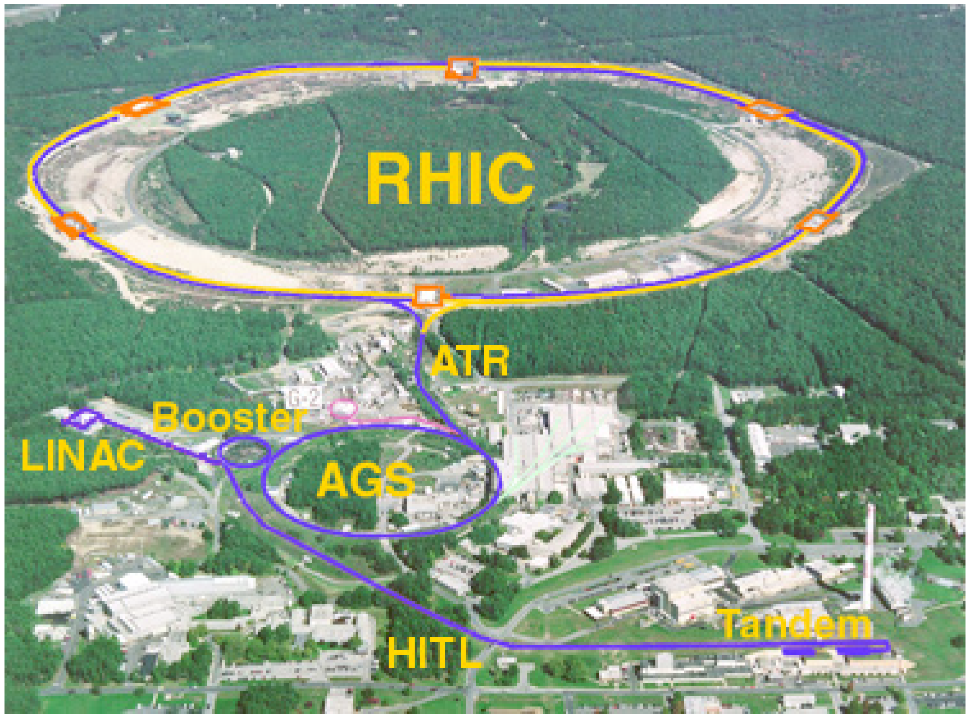
加速器
と
実験装置

Bevalac

- 今はもう無い
- Lawrence Berkeley Laboratory (LBL)
- Bevatron (反陽子の生成→ノーベル賞) + Hilac
- E_{max} = 2.1 （2Z/A） A GeV
- 1970年代中頃
～1980年代の終わり
- 高エネルギー重イオン
衝突実験の先駆け
  - 衝突のグローバルな様相
  - 基本的なアイデア
  - 測定方法

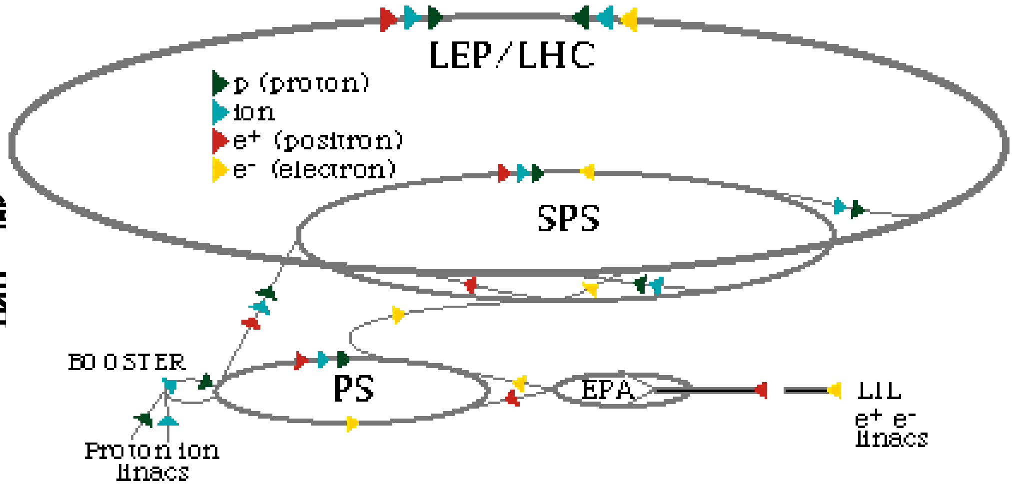
AGS

- Brookhaven National Laboratory (BNL)
- 世界初の強収束（陽子）加速器 (三つのノーベル賞)
- E_{max} = 15 （2Z/A） A GeV
- 1986年～
- 主な結果
  - 大きなバリオン密度
  - ストレンジ粒子生成
  - フロー
- RHICの前段加速器
  - 同時に陽子等の
    実験プログラム



SPS

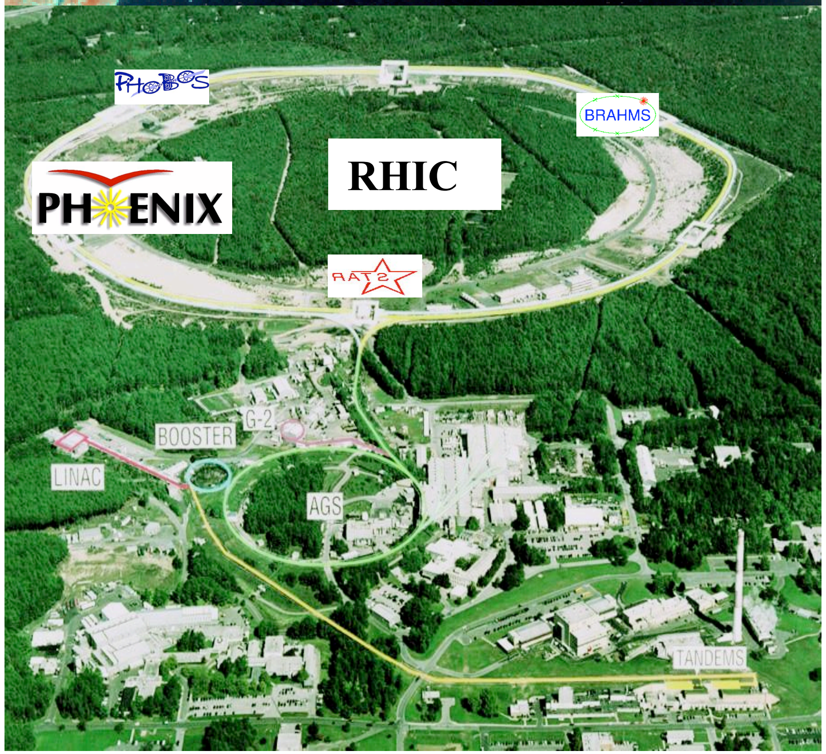
- CERN - European Organization for Nuclear Research
- 固定標的用陽子加速器
  ＋陽子・反陽子衝突型加速器
- W、Z の発見
- E_{max} = 400 （2Z/A） A GeV
- 1986年～
- QGPを示唆する結果
  - J/□ 収量の異常
  - 粒子収量とスペクトル
  - 低質量レプトン対収量異常
- 将来、LHCの前段加速器



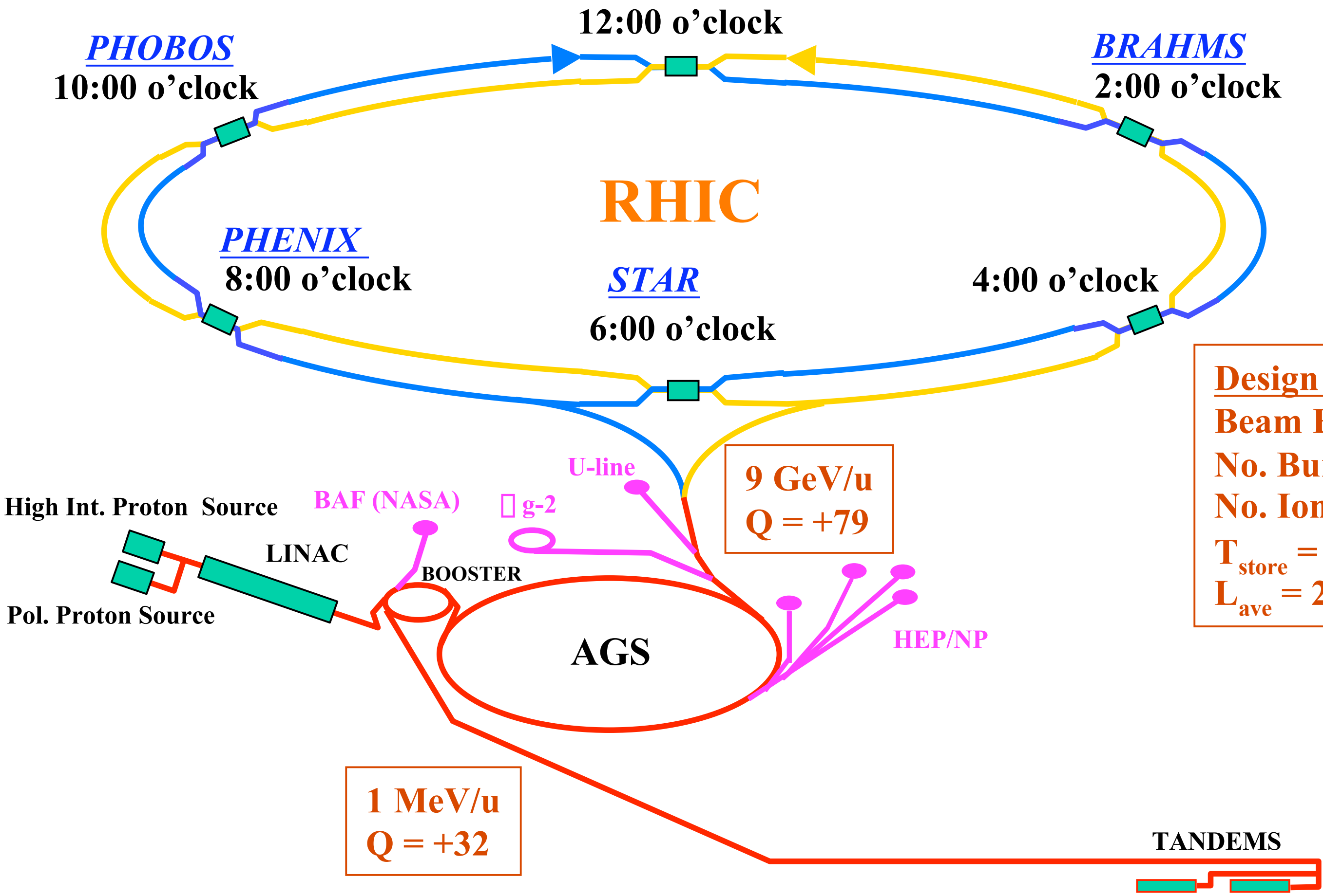
The Relativistic Heavy Ion Collider at BNL

- Two independent rings 3.83 k in circumference
  - 120 bunches/ring
  - 106 ns crossing time
- Maximum Energy
  - $\sqrt{s}$ = 500 GeV p-p
  - $\sqrt{s}$ = 200 GeV Au-Au

    per N-N collision
- Design Luminosity
  - Au-Au 2×10^{26} $cm^{-2}s^{-1}$
  - p - p 2×10^{32} $cm^{-2}s^{-1}$ (polarized)
- Capable of colliding any nuclear species on any other nuclear species



the lay of the land



Design Parameters:

Beam Energy = 100 GeV/u

No. Bunches = 57

No. Ions /Bunch = 1×10^9

T_{store} = 10 hours

$L_{ave} = 2 \times 10^{26}\ cm^{-2}\ sec^{-1}$

The PHENIX Collaboration

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Academia Sinica, Taipei 11529, China
China Institute of Atomic Energy (CIAE), Beijing, P. R. China
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LPNHE-Palaiseau, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
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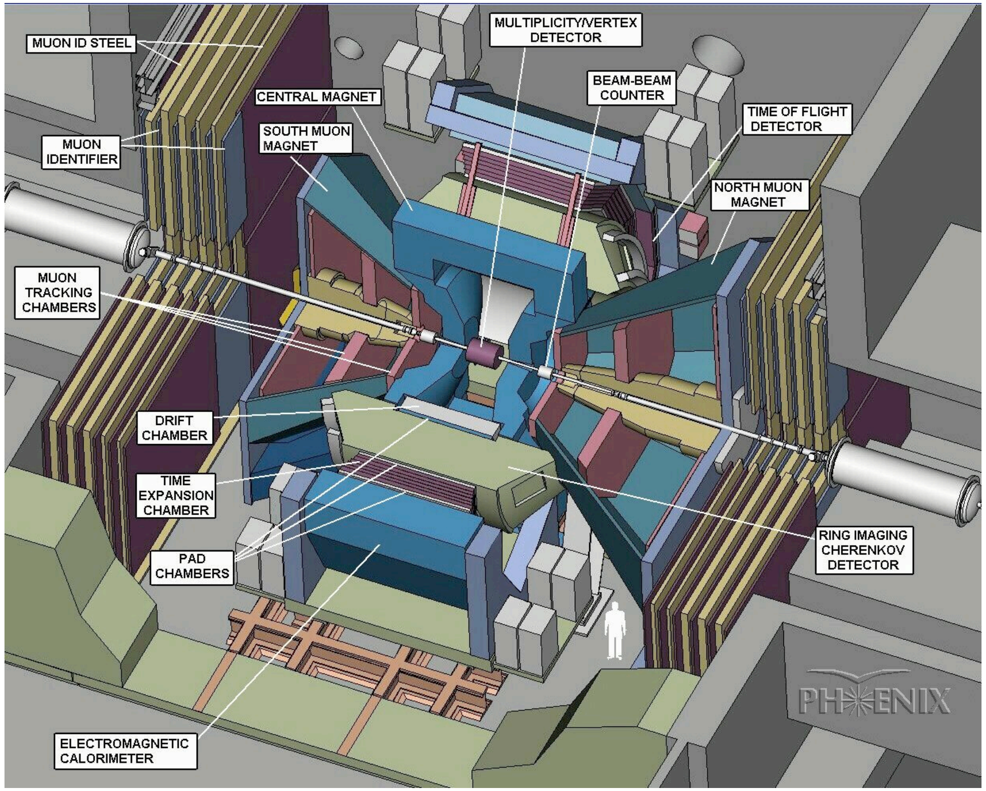
New Mexico State University, Las Cruces, New Mexico, USA
Department of Chemistry, State University of New York at Stony Brook (USB), Stony Brook, NY 11794, USA

Welcome to PHENIX

Tale of the Tape:

- Begun Operation June 2000
- 12 Detector subsystems
- 4 Spectrometer arms
- Total weigh = 3000T
- 315,000 readout channels
- >125 Varieties of custom printed circuit boards
- 13 ASICs designed specifically for PHENIX
- Pipe-lined DAQ Front-end
- 500, GHz Optical Data Links



The PHENIX Experiment is designed to probe fundamental features of the strong nuclear force including:

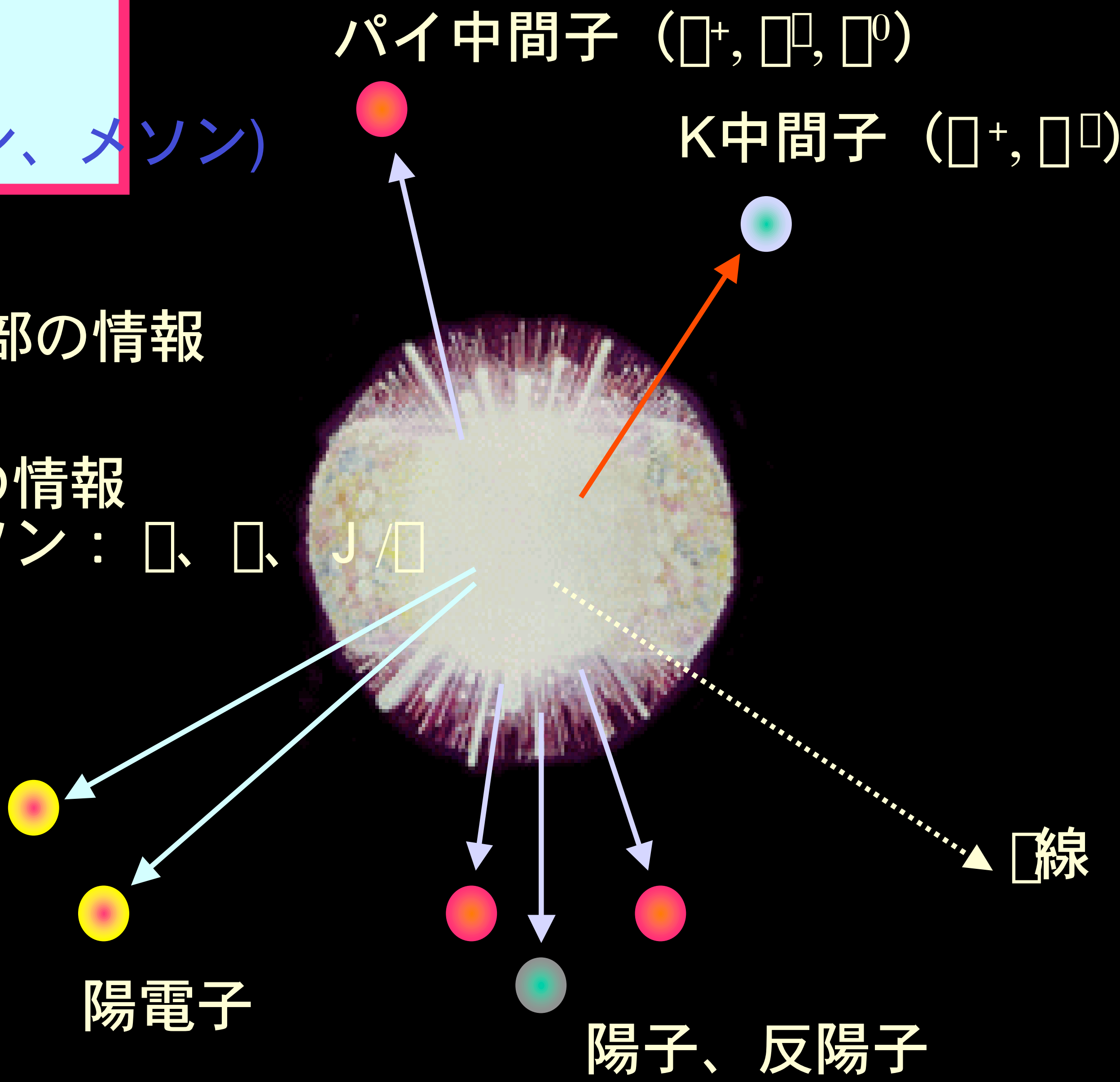
- The detection and characterization of the Quark-Gluon Plasma
- The spin structure of the nucleons

The Configuration:

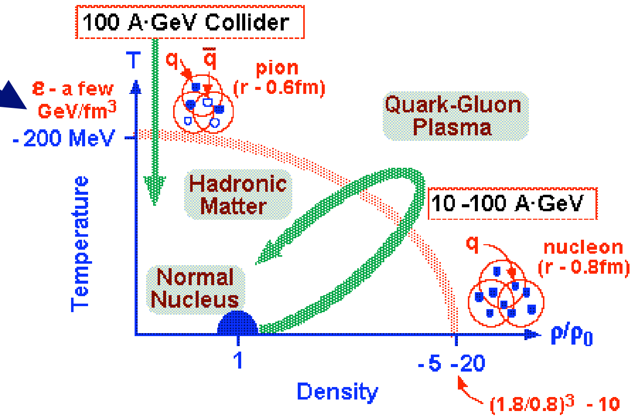
- 2 Forward Muon Arms
- 2 Central Spectrometer Arms to measure photons, electrons, and hadrons
- Event Characterizing Detectors

- 電子・陽電子対、
- 光子（□線）、
- ハドロン(バリオン、メソン)

- □線 ：火の玉の内部の情報
- 電子・陽電子対：
  - 火の玉の内部の情報
  - ベクター・メソン：□、□、J /□

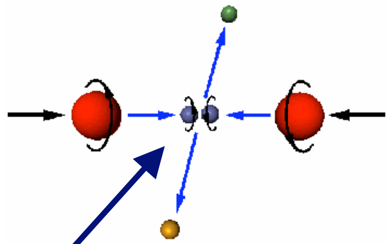


The Physics of PHENIX



QGP:

- Temperature and Energy Density
  - dN/dy, E_T , Single particle spectra
- Jet Quenching
  - High p_T jets using leading □^{0}, □$^\pm$
- Space –Time Evolution
  - HBT(□□, KK,pp), Flow
  - Event by Event Fluctuations
- Deconfinement
  - J/□ , □ ’□ e+e-,□+□-, □□ □□
- Chiral Symmetry Restoration
  - □□ e+e-,K+K-, □,□,□ width/shift
  - DCC’s □^{0}/□$^\pm$
- Heavy Quark Production
  - K/ □ , □, J/□ , □ ’, □, D, B mesons
- Thermal Radiation
  - □, □□□ e+e-, □+□-

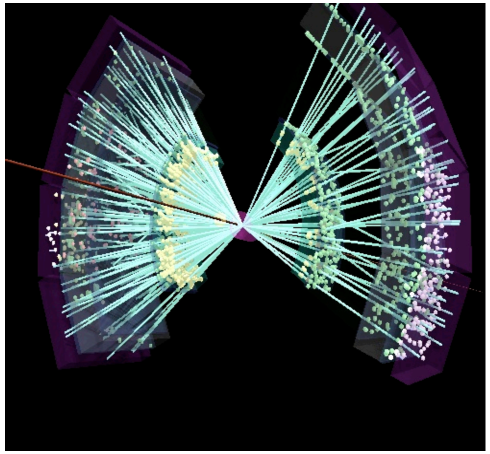


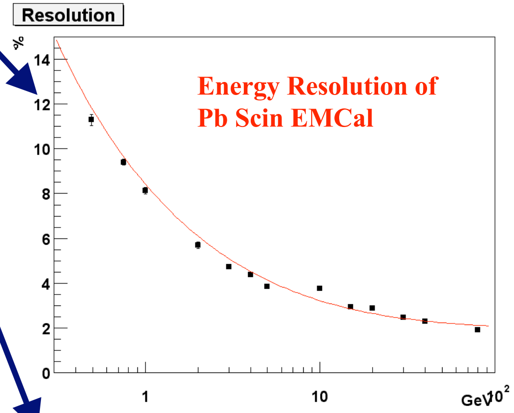
Nucleon Spin:

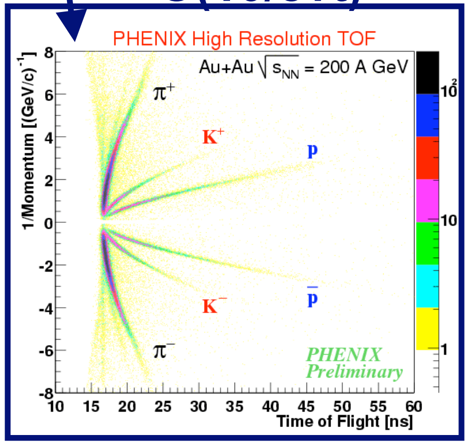
- Gluon spin: □G
  - Direct □, high p_T □’s
- Sea quark spin: □u, □d
  - W^+/W^- production
  - Drell-Yan Polarization

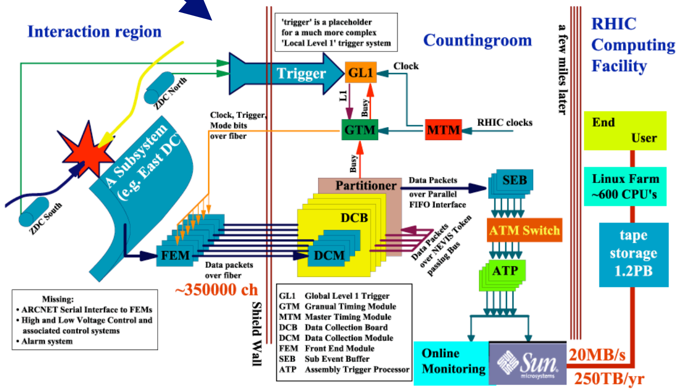
Challenges for the Detector Design

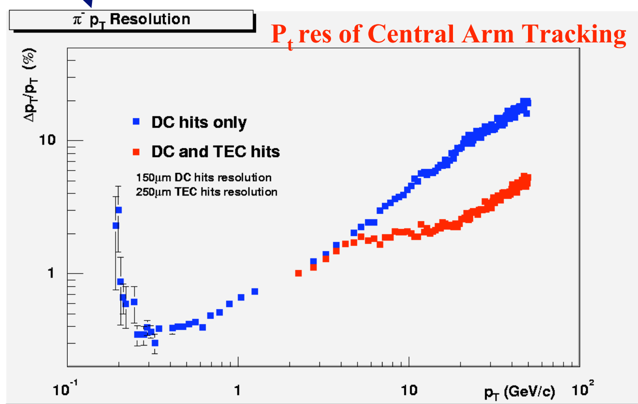
- High Particle Multiplicity/Event
  (dN_c/dy □ 1000)
- Maintain performance over large dynamic range in E and pt (300 MeV – 50 GeV)
- Significant particle ID rejections
  $e/\square = 10^{-4}$, $\square/\square = 10^{-4}$, $\square/K/p = 10^{-3}$
- DAQ/Trigger operates in varying environments
  - Event rate O(10 kHz), Particle mult. O(1000/evt)
  - Event rate O(1 MHz), Particle mult. O(10/evt)





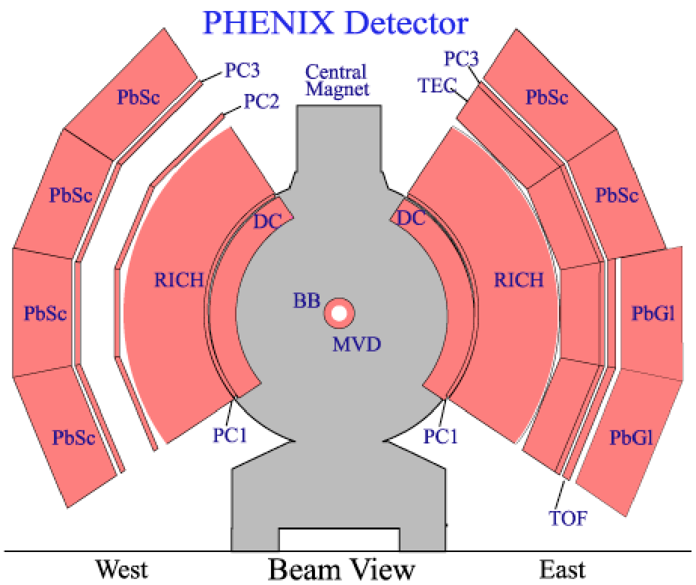






The Detector's Design Strategy

- Detector Redundancy
- Fine Granularity, Mass Resolution
- High Data Rate
- Good Particle ID
- Limited Acceptance

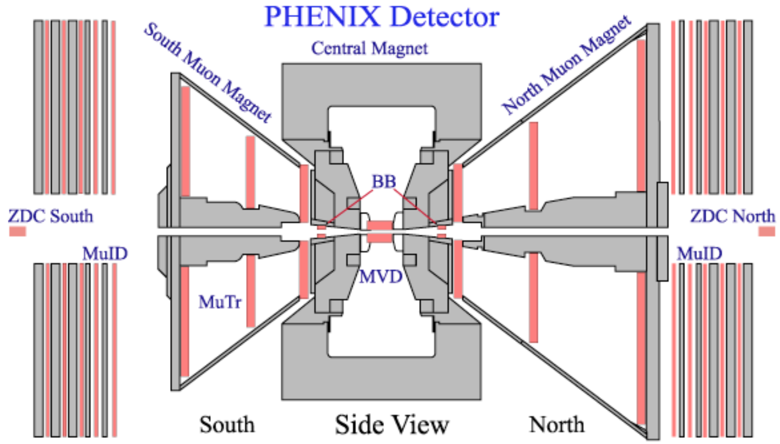


Charged Particle Tracking:

Drift Chamber
Pad Chamber
Time Expansion Chamber/TRD
Cathode Strip Chambers

Particle ID:

Time of Flight
Ring Imaging Cerenkov Counter
TEC/TRD
Muon ID (PDT's)



Calorimetry:

Pb Scintillator
Pb Glass

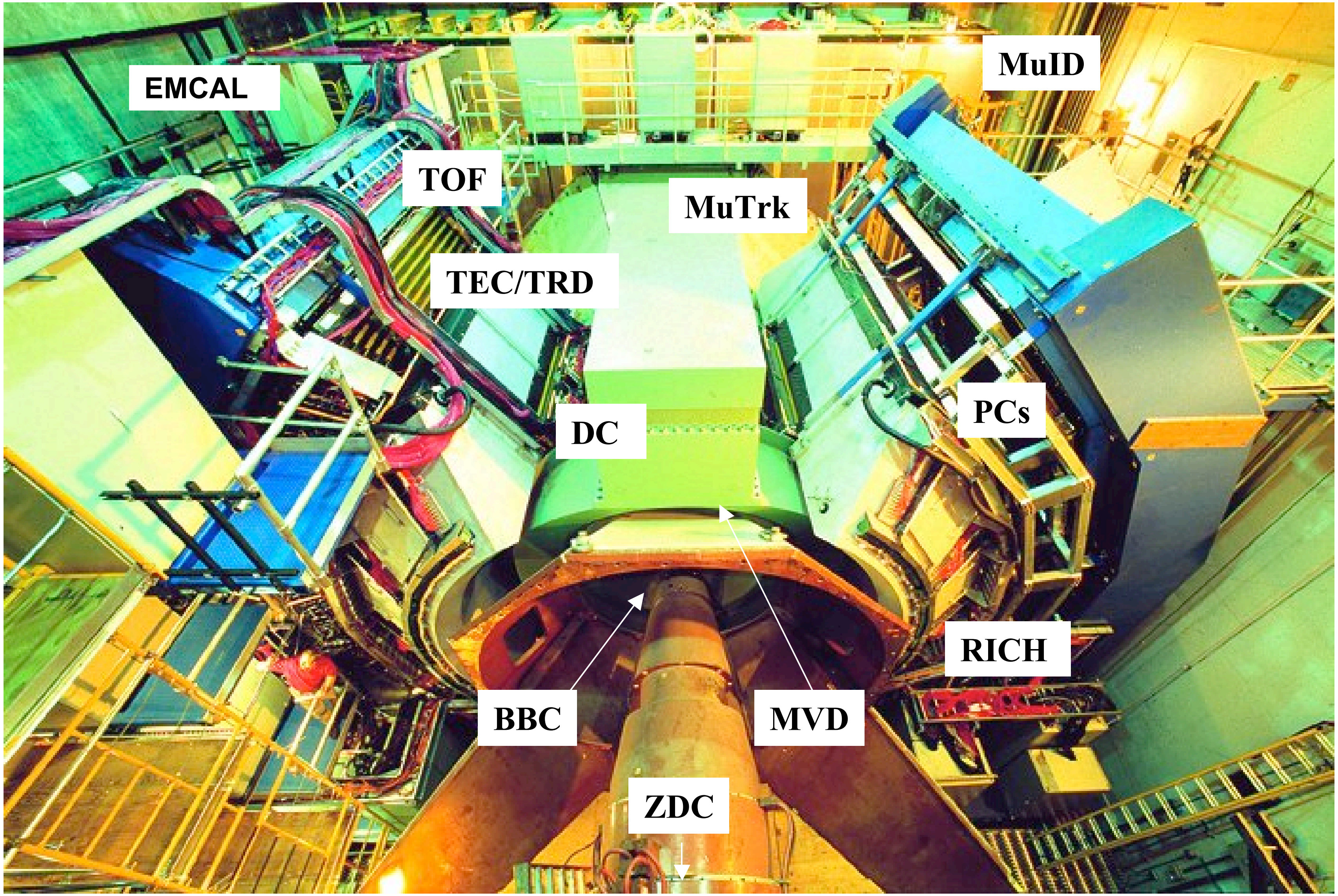
Event Characterization:

Multiplicity Vertex Detector (Si Strip,Pad)
Beam-Beam Counter
Zero Degree Calorimeter

Some Unique PHENIX Technologies

- **Large Area Cathode Strip Chamber with 100 □m position resolution**
- **Fine-segmented EMCal (0.01 □, 0.01 □) with $\square_t$ < 0.5 ns**
- **Time Expansion Chamber that combines tracking, dE/dx and TRD**
- **Drift Chamber configured as focusing –jet chamber**
- **Ring Imaging Cerenkov Counter readout with 5000+ PMTs**
- **Low mass, non-projective pixel-pad wire chambers covering ~100 m^2**
- **Time of Flight system with $\square_t$ < 100 ps**
- **Fully data-pipelined front-end electronics**
- **All data, timing, control and serial communication between detector and counting house is via optical link.**

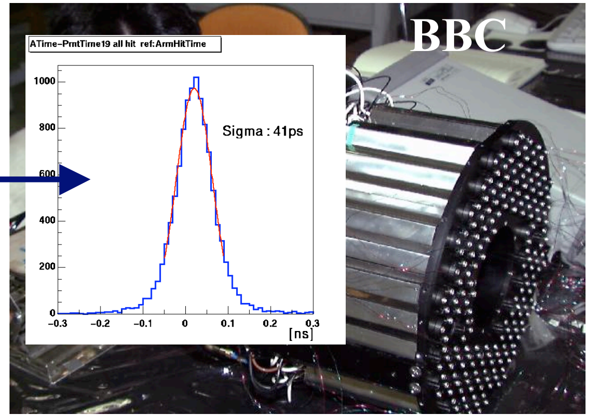
A Crowded Experimental Hall

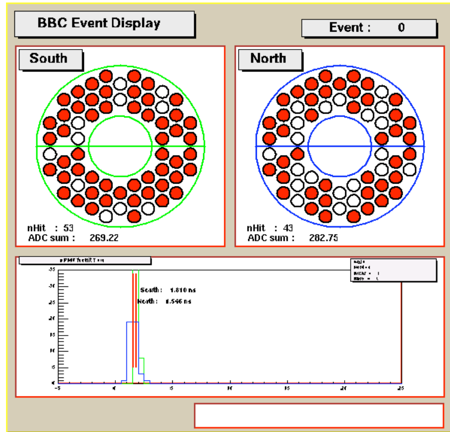


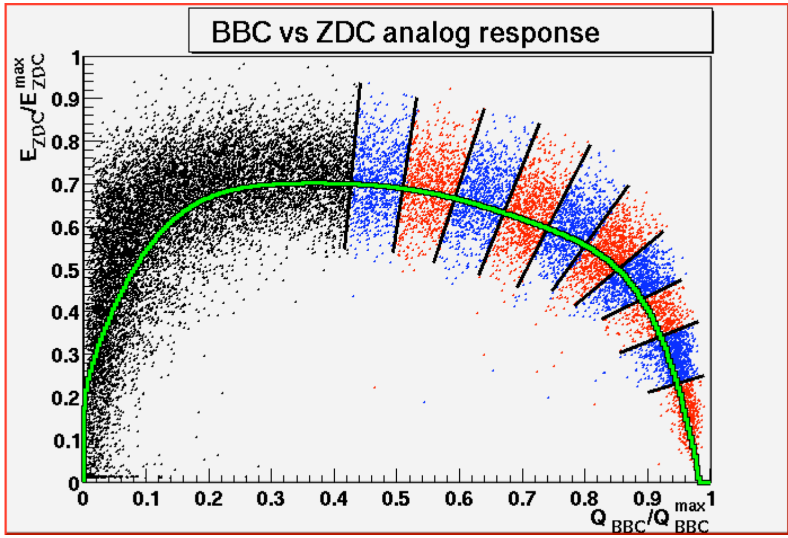
Event Characterization Detectors

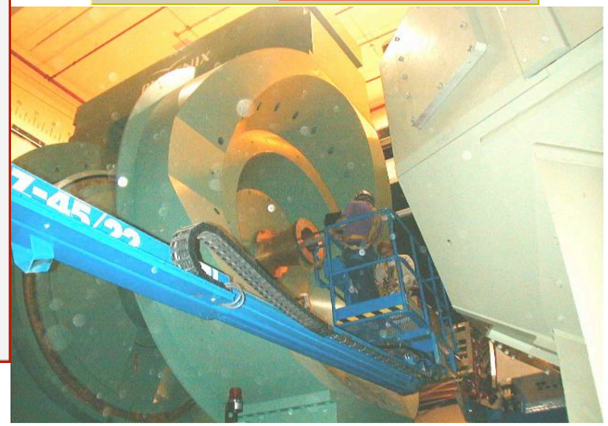
Beam-Beam Counter and Zero Degree Calorimeter

- BBC is 2 arrays of 64 PMTs with quartz radiators
  - Provides T0 for PHENIX. σ_t = 41 ps
- ZDC is Cu-W calorimeter with fiber readout.
  - Common centrality measure for all 4 RHIC experiments
- Combined they provide **the PHENIX LVL1** centrality trigger





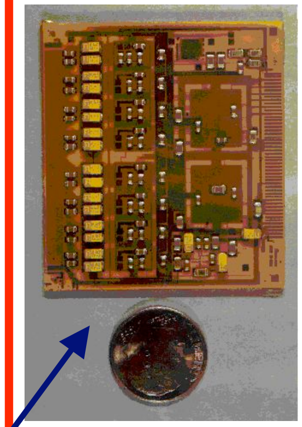


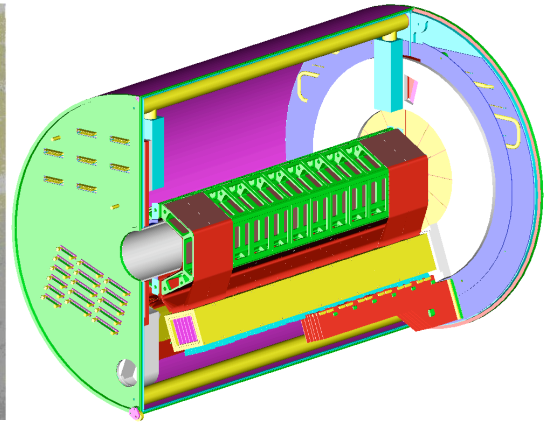


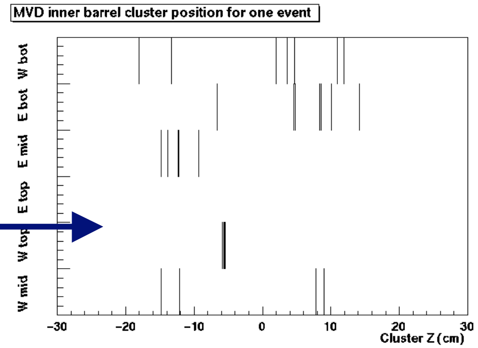
Event Characterization Detectors

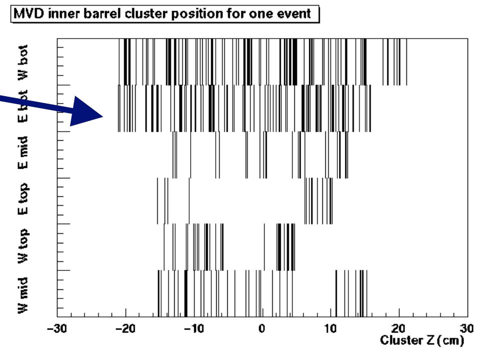
Multiplicity Vertex Detector

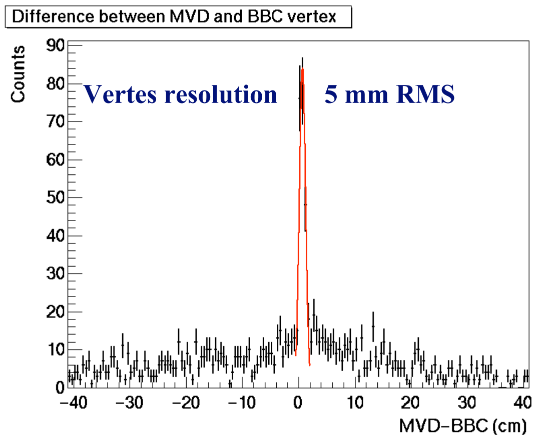
- Two concentric barrels of 300 μm Si strips
- Two endplates of Si pads
- Total coverage of $-2.5 < \eta < +2.5$
- 28,672 Si strips, 6048 Si pads
- Determines event vertex and measures particle multiplicity/event
- Electronics is bare die on ceramic Multi- Chip Module

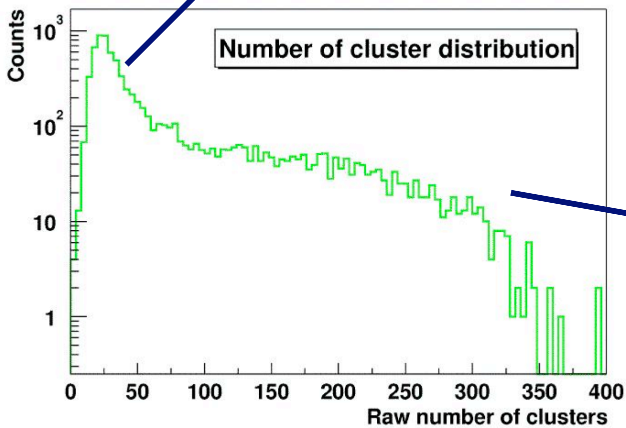






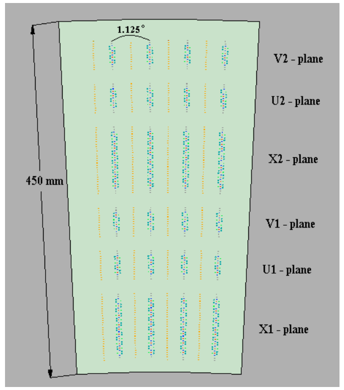


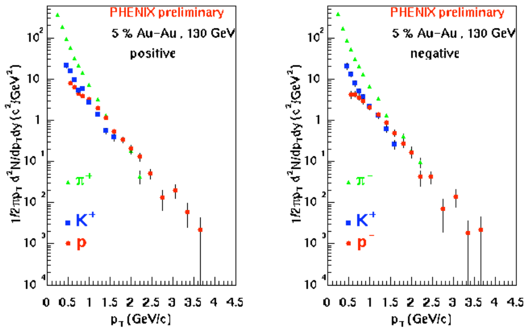




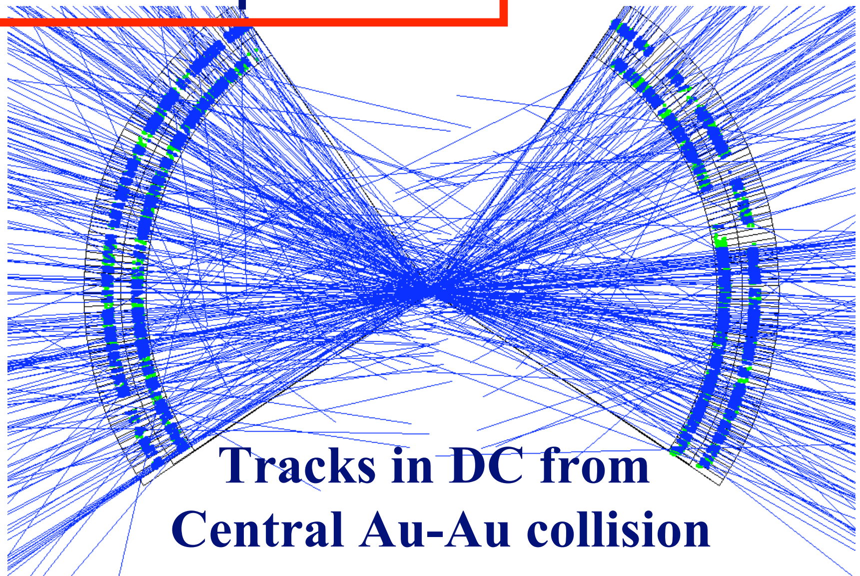
Tracking Detectors: Drift Chamber

- Jet -chamber anode/cathode structure modified for HI high multiplicity
- Joint Russia/US design & construction
- All Titanium frame
- $\sigma_x = 120\ \mu m$, two-track sep = 2mm

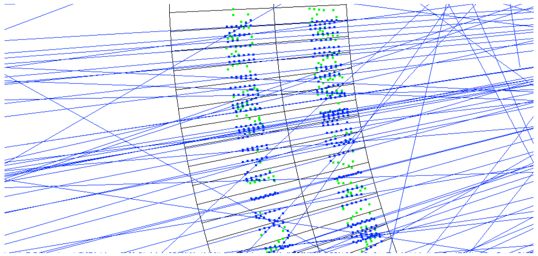




Identified particle spectra using tracking system and TOF



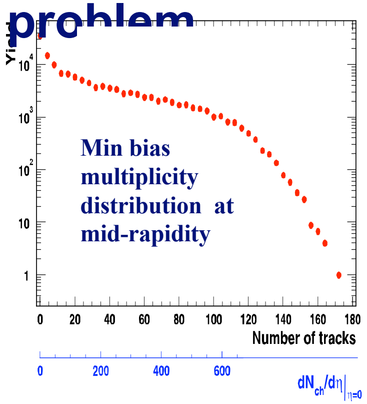
Tracks in DC from Central Au-Au collision



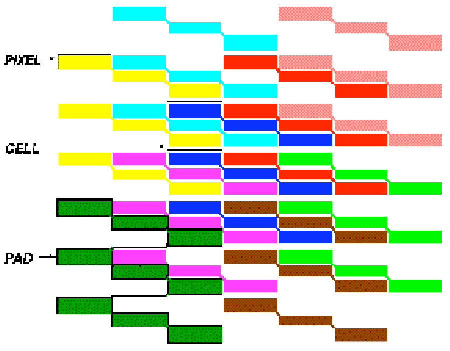
DC wires with kapton wire dividers

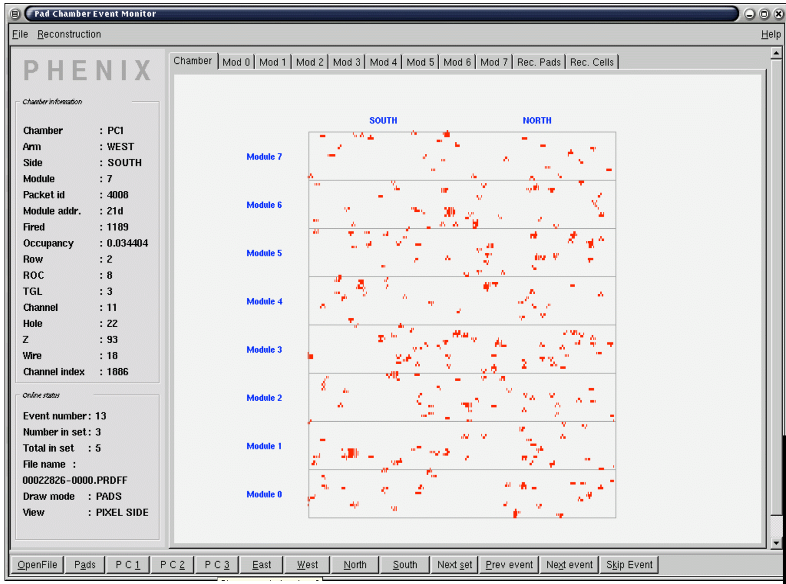
Tracking Detectors: Pad Chambers

- Cathode wire chambers using fine granularity pixel pad readout
  - 2-D hit position, $\sigma_x = \sigma_y$ ~ O(mm)
  - 173k channels total, ~ 100 m^2 detector coverage
- Low-mass , rigid honeycomb/circuit board construction
- All signal digitization takes place on-board in detector active region. Solves interconnect problem



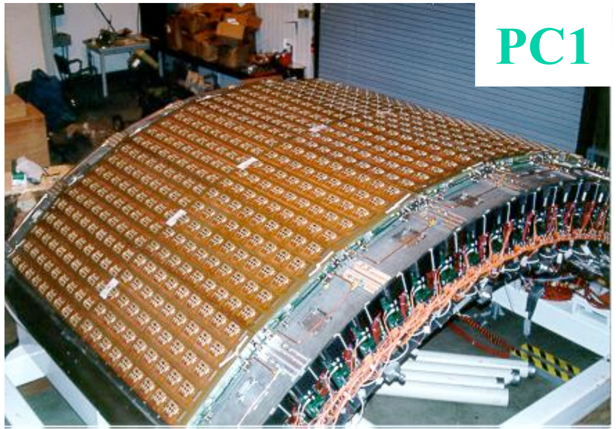
Pixel Pad Cathode Pattern





Clusters in PC from Central Au-Au collision

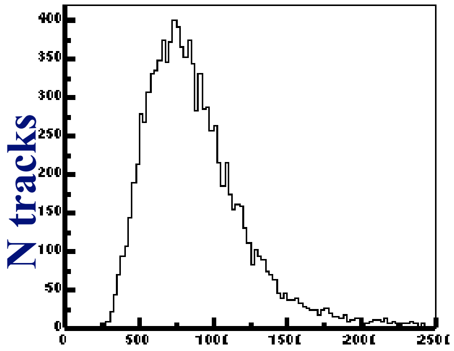
PC1



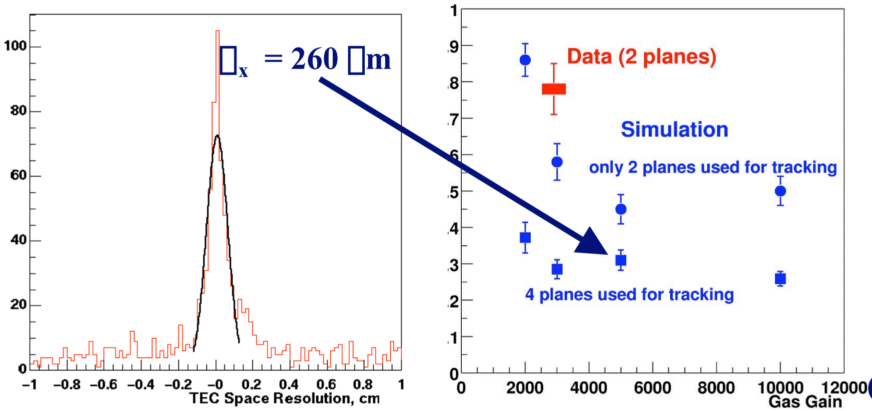
PC3

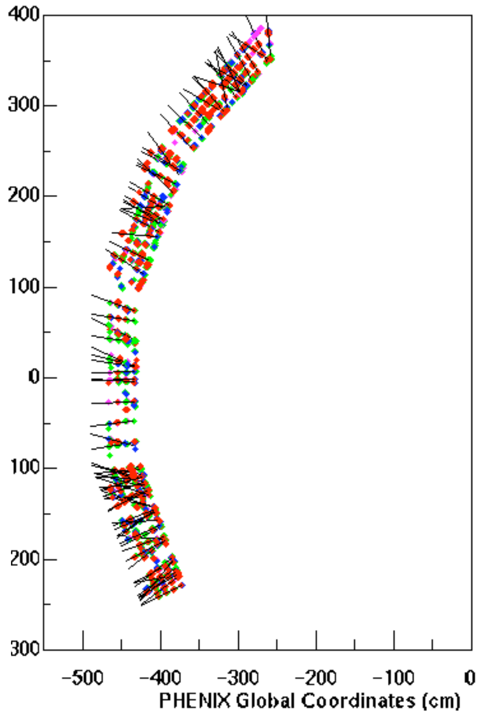
Tracking Detectors: Time Expansion Chamber

- 24 TEC Chambers arranged in 4, 6-Chamber sectors
- Used for tracking and PID (dE/dx,TR). σ_x = 260 μm
- dE/dx: e/π = 5% at 500 MeV/c (4 pls), e/π = 1.5% (6pls) Important for momentum resolution p_T > 4.0 GeV/c
- Designed for TRD Upgrade . High momentum e/π

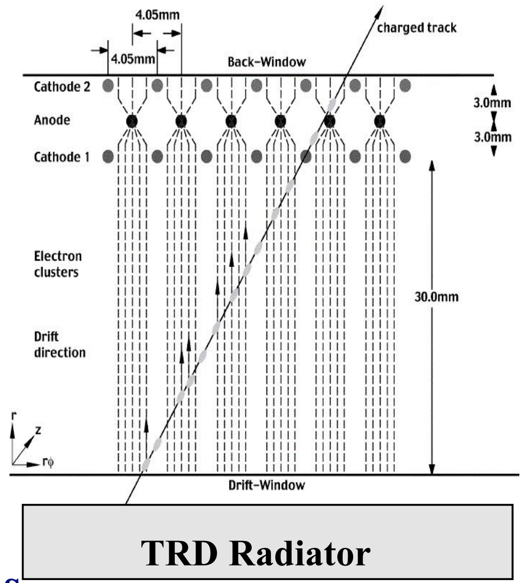


Sum FADC counts/recon. track



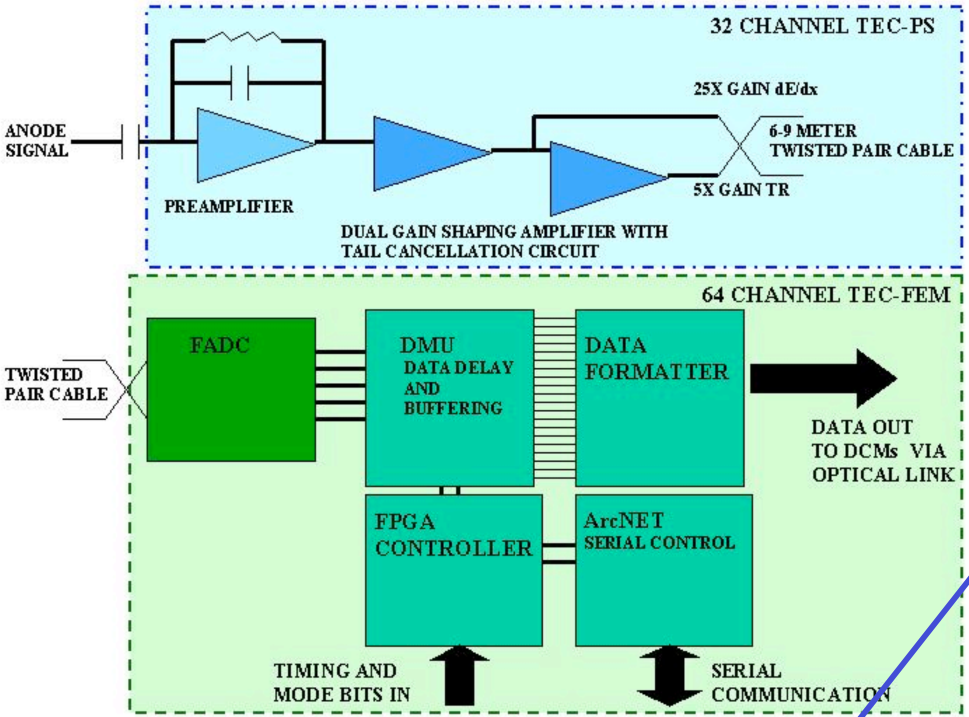


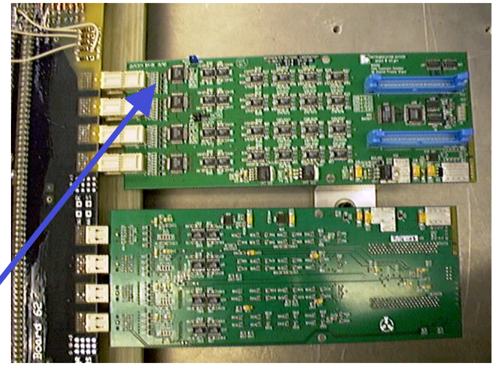
Tracks in TEC from Central Au-Au Collisions



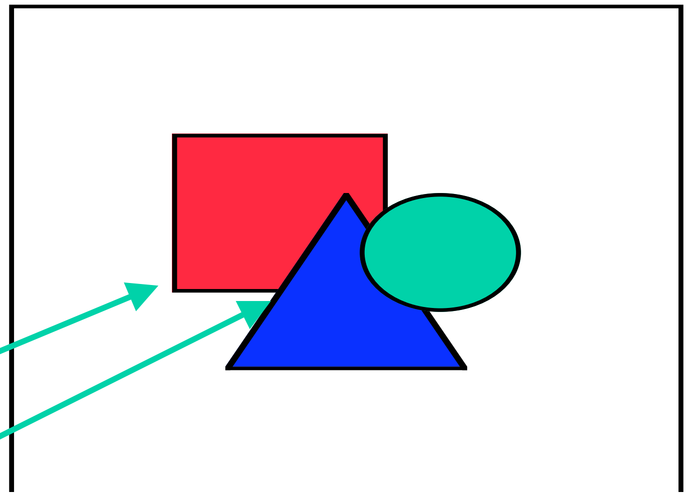
PHENIX TEC/TRD Electronics

Up to 20,500 Instrumented TEC/TRD Channels





32 channel Preamp/Shaper PCB w/ remote calibration control and ~1 fC RMS system noise



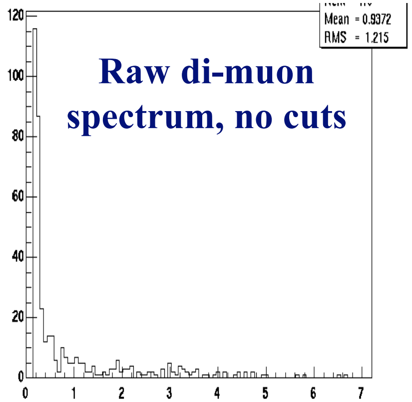
64 channel Front End Module(FEM) w/ digitizing , data formatting and optical data transmission

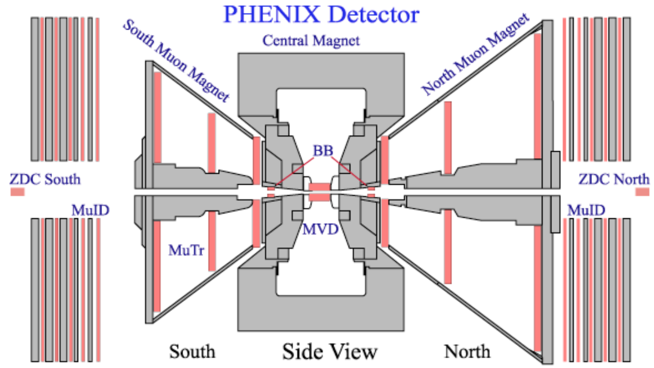
3 ASICs designed for TEC/TRD:

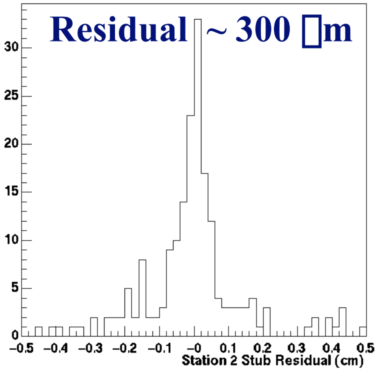
- **Octal Preamp/Shaper w/ tail cancellation and dual gain for both dE/dx and TR. Full serial control of gain, shaping time and tail cancellation.**
- **Non-linear, 40 MHz, FADC with 9-bit dynamic range, 9-bit precision and 5-bit encoding.**
- **Digital Memory Unit for data formatting with programmable delay and memory depth.**

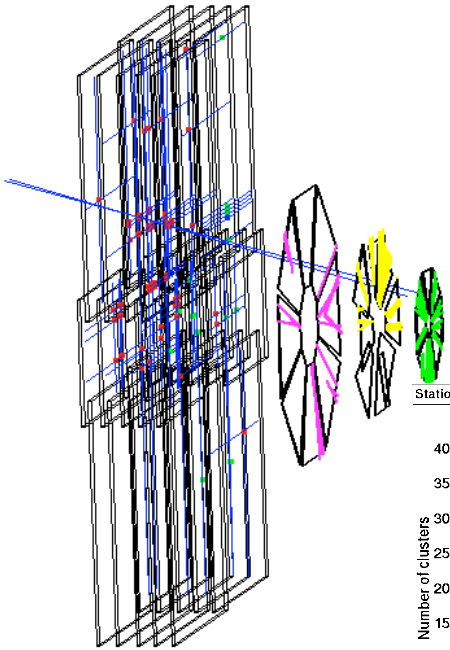
Tracking Detectors: Cathode Strip Chambers

- First cathode-strip chambers (CSC) used in an experiment
- Low mass honeycomb-printed circuit board and etched metalized-mylar design
- Each CSC station has a position resolution of σ_x=100 μm
- 20k electronics channels/spectrometer arm

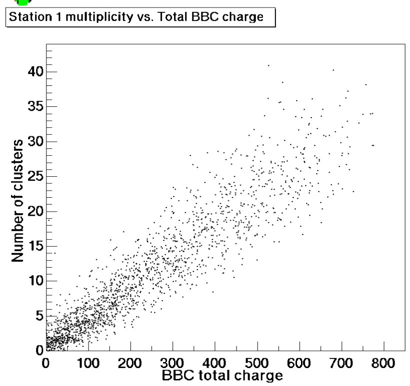






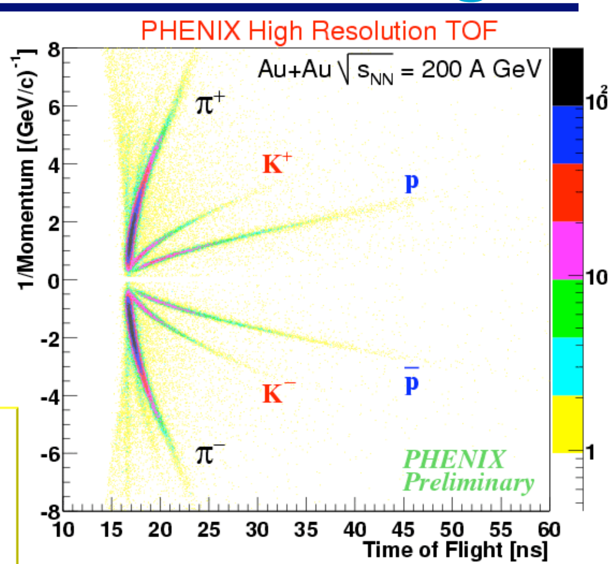


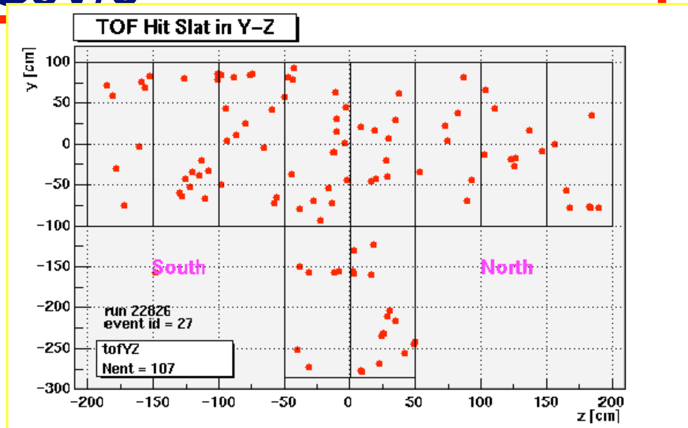
Reconstructed muon In Au-Au Collision

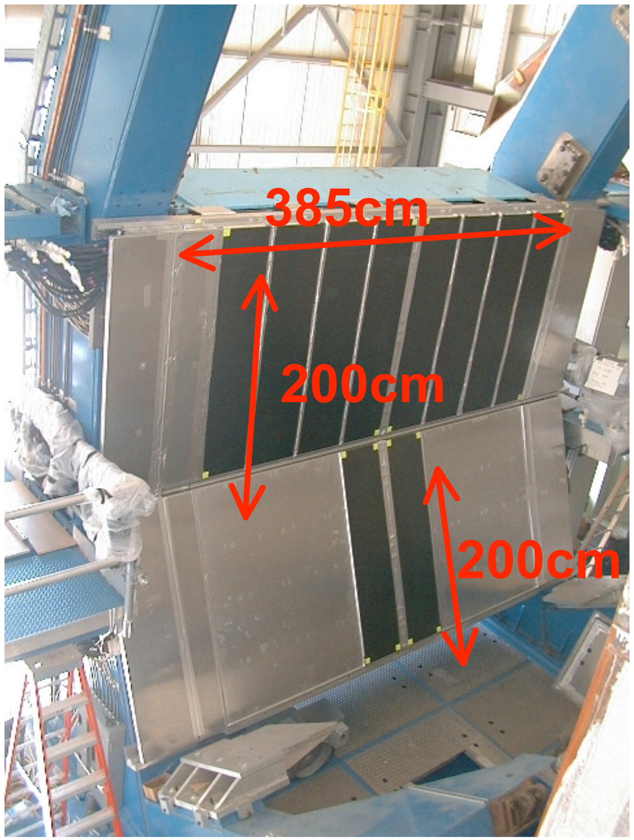


Particle ID Detectors: Time of Flight

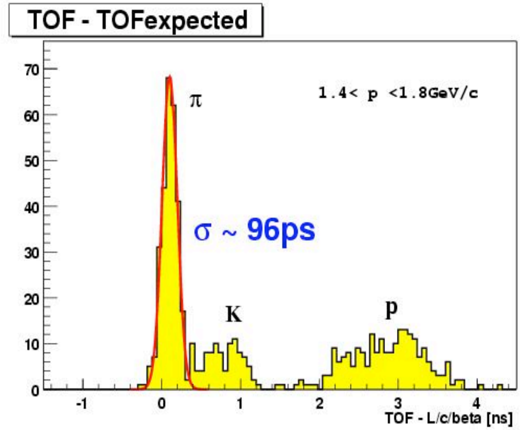
- **1000 finely segmented slats readout w/ 2000 PMTs**
- **Combines with BBC timing for an overall time resolution of σ_{TOF} < 96 ps**
- **K/π separation <~ 2 GeV/c**
- **p/K separation <~ 4 GeV/c**

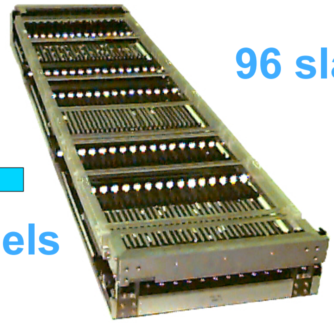






Clusters in TOF from Central Au-Au collision



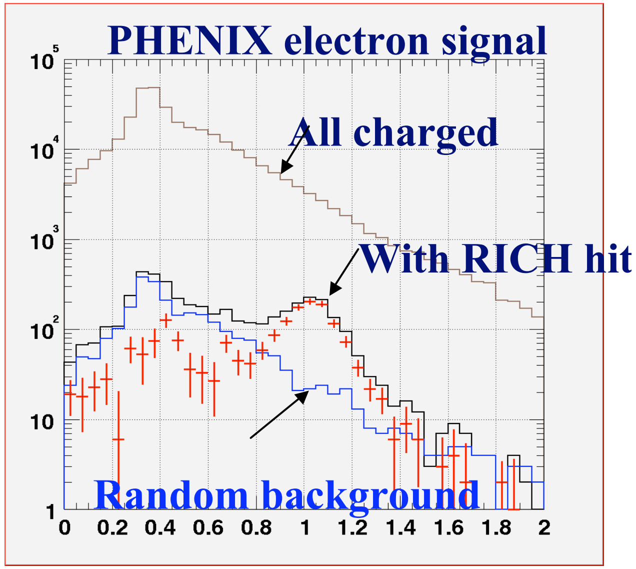


10 panels

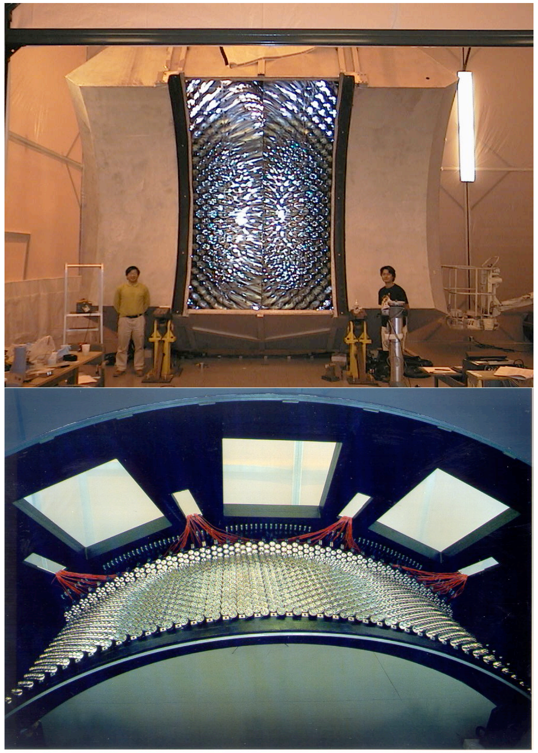
96 slats/panel

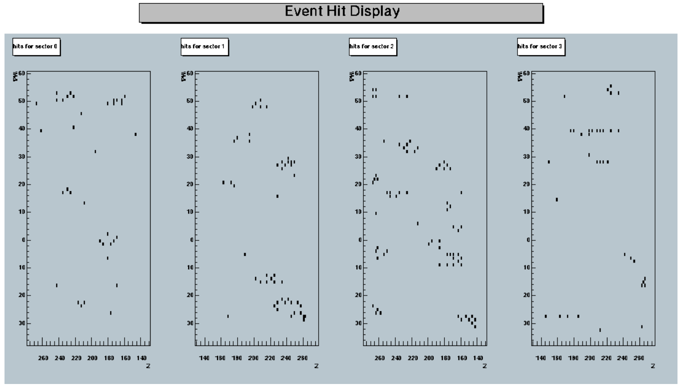
Particle ID Detectors: Ring Imaging Cerenkov Counter

- Gas radiator CO_2 , e/π separation for p < 5 GeV/c
- 5120 PMTs sensitive to single photoelectrons, σ_t < 1 ns
- Ring resolution ~1° in both θ and φ

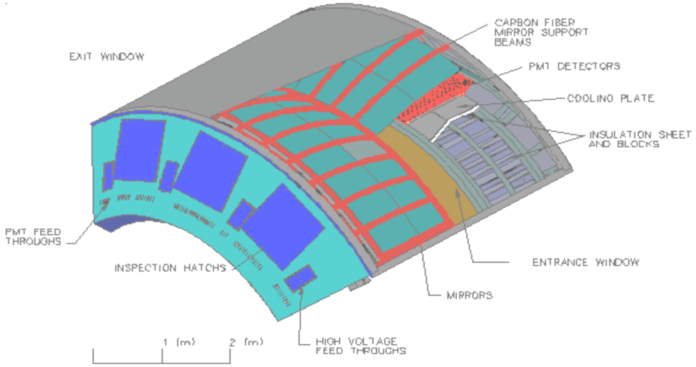


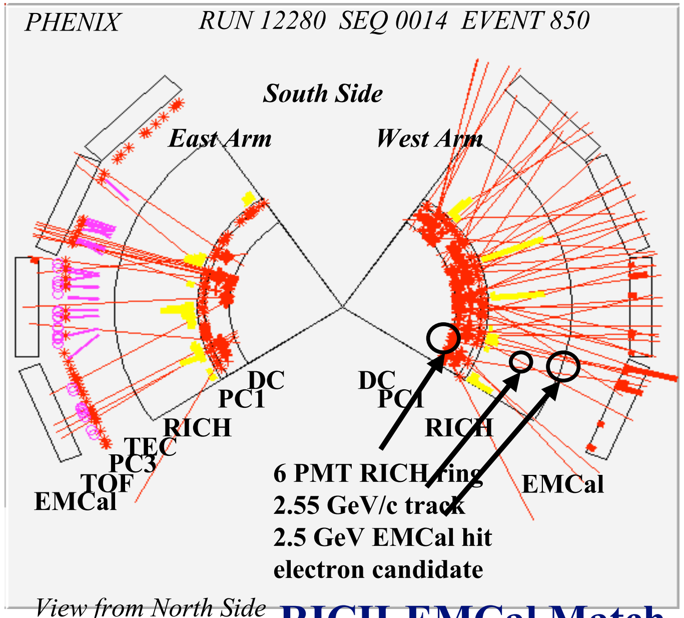
E/p ratio :RICH-EMCal





Rings in RICH from Central Au-Au collision

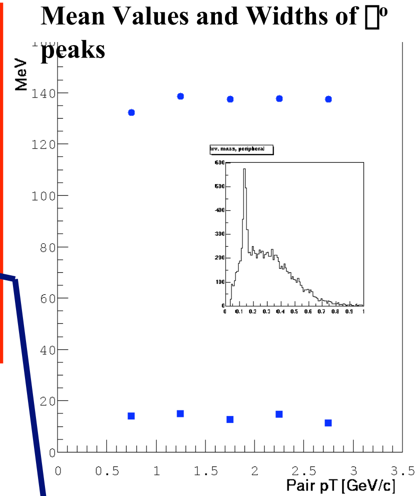




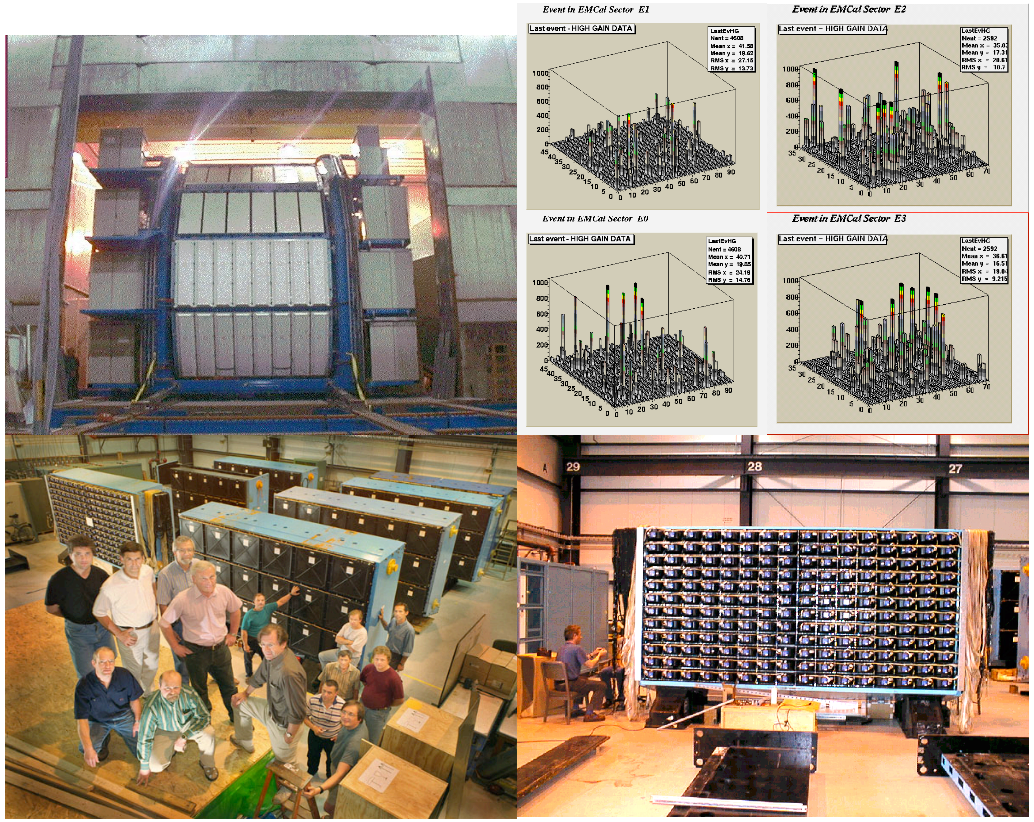
RICH-EMCal Match

Particle ID Detectors: EM Calorimeter

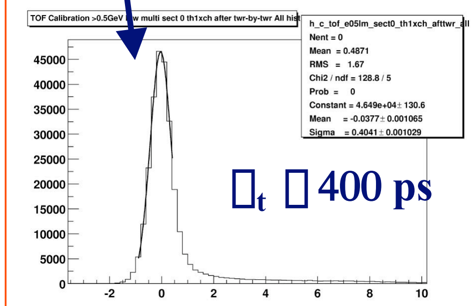
- 60 m^2 of calorimeter (6 Sectors Pb Scin, 2 Sectors PbGlass)
- Very Fine Segmentation .01 x .01 ($\Delta\eta$ x $\Delta\phi$)
- Timing σ_t ~ 400 ps Pb Glass σ_t ~ 400 ps Pb Scin
- σ_E = 8.2%/$\sqrt{E}$+1.9% Pb Scin, σ_E = 5.8%/$\sqrt{E}$+1.0% Pb Glass

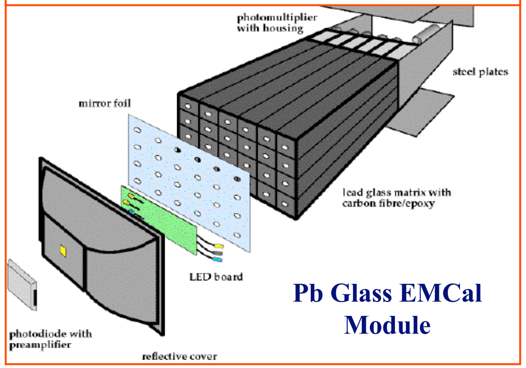


24,768 channels total, all PMTs



Clusters in EMCal from Central Au-Au Collisions

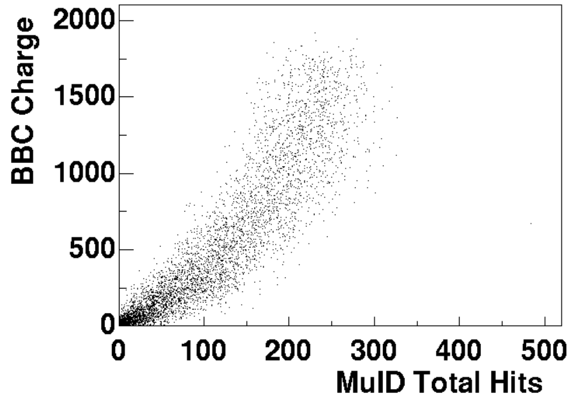


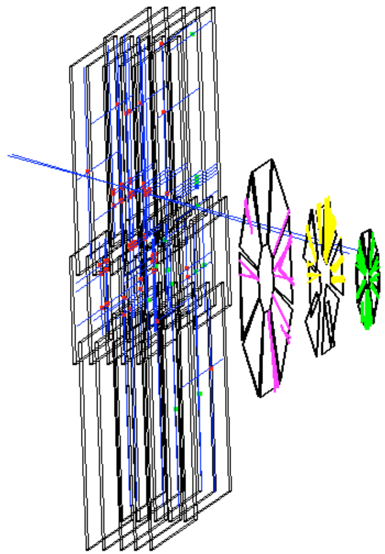


Pb Glass EMCal Module

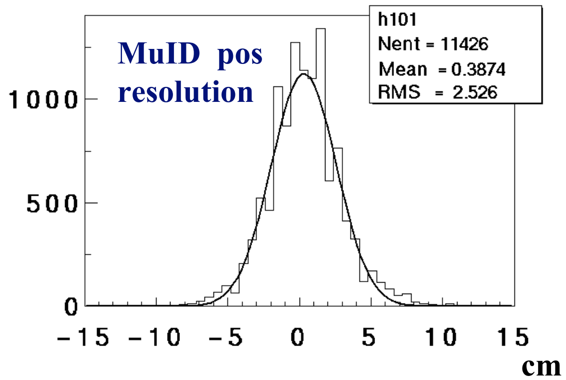
Particle ID Detectors: Muon ID

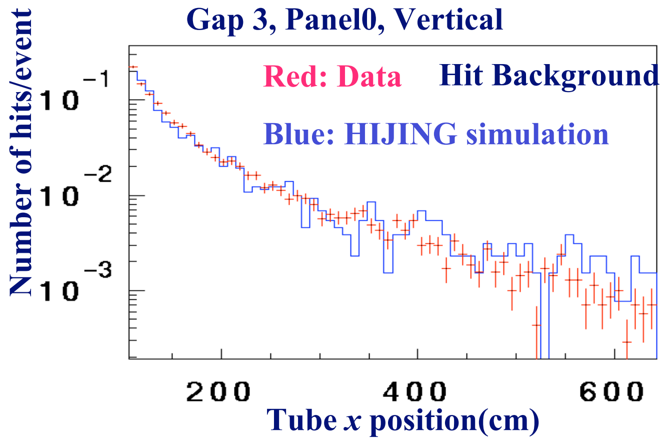
- 5 layers of steel absorber plate interleaved with 5 layers of Iarocci tubes (2x,2y 4 planes/layer)
- Active cross section of each wall 10m x 10m
- Muon low energy cutoff off 1.9 GeV/c
- Permanently sealed in place behind shield



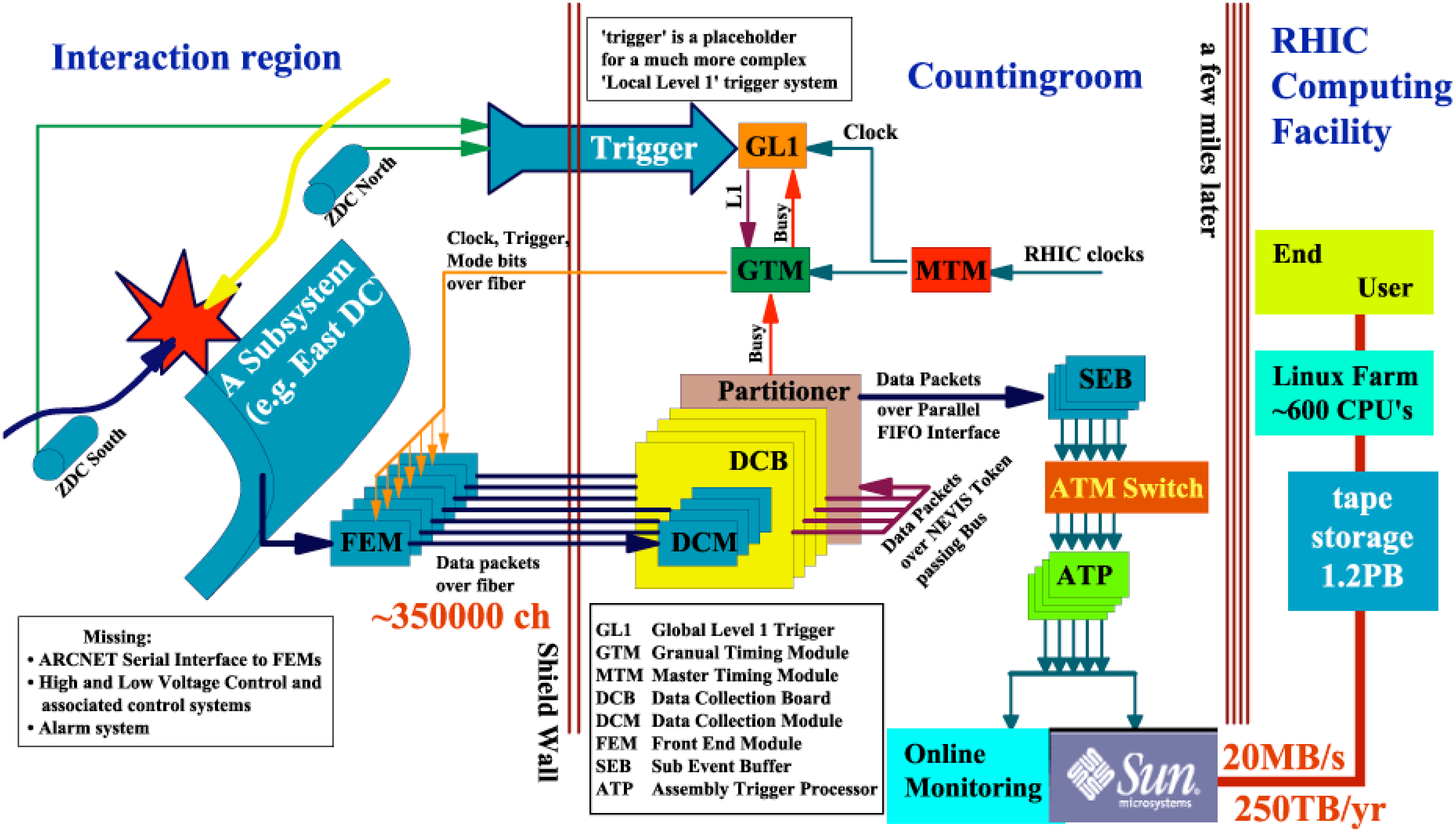


Reconstructed muon
In Au-Au Collision



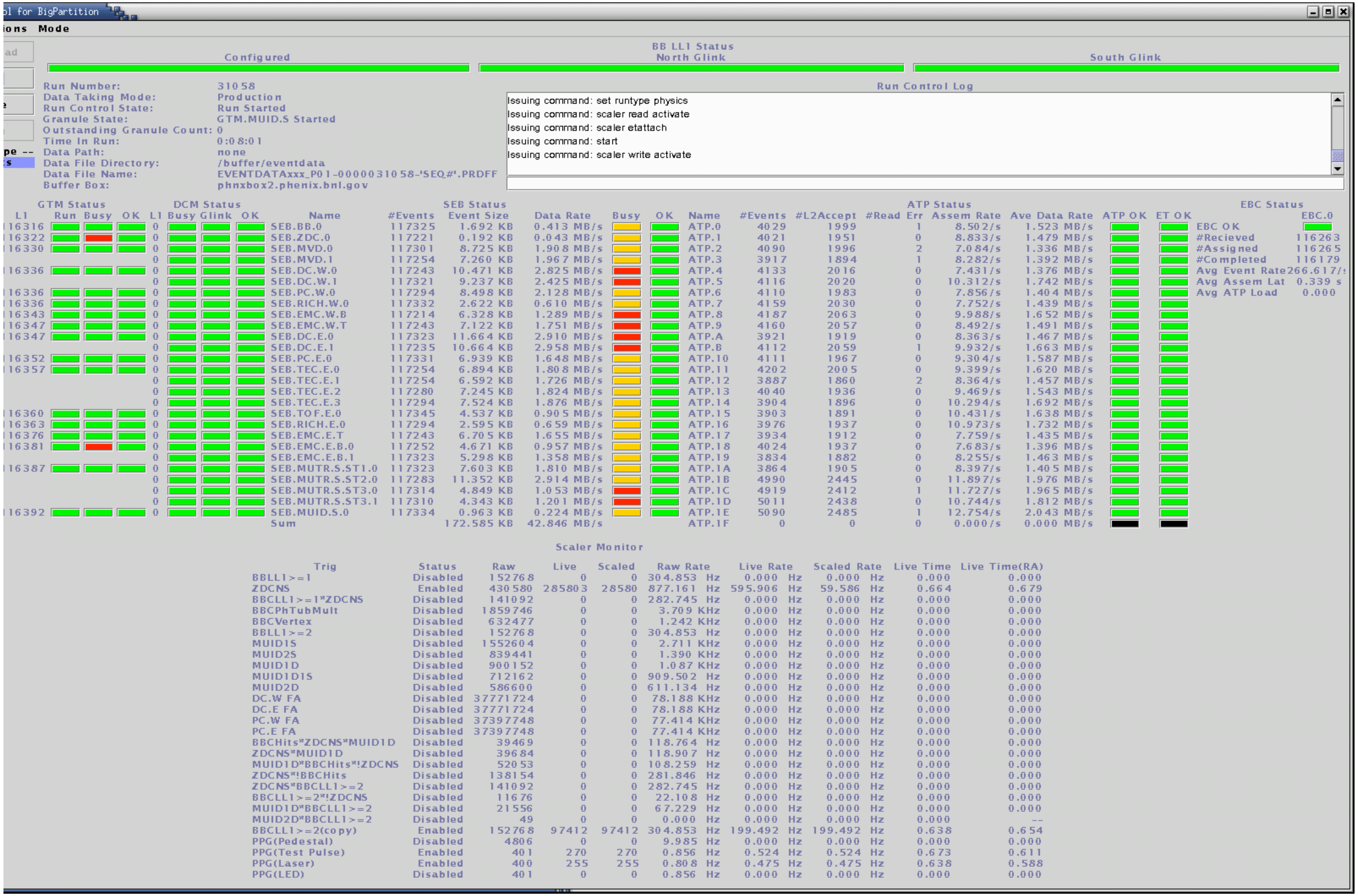


Data Acquisition System/Trigger



Data Acquisition System/Trigger

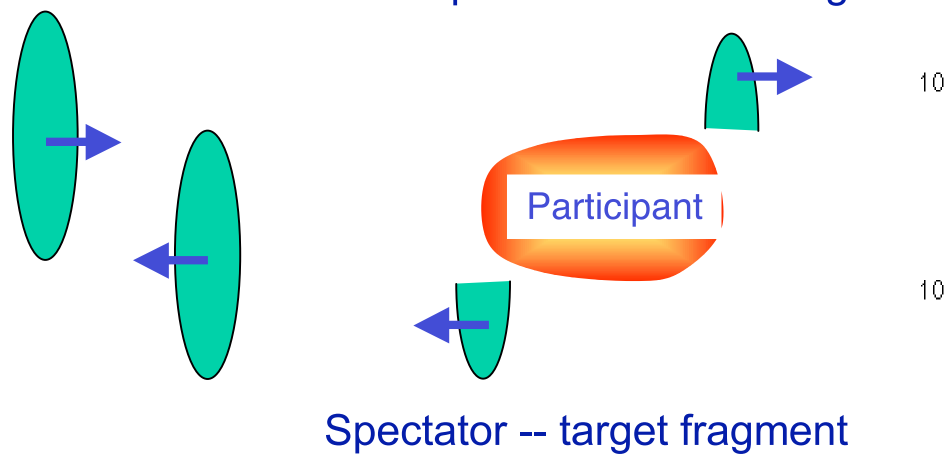
Run Control Display

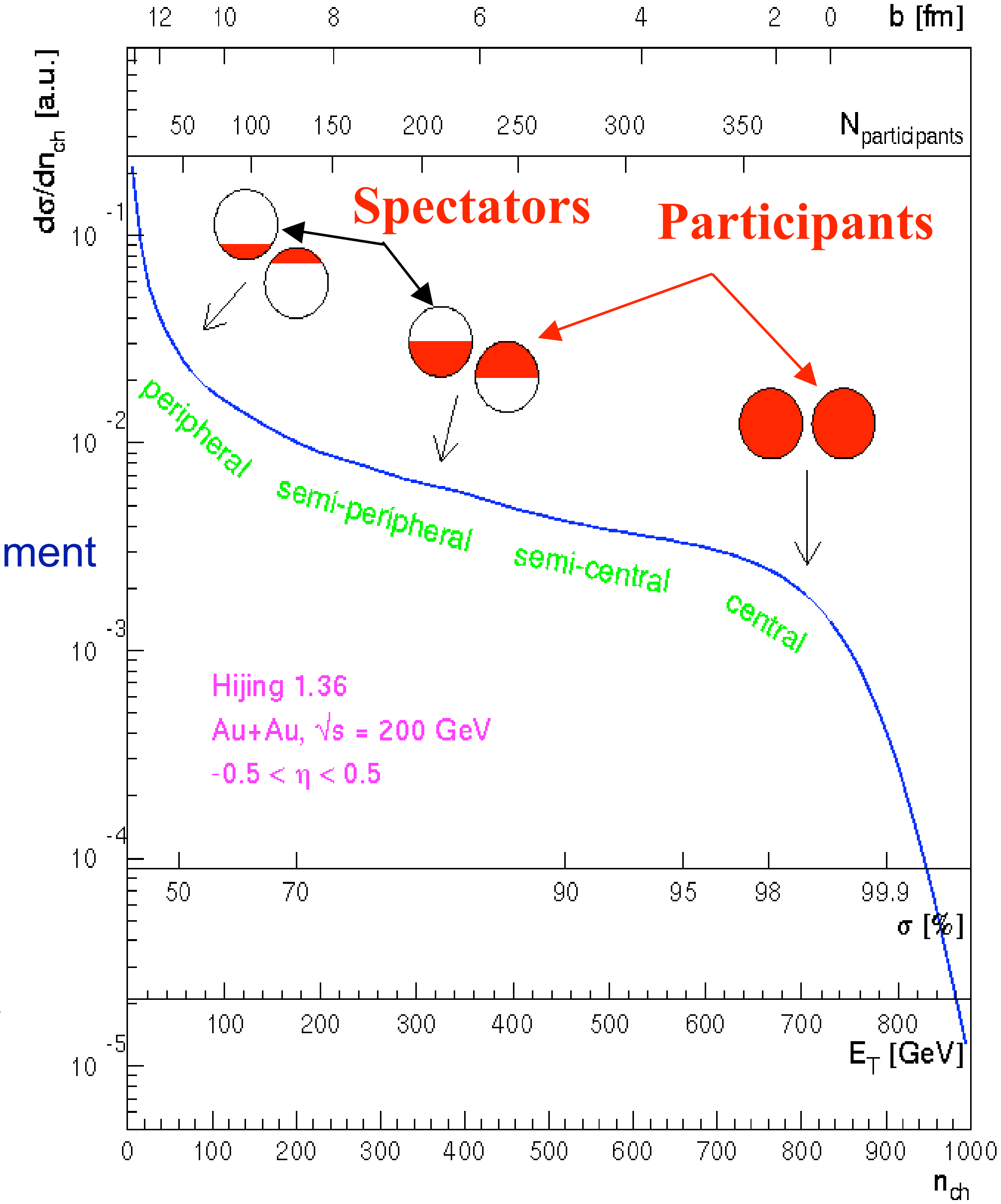


Participant-spectator model
と
衝突係数

Participant-spectator 描像

- impact parameter（衝突係数）によって、衝突の様相が決まる



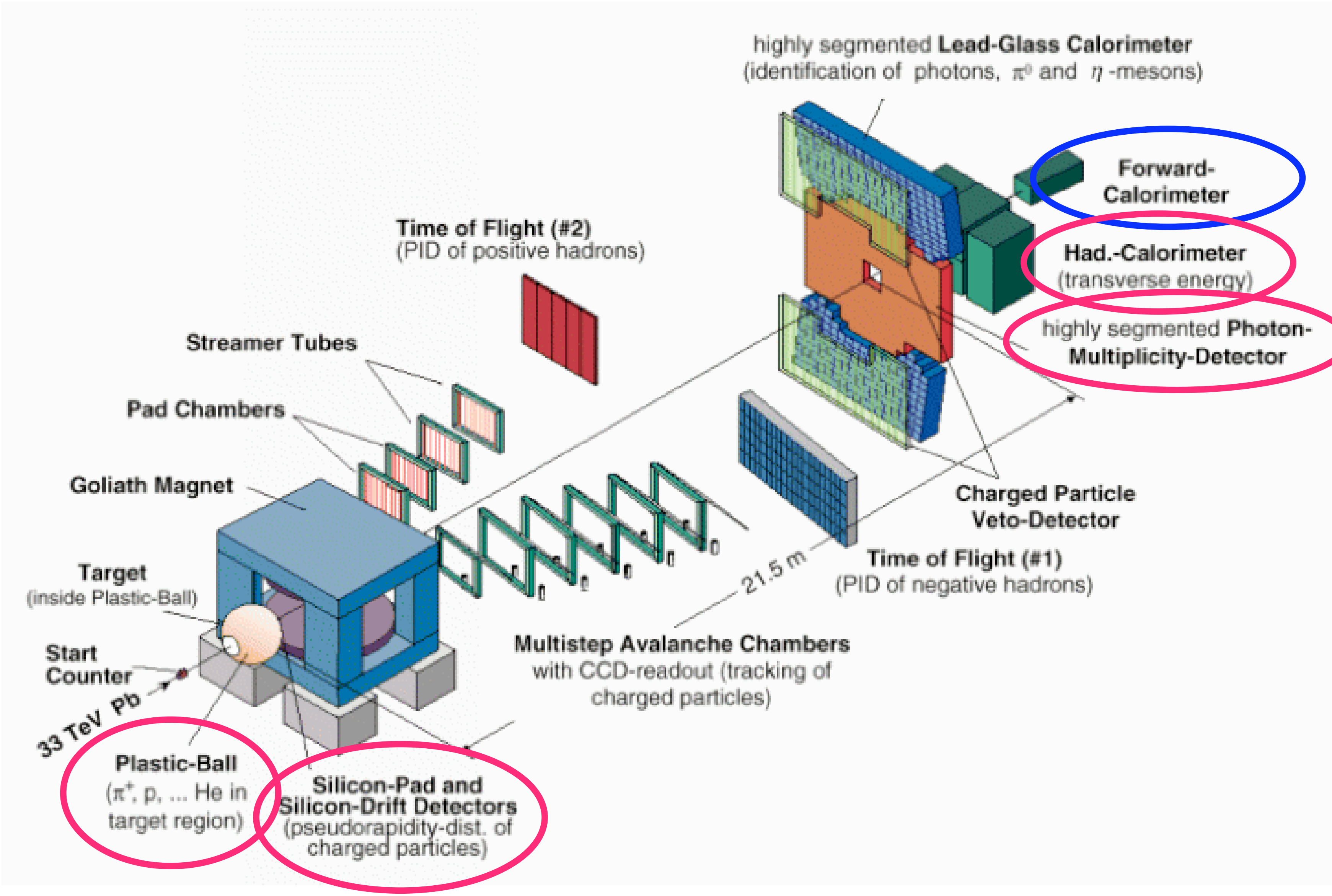


衝突係数の決定

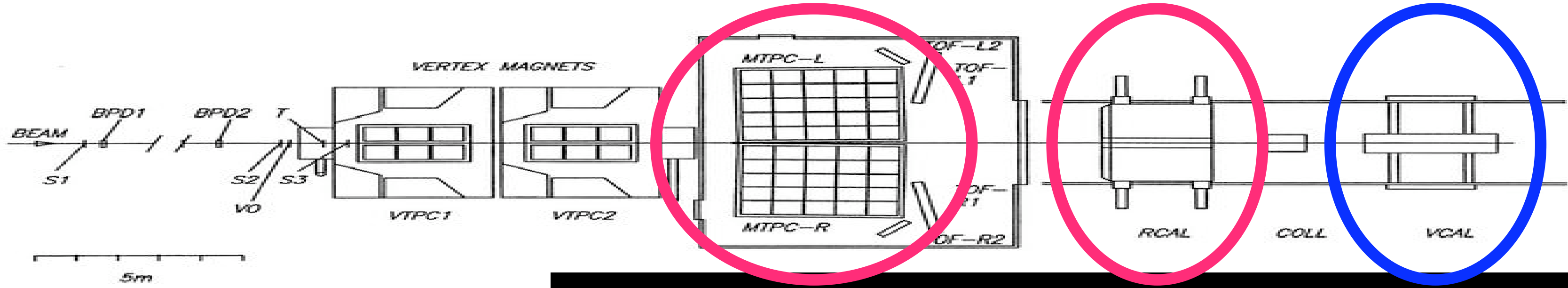
Participant-spectator 描像を利用する

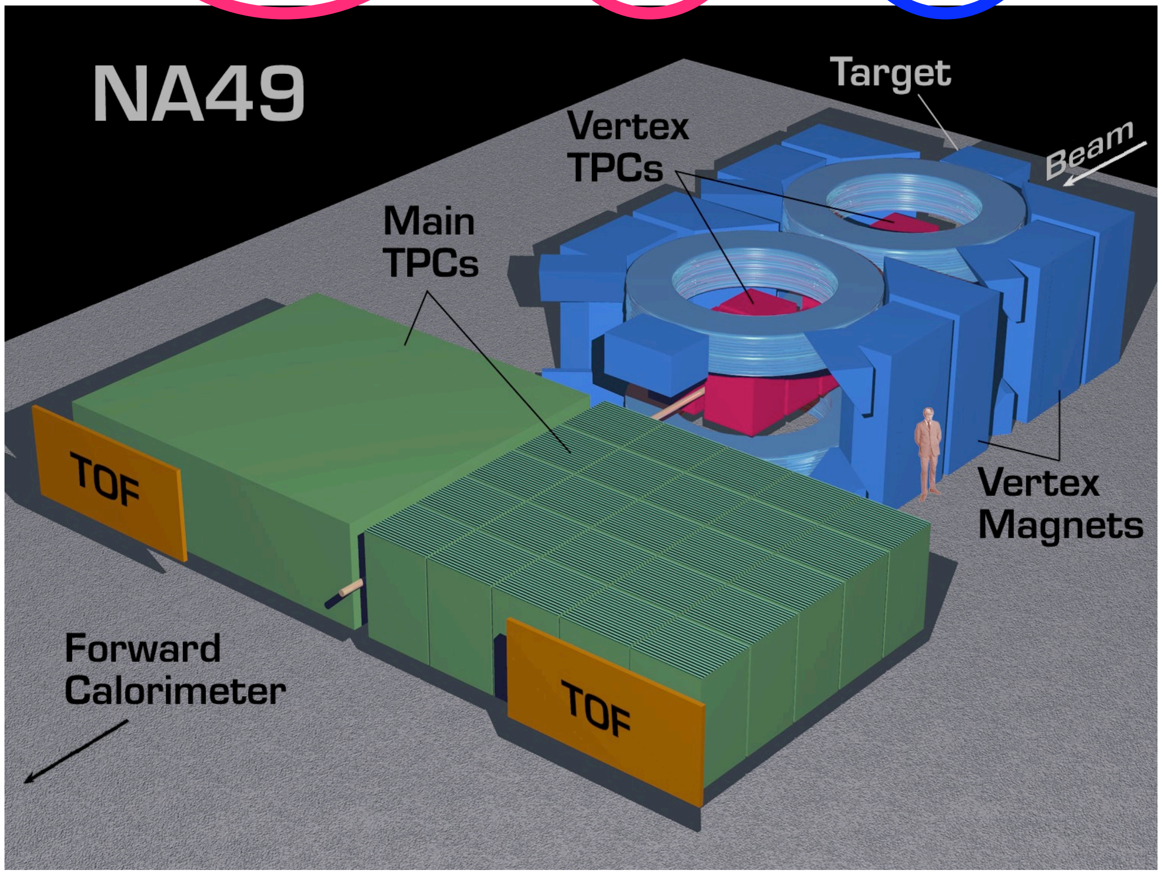
- Beam fragment の運動エネルギー
  - ハドロンカロリメータ
    - $\propto \quad A_F E_N \quad \rightarrow$ fragment の核子数
- 横エネルギー（E_T）
  - ハドロンカロリメータ、電磁カロリメータ
    - Participant 領域からの放出エネルギー
- 粒子多重度
  - 荷電粒子検出器
    - Participant 領域からの放出粒子数

CERN-SPS WA98 実験



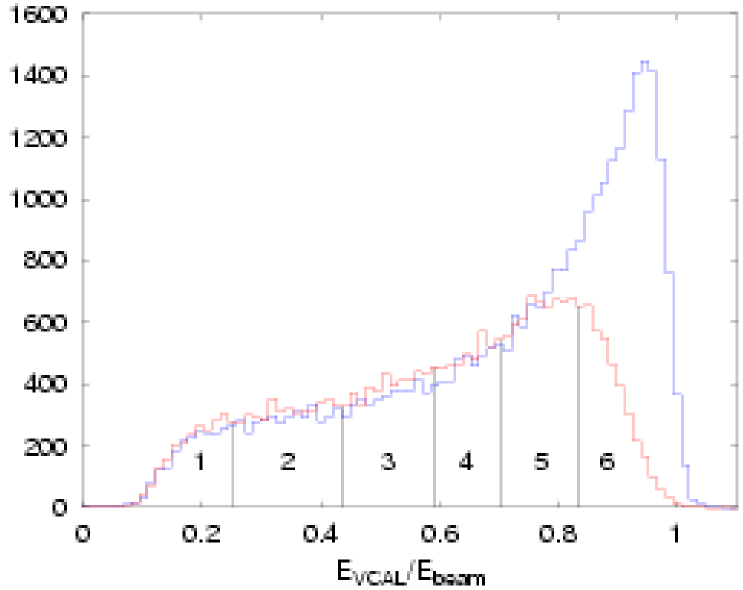
CERN-SPS NA49 実験

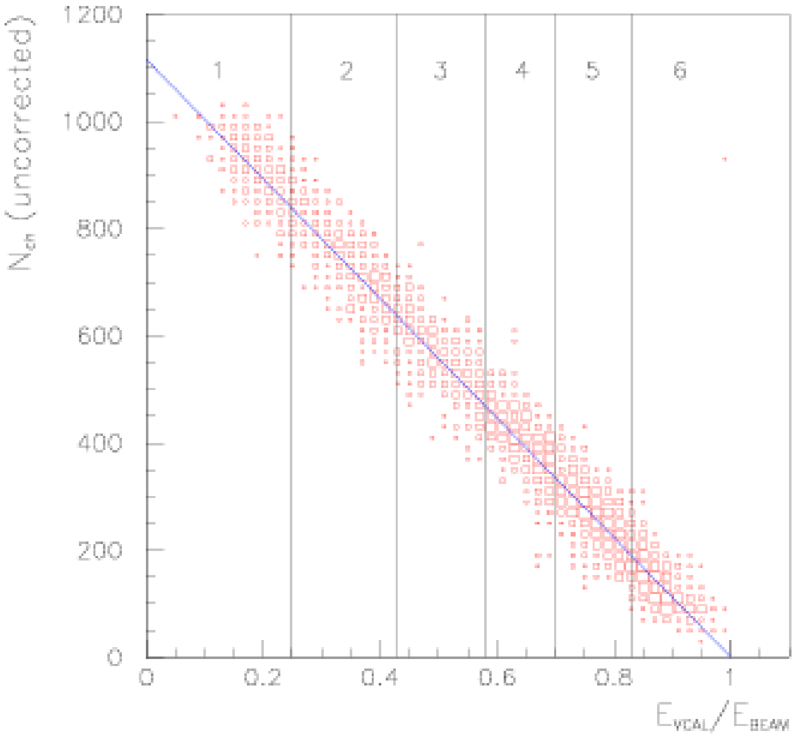




Centrality の決定（NA49）

- 前方ハドロンカロリメータ（VCAL）





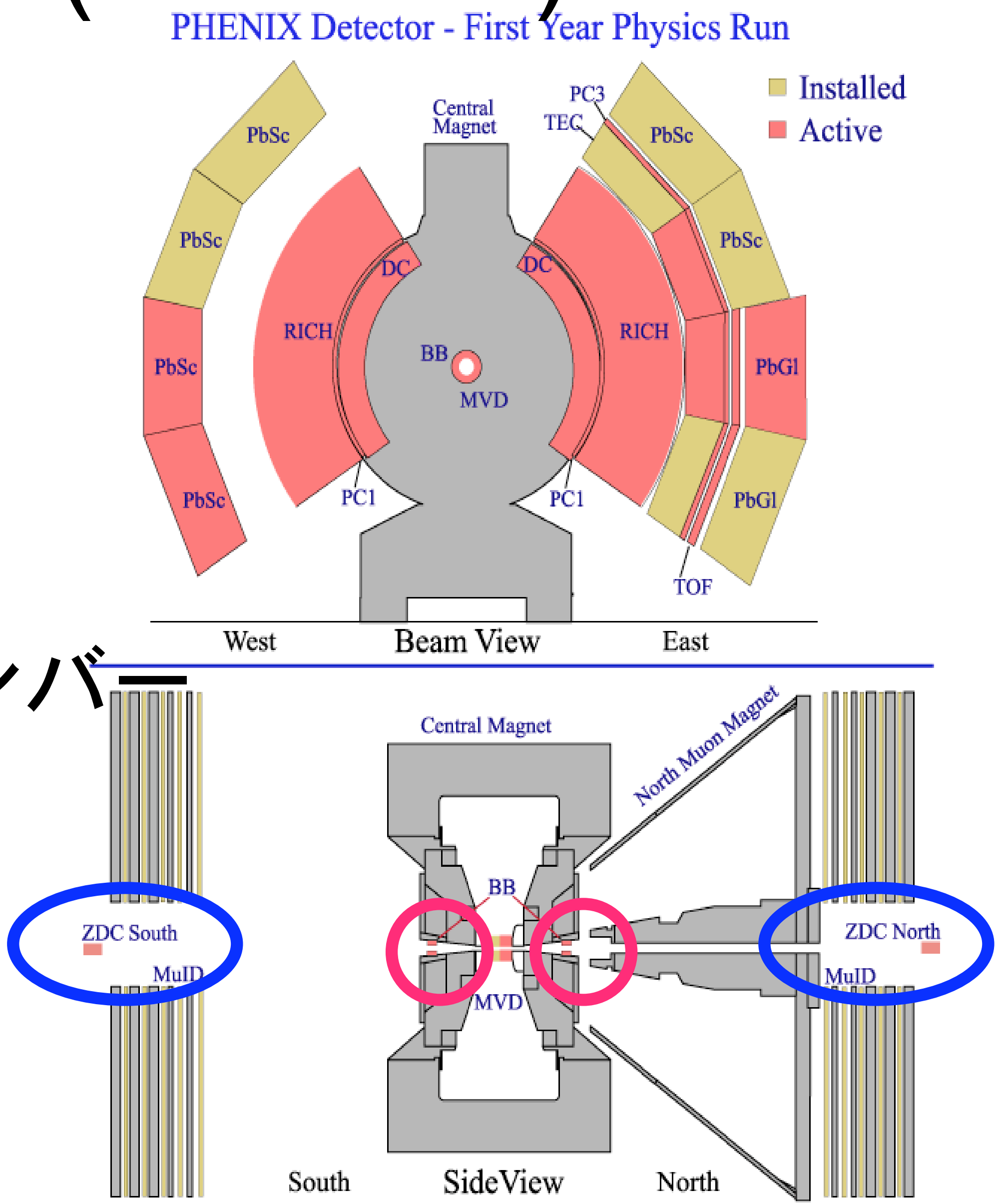
E_{VCAL} vs. N_{ch}

- N_{ch} ：TPC でのトラックの数
- 強い反相関

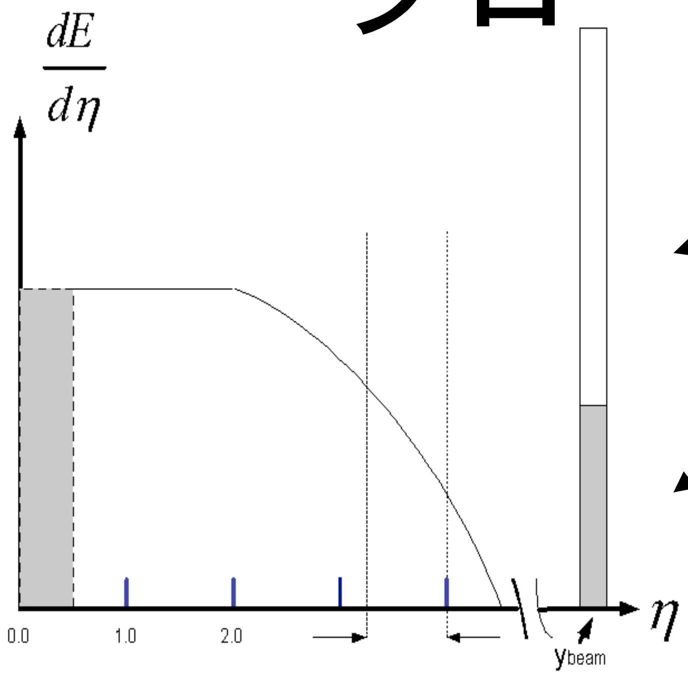
Centrality (PHENIX)

- BBC
- ZDC

- EMCal
  - PbSc+PbGl
- トラッキングチェンバー
  - PC1,PC2,PC3
  - DC
  - TEC

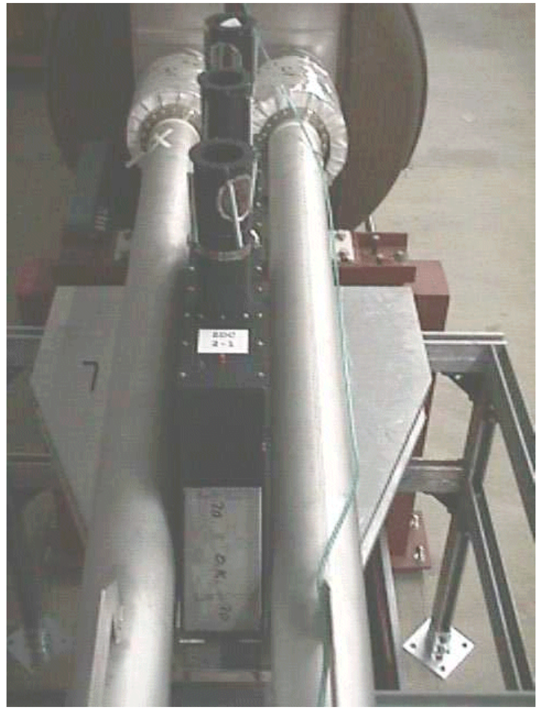


グローバル用検出器



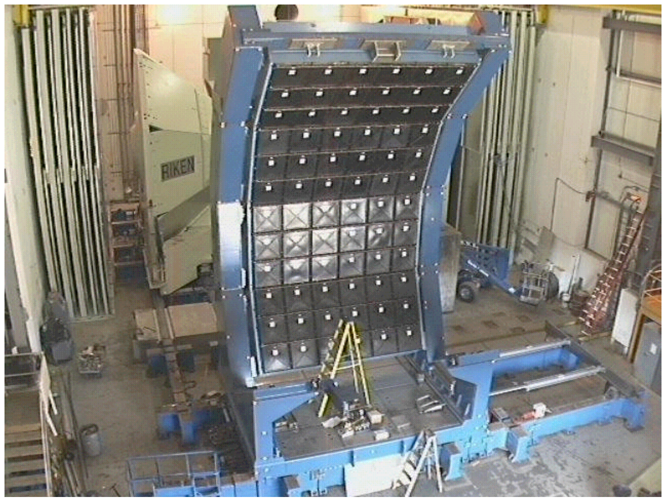
Forward, spectator Energy
charged, neutral

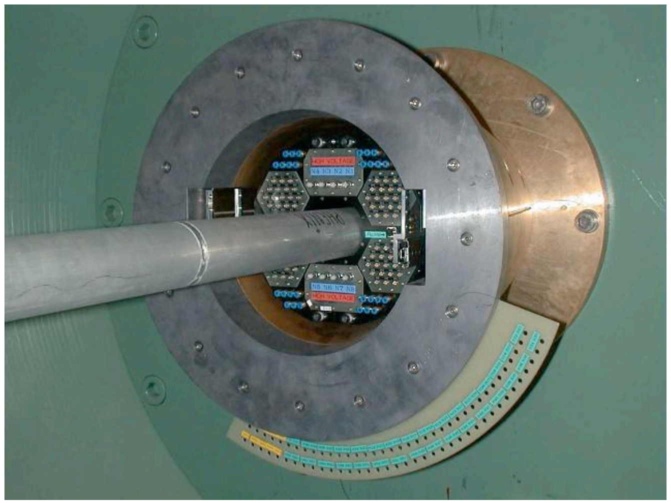
Zero Degree Calorimeter

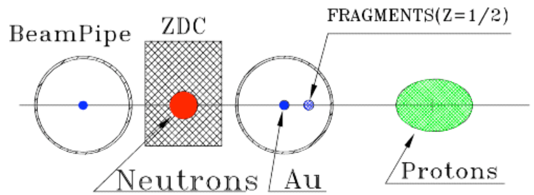


Beam-Beam
Counter

EMCal

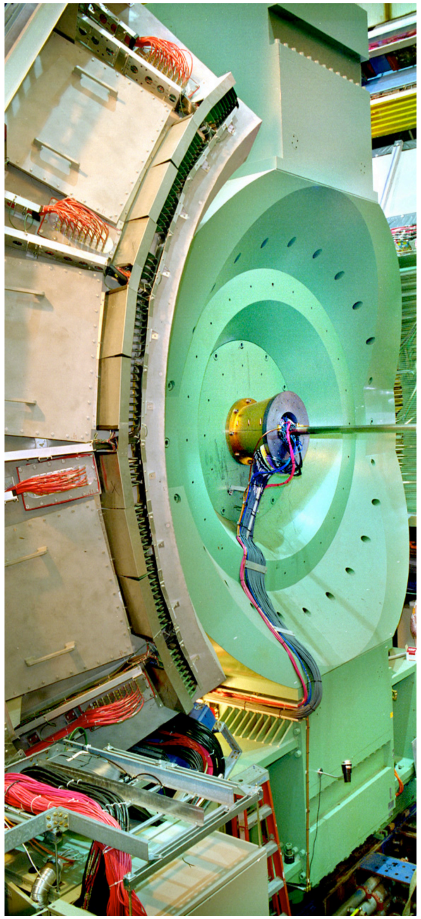


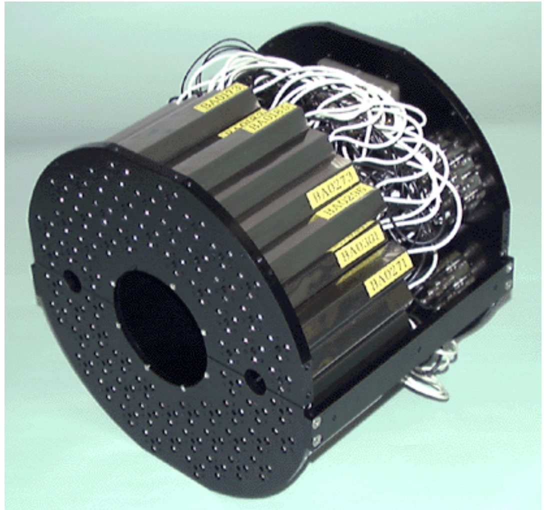




ビーム・ビーム検出器（BBC）

Hiroshima U, Columbia, LANL, and BNL

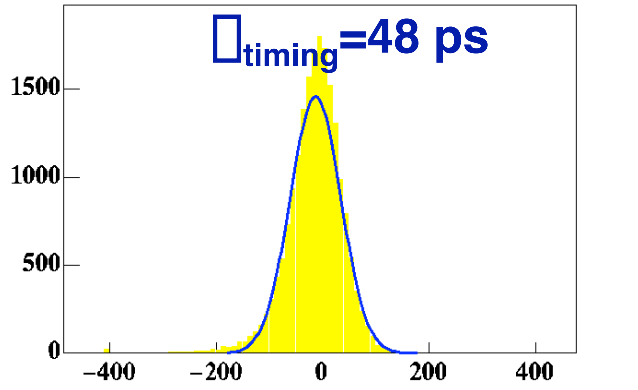




- 一対：ビーム軸に沿って超前方
(3.0<□＜3.9)に設置
- ビーム衝突事象を検出
→ 衝突位置、衝突時間、
　衝突係数を与える
- 64個の検出素子
- 各素子：
　チェレンコフ輻射体（石英）
＋１インチ径メッシュ型PMT

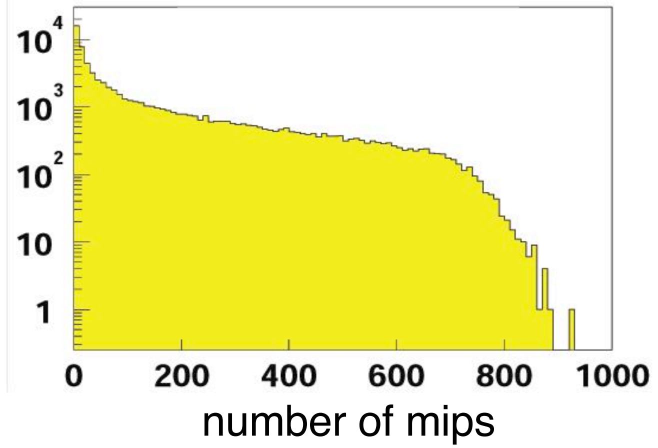
BBC Performance in Year-1

Timing resolution of an element

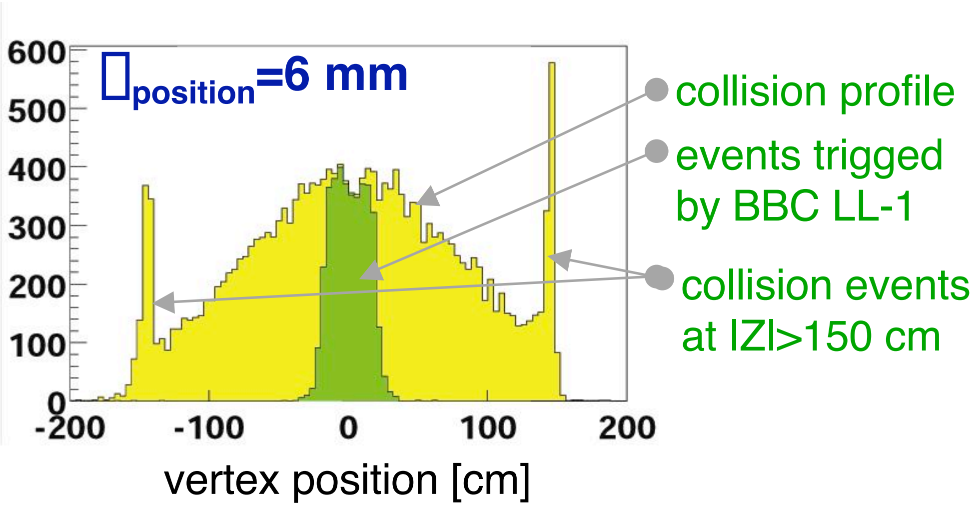


$$\Delta T_i\,[\mathrm{ps}] = T_i - T^{average}_{north/south}$$

Multiplicity distribution at BBC

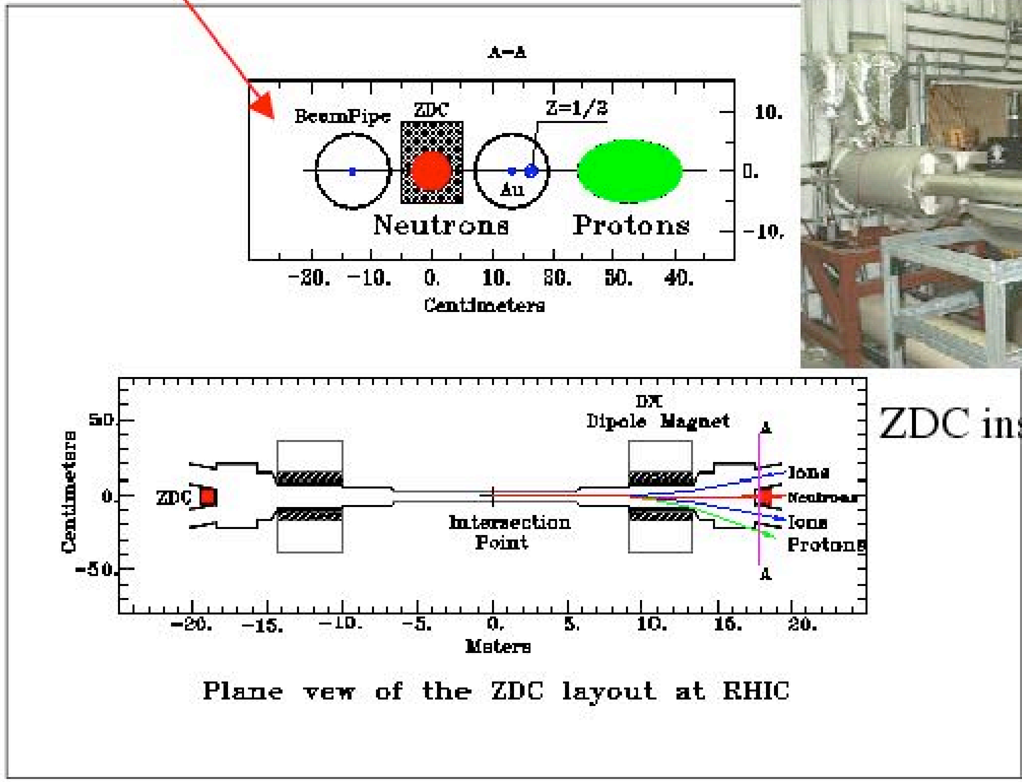


Online Vertex selection in LL-1



ZDC Layout

"Beam-eye" view of the ZDC location

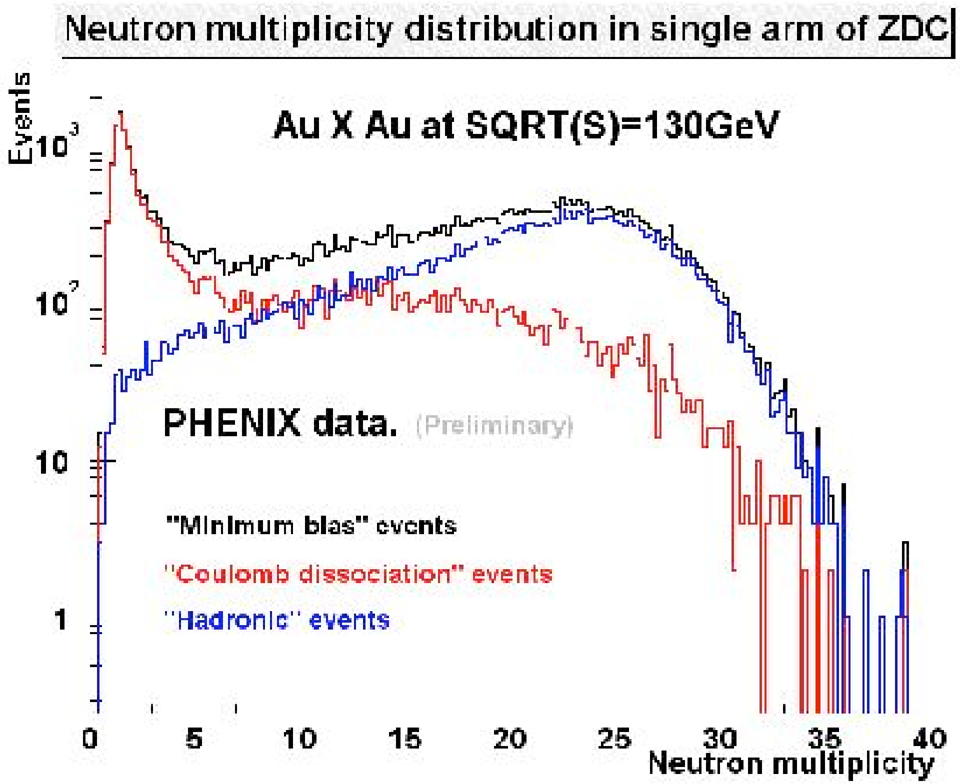


ZDC installation in 1999

- ハドロンカロリメータ：RHIC の 4 実験に共通
- 衝突型加速器では、spectator 全体を捕らえることは困難
- 0度方向の中性子数　→　衝突の中心度の単調関数ではない

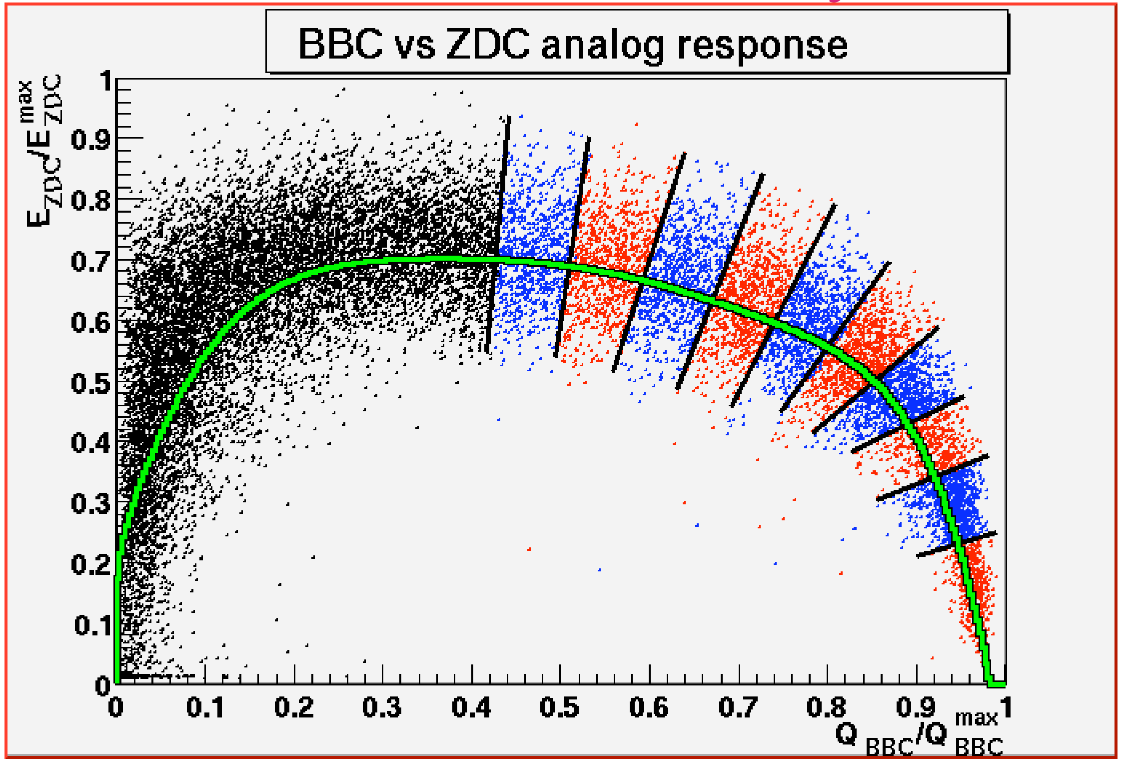
ZDCからのデータ

- 0度方向の運動エネルギー　→　中性子の数
- 金・金衝突
  – 全体の1/3は Coulo



Centrality の決定（PHENIX）

- BBC-ZDC プロット
  - ZDCエネルギー（∝中性子数）は中心衝突と周辺衝突で減少
  - 総ハドロン断面積に対する割合→centralityの決定



- Glauber model
  - N_p、N_{coll} を計算

N_p と N_{coll}

- N_p：関与部の核子数
  - 主に衝突係数によって決まる
  - Wounded nucleon 模型の wounded nucleon 数
    - 一度しかカウントしない
  - p-p 衝突では $N_p = 2$
- N_{coll}：核子の総衝突回数
  - 繰り返しを許す
  - 1個あたりの平均衝突回数：□~ $N_{coll}/(0.5N_p)$
  - ハードプロセスの場合、N_{coll} が良い指標