ÉCOLE DE PHYSIQUE
LES HOUCHES

UNIVERSITE JOSEPH FOURIER
SCIENCES TECHNOLOGIE MEDECINE

INP Grenoble

RHIC:
From colliding ions to physics results

Thomas Ullrich

QCD School, Les Houches
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YALE

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RHIC

Part II: The Experiments

Kinematics 101 (a)

Transverse Momentum (Lorentz invariant)

$$p_T = \sqrt{p_x^2 + p_y^2}$$

Rapidity (not Lorentz invariant)

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} = \tanh^{-1} \frac{p_z}{E}$$

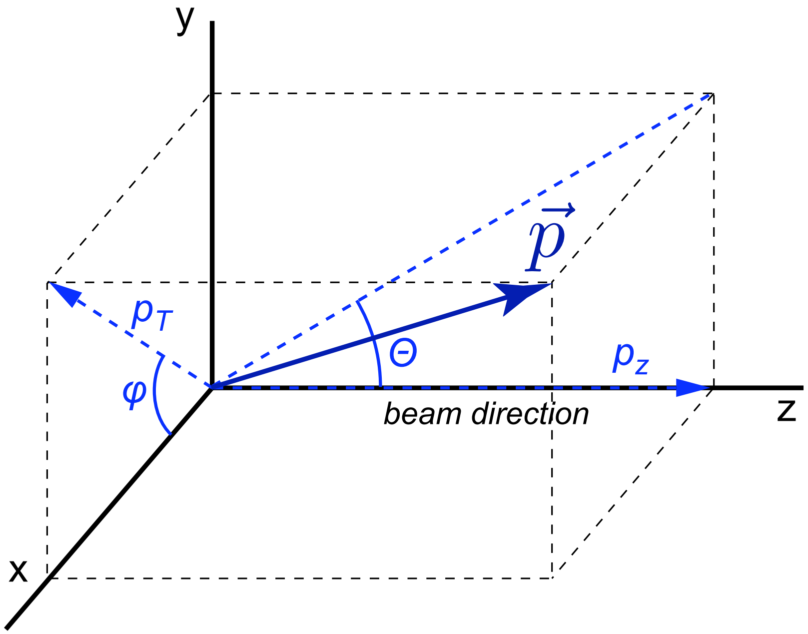
Boost in z:

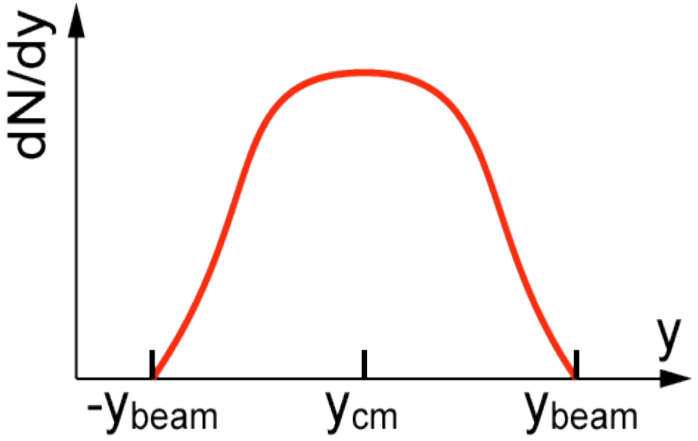
$$y \rightarrow y - \tanh^{-1} \beta$$

Pseudorapidity:

$$\eta = -\ln \tan \frac{\theta}{2}$$

$$y \approx \eta \text{ for } p \gg m$$





Kinematics 101 (b)

Strange but very common variables:

Transverse Energy: $E_T = E \sin\theta$

Transverse Mass: $m_T = \sqrt{p_T^2 + m^2}$

Useful relations:

$$\begin{aligned} \gamma &= \cosh y \\ \beta &= \tanh y \\ E &= m_T \cosh y \\ p_z &= m_T \sinh y \end{aligned}$$

Lorentz invariant cross-section:

$E\frac{d^3\sigma}{dp^3}$ always written but practically unusable

$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi}\frac{d^2\sigma}{p_T dp_T dy}$ in terms of variables we know and love

Physics Goals

Medium properties	Physical phenomenon	Experimental probes
Energy/Gluon density	Parton E_{loss} in the medium	High p_T particles, $\Delta\varphi$ and $\Delta\eta$ correlations, jets, heavy flavor (D, B)
Velocity of sound	Mach cones, collective phenomena	3-particle correlations, elliptic & radial flow
Temperature	Radiation	thermal γ, Intermediate mass dileptons
Partonic interactions, Mechanism of E_{loss}	Non-Abelian features of QCD - Color factor, path length effects of E_{loss}, Jet-medium coupling	High p_T particle production $\Delta\varphi$ and $\Delta\eta$ correlations, correlations with respect to reaction plane, jets, heavy flavor
Collectivity and Thermalization	Partonic collectivity, viscosity and interactions	Azimuthal correlations and fluctuations, thermal γ, thermal dileptons
Medium effect on particle production	Parton recombination, modified fragmentation, strangeness enhancement, yields	Identified particles – especially strangeness and heavy flavor
Initial state and hadronization effects	Fluctuations and correlations	Changes as a function of centrality or $\sqrt{s}$
Deconfinement	Color screening	Quarkonium production
Chiral Symmetry Restoration	Mass shift	low$-p_T$ $\rho\rightarrow ee$
Color Glass Condensate	Gluon saturation	low-x, forward physics, jets

The probes we want to measure ...

- Baseline (majority of produced particles)
  - $K^{\pm}$, $\pi^{\pm}$, π^0, p, $\bar{p}$
- Strangeness
  - K^0_s, K^*, ϕ, Λ, Ξ, Σ, Ω
- Real and Virtual Photons
  - γ
  - $\gamma^* \to \mu^+\mu^-$, $\gamma^* \to e^+e^-$
- Heavy Flavor
  - D^0, D^*, $D^{\pm}$, B
  - Λ_c
- Quarkonia
  - J/ψ, ψ', χ_c, Υ, Υ', Υ''
- Jets ⇒ high-p_T hadrons in cone
- Decay channels matters too: $\rho \to e^+e^-$ versus $\rho \to \pi^+\pi^-$

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- And all that over all p_T ?
- Acceptance (ideal 4π) ?
- All centralities, multiplicities ?
- Recording every collision ?

The Perfect Detector ?

- Momentum **p**
  - magnetic field × length: B×dl
  - high-pt ⇒ large B×dl ⇒ small p_T tracks curl up
  - low-pt ⇒ small B×dl ⇒ high p_T tracks care straight (p_T res. lost)
- Particle ID
  - γ, e ⇒ hadron blind, little material
  - hadrons ⇒ PID through interaction with material
- Acceptance
  - large acceptance ⇒ lots of data ⇒ slow
  - small acceptance ⇒ few data ⇒ fast
- Energy
  - γ, e ⇒ E.M. Calorimeter
  - hadrons ⇒ Hadronic Calorimeter
- Heavy flavor ID
  - secondary vertices ⇒ high precision Si detectors = material
  - semileptonic decays ($c, b \rightarrow e + X$, $B \rightarrow J/\psi\,(\rightarrow e\,e) + X$) ⇒ hadron blind, little material

Mission Impossible

Question: How to proceed with experimental design when

$$\sum \left(\overrightarrow{\text{Theoretical Opinion}}\right) \approx 0\,?$$

Design Guidelines for QGP Detection

- Big Plan:
  - Consistent framework for describing most of the observed phenomena
  - Avoid single-signal detectors
  - “Specialized” detectors but keep considerable overlap for comparison and cross-checks
  - Expect the unexpected
    - Preserve high-rate and triggering capabilities
    - Maintain flexibility as long as $’s allow

- Design Questions (years of sweat, discussion, and simulations)
  - What measuring techniques do you want to use?
  - What technologies (detectors) fit your goals, constraints?
  - Figure out how to combine them

Particle identification – long lifetime (>5 ns)

Examples: π, K, γ, p, n, …

Charge (if any!) and 4-momentum needed for PID

4-momentum from at least two of these quantities:

energy

↓

calorimetry

↓

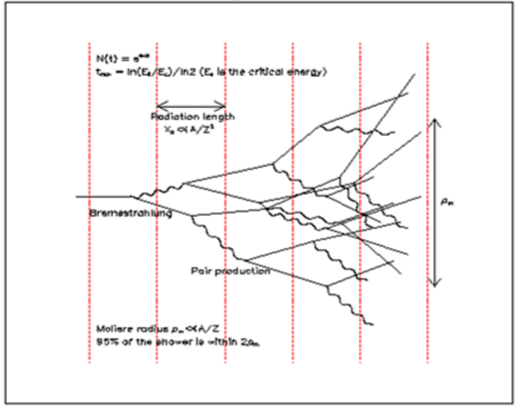
Fully stop the particle

Convert its energy to

- light, charge…

Collect and read out

Electromagnetic showers



3-momentum

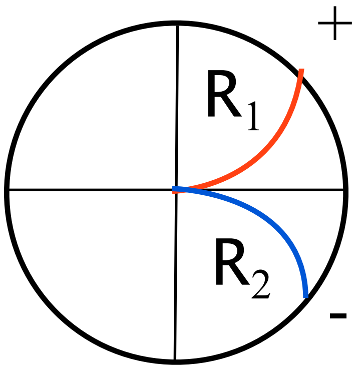
↓

tracking

↓

Follow path of charged particles in magnetic field – get momentum from curvature

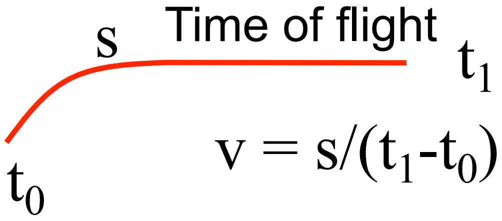
$$p_T = (q/c) \times B \times R$$



velocity

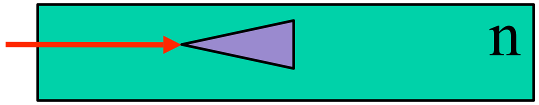
↓

time-of-flight + pathlength or Cherenkov-effect



$$v = s/(t_1 - t_0)$$

Cherenkov



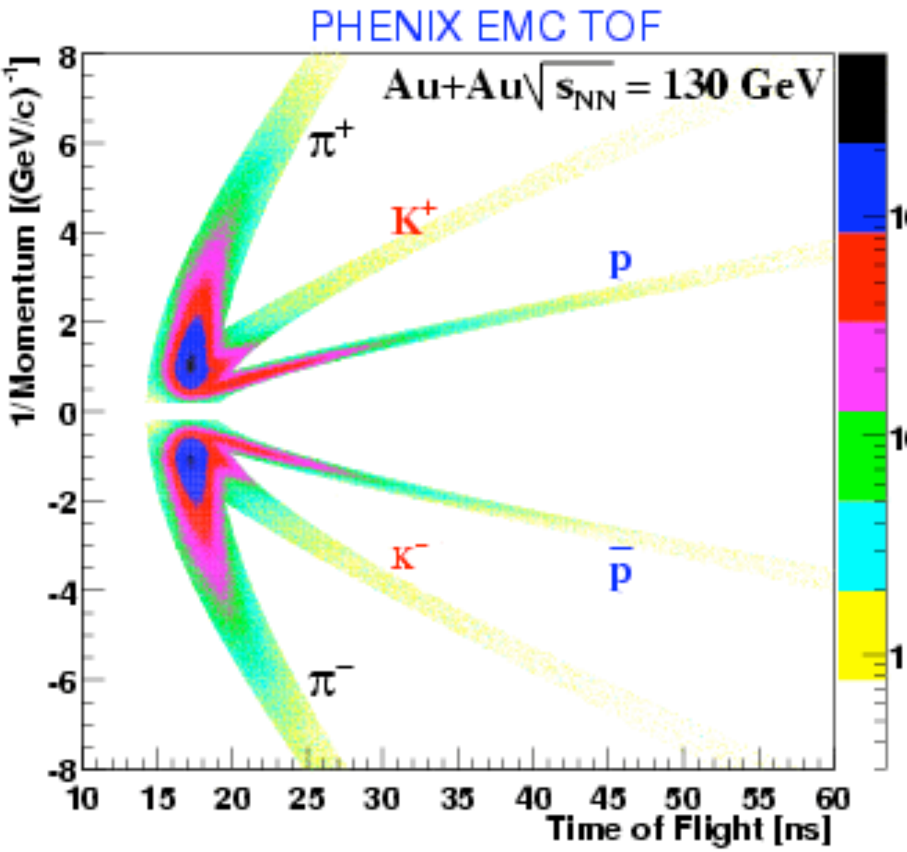
$$cos(\alpha) = 1/\beta n$$

Particle identification – long lifetime (> 5 ns)

Why do I emphasize long lifetime? Because the detectors are fairly large, and the particle produced at the vertex has to survive until it reaches the detector!

Example:
hadron identification with momentum and time-of-flight measurement

y axis: inverse of the momentum
x axis: time-of-flight



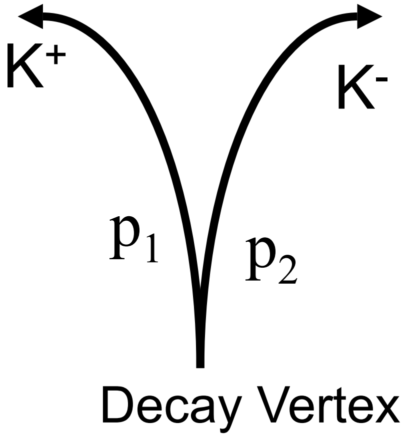
There are many more methods to identify long-lived particles

Particle identification – short lifetime (< 5 ns)

Examples: π^0, ϕ, Λ, …

Have to be reconstructed from their more stable decay products

Assume you want to measure the φ meson via its φ→KK decay by measuring both kaons and reconstructing its invariant mass



$$m^2 = (p_1 + p_2)^2$$

But what if there are more than 2 kaons in the event? Or you take a pion for a kaon? Which two go together?

S = Total - Background

Background could be like-sign pairs or pairs from different events

Particle identification – short lifetime (< 5 ns)

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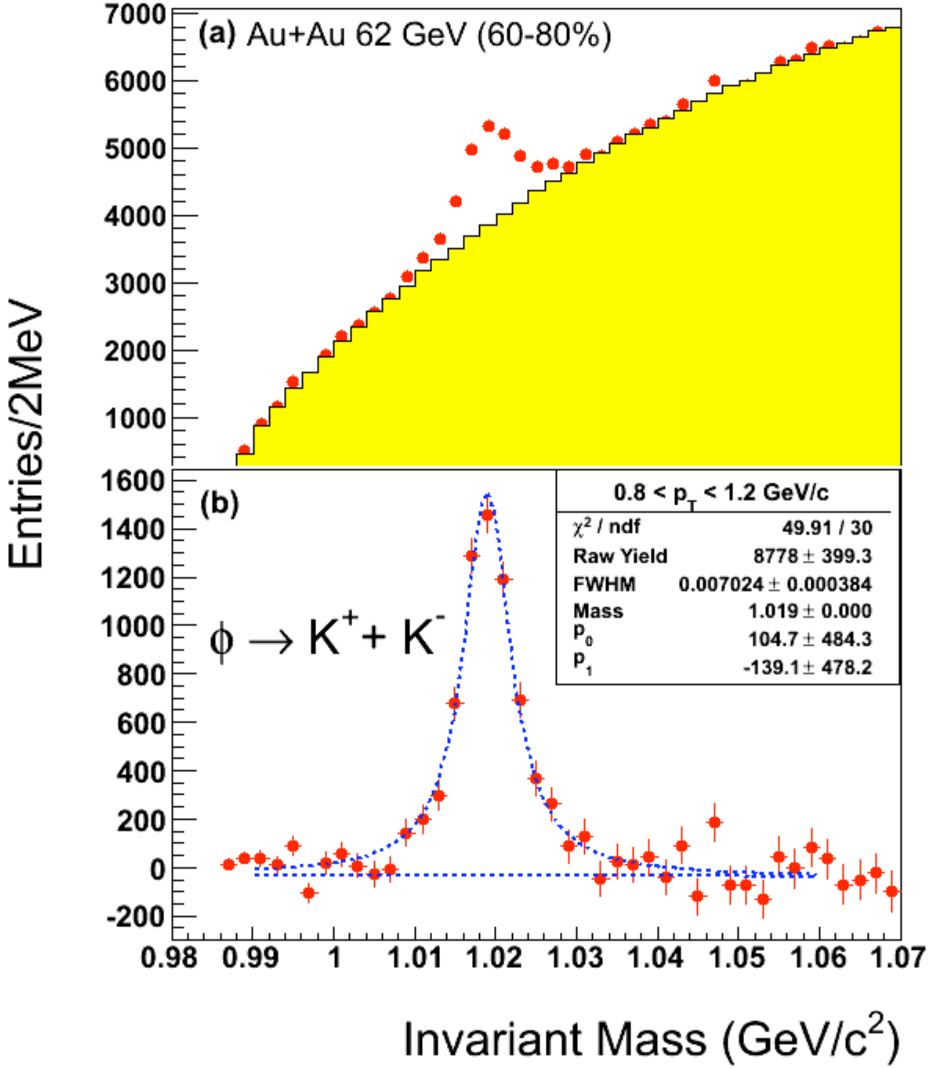
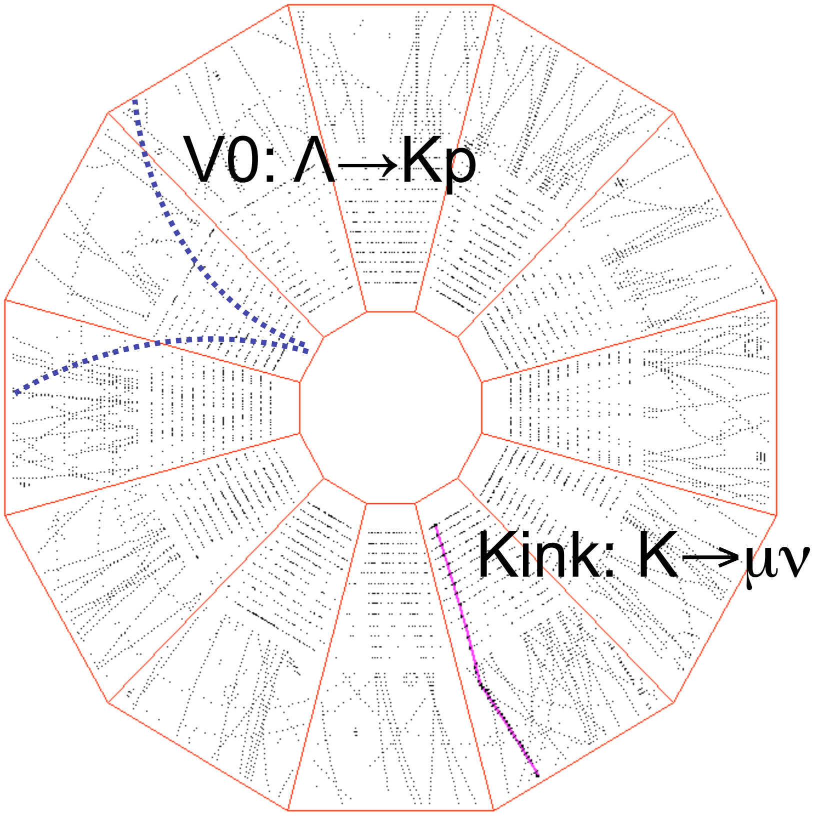
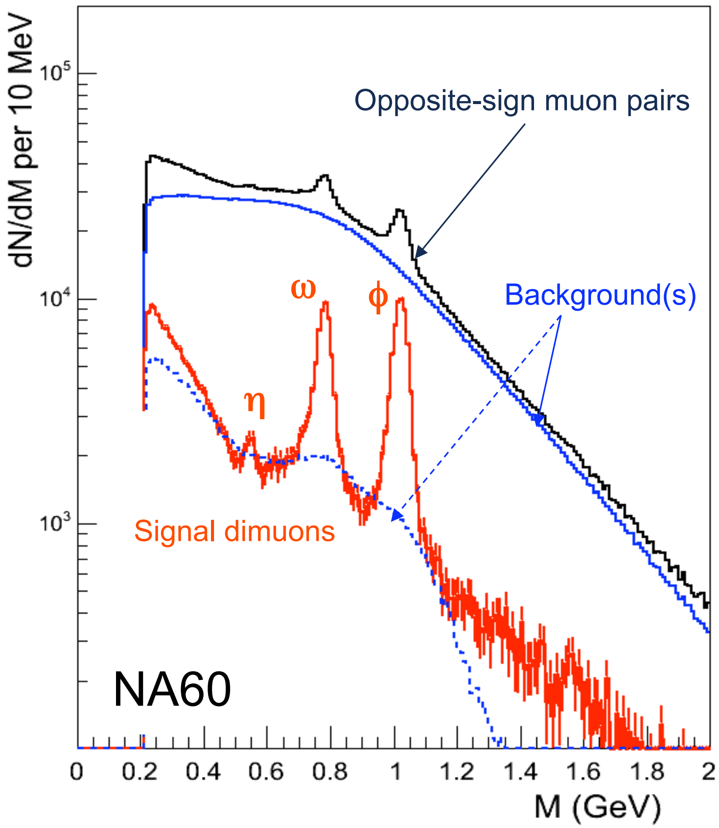


Particle identification – short lifetime (< 5 ns)

Different topologies



What if cτ ~ fm ?



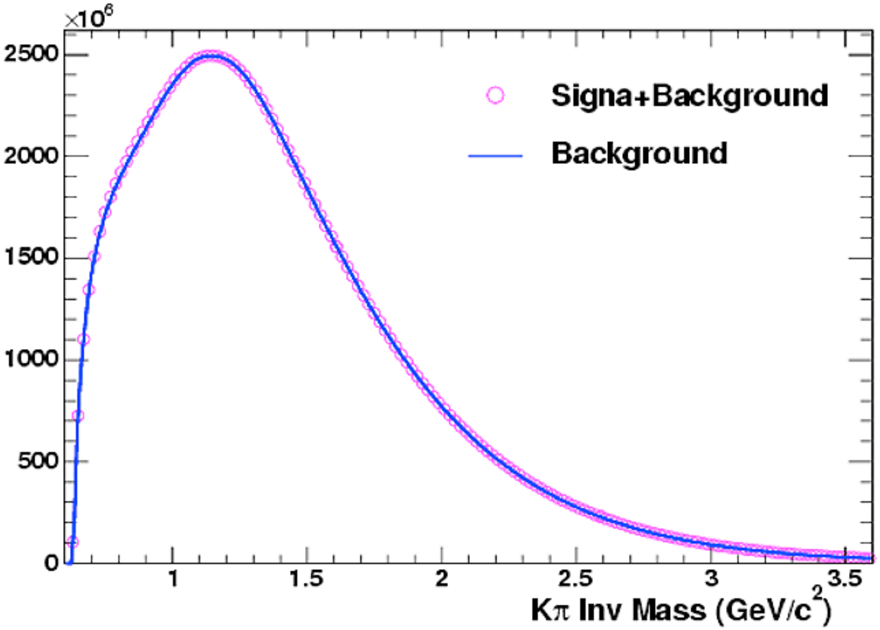
Note weak decaying particle (like Λ, Ω, K^0_s) decay cm away from the interaction vertex - cm are easy to deal with

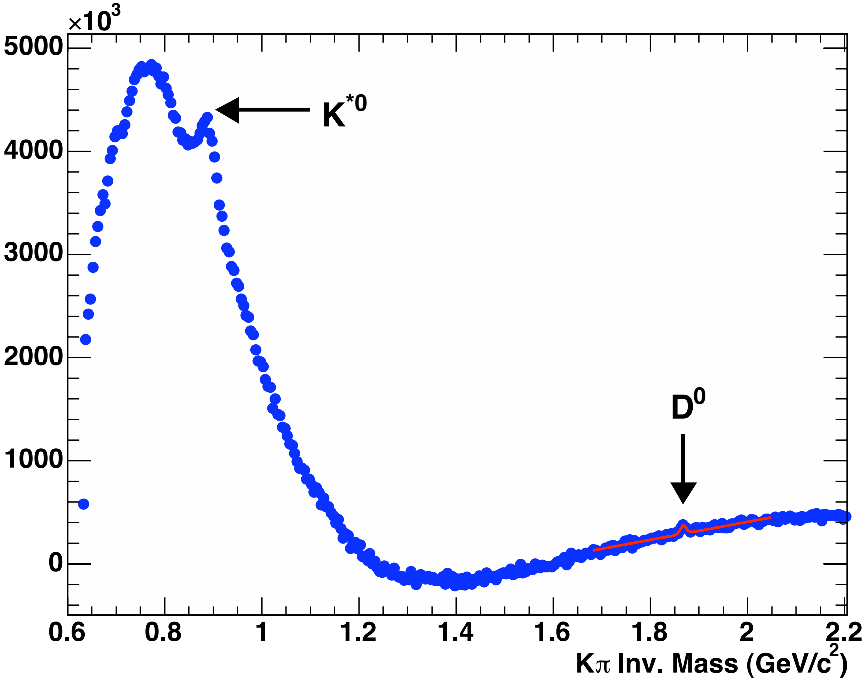
Works as well but usually more background

Particle identification – very short lifetime in <1 mm

Here $D^0 \rightarrow K\,\pi$ ($c\tau$ = 123 μm)

- Brute force method
  - select K and π tracks
  - combine all pairs from same events ⇒ signal+background
  - combine all pairs from different events ⇒ background
  - subtract background from signal+background ⇒ signal





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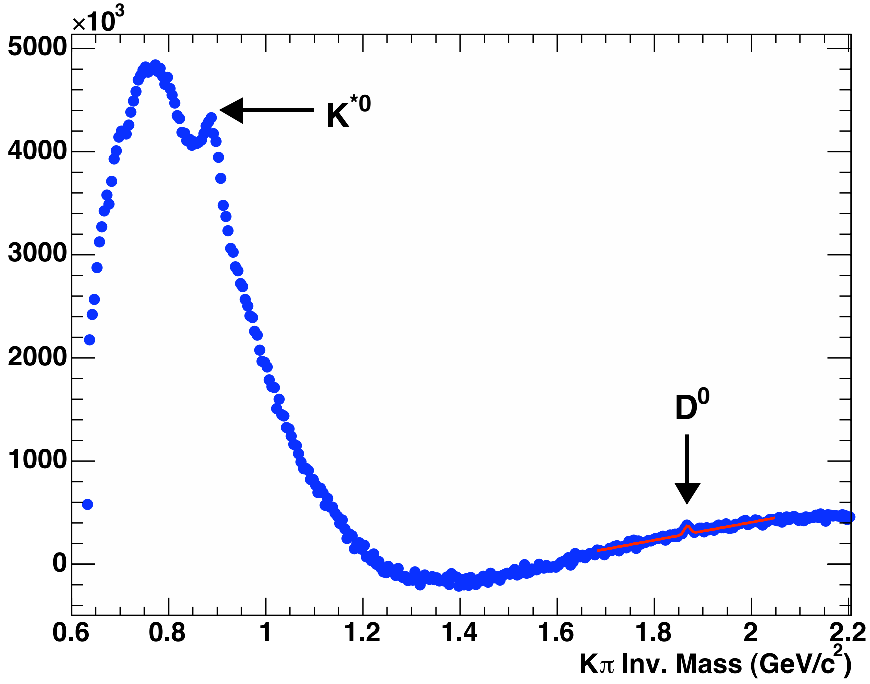
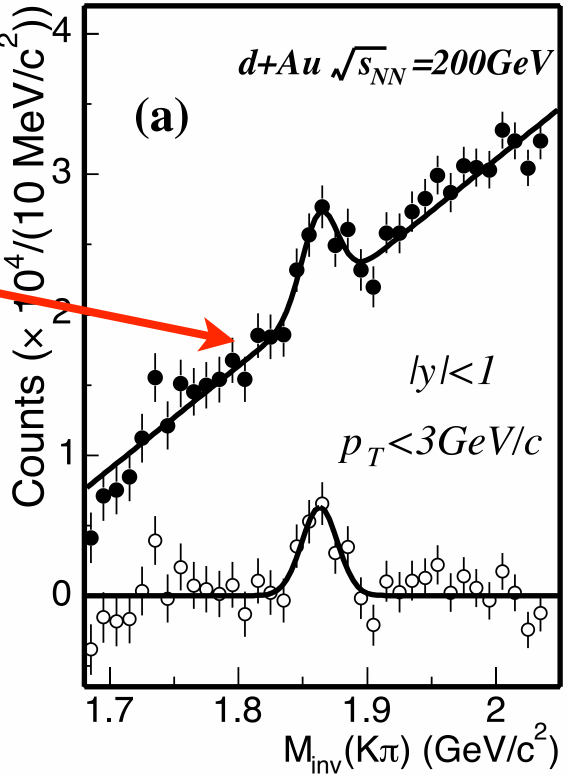


Residual background not eliminated. Needs further work to get to final spectra ....

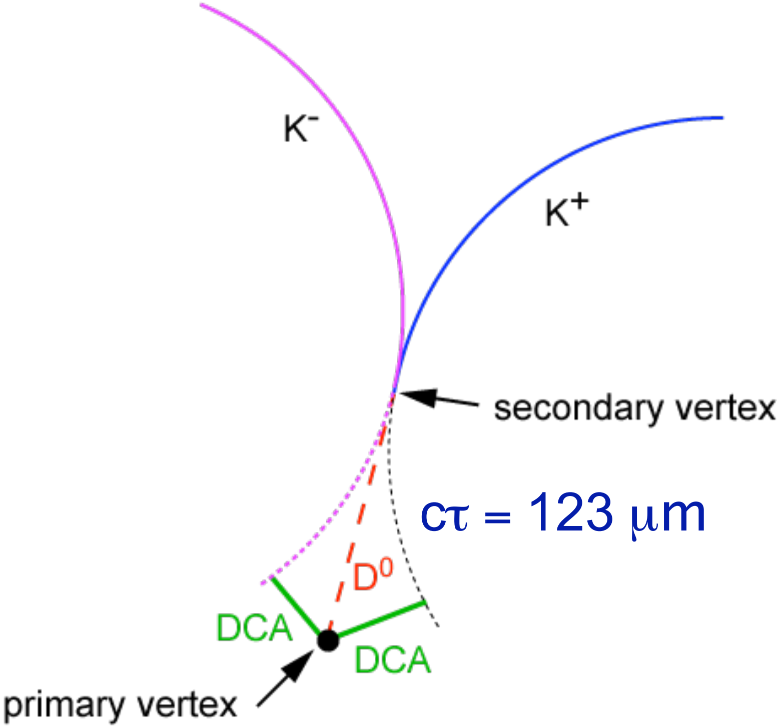


Particle identification – very short lifetime in <1 mm

This background problem can only be overcome by cutting on a key-feature: Secondary decay vertex

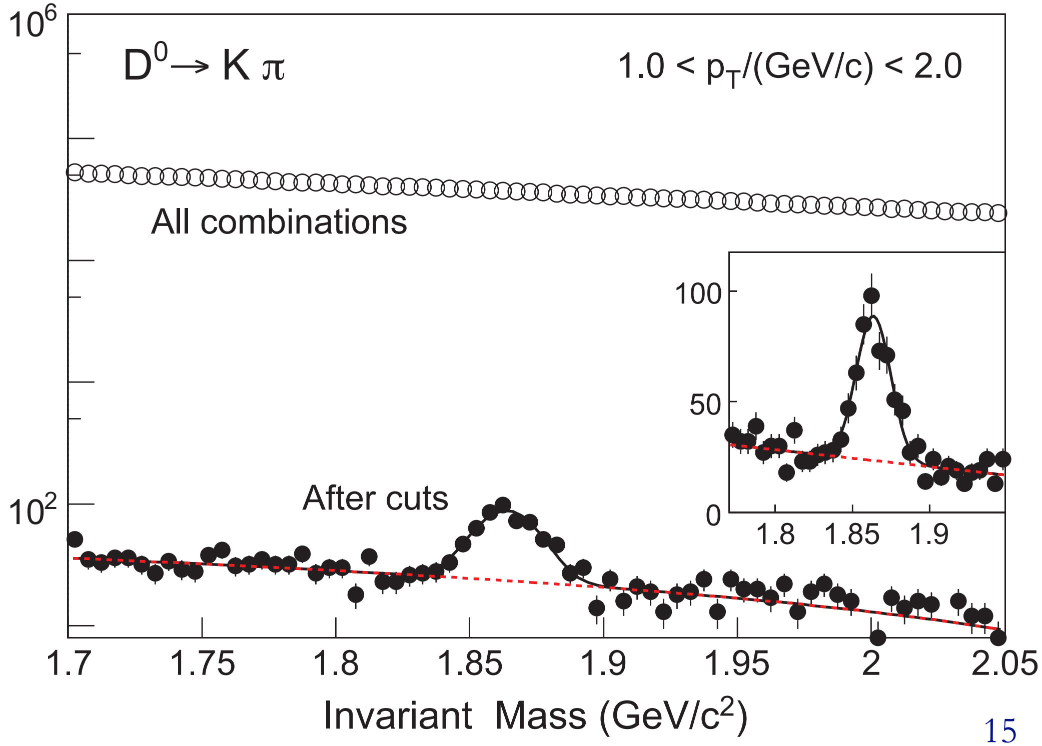
Reconstruction requires high resolution ($\delta x \sim c\tau/10$) Silicon detectors detectors

None of RHIC experiments has one - but soon will have



DCA: distance of closest approach

Simulation of STAR Heavy Flavor Tracker



Hermeticity

- A key factor in collider detectors
  - Goal of essentially complete event reconstruction
  - Discovery potential of missing momentum/energy now well established
  - Of course this due to manifestation of new physics via electroweak decays
- In heavy ion physics
  - $dN_{ch}/dy \sim 1000$

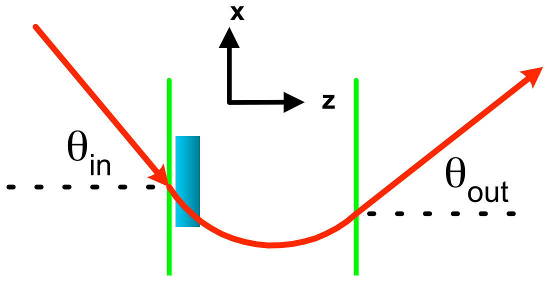
    ➡ exclusive event reconstruction “unfeasible”
  - But
    - Seeking to characterize a **state of <u>matter</u>**
    - Large numbers ➡ statistical sampling of phase space a valid approach

Magnetic Fields at RHIC

One way is: $\frac{dp^\mu}{d\tau} = \frac{e}{c} u_\nu F^{\mu\nu} \rightarrow \frac{d\vec{p}}{dt} = \frac{e}{c} \vec{v} \times \vec{B} \rightarrow \frac{d}{ds}\left(\frac{d\vec{r}}{ds}\right) = \frac{e}{c}\frac{d\vec{r}}{ds} \times \frac{\vec{B}}{|\vec{p}|}$

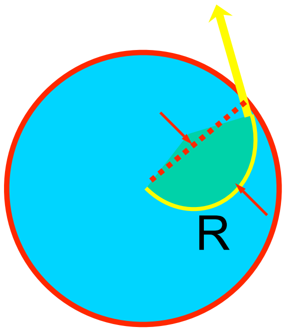
More useful: $p_T = 0.3 \cdot B \cdot R \, \frac{GeV/c}{T \cdot m}$

➡ 1 meter of 1 Tesla field deflects 1 GeV/c by ~17°

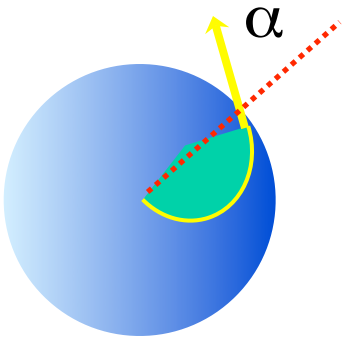


BRAHMS

PHOBOS



STAR



PHENIX

Real world: $\frac{\delta p}{p} = (\sim 1\%) \oplus (\sim 1\%) \times p$ [GeV/c]

~stuff in aperture

~spatial accuracy

RHIC experiments in a nutshell

BRAHMS

small experiment - 2 spectrometer arms
tiny acceptance $\Delta\phi$, $\Delta\eta$, measures p_T, has PID
movable arms ⇒ large $\Delta\eta$ coverage

PHOBOS

small experiment - “tabletop”
(i) huge acceptance $\Delta\phi$, $\Delta\eta$, no p_T info, no PID
(ii) small acceptance ⇒ very low - low p_T, moderate PID

PHENIX

large experiment - 2 central arms + 2 muon arms
moderate acceptance central arms: $\Delta\phi = \pi$, $\Delta\eta = \pm 0.35$
leptons (muons in forward arms), photons, hadrons

STAR

large experiment
large acceptance (barrel): $\Delta\phi = 2\pi$, $\Delta\eta = \pm 1$ + forward
hadrons, jets, leptons, photons

RHIC experiments in a nutshell

BRAHMS Decommissioned

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BRAHMS

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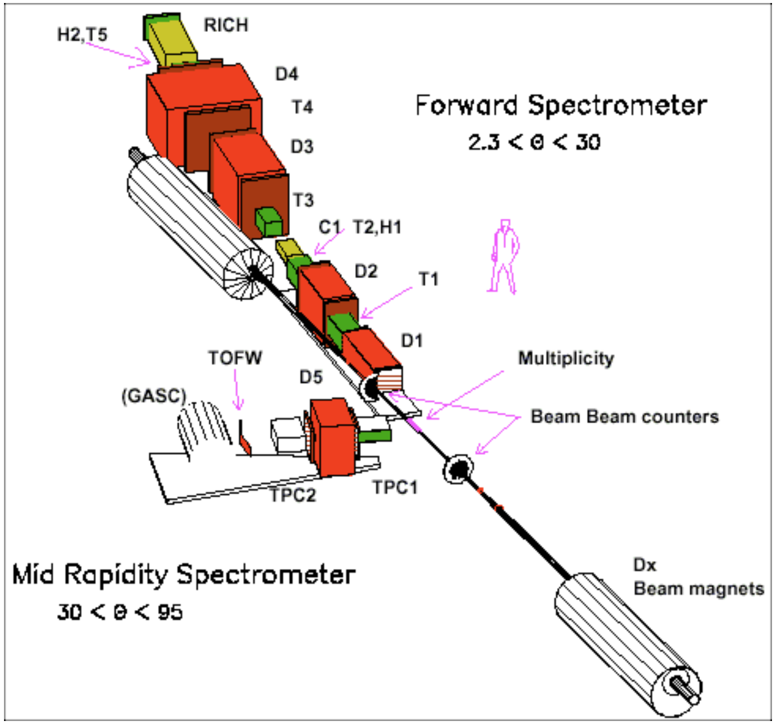
The Two “Small” Experiments at RHIC

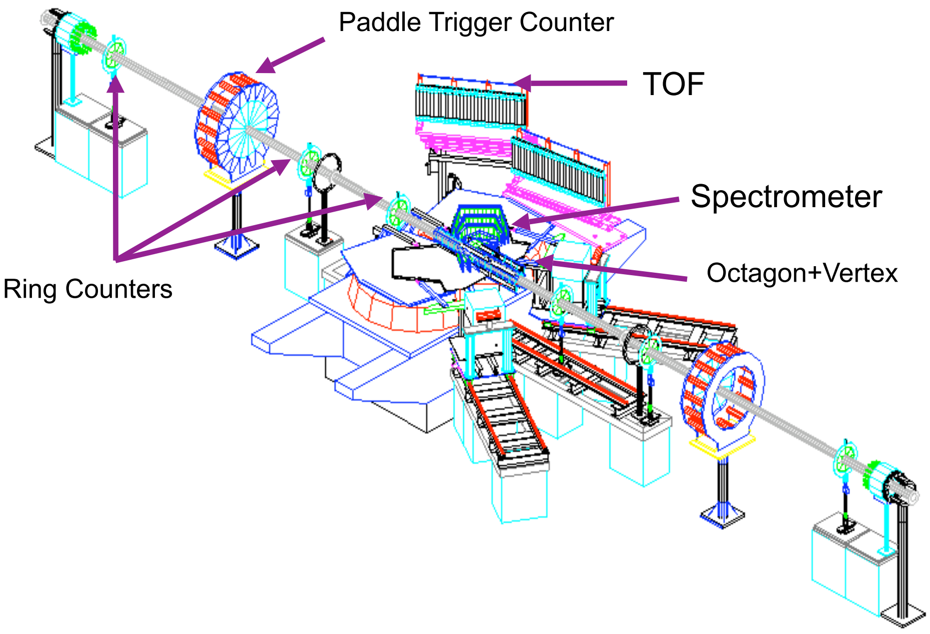
BRAHMS

2 “Conventional” Spectrometers
Magnets, Tracking Chambers, TOF, RICH, ~40 Participants

PHOBOS

“Table-top” 2 Arm Spectrometer
Magnet, Si μ-Strips, Si Multiplicity Rings, TOF, ~80 Participants





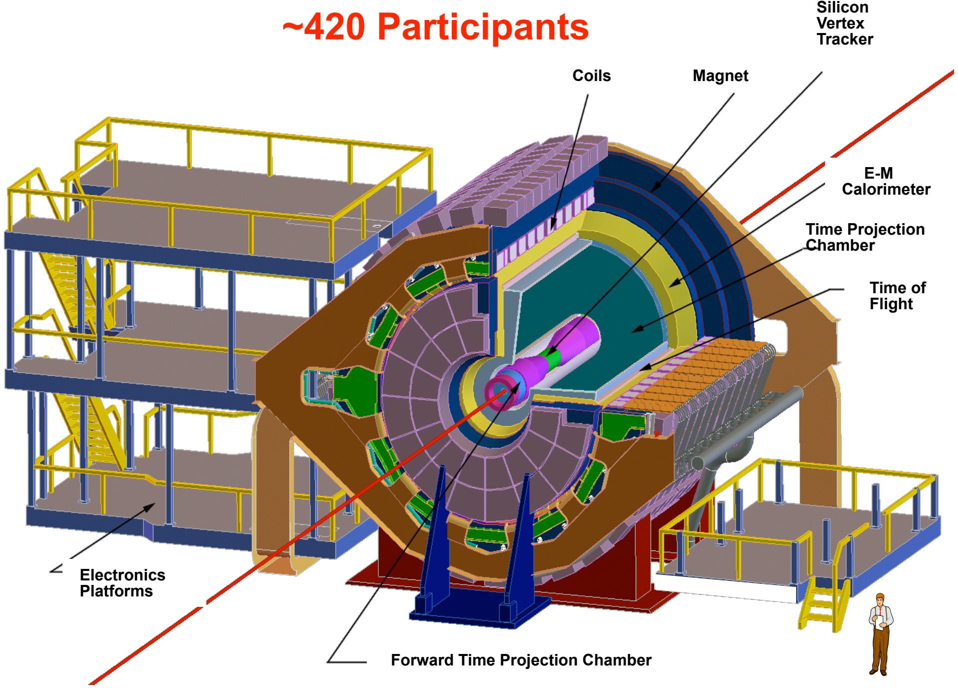
- **Inclusive Particle Production Over Large Rapidity Range**

- **Charged Hadrons in Select Solid Angle**
- **Multiplicity in 4π**
- **Particle Correlations**

The Two “Large” Detectors at RHIC

STAR

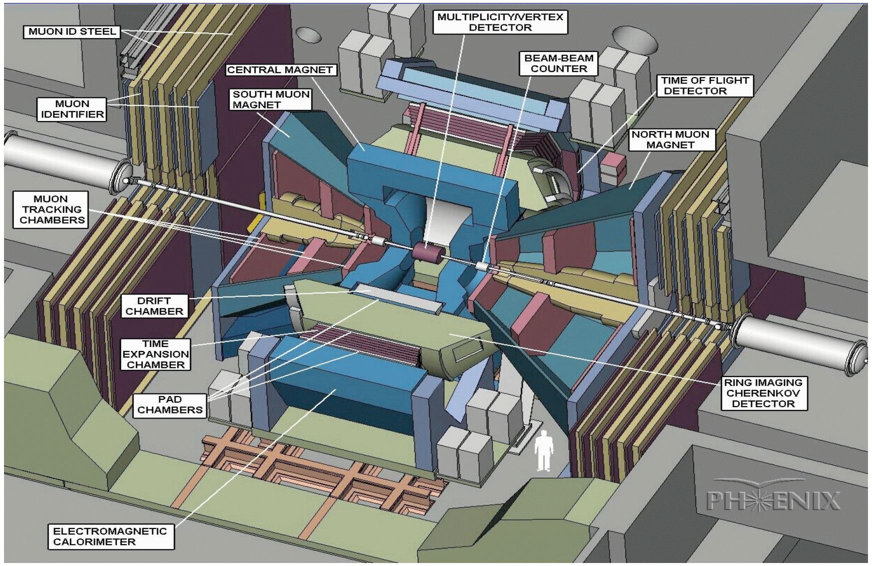
Solenoidal field
Large-Ω Tracking
TPC’s, Si-Vertex Tracking
RICH, EM Cal, TOF
~420 Participants



- **Measurements of Hadronic Observables using a Large Acceptance**
- **Event-by-Event Analyses of Hadrons and Jets, Forward physics, Leptons, Photons**

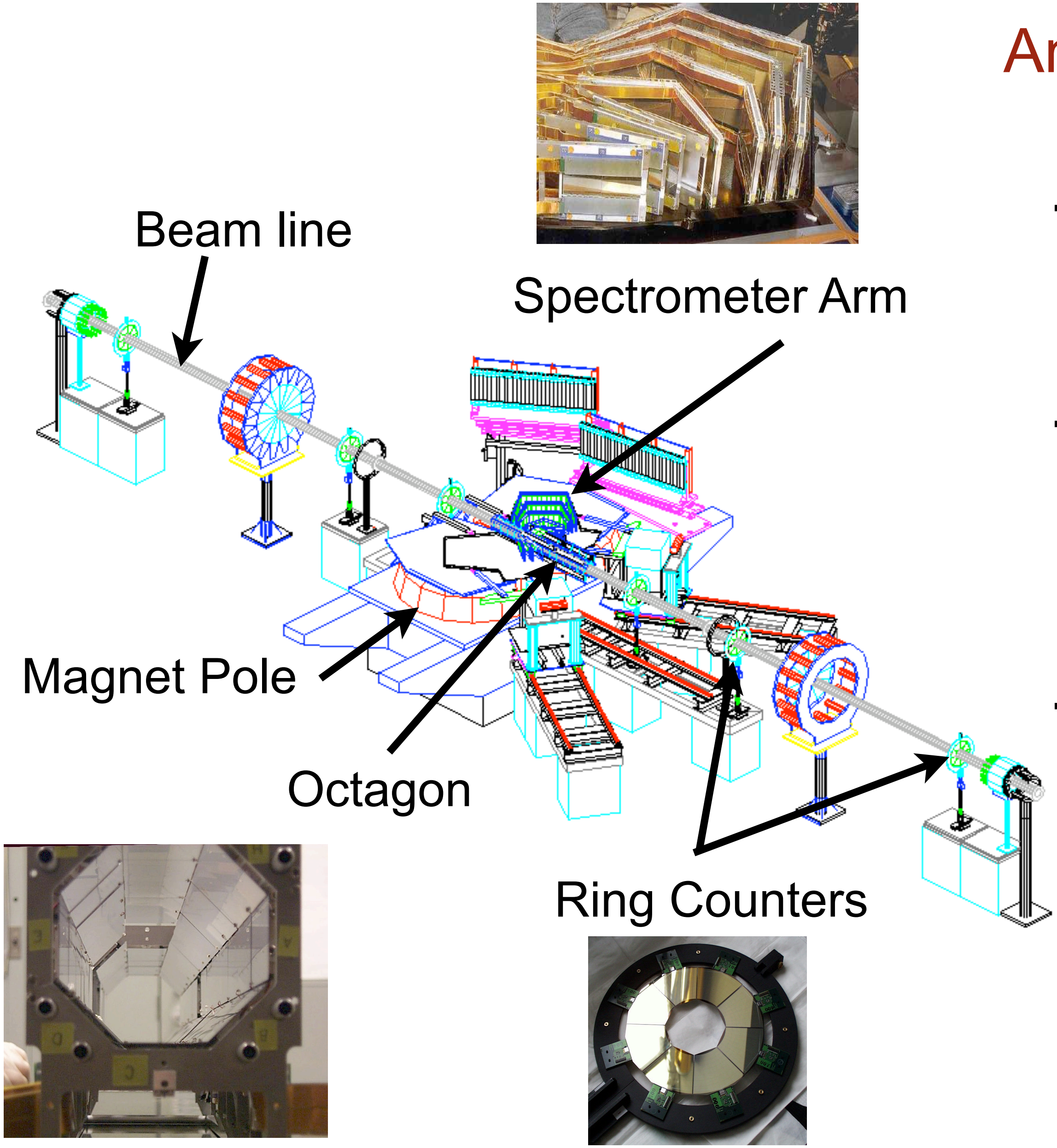
PHENIX

Axial Field
High Resolution & Rates
2 Central Arms, 2 Forward Arms
TEC, RICH, EM Cal, Si, TOF, μ-ID
~450 Participants



- **Leptons, Photons, and Hadrons in Selected Solid Angles**
- **Simultaneous Detection of Various Phase Transition Phenomena**

PHOBOS



An experiment with a philosophy:

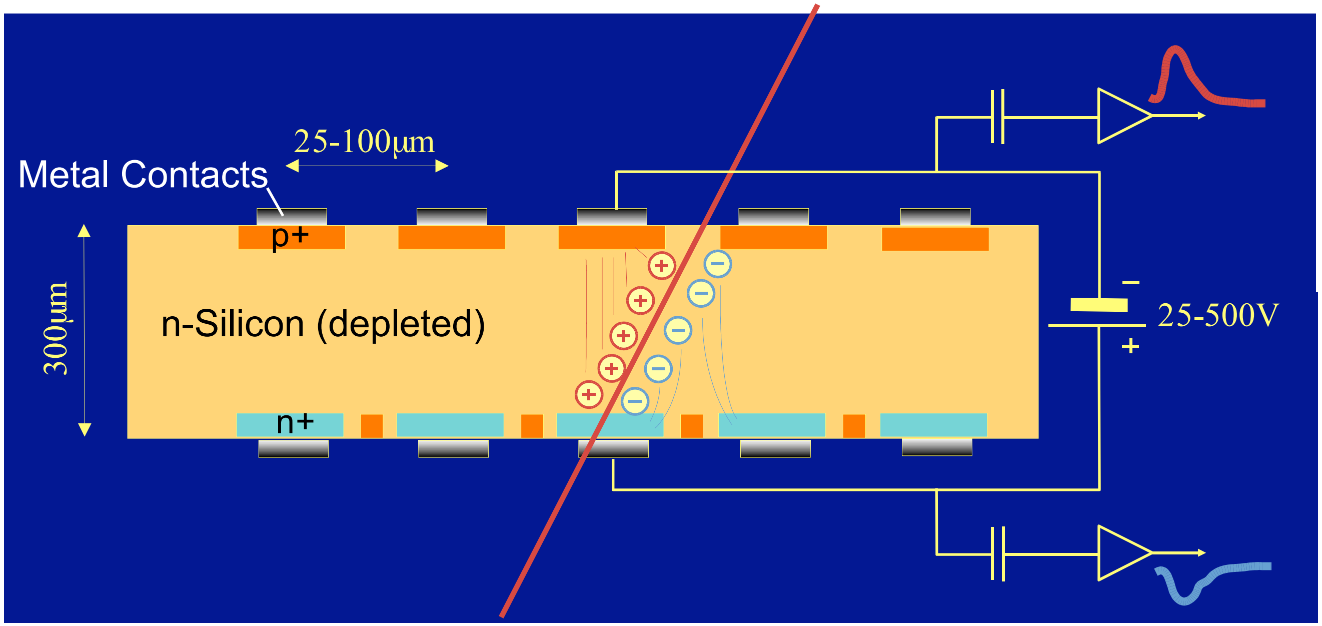
- Global phenomena
  - ➡large spatial sizes
  - ➡small momenta
- Minimize the number of technologies:
  - ▸ Si-strip for tracking
  - ▸ Si-pad for multiplicity
- Unbiased global look at very large number of collisions (~10^9)

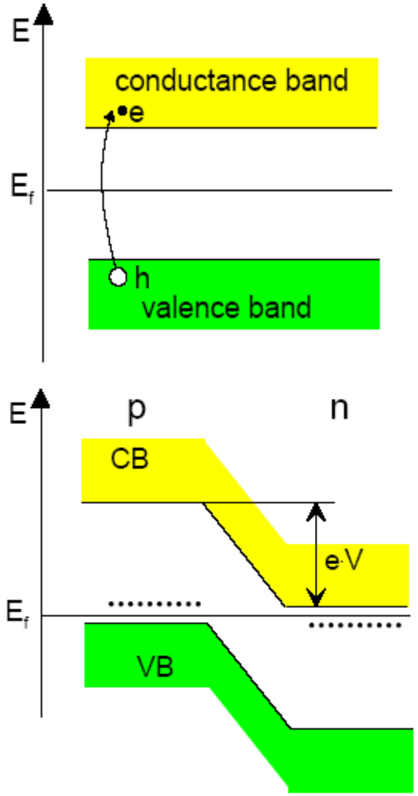
Silicon detectors in a nutshell

Basic motivation: charged particle position measurement

Use ionization signal left behind by charged particle passage

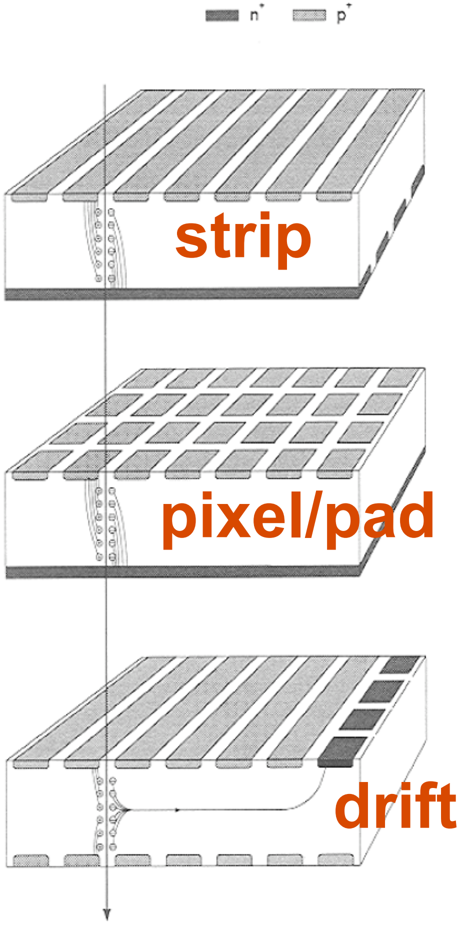
- Ionization produces electron-ion pairs, use an electric field to drift the electrons and ions to the oppositely charged electrodes.
- Si need 3.6 eV to produce one e-h pair. In pure Si, e-h pairs quickly recombine ⇒ n-doped (e carriers/donors) and p-doped (holes are carriers) silicon ⇒ p/n junction creates potential that prevents migration of charge carriers





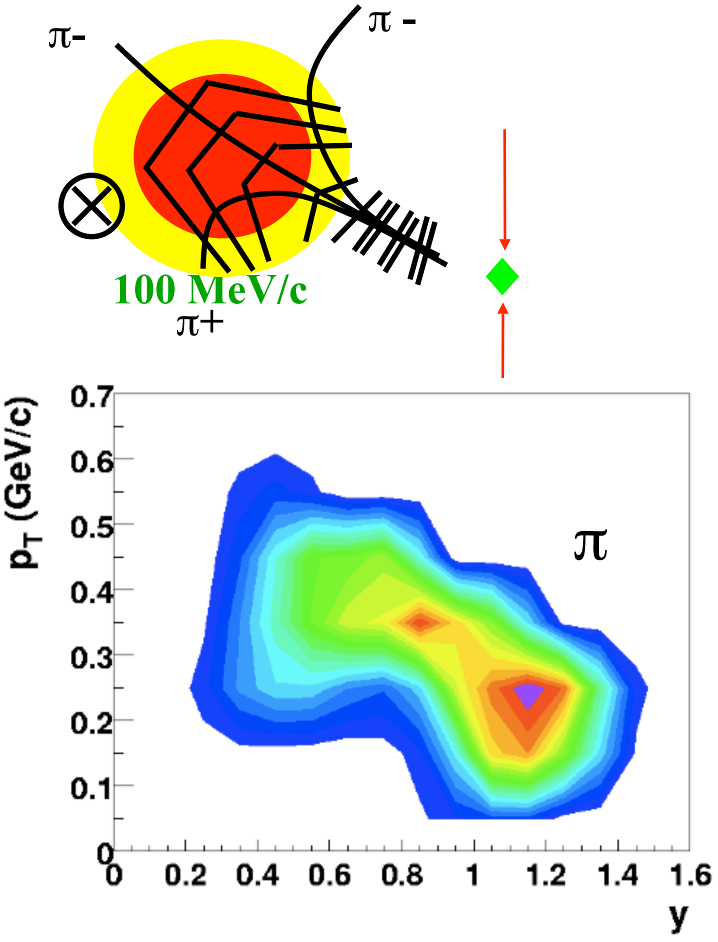
Types of silicon detectors

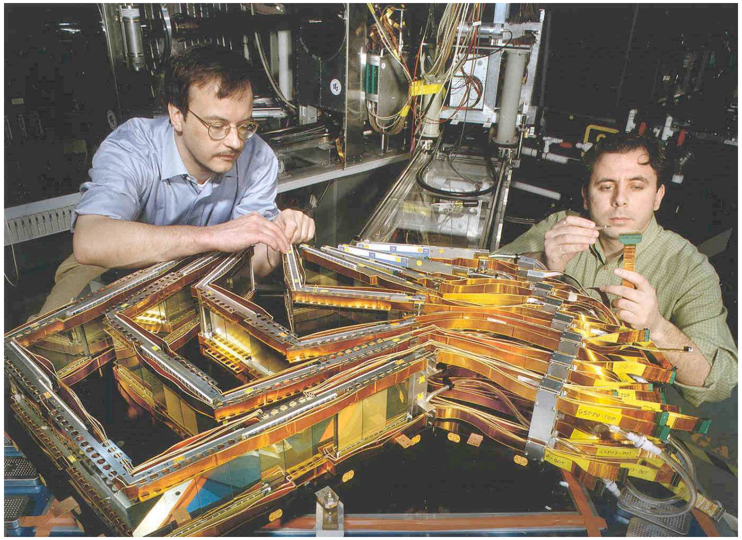
- Strip devices
  - High precision (< 5μm) 1D coordinate measurement
  - Large active area (up to 10cm x 10cm from 6” wafers)
  - Single-sided devices
  - 2nd coordinate possible (double-sided devices)
  - Most widely used silicon detector in HEP
- Pixel devices
  - True 2D measurement (20-400μm pixel size)
  - Small areas but best for high track density environment
- Pad devices (“big pixels or wide strips”)
  - Pre-shower and calorimeters
  - Multiplicity detectors
- Drift devices

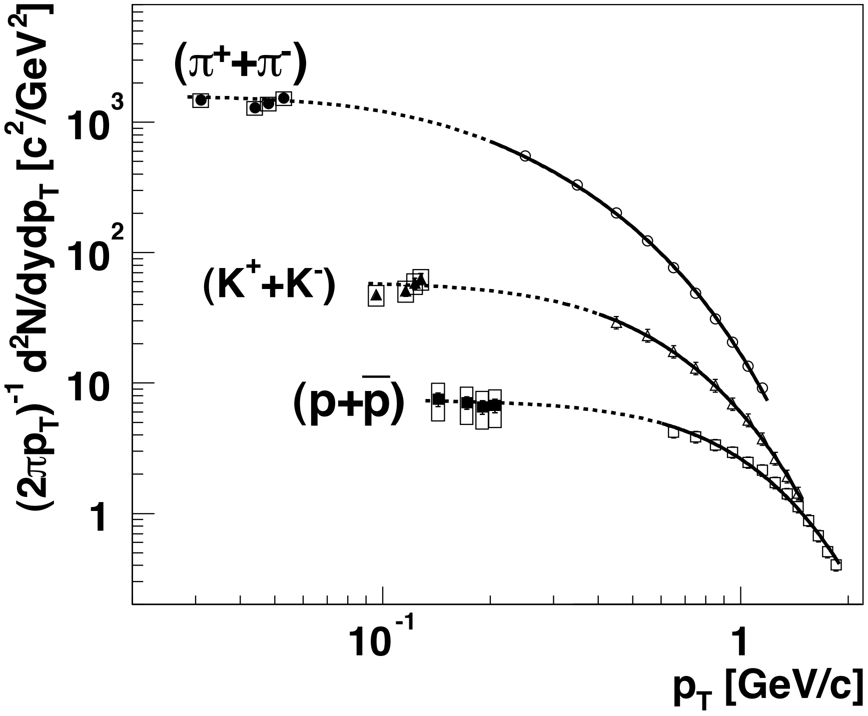


PHOBOS Spectrometer Arm

- Si Strip detectors
- Acceptance near <y> ~ 0.5
- low - very low-p_T spectra

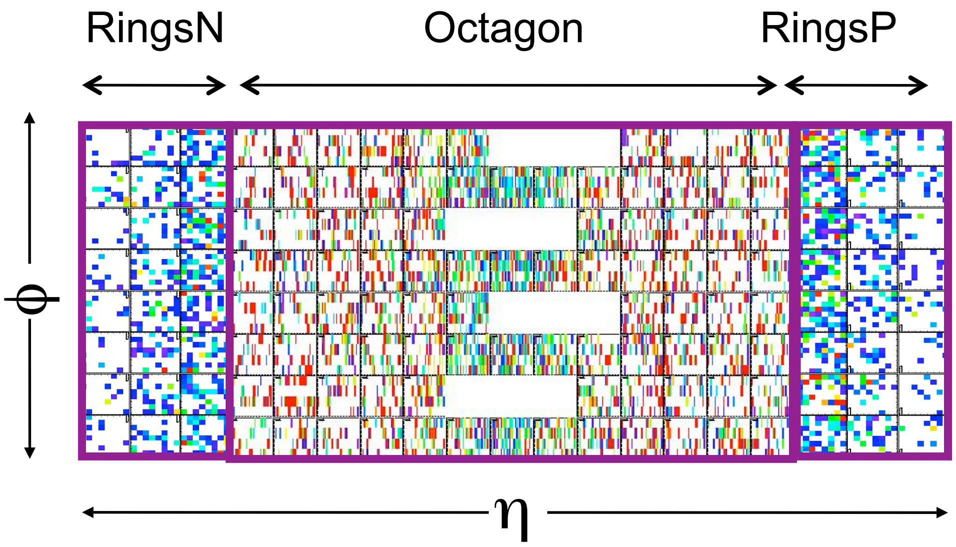


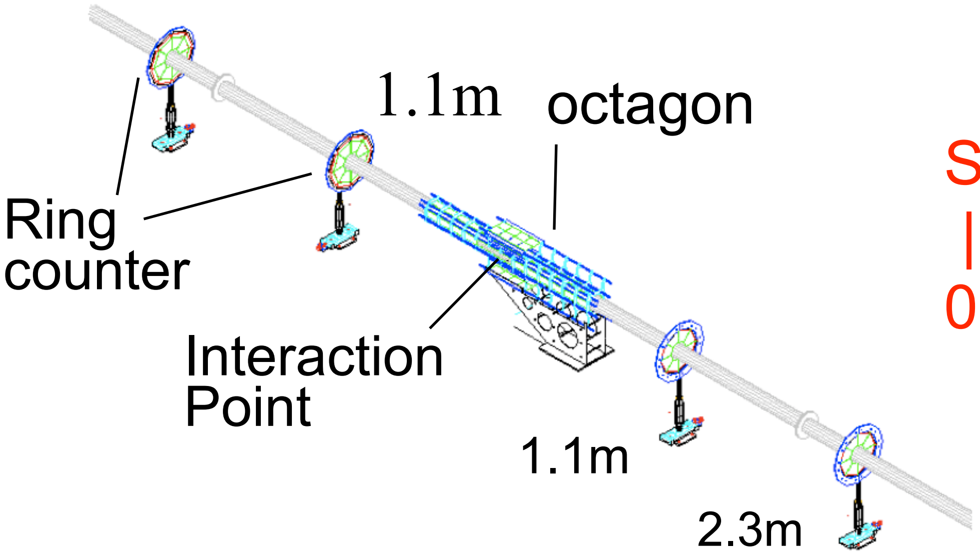


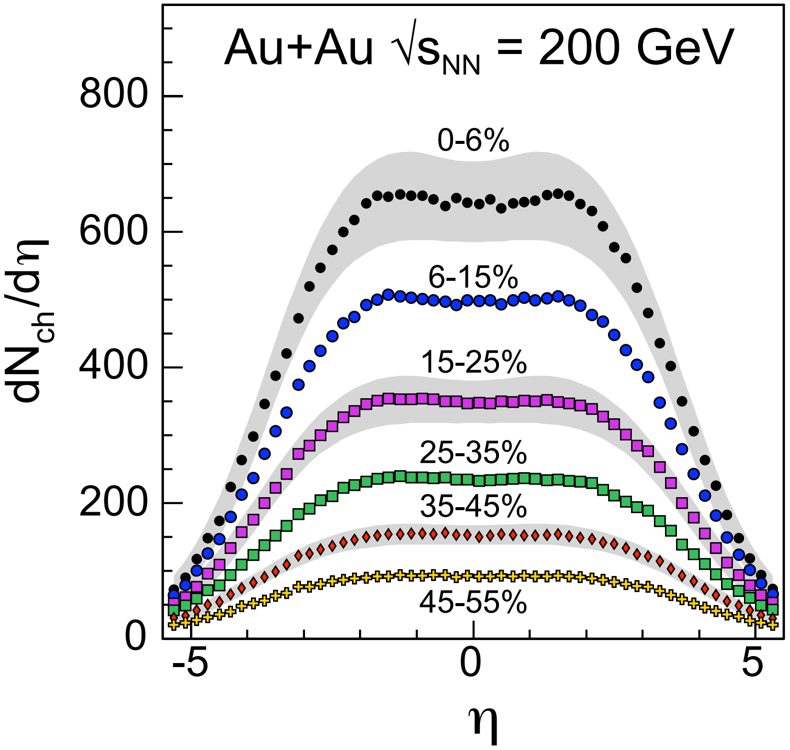


PHOBOS: Multiplicity in (almost) 4 π

"Unroll" the octagon and rings





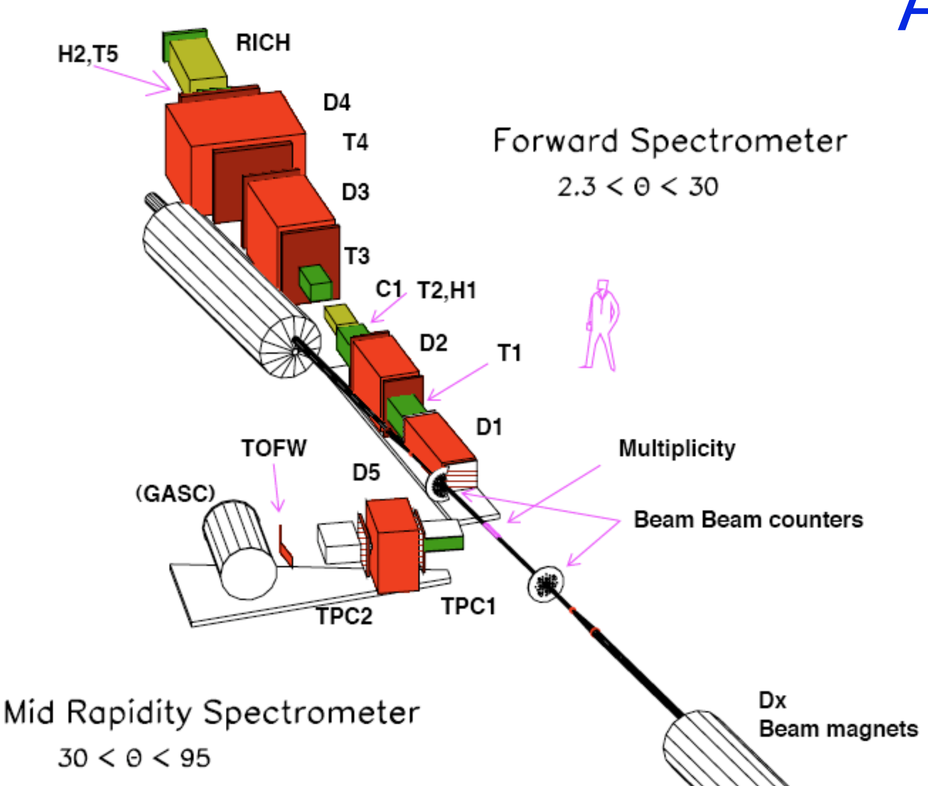


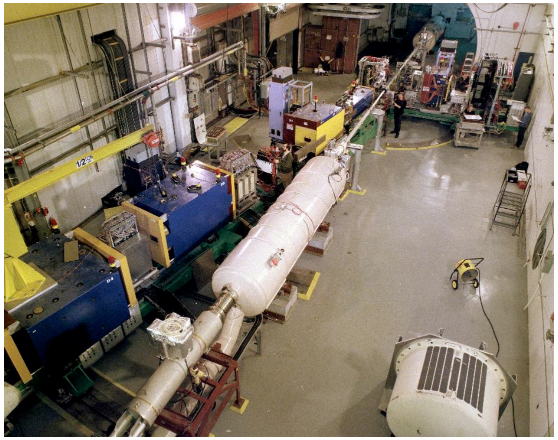
Si Strip detector coverage:

$|\eta| < 5.3$ ($\Delta\eta = 0.05-0.1$),

$0 \le \varphi \le 2\pi$ ($\Delta\varphi = 2\pi/32 - 2\pi/64$)

BRAHMS

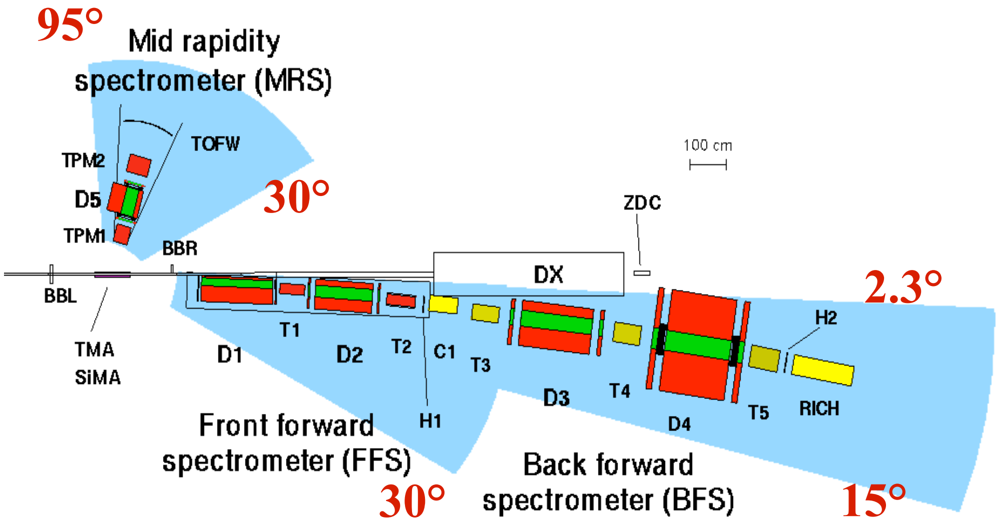


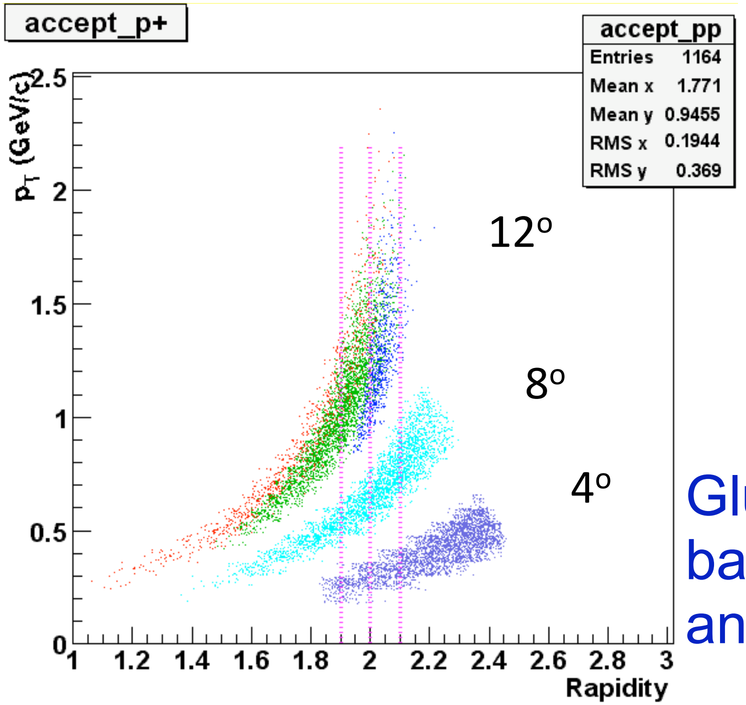


An experiment with an emphasis:

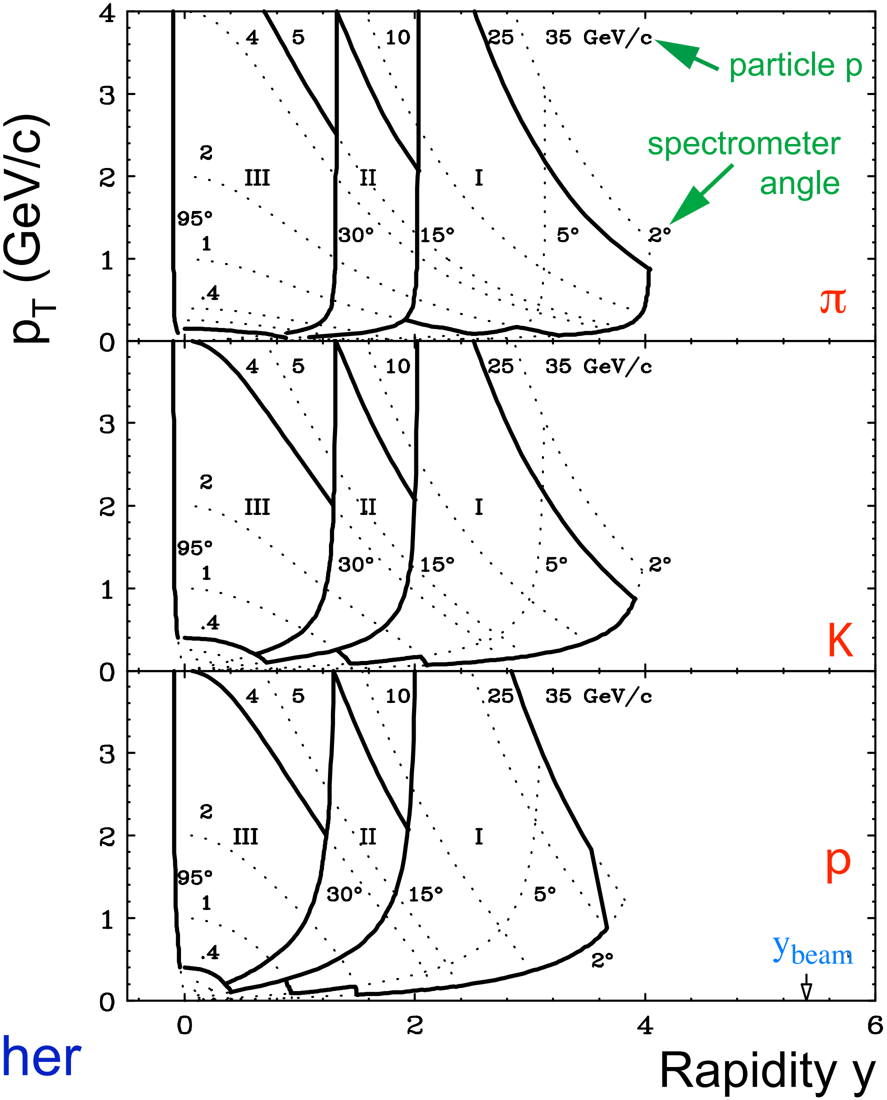
- Quality PID spectra over a broad range of rapidity and p_T
- Special emphasis:
  - Where do the baryons go?
  - How is directed energy transferred to the reaction products?
  - Low-x, R_{AA} at large η
- Two magnetic dipole spectrometers in “classic” fixed-target configuration

BRAHMS Acceptance Moves Around





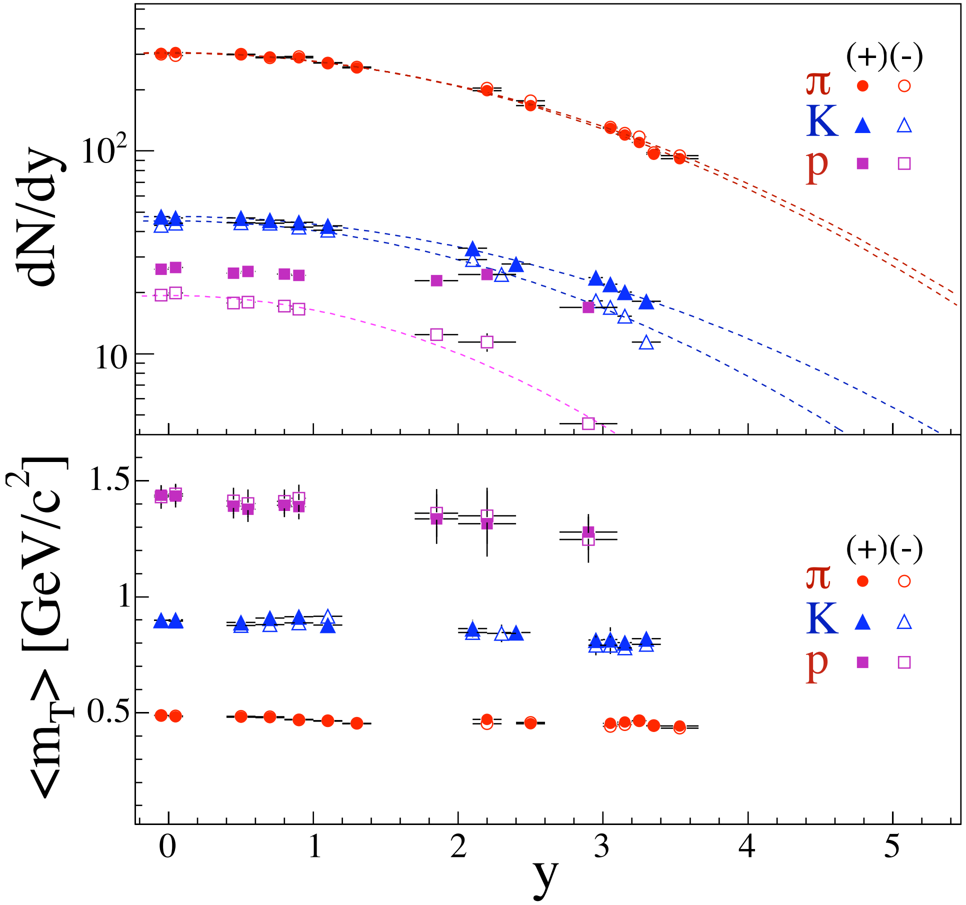
Gluing together bananas is not an easy task

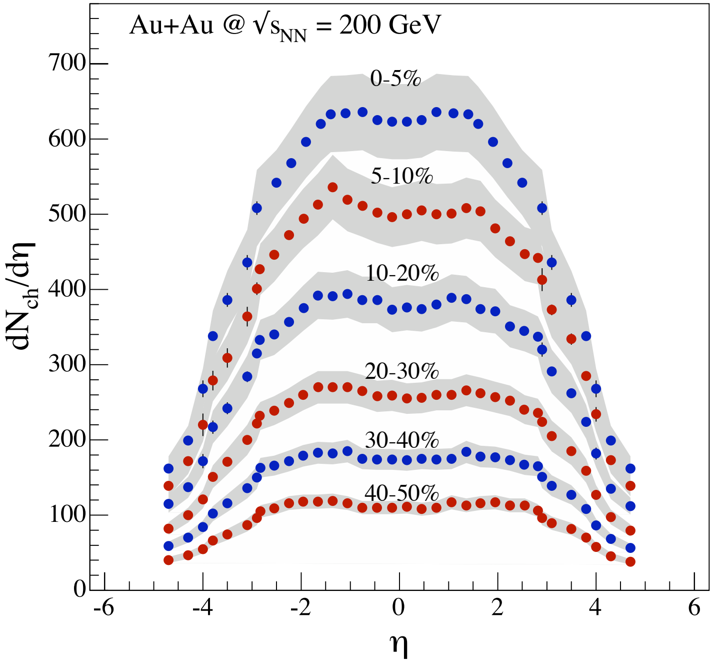


Region I : With the full Forward Arm
Region II : With the Forward Arm alone
Region III : With the Mid-Rapidity Arm

BRAHMS Features

- Combination of
  - Tracking
  - Time-of-Flight
  - Cerenkov
- provides
  - broad PID in y-pT
- Small dipole apertures
  - narrow in φ

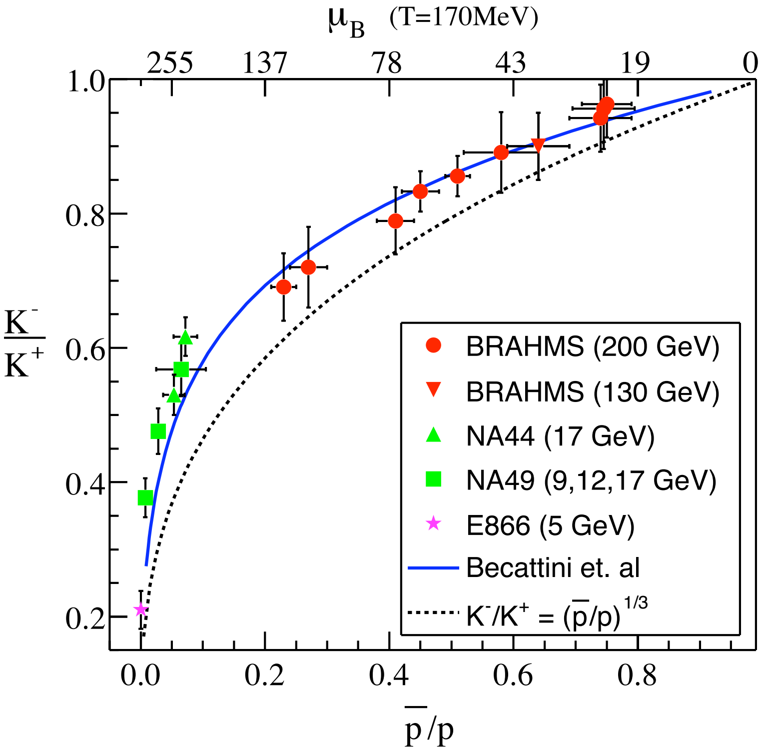


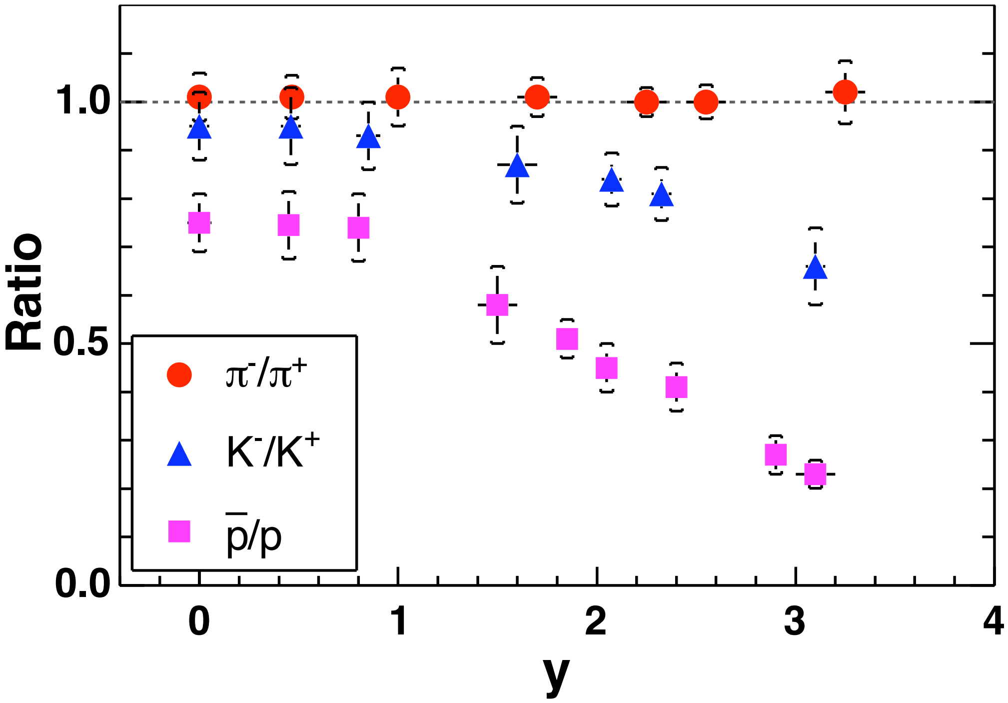


⇐ Recall the PHOBOS plot ?

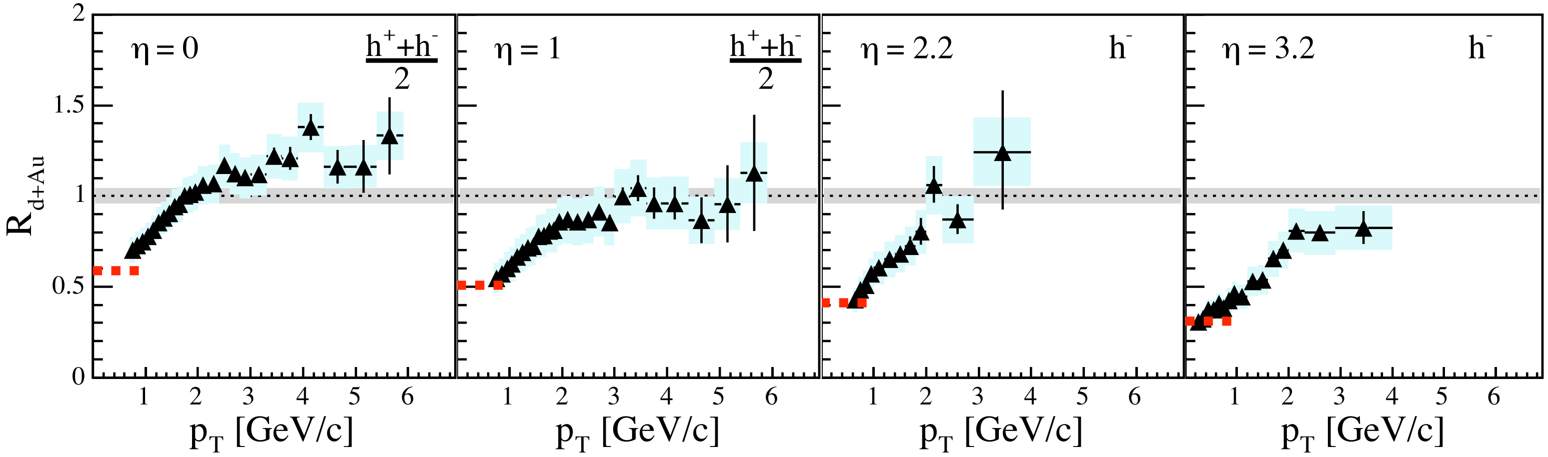
BRAHMS did the same using many different spectrometer settings while PHOBOS did it in “one” go. Result is the (almost) same.

BRAHMS Strength: forward rapidities



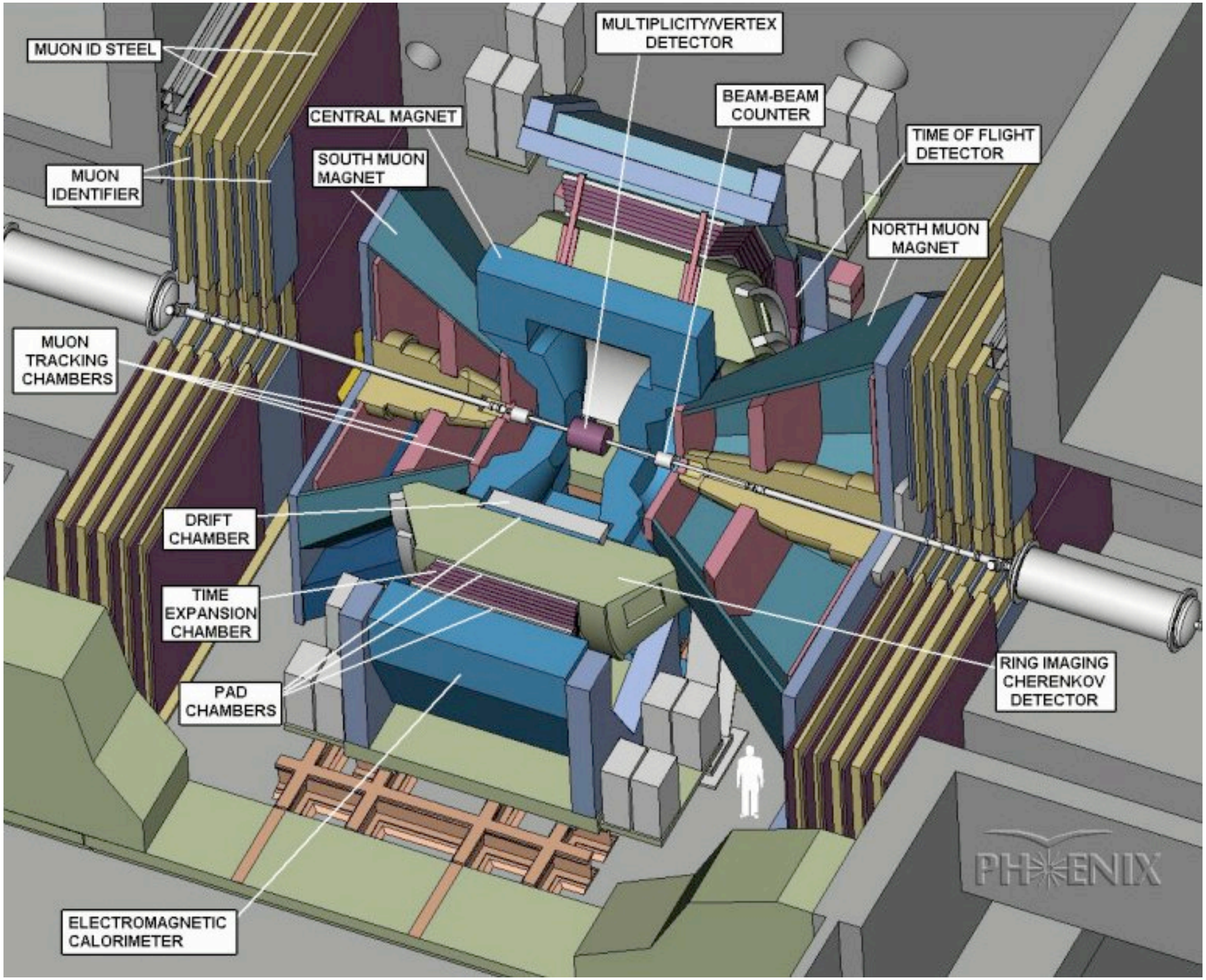


The Color Glass Condensate Plot



PHENIX

- An experiment with something for everybody
  - Muons
  - Electrons
  - Photons
  - Hadrons
- Features
  - High resolution
  - High granularity
  - High data taking rate
  - Moderate acceptance



PHENIX (1999)

PHENIX Components

Charged Particle Tracking:

Drift Chamber
Pad Chamber
Time Expansion Chamber/TRD
Cathode Strip Chambers(Mu Tracking)
Forward Muon Trigger Detector
Si Vertex Tracking Detector- Barrel
Si Vertex Endcap (mini-strips)

Particle ID:

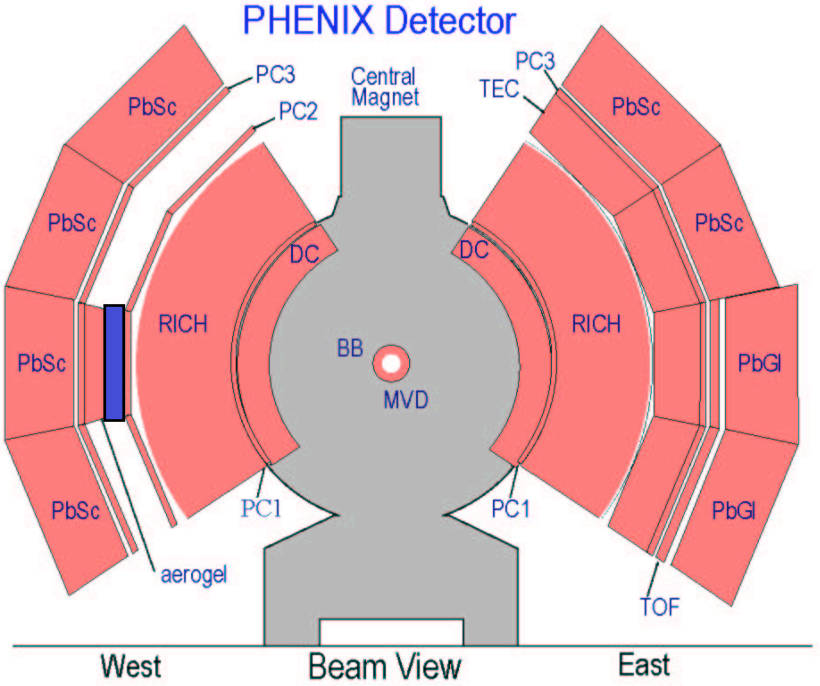
Time of Flight
Ring Imaging Cerenkov Counter
TEC/TRD
Muon ID (PDT's)
Aerogel Cerenkov Counter
Multi-Gap Resistive Plate Chamber ToF
Hadron Blind Detector

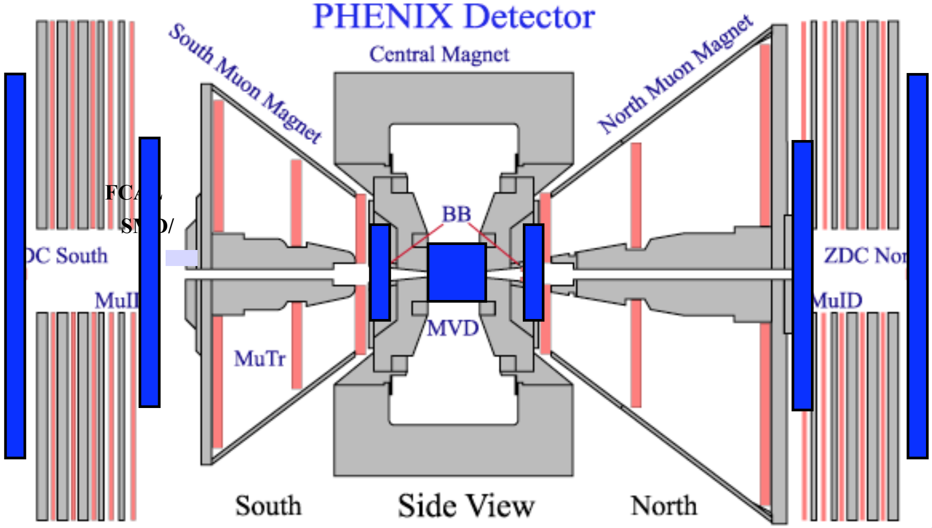
Calorimetry:

Pb Scintillator
Pb Glass
Nose Cone Calorimeter
Muon Piston Calorimeter

Event Characterization:

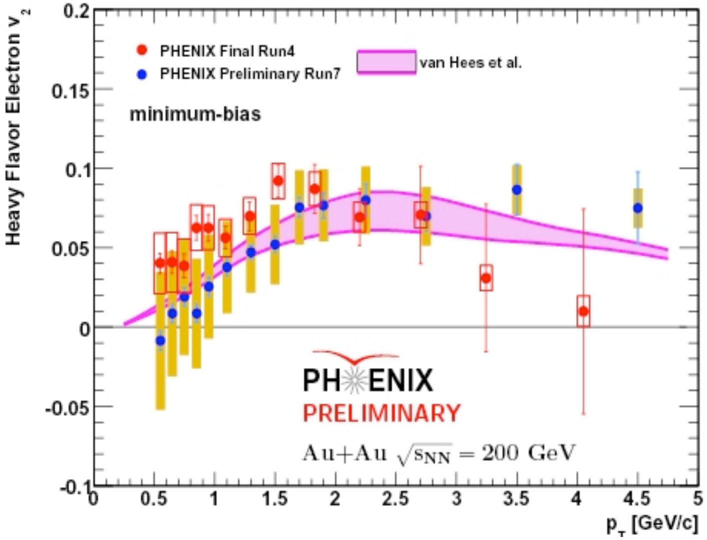
Beam-Beam Counter
Zero Degree Calorimeter/Shower Max Detector
Forward Calorimeter
Reaction Plane Detector

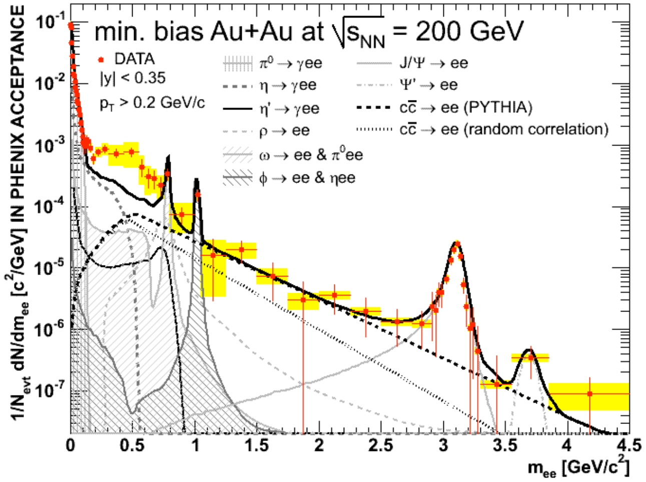


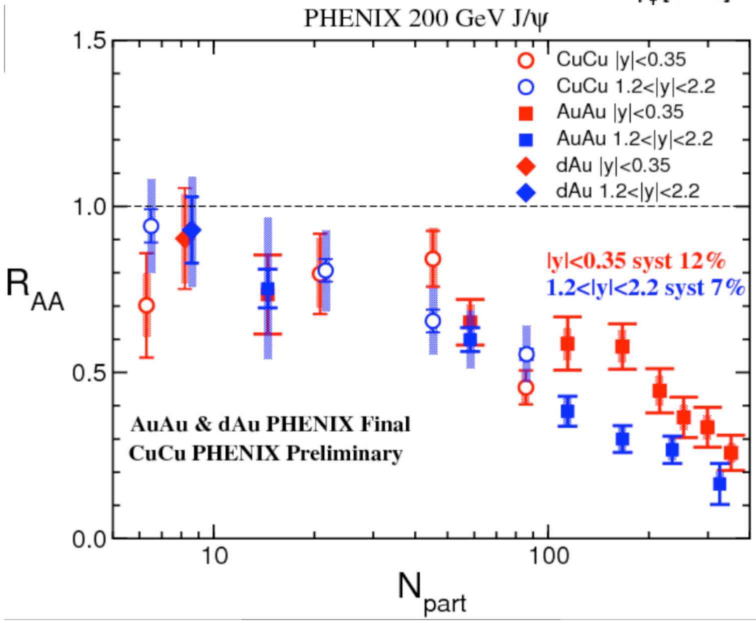


Why emphasis on electrons?

- Open heavy flavor production, flow, suppression
  - $D^0 \to e$ + anything (BR=6.7%)
  - $D^\pm \to e$ + anything (BR=17.2%)
  - $B^\pm \to e$ + anything (BR=10.9%)
  - $B^0 \to e$ + anything (BR=10.4%)
- Quarkonia suppression
  - $J/\psi, \psi', \chi_c, \Upsilon, \Upsilon', \Upsilon'' \to e^+e^-$
- Chiral symmetry restoration
  - $\rho \to e^+e^-$

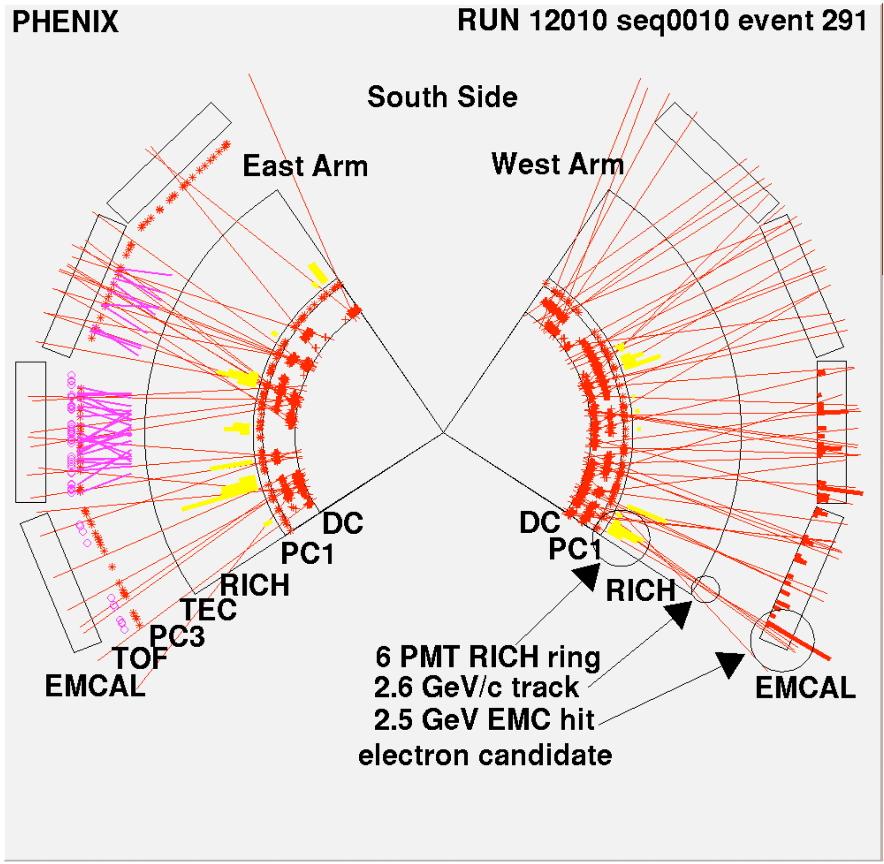


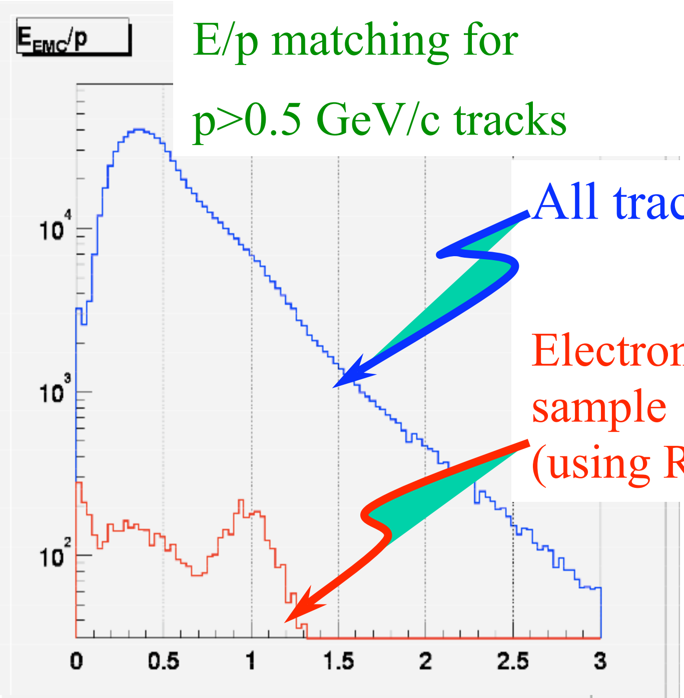




Electron Identification

- Problem: They’re **rare**
- Solution: Multiple methods
  - Čerenkov(RHIC)
  - E(Calorimeter)/p(tracking) matching

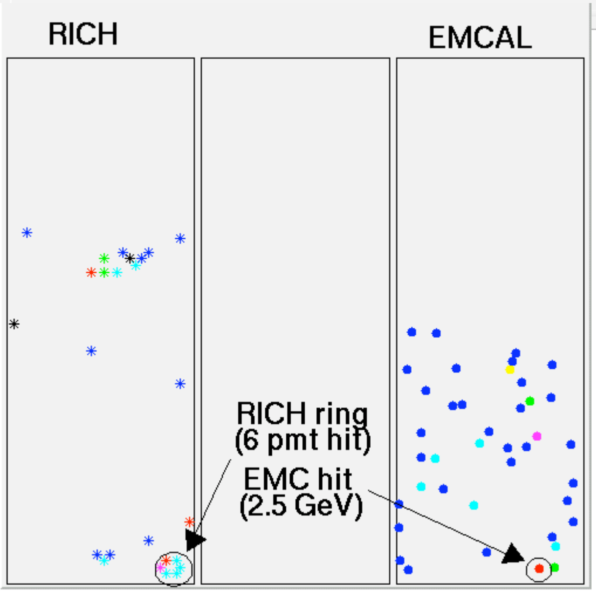




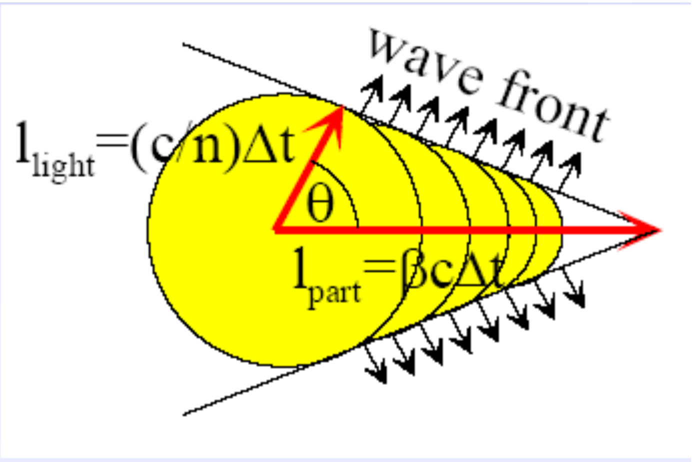
E/p matching for p>0.5 GeV/c tracks

All tracks

Electron enriched sample (using RICH)



Cherenkov (Čerenkov) detectors

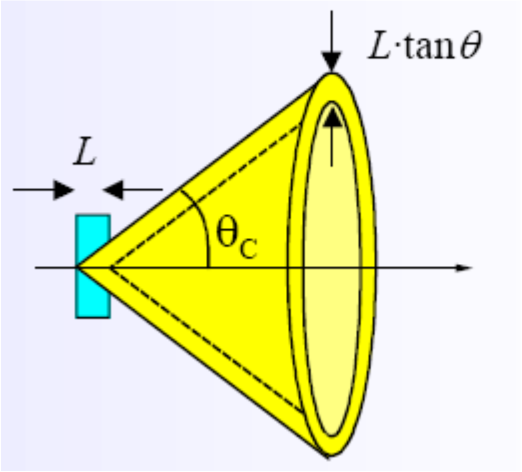


Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity

$\beta \geq \beta_{thr}=1/n$ n: refractive index

may emit light along a conical wave front.

$$\cos\theta_C = \frac{1}{n\beta}$$

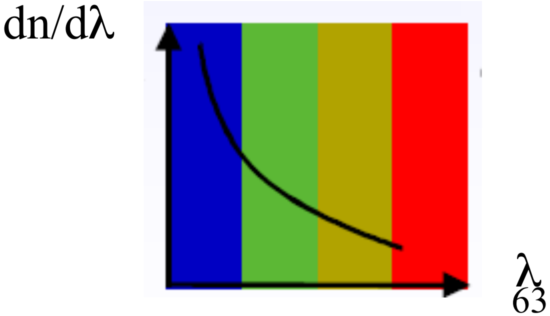


Energy loss by Cherenkov radiation small compared to ionization (≈0.1%). Cherenkov effect is a very weak light source,→need highly sensitive photodetectors.

Number of detected photo electrons: $N_{pe}= N_0\,L\,\sin^2\theta$

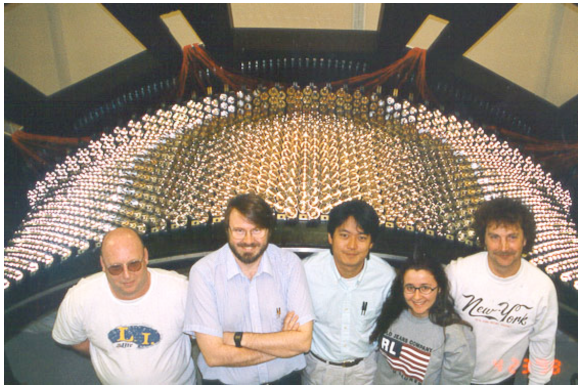
N_0: number of merit for a Cherenkov detector

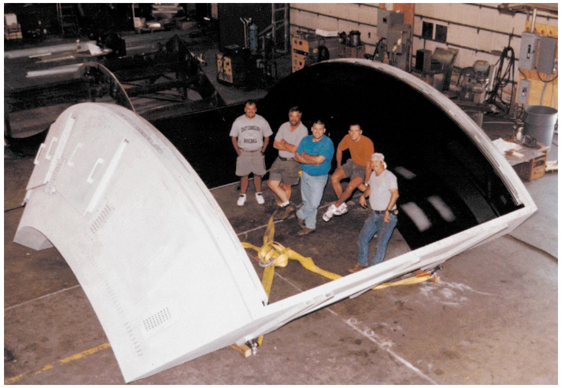
medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

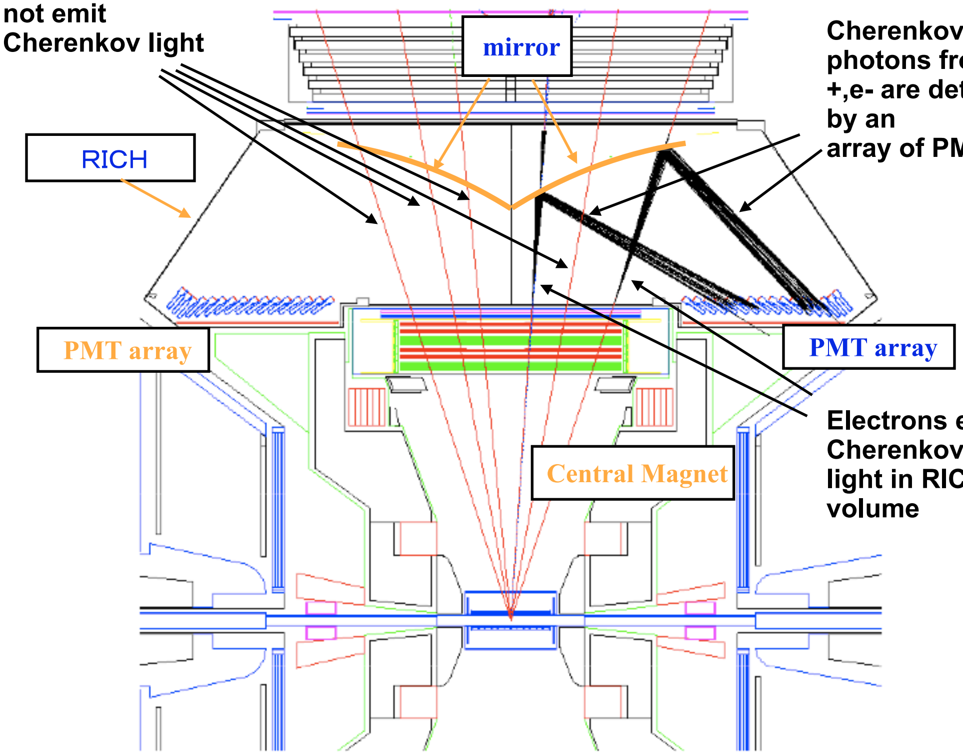


PHENIX PID via Cherenkov

- Key Features:
  - Ring imaging Cherenkov with gaseous radiator
  - Radiator gas:
    - ethane (n = 1.00082)
    - or methane (n = 1.00044)
  - Electron identification efficiency:
    Close to 100% for a single electron with momentum less than ~ 4 GeV/c
  - Pion rejection factor:
    > 10^3 for a single charged pion with momentum < 4 GeV/c
  - Limit: 5 GeV/c $\Rightarrow R_e \cong R_\pi$
  - Two ring separation:
    ~ few degrees in both θ and φ







Most hadrons do not emit Cherenkov light

Cherenkov photons from e+,e- are detected by an array of PMTs

Electrons emit Cherenkov light in RICH gas volume

Calorimeter in a nutshell

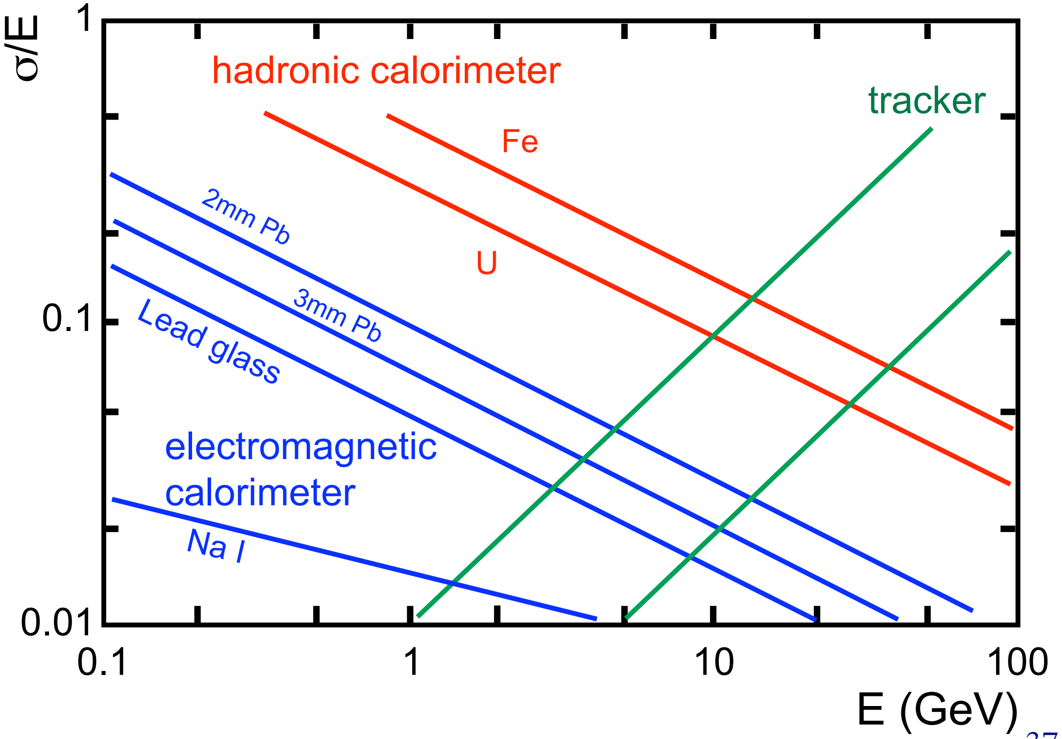
Calorimetry= Energy measurement by total absorption, usually combined with spatial reconstruction.

Tracking in B field: $\delta p/p \propto p_T/L^2$
⇒ resolution degrades with increasing energy (unless $L \propto \sqrt{E}$)
also: works only for charged particles

Calorimetry: $\delta E/E \propto 1/\sqrt{E}$

⇒ for high energy detectors calorimeters are essential components

RHIC: only EMcals



Calorimeters in a nutshell

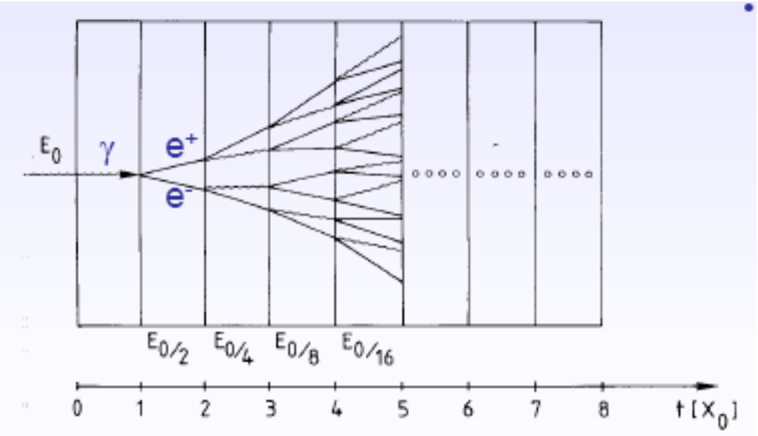
- EM Shower
  - above 10 MeV (γ, e)
  - pair production: $\gamma \rightarrow e^+e^-$
  - bremsstrahlung: $e \rightarrow e\,\gamma$
  - characterized by radiation length X_0
  - longitudinal:
    - $dE/dt \sim t^{\alpha} e^{-t}$ where $t = x/X_0$
    - shower maximum
  - transverse:
    - 95% of shower in cylinder with 2 R_M (Moliere radius)
    - $R_M \sim X_0$ typical R_M = 1-2 cm
- Resolution

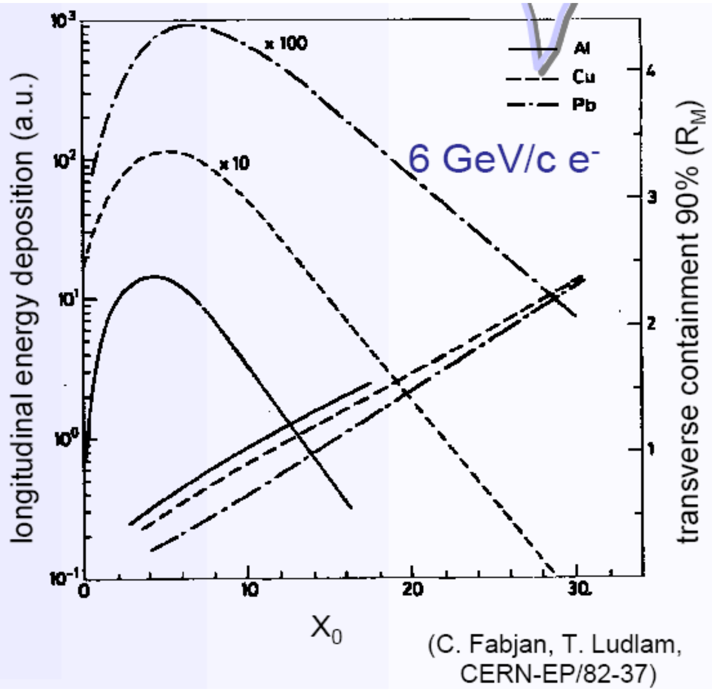
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

stochastic term

constant term

noise term



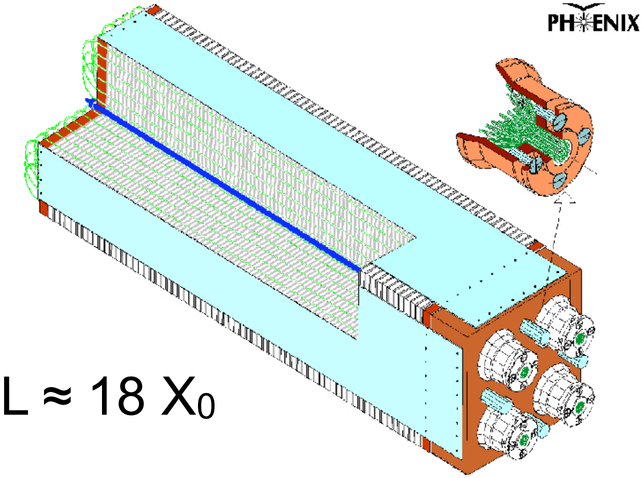


(C. Fabjan, T. Ludlam, CERN-EP/82-37)

Two PHENIX Calorimeters

PbSc Calorimeter

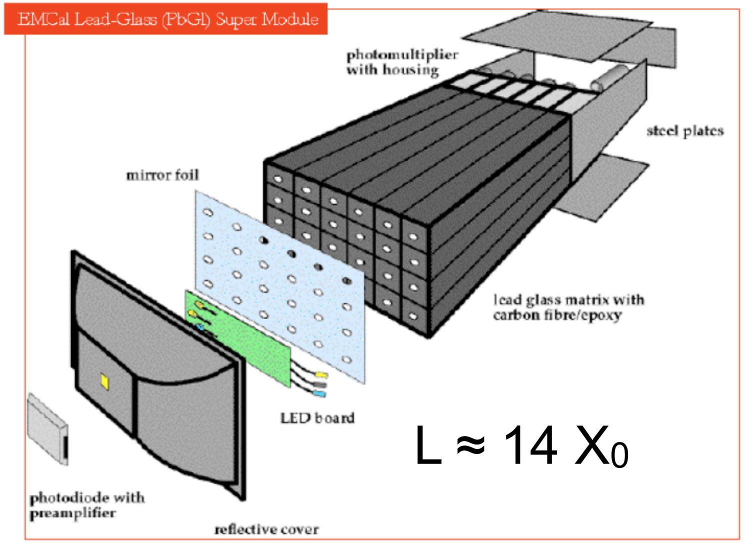
Lead-scintillator sandwich (sampling)
Wavelength-shifting fiber light transport
Photomultiplier readout



L ≈ 18 X_0

PbGl Calorimeter

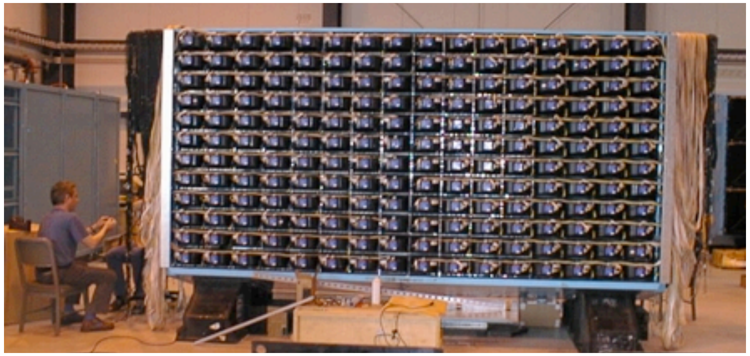
Lead-glas scintillator array
re-used WA80/WA98 calorimeter
Photomultiplier readout



L ≈ 14 X_0

PbSc: $\sigma(E)/E \approx 8\%/\sqrt{E}$

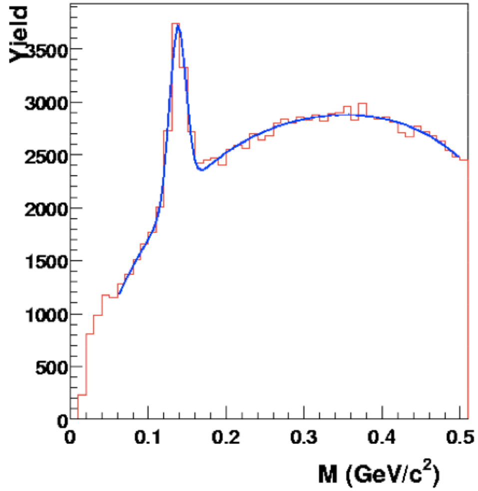
PbGl: $\sigma(E)/E \approx 6\%/\sqrt{E}$

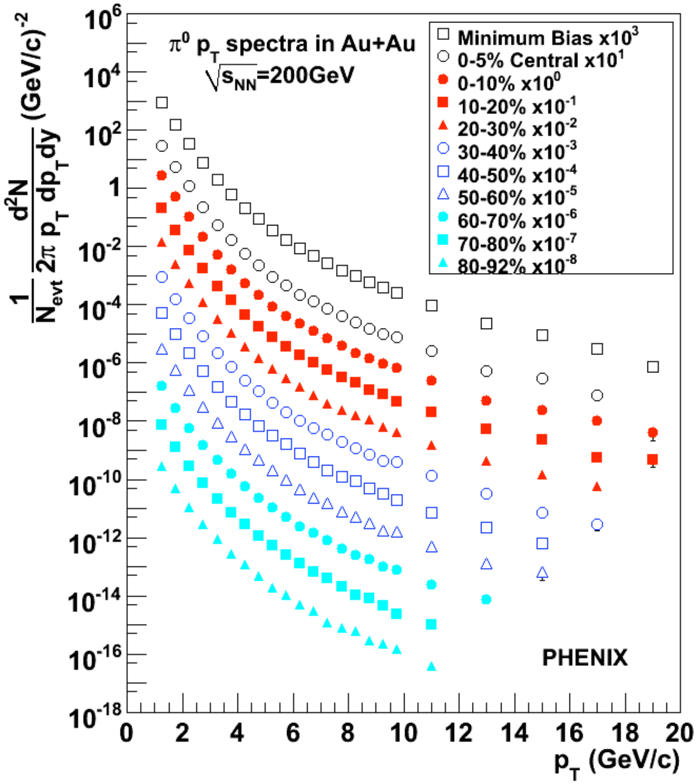


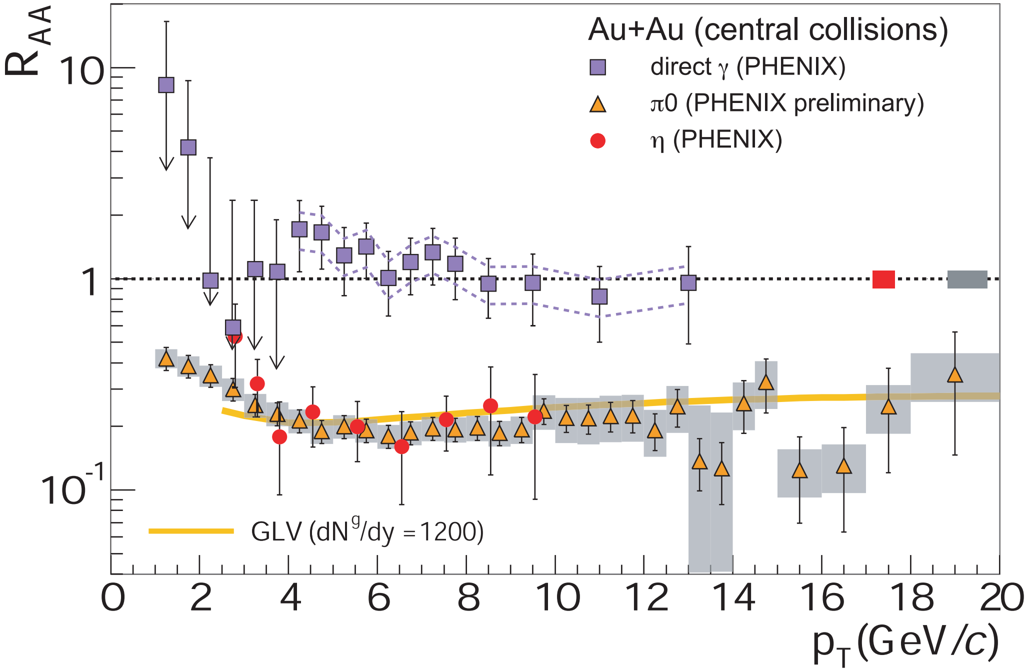
PHENIX calorimeter highlights: π^0

- Measured via $\pi^0 \to \gamma\gamma$ decay (invariant mass)
- Unfortunately, nature doesn't use *subscripts* on photons
- With n photons in an event, ~$n^2/2$ combinations, most fake ⇒ "combinatorial background"
- "event mixing" to get rid of it

π^0 mass spectra for $p_T > 2$ GeV/c

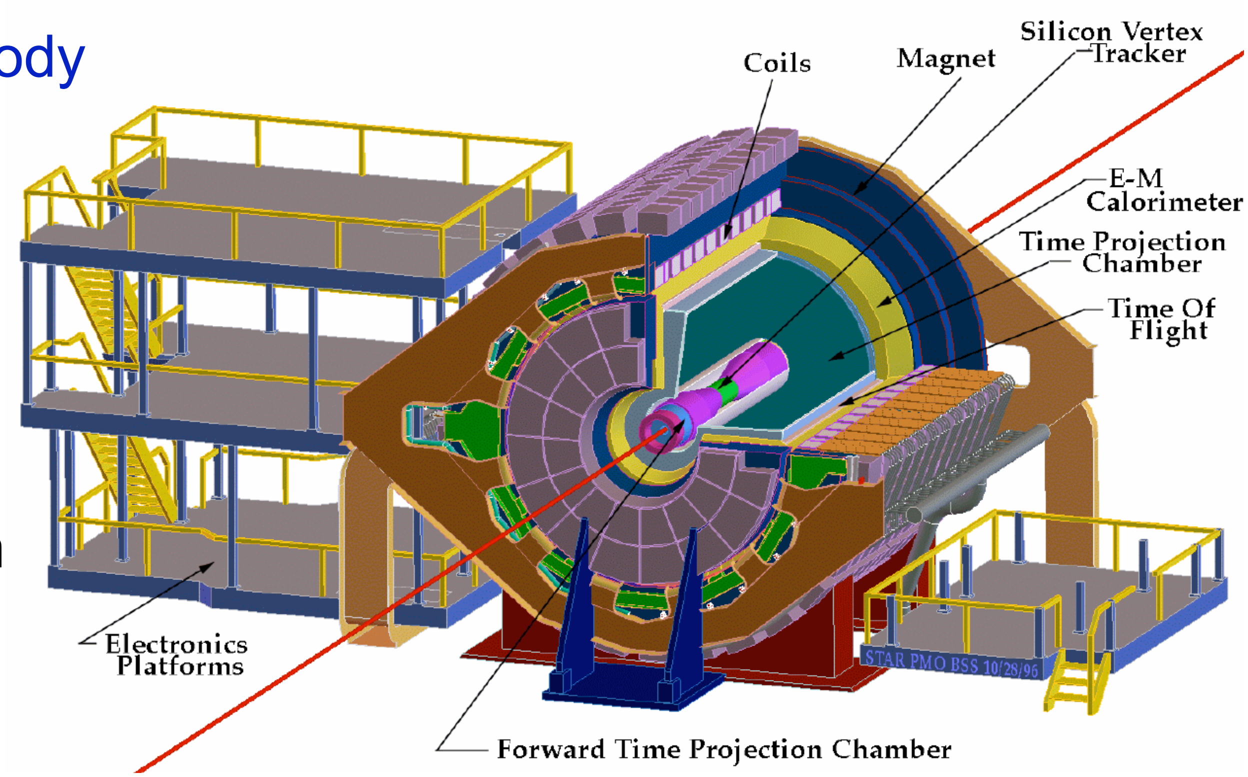




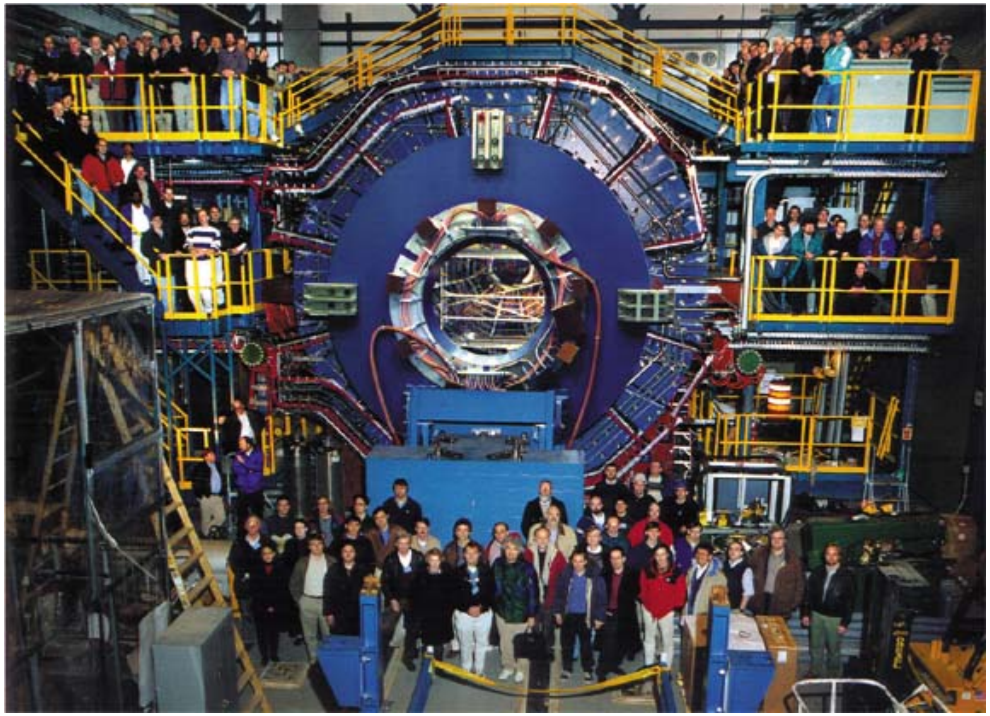


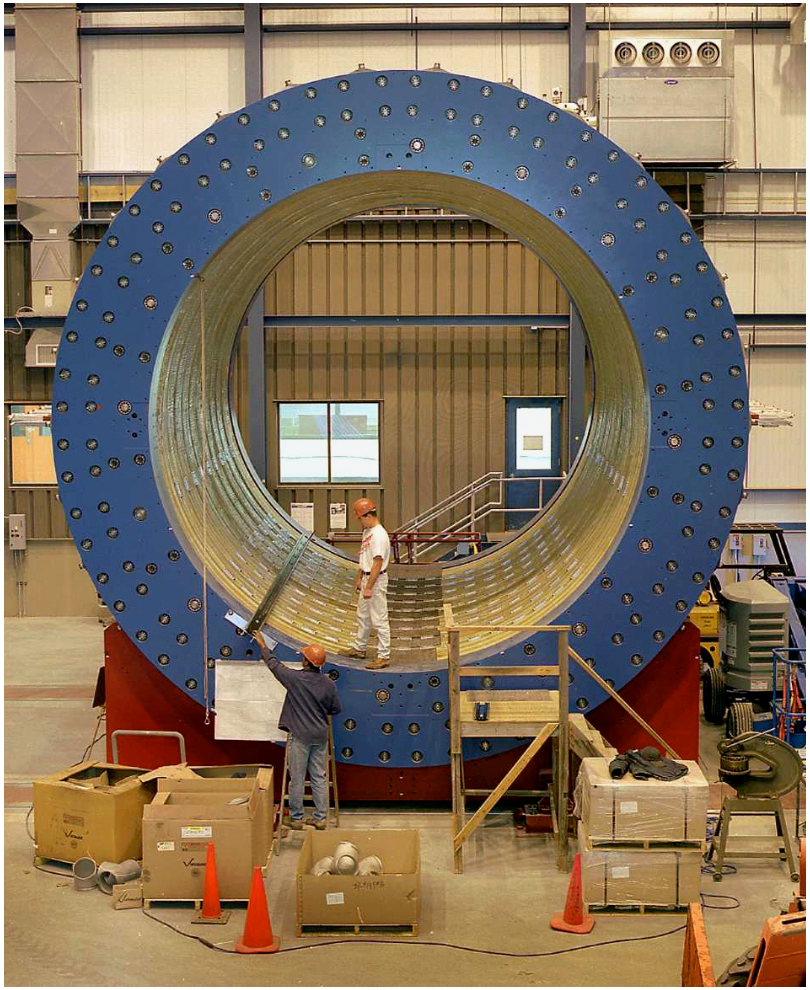
STAR

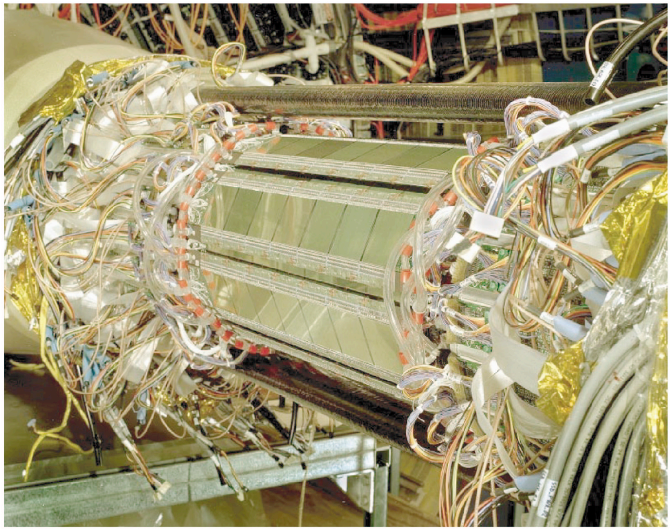
- An experiment with something for everybody
  - Hadrons
  - Jets
  - Electrons
  - Photons
- Features
  - Typical HEP Design
  - Large acceptance
  - Solenoidal field
  - Main detector: TPC
  - E.M. Calorimetry (central + forward)
  - Huge data volume/event
  - Moderate data taking rate



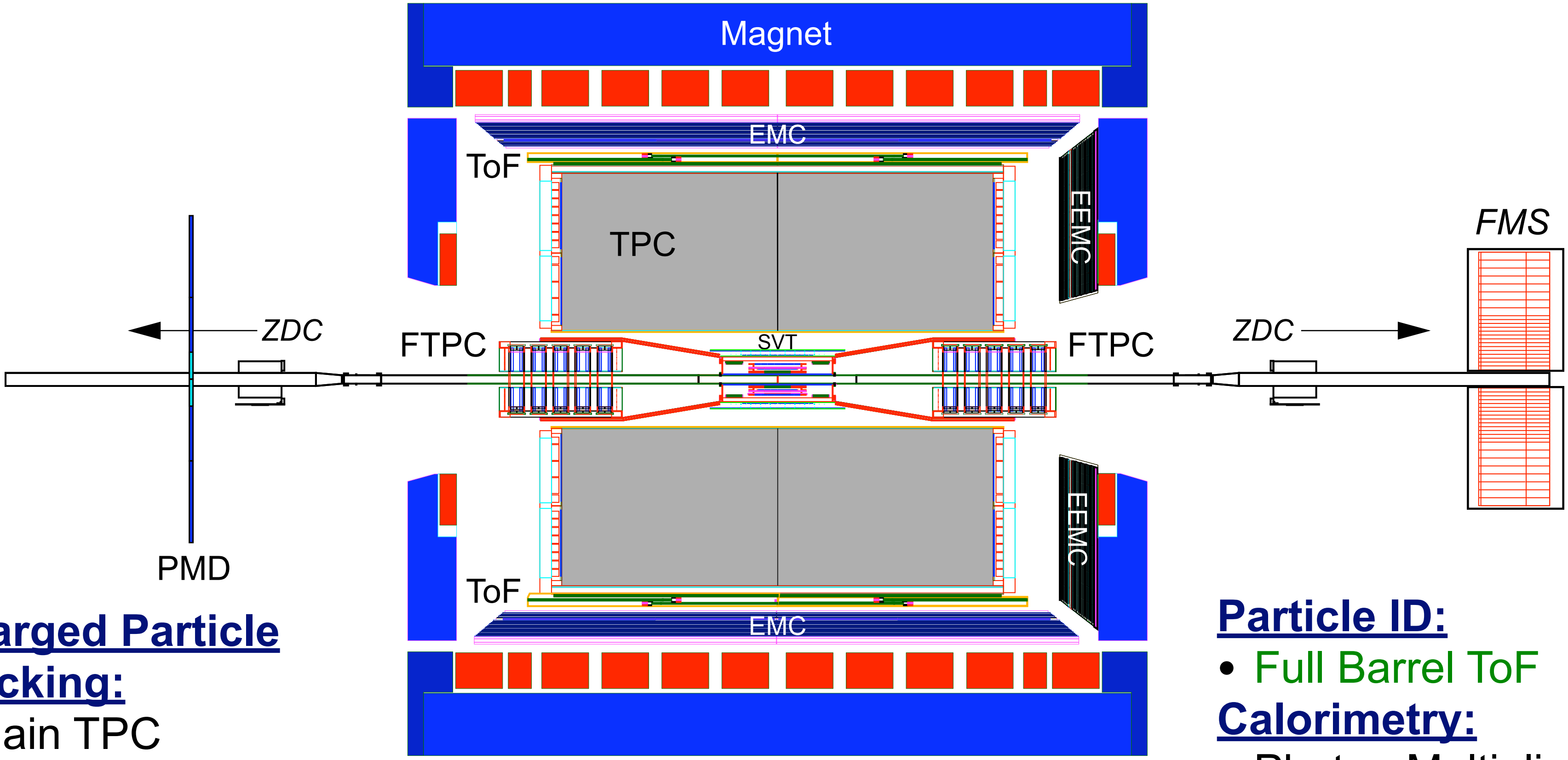
STAR (2001)







STAR Components



Charged Particle Tracking:

- Main TPC
- Forward TPC (FTPC)
- SSD + Intermediate Tracker + Active Pixel Detector = HFT(was SSD+SVT)
- Forward GEM Tracker

Event Characterization & Trigger:

- Beam-Beam Counter (BBC)
- Zero Degree Calorimeter (ZDC)
- Forward Pion Detectors (FPD)

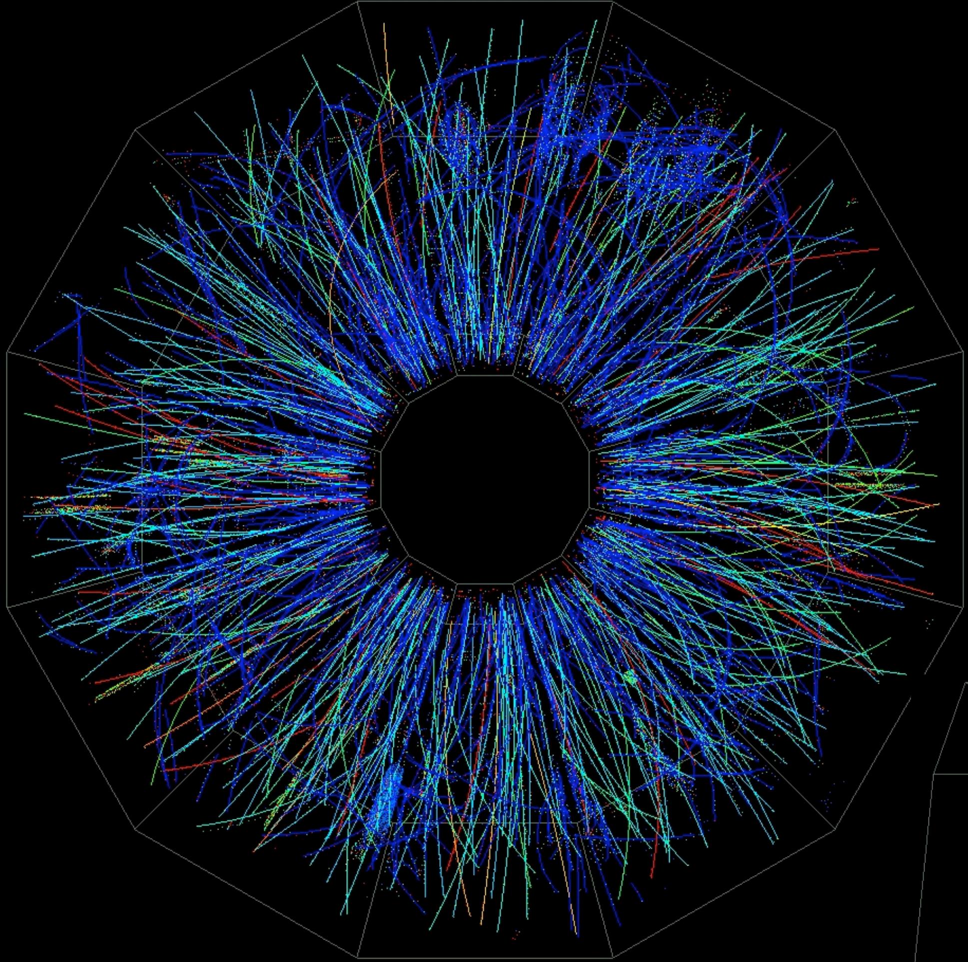
Particle ID:

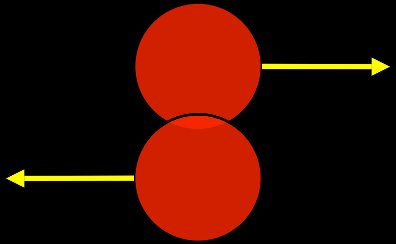
- Full Barrel ToF

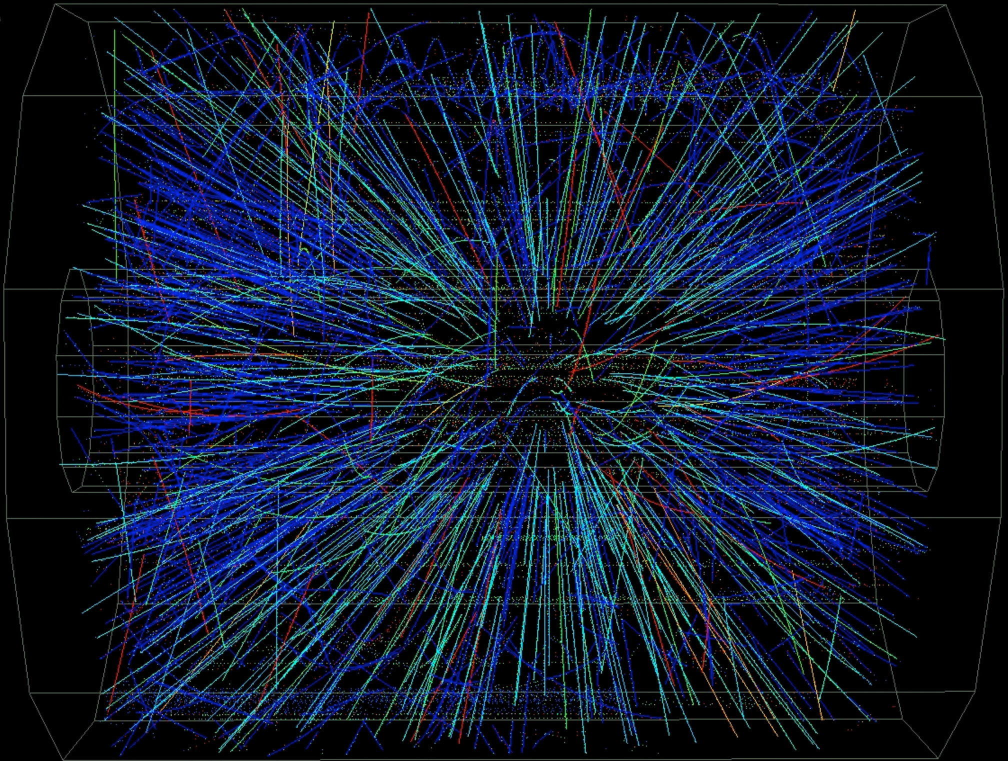
Calorimetry:

- Photon Multiplicity Detector (PMD)
- Barrel EMC
- Endcap EMC
- Forward Meson Spectrometer

Peripheral Event

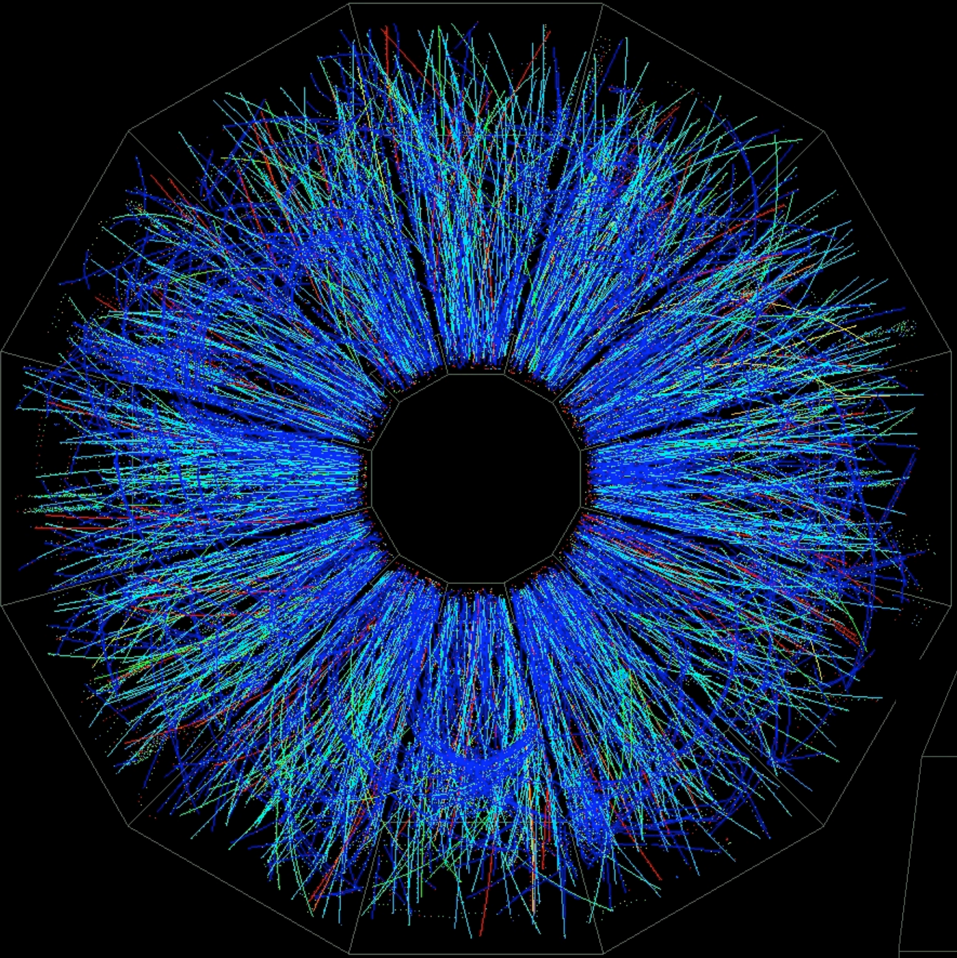




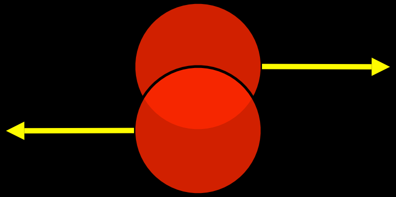


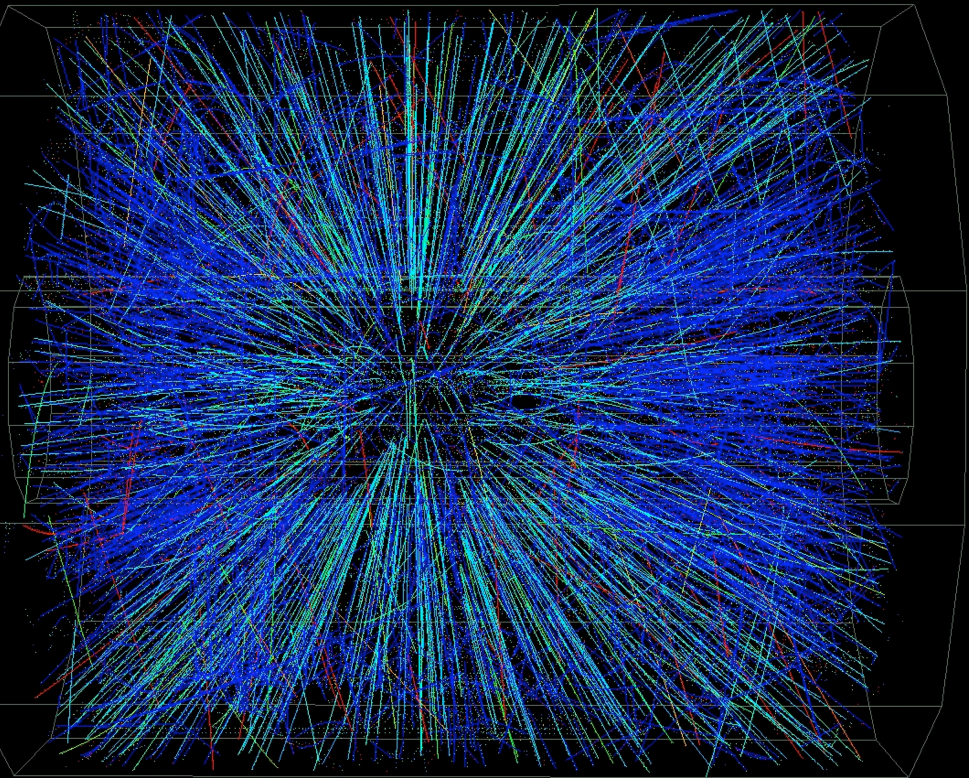
color code ⇒ energy loss

STAR



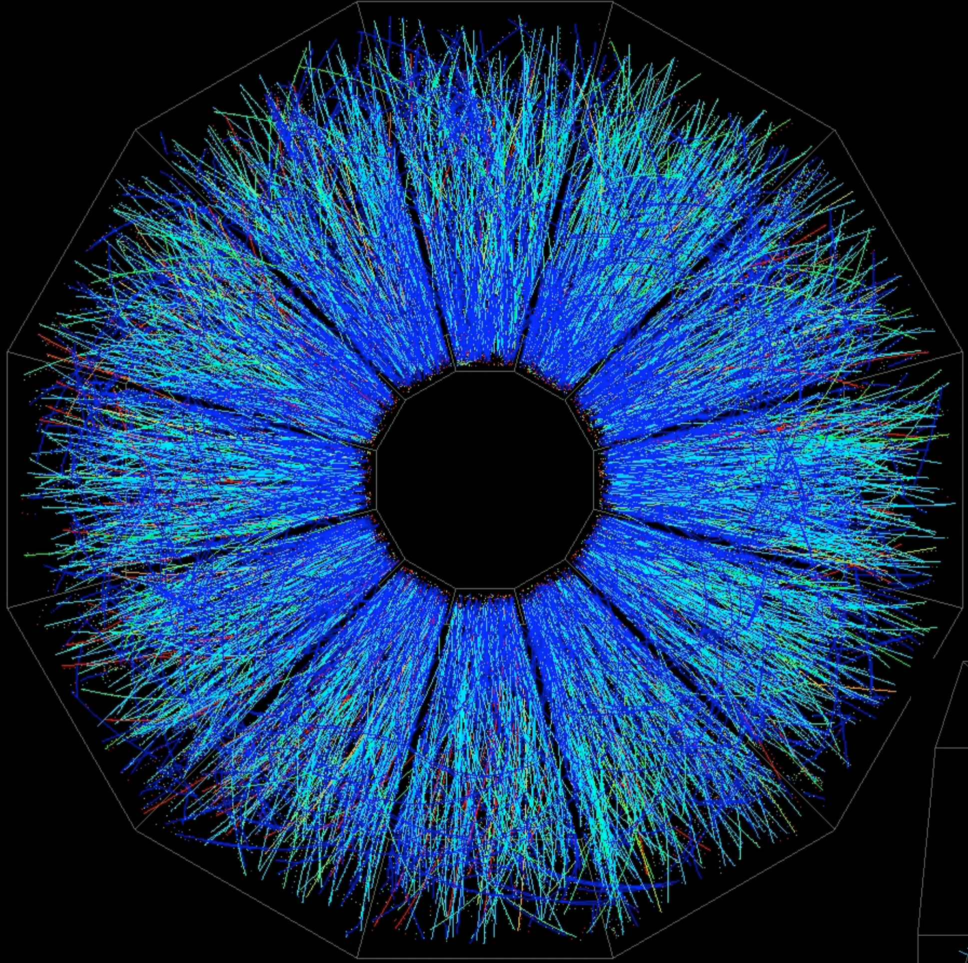
Mid-Central Event

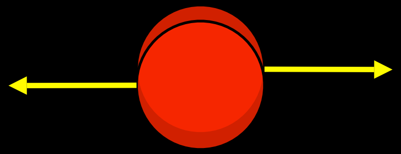


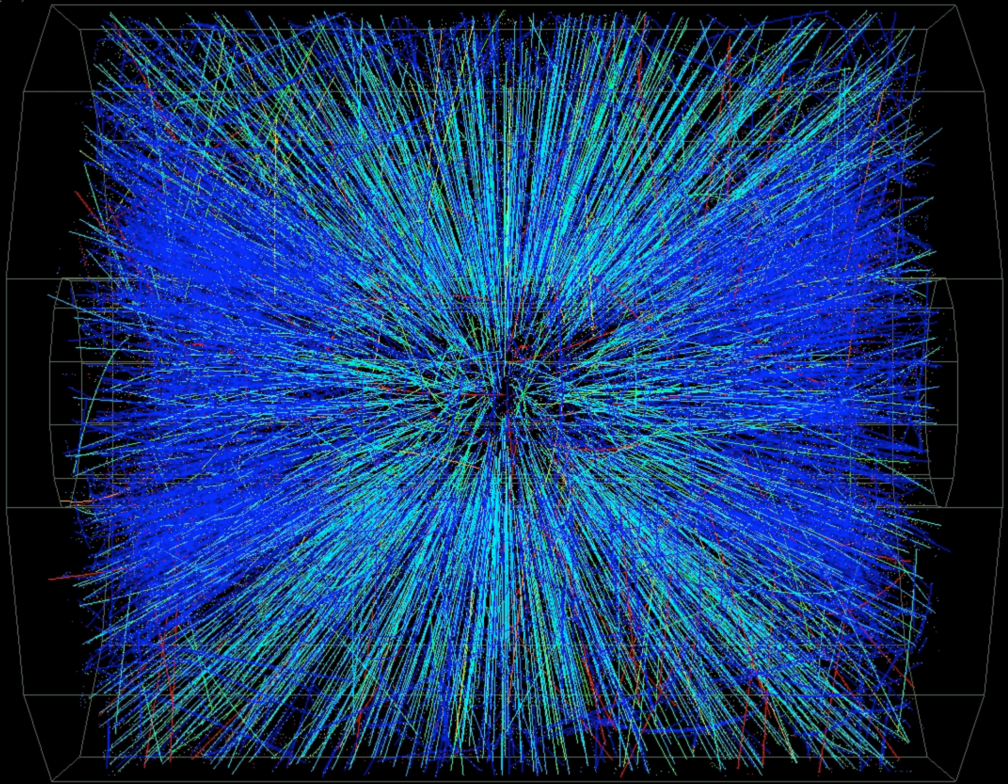


STAR

Central Event



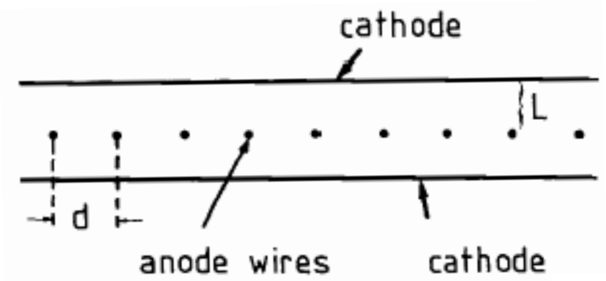




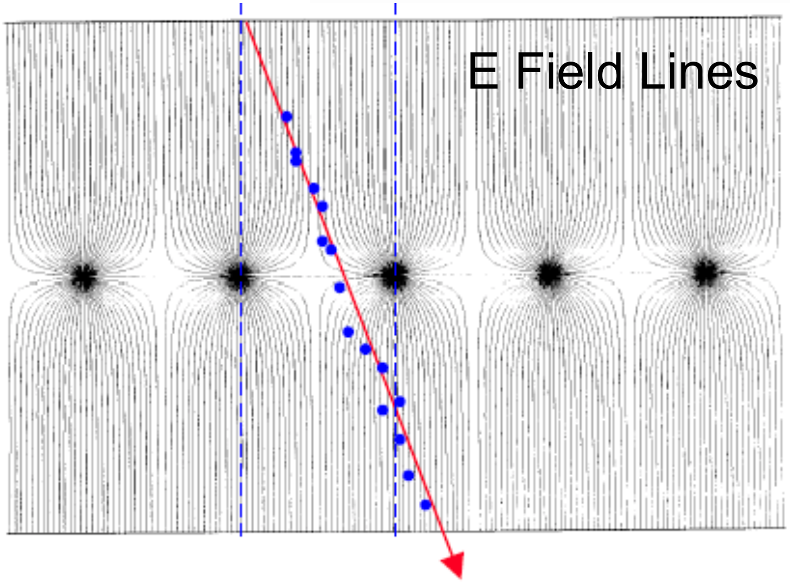
Drift chamber in a nutshell

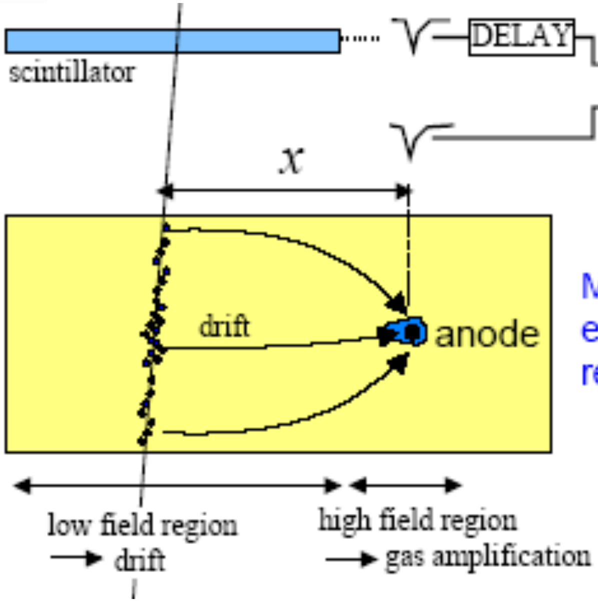
Multi Wire Proportional Chamber

G.Charpak 1968 ,nobel prize 1992



Typical parameters: L=5~8 mm, d=2mm, $\varnothing_{wire}$ =20 µm.





Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$

- Address of fired wire(s) give one dimensional information ⇒ $\sigma_x \approx d/\sqrt{12}$
- Improve using drift length time information: typical ~200 µm
- Resolution limits: drift and diffusion effects driven by **E** × **B** effects

Time Projection Chamber (TPC)

Error of momentum measurement: $\frac{\sigma(p_T)}{p_T} \propto \frac{\sigma(x) \cdot p_T}{B \cdot L^2}$

⇒ L has to be large ⇒ detector has to be wide (small R_{in}, large R_{out})

Want large η coverage ⇒ z dimension has to be large ⇒ detector has to be long

Cannot achieve this with drift chambers:

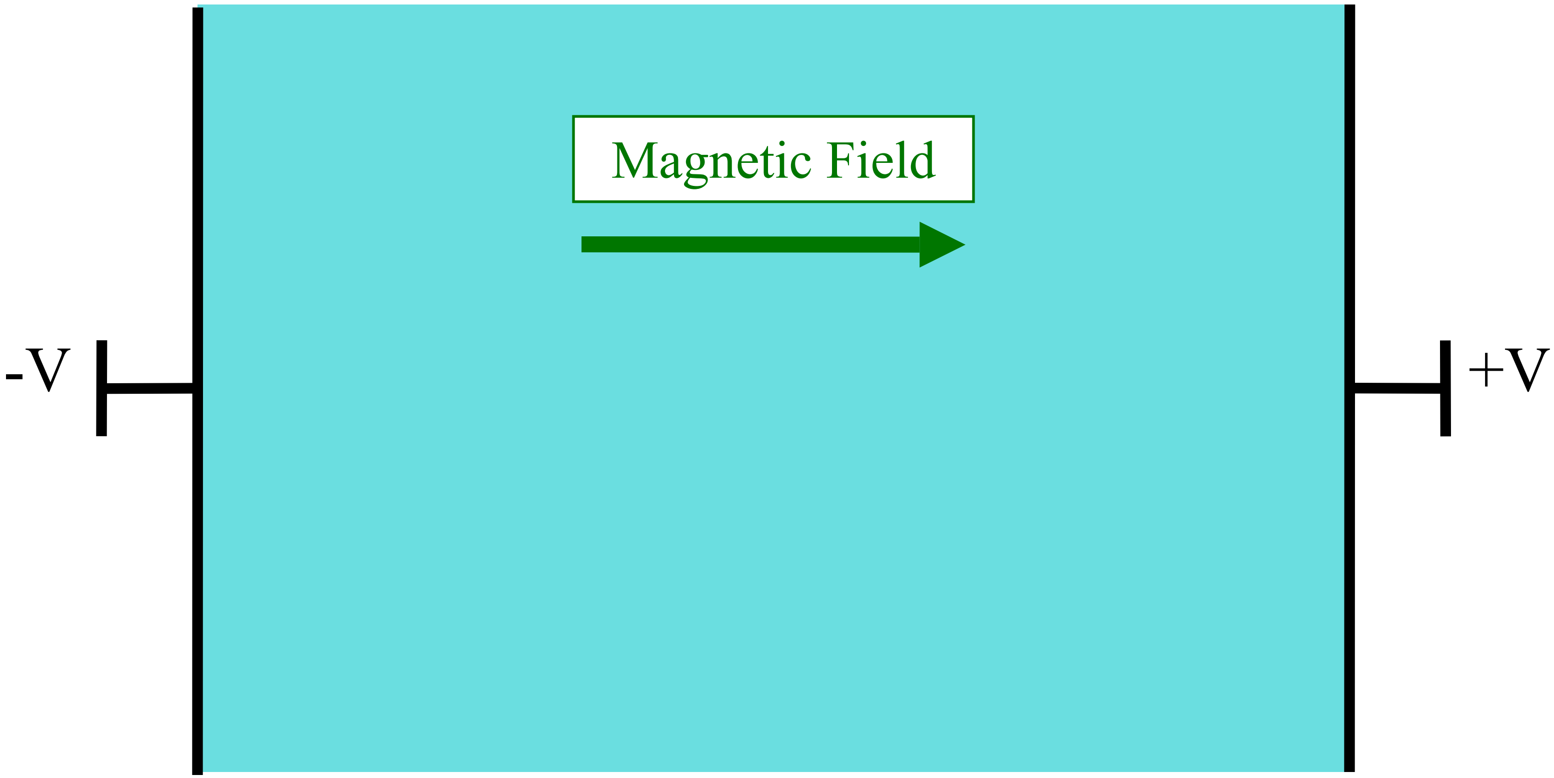
- thousands of wires
- long wires
- complex construction (dead zones)

Solution: let the electrons drift over long distances

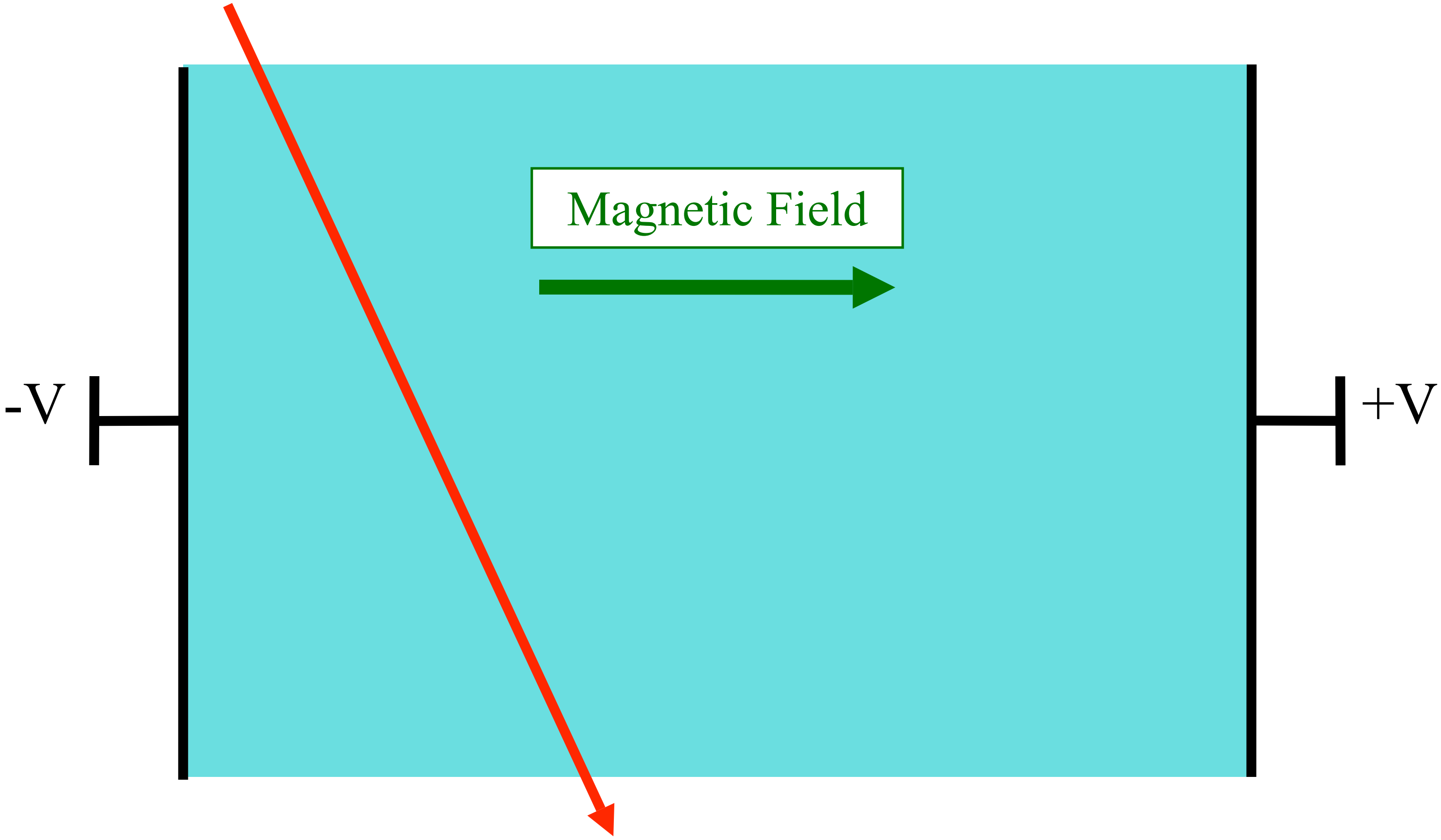
⇒ TPC: essentially a huge gas filled box

Think of a TPC as a 3D CCD camera

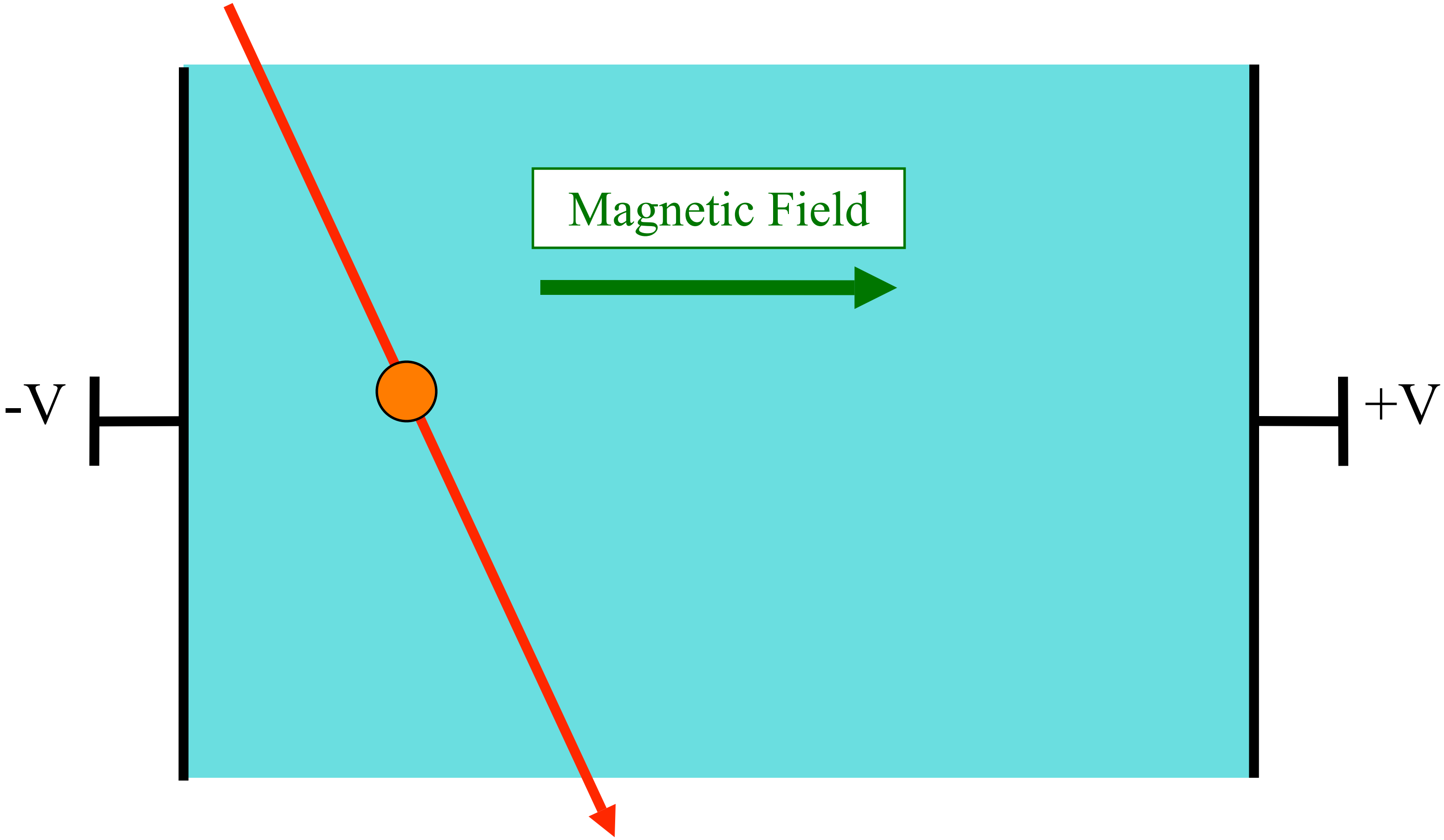
The basic concept of a TPC



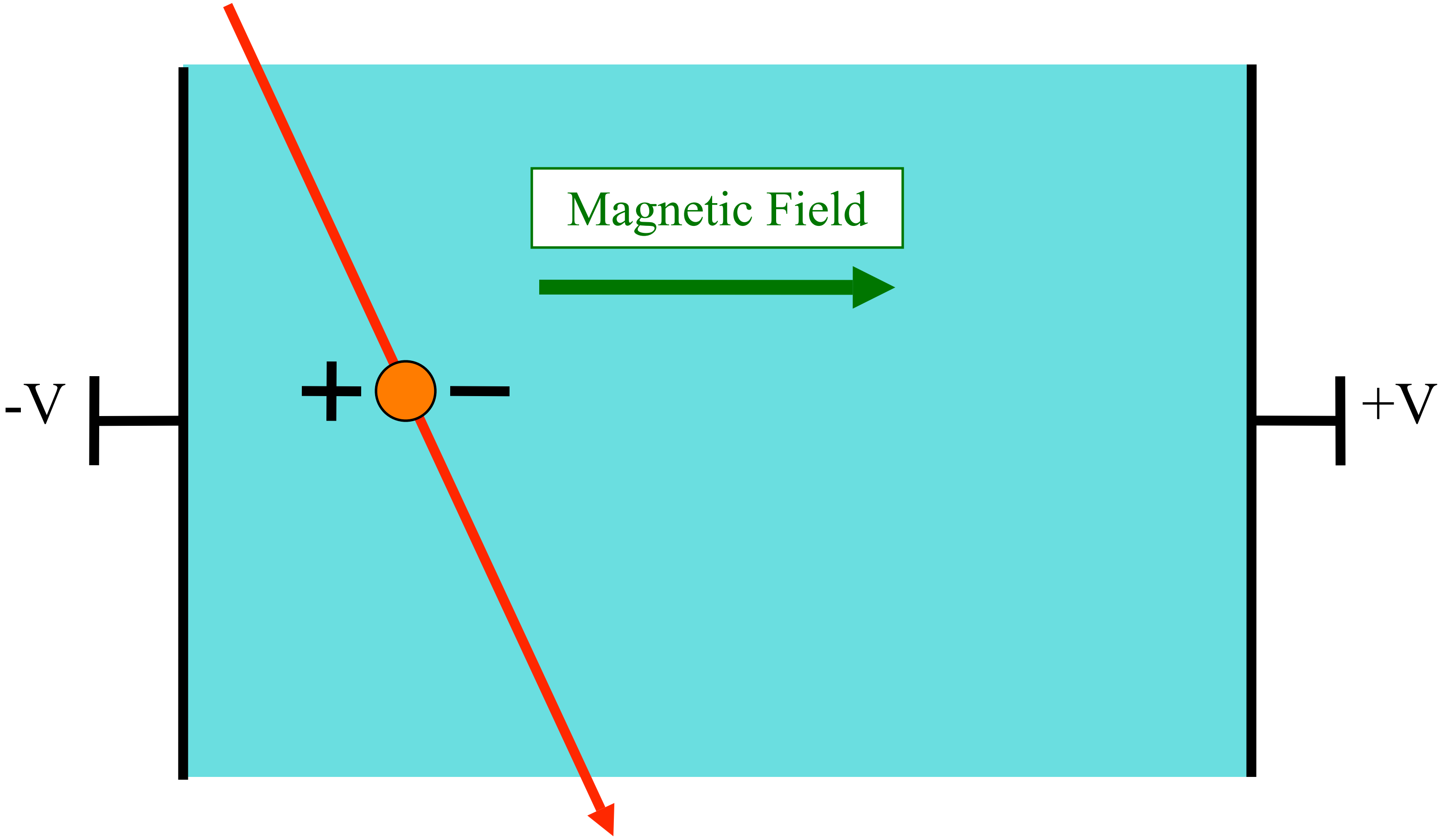
The basic concept of a TPC



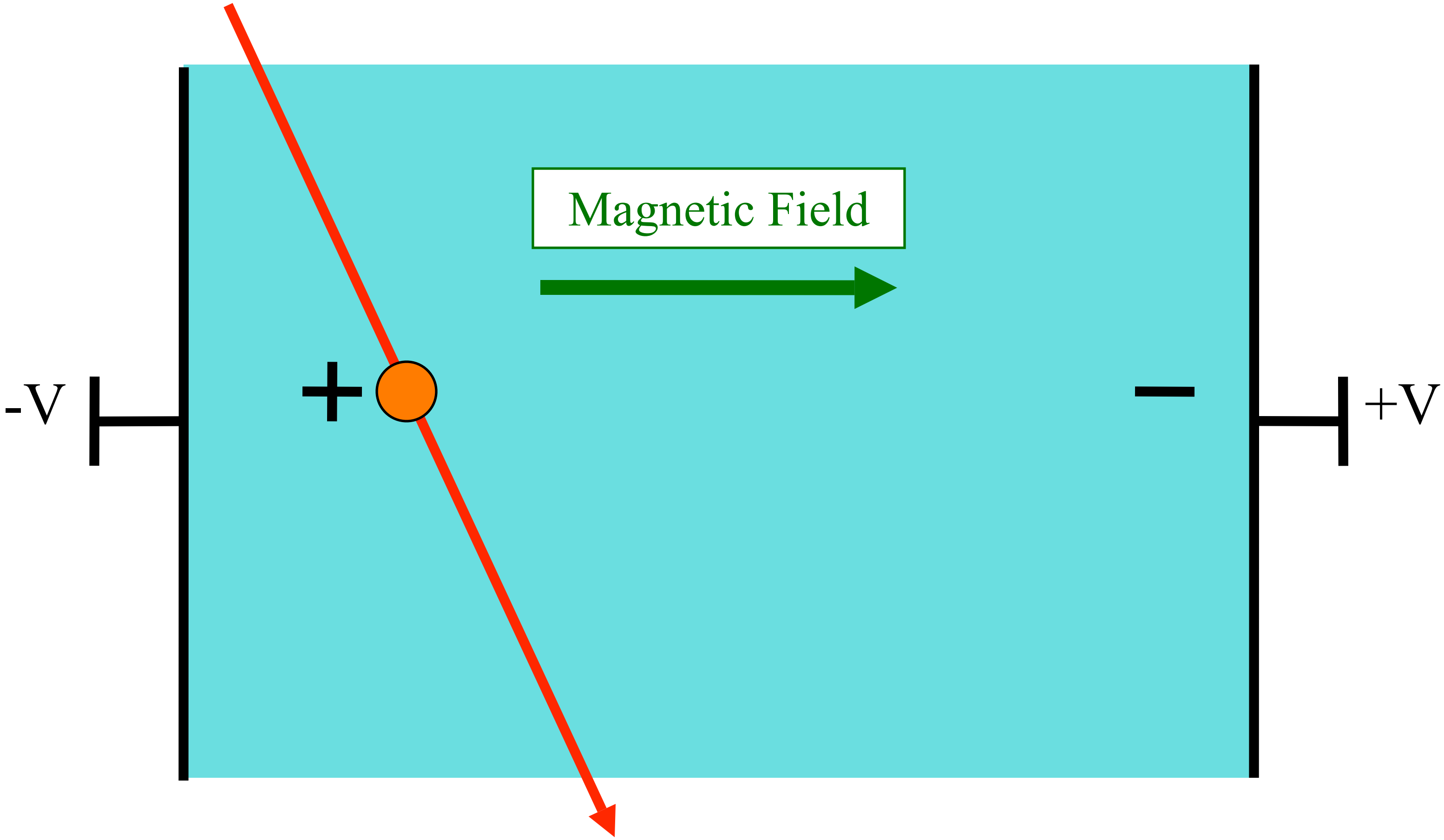
The basic concept of a TPC



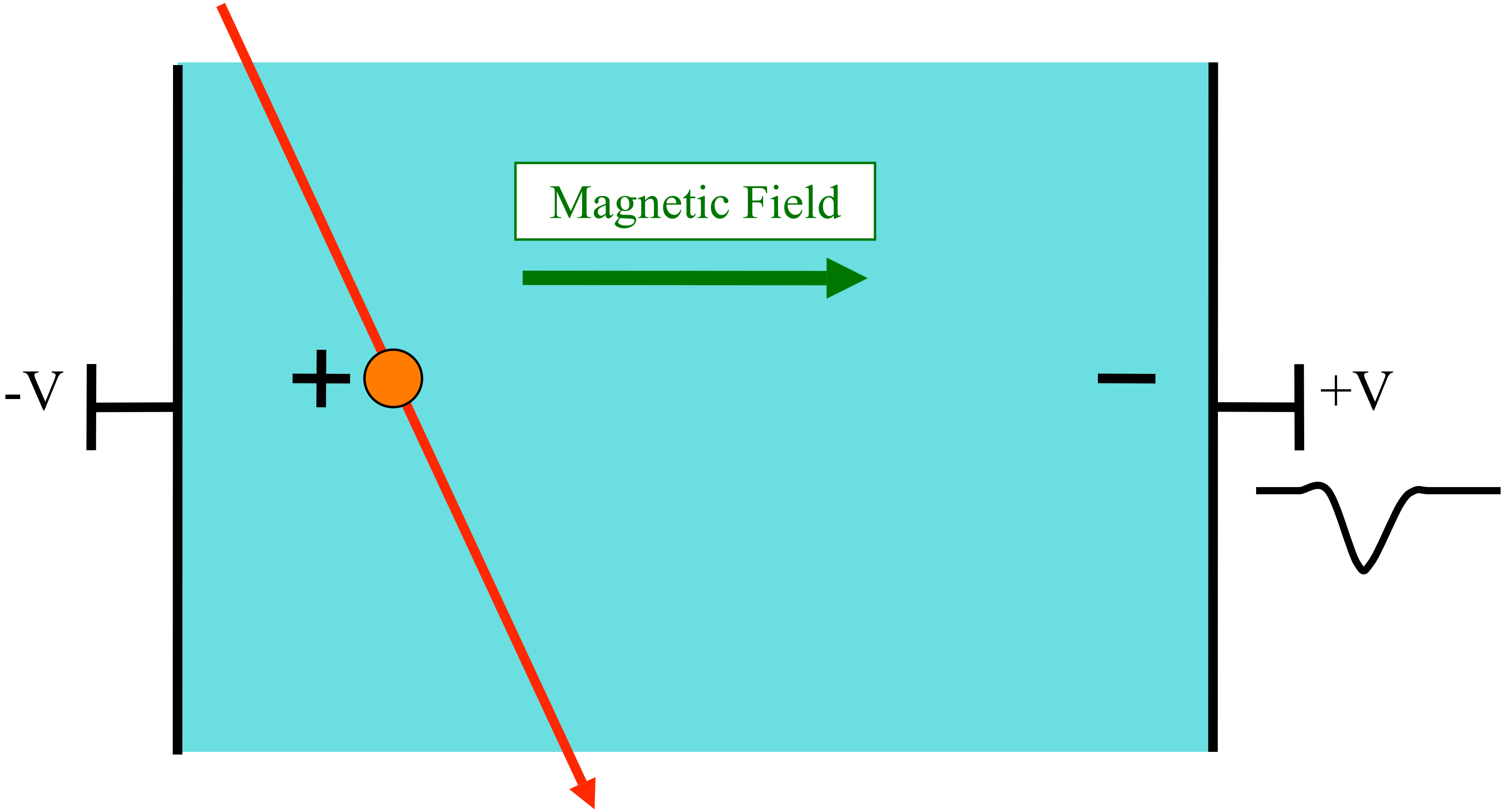
The basic concept of a TPC



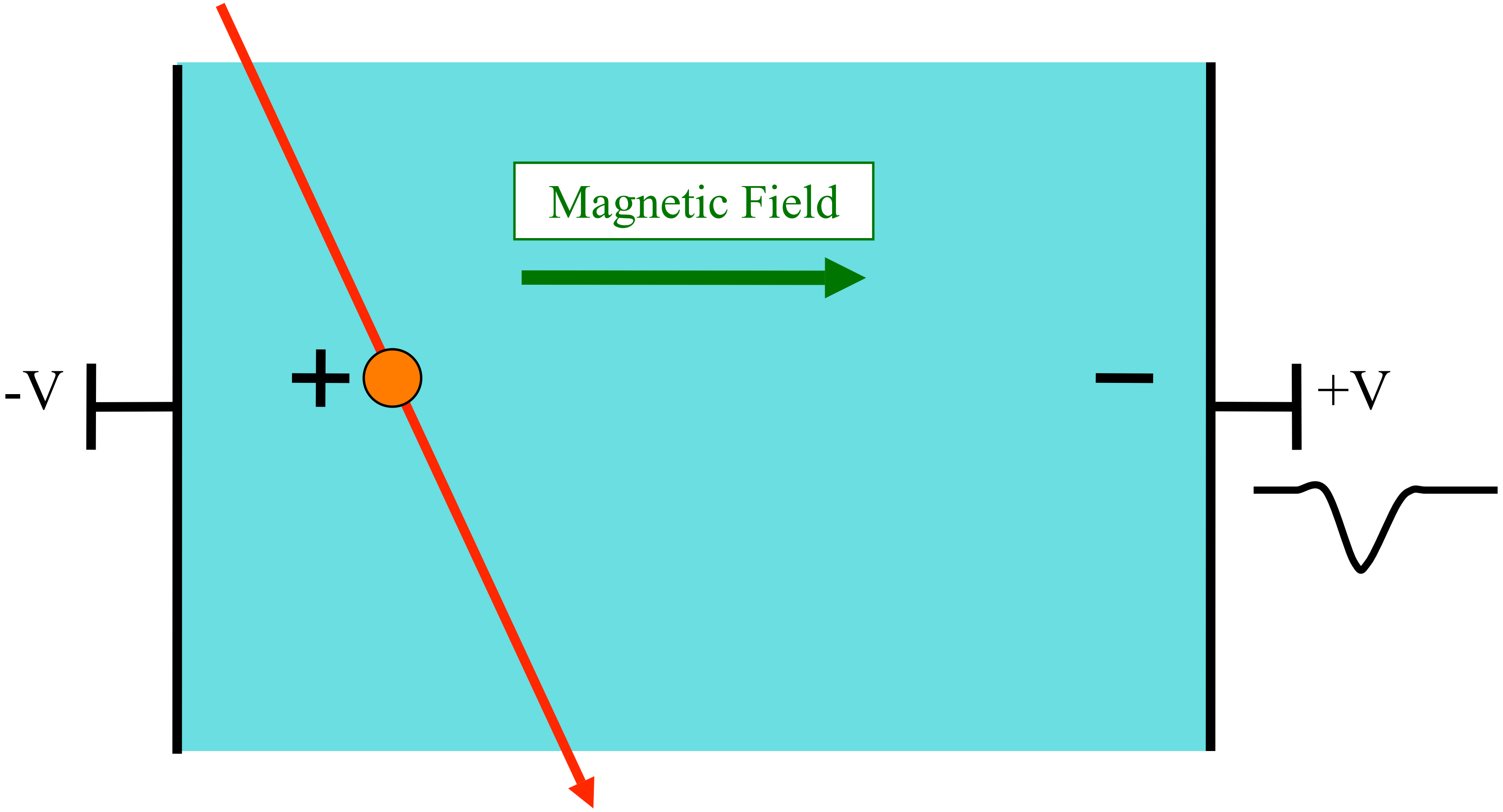
The basic concept of a TPC



The basic concept of a TPC



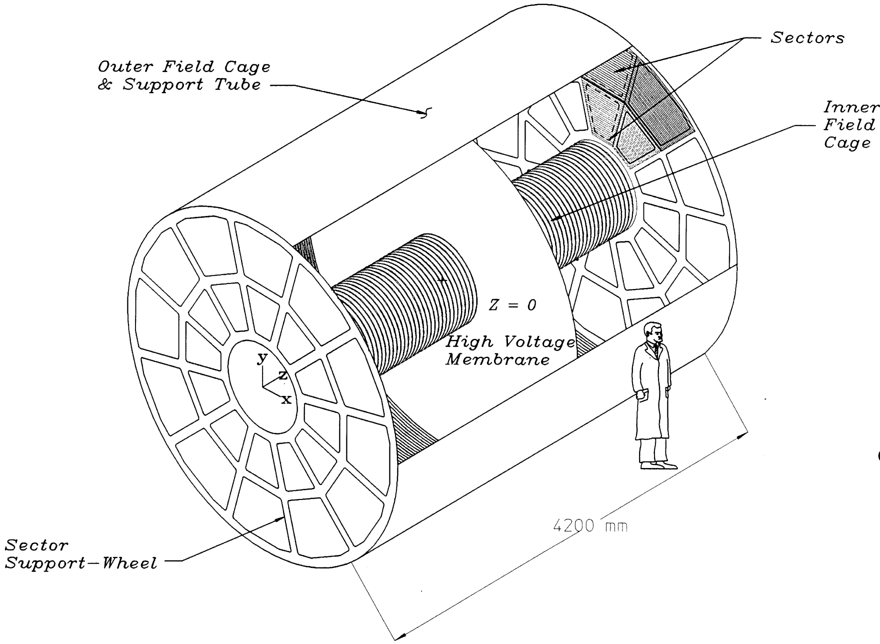
The basic concept of a TPC

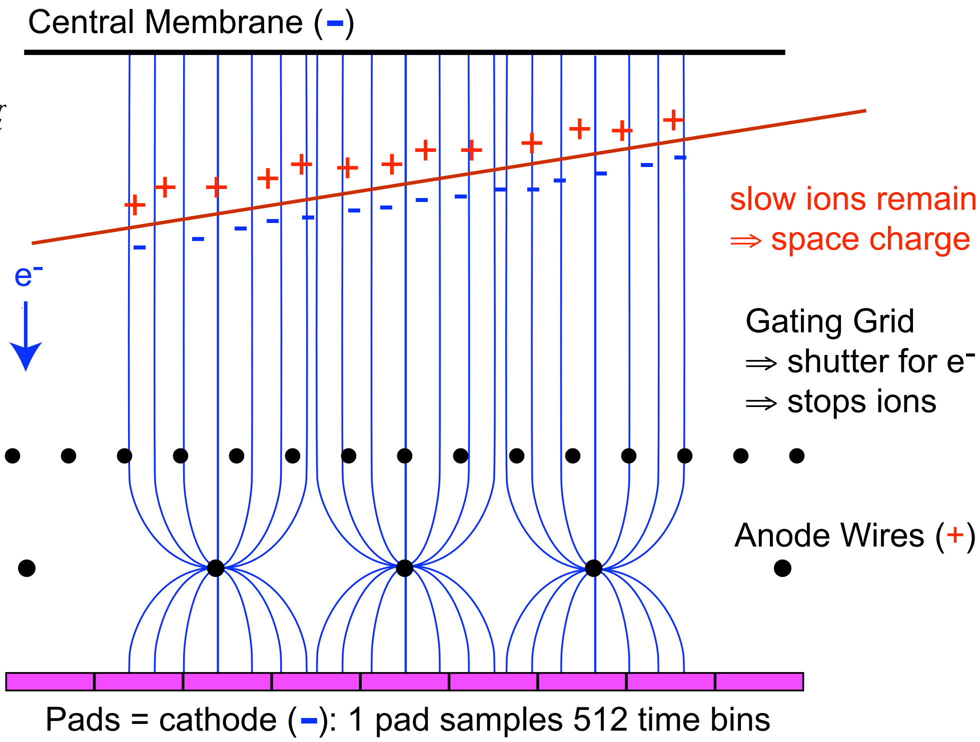


The time to reach the end of the TPC determines the distance drifted in the gas.

A **3-D camera** to measure particle positions.

TPC Details




Central Membrane (−)

slow ions remain
⇒ space charge

e⁻

Gating Grid
⇒ shutter for e⁻
⇒ stops ions

Anode Wires (+)

Pads = cathode (−): 1 pad samples 512 time bins

STAR TPC

- 140,000 electronics channels (pads)
- 512 time bins
- 140,000 x 512 = 72 million pixel
- With new electronics can run at 1000 Hz

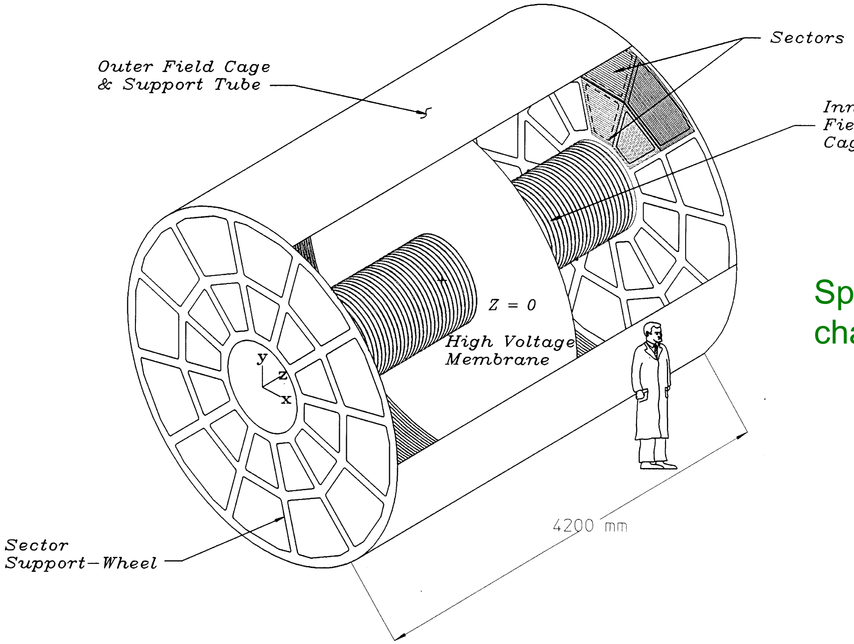
Gating Grid:

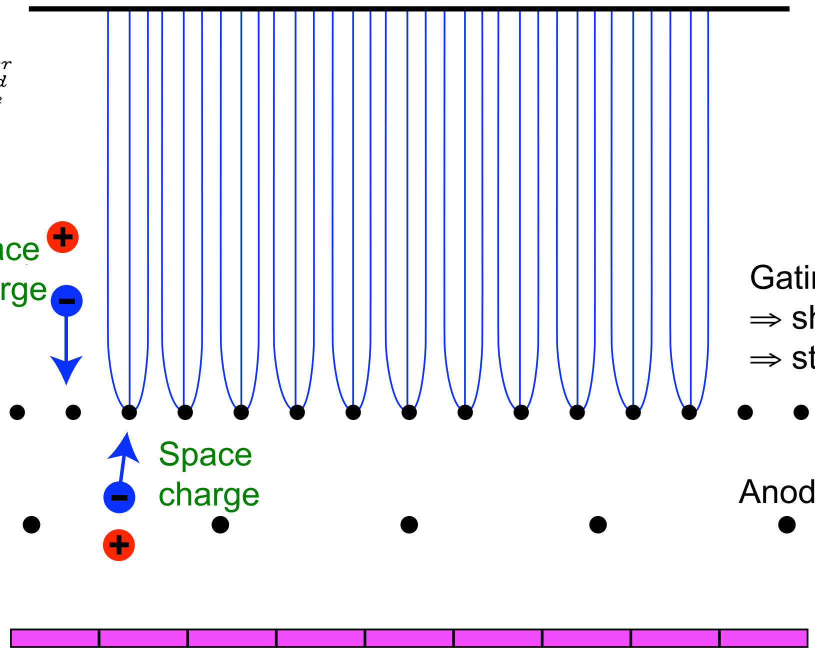
- Designed to reduce charge injection into amplifiers

Slow ions left in volume:

- accumulate, create space charge
- space charge creates distortions

TPC Details





Central Membrane (−)

Space charge

Gating Grid
⇒ shutter for e^-
⇒ stops ions

(+)

Space charge

Anode Wires (+)

Pads = cathode (−): 1 pad samples 512 time bins

STAR TPC

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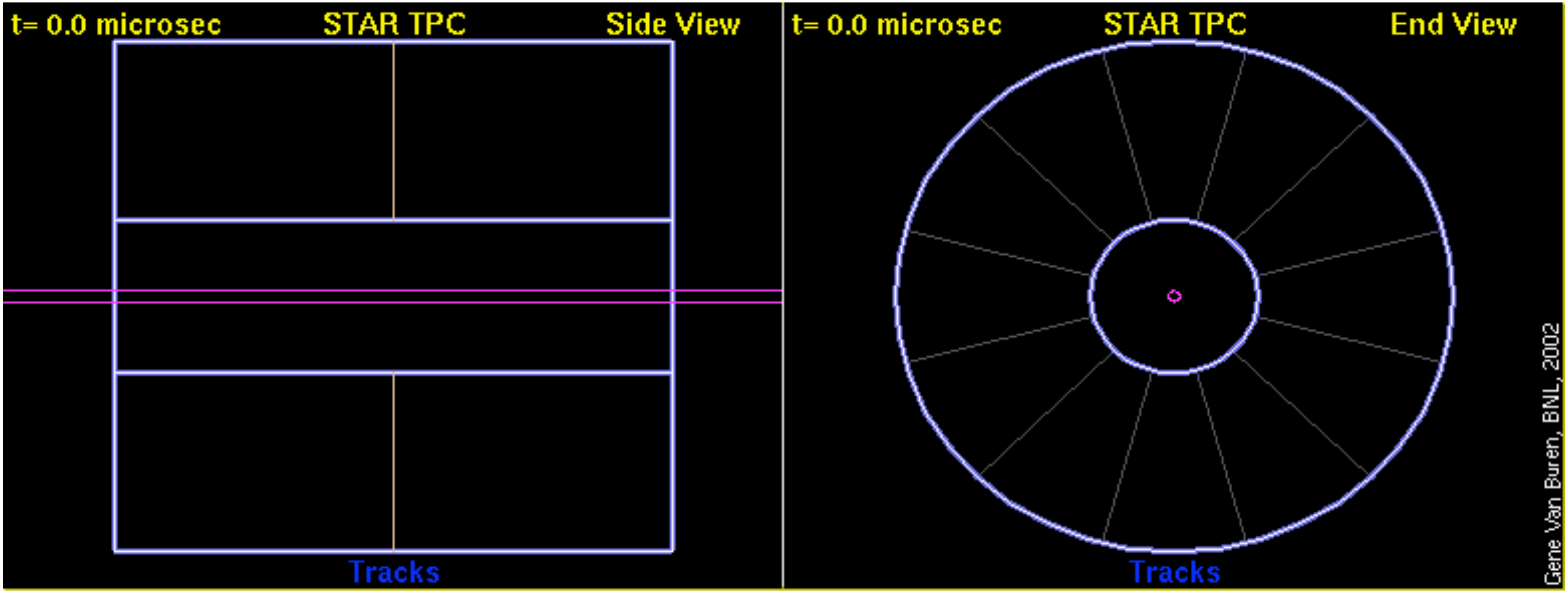
The STAR TPC

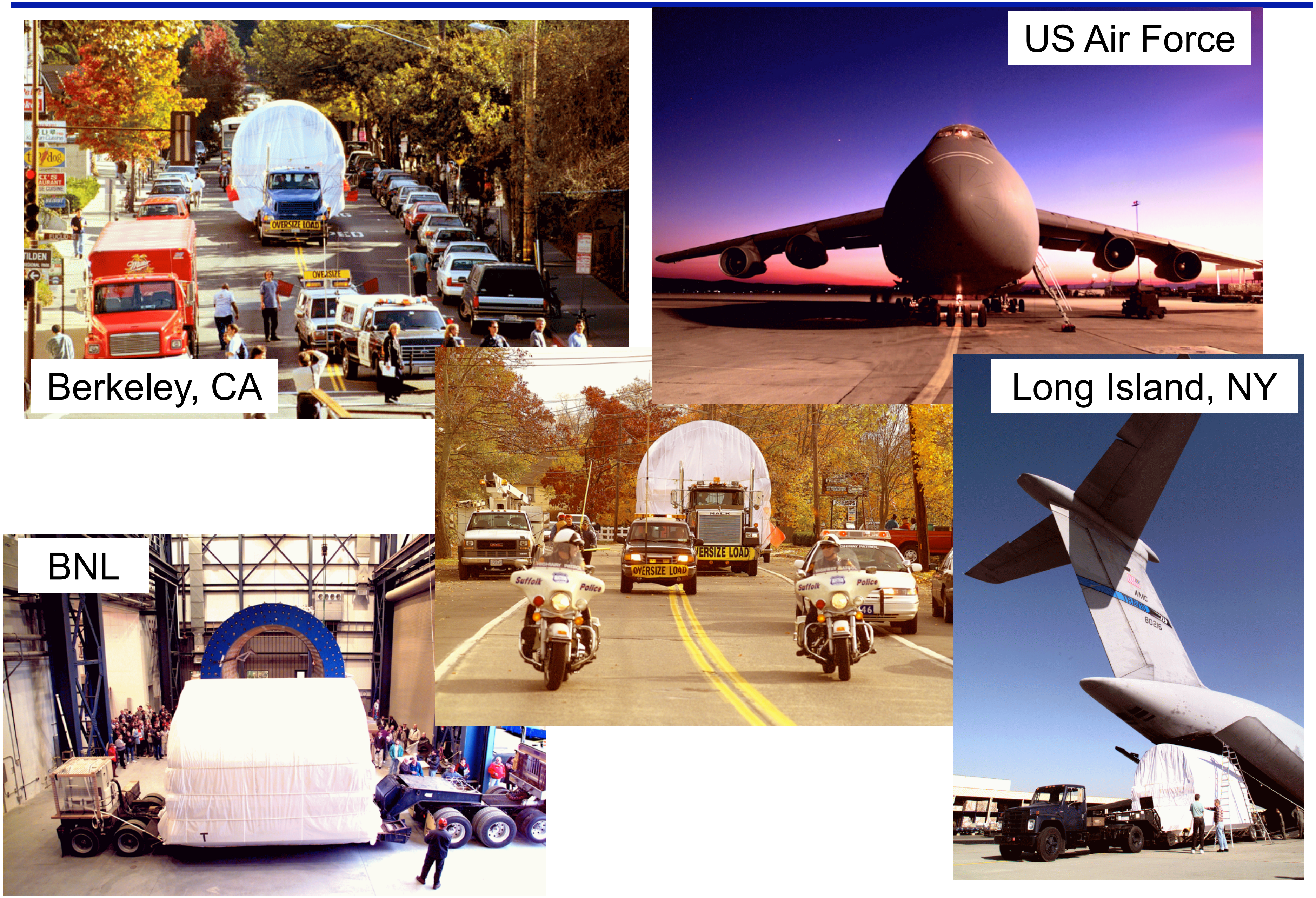
Simulation and animation by Gene Van Buren, movie by Jeff Mitchell.

The STAR TPC



Simulation and animation by Gene Van Buren, movie by Jeff Mitchell.

STAR TPC: from West to East Coast


Berkeley, CA

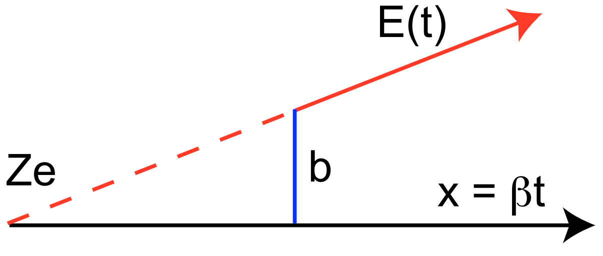
US Air Force

Long Island, NY

BNL

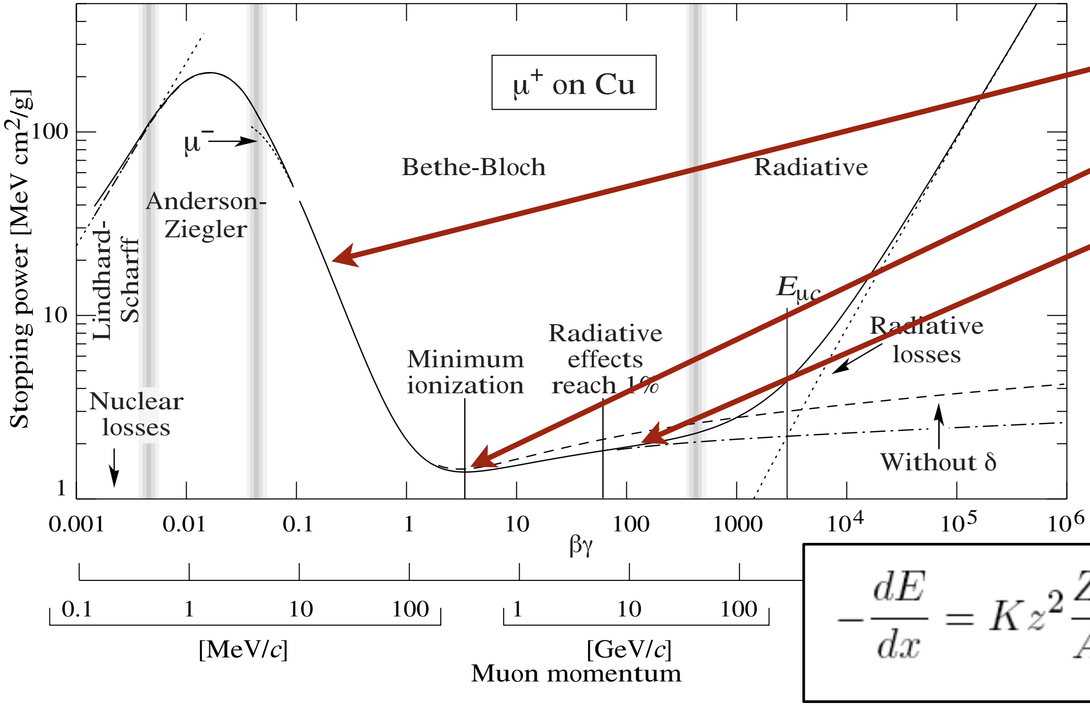
Particle Identification by dE/dx in STAR's TPC

- Elementary calculation of energy loss:
  - Charged particles traversing material give impulse to atomic electrons:



$$p_y^e = e\int E_y(t)\,dt = e\int E_y(t)\frac{dx}{\beta} = \frac{2Ze^2}{\beta b}$$

$$\text{Energy transfer} = \frac{(p_y^e)^2}{2m_e} \propto \frac{1}{\beta^2}$$



- <dE/dx> ~ 1/β^2 region
- MIP βγ ≈ 3-4
- relativistic rise <dE/dx> ~ ln$\gamma^2\beta^2$

Bethe-Bloch Formula

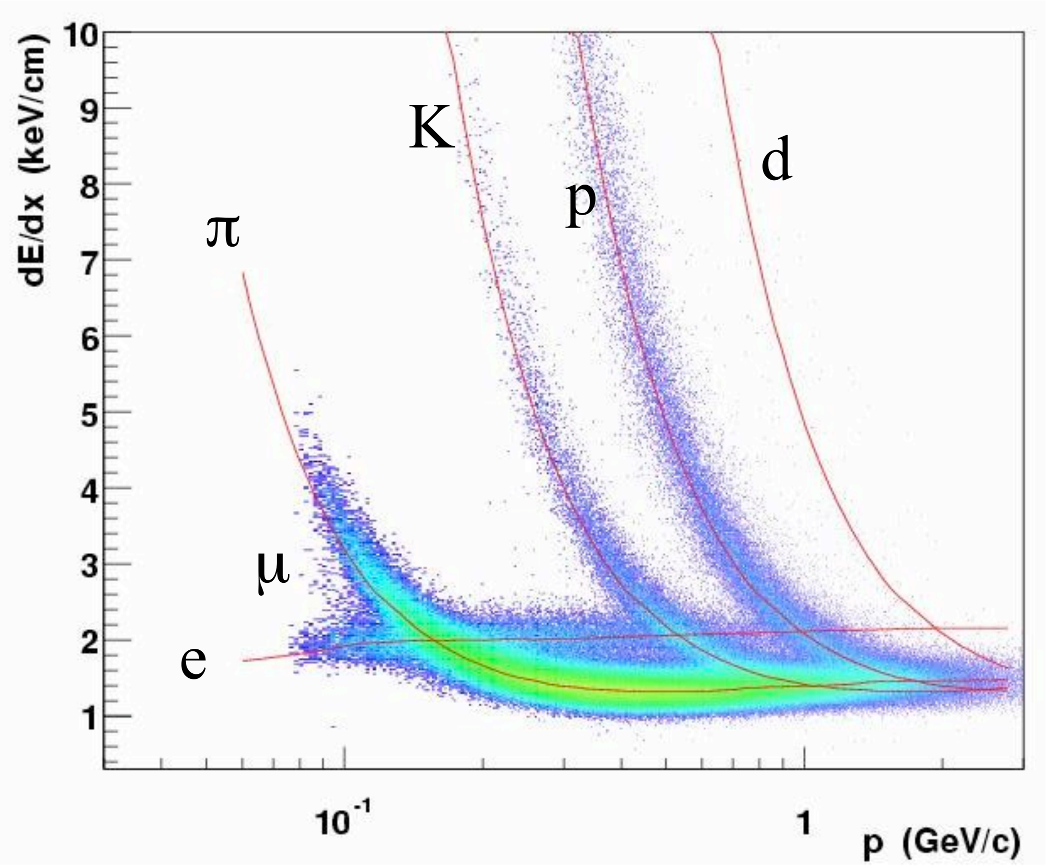
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Particle Identification by dE/dx in STAR's TPC

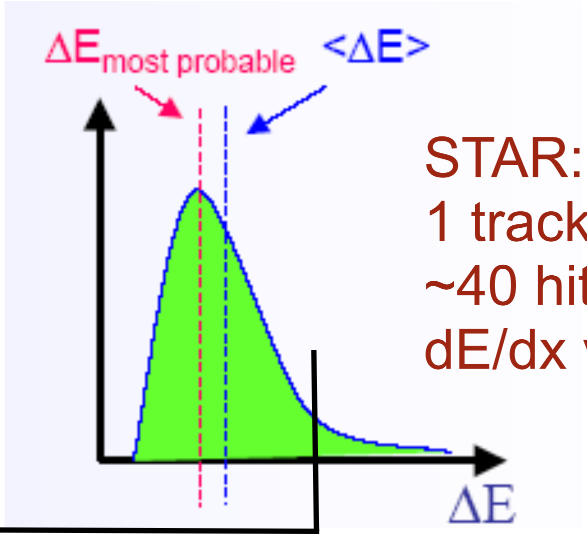
$$p = mv = m_0\beta\gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} ln(\beta^2\gamma^2)$$

Simultaneous measurement of **p** and **dE/dx** defines mass m_0 ⇒ particle ID



Real detector (limited granularity) can not measure <dE/dx> !
It measures the energy ΔE deposited in a layer of finite thickness δx.
For thin layers or low density materials:
→ Few collisions, some with high energy transfer.
Energy loss distributions show large fluctuations towards high losses: "Landau tails"

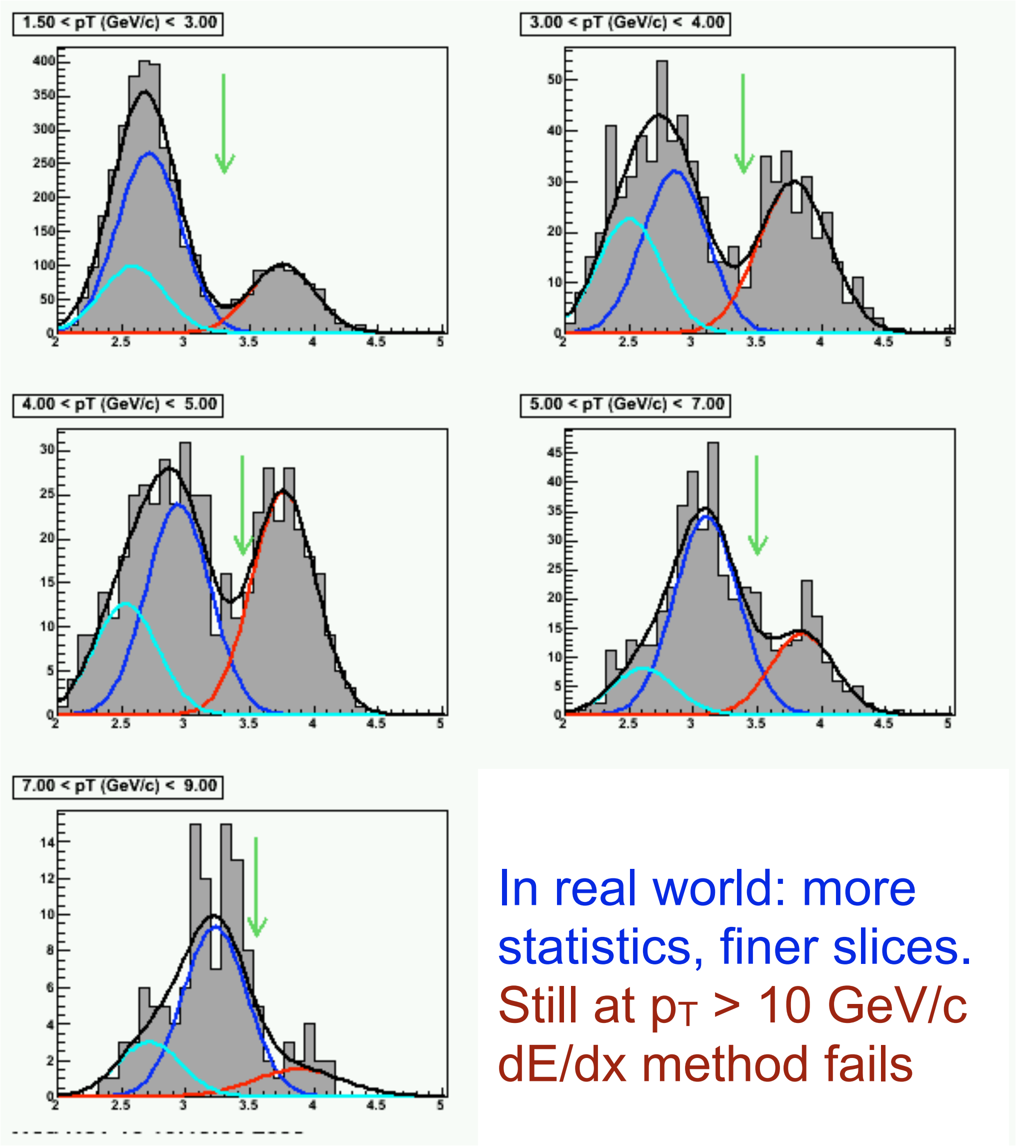


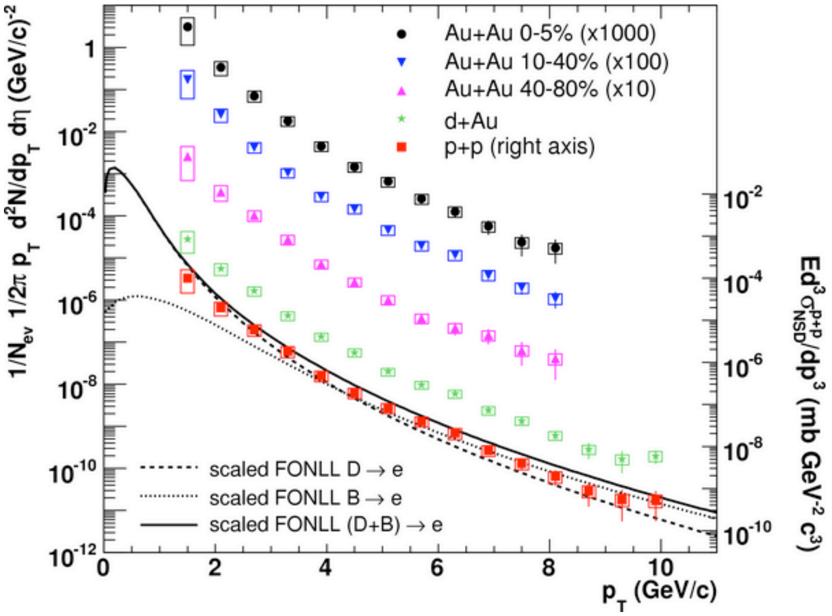
STAR:
1 track has ~40 hits = 40 dE/dx values

Truncated Mean (G. Igo, UCLA)

Electrons via dE/dx

- Select tracks
  - pre-select electron candidates with EMC (p/E ~ 1)
- Plot electron candidates in p_T slices
- Fit dE/dx(p_T) for K,π,e
- integral of electron fit ⇒ yield
- correct yield for efficiency + acceptance
- ⇒ dN/dp_T





In real world: more statistics, finer slices.

Still at p_T > 10 GeV/c dE/dx method fails

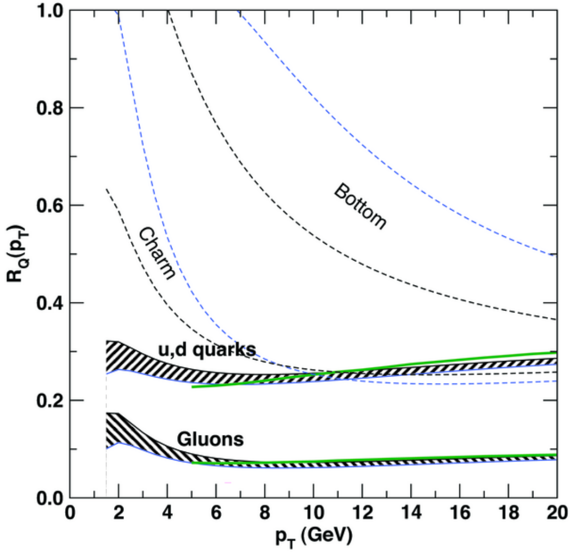
PID at High-p_T is essential !

- Example: the hunt for the Casimir factor

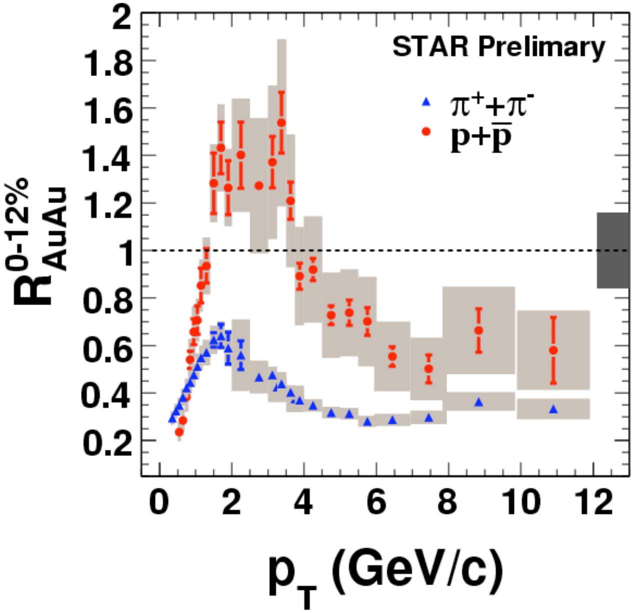
Mechanism of energy loss : Medium induced gluon radiation

$$\langle \Delta E \rangle \propto \alpha_s C \langle \hat{q} \rangle L^2$$

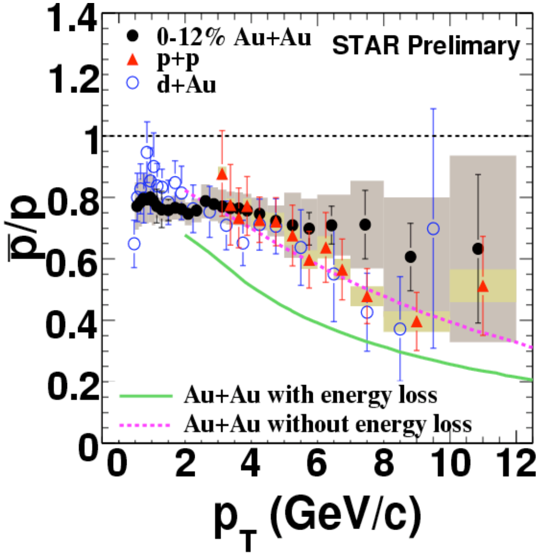
The Color Factor Effect $$\frac{\Delta E_g}{\Delta E_q} = 9/4$$


Wicks et al, Nucl. Phys. A784 (2007) 426

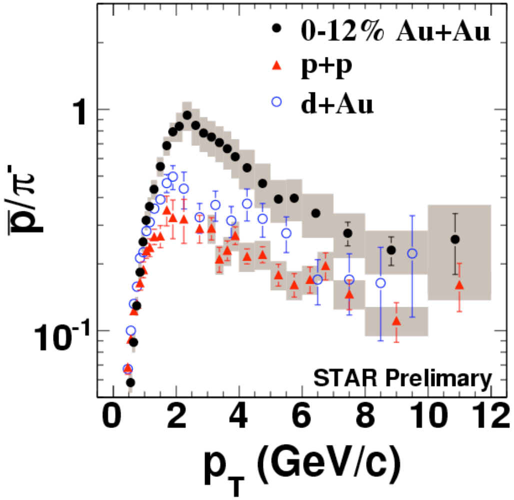
Baryon & meson NMF



Anti-particle/particle



Anti-Baryon/meson

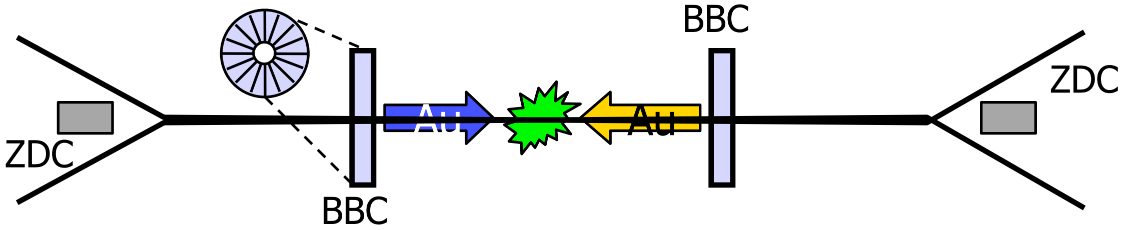


Trigger

- Every experiment has *1-N* triggers - can't do without
- Hierachy:
  - Level-0, Level-1, Level-2, ...
  - L0, L1: fast and simple using fast detectors
  - PHENIX & STAR use (L0):
    - ZDC (Zero Degree Calorimeter)
    - BBC (Beam-Beam Counter)
  - L2 and higher: online processor farms
- What does a L0 trigger do at RHIC:
  - tell that there was an interaction (not trivial)
  - select interaction according to centrality
  - select a range of allowed event vertices
  - select rare processes (jets, high-pt particles)
- What do higher level trigger do:
  - the rest ...
  - examples: trigger on quarkonia, complicated event topology, correlations

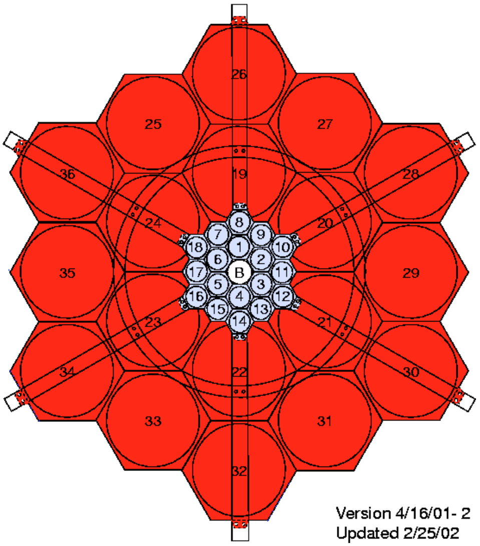
What all RHIC experiments have: ZDC, BBC

Trigger always on ZDC (BBC) coincidence

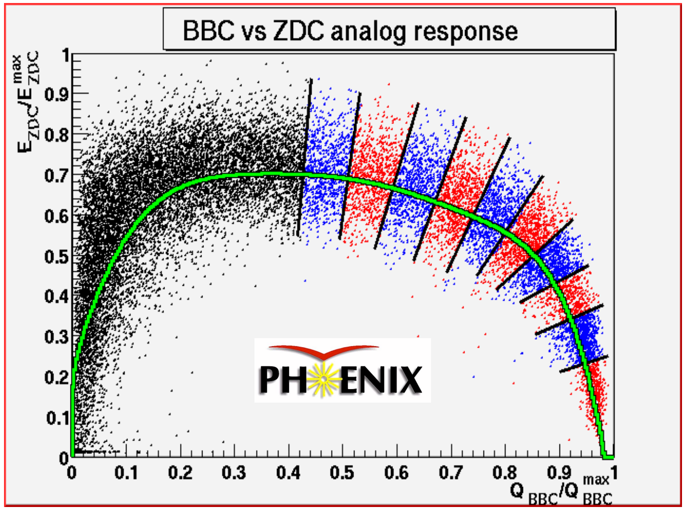


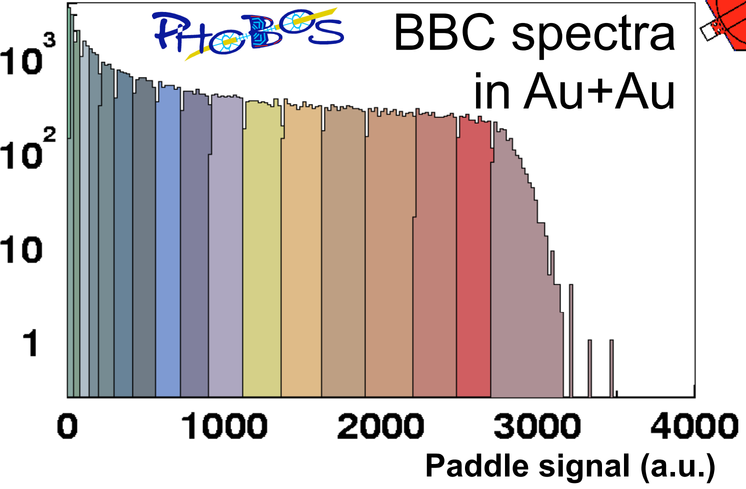
Only free neutrons hit ZDC
central: few hits
peripheral: few hits
ZDC alone is ambiguous

STAR Beam-Beam Counter Schematic
Front View



Version 4/16/01- 2
Updated 2/25/02





ZDC: simple calorimeter, low granularity
optimized for 200 GeV

BBC: scintillator paddles $\sim 2.5 < \eta < 4.5$

Summary

- Four RHIC experiments
  - large: PHENIX, STAR (upgrade in progress)
  - small: BRAHMS, PHOBOS (now decomissioned)
- STAR and PHENIX have considerable overlap
  - cross-checks
- No such thing as a perfect detector
  - STAR and PHENIX had to make compromises but still capture the majority of probes and signatures
  - hardly any detector concept that is not used at RHIC
    - TPC, TRD, ToF, RICH, EM-Calorimeters, Driftchambers, muon chambers, Si-Pad/Strip/Drift, scintillator counters
  - Both experiments are being continuously improved
- A simple fact of operating RHIC: 1 event ~ $1