The STAR Detector at RHIC

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Interdisciplinary Instrumentation Colloquium
Lawrence Berkeley National Laboratory
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Who is RHIC and What Does He Do?

RHIC

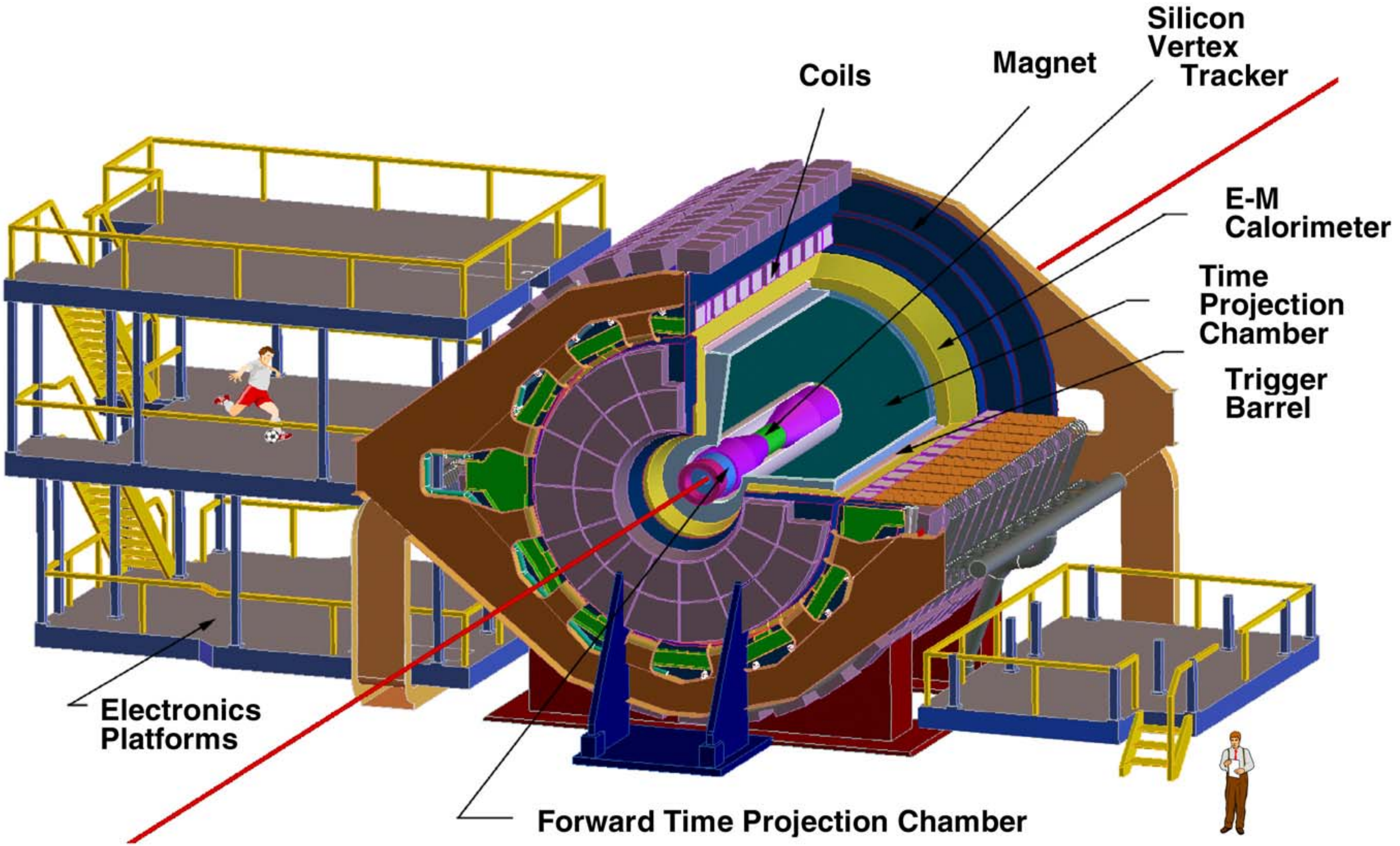
- **Two independent rings**
- **3.83 km in circumference**
- **Accelerates everything, from p to Au**

	$\sqrt{s}$	L
p-p	500	10^{32}
Au-Au	200	10^{27}

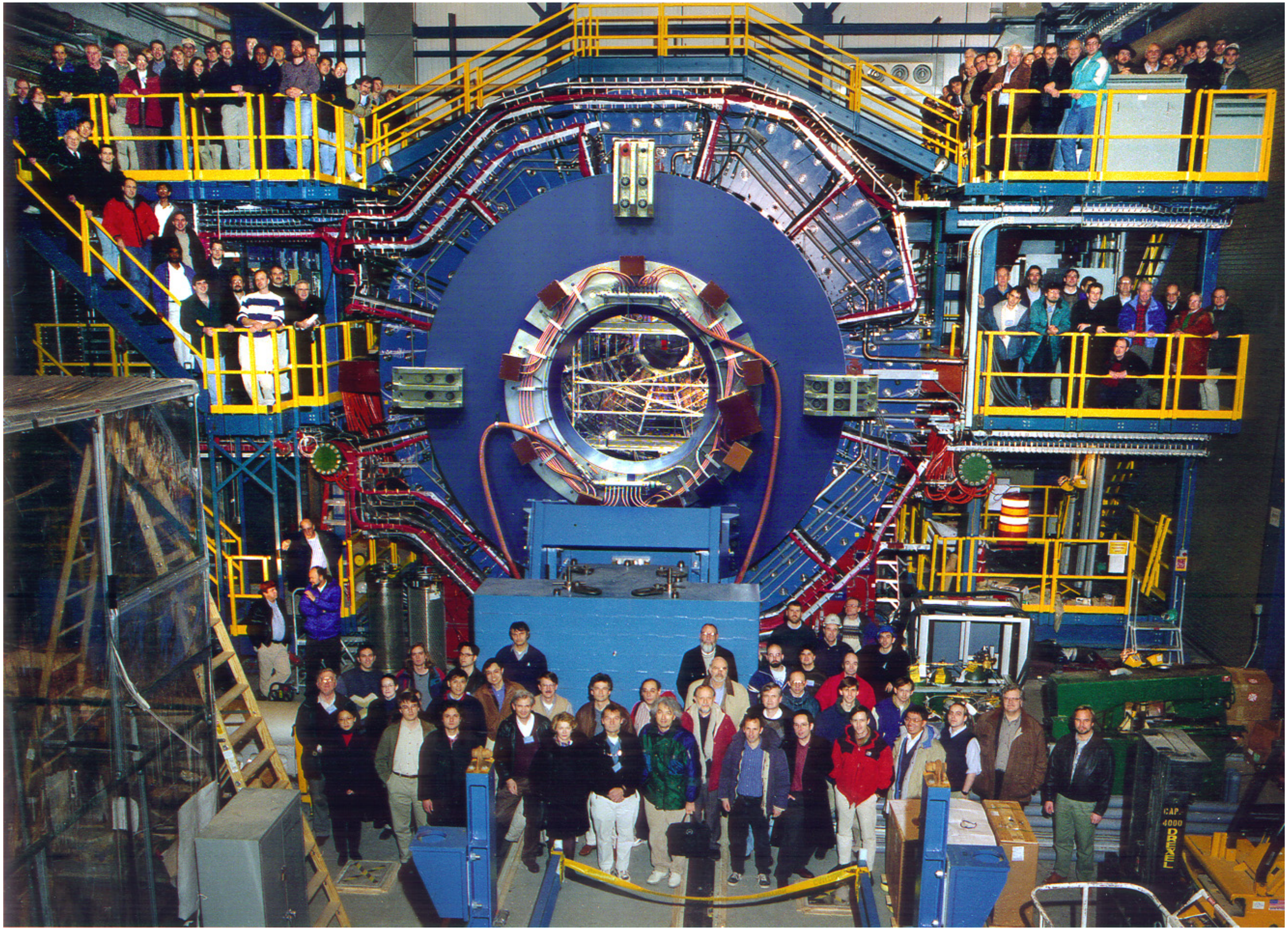
(GeV and $cm^{-2}\ s^{-1}$)

- **Polarized protons**
- **Two Large and two small detectors have been built**

The STAR Detector at RHIC



Yes, it really is that big …



Outline

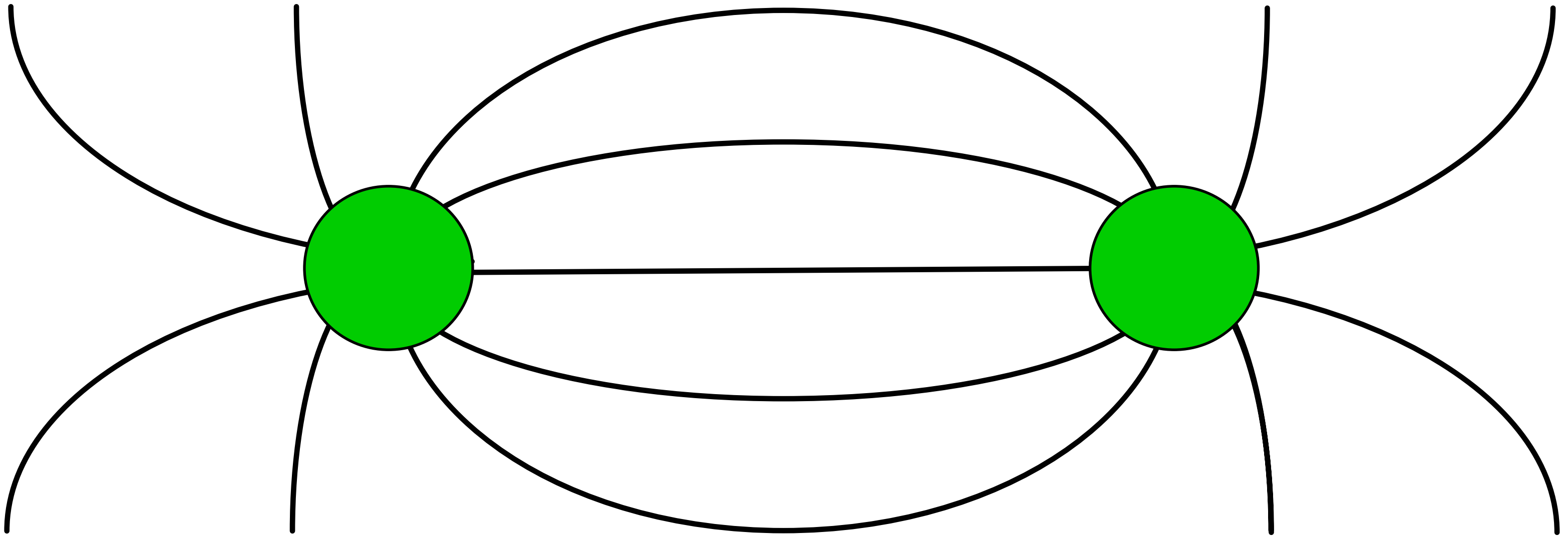
- One of my interests is the integration of detector elements into a suite of detectors to do physics
  - its an odd interest
  - so I'll try to share a limited set of my quirks with you by taking a random walk through the detector system I know best
- The STAR detector at RHIC
  - the goal
  - the challenge
  - the implementation
- STAR upgrades
  - Silicon
  - TOF
  - DAQ
- A brief look at some future trends
  - perhaps of interest to NLC/ILC designers and other future detector builders

The Goal: to see what others cannot see …

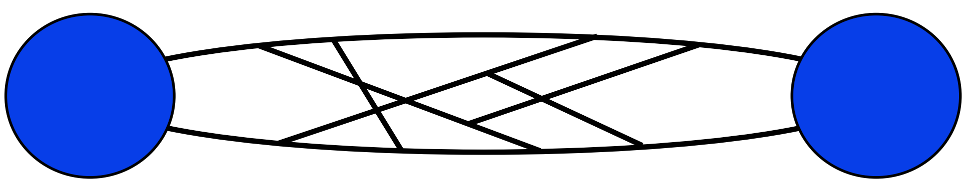
The bigger picture

Quarks. Gluons. Neutrinos. All those damn particles you can't see. That's what drove me to drink. But now I can see them!

The Goal at RHIC – to study the strong interaction



The E&M interaction is mediated by a non-self interacting particle … the photon

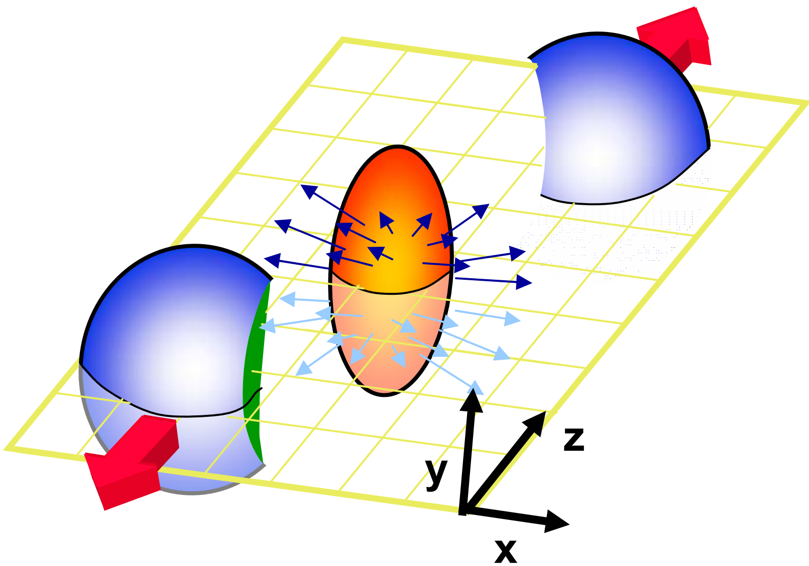


The strong interaction is mediated by a self interacting particle … called the gluon

We want to solve the many body problem in QCD

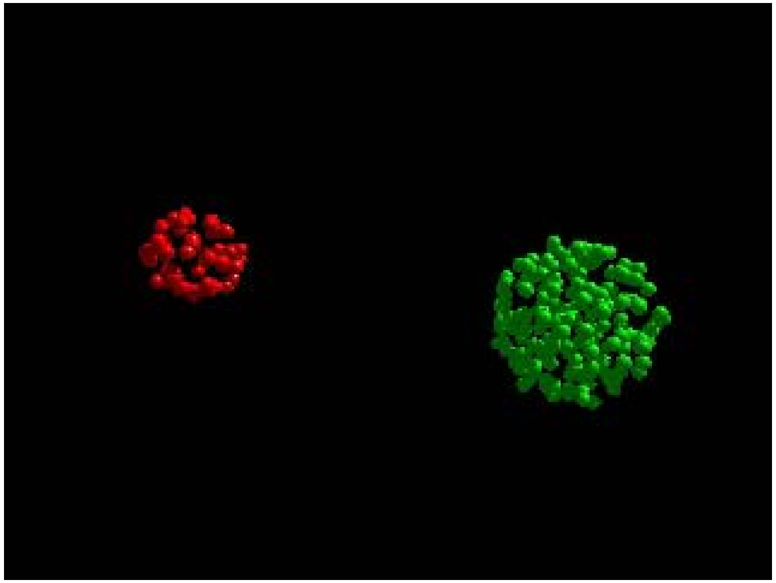
- **Particle physicists are interested in understanding the strong force (QCD) via the interaction of <u>individual</u> particles**

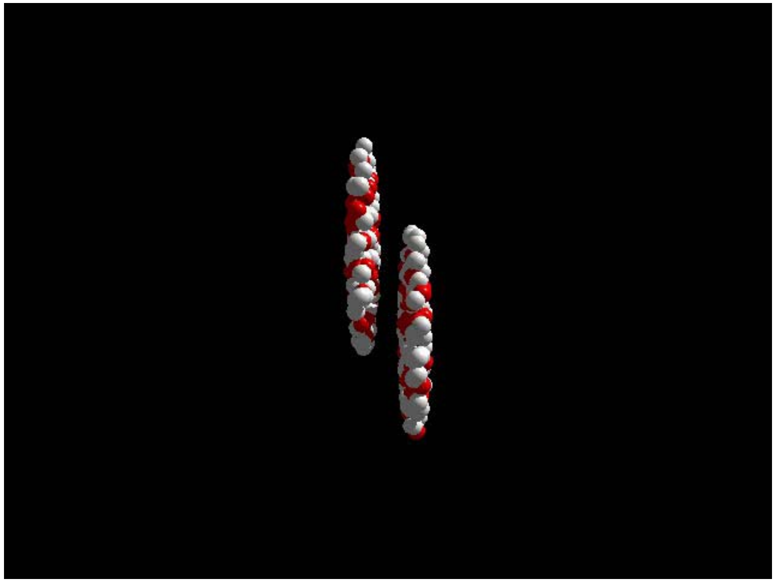
- **In Nuclear Physics, we want to solve the <u>many body problem</u>**
  - **Experimentalists want to "see" a nuclear collision and measure its geometric size and shape (… and density and viscosity …)**
  - **Theorists want to reduce it all to mathematics**



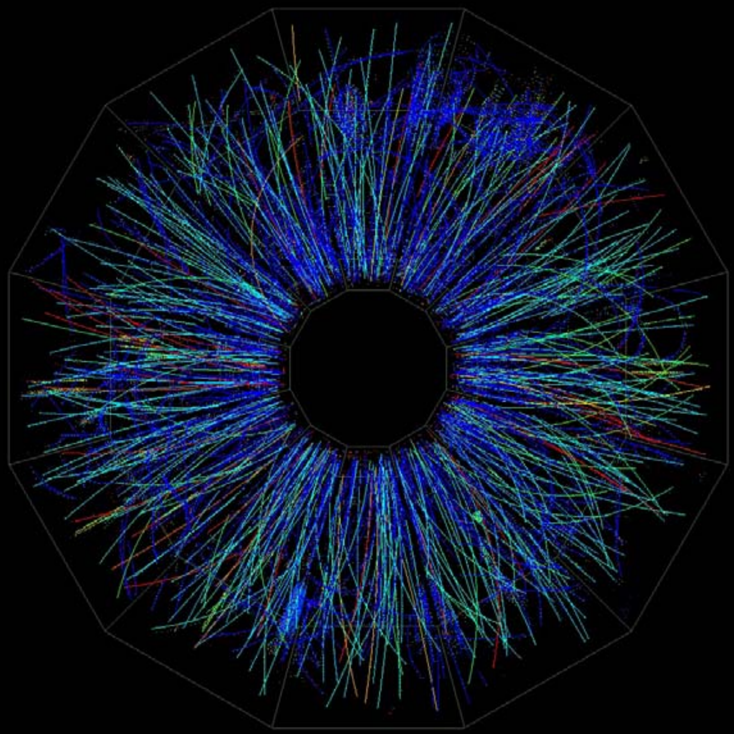
A "peripheral" collision

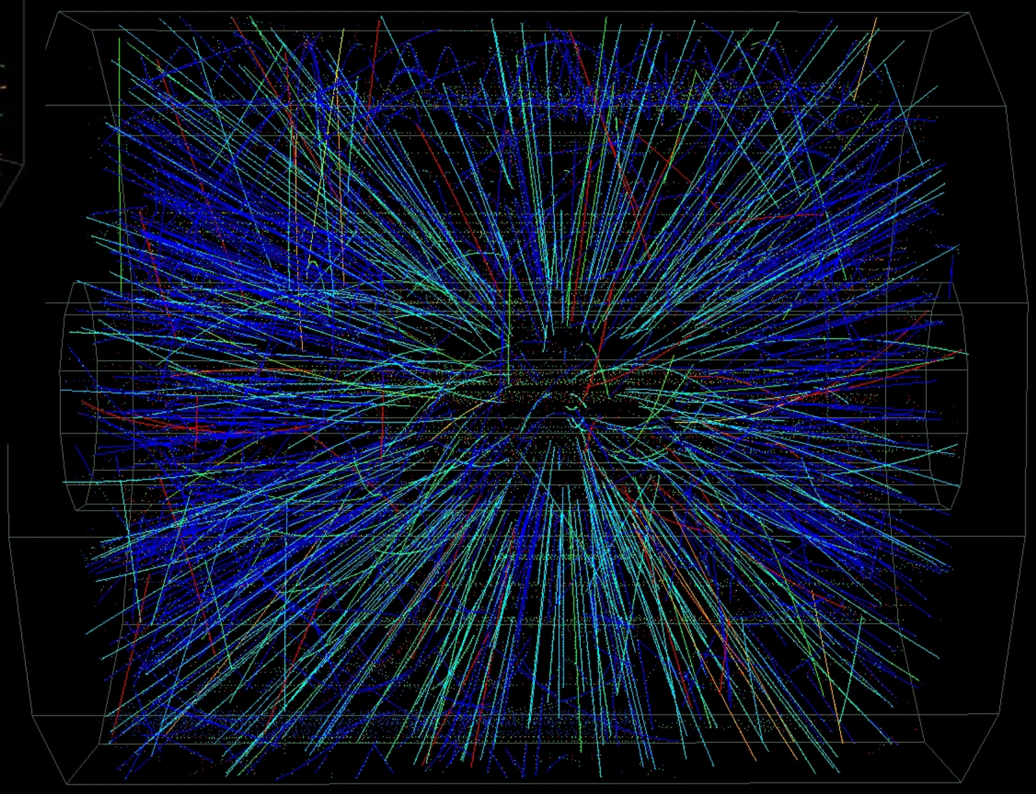
RHIC Physics is Relativistic Nuclear Physics



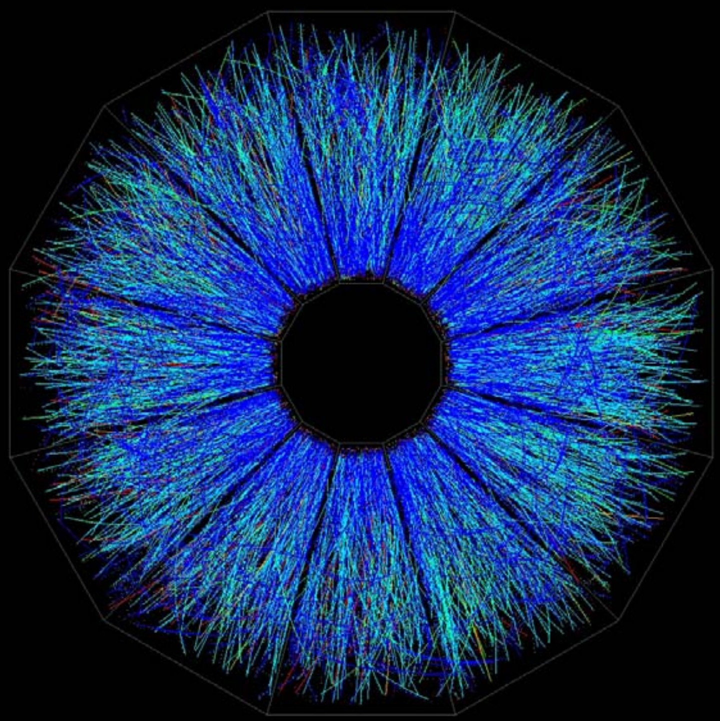


The Challenge … (too) Many Tracks in the TPC



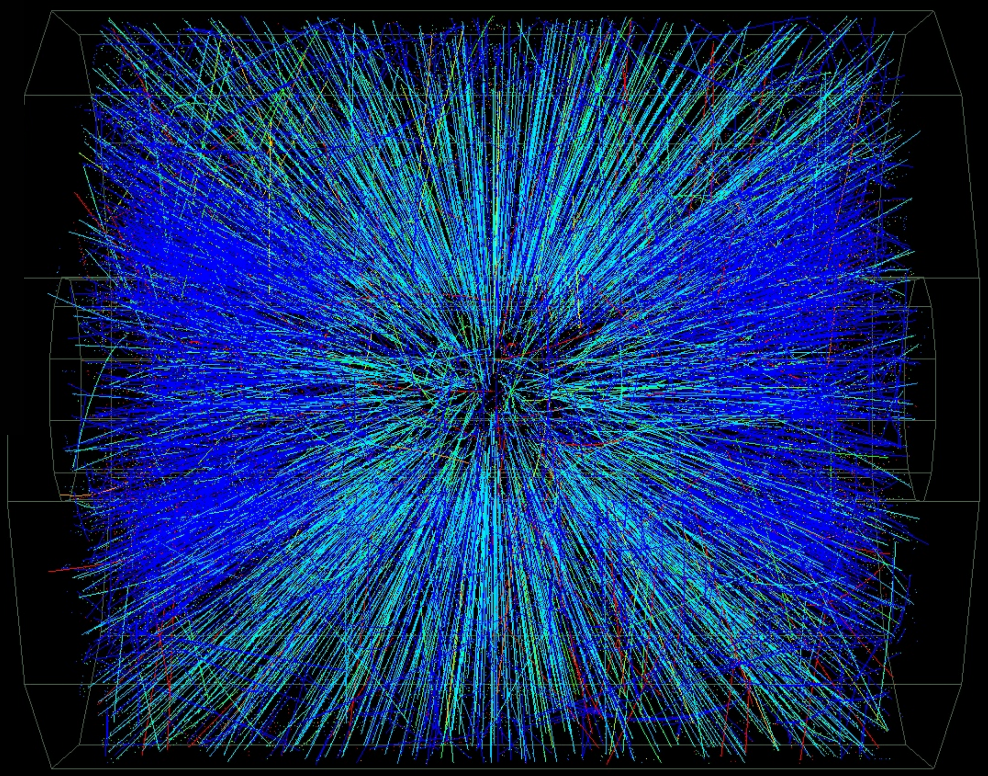


A Central Event (b=0)



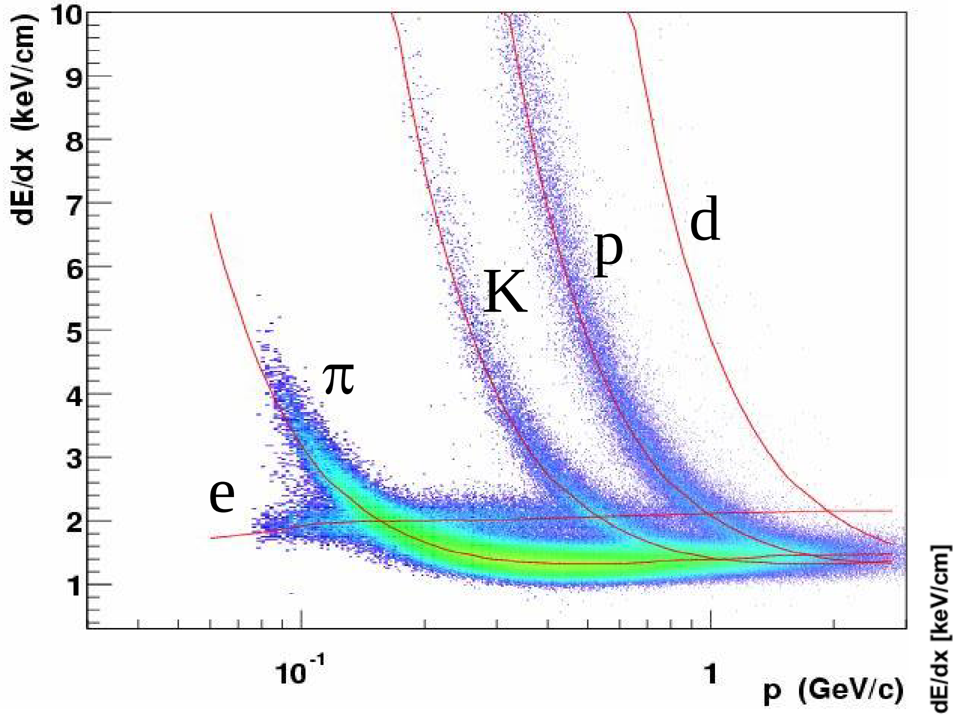
A Central Event

Typically 1000 to 2000 tracks per event into the TPC



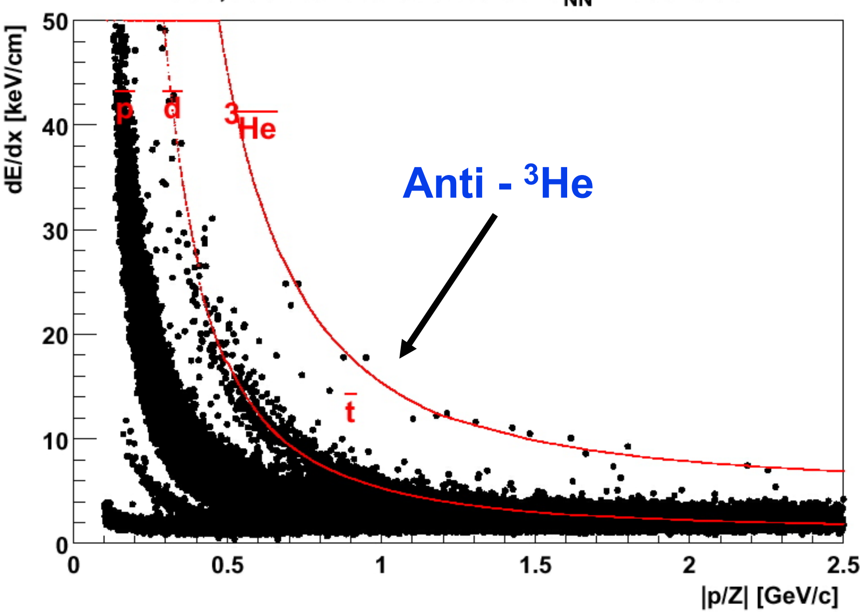
The primary tracks create secondary electrons in the gas which become the observed tracks in the TPC.

Ideally, we want to measure the properties of every track

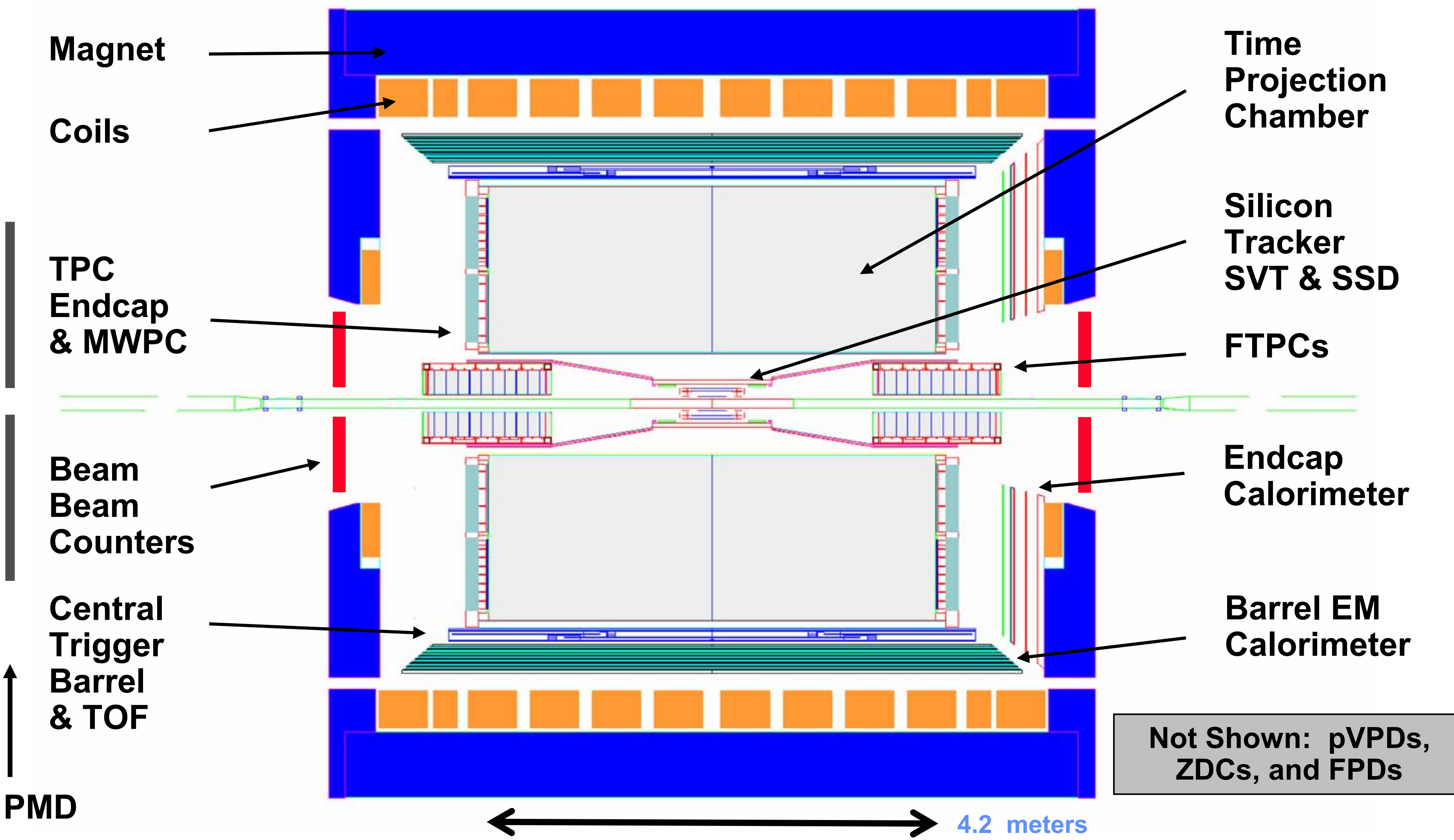


- Momentum measurement via precision tracking in a magnetic field
- PID via dE/dx and TOF
- Energy measurement by calorimetric techniques

- For all particles
  - even anti-particles
- For all possible momenta
- and into all space with 4π coverage



STAR is a Suite of Detectors

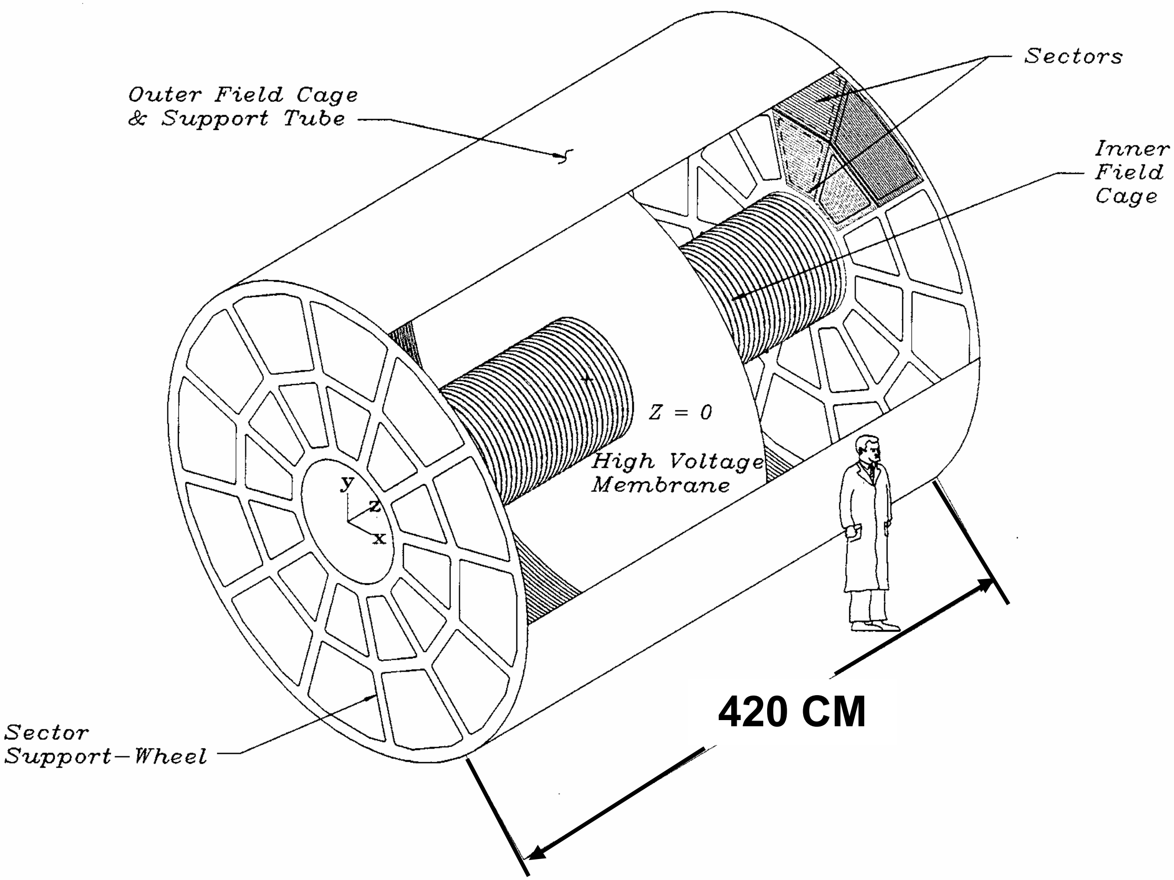


A TPC lies at the heart of STAR

The Heart of STAR

- **The Biggest TPC in the World**
  - For a couple more years
- **Basic Features**
  - A Central Membrane
  - Two end-wheels
  - The TPC has 24 Sectors
  - 137,000 channels
  - 70,000,000 voxels
  - and it is read out at 100 Hz

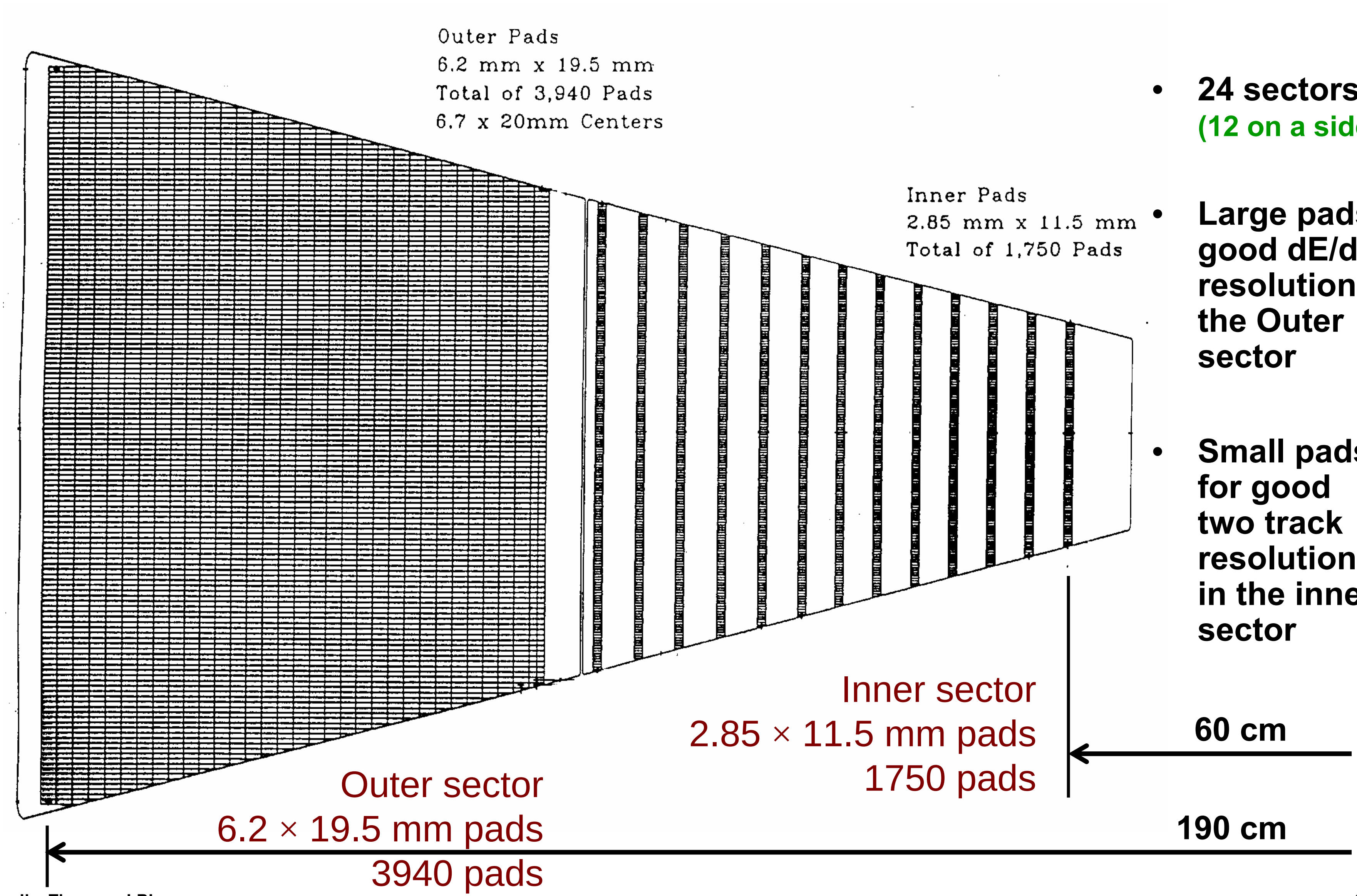
TPC Gas Volume & Electrostatic Field Cage



- **Gas: P10 (Ar-CH_4 90%-10%) @ 1 atm**
- **Voltage : - 28 kV at the central membrane**
  135 V/cm over 210 cm drift path

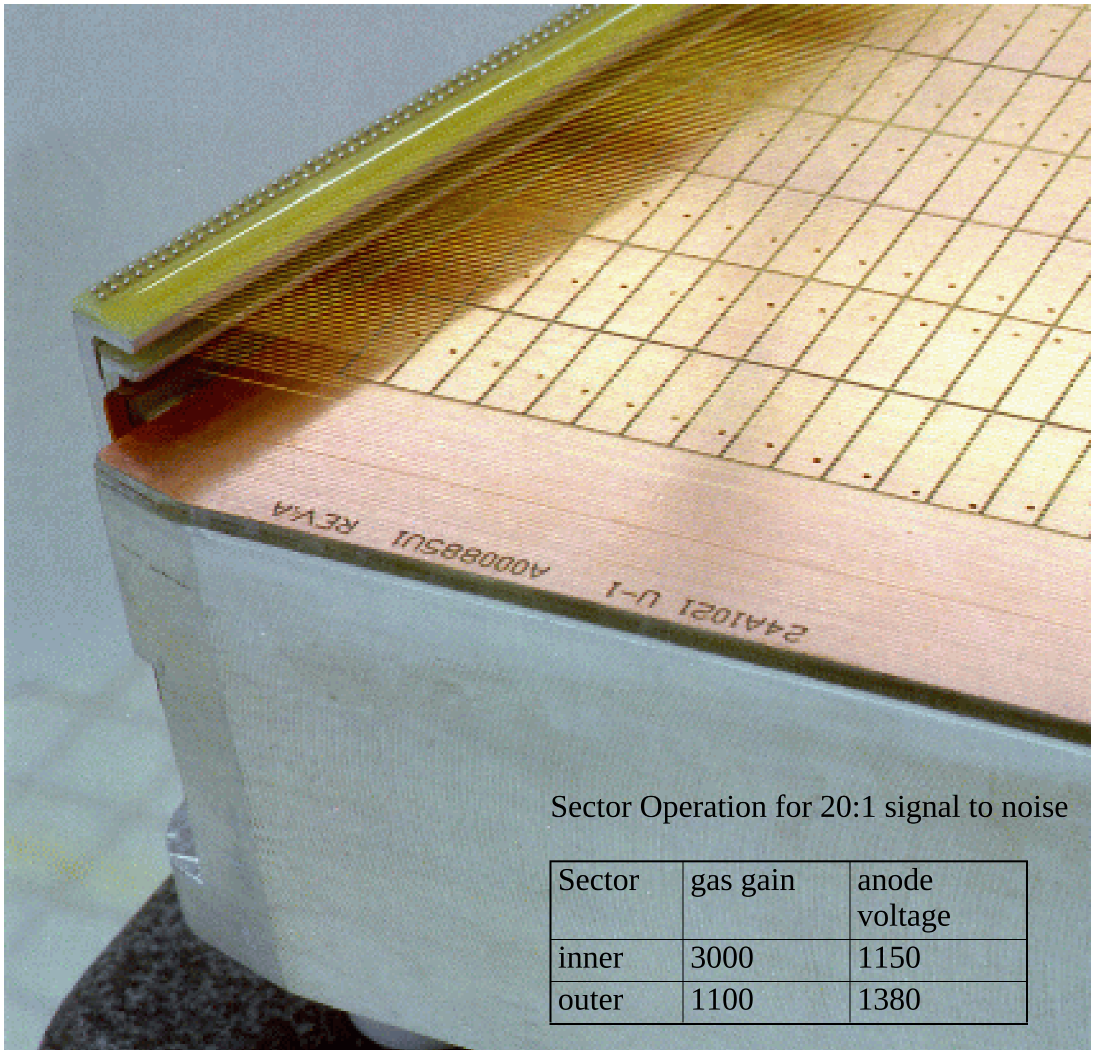
Self supporting Inner Field Cage:
Al on Kapton using Nomex honeycomb; 0.5% rad length

Outer and Inner Sectors of the Pad Plane



- **24 sectors** **(12 on a side)**
- **Large pads good dE/dx resolution in the Outer sector**
- **Small pads for good two track resolution in the inner sector**

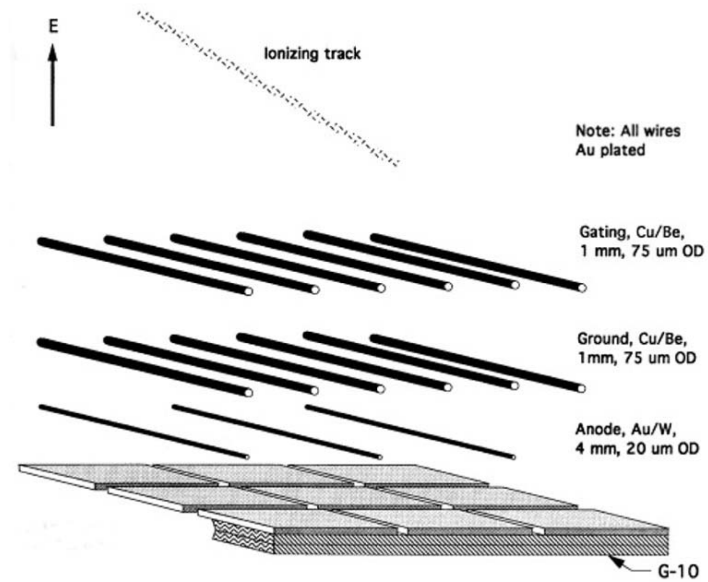
TPC Sector Detail



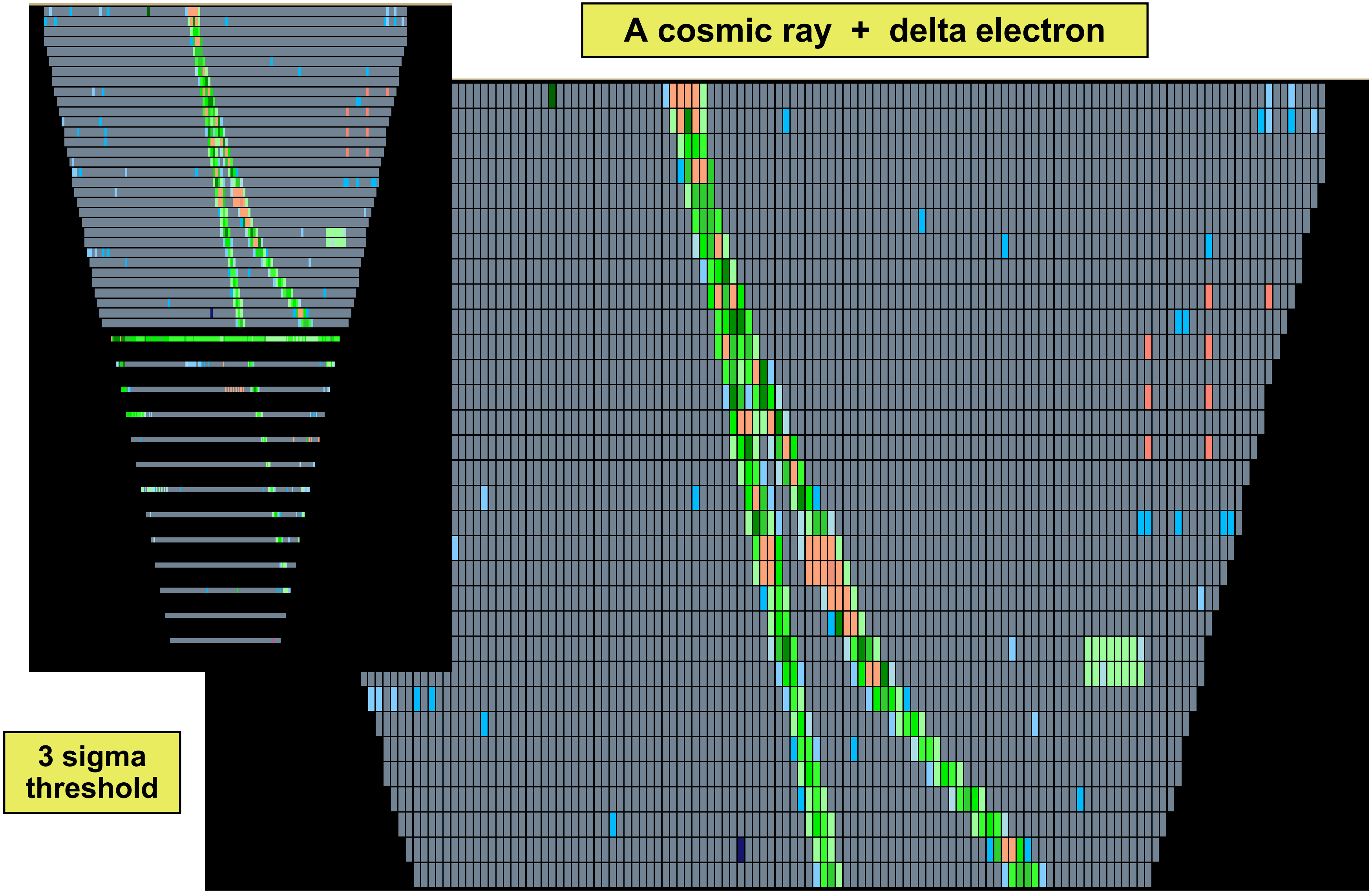
Sector Operation for 20:1 signal to noise

Sector	gas gain	anode voltage
inner	3000	1150
outer	1100	1380

- Gating Grid
- Ground Plane of Wires
- Anodes
  - No field shaping wires
    - Simple and reliable
  - Individually terminated anode wires limit cross-talk
  - Low gain
- Pad Plane



Pixel Readout of a Pad Plane Sector

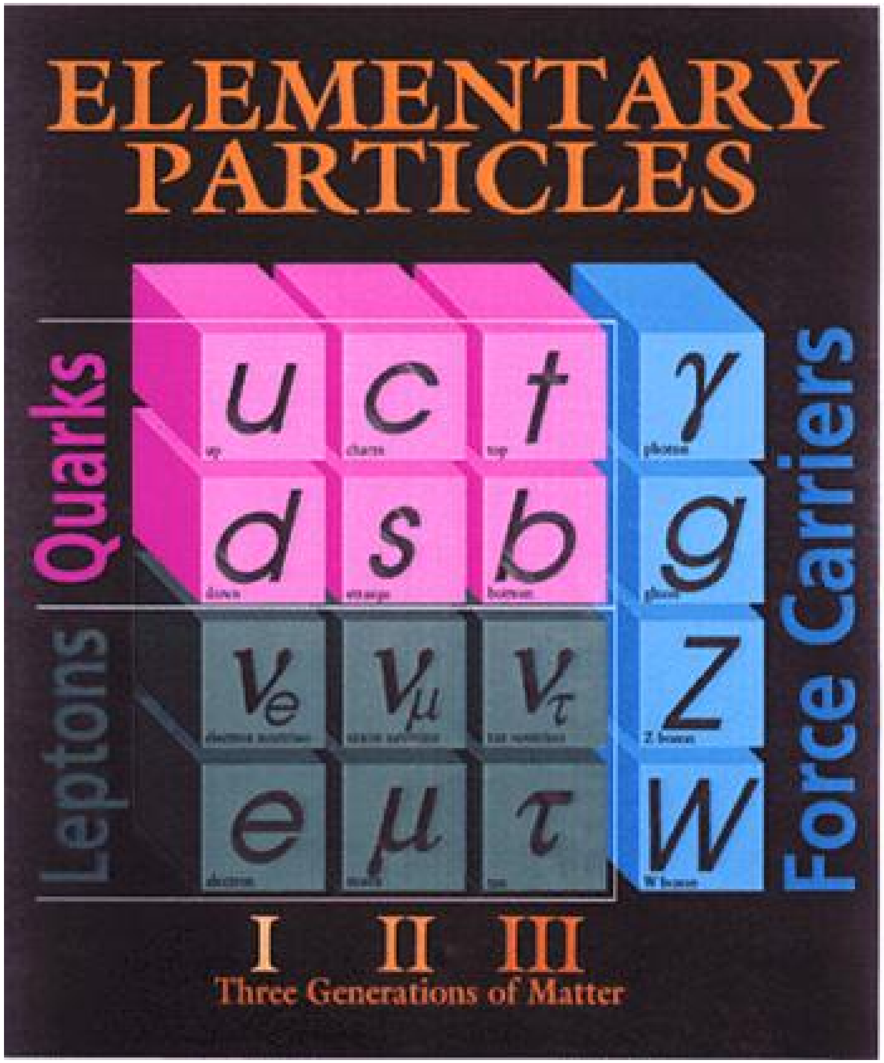


It works!

- Those of us who are close to the program take pride in the fact that it works.
  - The STAR TPC recorded the first event produced by RHIC
  - In 5 years of running STAR has produced
    - 28 Phys. Rev. Letters
    - 15 Phys. Rev. C’s
    - 55 Ph.D.’s
    - 11 Masters degrees
    - roughly 3000 citations in the refereed literature

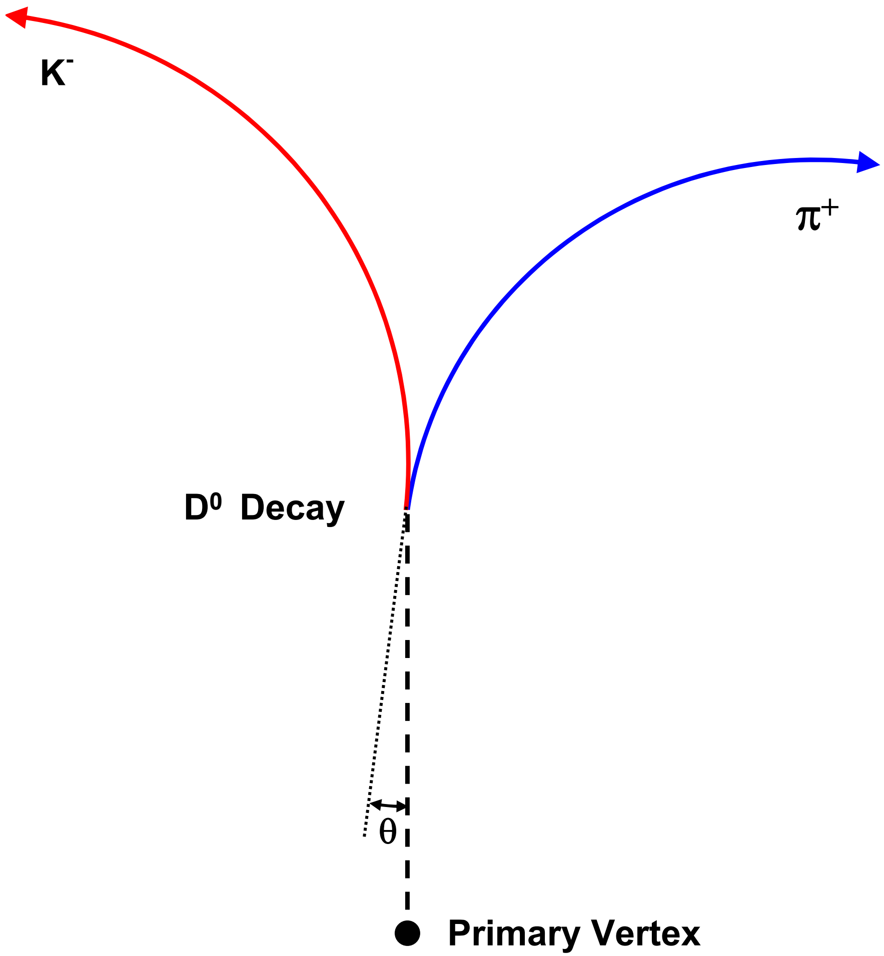
- How can we do better?
  - Ideally we are looking to identify every track going into all space
  - Infinitely precise tracking; helps with momentum analysis and improves PID capabilities with topologically based tracking
  - Improve PID with TOF
  - Additional coverage in the forward direction … try to be hermetic
  - Take more data, faster DAQ
  - …

Extend the Physics in New Directions

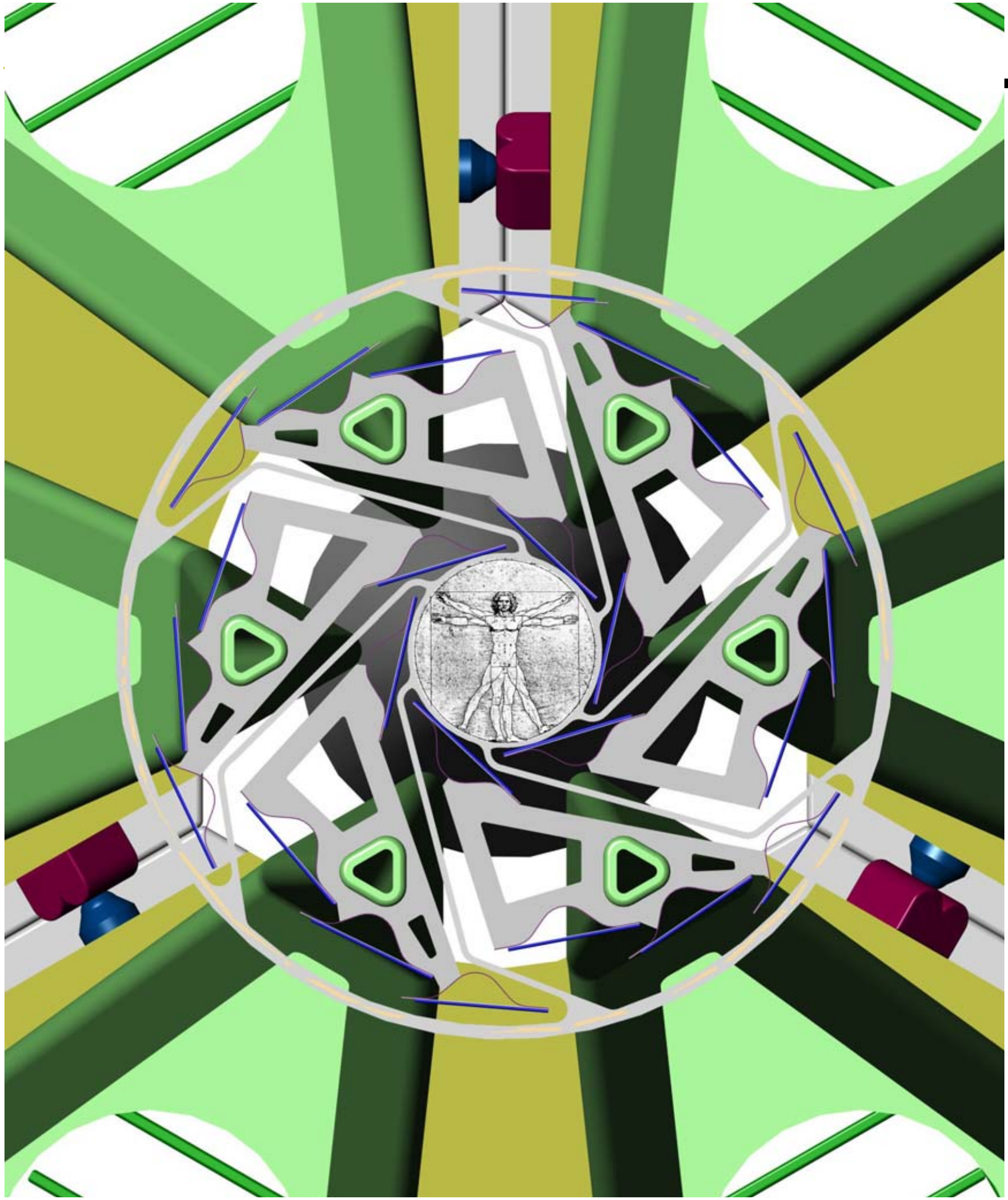


- Elementary particles – microscopic laws:
  - – Electromagnetism / weak
  - – Hunt for ***Strong Force !***
  - – Gravitation

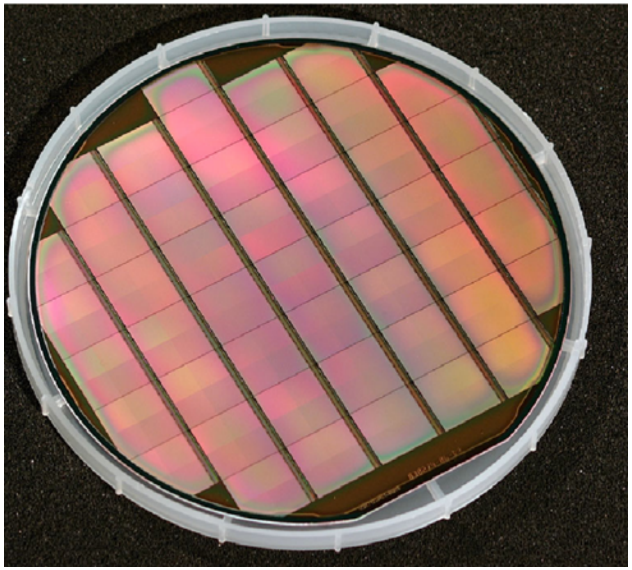
Topological Identification of Open Charm – the D^0



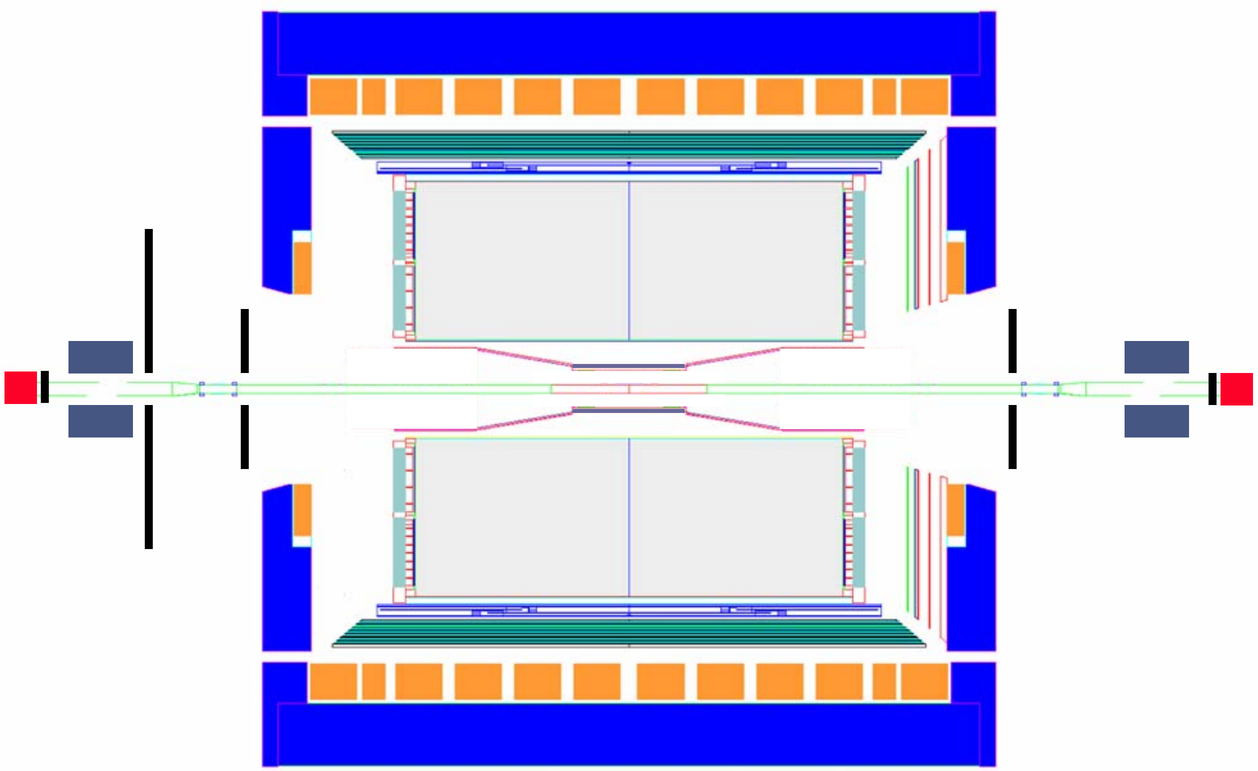
- The HFT is unique at RHIC
- It will be thin
  - 50 μm Silicon
  - 0.36% radiation length
- It will have high spatial resolution
  - cτ for the D^0 is 124 μm
  - Cut on $DCA_{\pi K}$ < 50 μm
  - Requires ~10 μm point resolution
- It will track all charged particles
  - From the lowest momentum accepted by STAR, 150 MeV/c, to the highest
- The HFT will cover the full azimuth of STAR (2π)



A Heavy Flavor Tracker for STAR



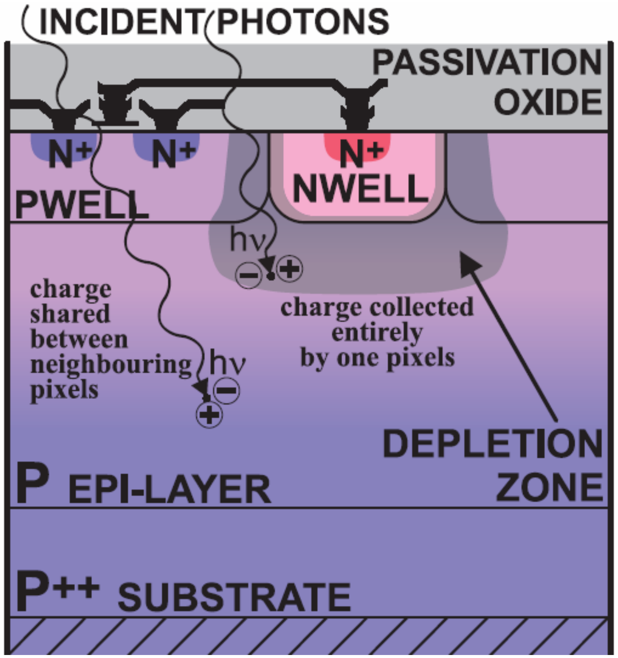
The Heavy Flavor Tracker Upgrade



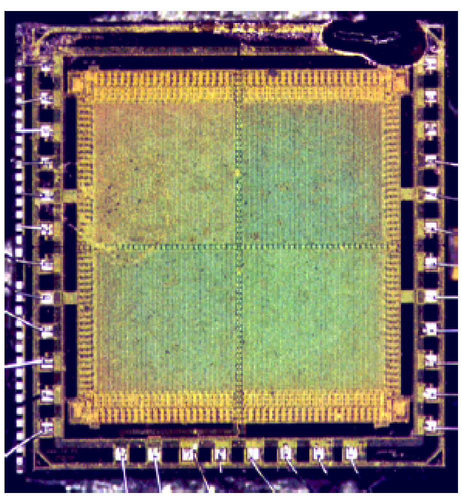
- A new detector based on 30 μm silicon pixels to get 10 μm space point resolution near the vertex
- Detect charm decays with small ct, including D^0s and open charm

- Does open charm flow at RHIC? If so, …
- Desirable to have it in time for the next 200 GeV Au-Au run (2010)
- Proposal submitted to the collaboration

MIMOSA Active Pixel Sensor

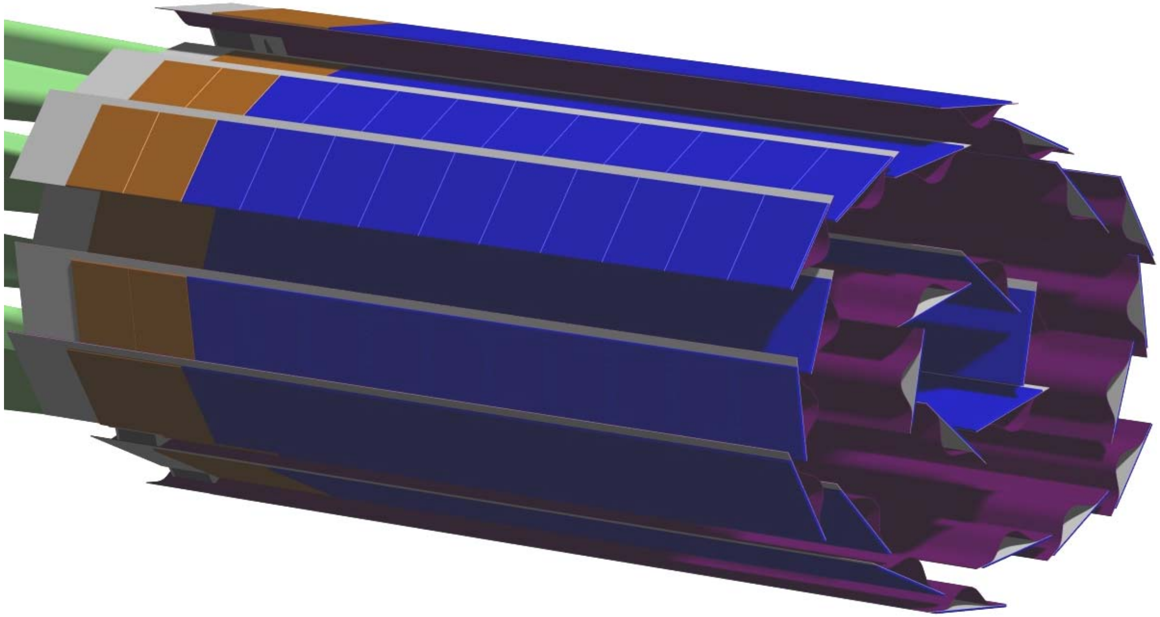


MIMOSA I
die size 3.6 × 4.2 mm^2

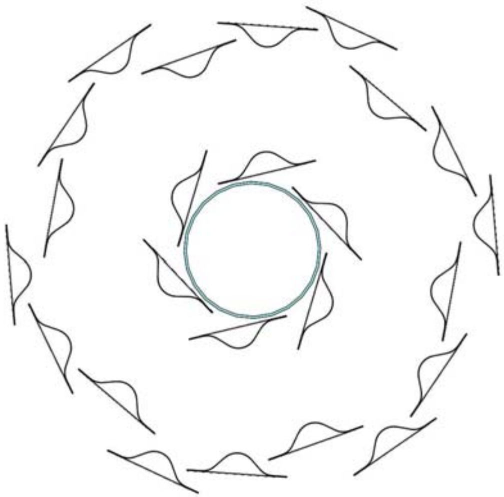


- ❑ CMOS technology
- ❑ Charge generated in non-depleted region collected through thermal diffusion
- ❑ 100% fill factor in active volume
- ❑ active sensor thinned to 50μm
- ❑ total thickness 0.36% X0 (ALICE: 1.0 – 1.5%)

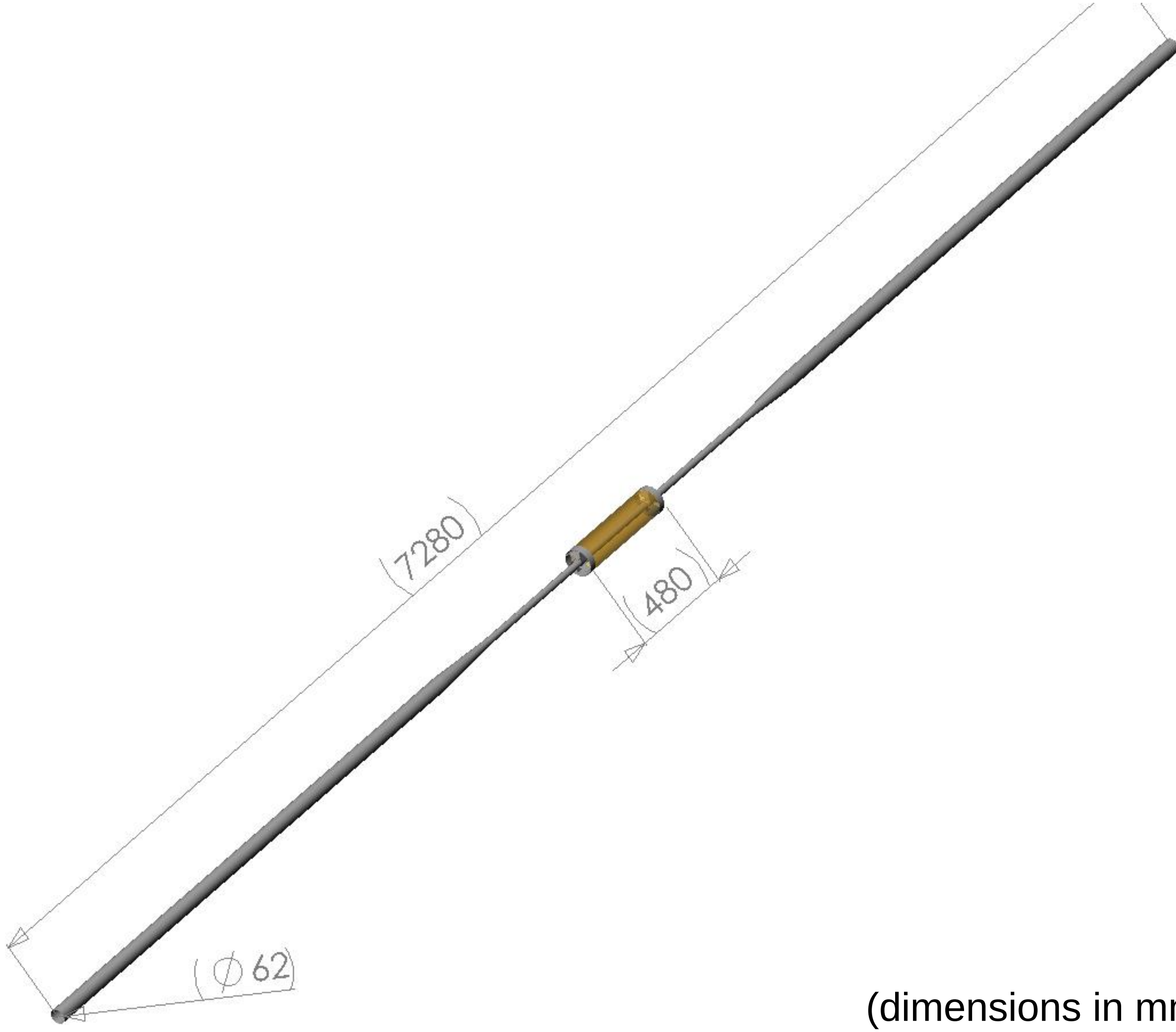
The Heavy Flavor Tracker Mechanical Design



- Two Layers of Si
  - 1.5 cm radius
  - 4.5 cm radius
- High Resolution
  - 100,000,000 pixels
  - 30 μm x 30 μm
  - 10 μm resolution
- Thin – with low MCS
  - 50 μm thinned Si
  - 0.36% radiation length
  - 0.5 mm Beam Pipe
  - CMOS technology (Industry Standard)
- 24 Ladders
  - 10 chips, 2 cm wide by 20 cm long
  - 100 mW/cm^2 power budget
  - air cooled



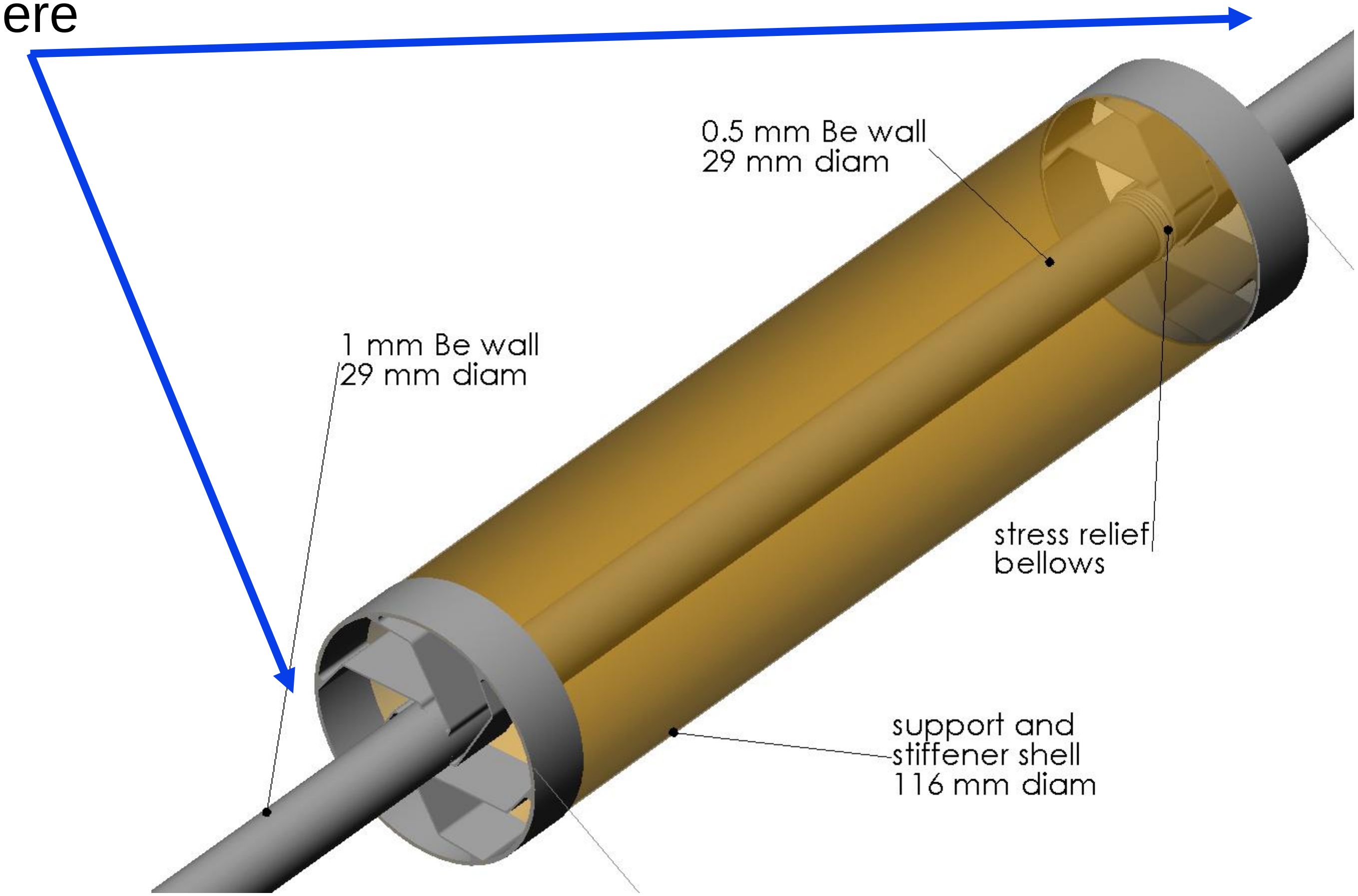
Beam pipe concept required for HFT



(dimensions in mm)

Beam pipe concept required for HFT (central region)

Beam pipe supports attach here



Mounting Support

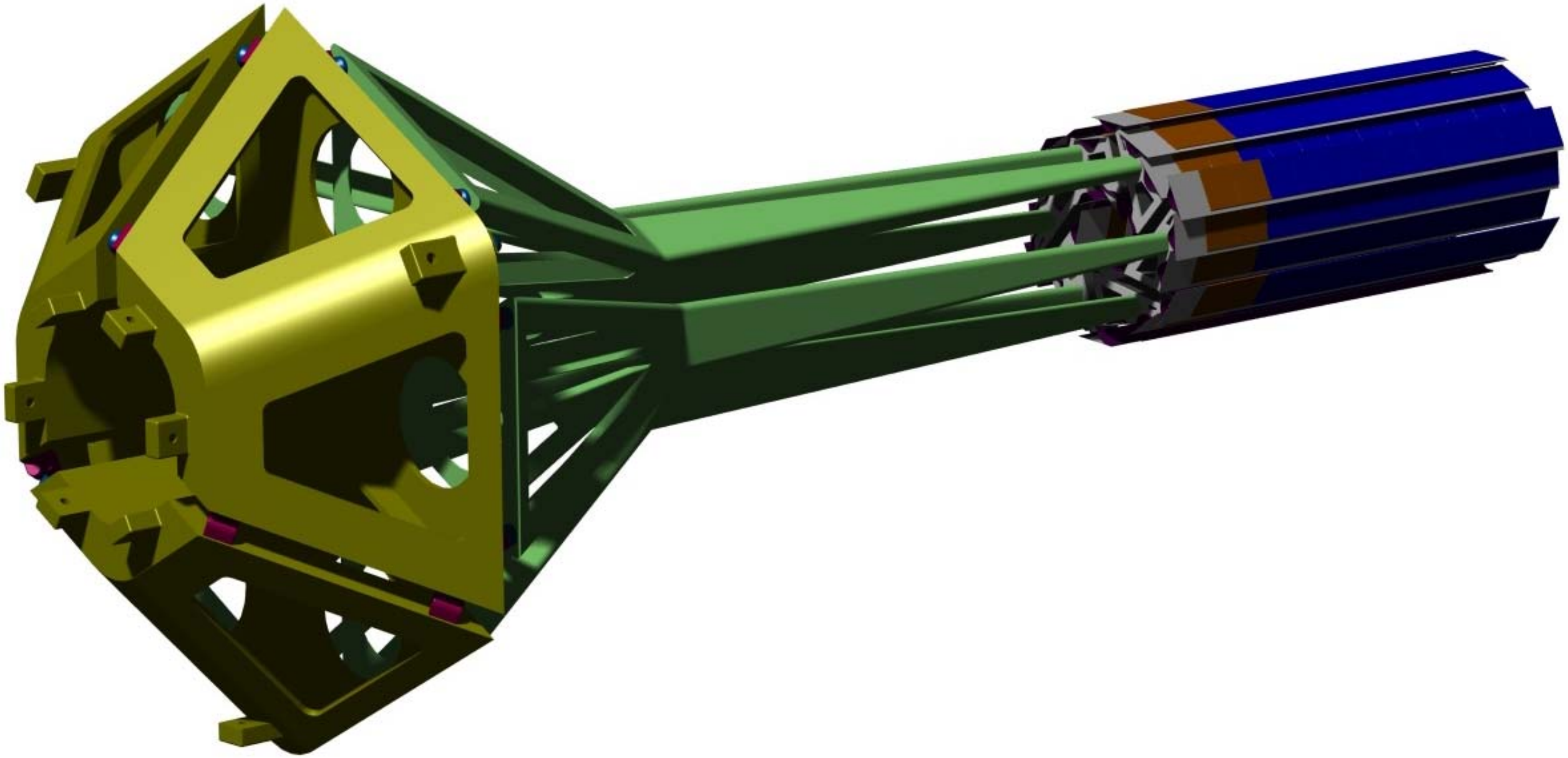
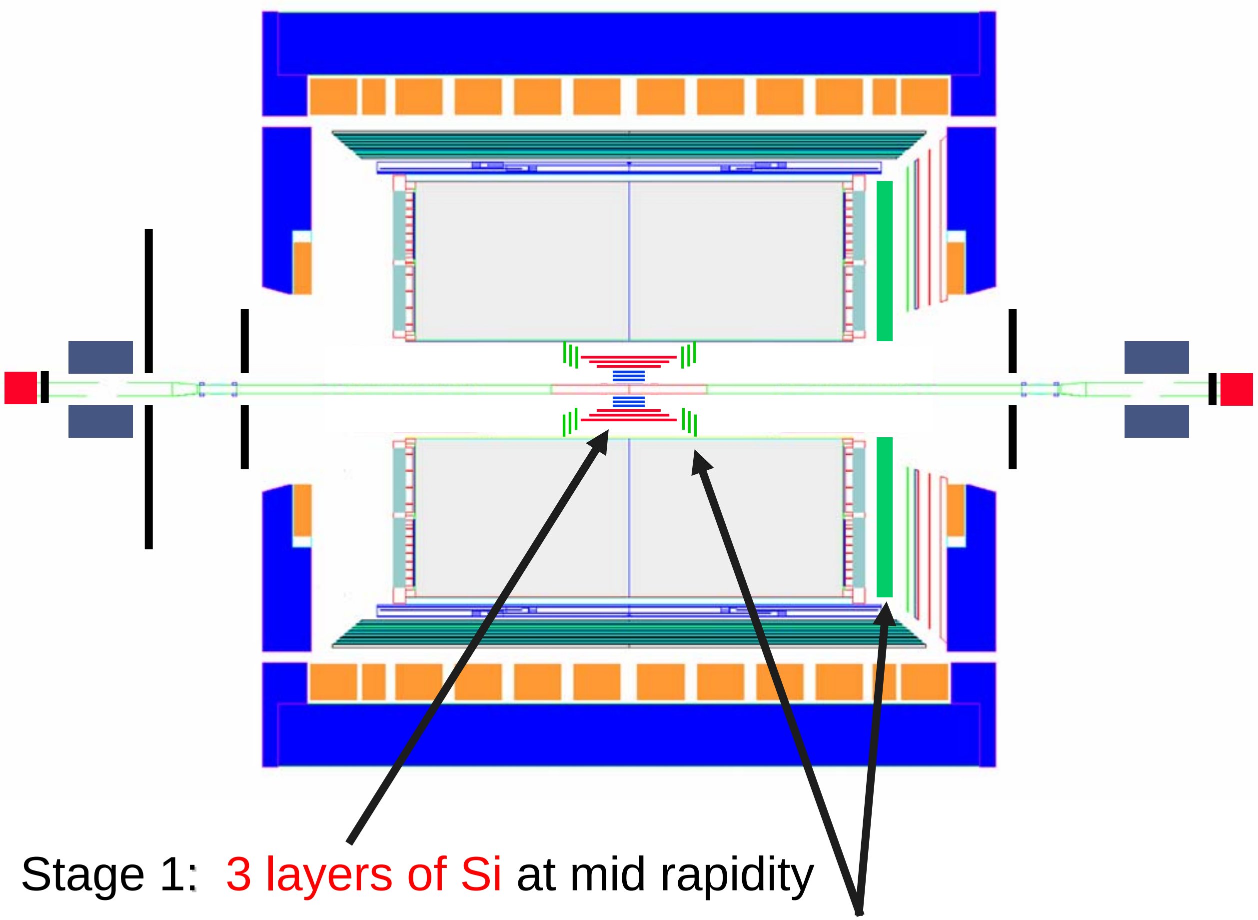


Figure 31: Detector support structure with kinematic mounts to insure repeatable detector positioning.

Integrated Forward Tracking Upgrade



- **High Rate - High Quality tracking at 1 < η < 2 for heavy flavor and W production**
- **Break the 100 Hz barrier for inner tracking by replacing the existing Si with a new silicon tracker surrounding the HFT detector**
- **Add high quality space points to tracks at high rapidity in the TPC by putting a triple-GEM detector in the gap between the TPC electronics and the EEMC**

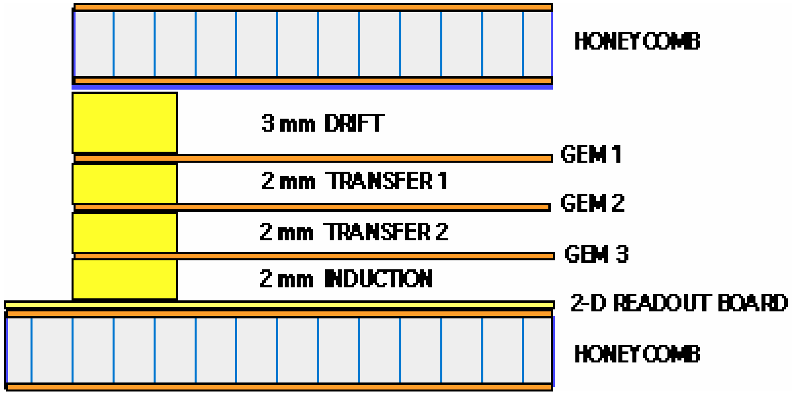
Stage 1: 3 layers of Si at mid rapidity

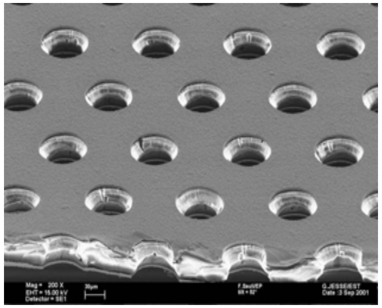
Stage 2: 3 layers of Si + 2 layers of GEM at forward angles

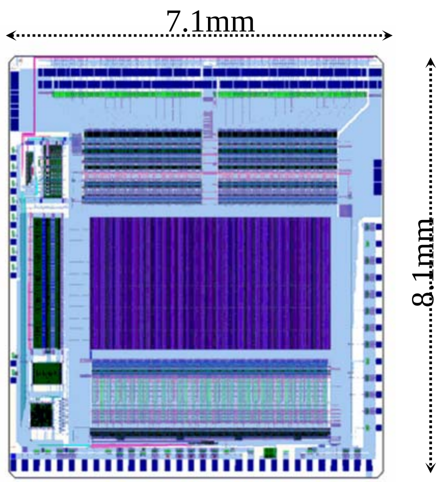
STAR triple-GEM prototype effort

Goal of triple-GEM R&D effort

- Design of triple-GEM chambers to be installed and tested at STAR under beam conditions:
  - Profit from experience by COMPASS with triple-GEM technology (fast, precise)
  - Establish collaboration to a US company to develop and manufacture GEM foils
  - Manufacture 2D-readout structures
  - Design of readout system using existing chip: APV25-S1







APV25-S1 chip

- R&D team:
  - Collaboration between ANL, BNL, MIT, Yale
- Tech-Etch Inc. (Plymouth, MA):
  - TechEtch is capable of producing GEM foils
  - SBIR proposal to DOE from TechEtch in collaboration with R&D team: Submitted December 10, 2004

SBIR initiative

TechEtch contact

- **Company profile:**
  - Manufacturer of precision flexible printed circuits primarily for the medical imaging (ultrasound) market
  - Extensive experience in the etching of copper traces and polyimide and other dielectrics with feature sizes of .002" (.05mm) or less
  - Strong ties with several research institutions such as BNL, MIT and Yale
  - Advantage of small company size:
    - Capability to produce a large variety of part configurations
    - Flexibility to shift production methods, equipment, and chemistry to optimize the GEM foil manufacturing process without being constrained by existing work running on high volume continuous coil equipment.

TechEtch Inc.

http://www.tech-etch.com

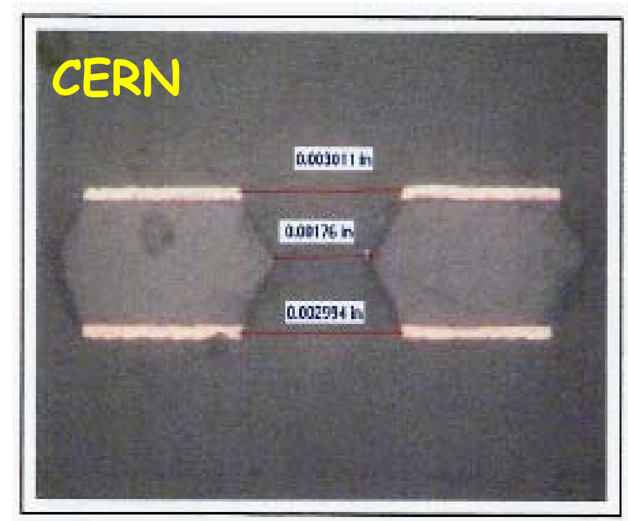
Critical for collaborative effort to produce GEM foils which meet the requirements by the High-Energy and Nuclear Physics community!

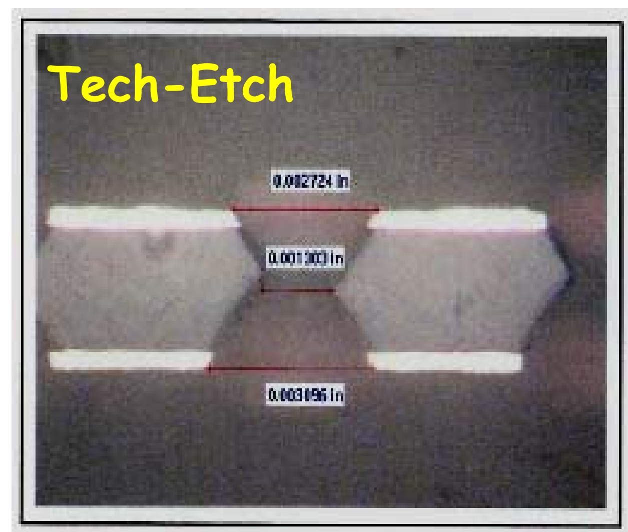
SBIR initiative

Comparison of CERN and Tech-Etch produced GEM foils: 10 X 10 cm^2 samples

- **CERN**
  - **Base material: Apical**
  - **Pitch: 140μm**
  - **Hole size: 76μm tapering to 45μm (symmetric top and bottom)**

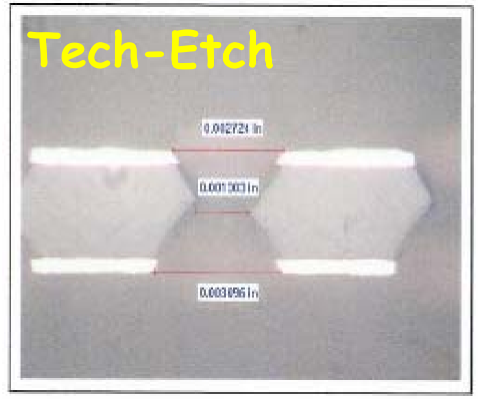
- **Tech-Etch foils**
  - **Base material: Kapton**
  - **Pitch: 140μm**
  - **Hole size: 74μm tapering to 33μm (slight misalignment)**

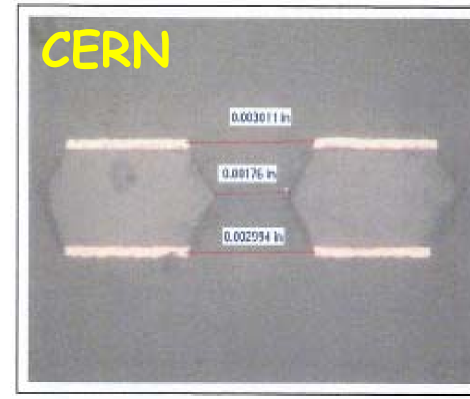


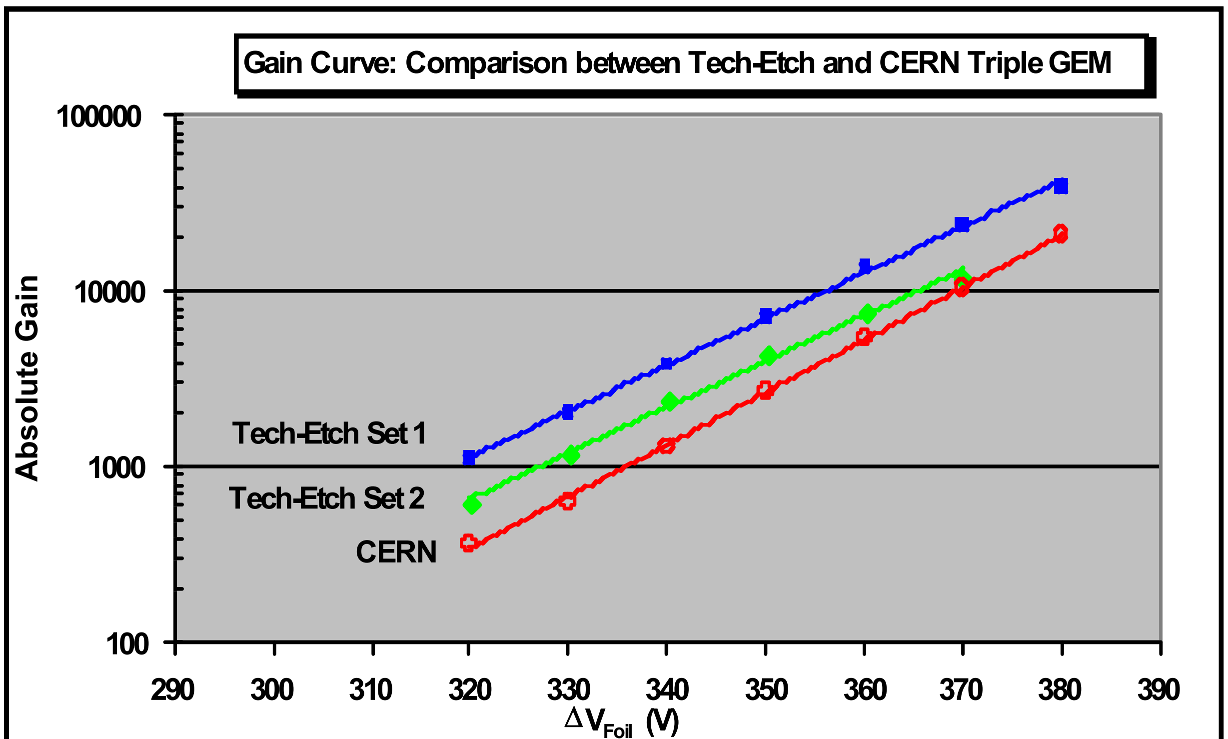


SBIR initiative

- **Gain performance**
  - **Initial screening of Tech-Etch foils**
    - **Impedance greater than 10GΩ**
    - **Leakage current < 1nA**
    - **Gas mixture $ArCO_2$ (70%/30%)**



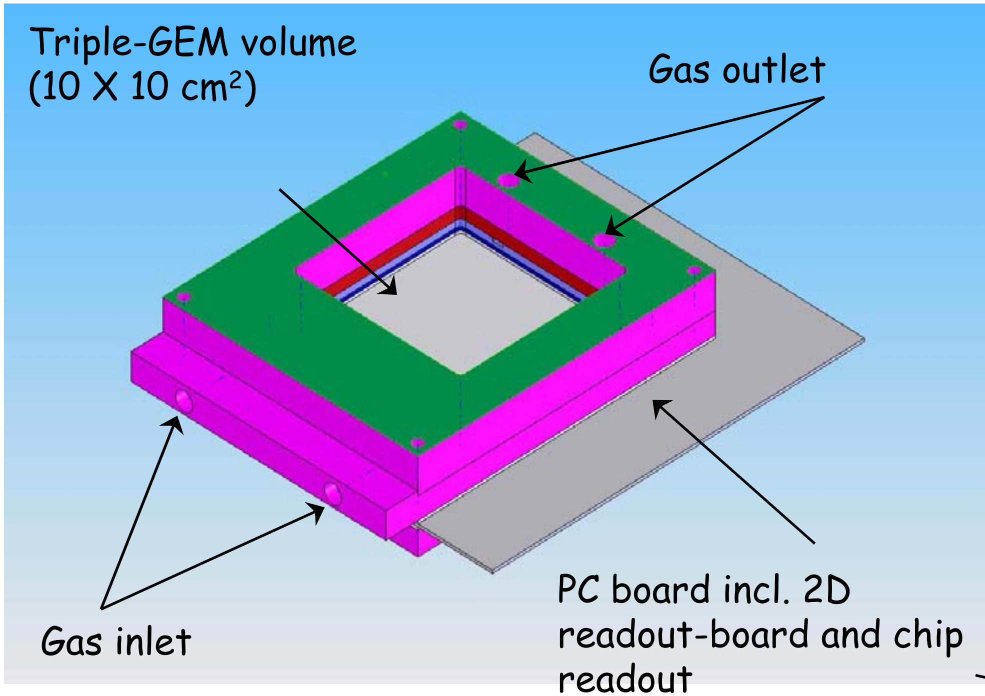


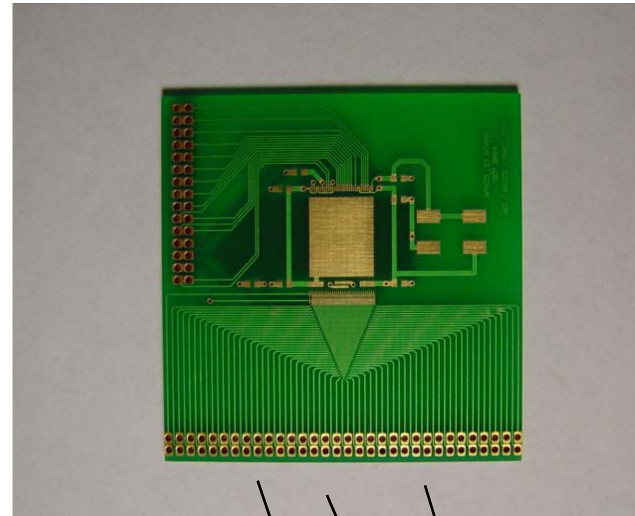


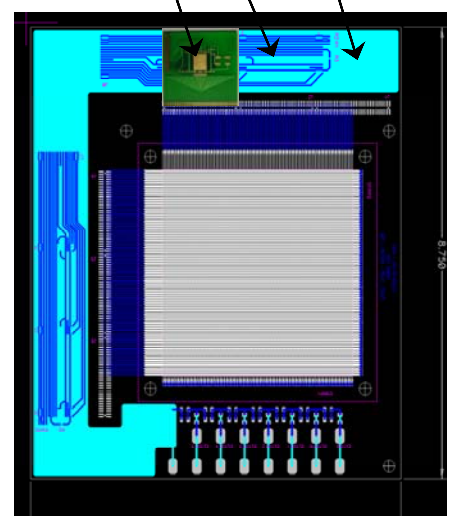
- Tech-Tech./ CERN foils: Similar gain-HV dependence
- Maximum gain for Tech-Etch foils: > 10^4

STAR triple-GEM prototype effort

Layout of triple-GEM prototype chamber



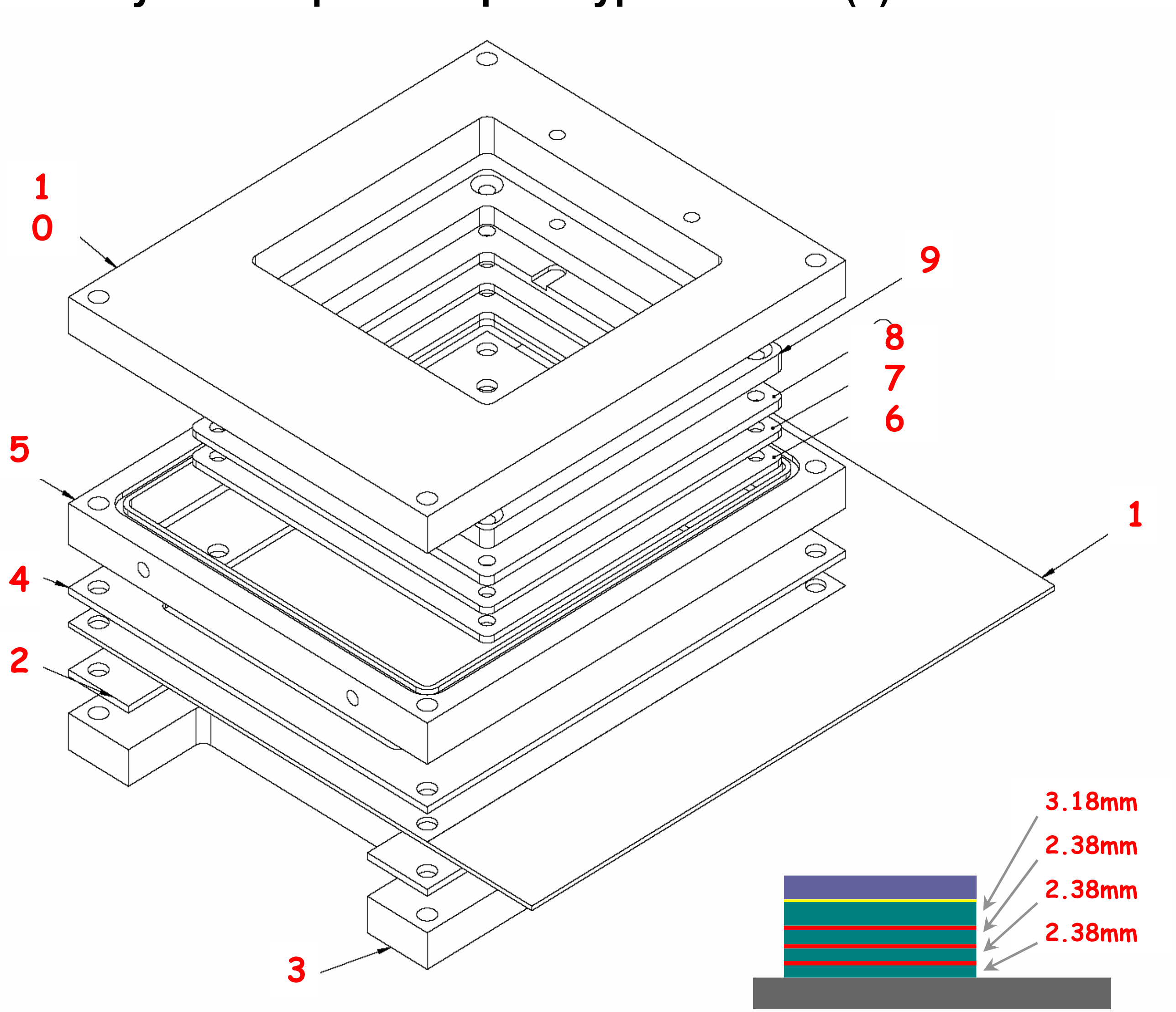




- **2D-readoutboard:** **Compunetics Inc.**
- **Chamber mechanics:** **completed**
- **Chip readout board:** **Compunetics Inc.**
- **DAQ system:** **Under preparation**

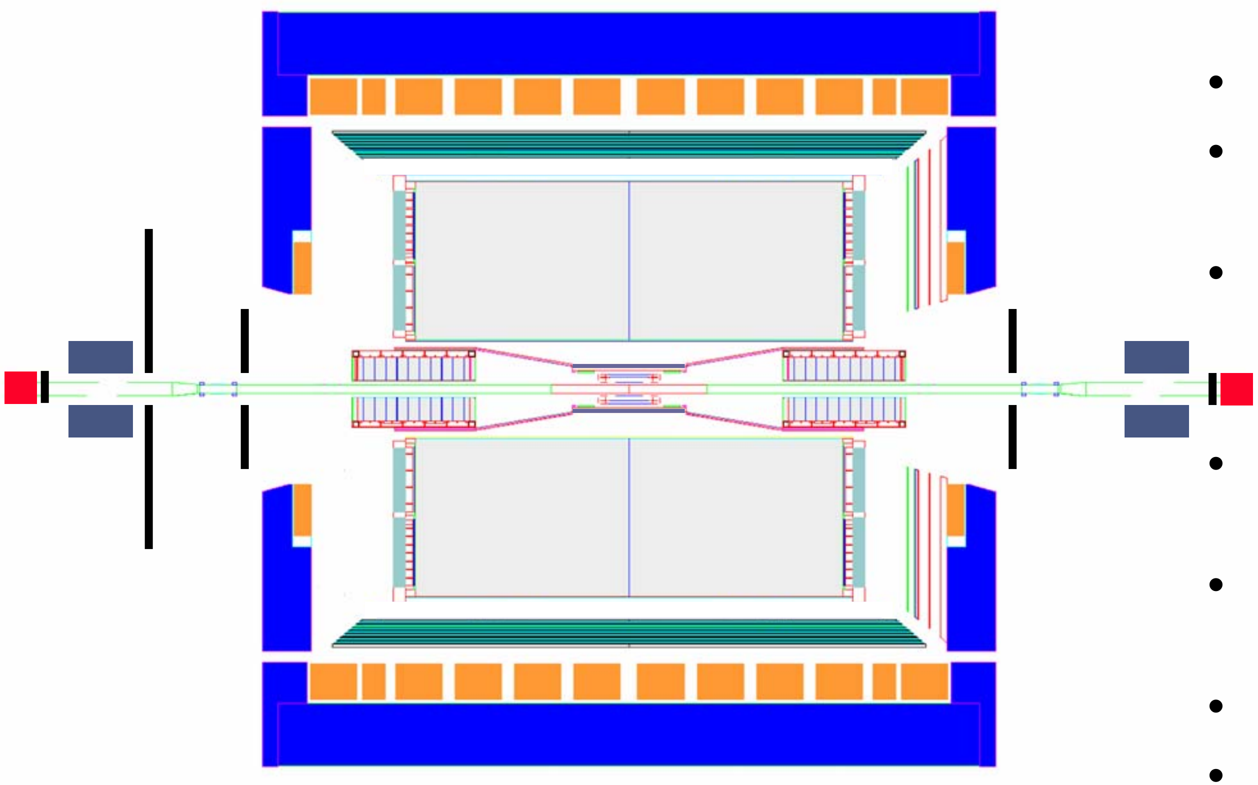
An Integration Issue? e.g. triple-GEM prototype

Layout of triple-GEM prototype chamber (2)



- All basic components are easily interchangeable to allow maximum flexibility in chamber R&D:
  - GEM frames
  - 2D readout board
  - Chip readout board
- Components:
  1. 2D readout board
  2. Bottom spacer (G10)
  3. Bottom Al support plate
  4. Top spacer (G10): 2.38mm
  5. Al gas seal frame
  6. GEM 1 frame (G10): 2.38mm
  7. GEM 2 frame (G10): 2.38mm
  8. GEM 3 frame (G10): 3.18mm
  9. Drift frame (G10)
  10. Top Al support cover

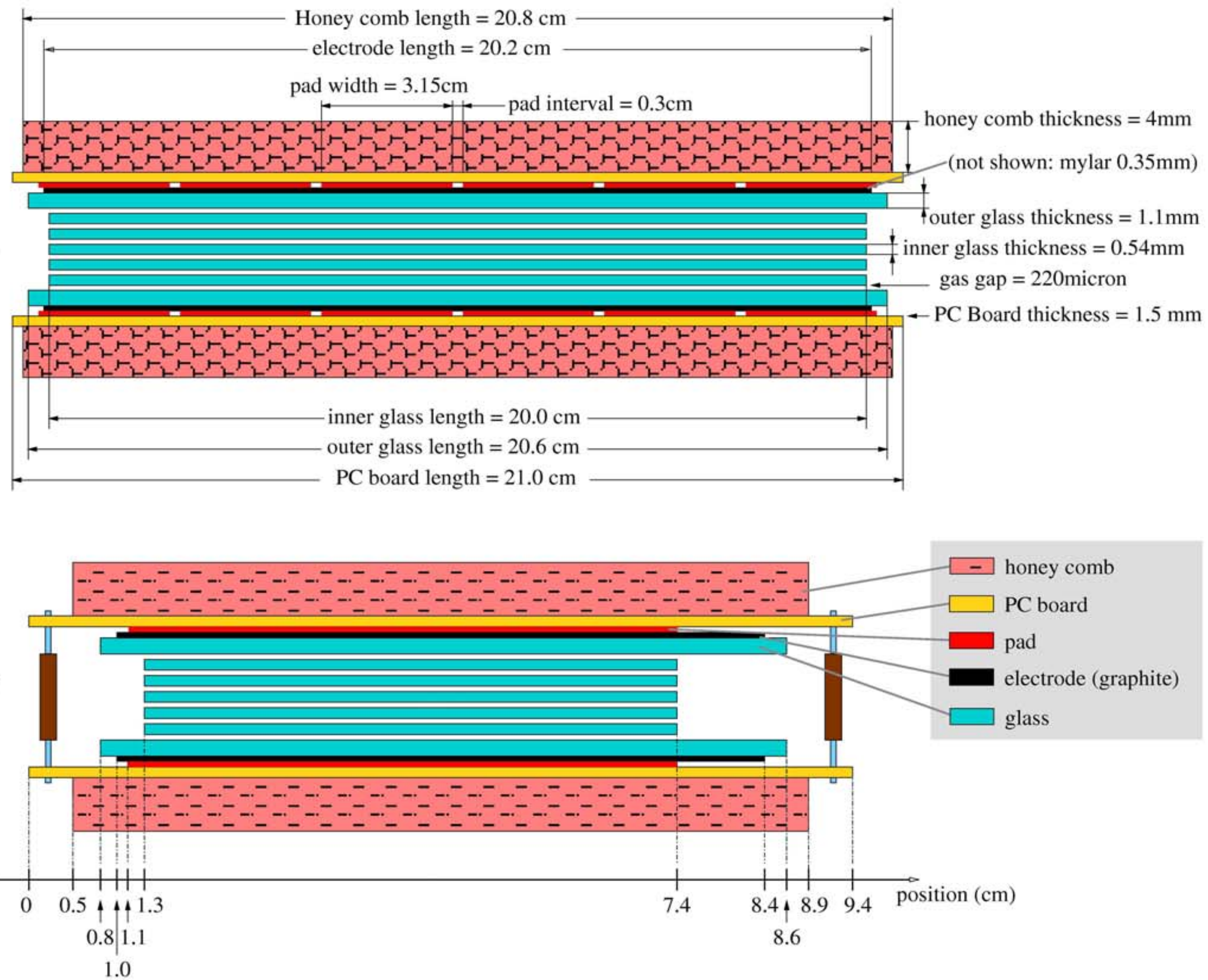
The TOF Upgrade



- Multiplate RPC technology
- Beautiful electron ID
- 85 ps timing resolution after slewing corrections
- Each tray has 72 channels

- 1 full tray this year, with new electronics
- Proposal submitted to the DOE
- Creative funding in 2005
- Construction and useful installation in 2006, 2007, and 2008

mRPC Technology to Measure Time of Flight

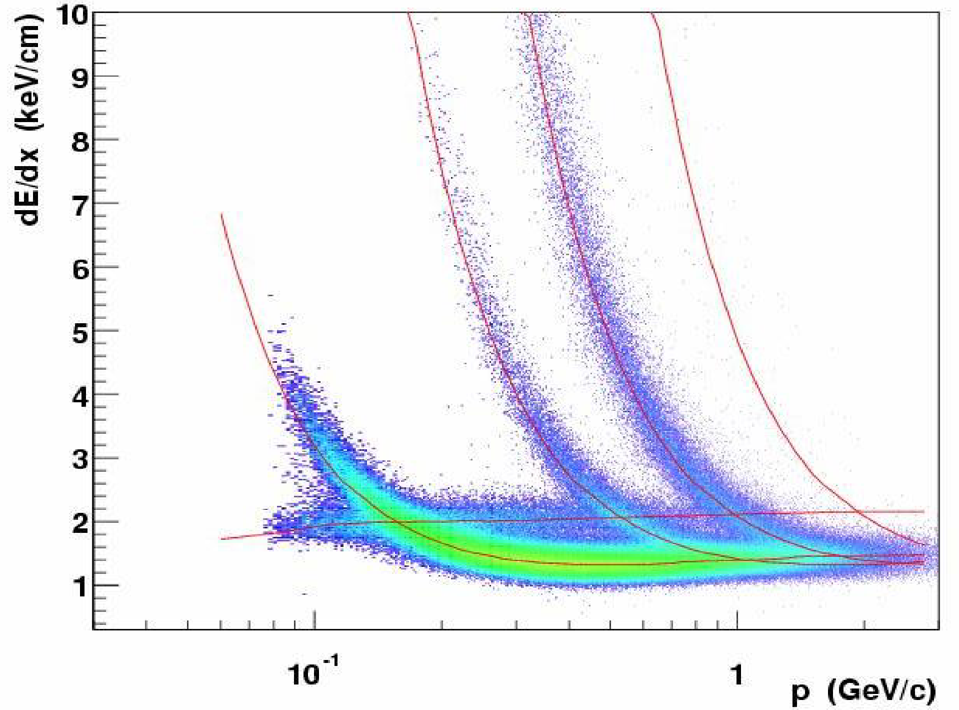


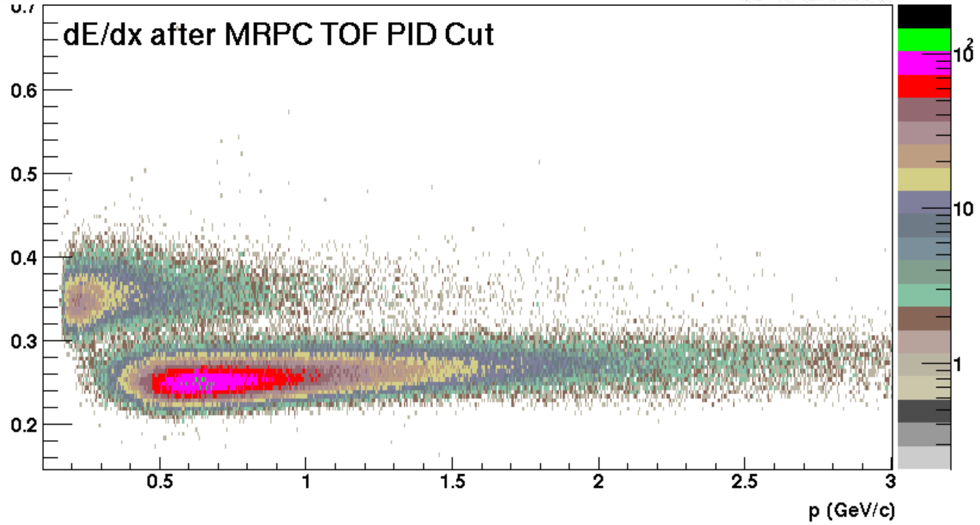
Chambers are multiple narrow gaps (6 x 220μm) separated by glass. Module sensitive area is approximately 6 *x* 20 cm

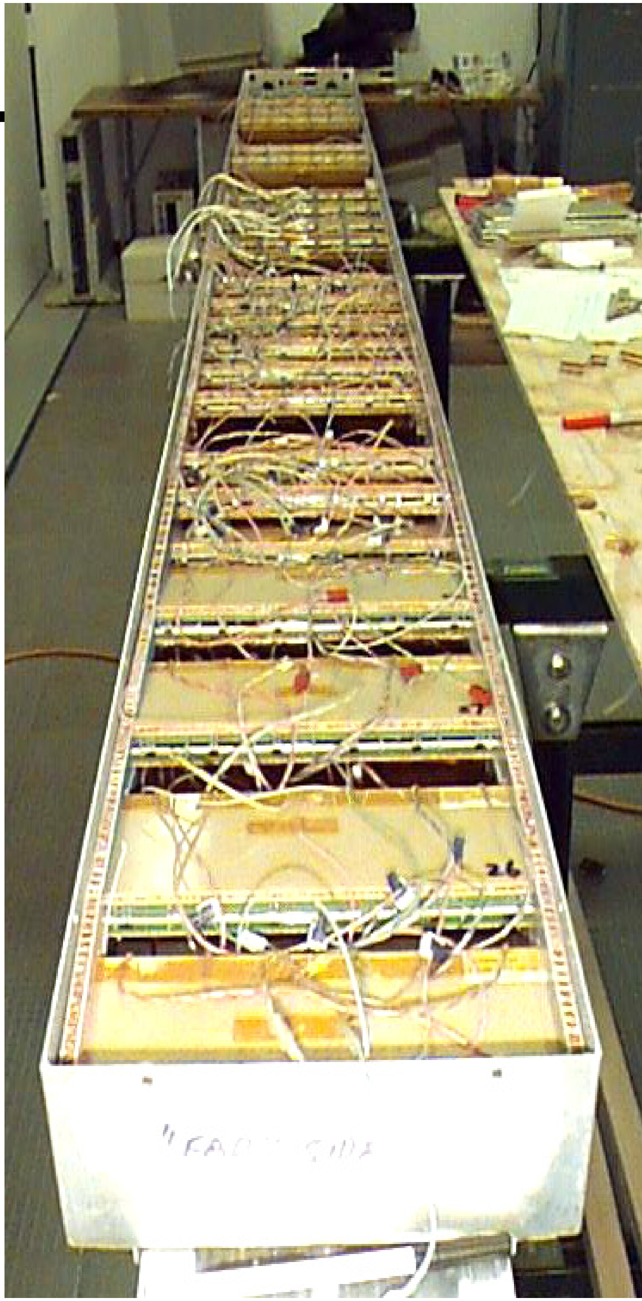
applied potential ±7-8kV

Gas will be 96% Freon R134a, 4% CO_2

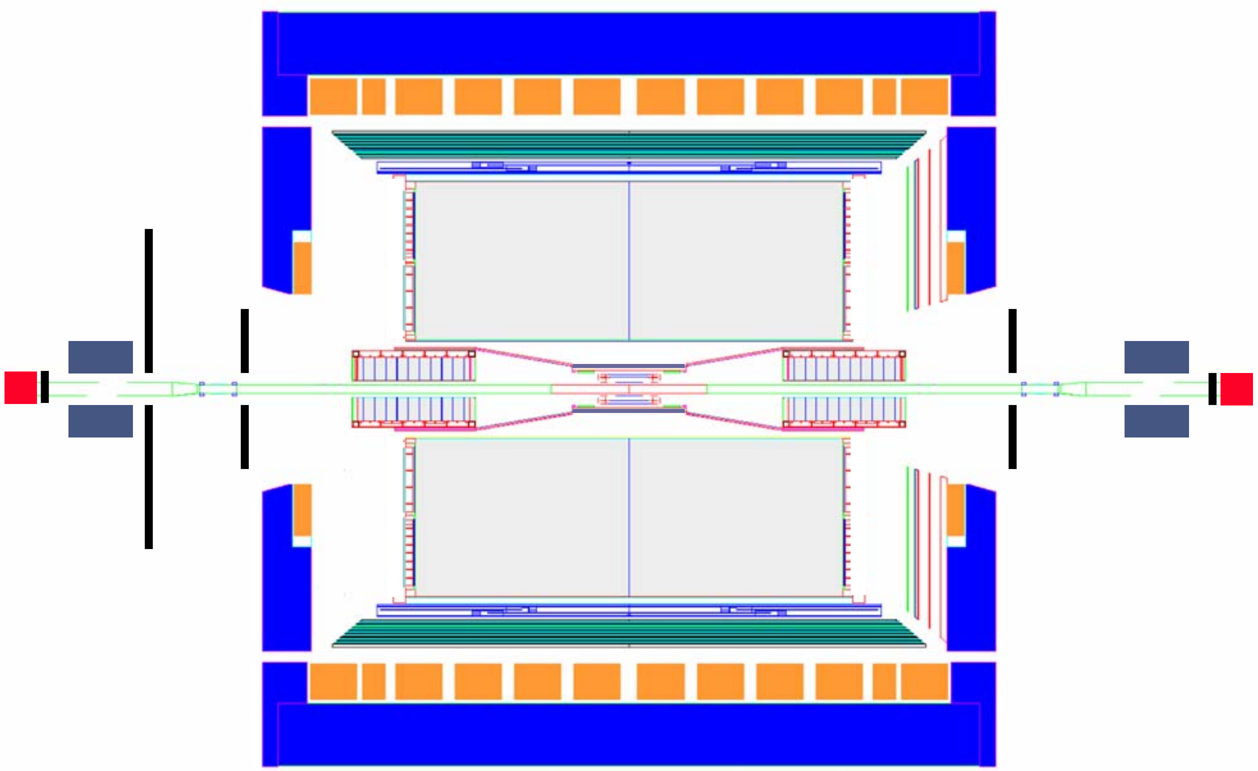
One "tray" test of TOF electron tagging





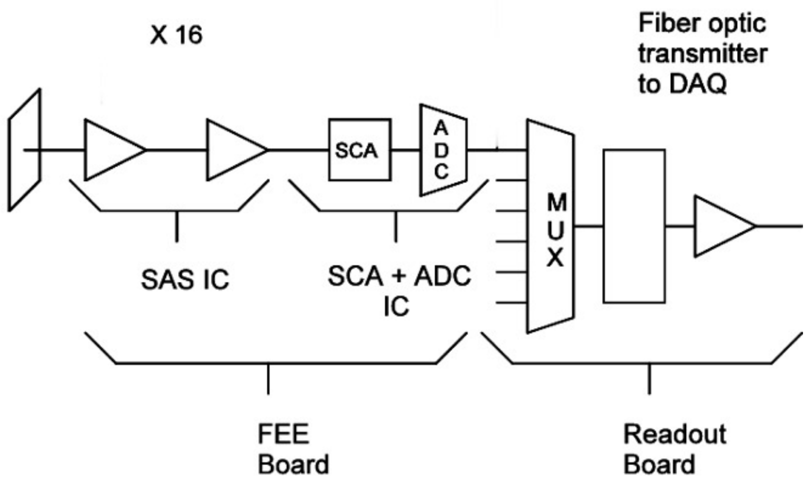


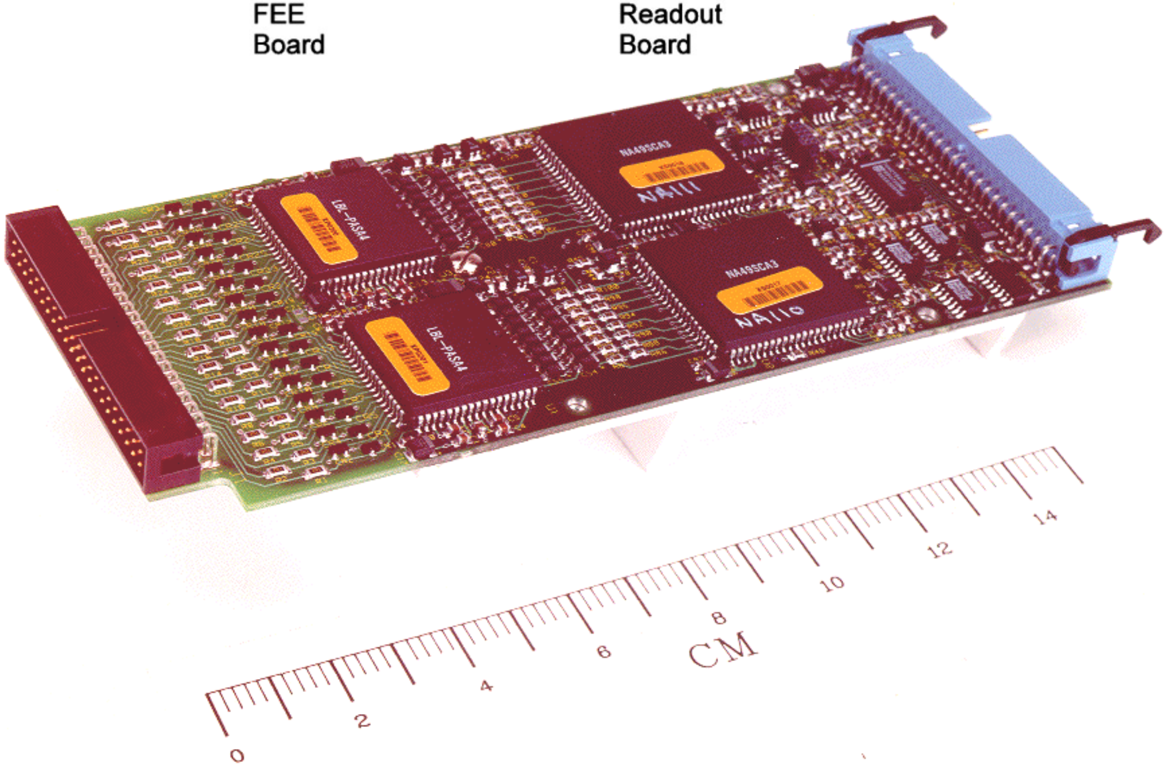
TPC FEE and DAQ Upgrade – DAQ 1000



- Faster, smaller, better … (10x)
- Current TPC FEE and DAQ limited to 100 Hz
- Replace TPC FEE with next generation CERN based chips … 1 kHz readout
- Make the FEE smaller to provide space for a forward tracking upgrade
- Further improvements by only archiving "associated" clusters – build on L3 algorithms … 5 kHz !
- "First light" data taken at 1 Hz

STAR TPC Front End Electronics

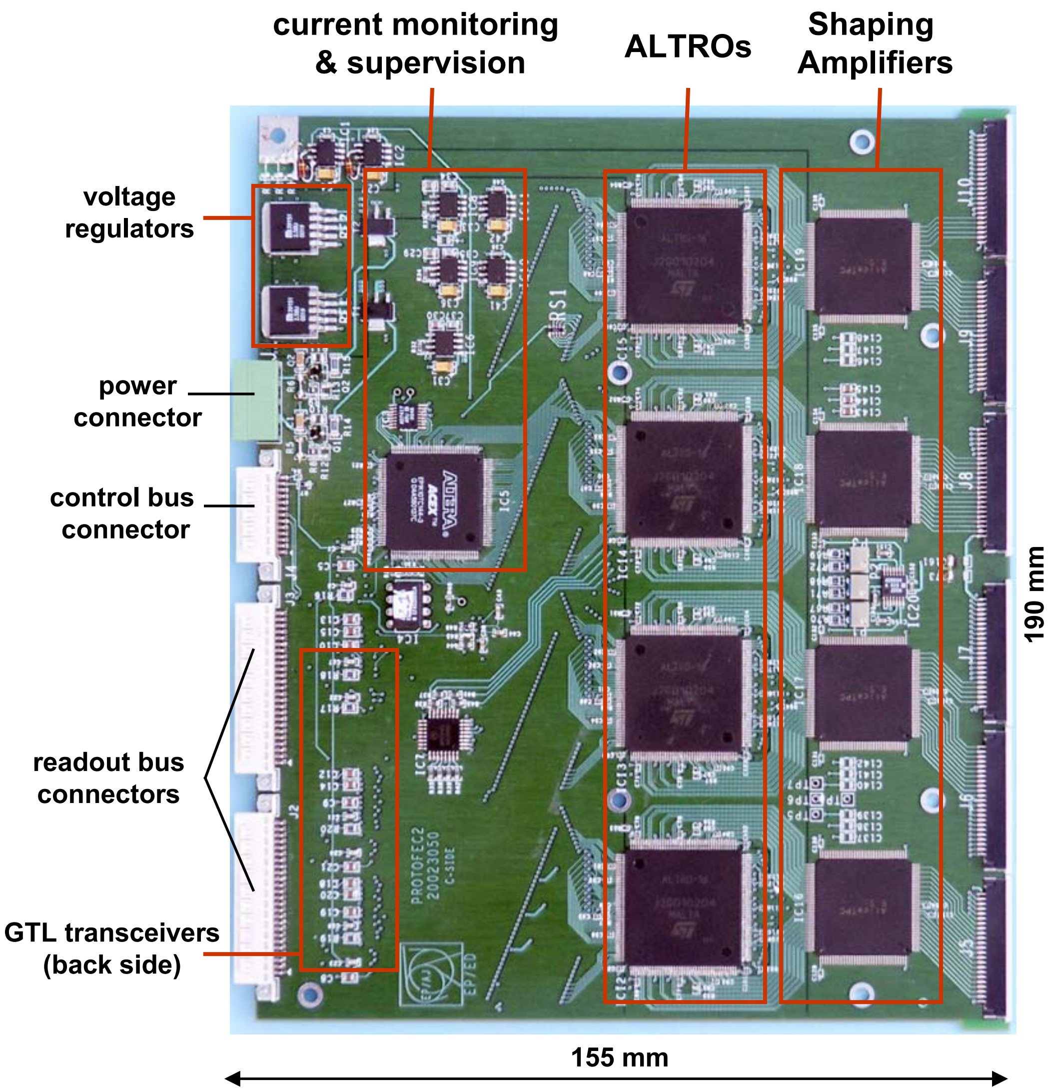


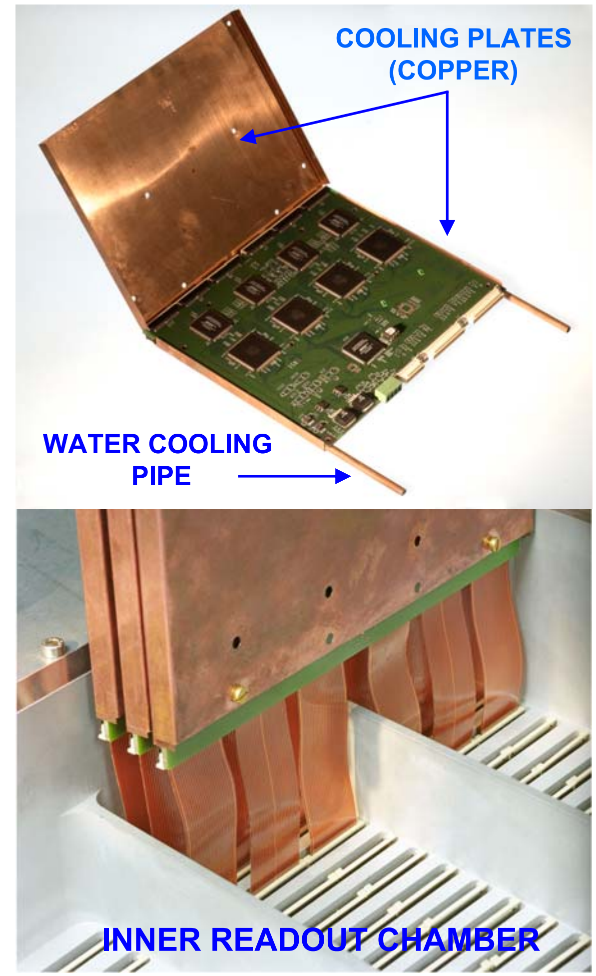


- **FEE**
  - 3rd generation electronics
  - very compact
  - First chip is pre-amp, shaper & buffer
  - Second chip is switched capacitor array & (slow) ADC
  - 512 time buckets per ch
  - 32 channels per board

Readout (RDO) board
  - Multiplex and tag data
  - 6 RDOs per sector
  - 144 total
  - Data sent to DAQ on gigabit fiber link

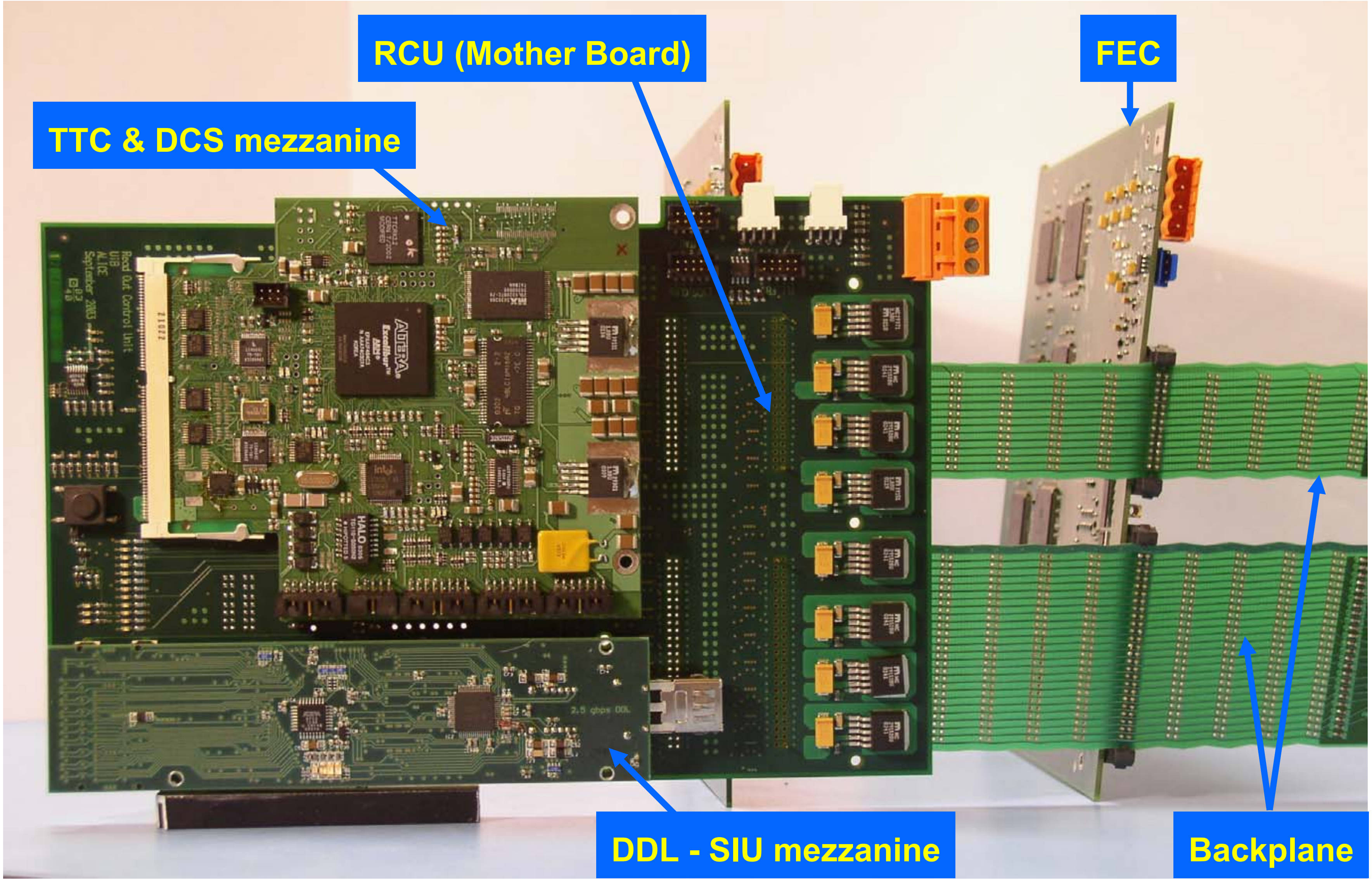
ALICE Front End Card





STAR will use use the same components but boards will be ¼ as wide

ALICE FEE Card and RCU: fast and compact

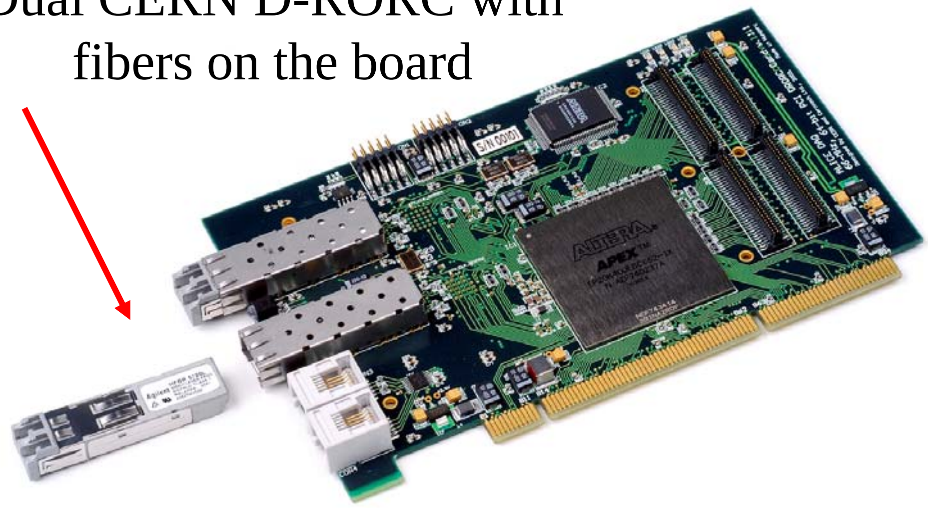


One RCU board can drive 32 STAR sized FEE cards at 200 Mbytes / sec

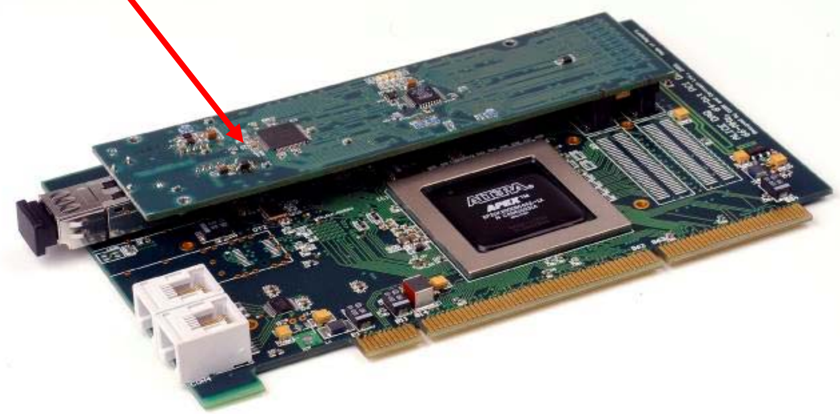
ALICE FEE & DAQ

- **Four steps to a better, faster and more compact DAQ system**
  - TPC FEE (LBL/BNL)
  - TPC RDO (CERN/BNL)
  - DAQ Transmitter (CERN)
  - DAQ Receiver (CERN)
- **1000 Hz and beyond at STAR!**
  - we started at 1 Hz

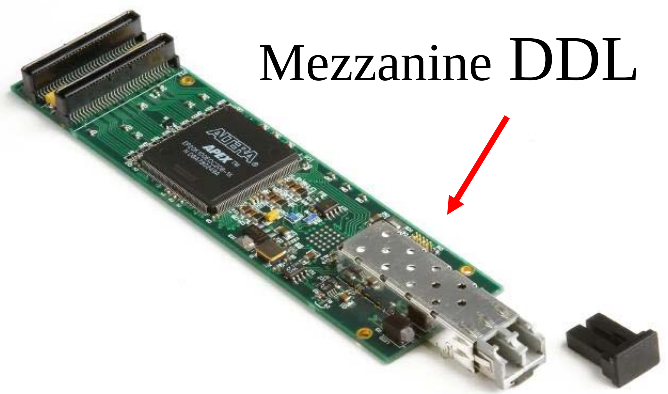
Dual CERN D-RORC with fibers on the board



Single D-RORC with 1 fiber mezzanine



Mezzanine DDL



Contact: Luciano Musa … http://ep-ed-alice-tpc.web.cern.ch/ep-ed-alice-tpc/

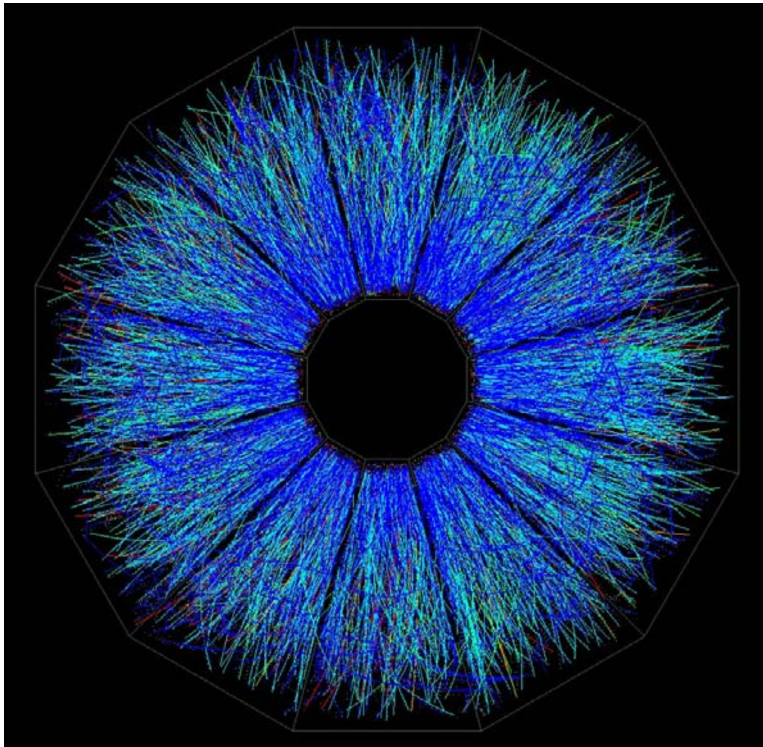
Isn't that enough?

greedy greedy scientists

They always want to push orders of magnitude beyond design specification

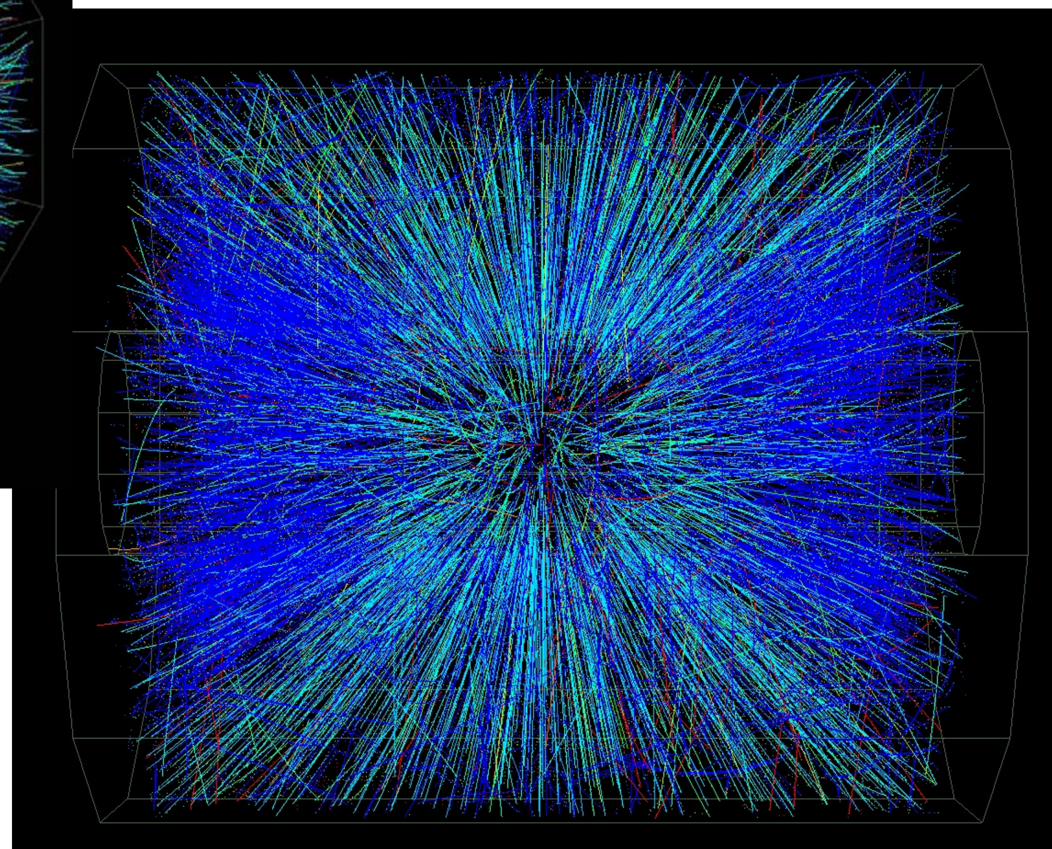
The amazing thing is that sometimes this is possible

Huge growth in Luminosity at RHIC



A Central Event

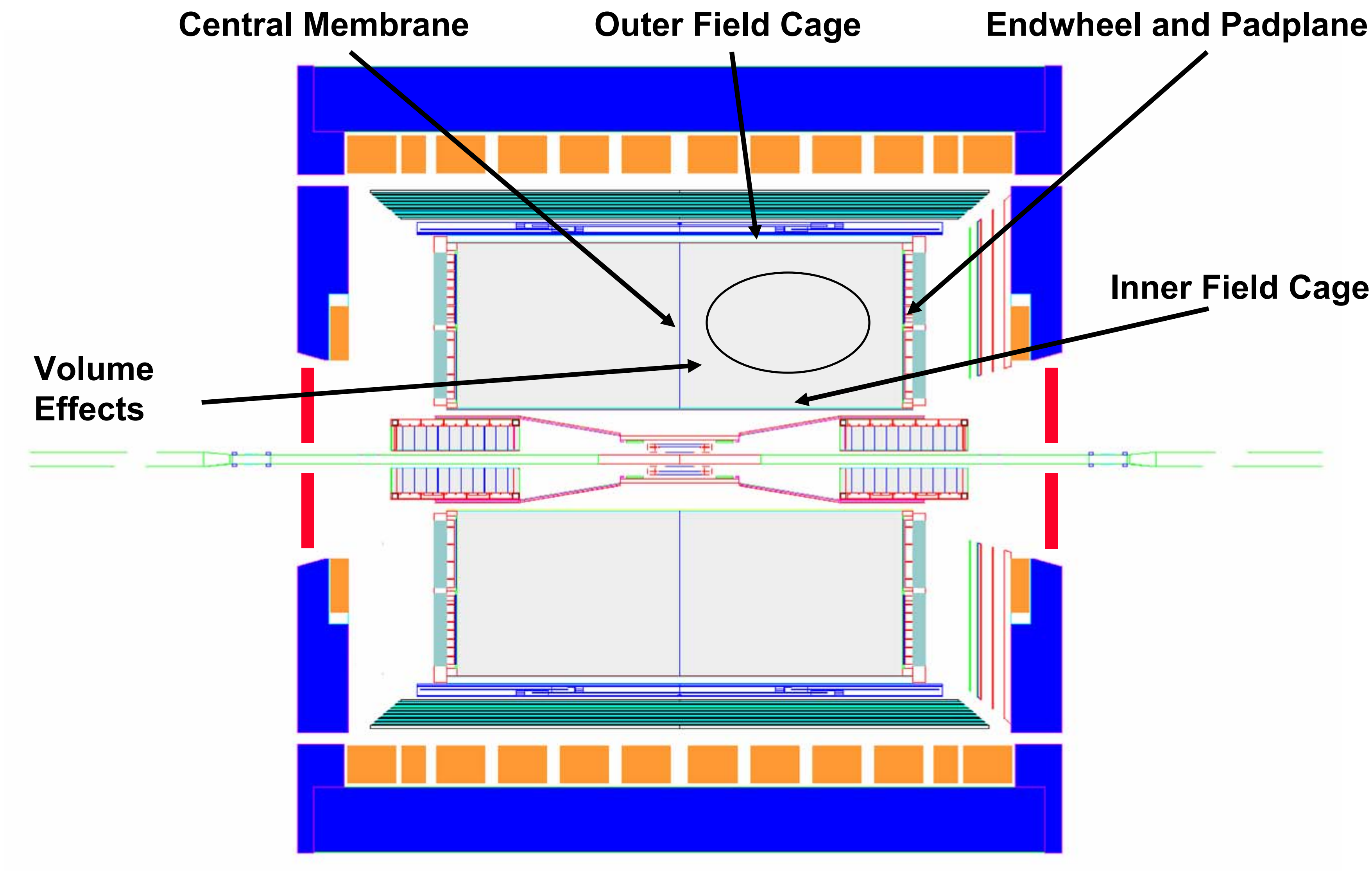
Typically 1000 to 2000 tracks per event into the TPC



Driven by our success …

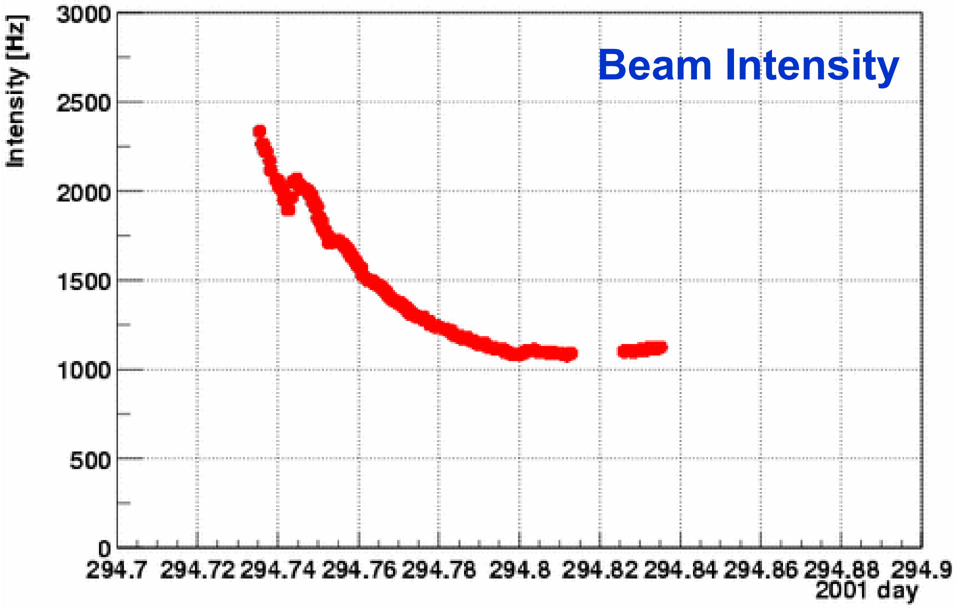
Dynamic E field distortions

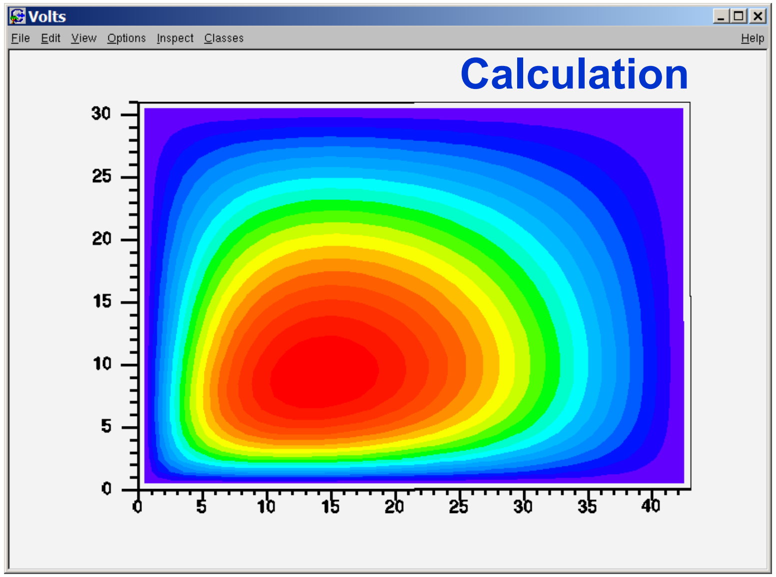
There Are Many Possible Distortions



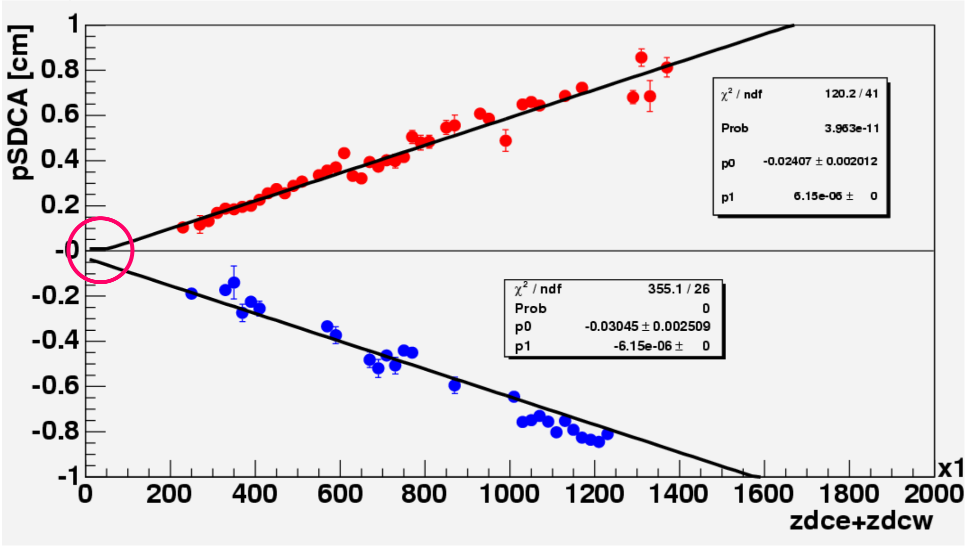
Spacecharge is one of them

Space Charge – Monitor, Calculate & Correct

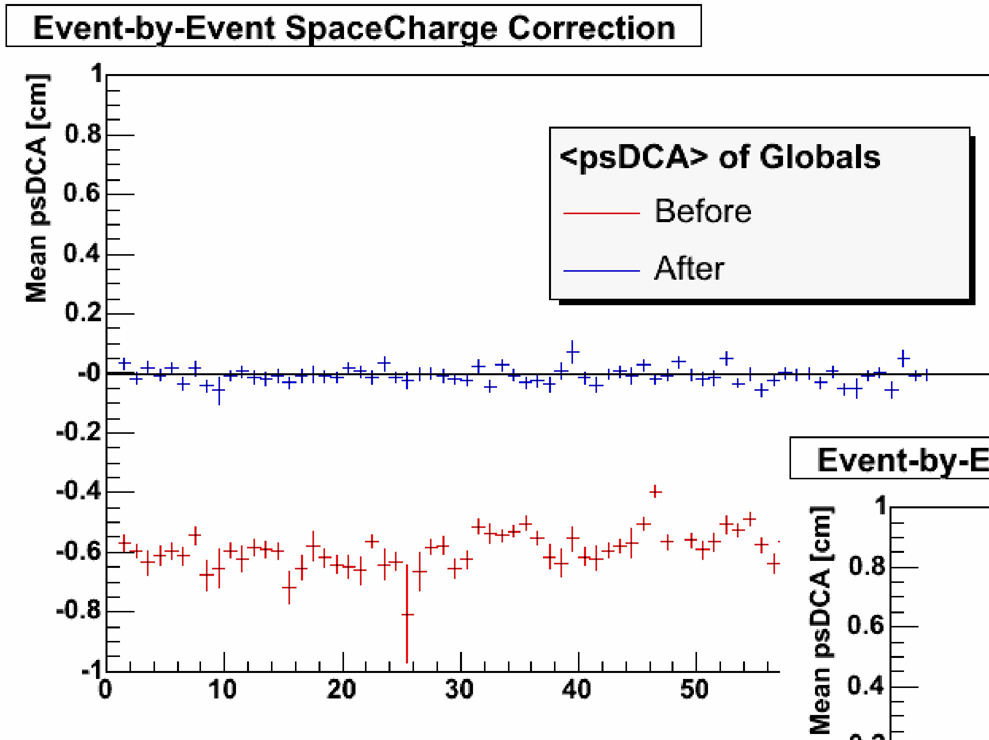


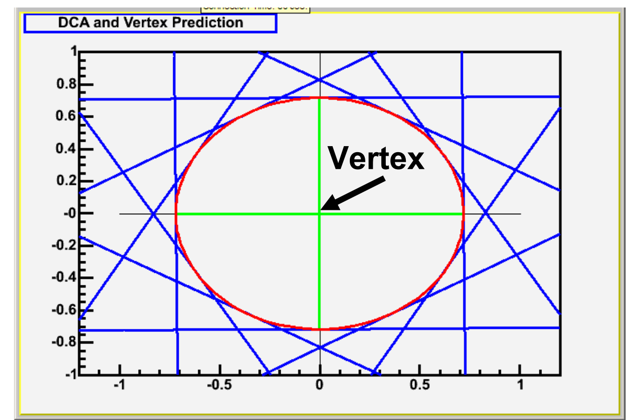


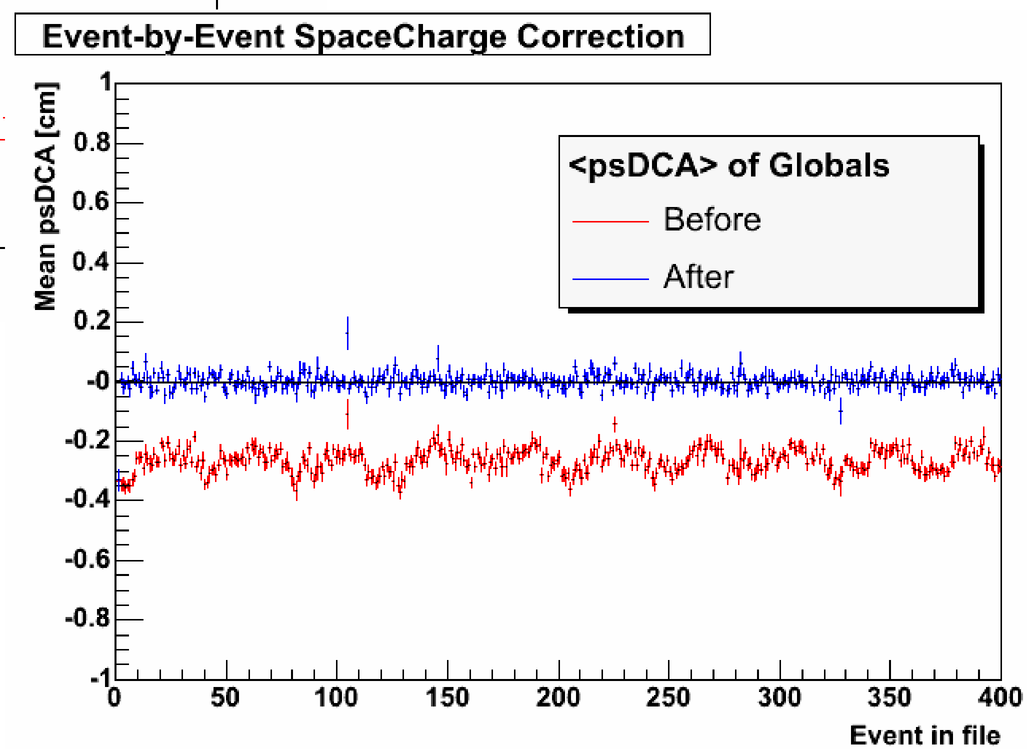
- Normal events leave a $1/R^2$ distribution of charge in the TPC volume
- Background seems to have a similar shape … or is low
- Model and calculate effects



A new method … now EbyE

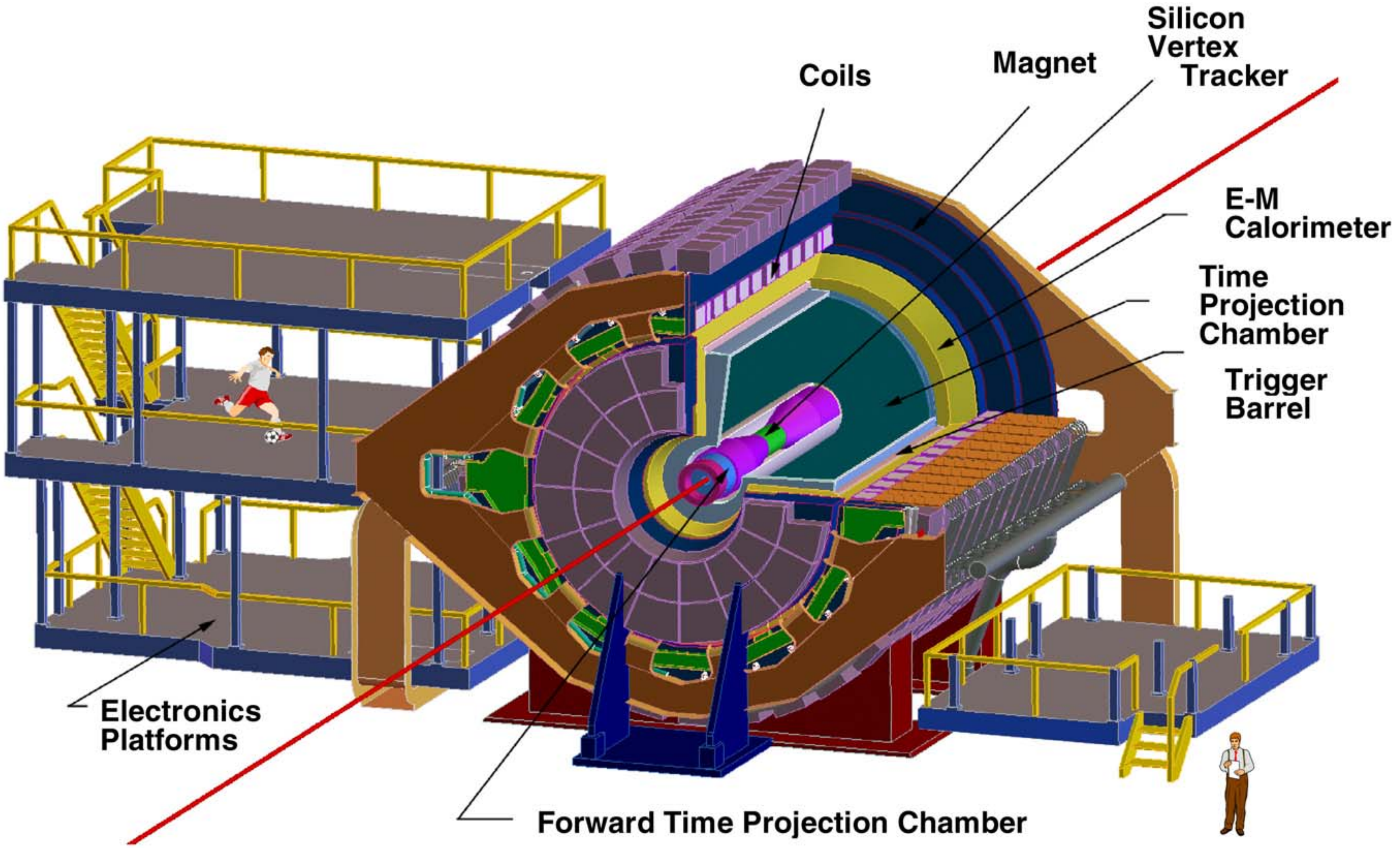






Very impressive work from Gene Van Buren

The STAR Detector at RHIC

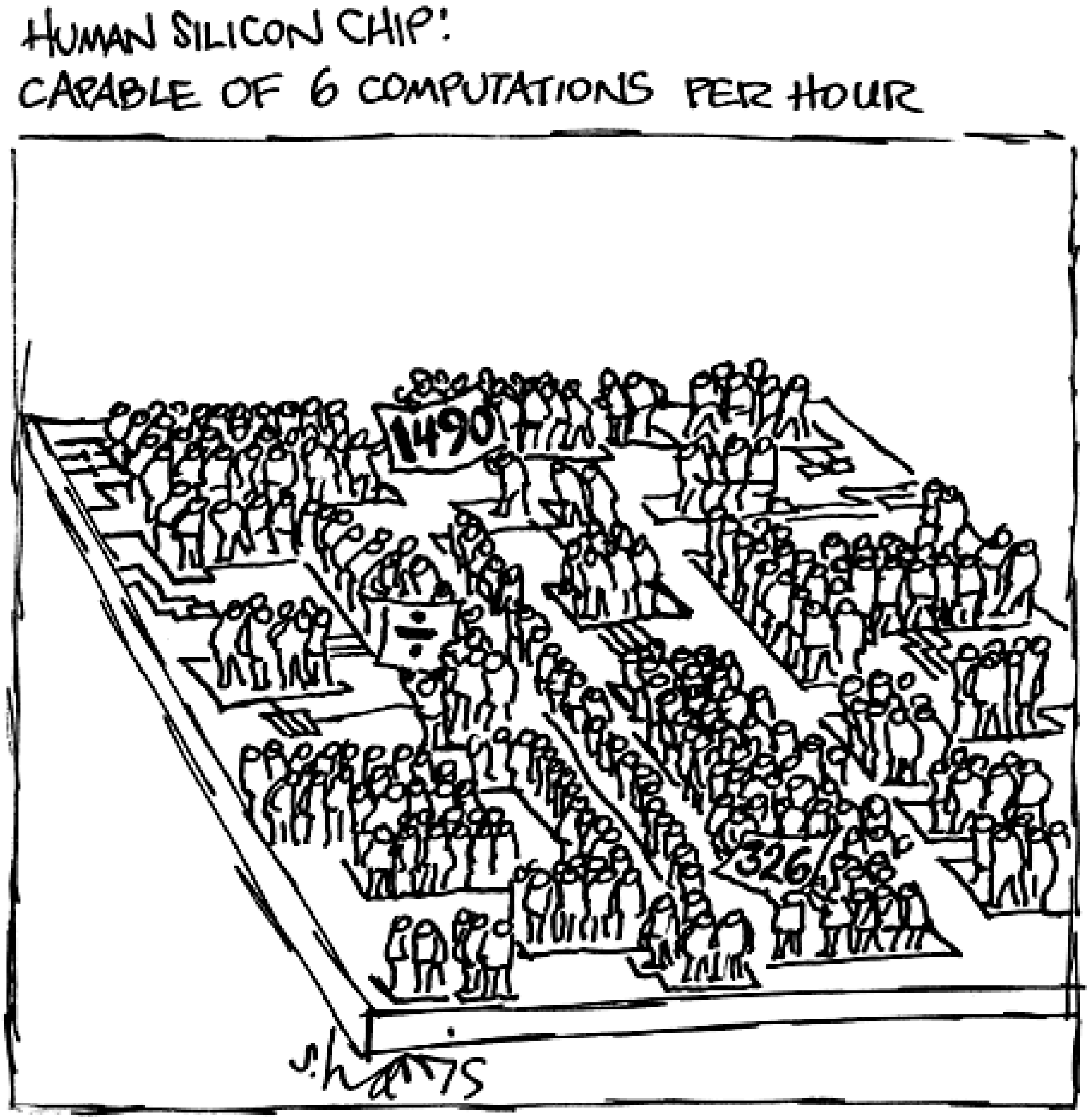


What have we learned? (not so) Subtle Messages

Thoughts for the future regarding TPCs

- **Calibrate online**
  - STAR does 1.2 passes over the data *and* people are serious about publishing the data 6 months after it is taken.
  - Data volume are so large that you can no longer do 3 data passes nor even 2.
  - This is a significant challenge. You can't simply anticipate a calibration need, you have to write the code and make it work before the run starts … and do it with ~zero statistics.
- **We will always exceed our design specifications**
  - Accelerator performance will increase each year (luminosity, stability, control)
  - DAQ is always "tape limited". This bottle neck is only constrained by Moore's law and so expect to increase your DAQ rate each year
- **Silicon & Spare parts – no inventory on the shelf anymore**
  - Electronics gets better and better
  - But it is often only available for a small window in time
- **GEM detectors will be available soon**
  - They offer fantastic resolution, but the real issue may be how to stitch them together to make a large detector

Silicon is a Designer Technology



- CMOS and other processes are cheap and even Graduate Students can design new chips
- Everything has an FPGA
  - Fewer accesses to the detector are required
- Moore's law applies
  - Radiation damage may limit Moore's law induced migration of intelligence onto the detector
- Cable counts are decreasing even as we add more channels
  - More intelligence is moving onto the detector

Trends

"The databank would be glad to give you information about yourself, but unfortunately the databank is not convinced that you are really you."

- **Bandwidth limits DAQ at the output stage**
  - **Bandwidth does not follow Moores law**
  - **nor does tape storage**
- **But more intelligence at the detector means we can do track finding, locally, not in a farm.**
  - **Local track finding is a form of data compression**
- **Tape is expensive. In the era of petabytes … all data may go on disk**
- **Databases are convenient to store a huge amount of data … but they are slow and complex.**
  - **Google experience suggests storing huge files in memory**

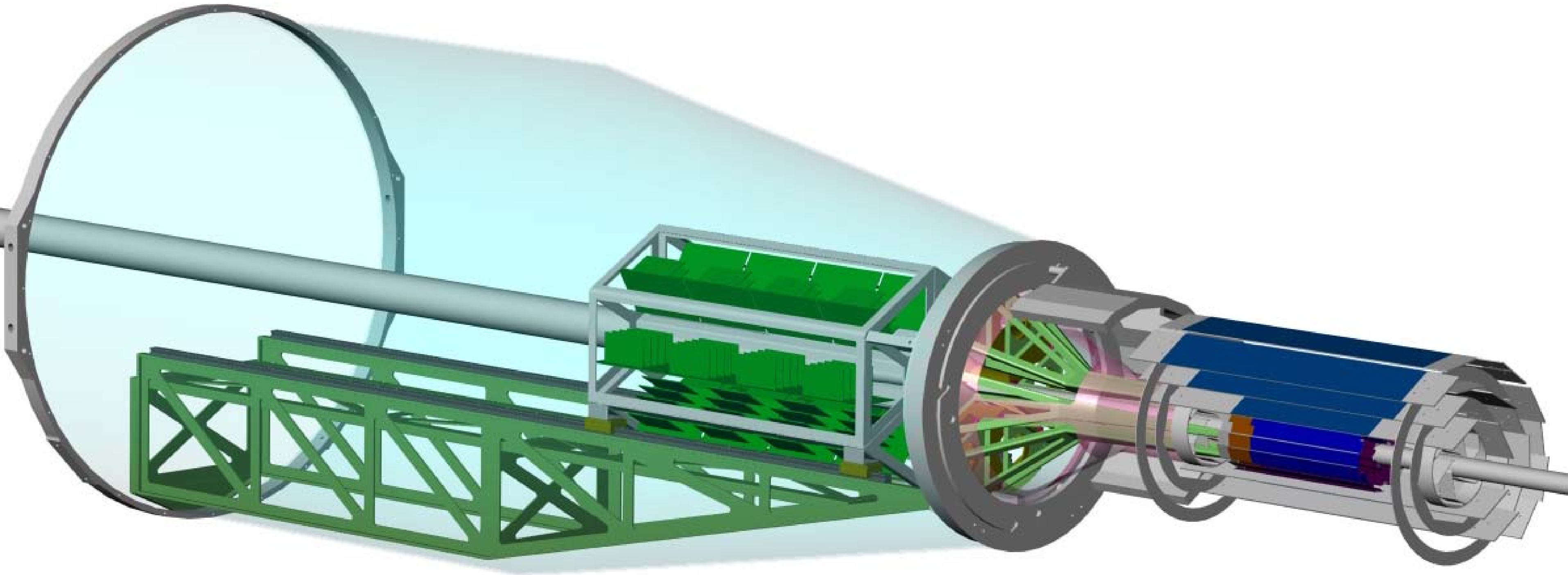
The End

Summary of Performance Achieved to date

- Features of the STAR TPC
  - 4 meters in diameter, 210 cm drift
  - No field wires in the anode planes
  - Pad readout, Low gain on anodes
  - Low drift field
  - Very compact FEE electronics
  - Analog Delay with SCA then onboard ADC
  - Data delivered via optic fiber
  - Uniform E and B fields
  - 'ExB' and most Electrostatic distortions correctable to the 100 μm level
- Position resolution
  - 500 μm in the real world with calibration errors
  - Space point resolution ~ 100 μm for select laser events, 250 - 350 μm for select tracks
  - Function of dip angle and crossing angle
- Good particle separation using dE/dx
  - 6.5% dE/dx resolution @ 100 cm
  - π-proton separation : > 1 GeV/c
- 2-Track resolution
  - 2.5 cm for HBT pairs
  - 1.5 cm for laser tracks
  - limited by 3 pad response function and desire for fast algorithms
- Momentum resolution
  - 2% minimum at 0.25 Tesla (half field)
  - for p_T > 1.5 GeV in 0.25 T field
    - $dk/k = 0.016\, p_T + 0.012$ (central)
    - $dk/k = 0.011\, p_T + 0.013$ (peripheral)
    - 2.9% ⇨ 3.3% peripheral/central @ 1.5 GeV

STAR performance is excellent and meets essentially all design specifications!

HFT Conceptual Mechanical Design



Selected HFT Parameters and Specifications

Min I efficiency	98%
Accidental rate	< 100 /cm^2
Position resolution	< 10 μm
Number of pixels	98,304,00
Pixel dimension	30 μm $\times$ 30 μm
Detector chip active area	19.2 mm $\times$ 19.2 mm
Detector chip pixel array	640 $\times$ 640
Number of ladders	24
Ladder active area	192 mm $\times$ 19.2 mm
Number of barrels	2
Inner barrel (6 ladders)	r = 1.5 cm
Outer barrel (18 ladders)	r = 4.5 cm

Selected HFT Parameters and Specifications

Frame read time	4 ms
Pixel read rate, after zero suppression	63 MHz
Ladder % X_0	0.26%
Cooling	Room temperature air, 1 m/s
Power	100 mW/cm^2