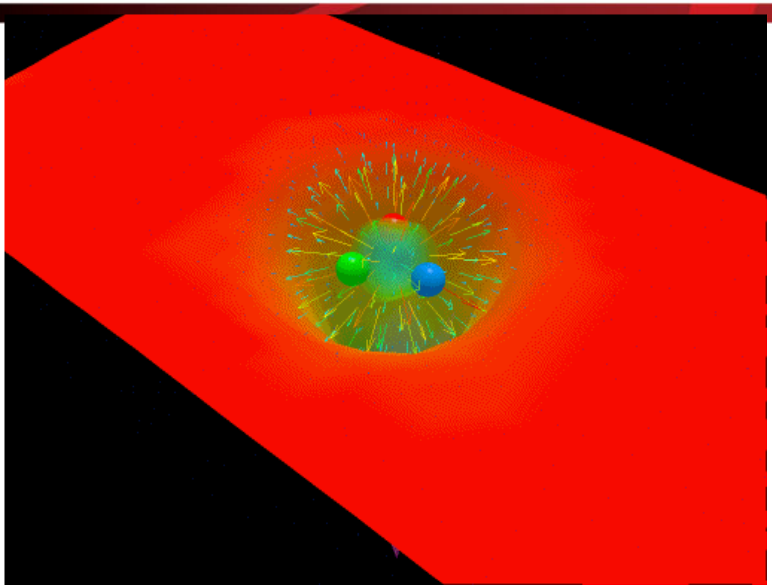
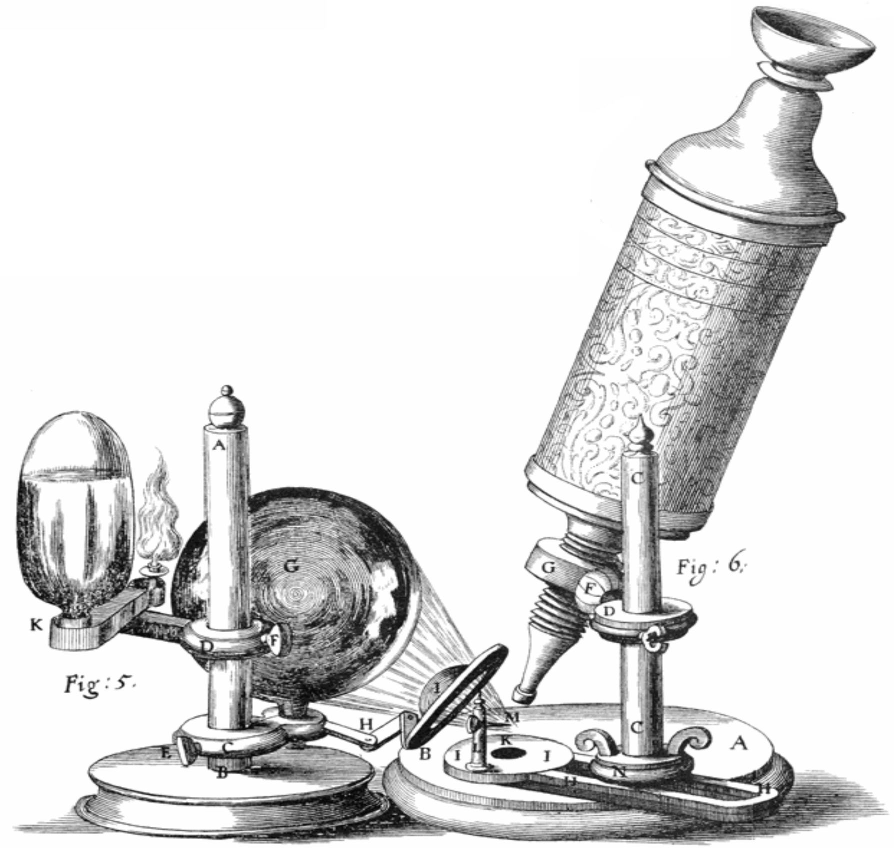


Nuclear Physics
Exploring the Heart of Matter

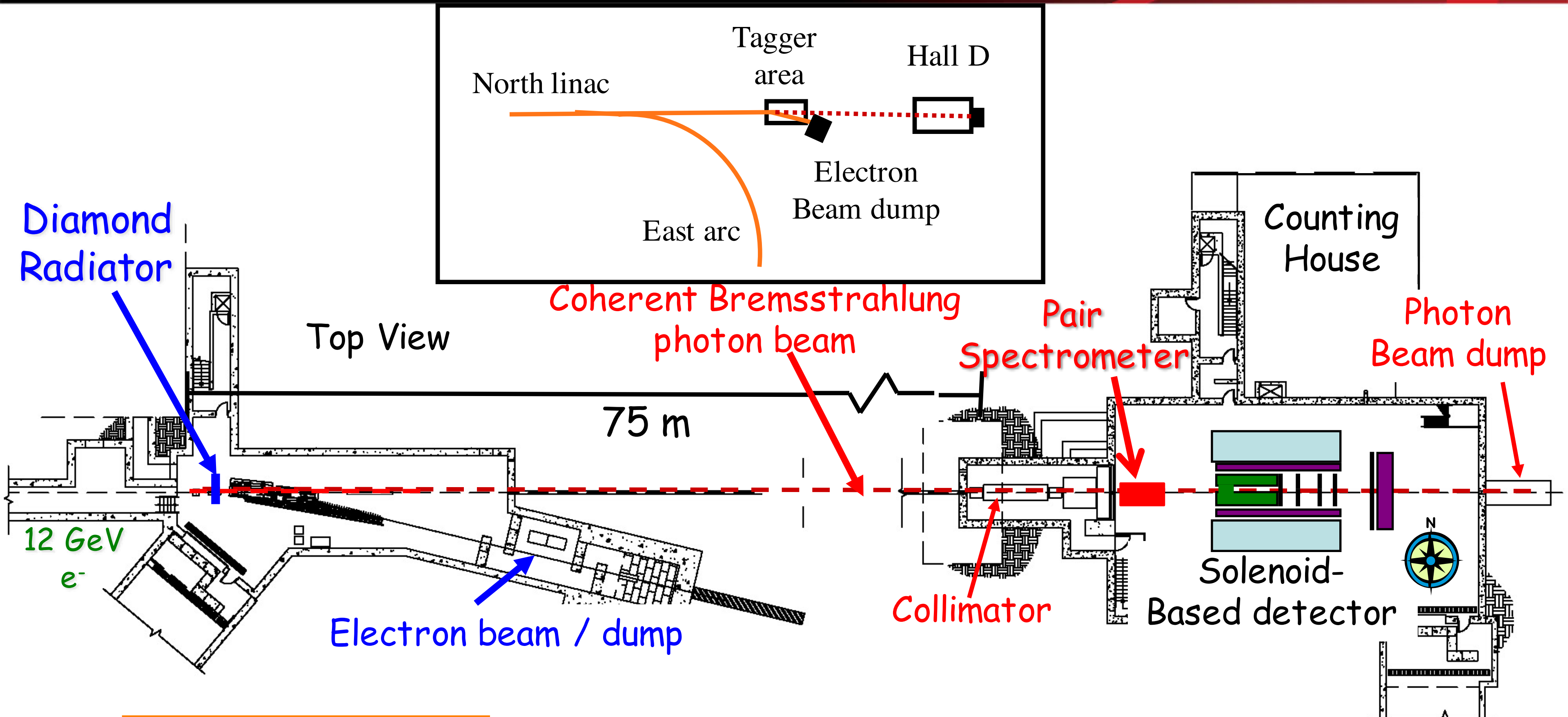
David Lawrence
Jefferson Lab Newport News VA, USA

With slides provided by Latifa Elouadrhiri



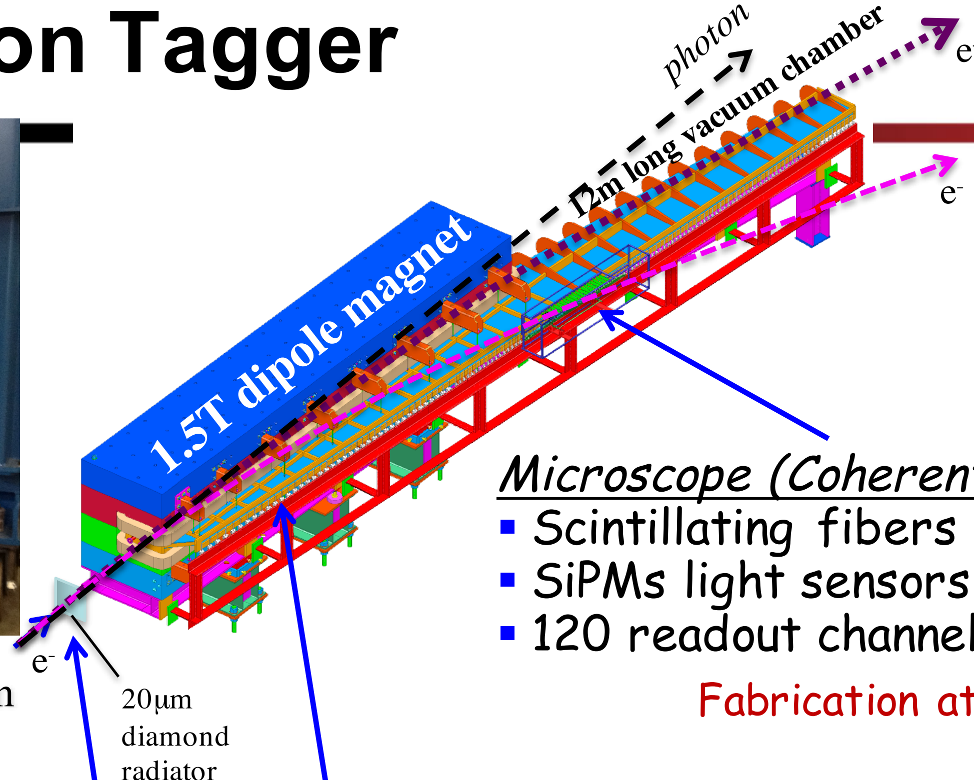
Part –III Detectors and Software

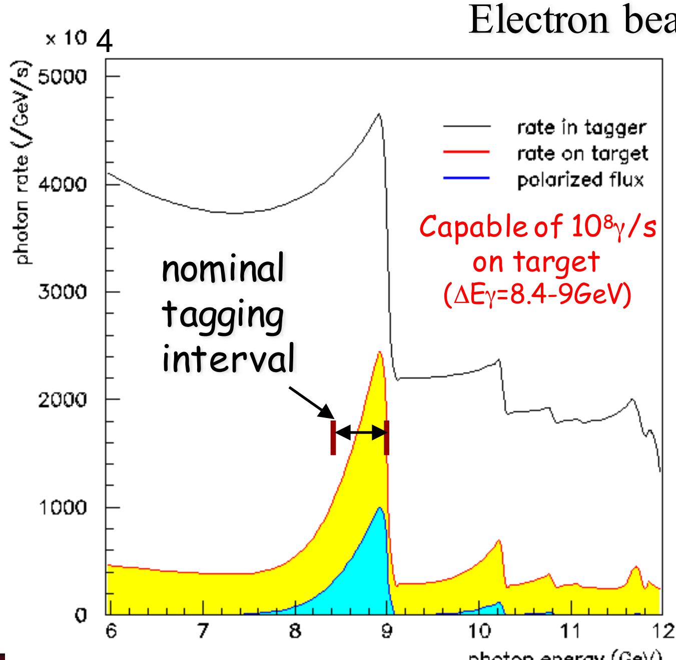
Photon beam and experimental area



Tagger Area	Collimator Cave	Experimental Hall D
Radiation $e^- Z \rightarrow \gamma e^- Z$	Selection $\theta < 25\mu r$ polarized photons	Target, Spectrometer

The Photon Tagger





Microscope (Coherent Peak)

- Scintillating fibers
- SiPMs light sensors
- 120 readout channels

Fabrication at UConn

Fixed Array (Eγ ~ 3-11.6 GeV)

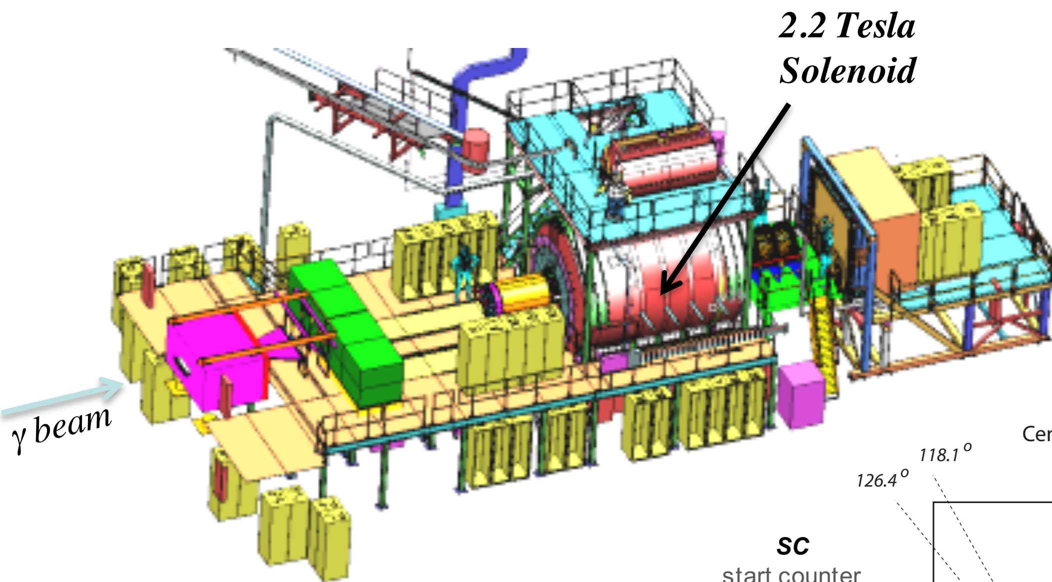
- Small scintillators
- R9800 photomultipliers

Fabrication at CUA

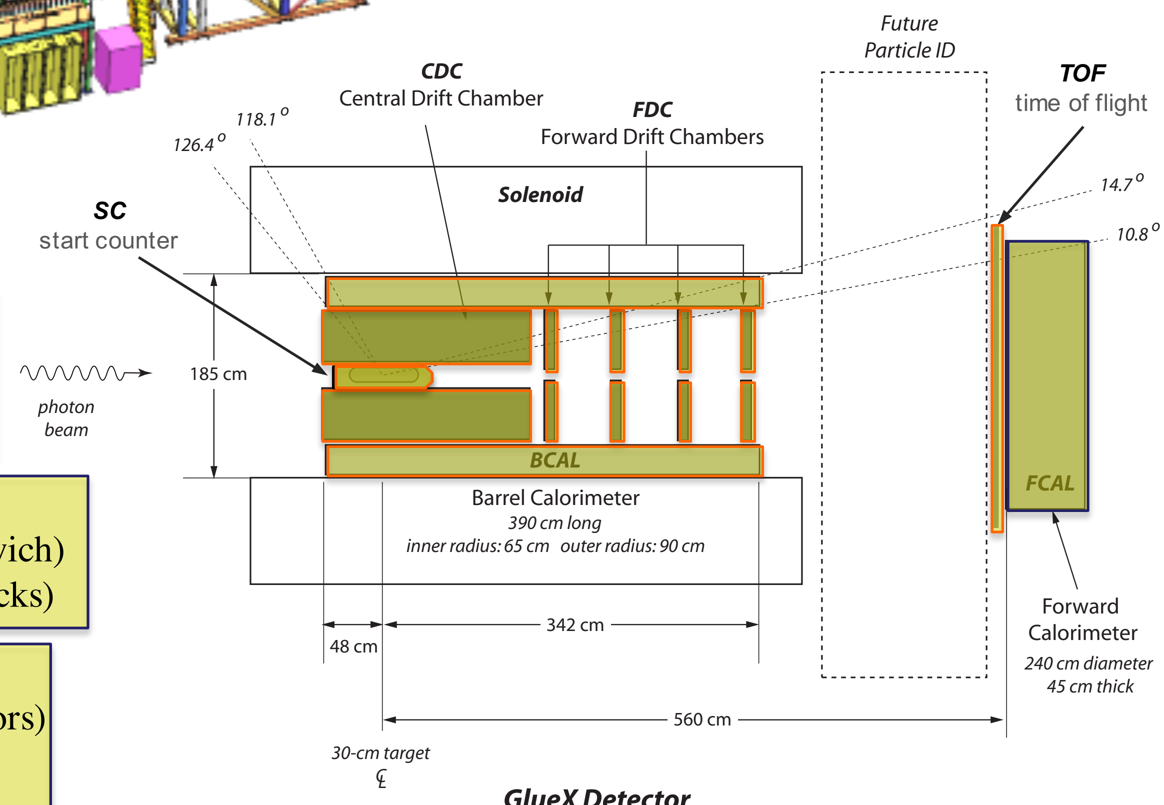
Thinning and testing of thin crystals

- UConn thinned a diamond to 40µm, ~25µr
- GlueX goal is 20µm

The GlueX Detector



- 2.2T superconducting solenoidal magnet
- Fixed target (LH_2)
- 10^8 tagged γ/s (8.4-9.0GeV)
- hermetic



Charged particle tracking

- Central drift chamber (straw tube)
- Forward drift chamber (cathode strip)

Calorimetry

- Barrel Calorimeter (lead, fiber sandwich)
- Forward Calorimeter (lead-glass blocks)

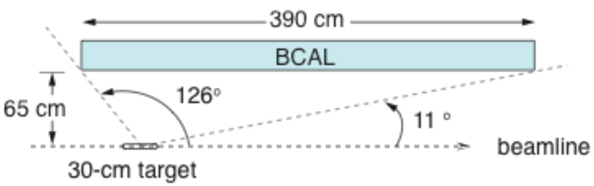
PID

- Time of Flight wall (scintillators)
- Start counter
- Barrel Calorimeter

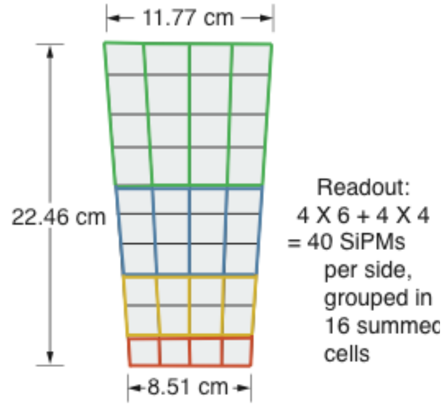
BCAL: Barrel Calorimeter

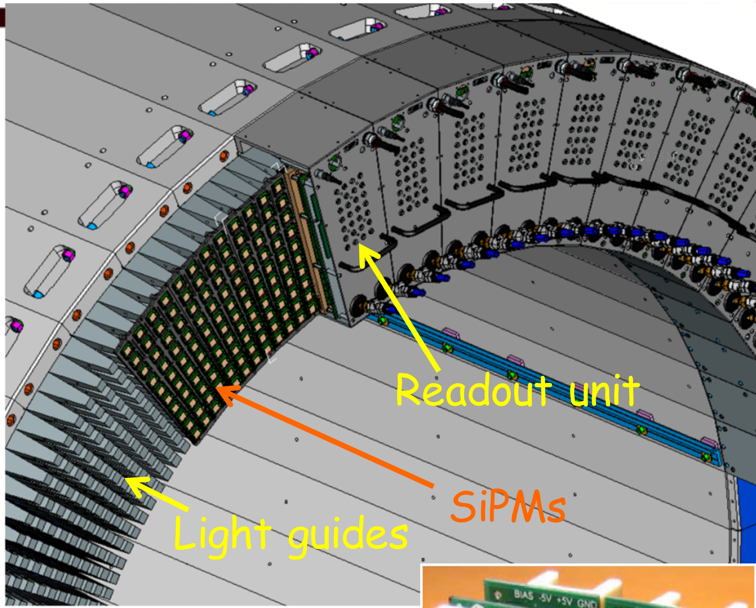
BCAL design modeled after KLOE EMC

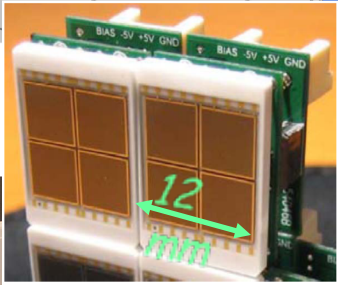
48 modules (phi sectors)



BCAL top half cutaway

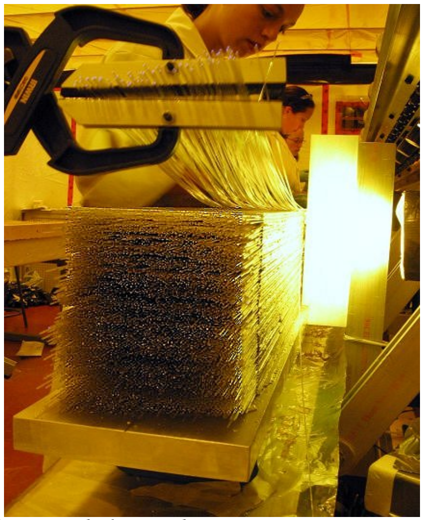




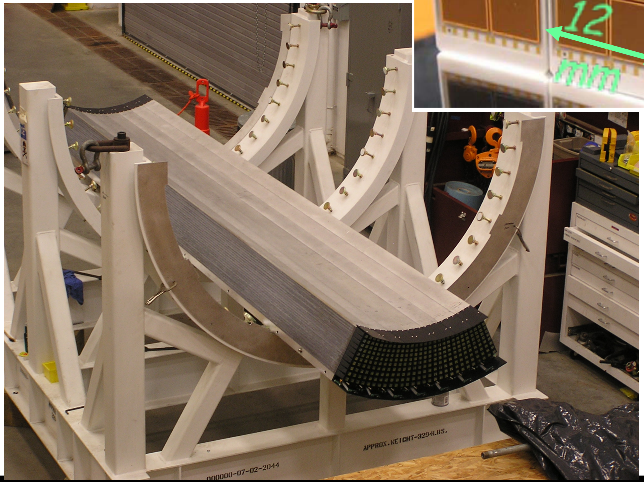


Immune to magnetic fields!

Completed BCAL module. The iPhone is placed against the opposing surface of the 4 meter module.



BCAL module under construction. Approximately 30k plastic fibers are used in 191 layers to make one module. Pb/Sc/Glue = 37/49/14 % (by volume)



Forward Calorimeter

Lead Glass Calorimeter

- 2800 lead glass F8-00 blocks $4 \times 4 \times 45 cm^3$
- PMTs FEU84-3
- Cockroft-Walton bases

Fabricated at Indiana University

Beam test with e^- in Hall B, 2012

- σ_E/E=20% at 100 MeV – as expected

Calorimeter assembled in Hall D

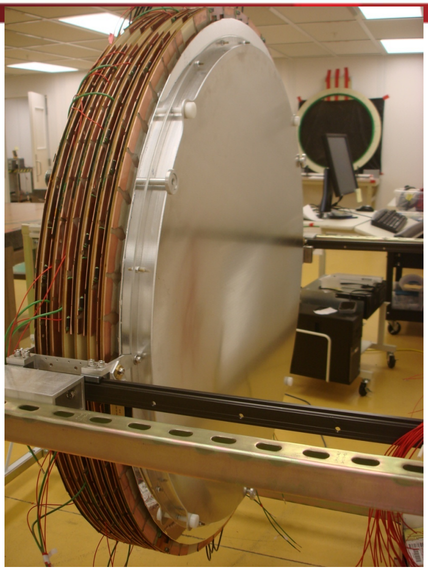
Cockroft-Walton bases under test at IU

Single parts for module assembly

Charged Particle Tracking

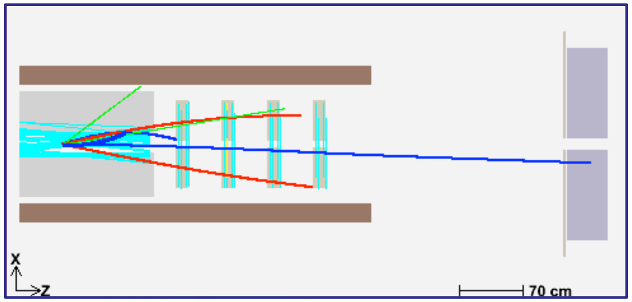
The Central Drift Chamber (CDC) being constructed at Carnegie Melon University. Construction is done with the device in the vertical position, but it will be turned sideways for installation.

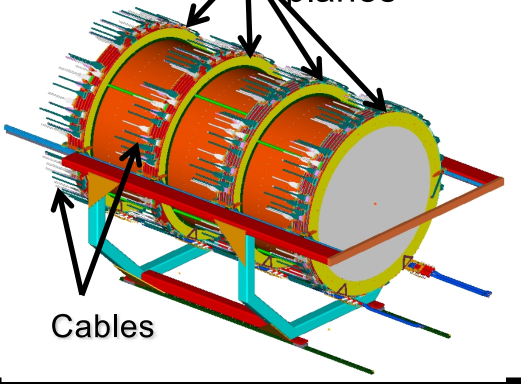
Central Drift Chamber (CDC):
Gas mixture: ~60/40 Ar/CO_2
Angular Coverage: 6^o-155^o
3500 straw tubes r=8mm
dE/dx for p < 450 MeV/c
Readout: FADC-125MHz
Resolution: $\sigma_{r\phi}$ ~ 150 μm
σ_z~1.5 mm
28 layers total
stereo layers: +/- 6^0



A Forward Drift Chamber (FDC) being tested in the lab. The GlueX detector will have 4 of these custom made chambers.

Forward Drift Chamber (FDC):
Gas Mixture: 40/60 Ar/CO_2
Angular Coverage: 1^o – 30^o
Readout:
2300 anode wires → F1TDC
10200 cathode strips → FADC-125
3 measured projections per plane
Resolution: 200μm wires
200μm strips



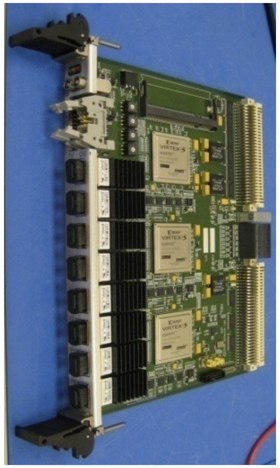


Electronics and Data Rates

Electronics

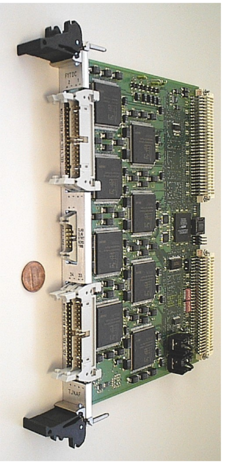
- All digitization electronics are fully pipelined (VME64x-VXS)
    - F1TDC (60 ps, 32 ch. or 115 ps 48 ch.)
    - 125 MHz fADC (12 bit, 72 ch.)
    - 250 MHz fADC (12 bit, 16 ch.)
        - integrated into L1 trigger
- Trigger latency ~3 μs
- 3GB/s readout from front end
- 300MB/s to mass storage
- 3PB/yr to tape

Sub-system Processor



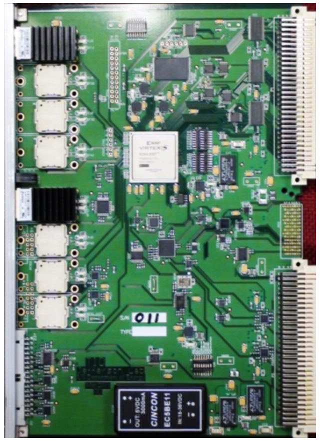
Global Trigger Processor

F1TDC

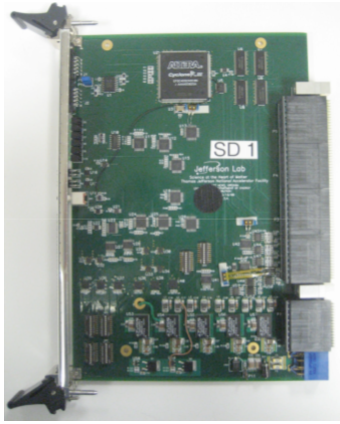


250MHz Flash ADC

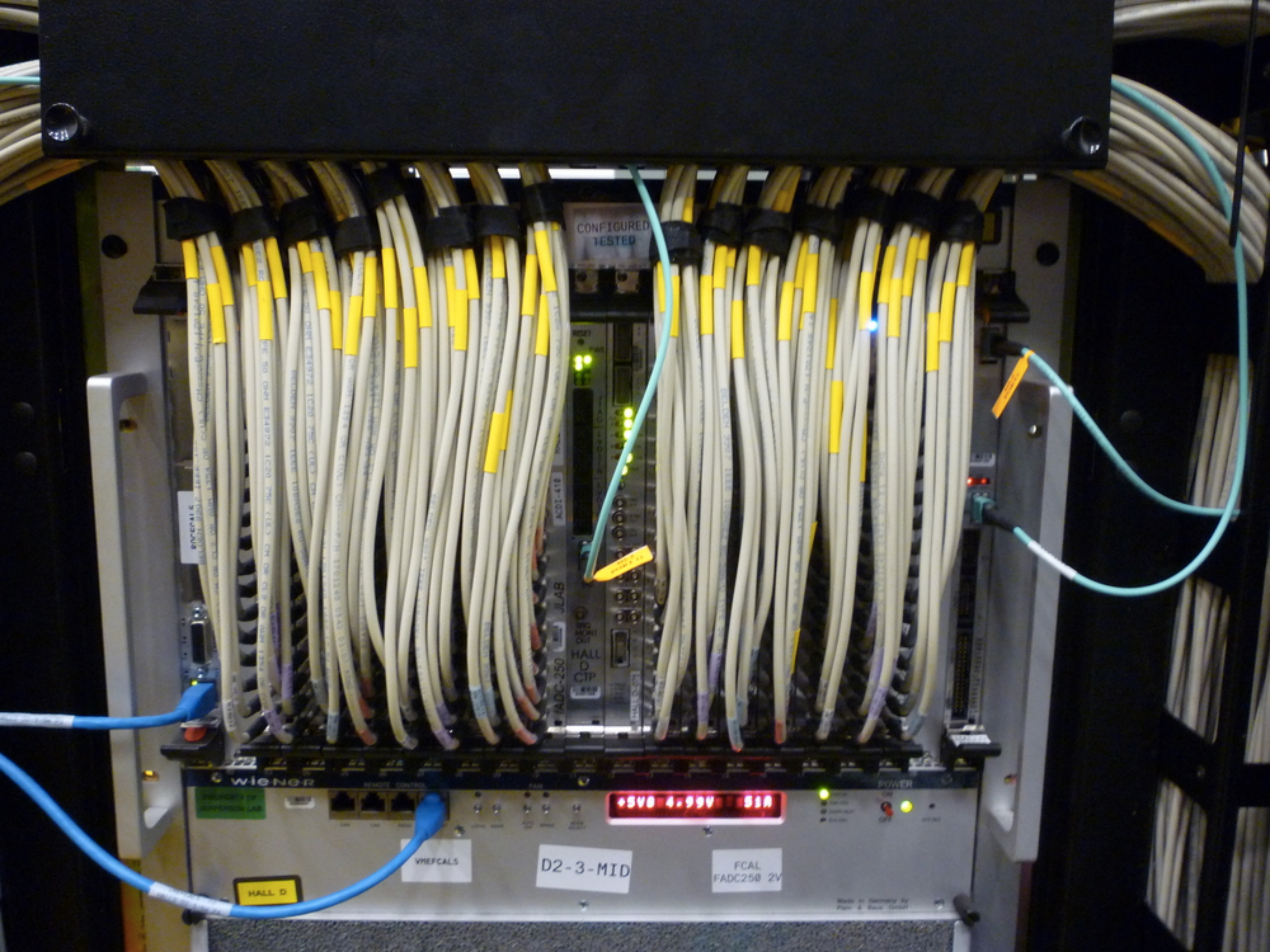
Trigger Interface



Signal distribution board



Crate Trigger Processor


CONFIGURED
TESTED
FADC-250
JLAB
HALL D CTP
+5V0 4.99V 51A
POWER
PROPERTY OF JEFFERSON LAB
VMEFCAL5
D2-3-MID
FCAL FADC250 2V
HALL D

GlueX Data Rates

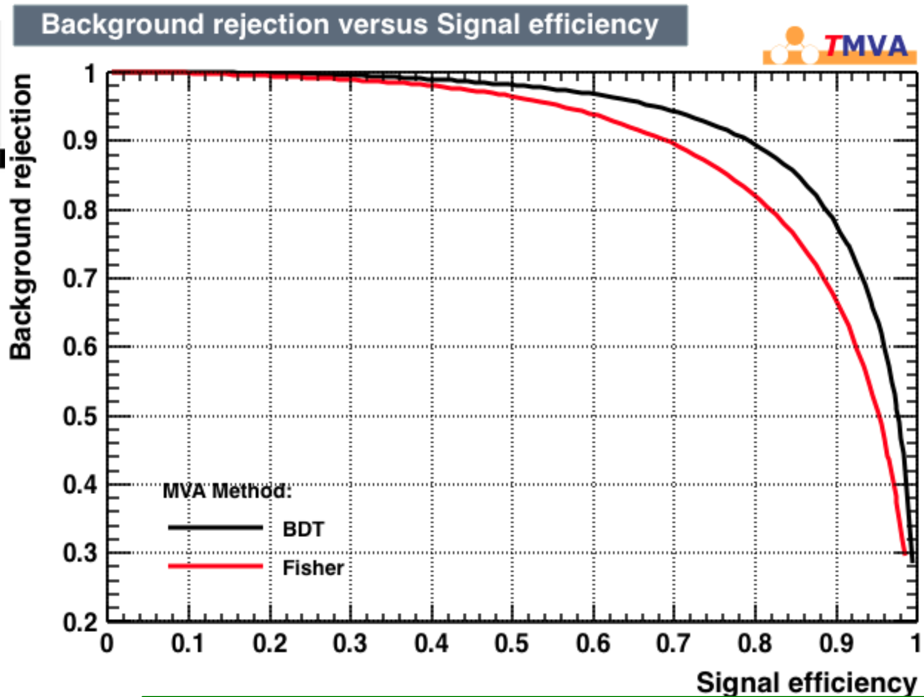
David Lawrence, Jefferson Lab

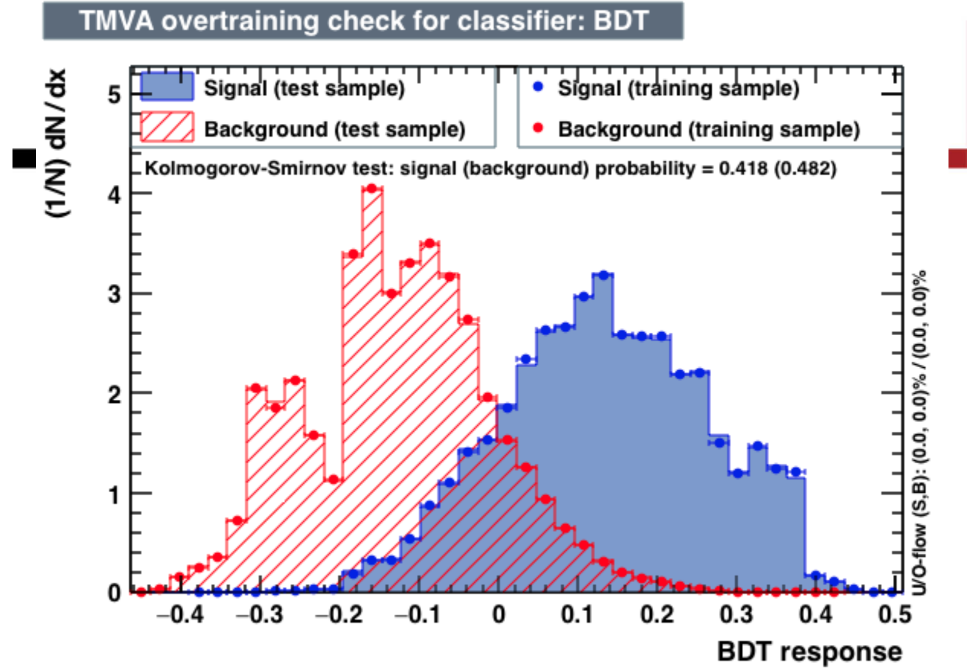
		Front End DAQ Rate	Event Size	L1 Trigger Rate	Bandwidth to mass Storage	
JLab	GlueX	3 GB/s	15 kB	200 kHz	300 MB/s	privat comm.
JLab	CLAS12	0.1 GB/s	20 kB	10 kHz	100 MB/s	privat comm.
LHC	ALICE	500 GB/s	2,500 kB	200 kHz	200 MB/s	CHEP2007 talk Sylvain Chapelin
LHC	ATLAS	113 GB/s	1,500 kB	75 kHz	300 MB/s	CHEP2007 talk Sylvain Chapelin
LHC	CMS	200 GB/s	1,000 kB	100 kHz	100 MB/s	CHEP2007 talk Sylvain Chapelin
LHC	LHCb	40 GB/s	40 kB	1000 kHz	100 MB/s	CHEP2007 talk Sylvain Chapelin
BNL	STAR	50 GB/s	1,000 kB	0.6 kHz	450 MB/s	*
BNL	PHENIX	0.9 GB/s	~60 kB	~ 15 kHz	450 MB/s	**

WARNING: This table is old and some numbers are out of date

* Jeff Landgraf Private Comm. 2/11/2010

** CHEP2006 talk Martin L. Purschke. current capability is






```
--- BDT      : Ranking result (top variable is best ranked)
--- BDT      : ----------------------------------------------------
--- BDT      : Rank : Variable          : Variable Importance
--- BDT      : ----------------------------------------------------
--- BDT      :   1 : Efcal_clusters      : 1.917e-01
--- BDT      :   2 : Ntrack_candidates : 1.710e-01
--- BDT      :   3 : Nfcal_clusters      : 1.279e-01
--- BDT      :   4 : Nbcal_points        : 1.258e-01
--- BDT      :   5 : Npshits             : 8.291e-02
--- BDT      :   6 : Ebcal_points        : 7.186e-02
--- BDT      :   7 : Ebcal_clusters      : 6.445e-02
--- BDT      :   8 : Ntof                : 6.424e-02
--- BDT      :   9 : Nstart_counter      : 5.138e-02
--- BDT      :  10 : Nbcal_clusters      : 4.873e-02
--- BDT      :  11 : Ptot_candidates     : 0.000e+00
--- BDT      :  12 : Npschits            : 0.000e+00
```

Multivariate Analysis

- Boosted Decision Tree
- Artificial Neural Network
- ...

Preparing for Level-3 triggering with Spring 2016 commissioning data

- “signal” events had **>4GeV** of fully reconstructed energy*

Types of “Parallel” Computing

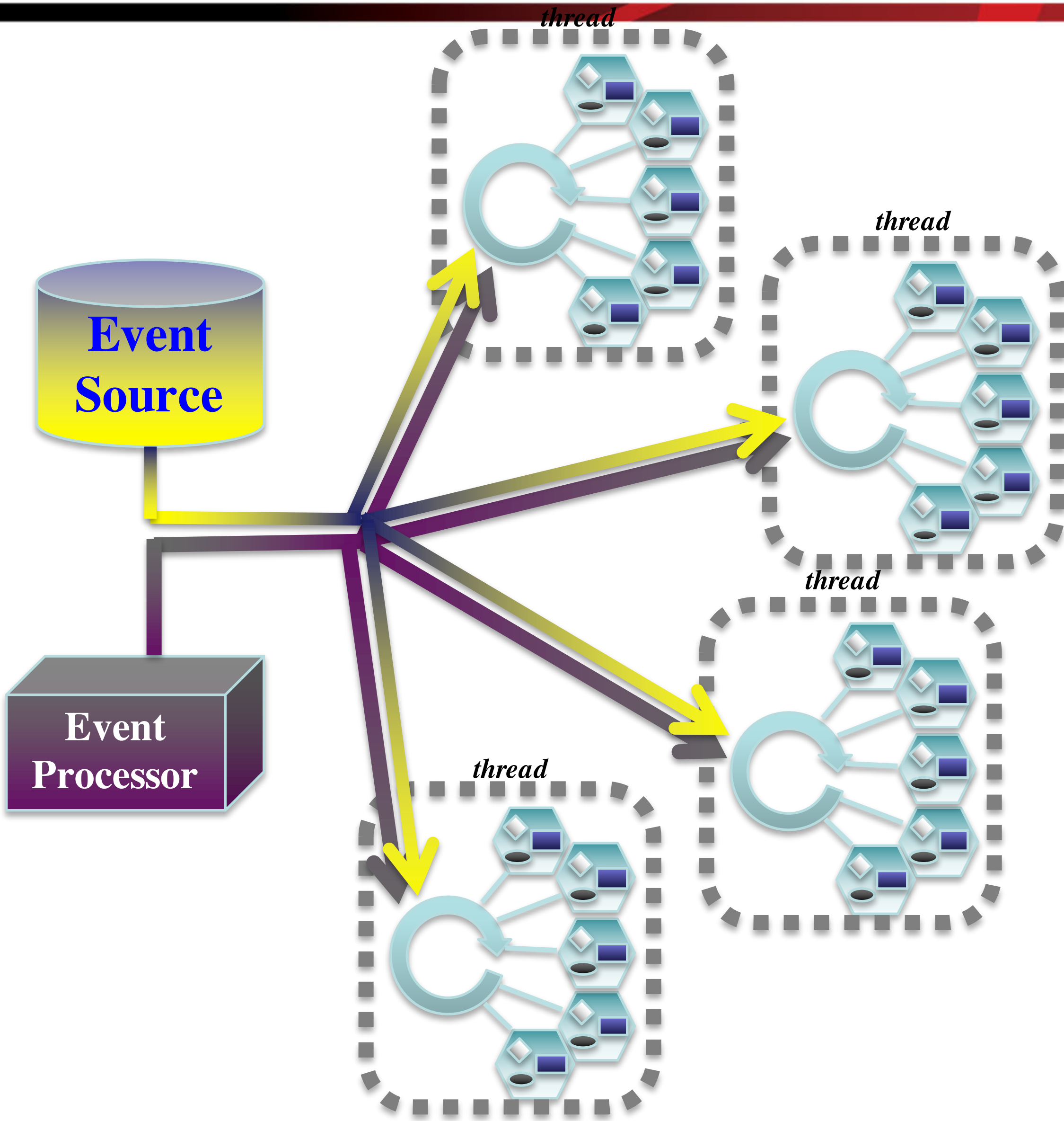
- Nomenclature
  - Parallel vs. concurrent
  - Bit-level vs. data level
- Multi-threaded
- Multi-process
- Distributed
- Grid
- SIMD
- GPU/GPGPU
- MIC

Multi-threading

- *Each thread has a complete set of factories making it capable of completely reconstructing a single event*

- *Factories only work with other factories in the same thread eliminating the need for expensive mutex locking within the factories*

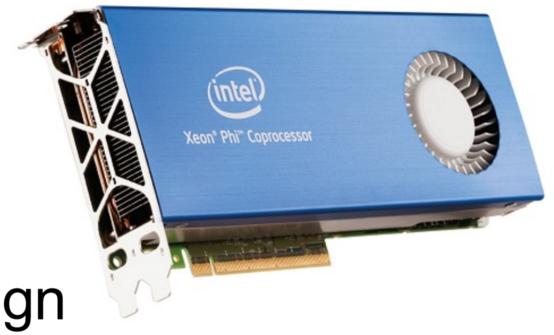
- *All events are seen by all Event Processors (multiple processors can exist in a program)*



SIMD = Single Instruction Multiple Data

```
// Multiply a 5x1 matrix by its transpose
inline DMatrix5x5 MultiplyTranspose(const DMatrix5x1 &m1){
  ALIGNED_16_BLOCK_WITH_PTR(__m128d, 5, p)
  __m128d &b1=p[0];
  __m128d &b2=p[1];
  __m128d &b3=p[2];
  __m128d &b4=p[3];
  __m128d &b5=p[4];
  b1=_mm_set1_pd(m1(0));
  b2=_mm_set1_pd(m1(1));
  b3=_mm_set1_pd(m1(2));
  b4=_mm_set1_pd(m1(3));
  b5=_mm_set1_pd(m1(4));
  return DMatrix5x5(_mm_mul_pd(m1.GetV(0),b1),_mm_mul_pd(m1.GetV(0),b2),
            _mm_mul_pd(m1.GetV(0),b3),_mm_mul_pd(m1.GetV(0),b4),
            _mm_mul_pd(m1.GetV(0),b5),
            _mm_mul_pd(m1.GetV(1),b1),_mm_mul_pd(m1.GetV(1),b2),
            _mm_mul_pd(m1.GetV(1),b3),_mm_mul_pd(m1.GetV(1),b4),
            _mm_mul_pd(m1.GetV(1),b5),
            _mm_mul_pd(m1.GetV(2),b1),_mm_mul_pd(m1.GetV(2),b2),
            _mm_mul_pd(m1.GetV(2),b3),_mm_mul_pd(m1.GetV(2),b4),
            _mm_mul_pd(m1.GetV(2),b5));
}
```

MIC = Many Integrated Cores



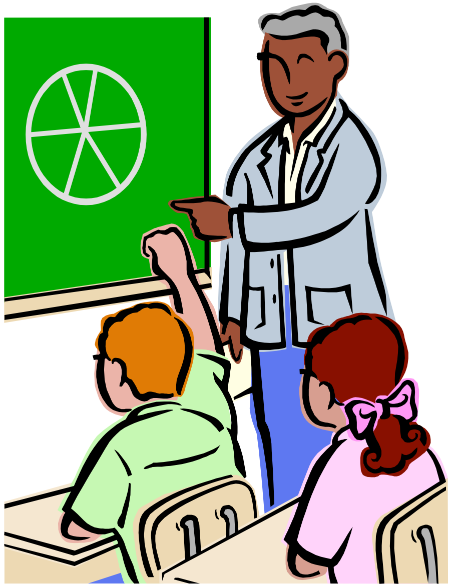
- Xeon Phi = Intel's MIC system
  - 60 cores, 1GHz on a PCIe x16 card
  - 512 bit wide vectors
  - Original project: Larrabee
    - Attempt to make GPU from older x86 design
- Linux variant runs on MIC card independent of host OS
  - MIC system is based on 2.4 Linux kernel
  - File system not automatically shared
    - MIC cards can be configured to mount host's filesystem via NFS
- Must use intel-provided cross-compiler to build executables
  - Could not build sim-recon because ROOT was needed
  - Could not build ROOT because libX11-devel was needed

GPU = Graphics Processing Unit

Summary

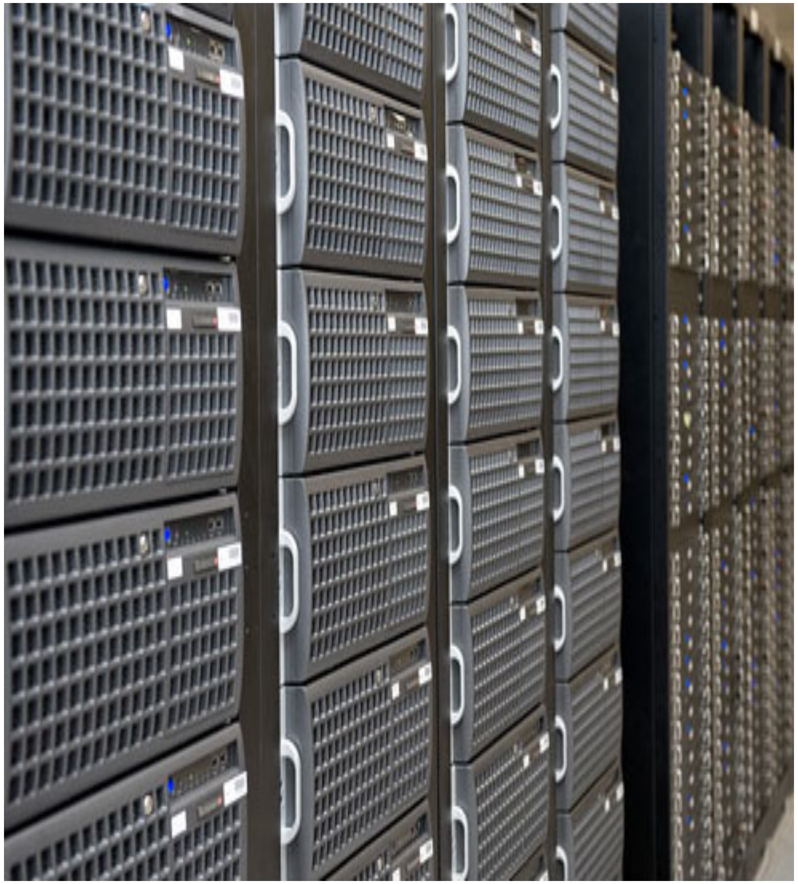
- Many hardware and software technologies are needed to perform modern particel physics experiments
  - Faster detectors
  - Faster Data Acquisition
  - Faster Computing
  - Faster Networks/Storage
- These require more and more expert knowledge and therefore, more specialization from those in the field

Backup Slides



Distributed Computing
(Let's just call it "farms")

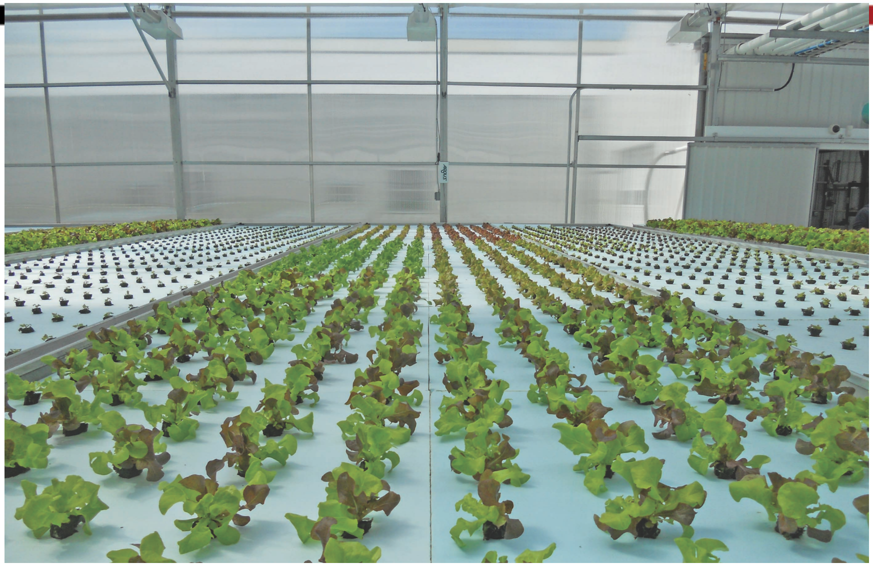
- large cluster of computers, housed in same location, and connected via fast LAN
- jobs run independently on single node *(… or maybe not …)*
- focuses significant compute power to dedicated job
- "clouds" tend to be made up of multiples of these connected via WAN



Farms in the Future

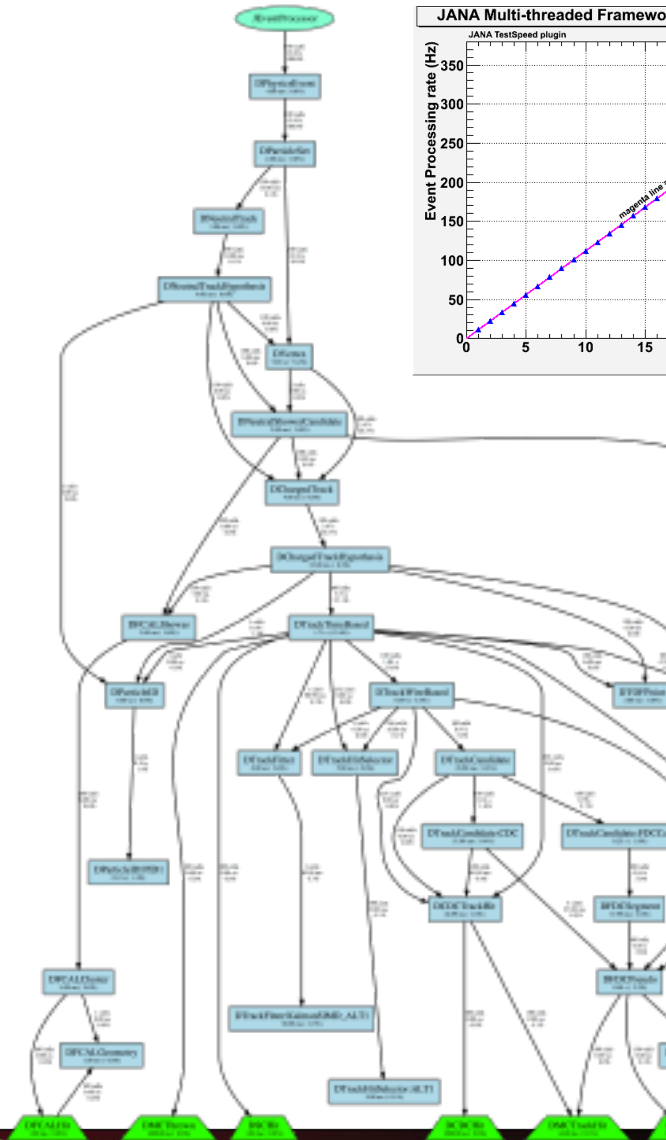
Farms will play a role in the future due to power supply and dissipation

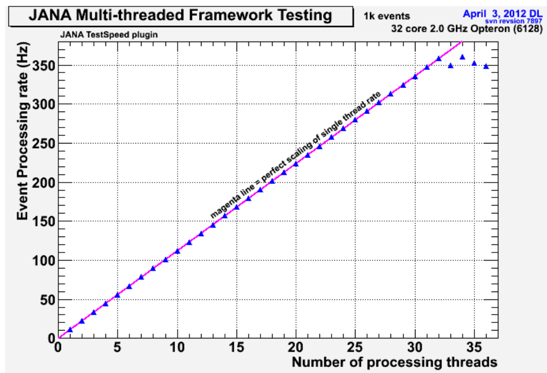
(i.e. You can't pack too many teraflops into a small volume without burning everything up!)



Offline Computing

Multi-threaded event reconstruction





Amplitude Analysis on GPUs

Fit Configuration	Time to Converge (seconds)
Single CPU	150.7
Single CPU + 1 GPU	23.6
CPU Master + 4 (CPU + GPU)	6.3
CPU Master + 11 CPU Workers	17.8

(All fits converge to the same minimum with variations in iterations of ±1-2%)

Time for 10^6 Amplitude Computations (ms)

Amplitude	CPU	GPU*
Breit-Wigner	800	8
Ang. Dist. (D-functions)	15,000	87

* includes time to copy result from GPU memory

- Computers are responsible for storing, transporting, and processing information
- All experiments gather and process information

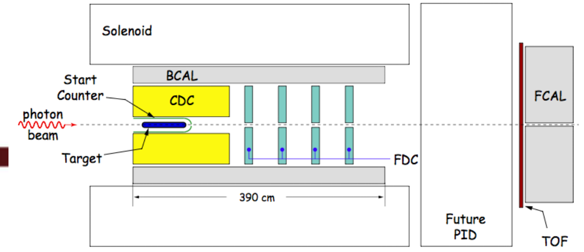
Exercise: handedness

- *~10% of people are left-handed*
- *Theory: this is due to need for physical cooperation*
- *My hypothesis: Physicists need less physical cooperation so have higher percentage of lefties*

Hall D: Detector Design Parameters

Capability	*Quantity*	*Range*
Charged particles	**Coverage**	$1^o < \theta < 160^o$
	Momentum Resolution (5^o-140^o)	$\sigma_p/p = 1 - 3\%$
	Position resolution	$\sigma \sim 150\text{-}200\ \mu m$
	dE/dx measurements	$20 < \theta < 160^o$
	Time-of-flight measurements	$\sigma_{ToF} \sim 60$ ps; $\sigma_{BCal} \sim 200$ps
	Barrel time resolution	$\sigma_t^{\gamma} < (74 / \sqrt{E} \oplus 33)$ ps
Photon detection	**Energy measurements**	$2^o < \theta < 120^o$
	LGD energy resolution (E > 60 MeV)	$\sigma_E/E = (5.7/\sqrt{E} \oplus 2.0)\%$
	Barrel energy resolution (E > 60 MeV)	$\sigma_E/E = (5.54/\sqrt{E} \oplus 1.6)\%$
	LGD position resolution	$\sigma_{x,y,} \sim 0.64$ cm$/\sqrt{E}$
	Barrel position resolution	$\sigma_z \sim 0.5$cm $/\sqrt{E}$
DAQ/trigger	**Level 1**	**< 200 kHz**
	Level 3 event rate to tape	**~ 15 kHz**
	Data rate	**300 MB/s**
Electronics	**Fully pipelined**	**250 / 125 MHz fADCs, TDCs**
Photon Flux	**Initial: 10^7 γ/s**	**Final: 10^8 γ/s**

Particle ID

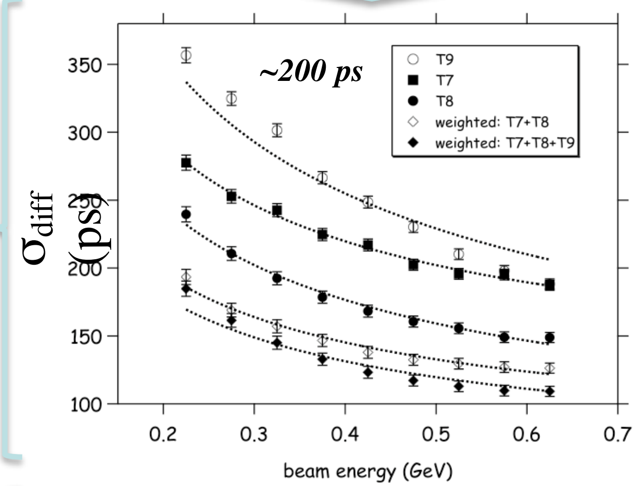


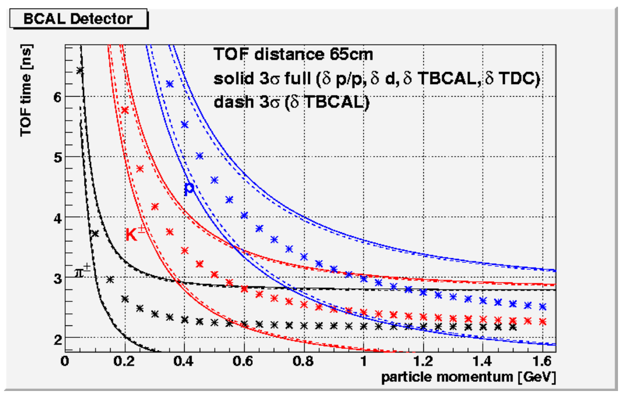
Detector is cylindrically symmetric about the beamline

Particle ID is done primarily through time of flight with some help from dE/dx in chambers. Space is left in design for a future PID detector.

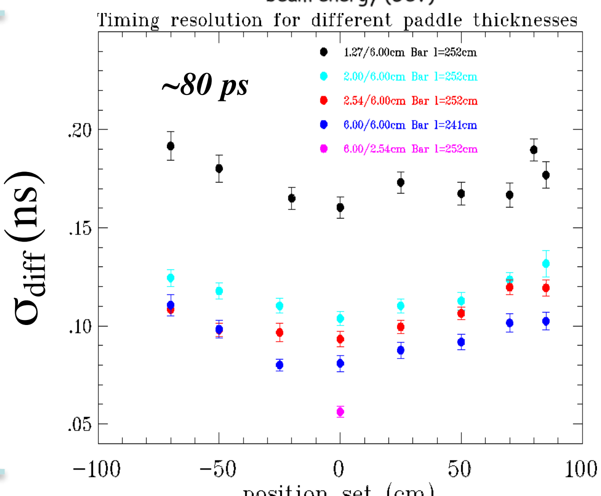
Beam Test Data | Expected Separation

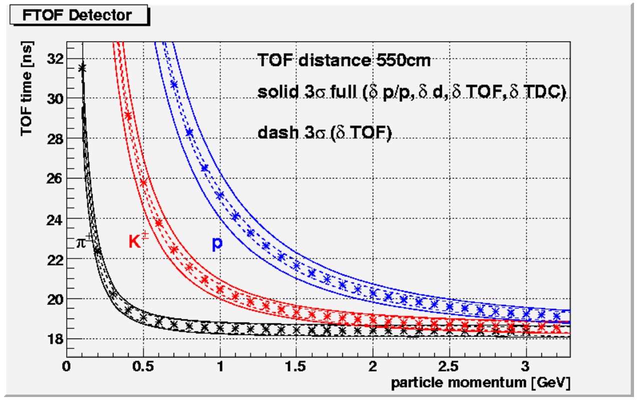
Barrel Calorimeter



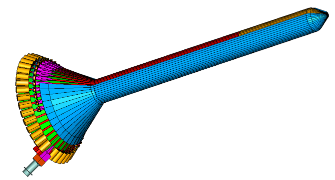


Forward TOF



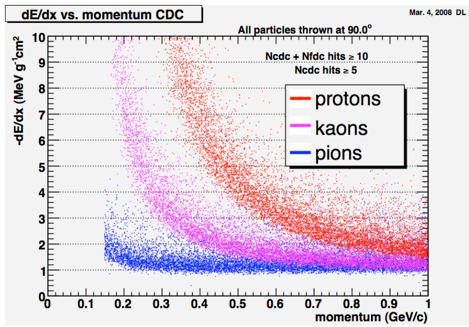


Start Counter



- 40 scintillators
- 300 ps (w/tracking)
- Used for start-up

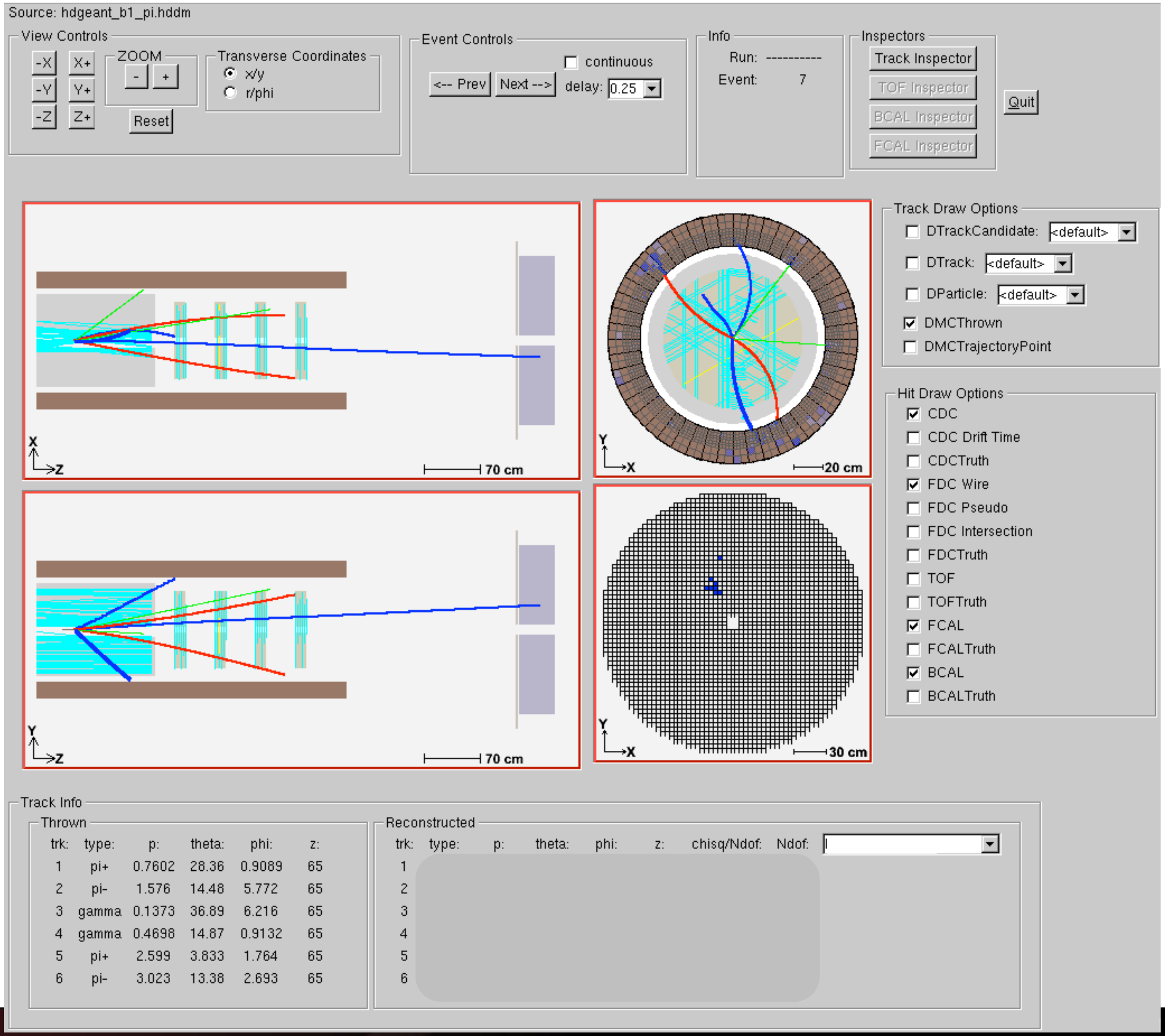
CDC dE/dx



- πp separation <450MeV/c
- πK separation <275MeV/c

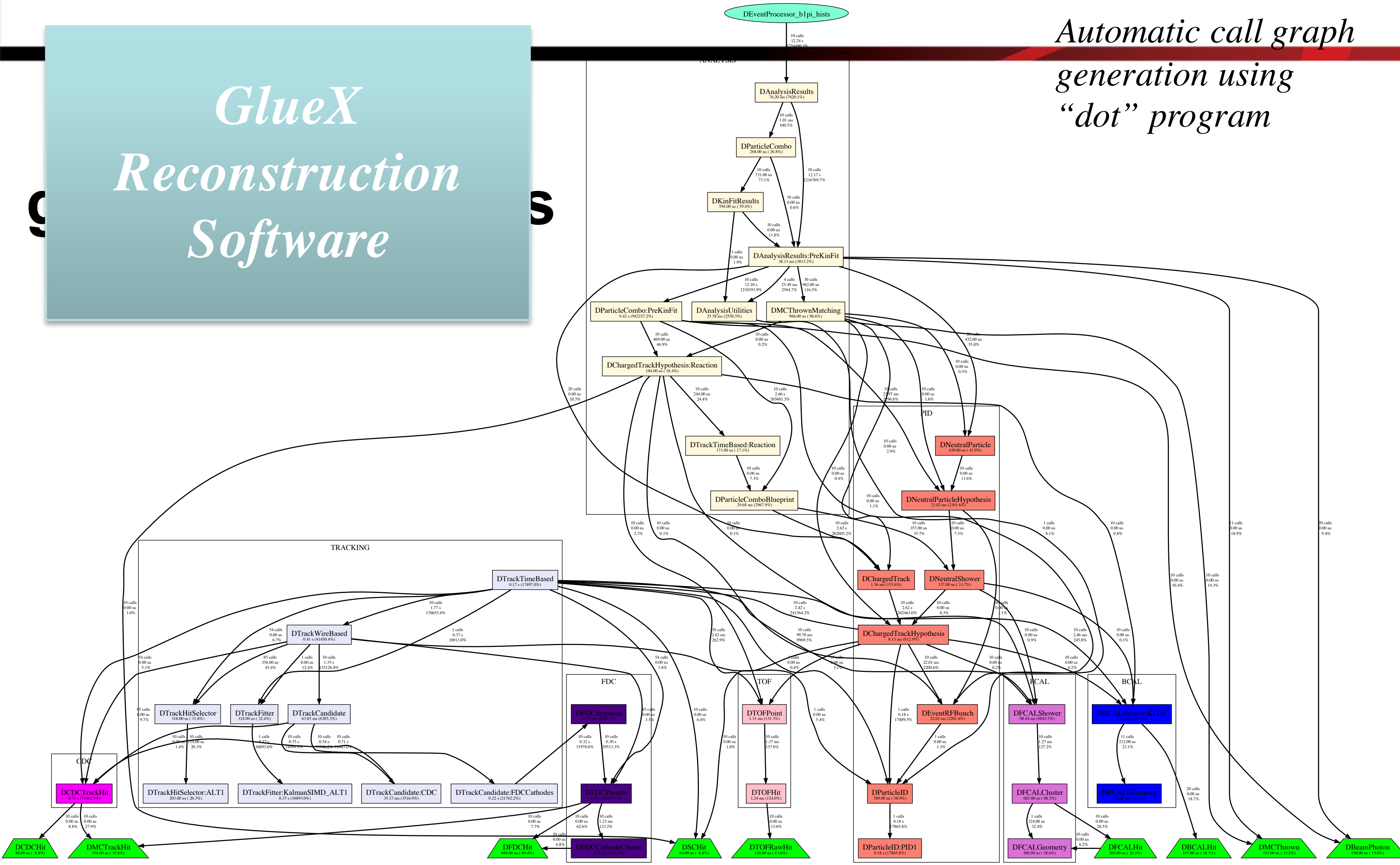
A single γ p → $pb_1\pi$ event

Final state: $p\ \pi^+\pi^+\pi^-\pi^-\pi^0$



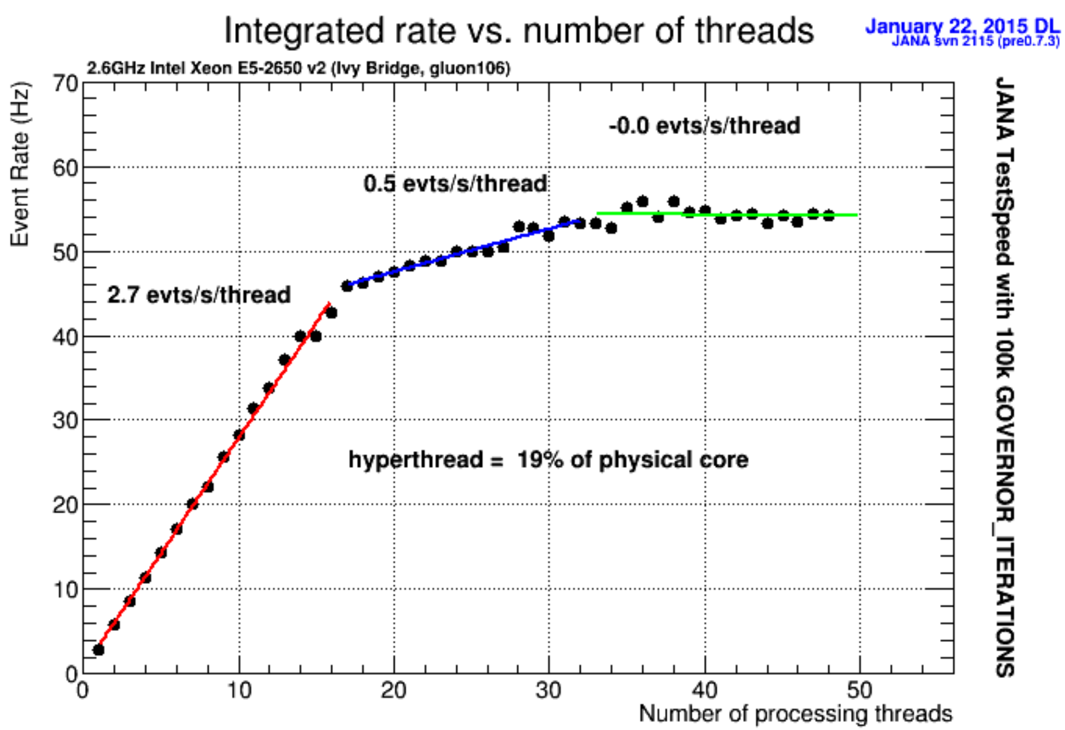
GlueX Reconstruction Software

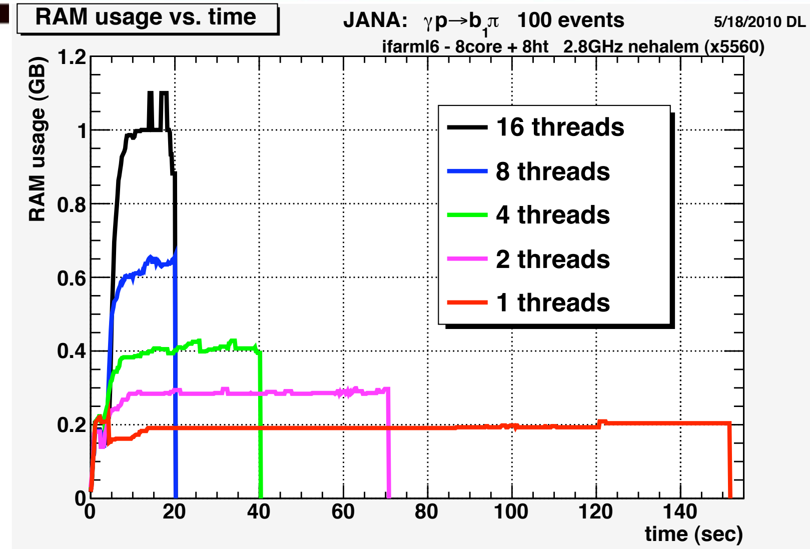
Automatic call graph generation using "dot" program

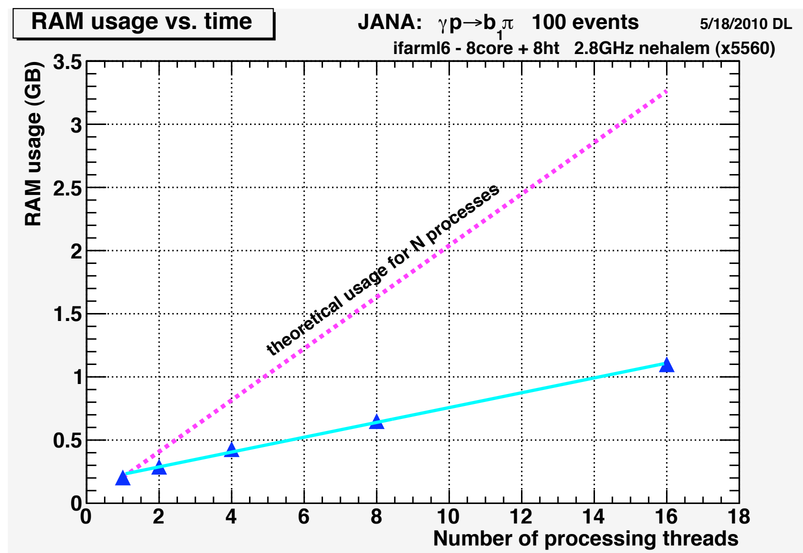


JANA RAM usage

JANA rate scaling for CPU intensive task







Multi-threaded GB/thread is about 1/3 that of multi-process

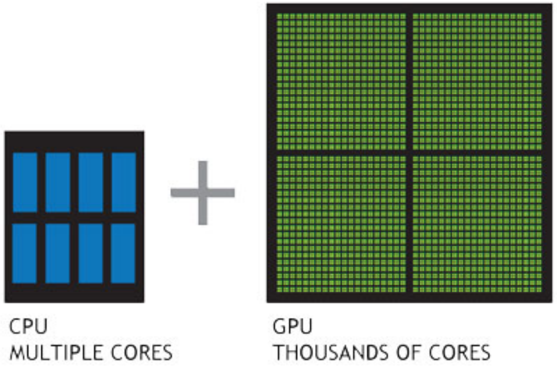
SIMD = Single Instruction Multiple Data

- Special registers on CPU where multiple numbers can be packed and operated on simultaneously
- Also known as "vectorization"
  - *gcc: "…vectorization is enabled by the flag -ftree-vectorize and by default at -O3"*
- CPU vendors have their own implementations and evolutions

(e.g. Intel has …)

- MMX (1997, Pentium 5) 64bit
- SSE (1999) – SSE4(2006) 128 bit
- AVX (2008) 256 bit
- MIC/VPU 512 bit

GPU – Example CUDA code



Standard C Code

```c
void saxpy(int n, float a,
           float *x, float *y)
{
  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}

int N = 1<<20;



// Perform SAXPY on 1M elements
saxpy(N, 2.0, x, y);
```

C with CUDA extensions

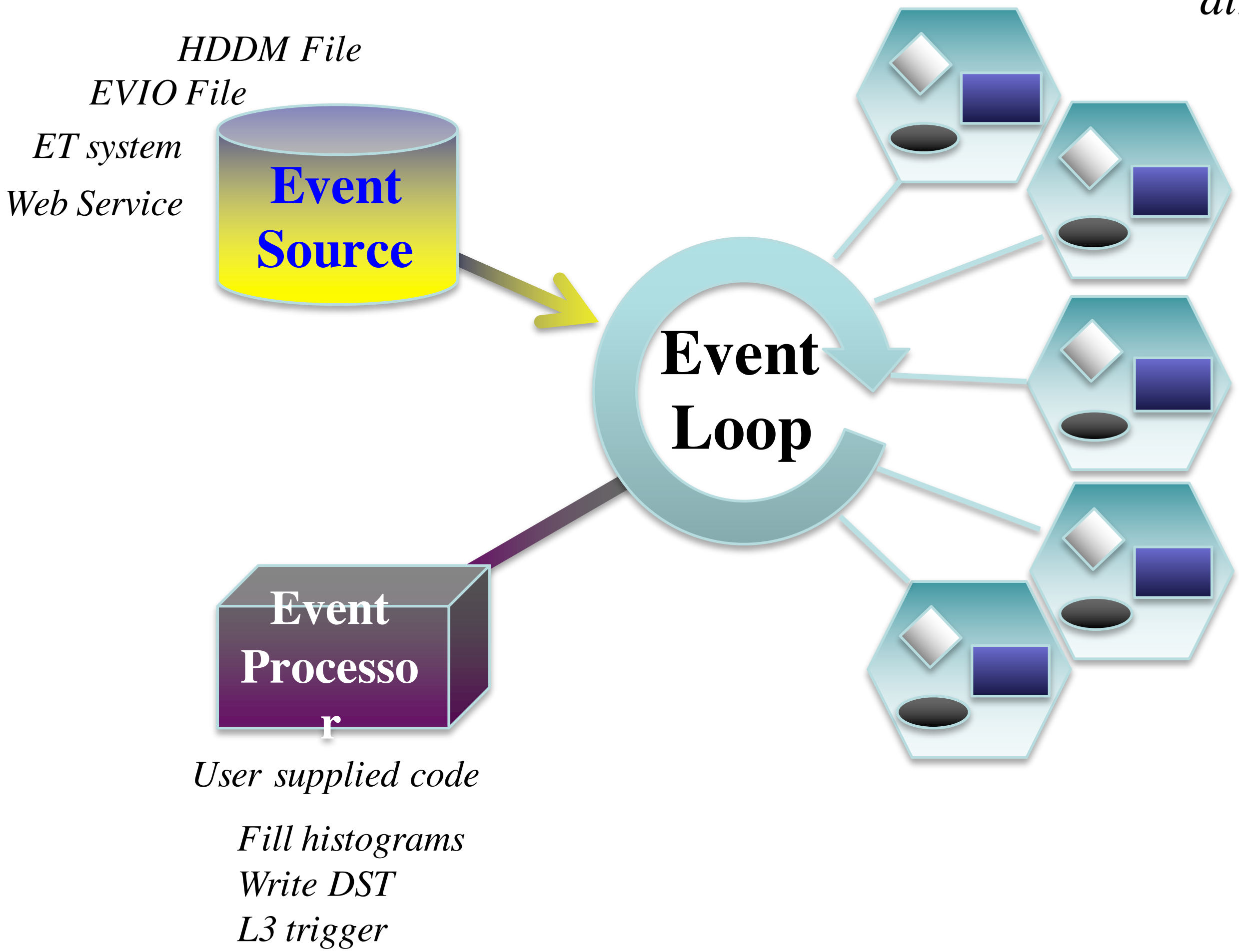
```c
__global__
void saxpy(int n, float a,
           float *x, float *y)
{
  int i = blockIdx.x*blockDim.x + threadIdx.x;
  if (i < n) y[i] = a*x[i] + y[i];
}

int N = 1<<20;
cudaMemcpy(x, d_x, N, cudaMemcpyHostToDevice);
cudaMemcpy(y, d_y, N, cudaMemcpyHostToDevice);

// Perform SAXPY on 1M elements
saxpy<<<4096,256>>>(N, 2.0, x, y);

cudaMemcpy(d_y, y, N, cudaMemcpyDeviceToHost);
```

Complete Event Reconstruction in JANA



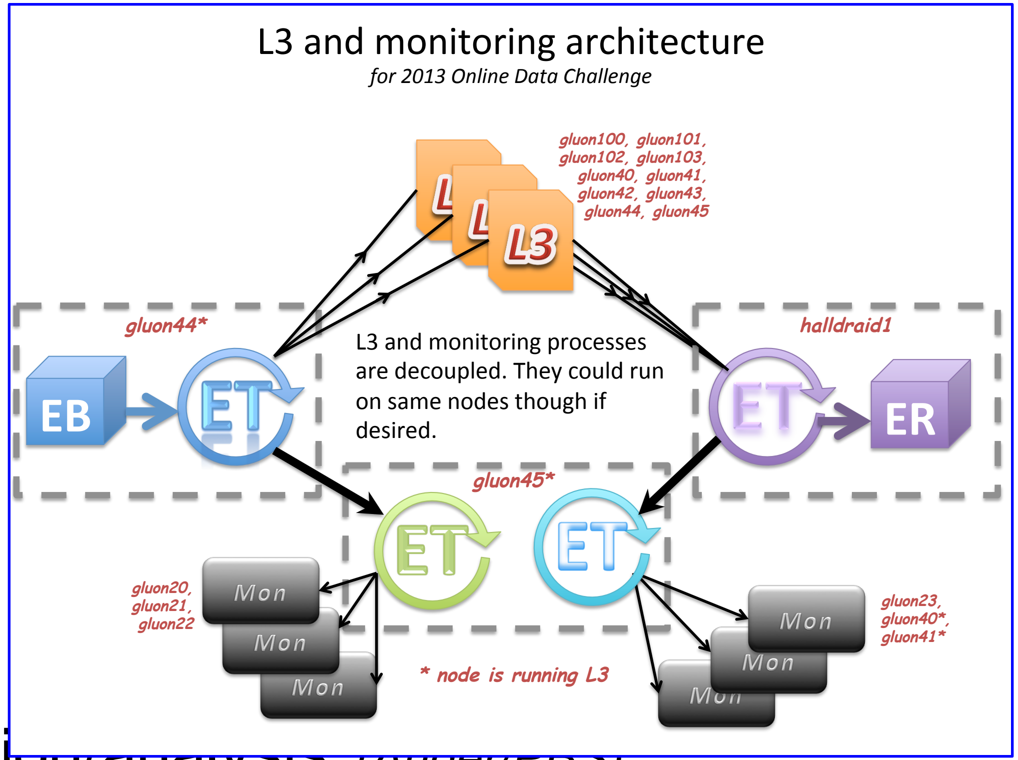
Framework has a layer that directs object requests to the factory that completes it

Multiple algorithms (factories) may exist in the same program that produce the same type of data objects

This allows the framework to easily redirect requests to alternate algorithms specified by the user at run time

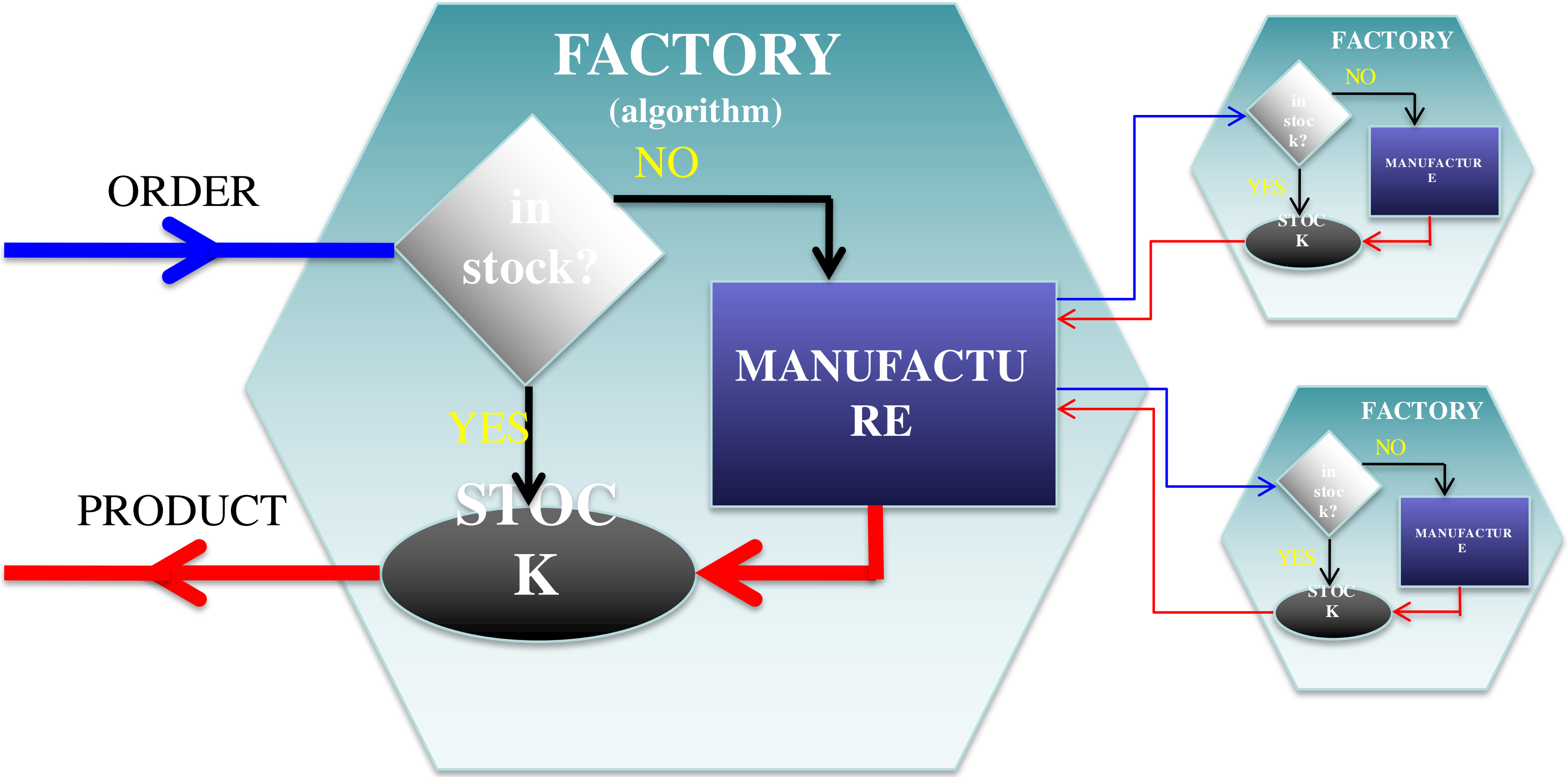
Distributed Computing with JANA

- Online systems
  - Monitoring farm *(ET)*
  - L3 trigger farm *(ET)*



- Offline systems
  - Raw data reconstruction/analysis *(Auger/PBS)*
  - Simulation *(Open Science Grid/Auger/PBS)*

Factory Model

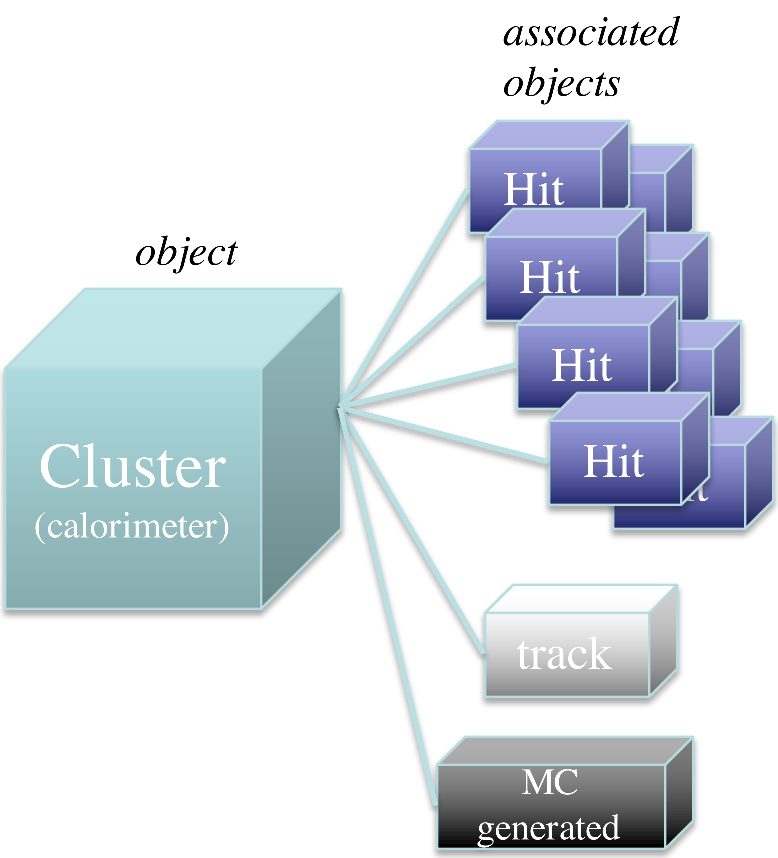


Data on demand = Don't do it unless you need it

Stock = Don't do it twice

Conservation of CPU cycles!

Associated Objects



- A data object may be associated with any number of other data objects having a mixture of types
  - Each data object has a list of "associated objects" that can be probed using a similar access mechanism as for event-level object requests

```
vector<const DCluster*> clusters;
loop->Get(clusters);
for(uint i=0; i<clusters.size(); i++)
{
        vector<const DHit*> hits;
        clusters[i]->Get(hits);
        // Do something with hits …
}
```