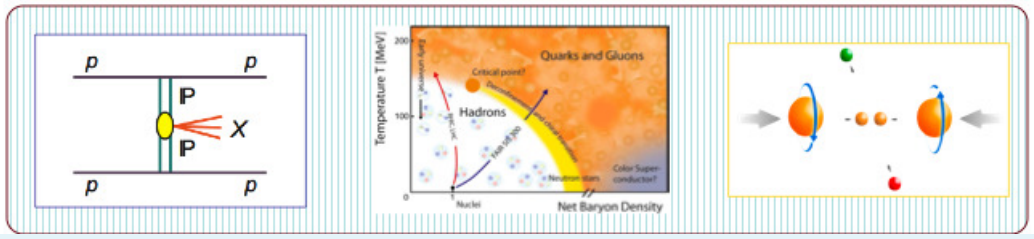


The Future of Heavy Flavor Measurements Using Silicon Vertex Detectors in PHENIX

"Physics Capabilities and Detector Technology"

Rachid Nouicer

Brookhaven National Laboratory
for the PHENIX Collaboration

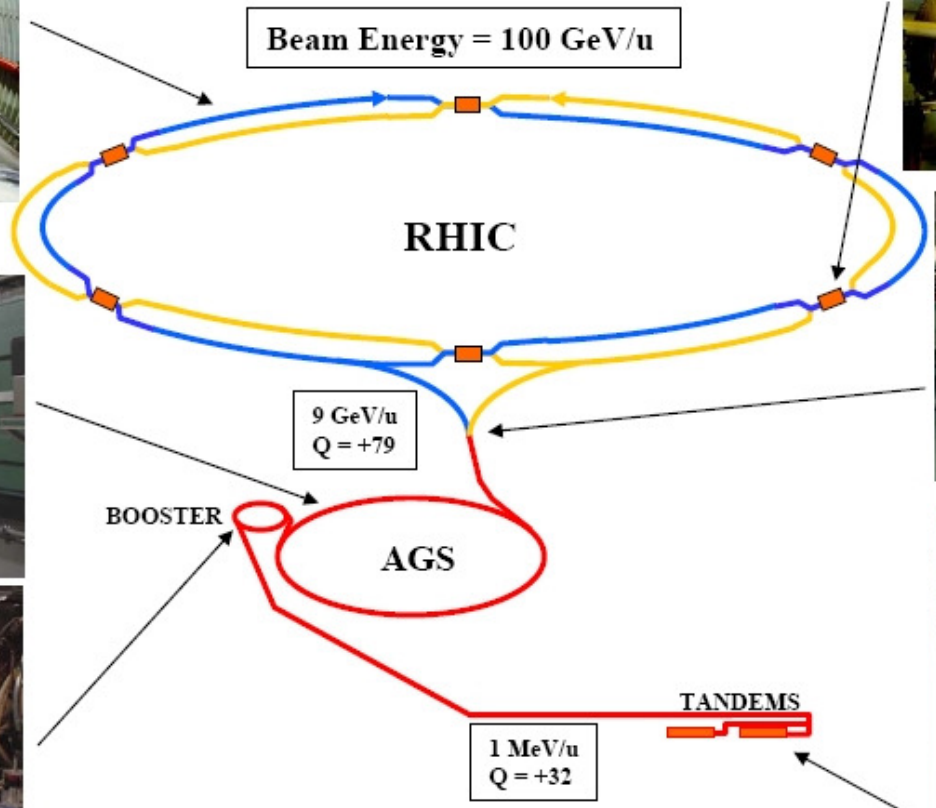
1. Physics Motivation for the PHENIX Upgrade
2. Silicon Vertex Tracker Concept and Simulations
3. Performance Results using 120 GeV Proton Beam
4. Status and Schedule

XVII International Workshop on Deep-Inelastic Scattering and Related Subjects
DIS 2009, 26-30 April 2009, Madrid

Relativistic Heavy Ion Collider (RHIC)

What have we done at RHIC so far?

- 2 concentric rings of 1740 superconducting magnets
- 3.8 km circumference



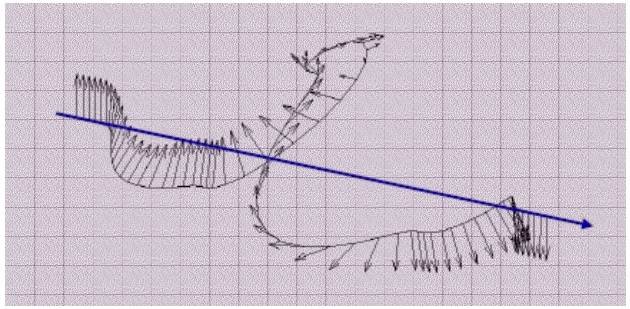
Relativistic Heavy Ion Collider (RHIC)

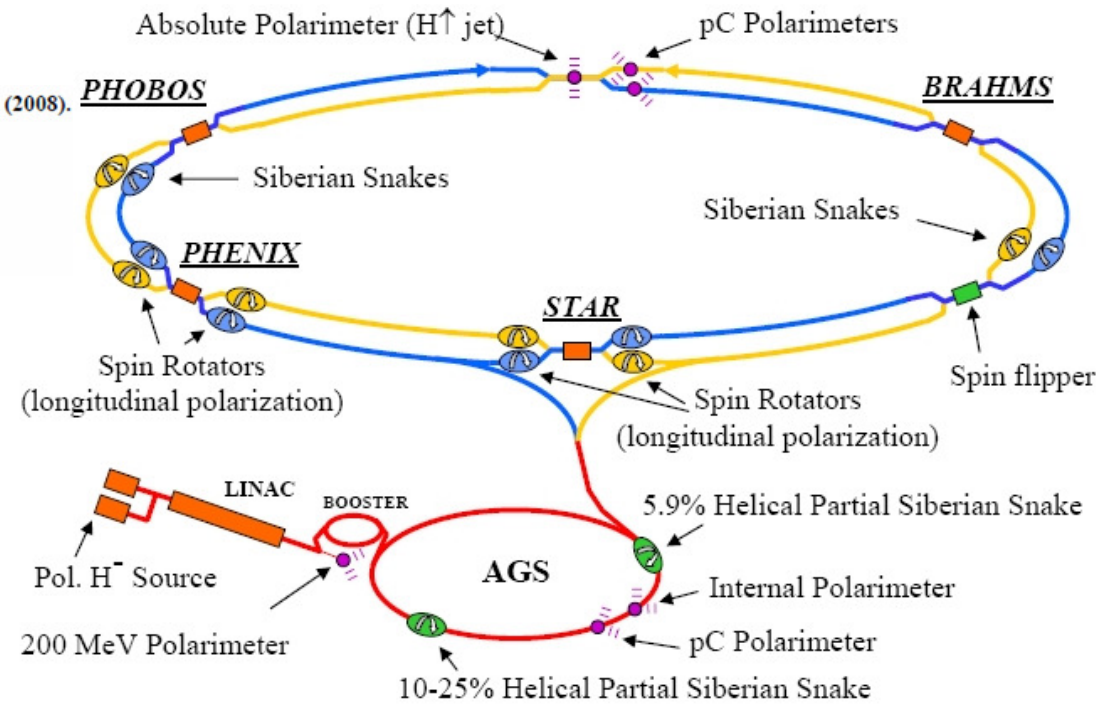
Locations of Siberian Snakes for Polarization

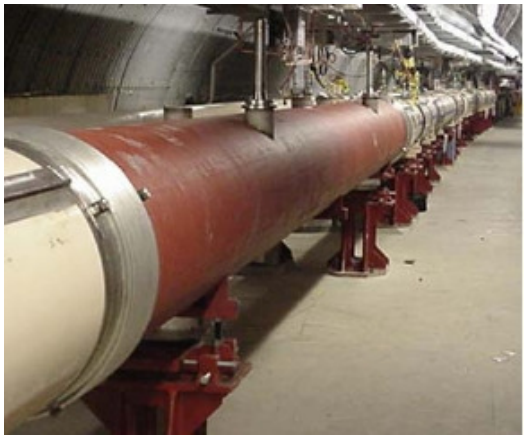
RHIC-II vs. RHIC

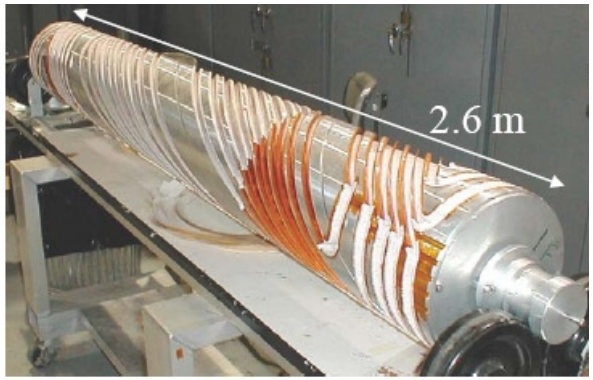
Summary of luminosities used in these rate calculations for RHIC-II and RHIC-I (2008).

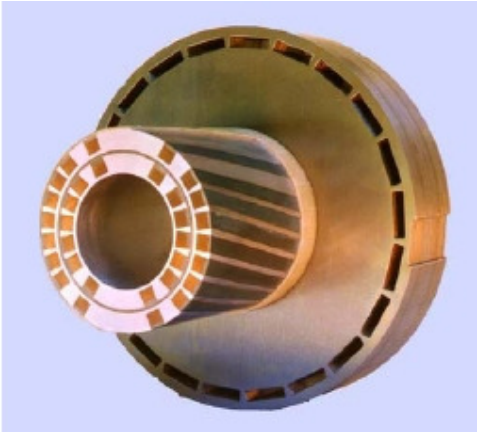
collision	RHIC-II	RHIC-I (2008)
Pp	33 pb^{-1}/wk	9.9 pb^{-1}/wk
dAu	62 nb^{-1}/wk	2.8 nb^{-1}/wk
AuAu	2.5 nb^{-1}/wk	0.327 nb^{-1}/wk



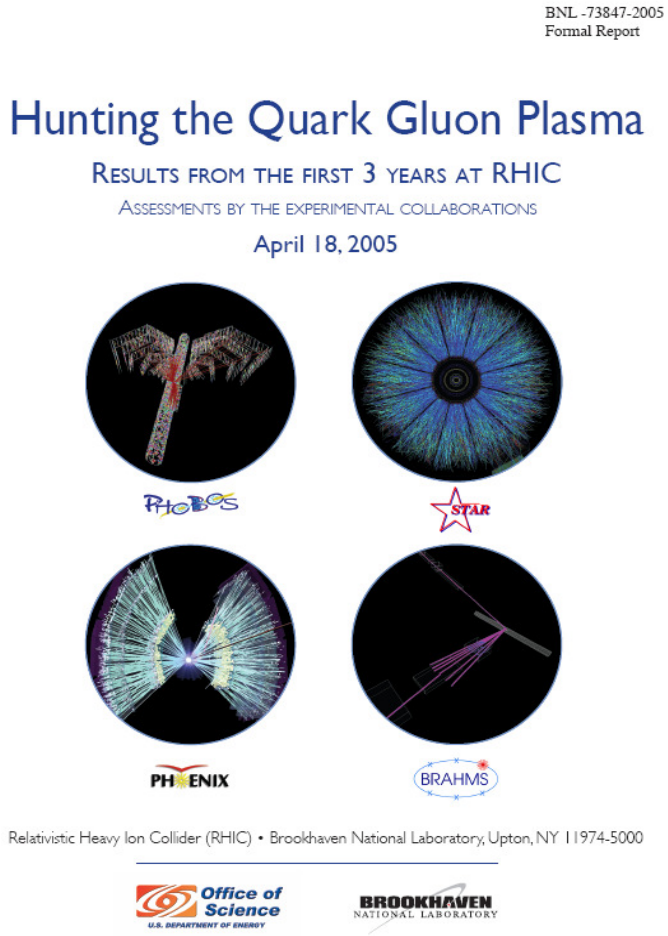








Motivations for the Upgrade: Discoveries



The Collaboration of the four experiments: PHENIX, BRAHAMS, PHOBOS and STAR at RHIC

CONCLUDE

that **highly interacting medium**

have been discovered in

most central Au+Au collisions

at 200 GeV

BRAHMS: I. Arsene et al., Nucl. Phys. A757, (2005) 1
PHOBOS: B. B. Back et al., Nucl. Phys. A757, (2005) 28
STAR: J. Adams et al., Nucl. Phys. A757, (2005) 102
PHENIX: K. Adcox et al., Nucl. Phys. A757, (2005) 184

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

Motivations for the Upgrade: Discoveries

In the Press

Science — Iran Daily — April 20, 2005 — 4

Early Universe Liquid-Like

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence, AP reported.

By revising physicists' concept of the early universe, the new discovery offers opportunities to better learn how subatomic particles interact at the most fundamental level. It may also reveal intriguing parallels between gravity and the force that holds atomic nuclei together, physicists said Monday at a Tampa, Fla., meeting of the American Physical Society.

"There are a lot of exciting questions," said Sam Aronson, associate director for high energy and nuclear physics at Brookhaven National Laboratory, which is located on Long Island about 65 miles east of New York city.

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider, known as RHIC, repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside atomic nuclei, were thought to have flown around like BBs in a blender.

But by reproducing the conditions of the early universe, RHIC has shown that unconstrained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

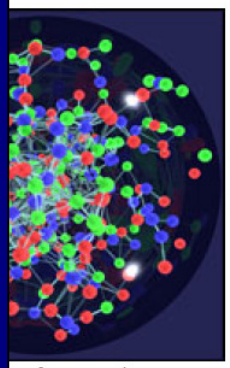
When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that affects a fluid's ability to flow and the resistance to objects trying to swim through it. Honey has a high viscosity; water's viscosity is low. A perfect liquid has no viscosity at all, which is impossible in reality but useful for theoretical discussions.

Theoretical physicists have recently proposed that material swallowed by black holes might also have extremely low viscosity. That notion, based on a branch of mathematical physics known as string theory, has led some physicists to hypothesize that there might be a deeper connection between what happens in a black hole and what goes on when two gold nuclei collide at RHIC.

New State o … e'

Physicists … Laboratory announ… created what appe… out of the building … and gluons. The re… findings--which co… composition of the … big bang--today in … American Physica…

There are four coll… PHENIX, PHOBO… Brookhaven's Rela… (RHIC). All of them … interacting beams … another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."



…s of matter that is more strongly interacting than predicted

Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

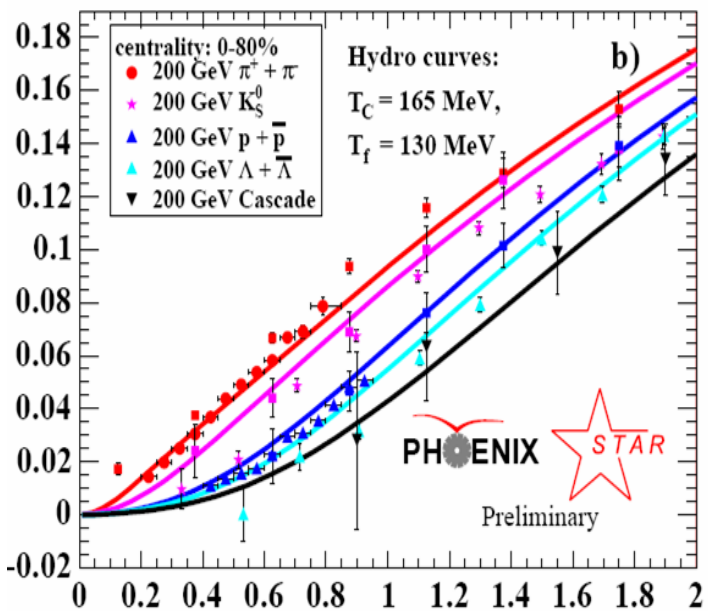
The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

> When physicist talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity

Motivations for the Upgrade: Discoveries

Elliptic Flow of Hadrons

$v_2(p_T,m)$

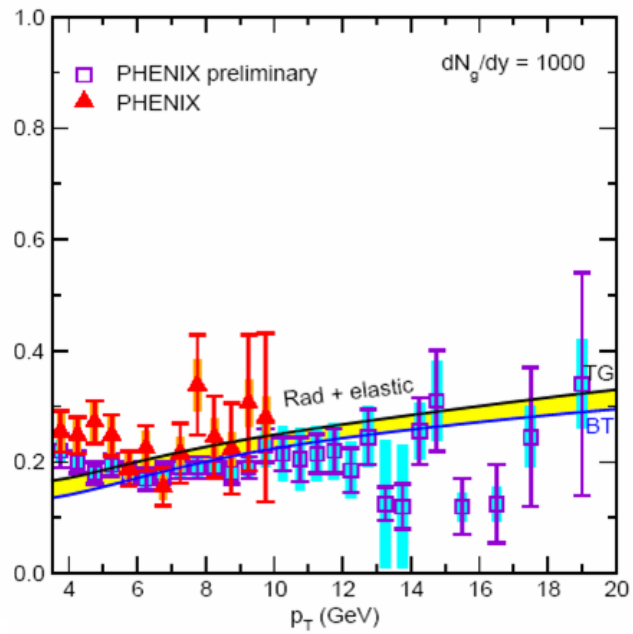


Collective Expansion:

ideal hydrodynamics (QGP equation of state)

Suppression of High-Energy Pions

$R_{AA}(p_T)=(spec)_{AA}/(spec)_{pp}$

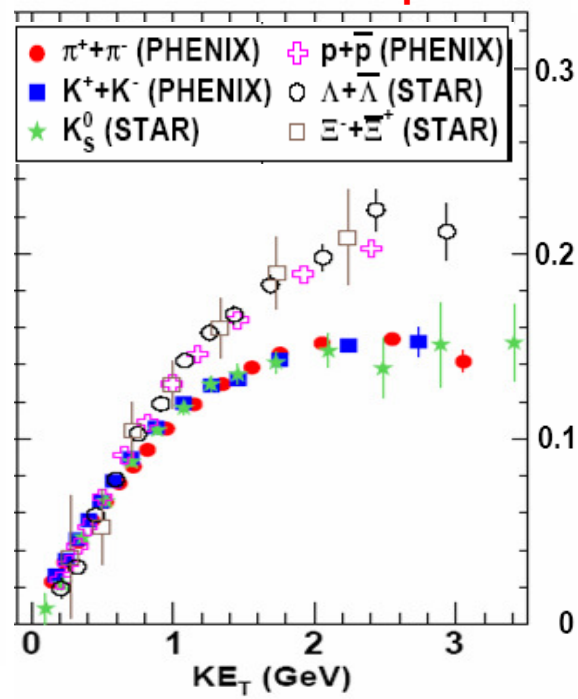


Quark Energy-Loss:

perturbative QCD (gluon radiation)

Baryon-Meson Separation

$v_2(KE_T,n_q)$



Hadronization:

quark coalescence

rapid thermalization, "perfect liquid" ⇒ strongly-interacting QGP

Motivations for the Upgrade: Spin Program

- Deep-Inelastic Scattering data indicate that only a small fraction of the spin of the proton is carried by the quarks and anti-quarks

$$\text{EMC:} \quad \Delta\Sigma = \int_0^1 dx \sum_i (\Delta q_i(x) + \Delta \bar{q}_i(x)) = 0.31 \pm 0.04$$

The Spin Structure of the Proton is:

$$\boxed{J_z^p = \frac{1}{2}\Delta\Sigma + \Delta G + L_z = \frac{1}{2}}$$

contribution of quarks and anti-quarks

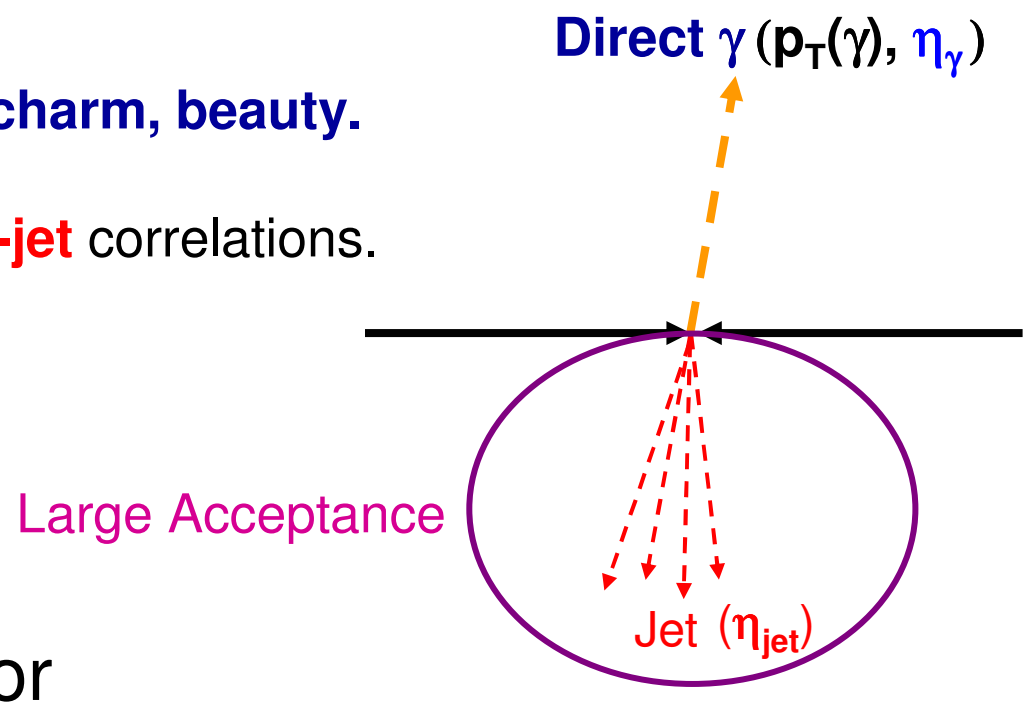
orbital angular momentum

polarized gluon distribution function

gluon contribution to the proton spin: $\Delta G = \int_0^1 dx\, \Delta g(x)$

Motivations for the Upgrade: Spin Program

- Gluon spin structure of the nucleon
  - Gluon polarization **$\Delta G/G$** with **charm, beauty.**
  - **x dependence** of **$\Delta G/G$** with **γ-jet** correlations.



- Requirements for detector
  - Heavy flavor tagging and beauty and charm separation : **Good vertex resolution**
  - x reconstruction with recoil jet **($p_T(\gamma)$, η_g , η_{jet}) : Large solid angle coverage**

What Next?

- Detailed study of the properties of the prod matter
  - Does energy loss mechanism depend ark mass?
  - Does flow strength depend on mas k mass
  - ➔ Identify heavy flavors (charm tom)
  - How is the jet correlation mo n large solid angle?
  - Jet shape recoiled agains photon
  - ➔ Measure charged part n large solid angle

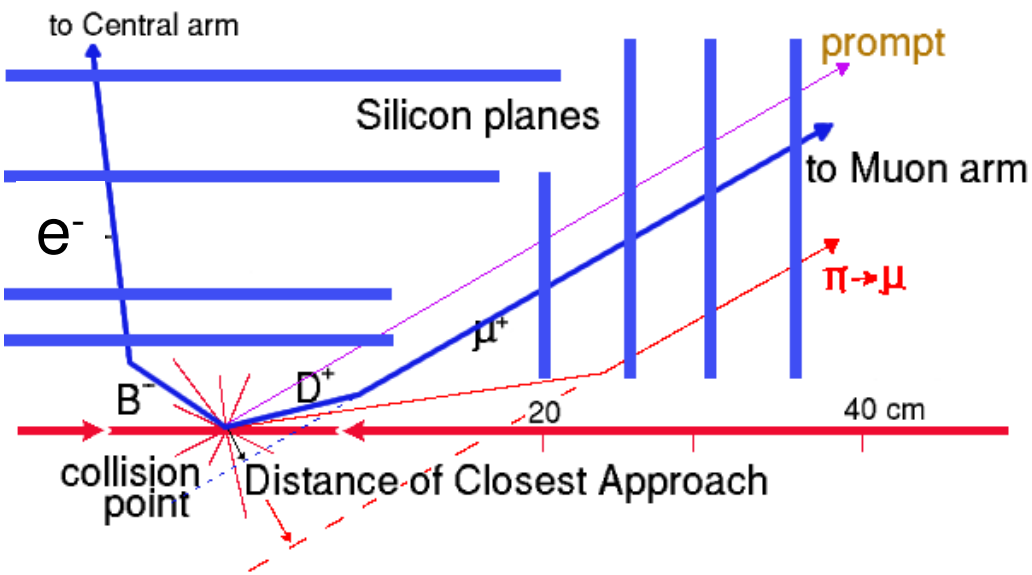
- Detailed study of nu structure
  - A_{LL} of charm a tom production
  - ➔ Identify ch nd bottom
  - Direct ph - jet measurement to constrain parton level kinem
  - ➔ Me e recoil jet in large solid angle

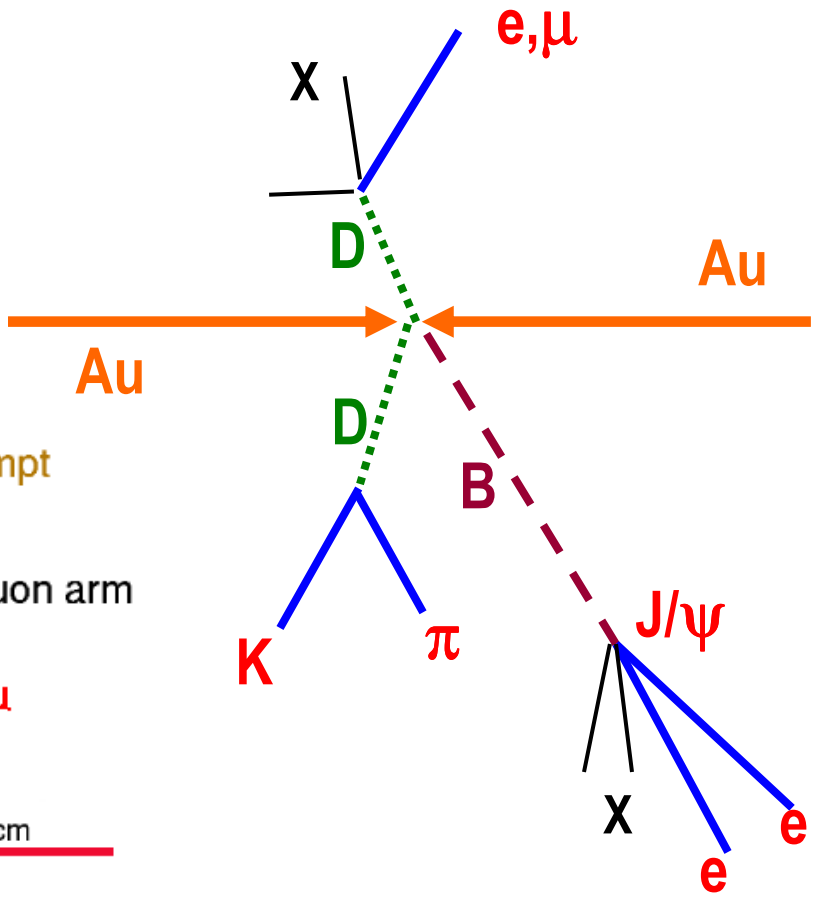
Key word = Heavy Flavor production

Why Heavy Flavor?

- Heavy flavor (c and b quarks) are produced in the early stages of heavy ion collision
- Experimentally easy to observe ($D \rightarrow K\pi$ decays or Semi-leptonic decays)

	Mass (GeV)	$c\tau$ (μm)
D^0	1865	125
$D^{\pm}$	1869	317
B^0	5270	464
$B^{\pm}$	5279	496





PHENIX Detector : Present

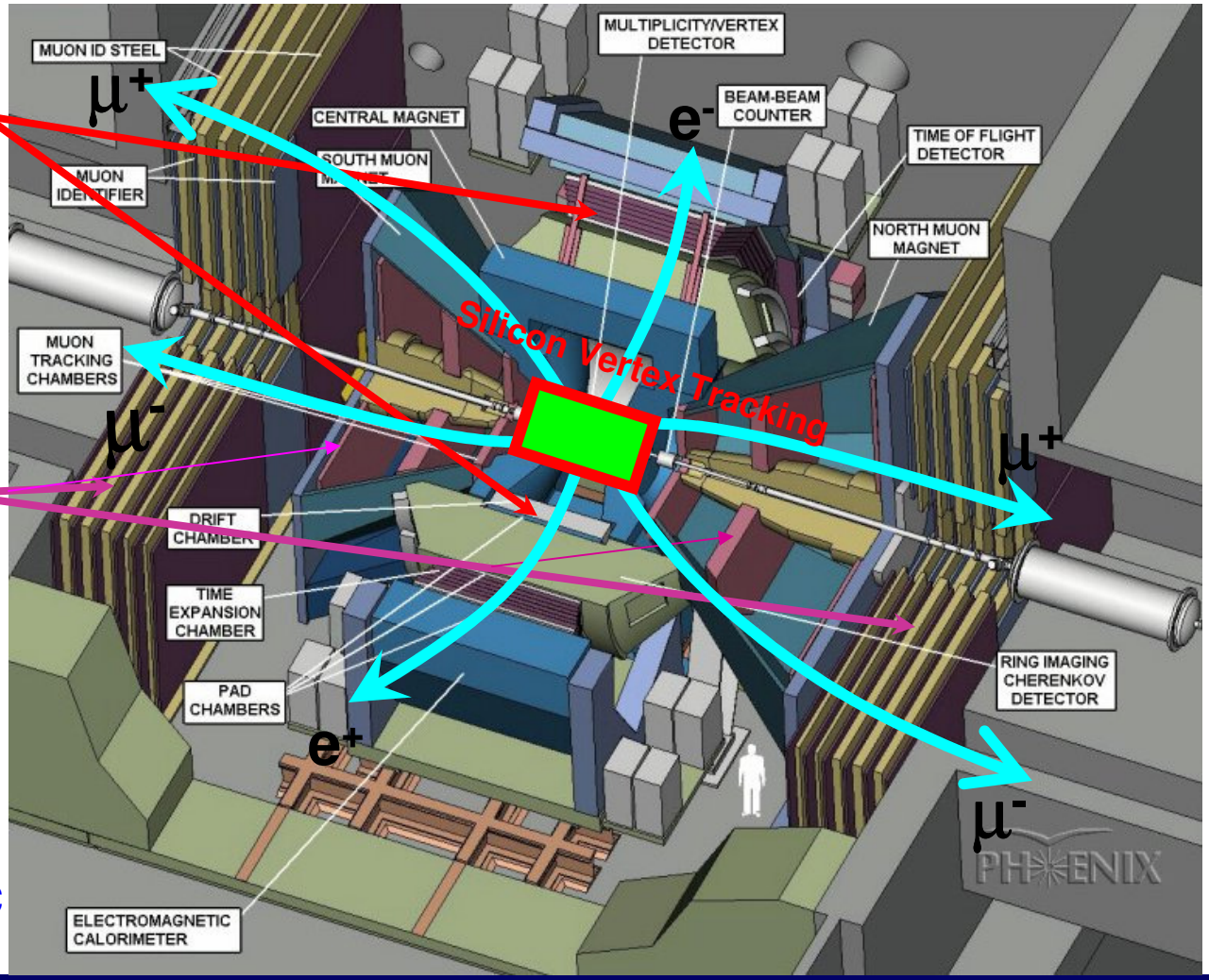
- **2 central spectrometers**

Photon, hadron, electron
$|\eta|<0.35$, $\Delta\phi=\pi$

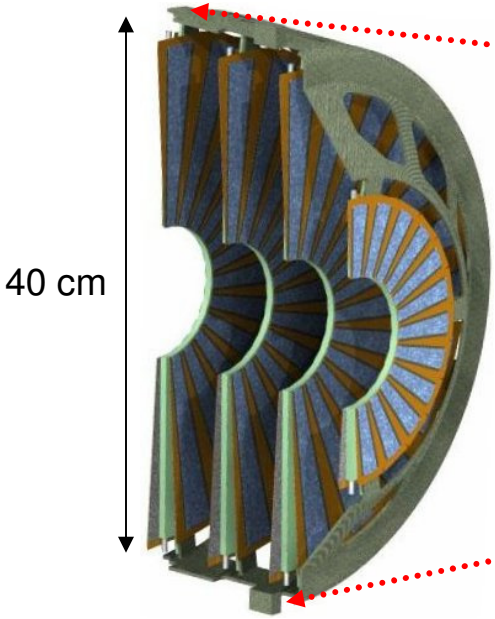
- **2 forward spectrometers**

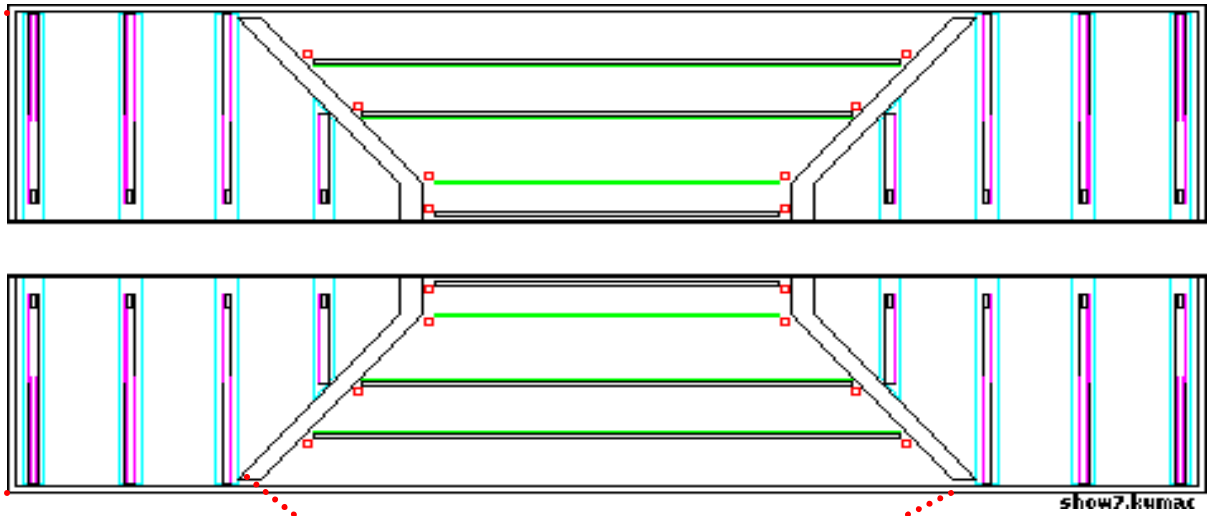
μ detection
$1.2<|\eta|<2.4$, 2π in ϕ

- **3 global detectors**
  - **Luminosity Monitoring (BBCN,BBCS)**
  - **Centrality (BBC vs ZDC)**
  - **Local polarimetery (ZDC & SMD)**

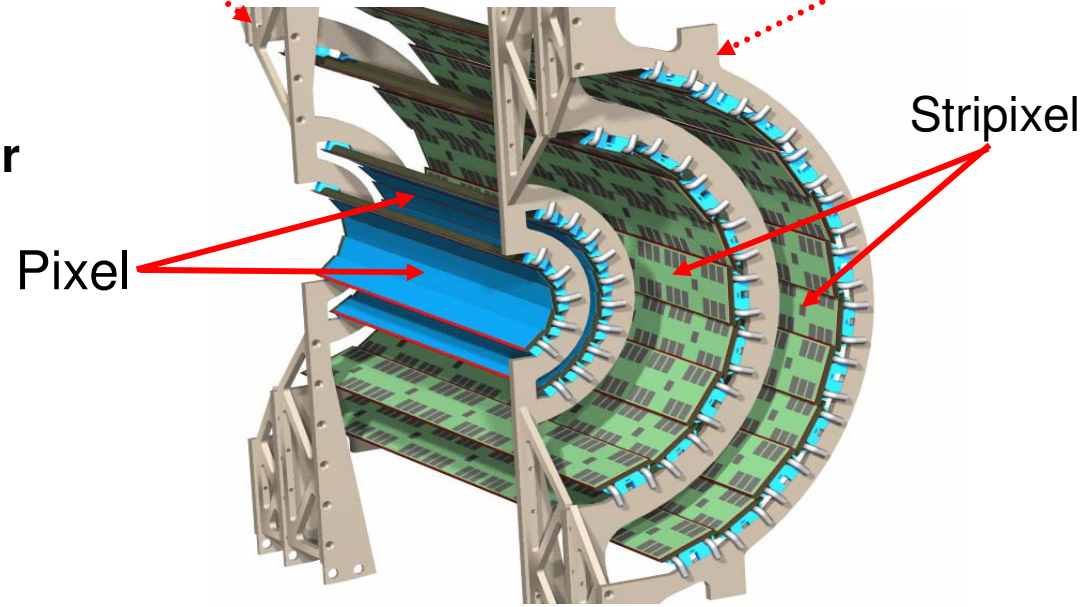


PHENIX Silicon Vertex Tracking Upgrades



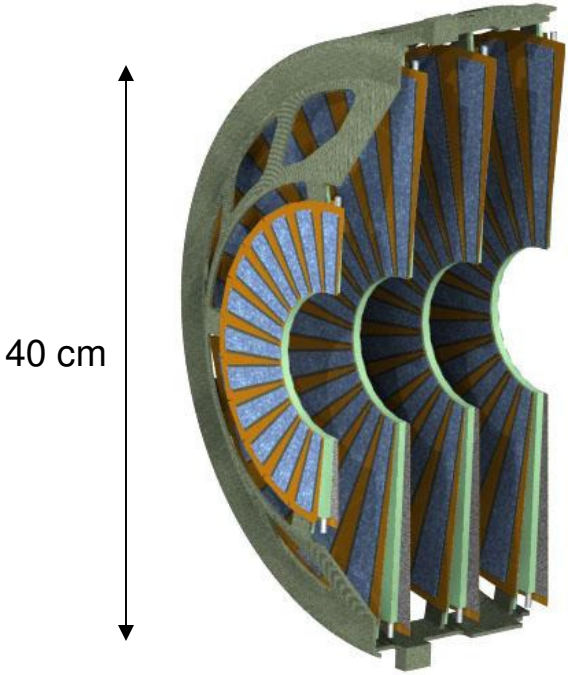


FVTX:
Forward silicon VerTeX tracker

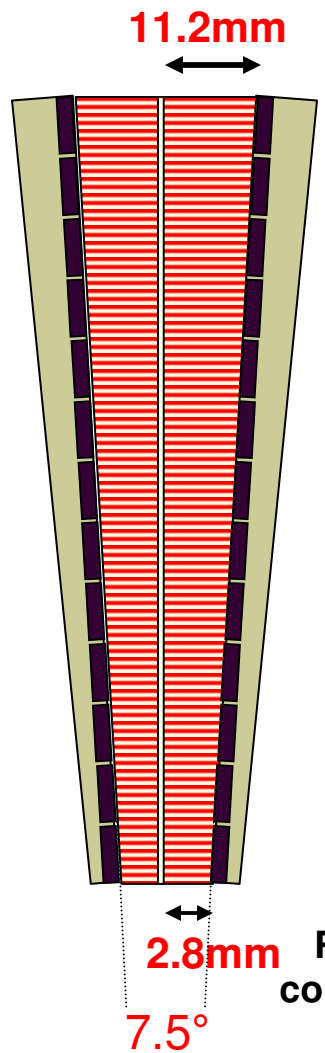


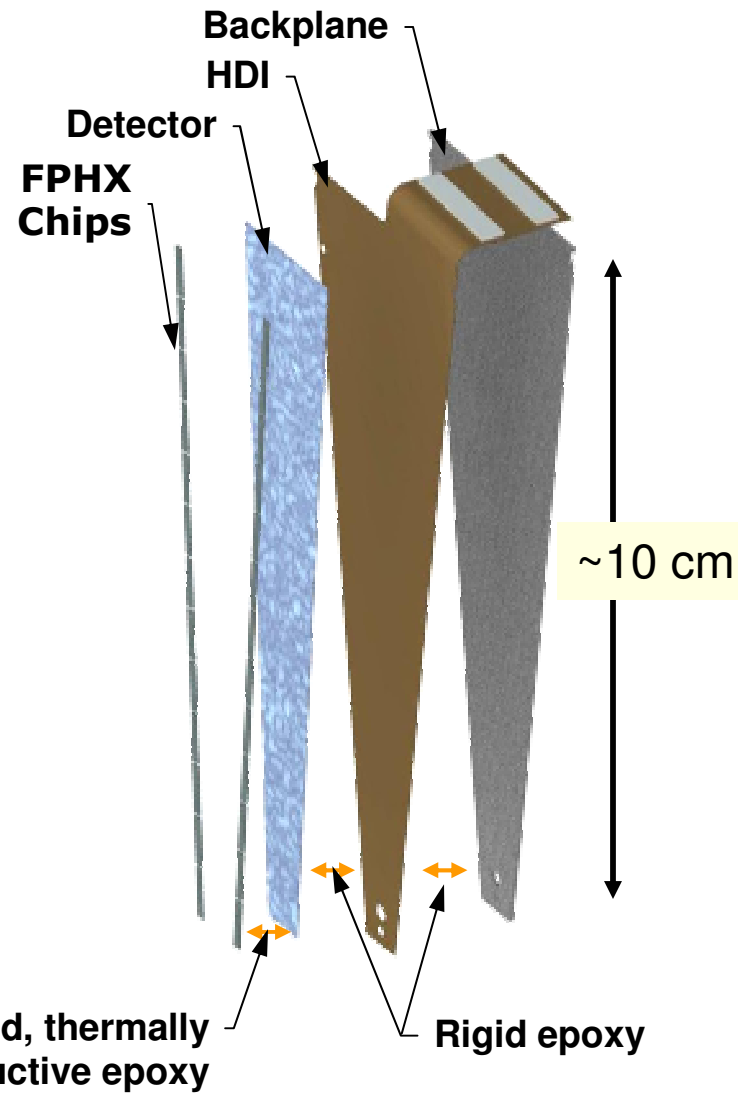
VTX: silicon VerTeX barrel tracker

FTX: Forward silicon VerTeX Detector

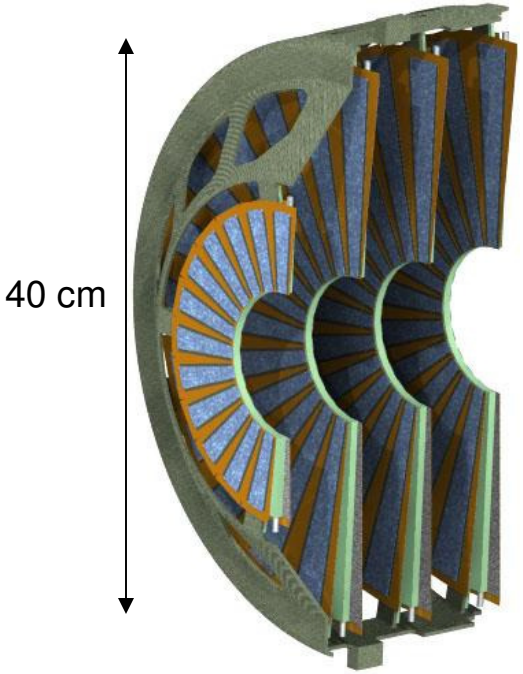


- 4 disks / side
- 48 wedges/disk
- 75 μm strips,
- 2.8-11.2 mm long
- 1664 strips/column
- 1.1M channels total
- Readout with FPHX chip





FTX: Forward silicon VerTeX Detector



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- 1.1M channels total
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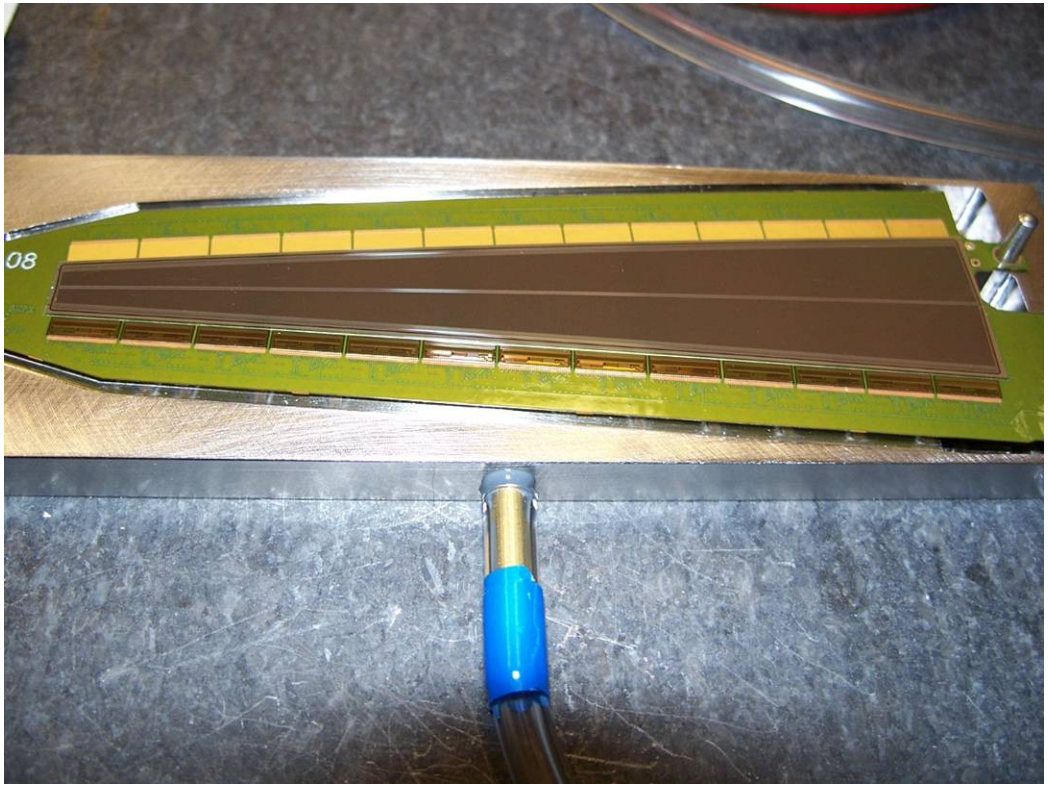


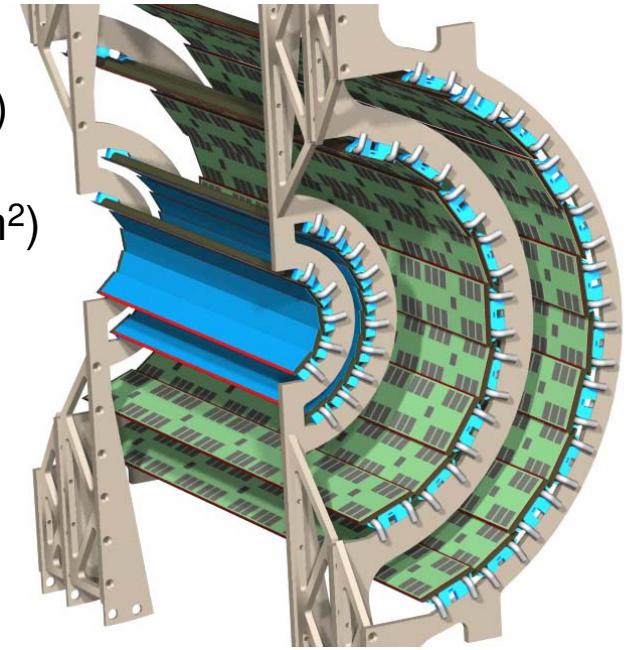
First prototype wedge and the tests are in progress (assembled at FNAL)

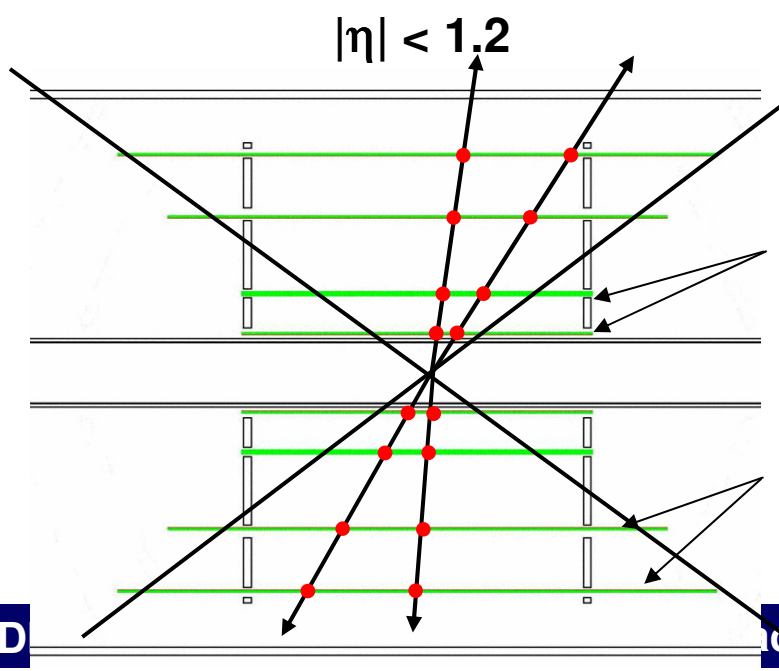
VTX: silicon VerTeX Barrel Tracker

- Four-Layer Barrel Detector
  - **Pixel Sensor** (Inner 2 Layers) (50 x 425 μm^2)
    required for high occupancy
  - **Strip Sensor** (Outer 2 Layers) (80 x 1000 μm^2)

- Good DCA resolution
  σ_{DCA}~ **50 μm**

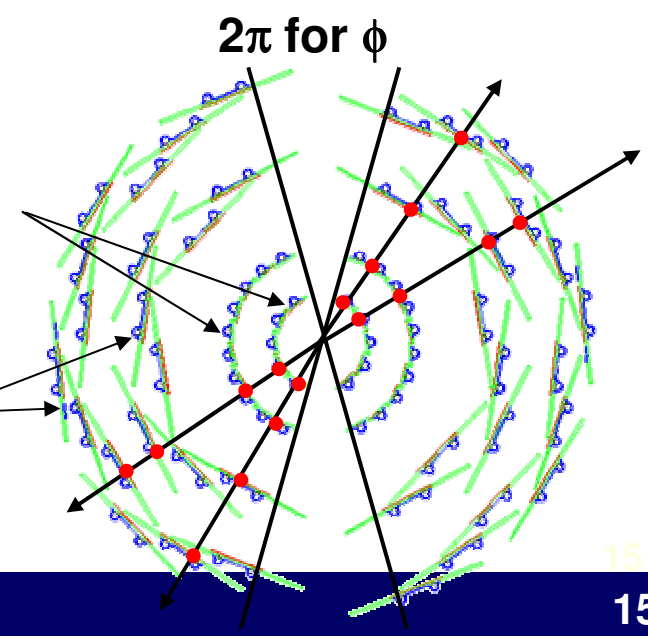
- Large Acceptance
  $|\eta| < 1.2$, 2π for ϕ





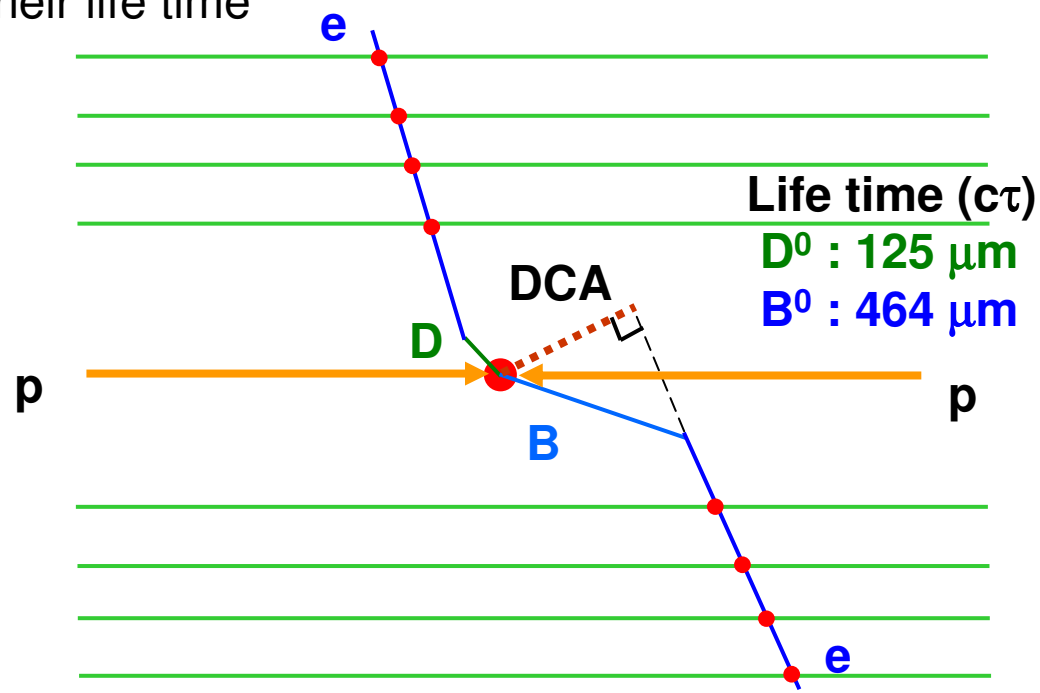
Pixel Layers
r=5.0cm Δz=±10cm
r=2.5cm Δz=±10cm

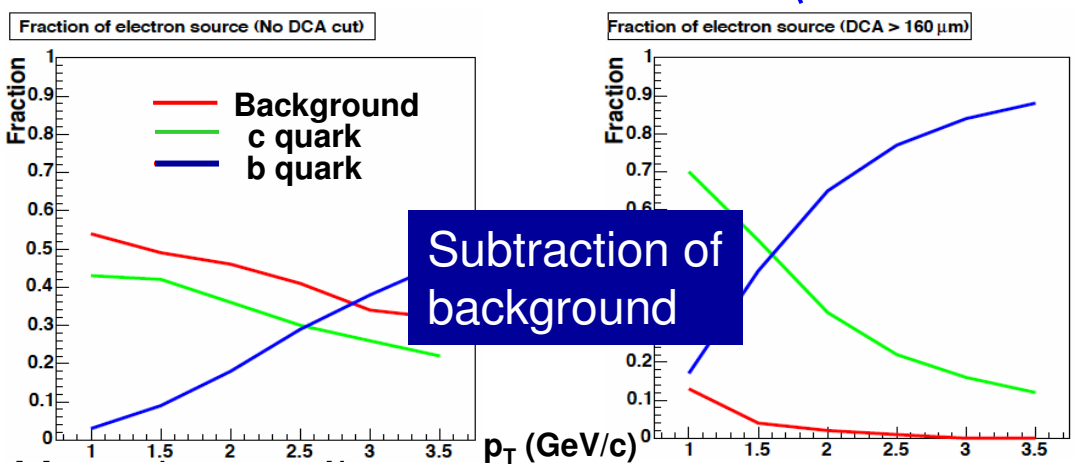
Strip Layers
r=10cm Δz=±16cm
r=14cm Δz=±19cm



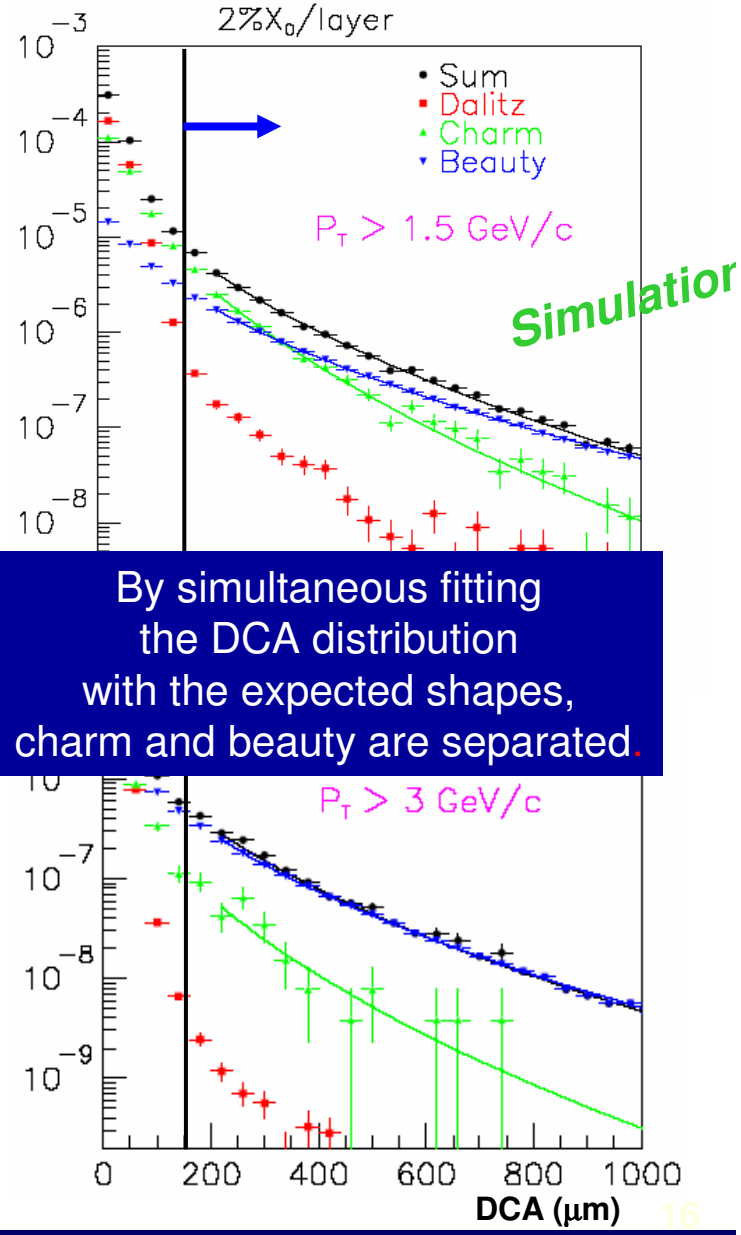
Advantage with VTX Detector (Heavy Flavor)

charm and beauty separation with difference of their life time



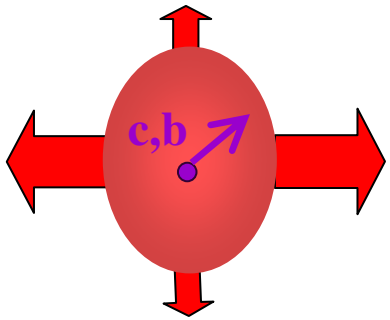


Subtraction of background



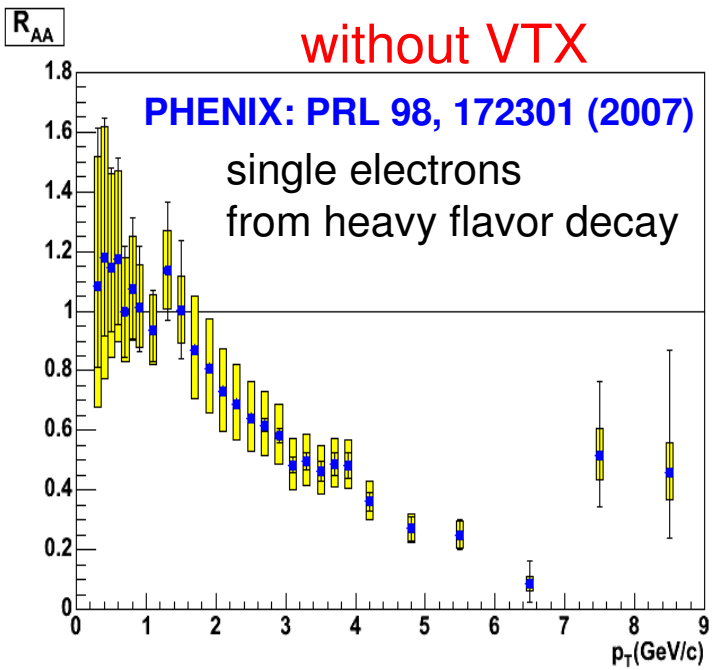
By simultaneous fitting the DCA distribution with the expected shapes, charm and beauty are separated.

Advantage with VTX Detector (Heavy Flavor)



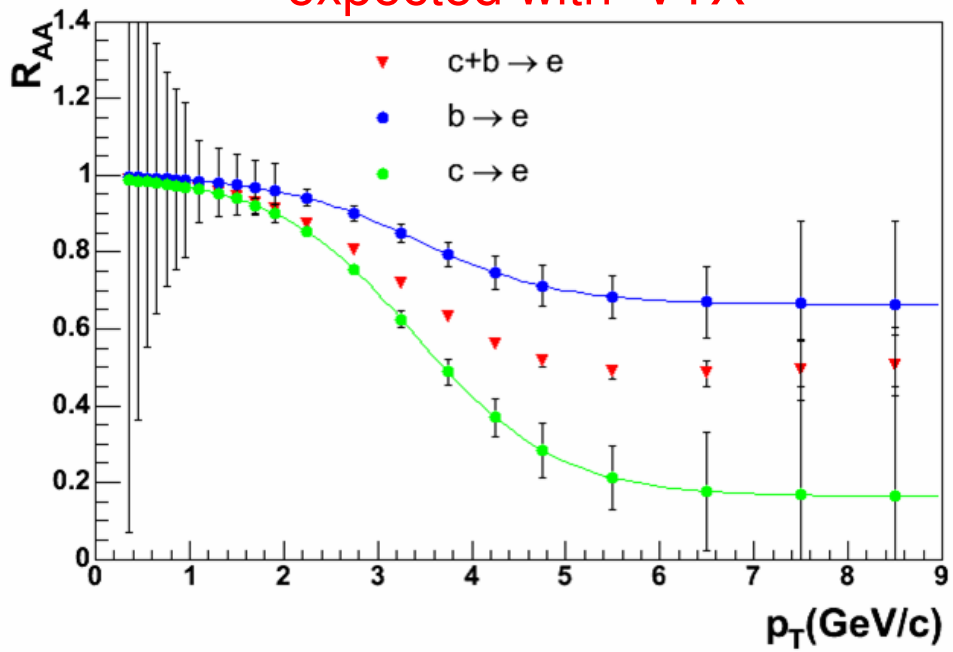
- **m_{charm}=1.5 GeV, m_{bottom}=5 GeV >> T ≈ 300 MeV**
- **sQGP:** energy loss, thermalization, **v_2**
- Experimental tool: electron spectra D,B → eX

Nuclear Modification Factor
without VTX



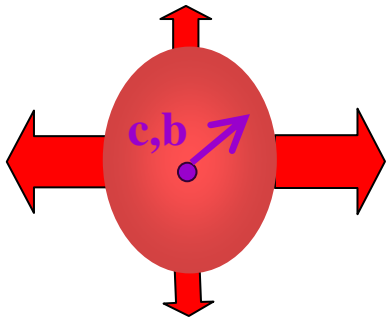
- factor 4-5 suppression!
- perturbative QCD?

Nuclear Modification Factor
expected with VTX



- VTX can separately measure R_{AA} of b→e and c→e

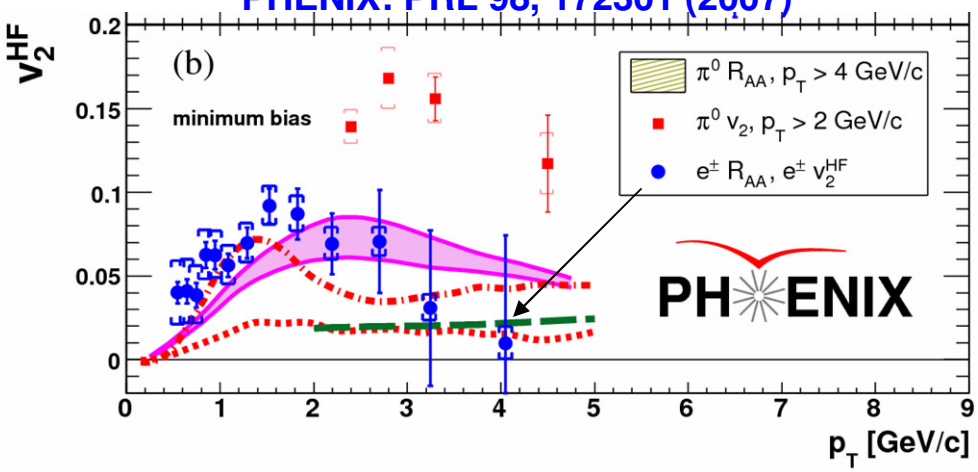
Advantage with VTX Detector (Heavy Flavor)



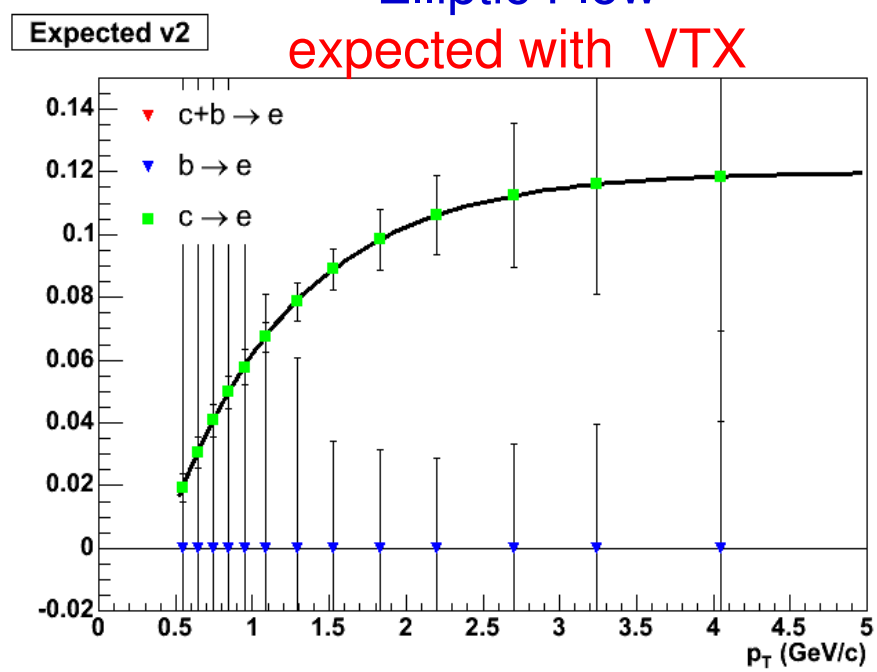
- **m_{charm}=1.5 GeV, m_{bottom}=5 GeV >> T ≈ 300 MeV**
- **sQGP:** energy loss, thermalization, **v_2**
- Experimental tool: electron spectra D,B → eX

Elliptic Flow
without VTX

PHENIX: PRL 98, 172301 (2007)



Elliptic Flow
expected with VTX

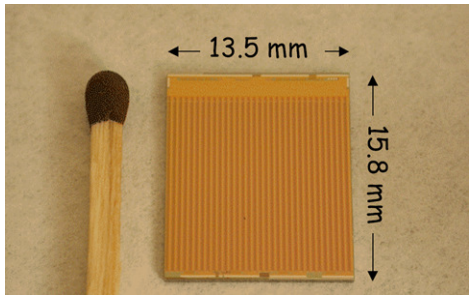


✪ substantial collectivity

VTX: Silicon Pixel Detector (barrels 1 &2)

ALICE1LHCb readout chip:

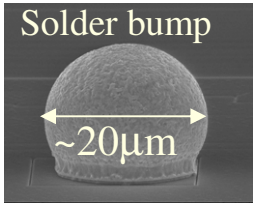
- Pixel: 50 µm (ϕ) x 425 µm (Z).
- Channels: 256 x 32.
- Output: binary, read-out in 25.6µs@10MHz.
- Radiation Hardness: ~ 30Mrad



active area
ΔrΦ
1.28 cm = 50mm x 256
Δz
1.36 cm = 425mm x 32

Sensor module:

- 4 ALICE1LHCb readout chips.
- Bump-bonded (VTT) to silicon sensor.
- Thickness: 200 µm
- Thickness: r/o chips 150 µm



Half-ladder (2 sensor modules+bus)

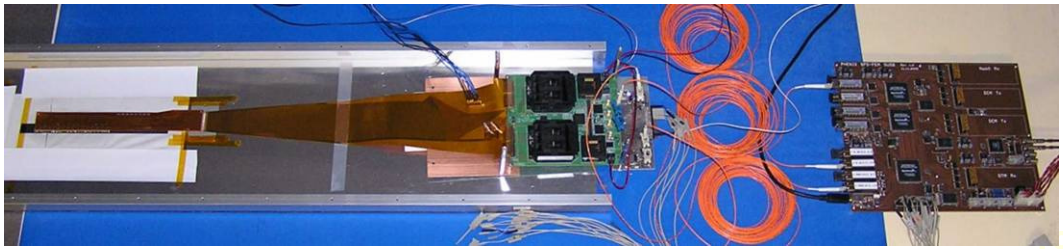
- 1.36 cm x 10.9 cm.
- Thickness bus: < 240 µm.

SPIRO module

- Control/read-out a half ladder
- Send the data to FEM

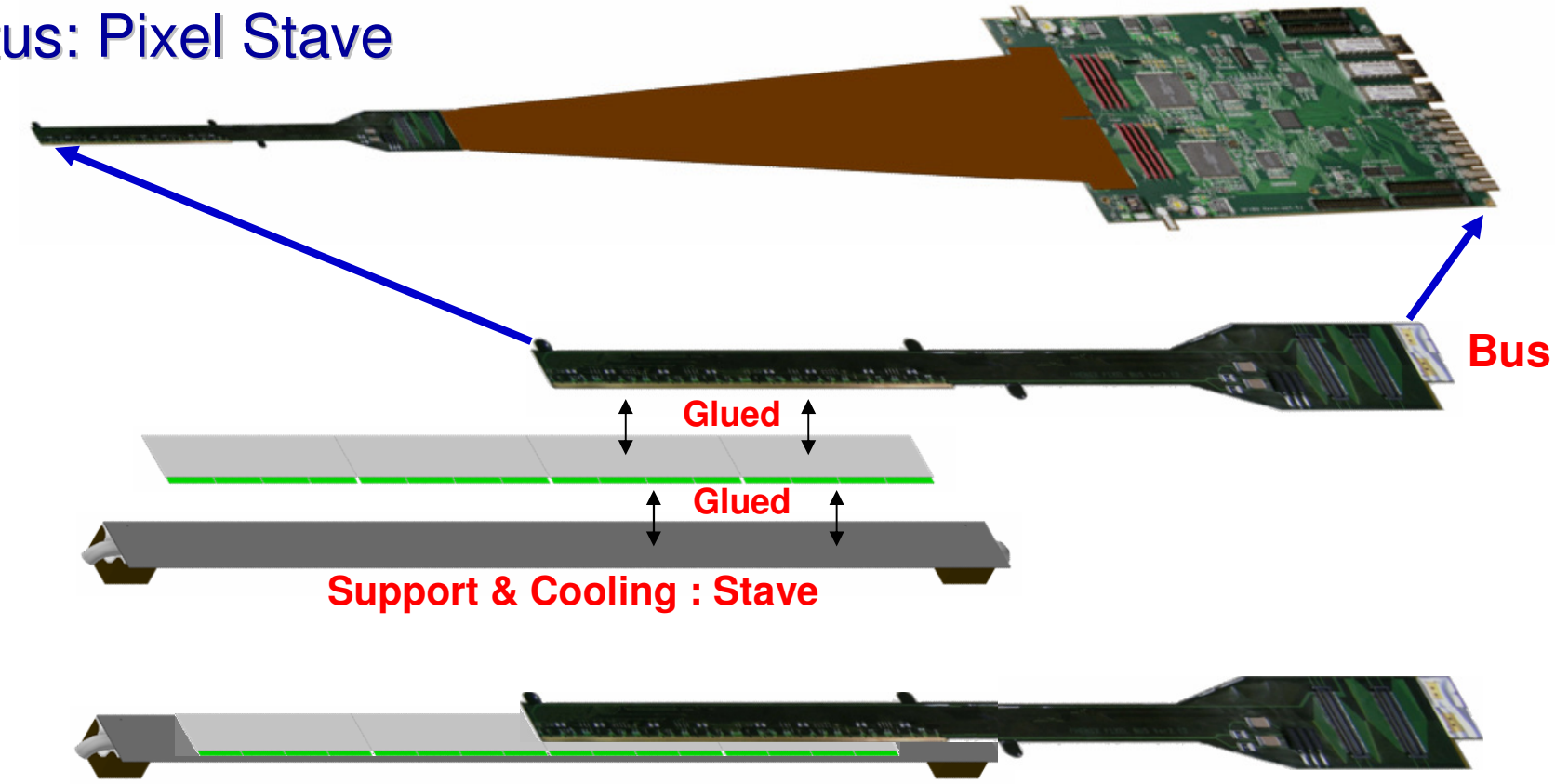
FEM (interface to PHENIX DAQ)

- Read/control two SPIROs
- Interface to PHENIX DAQ

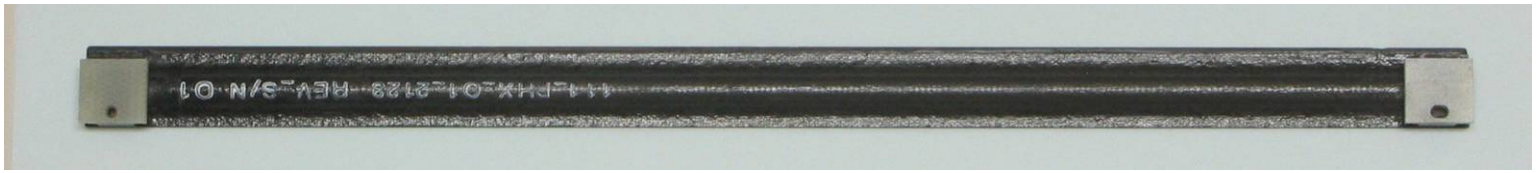


VTX: Silicon Pixel Detector (Barrels 1 &2)

Status: Pixel Stave



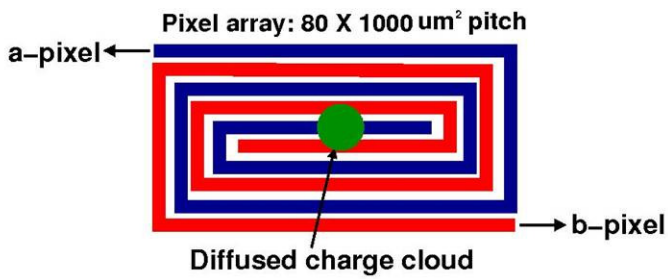
✪ Prototype stave has been delivered by HYTEC:



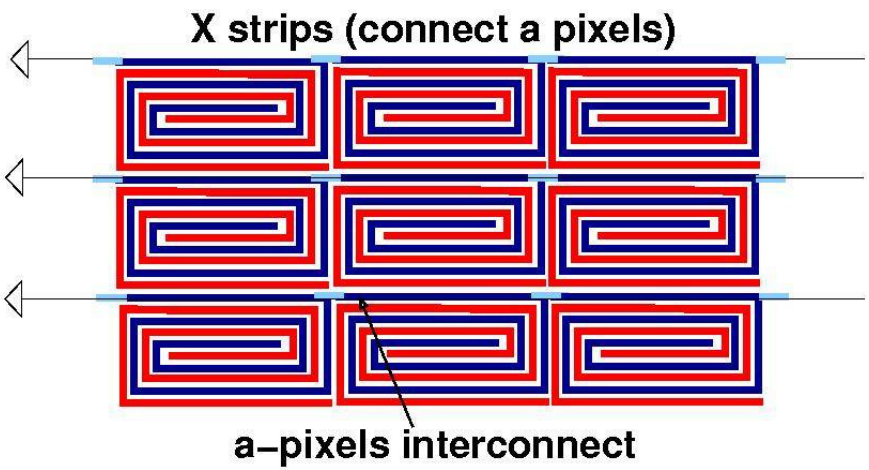
VTX: Silicon Stripixel Concept (Barrels 3 &4)

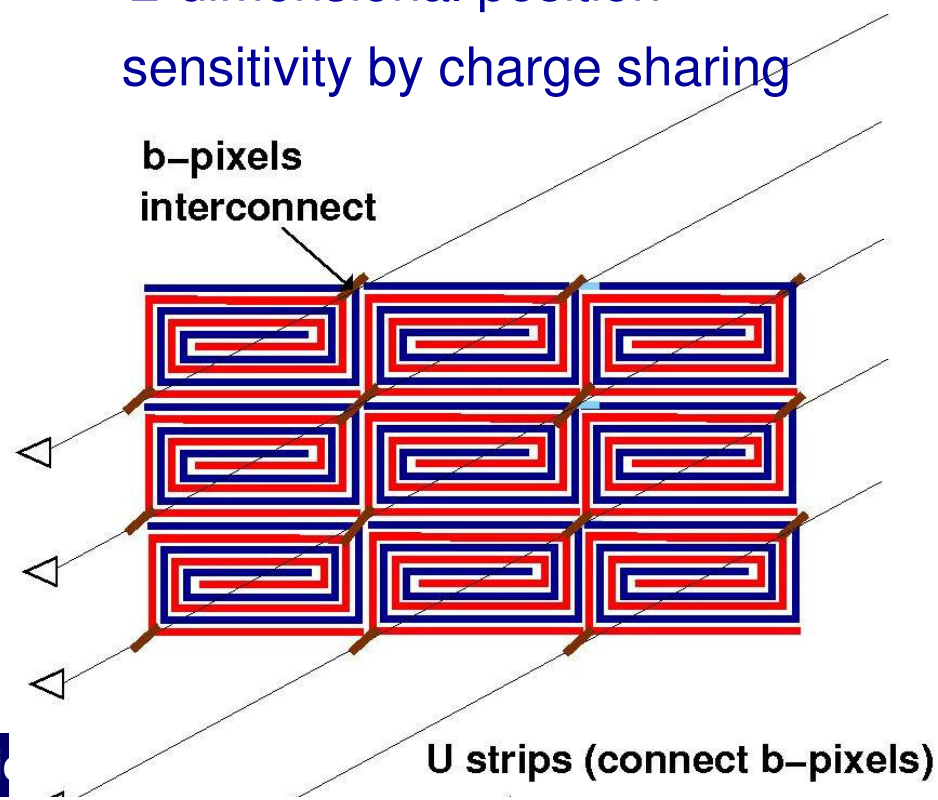
"New technology: unique to PHENIX"

- Innovative design by BNL Instr. Div. : Z. Li et al., NIM A518, 738 (2004);
- R. Nouicer et al., NIM B261, 1067 (2007);
- R. Nouicer et al., Journal of Instrumentation, 4, P04011 (2009)



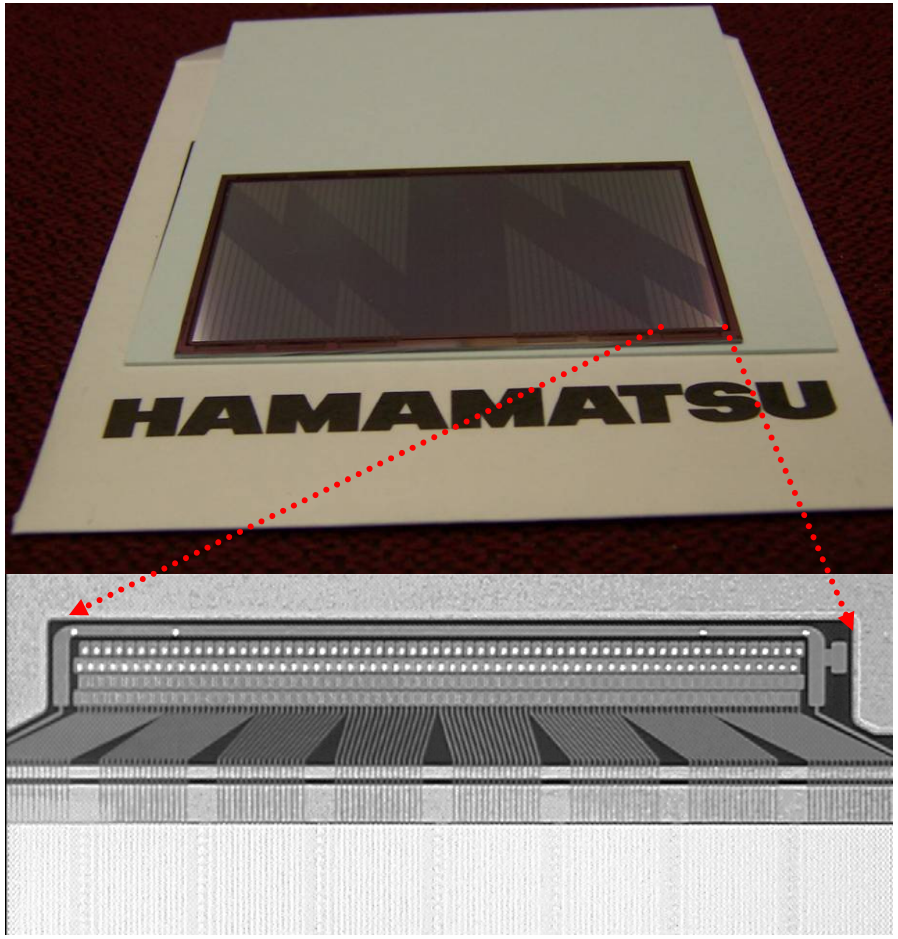
- DC-Coupled silicon sensor
- Sensor single-sided
- 2-dimensional position sensitivity by charge sharing





VTX: Silicon Stripixel Concept (Barrels 3 &4)

- Sensors produced by HPK and the thickness of the sensor is 625 μm
- Point symmetric structure of readout lines wrt the center of the sensor
- Readout pads in longer edges for ladder structure design
- No dead space in the middle
- Sensor size : 3.4×6.4 cm^2
- Pixel array : 80×1000 μm^2 pitch
- # readout strip
  - x-strip : 128×3×2
  - u-strip : 128×3×2
  - Total : 1536 channels/sensor

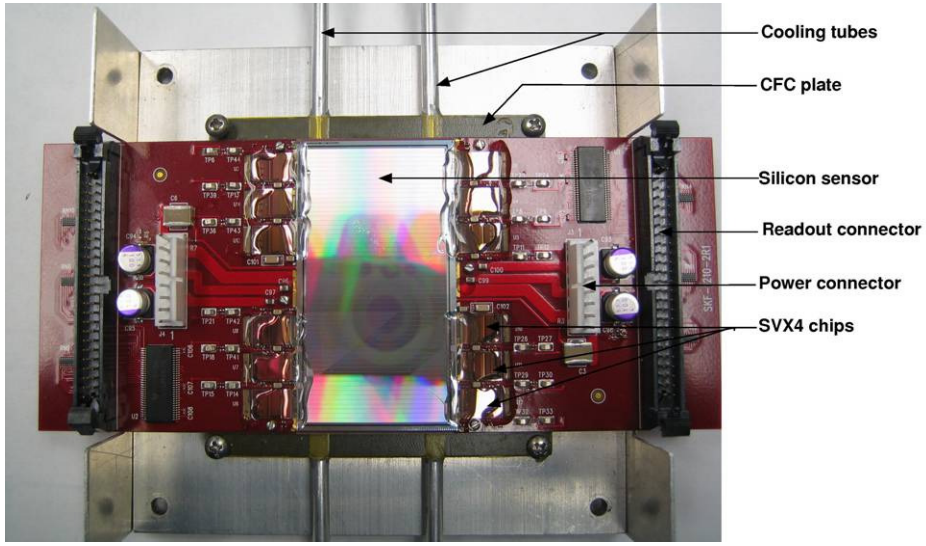


- Current per strip: 0.12 nA

- Note: Stripixel sensor technology, including the mask design and processing technology has transferred from BNL to HPK.

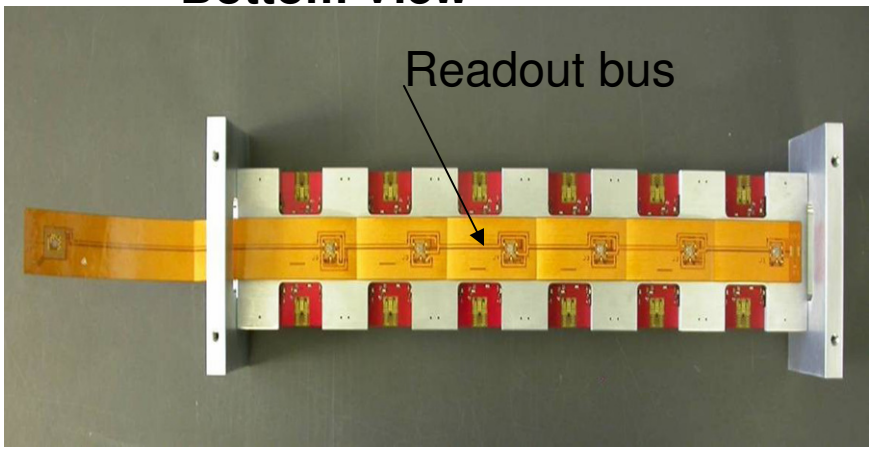
VTX: Silicon Stripixel Concept (Barrels 3 &4)

Prototype Silicon module used in:
-Source test
- cosmic ray test
- beam test 120 GeV proton beam at FNAL

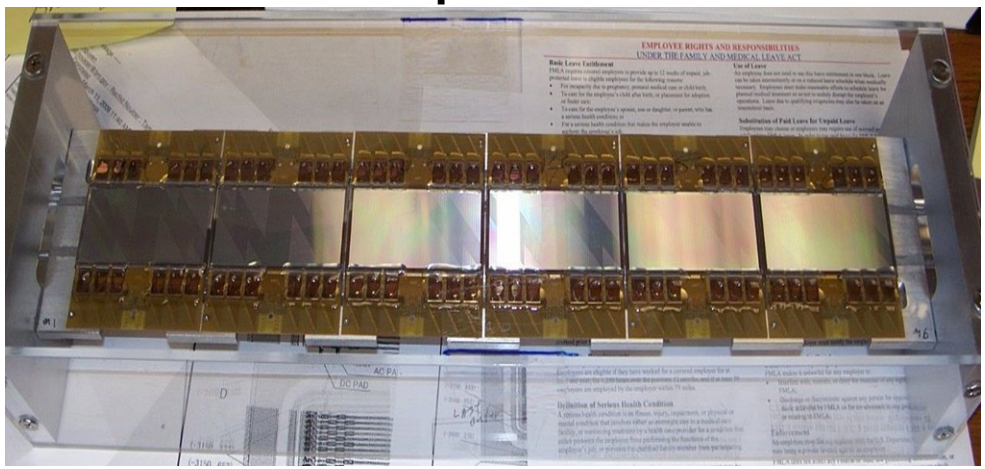


Good test results leaded to pre-production

Bottom View



Top View

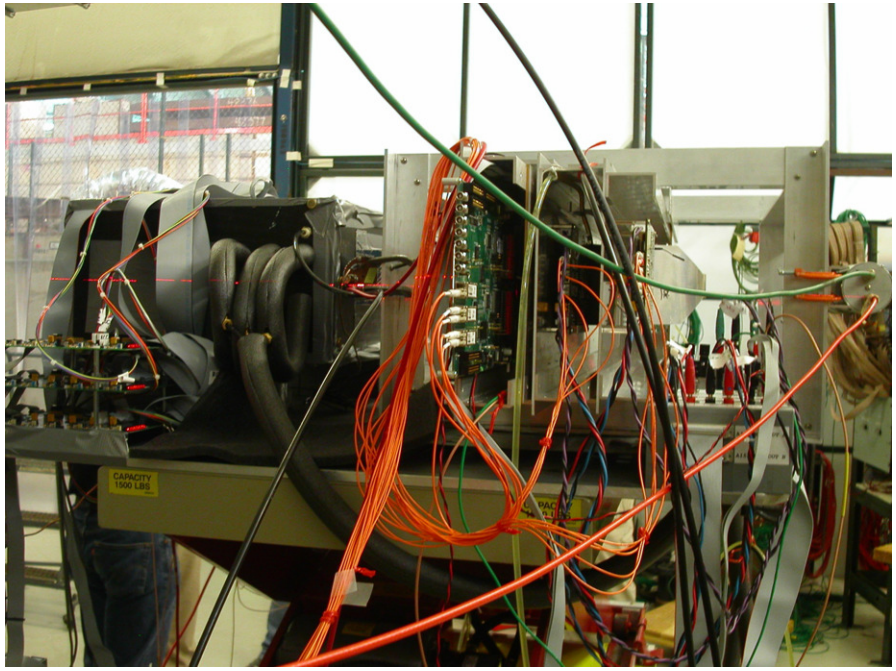


First Stripixel ladder mounted on aluminum stave (Final stave: CFC+ Carbon Foam)

Performance Results of VTX: silicon VerTeX Barrel Tracker

- **Response to proton beam at 120 GeV**

done for Pixel and Stripixel detector together at FNAL (T984)

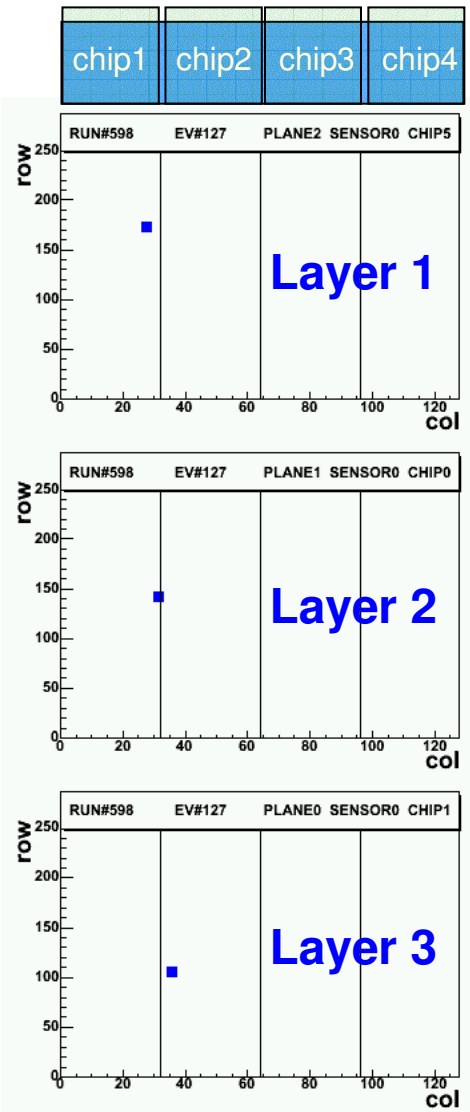


For details see:

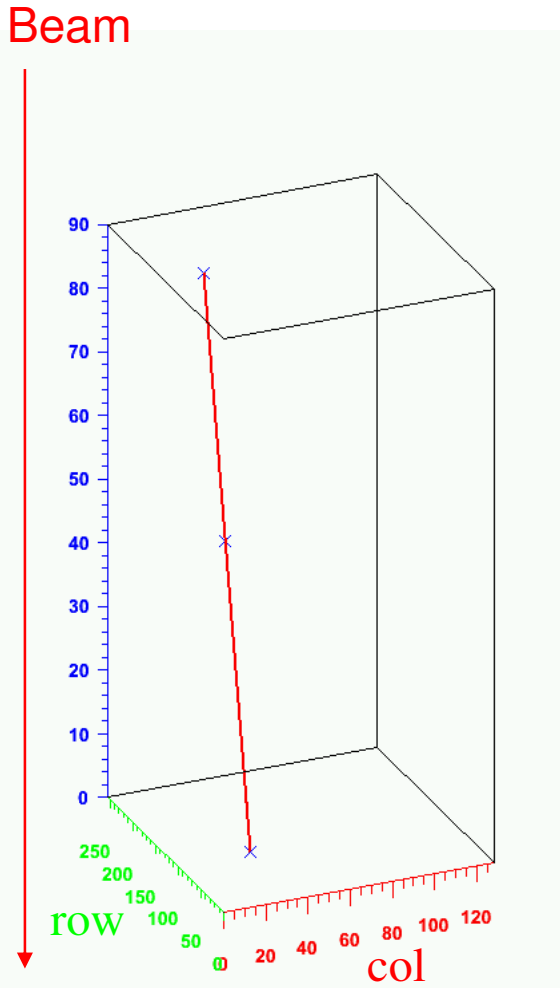
- Stripixel see: R. Nouicer et al., Journal of Instrumentation, 4, P04011 (2009)
- Pixel see: R. Ichimiya et al., Journal of Instrumentation, 4, ? (2009)

Performance Results: Pixel detector

Event Display

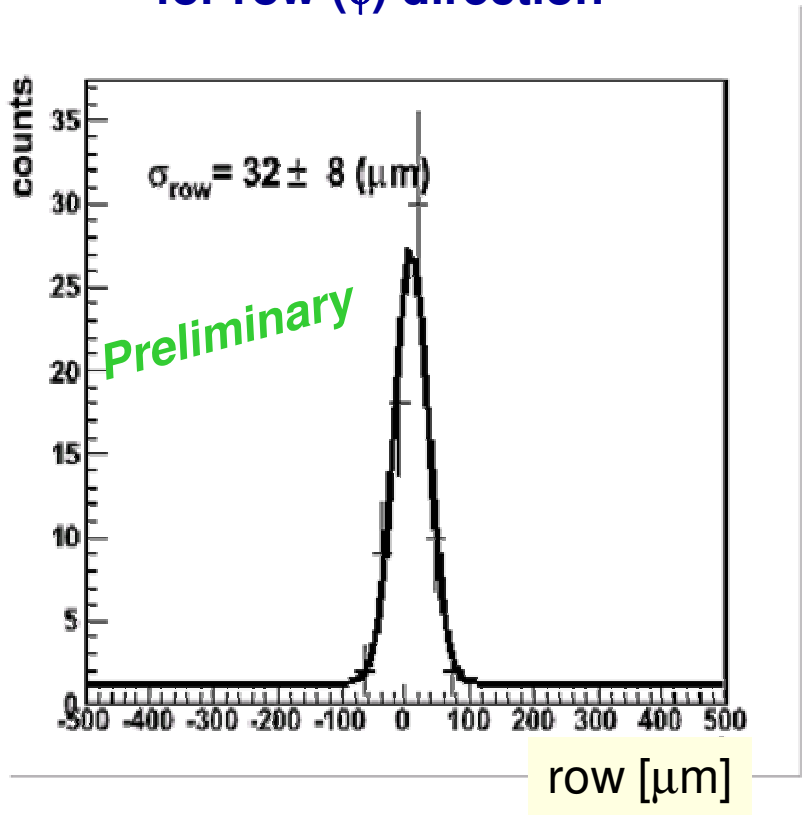


120 GeV proton beam at FNAL (T984)



Clear tracking

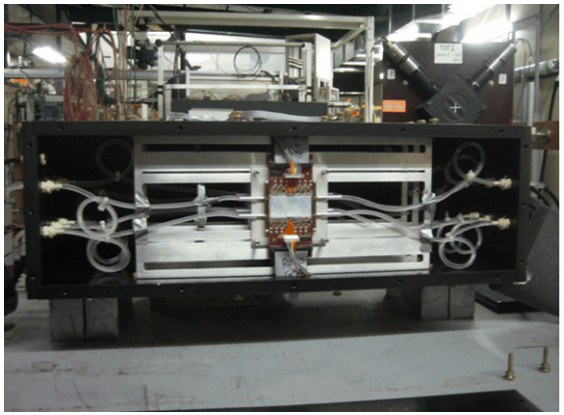
Intrinsic Resolution for row (ϕ) direction

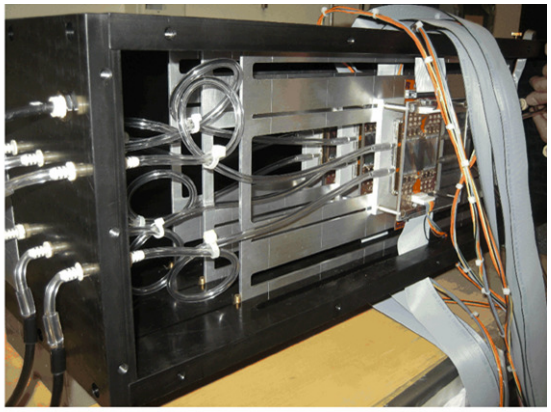


Performance Results: Stripixel detector

120 GeV proton beam at FNAL (T984)

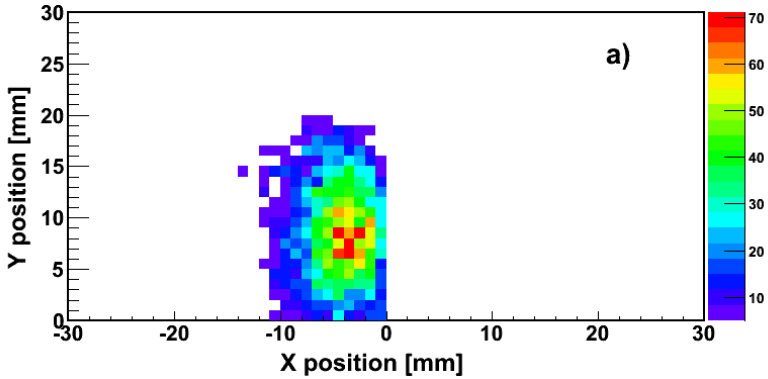
1) Setup:



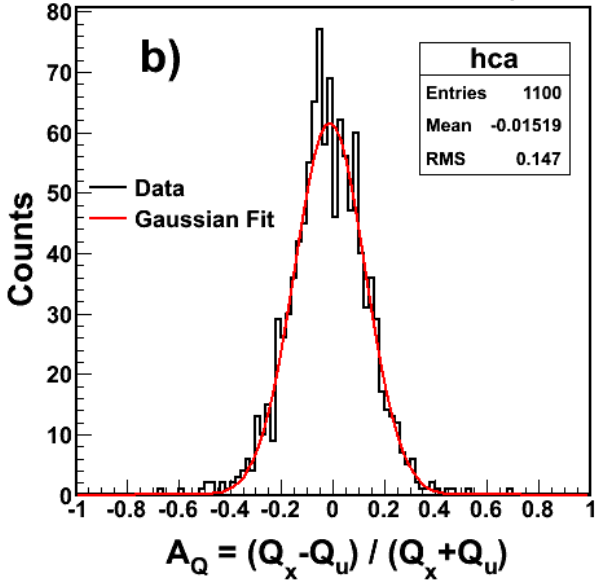


2) Results:

Profile of the proton beam on layer 1



charged correlations (charge sharing) in between the X- and U-stripixels

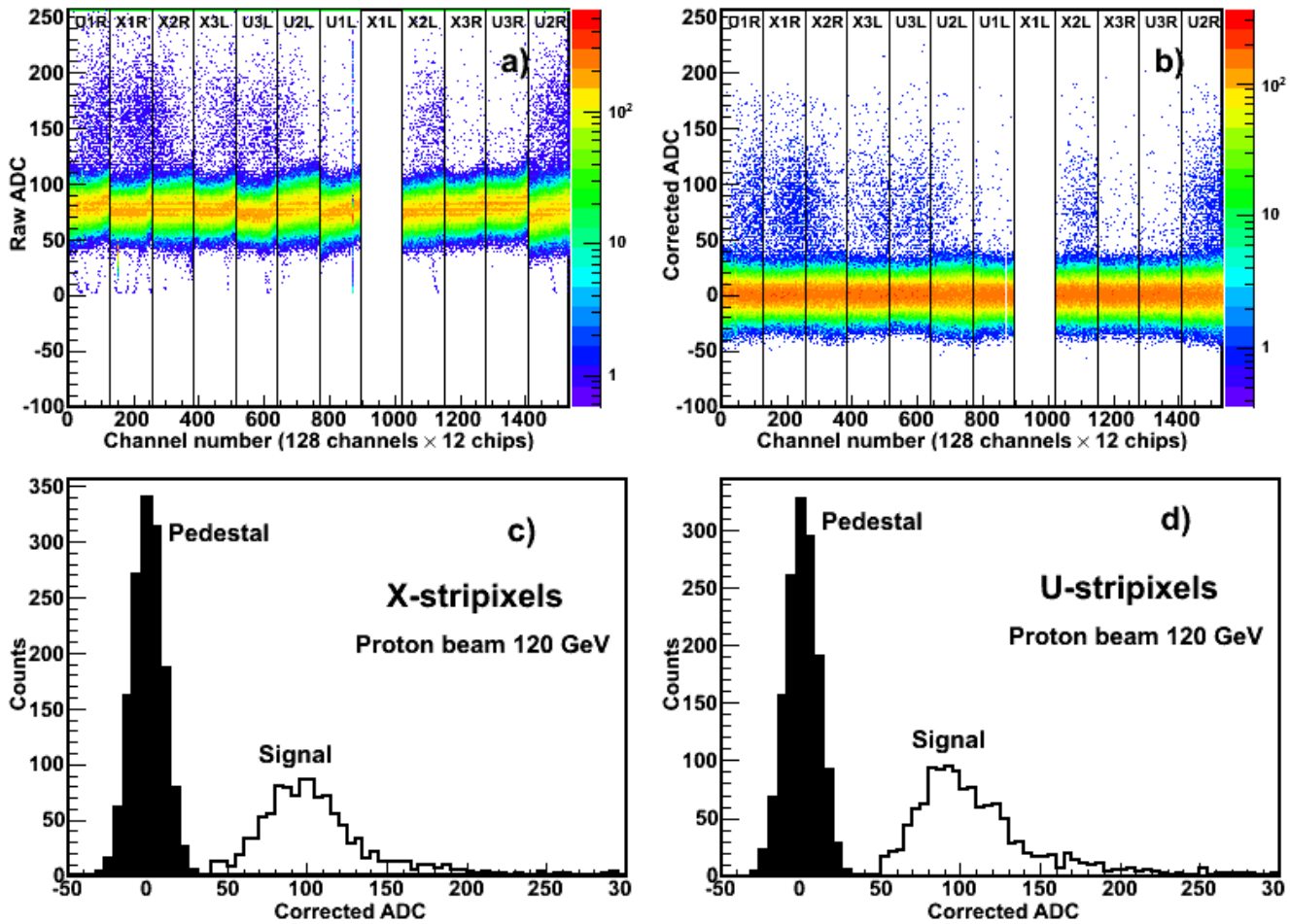


Results demonstrate that the principle of two-dimensional position sensitivity based on charge sharing works.

Performance Results: Stripixel detector

120 GeV proton beam at FNAL (T984)

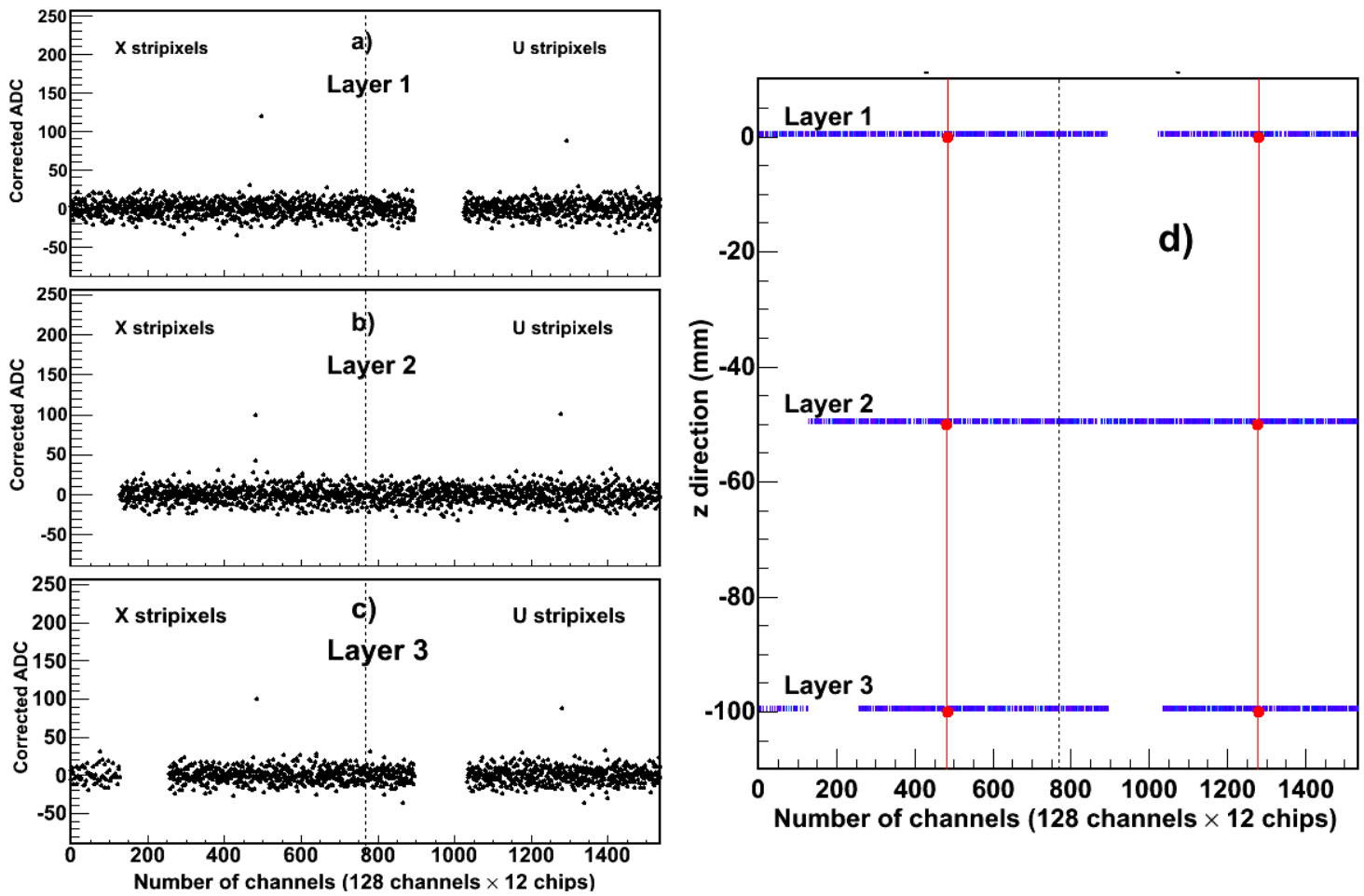
- Results of signal to Noise: X-stripixel channel: S/N = 10.3
  U-stripixel channel: S/N = 10.1



Performance Results: Stripixel detector

120 GeV proton beam at FNAL (T984)

- Event structure of a single event from three layers (three stripixel detectors) :



Good correlation between the X and U stripixels

Performance Results: Stripixel detector

120 GeV proton beam at FNAL (T984)

- **Hit residuals from tracks obtained from the stripixel detectors:**

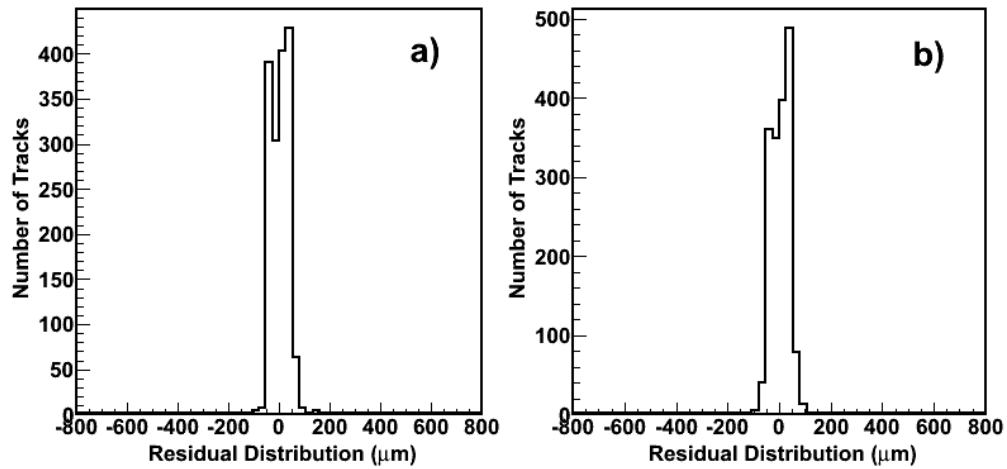
in X stripixel:

0.42 x 80 (μm) = 33.6 (μm)

in U stripixel:

0.44 x 80 (μm) = 35.2 (μm)

from the RMS values.



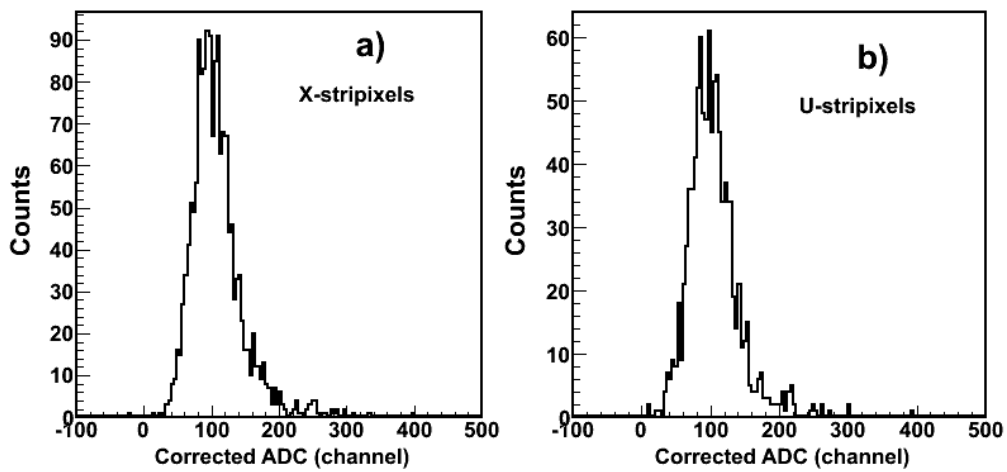
- **Tracking efficiency using the stripixel detector (middle layer)**

in X stripixel: 99.5 ± 0.2%

in U stripixel: 98.9 ± 0.2%

Tracking efficiencies in

both stripixels are very good



Summary

- The Silicon Vertex Tracker is an important upgrade of the PHENIX detector and will extend its physics capabilities to new observables for the physics at RHIC and the polarized proton program

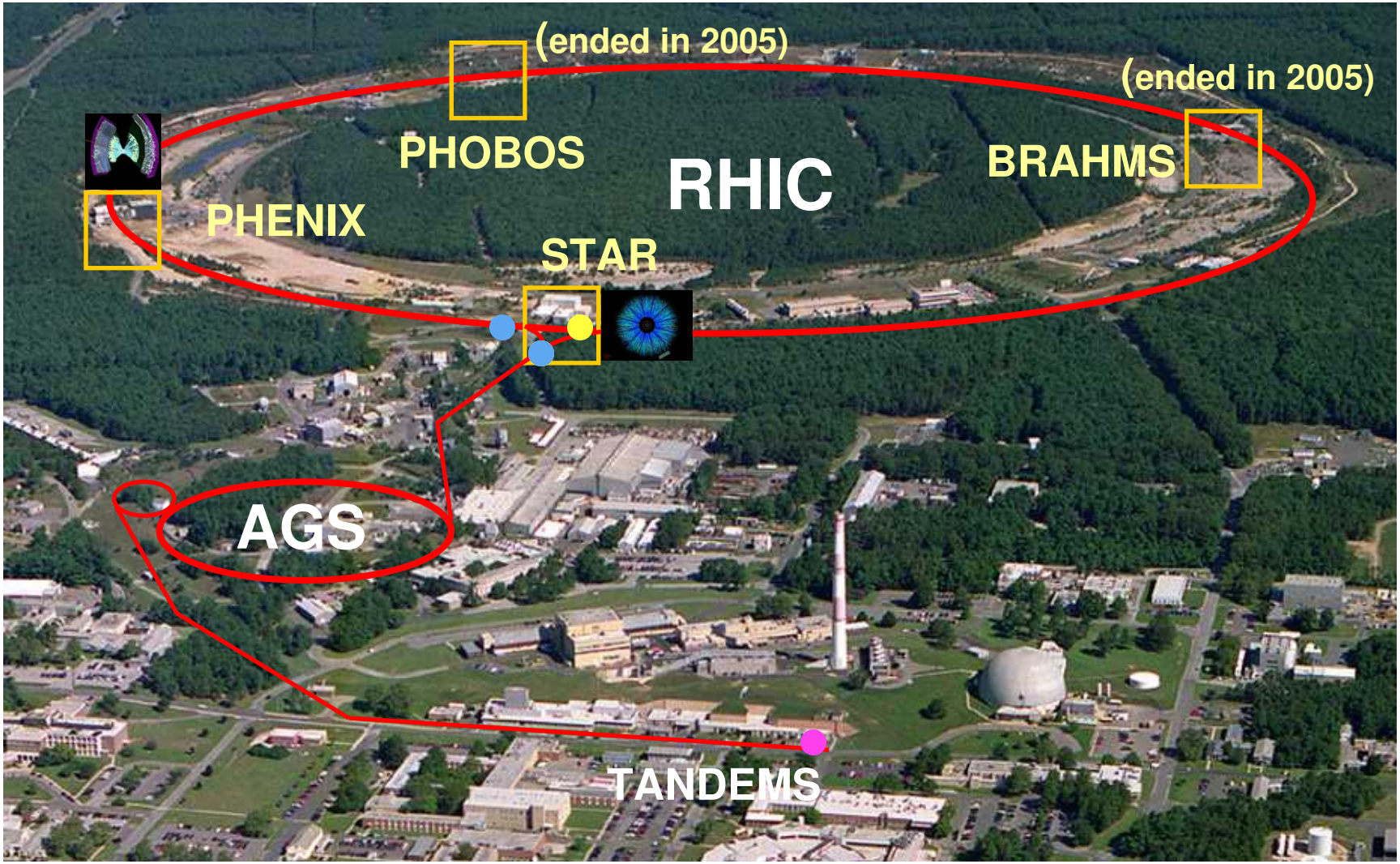
- **VTX**: silicon VerTeX Barrel Tracker (Pixel and Stripixel detectors)
  - Complete installation in the fall of 2010

- **FVTX**: Forward silicon VerTeX Detector:
  - Complete installation in the fall of 2011

Stay tuned more to come on Heavy Flavor from PHENIX Experiment at RHIC

Auxiliary Slides

Relativistic Heavy Ion Collider (RHIC)



A=1~200, $\vec{p}\,\vec{p}$, pA, AA, AB; $\sqrt{s_{NN}}$: 20-200 GeV (AA), $\sqrt{s}$:48-500 GeV (pp)

- Silicon Vertex Tracker (VTX) can enhance physics capability of the PHENIX detector.

- PYTHIA simulation was performed under the condition of $\sqrt{s} = 500 GeV$ and $L = 300 pb^{-1}$.
  Improvement for x reconstruction with gamma-jet production.
  Estimation of A_{LL} as a function of x_g.

- FNAL beam test was performed to confirm the functionality of detector and DAQ system. The system worked properly.

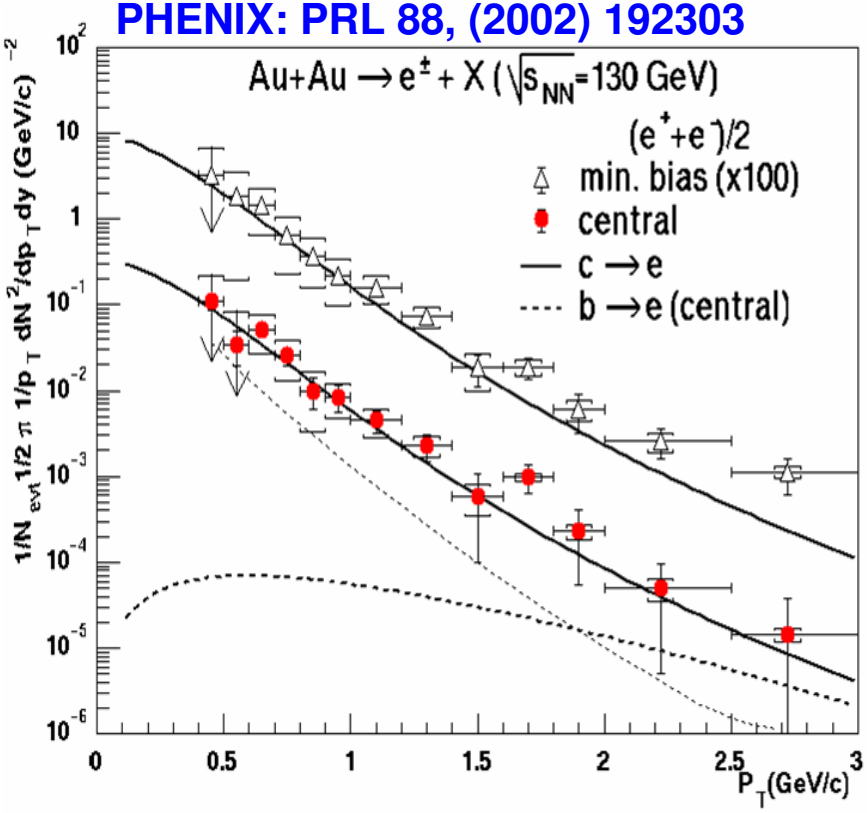
- Preparation for mass production is under way.

- VTX detector will be installed into PHENIX in 2010.

Heavy-Quark Probes at PHENIX

- **Present PHENIX**: Access signal from heavy quarks via single electron measurement

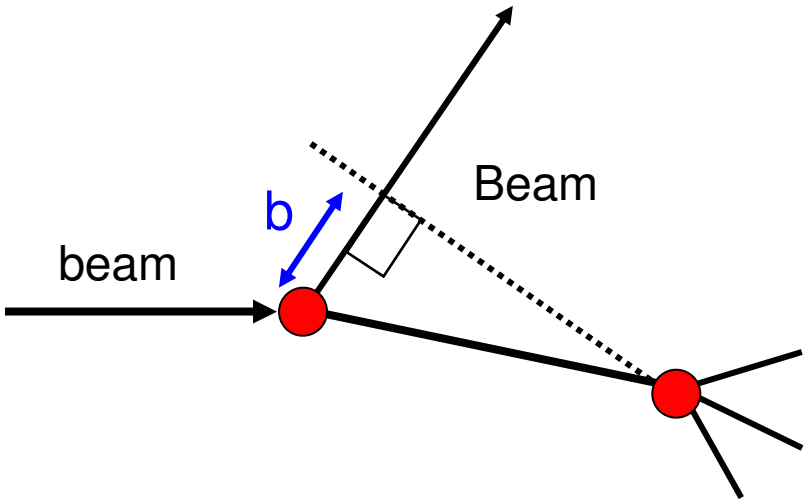
PHENIX: PRL 88, (2002) 192303



- **Precision of the measurement limited by systematic uncertainty because,**
  - Huge background contribution
    - π^0 and η Dalitz decay
    - γ conversion ($\gamma \rightarrow e^+e^-$)
- **Cannot Separate charm and beauty contribution model independently**
- **Lifetime (ct) of mesons with charm and beauty**
  - $D^{\pm}$ = 312 μm, D^0 = 123 μm
  - $B^{\pm}$ = 501 μm, B^0 = 460 μm
- **Secondary vertex identification allows us to suppress background on non-photonic electrons and will make it possible to distinguish if an electron originates from charm or beauty.**

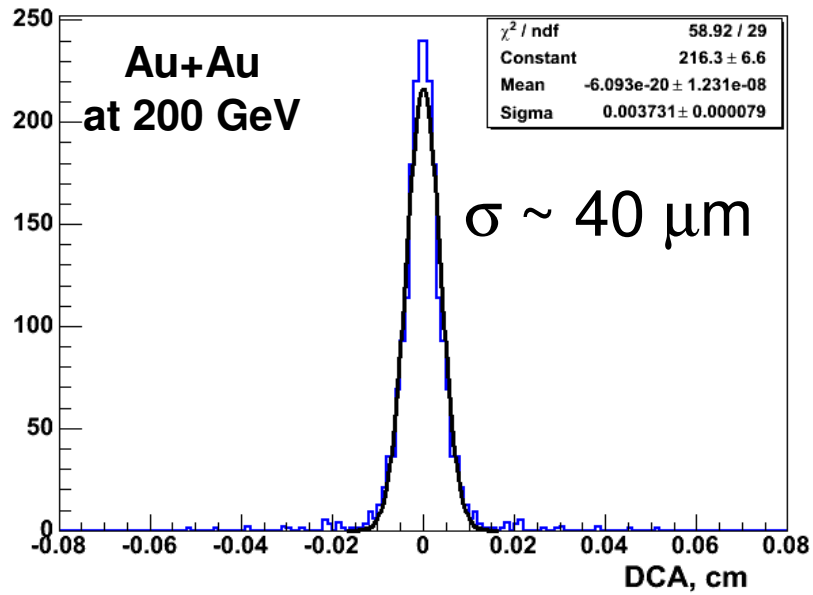
DCA

- What is measured?
  - Distance of Closest Approach (DCA)



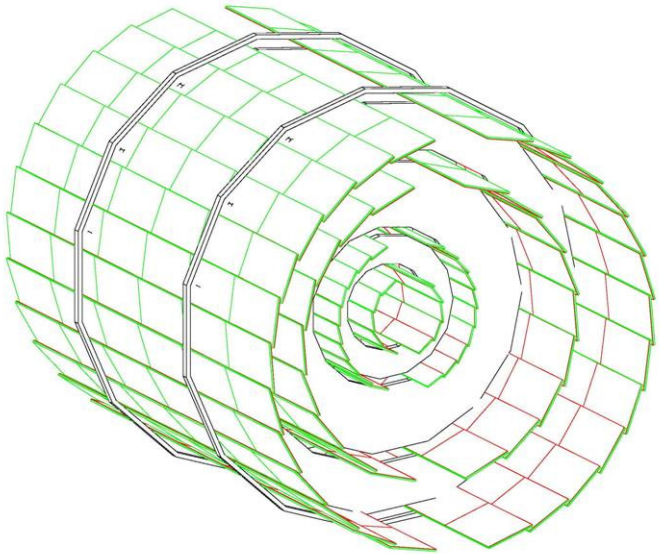
b = distance of closest approach of a **reconstructed** track to the true interaction point

Expected DCA resolution of VTX

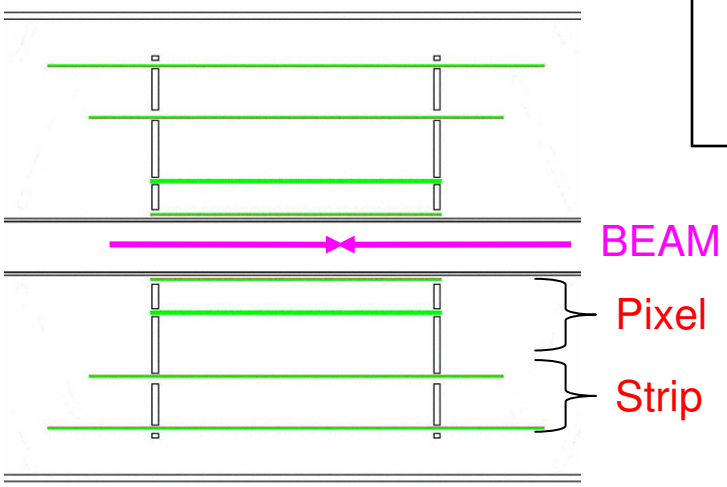


DCA distribution for single simulated pions in $3<p_T<4$ GeV/c. Simulation is done with 200 micron pixel layers and 650 micron strip layer. The passive material is 1.0% per pixel layer and 2.75% per strip layer.

Pixel detector Strip detector



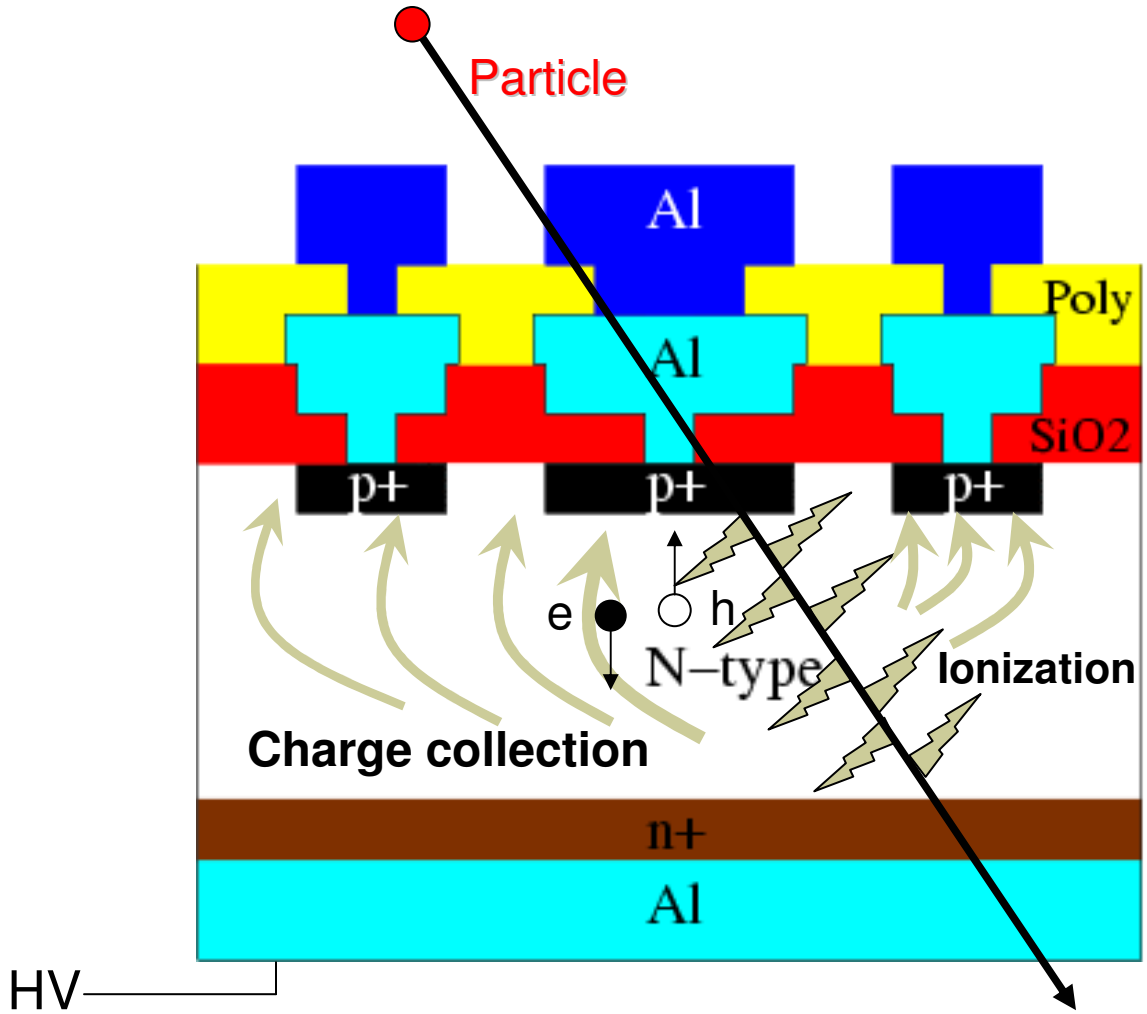
VTX	Layer	R1	R2	R3	R4
Geometrical dimensions	R (cm)	2.5	5	10	14
	Δz (cm)	21.8	21.8	31.8	38.2
	Area (cm^2)	280	560	1960	3400
Channel count	Sensor size R × z (cm^2)	1.28 × 1.36 (256 × 32 pixels)		3.43 × 6.36 (384 × 2 strips)	
	Channel size	50 × 425 μm^2		80 μm × 3 cm (effective 80 × 1000 μm^2)	
	Sensors/ladder	4 × 4		5	6
	Ladders	10	20	18	26
	Sensors	160	320	90	156
	Readout chips	160	320	1080	1872
	Readout channels	1,310,720	2,621,440	138,240	239,616
Radiation length (X/X0)	Sensor	0.22%		0.67 %	
	Readout	0.16%		0.64 %	
	Bus	0.28%			
	Ladder & cooling	0.78%		0.78 %	
	Total	1.44%		2.1 %	



Layer	radius	Detector	Occupancy in Central Au+Au collision	
Layer 1	2.5 cm	Pixel	0.53 %	
Layer 2	5.0 cm	Pixel	0.16%	
Layer 3	10.0 cm	Strip	4.5 % (x-strip)	4.7 % (u-strip)
Layer 4	14.0 cm	Strip	2.5 % (x-strip)	2.7 % (u-strip)

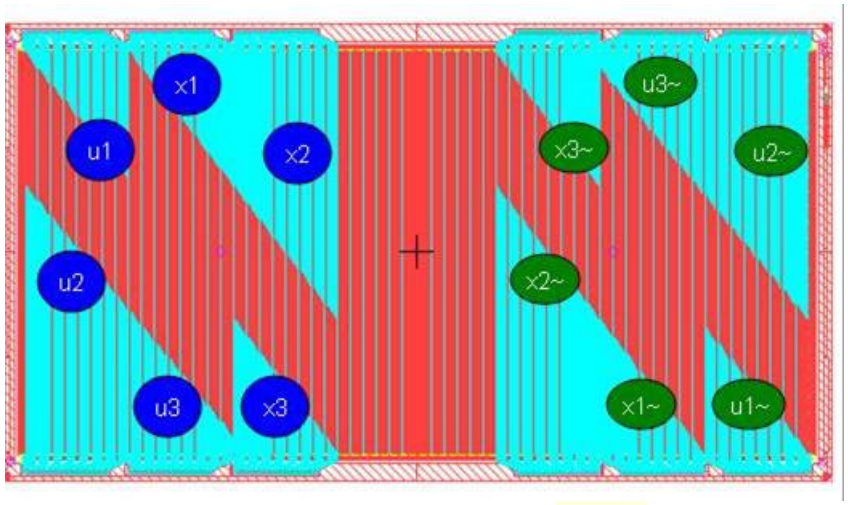
Silicon Sensor Stripixel Concept

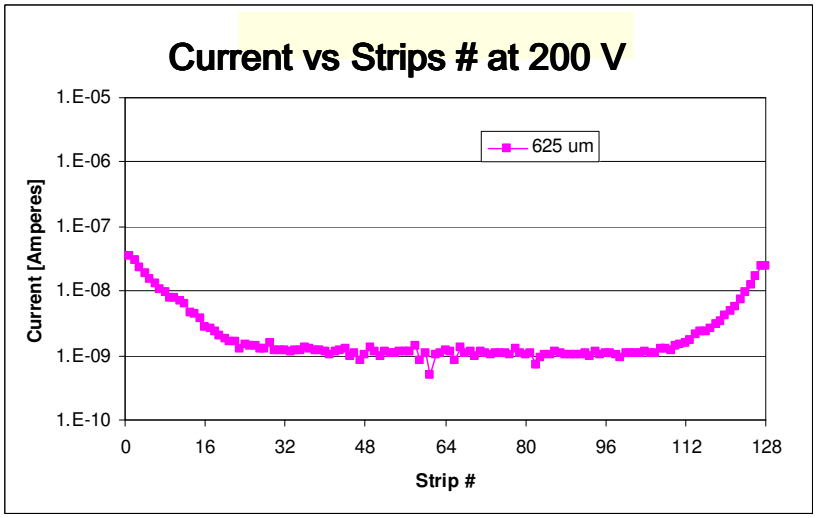
- Cross section view of double meta; layout of Silicon Strip detector via contacts on *U sub-pixels*

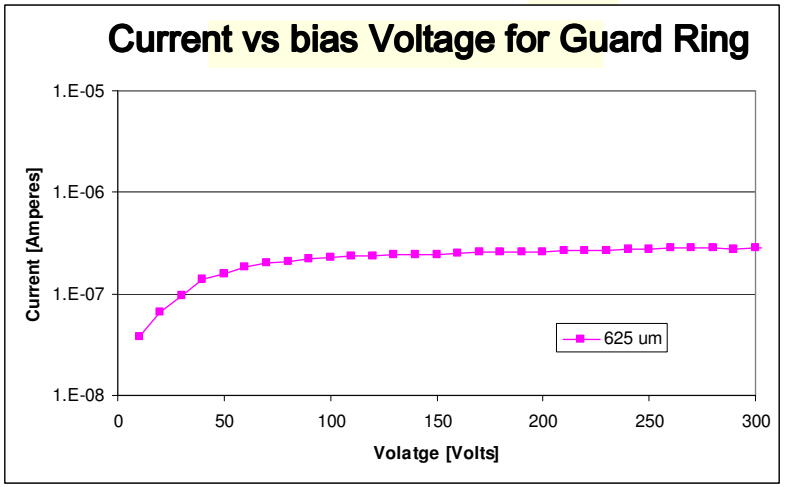


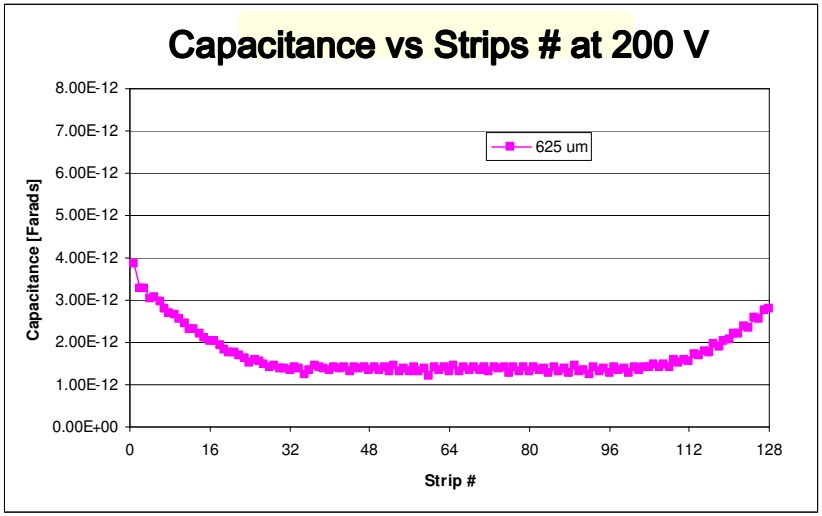
Details Measurements: Q/A Tests

- Inspection
- Diodes tests
- Guard Ring test
- Strips tests





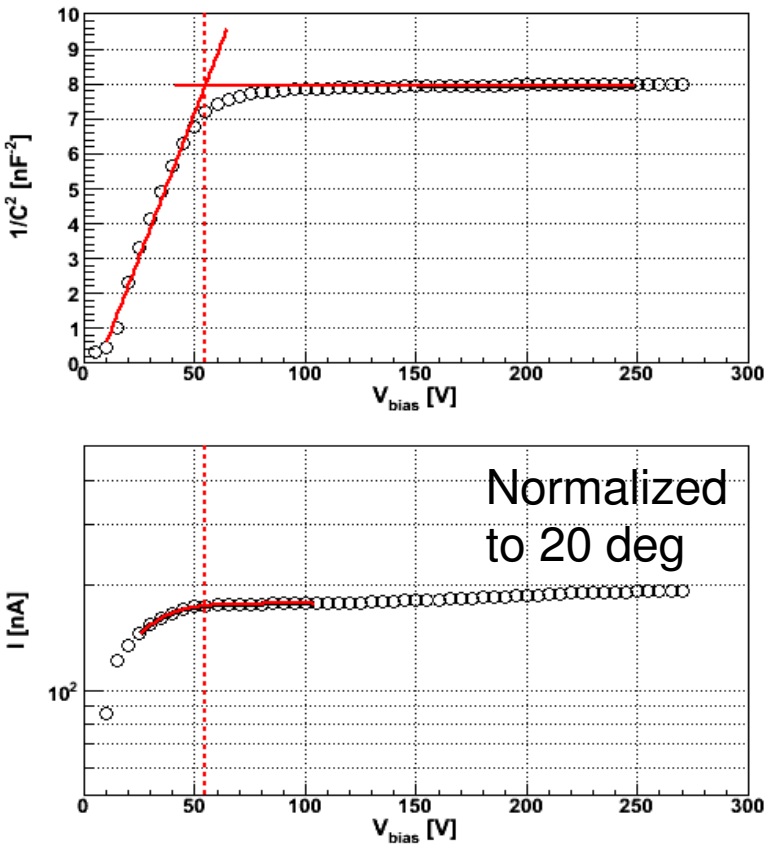




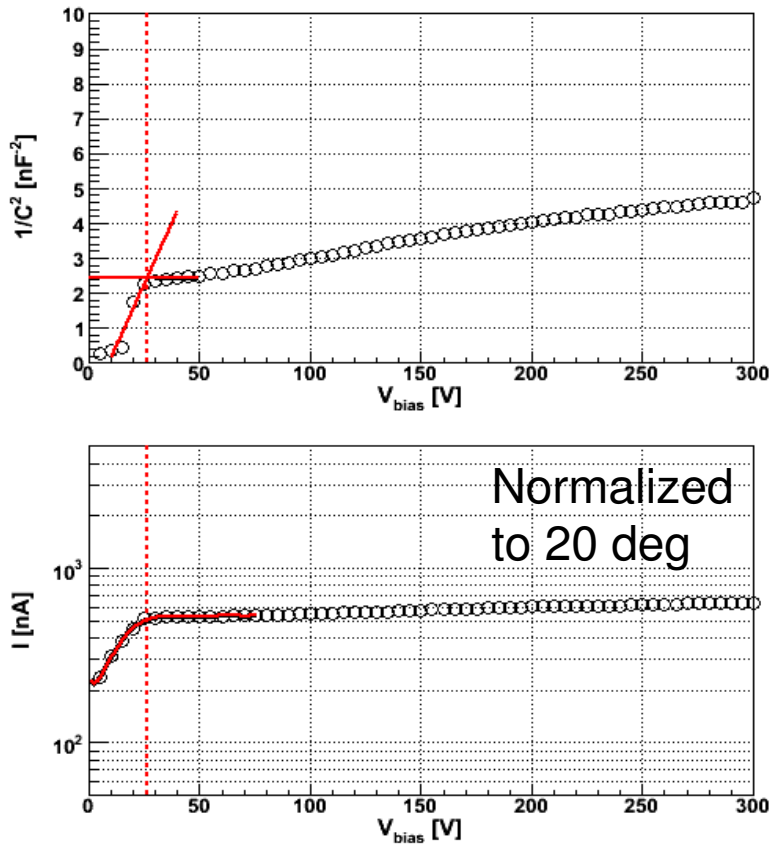
Radiation Measurements in IR PHENIX

✪ Measurement obtained from silicon stripixel sensor

Before irradiation



After annealing

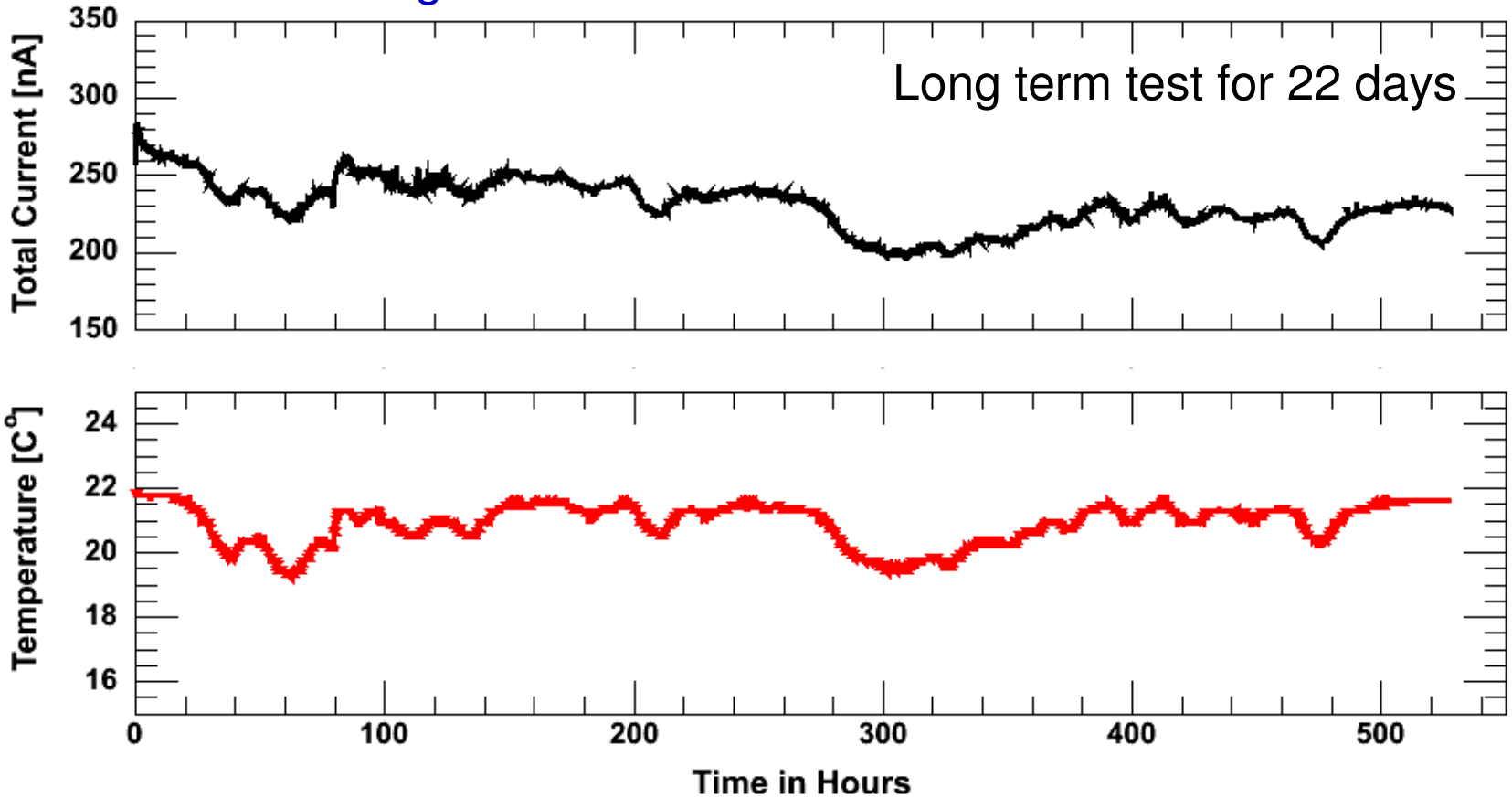


V_{FD} = 54.820 +- 13.874 [V]
I_{FD} = 1.748e+02 +- 8.804e-01 [nA]

V_{FD} = 26.146 +- 18.765 [V]
I_{FD} = 5.083e+02 +- 1.083e+01 [nA]

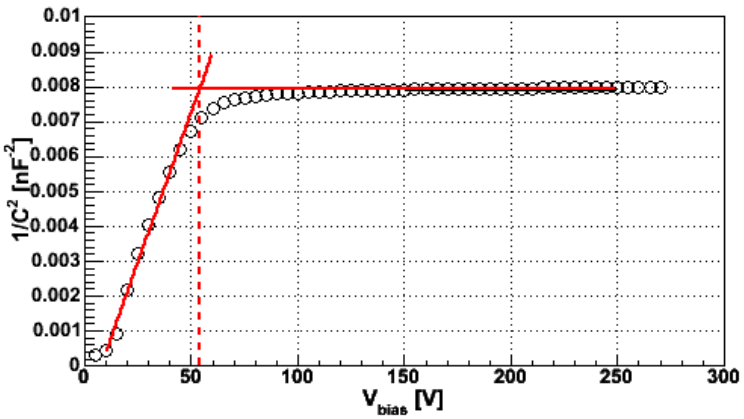
Stability of Leakage Current vs Time

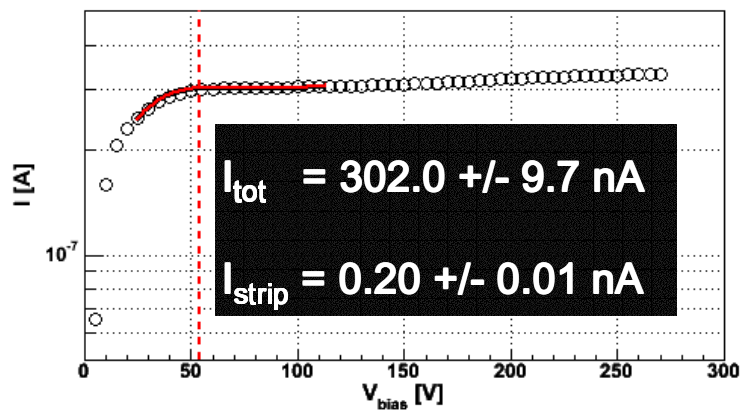
- Leakage current measurements from stripixel sensor biased at 120 Volts for 22 days
  - Good correlation between current and temperature
  - Leakage current is stable

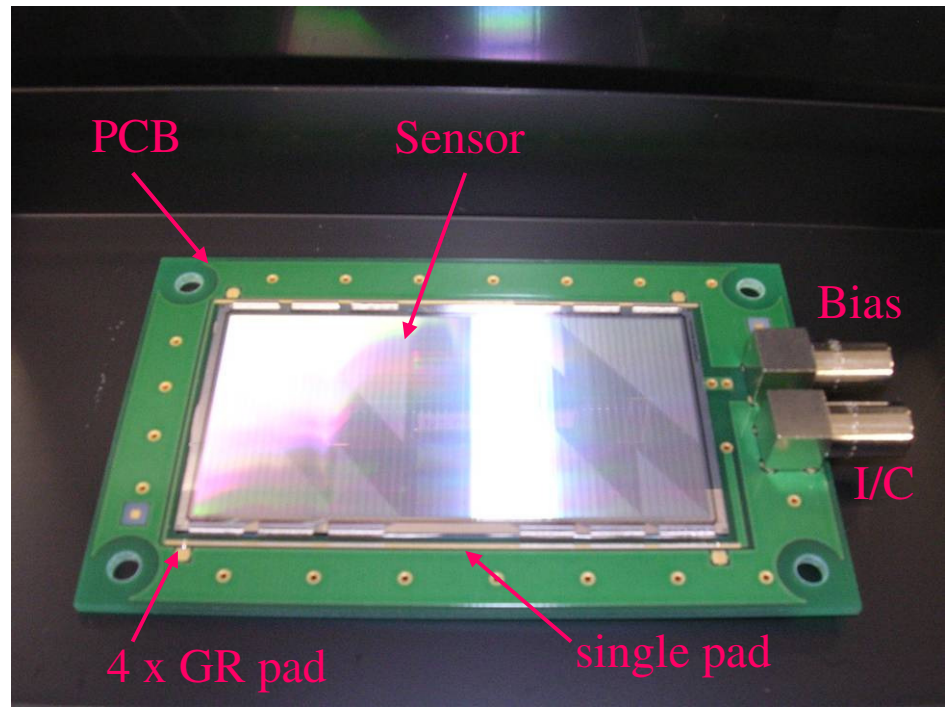


Total Leakage Current Measurements

- Measure total leakage current of 1532 strips (I_{tot})
- Define $I_{strip} = I_{tot}$ / #strip, where #strip = 12 x 128 = 1,536

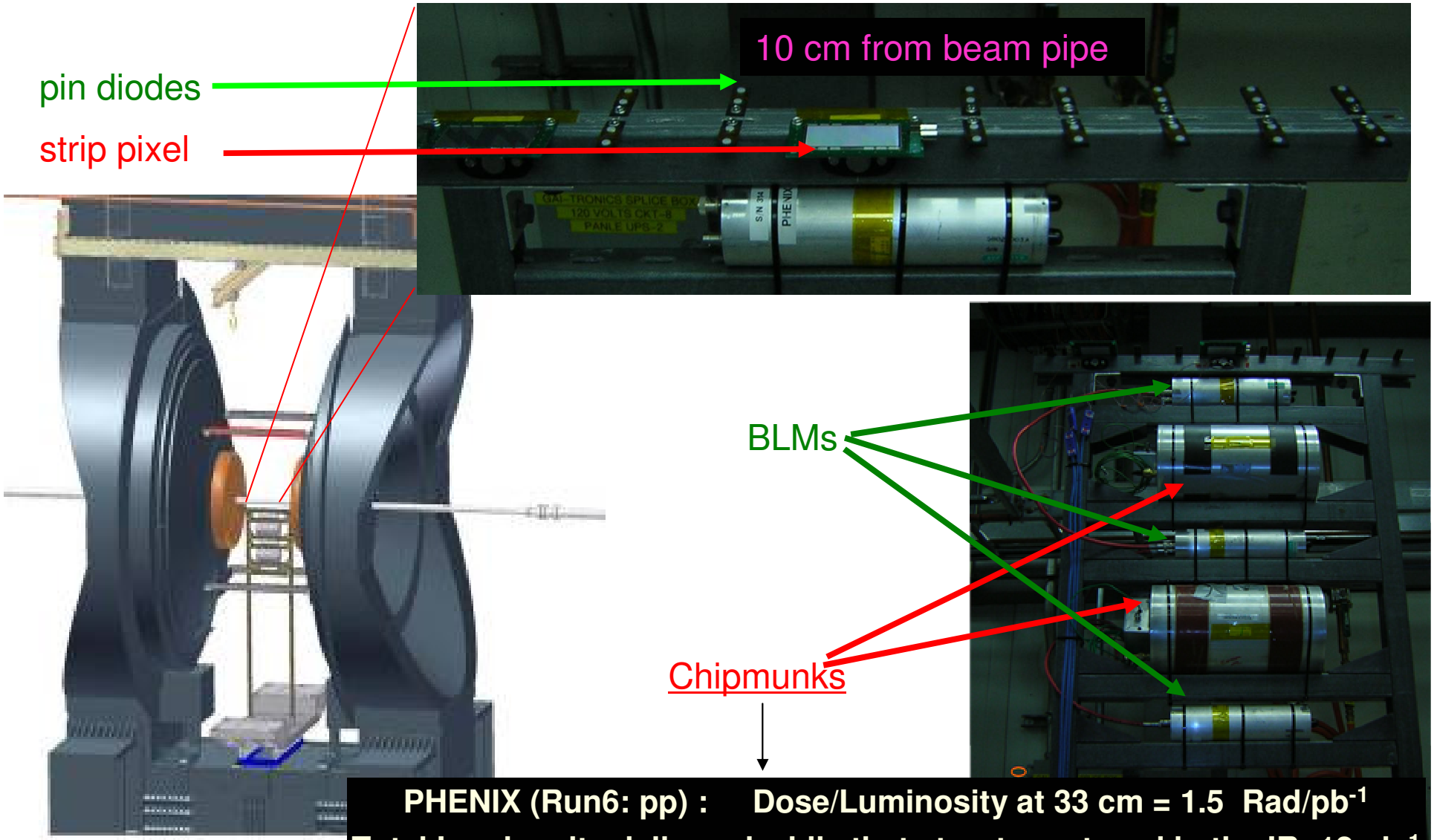






The 625 μm sensors bonded to the SVX4 chip; leakage current : 0.4 nA/strip well below the saturation limit of the SVX4 chip: 15 nA/Strip.

Radiation Measurements in IR PHENIX: Run 6

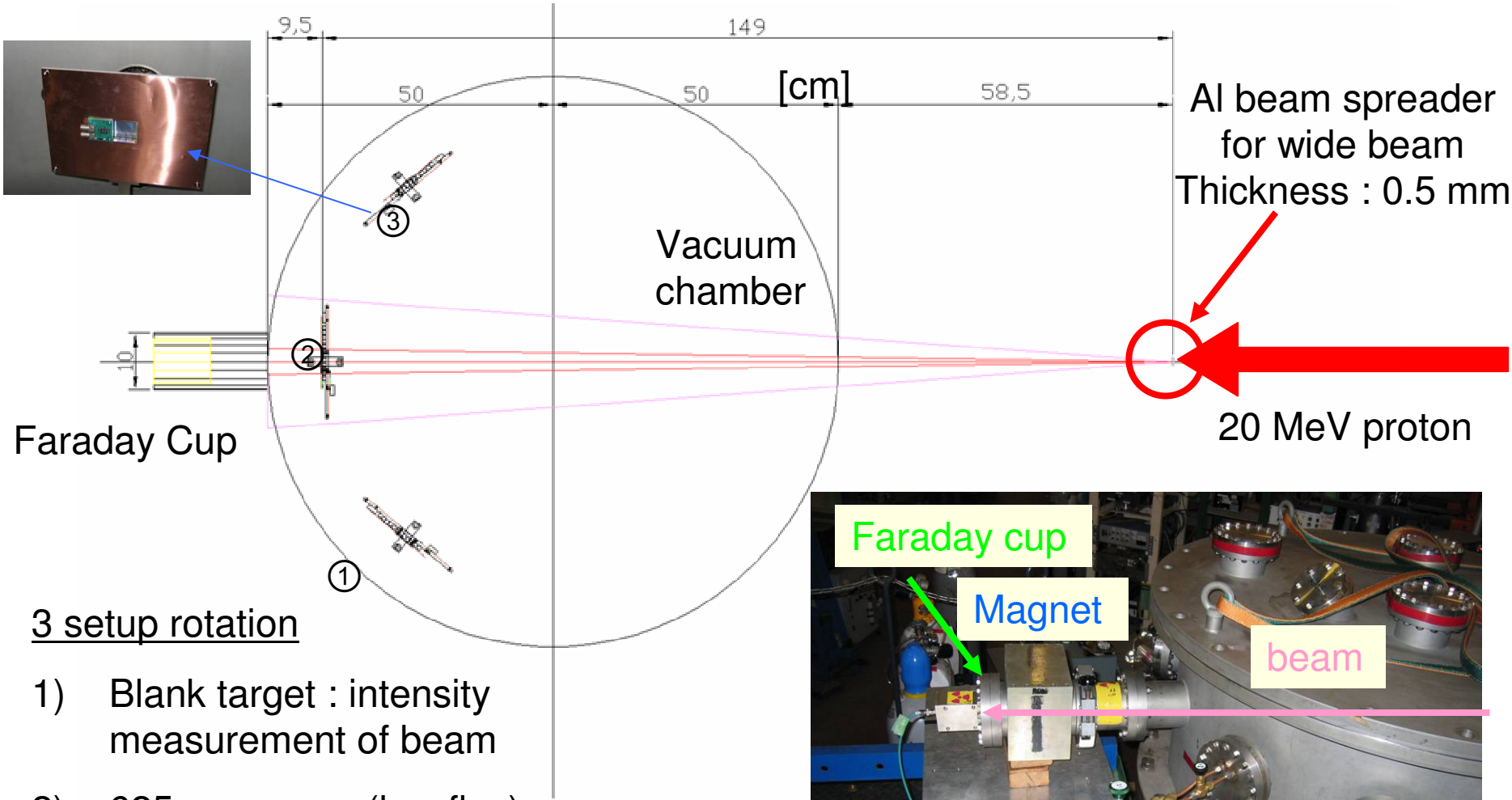


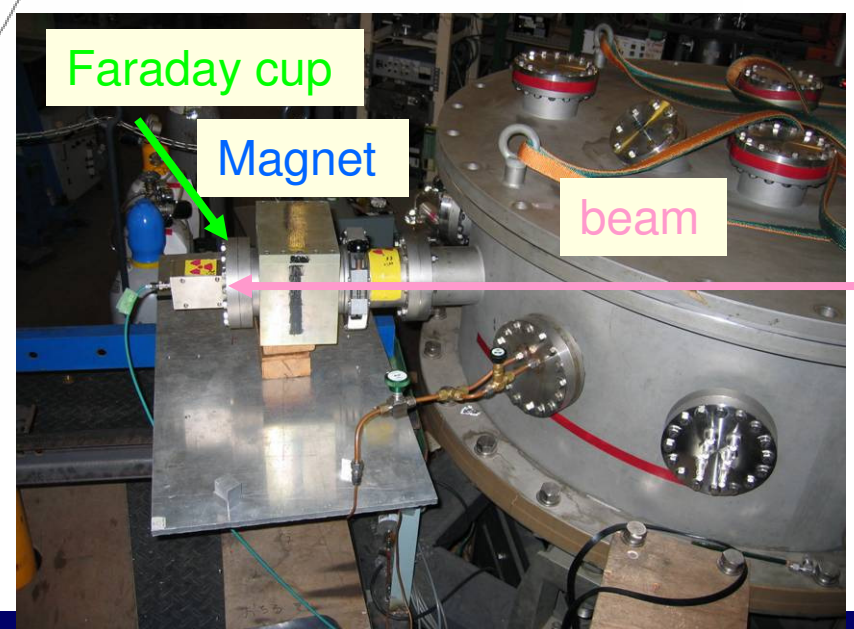
PHENIX (Run6: pp) : Dose/Luminosity at 33 cm = 1.5 Rad/pb^{-1}

Total Luminosity delivered while that structure stayed in the IR: 12 pb^{-1}

total dose observed = 30 Rad

Radiation: 20 MeV Proton Beam at Tsukuba





3 setup rotation

1) Blank target : intensity measurement of beam

2) 625um sensor (low flux)

3) 500 um sensor (high flux)

Fluence of 625 μm Stripixel Sensor

- **$\Delta I/V = \alpha \Phi$ (Φ = fluence, 1 MeV neutron equivalent fluence)**

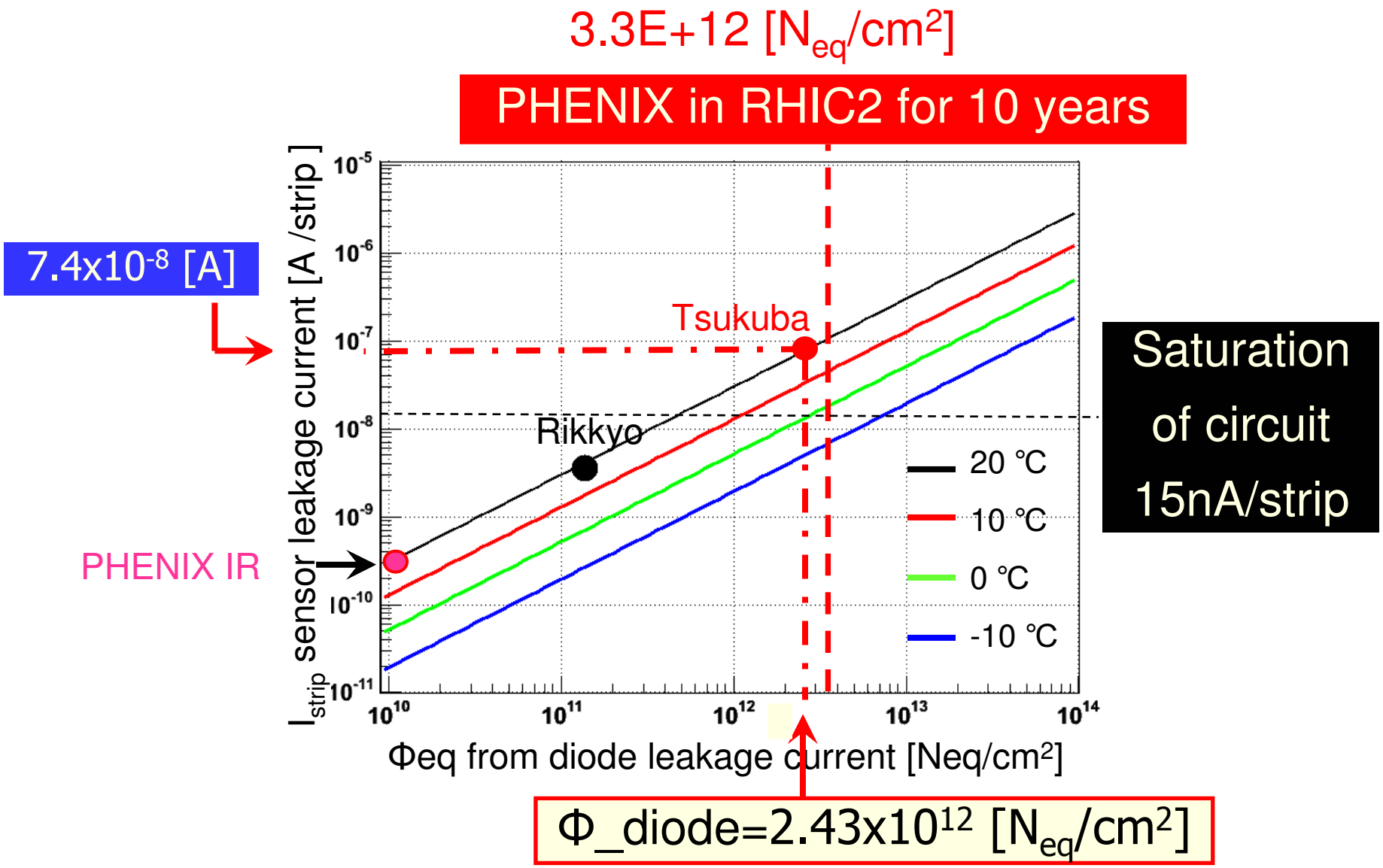
  α : proportionality factor (current related damage rate)

  - $V_{total} = 3 \times 6 \times 0.0625 = 1.125$ [cm^3]
  - ΔI_{total} (20°C) = $3.3\ 10^{-7}$ [A]
    - Calculating increase of single strip

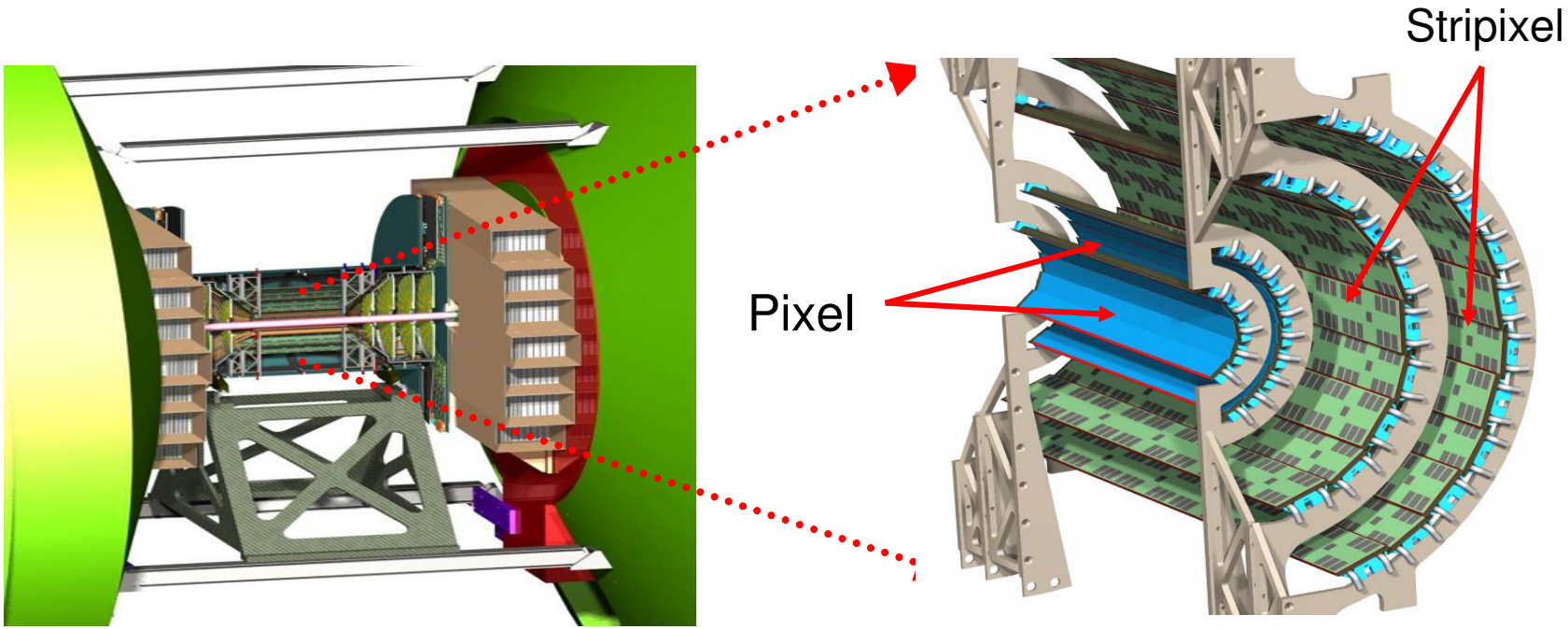
      $\Delta I_{total}/1536 = 2.2\ 10^{-10}$ [A/strip]
  - $\alpha_{IR} = 3\ 10^{-17}$ [A/cm]
  - **$\Phi_{total} = 9.9\ 10^{+9}$ [N_{eq}/cm^2]**

- In the same way, fluences of diodes were estimated.

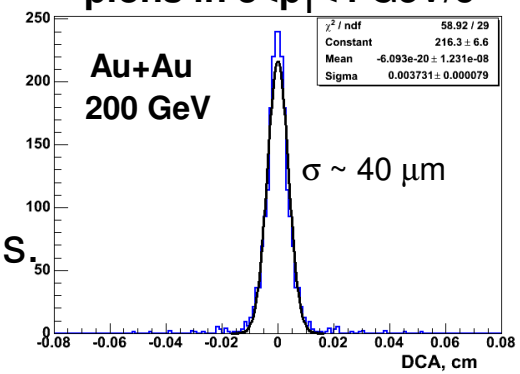
Leakage current of Stripixel sensor



Central Silicon Vertex Trackers "VTX"

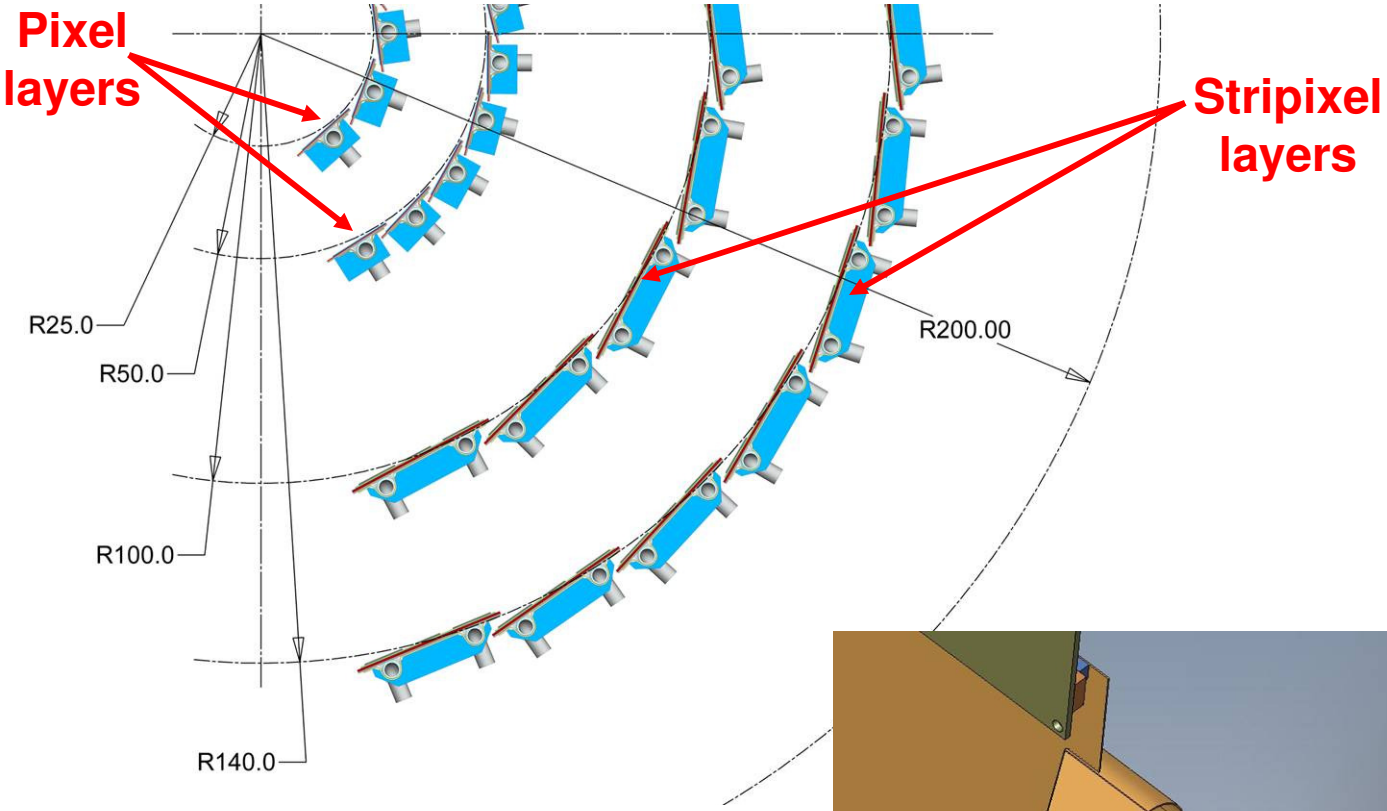


Expected DCA resolution
pions in $3<p_T<4$ GeV/c

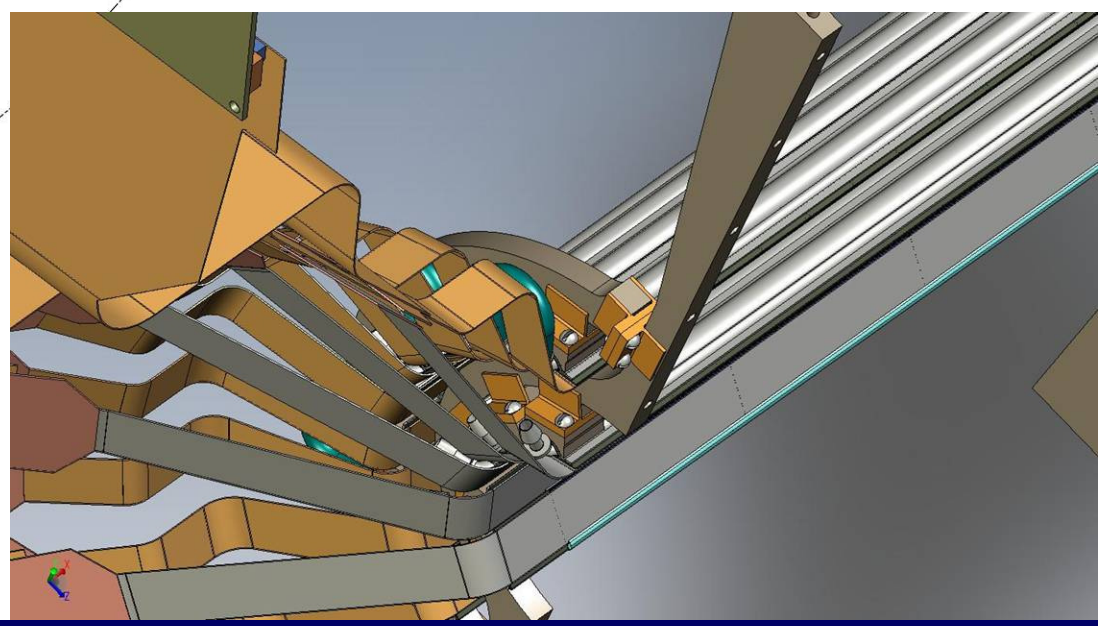


- **Specifications:**
  - Large acceptance ($\Delta\phi \sim 2\pi$ and $|\eta| < 1.2$)
  - Displaced vertex measurement $\sigma < 40$ μm
  - Charged particle tracking $\sigma_p/p \sim 5\%$ p at high pT
  - Detector must work for both of heavy ion and pp collisions.
- **Technology Choice**
  - Hybrid pixel detectors developed at CERN for ALICE
  - Strip detectors, sensors developed at BNL with FNAL's SVX4 readout chip

Conceptual Mechanical Structure (HYTEC Work)

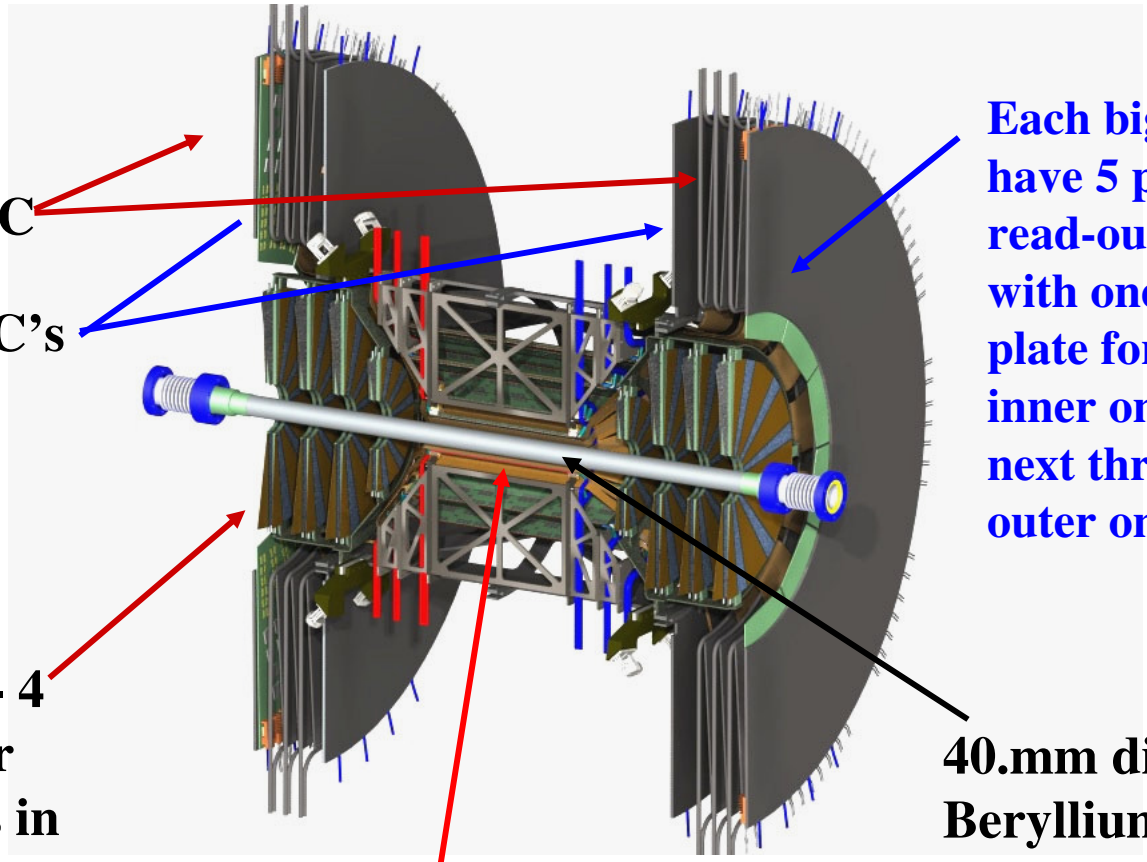


End on view of VTX four layers



Conceptual Mechanical Structure (HYTEC Work)

Baseline design for the VTX and FVTX detectors;



FVTX-ROC

VTX ROC's

Each big wheel will have 5 planes of read-out electronics, with one cooling plate for each plane; inner one for strips, next three for pixels, outer one for FVTX.

FVTX - 4 detector stations in each end

VTX – 4 layers ~ 2π

40.mm diameter Beryllium beam pipe