts were tuned a bit based on my SoLID studies)
- Number of recon hits drop by about 4.5 times compared to tv0, but efficiency reduced by about 20% at 100% bg





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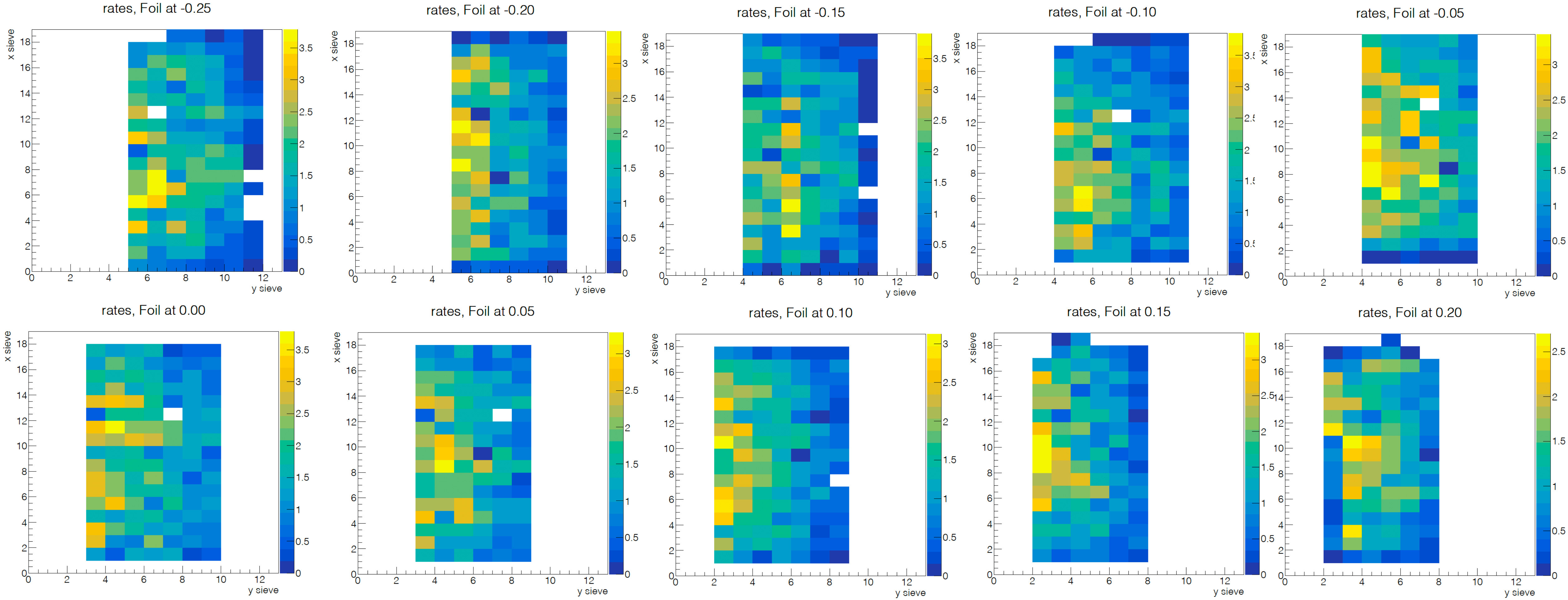
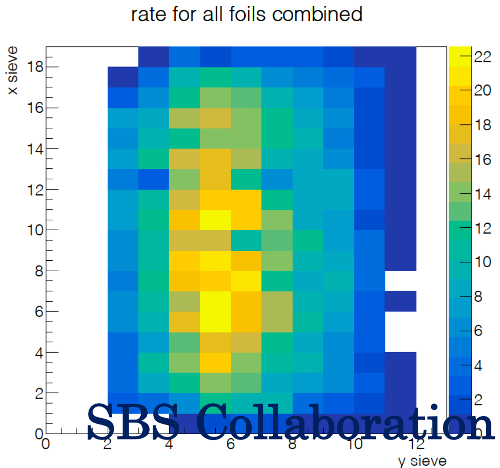
- Testing/optimizing cluster-finding efficiency/resolution at high background level (Weizhi Xiong, Syracuse):
- Left: Testing the effects of different timing cuts with background expected at full GEP luminosity
- Right: Testing "tv4" cut at different background levels

Backups

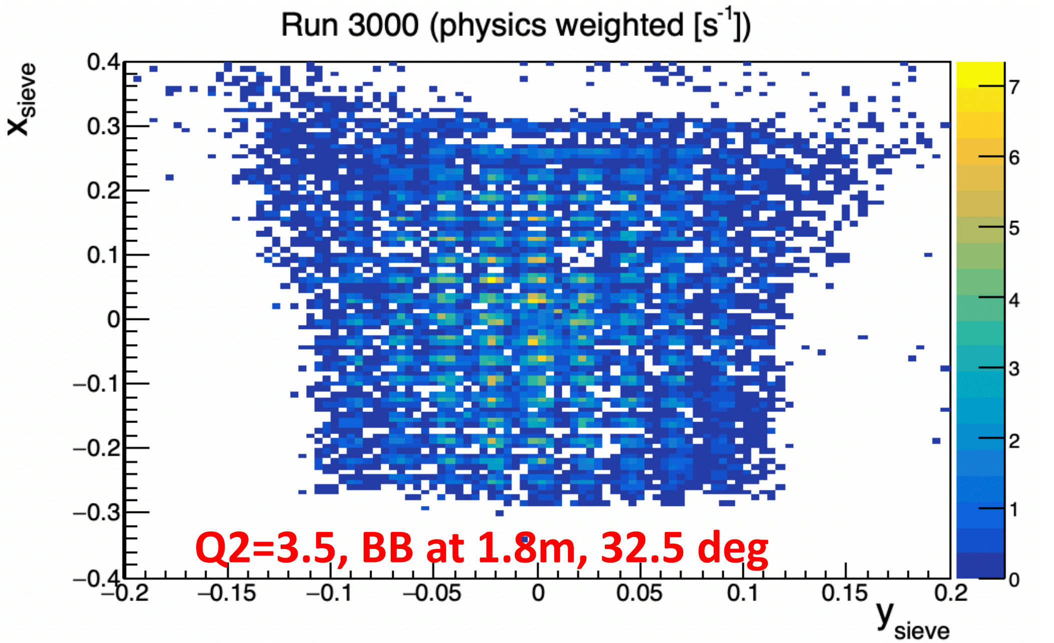


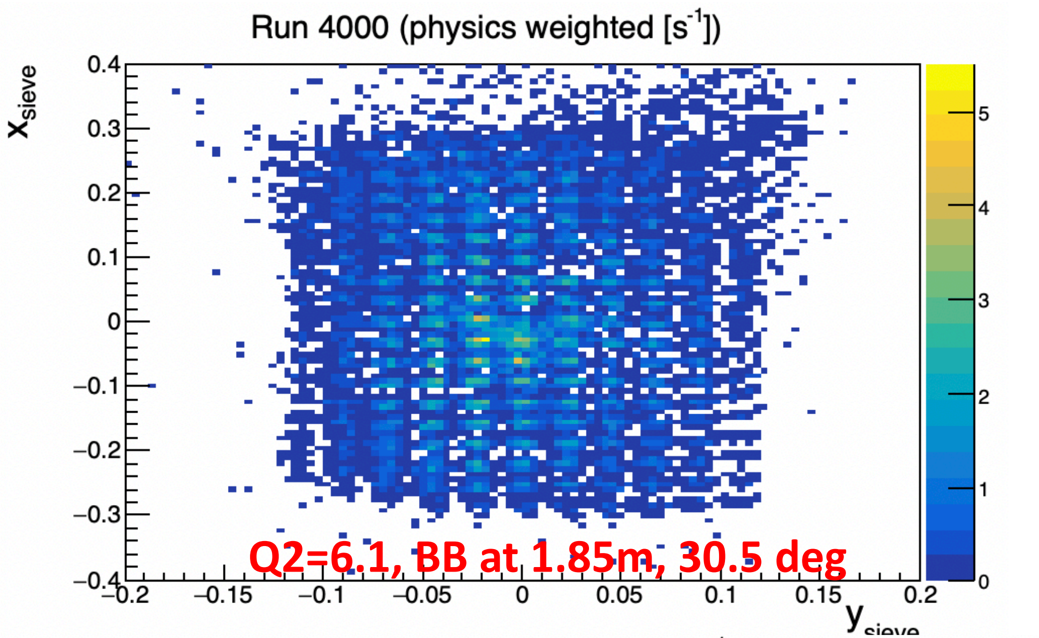


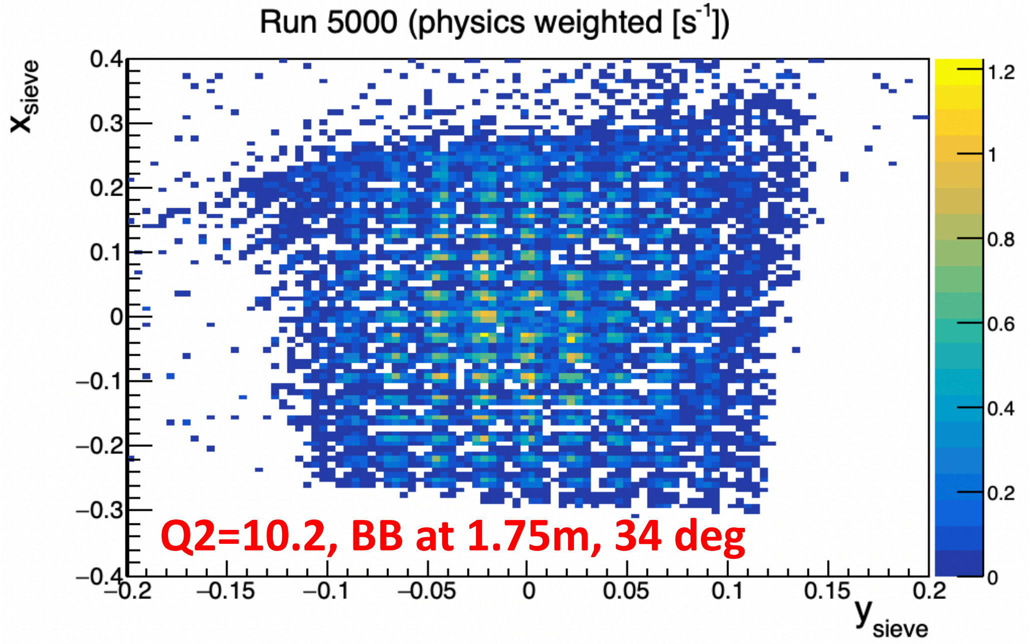
Rates in [Hz] per hole

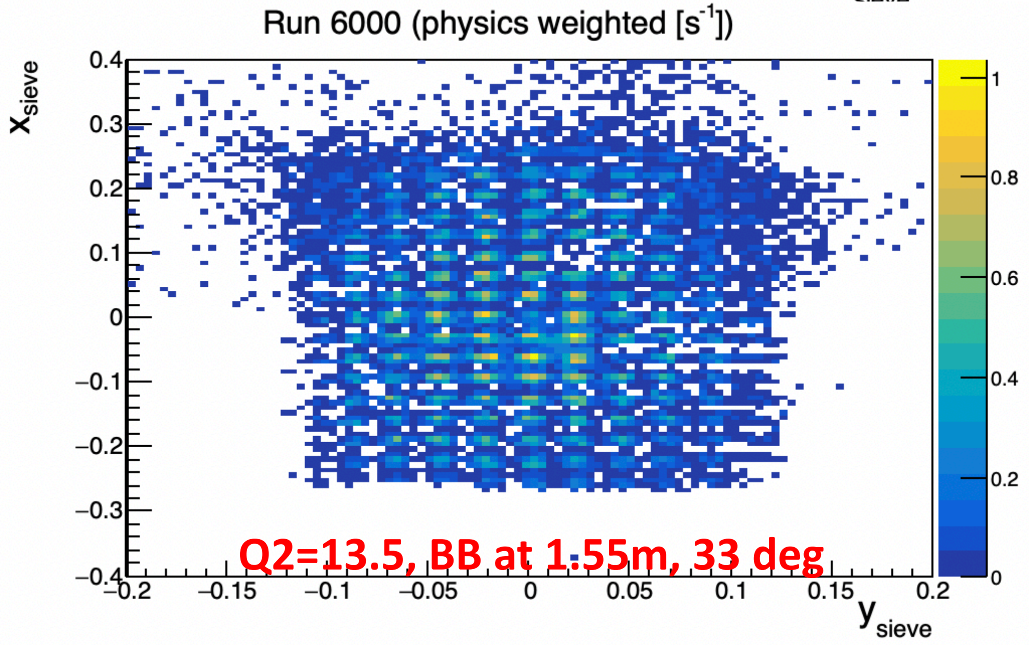
After all event selection cuts (total 1.6 kHz)

Q2=3.5, BB at 1.8m, 32.5 deg

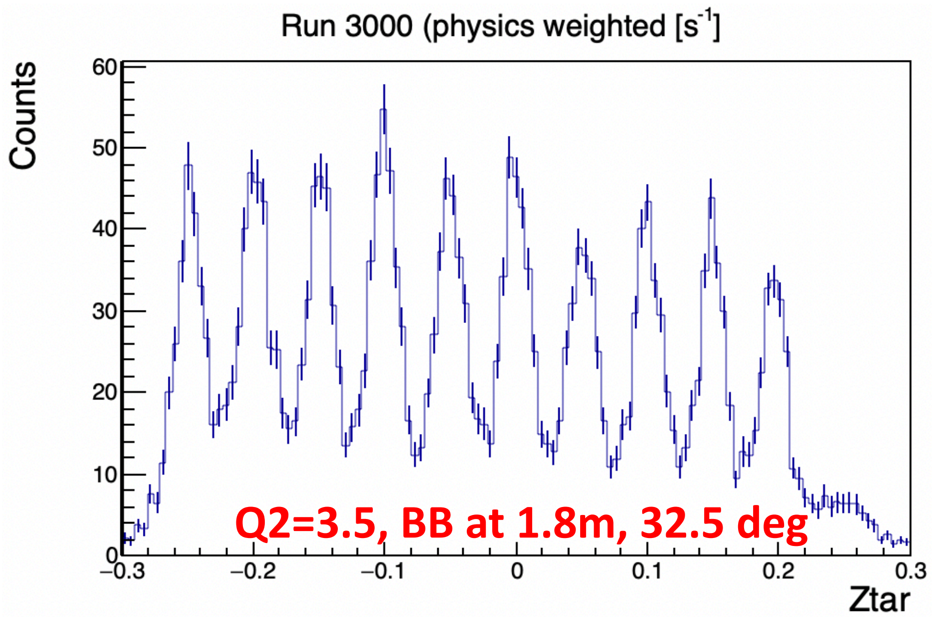


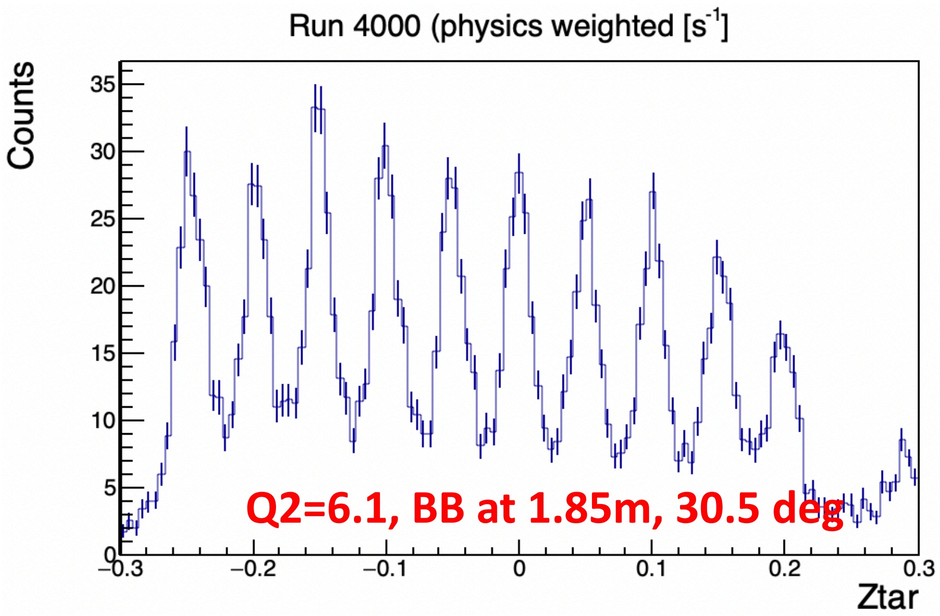


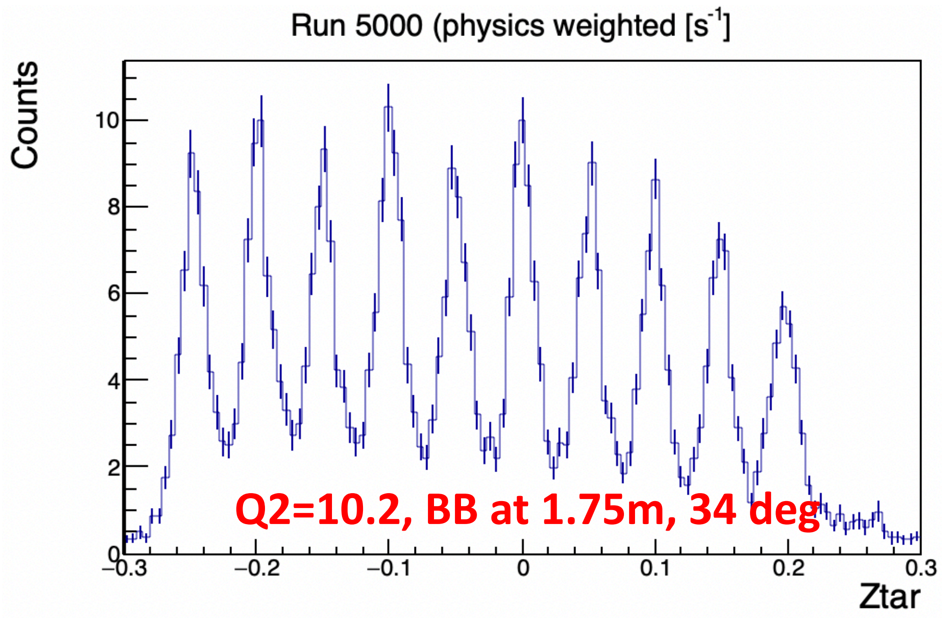


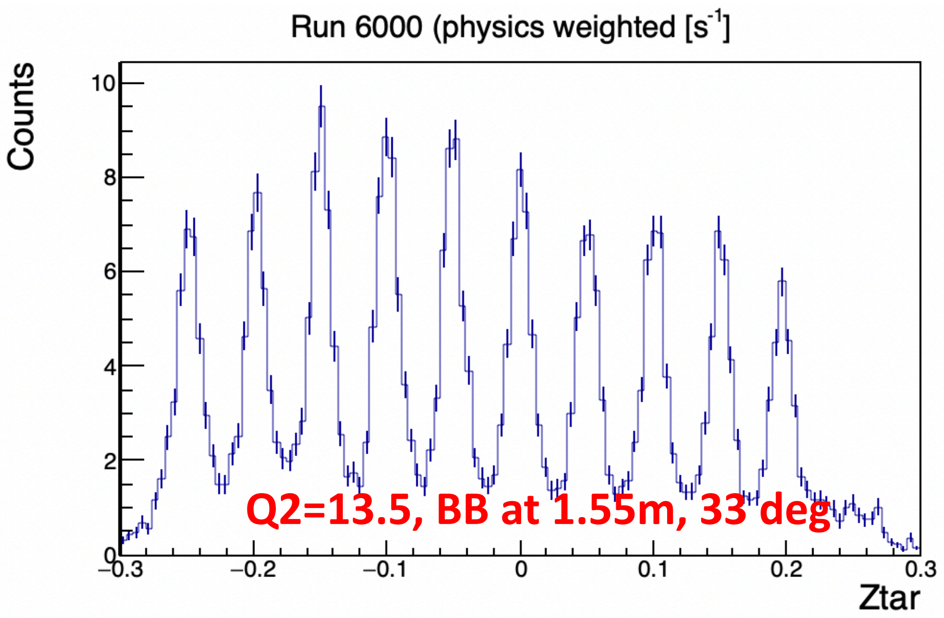


Sieve distribution with initial cuts and not final sieve hole selection cuts, aggregate for all foils









zTarget distribution with initial cuts and not final sieve hole selection cuts

Projected trigger rates for GEn-II

Single-Arm BigBite Trigger Rates Estimation for Gen-II Experiment:

Table 1: Summary of estimated single-arm BigBite trigger rates for elastic kinematics as well as for all the dominant background processes in GEn-II experiment for all the proposed Q^2 points with the threshold set at 2σ below the elastic peak. Q^2 is the central Q^2, E_e is the beam energy, θ_{BB} (d_{BB}) is the BigBite central angle (target-magnet distance), E'_e is the average scattered electron energy, "Thrsh." is the BigBite trigger threshold, and "Eff." is the trigger efficiency for quasi-elastic events. "El." is the quasi-elastic rate (the "signal" process). "Inel." is the rate due to inclusive inelastic electron scattering, and $\pi^{+/-/0}$ are the rates due to inclusive single pion production. We have assumed 60 μA beam current and 60 cm target length for all the simulations.

Q^2 (GeV^2)	E_e (GeV)	θ_{BB}/d_{BB} (deg)/(m)	E'_e (GeV)	Thrsh. (GeV)	Eff. %	Time to 50k ev.(h)	Trig. Rate. (kHz) El.	Inel.	π^+	π^0	π^-	Total (kHz)
1.46	2.2	40.0/1.50	1.2	0.90	87.5	1	1.2	21.1	0.5	16.4	0.5	39.7
3.68	4.4	34.0/1.50	2.1	1.64	85.5	15	4e-2	1.6	2e-2	1.4	1e-2	3.0
6.77	6.6	34.0/1.50	2.6	1.98	85.4	174	2e-3	0.3	6e-3	0.4	2e-3	0.7
10.18	8.8	34.0/1.50	2.9	2.19	85.5	1072	0.2e-3	0.1	3e-3	0.2	4e-3	0.3

Table 2: Same as Table 1, except for threshold has been set at 2.5σ instead of 2σ below the elastic peak.

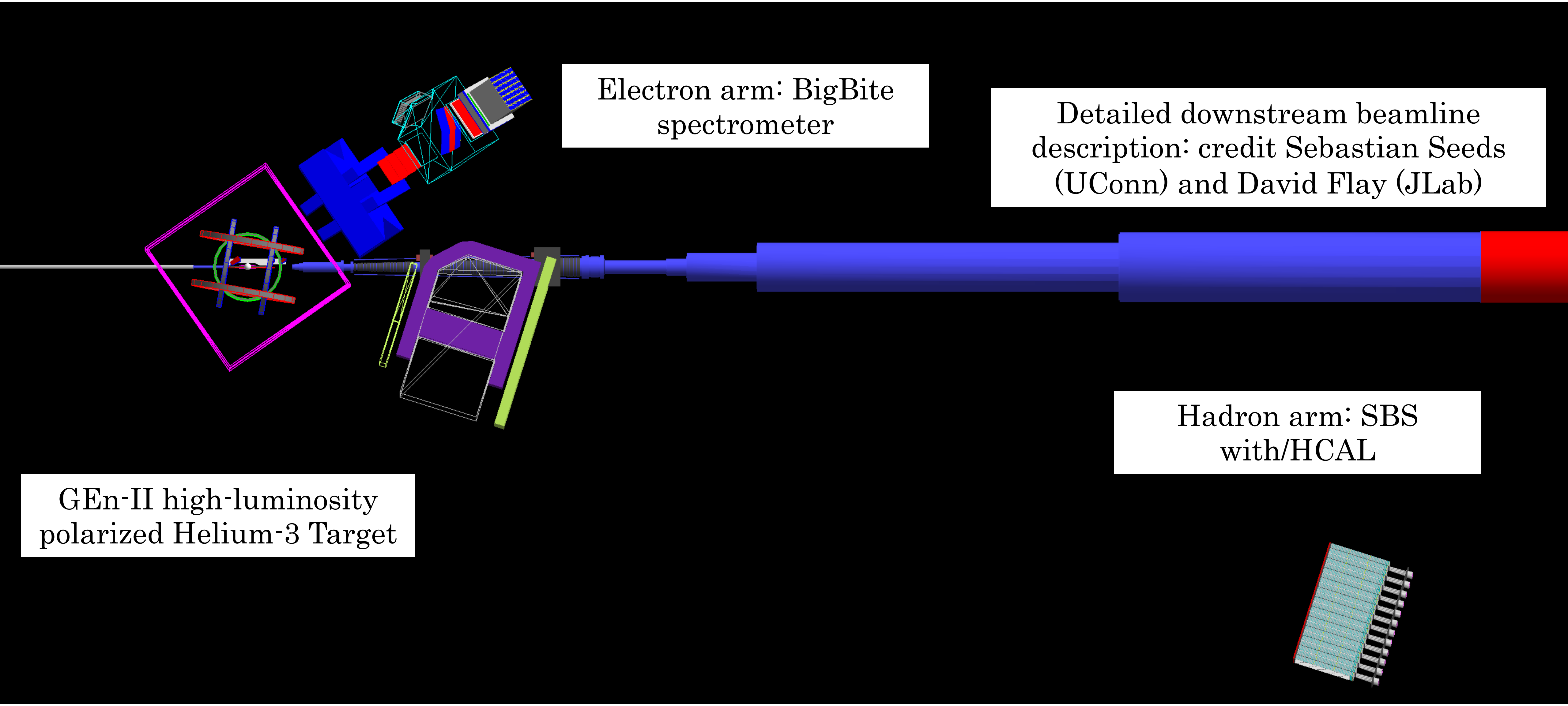
Q^2 (GeV^2)	E_e (GeV)	θ_{BB}/d_{BB} (deg)/(m)	E'_e (GeV)	Thrsh. (GeV)	Eff. %	Time to 50k ev.(h)	Trig. Rate. (kHz) El.	Inel.	π^+	π^0	π^-	Total (kHz)
1.46	2.2	40.0/1.50	1.2	0.83	89.9	1	1.3	31.9	1.0	37.3	1.3	72.8
3.68	4.4	34.0/1.50	2.1	1.52	87.5	14	4e-2	2.7	7e-2	3.5	7e-2	6.2
6.77	6.6	34.0/1.50	2.6	1.83	87.5	172	2e-3	0.6	1e-2	1.0	9e-3	1.6
10.18	8.8	34.0/1.50	2.9	2.0	87.5	1056	0.2e-3	0.2	9e-3	0.6	8e-3	0.8

Table 3: Same as Table 1, except for threshold has been set at 3σ instead of 2σ below the elastic peak.

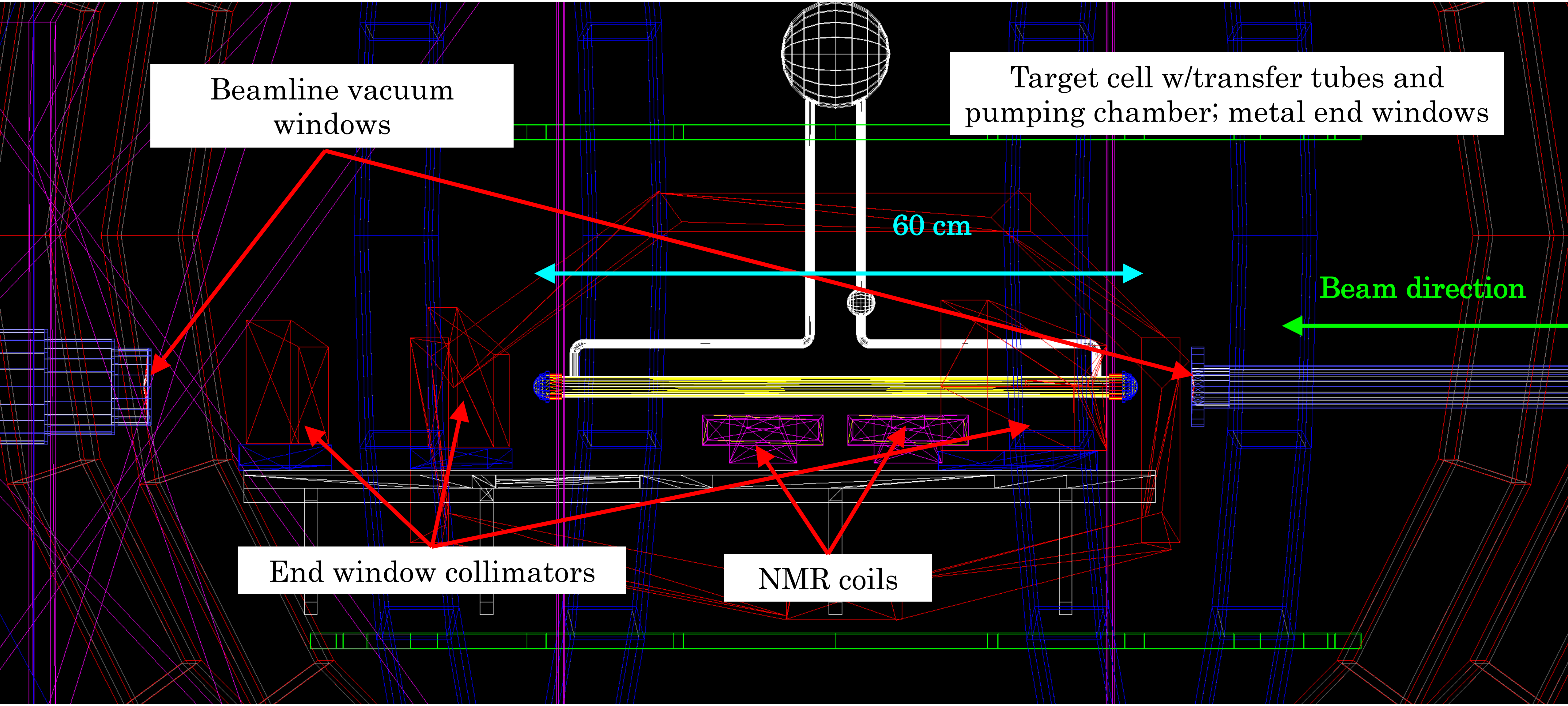
Q^2 (GeV^2)	E_e (GeV)	θ_{BB}/d_{BB} (deg)/(m)	E'_e (GeV)	Thrsh. (GeV)	Eff. %	Time to 50k ev.(h)	Trig. Rate. (kHz) El.	Inel.	π^+	π^0	π^-	Total (kHz)
1.46	2.2	40.0/1.50	1.2	0.77	91.2	1	1.3	42.4	2.4	70.6	2.9	119.6
3.68	4.4	34.0/1.50	2.1	1.41	88.8	14	4e-2	3.9	0.1	7.9	0.2	12.1
6.77	6.6	34.0/1.50	2.6	1.68	88.7	171	2e-3	0.9	6e-2	2.7	3e-2	3.6
10.18	8.8	34.0/1.50	2.9	1.82	88.8	1047	0.3e-3	0.4	3e-2	1.8	3e-2	2.2

- GEn-II trigger is based on the BigBite calorimeter signals (sum of shower and preshower)
- Threshold set ~2-3 σ below elastic peak
- Trigger rates are easily kept below canonical DAQ rate capability of ~5 kHz
- For the two higher-Q^2 points, rates allow use of lower threshold to achieve higher elastic efficiency
- Table at left is for an assumed beam current of 60 μA
- For the lowest-Q^2 points, the elastic rate is high enough to run at ~10X lower current
- Data rates/volumes much more forgiving compared to; e.g., GEN-RP (E12-17-004).

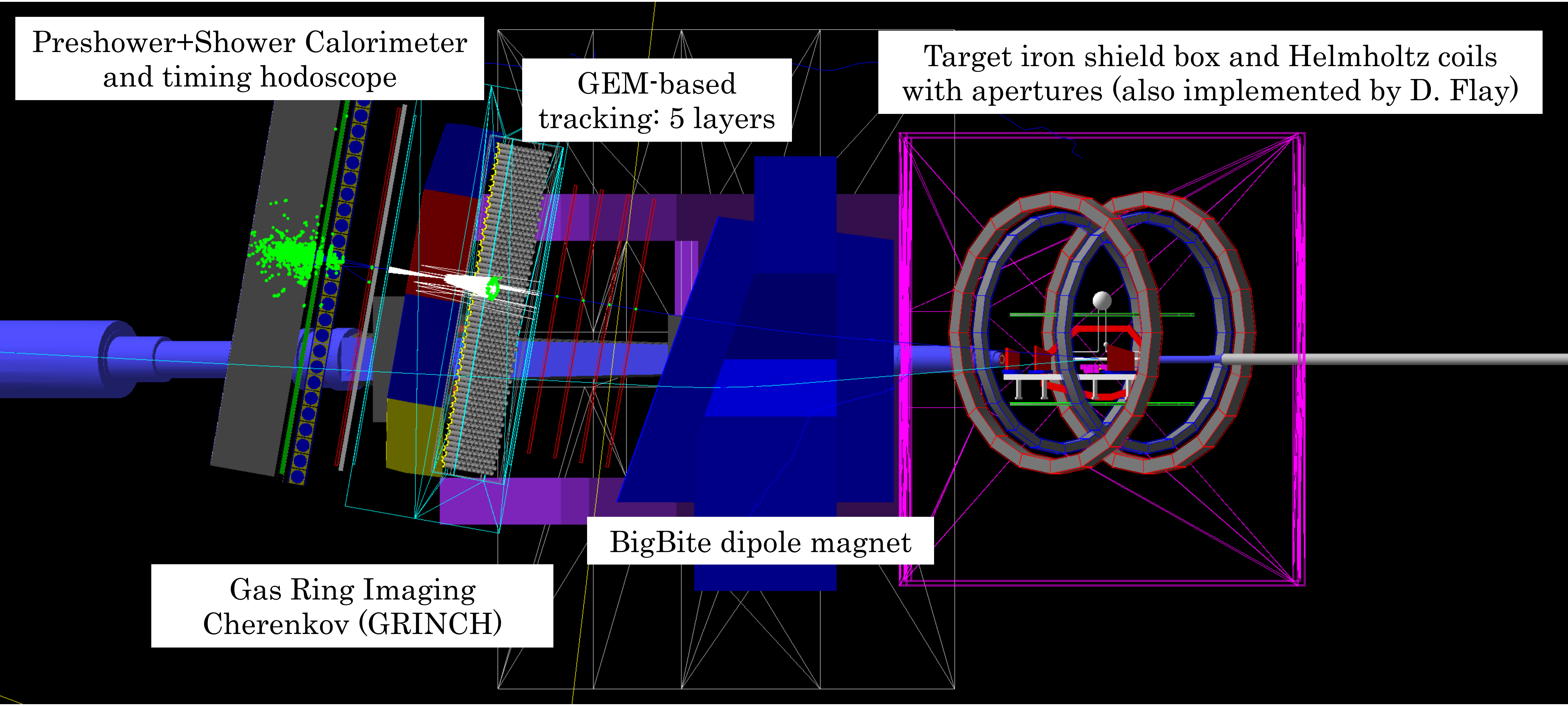
GEN in *g4sbs*: Overview



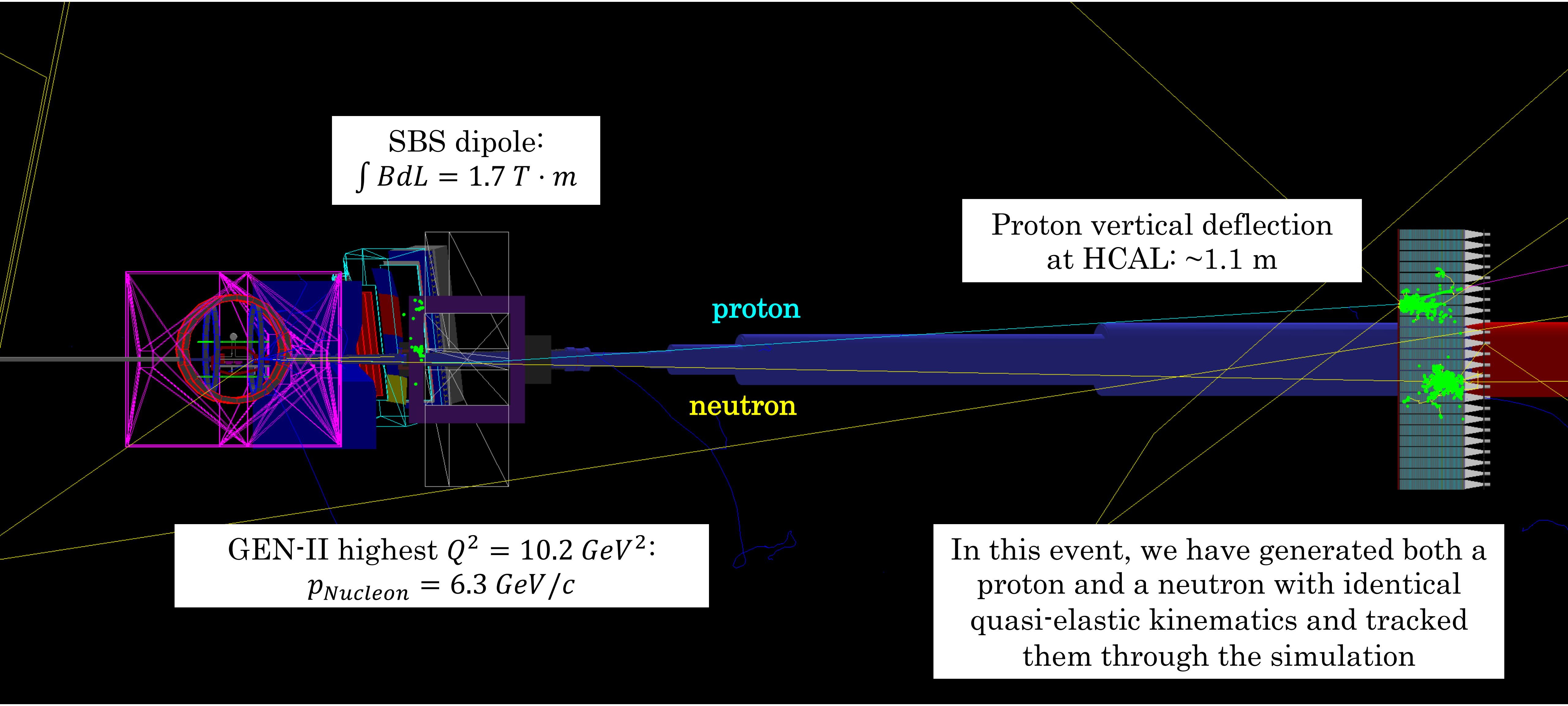
GEN target details: Credit David Flay (JLab)



BigBite Spectrometer in GEN (electron arm)



GEN simulations: nucleon charge ID



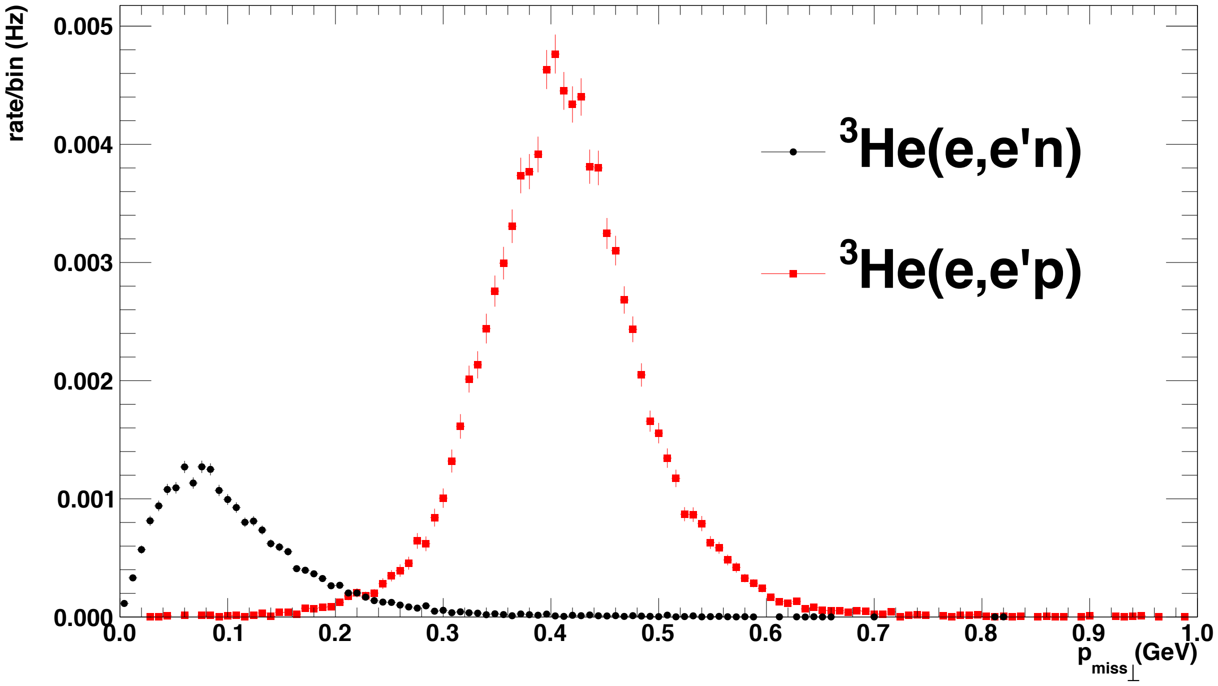
SBS dipole:
$\int BdL = 1.7\ T \cdot m$

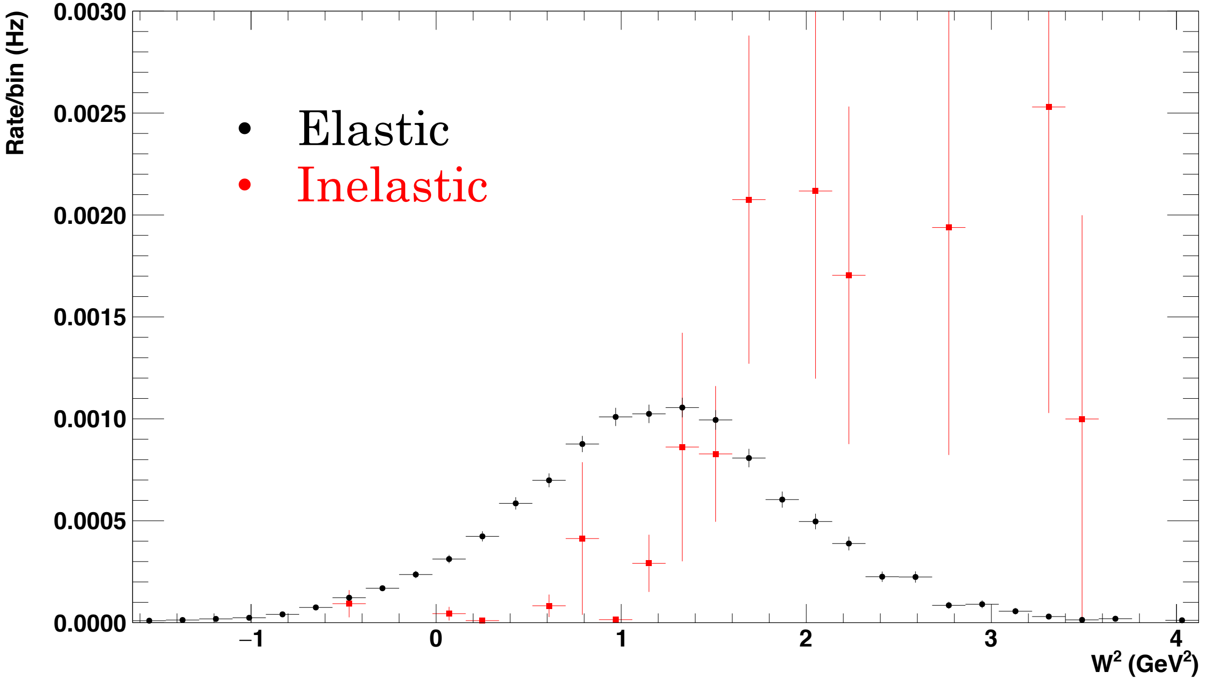
Proton vertical deflection at HCAL: ~1.1 m

GEN-II highest $Q^2 = 10.2\ GeV^2$:
$p_{Nucleon} = 6.3\ GeV/c$

In this event, we have generated both a proton and a neutron with identical quasi-elastic kinematics and tracked them through the simulation

Quasi-elastic Event Selection ($Q^2 = 10.2\ GeV^2$)





- *np* separation for quasi-elastics based on missing perp. momentum
- Expected contamination from quasi-elastic protons negligible for canonical cut of $p_{\perp} < 0.1$ GeV

- PRELIMINARY: For $W^2 < 1.6$ GeV², we estimate fractional inelastic contamination of $26 \pm 8\%$ (consistent with original proposal estimate of ~25%) assuming TOF resolution of 1 ns, after cuts.
- Inelastic asymmetry can be measured precisely and corrected for; with much higher statistics than elastic asymmetry

Kinematics to check:

E12-09-016 kinematical settings for 2.2, 4.4, 6.6, and 8.8 GeV beam energies

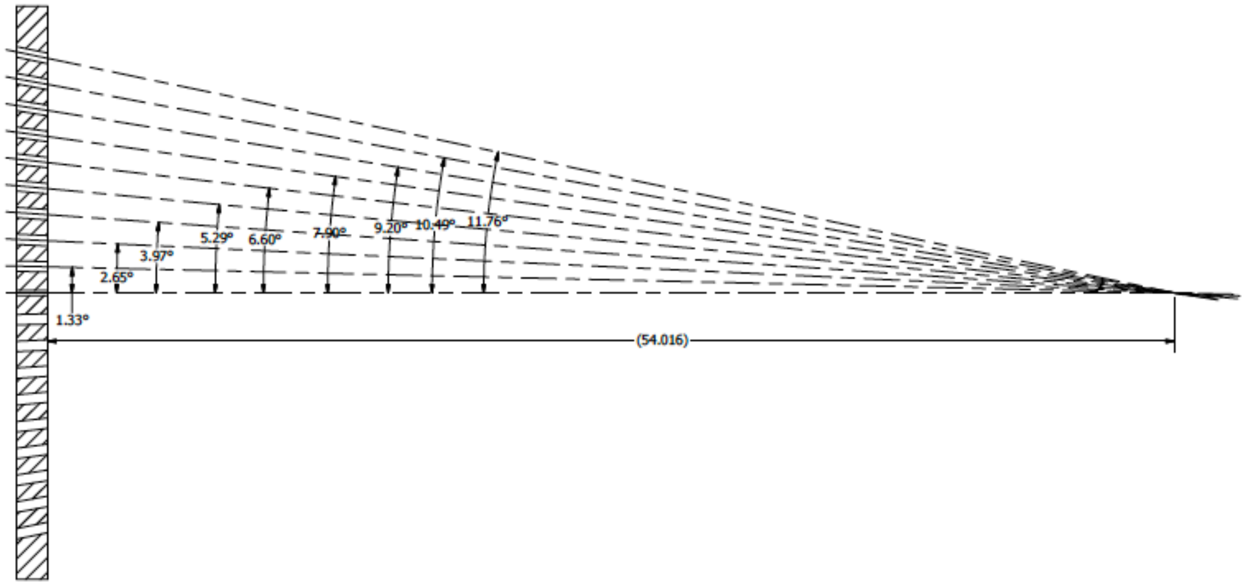
Q^2 [GeV^2]	θ_{BB} [deg]	d_{BB} [m]	θ_{48D48} [deg]	d_{48D48} [m]	d_{HCAL} [m]	
1.46	40.0	1.50	39.4	2.8	17	
3.68	34.0	1.50	29.9	2.8	17	2.7 kHz
6.77	34.0	1.50	22.2	2.8	17	
10.18	34.0	1.50	17.5	2.8	17	

*Rates shown:

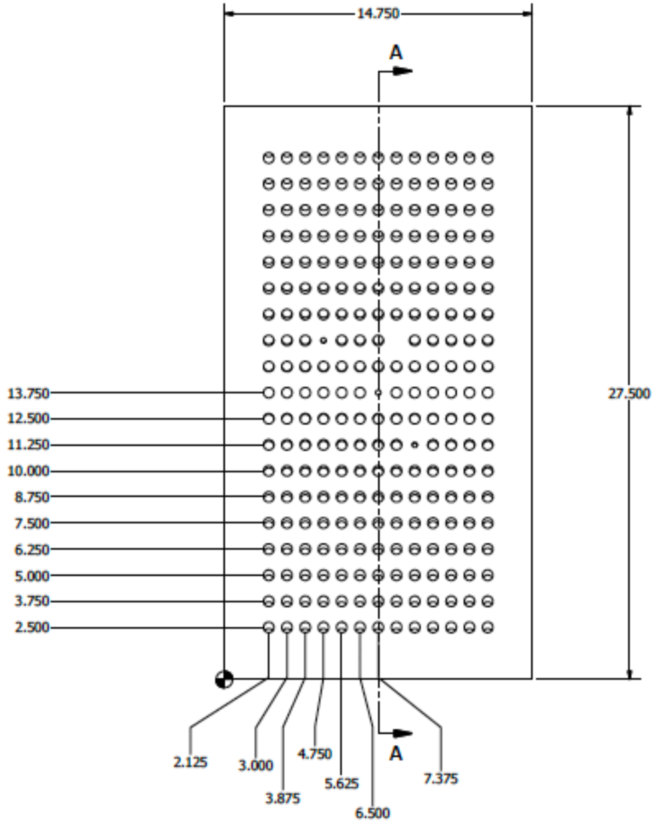
- Include all foils
- Include good electron track event selection
- Excludes xfp/xpfp and yfp/ypfp cuts for optimization (cut is about 65%)
- Assumes 60 uA

configuration	Q^2 (GeV/c)^2	E_{Beam} (GeV)	θ_{BB} (deg.)	θ_{SBS} (deg.)	d_{BB} (m)	d_{48D48} (m)	48D48 field integral (T·m)	Luminostiy (10^{38}/A/cm^2/s)	dHCal (m)	
GEN-RP	4.5	4.4	41.9	24.7	1.55	2.25	1.71	2.8	8.5	
WAPP		6.6	41.9	24.7	1.55	2.25	1.71	0.6	8.5	
2 (&TPE)	4.5	4.4	41.9	24.7	1.55	2.25	1.71	1.4	8.5	
3'	**6.1**	**6.6**	**30.5**	**24.7**	**1.85**	**2.25**	**1.71**	**2.8**	**8.5**	1.7 kHz
TPE	4.5	6.6	23.2	31.1	1.80	2.00			7.2	
1	3.5	4.4	32.5	31.1	1.80	2.00	1.71	0.7	7.2	2.8 kHz
4	8.1	6.6	43.0	17.5	1.55	2.25	1.65	2.8	11	
5	10.2	8.8	34.0	17.5	1.75	2.25	1.60	2.8	11	0.5 kHz
6	12.0	8.8	44.2	13.3	1.55	2.25	1.50	2.8	14	
7	13.5	11.0	33.0	14.8	1.55	3.10	0.97	2.8	17	0.4 kHz
			$\theta_{L\text{-}HRS}$							
8	6.06	4.4	61.1,64.3	14.8		3.10	1.71	0.93	17	
9	4.4	4.4	67.5,70.7 39.,42.	25.5		3.10	1.71	0.93	17	

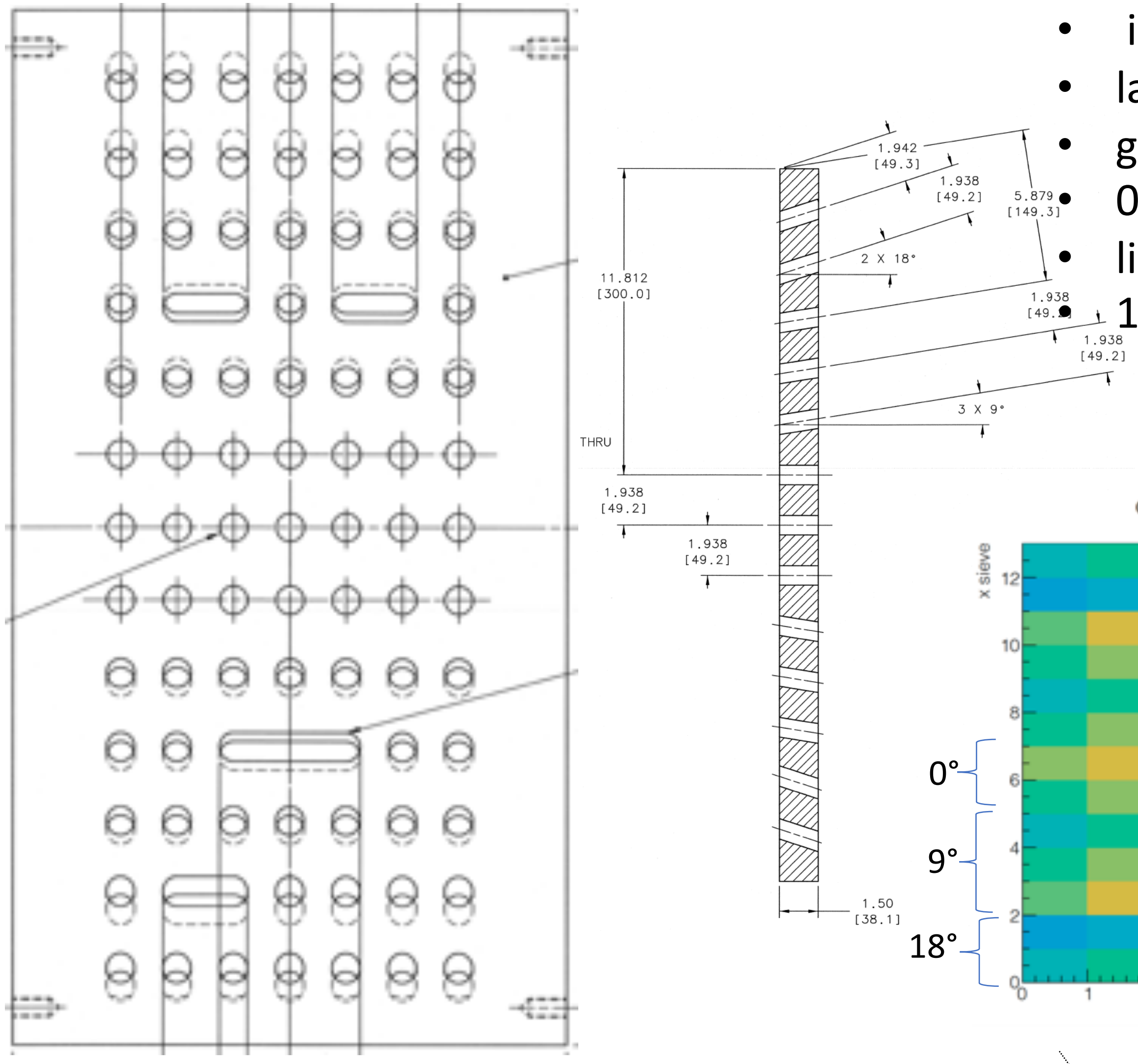
Note for both Q2=3.5 settings, BB at 1.5m and 1.8m, rates similar!



SECTION A-A
SCALE 1 / 4

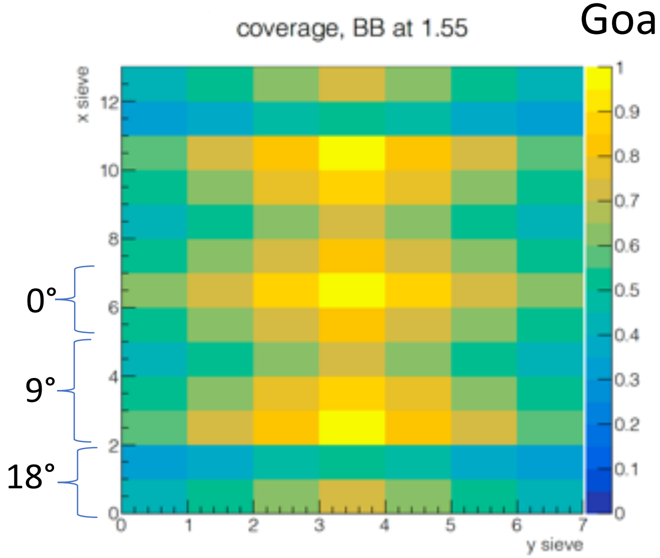


Old BB sieve



Original BB sieve design (left):

- includes slots (undesirable for precise reconstruction)
- large spacing and angled vertically in large bins
- gridding is 7x13
- 0.75” diameter holes
- limited sieve visibility per foil
- 1.5” thick plate



Goals for upcoming program:

- finer gridding
- good vertex reconstruction
- remove slots
- BB not a focusing spectrometer so angling must work for different distances
  [1.5, 1.55, 1.75, 1.8, 1.85, 2.1]m

Note: multiple scattering is about 1-2 mrad

Time to publication—Track record w/BigBite and other custom-installation experiments w/similar physics goals and observables

Similar experiment	Finished Data Taking	First publication date	Comments
E02-013 (GEn-I)	May 2006	December 2010	First BigBite experiment with MWDCs/BigHAND/etc.
E06-010 (Transversity)	February 2009	August, 2011	SIDIS SSA/polarized ^{3}He
E04-108/E04-019 (GEp-III/GEp-2g)	June 2008	June 2010	Polarization transfer→easier systematics
BigBite d2n/A1n	March 2009	July 2014	Inclusive DIS experiment w/polarized ^{3}He/BigBite
E99-117 (RCS)	March 2002	April 2007	Absolute cross section measurement, Compton scattering
E99-007 (GEp-II)	December 2000	February 2002	Polarization transfer, elastic ep
E93-027 (GEp-I)	August 1998	February 2000	Polarization transfer, elastic ep

- Projected timeline to publication based on past Hall A experiments with similar physics goals/apparatus is realistically ~2-3 years.
- GEn-II analysis will benefit from experience gained in first round of SBS experiments—**BigBite+HCAL will already be well calibrated/understood and reconstruction in GEn is *easier* than GMN, given the ~10X lower total luminosity**
- **SBS GEN also has several clear advantages over GEN-I that simplify the analysis:**
  - Magnetic deflection of protons—cleaner np separation and selection of (e,e'n) events
  - GEM-based tracking instead of MWDCs in BigBite
  - Gas Cherenkov in BigBite
  - Superior angular resolution for neutrons via HCAL coordinate resolution → less reliance on time-of-flight measurements for neutron ID and rejection of inelastics
- Dramatic increase in compute resources/simulation capability since 2006-2010