

Nuclear Physics

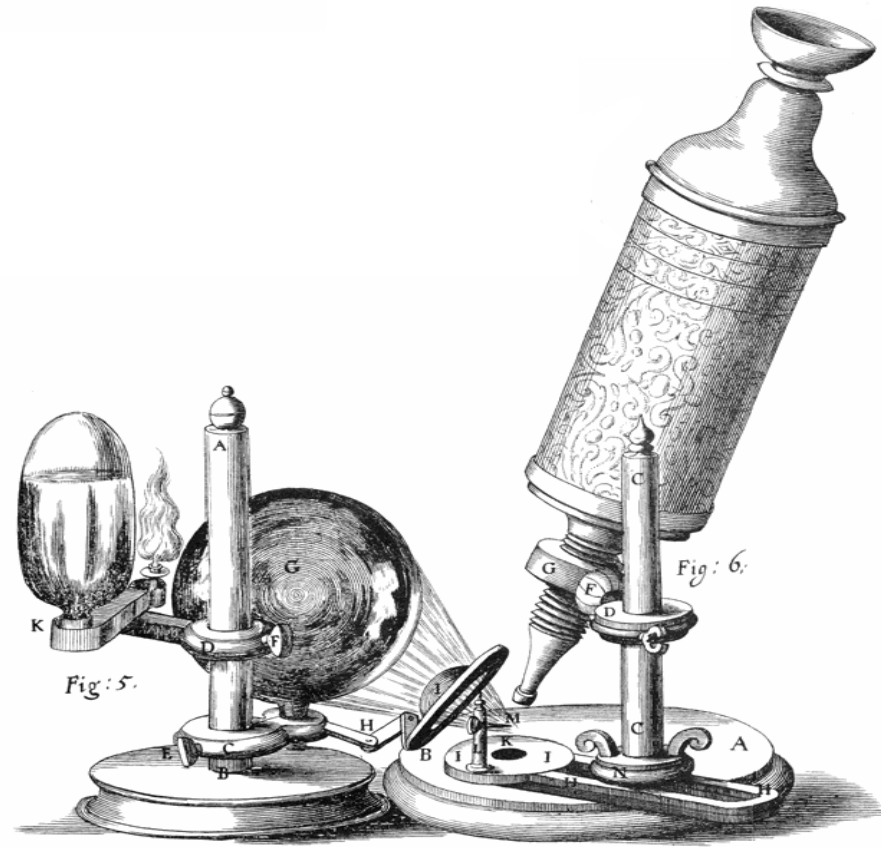
Exploring the Heart of Matter

David Lawrence
Jefferson Lab Newport News VA, USA

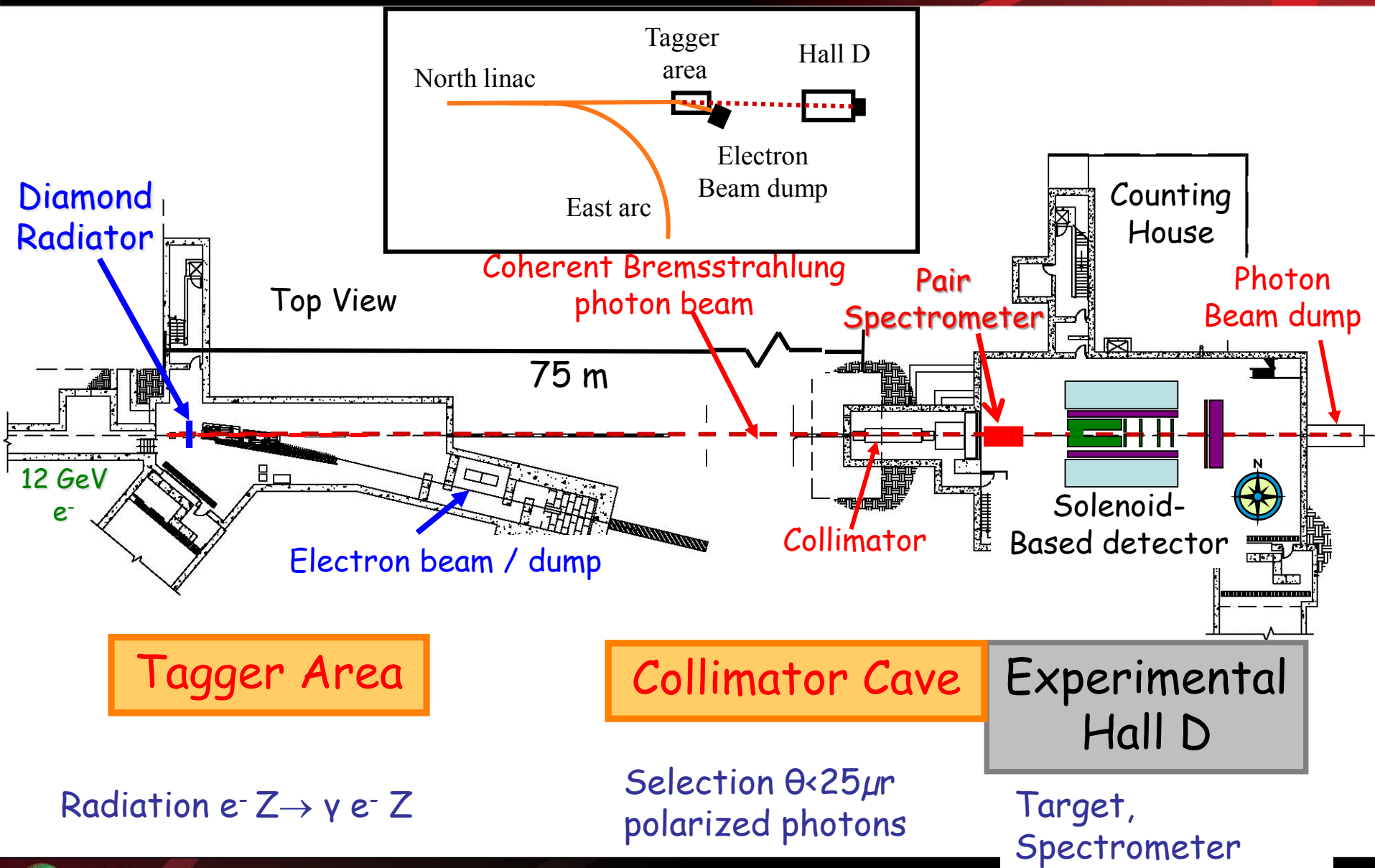
With slides provided by Latifa Elouadrhiri

Part –III

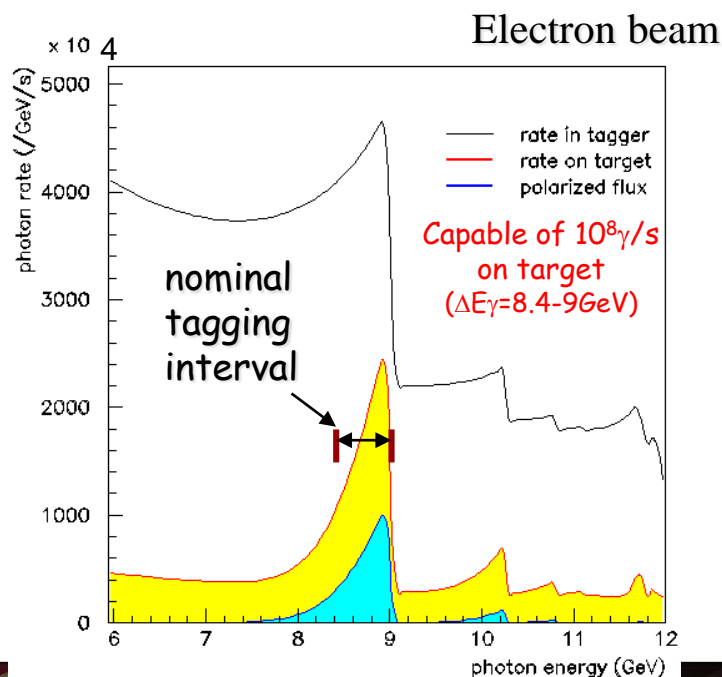
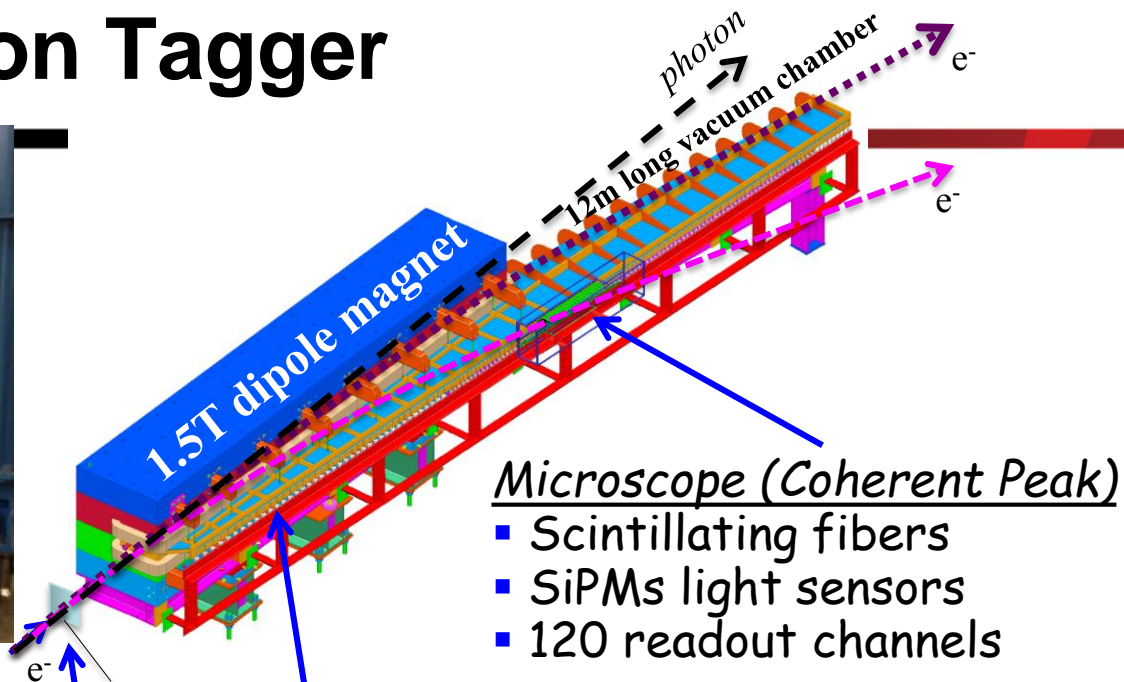
Detectors and Software



Photon beam and experimental area



The Photon Tagger



Fixed Array ($E_\gamma \sim 3-11.6 \text{ GeV}$)

- Small scintillators
- R9800 photomultipliers

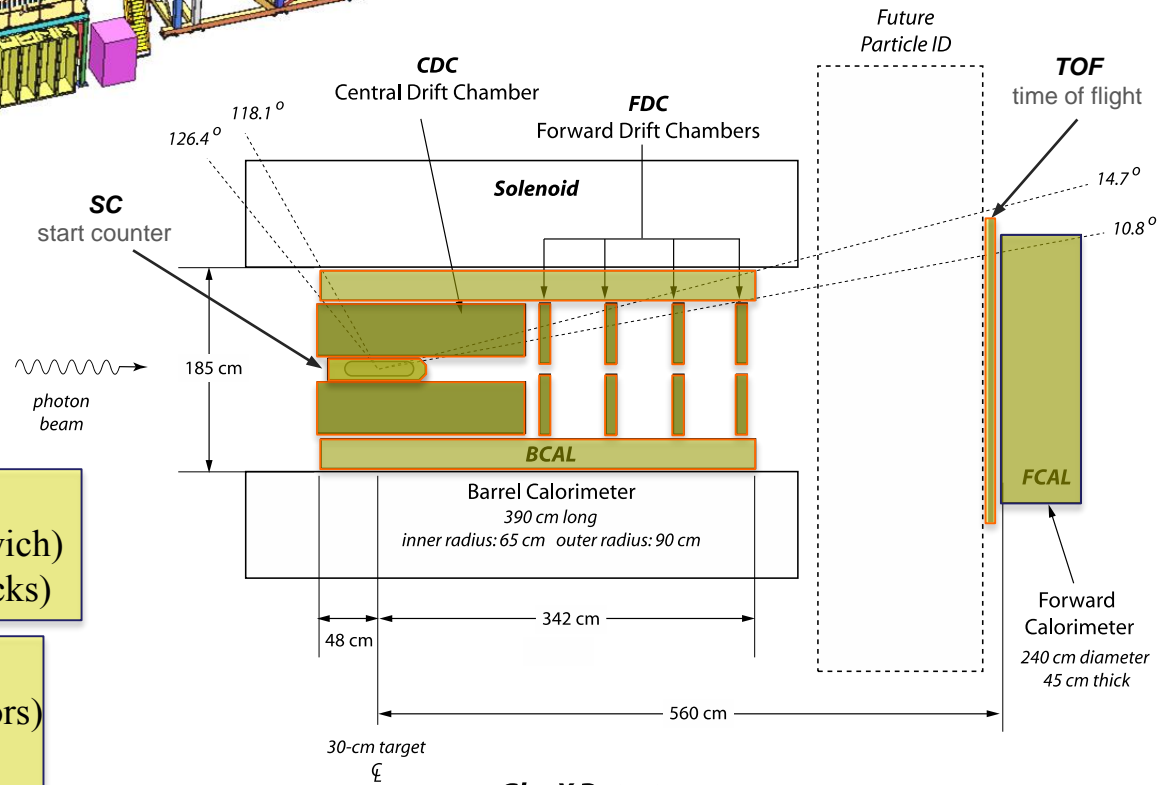
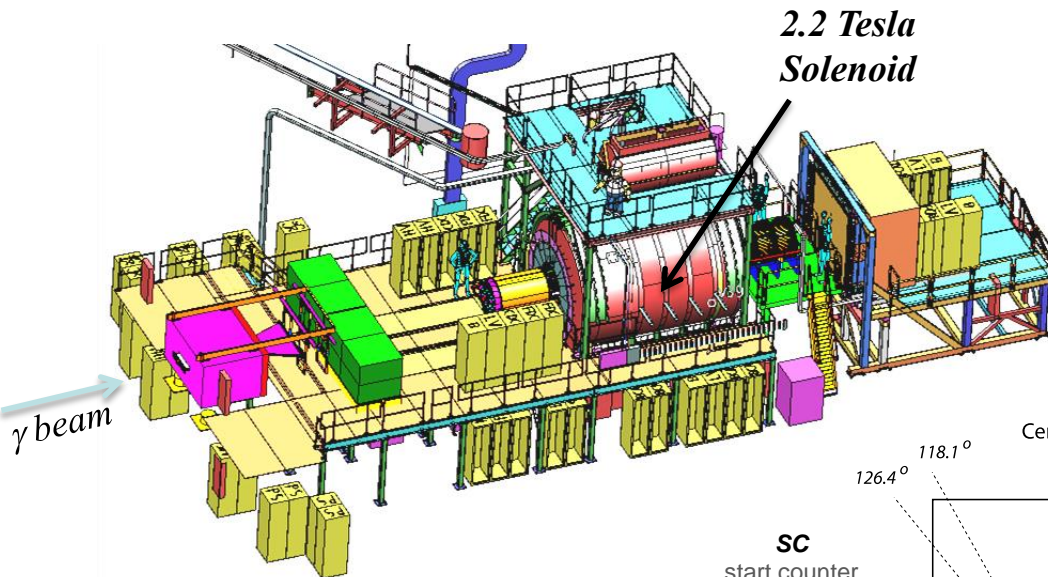
Fabrication at CUA

Thinning and testing of thin crystals

- UConn thinned a diamond to $40 \mu\text{m}$, $\sim 25 \mu\text{m}$
- GlueX goal is $20 \mu\text{m}$

The GlueX Detector

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

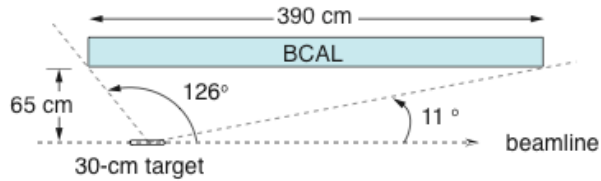
- Time of Flight wall (scintillators)
- Start counter
- Barrel Calorimeter

GlueX Detector

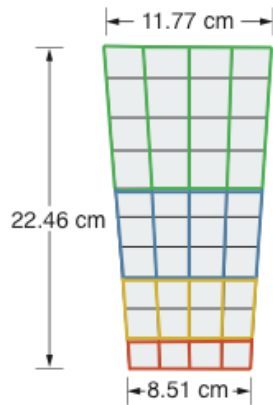
BCAL: Barrel Calorimeter

BCAL design modeled after KLOE EMC

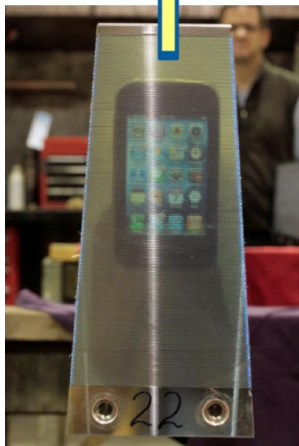
48 modules (phi sectors)



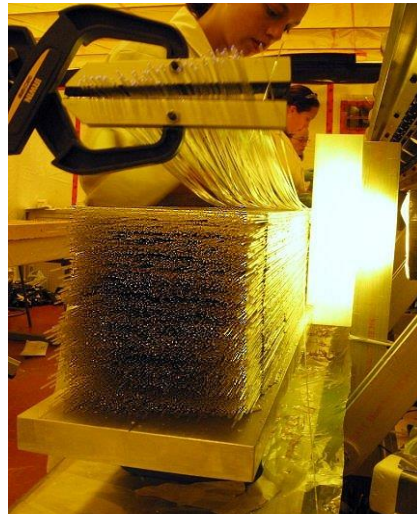
BCAL top half cutaway



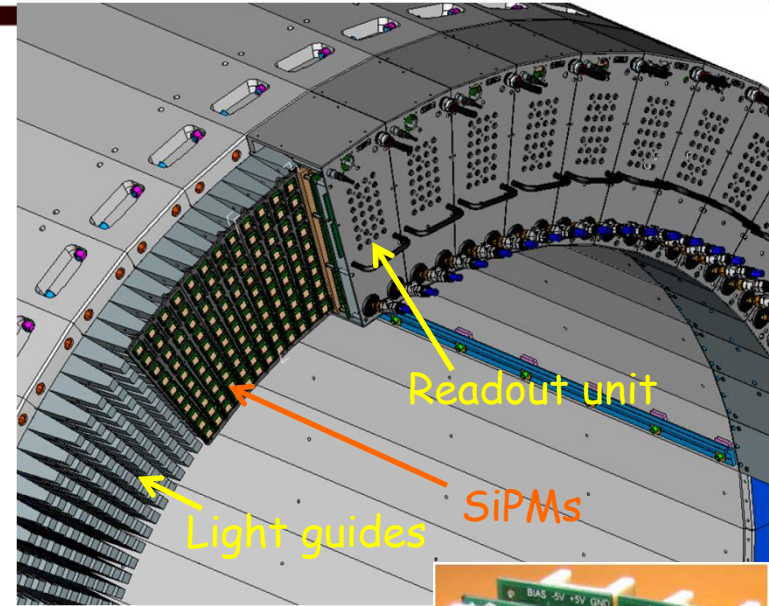
Readout:
4 X 6 + 4 X 4
= 40 SiPMs
per side,
grouped in
16 summecc
cells



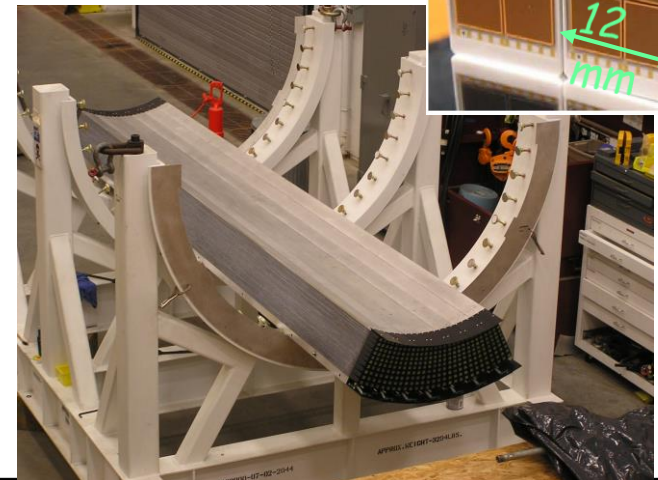
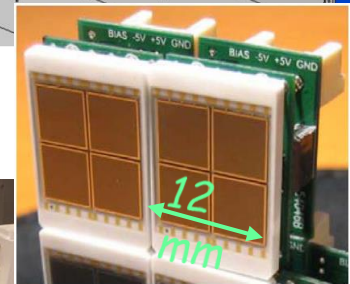
Completed BCAL module.
The iPhone is placed against
the opposing surface of the 4
meter module.



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)



Immune to
magnetic fields!



Forward Calorimeter

Lead Glass Calorimeter

- 2800 lead glass F8-00 blocks $4 \times 4 \times 45 \text{ cm}^3$
- PMTs FEU84-3
- Cockcroft-Walton bases

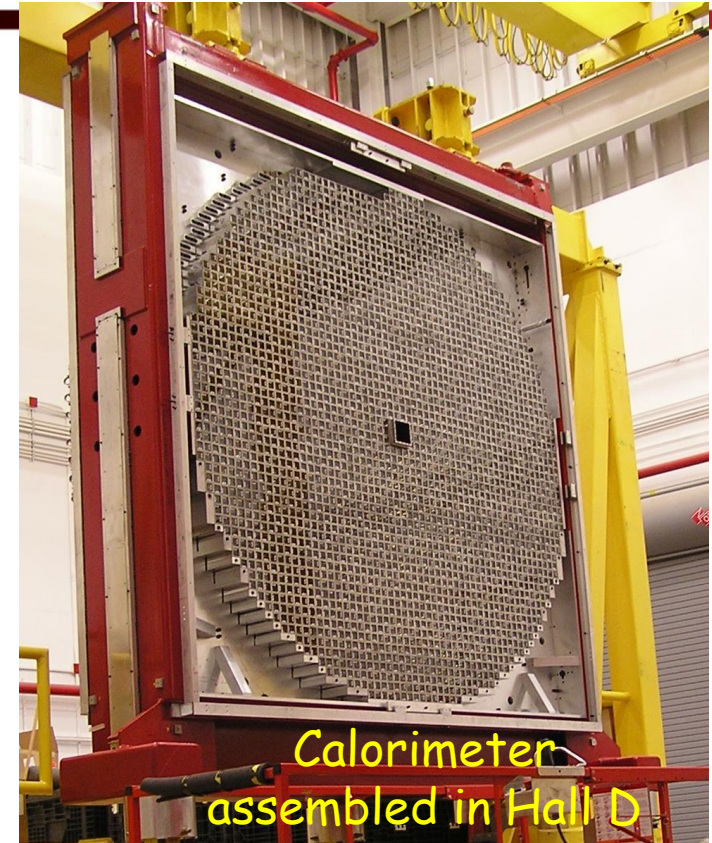
Fabricated at Indiana University

Beam test with e^- in Hall B, 2012

- $\sigma_E/E = 20\%$ at 100 MeV - as expected



Cockcroft-Walton bases
under test at IU



Calorimeter
assembled in Hall D



Single parts for module assembly

Charged Particle Tracking

Central Drift Chamber (CDC):

Gas mixture: ~60/40 Ar/CO₂

Angular Coverage: 6°-155°

3500 straw tubes r=8mm

dE/dx for p < 450 MeV/c

Readout: FADC-125MHz

Resolution: $\sigma_{r\phi} \sim 150 \mu\text{m}$

$\sigma_z \sim 1.5 \text{ mm}$

28 layers total

stereo layers: +/- 6°

Forward Drift Chamber (FDC):

Gas Mixture: 40/60 Ar/CO₂

Angular Coverage: 1° - 30°

Readout:

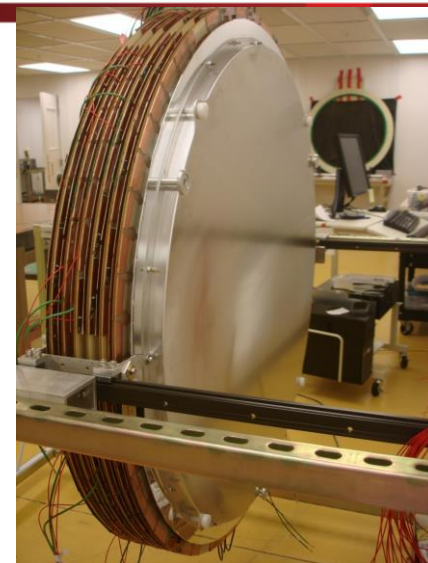
2300 anode wires → F1TDC

10200 cathode strips → FADC-125

3 measured projections per plane

Resolution: 200μm wires

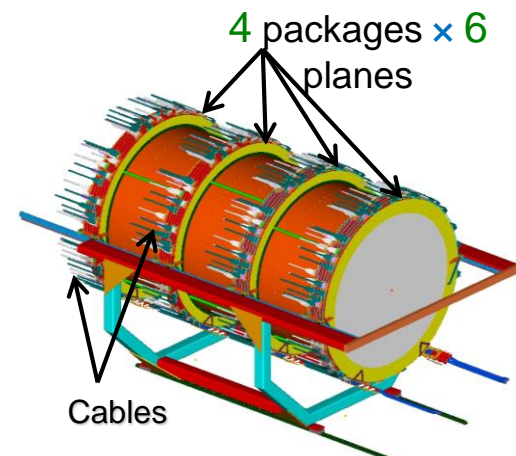
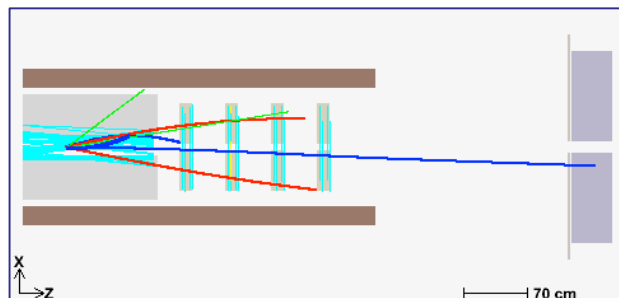
200μm strips



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



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



Electronics and Data Rates

Electronics

- All digitization electronics are fully pipelined (VME64x-VXS)
 - FITDC (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 $\sim 3 \mu\text{s}$
- 3GB/s readout from front end
- 300MB/s to mass storage
- 3PB/yr to tape

Sub-system Processor



Global Trigger Processor



FITDC



250MHz Flash ADC



Trigger Interface

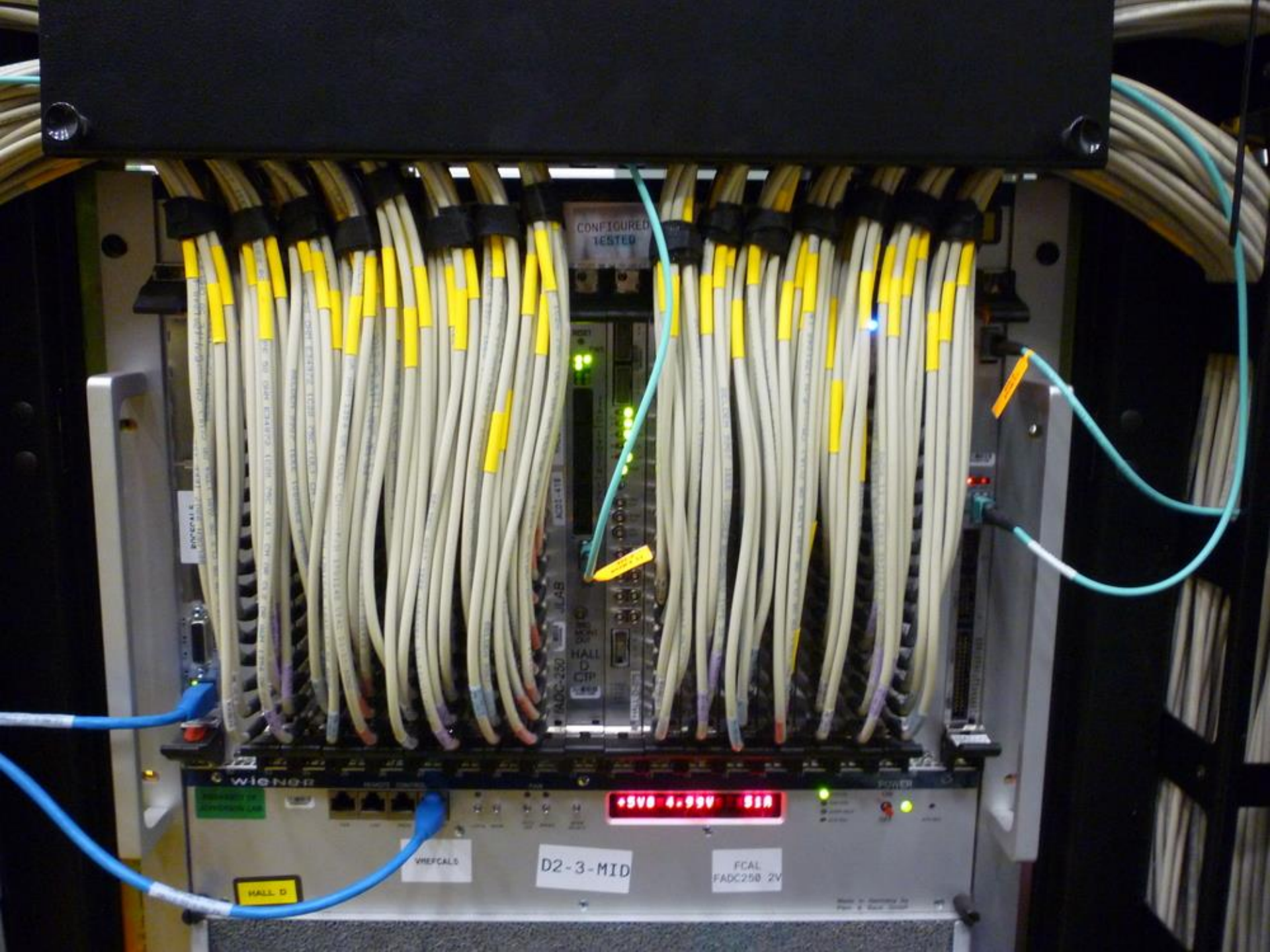


Crate Trigger Processor



Signal distribution board





CONFIGURED
TESTED

WRECAL5
FCAL FADC250 2V
D2-3-MID

FADC-250
LAB
HALL D
CTR

WISNER

+5V 4.99V 0.0A

WRECAL5

D2-3-MID

FCAL
FADC250 2V

HALL D

WISNER
FCAL FADC250 2V

GlueX Data Rates

David Lawrence, Jefferson Lab

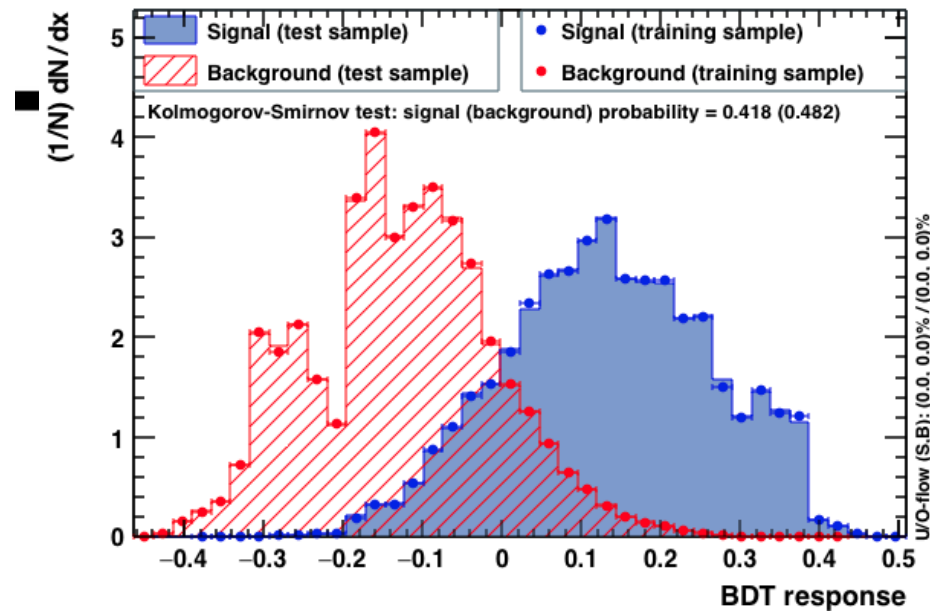
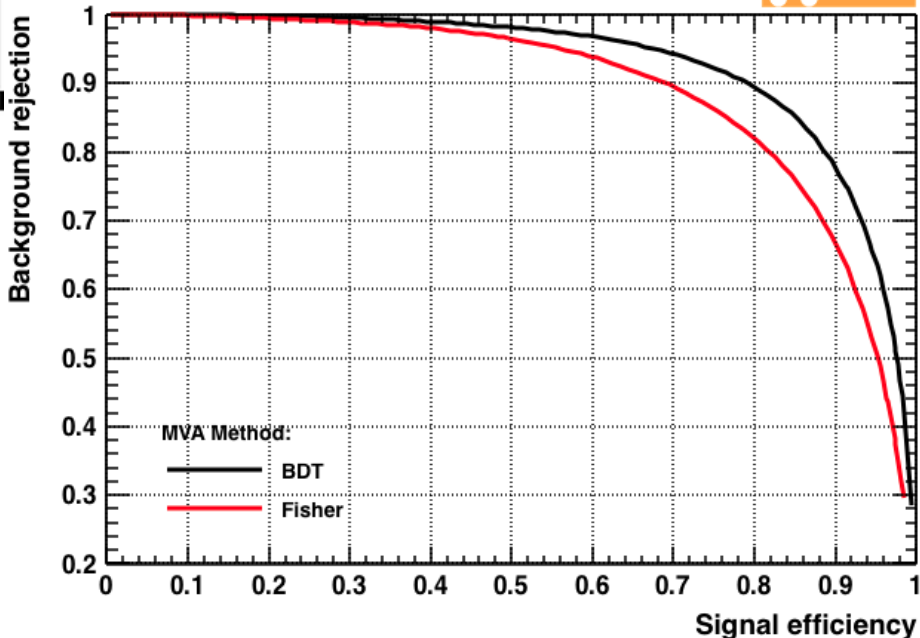
| | | Front End DAQ Rate | Event Size | L1 Trigger Rate | Bandwidth to mass Storage | |
|------|--------|-----------------------|---------------|--------------------|---------------------------------|-----------------------------------|
| JLab | GlueX | 3 GB/s | 15 kB | 200 kHz | 300 MB/s | private comm. |
| | CLAS12 | 0.1 GB/s | 20 kB | 10 kHz | 100 MB/s | |
| LHC | ALICE | 500 GB/s | 2,500 kB | 200 kHz | 200 MB/s | CHEP2007 talk Sylvain Chapelin |
| | ATLAS | 113 GB/s | 1,500 kB | 75 kHz | 300 MB/s | |
| | CMS | 200 GB/s | 1,000 kB | 100 kHz | 100 MB/s | |
| | LHCb | 40 GB/s | 40 kB | 1000 kHz | 100 MB/s | |
| BNL | STAR | 50 GB/s | 1,000 kB | 0.6 kHz | 450 MB/s | * |
| | 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 : Efcals_clusters : 1.917e-01
--- BDT      : 2 : Ntrack_candidates : 1.710e-01
--- BDT      : 3 : Nfcals_clusters : 1.279e-01
--- BDT      : 4 : Nbcals_points : 1.258e-01
--- BDT      : 5 : Npshits      : 8.291e-02
--- BDT      : 6 : Ebcals_points : 7.186e-02
--- BDT      : 7 : Ebcals_clusters : 6.445e-02
--- BDT      : 8 : Ntof         : 6.424e-02
--- BDT      : 9 : Nstart_counter : 5.138e-02
--- BDT      : 10 : Nbcals_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 $>4\text{GeV}$ of fully reconstructed energy*

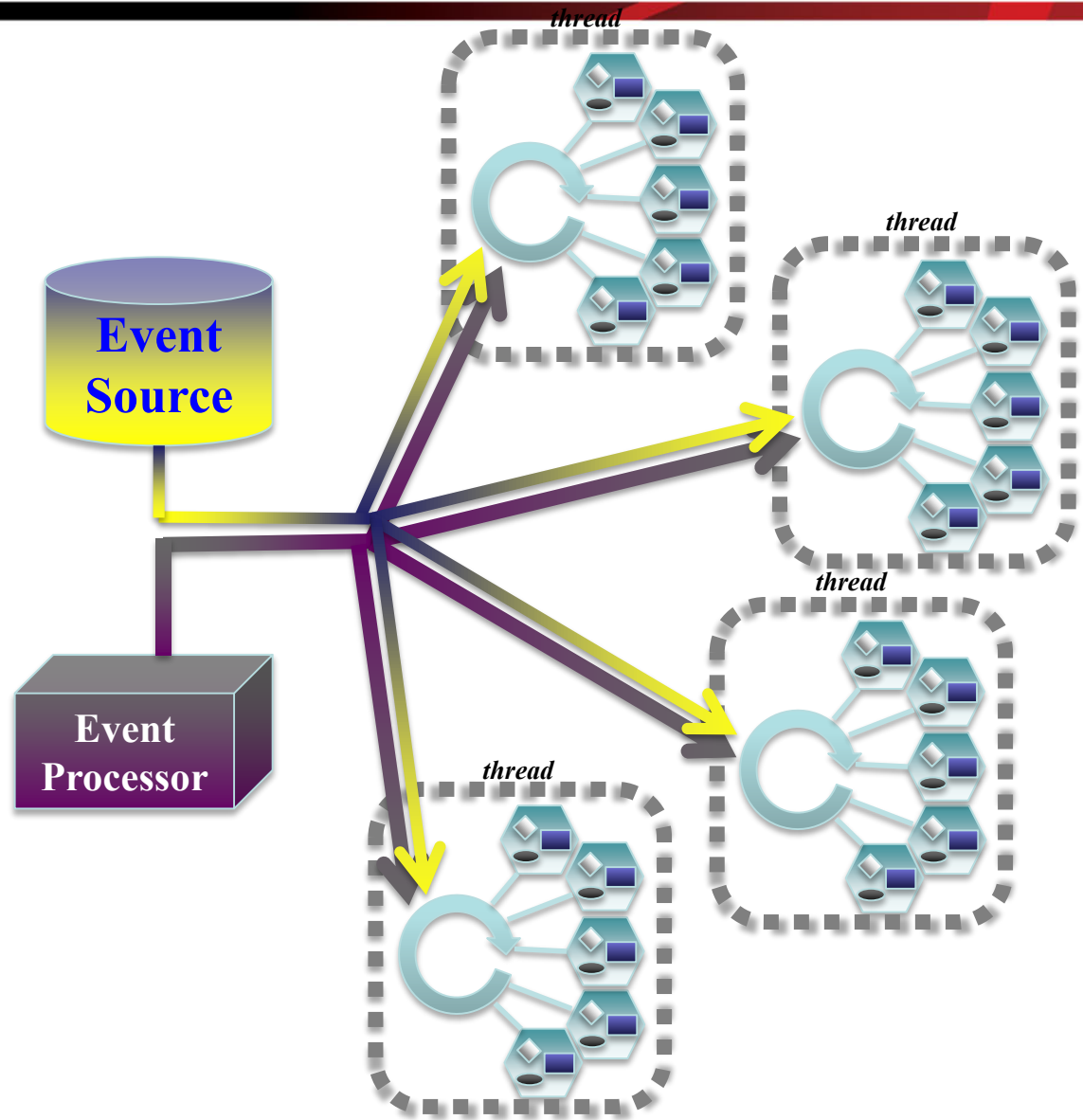
Types of “Parallel” Computing

- 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

```
297 // Multiply a 5x1 matrix by its transpose
298 inline DMatrix5x5 MultiplyTranspose(const DMatrix5x1 &m1){
299     ALIGNED_16_BLOCK_WITH_PTR(__m128d, 5, p)
300     __m128d &b1=p[0];
301     __m128d &b2=p[1];
302     __m128d &b3=p[2];
303     __m128d &b4=p[3];
304     __m128d &b5=p[4];
305     b1=_mm_set1_pd(m1(0));
306     b2=_mm_set1_pd(m1(1));
307     b3=_mm_set1_pd(m1(2));
308     b4=_mm_set1_pd(m1(3));
309     b5=_mm_set1_pd(m1(4));
310     return DMatrix5x5(_mm_mul_pd(m1.GetV(0),b1),_mm_mul_pd(m1.GetV(0),b2),
311         _mm_mul_pd(m1.GetV(0),b3),_mm_mul_pd(m1.GetV(0),b4),
312         _mm_mul_pd(m1.GetV(0),b5),
313         _mm_mul_pd(m1.GetV(1),b1),_mm_mul_pd(m1.GetV(1),b2),
314         _mm_mul_pd(m1.GetV(1),b3),_mm_mul_pd(m1.GetV(1),b4),
315         _mm_mul_pd(m1.GetV(1),b5),
316         _mm_mul_pd(m1.GetV(2),b1),_mm_mul_pd(m1.GetV(2),b2),
317         _mm_mul_pd(m1.GetV(2),b3),_mm_mul_pd(m1.GetV(2),b4),
318         _mm_mul_pd(m1.GetV(2),b5));
319 }
```

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

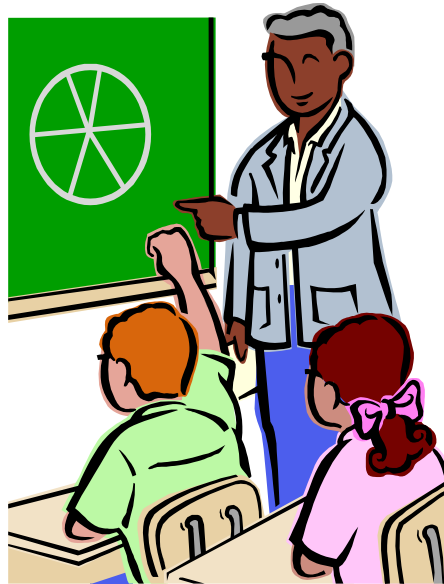
GPU 03011 CPU 100% FPS 6



Summary

- Many hardware and software technologies are needed to perform modern particle 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



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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

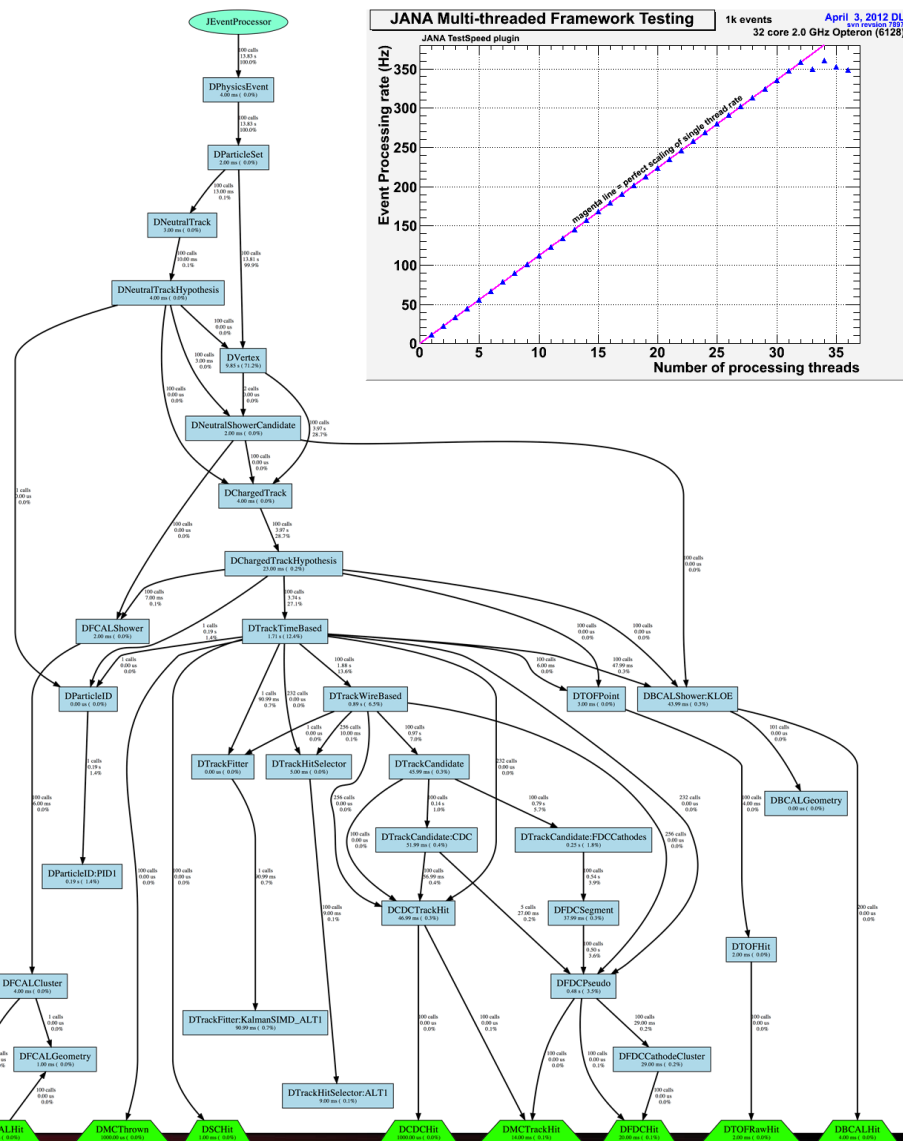
Farms will play a role in the future due to power supply and dissipation

(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 $\pm 1-2\%$)

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

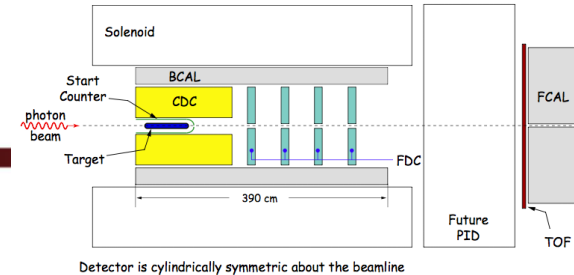
- *~10% of people are left-handed*
- *Theory: this is due to need for physical cooperation*
- *My hypothesis: Physicists need less physical cooperation so have higher percentage of lefties*

Hall D: Detector Design Parameters

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

Particle ID

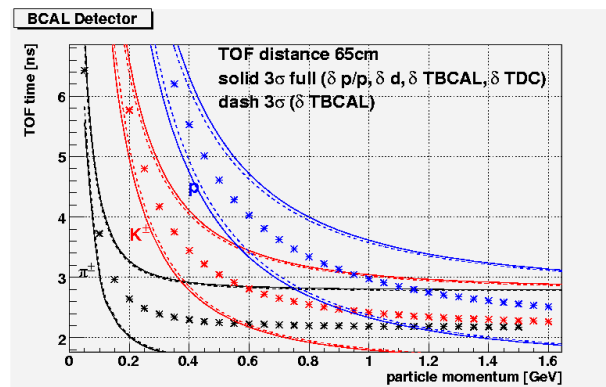
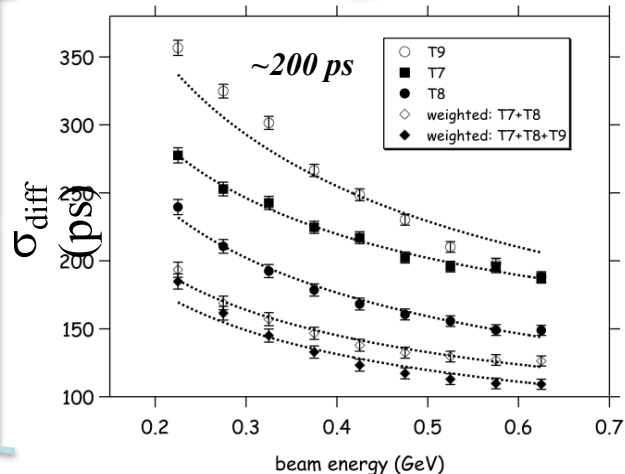
Particle ID is done primarily through time of flight with some help from dE/dx in chambers. Space is left in design for a future PID detector.



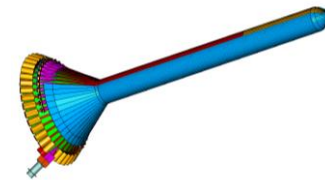
Beam Test Data

Expected Separation

Barrel Calorimeter

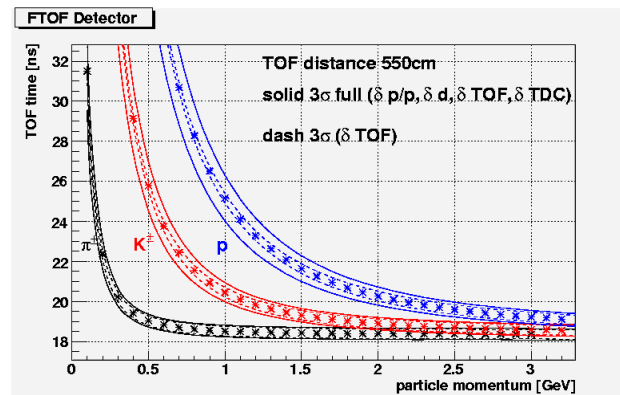
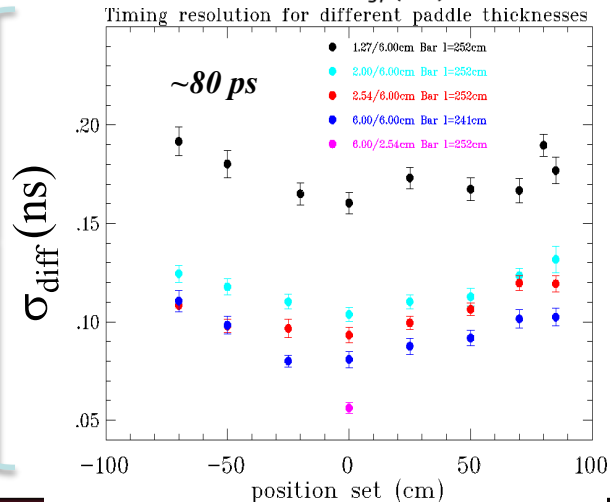


Start Counter

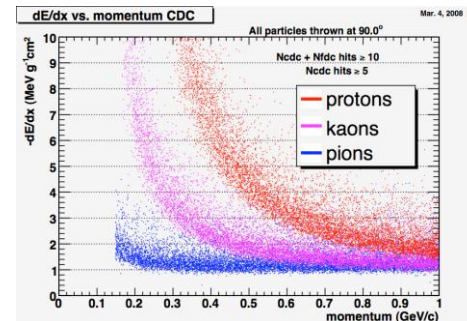


- 40 scintillators
- 300 ps (w/tracking)
- Used for start-up

Forward TOF



CDC dE/dx



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

A single $\gamma p \rightarrow pb_1\pi$ event

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

Source: hdgeant_b1_pi.hddm

View Controls

[-X] [X+] [ZOOM] [-] [+] Transverse Coordinates
 [-Y] [Y+] [x/y] [r/phi]
 [-Z] [Z+] [Reset]

Event Controls

continuous
 <-- Prev Next --> delay: 0.25

Info

Run: -----
 Event: 7

Inspectors

[Track Inspector]
 [TOF Inspector]
 [BCAL Inspector]
 [FCAL Inspector]

[Quit]

X
Z

70 cm

Y
X

20 cm

Track Draw Options

DTrackCandidate: <default>
 DTrack: <default>
 DParticle: <default>
 DMCThrown
 DMCTrajectoryPoint

Y
Z

70 cm

Y
X

30 cm

Hit Draw Options

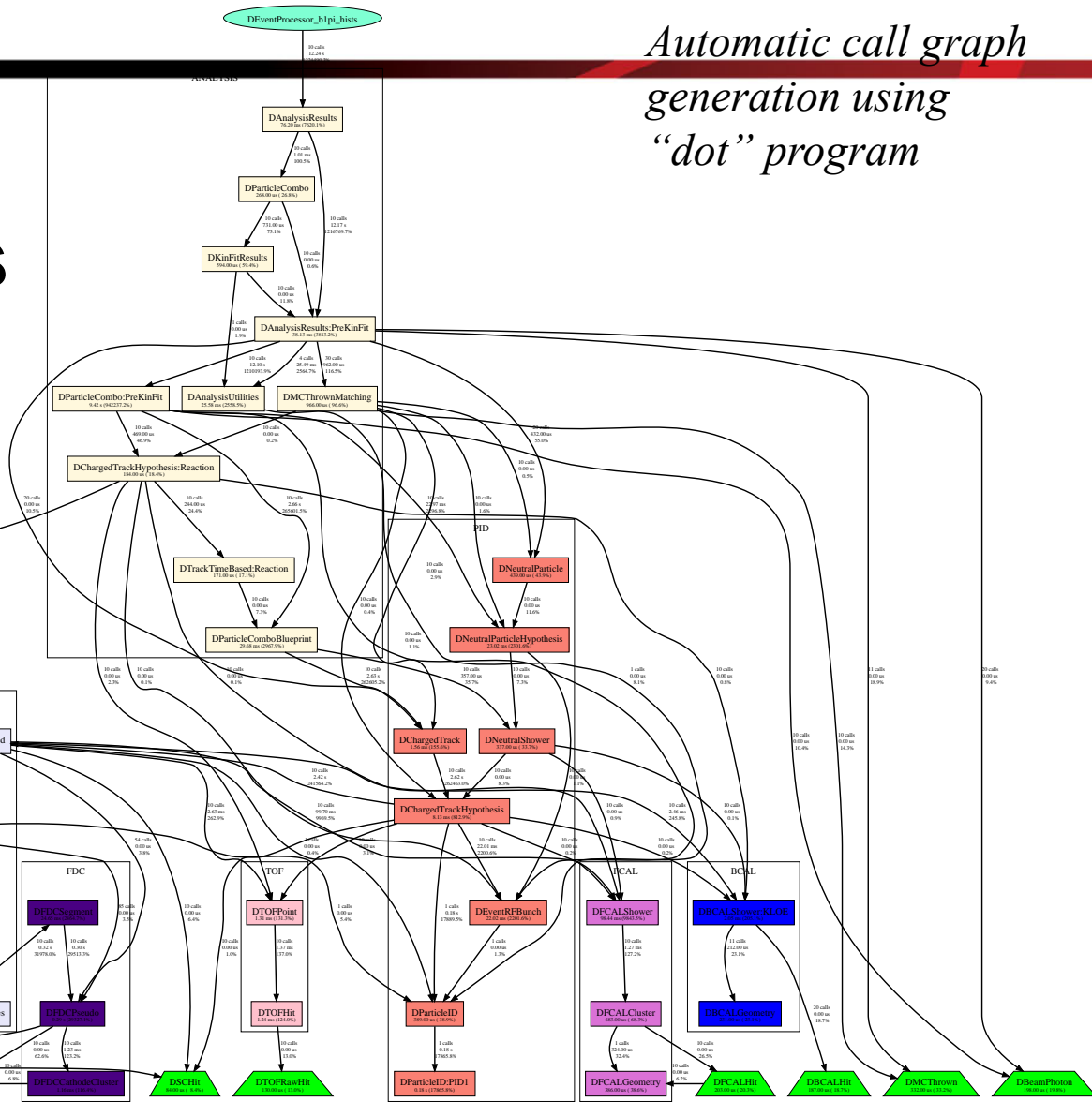
CDC
 CDC Drift Time
 CDCTruth
 FDC Wire
 FDC Pseudo
 FDC Intersection
 FDCTruth
 TOF
 TOFTruth
 FCAL
 FCALTruth
 BCAL
 BCALTruth

Track Info

| Thrown | | | | | | Reconstructed | | | | | | | |
|--------|-------|--------|--------|--------|----|---------------|-------|----|--------|------|----|-------------|-------|
| trk: | type: | p: | theta: | phi: | z: | trk: | type: | p: | theta: | phi: | z: | chisq/Ndof: | Ndof: |
| 1 | pi+ | 0.7602 | 28.36 | 0.9089 | 65 | 1 | | | | | | | |
| 2 | pi- | 1.576 | 14.48 | 5.772 | 65 | 2 | | | | | | | |
| 3 | gamma | 0.1373 | 36.89 | 6.216 | 65 | 3 | | | | | | | |
| 4 | gamma | 0.4698 | 14.87 | 0.9132 | 65 | 4 | | | | | | | |
| 5 | pi+ | 2.599 | 3.833 | 1.764 | 65 | 5 | | | | | | | |
| 6 | pi- | 3.023 | 13.38 | 2.693 | 65 | 6 | | | | | | | |

Automatic call graph generation using "dot" program

GlueX Reconstruction Software



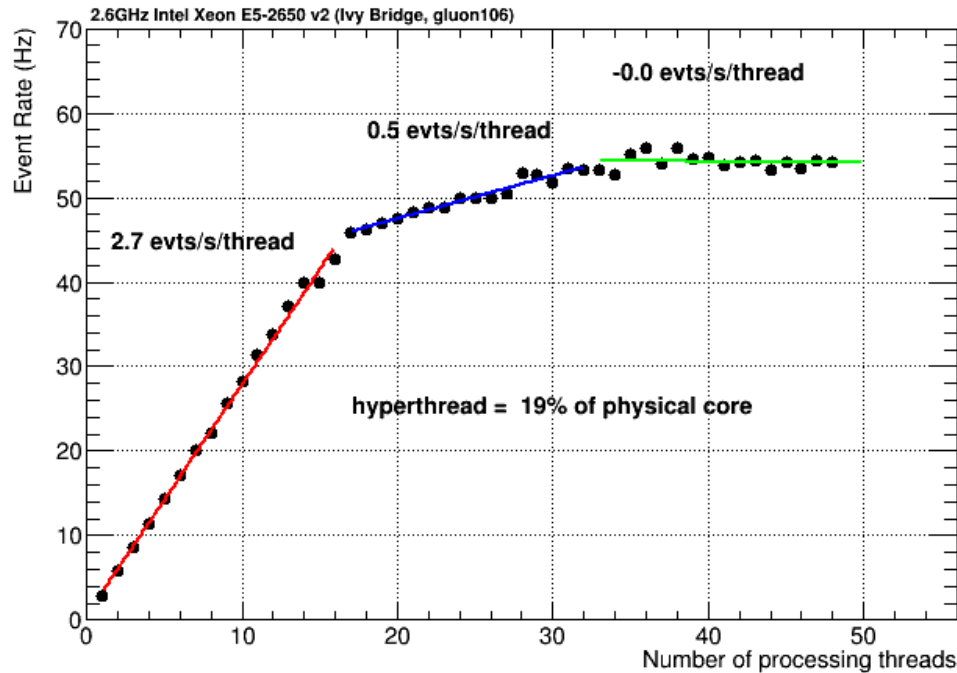
9/25/15

ANA

JANA rate scaling for CPU intensive task

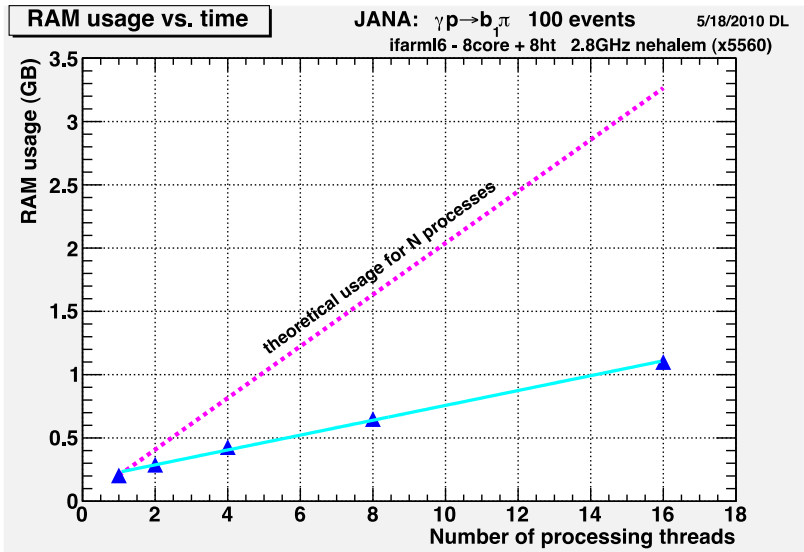
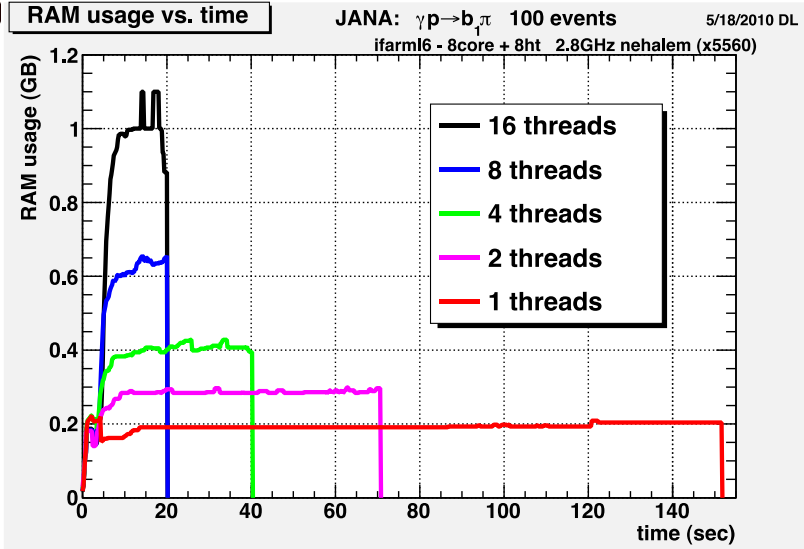
Integrated rate vs. number of threads

January 22, 2015 DL
JANA svn 2115 (pre0.7.3)



JANA TestSpeed with 100K GOVERNOR_ITERATIONS

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

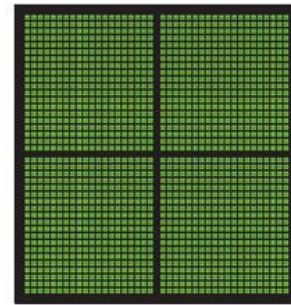
(e.g. Intel has ...)

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

GPU - Example CUDA code



CPU
MULTIPLE CORES



GPU
THOUSANDS OF CORES

Standard C Code

```
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

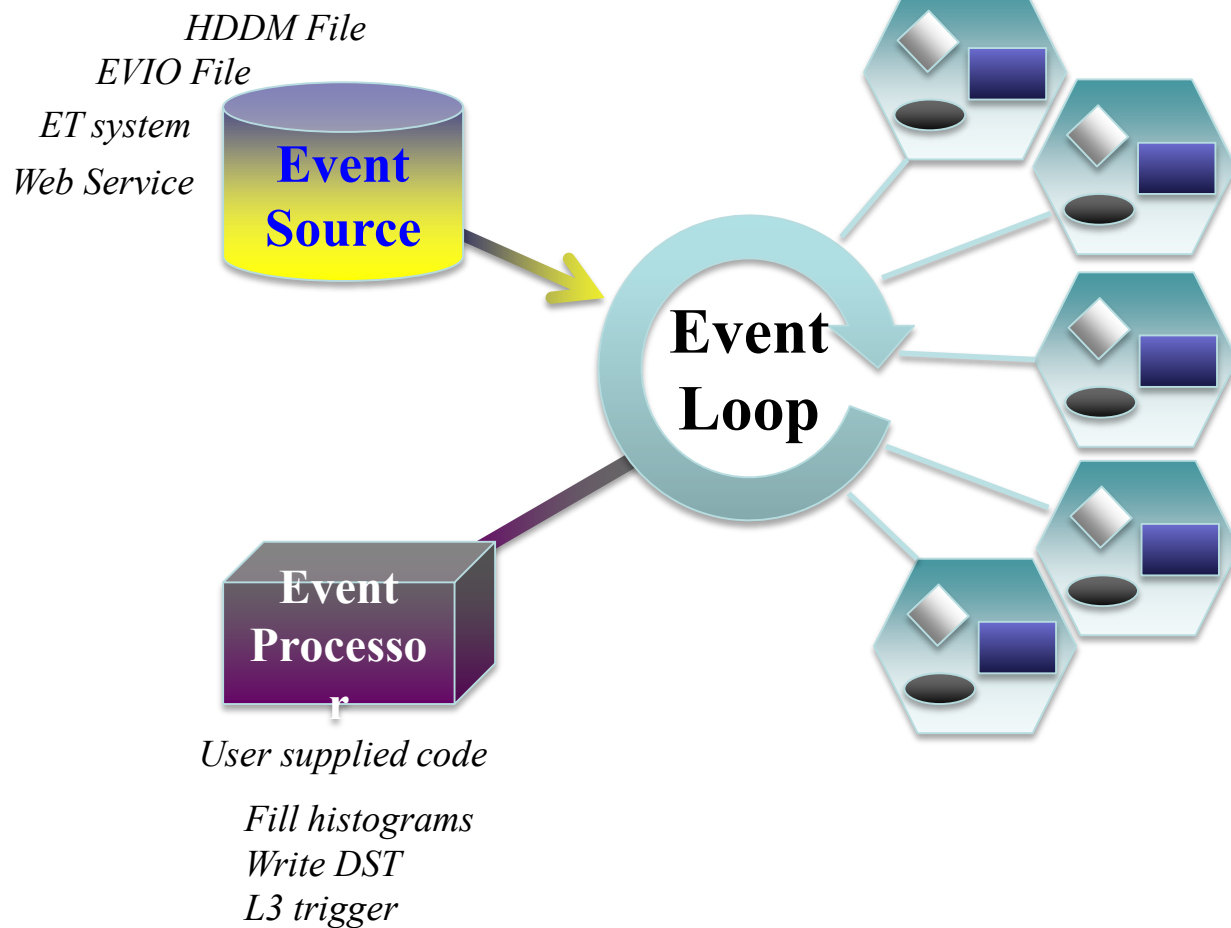
```
__global__
void saxpy(int n, float a,
           float *x, float *y)
{
    int i = blockIdx.x*blockDim.x + threadIdx.x;
    if (i < n) y[i] = a*x[i] + y[i];
}

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



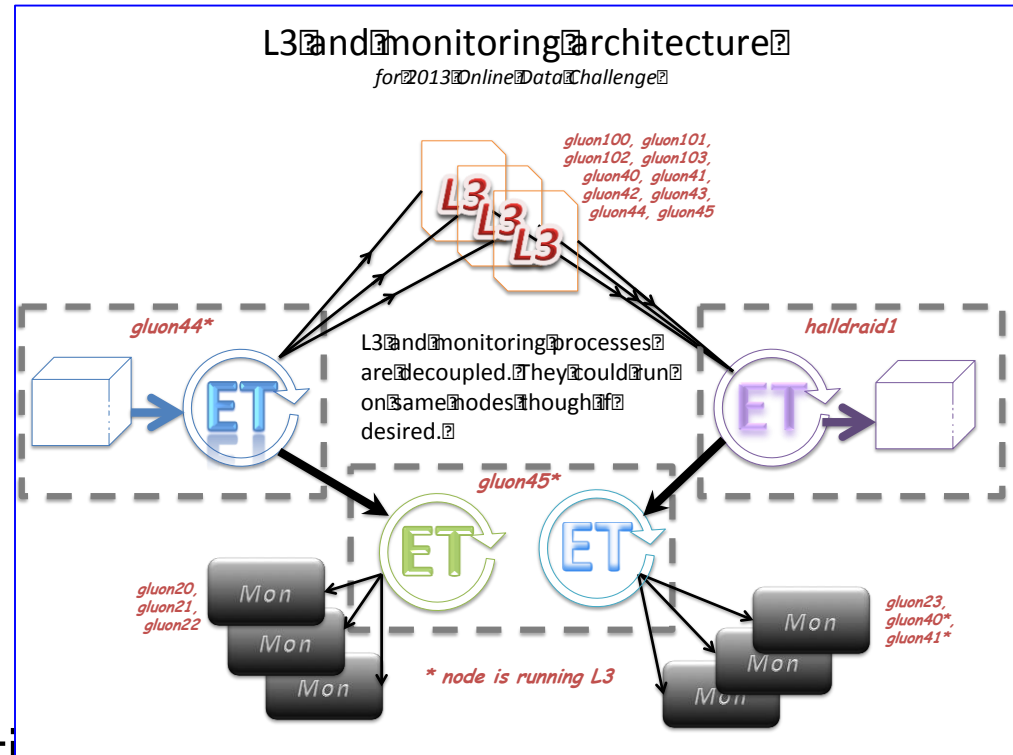
Framework has a layer that directs object requests to the factory that completes it

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

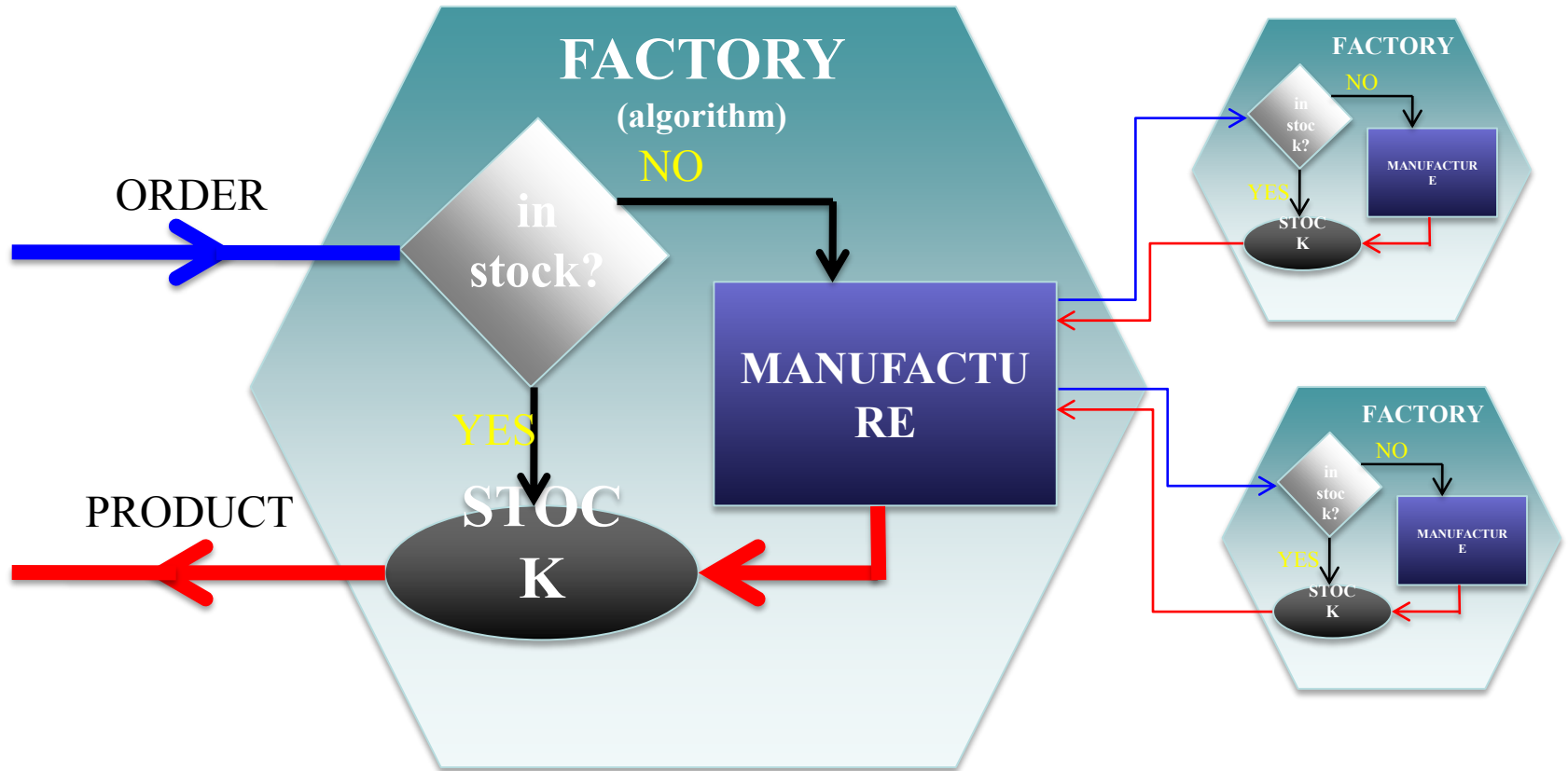
Distributed Computing with JANA

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



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

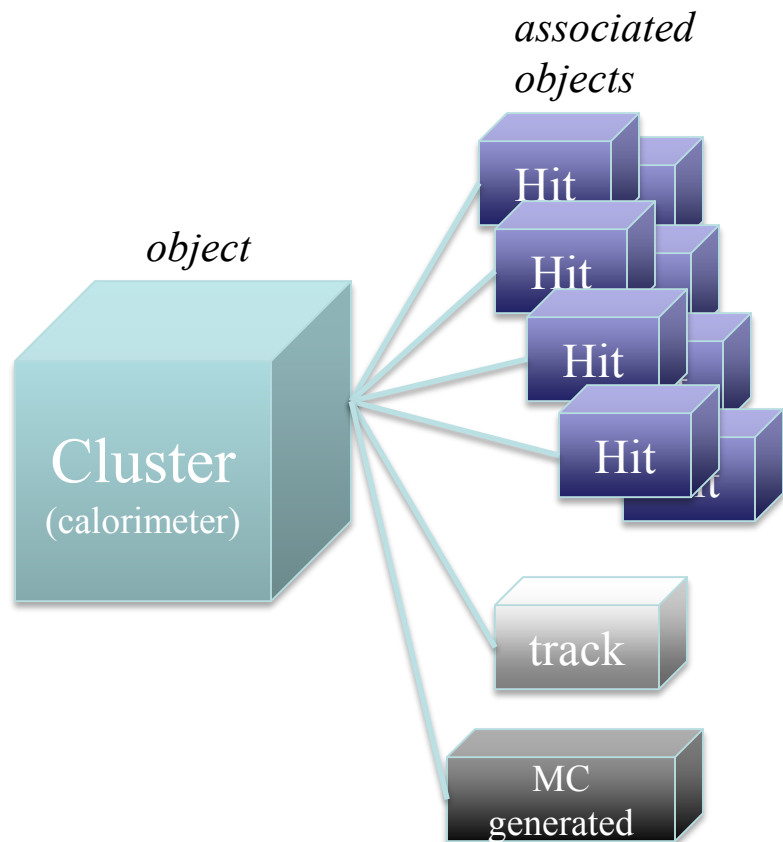
Factory Model



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 ...  
}
```