Detector Technologies in PHENIX at RHIC:

Memory Lane and Fantasy Land

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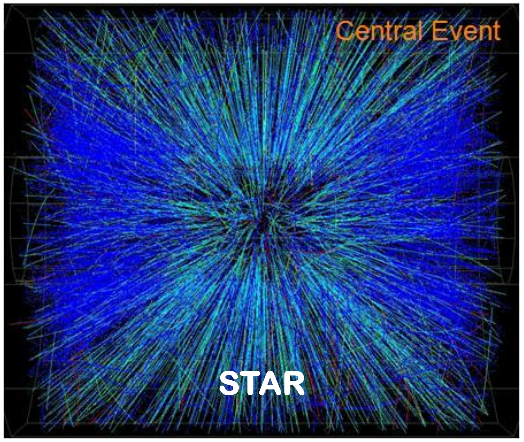
STONY BROOK
STATE UNIVERSITY OF NEW YORK

RHIC Specifications

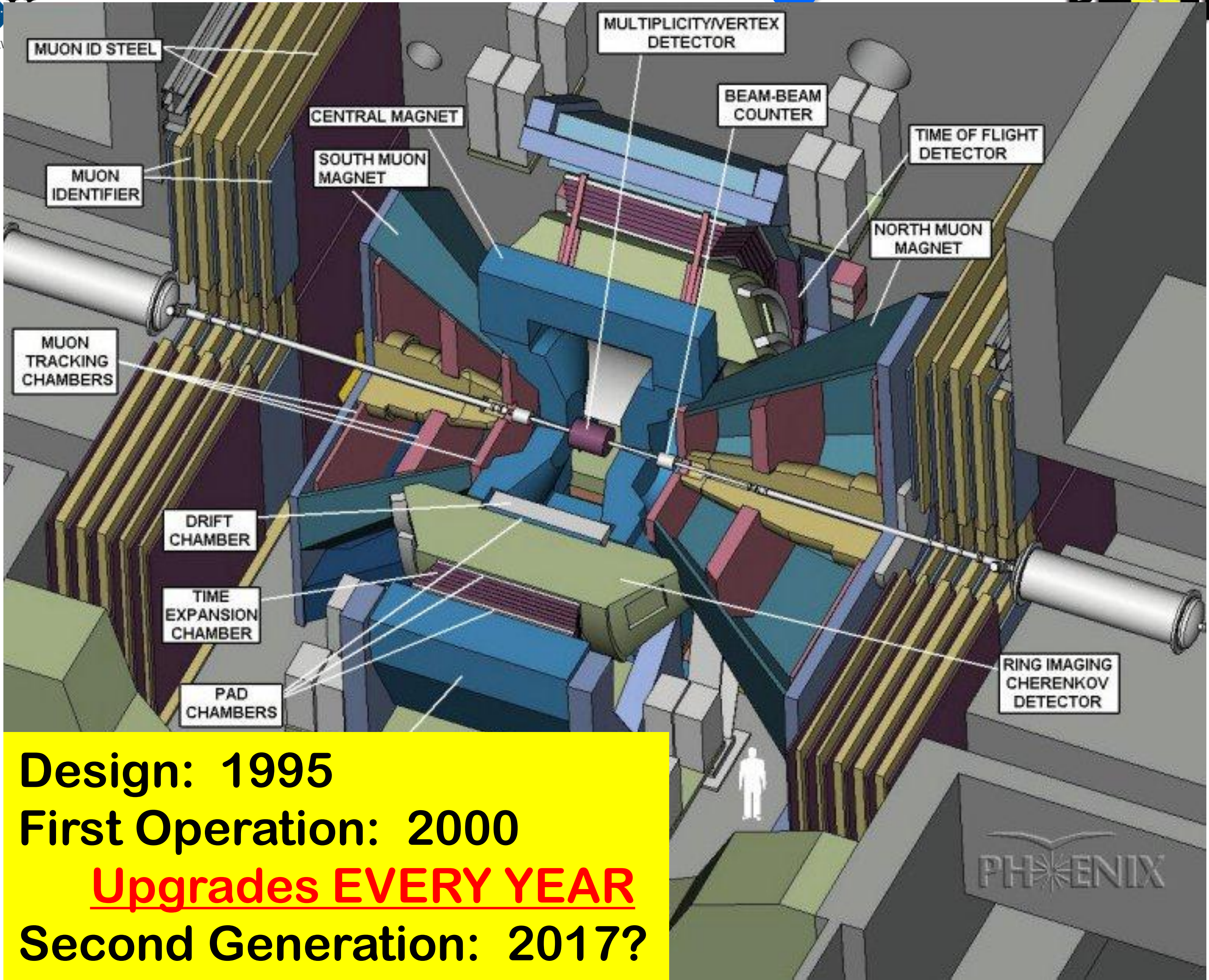
PHENIX

- **3.83 km circumference**
- **Two *independent* rings**
  - ❑ **120 bunches/ring**
  - ❑ **106 ns bunch crossing time**
- **Collides Any+Any**

  So far:
  - ❑ **AuAu, pp, dAu, CuCu, UU, CuAu**
- **Top Center-of-Mass Energy:**
  - ➔ **500 GeV for p-p**
  - ➔ **200 GeV/nucleon for Au-Au**



PHENIX Design



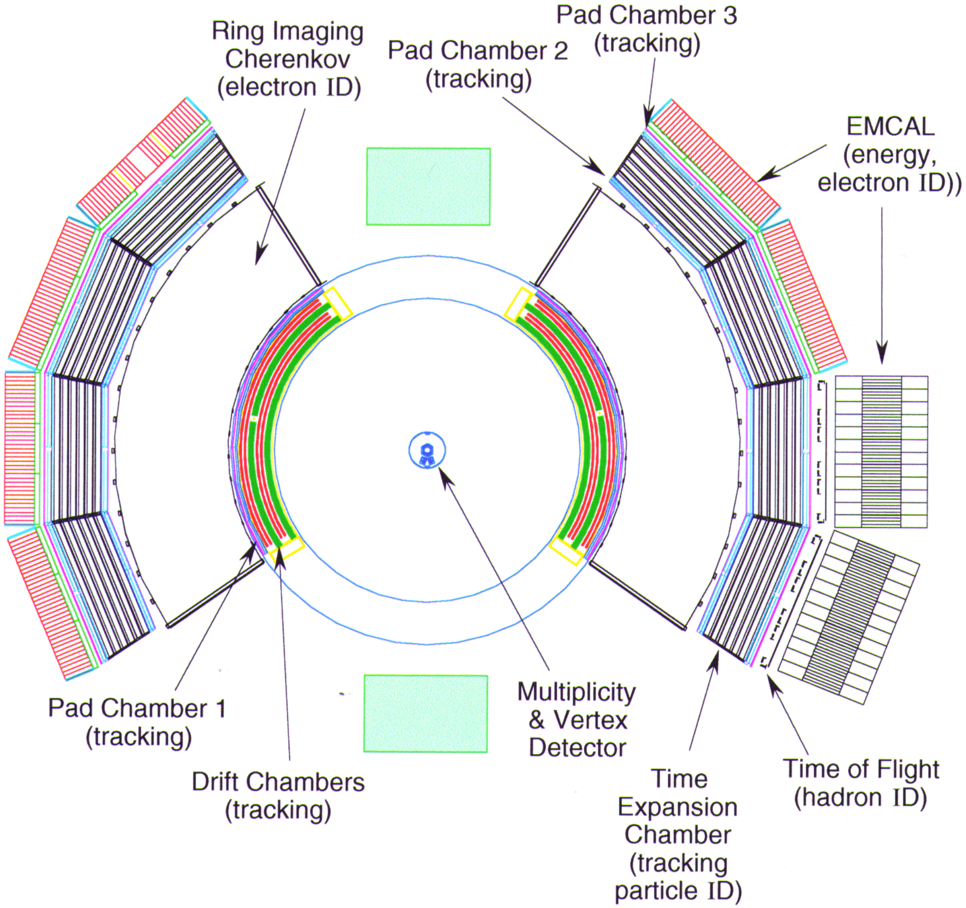
Design: 1995

First Operation: 2000

Upgrades EVERY YEAR

Second Generation: 2017?

Central Arms



Ring Imaging Cherenkov (electron ID)

Pad Chamber 2 (tracking)

Pad Chamber 3 (tracking)

EMCAL (energy, electron ID))

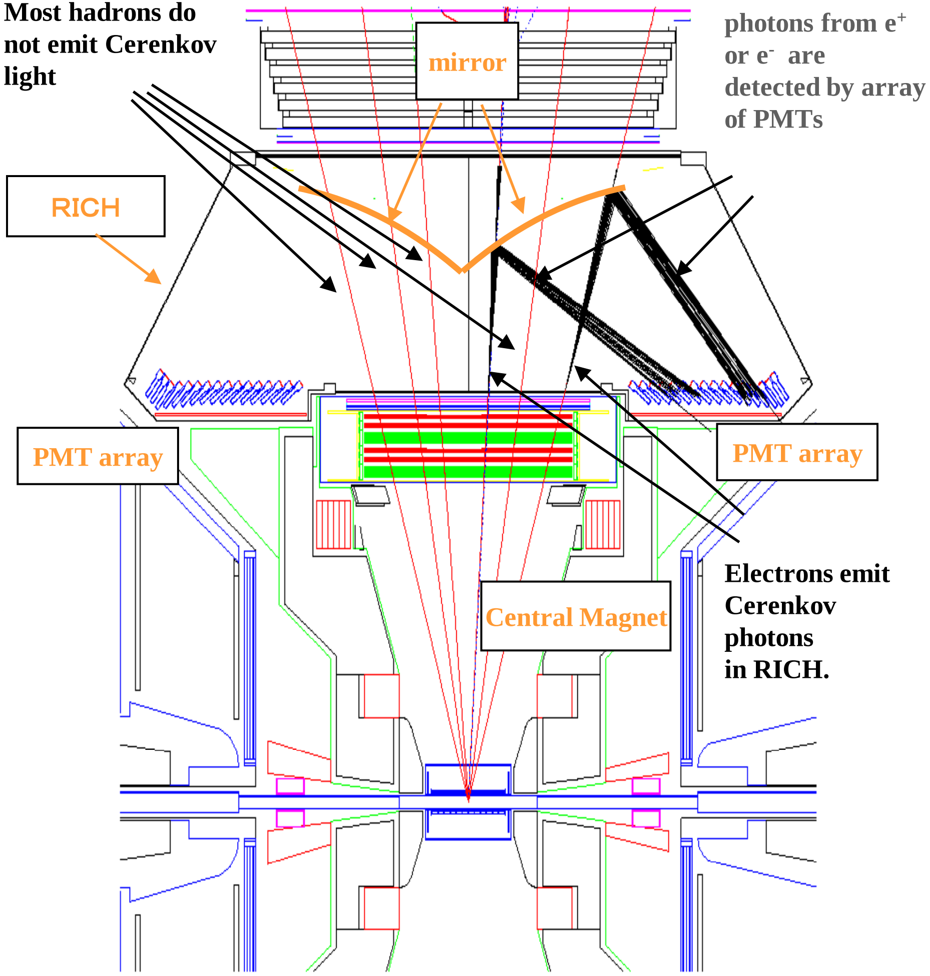
Pad Chamber 1 (tracking)

Drift Chambers (tracking)

Multiplicity & Vertex Detector

Time Expansion Chamber (tracking particle ID)

Time of Flight (hadron ID)



Most hadrons do not emit Cerenkov light

mirror

Cerenkov photons from e$^+$ or e$^-$ are detected by array of PMTs

RICH

PMT array

PMT array

Central Magnet

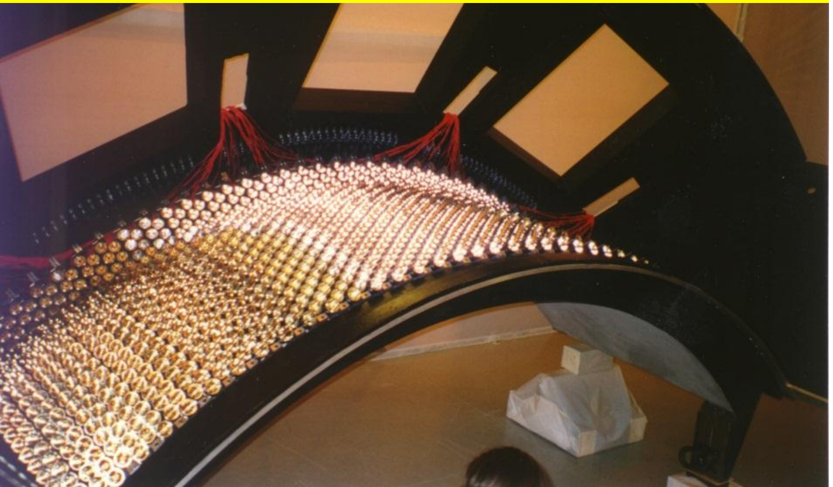
Electrons emit Cerenkov photons in RICH.

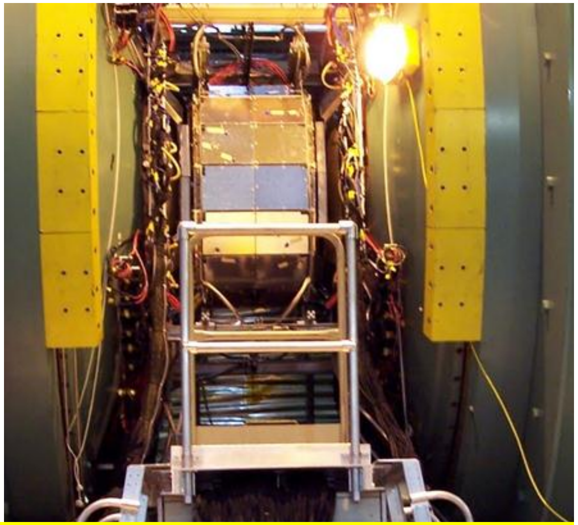
- Central Arms Optimized for electrons & photons

“Stony Brook” Detectors

Drift Chamber

Ring-Imaging Cherenkov Detector





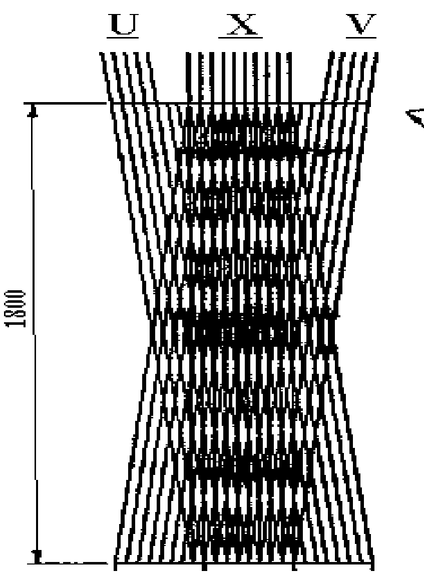
Hadron Blind Detector

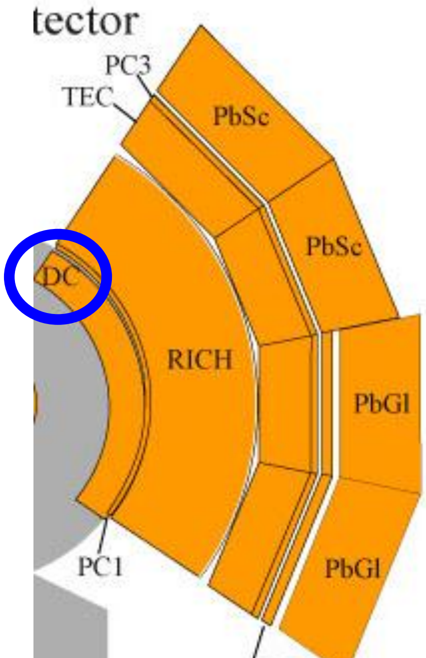
DC Construction


Second Drift Chamber

Designed and fabricated at PNPI (Gatchina, Russia).

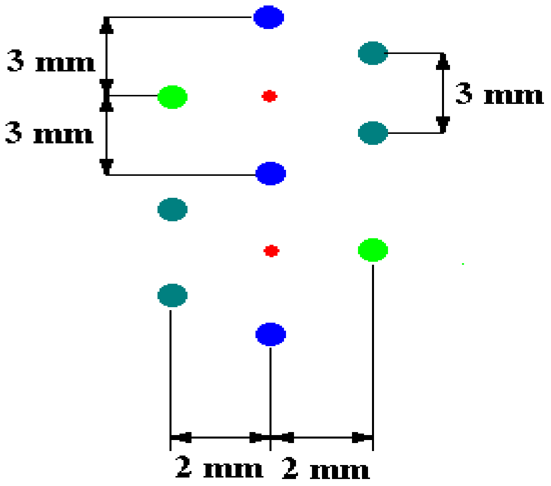
Components assembled at Stony Brook clean tent.

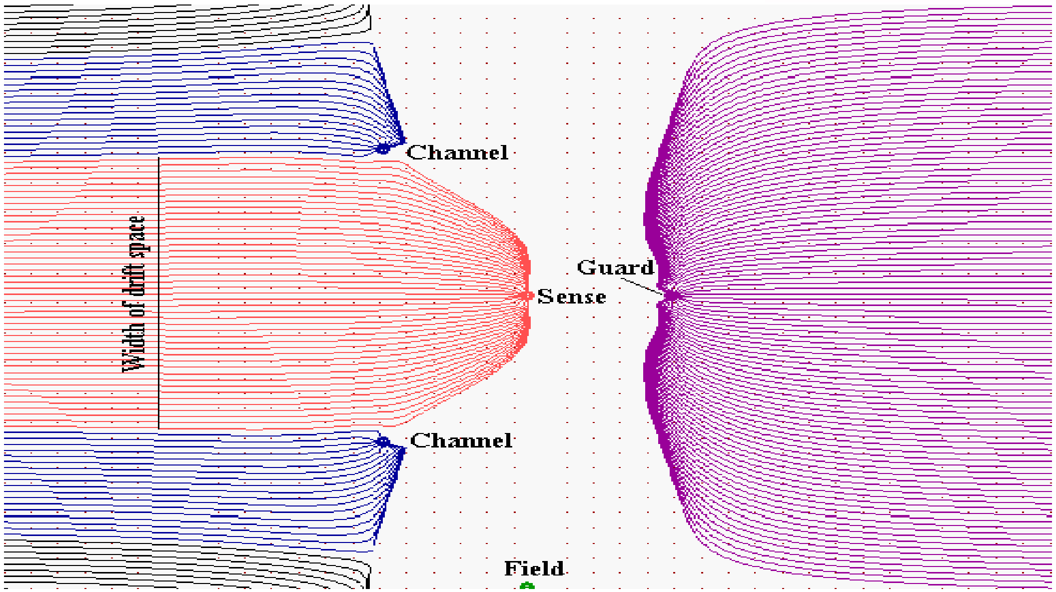





First Drift Chamber with Pad Chamber

Electrode Configuration





The PHENIX DC's utilize a focussing/protected field shape:

Anode (sense) wires are shielded from one side by a back (guard) wire.

(This configuration eliminates left-right ambiguity for most tracks.)

The drift space is controlled actively by gate (channel) wires.

(This minimizes charge collection time and improves two-track resolution.)

Potential (Field) wires control the gain of each cell.

Gain = ~1.4 x 10^4 **Sample Length = ~2.7 mm**

2-pulse separation = 1.5 mm **Efficiency = ~99% per wire**

Onboard Digitization

- All digitization onboard detector.
- ASD8 amp/discriminator.

2 fC w/o chamber, 5 fc with chamber.

- TMC time digitizer

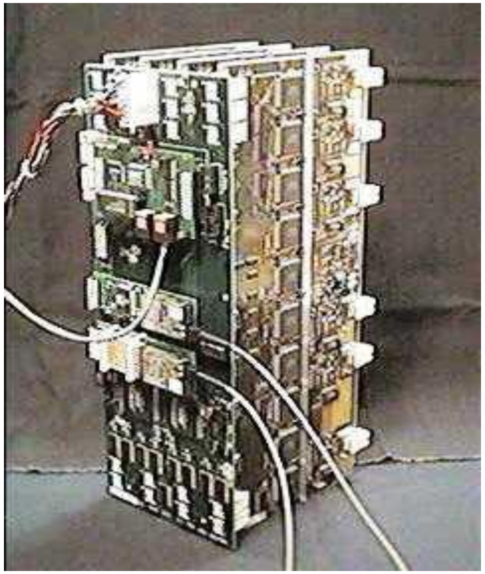
Multi-hit, 0.8 nsec least count,
6.4 μsec latency.

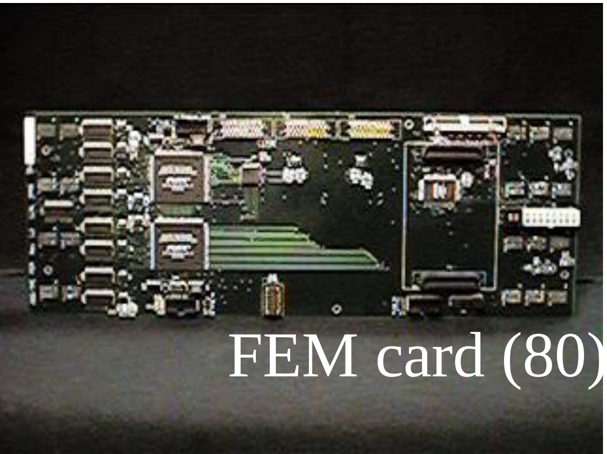
- Glink Optical Fibers

0.75 Gbps, carries triggers into FEM, carries data out of FEM.

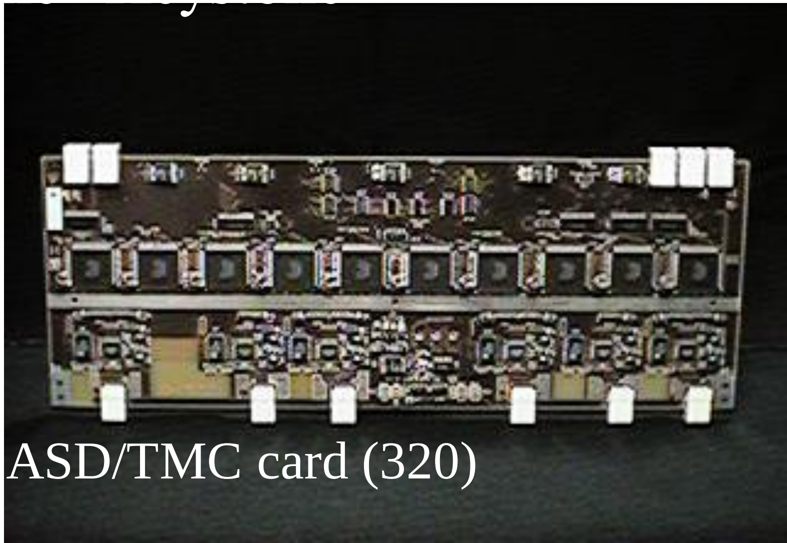
- ARCNet twisted pair

Slow controls, 2 Mbps, 100 Ω, user-defined protocol allows for compact messages.



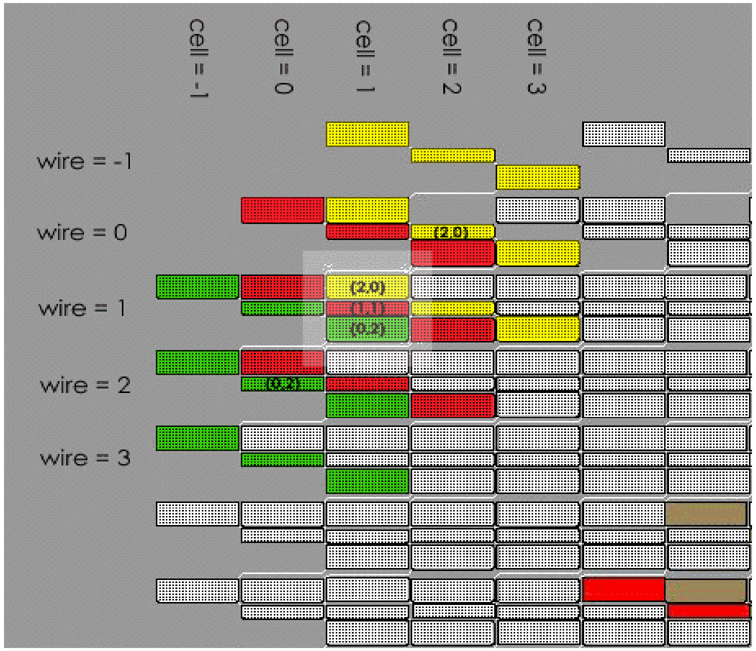


FEM card (80)



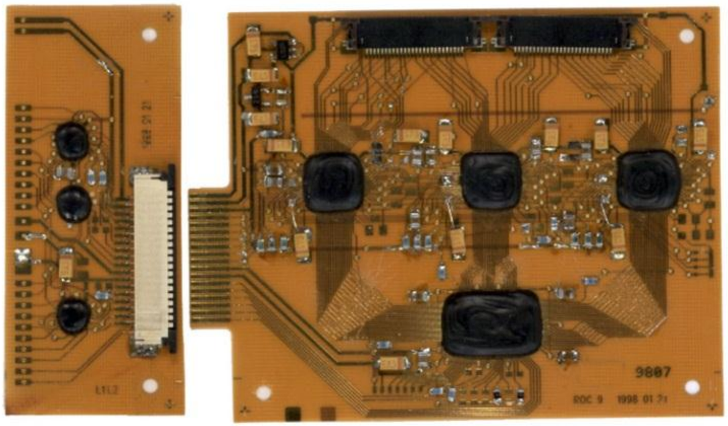
ASD/TMC card (320)

Pad Chamber Pixels



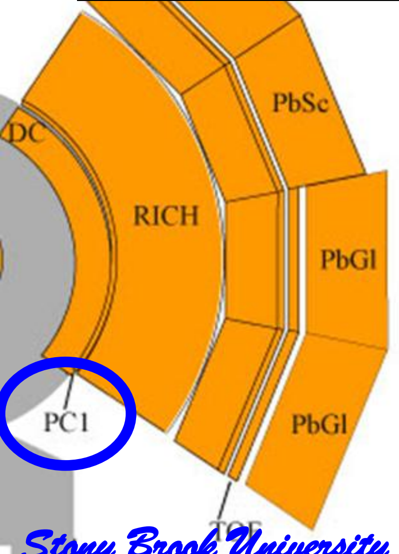
The highlighted area shows the first complete cell, with index cell=1, wire = 1.

PAD CHAMBER READOUT CARD



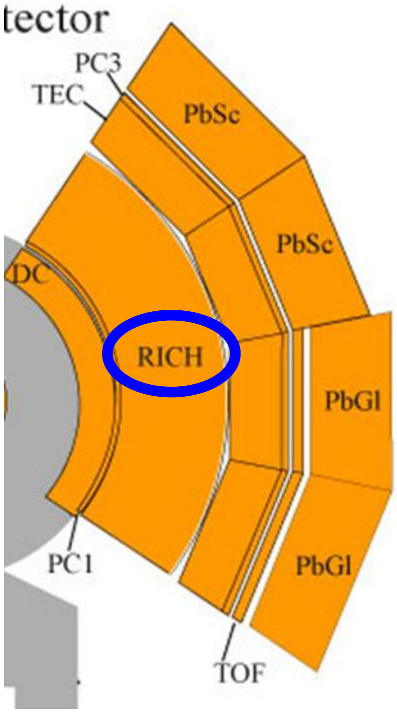
Connector card, solders on chamber.
3 RS485 diff-CMOS translator chips

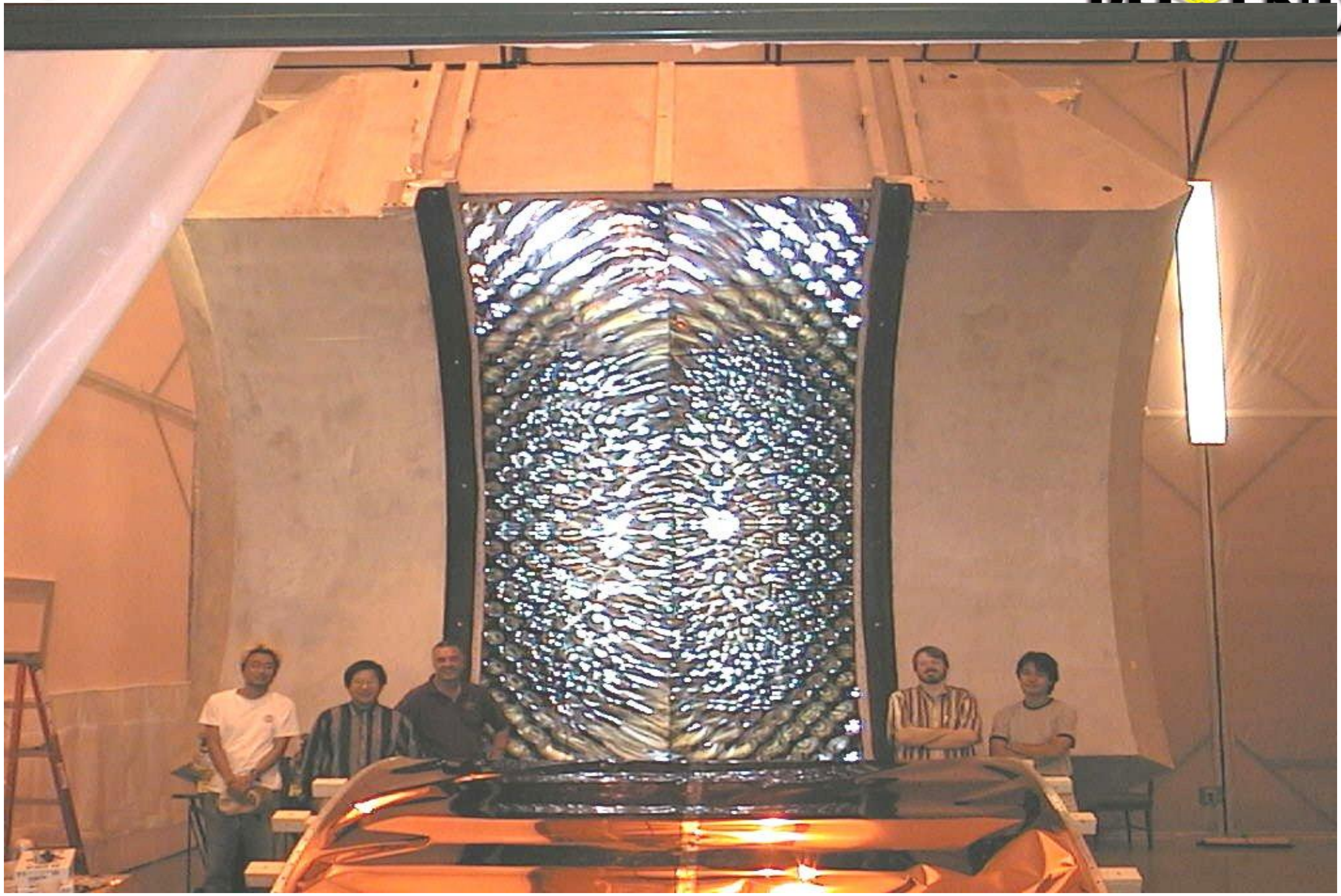
Readout card, for 48 channels. 3 amplifier/discriminator chips (TGL98) and one Digital Memory chip(DMU). Mounted on 0.1mm fiberglass enforced Kapton. Total weight of whole assembly is 4 grams. Size 55*65mm ^{2}



- **"PIXEL-PAD": one avalanche on 3 pixels.**
- **Noise/efficiency (minimum = 2 hits).**
- **Improves resolution by 3X.**
- **Read-Out-Card threshold typically 2 fC.**
- **Bare Si chips wire-bonded to kapton substrates and "capped" w/ epoxy.**

Optics of the RICH

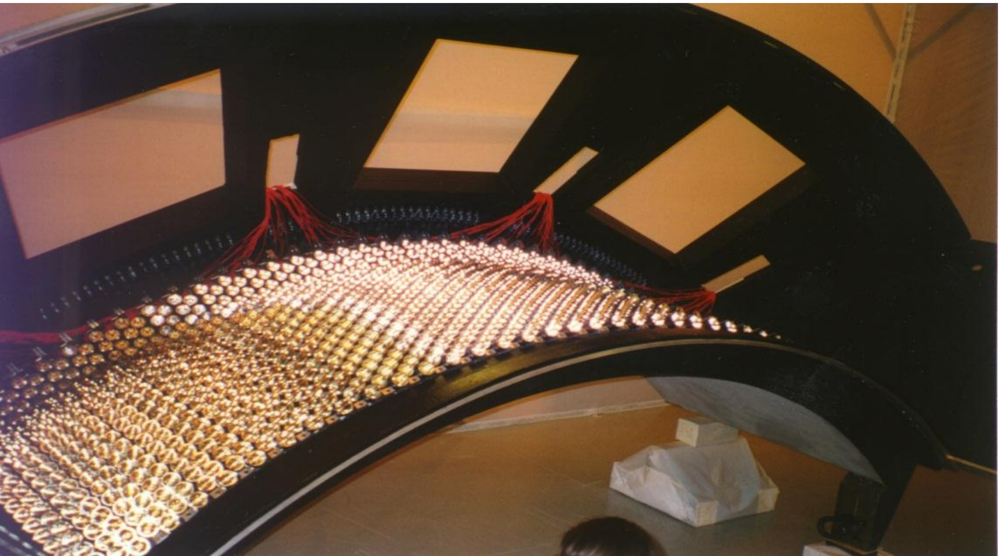




- Two spherical mirrors reflect light onto arrays of PMT’s.
- Magnet poles shield the PMTs from collision products.
- Offset focal plane has ellipse rather than circular images.

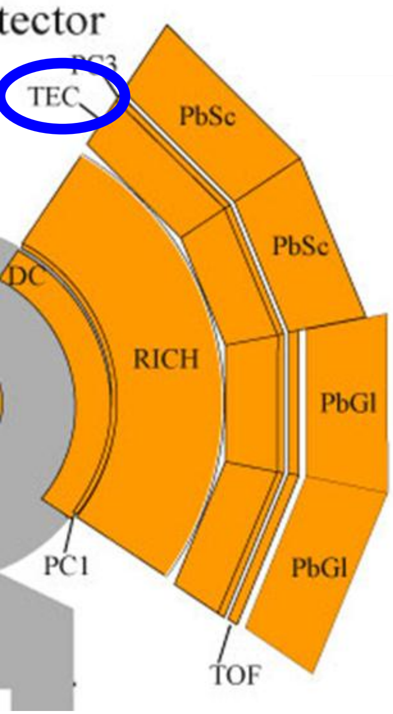
RICH Focal Place

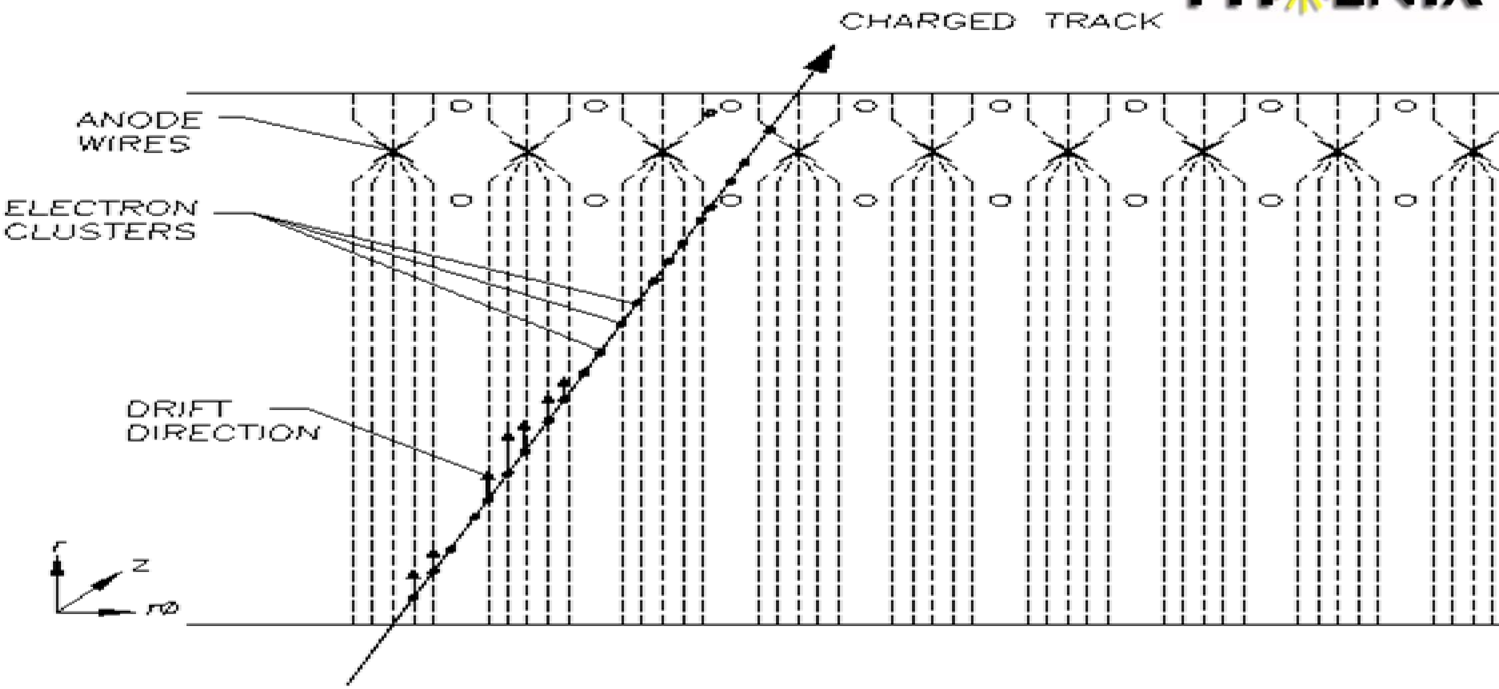
- 2560 PMTs, 10^7 gain.
- ~~Ethane~~ CO_2 radiator.
- 10^4 charge pion rejection.
- 1 degree ring res.
- N_0= 118.
- 12-18 p.e./ring
- C-fiber/Rohacell mirror 0.3% X_0



Thomas K Hemmick

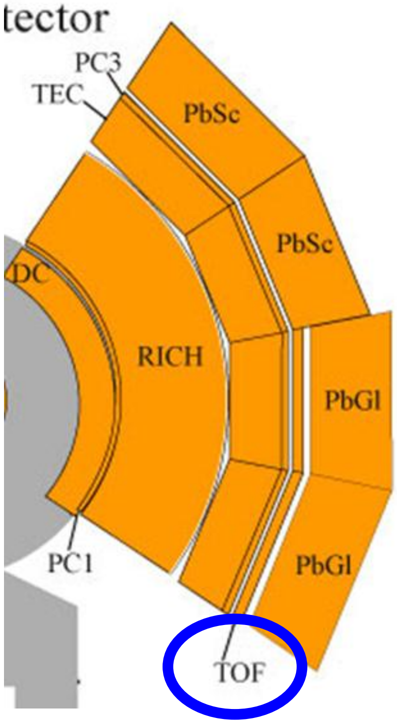
TEC Configuration





- **Drift direction primarily along track.**
- **Wire signal sampled at 40 MHz using 5-bit non-linear FADC (non-linear allows TRD upgrade).**
- **Maximum samples leads to excellent dE/dx meas.**
- **Single point res ~250 μm, 2-track separation ~5 mm.**
- **With Xe in gas and foam becomes TRD.**

PHENIX TOF

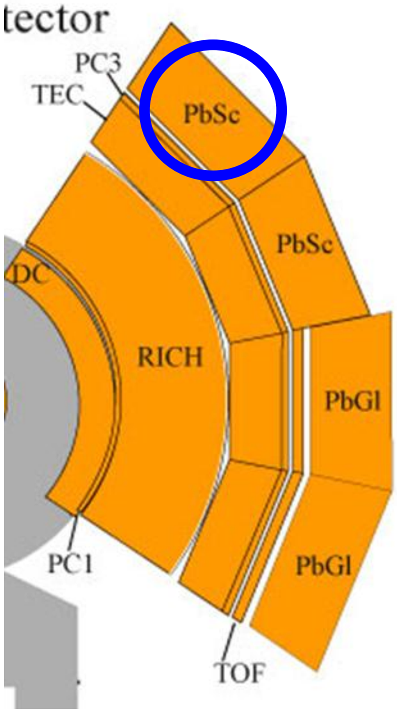


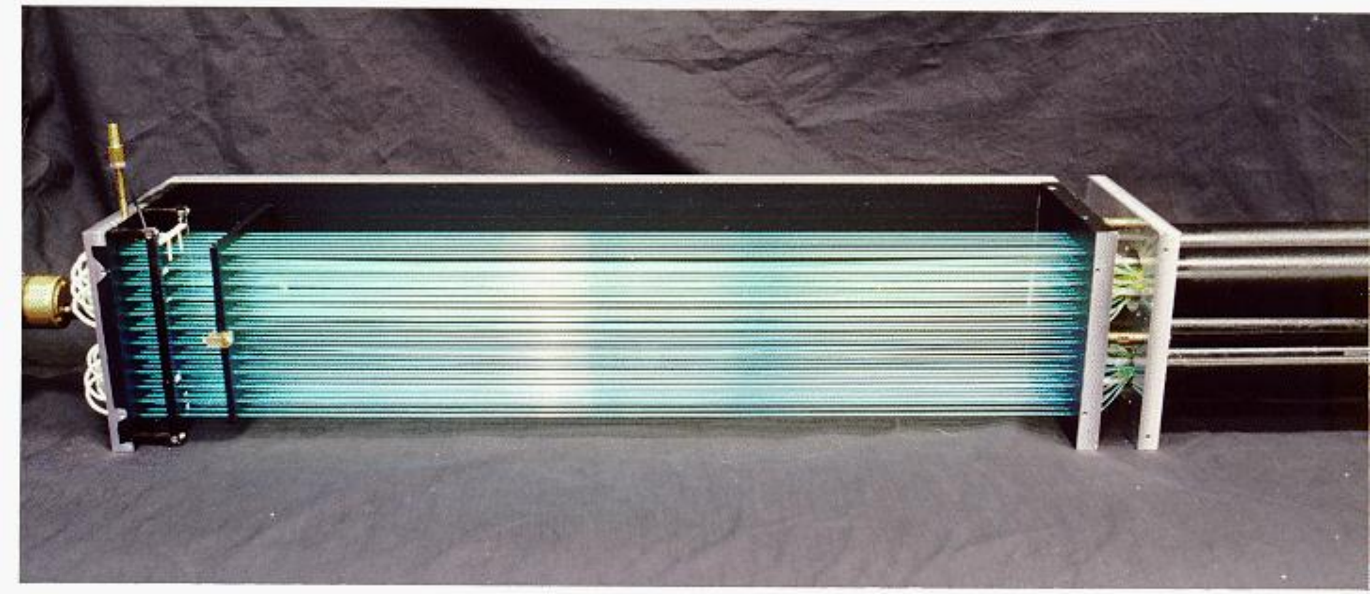
Prism turns light 180°

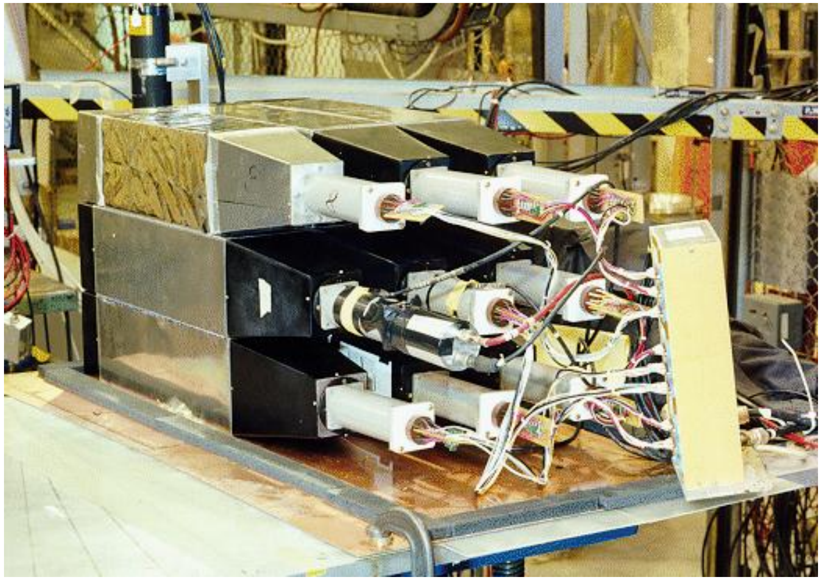
Hides PMT in slat area

- PHENIX TOF houses ~1000 scintillator slats.
- PMT pairs @ bar ends w/ prism readout.
- 100 psec TOF resolution and at 5 meters.

Pb-Scint Calorimeter

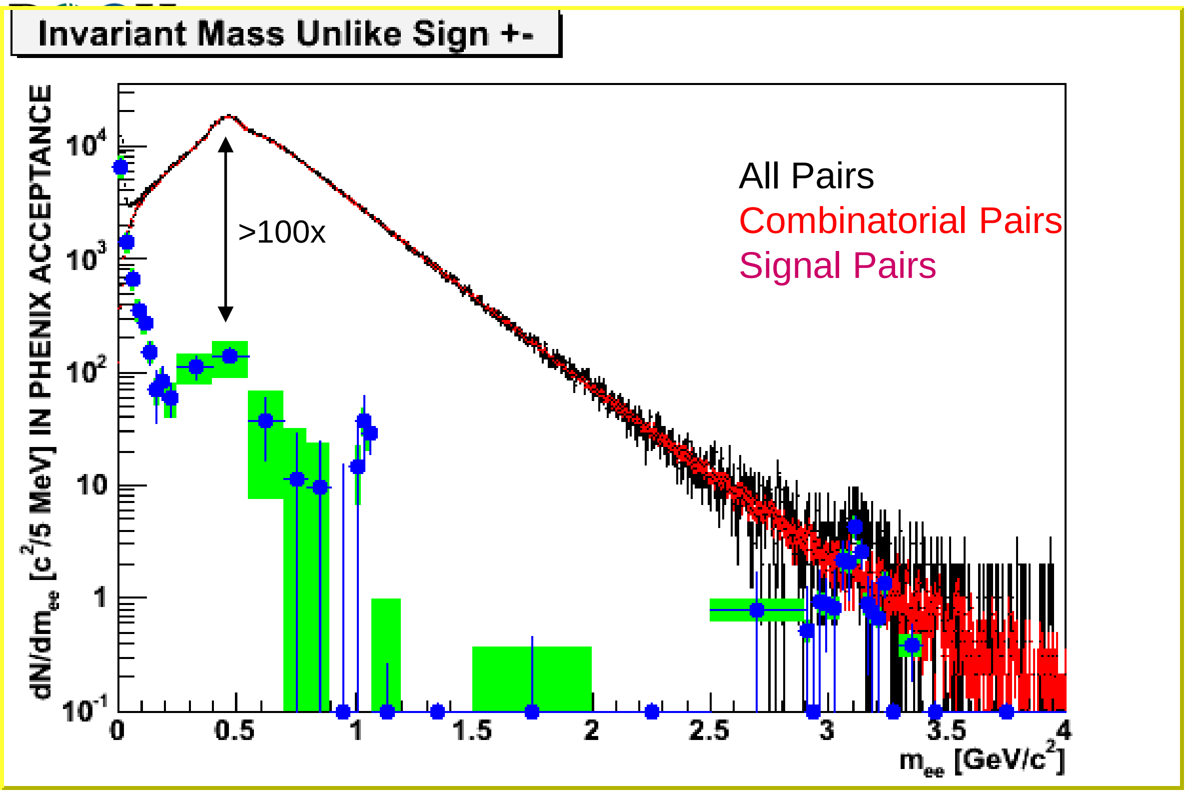


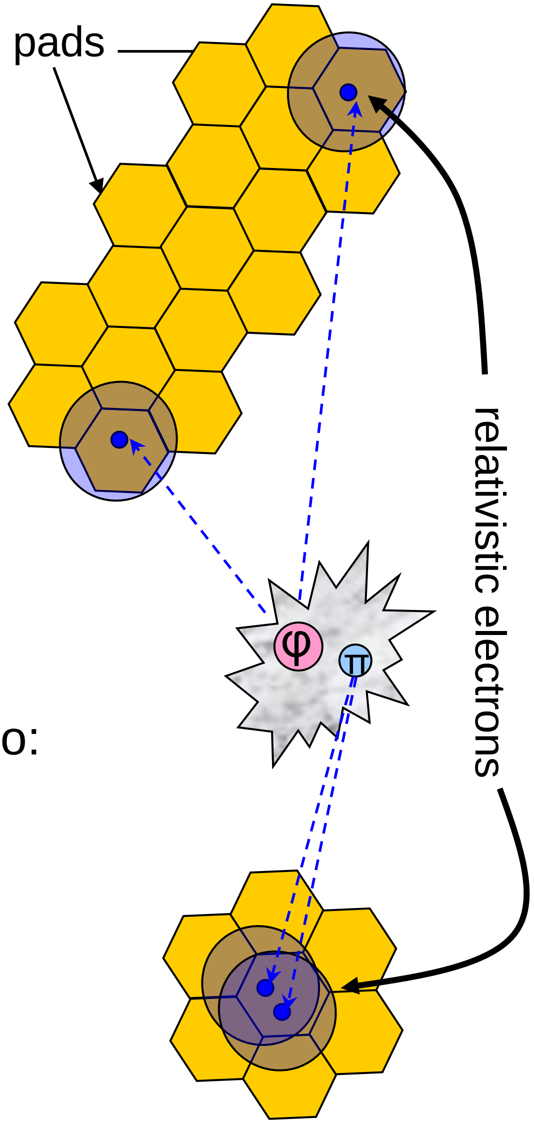




- EMC modules use the "Shish-Kebab" geometry.
- δE/E ~ 7%/sqrt(E)
- Timing (< 200 psec).

PHENIX HBD: The Issue

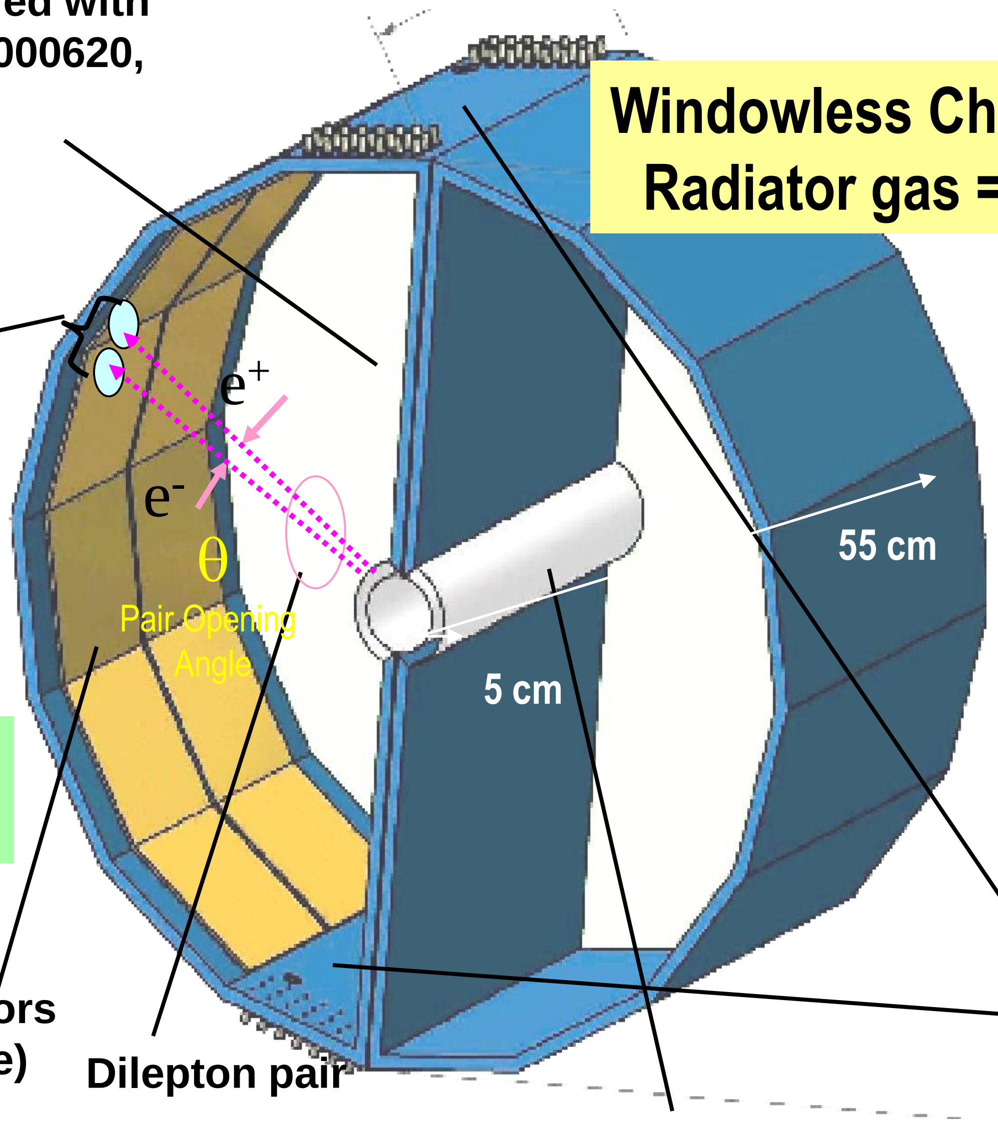




- **Major problem**: Huge combinatorial background mostly due to:
  - γ-conversions & π^0 Dalitz decays.
  - Small opening angle

- Need a new detector to identify the above by supplying:
  - eID @ zero opening angle
  - Distinguish isolated electrons from Overlapping
  - Unfocussed Cherenkov Detector!

PHENIX HBD: Geometry



HBD Gas Volume: Filled with CF_4 Radiator (n_{CF4}=1.000620, L_{RAD}=50 cm)

Windowless Cherenkov Detector
Radiator gas = Avalanche Gas

Cherenkov light forms "blobs" on an image plane (r_{BLOB}~3.36cm)

Pcb pad readout
(~ 2x2 cm²)

CsI photocathode covering GEMs

Electrons radiate, but hadrons with P < 4 GeV/c do not

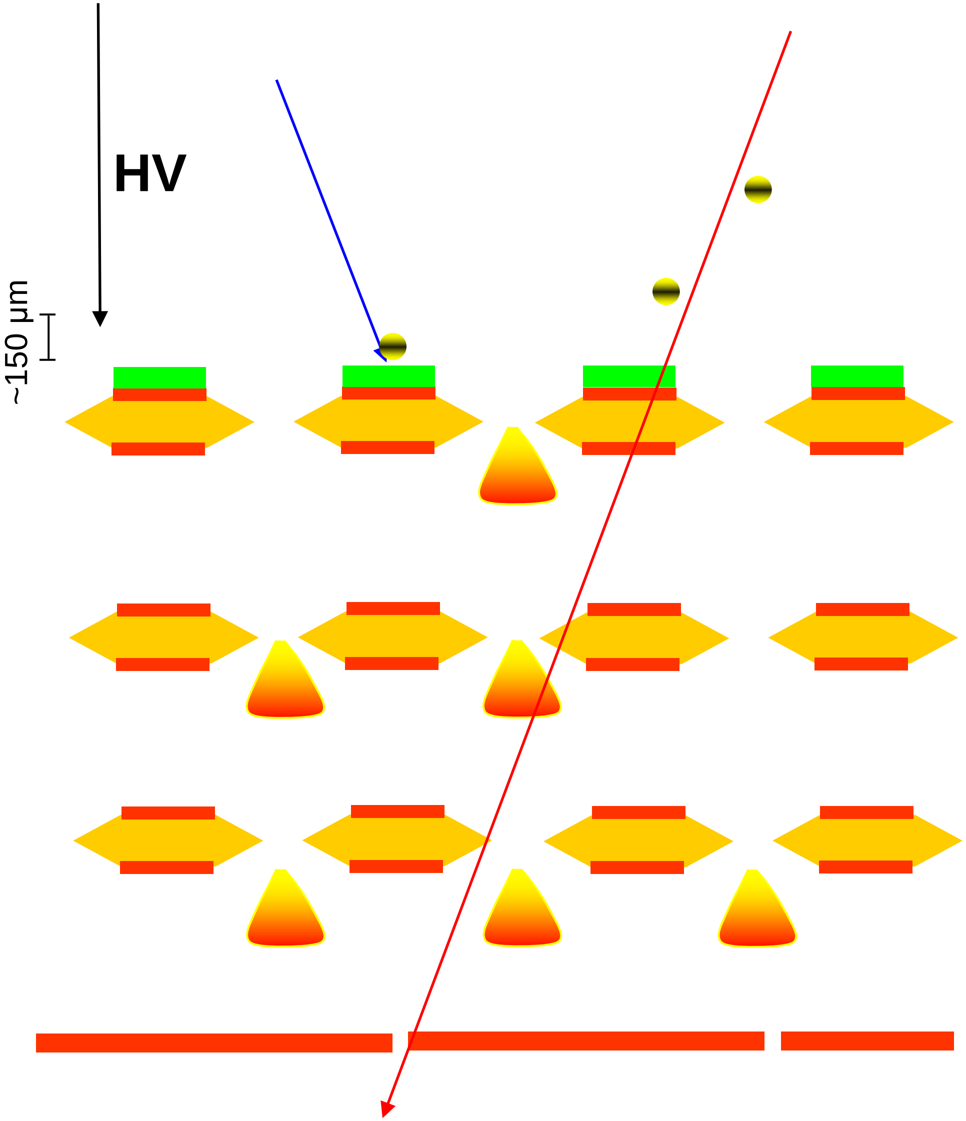
Triple GEM detectors
(12 panels per side)

Dilepton pair

Beam Pipe

Space allocated for services

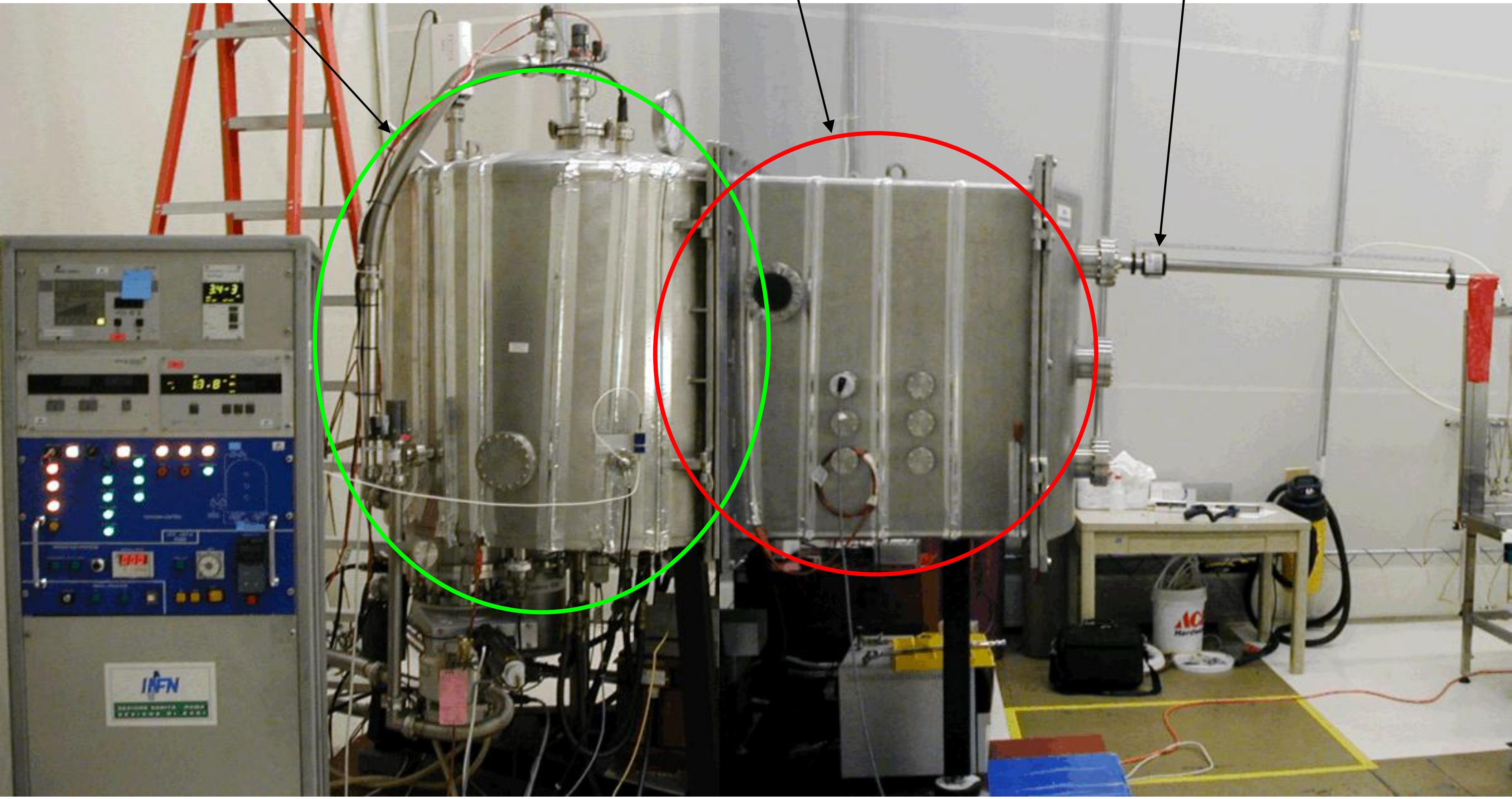
A PhotoSensitive MPGD



- Start with a GEM
- Put a photocathode (CsI) on top
- photoelectron from Cherenkov light avalanches in the high density E-field
- Use more GEMs for larger signal
- Pick up the signal on pads
- What about ionizing particles (hadrons)?
- We need a mesh with a reverse voltage on it to blow electrons away!!!
- We have a detector sensitive to UV and ~blind to ionizing particles!

The Evaporator

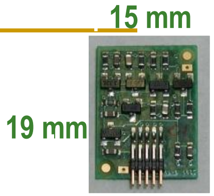
on loan from INFN Roma


Evaporation Chamber

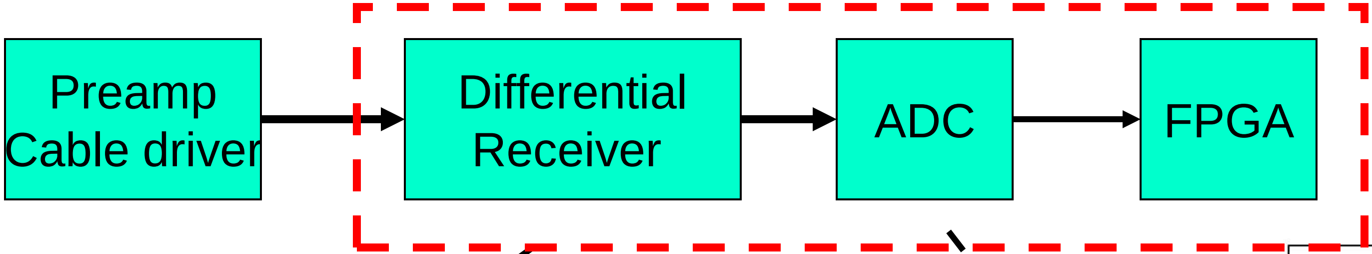
Quantum Efficiency Station

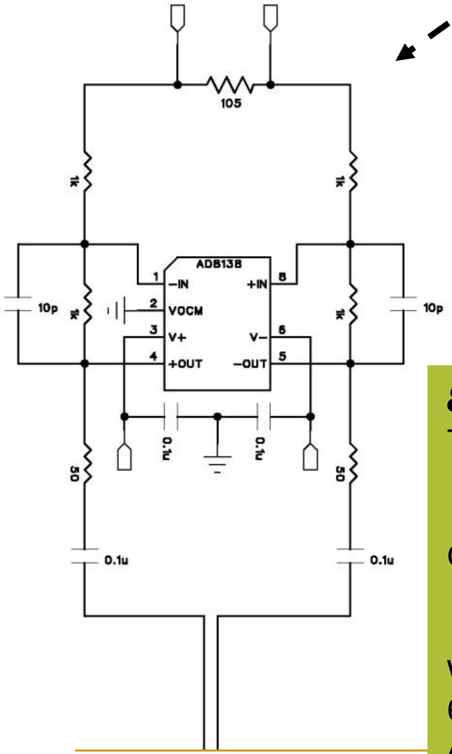
Magnetically coupled driver for moving the GEMs inside the vacuum.

FEM receiver + ADC



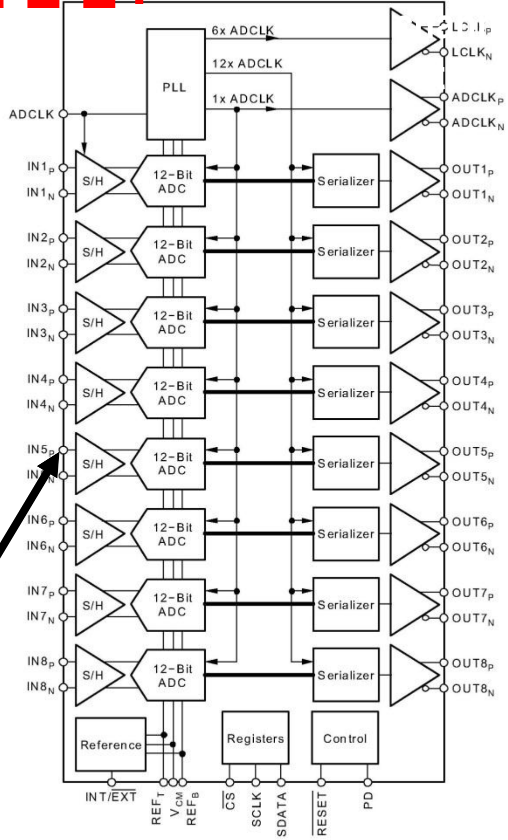
Preamp





Based on AD8138 receiver
Unity gain

TI ADS5272



8 CHANNEL 65 MHz 12 bits ADC (80 TQFP)

The +/- input can swing from 1V to 2V, V_{cm}=1.5V

+ side 2V, - side 1V -> highest count

- side 2V, + side 1V -> lowest count

Our +/- input will swing from 1.5 to 2V/ 1.5 to 1V

we will only get 11 bits out of 12 bits

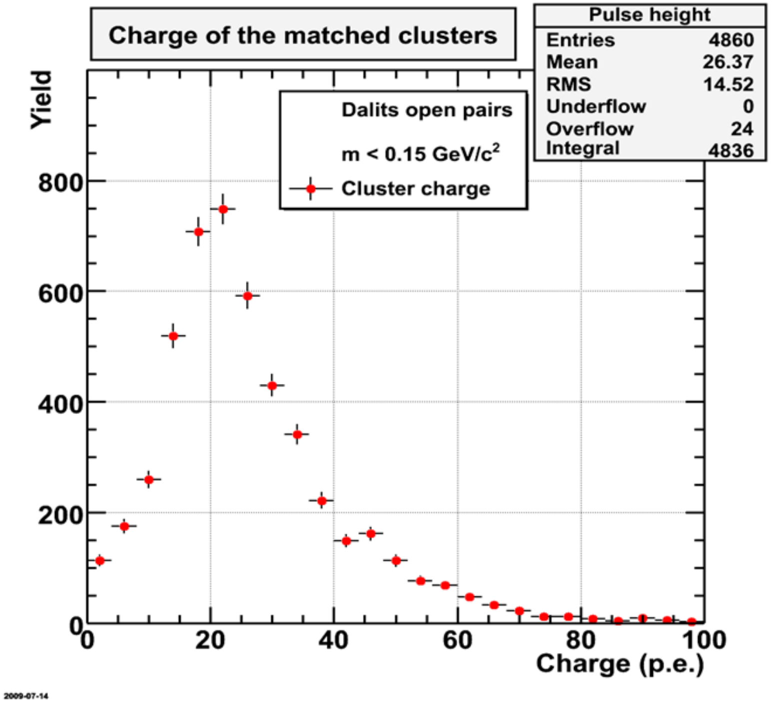
16fc will be roughly sitting at 200 count

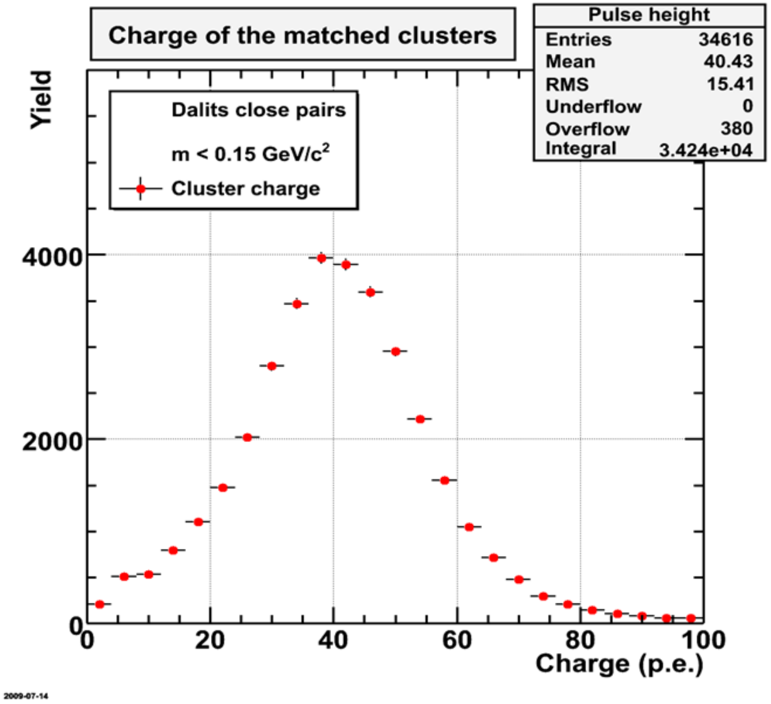
We will run the ADC at 6X beam crossing clock

6X9.4 MHz = 56.4 MHz or ~17.7ns per samples

ADC data are serialized LVDS at **12*56.4 MHz= 678 MHz**

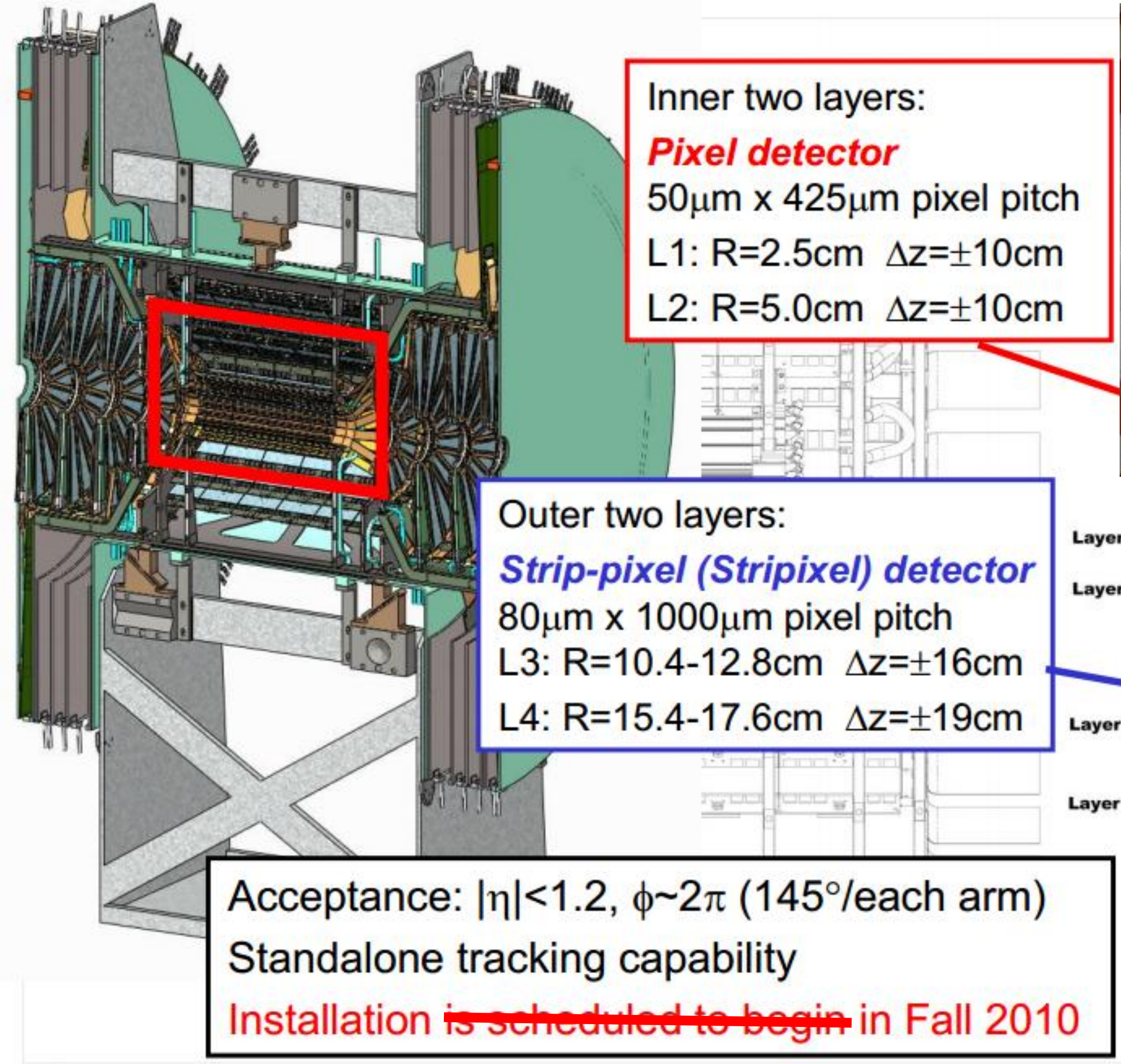
HBD Works!





- **PHENIX HBD holds world record for N_0~322.**

PHENIX VTX Upgrade.



Inner two layers:

Pixel detector

50μm x 425μm pixel pitch

L1: R=2.5cm Δz=±10cm

L2: R=5.0cm Δz=±10cm

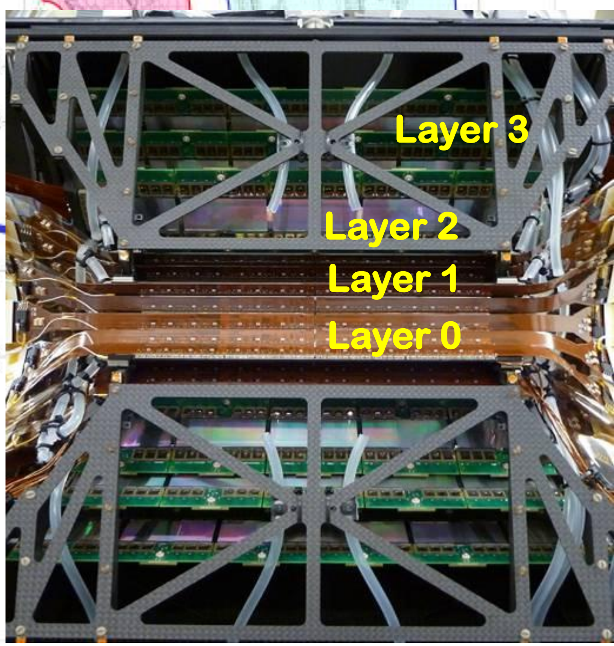
Outer two layers:

Strip-pixel (Stripixel) detector

80μm x 1000μm pixel pitch

L3: R=10.4-12.8cm Δz=±16cm

L4: R=15.4-17.6cm Δz=±19cm

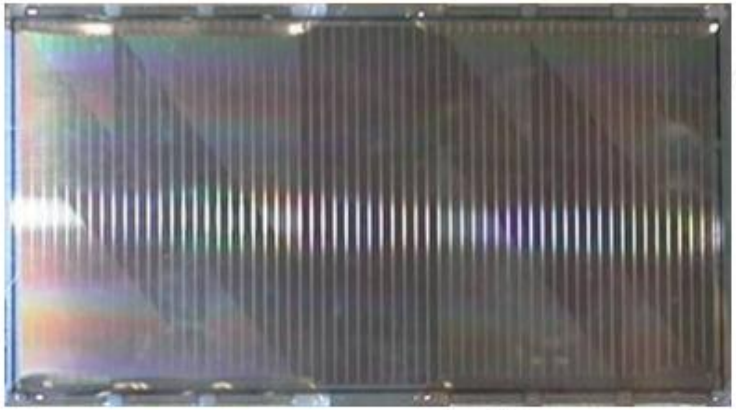


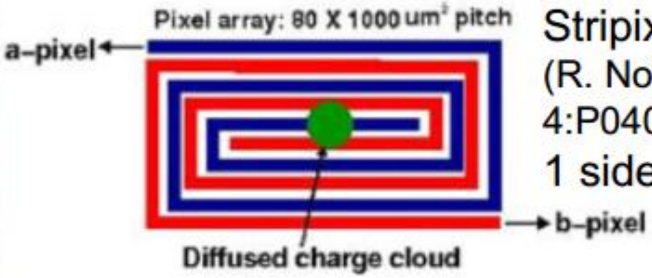
Acceptance: |η|<1.2, ϕ~2π (145°/each arm)

Standalone tracking capability

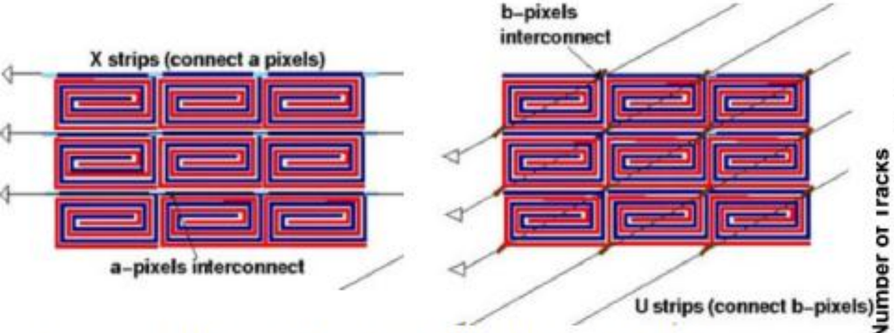
Installation ~~is scheduled to begin~~ in Fall 2010

Strip-pixel X-U readout



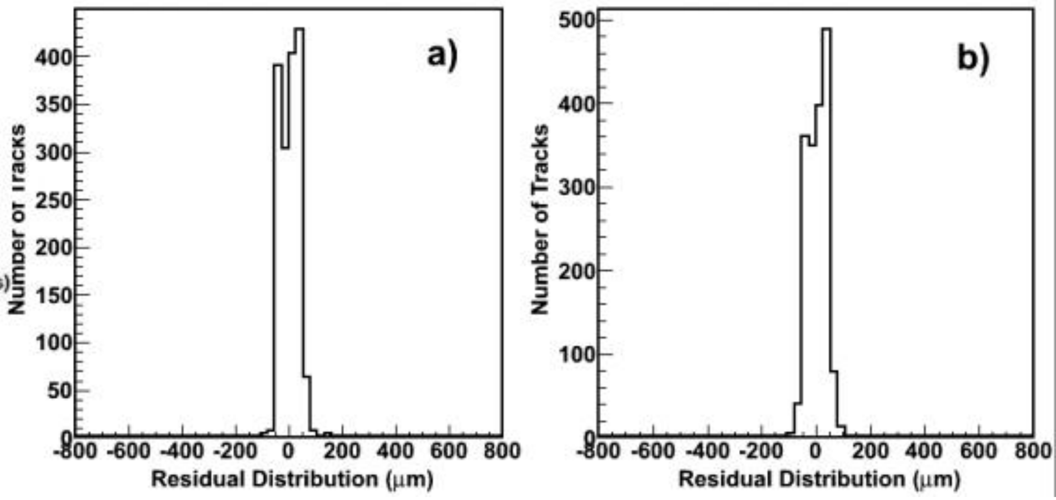


Stripixel sensor
(R. Nouicer et al. JINST 4:P04011,2009)
1 side, 2 direction read-out



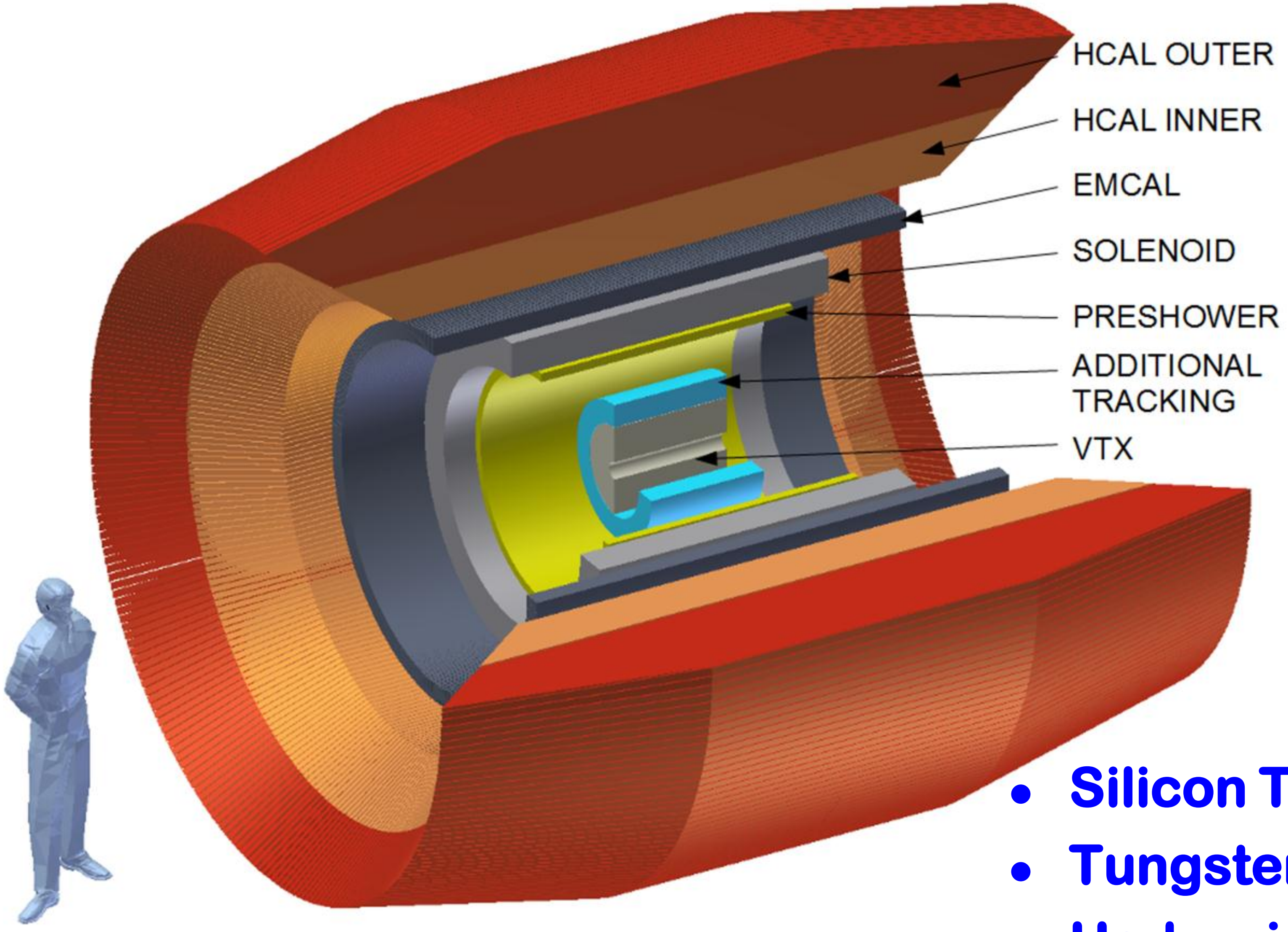
Size : 3.5 x 6.4 cm², thickness 625μm
80 μm x 1000 μm pixel size
768 X + 768 U strips = 1536 channels

FNAL test beam result



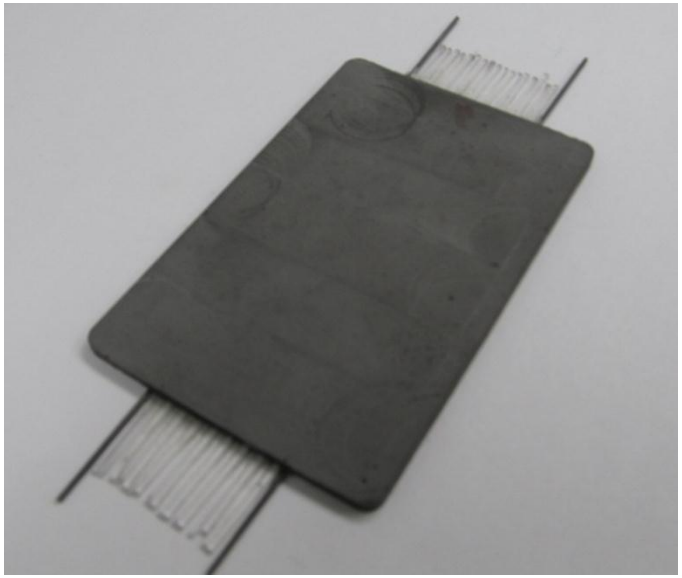
The FUTURE: #1 -- sPHENIX

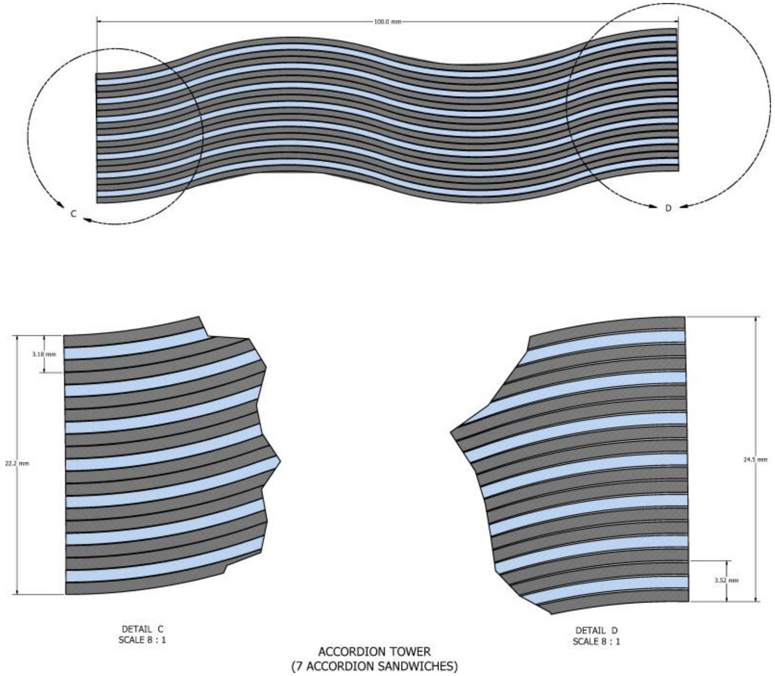
New Mantra: COMPACT!



- **Silicon Tracking.**
- **Tungsten EMC**
- **Hadronic Cal !!**

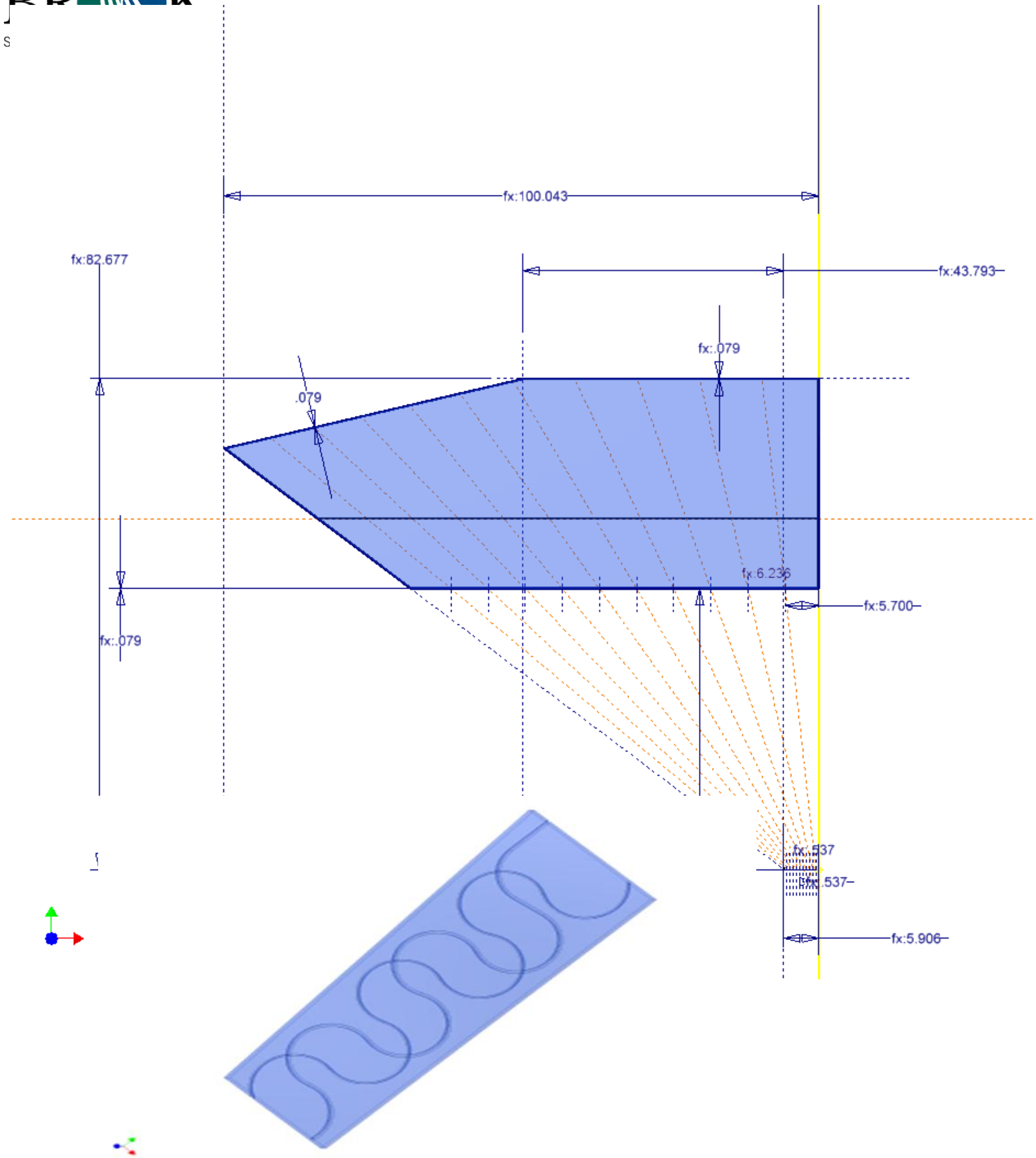
EM Calorimeter

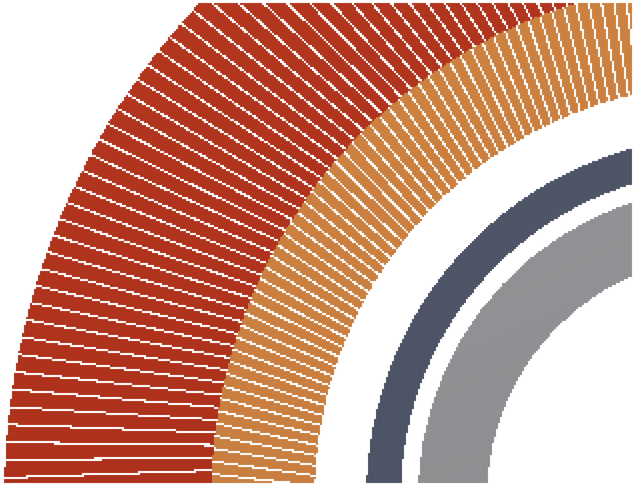


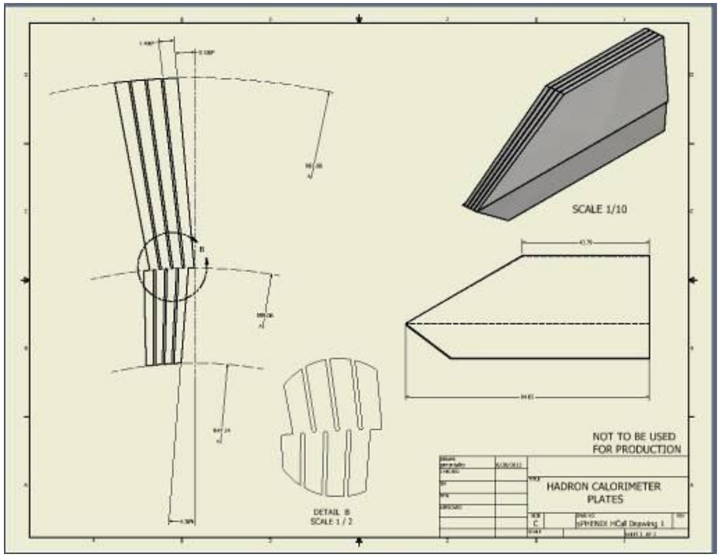


- Optical accordion
- Tungsten absorber
- Scintillating fiber

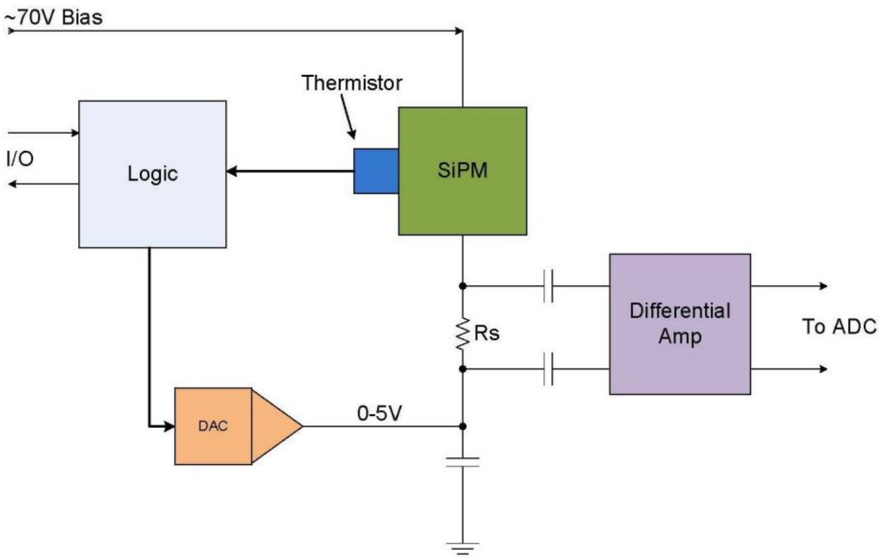
Hadronic calorimeter

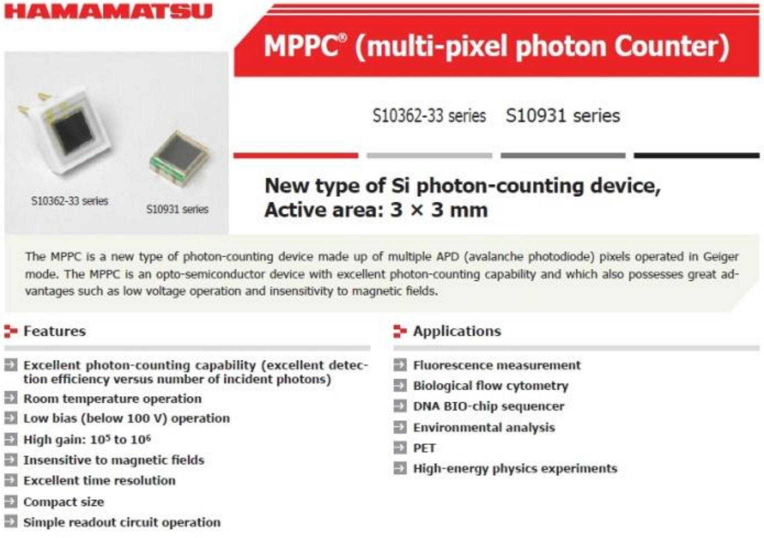






SiPM Readouts




HAMAMATSU

MPPC® (multi-pixel photon Counter)

S10362-33 series S10931 series

S10362-33 series

S10931 series

New type of Si photon-counting device, Active area: 3 × 3 mm

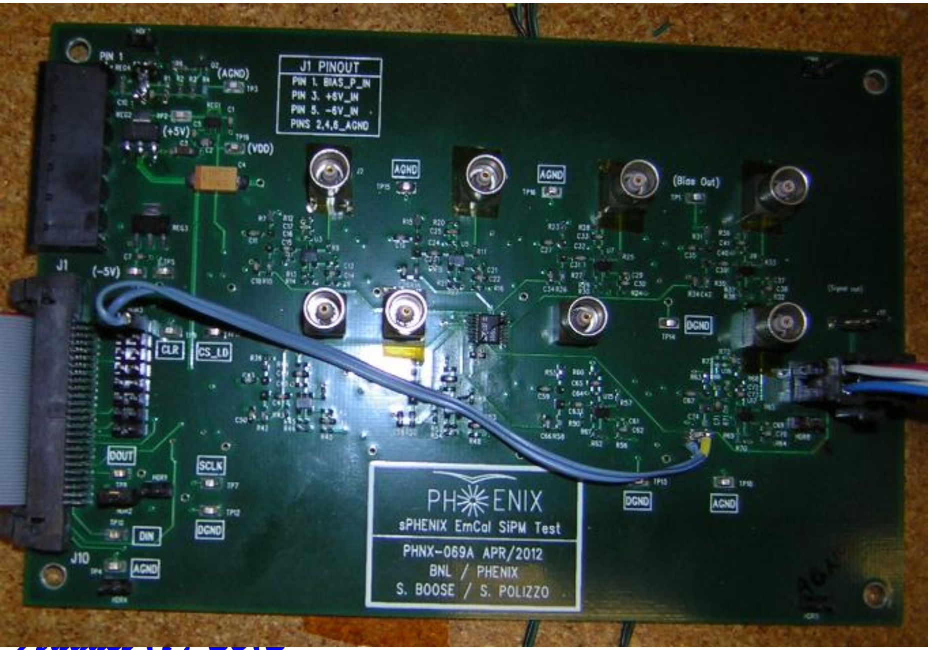
The MPPC is a new type of photon-counting device made up of multiple APD (avalanche photodiode) pixels operated in Geiger mode. The MPPC is an opto-semiconductor device with excellent photon-counting capability and which also possesses great advantages such as low voltage operation and insensitivity to magnetic fields.

Features

- Excellent photon-counting capability (excellent detection efficiency versus number of incident photons)
- Room temperature operation
- Low bias (below 100 V) operation
- High gain: 10^5 to 10^6
- Insensitive to magnetic fields
- Excellent time resolution
- Compact size
- Simple readout circuit operation

Applications

- Fluorescence measurement
- Biological flow cytometry
- DNA BIO-chip sequencer
- Environmental analysis
- PET
- High-energy physics experiments

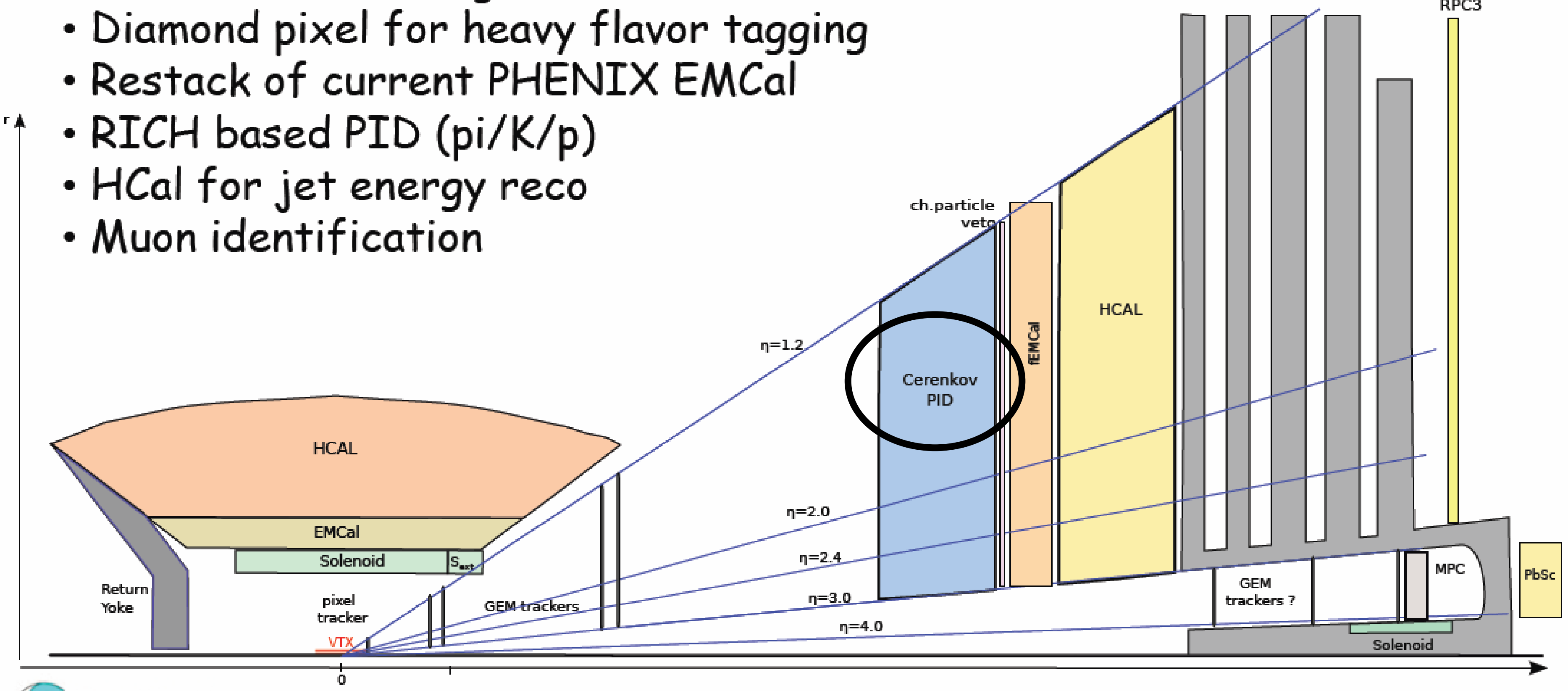


- Design based on existing parts
- Gain stabilization on detector
- Economical in large quantities

The Future #2: sPHENIX Forward

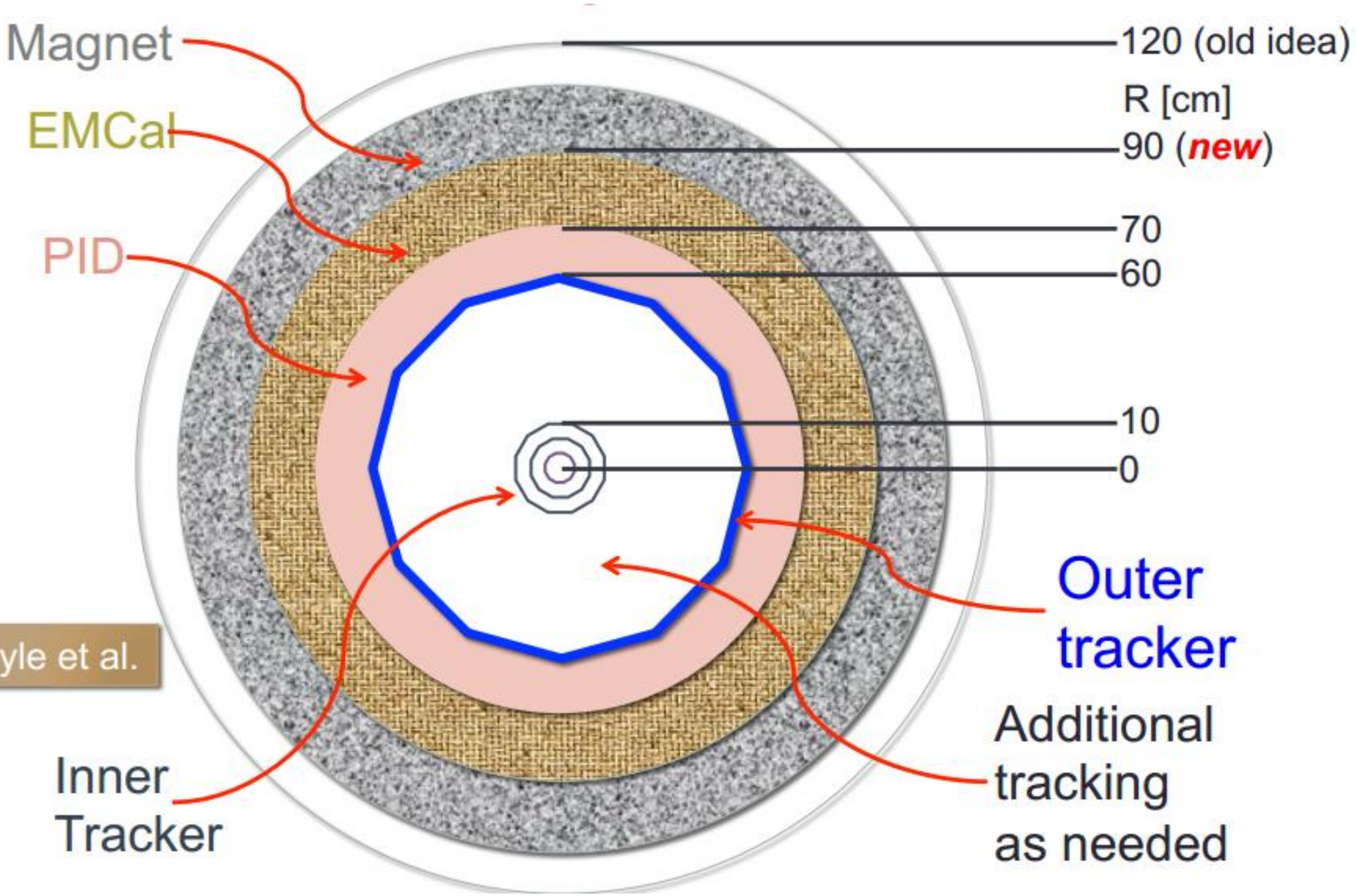
Optimized for jets and photons/DY over a large range in rapidity (η~4)

- Extension/modification of the central solenoid for B field
- GEM based tracking
- Diamond pixel for heavy flavor tagging
- Restack of current PHENIX EMCal
- RICH based PID (pi/K/p)
- HCal for jet energy reco
- Muon identification



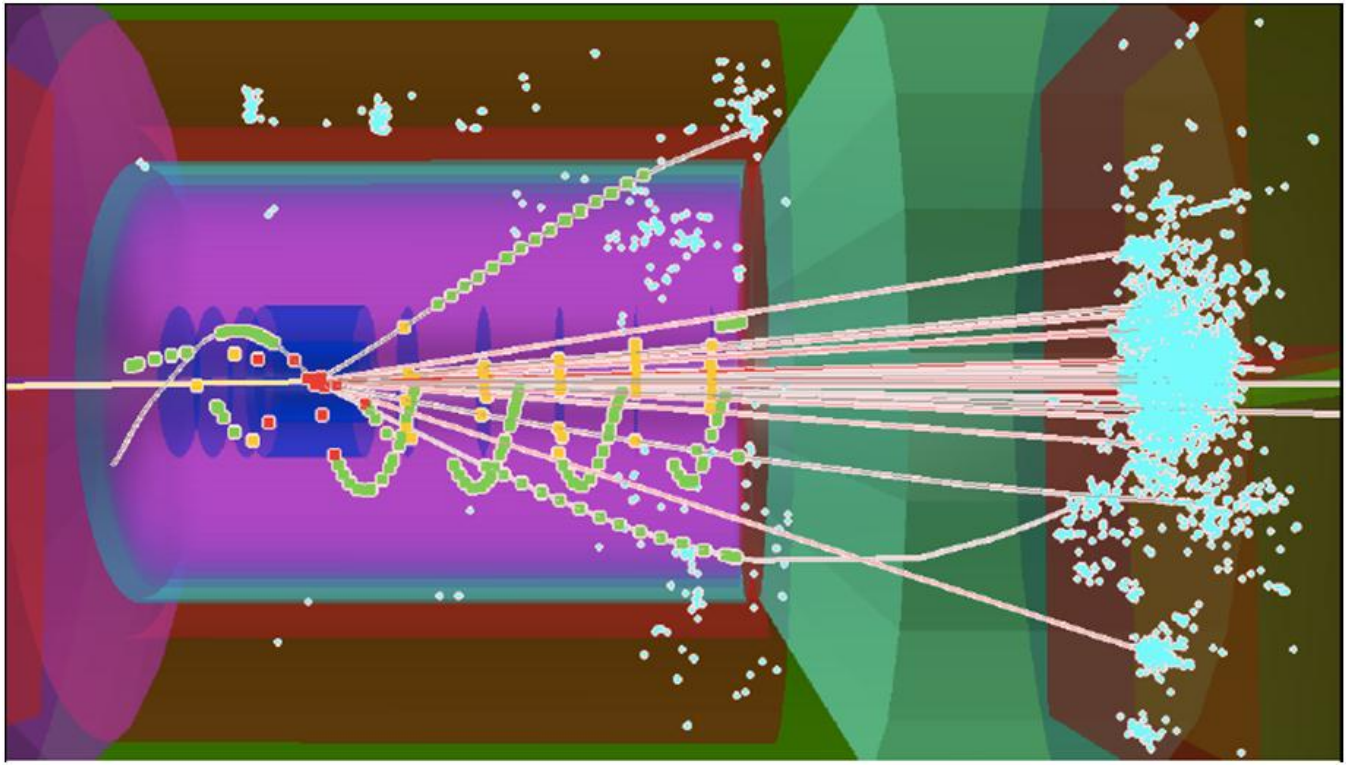
RIKEN BNL Research Center

The Future: #3 – ePHENIX



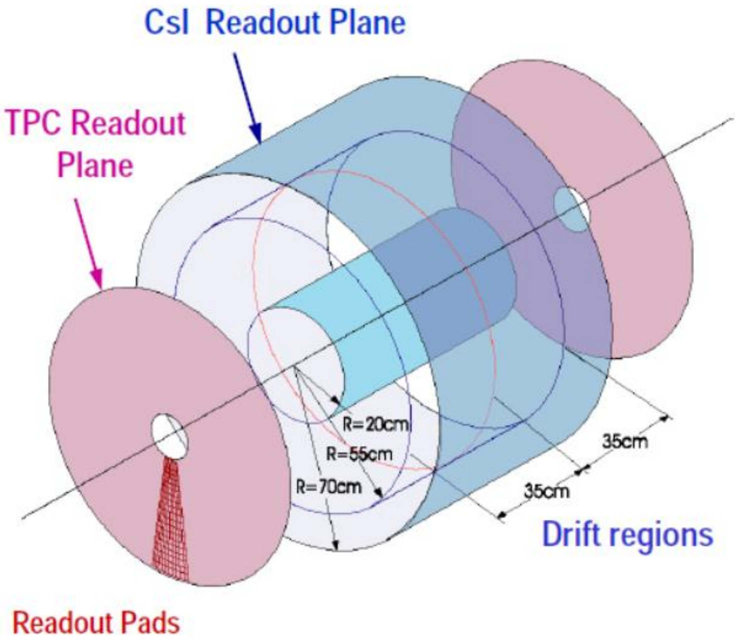
K. Boyle et al.

The Future #4: EIC



- Following the Heavy Ion Program, the next physics frontier will be the Electron-Ion Collider
- Initial, low energy, EIC running can be handled by PHENIX upgrades.
- The full energy program requires a new detector.

TPC with HBD outer readout.



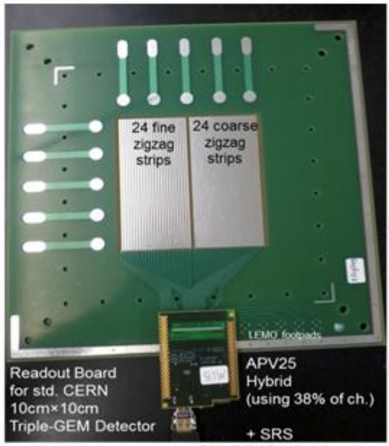
- ☐ Use CF_4 mixture to provide fast drift TPC.
- ☐ Design field cage to allow cherenkov light through
- ☐ Cherenkov "stripe" detected.

- **Natural follow-on to prior research of BNL, Yale, SBU.**
- **Provides broad spectrum PID.**
- **Never done before…requires 2-year development.**

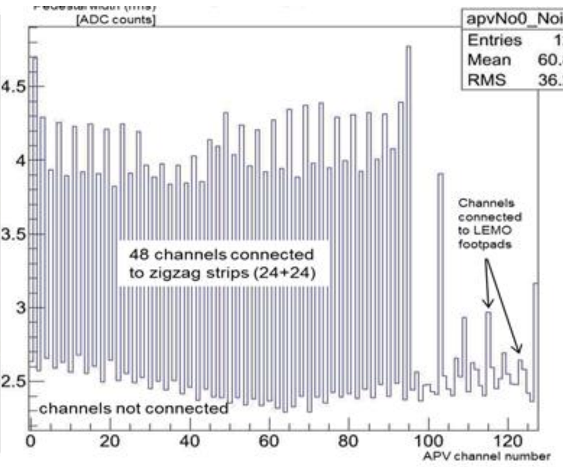
Sector Test

Soldering protection resistor on the GEM foil

X/Y readout board glued on the Honeycomb support

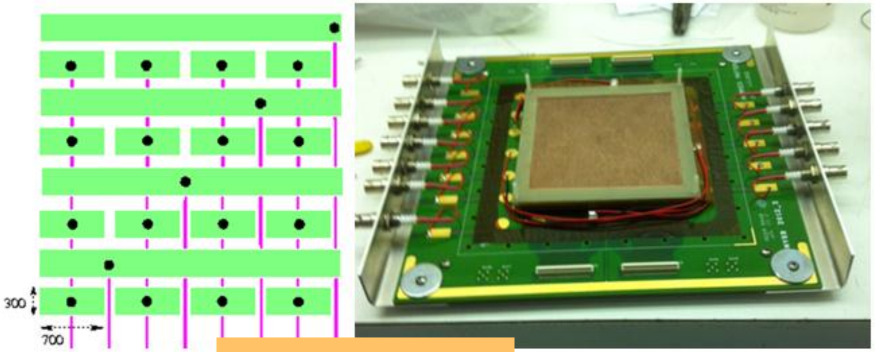


BNL/FIT/SBU Collaboration

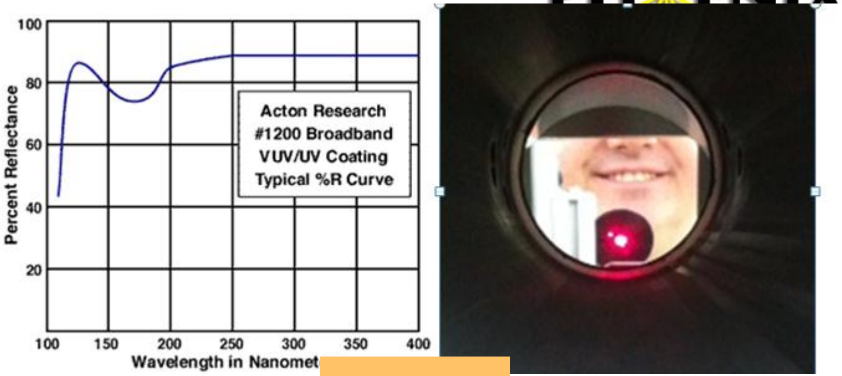


- **Large Planar GEM Trackers:**
  - ❑ **sPHENIX**
  - ❑ **Super BigBite & SoLID @ J-Lab**
  - ❑ **CMS**
  - ❑ **eIC**
- **Need to realize full-sized implementation of sector.**
- **Fits current UVa and FIT R&D.**
- **Goal is to develop and test full sector over next two years.**

Cherenkov Detector



Focal Plane



Mirror

Test Beam

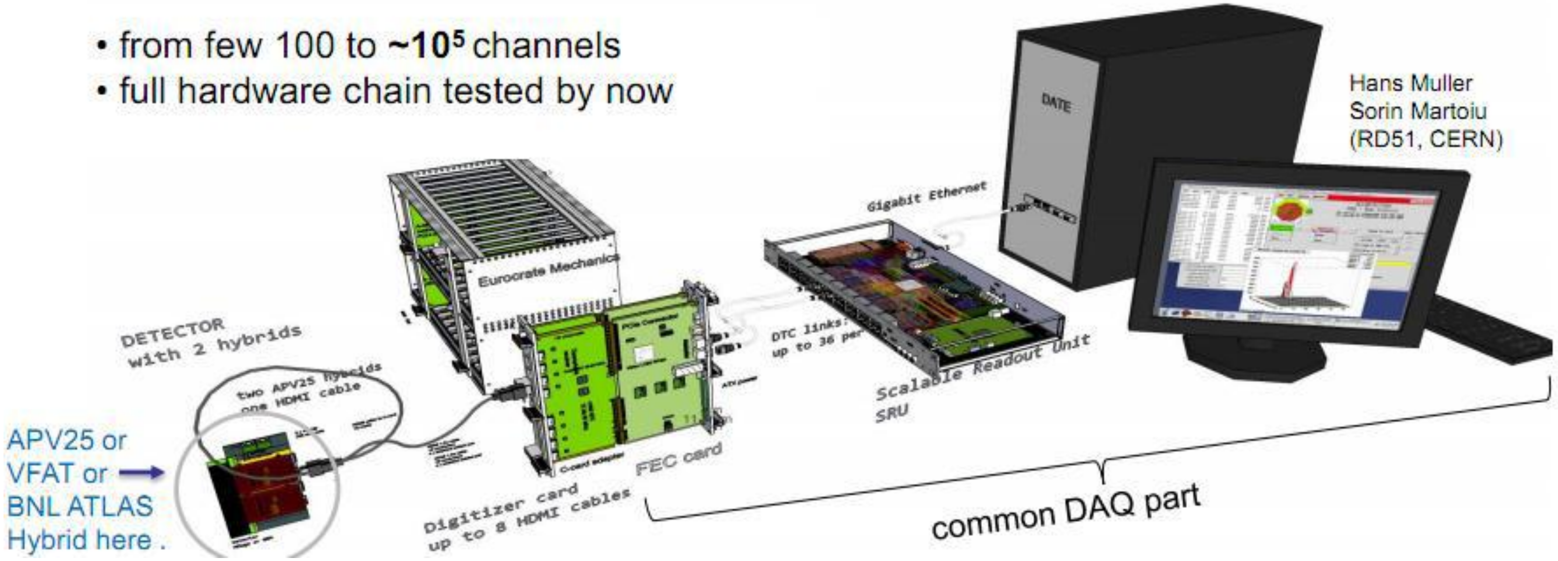
Future Evaporator

- **Extend HBD Technology to <u>focused</u> design.**
- **Hadron ID up to 80 GeV/c required.**
- **MIRROR R&D for Deep UV.**

Test Beam Readouts: SRS

RD51 coll. is developing a common *Scalable Readout System* for MPGD's

- from few 100 to ~10^5 channels
- full hardware chain tested by now

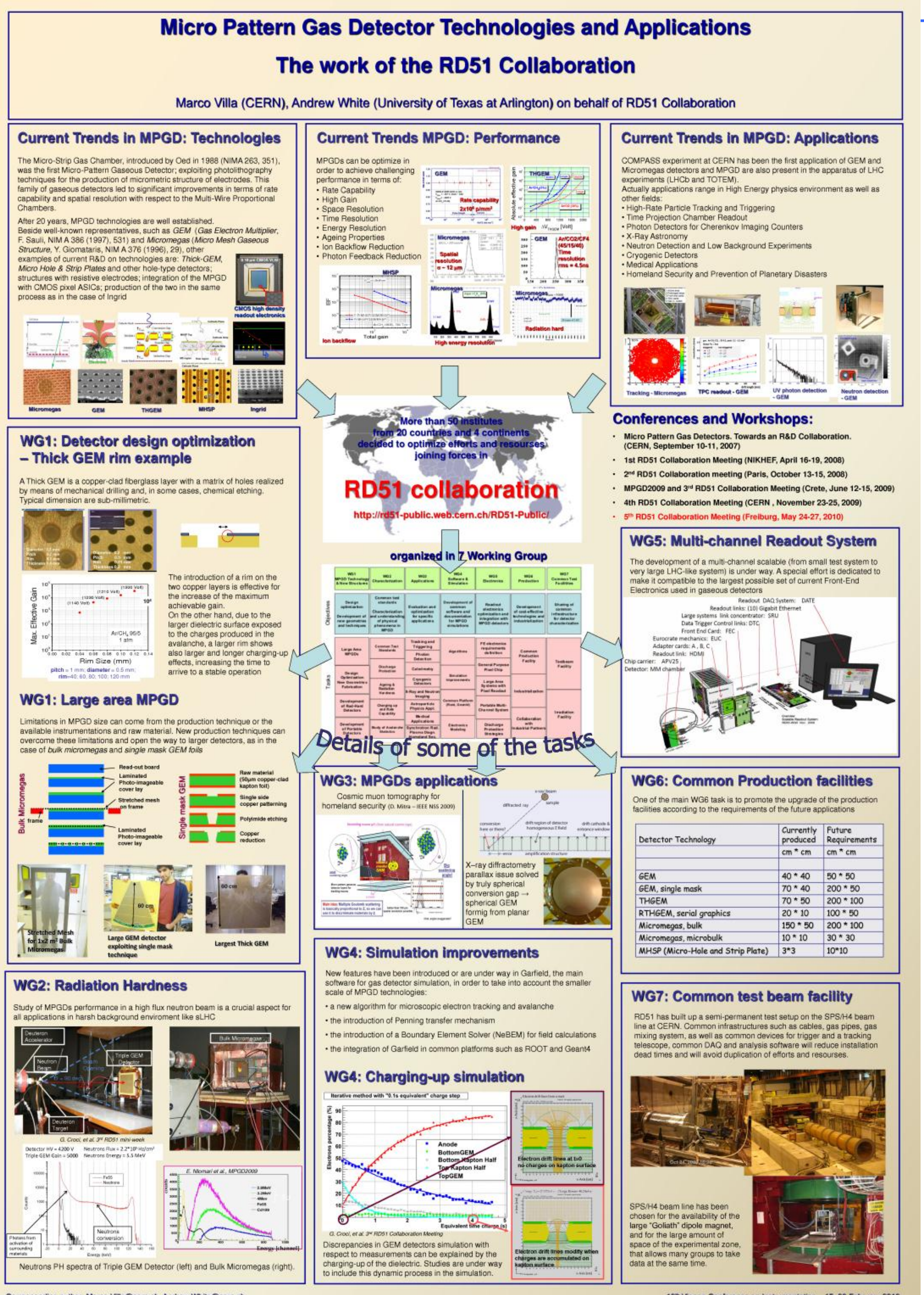


Hans Muller
Sorin Martoiu
(RD51, CERN)

APV25 or
VFAT or →
BNL ATLAS
Hybrid here .

- **The SRS DAQ system has proved a boon to our efforts.**
- **Initial expertise from FIT has spread through UVa, BNL, SBU and is rapidly becoming the common standard for all our test beam efforts.**
- **APV25-based, but will branch out.**
- **Cherenkov Test @ J-Lab used ~2500 channels.**

Welcome!



Micro Pattern Gas Detector Technologies and Applications

The work of the RD51 Collaboration

Marco Villa (CERN), Andrew White (University of Texas at Arlington) on behalf of RD51 Collaboration

Current Trends in MPGD: Technologies

The Micro-Strip Gas Chamber, introduced by Oed in 1988 (NIMA 263, 351), was the first Micro-Pattern Gaseous Detector; exploiting photolithography techniques for the production of micrometric structure of electrodes. This family of gaseous detectors led to significant improvements in terms of rate capability and spatial resolution with respect to the Multi-Wire Proportional Chambers.

After 20 years, MPGD technologies are well established. Beside well-known representatives, such as *GEM* (*Gas Electron Multiplier*, F. Sauli, NIM A 386 (1997), 531) and *Micromegas* (*Micro Mesh Gaseous Structure*, Y. Giomataris, NIM A 376 (1996), 29), other examples of current R&D on technologies are: *Thick-GEM*, *Micro Hole & Strip Plates* and other hole-type detectors; structures with resistive electrodes; integration of the MPGD with CMOS pixel ASICs; production of the two in the same process as in the case of Ingrid

Current Trends MPGD: Performance

MPGDs can be optimize in order to achieve challenging performance in terms of:

- Rate Capability
- High Gain
- Space Resolution
- Time Resolution
- Energy Resolution
- Ageing Properties
- Ion Backflow Reduction
- Photon Feedback Reduction

Current Trends in MPGD: Applications

COMPASS experiment at CERN has been the first application of GEM and Micromegas detectors and MPGD are also present in the apparatus of LHC experiments (LHCb and TOTEM).
Actually applications range in High Energy physics environment as well as other fields:

- High-Rate Particle Tracking and Triggering
- Time Projection Chamber Readout
- Photon Detectors for Cherenkov Imaging Counters
- X-Ray Astronomy
- Neutron Detection and Low Background Experiments
- Cryogenic Detectors
- Medical Applications
- Homeland Security and Prevention of Planetary Disasters

More than 50 institutes from 20 countries and 4 continents decided to optimize efforts and resourses joining forces in

RD51 collaboration

http://rd51-public.web.cern.ch/RD51-Public/

organized in 7 Working Group

	WG1 MPGD Technology & New Structures	WG2 Characterization	WG3 Applications	WG4 Software & Simulation	WG5 Electronics	WG6 Production	WG7 Common Test Facilities
Objectives	Design optimization Development of new geometries and techniques	Common test standards Characterization and understanding of physical phenomena in MPGD	Evaluation and optimization for specific applications	Development of common software and documentation for MPGD simulations	Readout electronics optimization and integration with MPGD detectors	Development of cost-effective technologies and industrialization	Sharing of common infrastructure for detector characterization
Tasks	Large Area MPGDs Design Optimization New Geometries Fabrication Development of Rad-Hard Detectors Development of Portable Detectors	Common Test Standards Discharge Protection Ageing & Radiation Hardness Charging up and Rate Capability Study of Avalanche Statistics	Tracking and Triggering Photon Detection Calorimetry Cryogenic Detectors X-Ray and Neutron Imaging Astroparticle Physics Appl. Medical Applications Synchrotron Rad. Plasma Diagn. Homeland Sec.	Algorithms Simulation Improvements Common Platform (Root, Geant4) Electronics Modeling	FE electronics requirements definition General Purpose Pixel Chip Large Area Systems with Pixel Readout Portable Multi-Channel System Discharge Protection Strategies	Common Production Facility Industrialization Collaboration with Industrial Partners	Testbeam Facility Irradiation Facility

Details of some of the tasks

Conferences and Workshops:

- Micro Pattern Gas Detectors. Towards an R&D Collaboration. (CERN, September 10-11, 2007)
- 1st RD51 Collaboration Meeting (NIKHEF, April 16-19, 2008)
- 2nd RD51 Collaboration meeting (Paris, October 13-15, 2008)
- MPGD2009 and 3rd RD51 Collaboration Meeting (Crete, June 12-15, 2009)
- 4th RD51 Collaboration Meeting (CERN , November 23-25, 2009)
- 5th RD51 Collaboration Meeting (Freiburg, May 24-27, 2010)

WG1: Detector design optimization – Thick GEM rim example

A Thick GEM is a copper-clad fiberglass layer with a matrix of holes realized by means of mechanical drilling and, in some cases, chemical etching. Typical dimension are sub-millimetric.

The introduction of a rim on the two copper layers is effective for the increase of the maximum achievable gain.
On the other hand, due to the larger dielectric surface exposed to the charges produced in the avalanche, a larger rim shows also larger and longer charging-up effects, increasing the time to arrive to a stable operation

pitch = 1 mm; diameter = 0.5 mm; rim=40; 60; 80; 100; 120 mm

WG1: Large area MPGD

Limitations in MPGD size can come from the production technique or the available instrumentations and raw material. New production techniques can overcome these limitations and open the way to larger detectors, as in the case of *bulk micromegas* and *single mask GEM foils*

Stretched Mesh for 1x2 m² Bulk Micromegas

Large GEM detector exploiting single mask technique

Largest Thick GEM

WG2: Radiation Hardness

Study of MPGDs performance in a high flux neutron beam is a crucial aspect for all applications in harsh background enviroment like sLHC

G. Croci, et al. 3rd RD51 mini-week

E. Nlomari et al., MPGD2009

Neutrons PH spectra of Triple GEM Detector (left) and Bulk Micromegas (right).

WG3: MPGDs applications

Cosmic muon tomography for homeland security (D. Mitra – IEEE NSS 2009)

X–ray diffractometry parallax issue solved by truly spherical conversion gap → spherical GEM formig from planar GEM

WG4: Simulation improvements

New features have been introduced or are under way in Garfield, the main software for gas detector simulation, in order to take into account the smaller scale of MPGD technologies:

- a new algorithm for microscopic electron tracking and avalanche
- the introduction of Penning transfer mechanism
- the introduction of a Boundary Element Solver (NeBEM) for field calculations
- the integration of Garfield in common platforms such as ROOT and Geant4

WG4: Charging-up simulation

G. Croci, et al. 3rd RD51 Collaboration Meeting

Discrepancies in GEM detectors simulation with respect to measurements can be explained by the charging-up of the dielectric. Studies are under way to include this dynamic process in the simulation.

WG5: Multi-channel Readout System

The development of a multi-channel scalable (from small test system to very large LHC-like system) is under way. A special effort is dedicated to make it compatible to the largest possible set of current Front-End Electronics used in gaseous detectors

Readout DAQ System: DATE
Readout links: (10) Gigabit Ethernet
Large systems link concentrator: SRU
Data Trigger Control links: DTC
Front End Card: FEC
Eurocrate mechanics: EUC
Adapter cards: A , B, C
Readout link: HDMI
Chip carrier: APV25
Detector: MM chamber

WG6: Common Production facilities

One of the main WG6 task is to promote the upgrade of the production facilities according to the requirements of the future applications

Detector Technology	Currently produced	Future Requirements
	cm * cm	cm * cm
GEM	40 * 40	50 * 50
GEM, single mask	70 * 40	200 * 50
THGEM	70 * 50	200 * 100
RTHGEM, serial graphics	20 * 10	100 * 50
Micromegas, bulk	150 * 50	200 * 100
Micromegas, microbulk	10 * 10	30 * 30
MHSP (Micro-Hole and Strip Plate)	3*3	10*10

WG7: Common test beam facility

RD51 has built up a semi-permanent test setup on the SPS/H4 beam line at CERN. Common infrastructures such as cables, gas pipes, gas mixing system, as well as common devices for trigger and a tracking telescope, common DAQ and analysis software will reduce installation dead times and will avoid duplication of efforts and resourses.

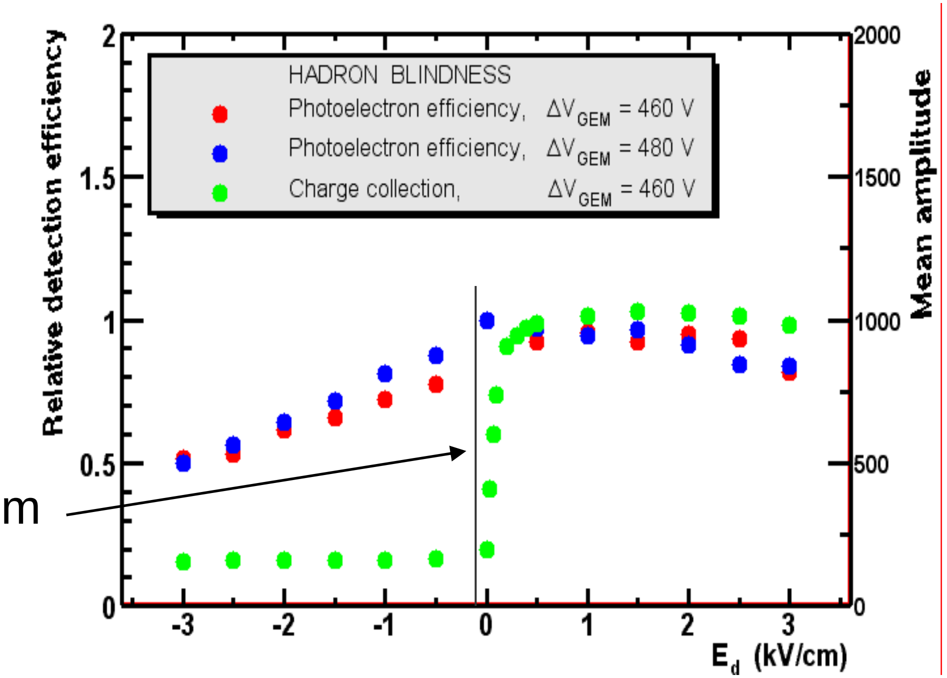
SPS/H4 beam line has been chosen for the availability of the large "Goliath" dipole magnet, and for the large amount of space of the experimental zone, that allows many groups to take data at the same time.

- **Stony Brook has a long tradition in detector development and construction.**
- **Future goals are well aligned with the RD51 research program.**
- **We are delighted to host the RD51 Collaboration!**

Thomas K Hemmick

Backups…

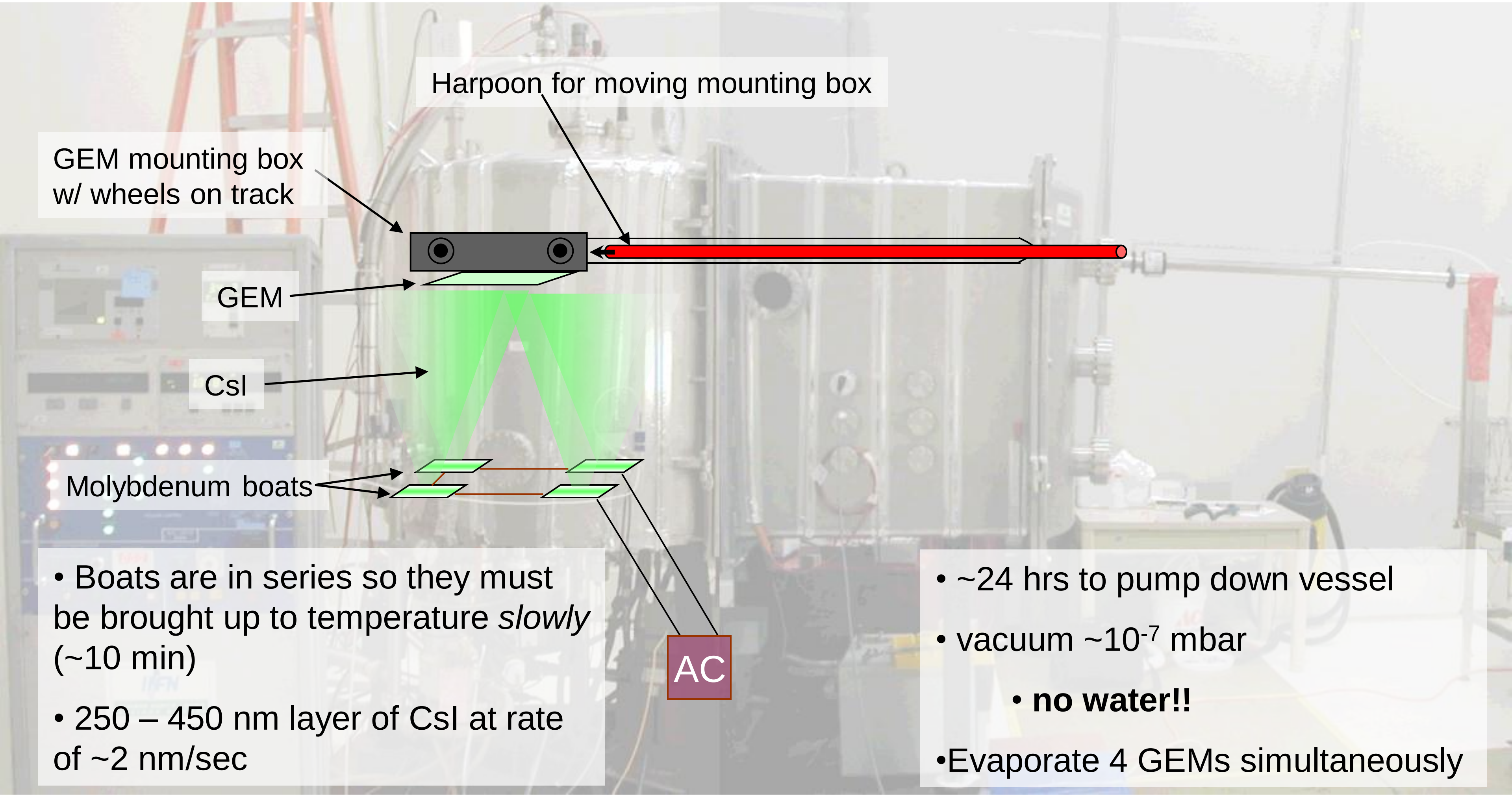
Hadron Blindness:
UV photons vs charged particles



Target E_d ~0.1 kV/cm

- At slightly negative E_d, photoelectron detection efficiency is preserved whereas charge collection is largely suppressed.
- Charge collected from ~150μ layer above top GEM

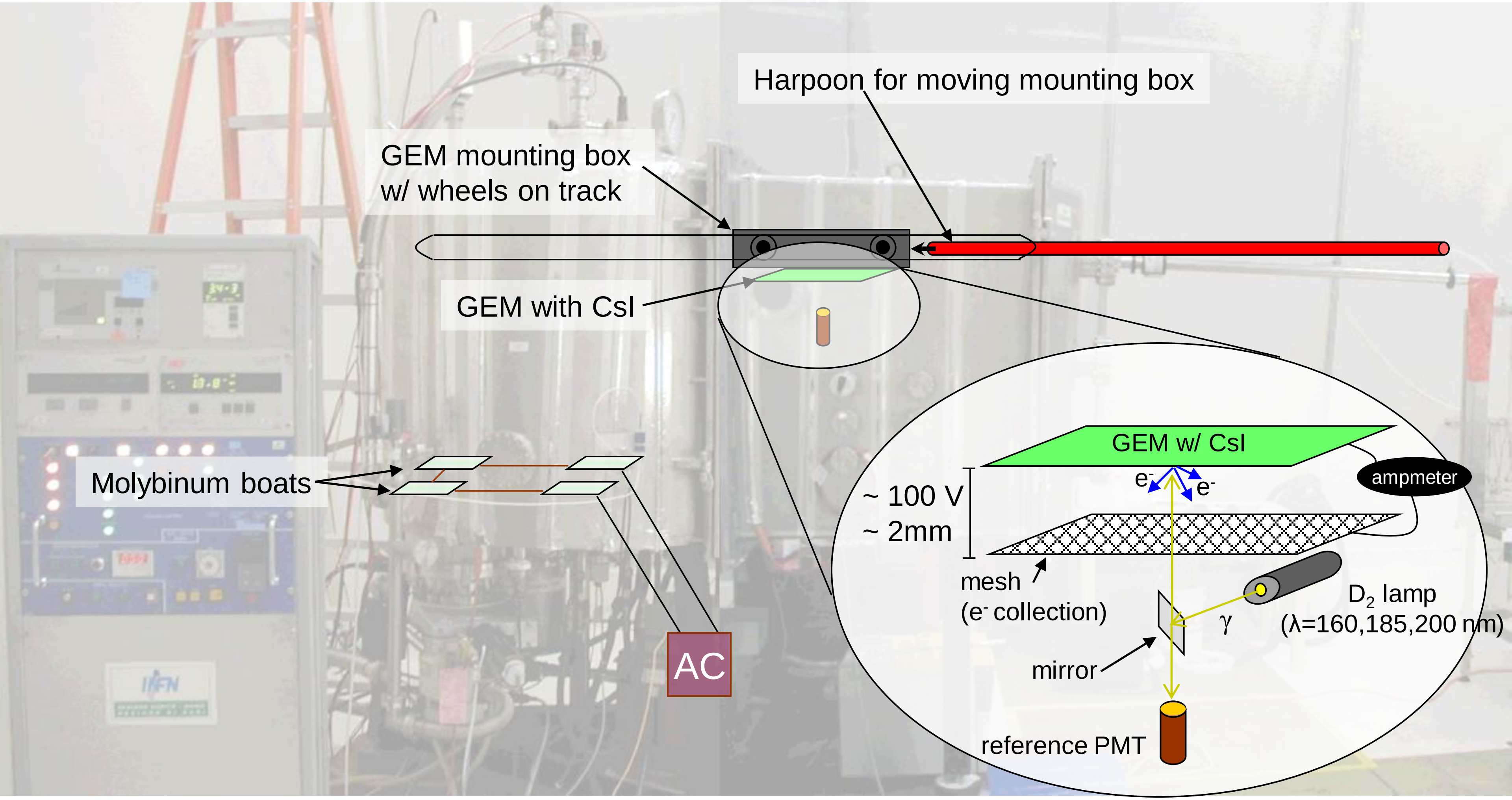
The Evaporation Chamber



- Boats are in series so they must be brought up to temperature *slowly* (~10 min)
- 250 – 450 nm layer of CsI at rate of ~2 nm/sec

- ~24 hrs to pump down vessel
- vacuum ~10^{-7} mbar
  - **no water!!**
- Evaporate 4 GEMs simultaneously

The Quantum Efficiency Station



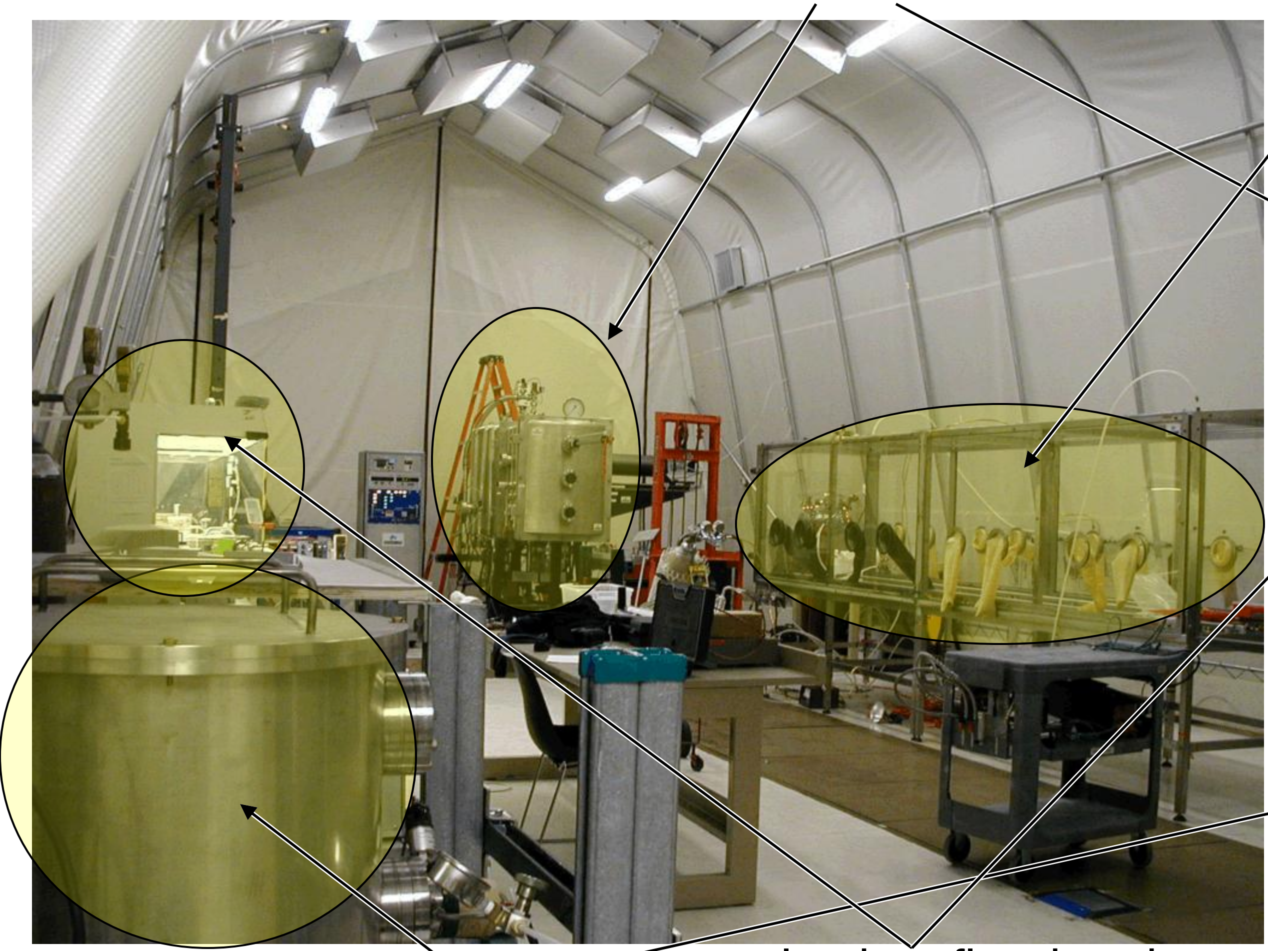
The Clean Tent at USB

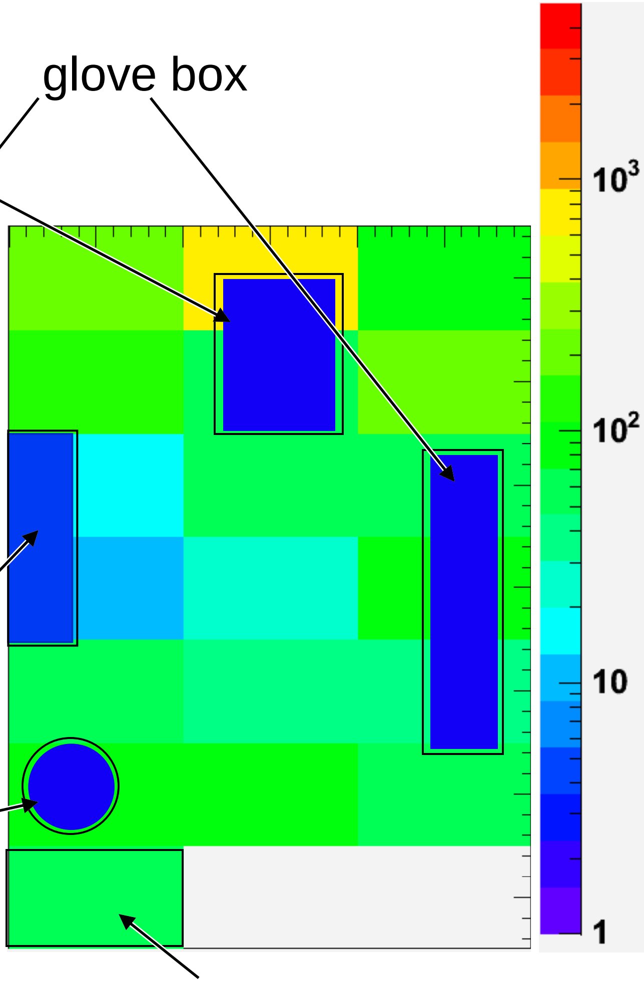
(“Class”: number of ≤0.5 μm particles/m^3)

“Class” of Clean Room

evaporator

glove box



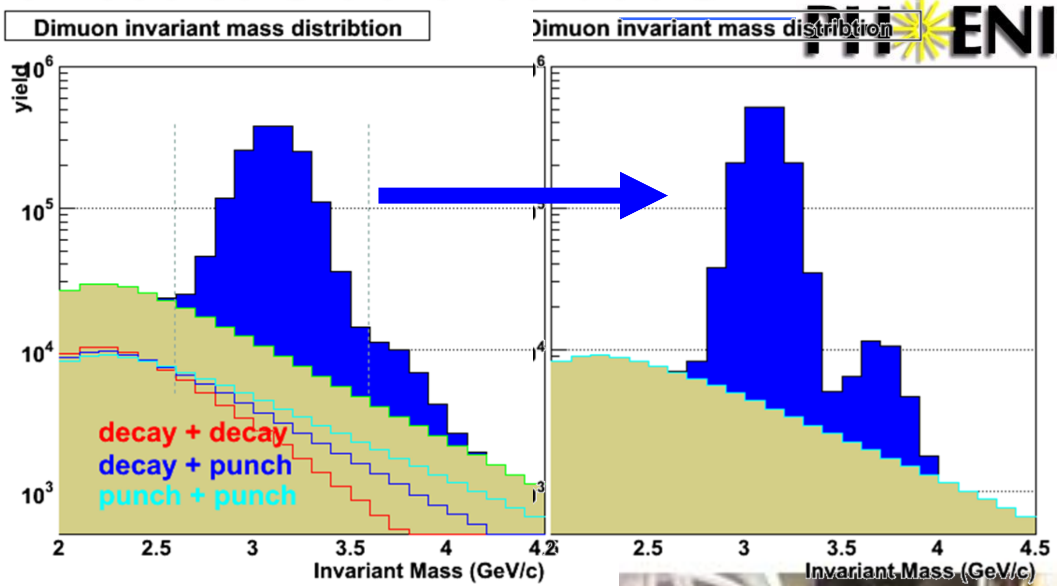


GEM storage vessel

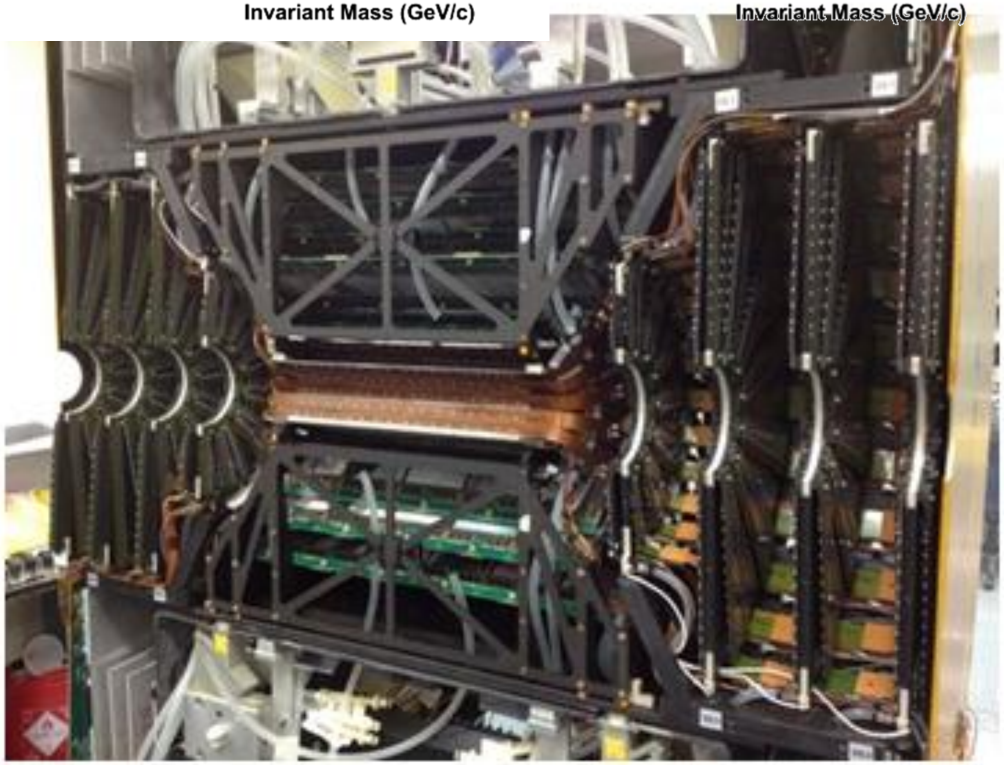
laminar flow hood

Entrance Foyer

FVTX for Muon Arms



- 4 planes per end-cap
- Covers
  - $1.2 < |\eta| < 2.4$
  - 2π in ϕ
  - $18.5\text{ cm} < |z| < 38\text{ cm}$
- Resolutuion:
  - Hit < 25μm
  - DCA < 200 μm



CASE

- Center for Accelerator Science and Education.
- Stony Brook has enjoyed a close connection with Brookhaven National Laboratory in many ways.
- Accelerator Science is a highlight of this connection with BNL scientists holding adjunct faculty positions at Stony Brook and mentoring Ph.D. students in Accelerator Physics.
- CASE formalizes and expands this relationship to foster its future growth.

Goals of CASE

- Joint venture of BNL and SBU.
  - ❑ To train scientists and engineers with the aim of advancing the field of accelerator science;
  - ❑ To develop a unique program of educational outreach that will provide broad access to a research accelerator; and,
  - ❑ To attract Federal and industrial funding for an expanding interdisciplinary research and education program that utilizes accelerators.
- Resources.
  - ❑ BNL has a panoply of state of the art accelerators engaged in a broad spectrum of sciences, with many outstanding scientists already affiliated with and teaching at SBU; many of the SBU faculty in various fields already use the existing accelerator based facilities at BNL for their own research;
  - ❑ SBU has a recently retired research accelerator – the Tandem Van de Graaff (TVdG) – whose control room has been renovated to become a modern Physics Teaching Laboratory (PTL) that serves graduate, undergraduate students as well as K-12 teachers and students.
- We expect to be able to develop programs and strong proposals that could generate major support from the National Science Foundation (NSF) and the Department of Energy (DoE) to meet the above goals.

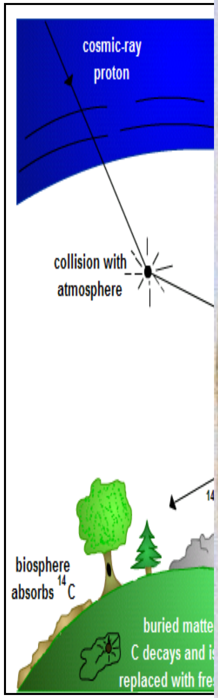
Present Status of CASE

- CASE has applied to become a Type I Institute within the University.
- We received the final approval of the provost.

^{14}C in Living Things

Production

- Carbon-14, or radiocarbon, is produced in the upper layers of the Earth's atmosphere by collisions of nitrogen molecules with the thermal neutrons created by cosmic rays.
- Unlike common carbon (carbon-12), ^{14}C is unstable and slowly decays.
- Like carbon-12, carbon-14 combines with oxygen in the atmosphere to form CO_2 (carbon dioxide.)



Equilibrium

- Carbon-14 decays slowly in a living organism but is continually replenished as long as the organism takes in air or food.
- The ratio of carbon-14 to carbon-12 stays constant in the Earth's atmosphere: one ^{14}C atom per trillion ^{12}C atoms.

$$\frac{^{14}C}{^{12}C} = 1.2\times10^{-12}$$


© Copyright Fortean Picture Library

Time of Death

- When a living thing dies, it stops exchanging carbon with the environment.
- The amount of carbon-14 in the organism gradually decreases with a 5760 ye
- Artifacts made of once-living material are eligible for ^{14}C dating.

Accelerator Mass Spectrometry

What is it?

- The sample is prepared, ionized, and accelerated as a beam through the tandem accelerator.
- Magnets select ions of the correct mass, velocity and charge continue along the beam line.

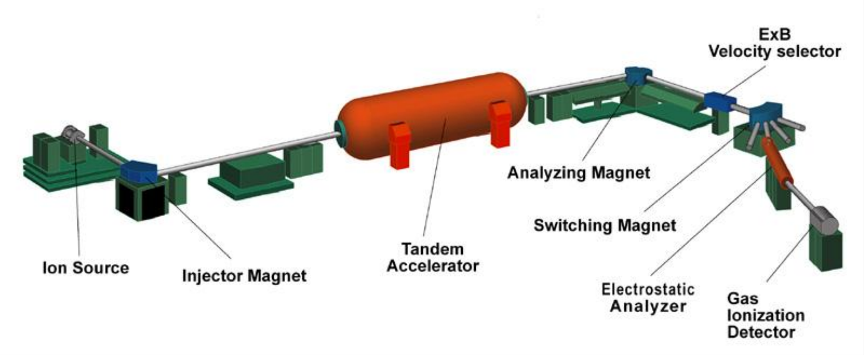
Stony Brook's Tandem Van de Graaff accelerator

High energy → single nucleus

- Magnets can be tuned to separate carbon-12 from carbon-14.
- Ionization detector measures the total energy of each nucleus as well as its rate of energy loss. Counts single nuclei

High energy eliminates molecules

- No molecules exist at charge states greater than +2.
- The stripping of electrons involved in accelerating the carbon beam also breaks up all molecules into their component atoms.



Outreach Concept

Concept

- In AMS carbon dating, the measurements are simple but the equipment is advanced.
- Our goal is to provide remote access to Stony Brook's Van de Graaff accelerator.
- Doing this will create a valuable science learning resource.
- Students will be able to conduct their own AMS carbon dating experiments, tuning the instruments and taking their own data through any web browser.

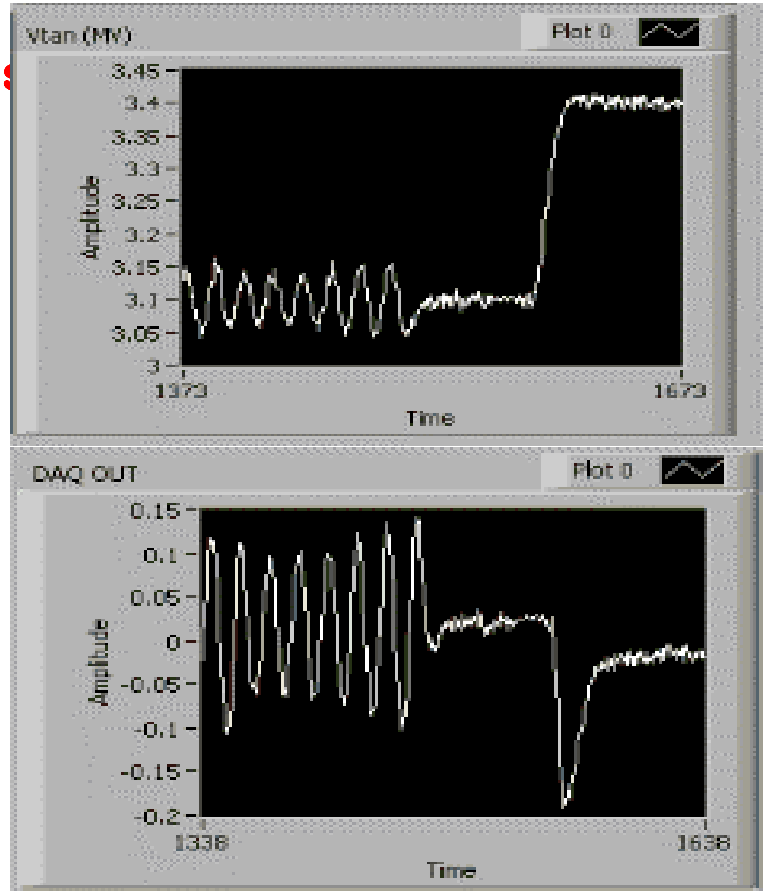
Stony Brook's Andrzej Lipski works with a summer research student to prepare samples for carbon dating in the accelerator.

Running Experiments Over the Net

- Once the development project is completed, students will be able to get behind the controls of Stony Brook's Van de Graaff accelerator from anywhere in the world.
- Measurements will be assisted via live videoconference with local expert.

Undergraduate Research

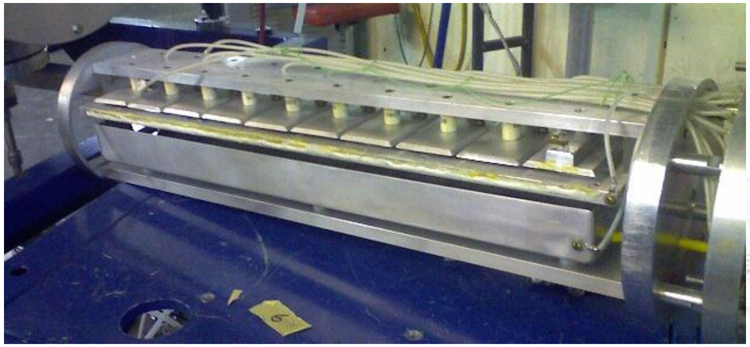
- **Undergrad Accomplishments**
  - **Remote Web-based Control of Tandem’ Injector.**
    - **Feister, REU – 2007**
  - **Remote Control of Analyzer Magnet**
    - **Drees, Visiting his Uncle - 2007**
  - **Gas Ionization Detection & Selection of ^{14}C**
    - **Turow, Simons - 2007**
  - **GVM stabilization of Tandem Terminal Voltage.**
    - **Ruzic, REU - 2008**
  - **CAMAC→USB→root DAQ System.**
    - **Miller, REU - 2008**

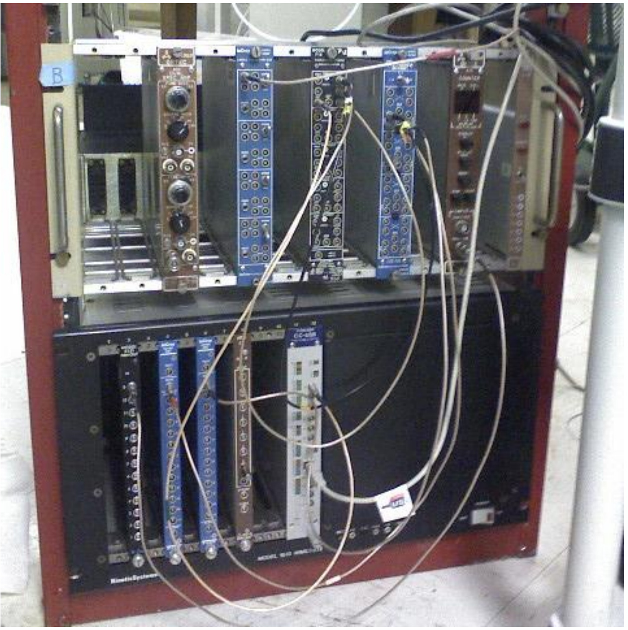


Grad Lab Experiments

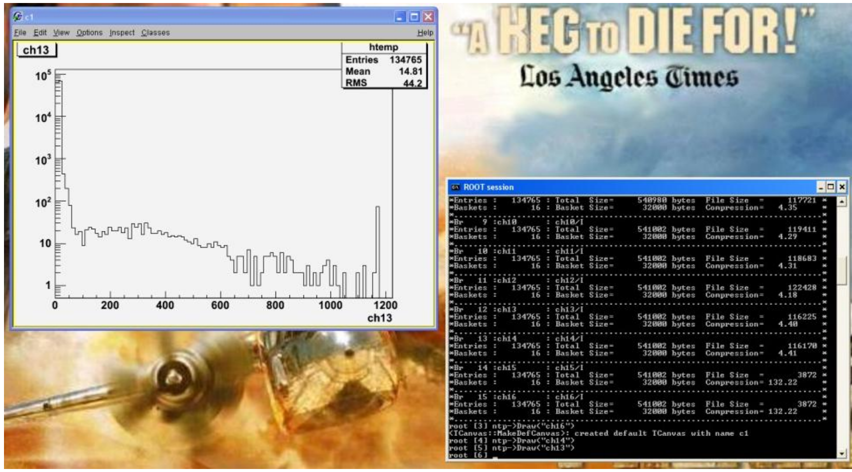
- Tandem Accelerator makes beams of any nuclear species.
- Multiple beam lines available for experiments.
- Ample Detectors available.
- New Tandem-based grad lab experiments will be available by Fall 2009.

Grad Lab Data Acquisition





- **A marriage of old & new.**
- **Detectors are digitized by CAMAC electronics (old)**
  and read out via USB 2.0
  (so last week...)
- **Event-by-event style data recorded as "nTuple" and analyzed via root (RHIC,LHC present standard).**



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Minor/Major/PhD Projects!

- We have a number of minor projects waiting involving establishing the ^{14}C program and also the grad lab experiments.
- We have major projects galore through BNL and Stony Brook.
- We have PhD projects at BNL in forefront accelerator science.
- PhD in AMS as well!

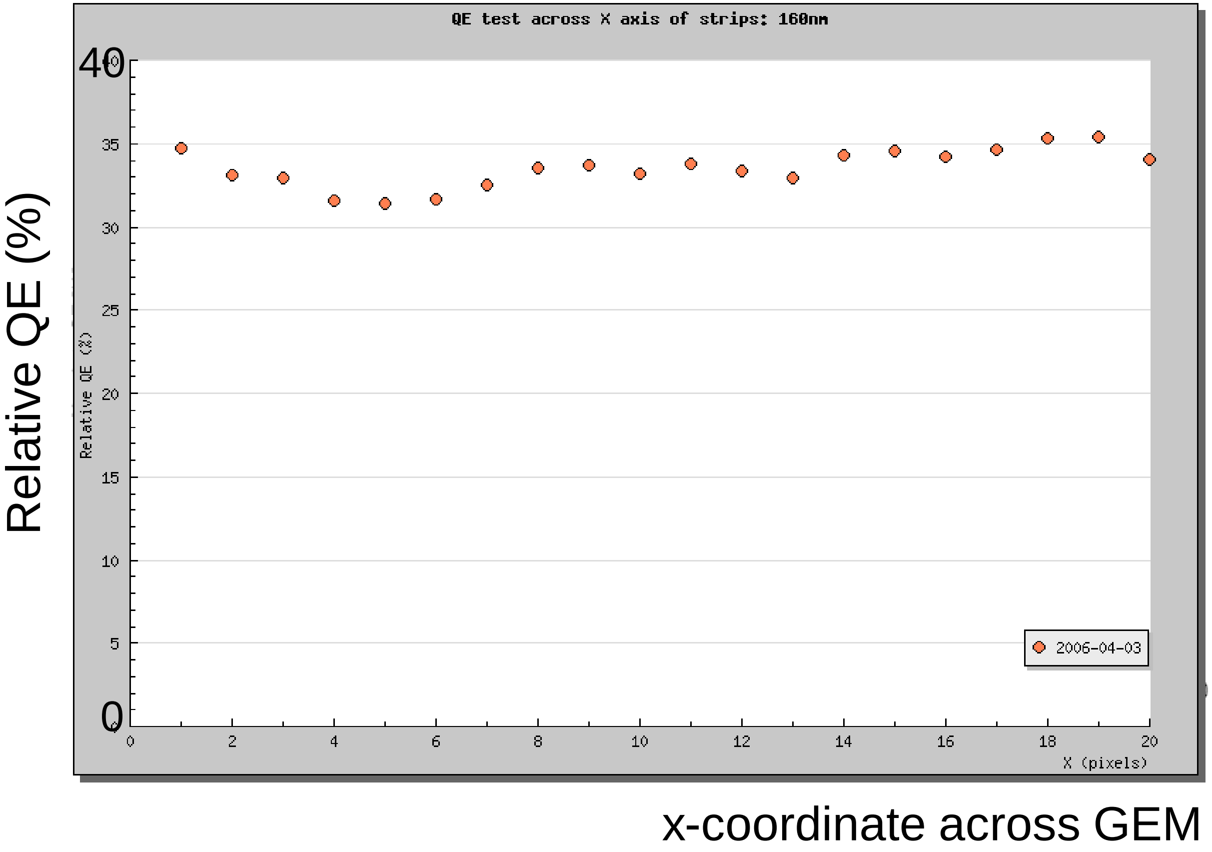
- **Backup**

In the beginning:

- Present understanding holds that all matter and energy of the universe sprang from a single point:
  - ❑ Extremely Dense; Extremely Hot
- Since that epoch, the history of the universe is dominated by cooling:
  - ❑ Today the universe is mostly ~2.7 K.
  - ❑ Exceptions exist in hot spots (like our solar system)
- As the universe cooled, different phases of matter and different forces of nature played the dominant role.

What can we learn in the laboratory about these events?

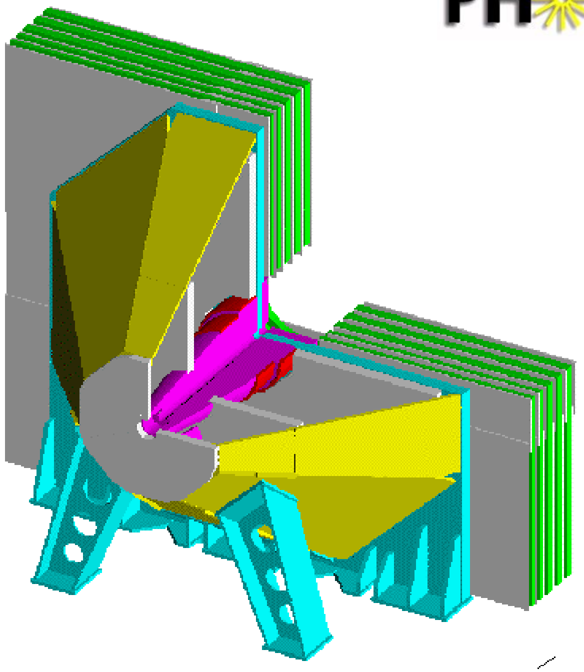
Quantum Efficiency

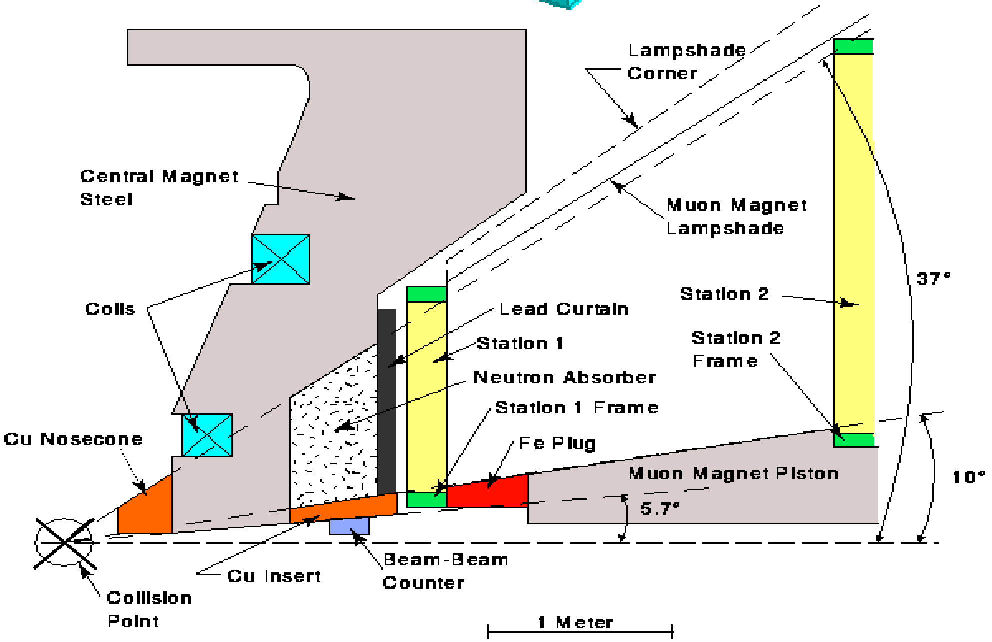


- **Excellent QE.**
- **Comparable to other research institutes throughout the world.**
- **QE constant across GEM.**
- **It’s crucial to maintain high QE after production.**

Muon Arms

- **The muon arms use the pole face of the central magnet as their primary absorber.**
- **Tracking occurs in a radial field.**
- **Muon ID is accomplishes by Iarocci tubes sandwiched between large steel plates**





TEC Design Goals

The four plane TEC is designed to achieve the following operation performance:

- Single point track resolution of 200-250 m in the r-ϕ direction
- Two track separation of 5 mm for tracks normal to the detector
- dE/dx measurement allowing e/π separation of 5x10 at 600 MeV/c and 2x10 at 2.0 GeV/c (for Xe gas)

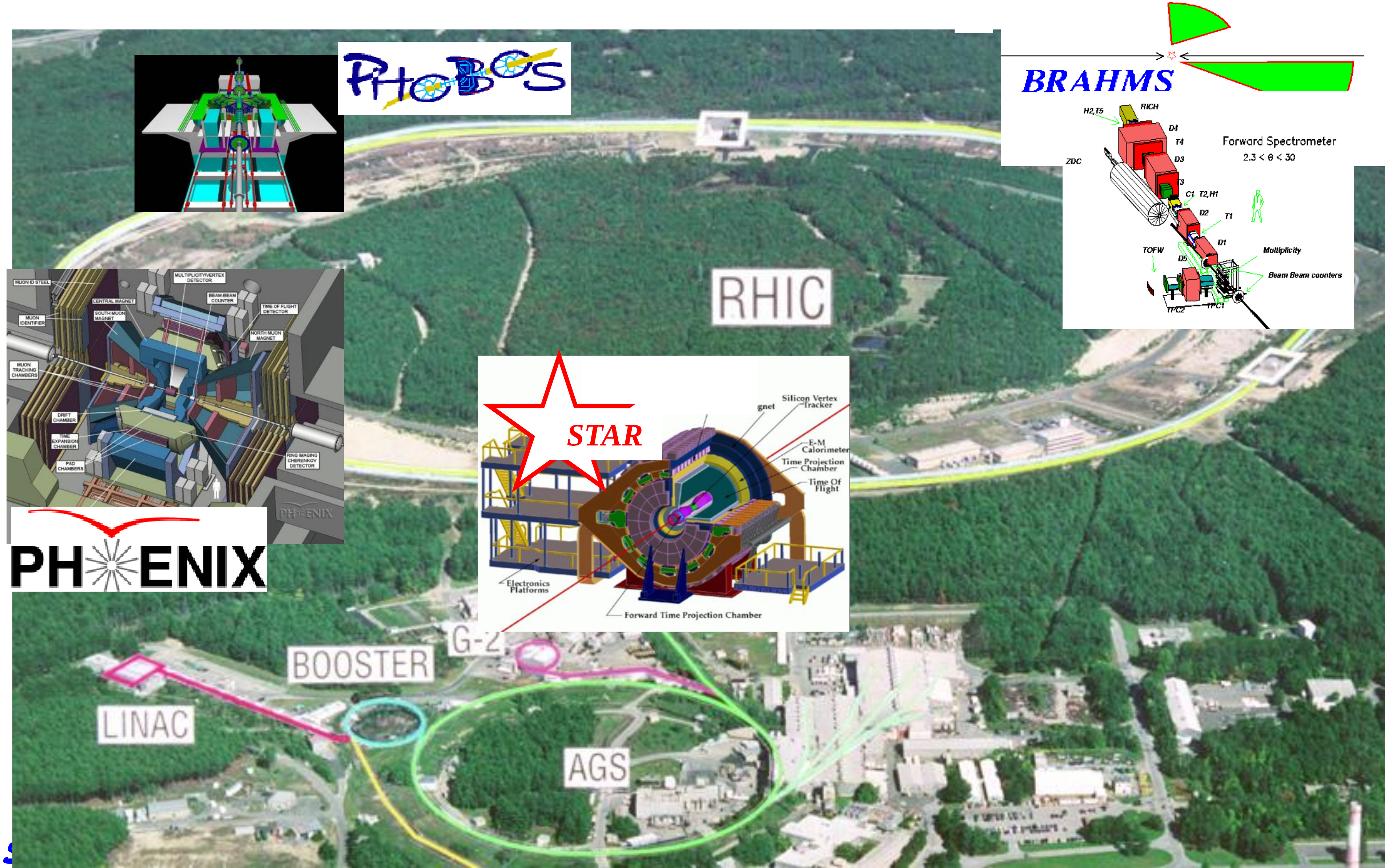
The detector parameters are:

- 4 planes of wire chambers built into two flat 45 segment in each arm located at z=4.35 m
- Active area covering = 0.35.
- Argon based gas mixture that will allow good tracking performance and dE/dx separation.
- Drift velocity in the range 15-30 mm/ s

6-pack of TEC

- The PHENIX TEC detector uses Flash-ADC digitization of dE/dx along the trajectory of the incoming particle.
- This technique maximizes the number of samples of ionization thereby improving the accuracy of the dE/dx measurement.
- The TEC wires run parallel to the beam. The TEC requires a pad chamber hit to determine "Z" location.

RHIC's Experiments

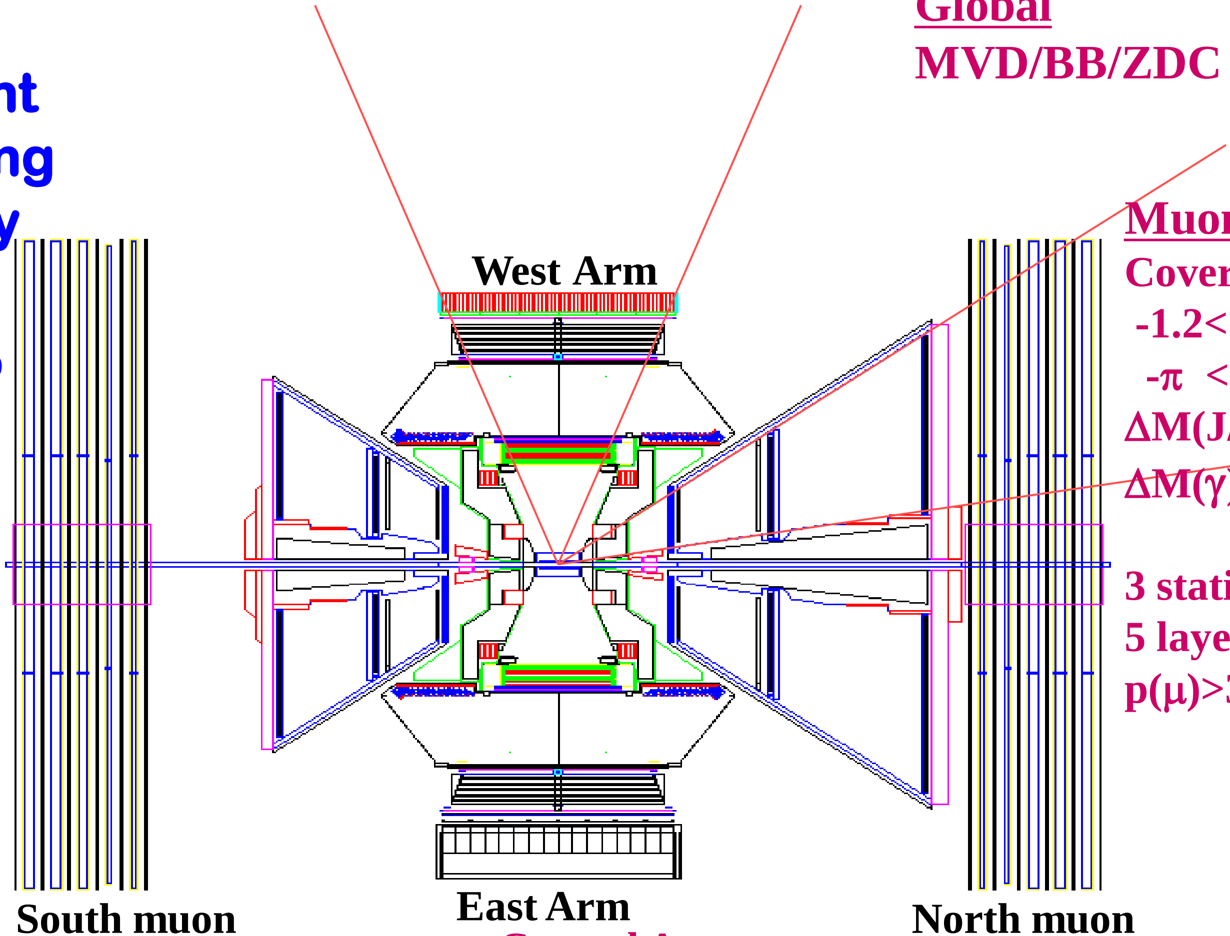


PHENIX

- An experiment with something for everybody
- A complex apparatus to measure
  - ❑ Hadrons
  - ❑ Muons
  - ❑ Electrons
  - ❑ Photons

Executive summary:

- ❑ *High* resolution
- ❑ *High* granularity



Global

MVD/BB/ZDC

Muon Arms

Coverage (N&S)

$-1.2 < |y| < 2.3$

$-\pi < \phi < \pi$

$\Delta M(J/\psi) = 105$MeV

$\Delta M(\gamma) = 180$MeV

3 station CSC

5 layer MuID $(10X_0)$

$p(\mu) > 3$GeV/c

Central Arms

Coverage (E&W)

$-0.35 < y < 0.35$

$30^o < |\phi| < 120^o$

$\Delta M(J/\psi) = 20$MeV

$\Delta M(\gamma) = 160$MeV

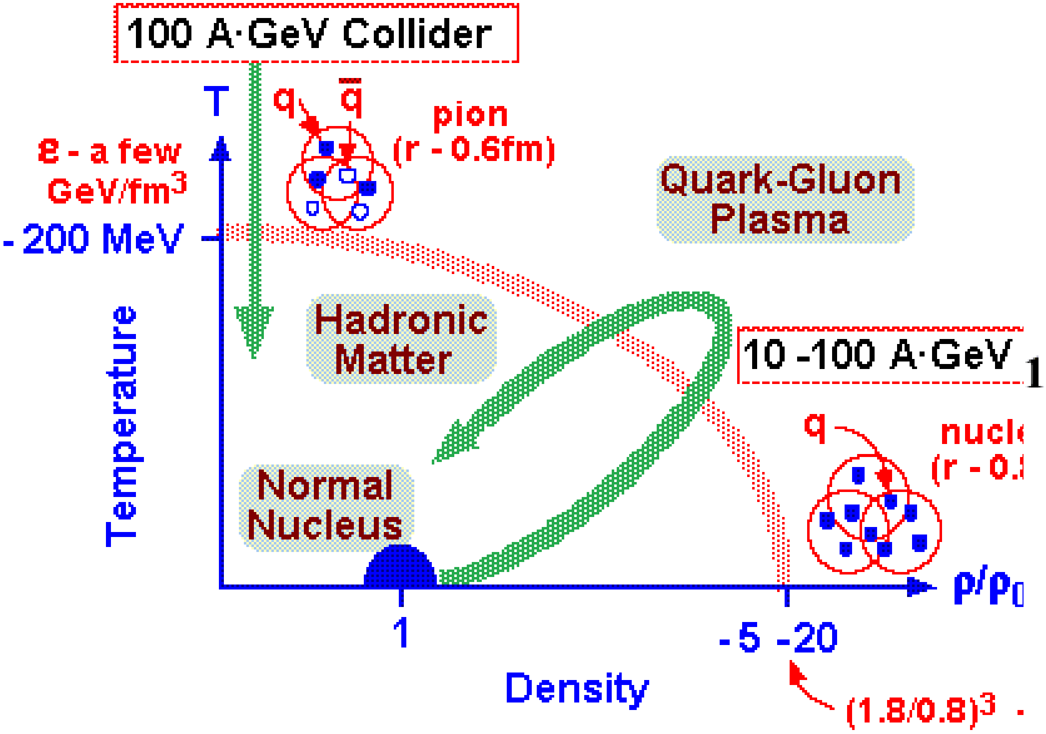
Summary

- Hadron Blind Detector is crucial to the low-mass dielectron spectrum (est. to reduce bkgrd by a factor of 10-100)
- Excellent QE is achieved at the Stony Brook production facility.
- The HBD prototype is installed in PHENIX and being tested. We have seen the light!! (it's working).
- Final HBD is scheduled to be installed in late Aug 2006.

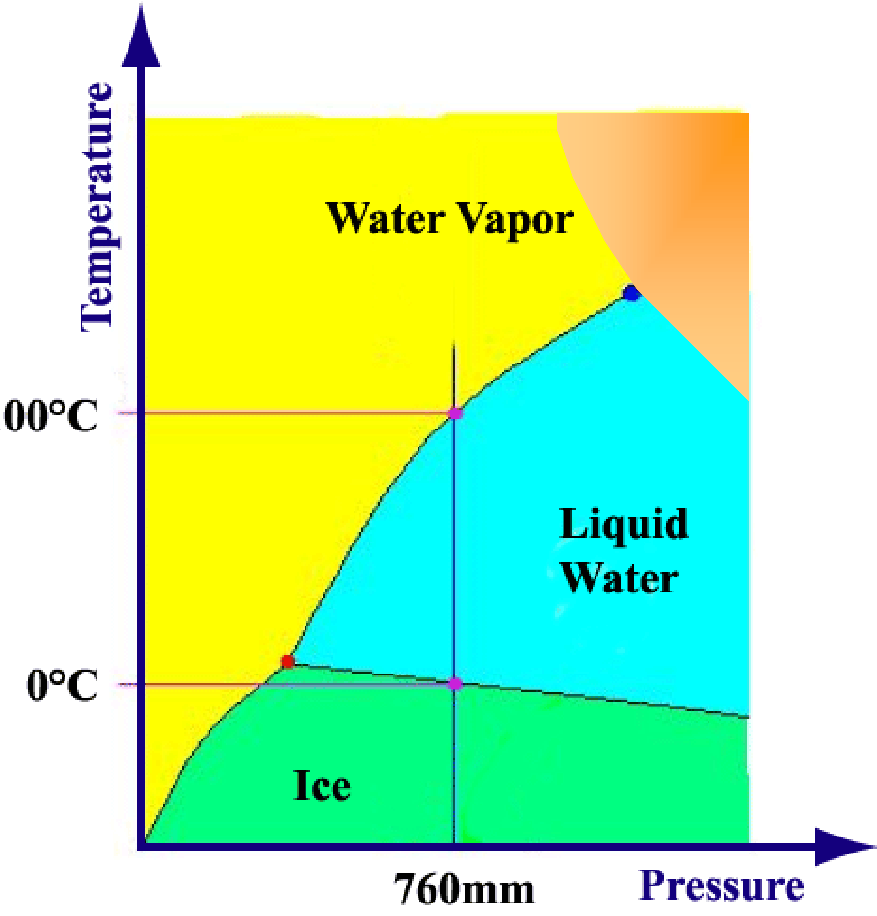
Making Plasma in the Lab

- **Extremes of temperature/density are necessary to recreate the Quark-Gluon Plasma, the state of our universe for the first few microseconds.**
  - ❑ **Density threshold is when protons/neutrons overlap**
    - ◆ **4X nuclear matter density = touching.**
    - ◆ **8X nuclear matter density should be plasma.**
  - ❑ **Temperature/Energy Density threshold:**
    - ◆ **When the temperature exceeds the mc^2 of the lightest meson (pion m=140 MeV/c^2)**
    - ◆ **Several light hadrons per volume of light hadron ε_c~1 GeV/fm^3**
    - ◆ **The necessary temperature is ~10^{12} Kelvin.**

Phase Diagrams



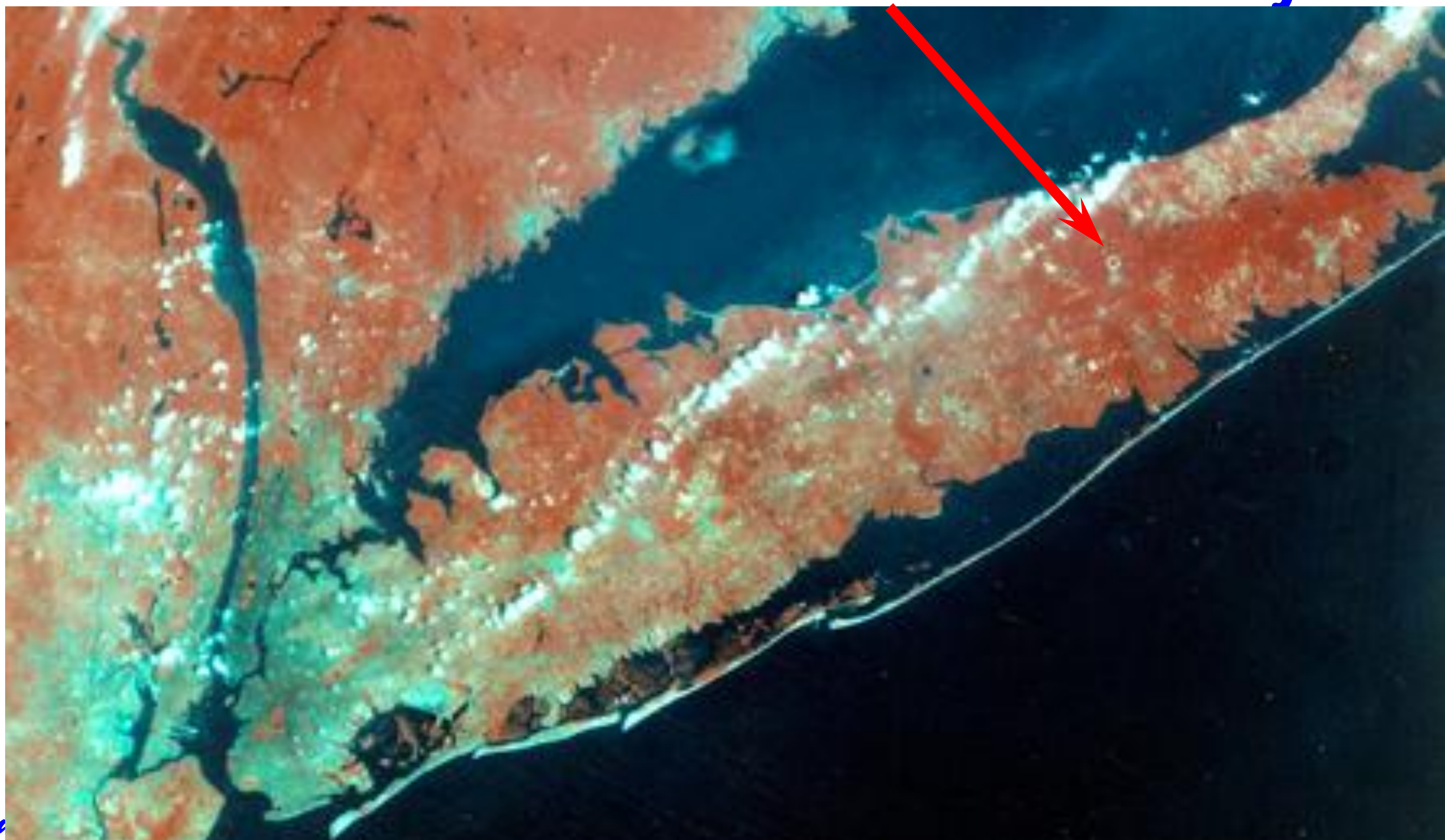
Nuclear Matter



Water

RHIC

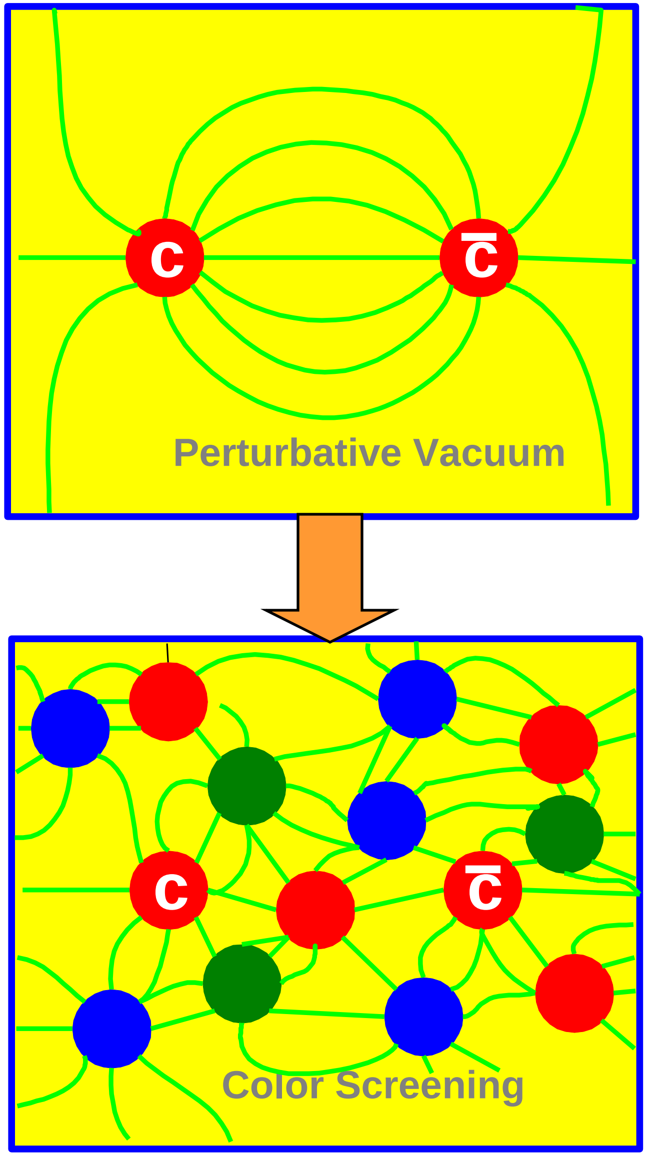
- RHIC = Relativistic Heavy Ion Collider
- Located at Brookhaven National Laboratory



How is RHIC Different?

- It’s dedicated to High Energy Heavy Ion Physics
  - ➔Heavy ions run 20-30 weeks/year
- It’s a collider
  - ➔Detector systematics independent of ECM
  - ➔(No thick targets!)
- It’s high energy
  - ➔Access to non-perturbative phenomena
    - ◆ Jets (very violent calculable processes in the mix)
    - ◆ Non-linear dE/dx
- Its detectors are comprehensive
  - ➔~All final state species measured with a suite of detectors that nonetheless have significant overlap for comparisons

RHIC in Fancy Language



- **Explore non-perturbative “vacuum” by *melting it***
  - ❑ Temperature scale $T \sim \hbar/(1\,\mathrm{fm}) \sim 200\,\mathrm{MeV}$
  - ➔ Particle production
  - ➔ Our ‘perturbative’ region is filled with
    - ◆ gluons
    - ◆ quark-antiquark pairs
  - ➔ A Quark-Gluon Plasma (QGP)
- **Experimental method:**
  Energetic collisions of heavy nuclei
- **Experimental measurements: Use probes that are**
  - ❑ Auto-generated
  - ❑ Sensitive to all time/length scales

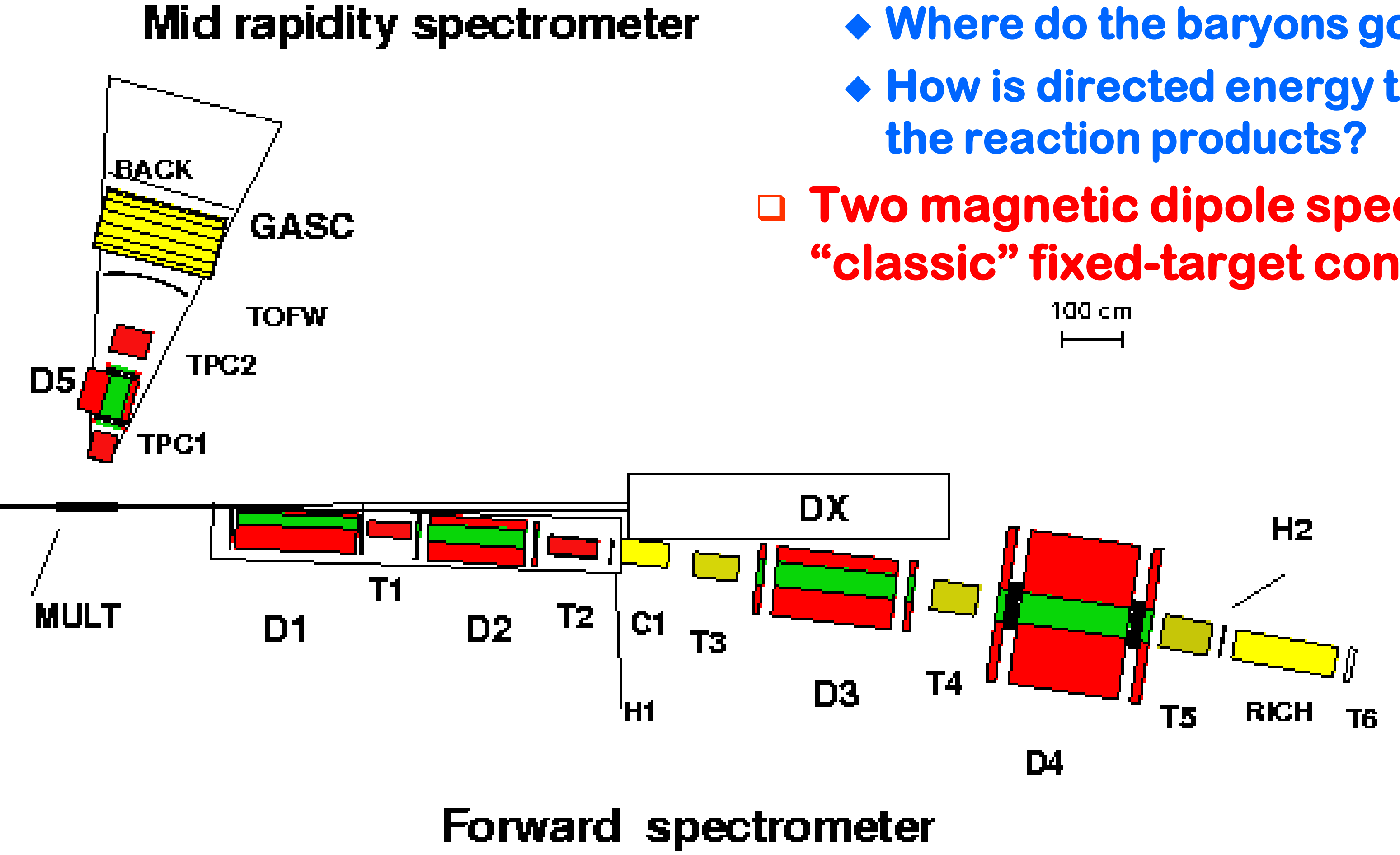
RHIC in Simple Language

- **Suppose…**
  - ☐ You lived in a frozen world where water existed only as ice
  - ☐ and ice comes in only quantized sizes ~ ice cubes
  - ☐ and theoretical friends tell you there should be a liquid phase
  - ☐ and your only way to heat the ice is by colliding two ice cubes
  - ☐ So you form a "bunch" containing a billion ice cubes
  - ☐ which you collide with another such bunch
  - ☐ 10 million times per second
  - ☐ which produces about 1000 IceCube-IceCube collisions per second
  - ☐ which you observe from the vicinity of Mars
- **Change the length scale by a factor of ~10^{13}**
  - ➔You're doing physics at RHIC!

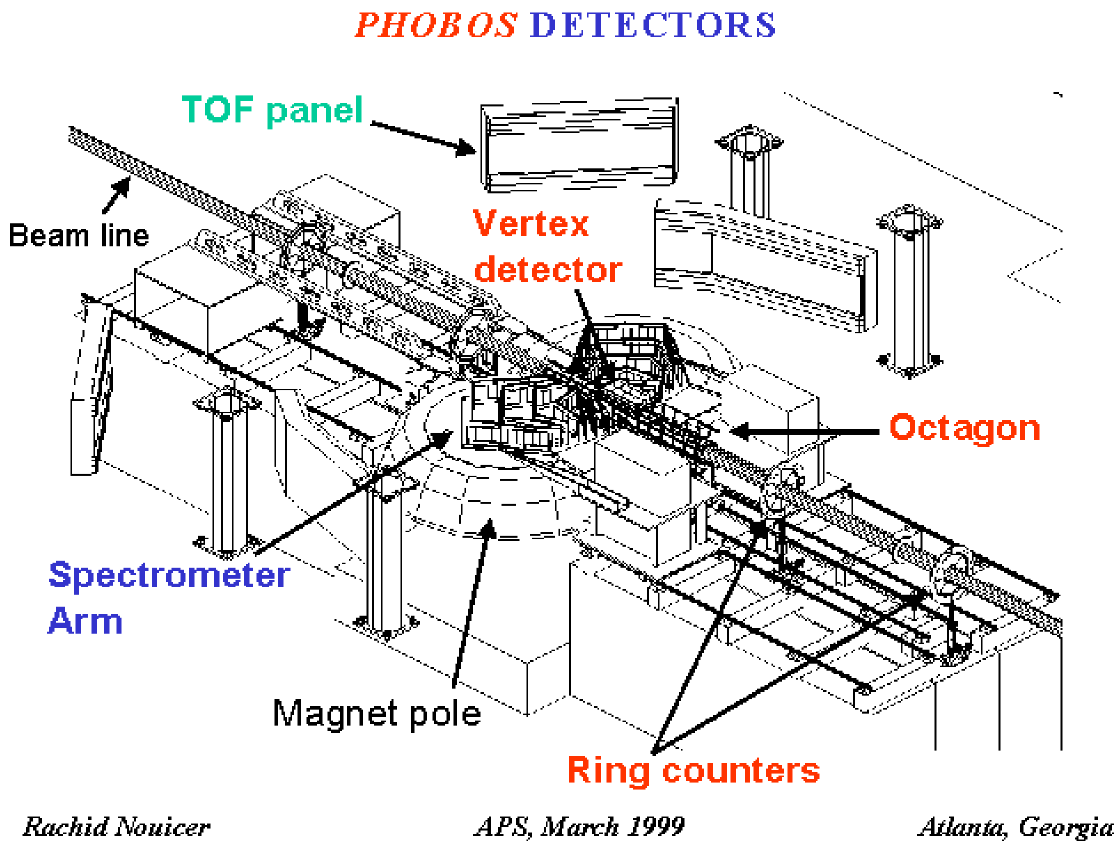
BRAHMS

An experiment with an emphasis:

- Quality PID spectra over a broad range of rapidity and p_T
- Special emphasis:
  - Where do the baryons go?
  - How is directed energy transferred to the reaction products?
- Two magnetic dipole spectrometers in "classic" fixed-target configuration



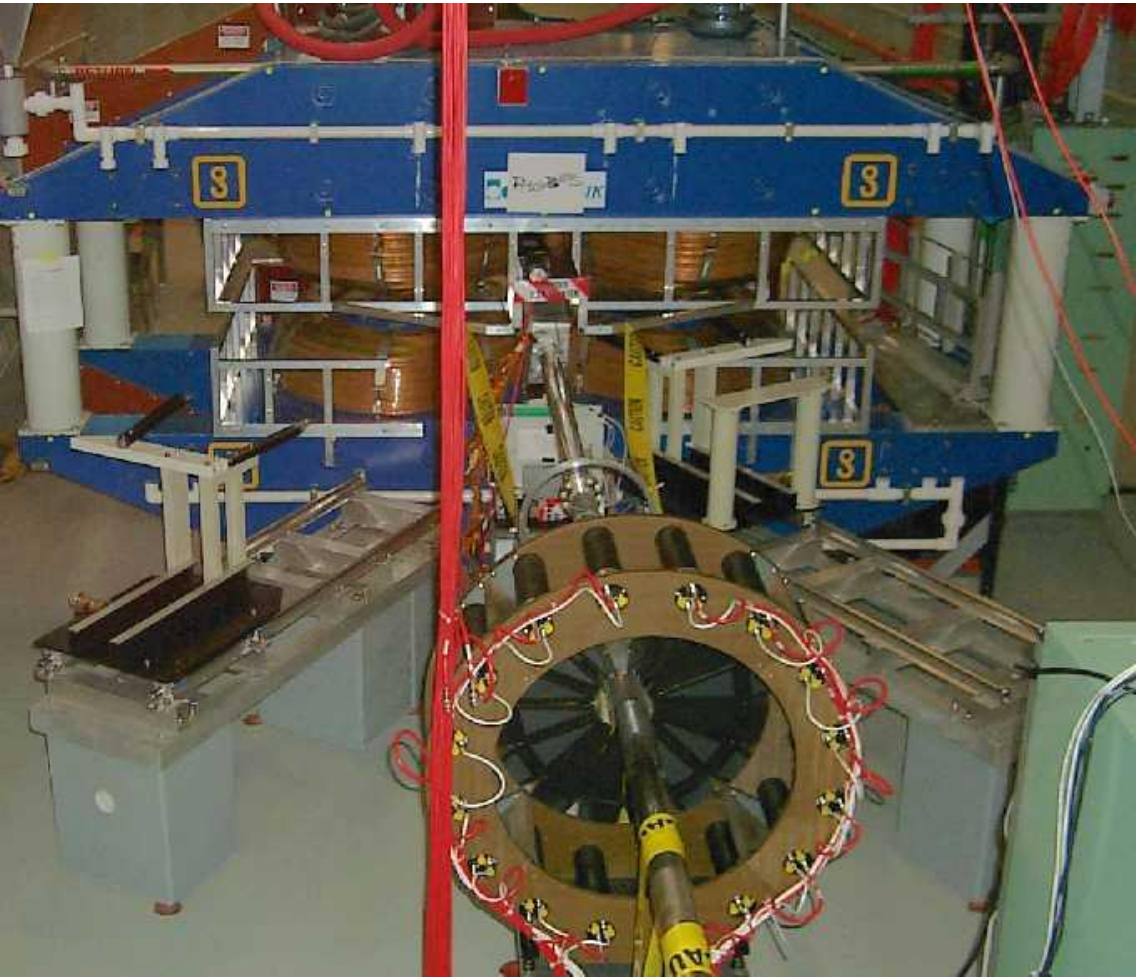
PHOBOS

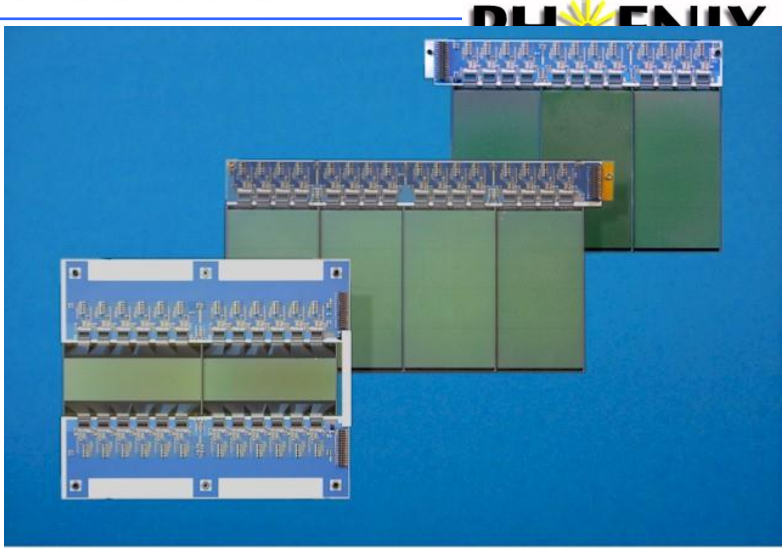


An experiment with a philosophy:

- ❑ **Global phenomena**
  - ➔large spatial sizes
  - ➔small momenta
- ❑ **Minimize the number of technologies:**
  - ◆ All Si-strip tracking
  - ◆ Si multiplicity detection
  - ◆ PMT-based TOF
- ❑ **Unbiased global look at very large number of collisions (~10^9)**

PHOBOS Details

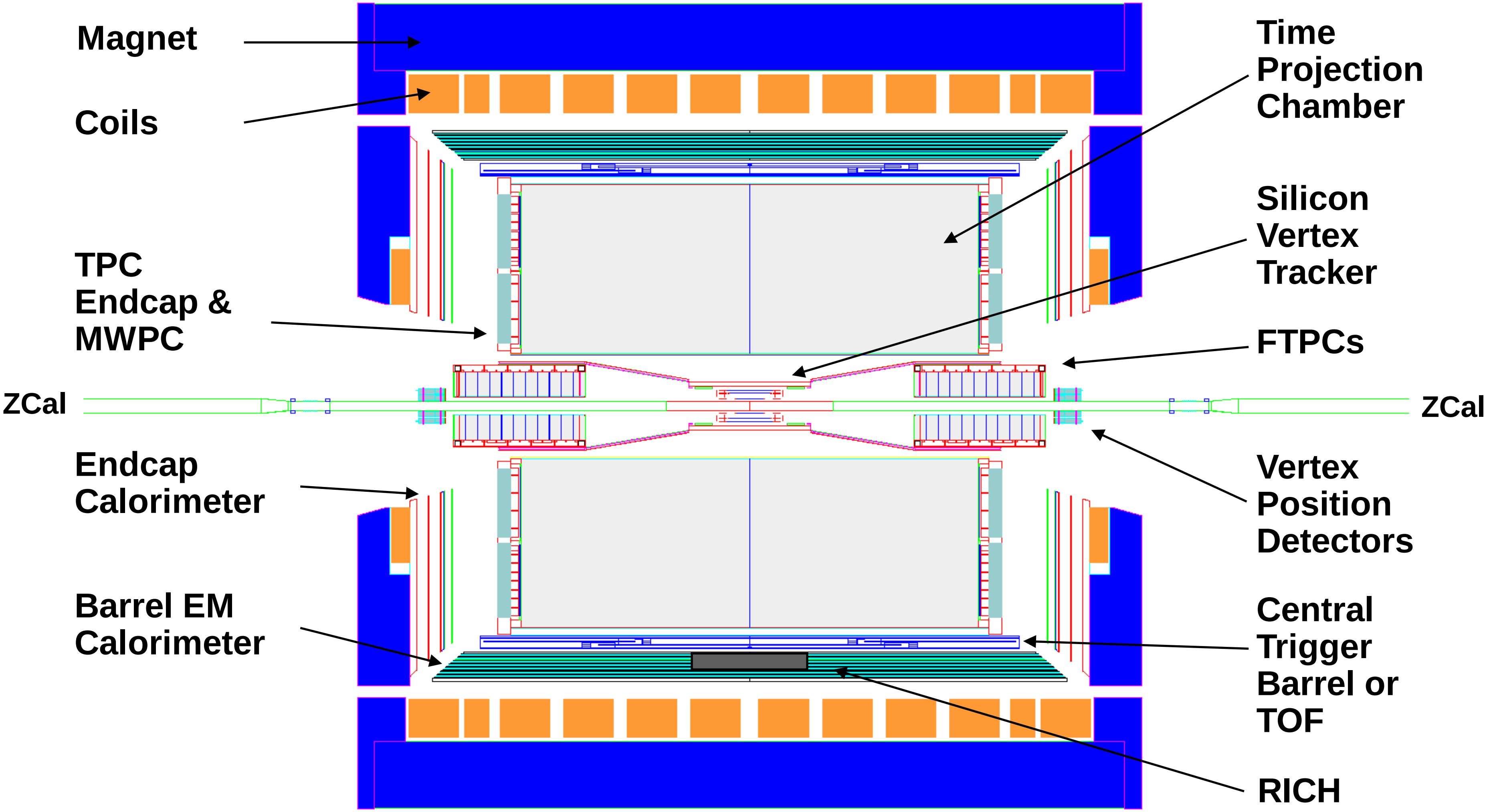




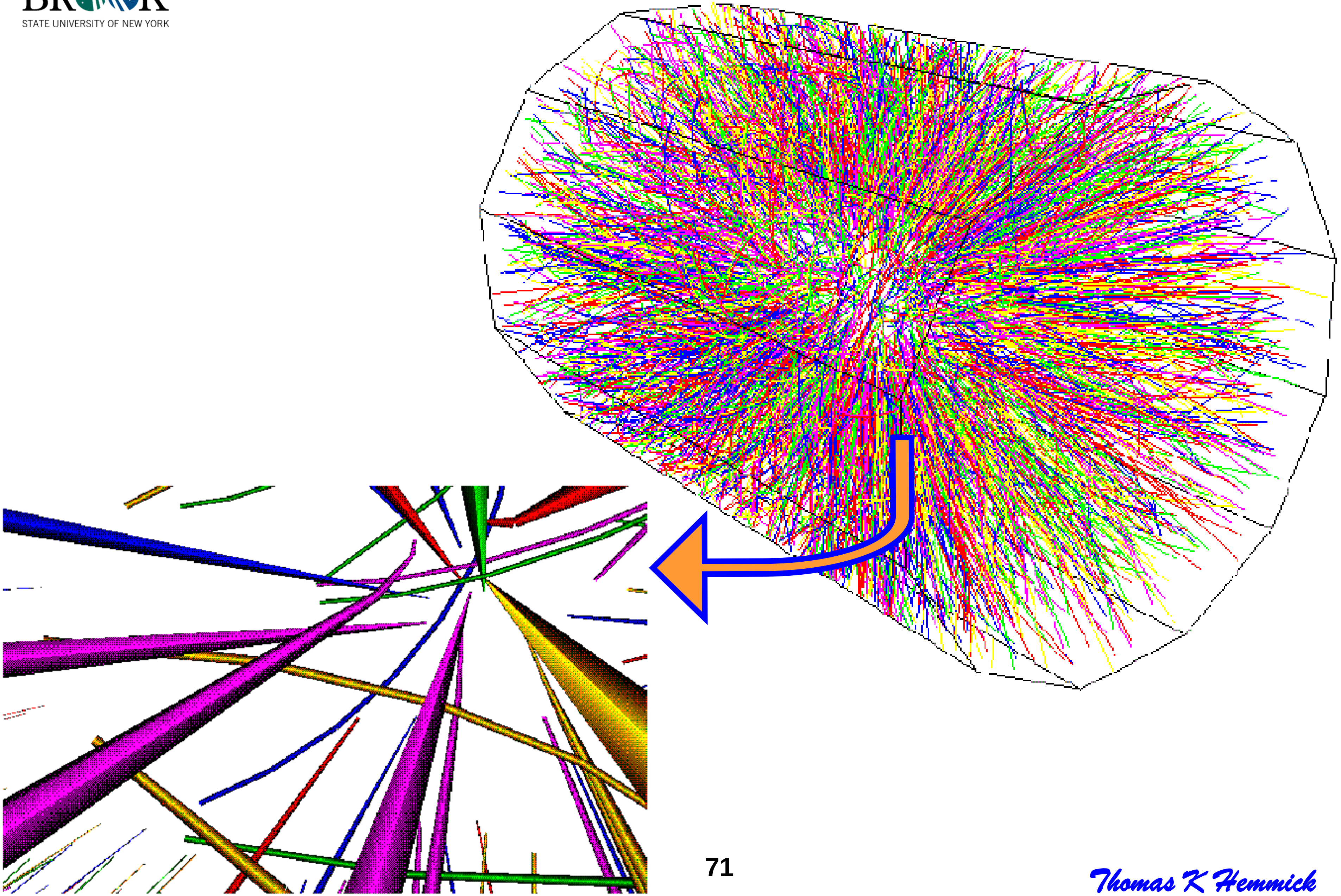
- **Si tracking elements**
  - 15 planes/arm
  - Front: “Pixels” (1mm x 1mm)
  - Rear: “Strips” (0.67mm x 19mm)
  - 56K channels/arm
- **Si multiplicity detector**
  - 22K channels
  - $|\eta| < 5.3$

STAR

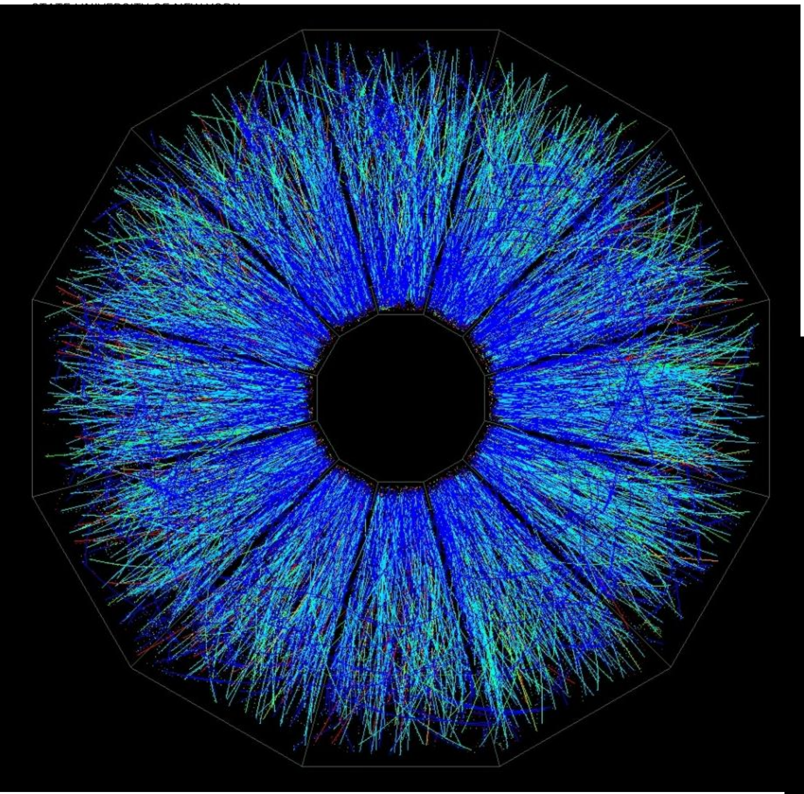
- **An experiment with a challenge:**
  - ☐ Track ~ 2000 charged particles in |η| < 1



STAR Challenge

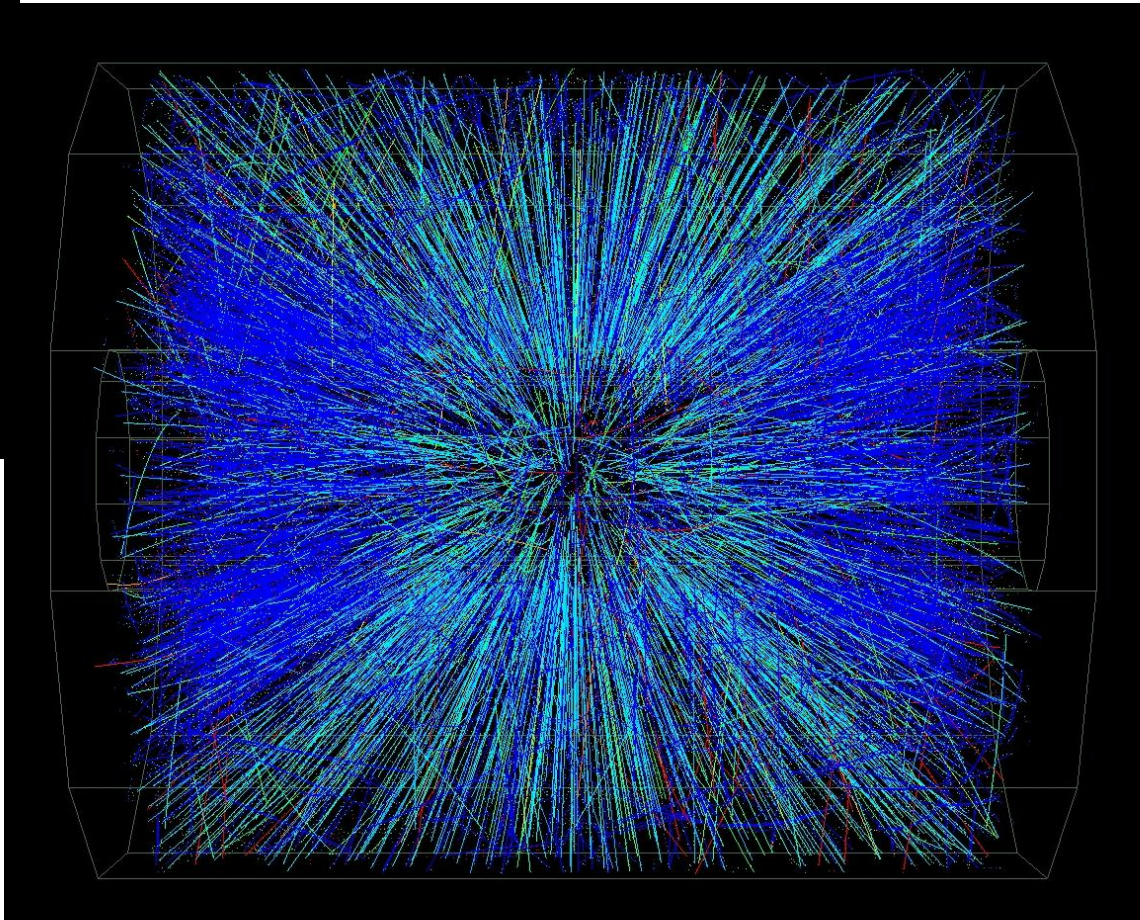


STAR Event

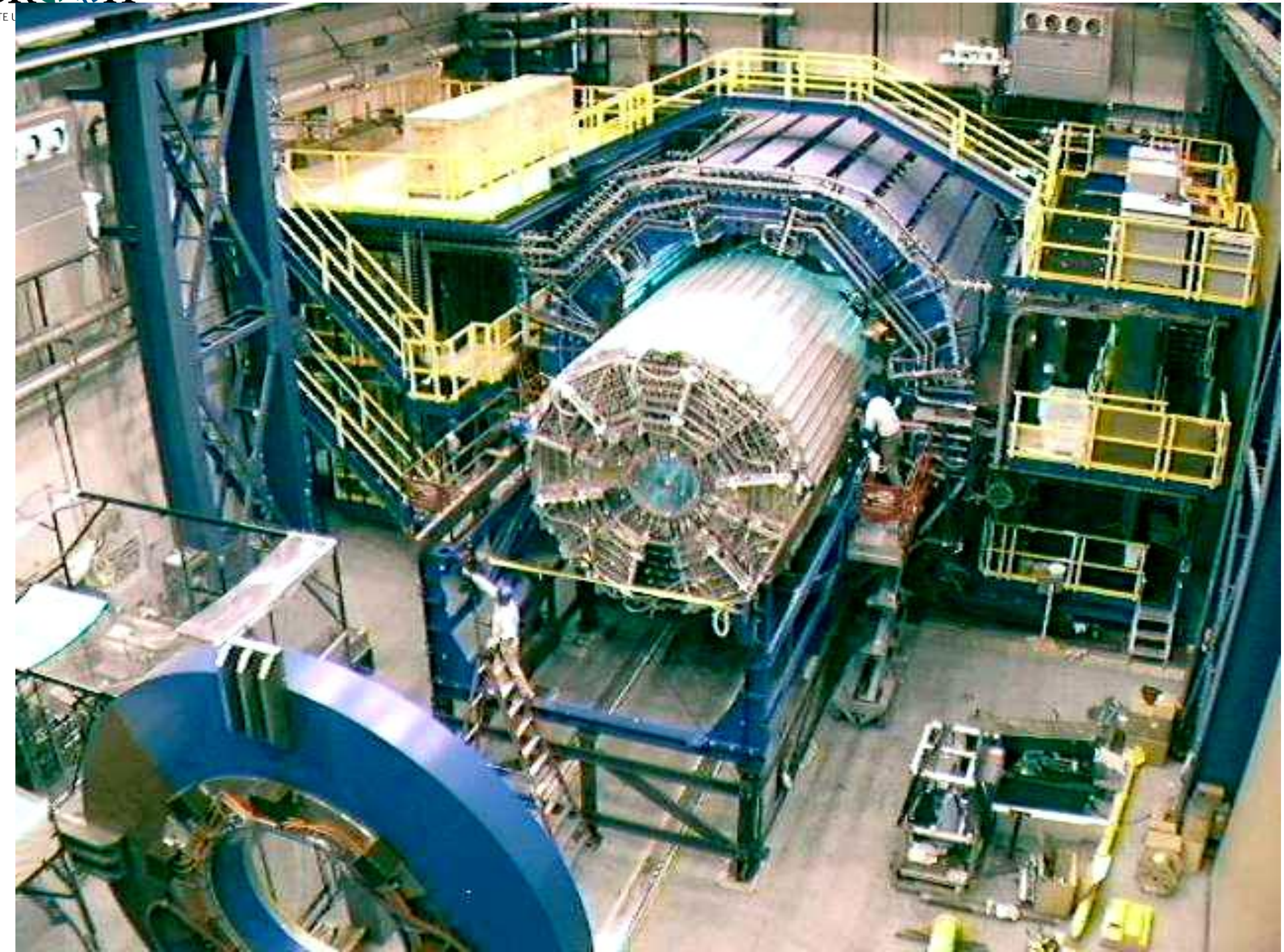


Data Taken June 25, 2000.

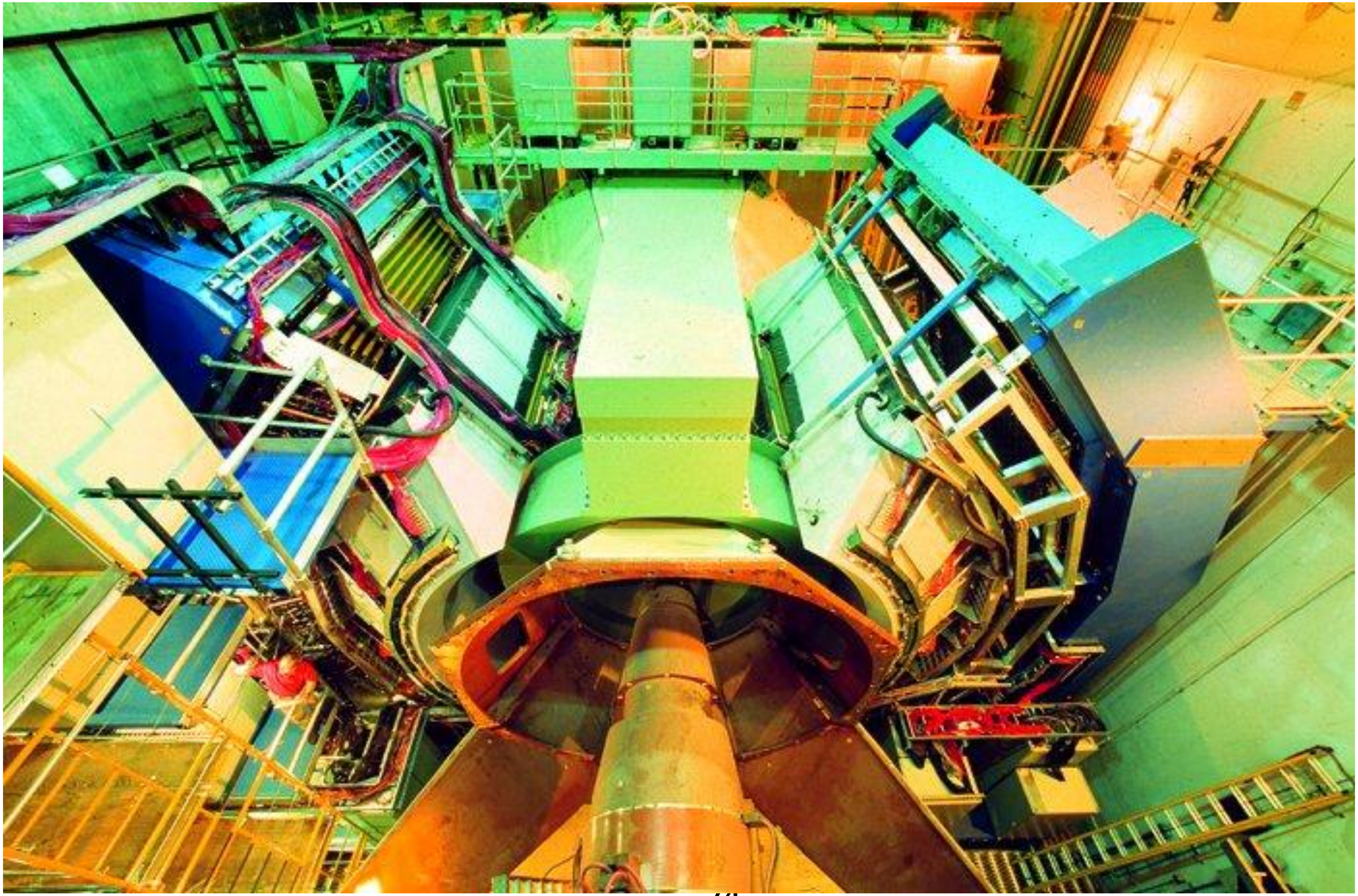
Pictures from Level 3 online display.



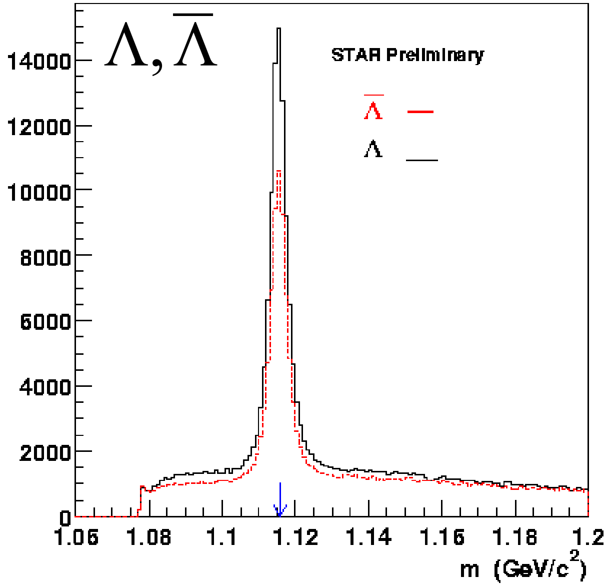
STAR Reality

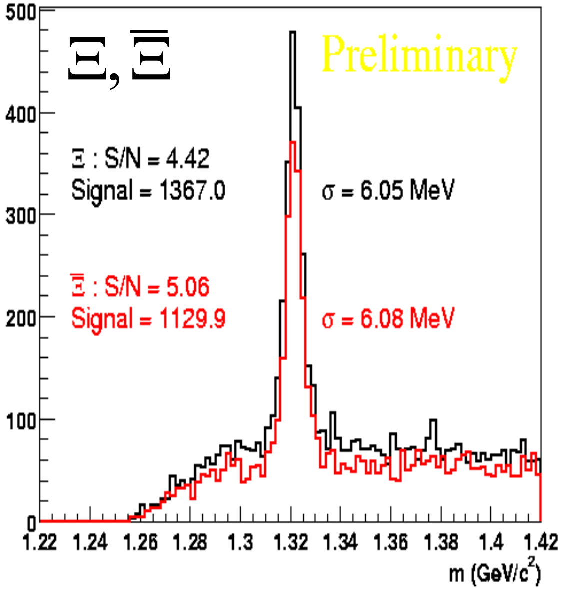


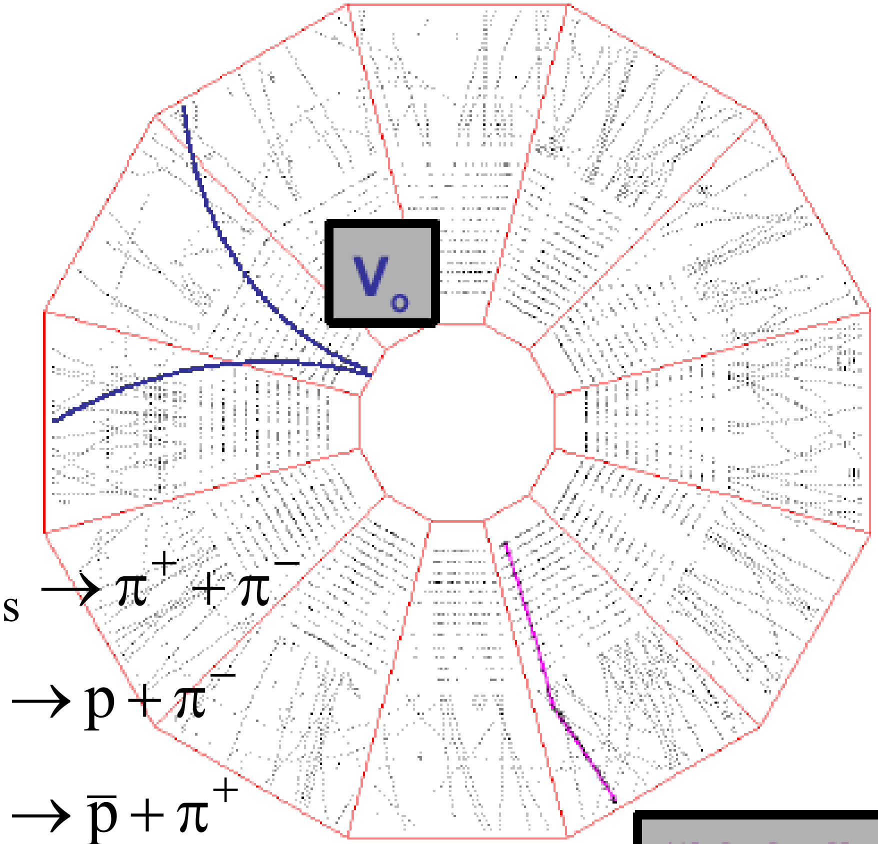
PHENIX Reality



Particle ID Techniques - Topology







$K_s \to \pi^+ + \pi^-$

$\Lambda \to p + \pi^-$

$\bar{\Lambda} \to \bar{p} + \pi^+$

$\Xi^- \to \Lambda + \pi^-$

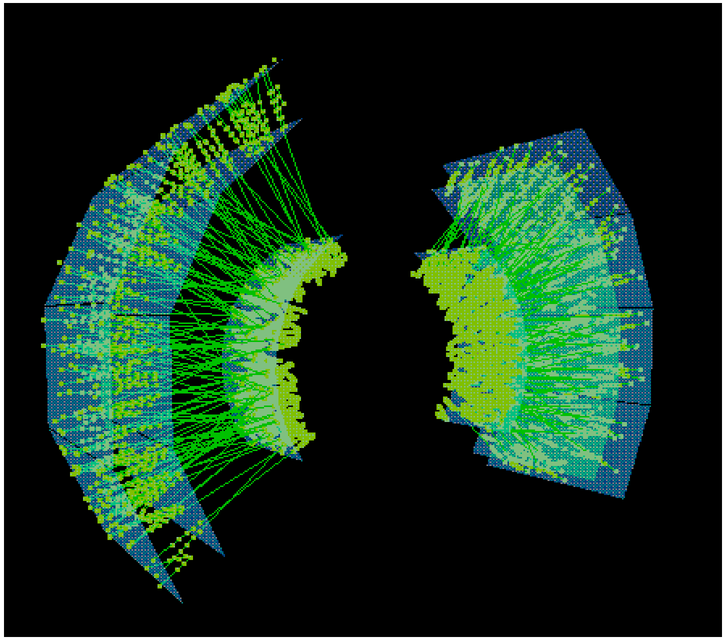
$\bar{\Xi}^+ \to \bar{\Lambda} + \pi^+$

$\Omega \to \Lambda + K^-$

“kinks”:

$K^\pm \to \mu^\pm + \nu$

Tracking Software



Stony Brook developed the software which sorts detector hits into tracks (pattern recognition) using global Hough Transforms.

We are working on software for mock analysis to be ready on Day One of RHIC.

Magnetic Spectrometers

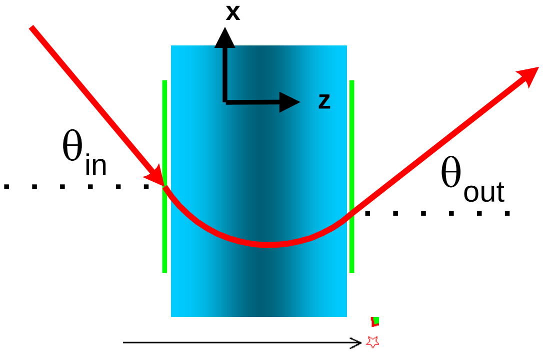
Cool Experiment:

- Hold a magnet near the screen of a **B&W** TV.
- The image distorts because the magnet bends the electrons before they hit the screen.

- **Why? :**

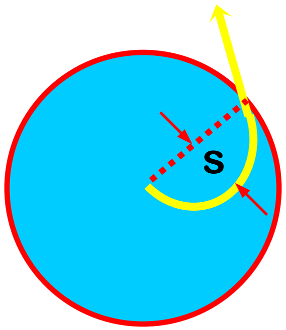
$$\frac{d\vec{p}}{dt} = \frac{e}{c}\vec{v}\times\vec{B} \qquad |\vec{p}_\perp| = \frac{e}{c}B\cdot R, \quad \frac{e}{c} = \frac{0.3\,GeV/c}{Tesla-meter}$$

1 meter of 1 Tesla field deflects p = 1 GeV/c by ~17°



BRAHMS

PHOBOS



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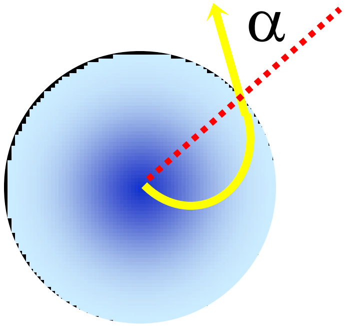


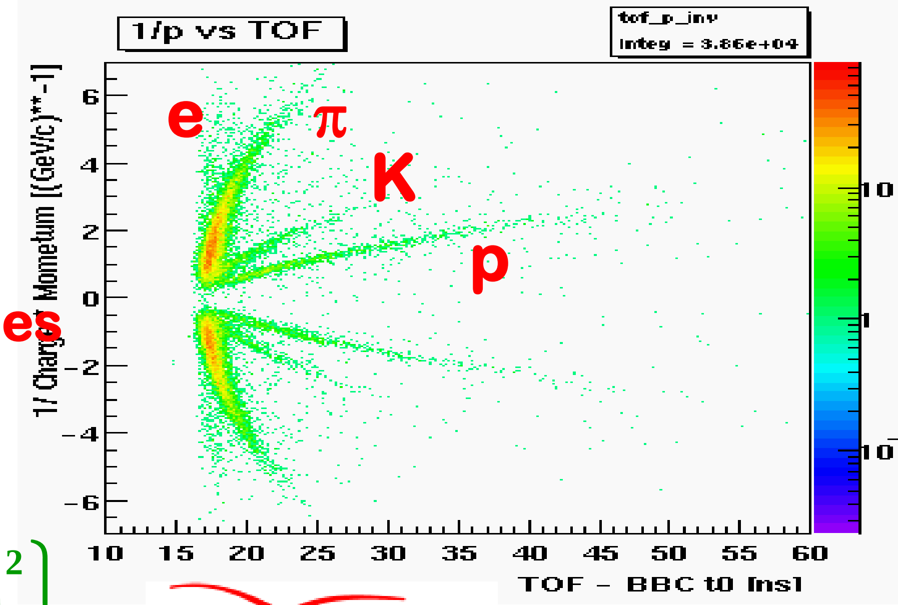
PHENIX

Particle Identification by TOF

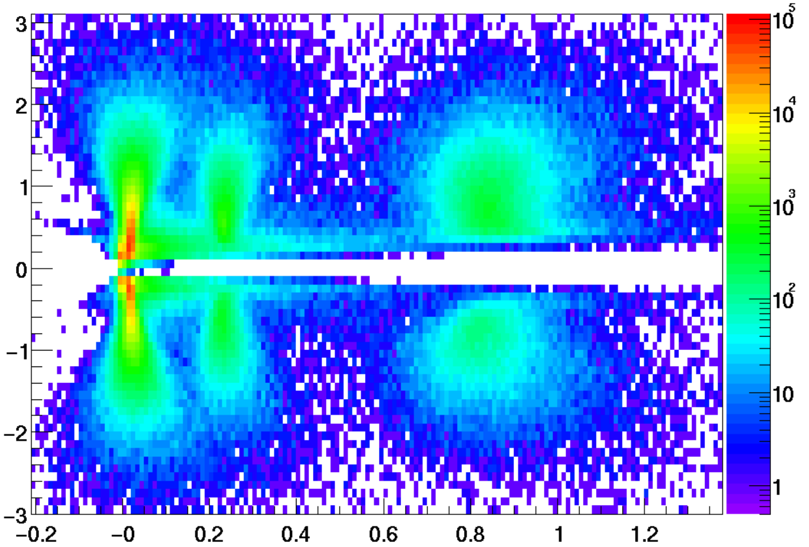
- **The most direct way**
  - Measure β by distance/time
  - Typically done via scintillators read-out with photomultiplier tubes
  - Time resolutions ~ 100 ps
  - Exercise: Show

$$\left(\frac{\delta m}{m}\right)^2 = \left(\frac{\delta p}{p}\right)^2 + \gamma^4 \left\{ \left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta s}{s}\right)^2 \right\}$$

- **Performance:**
  - δt ~ 100 ps on 5 m flight path
  - ➔ P/K separation to ~ 2 GeV/c
  - ➔ K/p separation to at least 4 GeV/c

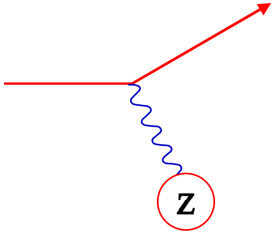


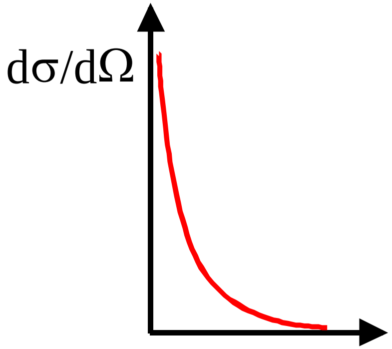
PHENIX



Interactions with Matter

Coulomb Scattering

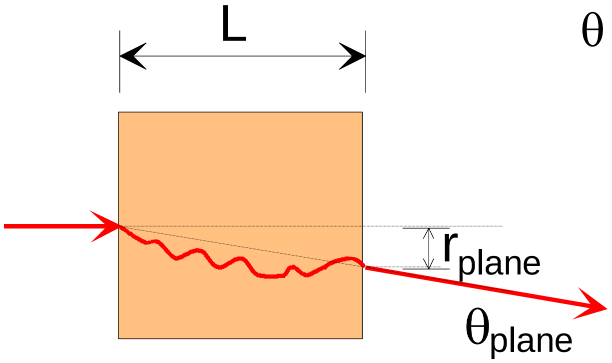




An incoming particle with charge z interacts with a target of nuclear charge Z. The cross-section for this e.m. process is

$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \theta/2}$$

Rutherford formula

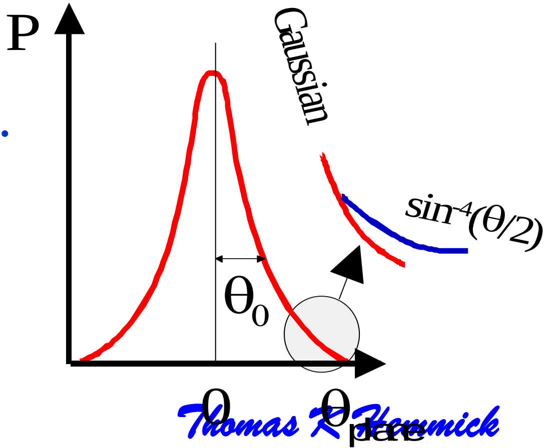


Average scattering angle $<\theta> = 0$

Cross-section for $\theta \to 0$ is infinite !

This implies that there will be many soft scattering events.

Multiple Coulomb Scattering



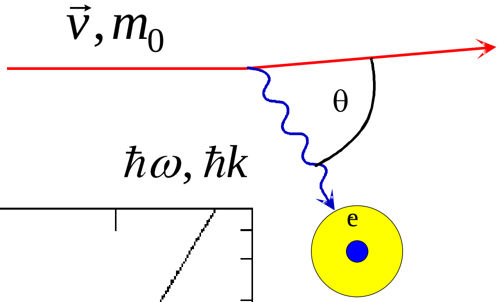
In sufficiently thick material layer → the particle will undergo multiple scattering. There will be angular deflections and energy loss.

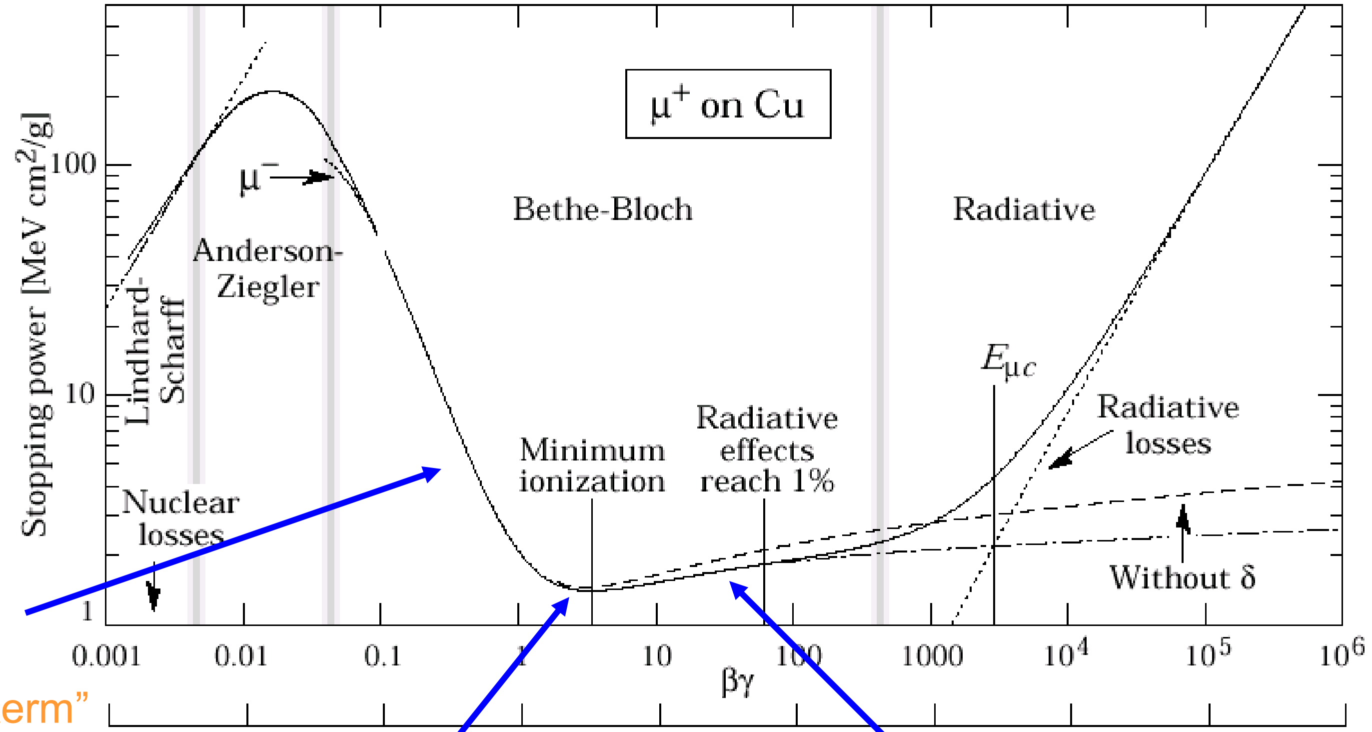
$$\theta_0 \approx \frac{13.6MeV}{\beta\ c\ p}\ z\sqrt{\frac{x}{X_0}}\left[1+0.20\ \ln\left(x/X_0\right)\right]$$

Radiation Length

How do particles lose energy in matter?

$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE}\hbar\, d\omega$$





$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

"kinematic term"

"minimum ionizing particles" βγ ≈ 3-4

"relativistic rise" $\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2\gamma^2$

Bethe-Bloch Formula

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

density effect

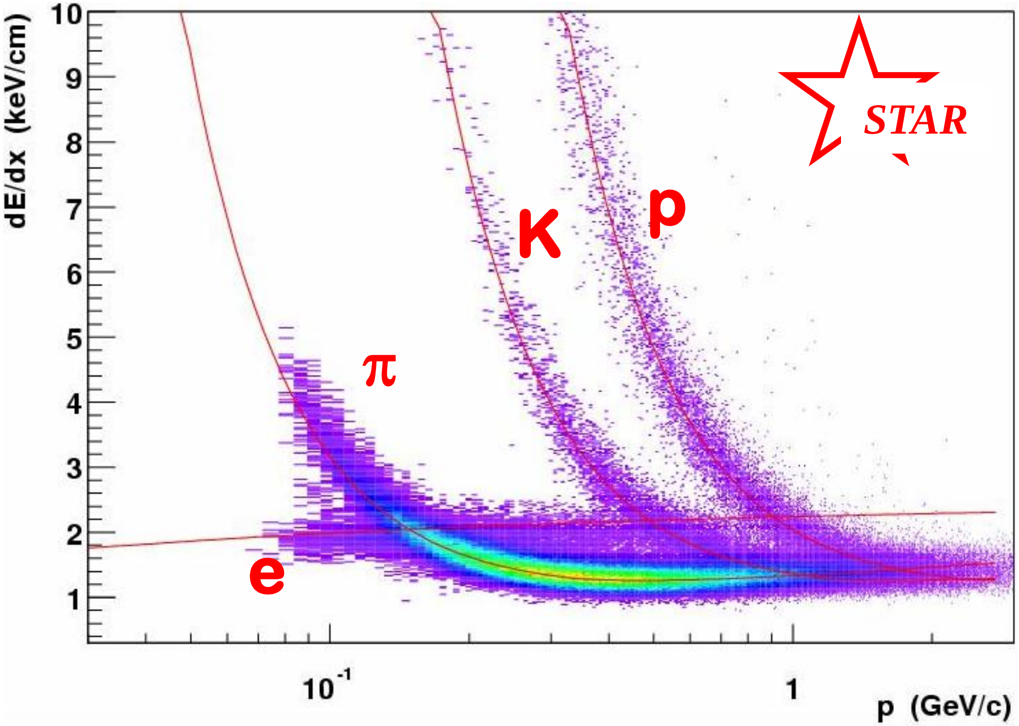
ionization constant

Particle Identification by dE/dx

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \gamma^2 \beta^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right]$$

$$\text{Energy transfer} = \frac{(p_y{}^e)^2}{2m_e} \sim \frac{1}{\beta^2}$$

- **dE/dx:**
  - ❑ The $1/\beta^2$ survives integration over impact parameters
  - ➔ Measure average energy loss to find b
  - ❑ Used in all four experiments



π^0 Reconstruction

- A good example of a "combinatoric" background
- Reconstruction is *not* done particle-by-particle
- Recall: $\pi^0 \rightarrow \gamma\gamma$ and there are ~200 π^0 's per unit rapidity
  - ❑ So:

$$\pi^0{}_1 \rightarrow \gamma_{1A} + \gamma_{1B}$$
$$\pi^0{}_2 \rightarrow \gamma_{2A} + \gamma_{2B}$$
$$\pi^0{}_3 \rightarrow \gamma_{3A} + \gamma_{3B}$$

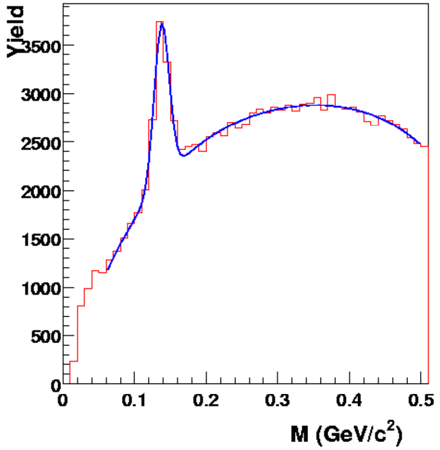
$$\pi^0{}_N \rightarrow \gamma_{NA} + \gamma_{NB}$$

PHENIX

π^0 reconstruction

$p_T > 2$ GeV/c

Asymmetry < 0.8



  - ❑ Unfortunately, nature doesn't use subscripts on photons

➔ N correct combinations: $(\gamma_{1A}\gamma_{1B}), (\gamma_{2A}\gamma_{2B}), \ldots (\gamma_{NA}\gamma_{NB})$,

➔ N(N-1)/2 – N *incorrect* combinations $(\gamma_{1A}\gamma_{2A}), (\gamma_{1A}\gamma_{2B}), \ldots$

⌛ Incorrect combinations ~ N^2 (!)

🗐 Solution: Restrict N by p_T cuts

use high granularity, high resolution detector

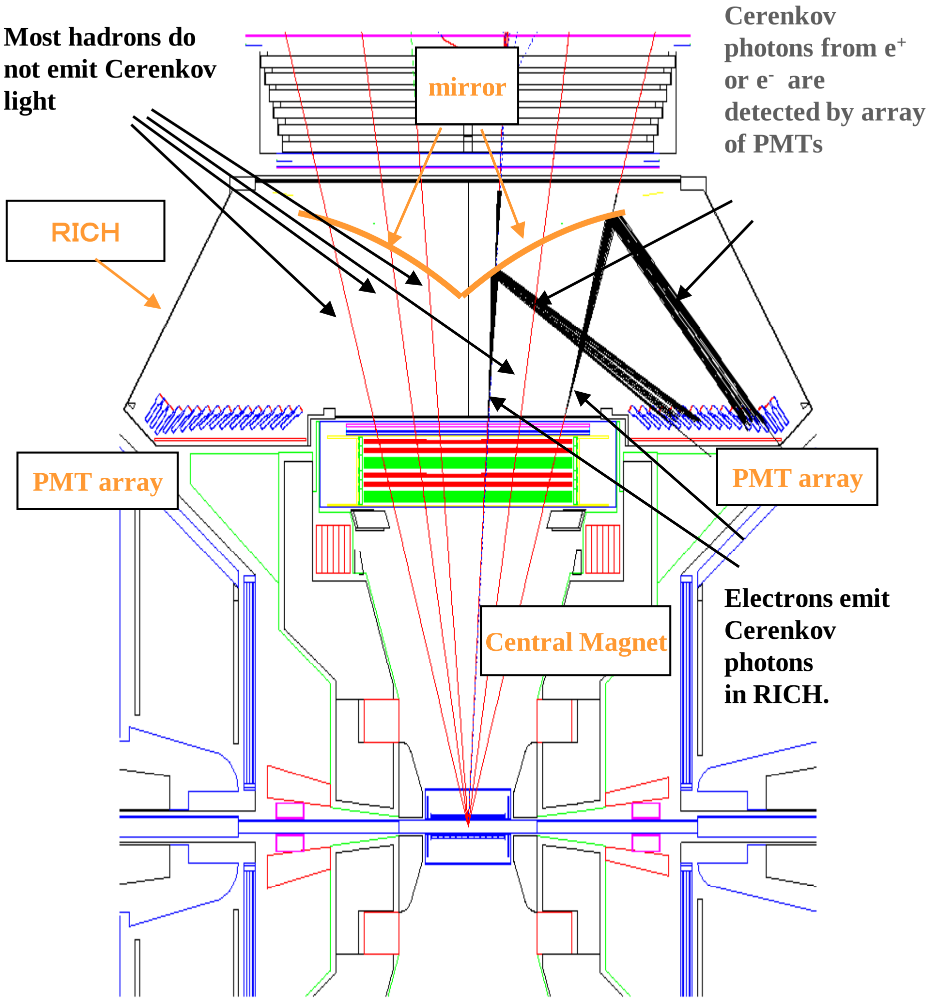
Electrons in PHENIX

Electrons are identified as

Cherenkov right in RICH

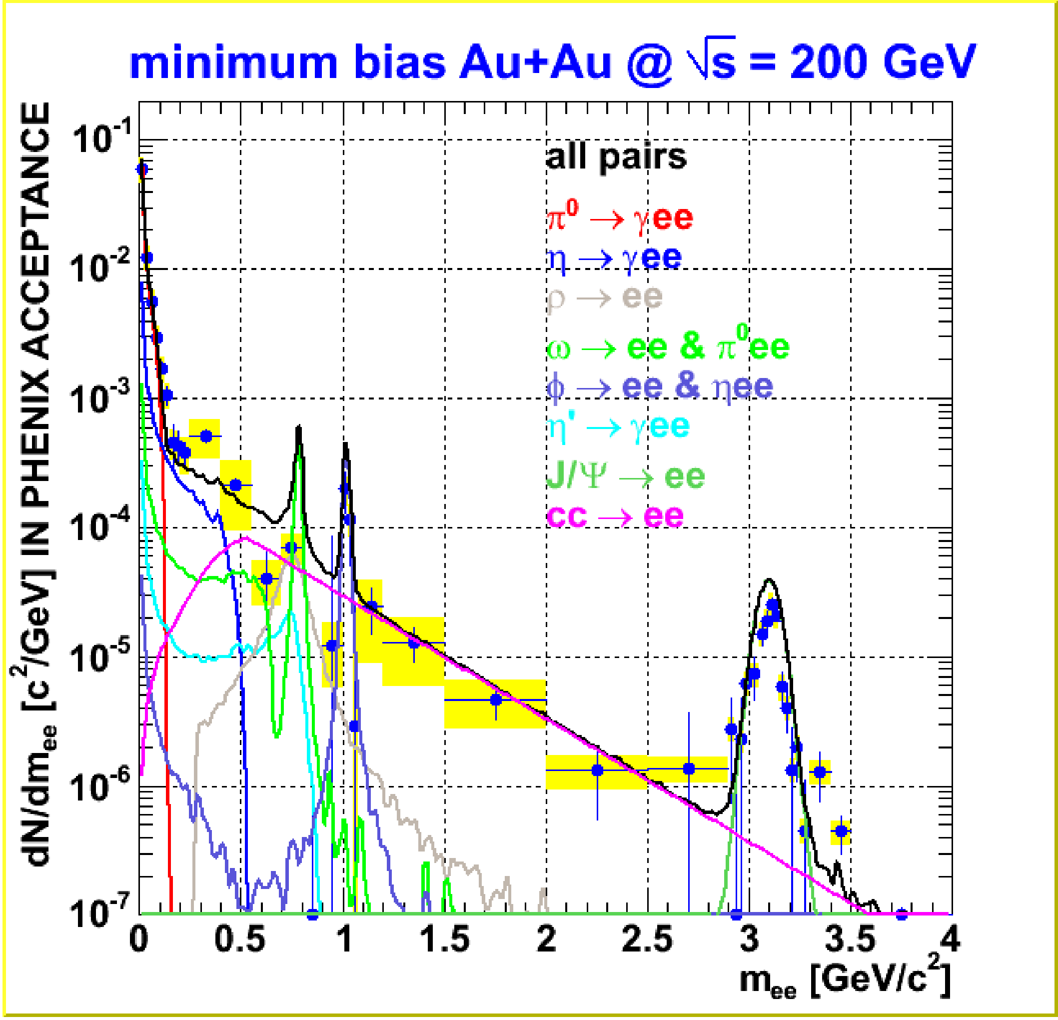
- p_t 0.2~4.9 GeV/c

- Number of hit PMT
- Ring shape
- E,p matching

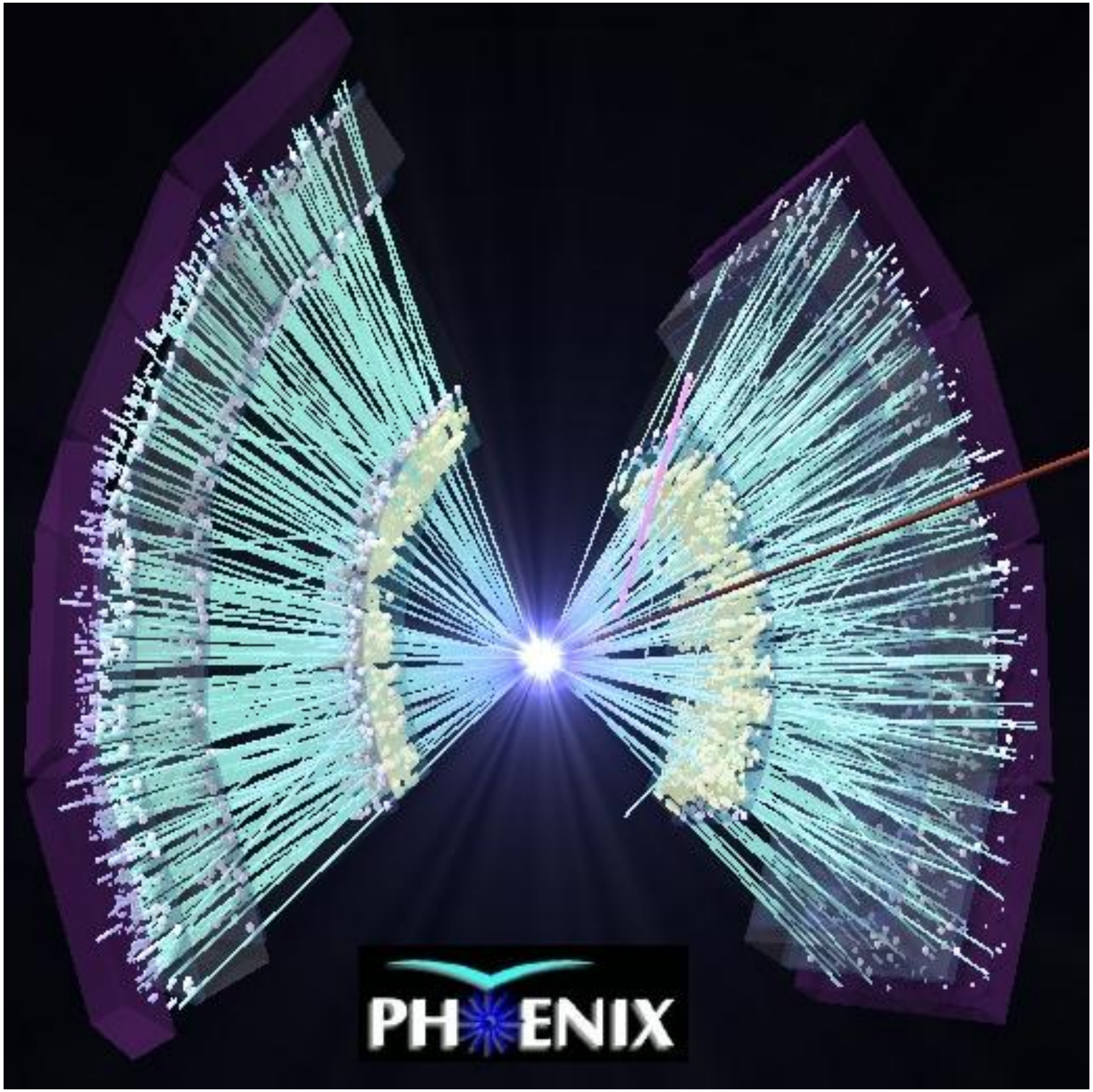


Di-lepton Physics

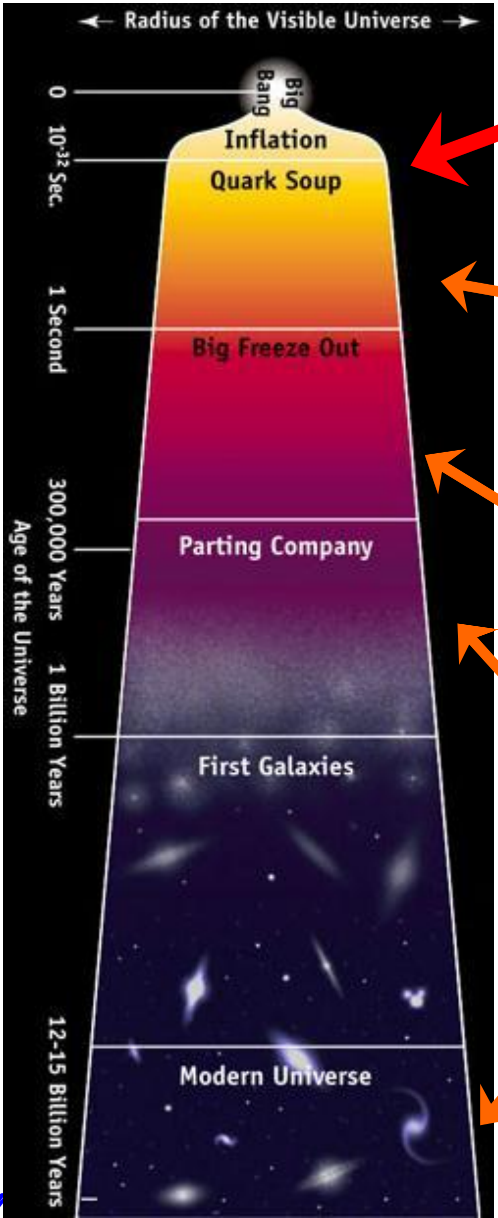
- Diverse Physics:
  - ❑ Vector Mesons
  - ❑ Dalitz
  - ❑ Correlated semi-leptonic decays.
  - ❑ Chiral Restoration??
- Very difficult measurement in Heavy Ion Physics
- (see Alberica Toia's talk 5/18/06, 10:30am)



PHENIX Single Event



Evolution of the Universe



Reheating Matter

T nd!!!

Standard Model (N/P) P

Too hot for nuclei to bin

Nuclear/Particle (N/P)

ynthesis builds

Nucl Force...Nucle

ec

) Physics

e

/General Relativity

Quark-

- Collisions of "Large" nuclei convert beam energy to temperatures above 200 MeV or 1,5 x 10^{12} K
    - ~100,000 times higher temperature than the center of our sun.
- "Large" as compared to mean-free path of produced particles.

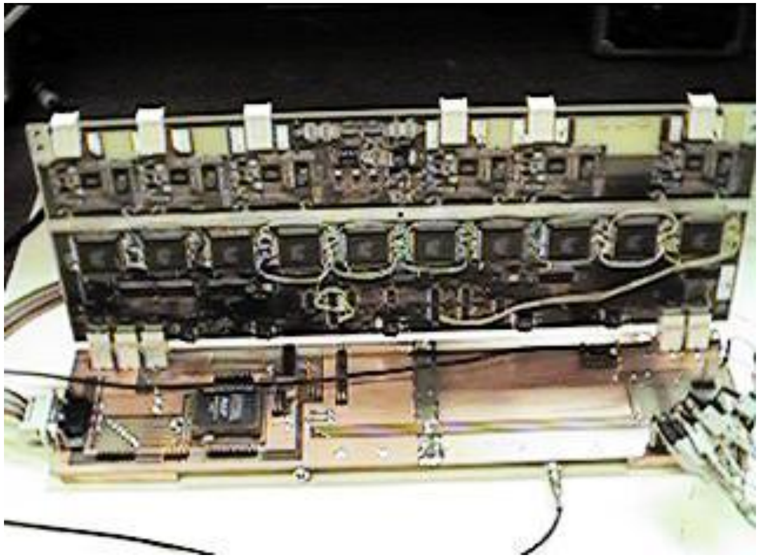
Stars convert gravitational energy to temperature.

They "replay" and finish nucleosynthesis

~15,000,000 K in the center of our sun.

Solid
Liquid
Gas

Onboard Digitization



Stony Brook developed the readout system for the PHENIX DC

The system operates with 2-3 fC (no wires) or 6 fC (with wires) thresholds on 6 nsec shaping times.

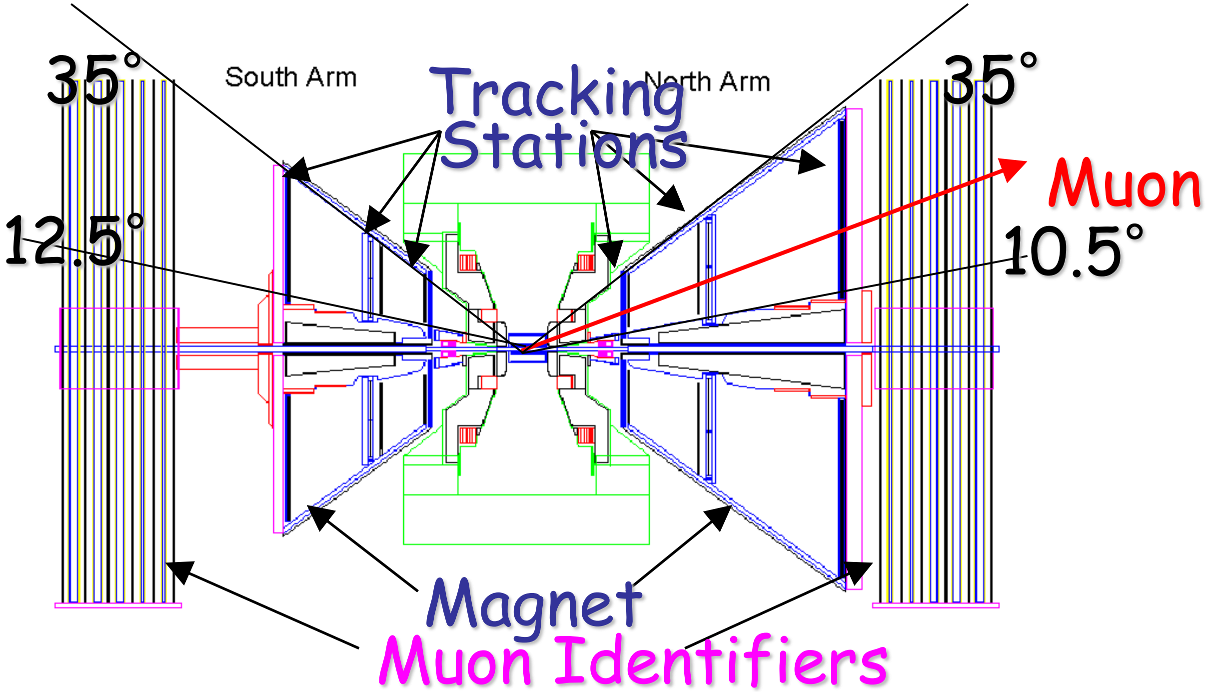
We digitize continuously (no deadtime) have feed output information onto 80 fibers each transferring 0.75 Gbits/second.

PHENIX Muon Arms

(Run-2 p-p and onwards: Electrons are still detected in the central arms..)

2 Muon Trackers =
2x3 stations

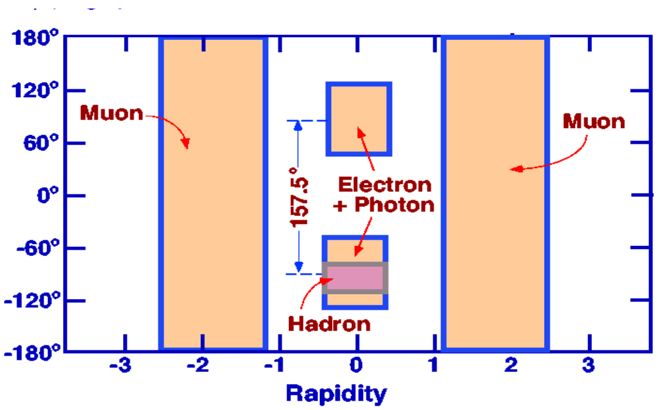
2 Muon Identifiers
= 2x5 planes



South Arm:
Began operations
in 2001: Run-2.

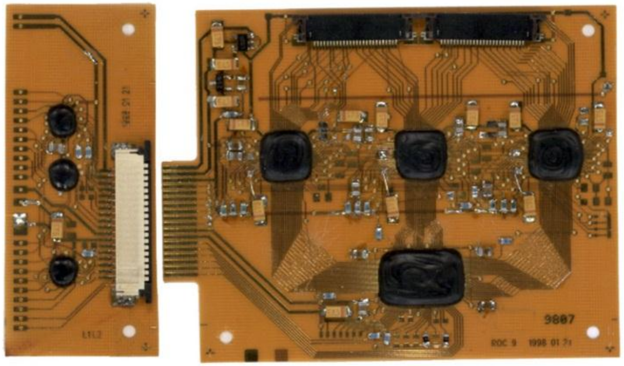
North Arm:
Installed in 2002.

Acceptance : $1.2 < |\eta| < 2.4$
$\Delta\Phi = 2\pi$
Muon minimum momentum ~ 2 GeV/c



Pad Chamber Electronic

PAD CHAMBER READOUT CARD

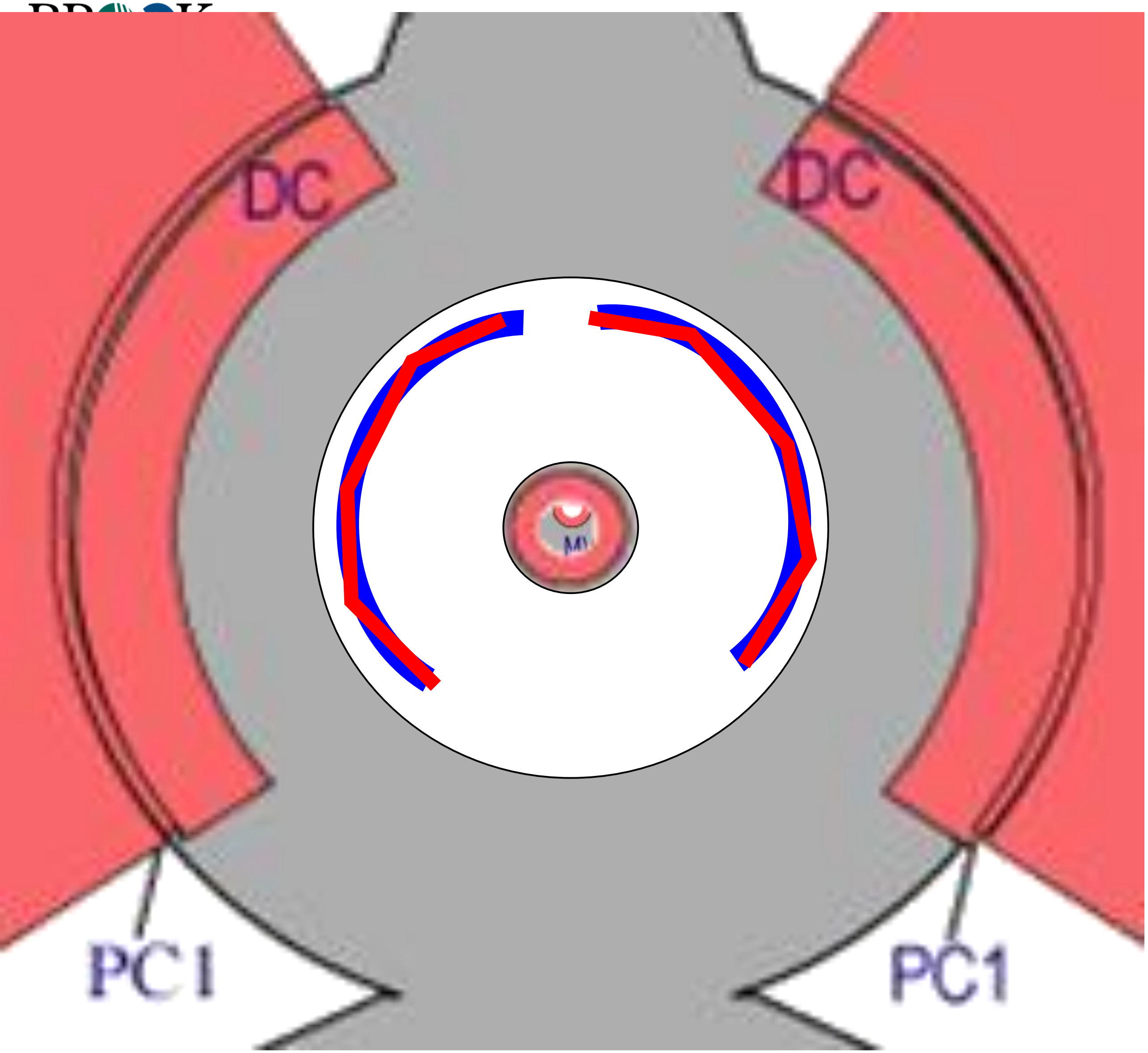


Connector card, solders on chamber.
3 RS485 diff-CMOS translator chips

Readout card, for 48 channels. 3 amplifier/discriminator chips (TGL98) and one Digital Memory chip(DMU). Mounted on 0.1mm fiberglass enforced Kapton. Total weight of whole assembly is 4 grams. Size 55*65mm^2

- **Pad chamber Read-Out-Card (ROC) compares pad signals to threshold (typically 2 fC).**
- **Binary output (hit/not hit) via serial line interface.**
- **Bare Si chips are wire-bonded to kapton substrates and “capped” w/ epoxy for low mass.**
- **Readout cards provide a latency of 4.2 μsec allowing for trigger delay.**
- **Developed by Lund group.**

Looking Closer…



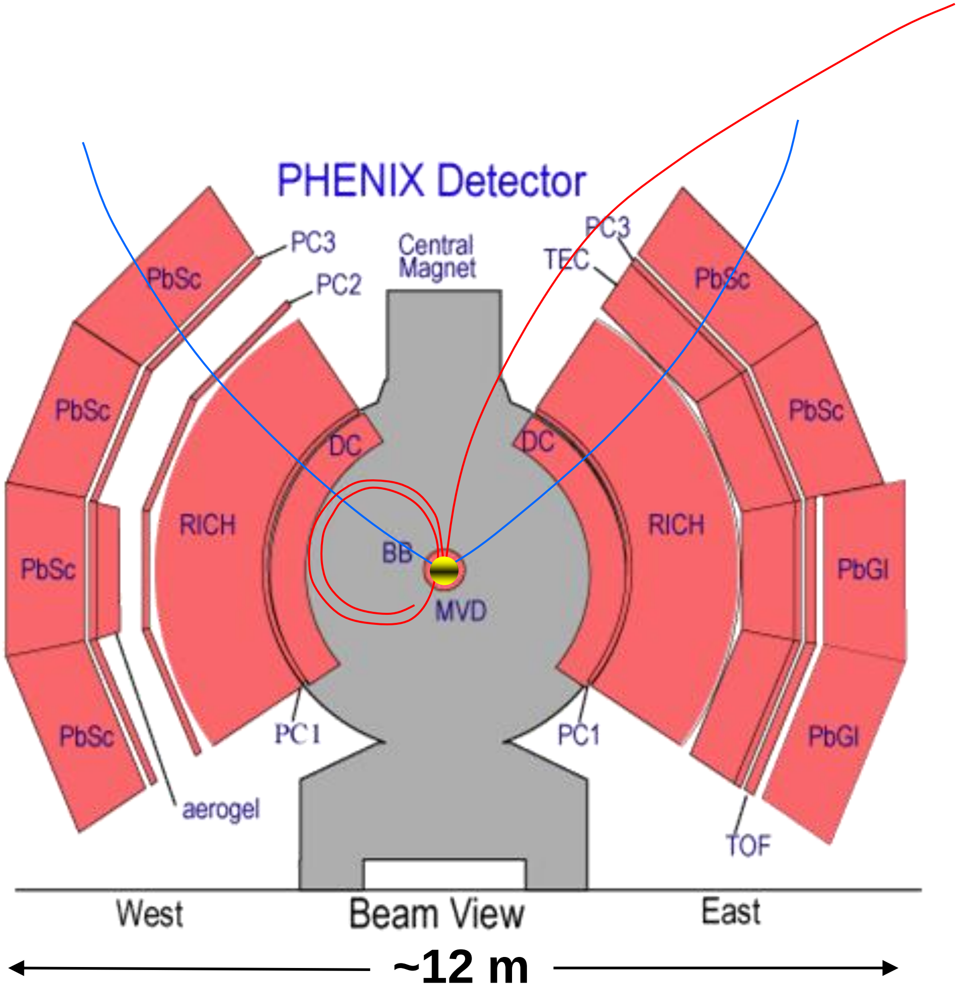
- Inner coil can cancel B-field at r < 60 cm

- Not enough room for traditional optics… mirrors won't work.

- Just put the detector right in the middle of things!

- Has potential, but…
  - must be thin
  - must detect a single UV photon and still be blind to all ionizing particles passing through it!!!

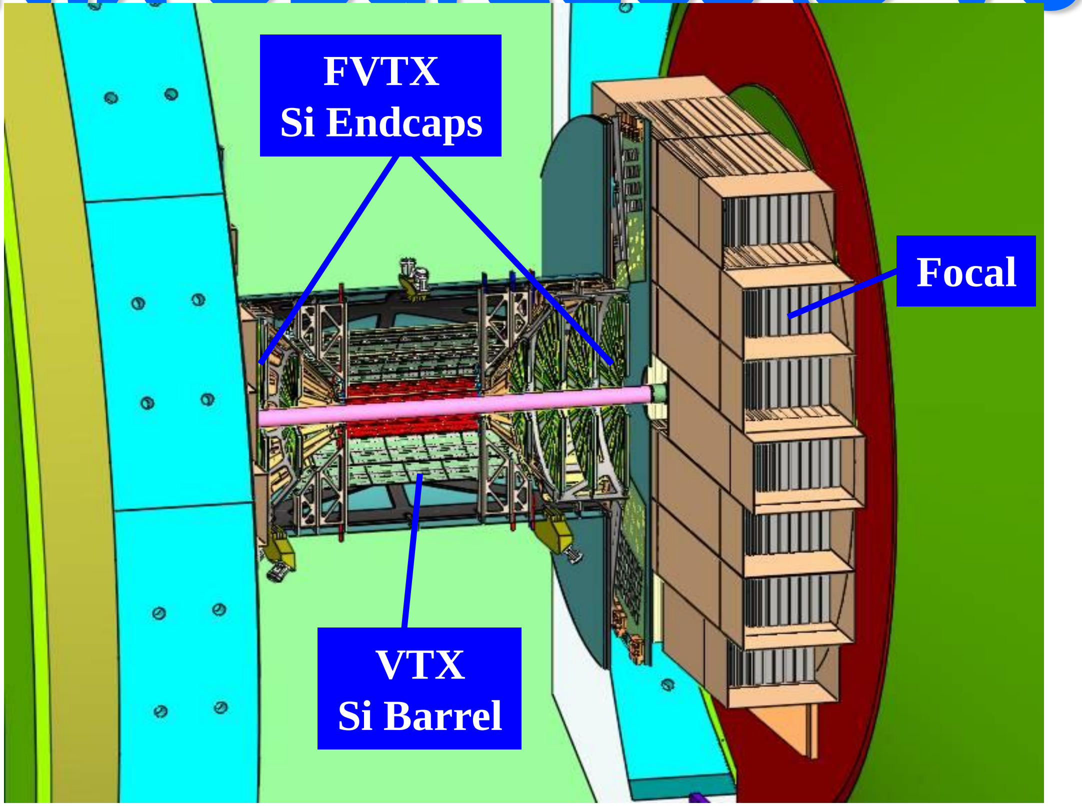
Why so much background?



- Typically only 1 electron from the pair falls in the acceptance.
  - The magnetic field bends the pair in opposite directions.
  - Some curl up in the magnetic field and never come out.

- The new detector needs:
  - >90% electron ID
  - sit near the collision
  - sit in zero B-field
    - catch $e^{+/-}$ before they get lost

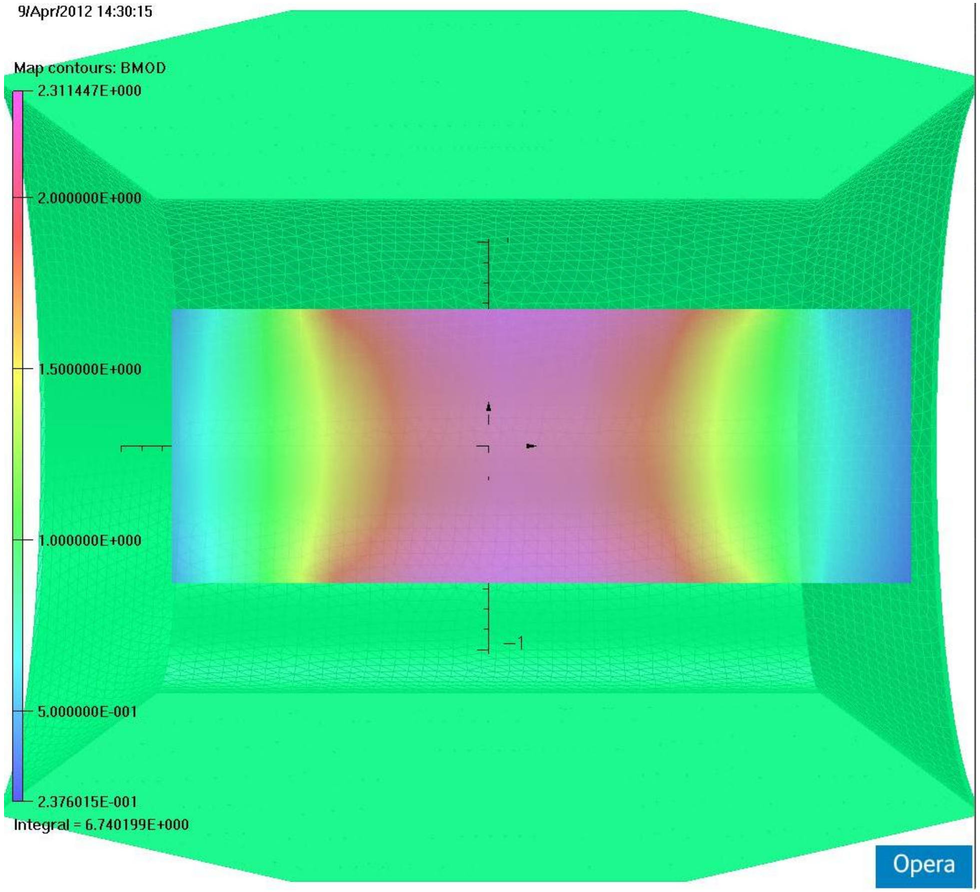
PHENIX Upgrades @ Vertex



VTX, FVTX and NCC add key measurements to RHIC program:

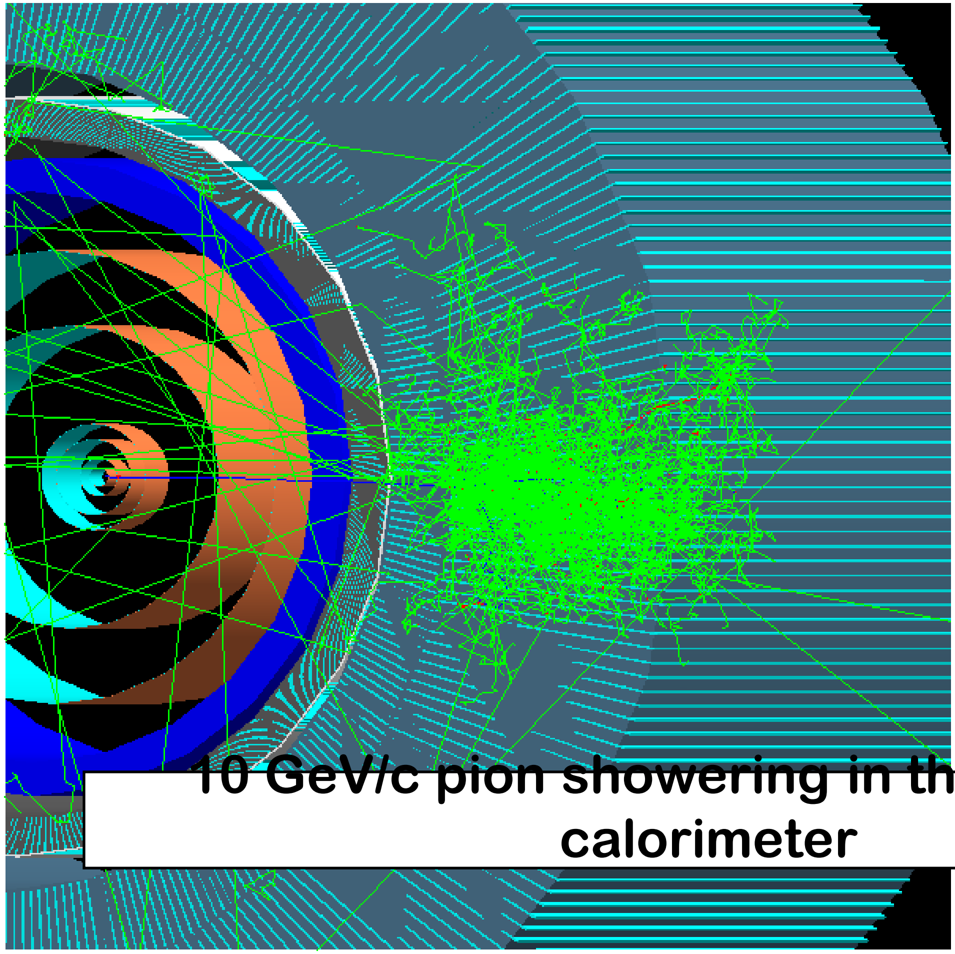
- Heavy quark characteristics in dense medium
- Charmonium spectroscopy (J/ψ, ψ’ , χ_c and Υ)
- Light qurak/gluon energy loss through γ-jet
- Gluon spin structure ($\Delta G/G$) through γ-jet and c,b quarks
- A-, p_T-, x-dependence of the parton structure of nuclei

radius



$\approx 1\ X_0$

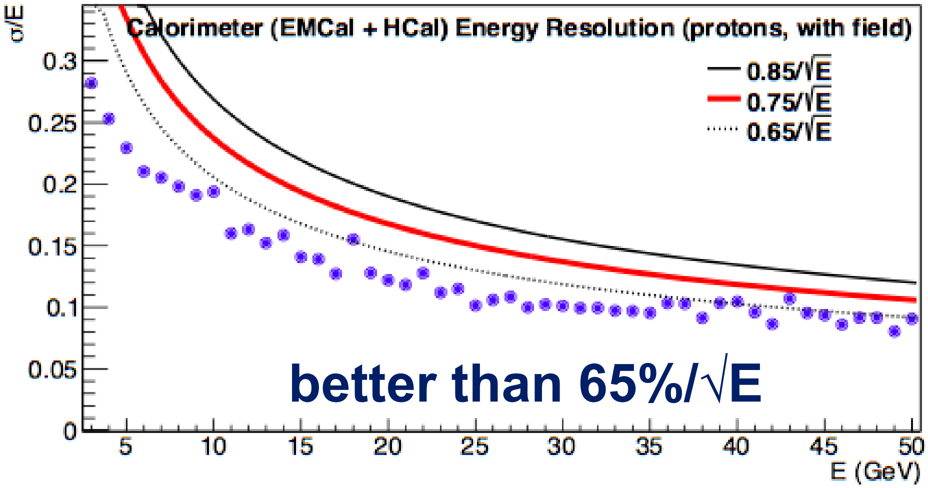
GEANT4 simulation



10 GeV/c pion showering in the hadronic calorimeter

calorimeters

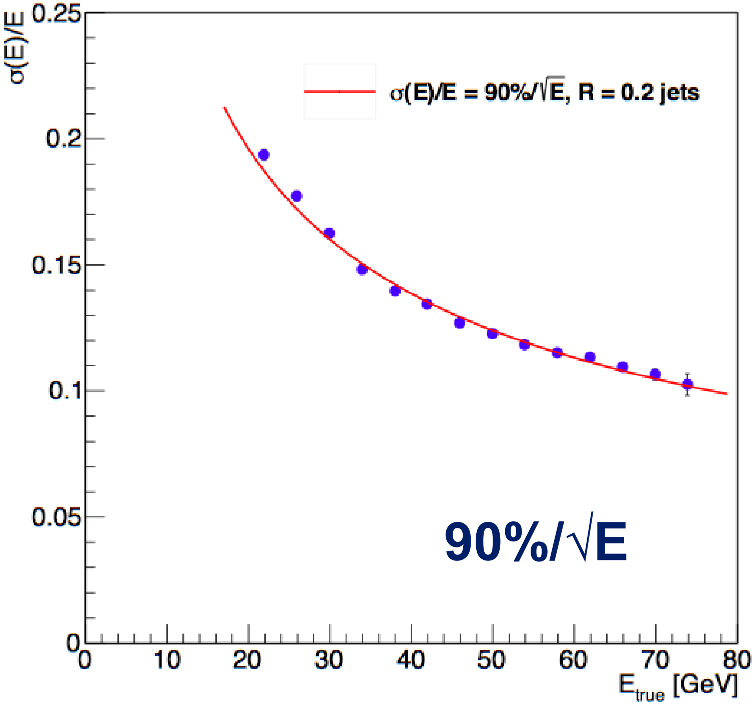
Single particle resolution in EMCal+HCal



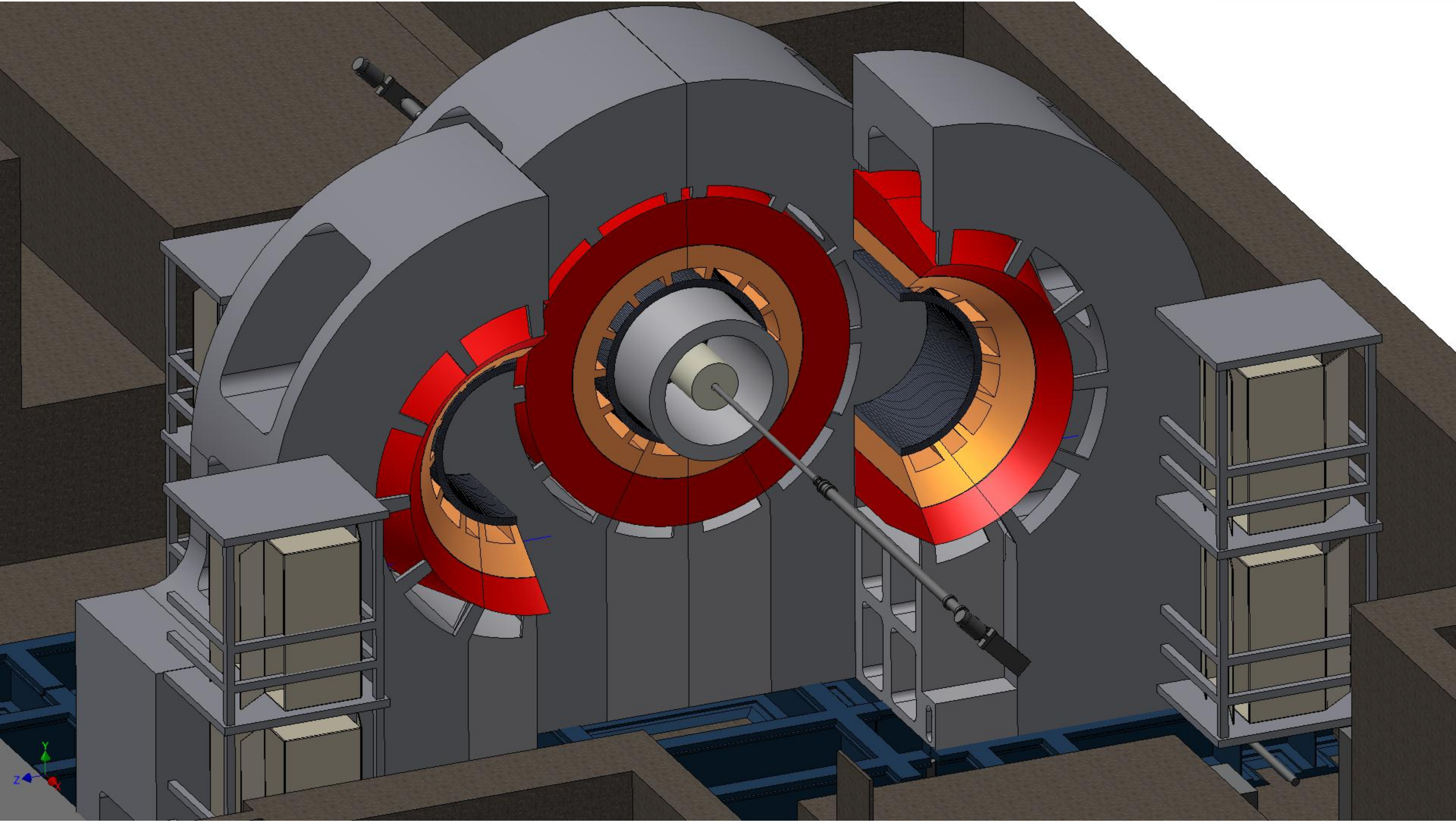
better than 65%/√E

Jet energy resolution

From GEANT4 in *p+p*

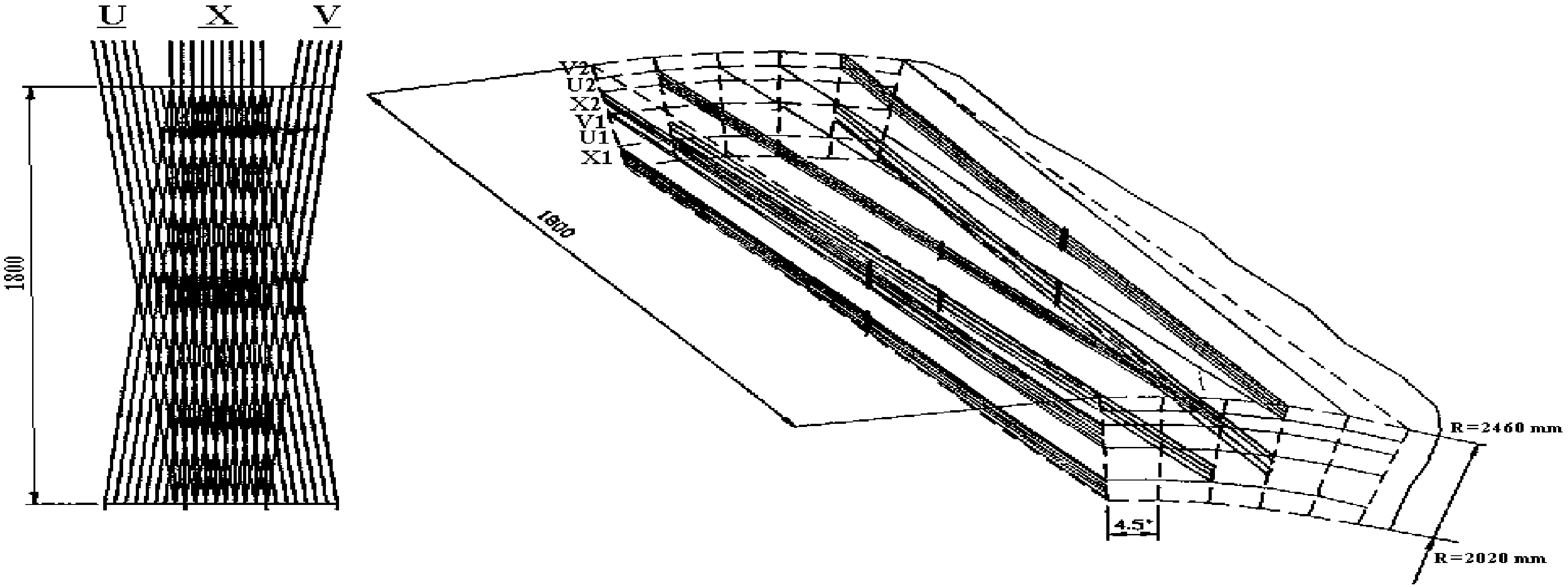


90%/√E


Y
Z

DC: Small Angle Stereo

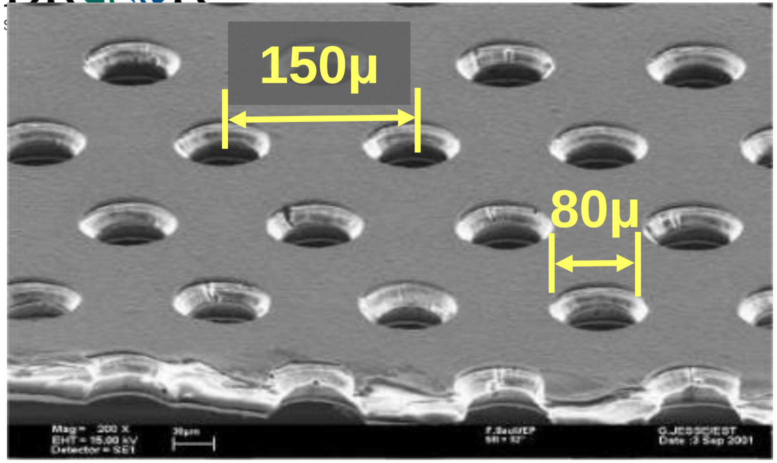
Schematic Drawing of X, U, V - planes wires location in the Drift Chamber



"X" wires run parallel to the collision axis while "U" and "V" are tipped for small angle (5-6° depending upon radius) stereo.

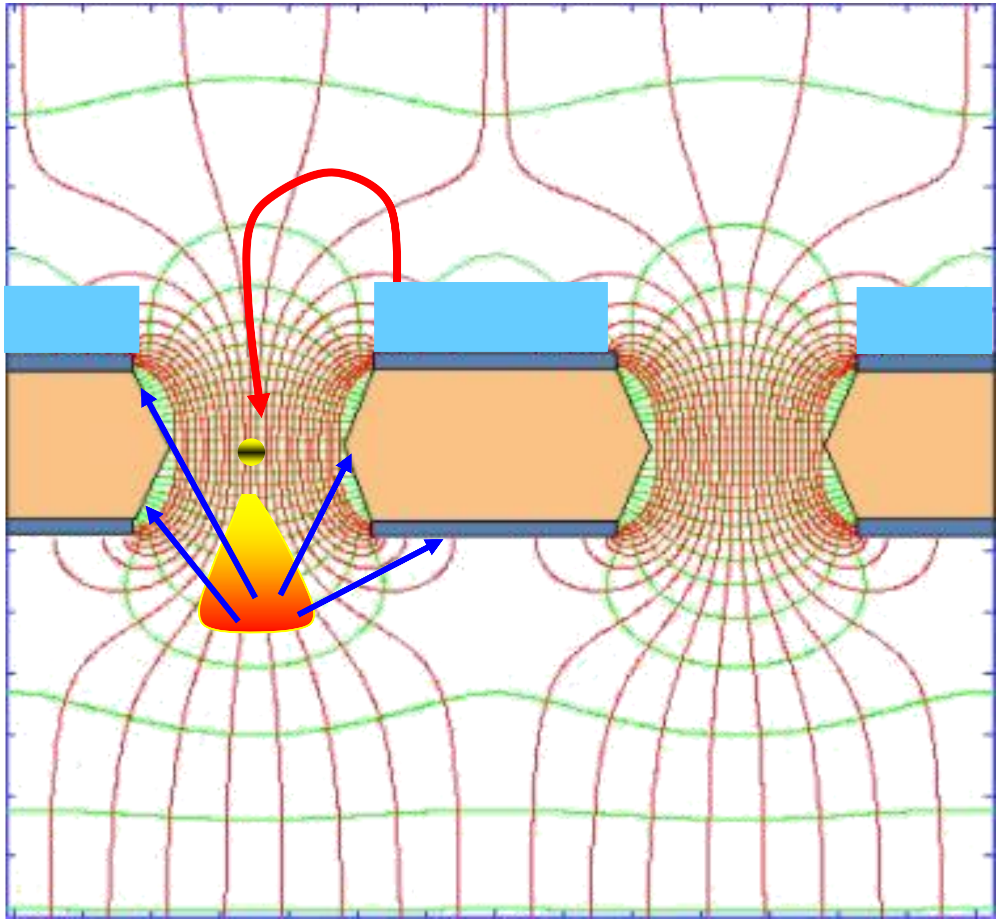
The Drift Chambers are required to have better than 95% single point efficiency, 150 μm resolution, and 1.5 mm two-track resolution.

Gas Electron Multiplier (GEM)



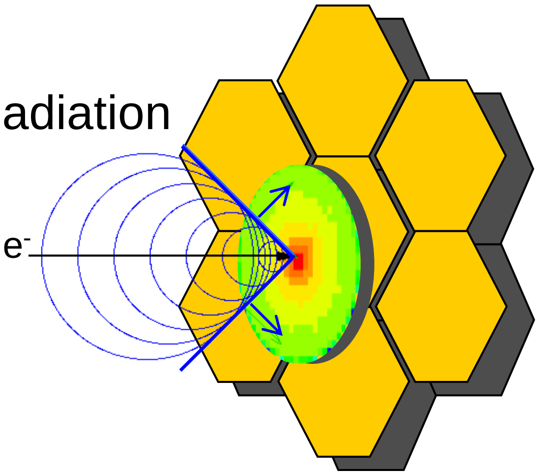
- The original idea by F.Sauli (mid 90s) US Patent 6,011,265
- Traditionally CHARGED PARTICLE detectors (not photons)

- Two copper layers separated by insulating film with regular pitch of holes
- HV creates very strong field such that the avalanche develops inside the holes
- Just add the photocathode
- By the way: no photon feedback onto photocathode



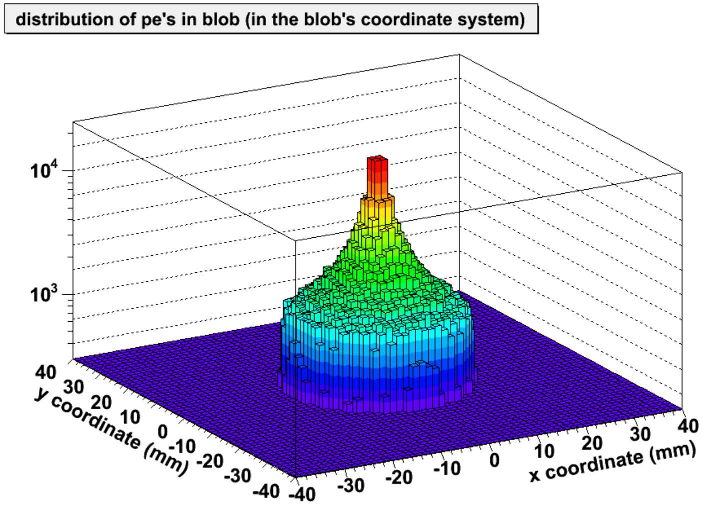
Unfocused Cherenkov “Blobs”

- Windowless: Radiator Gas = Avalanche Gas
  - CF_4 (n≈1.000620)
  - Blind to hadrons w/ <4 GeV



Some challenges:

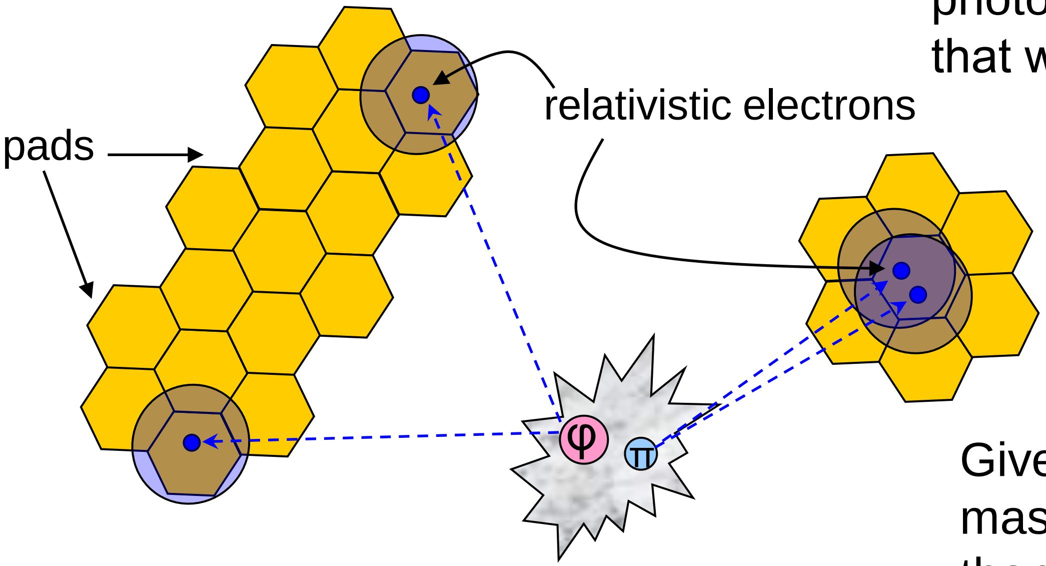
- No room for traditional optics (ie. focusing mirror).
- Cherenkov light collected as an unfocused blob.
- 1.5 m^2 photosensitive region
- Low radiation length:
  - minimize photon conversions.
- Charged particles from collision will pass through:
  - ionization must not interfere with photoelectron detection.



Is it a π or a φ?

Back to the basics (briefly)…

A lot of particles have e^+e^- decay channels. How can we tell the Dalitz decays and photon conversions apart from the decays that we're interested in??



Given the same initial momentum, more massive particles have lower velocities than lighter ones. Therefore, the opening angle of the decay is bigger.

Lighter particles have smaller opening angles!!

How about a Cherenkov Detector???

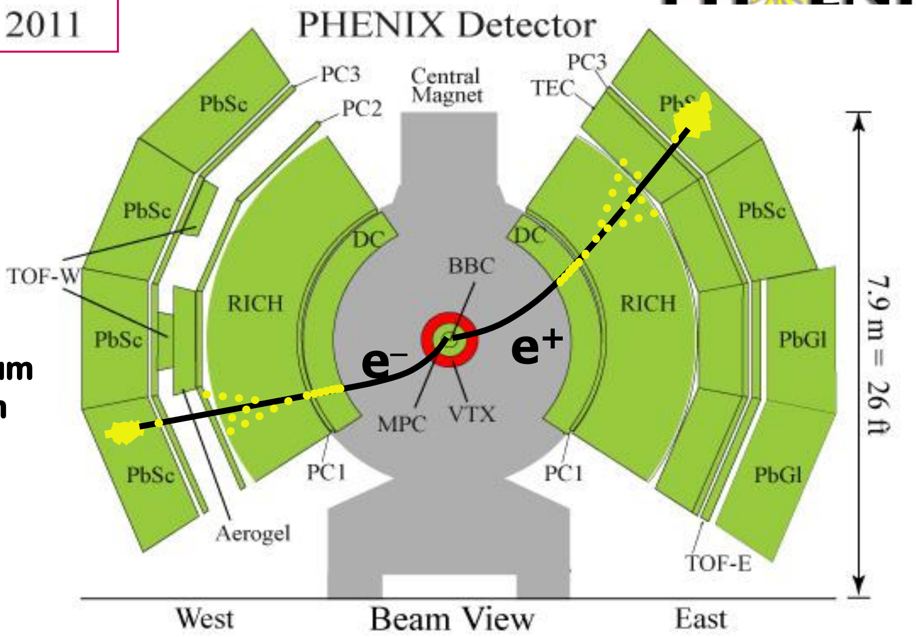
- ID electrons
- give directional information.

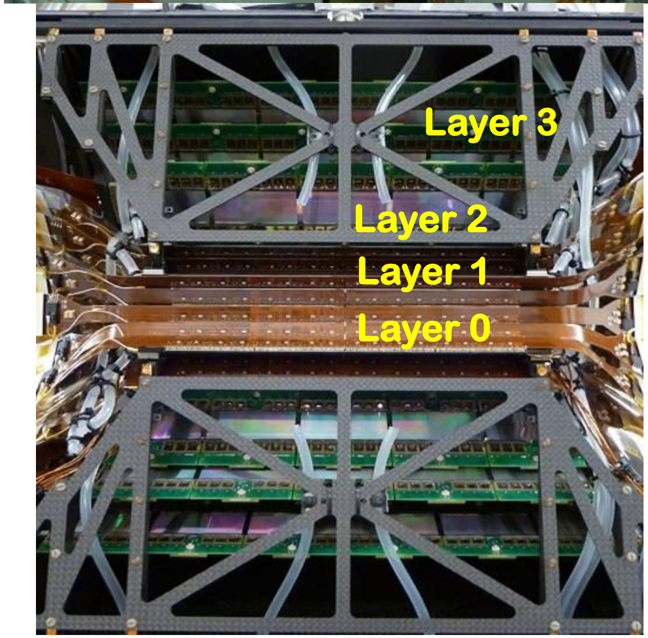
PHENIX VTX Upgrade.

VTX: Silicon Barrels ~ 2π

2011

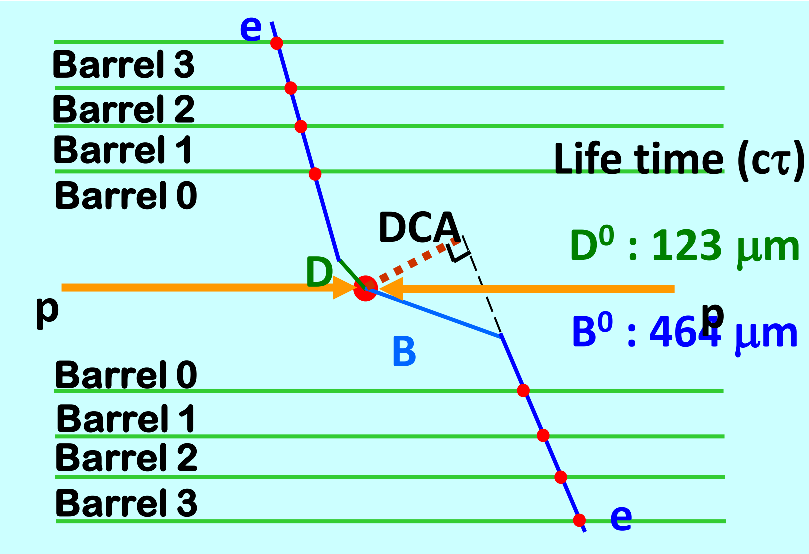
Berylium beam pipe





Main

Goal



Life time (cτ)

D^0 : 123 μm

B^0 : 464 μm