A New Physics Opportunity at RHIC with the sPHENIX experiment

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Many discussions with Y. Akiba, M. McCumber, Y. Kwon, C. da Silva, J. Huang, I. Nakagawa, M. Brooks, J. Kapustinsky and other sPHENIX collaborators

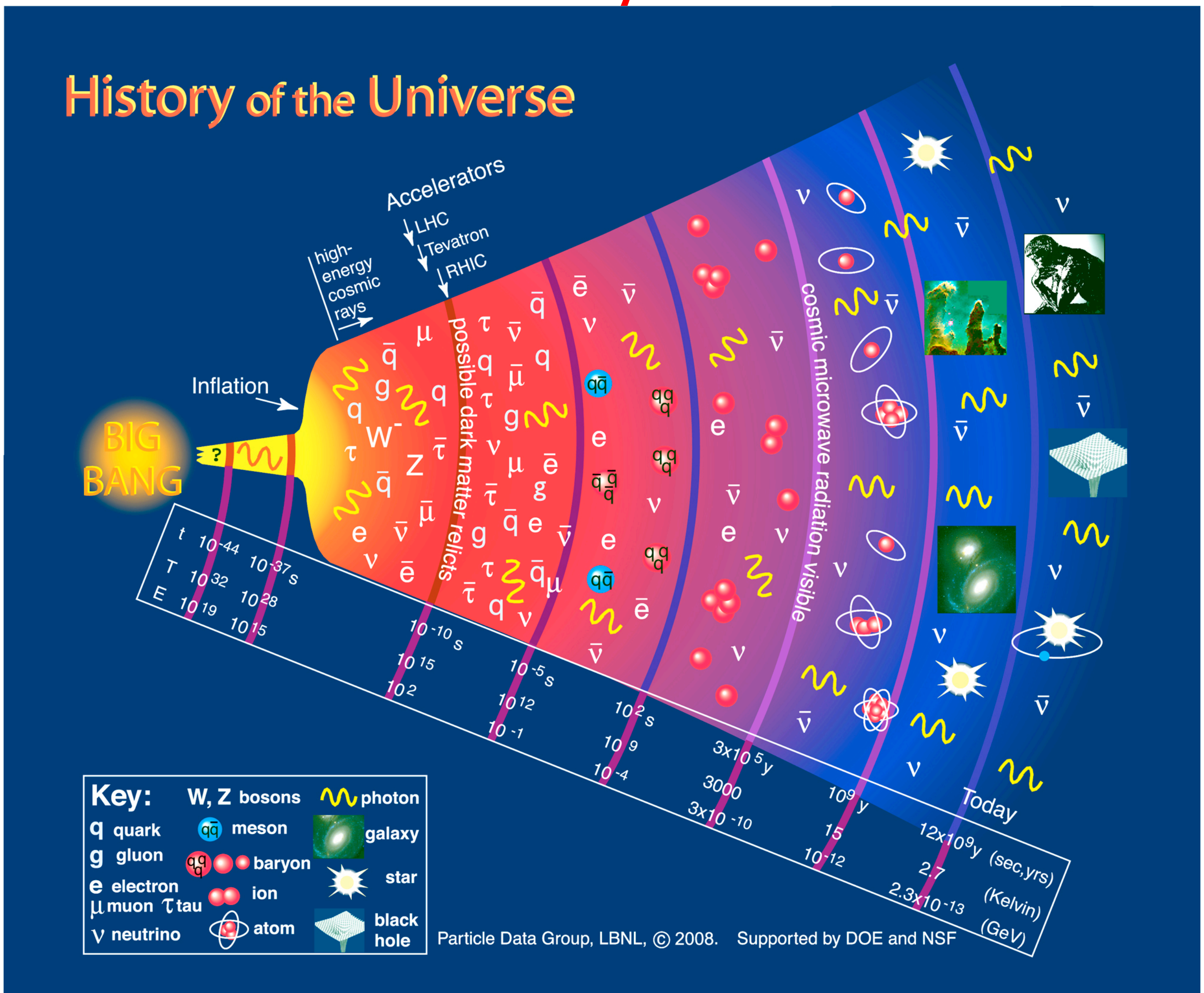
Outline

- Selected physics topics of the future sPHENIX
  - 15 years of RHIC operation, A+A, p/d+A, p+p
  - QGP physics at RHIC in the next decade

- Experimental challenges and prospects
  - Jet/Heavy quark measurements
  - Heavy quarkonia measurements
  - Importance of precision tracking

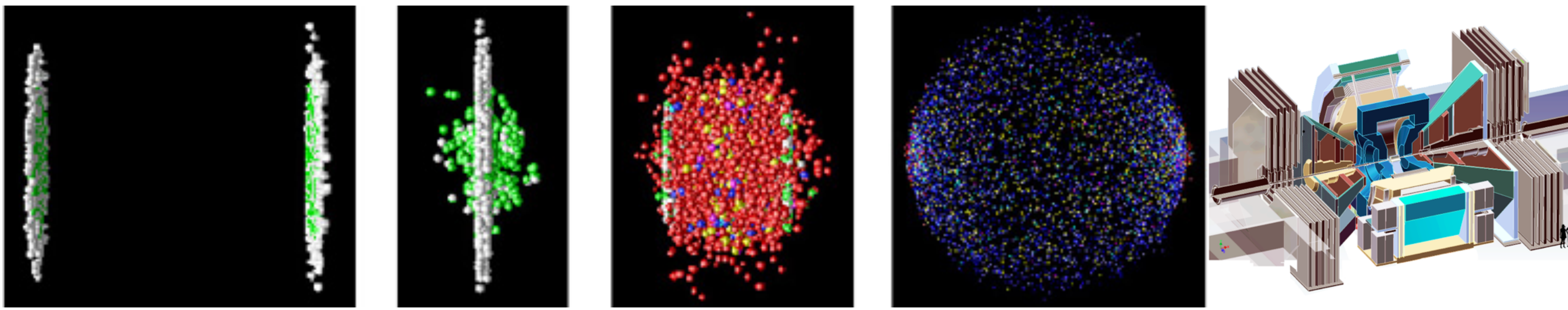
- Possible tracking detector options for sPHENIX
  - Si-strip sensors with FPHX readout (used by PHENIX FVTX)
    - Precision tracking
    - Hadron PID with dE/dx?
  - MAPS pixel detectors R&D
    - Thickness ~50um, pixel ~O(30um x 30 um)
    - Cost effective?
  - Opportunity to collaborate with Korean universities

Recreate a State of Matter/QGP of the Early Universe in Heavy Ion Collisions



Color screening, parton dE/dx and QGP properties

- Before collision
- Initial state CNM effects
- QGP
- Hadron gas CNM effects
- Hadrons/muons

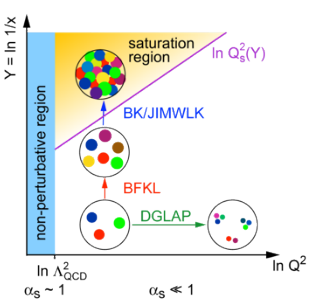


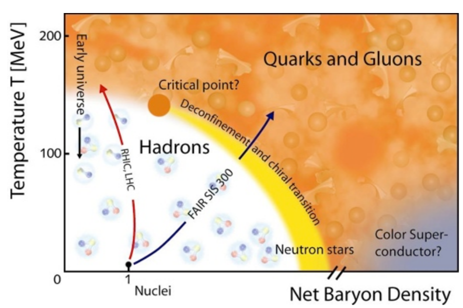
Heavy Ion Collision – Time Evolution

Time (fm/c)

1

10



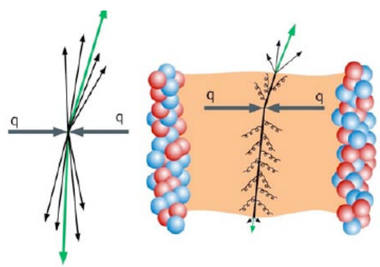


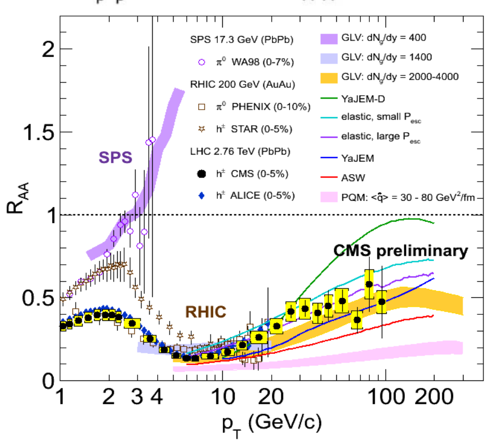
QGP is created in A+A collisions!

Two Major Discoveries at RHIC (LHC)

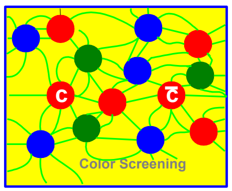
$$R_{AA} = \frac{\sigma^{A+A}}{< N_{collisions} > \cdot \sigma^{p+p}}$$

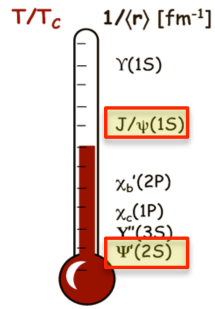
- High pT jet suppression
  - Parton energy loss
  - LHC expanded the pT range



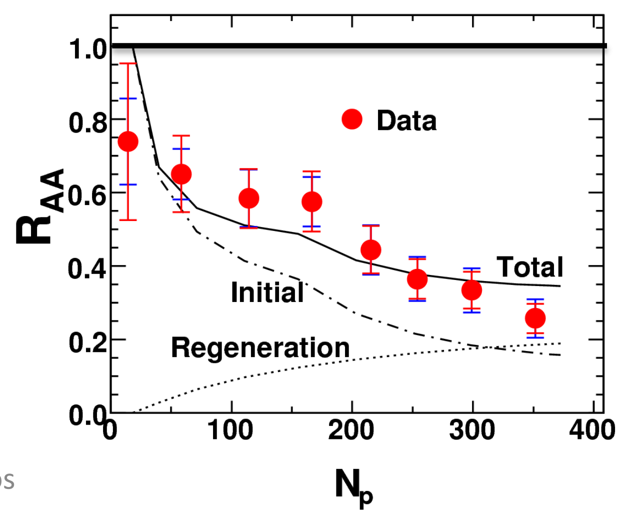


- Heavy quarkonia modification
  - Suppression
  - Recombination





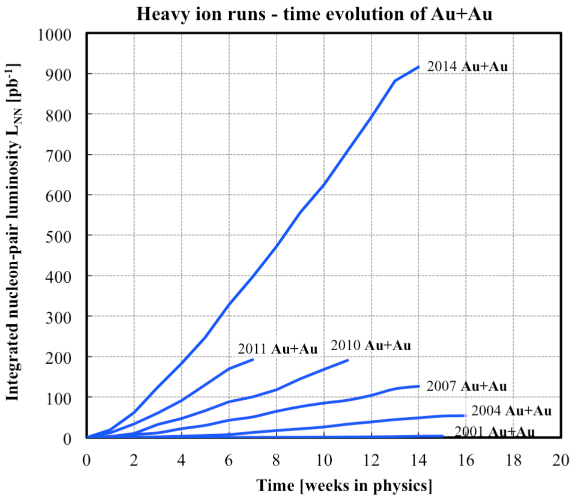
PHENIX J/Psi

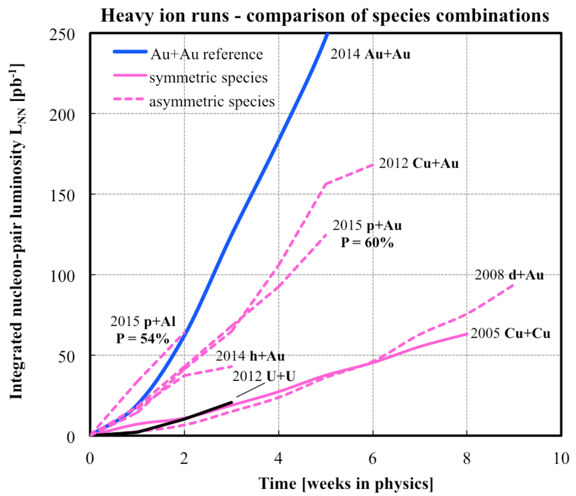


Discovery Science

15+ Years of RHIC Experiments

- RHIC runs 2001-2015
  - Discovery of perfect liquid – QGP
  - Cold Nuclear Matter effects in p/d+A
  - The polarized proton structure and spin dynamics in QCD
- Great progress in accelerator performance
  - Extended our physics reach
- Super-PHENIX(sPHENIX) is conceived as a second generation experiment
  - Building upon what has been learned at RHIC and LHC
  - Taking advantage of latest technologies
  - Serving as a Day-1 detector for the future Electron-Ion-Collider (EIC)





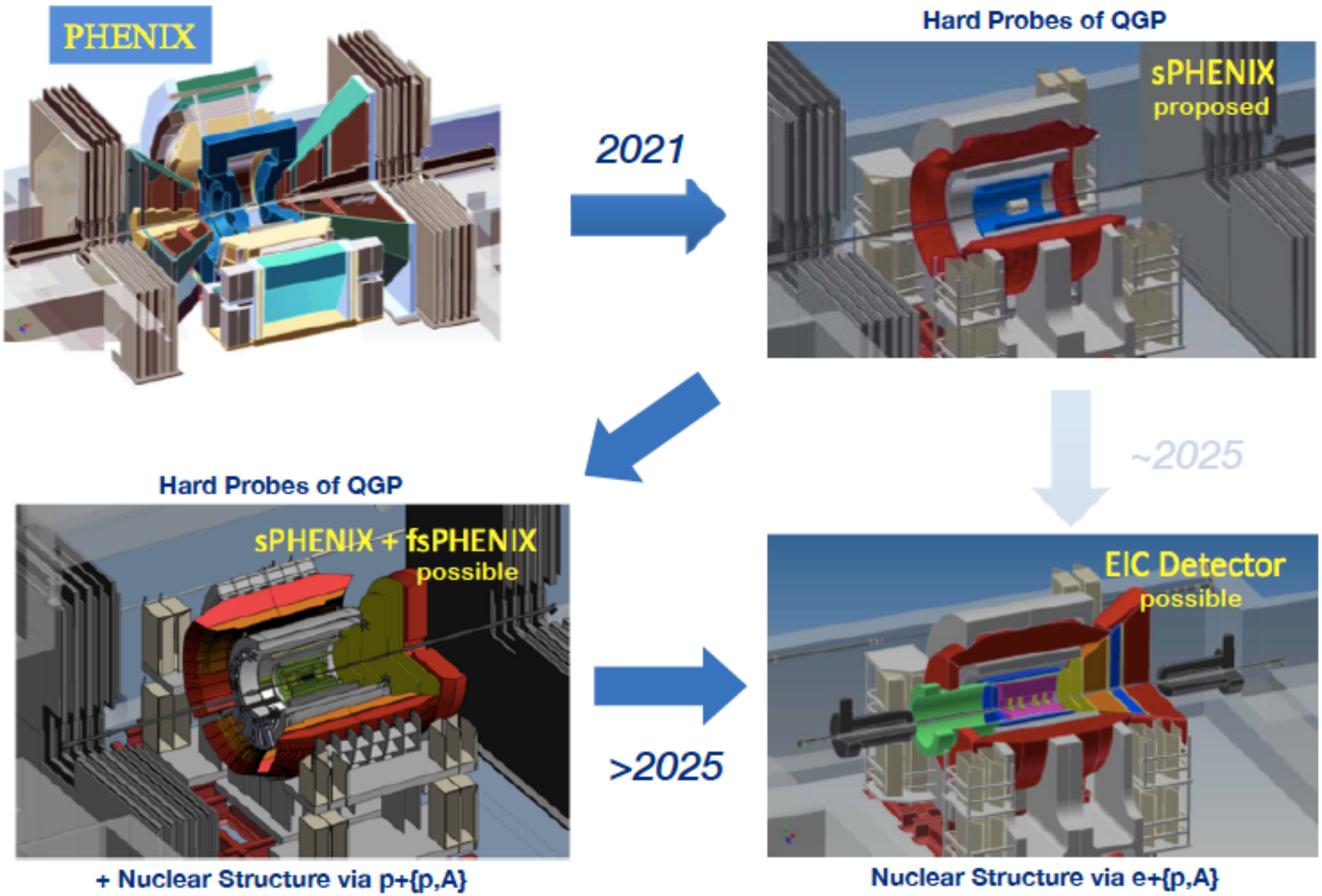
Proposed run schedule for RHIC

Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	$p^{\uparrow}+p^{\uparrow}$ at 200 GeV $p^{\uparrow}$+Au, $p^{\uparrow}$+Al at 200 GeV High statistics Au+Au Au+Au at 62 GeV ?	Extract η/s(T) + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	$p^{\uparrow}+p^{\uparrow}$ at 510 GeV	Transverse spin physics Sign change in Sivers function	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2021-22	Au+Au at 200 GeV $p^{\uparrow}+p^{\uparrow}$, $p^{\uparrow}$+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

sPHENIX

sPHENIX: Precision Study of QGP

A first step toward the next generation experiments



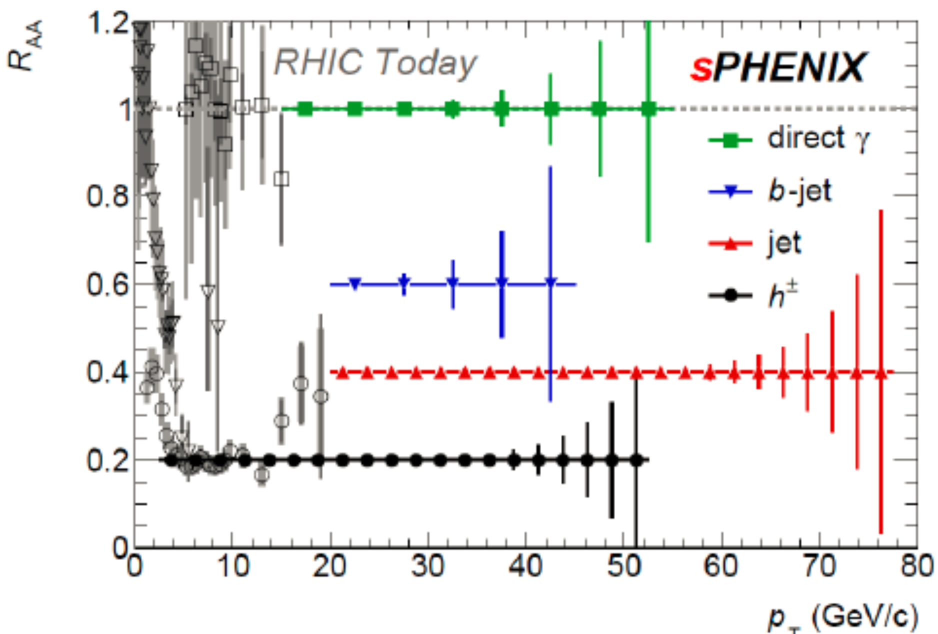
Goal of sPHENIX Program

A new precision study QGP properties over a wide range of length scale and temperatures

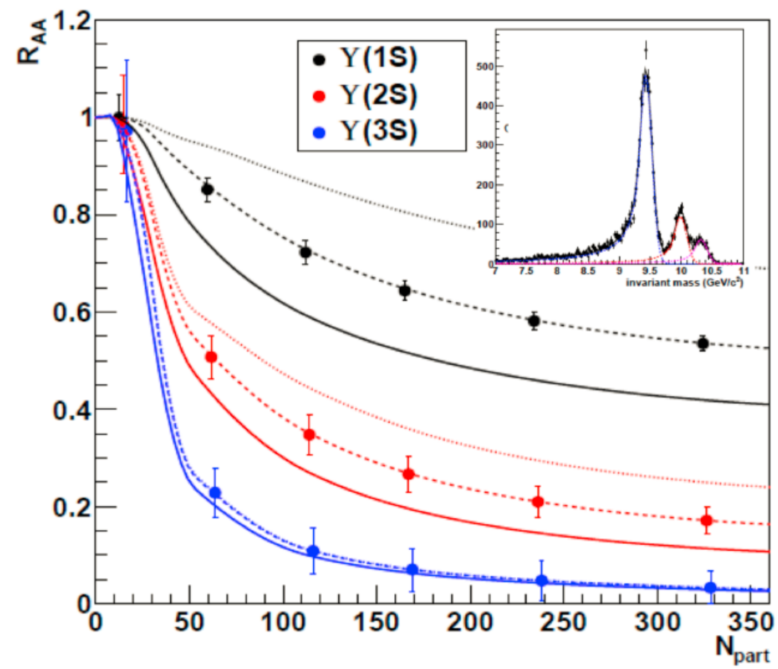
A new experimental tool to study QGP with the following probes

- Light and heavy quark jets
- Upsilon states

Jet – medium interactions

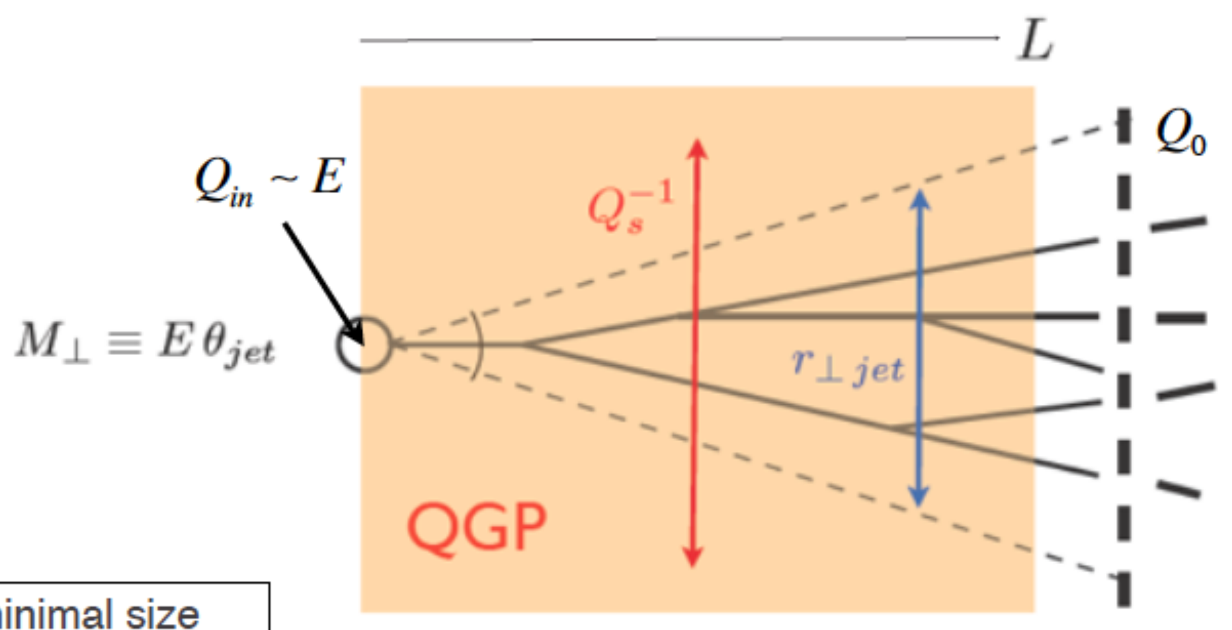


QGP color screening and suppression



Why Jets at RHIC?

- Access QGP properties/soft physics with hard probes



Q_S^{-1} = minimal size of probe to which the medium look opaque

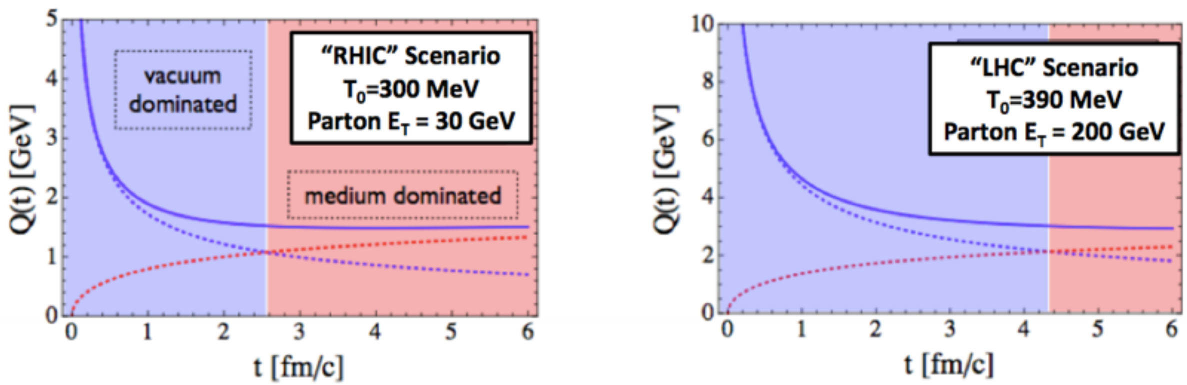
Momentum scale of medium $\quad Q_s = \sqrt{qL} \approx m_D \sqrt{N_{scatt}}$

Transverse size of jet $\quad r_{\perp \text{jet}} = \theta_{\text{jet}} L$

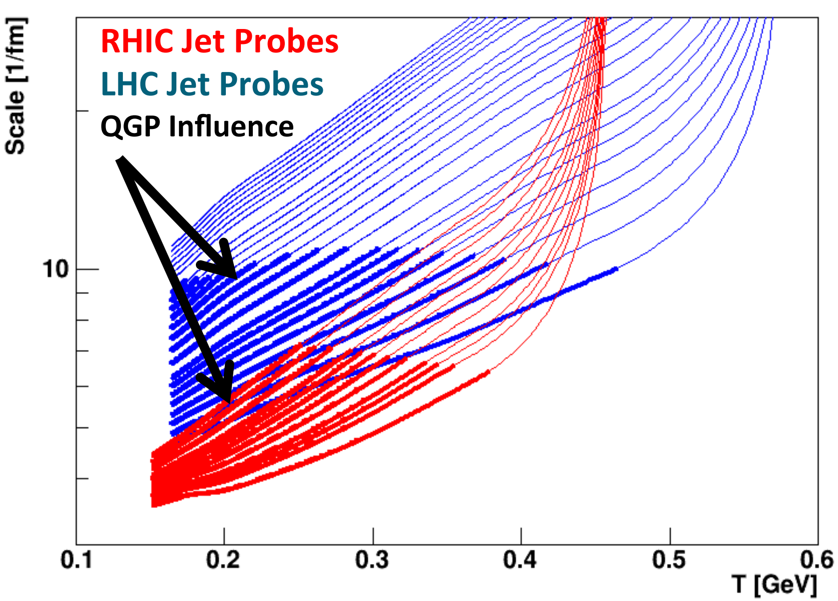
Jet Modification in QGP

B. Mueller Nucl. Phys., A855: 74-82, 2011

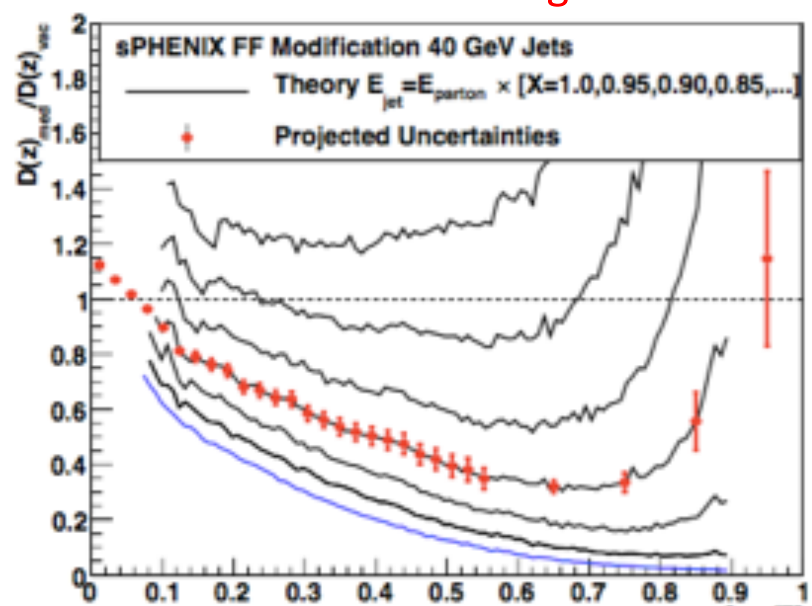
- At RHIC, QGP effects dominates jet evolution
  - Longer time
  - Close to T_c



Jet evolution probed by RHIC and LHC

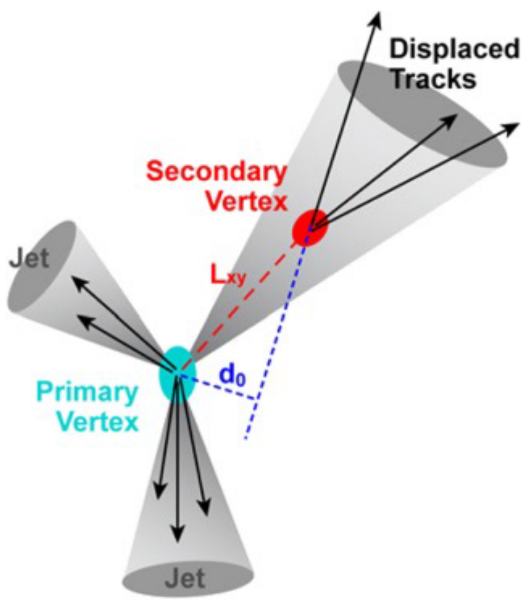


Modified Jet Fragmentation

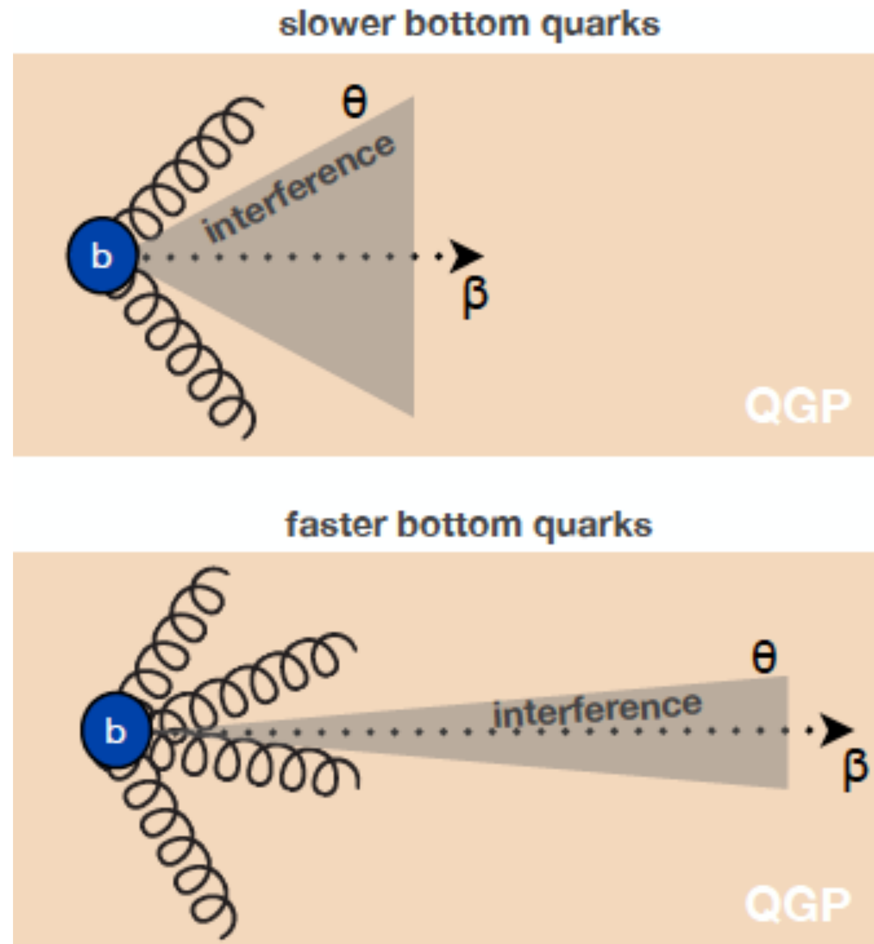


A New Tool: B-jets in Heavy Ion Collisions

- Mass dependent of dE/dX
  - Radiation vs collisional energy loss
  - "dead cone effects"
- Precision tracking required!
  - Displaced 2nd vertex identification



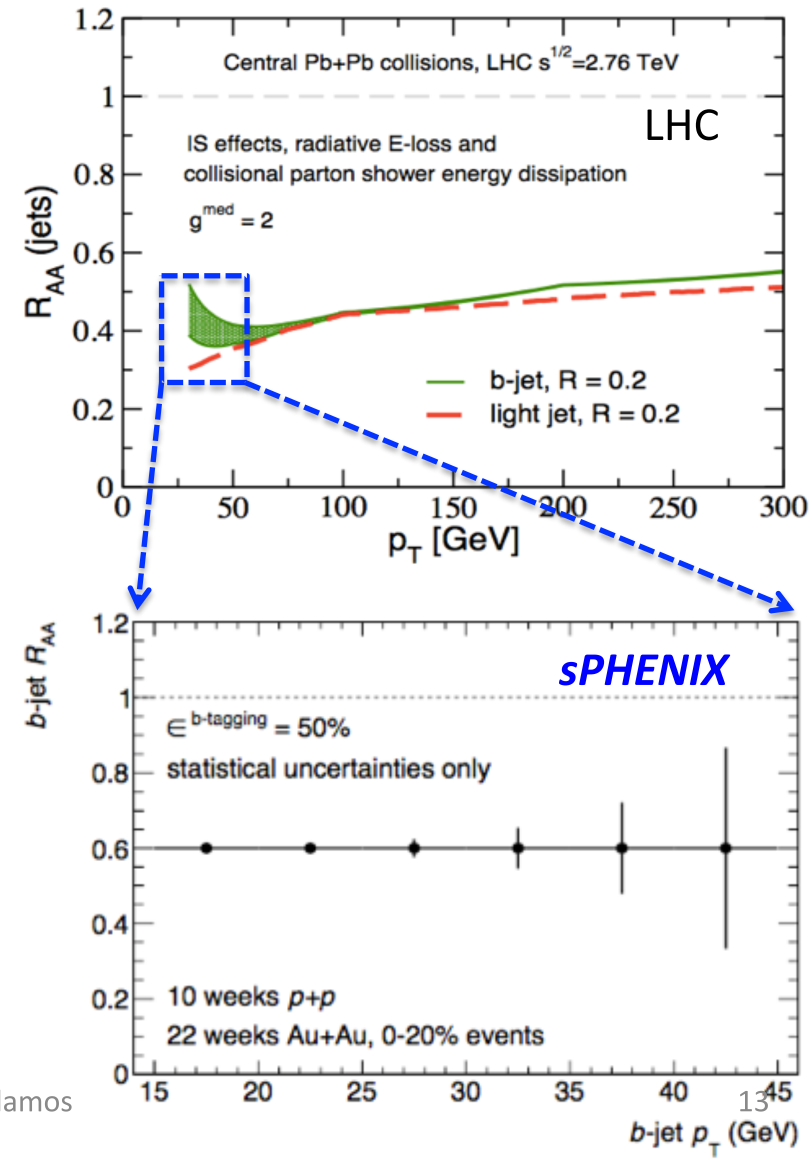
$$\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$$

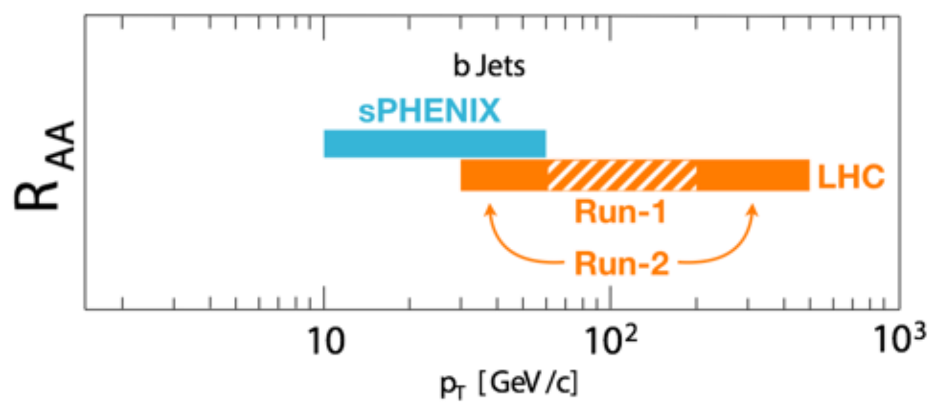


More on B-Jets: RHIC vs LHC

- B-Jet suppressions
  - High pT B-jets behave like light jets
  - Low pT B-jets most sensitive to quark mass-effects, pT ~ $O(M_B)$

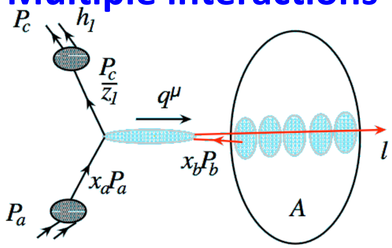
Huang, Kang, Vitev: hep-ph/1306.0909



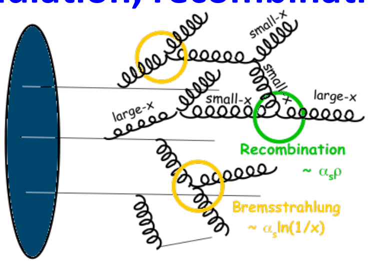


Quarkonia as a QGP thermometer

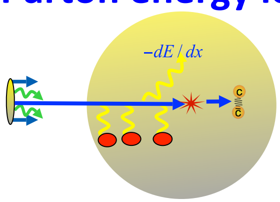
Multiple interactions



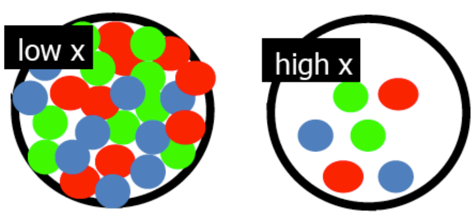
Radiation, recombinations

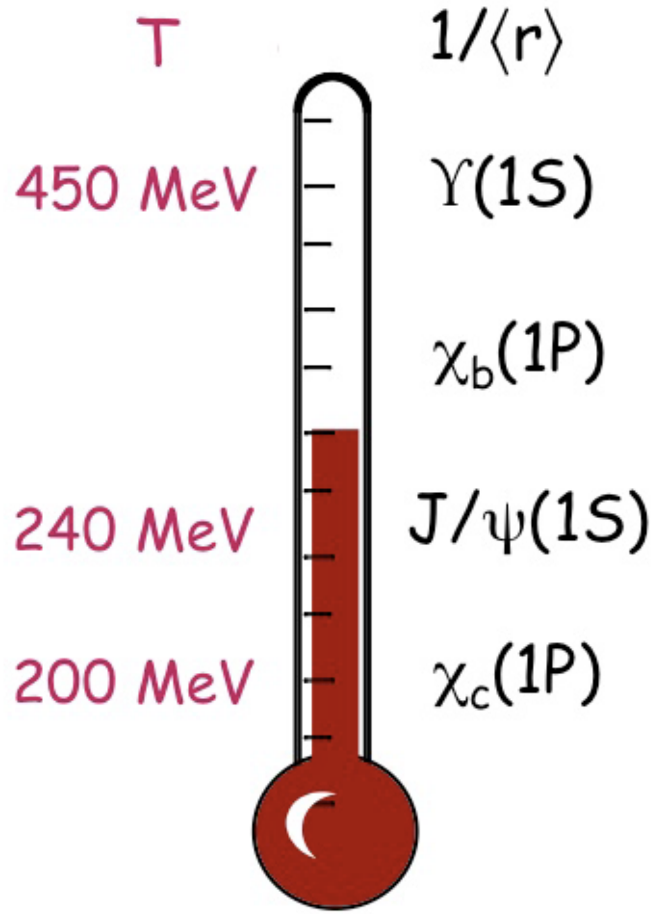


Parton energy loss

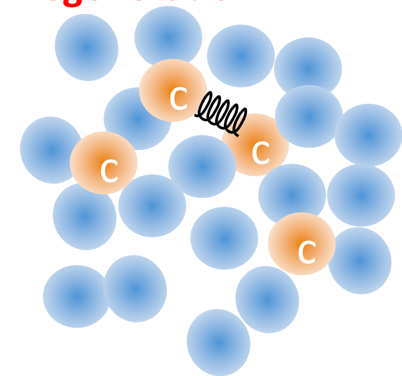


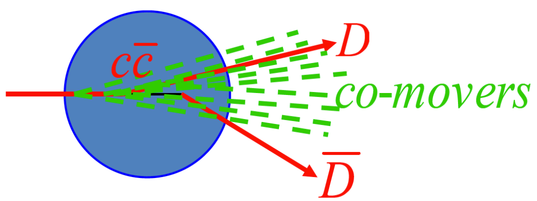
Gluon saturation





Coalescence, Regeneration





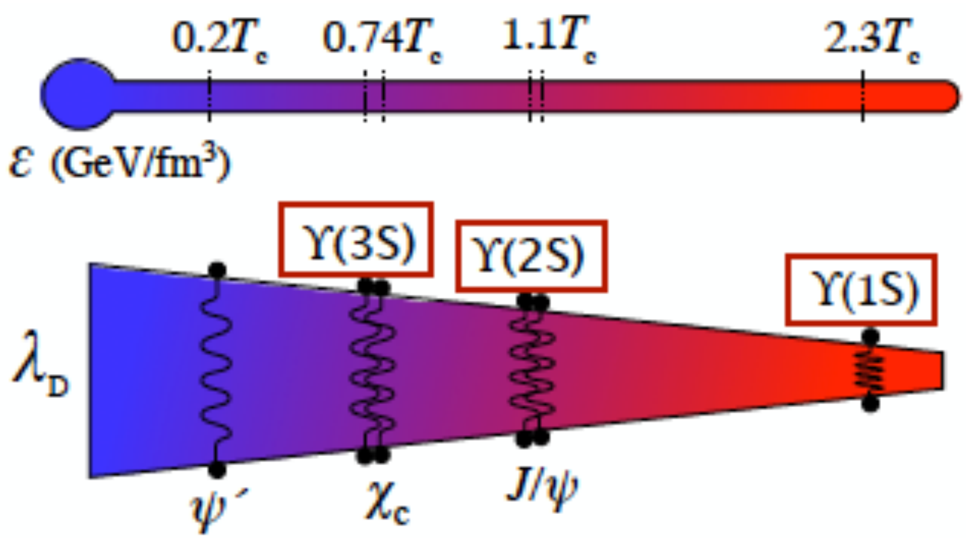
Need several measurements to isolate different effects.

Must have: p+p, p+A and A+A

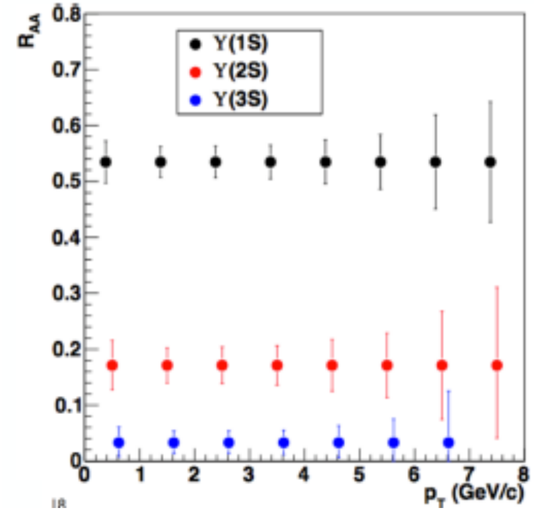
Upsilon States at RHIC

- Minimal "recombination" at RHIC
- Optimal "temperature range"

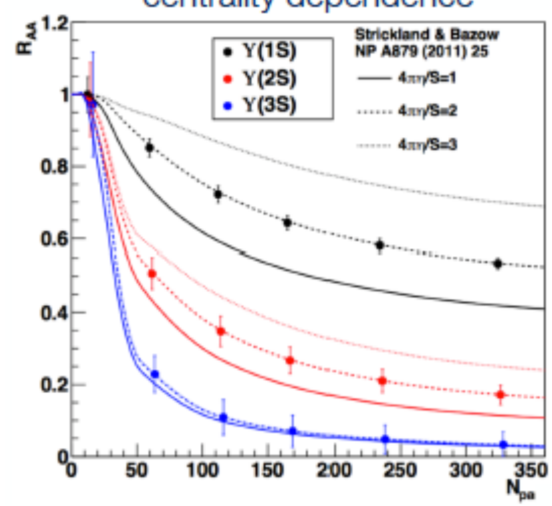
- Similar Stat. in p+p and p+A, good references



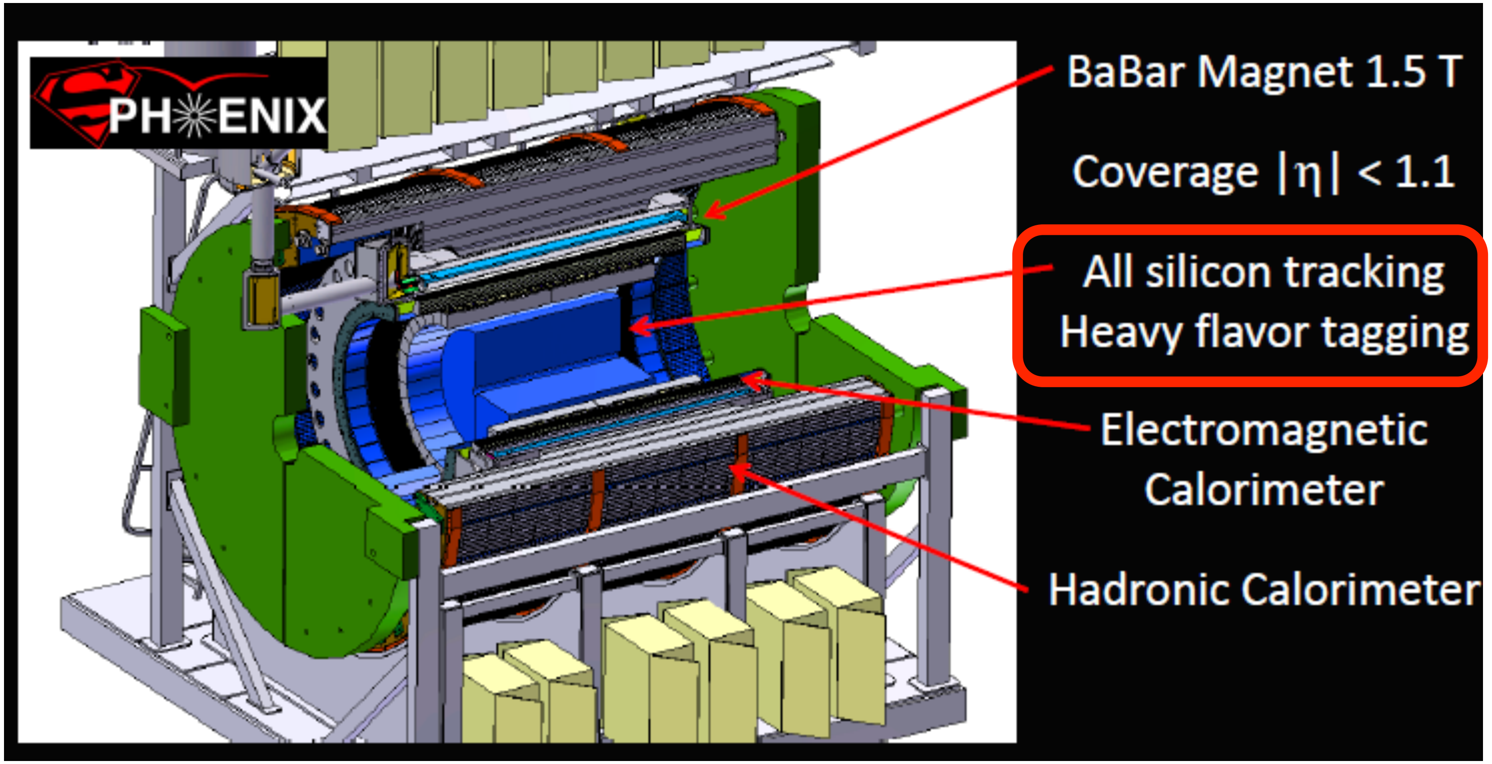
momentum dependence



centrality dependence



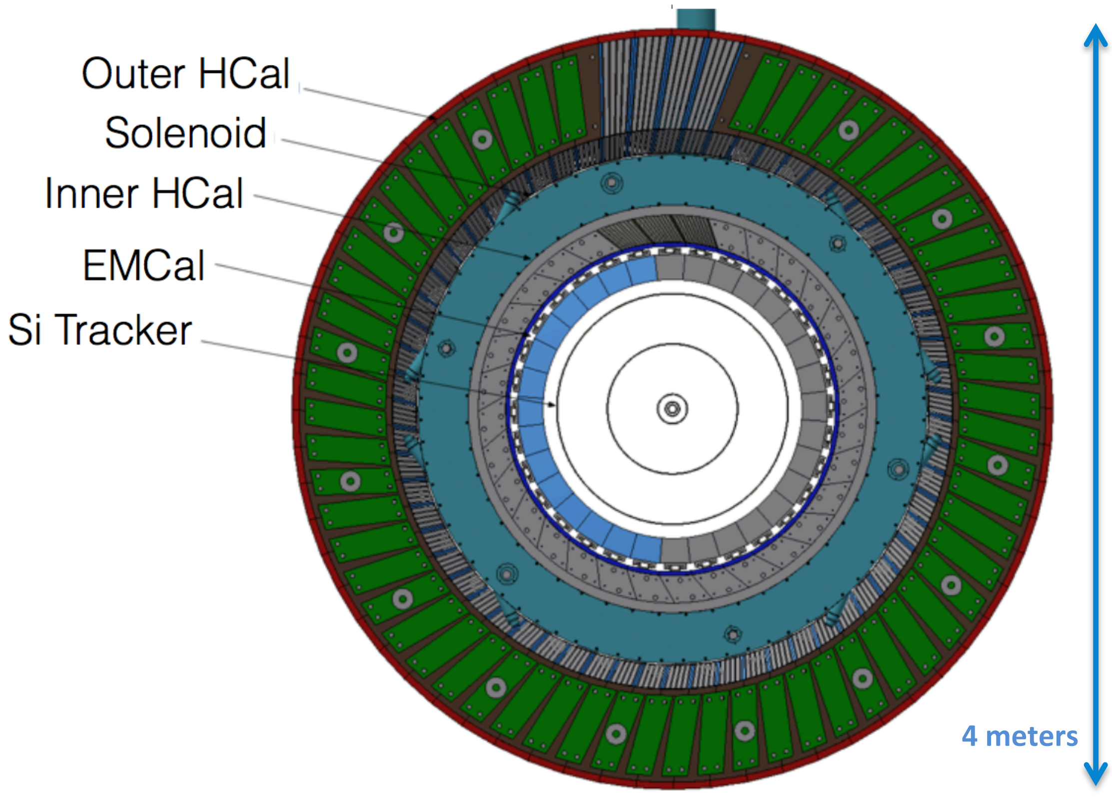
Reference Design and Requirements



- $|\eta|<1.1$ and $\Delta\phi=2\pi$
- High efficiency in central Au+Au to measure modified Jet FF
- High momentum resolution to separate Upsilon states ($\sigma_M < 100$MeV)
- Precision vertex measurement for heavy flavor measurements (D, B→J/Psi, b-tagged jets)
- High DAQ rate (~15kHz)

A collider detector!

sPHENIX Detector Calorimeters



SPACAL EmCal
12%/sqrt(E) resolution

Two longitudinal segments of HCal
5 interaction lengths

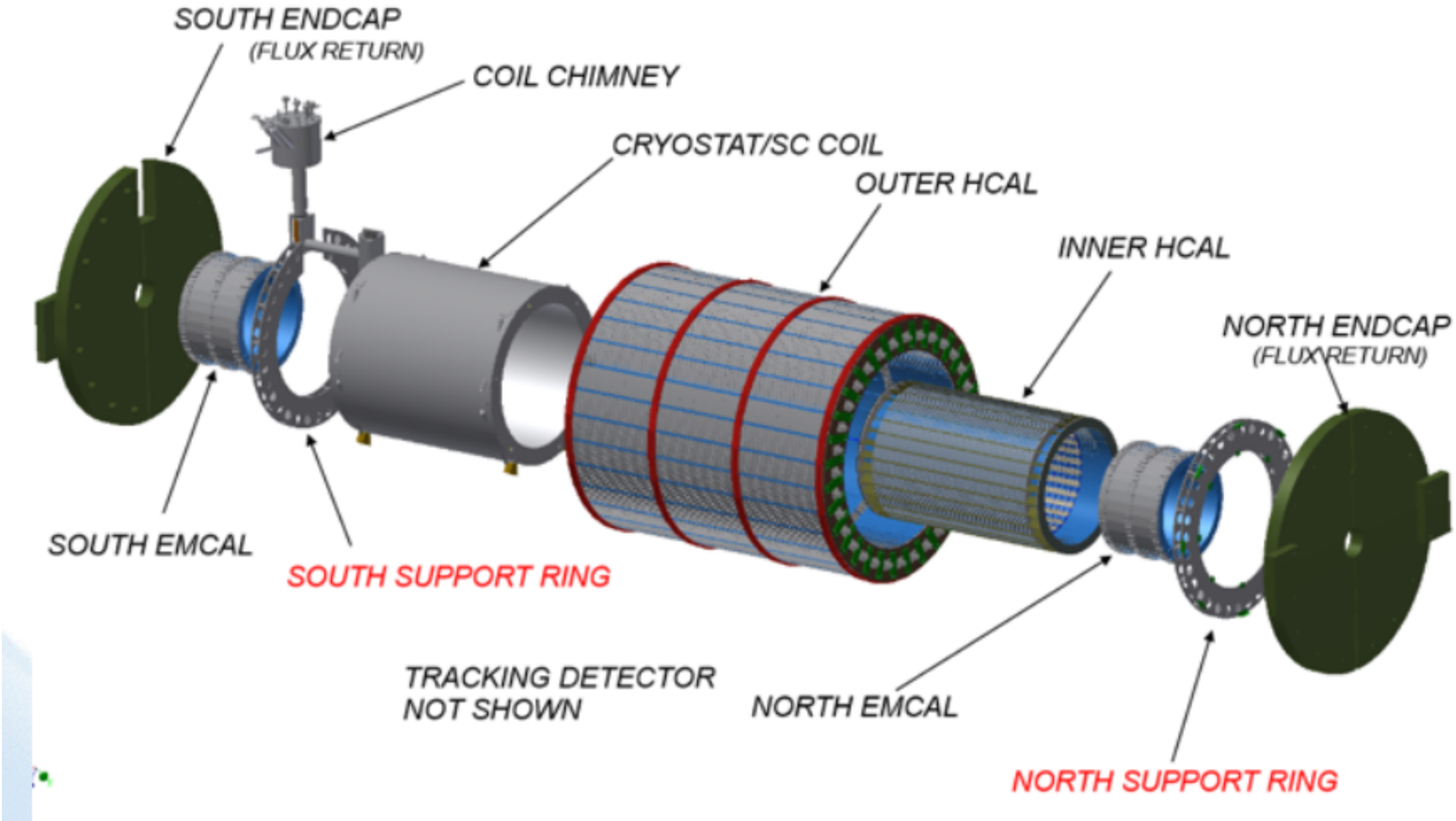
Jet resolution in p+p
~65% /sqrt(E)

- Common Silicon Photomultiplier (SiPM) readout for Calorimeters
- Full clock speed digitizers, digital information for triggering
- High data acquisition rate capability, ~ 15 kHz

  1-year RHIC run = massive 600B events, no trigger bias

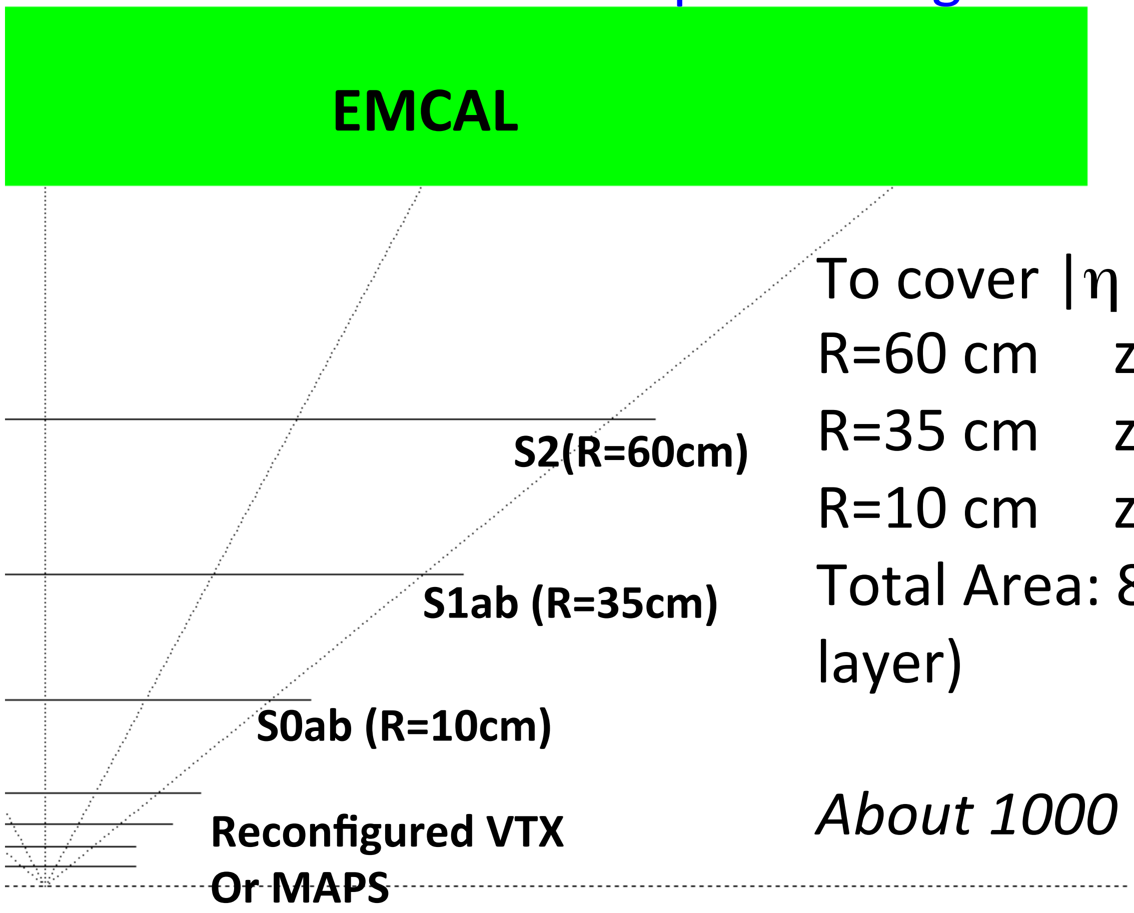
HCal and EMCal Status

- Well under development
  - Prototypes developed and beam tested!



Si-Strip Based Tracking System

A New Conceptual Design with FPHX Readout



Y. Akiba

To cover $|\eta|<1.1$

R=60 cm zmax = 80cm Area = 6.0m^2

R=35 cm zmax = 45cm Area = 2.0m^2

R=10 cm zmax = 14cm Area = 0.2m^2

Total Area: 8.2 m^2 of silicon (single layer)

About 1000 10x10cm sensors needed

In the MIE, the outer radius is enlarged to 80cm to achieve Upsilon resolution of less than 100MeV if the radiation length of S1ab is 2%. If we can reduce the radiation length to be less than 1.5% (FPHX air cooled), this 60cm radius version should have the same Upsilon resolution.

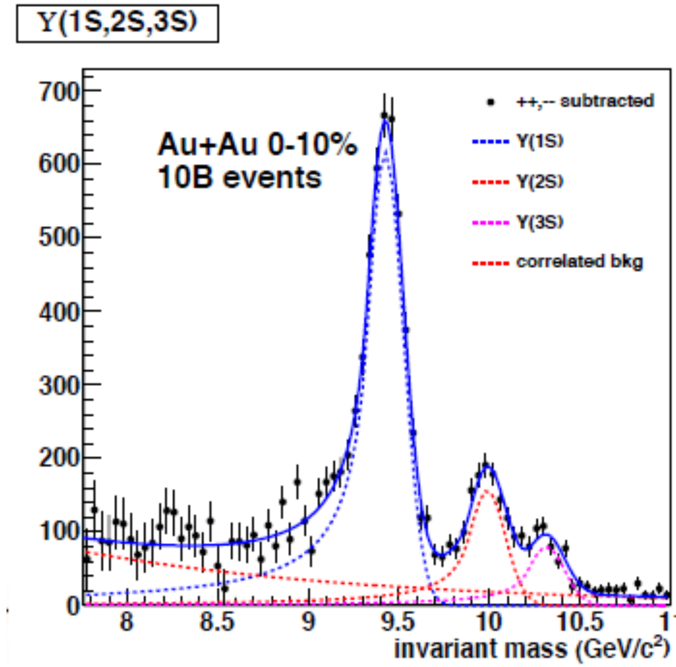
MIE Reference Design & Performance

A. Frawley DOE review 2015/04/30

2 pixel layers + 5 outer tracking layers
Layers 4 and 6 are for improved track-hit association
Layers 1, 2, 3, 5, 7 make the momentum measurement

	Layer	radius (cm)	sensor pitch (μm)	sensor length (mm)	sensor depth (μm)	total thickness % X_0	area m^2
Reconfiured VTX	1	2.7	50	0.425	200	1.3	0.034
	2	4.6	50	0.425	200	1.3	0.059
S0a/b	3	9.5	60	8	320	1.35	0.152
	4	10.5	240	2	320	1.35	0.185
S1a/b	5	44.5	60	8	320	1	3.3
	6	45.5	240	2	320	1	3.5
S2	7	80.0	60	8	320	2	10.8

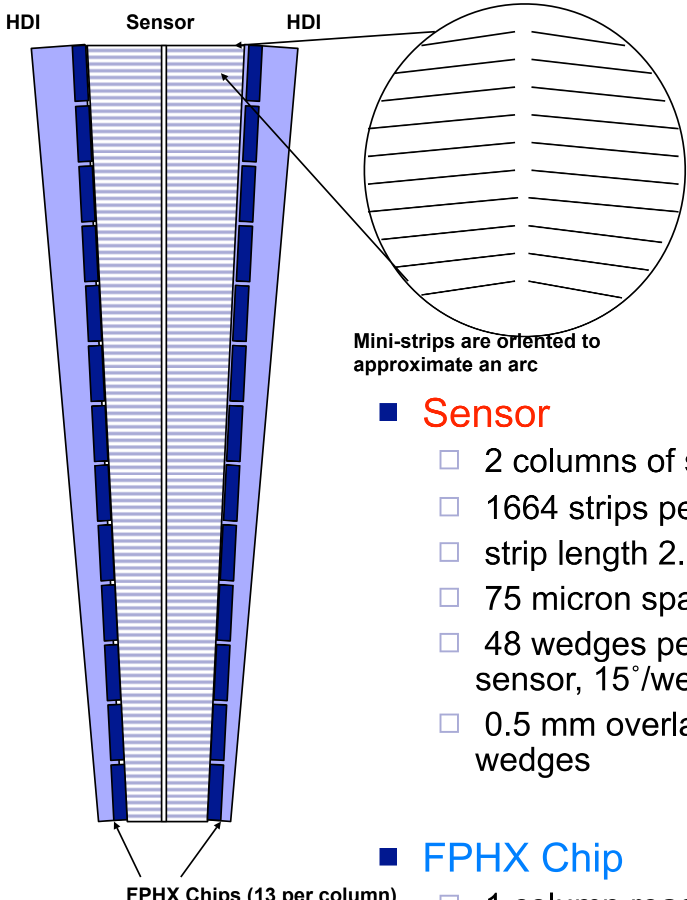
The overall tracker mass is $X/X_0 = 9.3\%$. We think it is conservative.



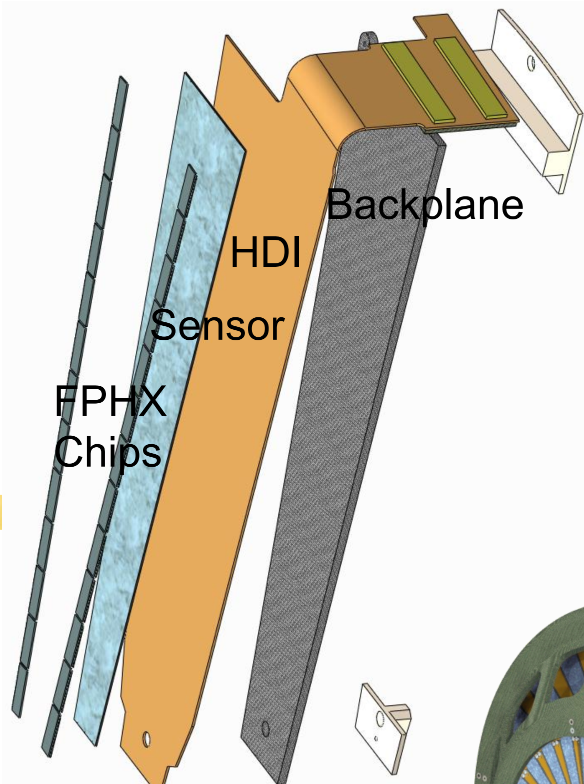
- This 7 layer baseline design was implemented in
- Simulation shows that this design can separate the three Upsilon states
- Much room for design optimization (performance, cost, etc)
  - FPHX readout could significantly reduce the material, thus R2: 80 -> 60 cm

The PHENIX Forward Vertex Detector (FVTX)

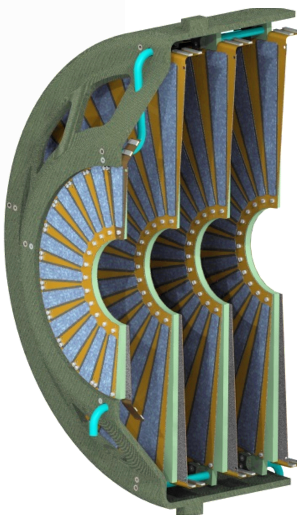
successful operation since 2012



- **Sensor**
  - 2 columns of strips
  - 1664 strips per column
  - strip length 2.8 to 11.2 mm
  - 75 micron spacing
  - 48 wedges per disk (7.5˚/ sensor, 15˚/wedge)
  - 0.5 mm overlap with adjacent wedges



- **FPHX Chip**
  - 1 column readout
  - 128 channels
  - ~ 70 microns channel spacing
  - Dimensions –9mm x 1.2 mm



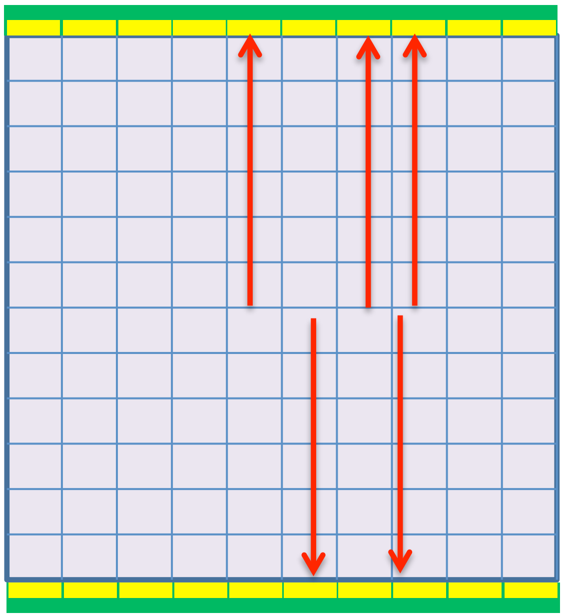
FPHX Readout Option

- AC coupled
  - Low noise and stable pedestal
- Low power consumption (~20% SVX4, original design)
  - Air cooling, less materials
- Push-through readout
  - High speed readout, 4 hits/4BCO
  - Triggering capability (FVTX multiplicity trigger for e.g.)
- Signal amplitude available
  - 3-bit ADC (5-bit possible)
  - 128 channels per chip
- Extensive good experience with the successful FVTX upgrade in PHENIX
  - ROC, FEM

Concept of FPHX Based Module

A. Akiba

ROC of 10 FPHX chip



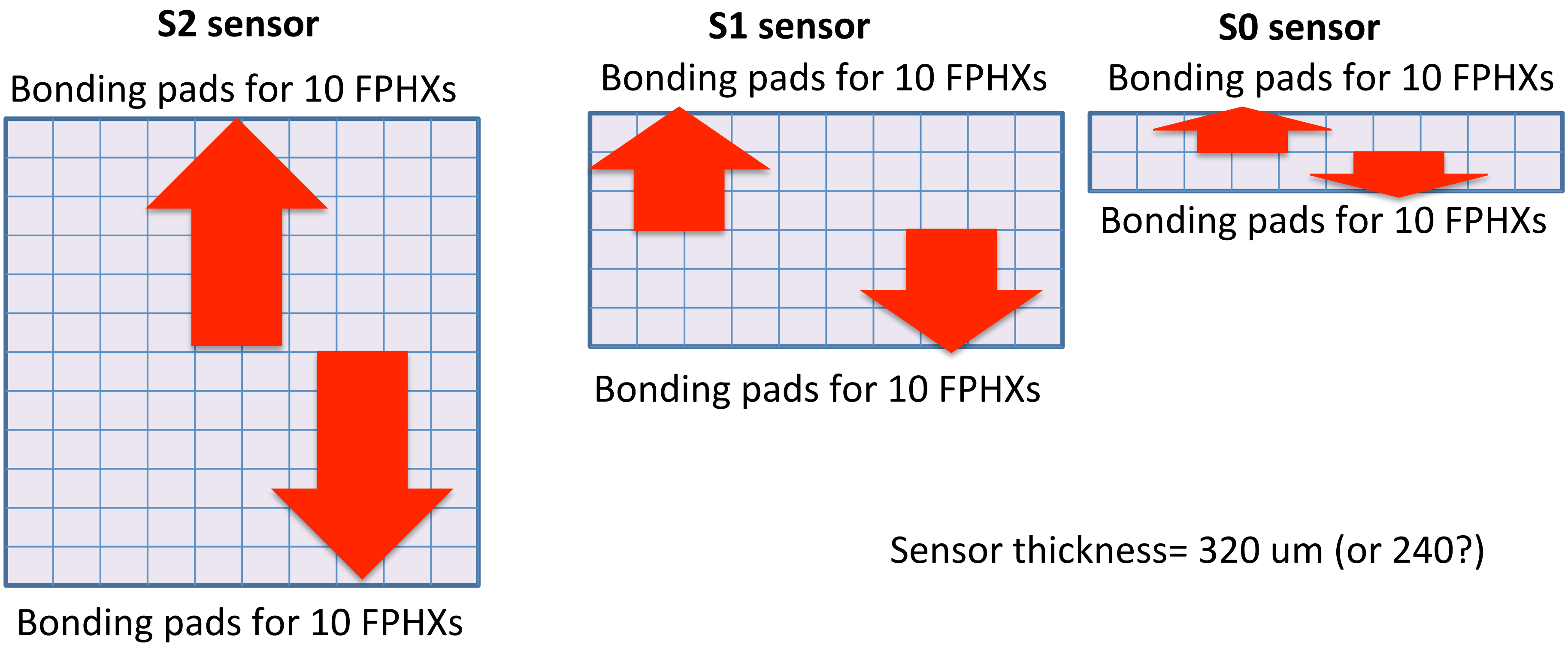
ROC of 10 FPHX chip

One FPHX reads out 6 cells

- Take advantage of existing FVTX readout system
  - Sensor of (12 x 10) cell structure. Each cell has 128ch of 75 um x 9.6mm strips
  - A "ROC" (or "HDI") of 10 FPHX chips. They are attached at the top and the bottom of the sensor
  - The "ROC" is electrically equivalent to the "small HDI" of FVTX so that it can be read-out by a FVTX ROC

3 Types of Sensors

A. Akiba



Sensor thickness= 320 um (or 240?)

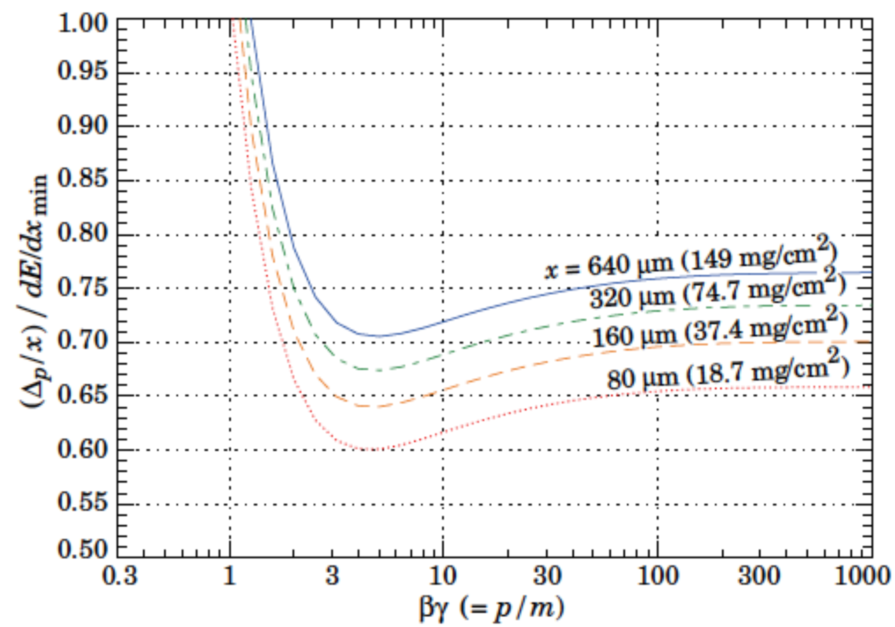
- If tracker use FPHX chip, one "cell" of the sensor becomes 9.6mm wide (to read-out by 9mm long FPHX chip).
- One edge of the sensor is read-out by a "ROC" (or HDI in FVTX terminology) of 10 FPHX chip.
- 10 FPHX chip "ROC" is electrically equivalent to the small FVTX HDI

Hadron PID with dE/dx?

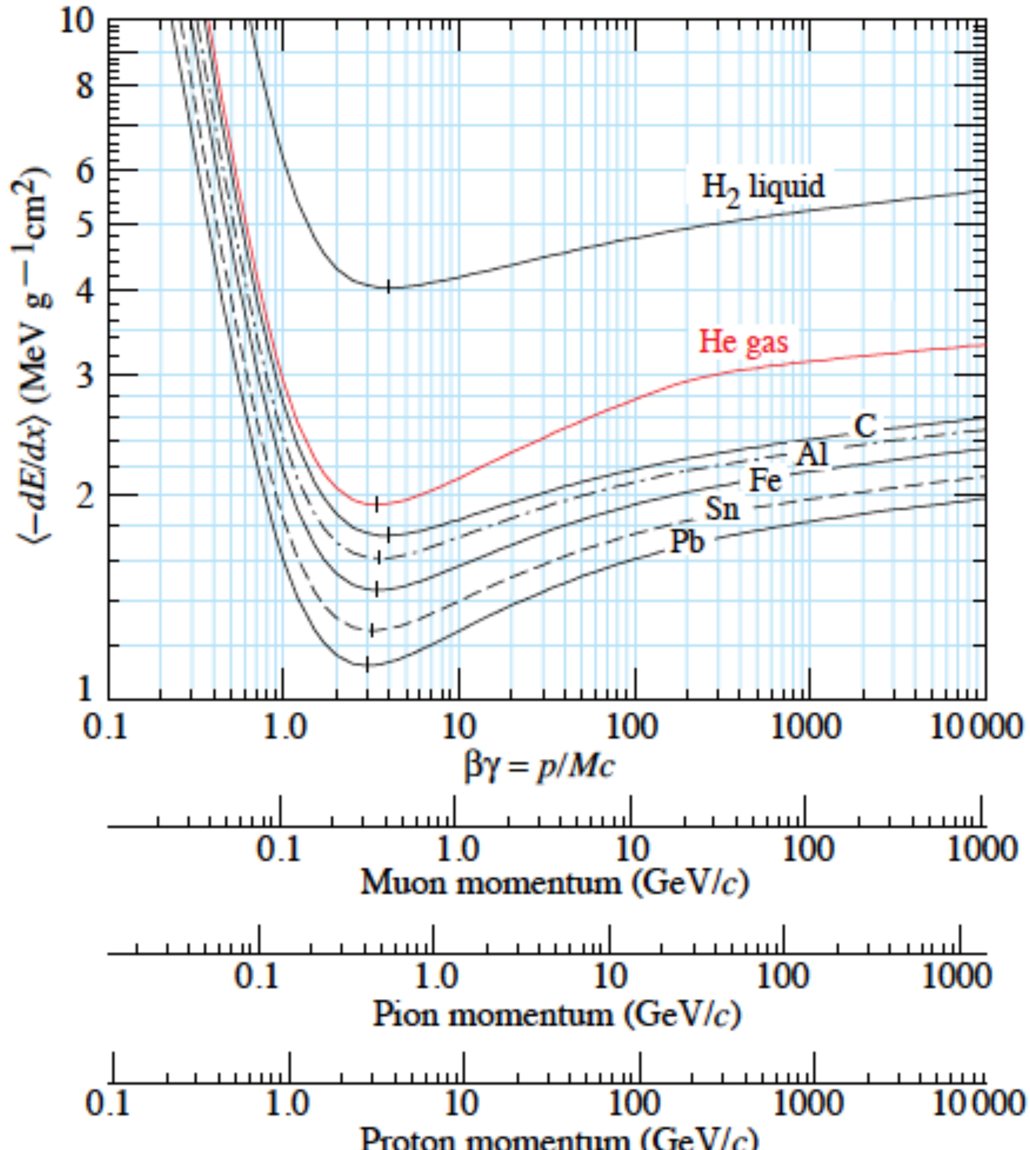
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- FPHX provide dE/dx information
  - FVTX: 3-bit ADC
  - 5-bit possible
- Charged pi/K/p identification at low pT
  - Jet energy loss and fragmentation
    - Where do the lost energy go? Low-z tracks!
    - CMS jet results
  - PID for pT <~ 2GeV
- Prefer thick sensors
  - 500um? (Korean Institutes)
  - Developed for MPC-EX

Most probable energy loss in Si-sensor
Normalized to MIP



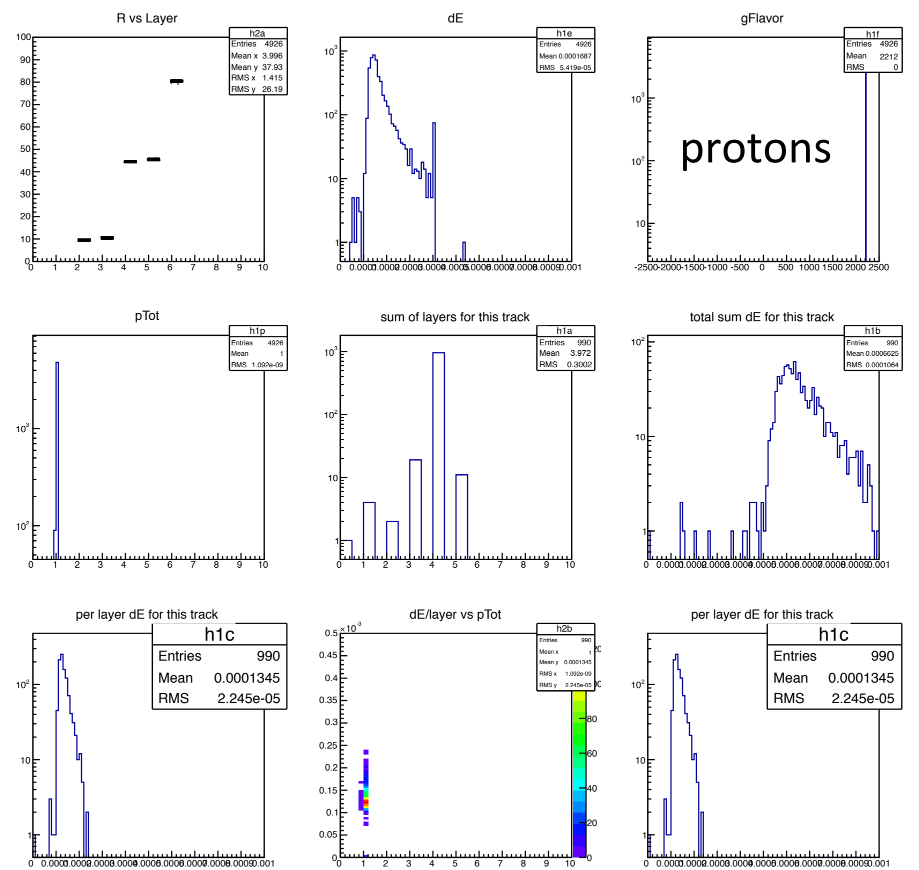
MIP dE/dx (PPG)

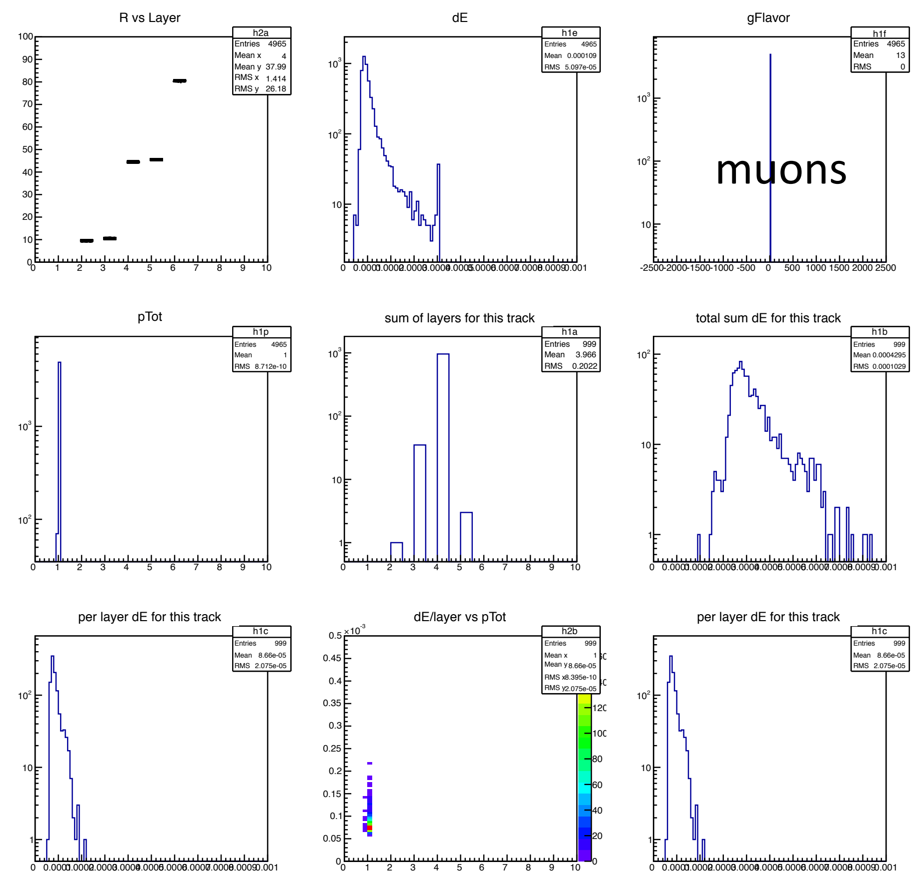


⟨−dE/dx⟩ (MeV g−1cm2)
10
8
6
5
4
3
2
1
H2 liquid
He gas
C
Al
Fe
Sn
Pb
0.1
1.0
10
100
1000
10 000
βγ = p/Mc
0.1
1.0
10
100
1000
Muon momentum (GeV/c)
0.1
1.0
10
100
1000
Pion momentum (GeV/c)
0.1
1.0
10
100
1000
10 000
Proton momentum (GeV/c)

GEAN4 Simulations with 300um Sensors

1GeV proton vs muon: ~2 sigma separation





Silicon Sensor Work in Korea

- Provided 500um thick sensors to PHENIX MPC-EX project
  - Excellent work!
- Thick sensors can be used for the S2 outer layer for optimal dE/dx measurements
  - Multiple scattering is not a concern for tracking
- Possible joint effort on Si-Tracker: 2016 - 2020
  - Japan/RIKEN
    - S0 and S1 layers (320um or 240um sensor)
  - Korea
    - S2 outer layer (500um sensor)
  - US/LANL
    - FPHX, ROC and FEM etc, following FVTX designs

sPHENIX: 2021-2022+

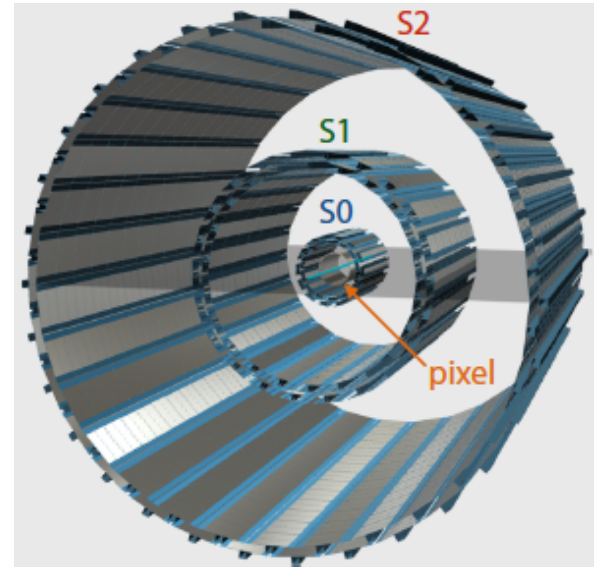
FPHX Based Silicon-Strip Tracker Summary

- FPHX chip for read-out.
  - FPHX is the read-out chip of FVTX
  - 128ch/chip. 3bit ADC /ch.
  - Low power (64mw per chip)

- 5 strip layers + 2 pixel (more options later)

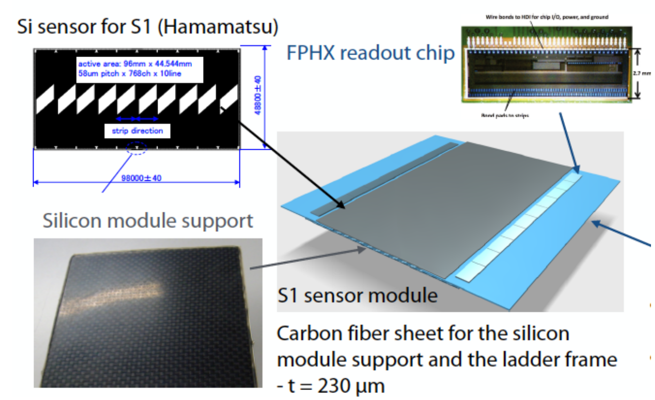
  S2: 1 strip layer at R~60 cm ~1% X0 (2% in ref. design)
  S1ab: 2 strip layer at R~34 cm ~1% X0 total (2% in ref. design)
  S0ab: 2 strip layer at R~ 8 cm ~1% X0 total (2.7% in ref. design)
  P1: pixel at R~5 cm (reconfigured VTXP) 1.3% X0
  P0: pixel at R~2.5cm (reconfigured VTXP) 1.3% X0

  - All strips are 75 μm x 9.6mm. S0b has a small stereo angle.
  - Overall material is ~5.6% radiation length.
  - Air cooling to achieve small radiation length
  - Small rad. length enables smaller over-all size and to keep the required momentum resolution to separate 3 Upsilon states
  - S0+S1+S2: ~8m^2 of silicon and 3.2M ch



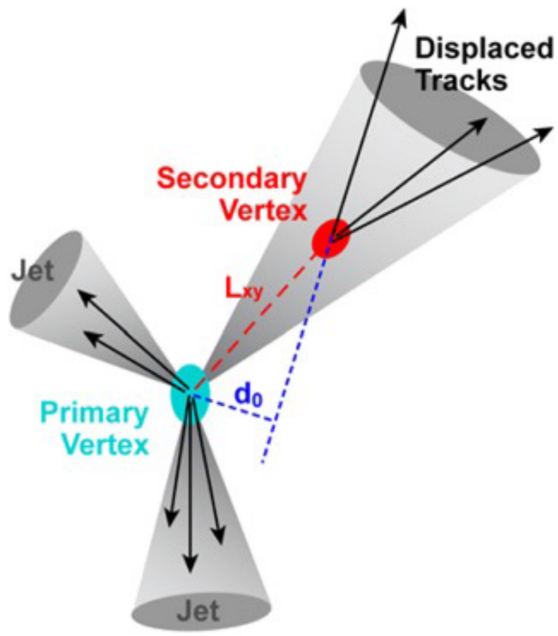
Proven technology !

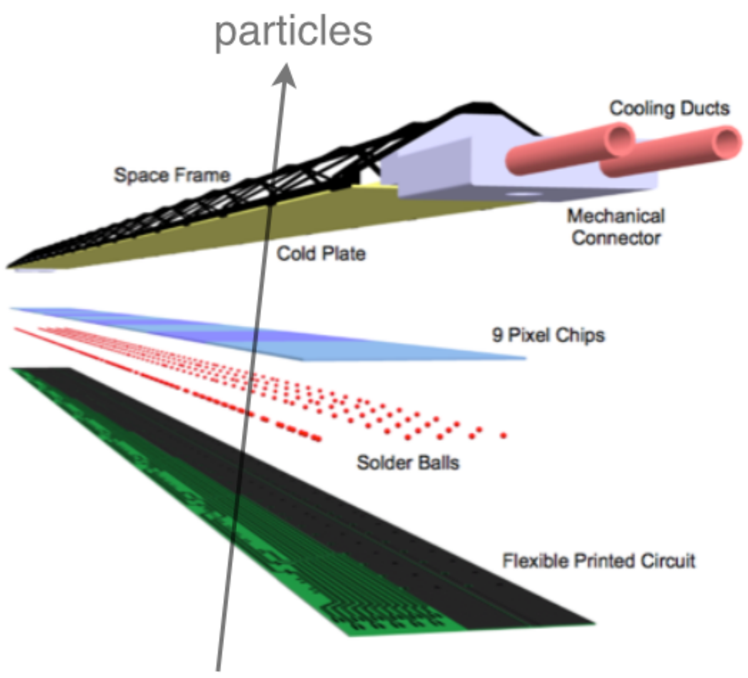
Cost: O(US $10M)



B-jet Physics in Heavy Ion Collisions

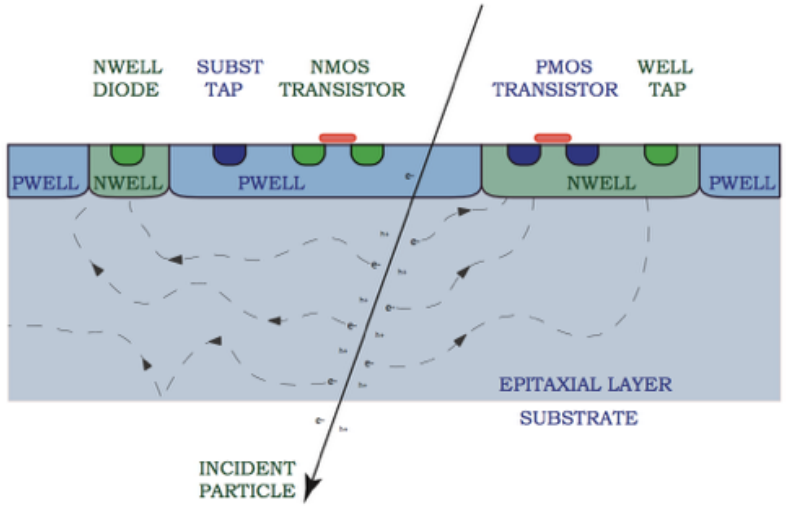
- Precision tracking required!
  - DCA based algorithm
  - 2nd vertex based algorithm

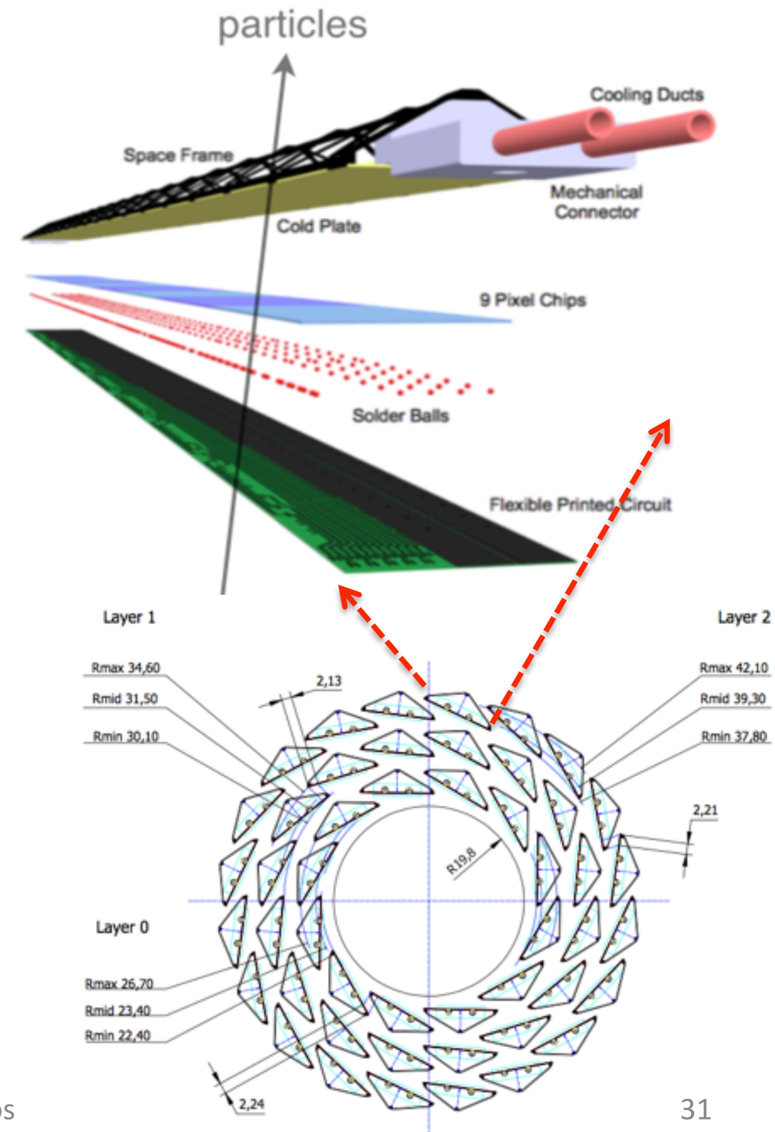




MAPS Based Inner Vertex Detectors

ALICE ITS Upgrade





Inner Silicon Concept:

- Thin, fine pitch (<30 um), large efficiency
- Optimizations for material thickness
- Fast readout possible , 4uS readout

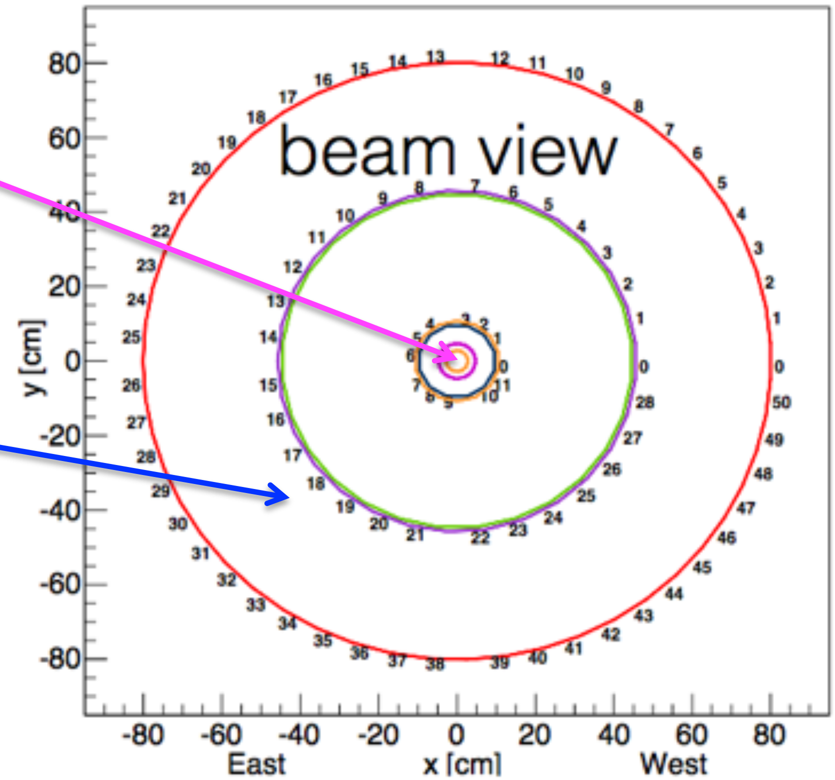
Goal:

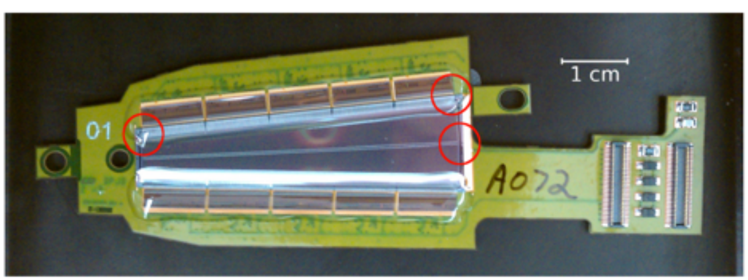
- Precision tracking & vertexing for b-jet identification
- and other tracking duties

MAPS + Si-Strip Tracker

- **Inner Tracking: MAPS**
  - High precision IP
  - Precision DCA, 2nd vertexing
  - 2~3 layers of MAPS
  - R < 10/20cm

- **Outer Tracking: Si-Strips**
  - Momentum resolution for Upsilons
  - Patter recognition in central HI collisions
  - FPHX readout
  - 10/20 cm < R < 80cm



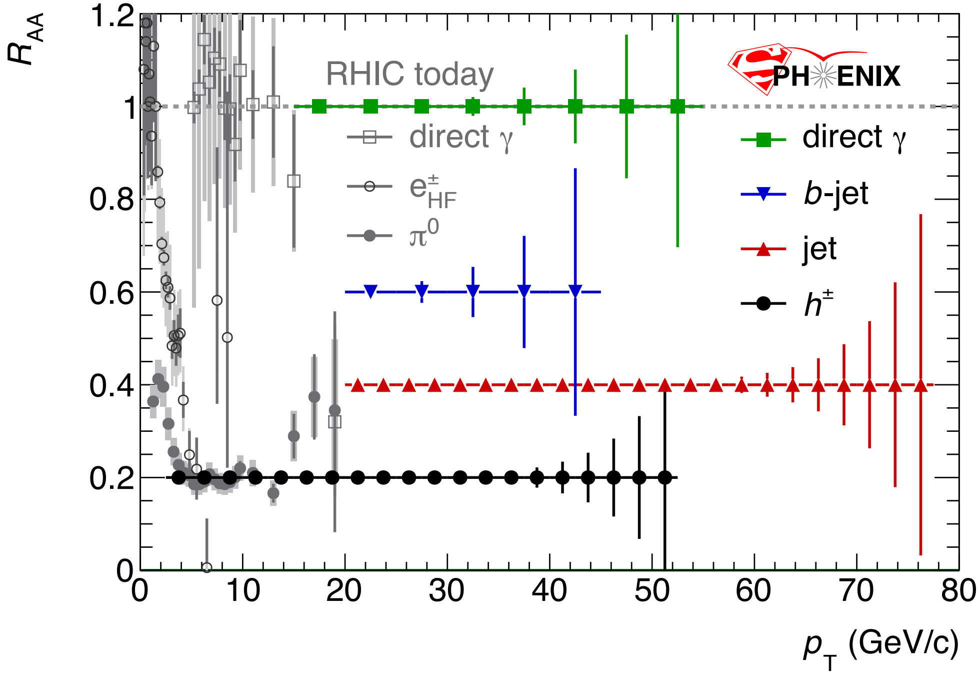


MAPS Work in Korea possible collaboration

- Production test facility in Korea
- Full production in Korea?

- Possible collaboration with ALICE to produce more sensor/chips for sPHENIX inner tracking system
  - Cost effective ~ $400K for ~10m^2
  - Korea+LANL+…

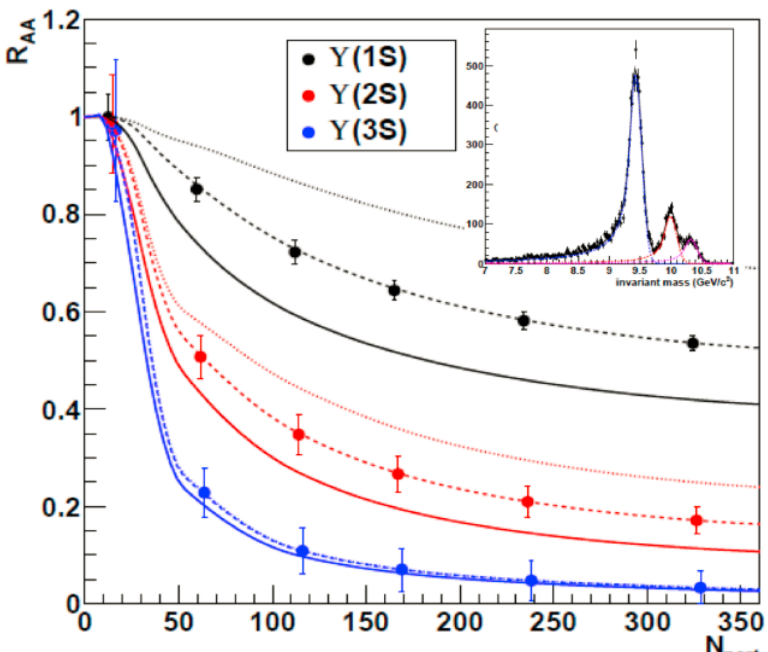
Physics Impact



Large statistics and new observables equals:

(1) Additional physics reach
(2) New differential measurements

Leading to a greater understanding of the energy loss and QGP structure.

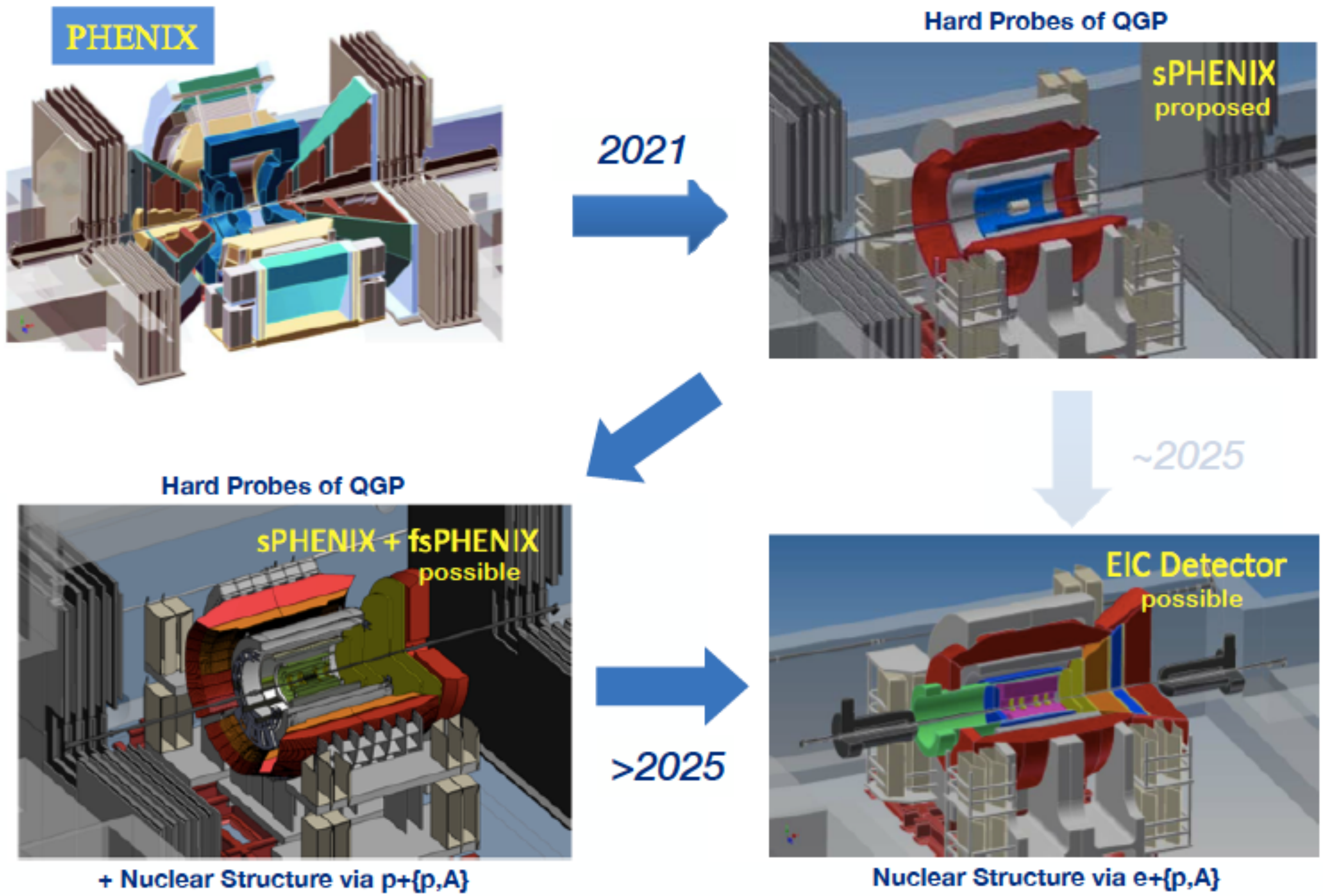


New RHIC program will both:
(1) Complement **LHC measurements** where medium differences can be directly studies
(2) Extend kinematic reach to lower energy, more heavily modified jets

Future: sPHENIX evolves into Electron Ion Collider detector.

Summary and Outlook

- Great potential Korean universities to make major contributions to sPHENIX program

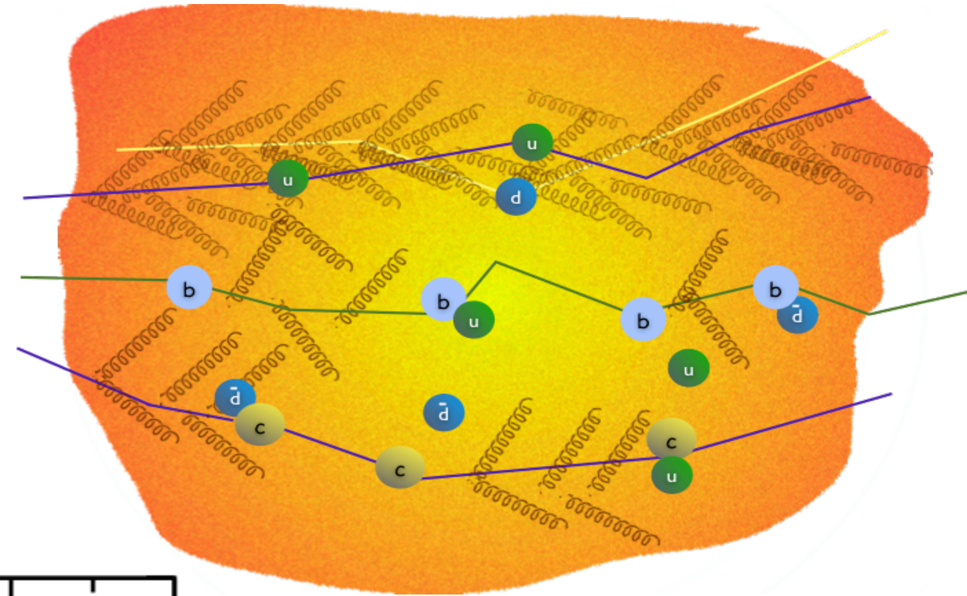


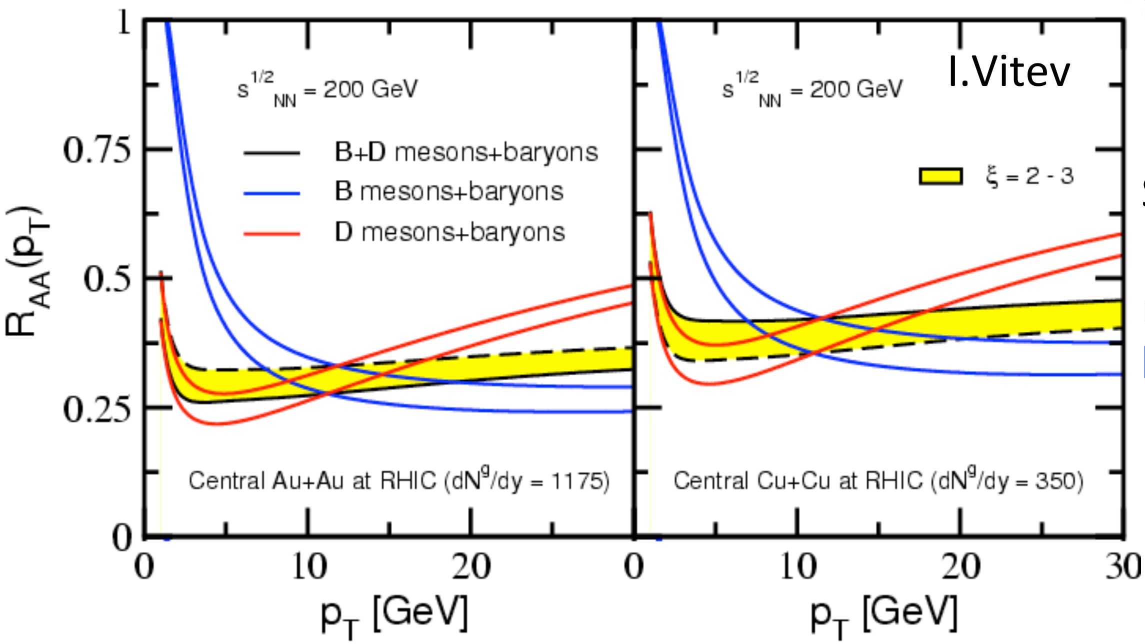
Backup slides

Light, Charm and Bottom Quarks in QGP

Energy loss:

- heavy quark radiation
- elastic collisions
- D,B meson dissociation in QGP which depends on different time formations
- strong dependence with unknown QGP properties





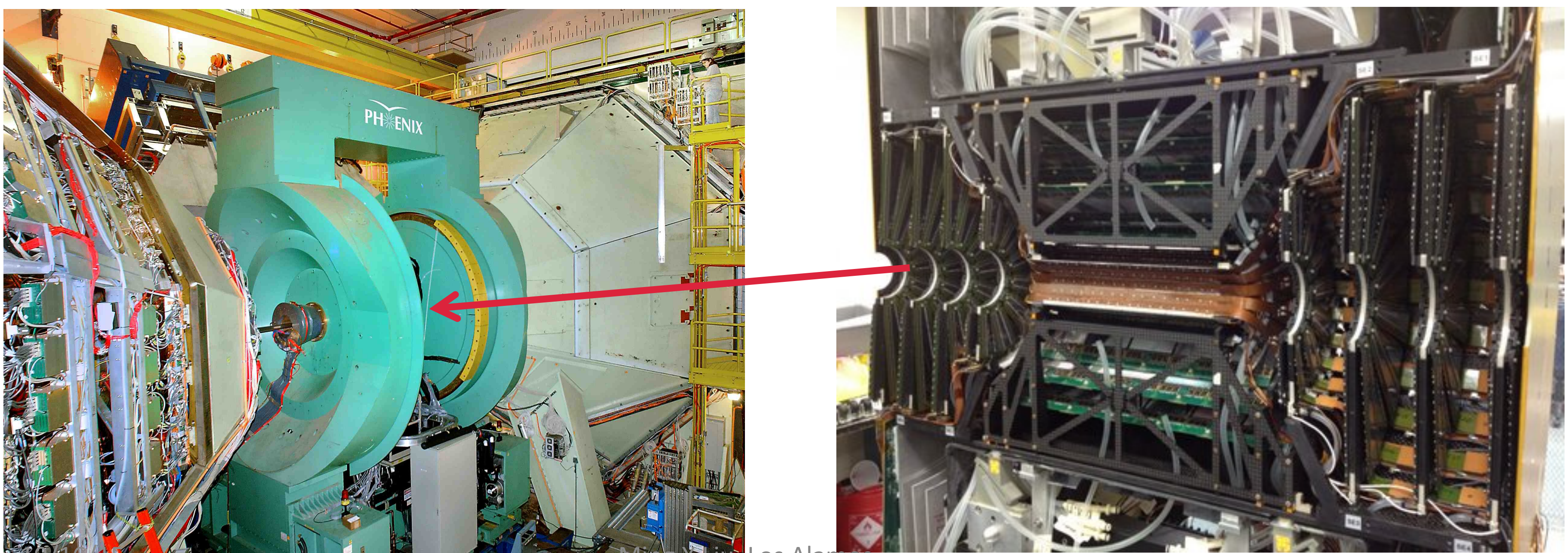
Some models which describe $R_{AA}(\pi)$~R_{AA}(charm) suggest a different nuclear modification for **charm** and **bottom** yields.

LANL Theoretical Division effort

Si-Strip Detector Design Issues

- The momentum resolution, in particular at lower pT, is limited by the multiple scattering . Minimizing the radiation length of this layer is one of most important issue
- The majority of the radiation length is from “stave” which provide mechanical support and cooling
- To achieve small radiation length, air cooling of S1 layer is desirable
- The current design assume SVX4 readout, since PHENIX had so far used this chip for two projects (stripixel and MPC-EX). A drawback of SVX4 is that it generates a relatively large amount of heat (~0.4 watt per chip = 128ch). It is unclear if air cooling is possible.
- FPHX chip used FVTX generates only 20 % of heat of SVX4.
  FPHX 64mW/chip,   SVX4 300mW/chip (both 128ch)
- We have done no engineering on this issue. We need thermal and mechancial design of stave to evaluate the feasibility of air cooling of either SVX4 or FPHX (or other) solution.

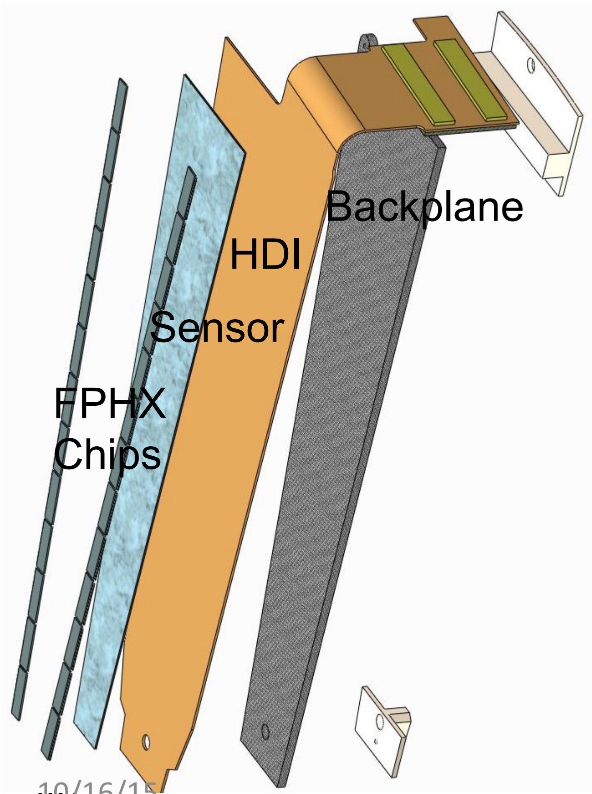
FVTX in PHENIX

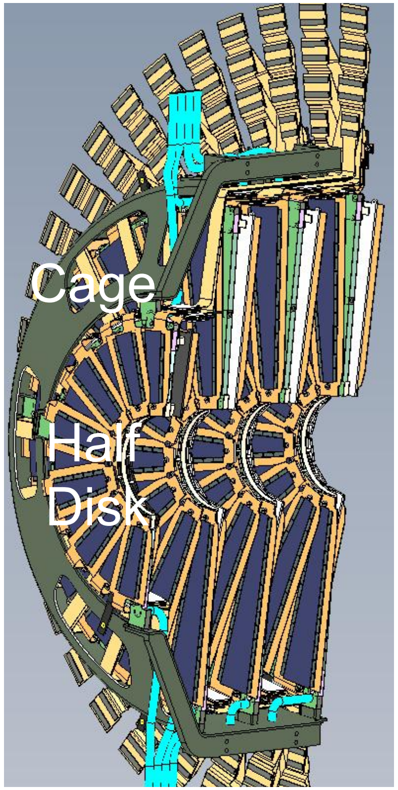


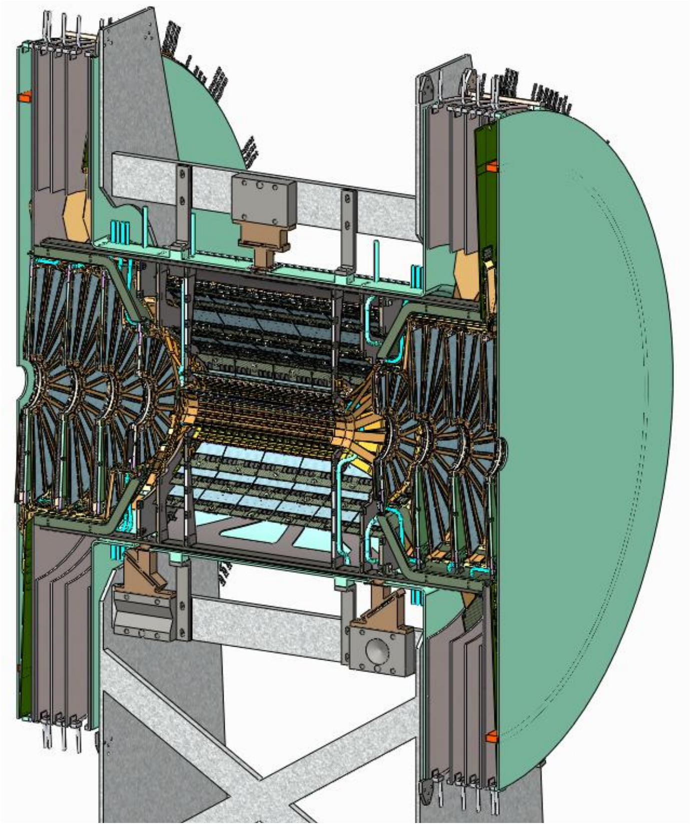
FVTX Geometrical Design

Four tracking stations with full azimuthal coverage

- 75 μm pitch strips in radial direction, 3.75° staggered phi strips
- Radiation length < 2.4%/wedge to minimize multiple scattering
- Outer Support and Cooling outside active area
- Kapton cable plant primarily outside active area

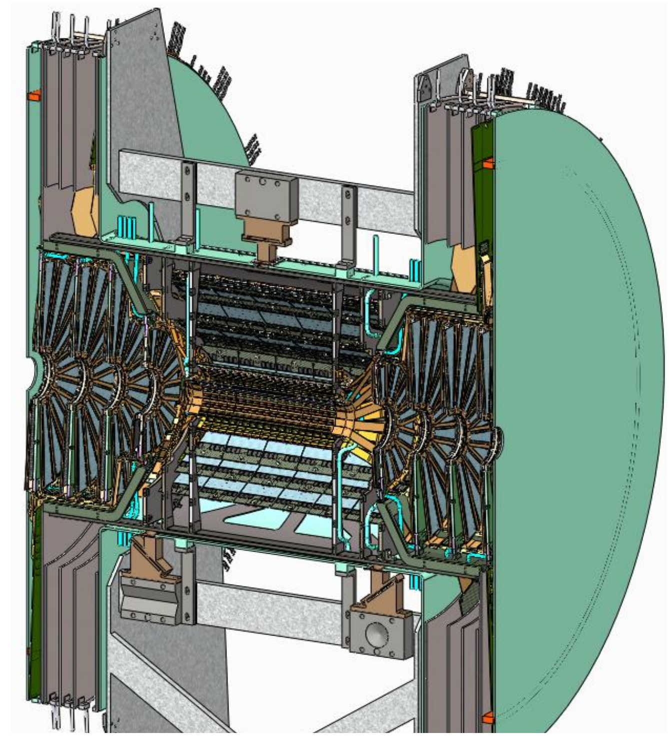


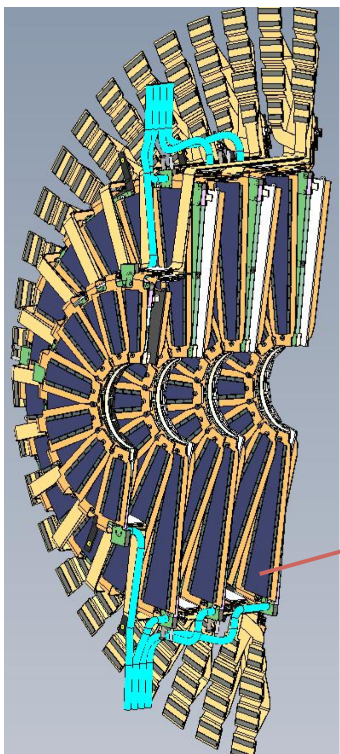


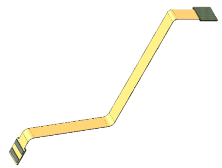


FVTX Electrical Design

- p on n ministrip sensor, 75 μm x 3.75° →
- Data push FPHX readout chip →
- High density interconnect cable →
- ROC (big wheel area in IR) →
- FEM (VME crate in counting house) →
- PHENIX DCMs





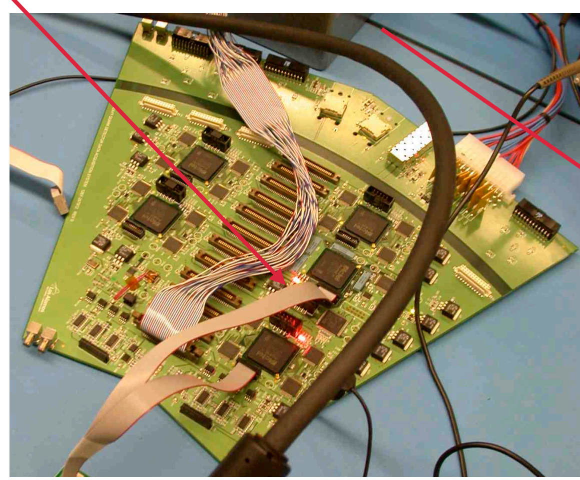


HDI

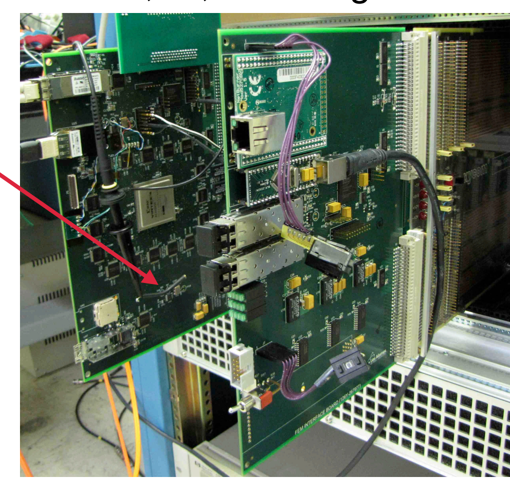
sensor

FPHX

ROC, IR

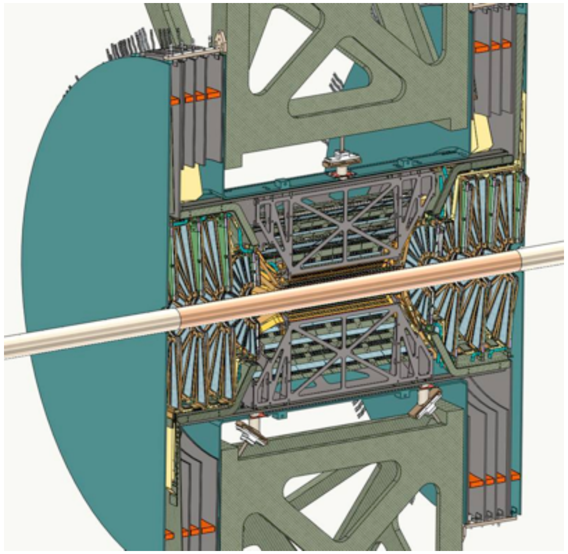
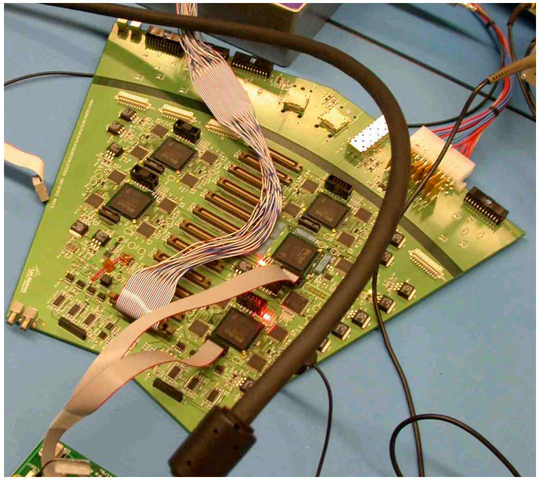
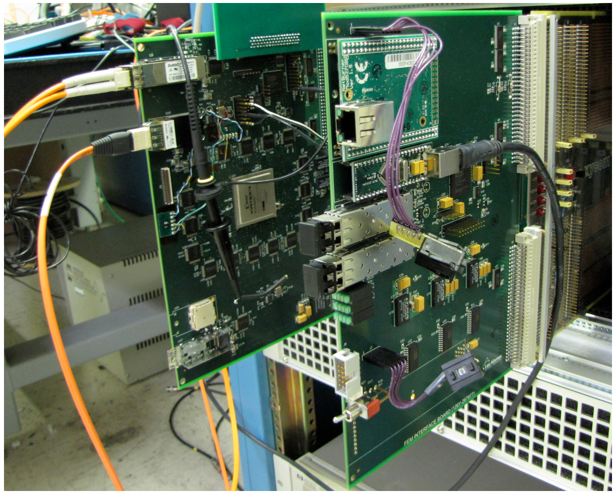
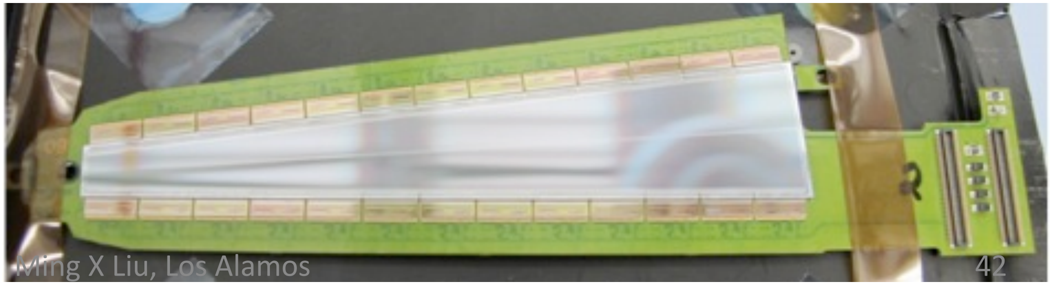


FEM, IB, Counting House



Forward Silicon Vertex Detector

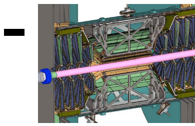
In Construction – FY09 – FY11, installation in summer 2011. Significant ongoing commitment needed to ensure successful delivery of project.
Physics Running – FY12, plus 5-10 years (multiple beam types, energies, etc.)
LANL Role – Project Management, oversight of commissioning, support throughout data taking runs, significant role in data analysis

FVTX Project History

Technical Design Report
of the
Forward Silicon Vertex
Tracker (FVTX)

5 January 2012



LANL LDRD Support to develop project (ER, DR 2003 – 2008) - both experimental and theoretical work supported

February 2007 – BNL Review - Go-ahead to proceed with DOE Review

July 2007 DOE Science Review – Additional work requested, response document produced Oct. 2007

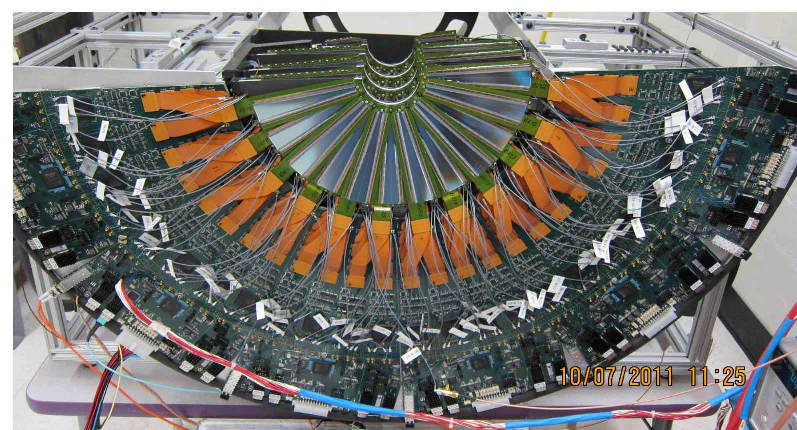
November 2007 Technical Review

Project Start – March 2008, $500k construction funds received April 2008, for FY08

Stimulus funds - FVTX approved for stimulus funding in 2008, remaining funds received 2009.

Construction

- 2008 – prototyping
- 2009 – first production modules
- 2010 – assembly started in earnest
- 2011 – assembly and installation COMPLETE
- 2012 – ongoing cabling/commissioning, first data



FVTX Project Deliverables

Item	**Number**	**Working Spares**
Wedge assemblies		
Large Sensors	288	25 in spare wedges
Small Sensors	96	8 in spare wedges
Large Wedges	288	25
Small Wedges	96	8
ROC boards	24	4
FEM boards	48	6
Mechanical		
Large ½ Disks	12	2
Small ½ Disks	4	1
Suspension system	1 (VTX funded)	0
Dry gas enclosure	1 (VTX funded)	0
Cooling system	1 (VTX funded)	0
Power supply system	1	Spare components available
DCM channels	48	4

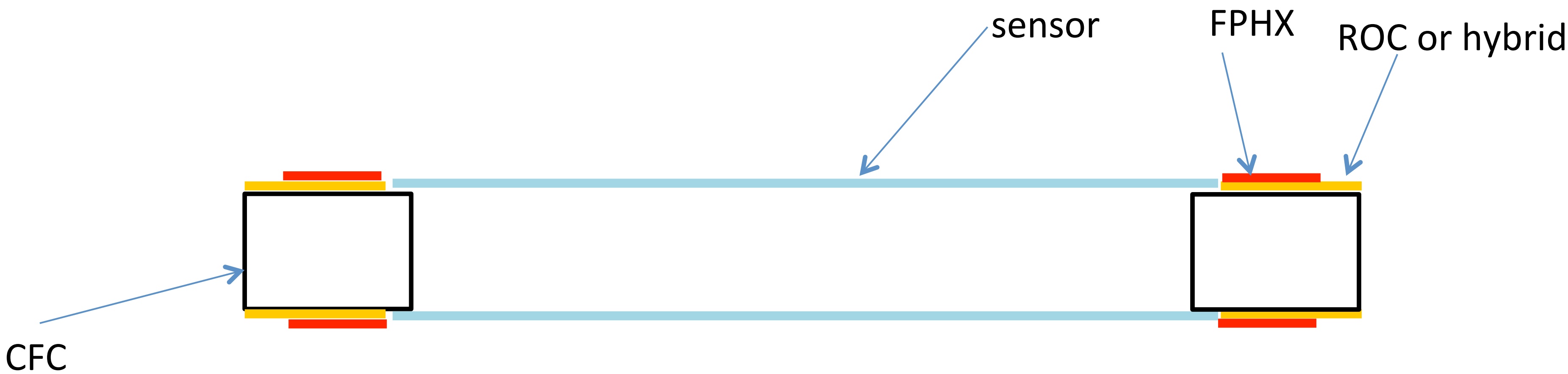
FVTX Functional Requirements

Mini strips active	>80%	(expect ~99%)
Hit efficiency	>85%	(expect ~99%)
Radiation length per wedge	< 2.4 %	
Detector hit resolution	< 25 μm	(can achieve without analog information)
Random noise hits/chip	<0.1%	(threshold:noise ~5:1)
Level-1 latency	4 μs	
Level-1 Multi-Event buffer depth	4 events	
Read-out time	< 40 μs	
Read-out rate	> 10 kHz	

*Primary bench test requirements. Others are met by design

Material budget for FPHX

Y. Akiba



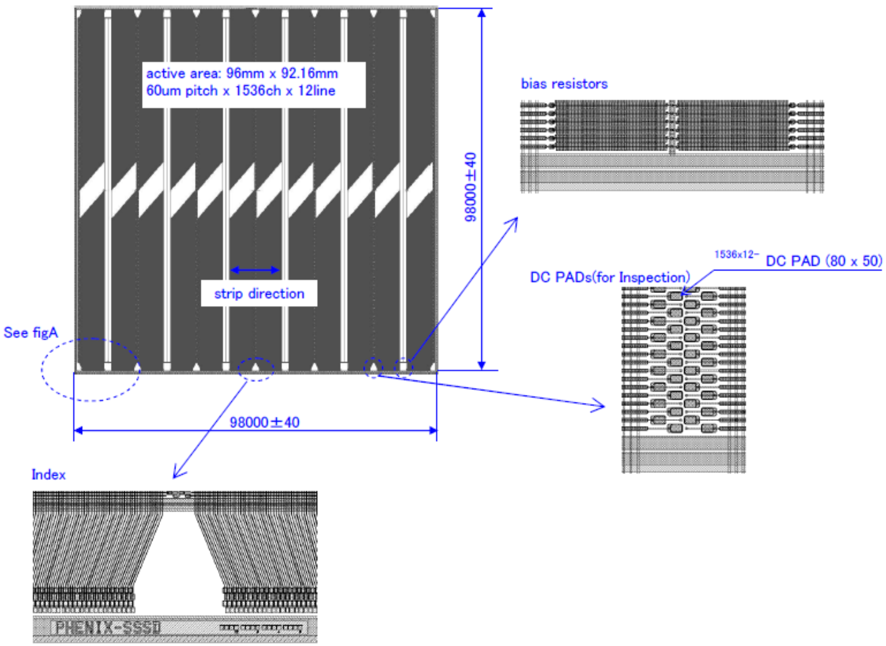
- Air cooling channel under ROC is probably sufficient to cool the system.

→~1% radiation length for double layer

This can reduce the size of the detector. (R~50cm)

Y. Akiba

sPHENIX silicon tracker R&D in Japan



- Silicon sensor R&D at RIKEN in JFY2014
- Large Prototype sensor for the outer most layer
  - 96 mm x 92.16mm active area
  - 320 μm thick
  - AC coupled
  - 6x128x24 mini-trips (60μm x 8mm)
  - 128x24 read-out channels
- 5 sensors manufactured at Hamamatsu and delivered to RIKEN in March 2015
- For all of 5 delivered sensors
  - No NG channels or strip
  - Vfd = 50 V
  - Vbreakdown > 250V (>500V for two)
- All 5 sensors are now at BNL for testing