Elliptic flow at forward rapidity in Au+Au collisions using the PHENIX Detector at RHIC

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What does this mean?

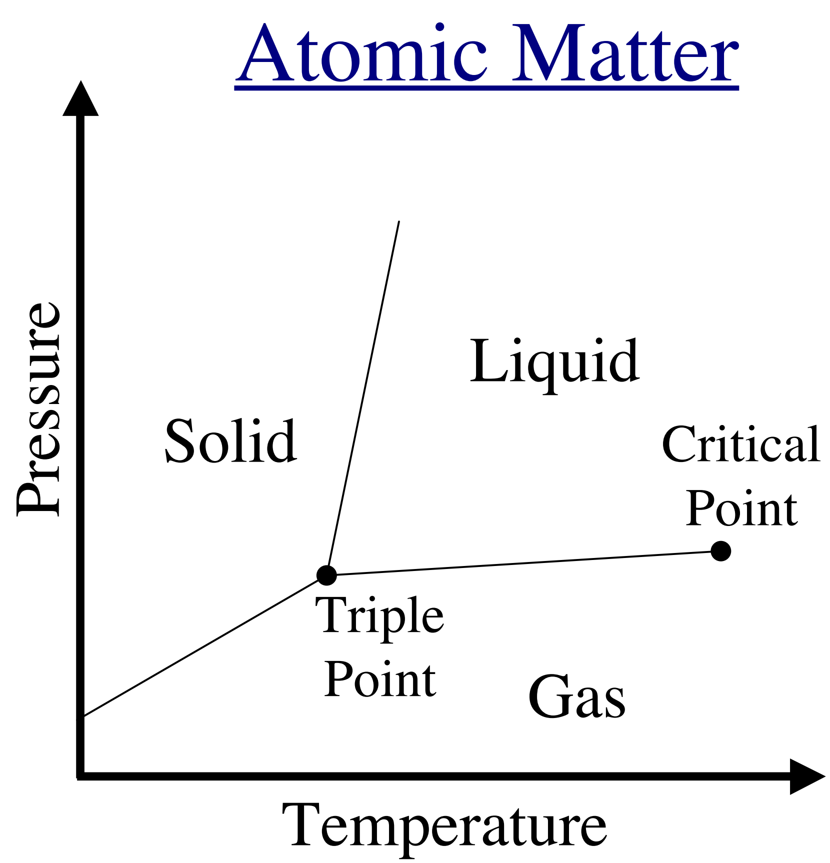
Elliptic flow at forward rapidity in Au+Au collisions using the PHENIX Detector at RHIC

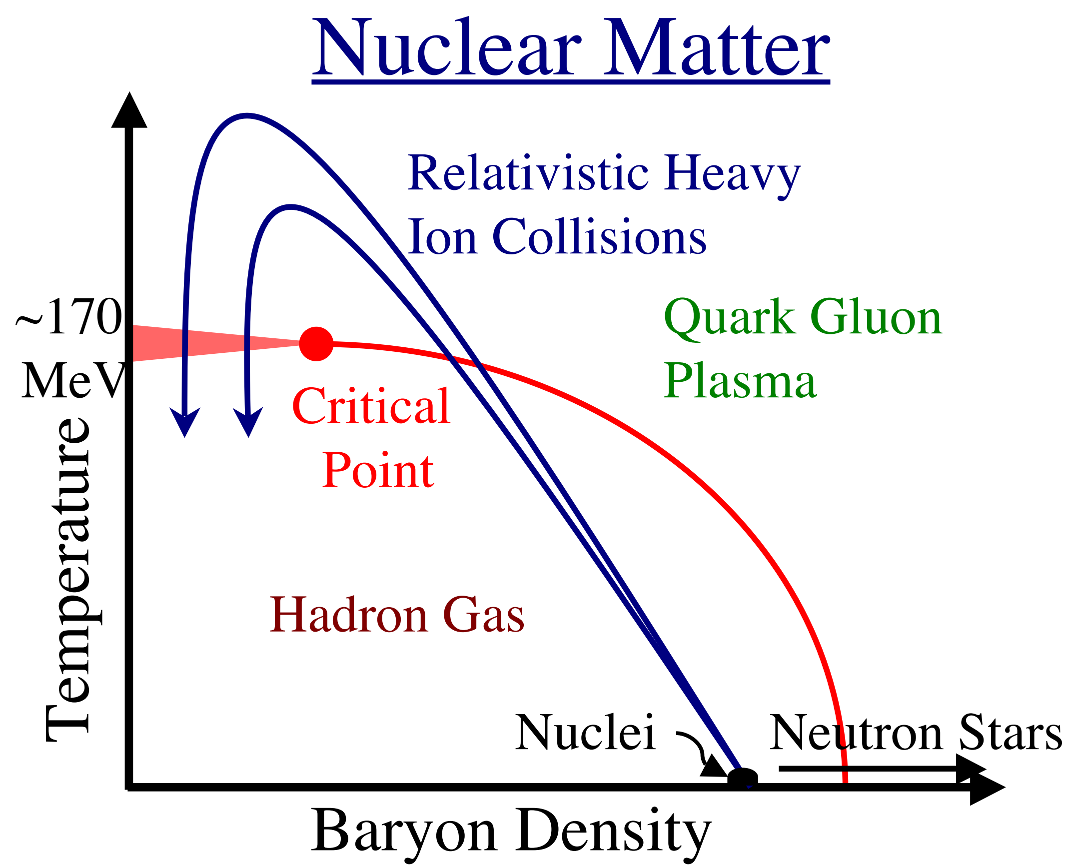
Outline

1. Brief introduction to relativistic heavy-ion collisions
2. Elliptic flow
3. Challenges to measuring elliptic flow at forward rapidity
4. Reaction Plane Detector upgrade
5. Forward rapidity elliptic flow results

(1) Relativistic Heavy Ion Collisions

Phase Diagrams



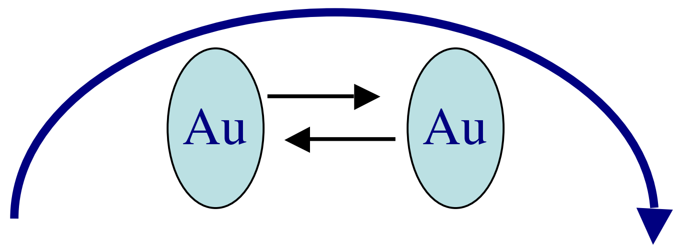


We are able to access and study the QGP with heavy-ion collisions by increasing temperature

Quark Gluon Plasma

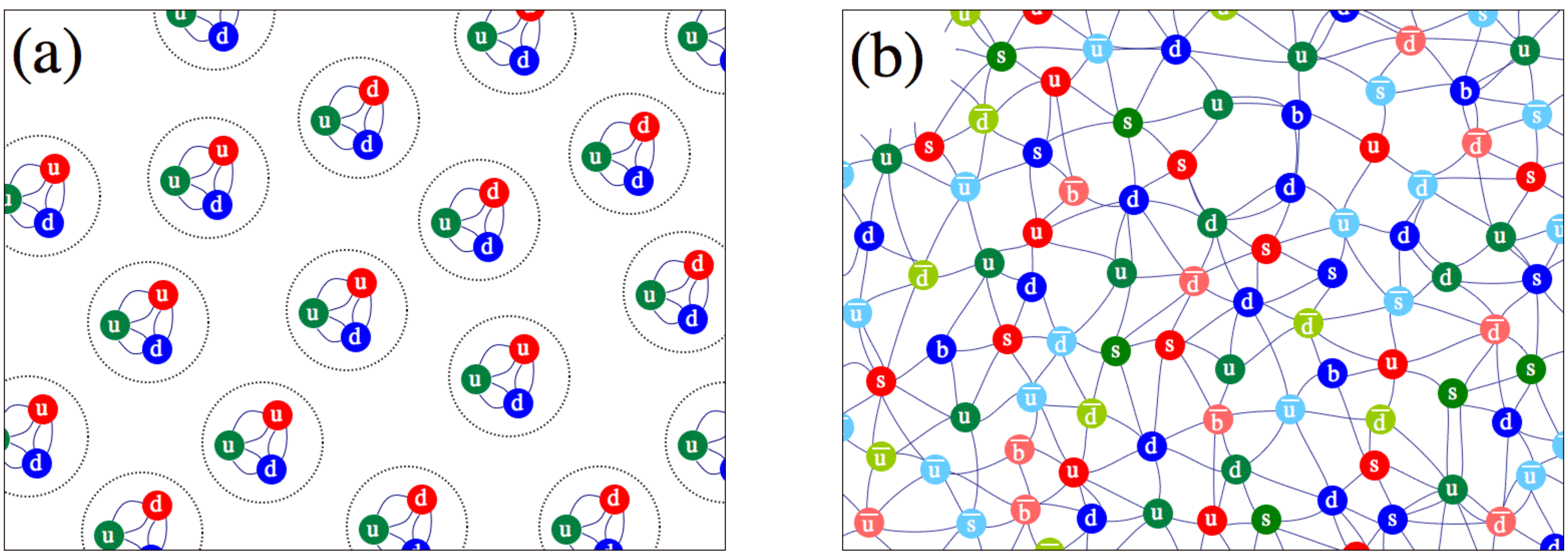
- Defined as: free movement of quarks and gluons - no longer confined to hadrons (e.g. protons, neutrons)

Increase temperature → particle production → increase density

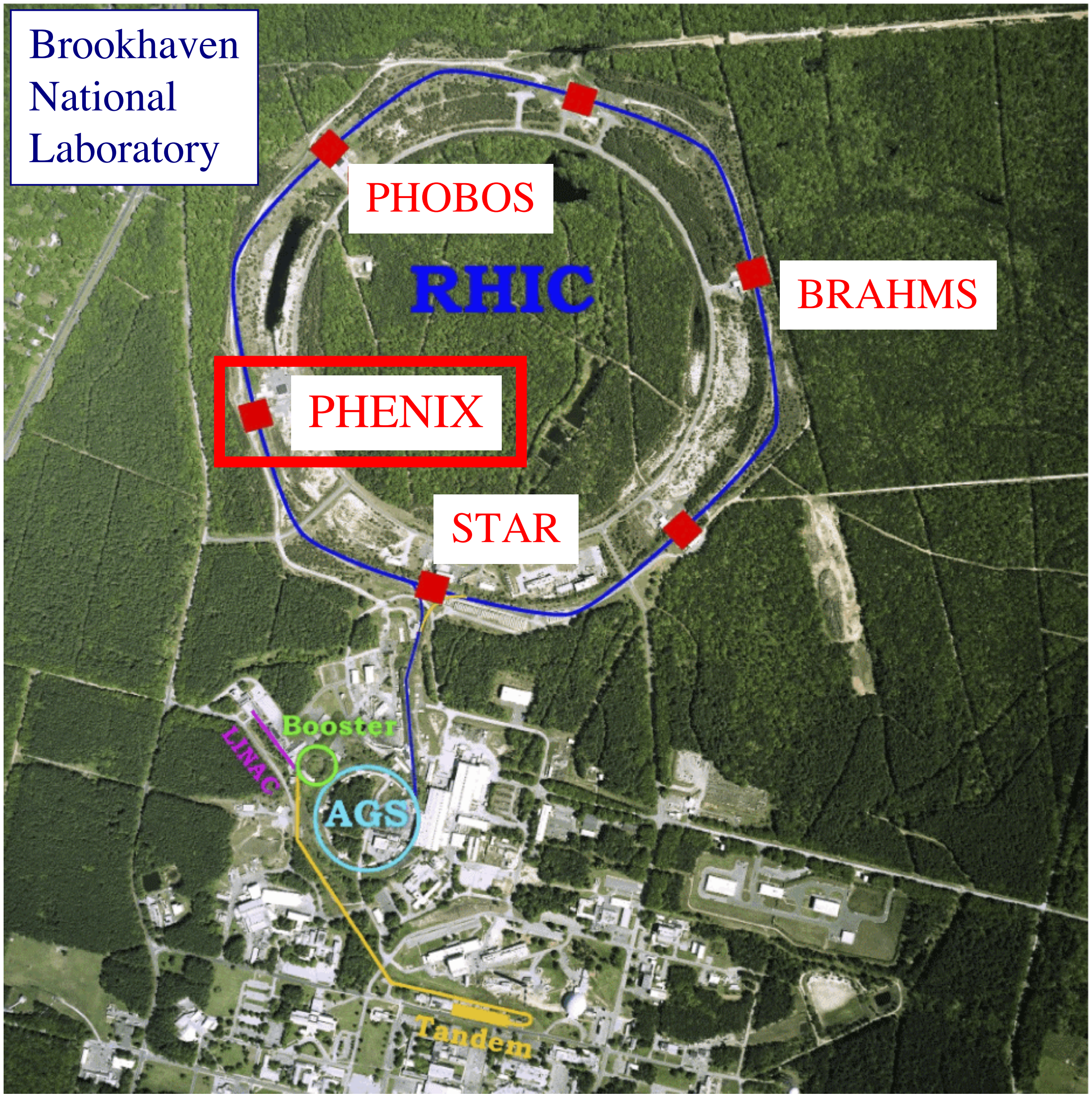


Normal Nuclear Matter

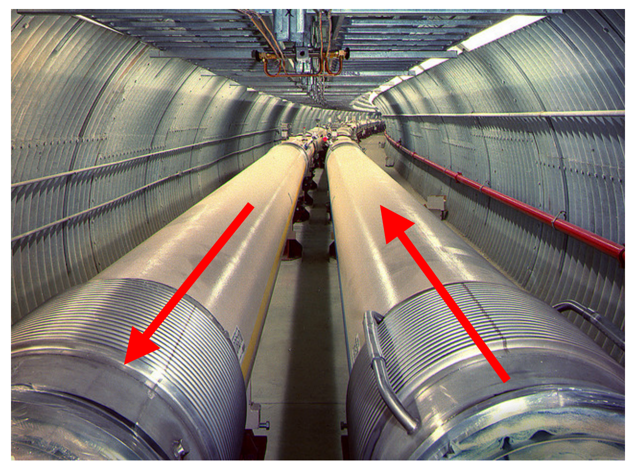
Quark Gluon Plasma

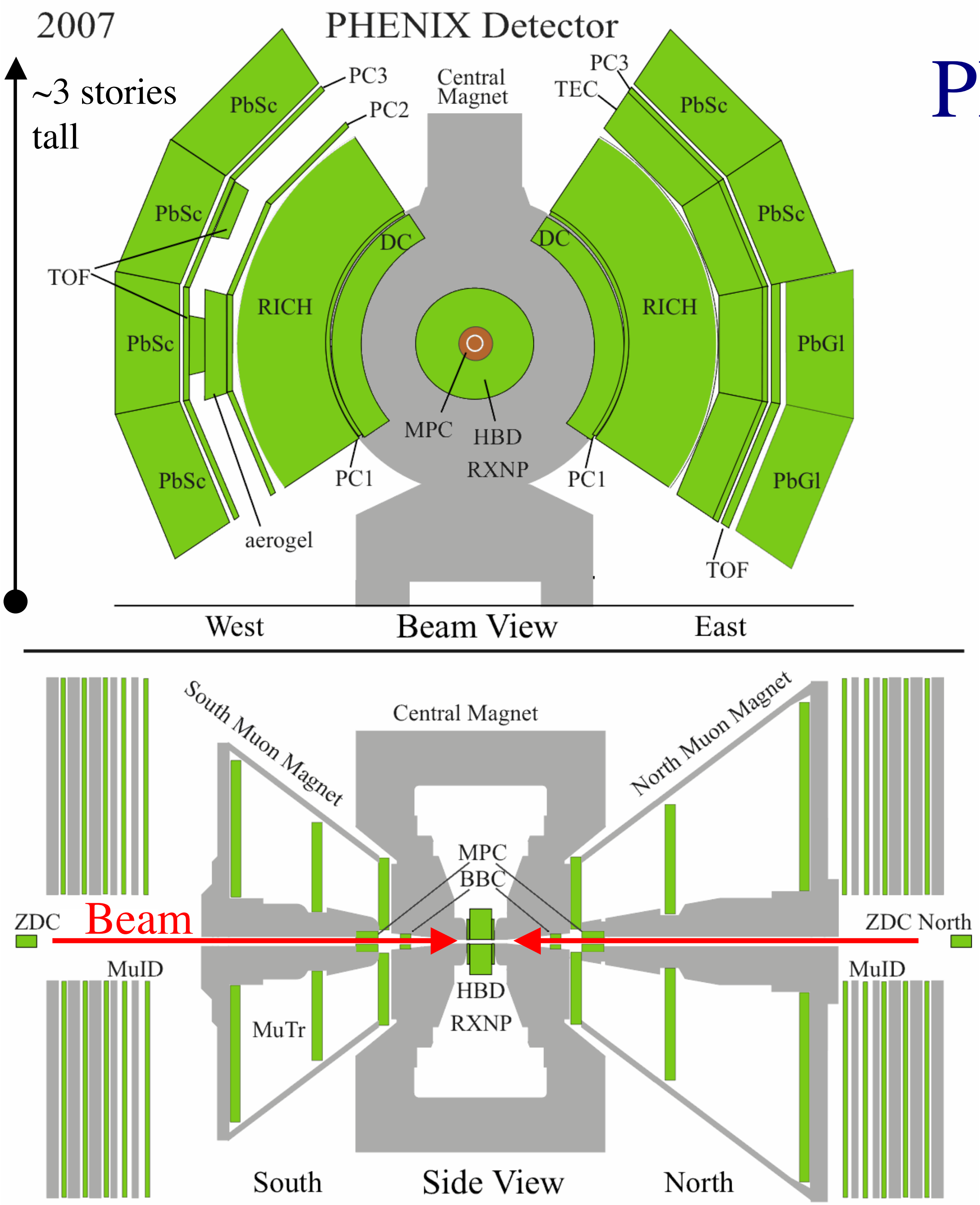


Relativistic Heavy Ion Collider (RHIC)



- RHIC ~2.4 mile circumference
- Collides Au+Au using counter circulating beams at $\sqrt{s_{NN}}$ = 200 GeV
- PHENIX at 8 o'clock position





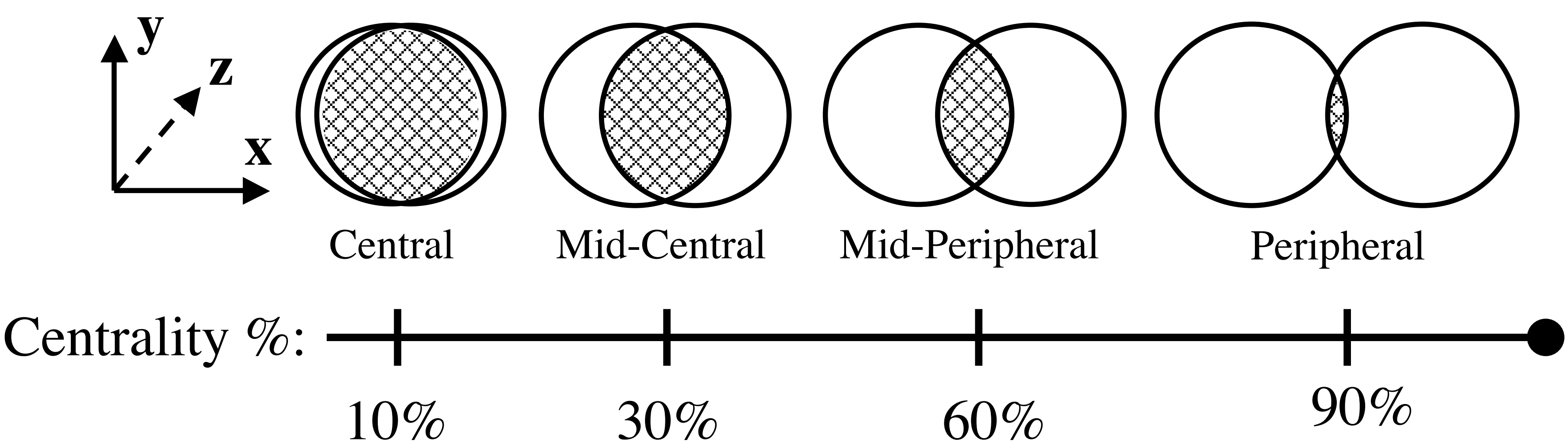
PHENIX Detector

- Central Arms
  - Drift Chamber
  - Pad Chamber
  - EMCal
  - Time of Flight
  - And others
- Muon Arms
  - Drift Chamber
  - Drift Tubes

Collision Centrality

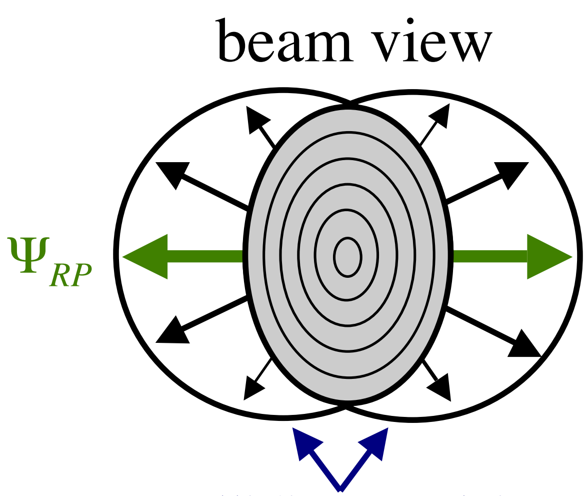
- Centrality: the percent of collisions having more geometric overlap than current collision
- A centrality of 10% means 10% of collisions have more geometric overlap than the current collision

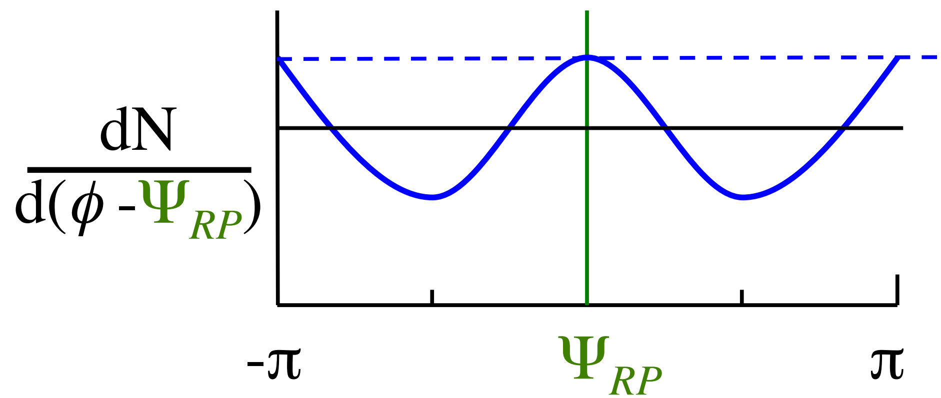
Schematic Illustration



(2) Introduction to Elliptic Flow

Asymmetric Distribution of Emitted Particles

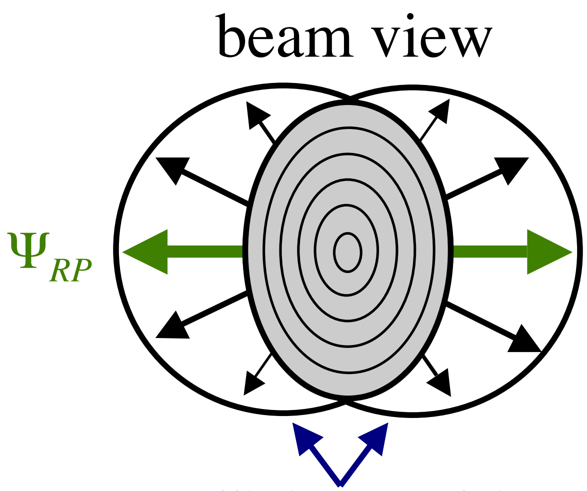


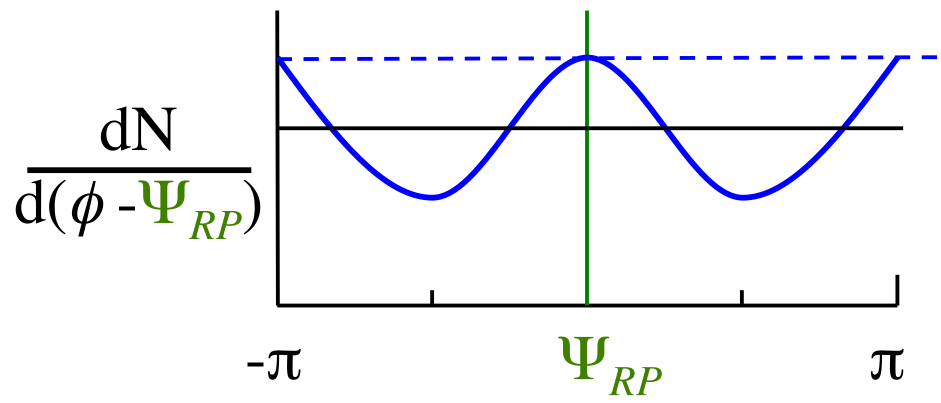


ϕ = particle's azimuthal angle about the beam axis

- If medium created from the collision thermalizes before "evaporation", pressure gradients will develop
- From the eccentricity of the collision shape, a steeper gradient develops in direction of short axis called the reaction plane and given the angle Ψ_{RP}
- Causes momentum anisotropy, resulting in more particles moving in direction of Ψ_{RP} - termed "Elliptic Flow"

Asymmetric Distribution of Emitted Particles





$$\frac{dN}{d(\phi - \Psi_{RP})} \propto 1 + 2v_2 \cos\left[2\left(\phi - \Psi_{RP}\right)\right]$$

- v_2 - elliptic flow parameter (quantifies magnitude of flow)
- N - number of particles
- ϕ - angle of particle
- Ψ_{RP} - angle of RP

Measuring Ψ_{RP}

- Ψ_{RP} is measured from the same particle asymmetry used to measure elliptic flow
- Sum **X** and **Y** event flow vectors

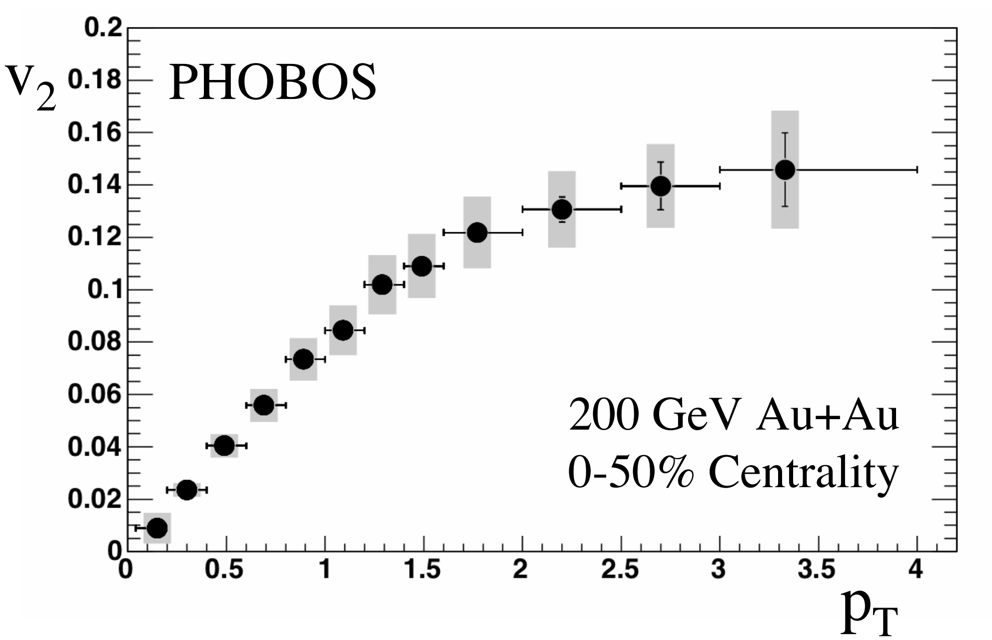
$$\Psi_{RP} = \frac{1}{2}\tan^{-1}\left(\frac{\mathbf{Y} = \sum_i \sin(2\phi)}{\mathbf{X} = \sum_i \cos(2\phi)}\right)$$

ϕ = particle's azimuthal angle about the beam axis

Why study Elliptic Flow?

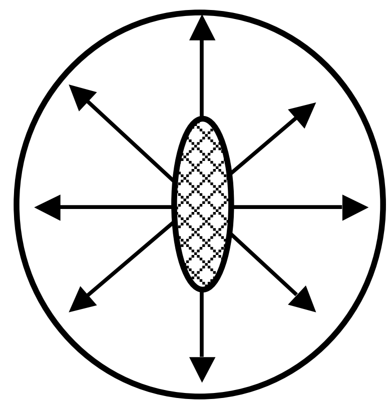
- Provides insights on
  - How strongly the medium interacts
  - If and when the medium thermalizes
  - Energy loss
  - Viscosity
  - Critical point in nuclear phase diagram
  - Etc…

PHOBOS $v_2(p_T)$



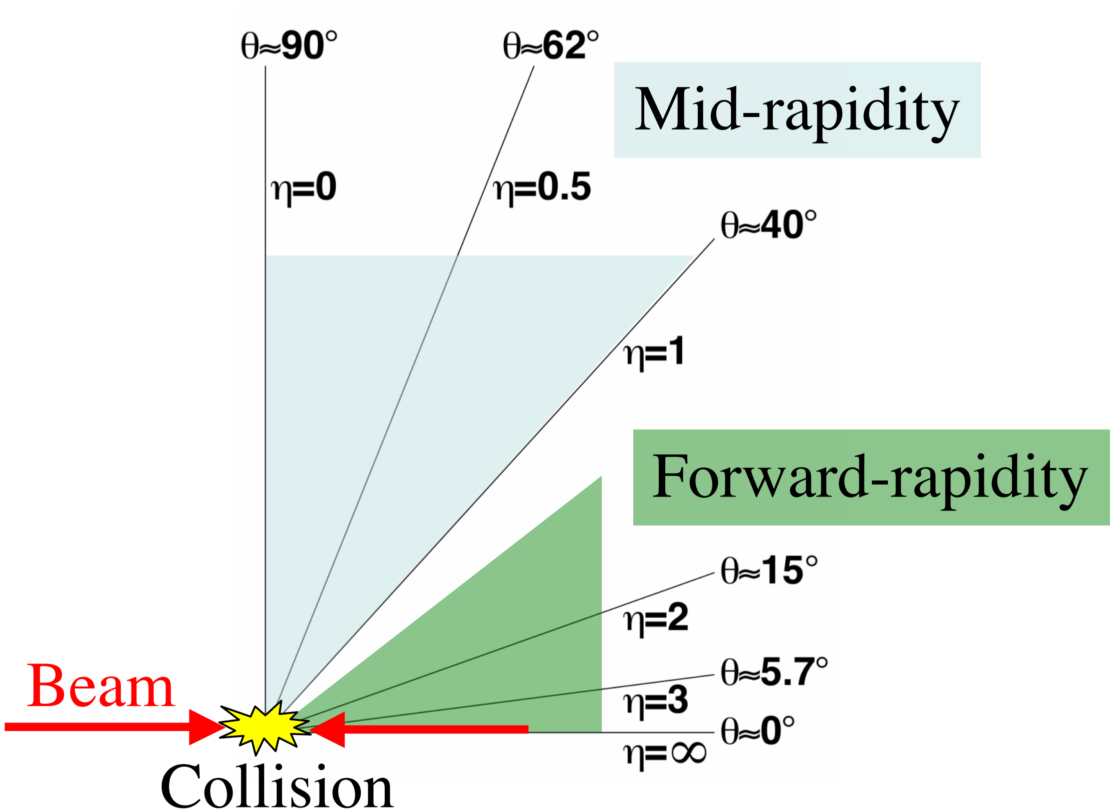
p_T = transverse momentum, comes from medium interactions (not from beam momentum)

- Measure strong v_2 signal
  - Indicates medium thermalized quickly before significant expansion
  - If thermalized later after significant expansion, medium shape would be nearly circular and pressure gradients nearly isotropic, $v_2 \approx 0$



(3) Challenges of Measuring Elliptic Flow at Forward Rapidity

Angular Emission

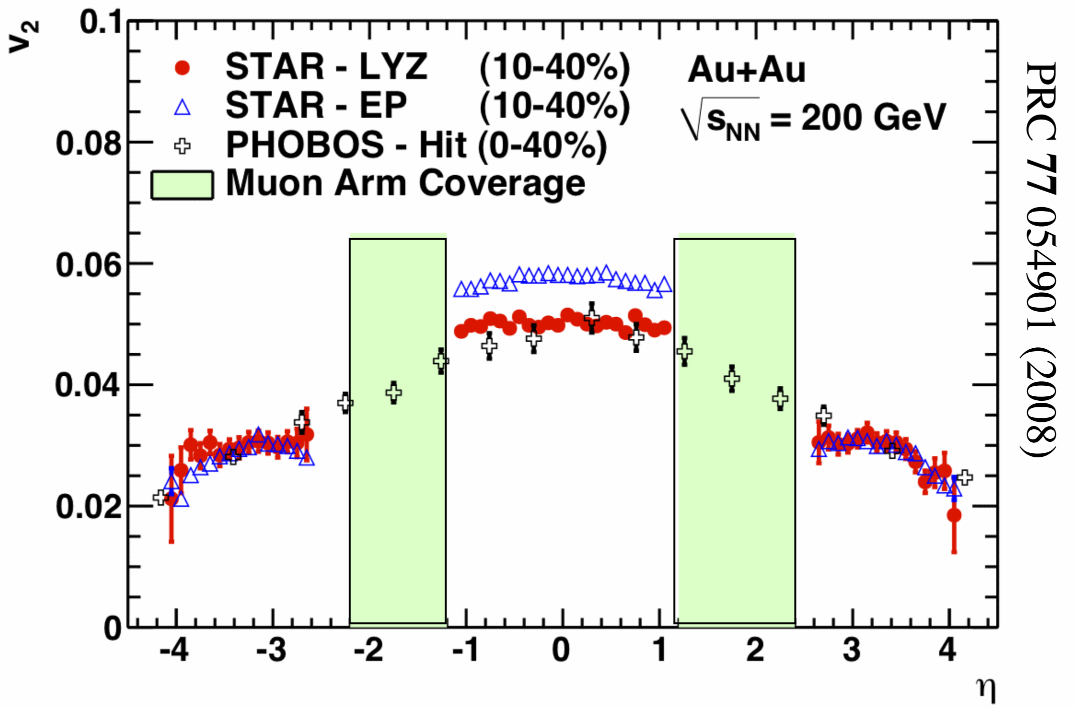


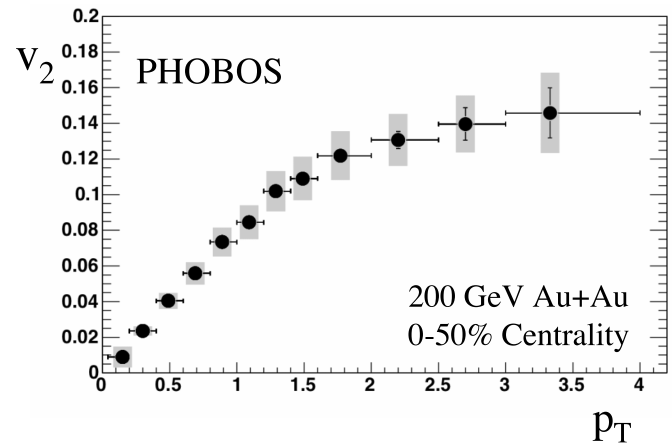
Pseudorapidity

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

- Most v_2 measurements have been done at mid-rapidity
- How does v_2 at forward rapidity compare? Same behavior? How is it different?

STAR & PHOBOS $v_2(\eta)$

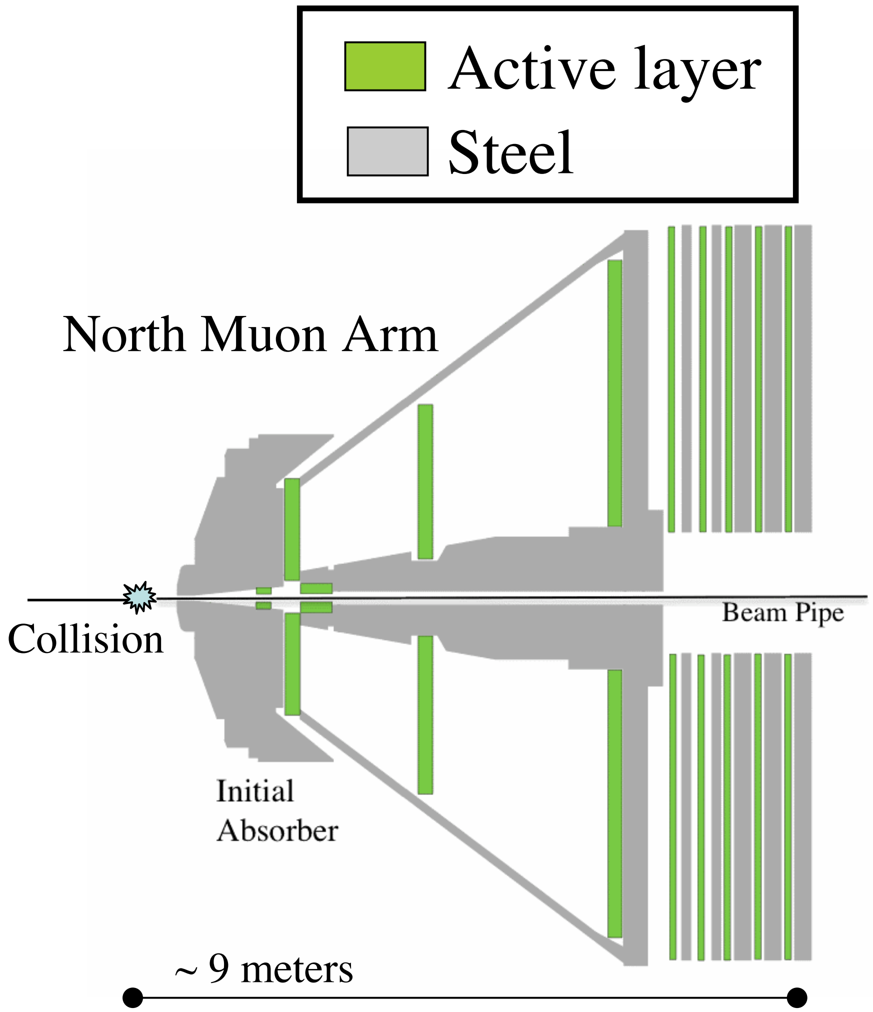




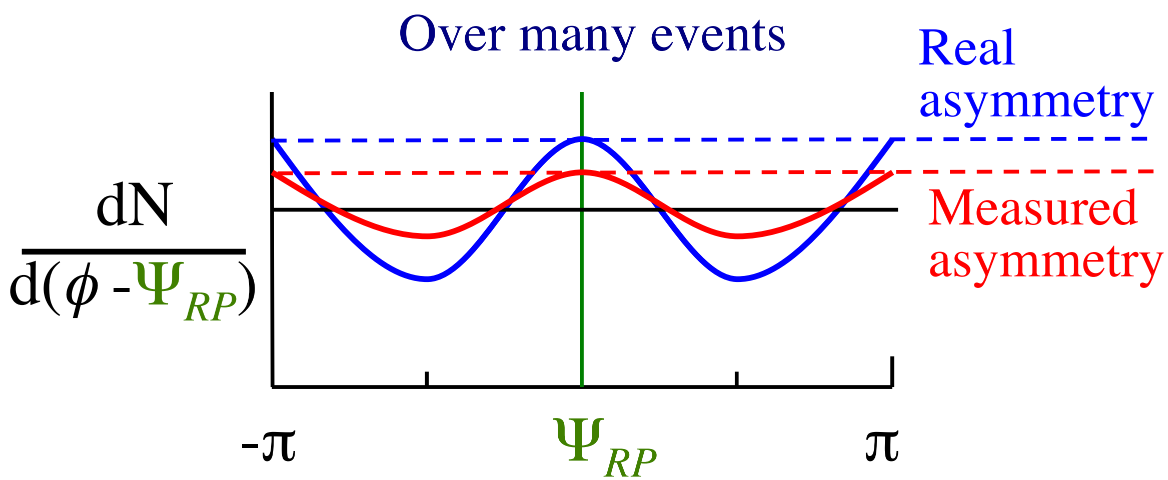
- STAR and PHOBOS measured a significant decrease in v_2 at forward η for central collisions (< 40% centrality)
- Didn't take p_T into account, which v_2 is greatly dependent upon
- Is created medium changing or is it just a decrease in $\langle p_T \rangle$?
- Measure forward rapidity v_2 using PHENIX's Muon Arms ($1.2 < |\eta| < 2.4$) which can take p_T into account.

Measurement Challenges

- Muon Arms have ~120 cm of steel to absorb hadrons, while muons are able to penetrate
- Pion rejection rate of $\sim 10^{-4}$
- Causes statistical challenges to measuring elliptic flow



Additional Challenges



- Can't perfectly measure Ψ_{RP} due to finite particle statistics and detector granularity
- Causes particle dispersion that must be corrected for

Reaction Plane (RP) Resolution

- Quantitative expression of how well Ψ_{RP} can be measured

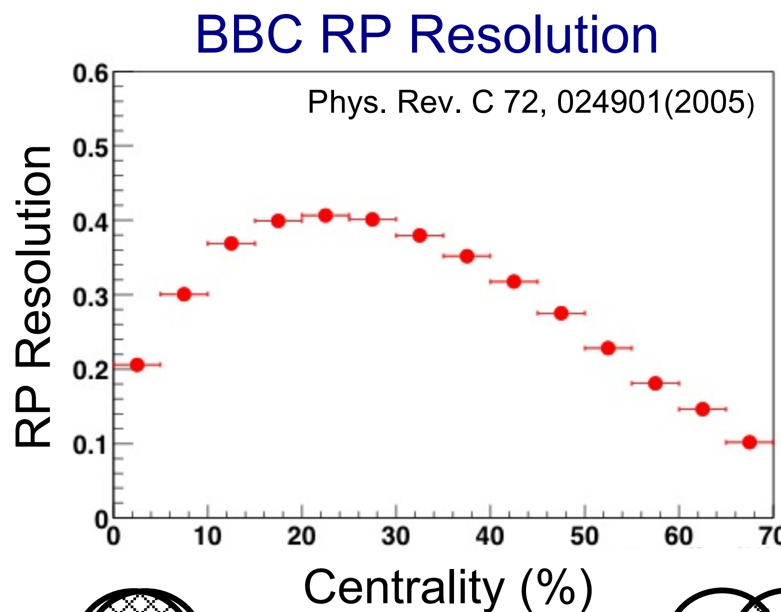
$$\text{Res} = \sqrt{2}\left\langle \cos 2\left(\Psi^{a} - \Psi^{b}\right)\right\rangle$$

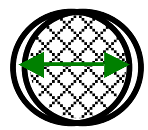
$\Psi^{a/b}$ are independent measurements of Ψ_{RP} from different detectors

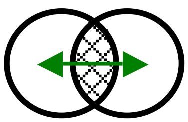
$$v_2^{corr} = \frac{v_2^{meas}}{\text{Res}}$$

BBC RP Resolution

- PHENIX's resolution using Beam Beam Counter (BBC) arms
- Resolution of 1.0 means perfect accuracy in measuring Ψ_{RP}
- BBC resolution is good enough for measuring abundant or low momentum particles
- To study rare or higher momentum particles, or to measure elliptic flow from the low particle statistics in Muon Arms, a higher resolution detector is needed → Reaction Plane Detector





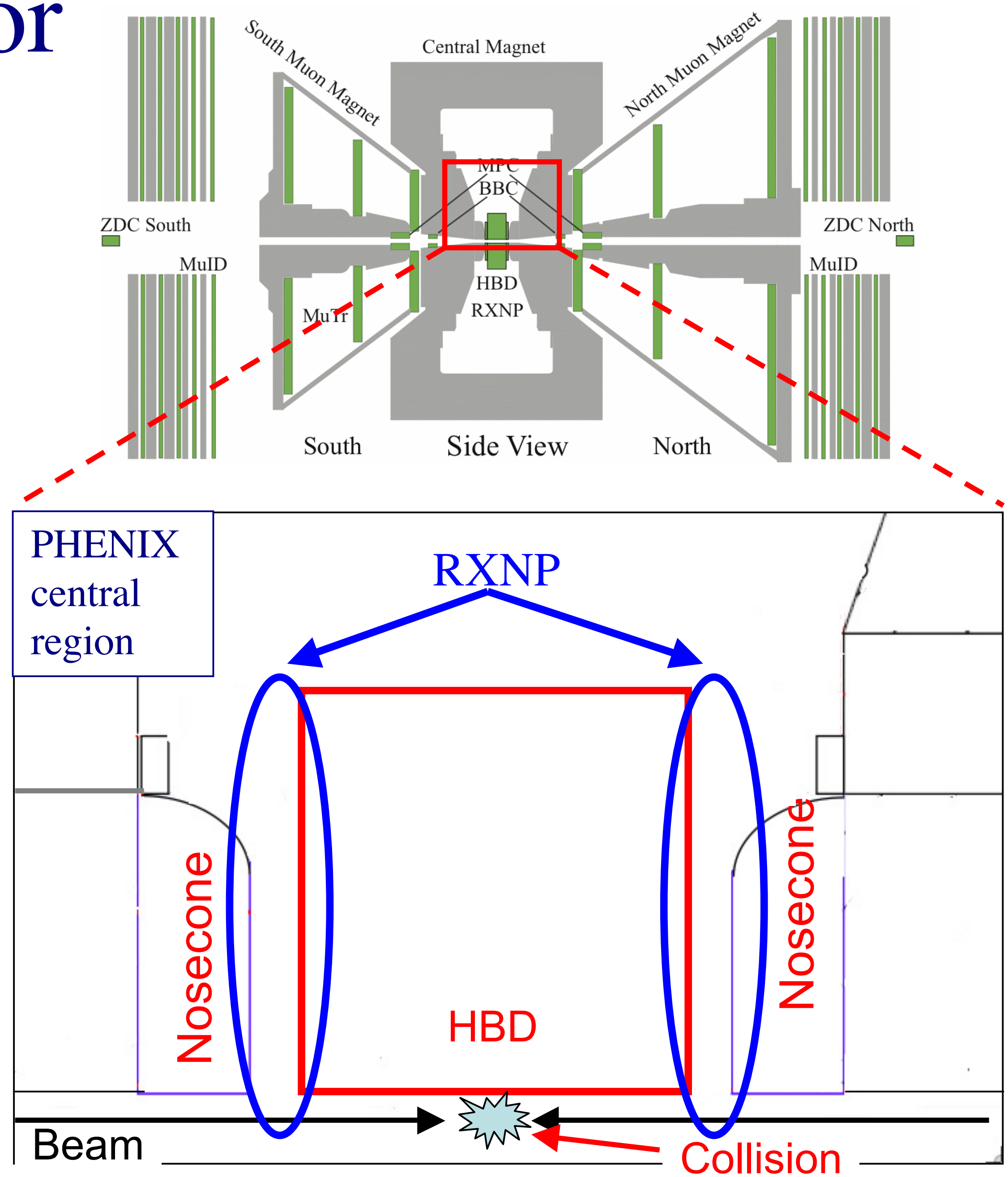


$$v_2^{corr} = \frac{v_2^{meas}}{\text{Res}}$$

(4) Reaction Plane Detector (RXNP) Upgrade

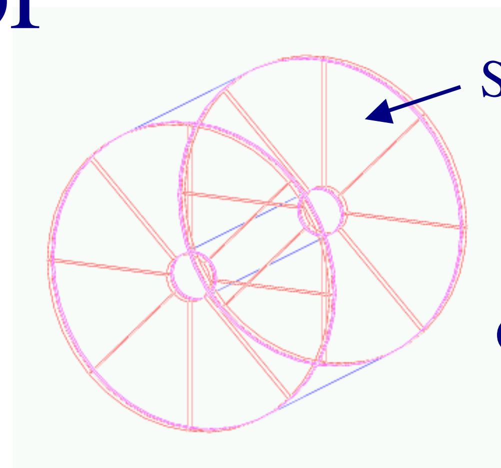
Initial Detector Concept

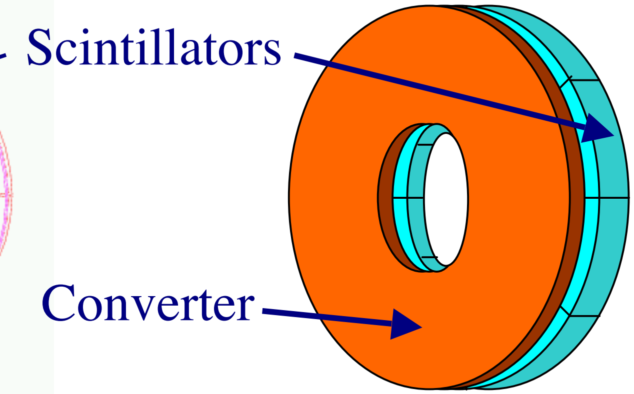
- Locate in PHENIX central region in-between each magnet nosecone and Hadron Blind Detector (HBD) - 7 cm of space

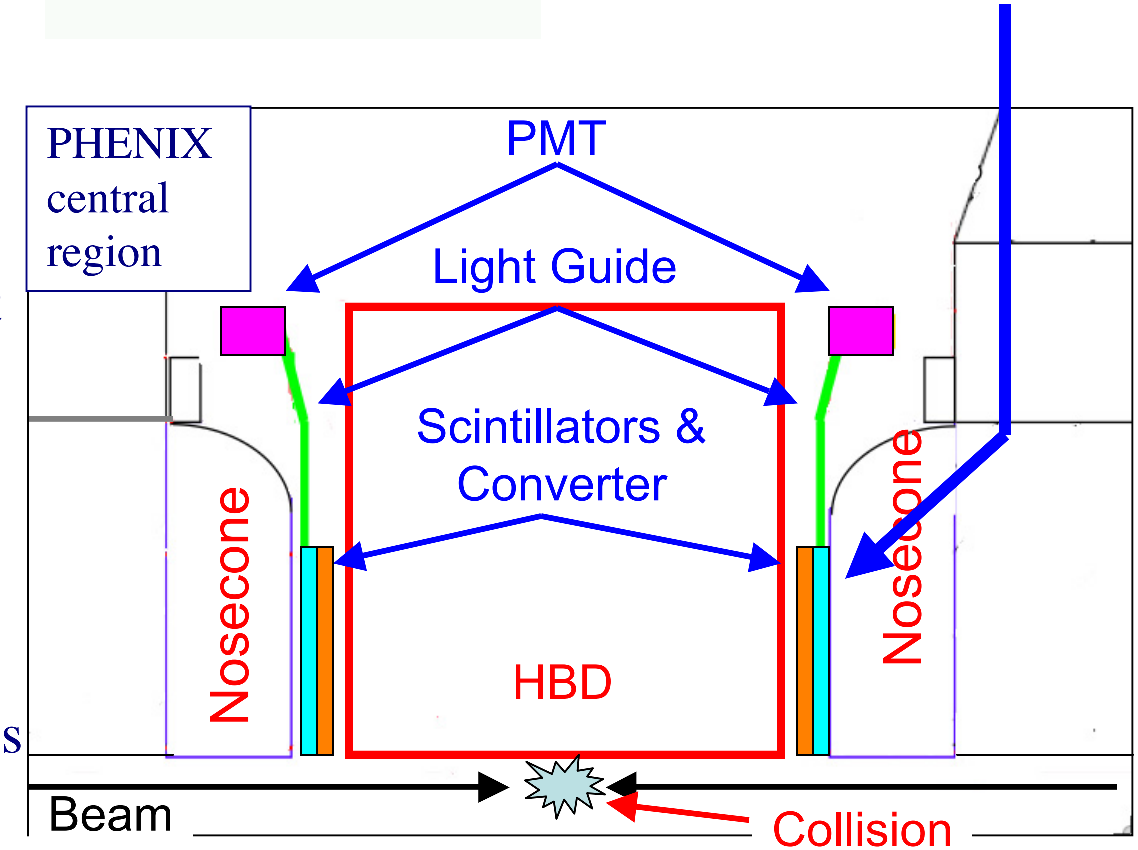


Initial Detector Concept

- Locate in PHENIX central region in-between each magnet nosecone and Hadron Blind Detector (HBD) - 7 cm of space
- Disc shape scintillator with azimuthal segmentation
- Place metal converter in front of scintillators to increase energy deposition via conversion electrons
- Detect and amplify signal with PMTs
- Connect scintillator and PMTs with light guide

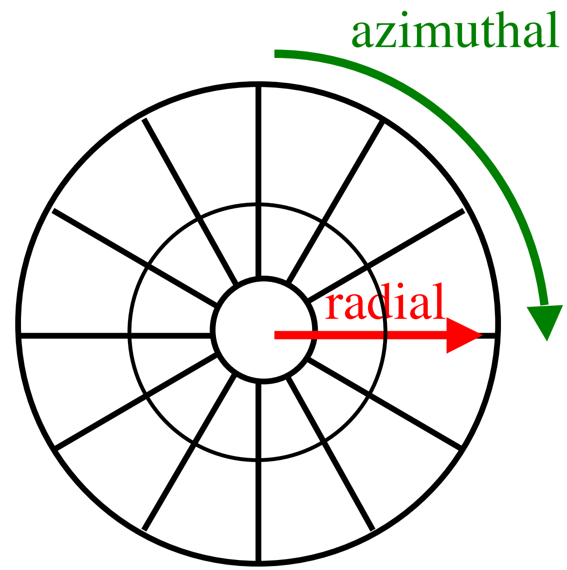






RXNP Design Optimization

- GEANT simulations - optimize detector design by maximizing reaction plane resolution while not exceeding spatial allowance
- From simulations decided to use
  - 2 cm thick lead converter
  - 2 cm thick scintillator
  - 12 azimuthal segments
  - 2 radial segments

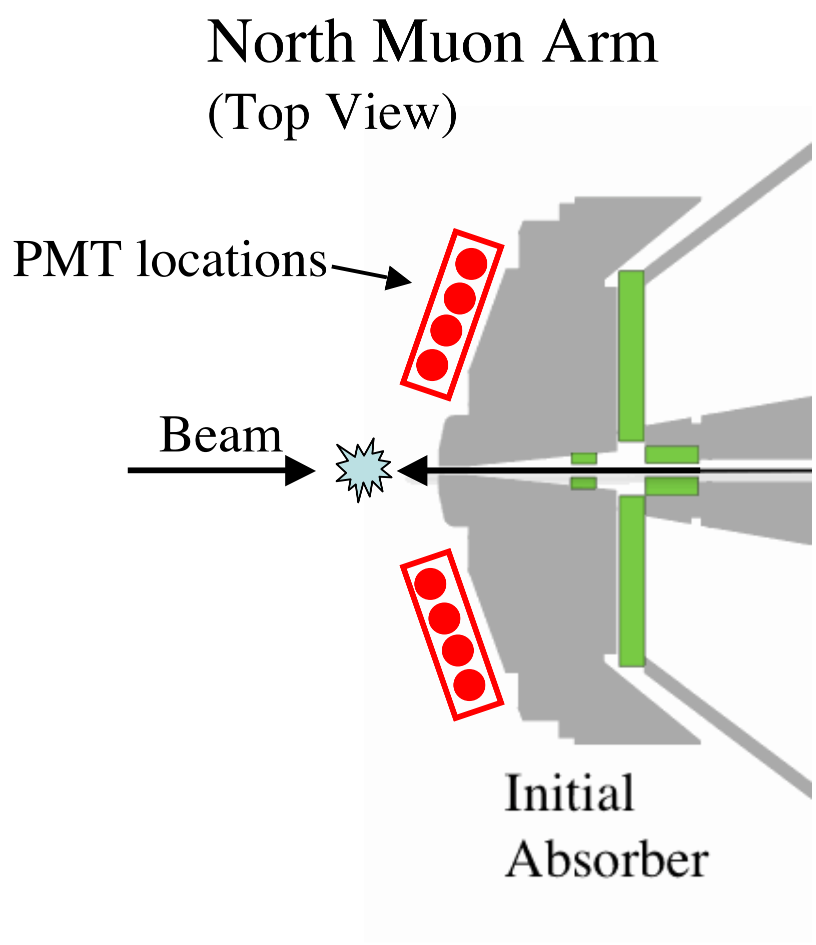


Beam View

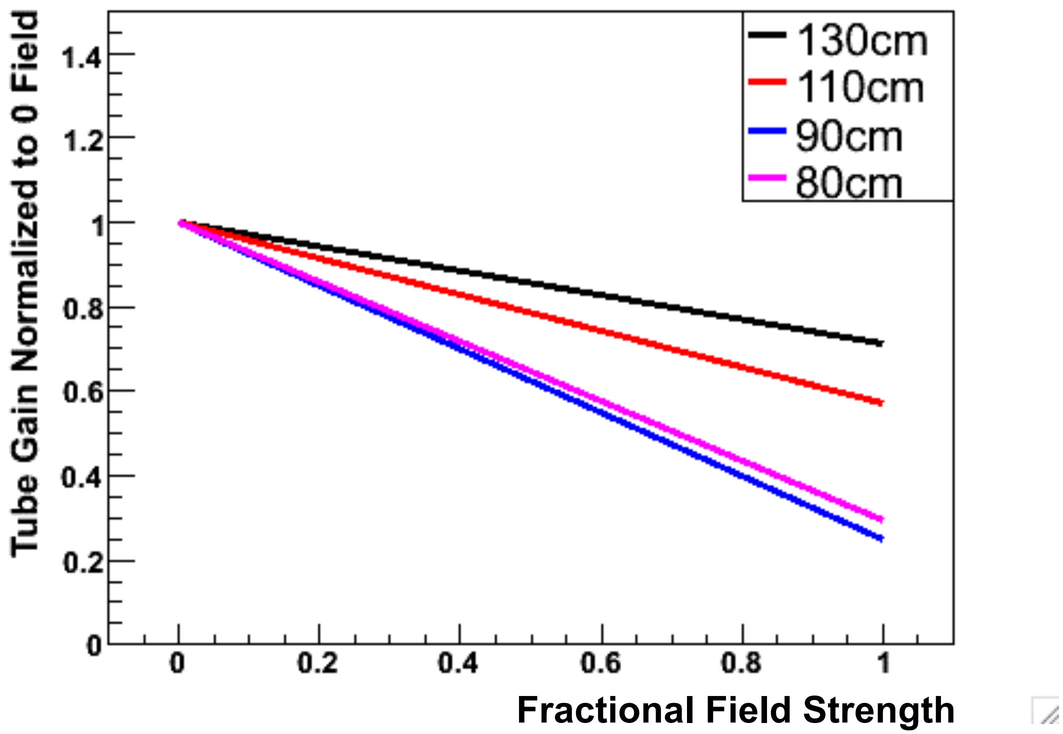
- KEK-PS Beam Tests
  - Overall best performance was scintillator + fiber light guide combination
  - Rather than substituting with either Cherenkov radiator or solid light guide

Testing PMT performance in Magnetic Field

- Predetermined location where PMT performance is expected to be best
- PMTs located 80, 90, 110, and 130 cm from beam pipe
- Used and LED pulse generator and compared PMT gain at 0 field to full field

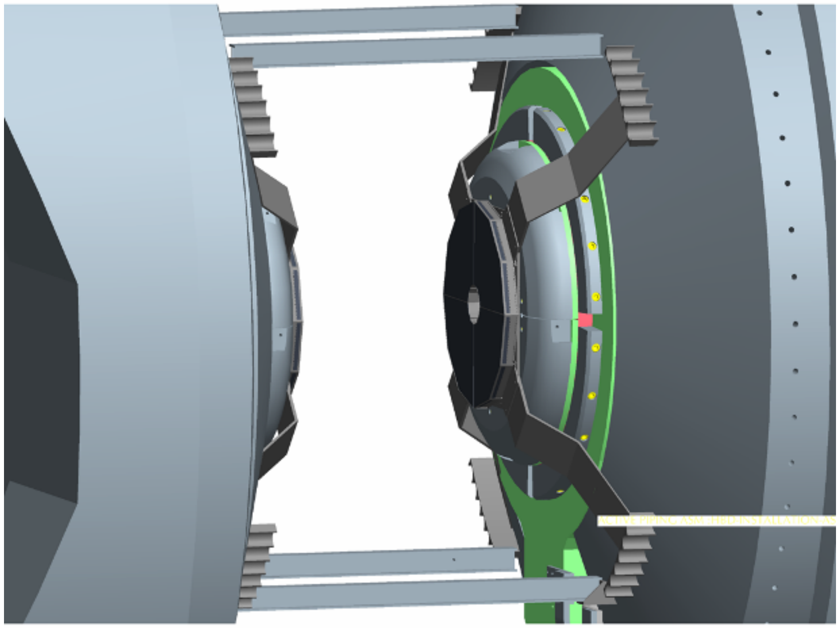


PMT Magnetic Field Test

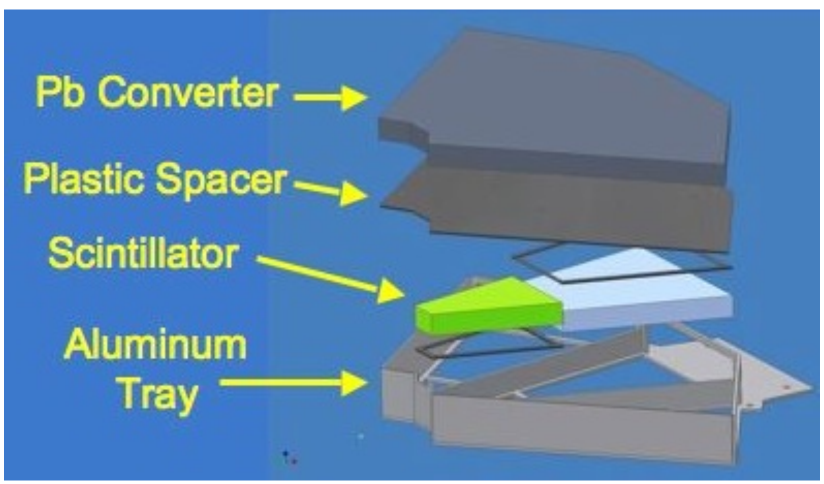


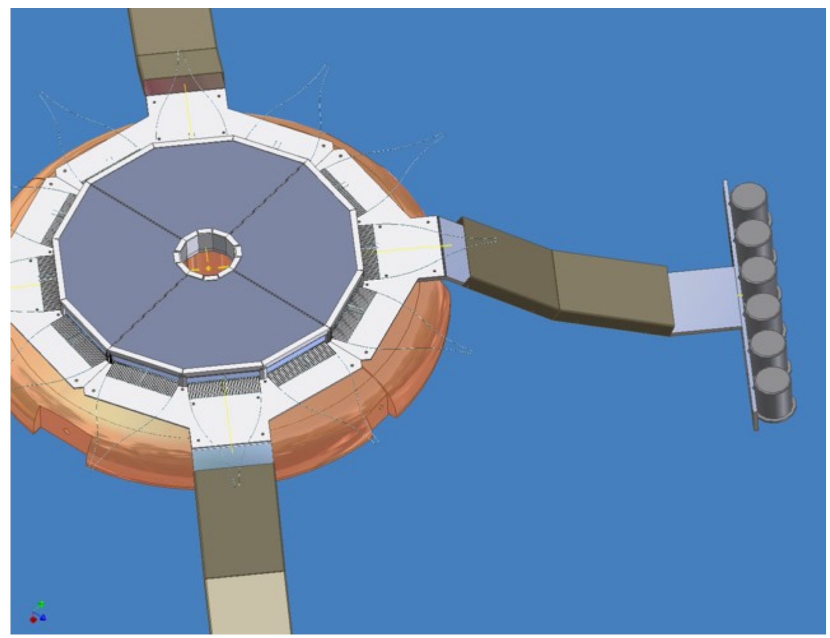
- Results show strongest PMT gain when 130 cm from beam pipe

Final Detector Conceptual Drawings



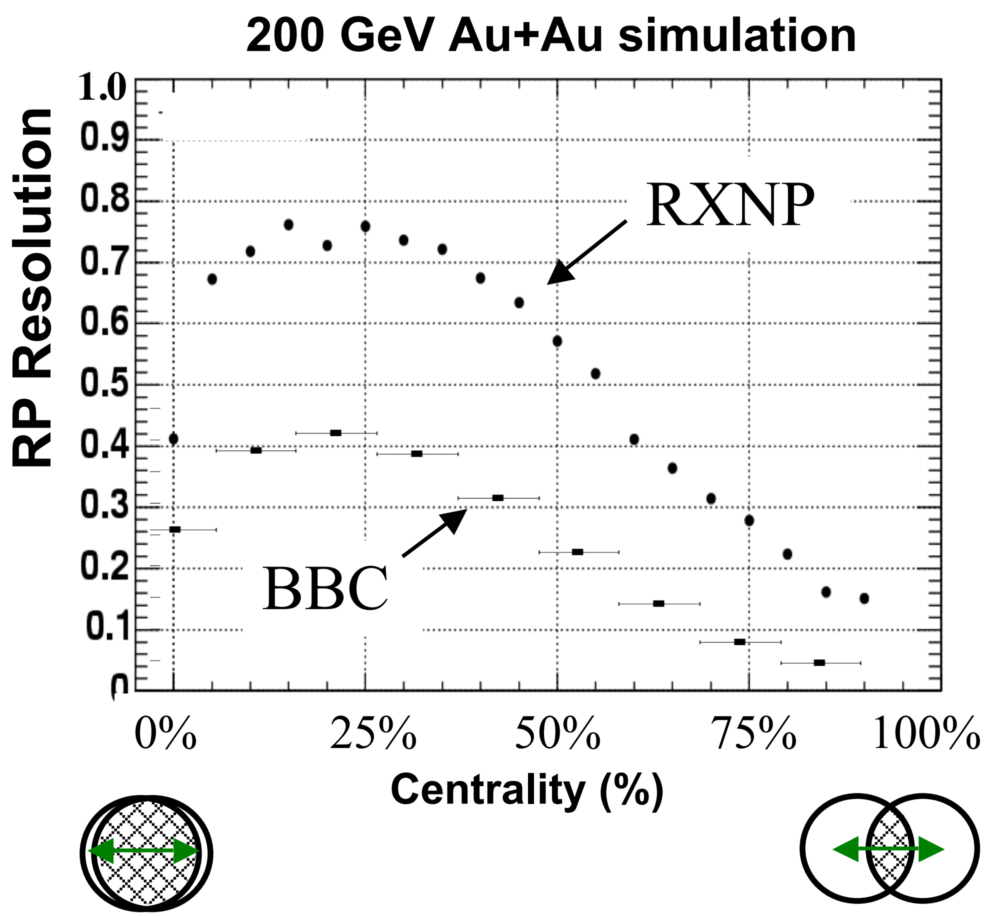
- Detector has North and South arms
- Each arm divided into quadrants
- Each quadrant contains:
  - 1 Pb converter
  - 3 inner & 3 outer scintillators
  - 6 fine mesh PMT's





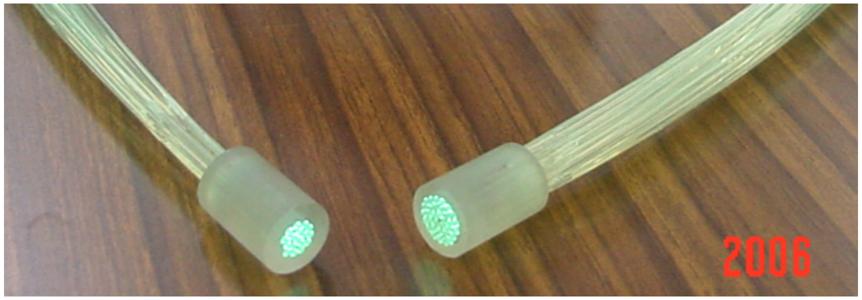
Expected RP Resolution

- RXNP expected to have a resolution ~2x better than BBC
- Equivalent to collecting ~3.5x more statistics while using BBC resolution



Detector Components

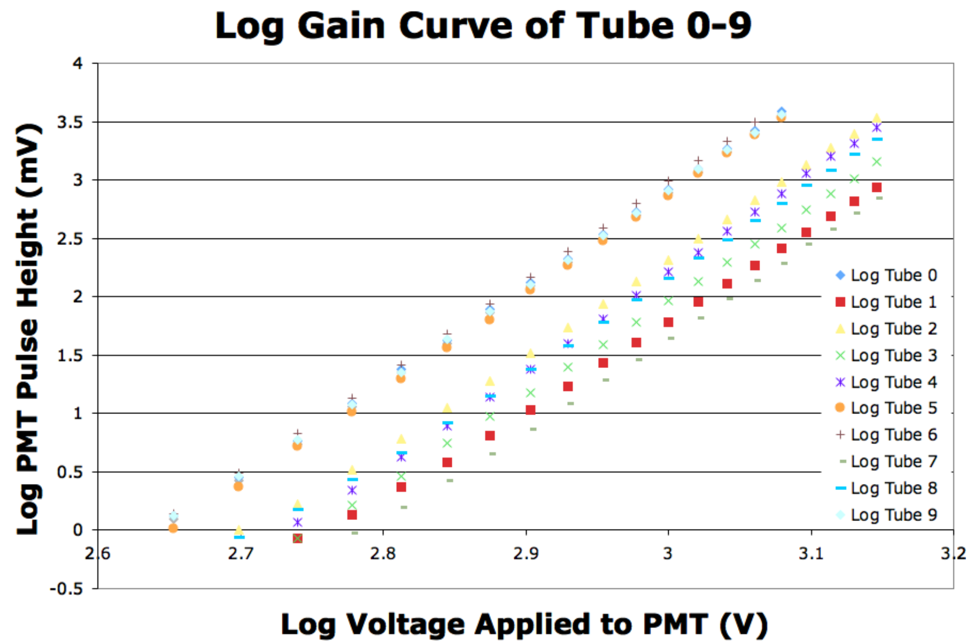
- Converter - 98% Lead + 2% Antimony to increase hardness
- Fibers - wavelength shifting to optimize PMT response



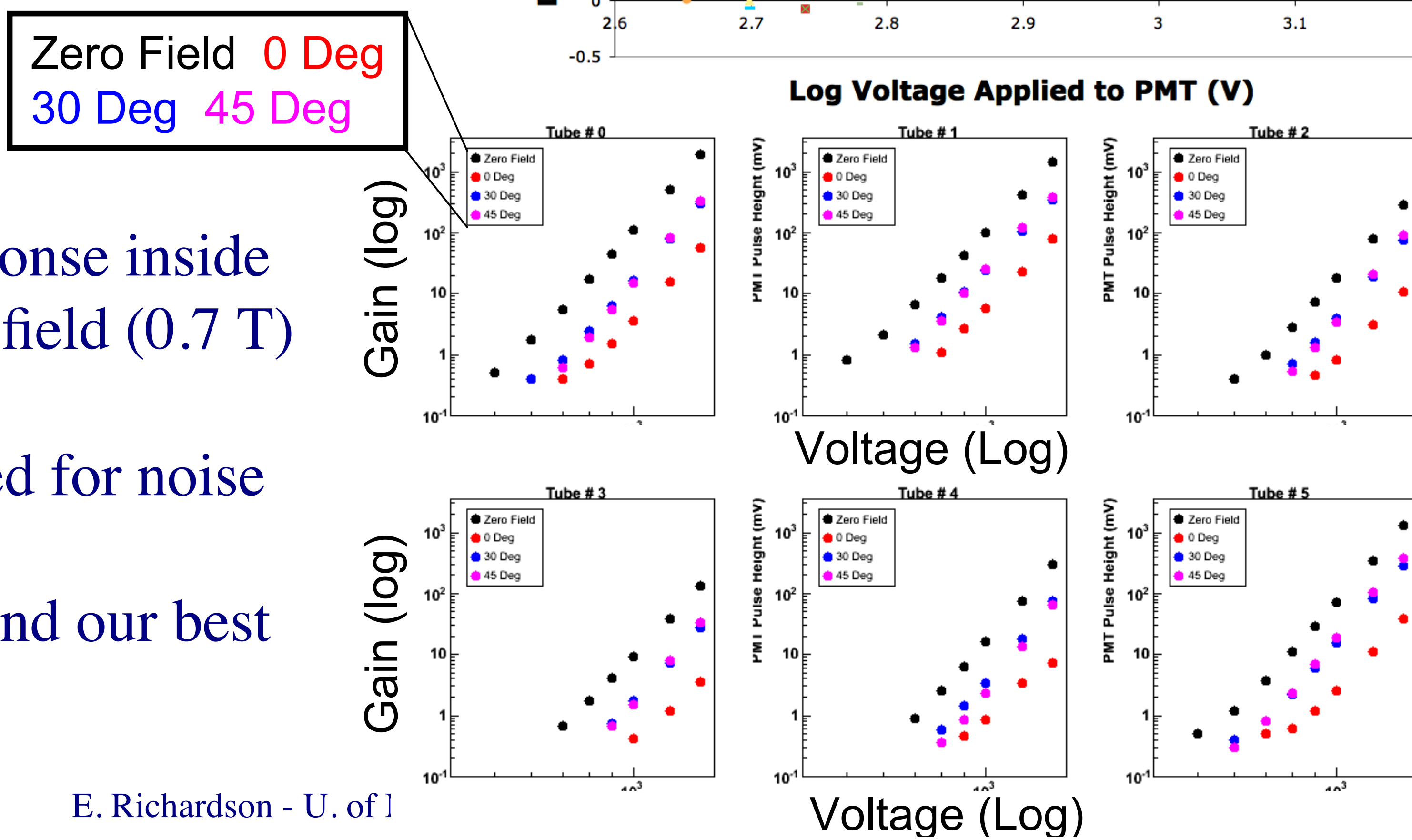
- PMTs
  - 3-in fine mesh from Hamamatsu (R5543)
  - Borrowed 52 PMTs from a KEK experiment E325

PMT Tests

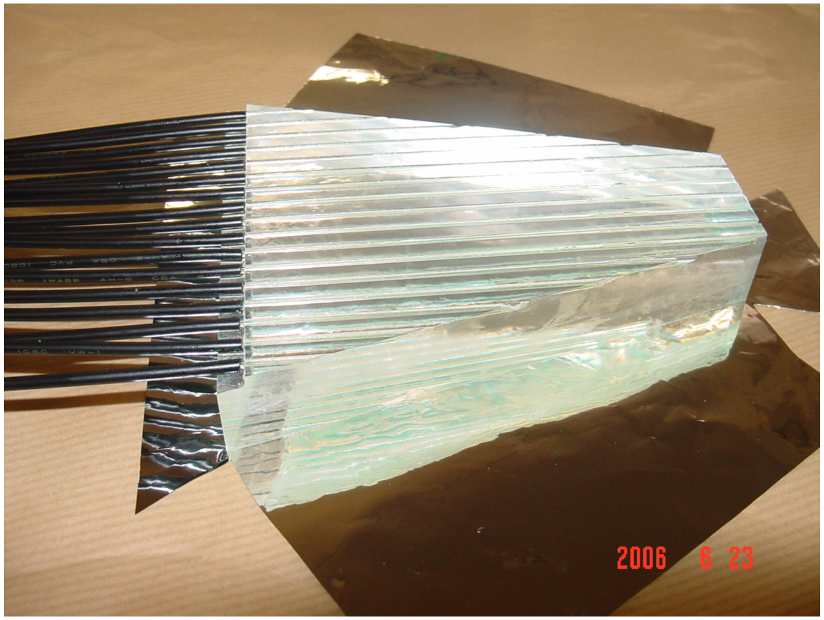
- Gain response outside magnetic field

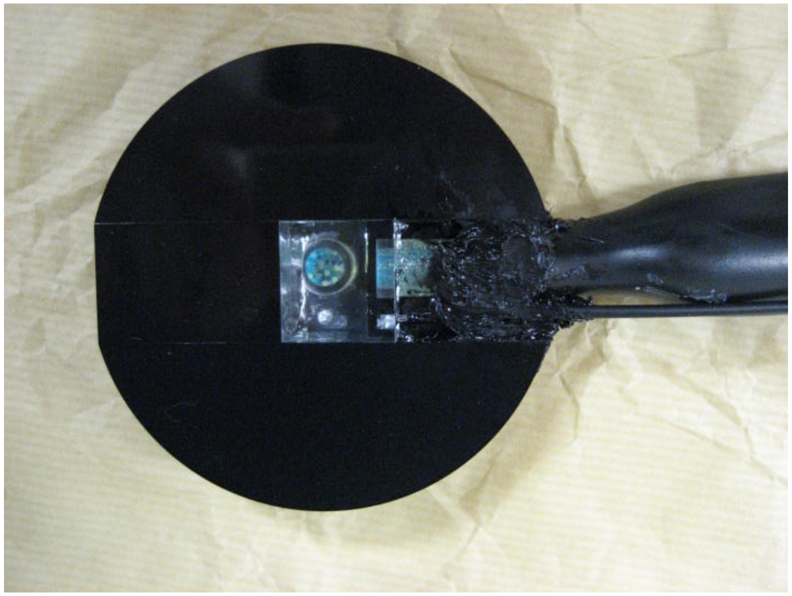


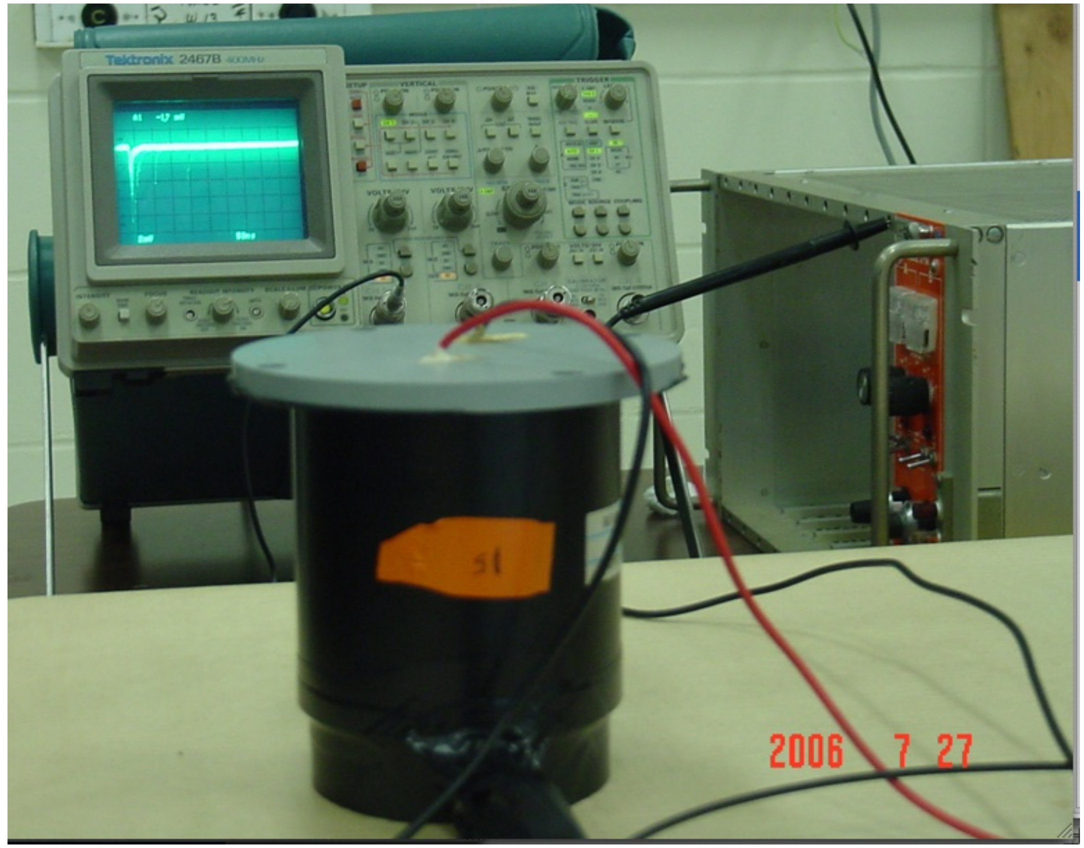
- Gain response inside magnetic field (0.7 T)
- Also tested for noise
- Used to find our best 48 PMTs



Assembly Photos



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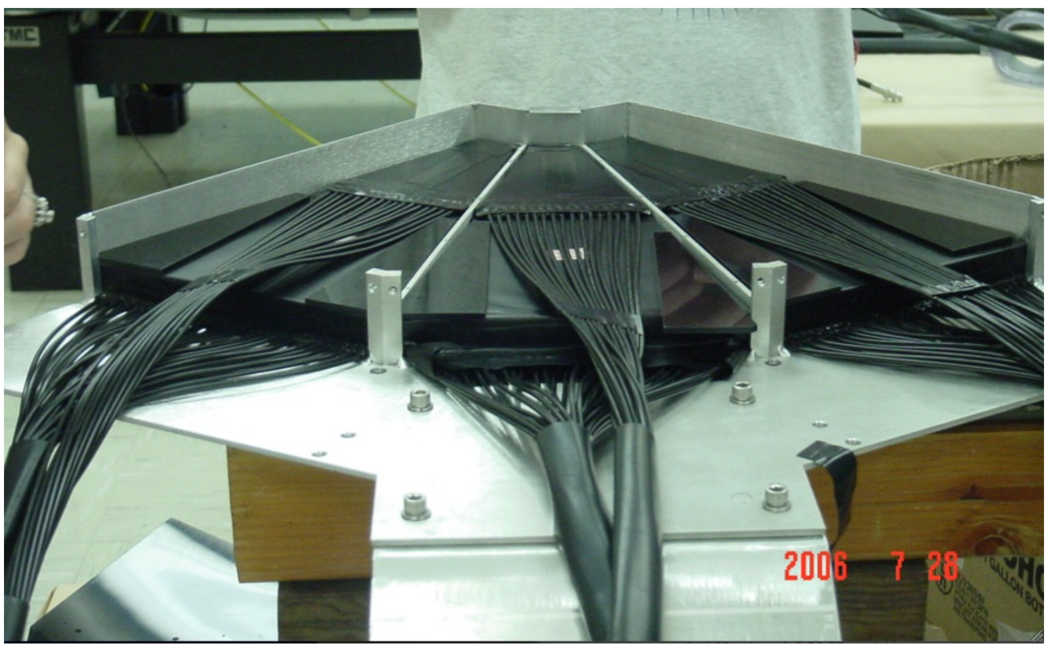
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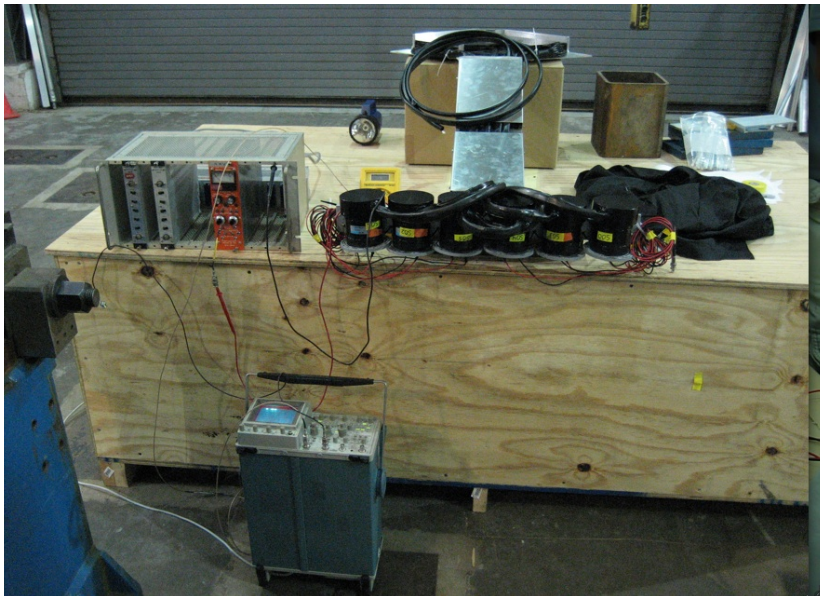
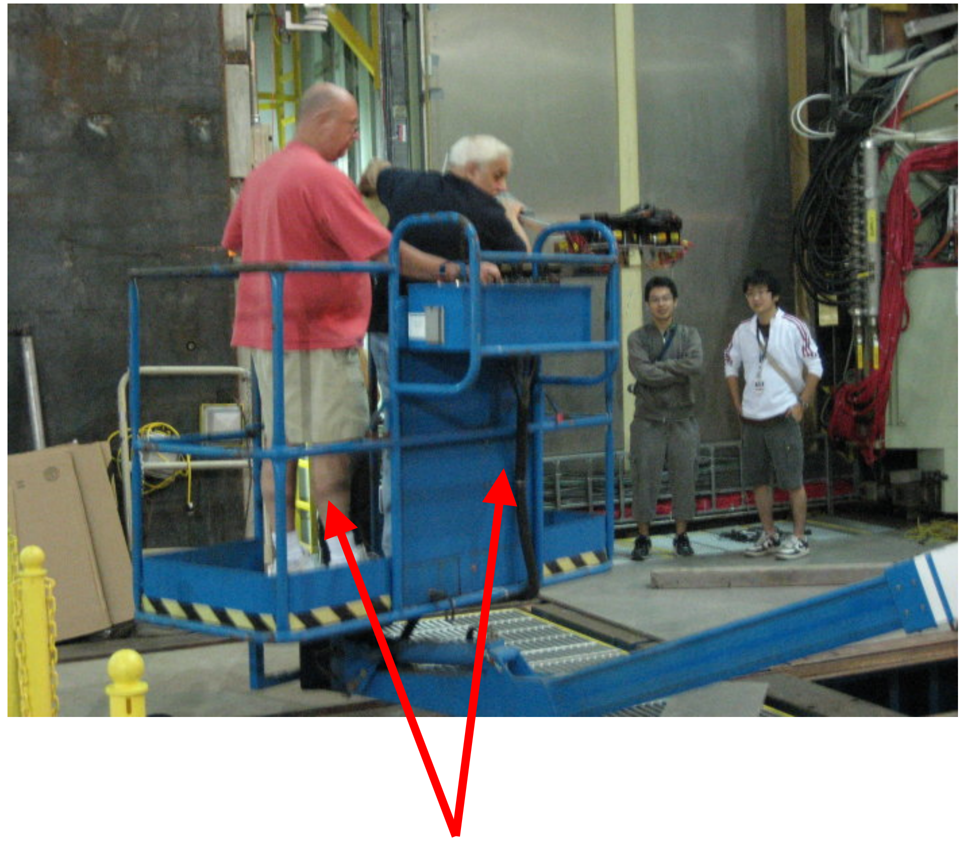
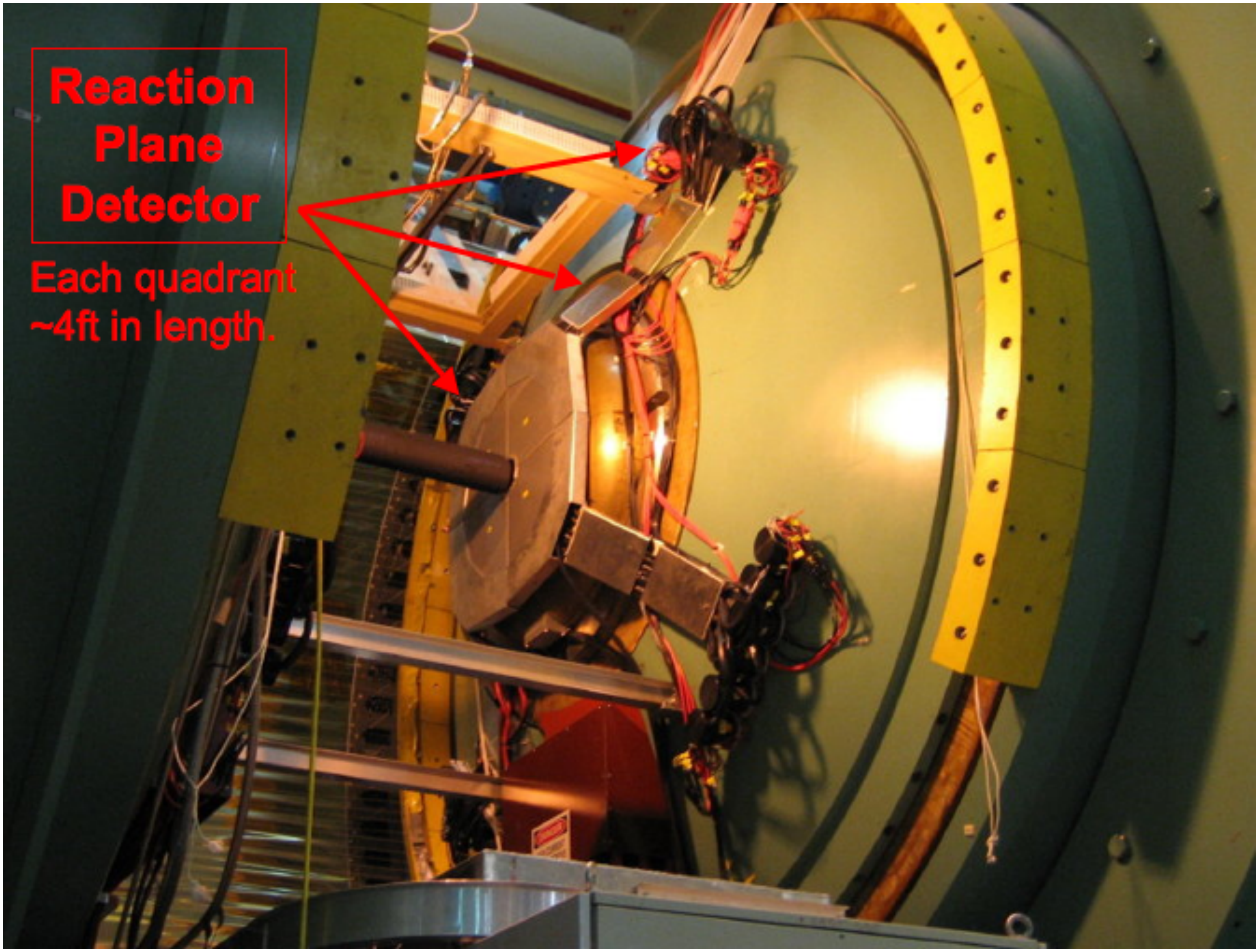
Installation



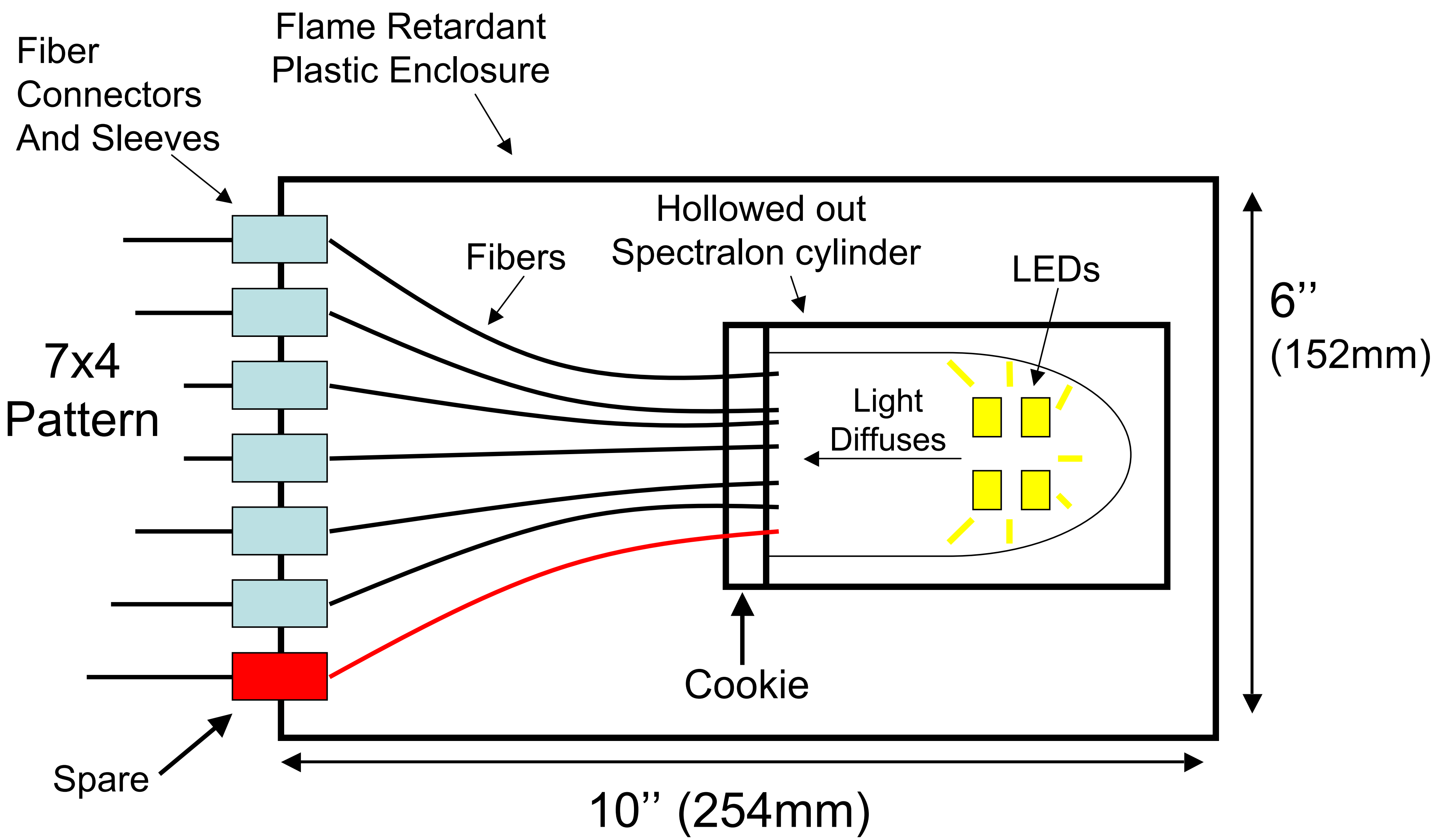


PHENIX technicians

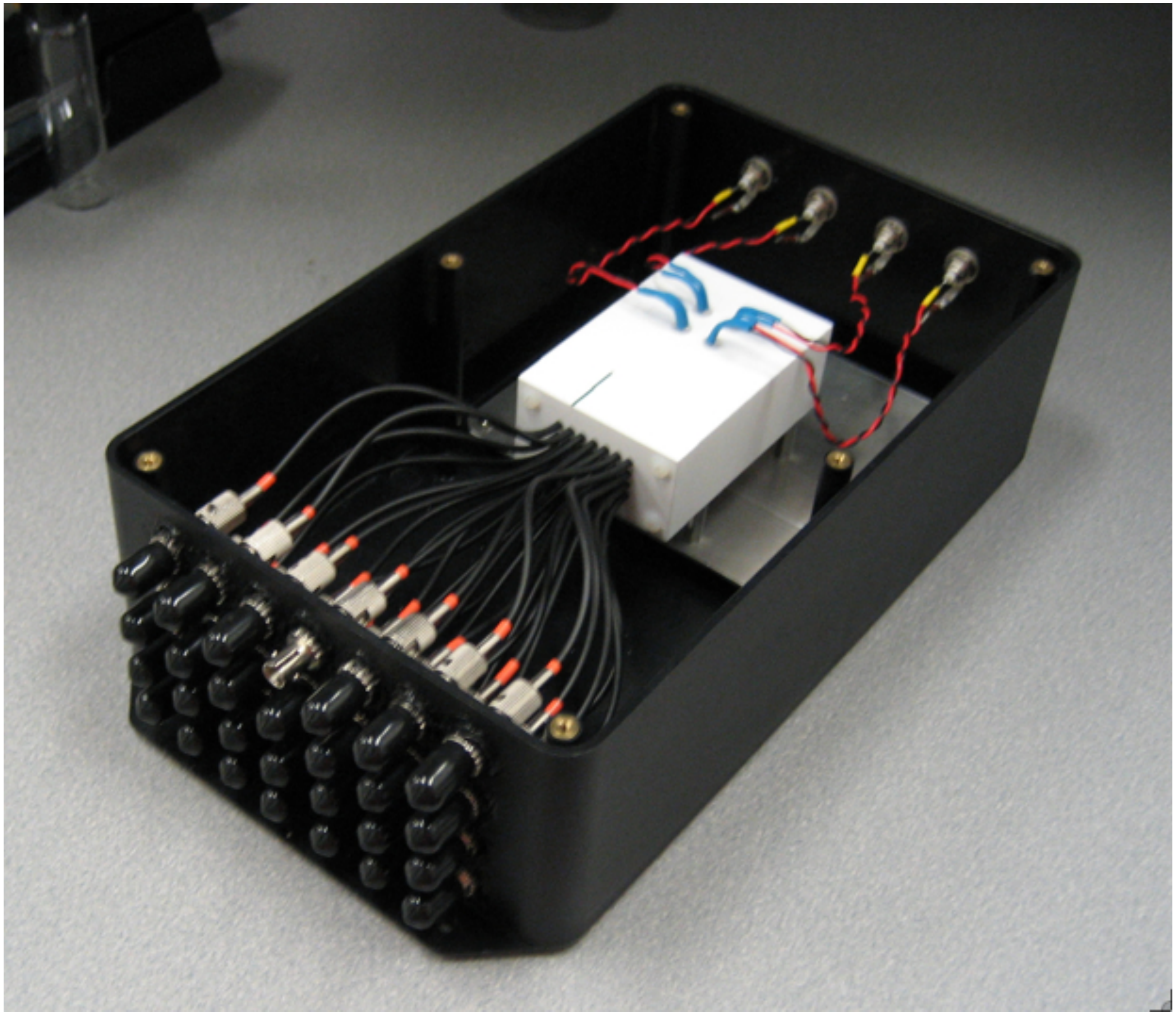
Fully Installed!!!



LED Calibration Box (Top View)

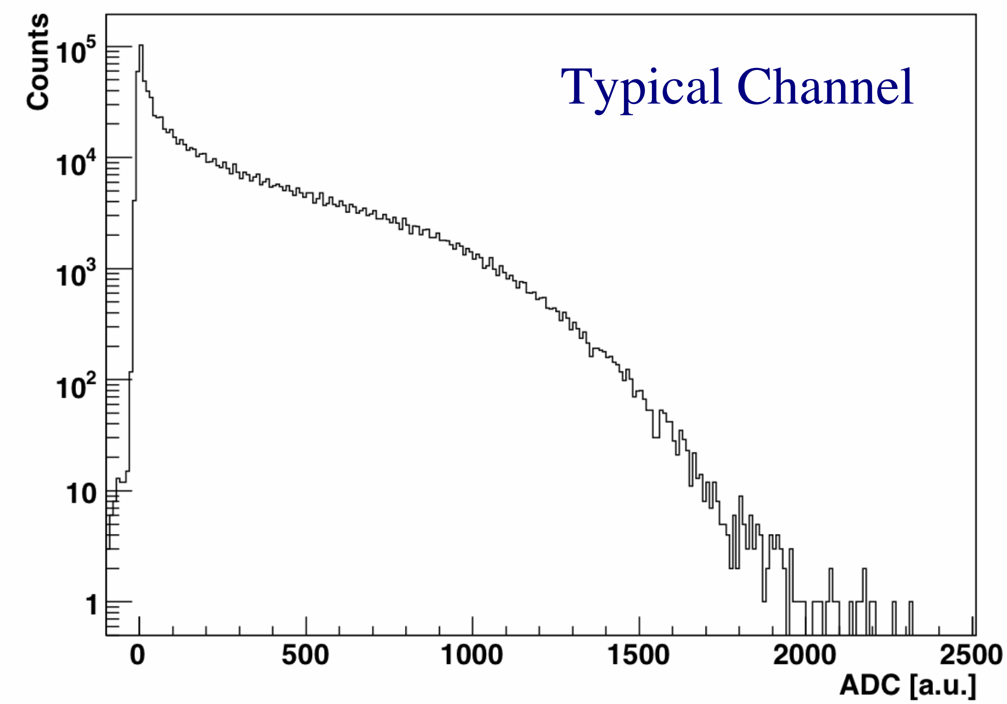


LED Box



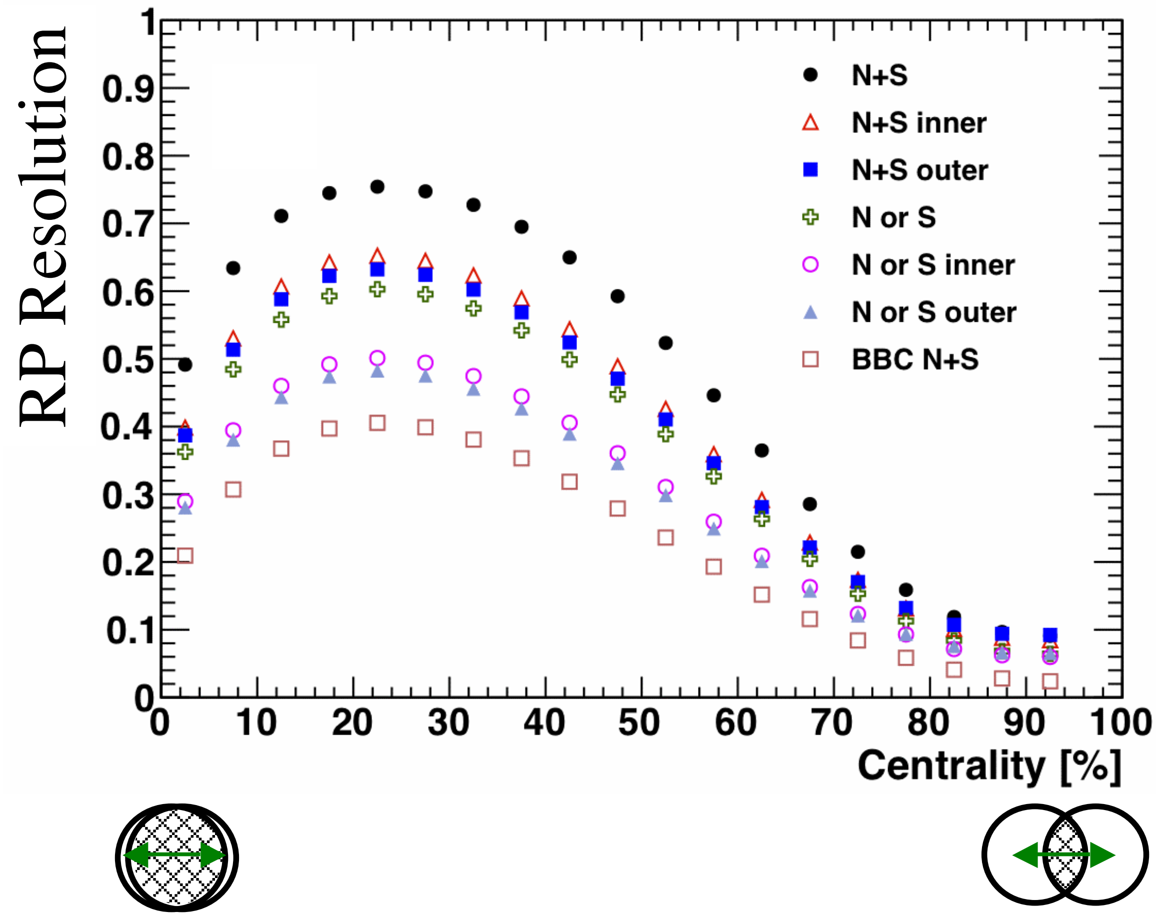
Detector Performance During 4 Years of Running

- 47 of 48 PMTs operational, ~98% of design
- RXNP collected data on all Physics runs



RP Resolution

- RXNP can measure Ψ_{RP} from 9 different detector segments
- RXNP_N+S ~2x higher than BBC_N+S
- Matches simulated expectations



RXNP NIM Paper

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Technical Notes

A reaction plane detector for PHENIX at RHIC[☆]

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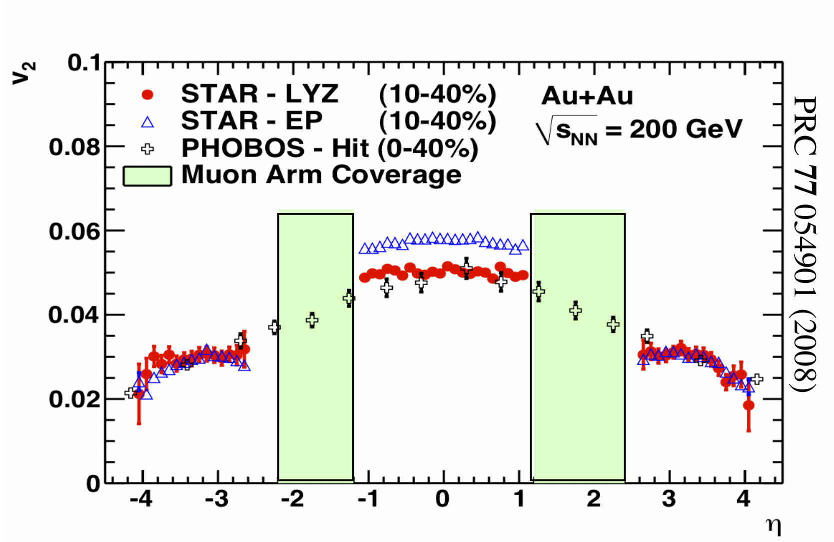
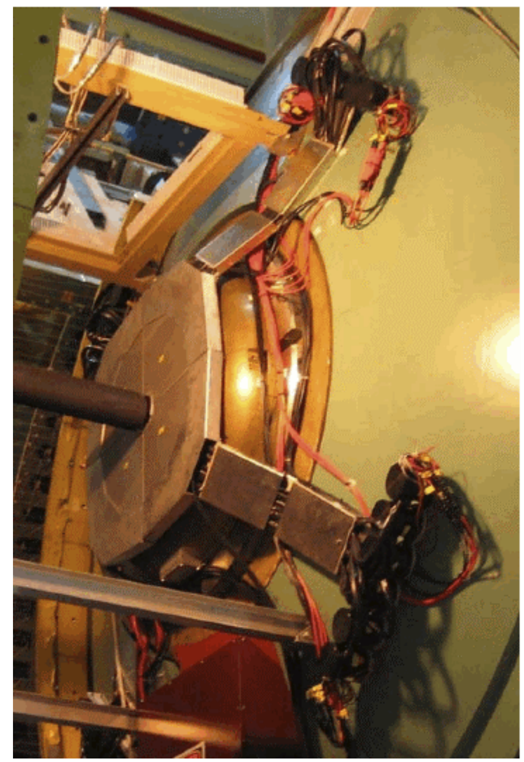
Conclusion - Parts 1-4

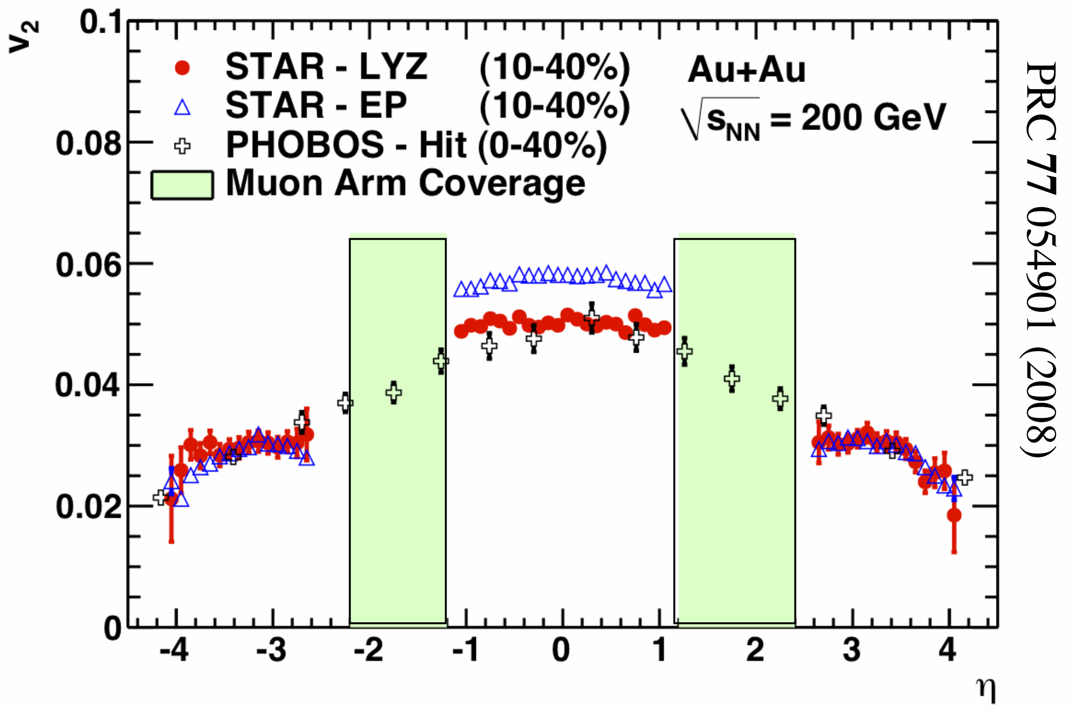
- Elliptic flow is a powerful tool to study the hot and dense medium created from heavy-ion collisions
- To measure elliptic flow at forward rapidity using PHENIX Muon Arms a new detector was needed to more accurately measure Ψ_{RP}
- RXNP was built which increased PHENIX's RP resolution by ~2x, equivalent to increasing particle statistics by ~3.5x
- Resolution now good enough to measure elliptic flow in Muon Arms

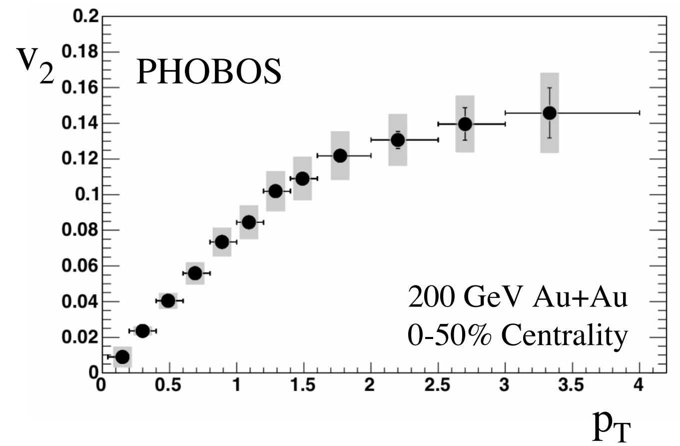




(5) Forward Rapidity Elliptic Flow Results

STAR & PHOBOS $v_2(\eta)$

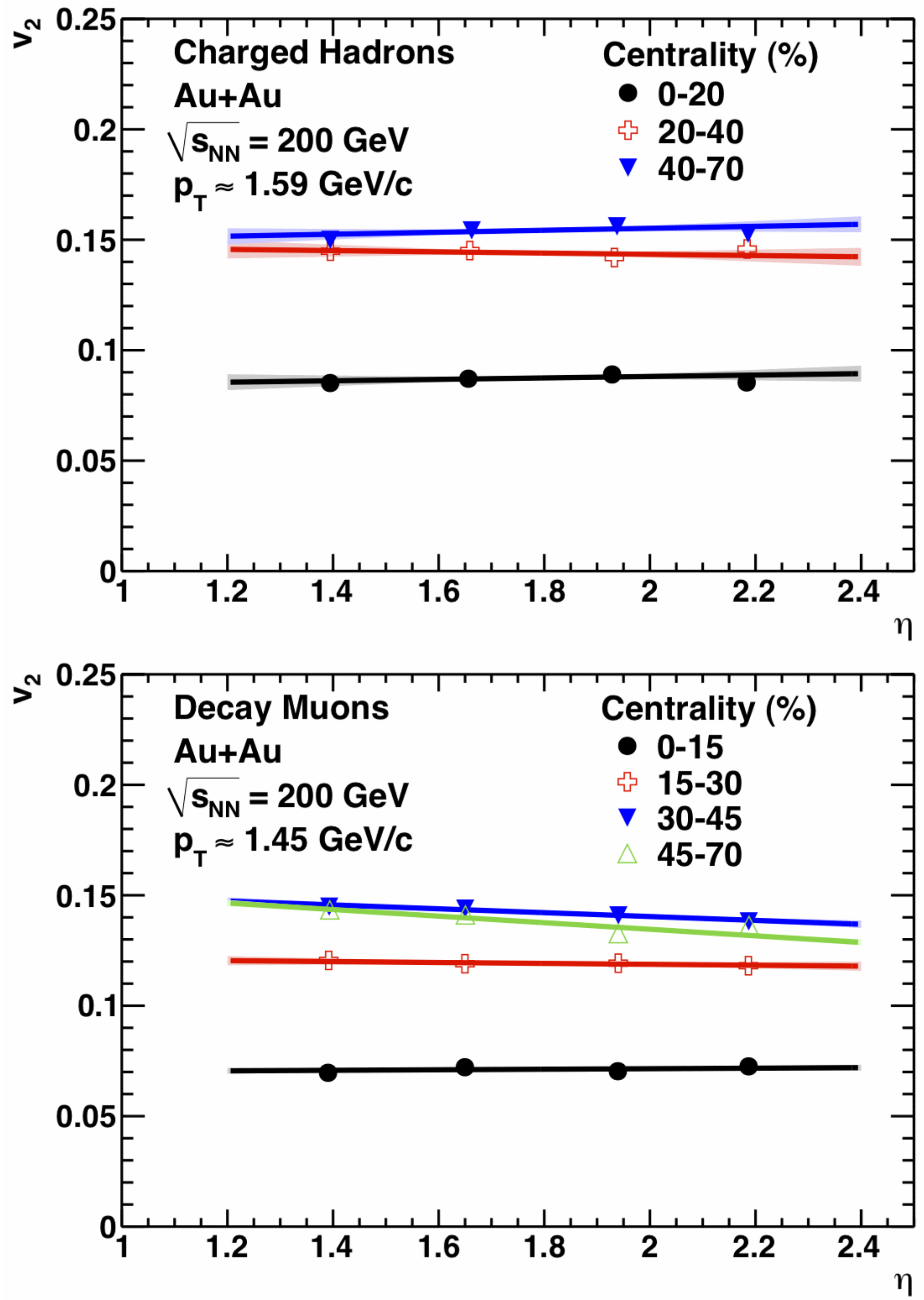




- STAR and PHOBOS measured a significant decrease in v_2 at forward η for central collisions (< 40% centrality)
- Didn't take p_T into account, which v_2 is greatly dependent upon
- Is created medium changing or is it just a decrease in $\langle p_T \rangle$?
- Measure forward rapidity v_2 using PHENIX's Muon Arms (1.2 < |η| < 2.4) which can take p_T into account.

Muon Arm $v_2(\eta)$

- Hadrons show flat v_2 for all centralities
- Decay muons show flat v_2 for central collisions, modest decrease for peripheral
- Indicate stable $v_2(\eta)$ for central events
- Challenge interpretation of STAR and PHOBOS $v_2(\eta)$ results that show significantly decreasing signal for central events

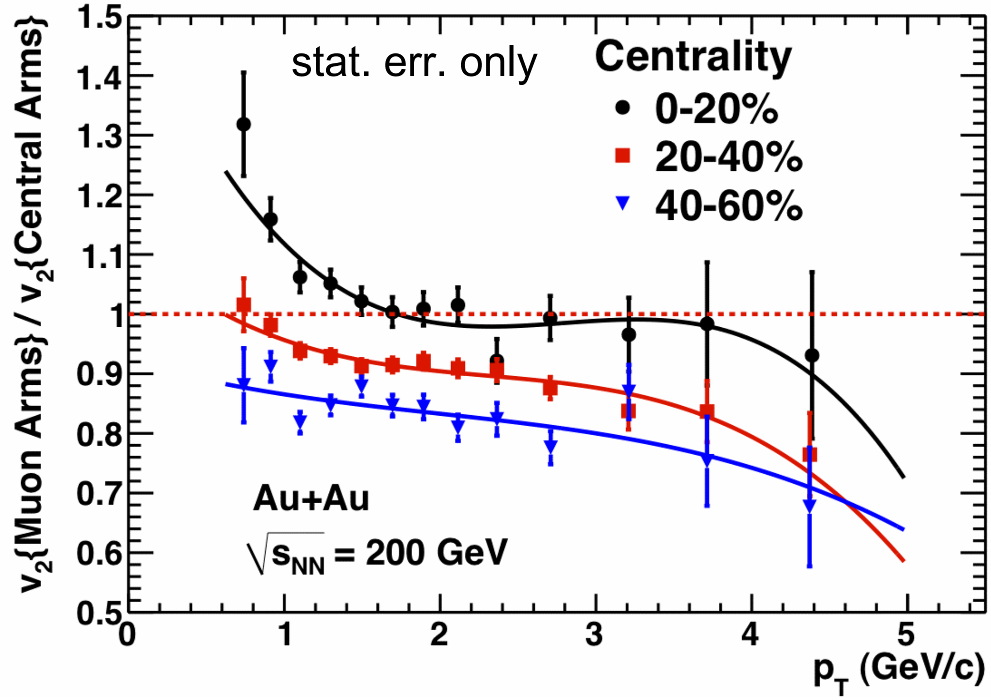


$v_2(p_T)$ Ratio

- Ratio near unity for 0-20% centrality for $p_T > 1.5$ GeV/c
- Suggests longitudinally extended thermalized medium with similar eccentricity
- Consistent with previous slide
- Decreasing ratio with more peripheral events
- Suggests differences in medium conditions

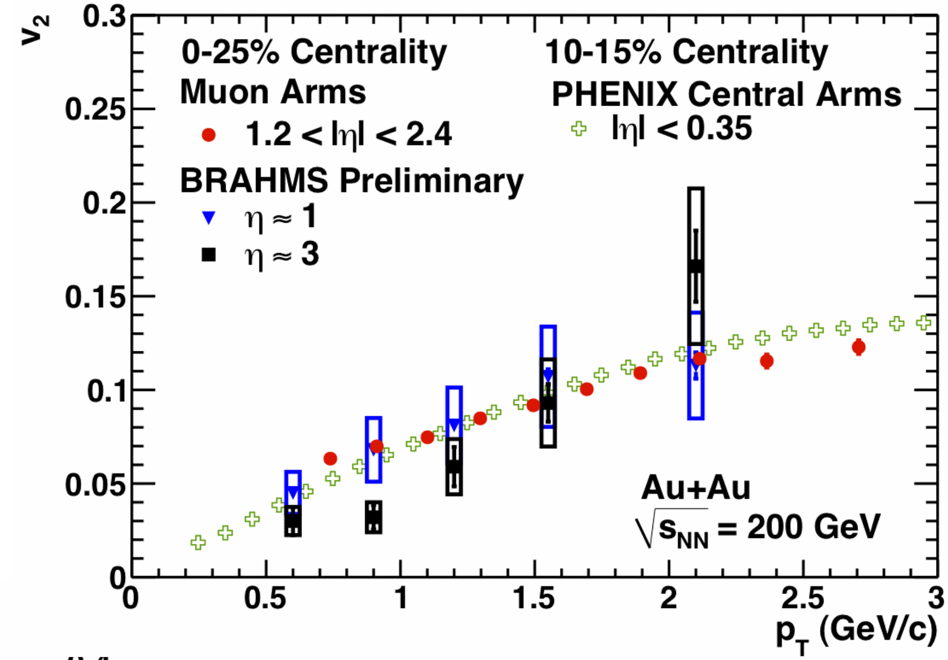
- Below $p_T < 1.5$ GeV/c signal affected by misidentified high p_T partices

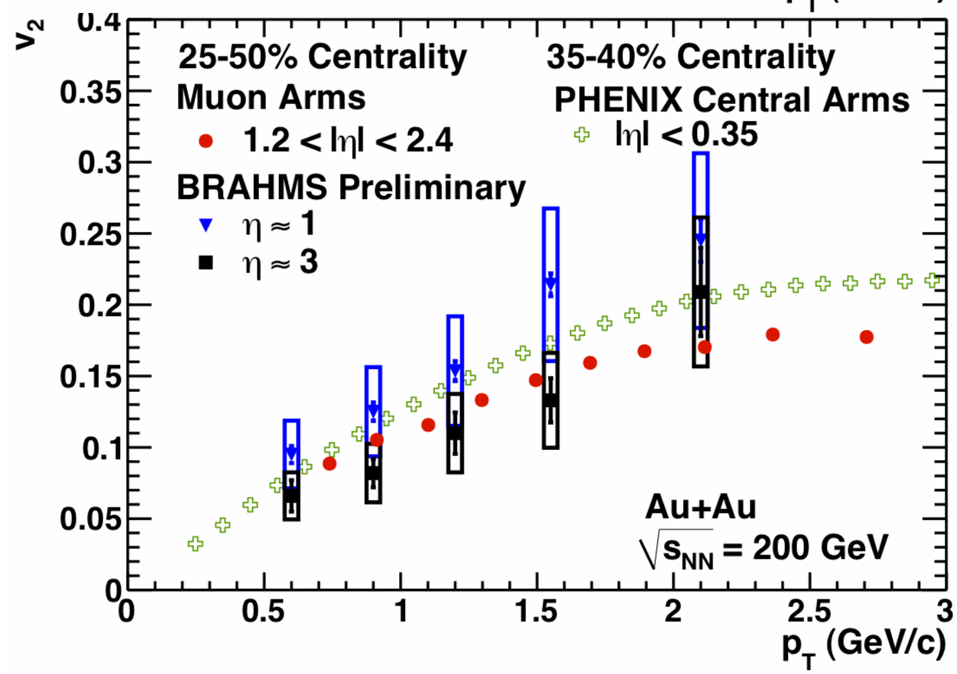
Central Arms: $|\eta| < 0.35$
Muon Arms: $1.2 < |\eta| < 2.4$



$v_2(p_T)$

- For 0-25% see a dip in v_2 at low p_T for $\eta \approx 3$
- For 25-50% see trend of decreasing v_2 toward forward η

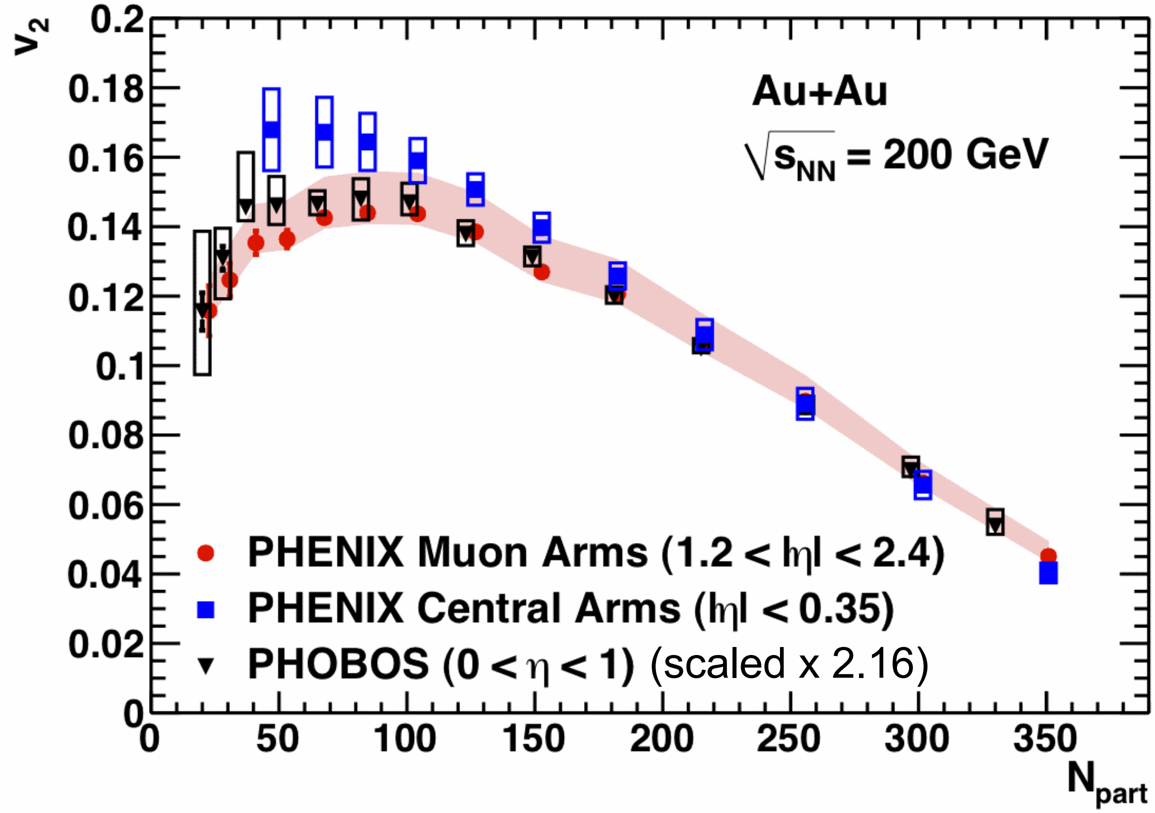


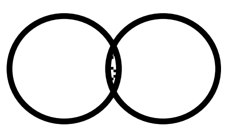


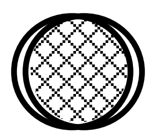
$v_2(N_{part})$

- Similar signal shape for central collisions
- PHENIX Central Arms and Muon Arms diverge at $N_{part} \approx 150$ or a centrality of 25%
- Further evidence medium changes at forward η for peripheral collisions

N_{part} = number of participants in collision



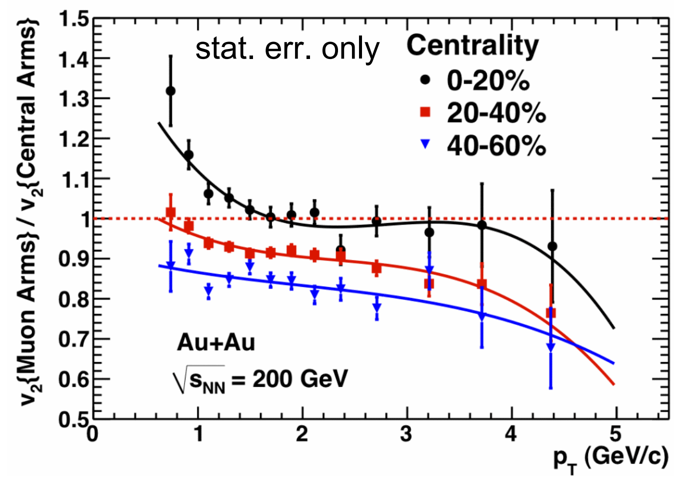


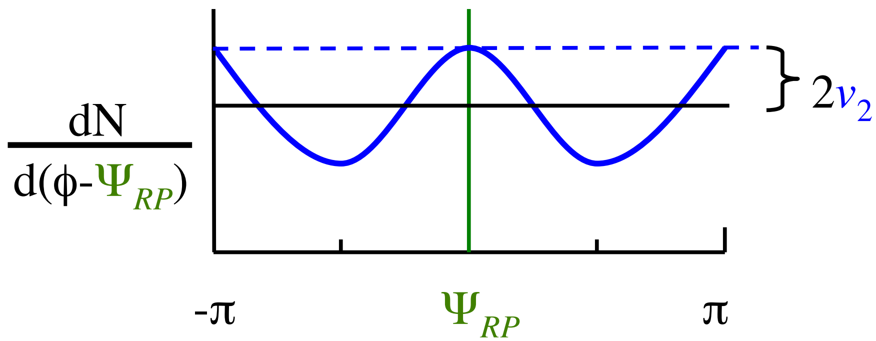


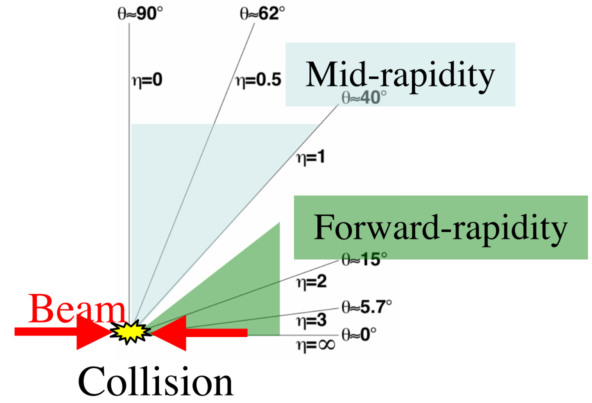
Conclusion - Part 5

- Central Collisions (< 20-30%)
  - Forward rapidity v_2 is consistent with mid-rapidity measurements out to Muon Arm region (1.2 < |η| < 2.4)
  - Suggests longitudinally extended thermalized medium with similar eccentricity throughout
  - Challenges interpretation of PHOBOS and STAR $v_2(\eta)$ results
  - Only at very forward angles (η ≈ 3) is a difference seen with mid-rapidity
- Peripheral collisions
  - v_2 decreases toward forward η
  - Suggests changes in the medium's properties from mid-rapidity (medium not fully thermalized?)

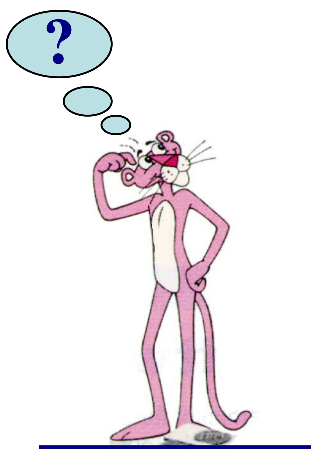
Central Arms: |η| < 0.35
Muon Arms: 1.2 < |η| < 2.4

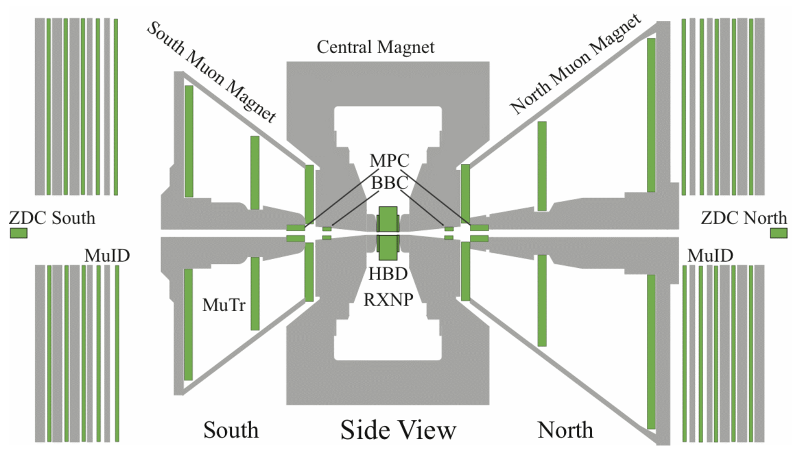


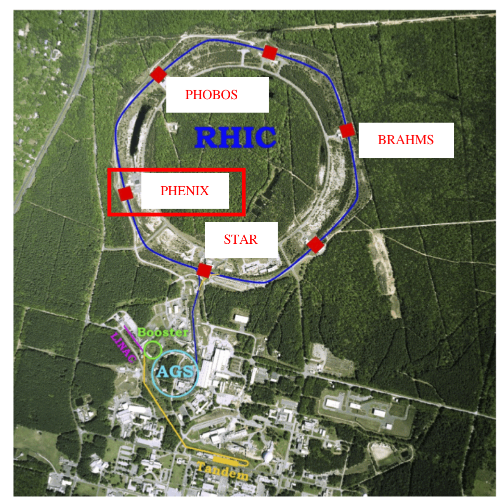




Elliptic flow at forward rapidity in Au+Au collisions using the PHENIX Detector at RHIC







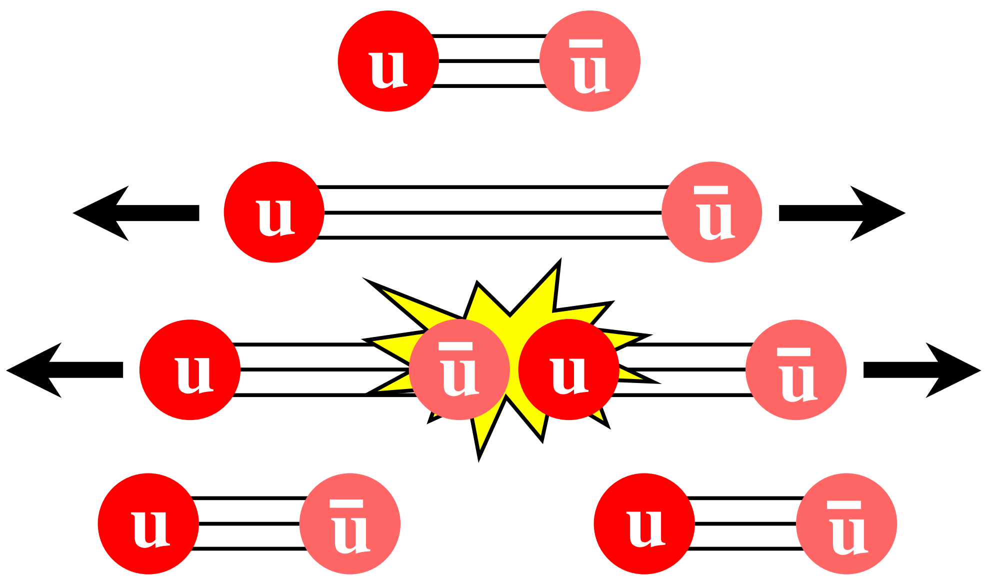
Thank You!

The PHENIX Collaboration thanks the staff of the Collider-Accelerator and Physics Departments at BNL for their vital contributions. We acknowledge support from the Office of Nuclear Physics in DOE Office of Science and NSF (USA); MEXT and JSPS (Japan); CNPq and FAPESP (Brazil); NSFC (China); MSMT (Czech Republic); IN2P3/CNRS and CEA (France); BMBF, DAAD, and AvH (Germany); OTKA (Hungary); DAE and DST (India); ISF (Israel); NRF (Korea); MES, RAS, and FAAE (Russia); VR and KAW (Sweden); US CRDF for the FSU; US-Hungary Fulbright; and US-Israel BSF.

Backup

Quarks are Confined to Hadrons

- Unlike electrons, quarks cannot be measured or observed one at a time



Confinement

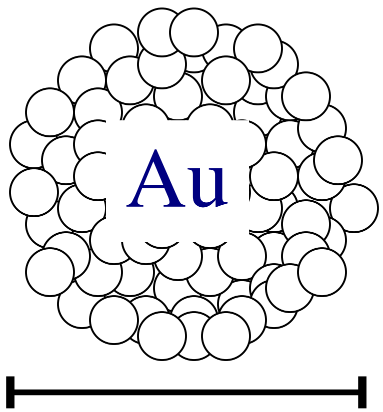
Add Energy

$E = mc^2$

Color neutrality satisfied

- As quarks separate, it becomes more energetically favorable to create a new color neutral quark-antiquark pair from the vacuum than separate any further
- Think of as pulling apart a rubber band

Accelerating Au Nuclei

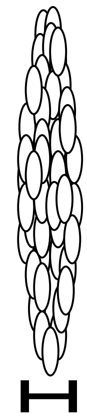


~14 fm

79 protons 118 neutrons 0 electrons

Accelerate to 100 GeV/nucleon

β = 99.996% speed of light



~0.13 fm

Lorentz Contraction

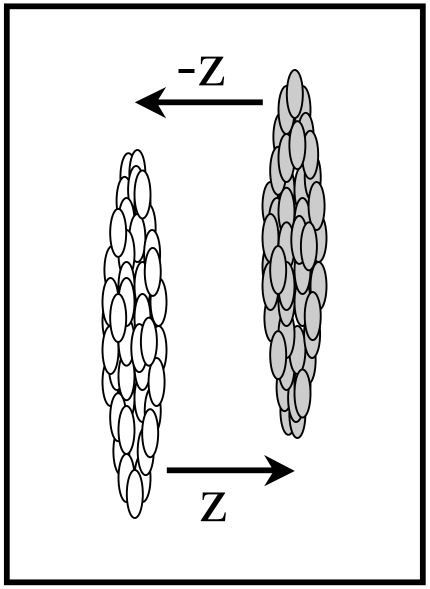
Lorentz Factor $\gamma = \frac{1}{\sqrt{1-\beta^2}} = 106.5$

$$Length = \frac{Length_0}{\gamma} = 0.13 \text{ fm}$$

Equivalent to compressing a basketball to the thickness of 2 mm

Colliding Au Nuclei

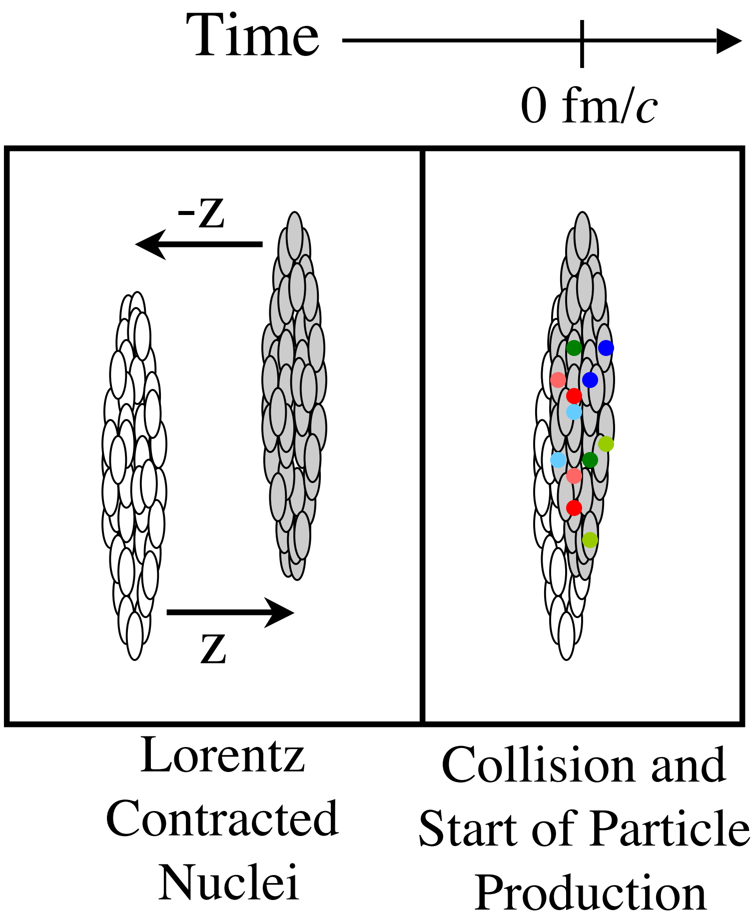
Time ⟶



Lorentz
Contracted
Nuclei

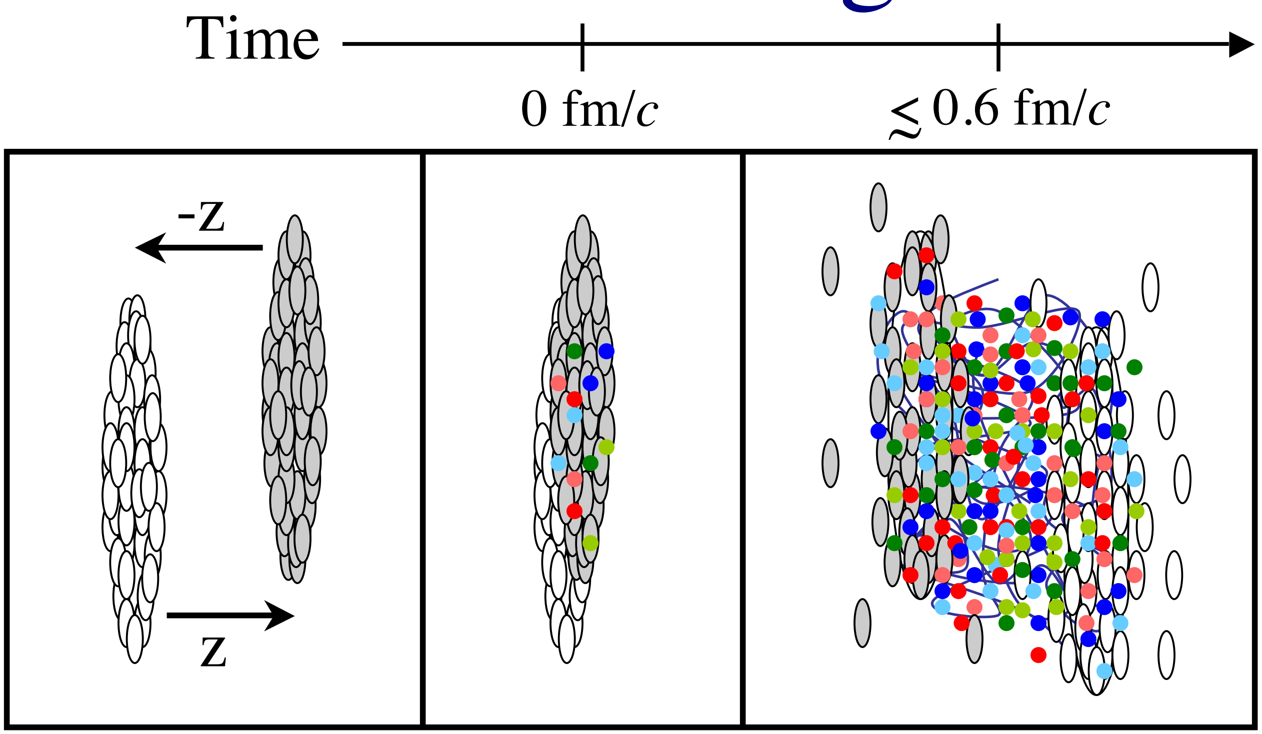
Au nuclei accelerated toward one another at 200 GeV per nucleon pair

Colliding Au Nuclei



- Au nuclei overlap one another for 4×10^{-25} s
- Mean energy density of 2920 GeV/fm^3 (normal nuclear matter = 0.14 GeV/fm^3)
- Nuclei excite one another and particle production begins

Colliding Au Nuclei

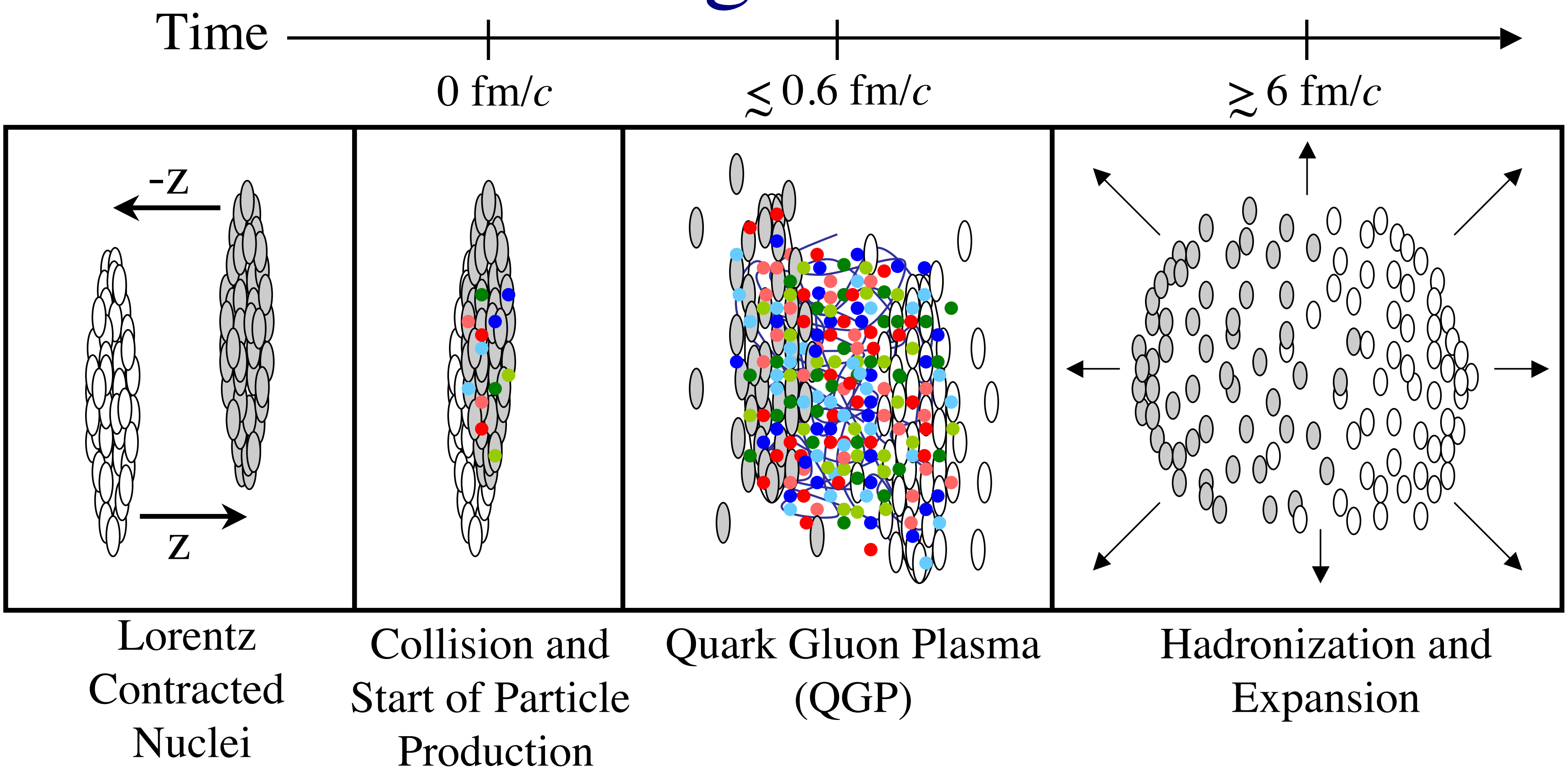


Lorentz Contracted Nuclei | Collision and Start of Particle Production | Quark Gluon Plasma (QGP)

- System expands and particle production continues
- If particle density high enough a QGP is formed
- Measurements show thermalization reached at 300-600 MeV or 3.5—7 x 10^{12} K, energy density of 9 GeV/fm^3

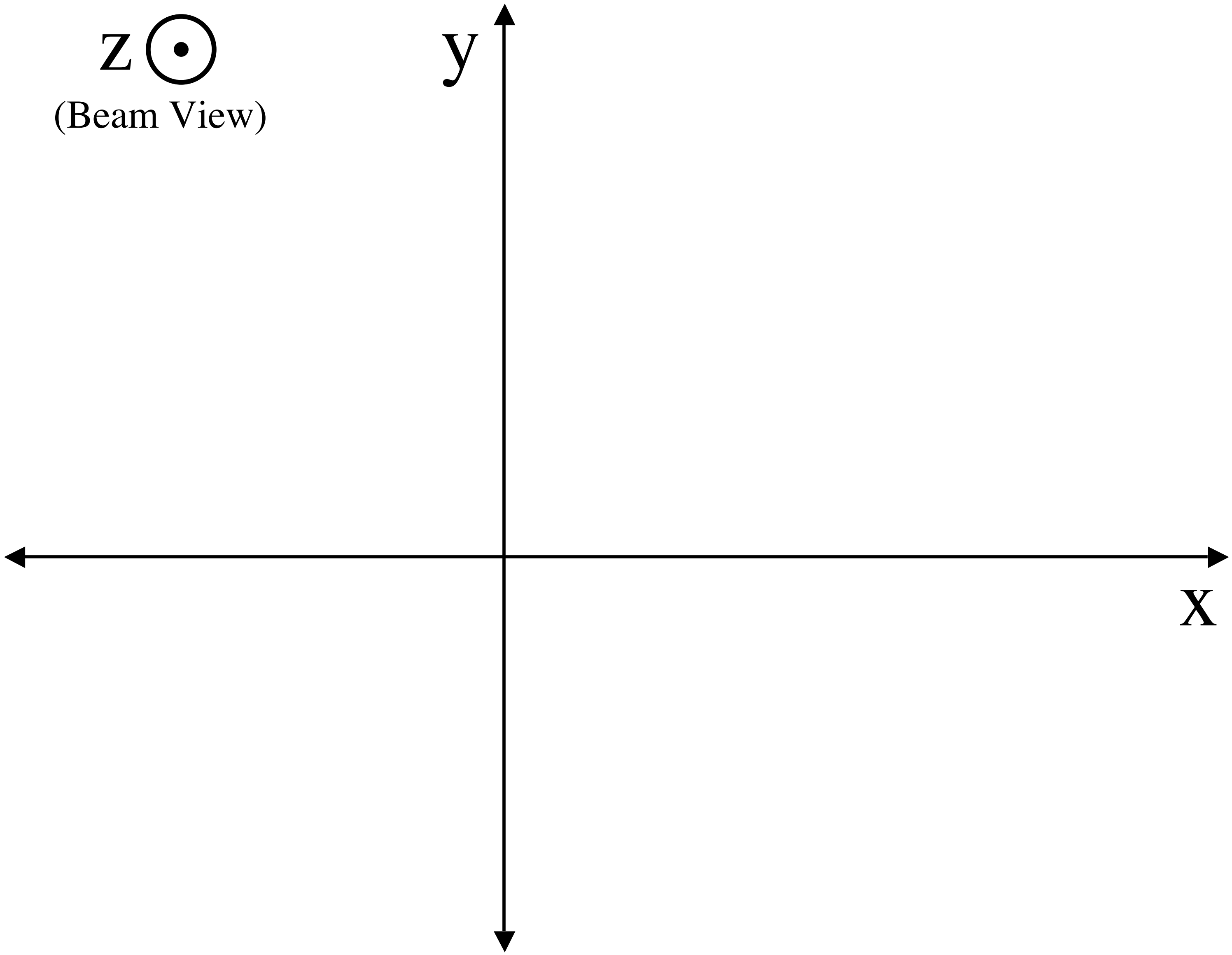
QGP Phase Transition
- 170 MeV
- 1 GeV/fm^3

Colliding Au Nuclei

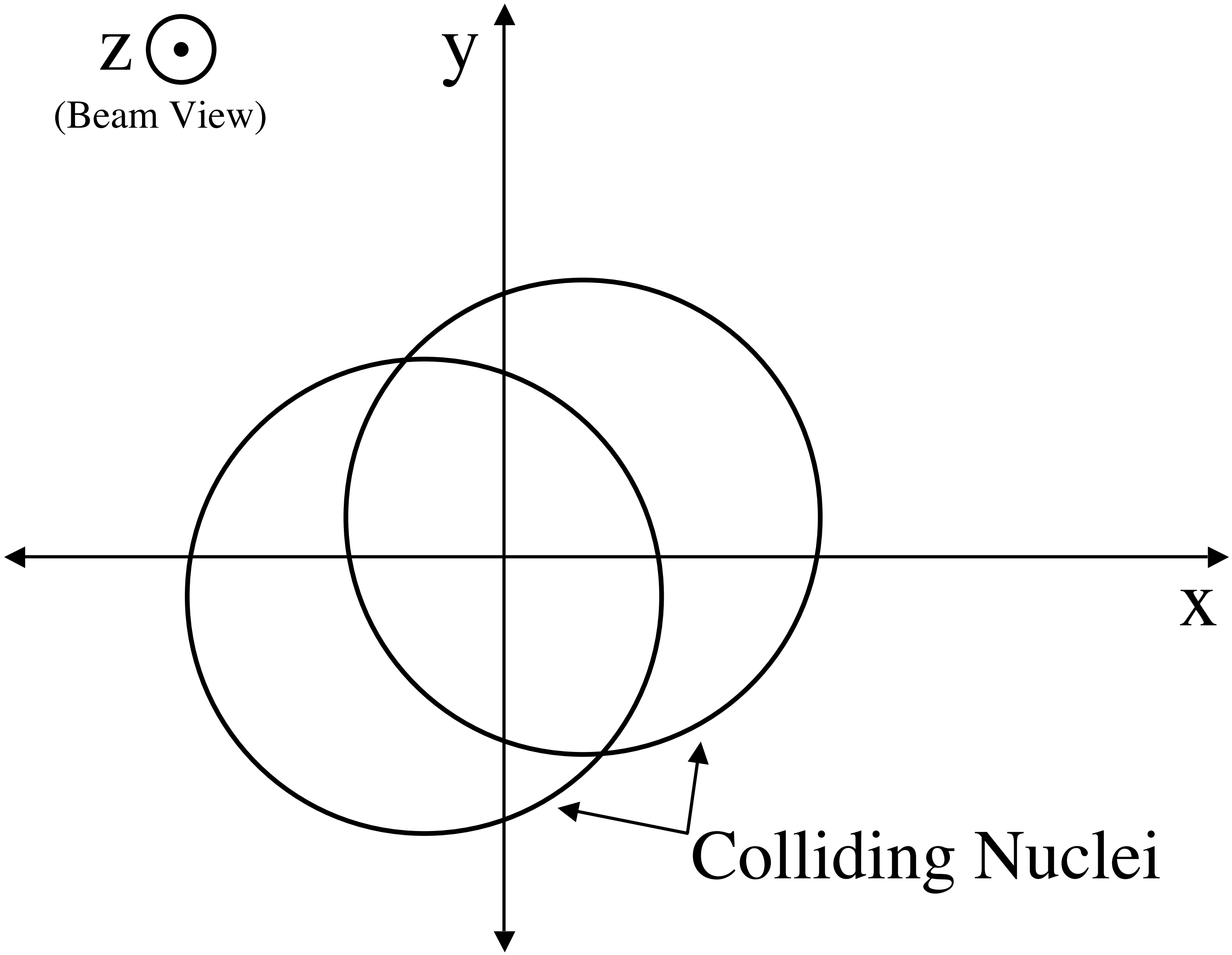


- Medium continually expands, cools, and eventually hadronizes
- Chemical freeze-out reached when quark flavors inside hadrons no longer change
- Thermal freeze-out reached when hadrons no longer interact with each other

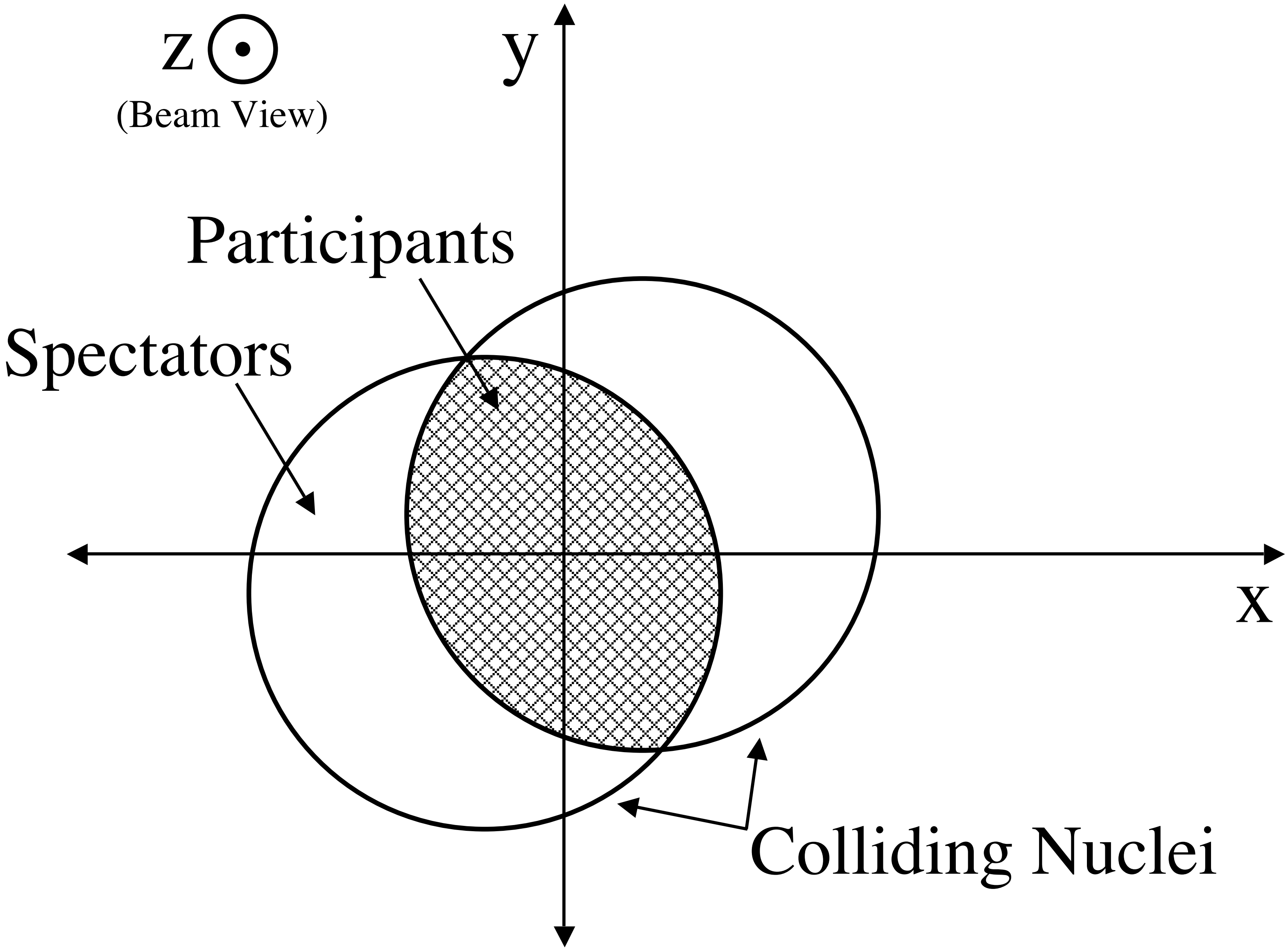
Event Characterization



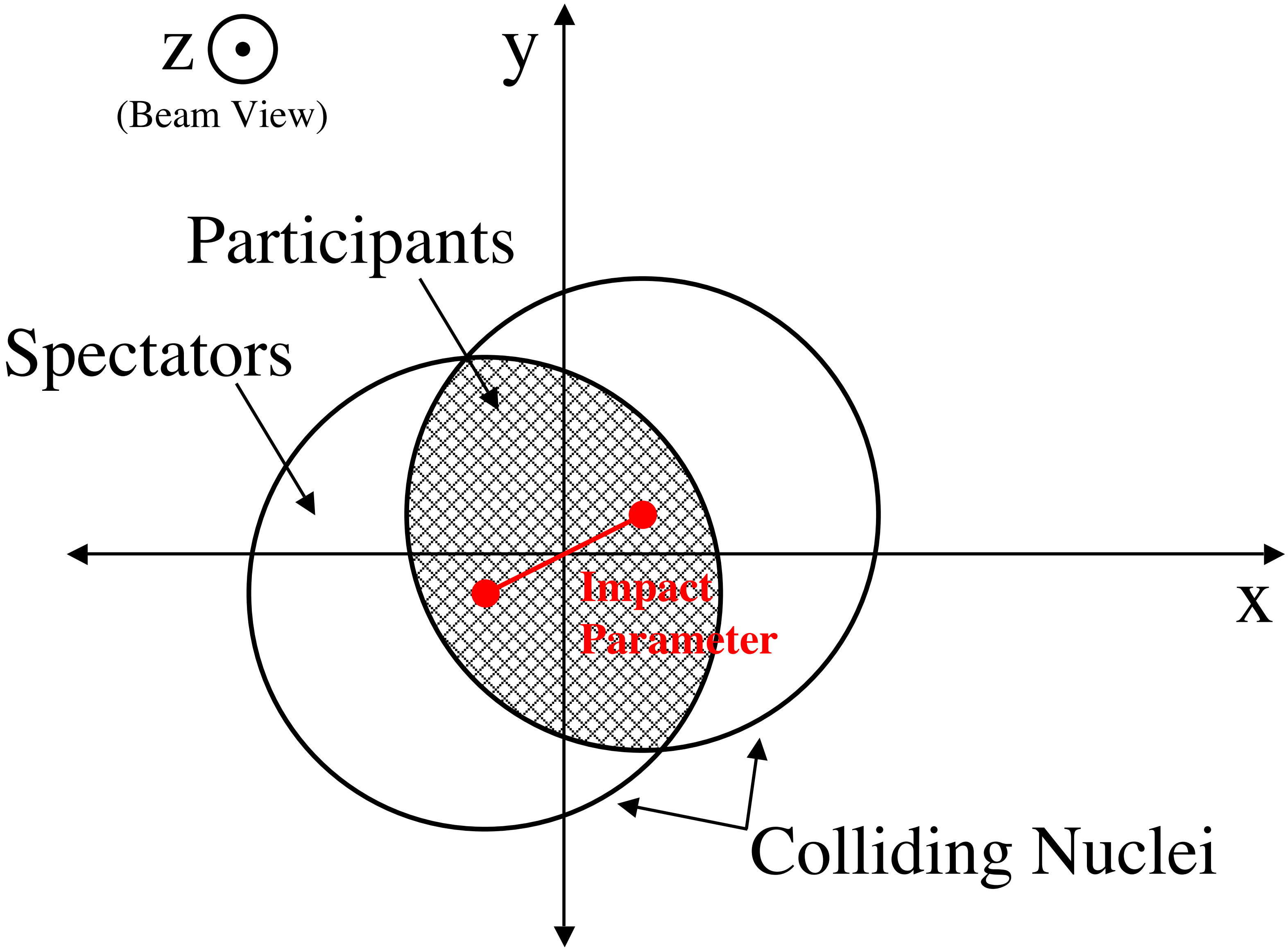
Event Characterization



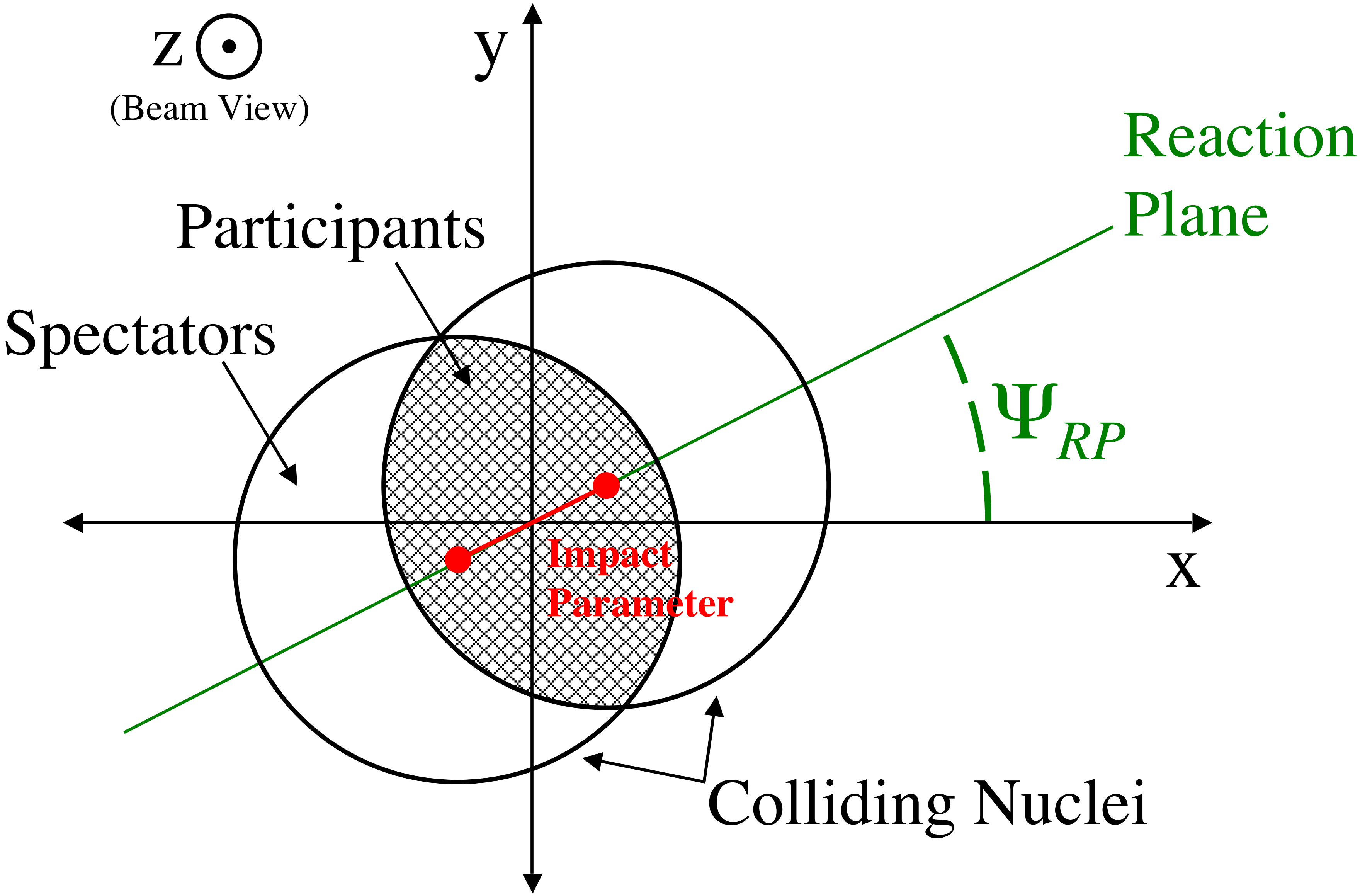
Event Characterization



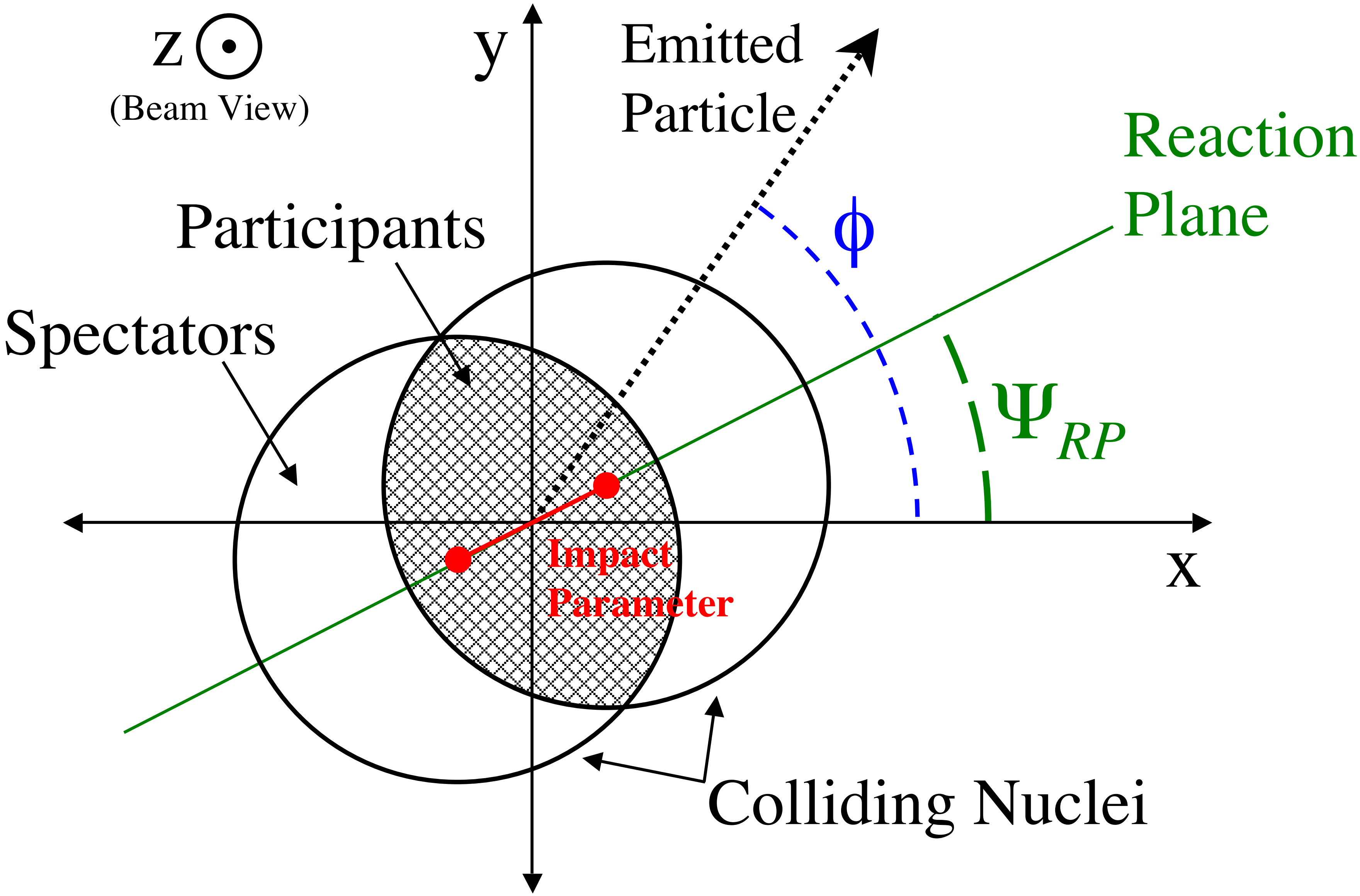
Event Characterization



Event Characterization



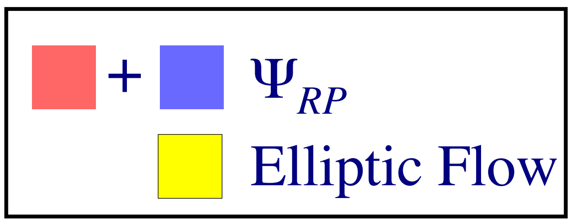
Event Characterization



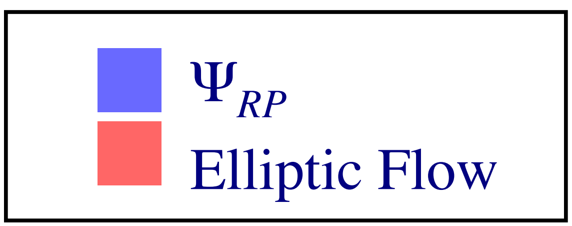
Measuring Ψ_{RP}

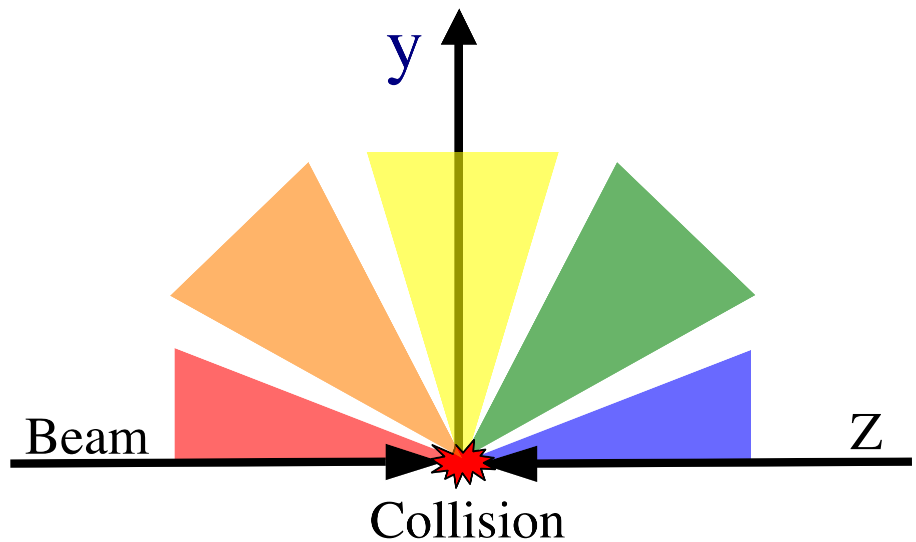
- Ψ_{RP} is measured from the same particle asymmetry used to measure elliptic flow
- To avoid artificial correlations each is measured in a distinct angular "window"

Examples



Or



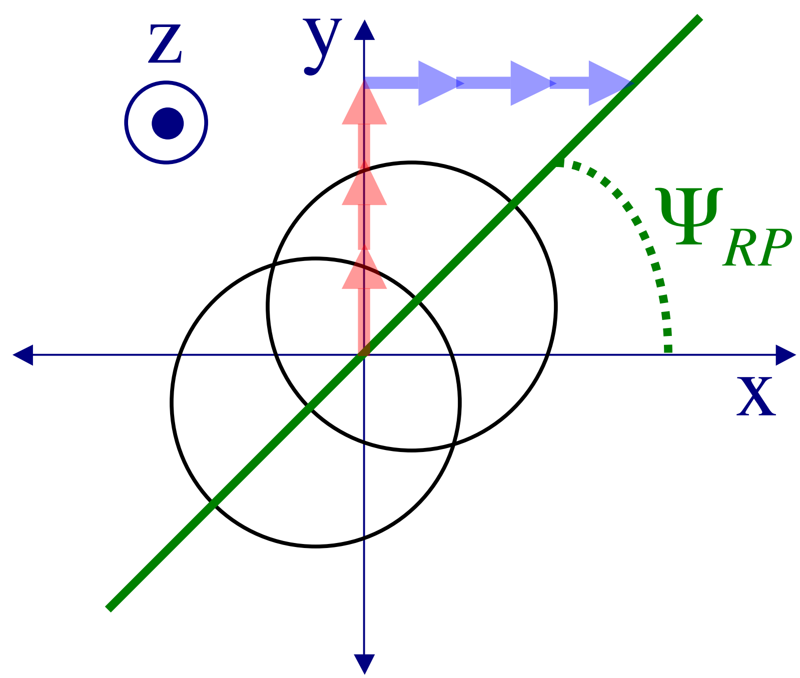


Measuring Ψ_{RP}

- Ψ_{RP} is measured from the same particle asymmetry used to measure elliptic flow
- Sum **X** and **Y** event flow vectors

$$\Psi_{RP} = \frac{1}{2}\tan^{-1}\left(\frac{\mathbf{Y} = \sum_i \sin(2\phi)}{\mathbf{X} = \sum_i \cos(2\phi)}\right)$$

ϕ = particle's azimuthal angle about the beam axis

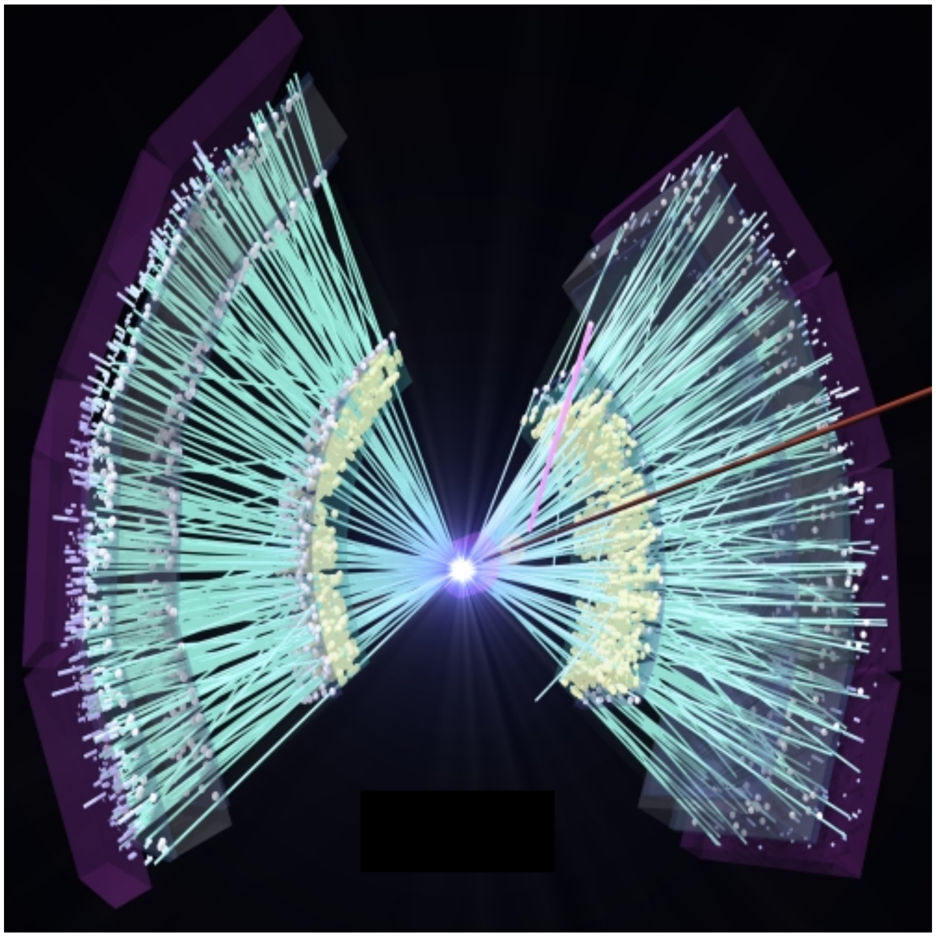


Static x,y axis from lab frame

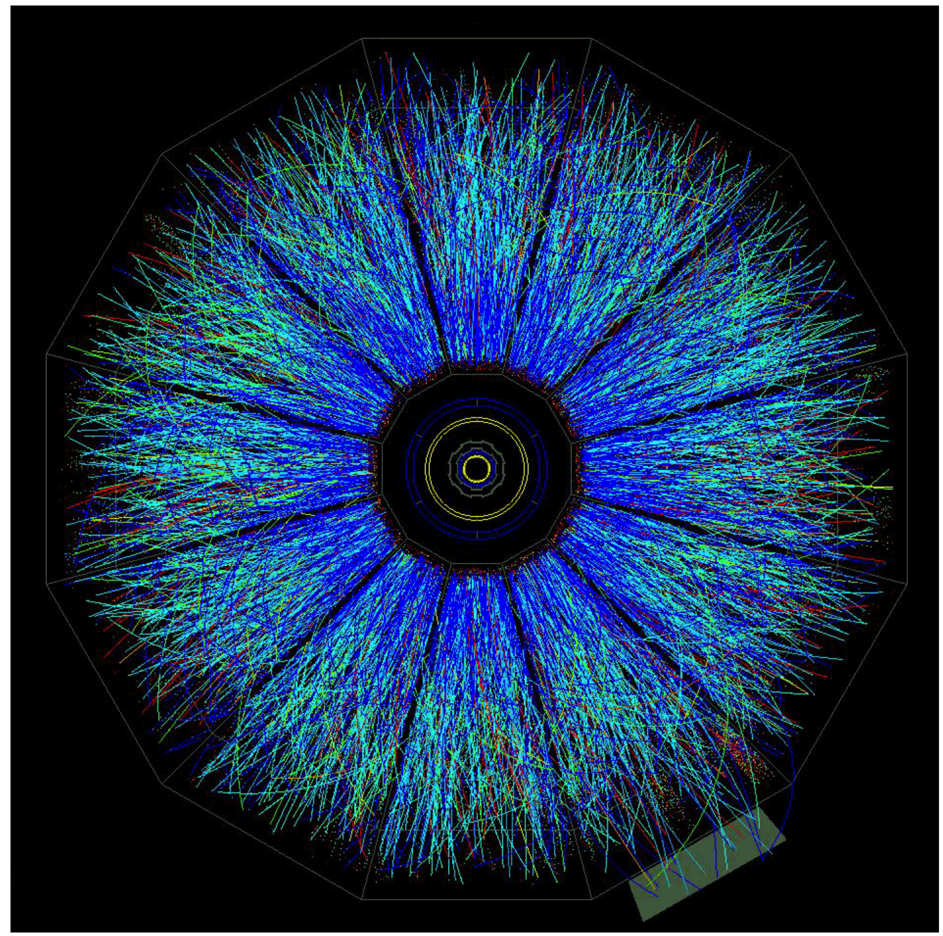
Collision Snapshot

(Beam View)

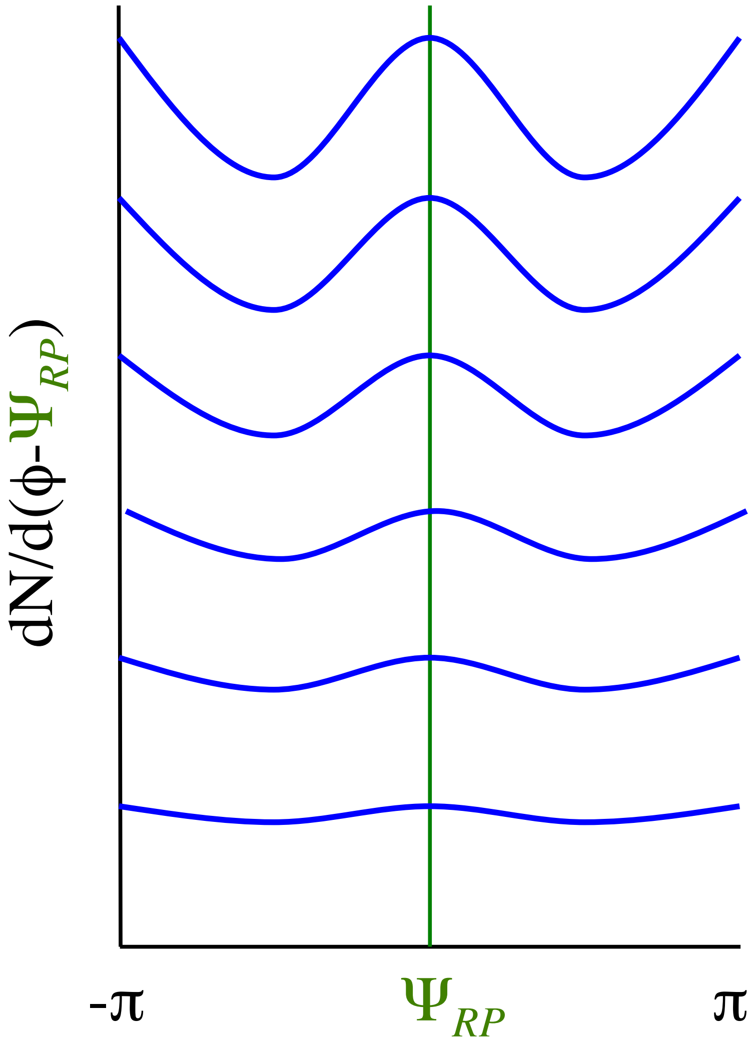
PHENIX

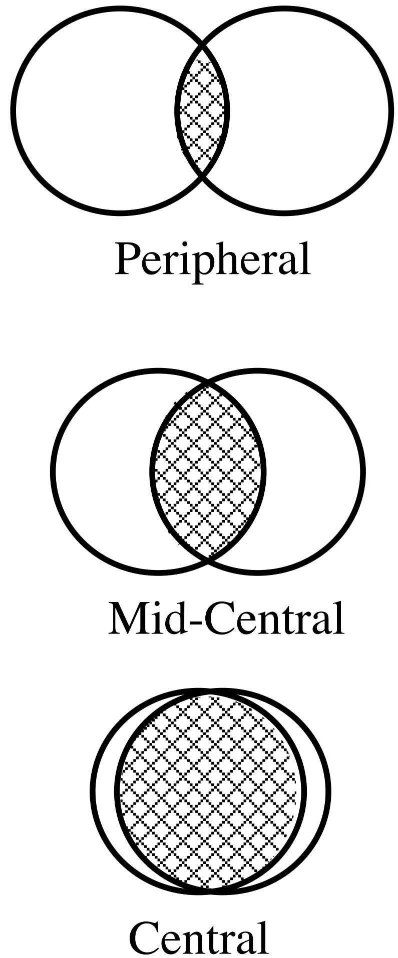


STAR



v_2 Dependence on Collision Shape



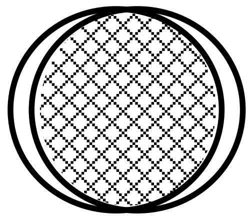


- v_2 magnitude varies with eccentricity of collision shape
- **% Centrality**: the percent of collisions having more geometric overlap than current event
- A 10% centrality event means 10% of collisions had more geometric overlap than the current event

Elliptic Flow Dependence on Centrality

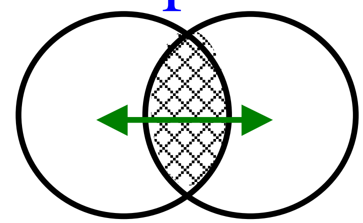
(beam view)

Central

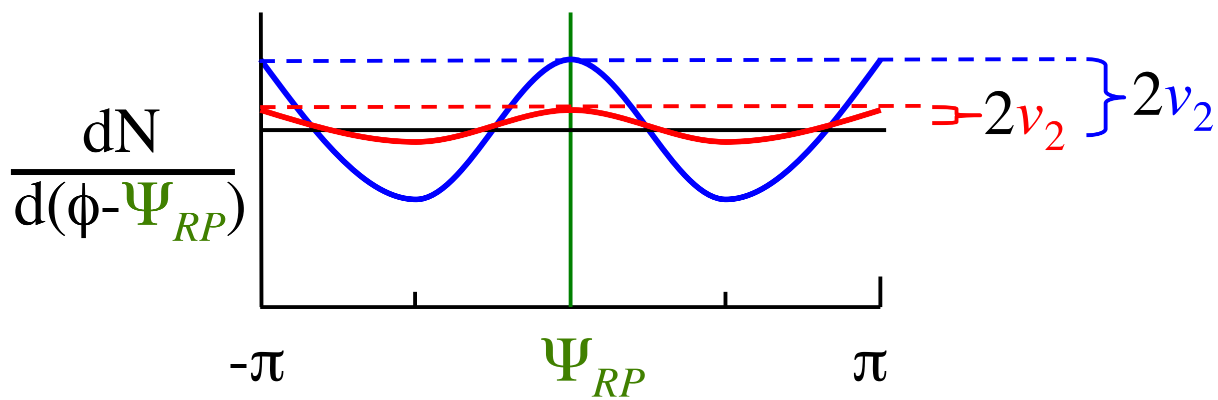


- Almost circular participant shape
- Nearly isotropic pressure gradients = isotropic particle distribution
- Small v_2 signal

Peripheral

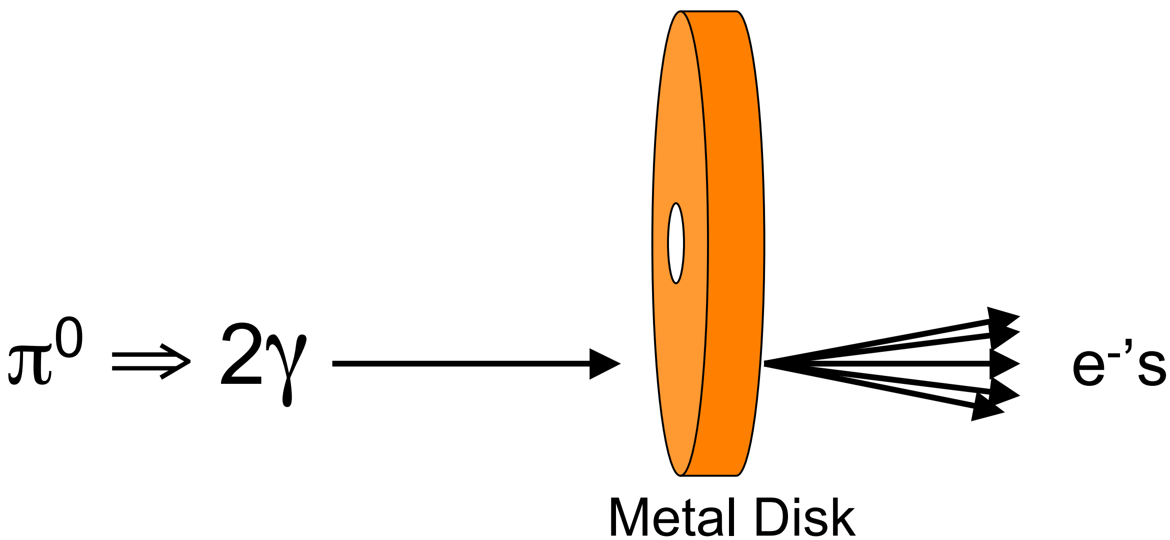


- Elliptic participant shape
- Asymmetric pressure gradients steeper in direction of reaction plane
- Large particle anisotropy = large v_2 signal



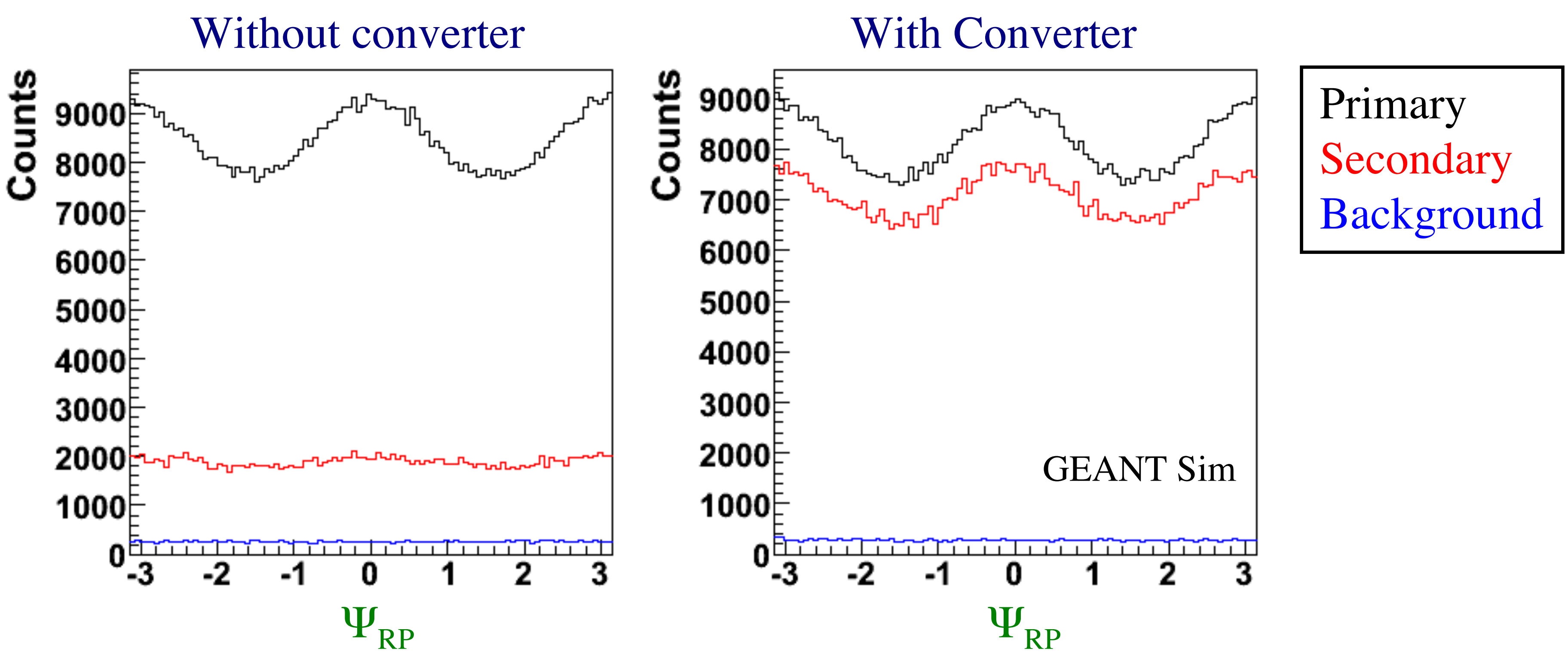
Converter Basics

- Particles hit thin metal disc, expelling many electrons
- This increases number of charged particles that hit scintillator (located behind disc), which increases energy deposition
- A way to amplify the signal
- Allows neutral particles to contribute to signal
- Also helps to reduce low energy background



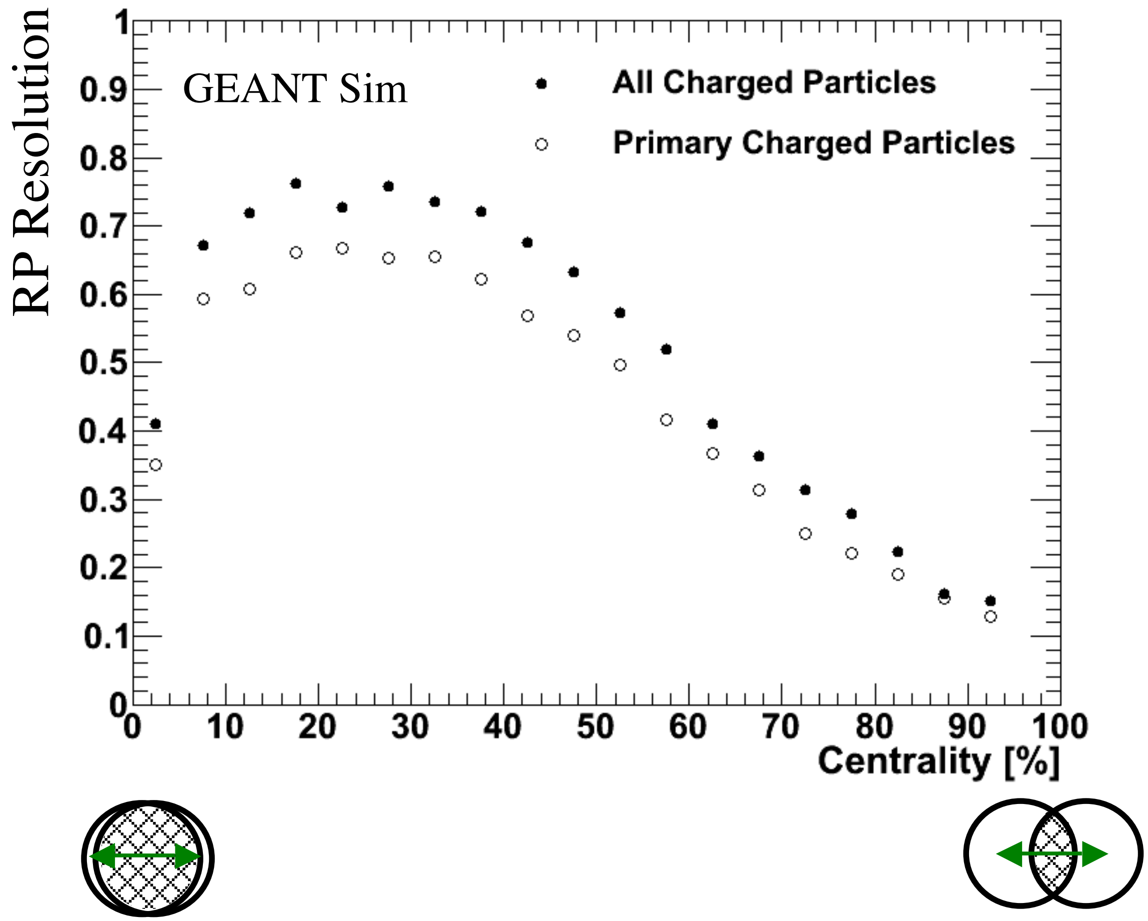
Improved Azimuthal Distribution

- Without converter, secondary particles dilute particle asymmetry converter
- With converter, secondary particles show strong asymmetric distribution, reinforcing signal



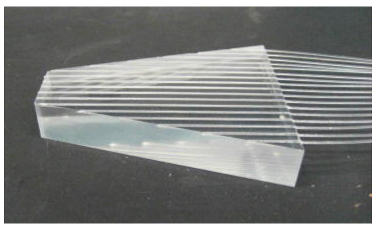
Improved RP resolution

- With converter RP resolution is ~16% higher than using just primary particles



KEK-PS Beam Tests

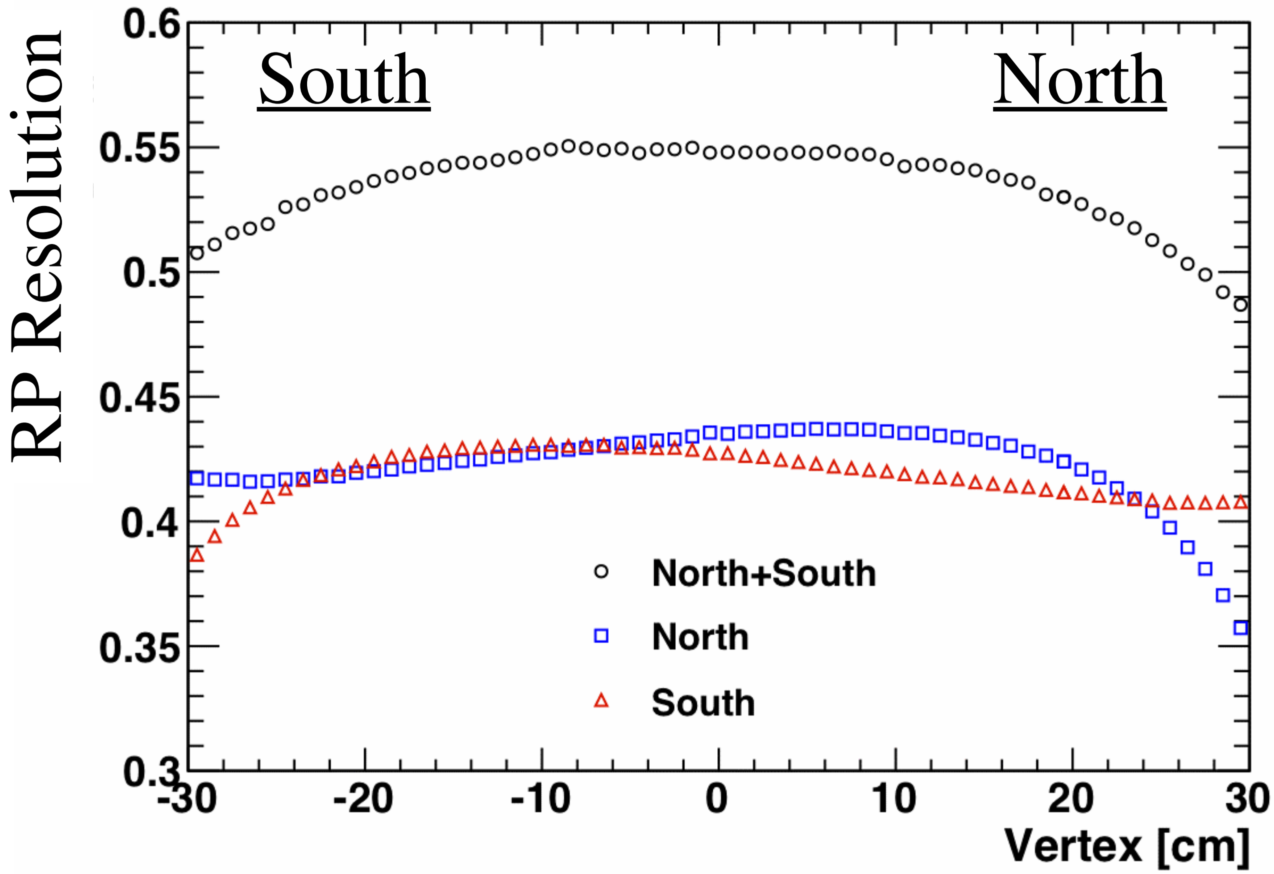
- Used 1-2 GeV/c p/pion/e beam



	Scintillator	Cherenkov
Solid Light Guide		
Embedded Fiber Light Guide		

- Of all combinations, found scintillator + embedded fiber light guide was best
  - Reasonable pulse height (~120mV), small signal tail
  - Allows flexibility for PMT positioning
  - More uniformity in light collection w.r.t. particle position

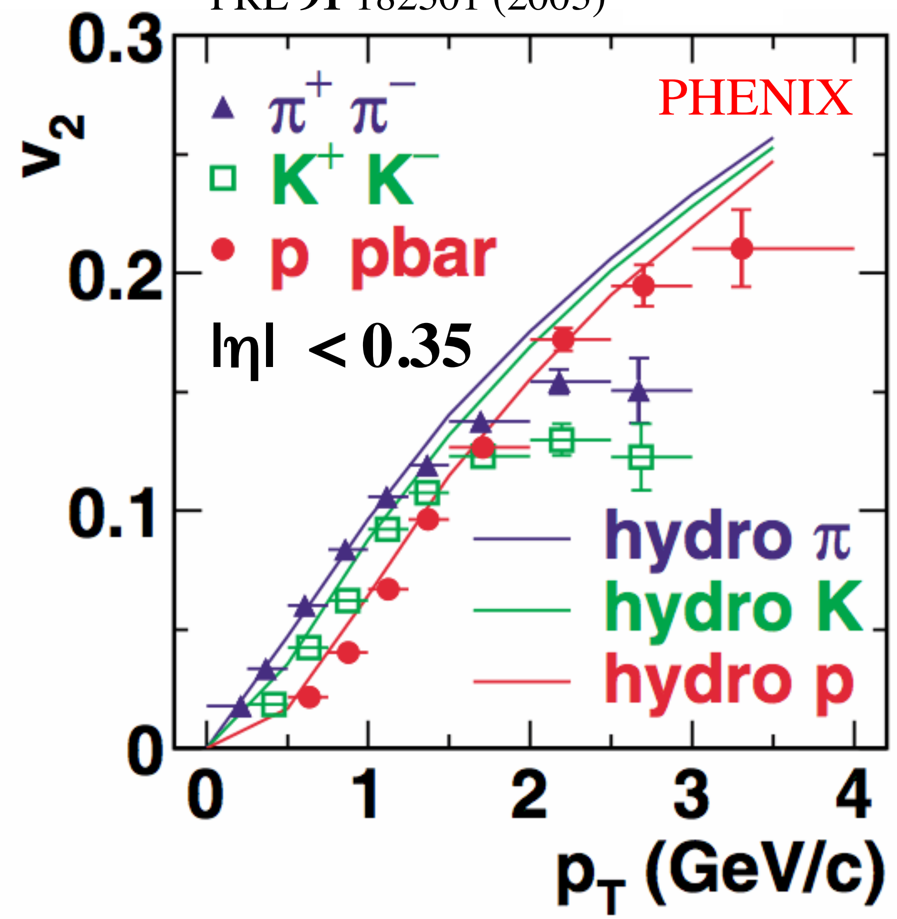
RP Resolution vs. Vertex



- Resolution decreases when collision is near arm due to decreasing detector acceptance

Hydrodynamic Behavior

PRL **91** 182301 (2003)



- v_2 described well at low p_T by hydrodynamic models having very little viscosity
- Hydrodynamics requires approximate local equilibrium
- Further evidence of thermalization

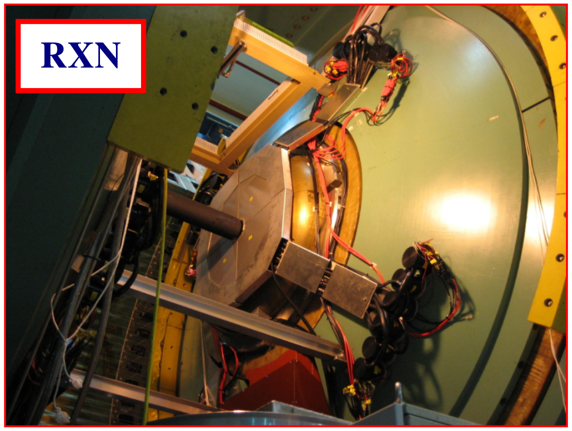
Detectors

Reaction Plane Detector

Scintillator Paddles

Inner Ring: $1.5 < |\eta| < 2.8$

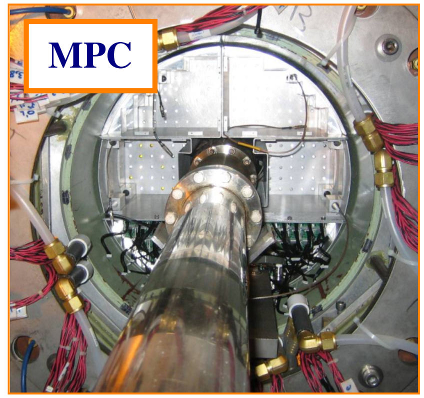
Outer Ring: $1.0 < |\eta| < 1.5$



Muon Piston Calorimeter

$PbWO_4$ Calorimeter

$3.1 < |\eta| < 3.9$

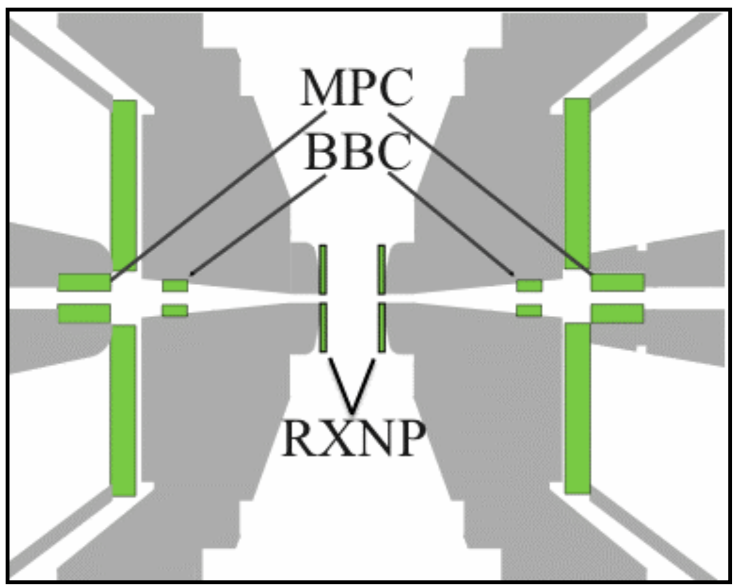


Beam Beam Counter

Quartz Cherenkov

$3.1 < |\eta| < 3.9$

PHENIX Central Region (zoomed in)



Used to measure Ψ_{RP}

Identify Hadrons

- Most tracks in Muon Arms are decay muons from $\pi^{\pm}$ and $K^{\pm}$.
- Hadrons distinguished from muons by examining p_z distribution of stopped tracks in MuID.
- Peak is muons "ranging out" from EM interactions
- Tail is hadrons that experienced a strong interaction