Lecture III

The Detectors at RHIC

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Kinematics

Transverse Momentum (Lorentz invariant)

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

Rapidity (not Lorentz invariant)

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

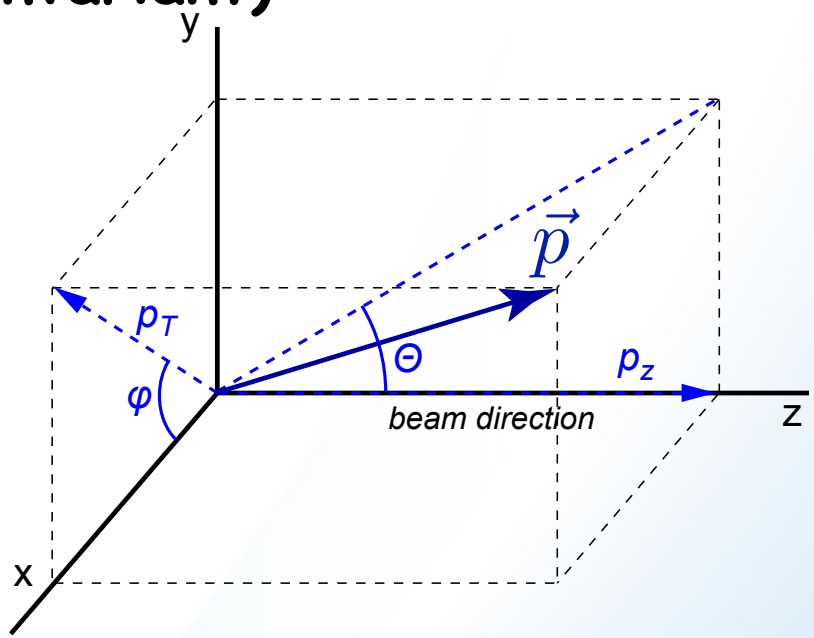
Boost in z:

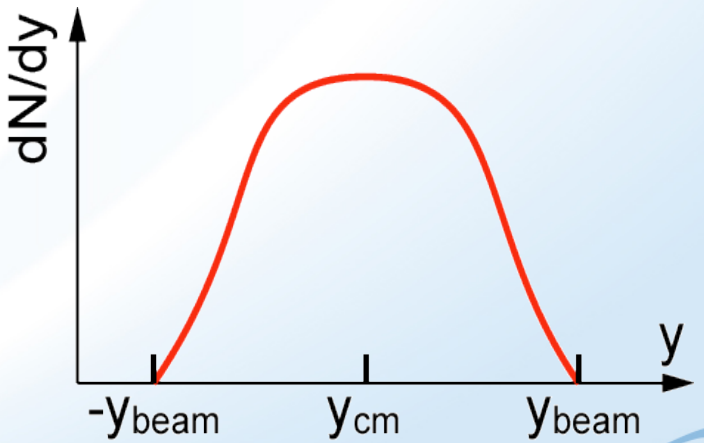
$$y \rightarrow y - \tanh^{-1} \beta$$

Pseudorapidity:

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

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





Kinematics

Strange but very common variables:

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

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

Useful relations:

$$\gamma = \cosh y$$
$$\beta = \tanh y$$
$$E = m_T \cosh y$$
$$p_z = m_T \sinh y$$

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

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
- ➡ $\gamma^{*}\rightarrow\mu^{+}\mu^{-}$, $\gamma^{*}\rightarrow e^{+}e^{-}$

★ **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: $\rho\rightarrow e^{+}e^{-}$ versus $\rho\rightarrow\pi^{+}\pi^{-}$**

- **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 → e + X, B → J/ψ (→ e e) + X) ⇒ hadron blind, little material

Collider Detector Concept

Particle types:

- neutrinos (missing energy)
- muons μ
- hadrons π, K, p
  - quarks, gluons jets
- electrons, photons, π^0
- charged particles

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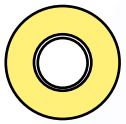

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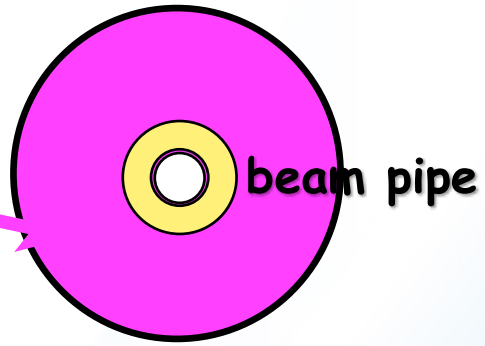
Rough Classification

track detectors for charged particles

- "massless" detectors
  - gas detectors
  - solid state detectors



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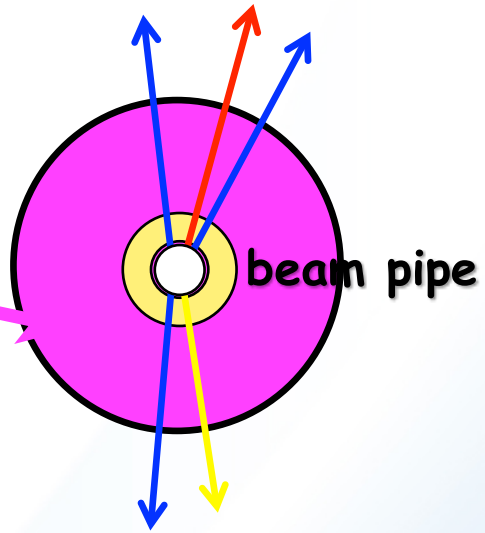

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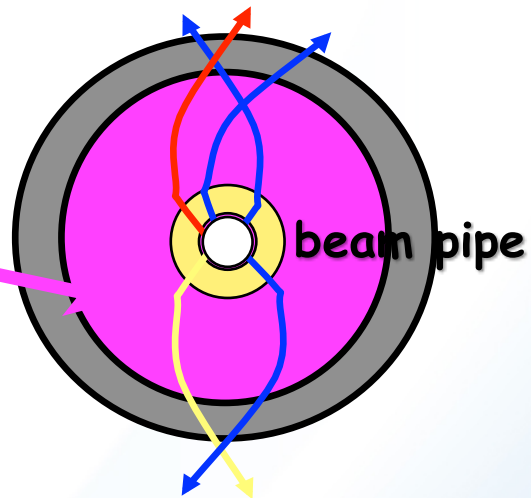
- magnet coil
  - (solenoid, field || beam axis)



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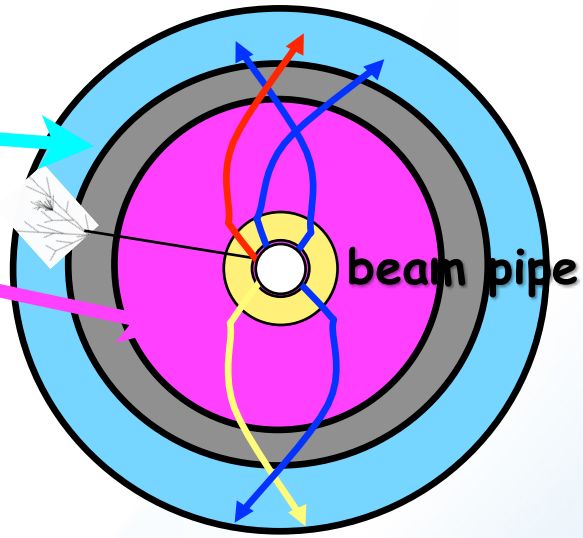
Calorimeter for energy measurement

electromagnetic
- high Z material (Pb-glas)



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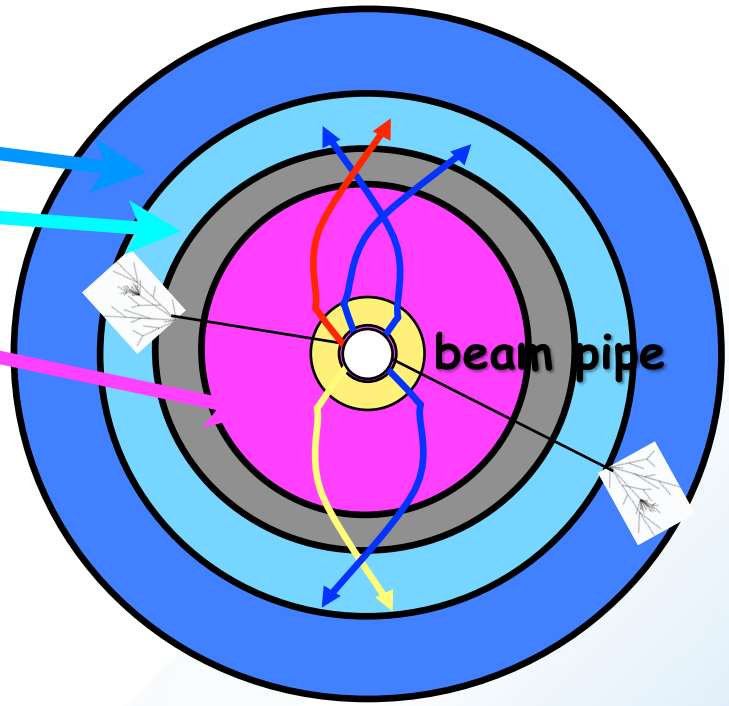
Calorimeter for energy measurement

- electromagnetic
  - high Z material (Pb-glas)
- hadronic
  - heavy medium (Fe, Cu, U)
    - + active material



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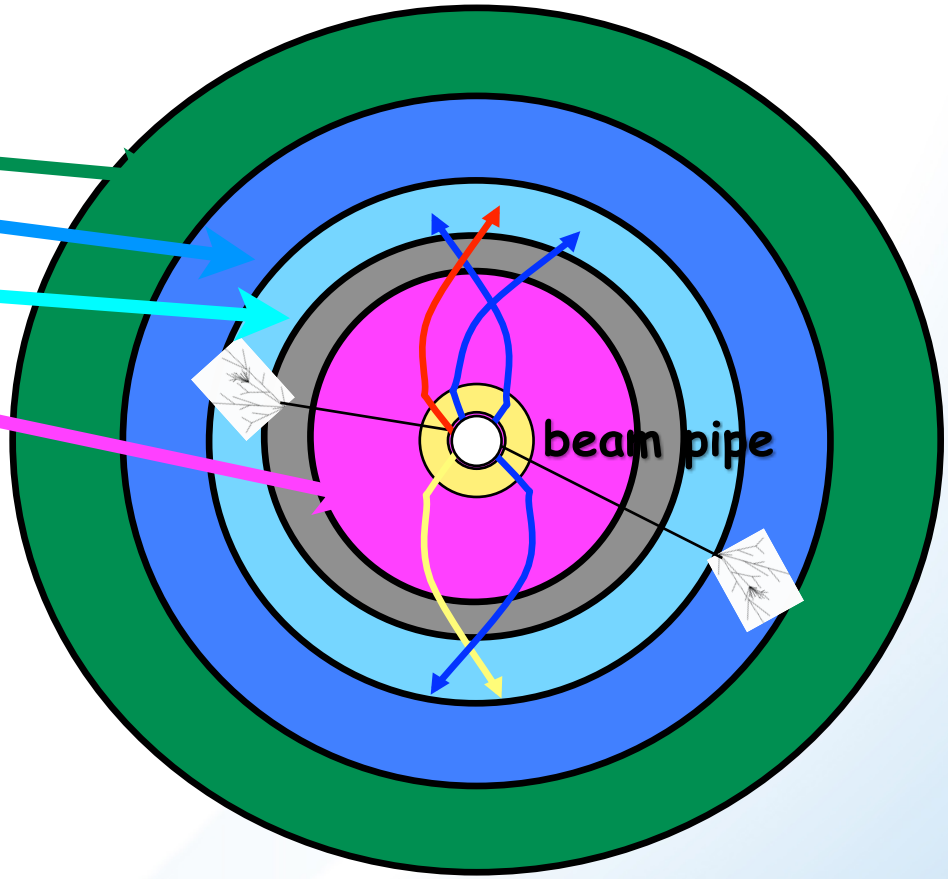

Rough Classification

track detectors for charged particles

"massless" detectors

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(solenoid, field || beam axis)

Calorimeter for energy measurement

electromagnetic

high Z material (Pb-glas)

hadronic

heavy medium (Fe, Cu, U)

+ active material

absorber (mostly Fe)

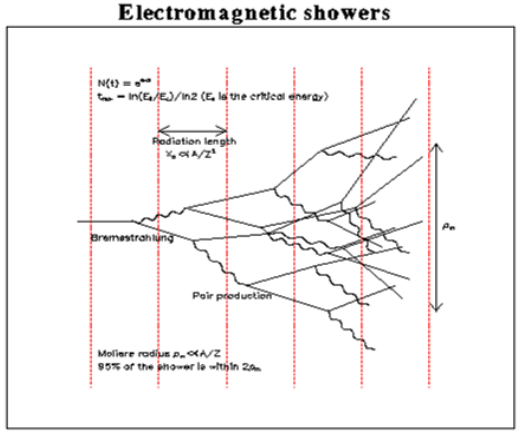
flux return yoke +

active material

Particle identification – long lifetime (>5 ns)

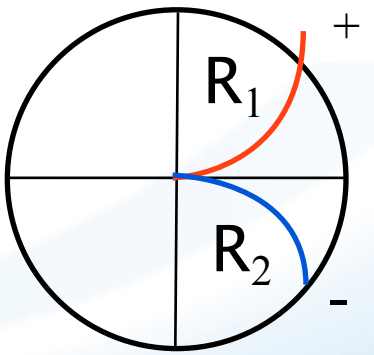
Examples: π, K, γ, p, n, …
Charge (if any!) and 4-momentum needed for PID
4-momentum from at least two of these quantities:

energy → **calorimetry** → Fully stop the particle
Convert its energy to
- light, charge…
Collect and read out

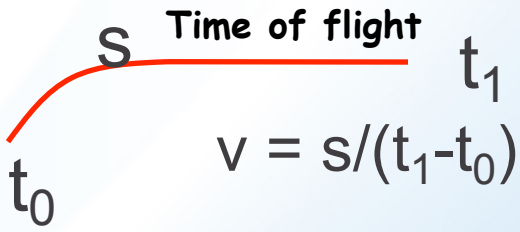


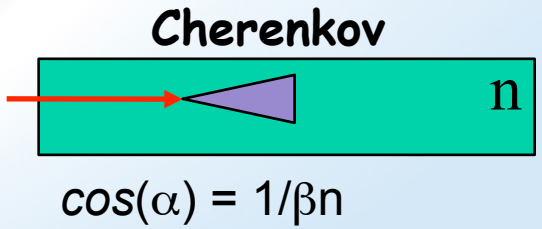
3-momentum → **tracking** → Follow path of charged particles in magnetic field – get momentum from curvature

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



velocity → **time-of-flight + pathlength or Cherenkov-effect**





Particle identification – long lifetime (>5 ns)

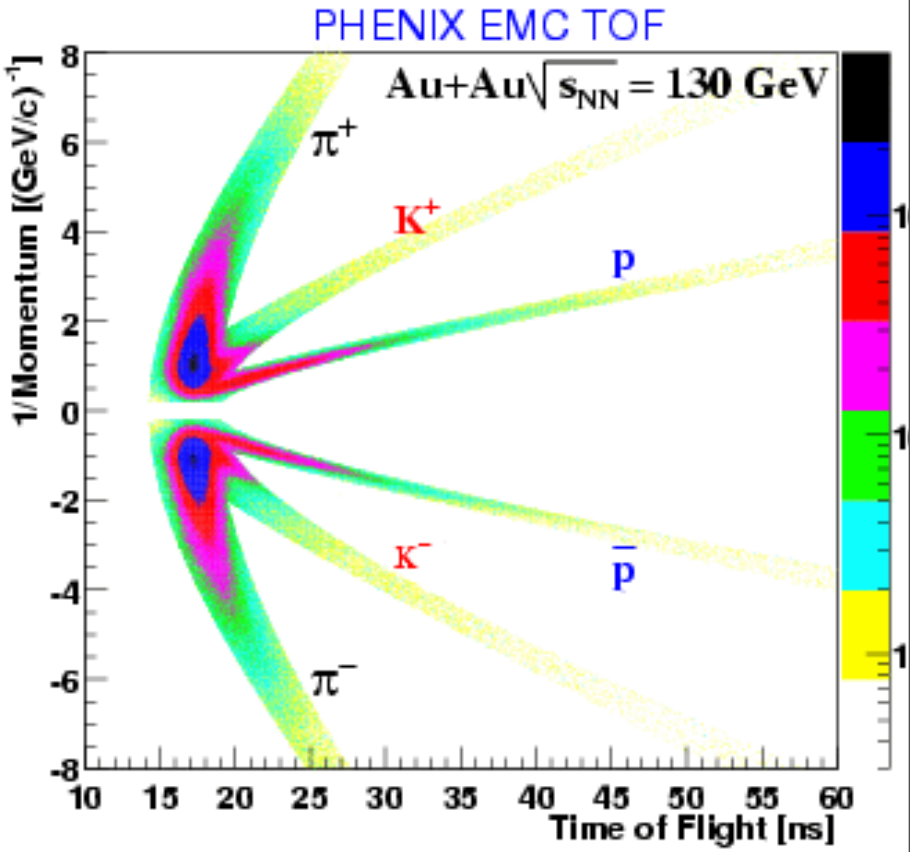
Why do I emphasize long lifetime? Because the detectors are fairly large, and the particle produced at the vertex has to survive until it reaches the detector!

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

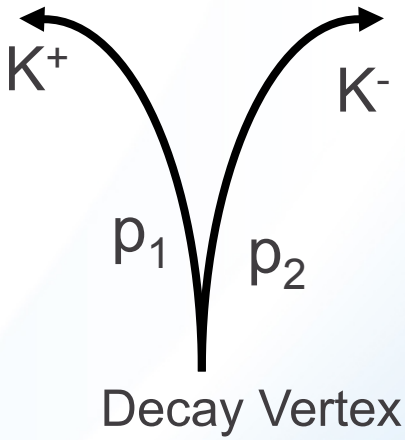
Particle identification – short lifetime (<5 ns)

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

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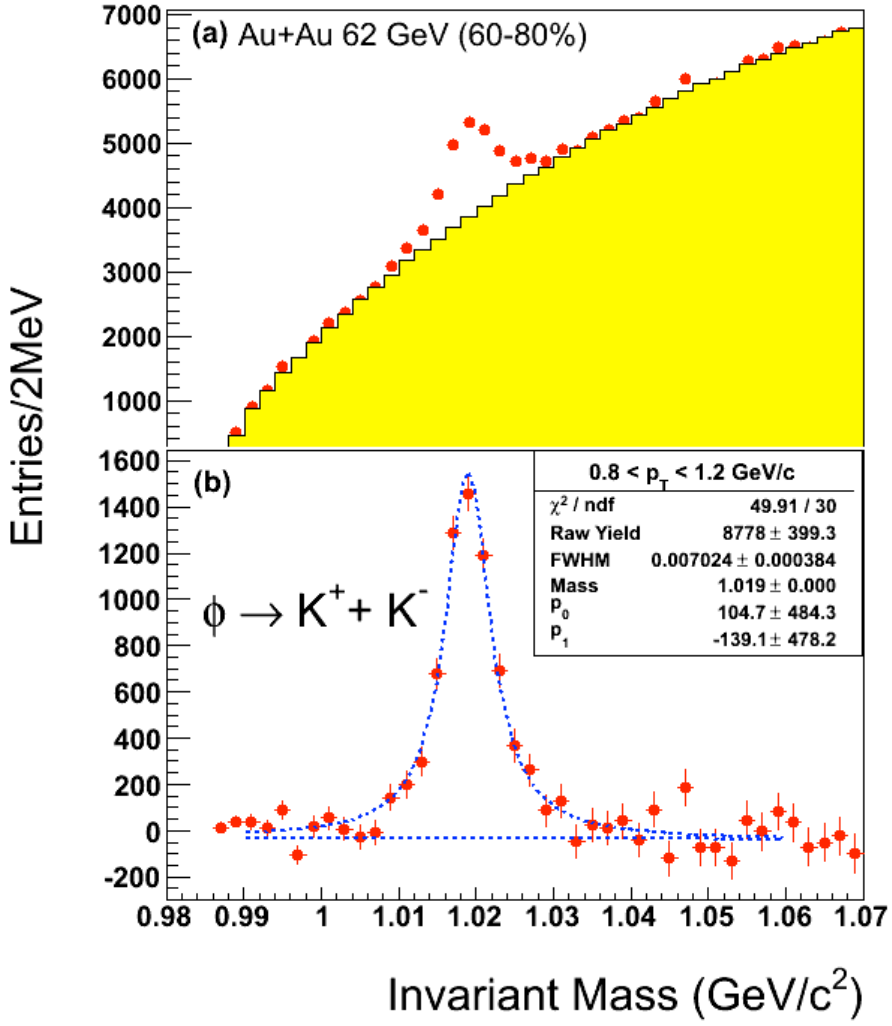
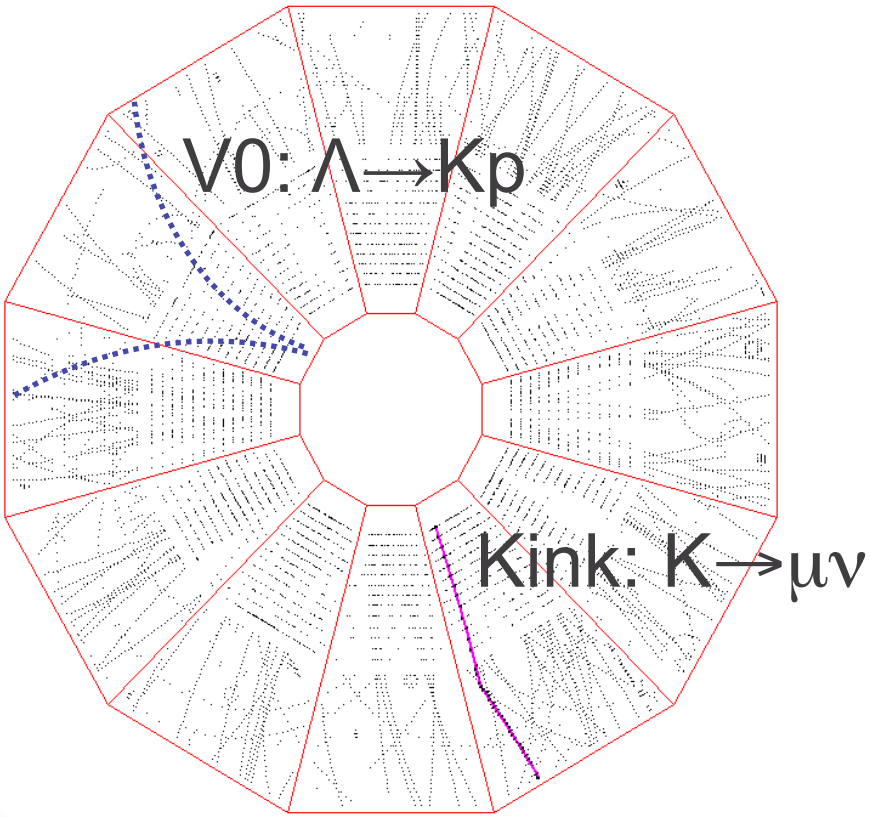


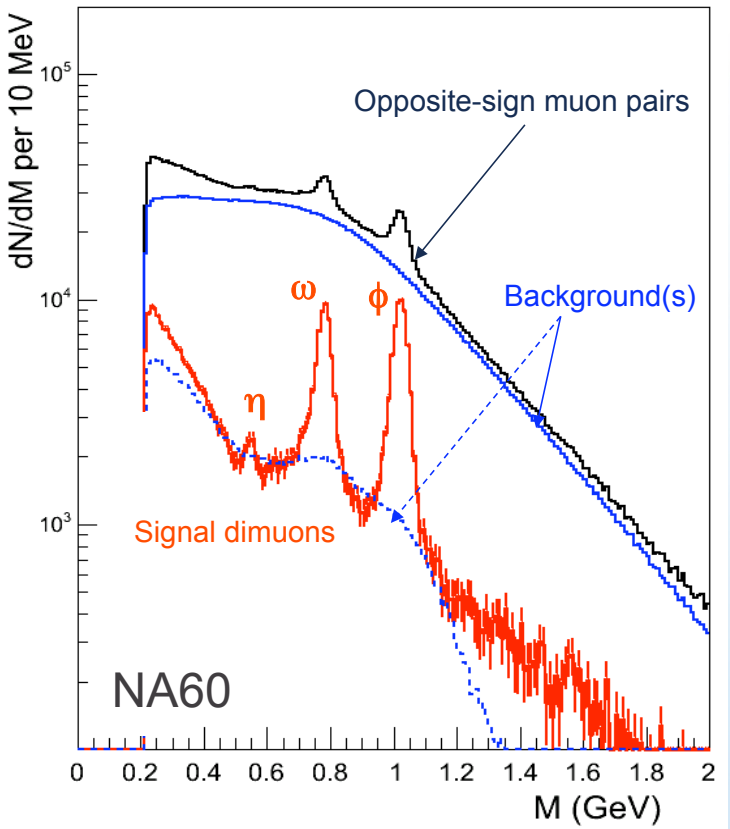
Particle identification – short lifetime (<5 ns)

Different topologies



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

What if cτ ~ fm ?



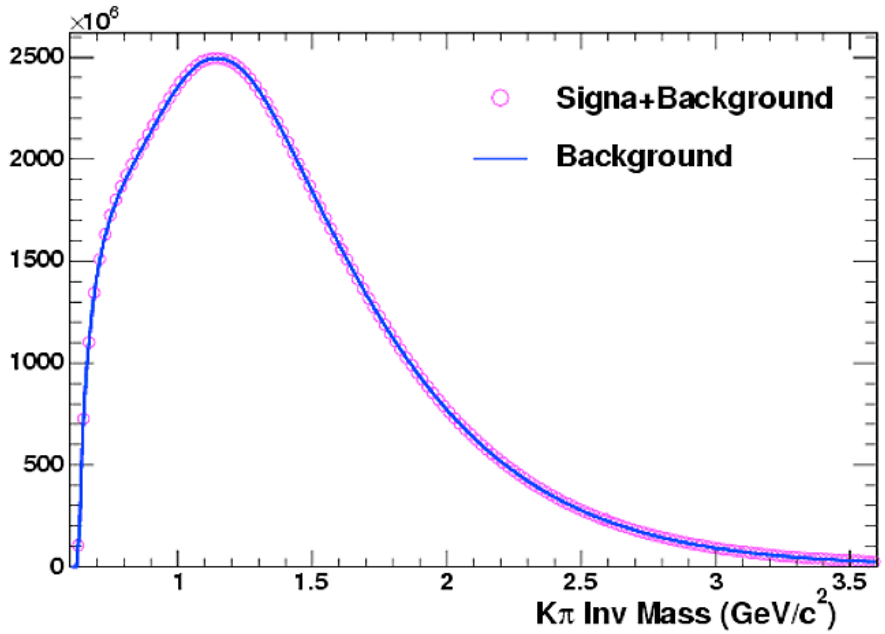
Works as well but usually more background

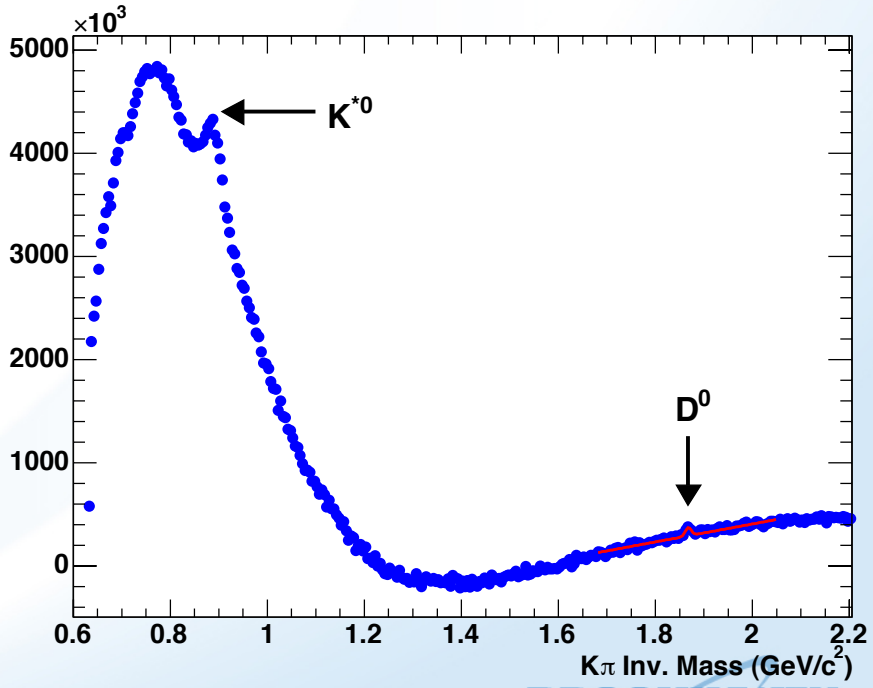
Particle identification – very short lifetime <1mm

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

★ 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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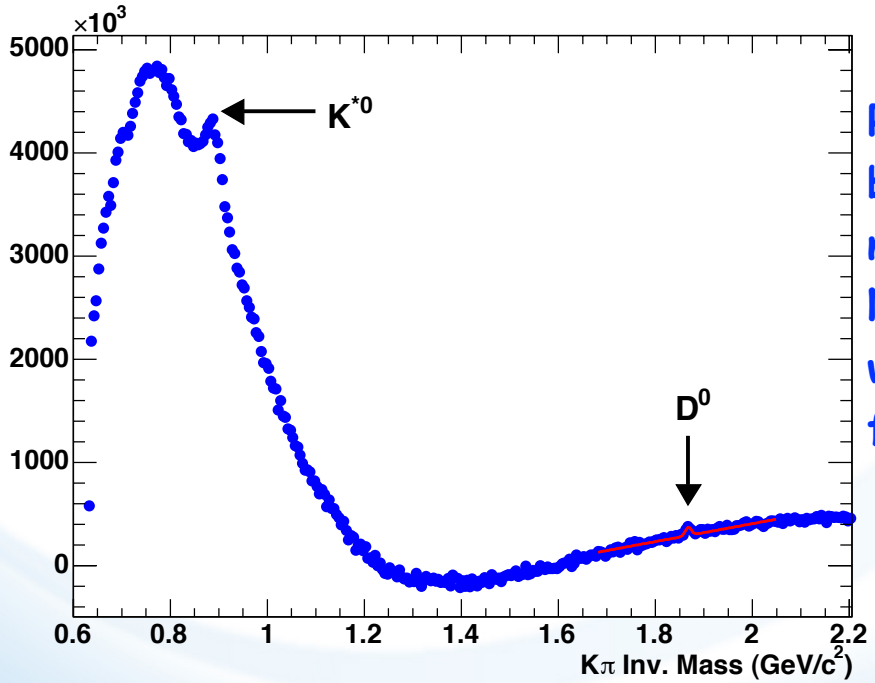
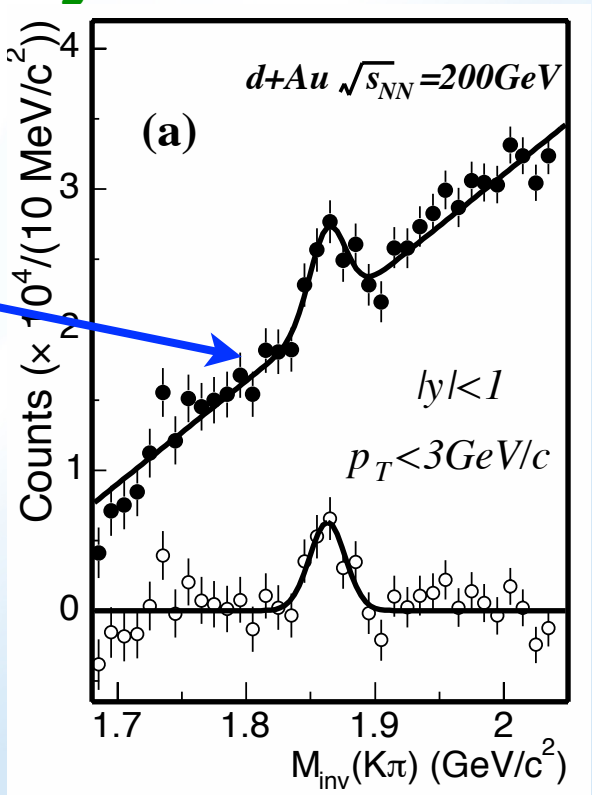


Residual background not eliminated. Needs further work to get to final spectra..



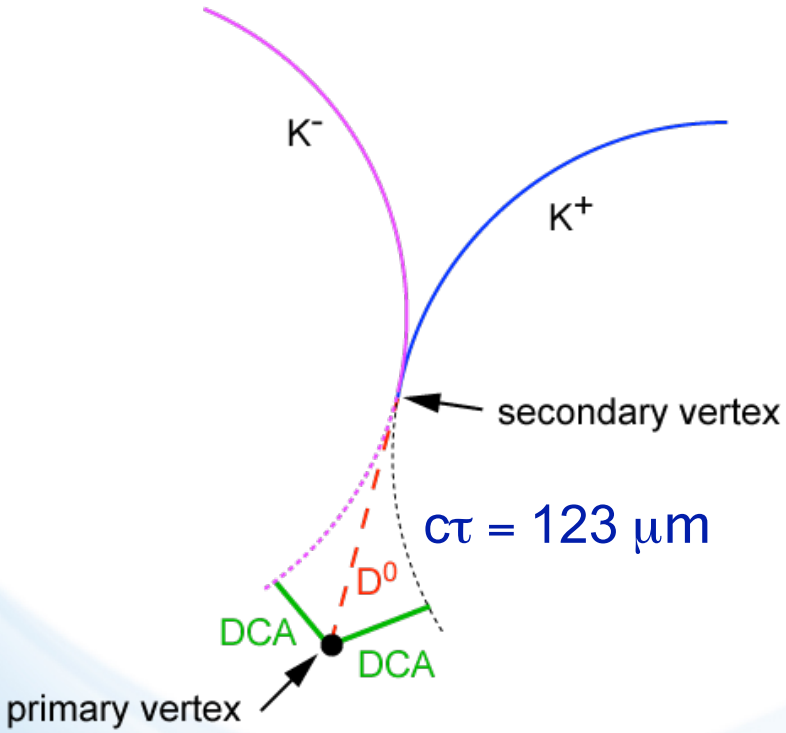
Particle identification – very short lifetime <1mm

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

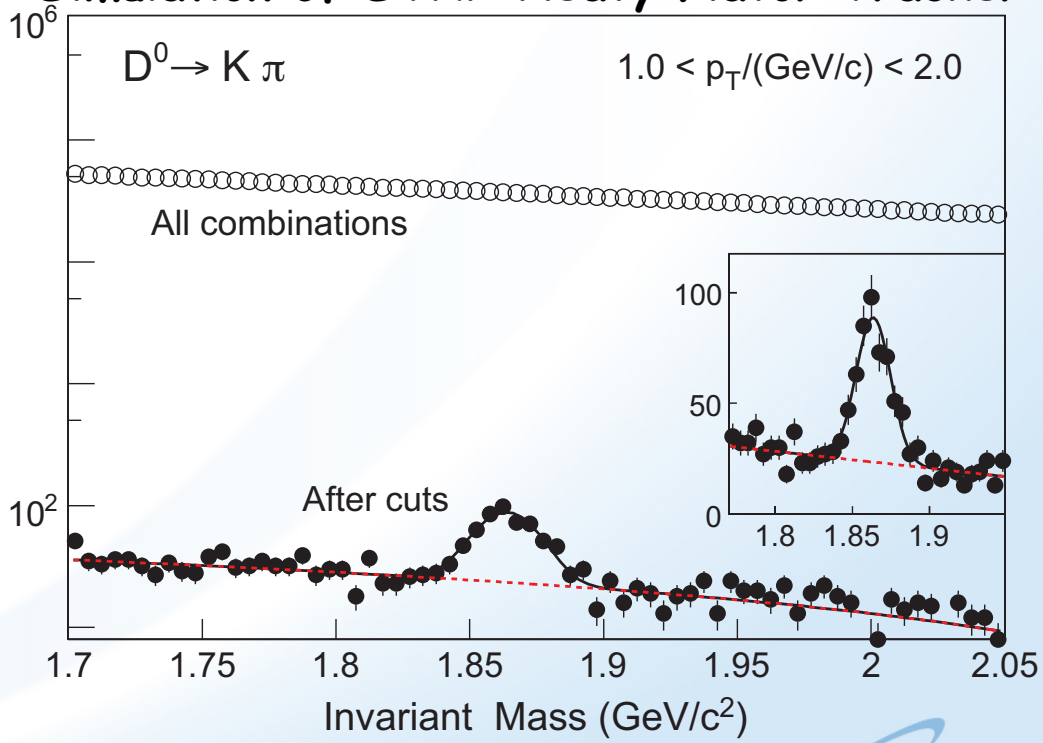
Secondary decay vertex

Reconstruction requires high resolution (δx ~ cτ/10) Silicon detectors detectors

The RHIC experiments soon get one (STAR) or just got one (PHENIX)



Simulation of STAR Heavy Flavor Tracker



DCA: distance of closest approach

RHIC experiments in a nutshell

BRAHMS

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

PHOBOS

small experiment - "tabletop"
(i) huge acceptance $\Delta\varphi$, $\Delta\eta$, no p_T info, no PID
(ii) small acceptance $\Rightarrow$ very low - low p_T, moderate PID

PHENIX

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

STAR

large experiment
acceptance central arms: $\Delta\varphi = 2\pi$, $\Delta\eta = \pm 1$ + forward
hadrons, jets, leptons, photons

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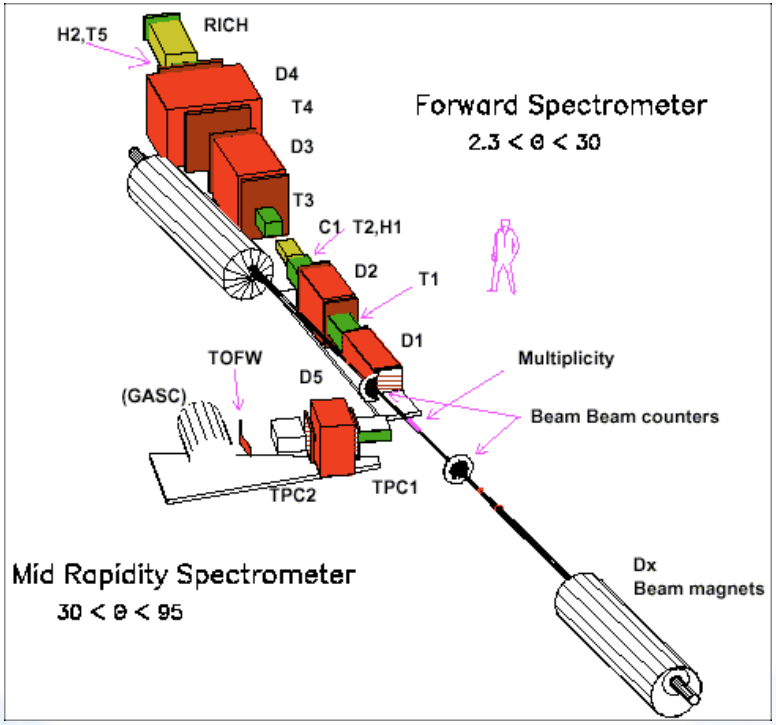
The Two "Small" Experiments at RHIC

BRAHMS

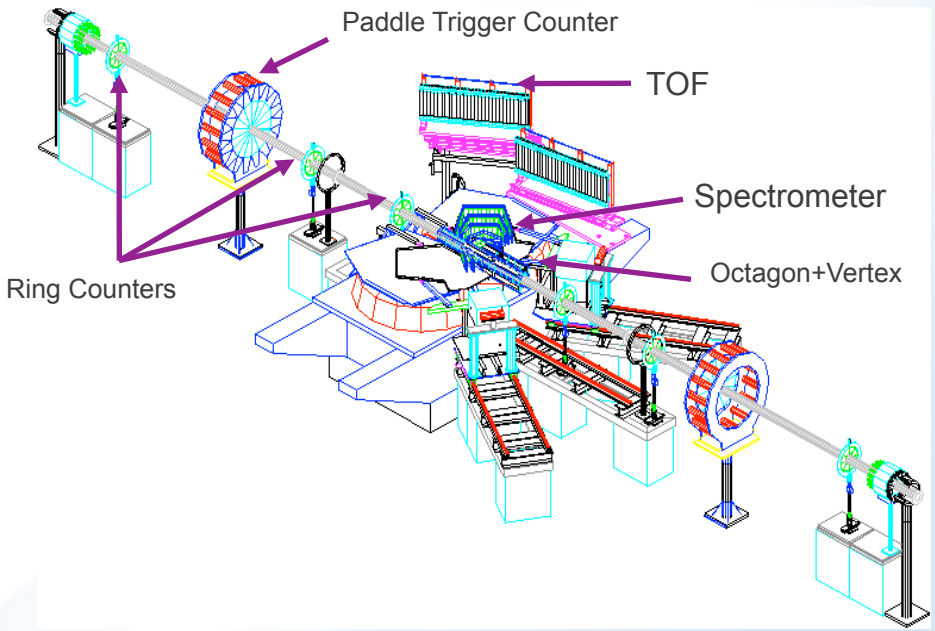
2 "Conventional" Spectrometers
Magnets, Tracking Chambers,
TOF, RICH, ~40 Participants



- Inclusive Particle Production Over Large Rapidity Range

PHOBOS

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



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

The Two "Large" Detectors at RHIC

STAR

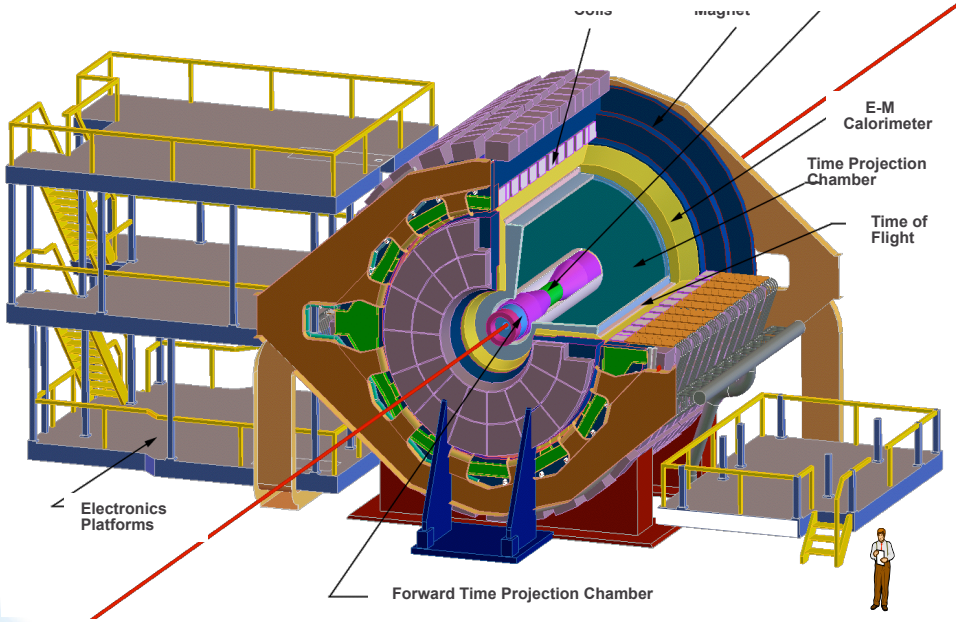
Solenoidal field

Large-Ω Tracking:

TPC's, Si-Vertex Tracking

RICH, EM Cal, TOF

~420 Participants



PHENIX

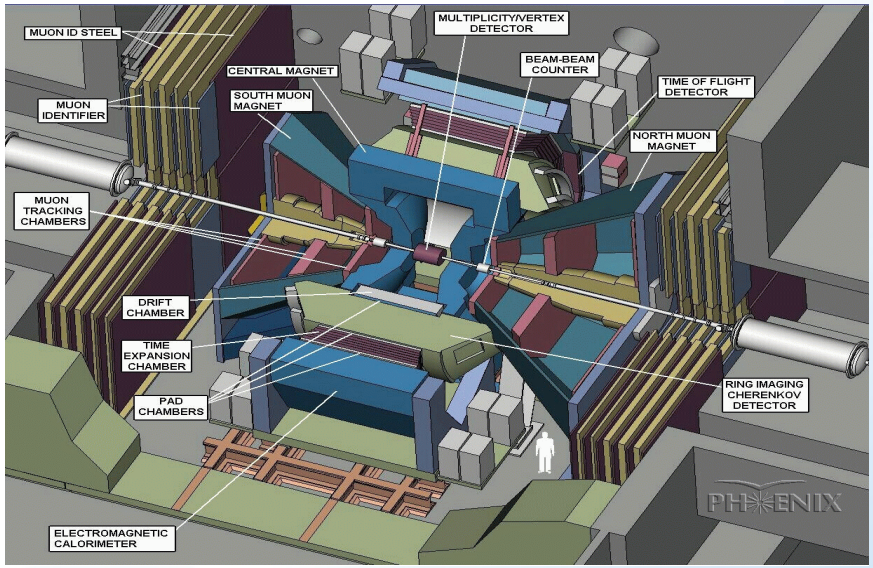
Axial Field

High Resolution & Rates

2 Central Arms, 2 Forward Arms

TEC, RICH, EM Cal, Si, TOF, μ-ID

~450 Participants



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

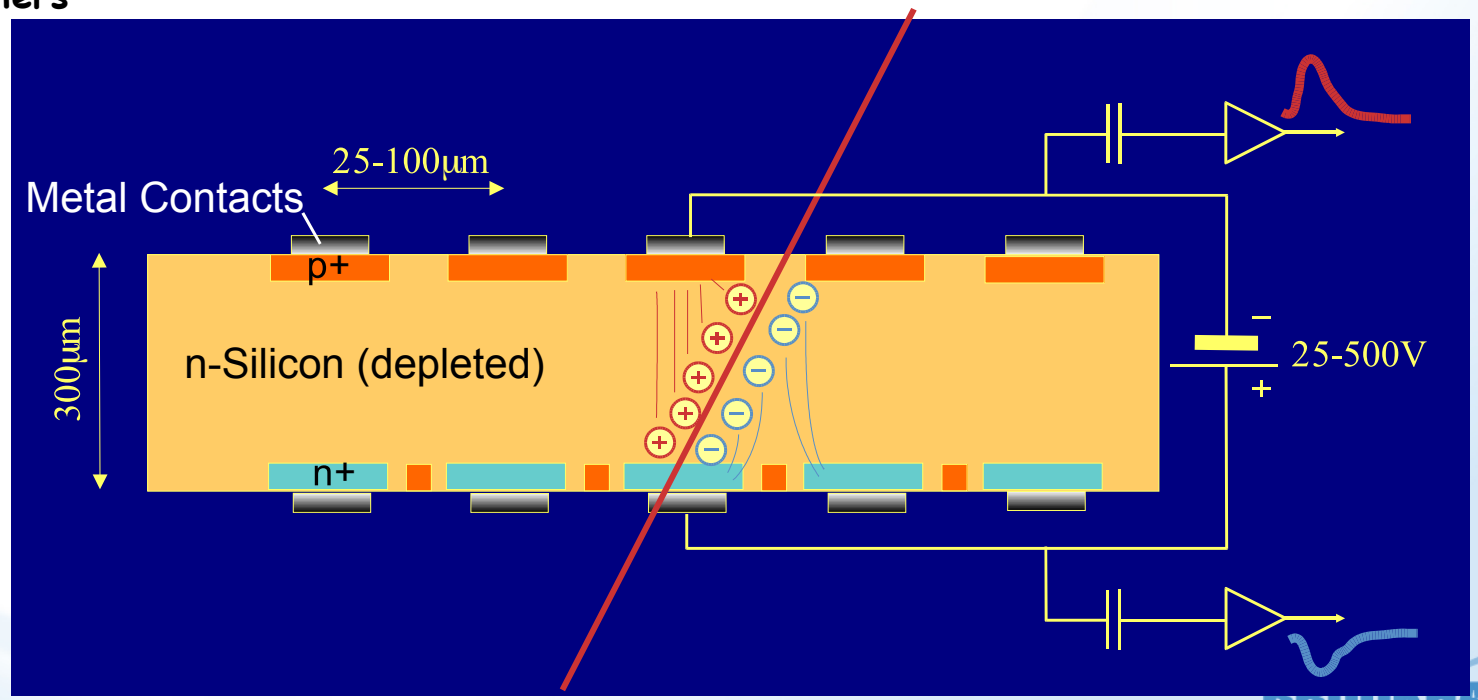
- ✓ Leptons, Photons, and Hadrons in Selected Solid Angles
- ✓ Simultaneous Detection of Various Phase Transition Phenomena

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.**
- **In a solid semiconductor, ionization produces electron-hole pairs. For 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

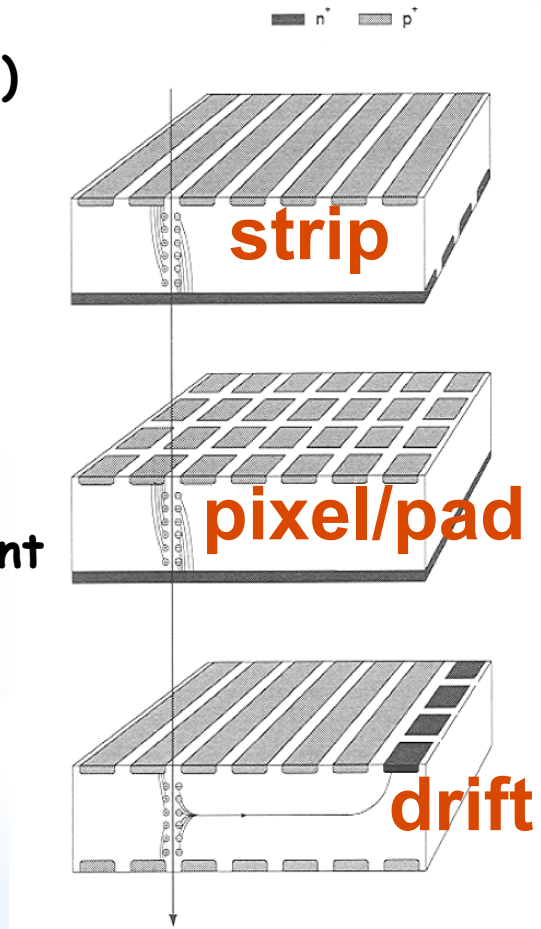
➡ Pixel devices

- True 2D measurement (20-400μm pixel size)
- Small areas but best for high track density environment

➡ Pad devices ("big pixels or wide strips")

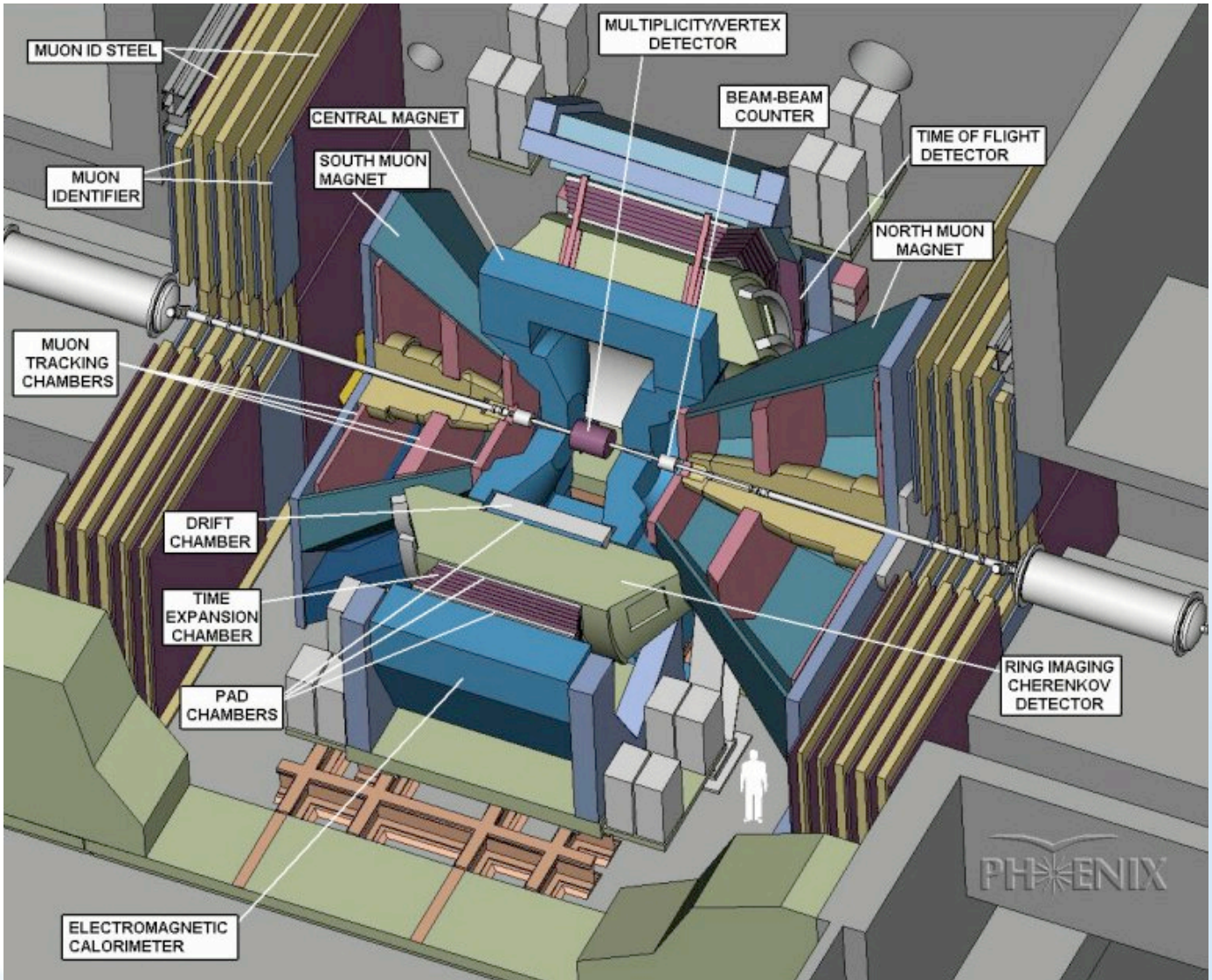
- Pre-shower and calorimeters
- Multiplicity detectors

➡ Drift devices



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:

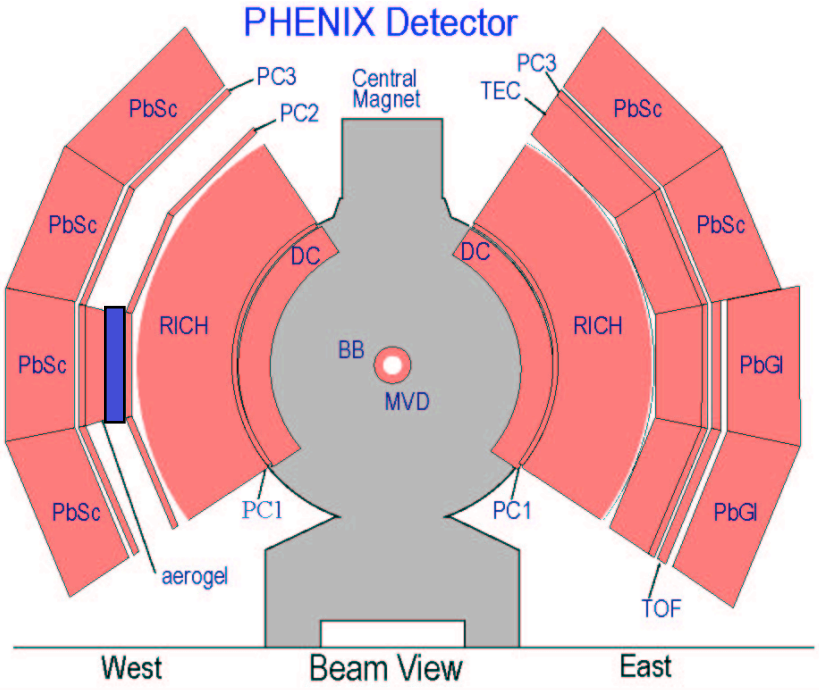
- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Gap Resistive Plate Chamber ToF
- Hadron Blind Detector

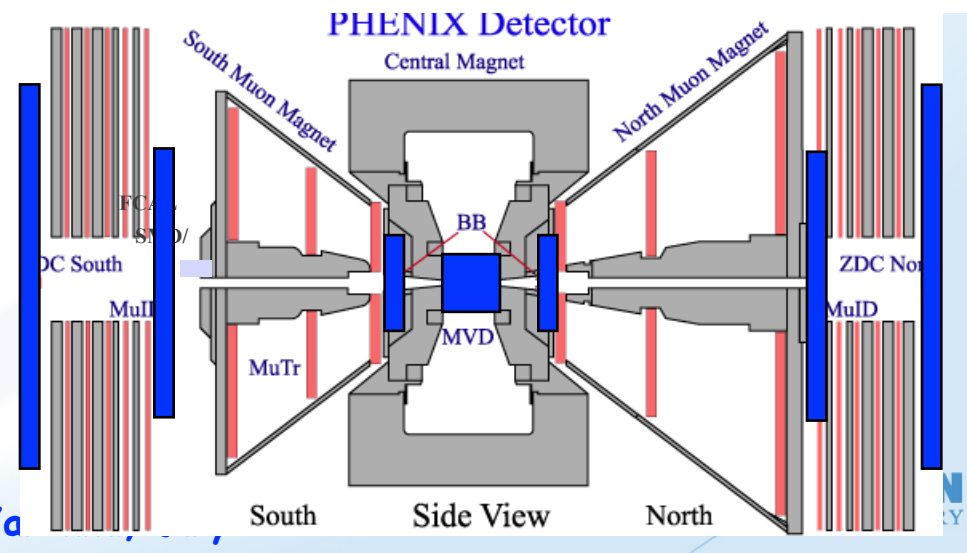
Calorimetry:

- Pb Scintillator
- Pb Glass
- Muon Piston Calorimeter

Event Characterization:

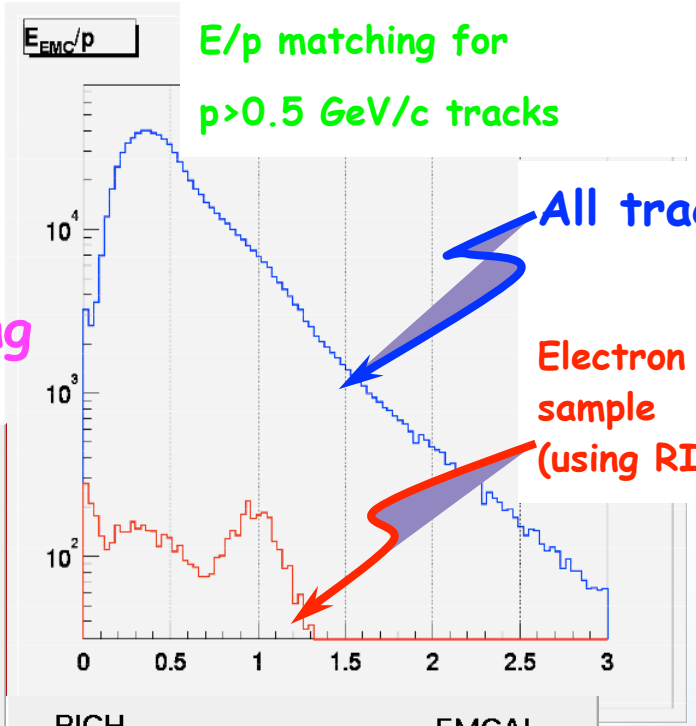
- Beam-Beam Counter
- Zero Degree Calorimeter/Shower Max Detector
- Forward Calorimeter
- Reaction Plane Detector

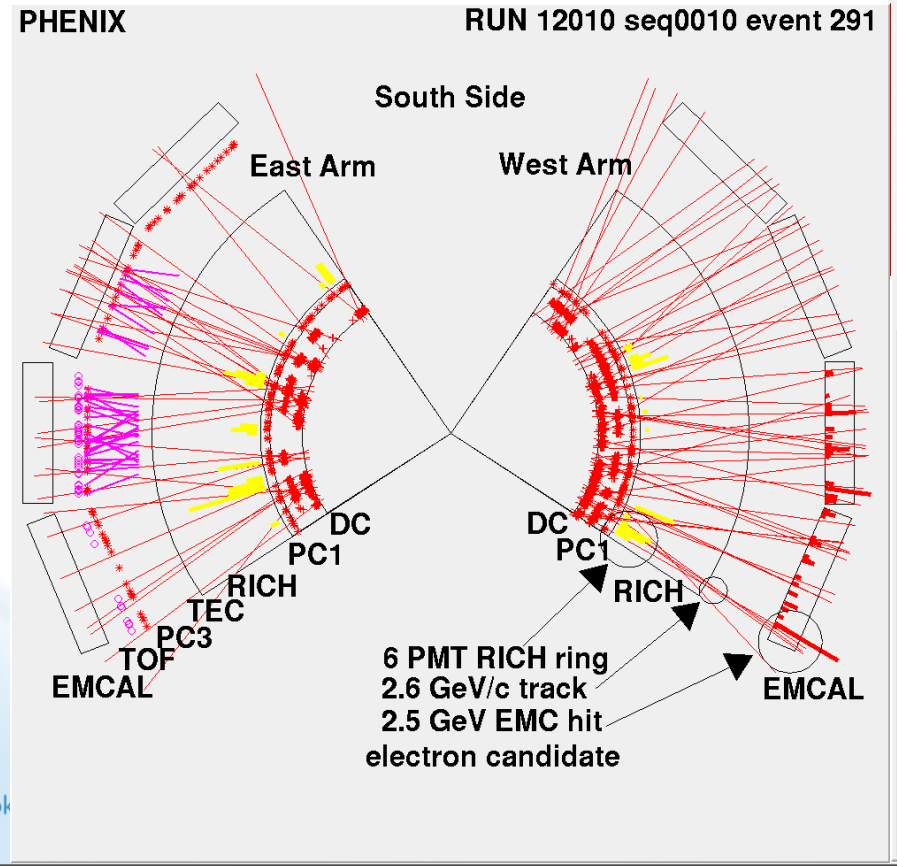


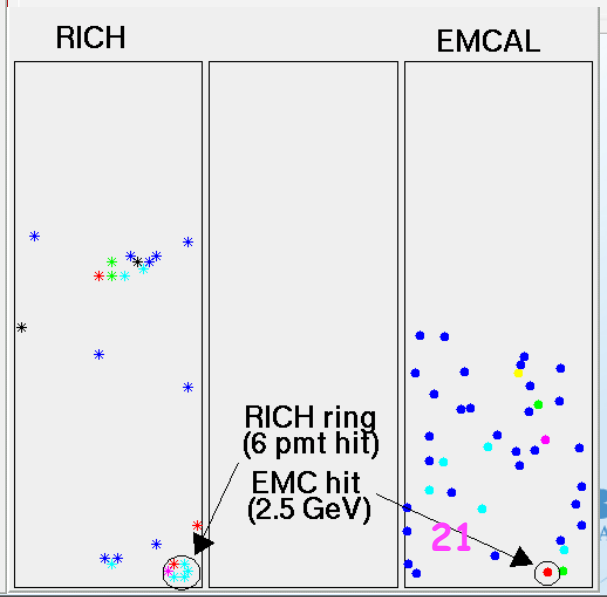


Electron Identification

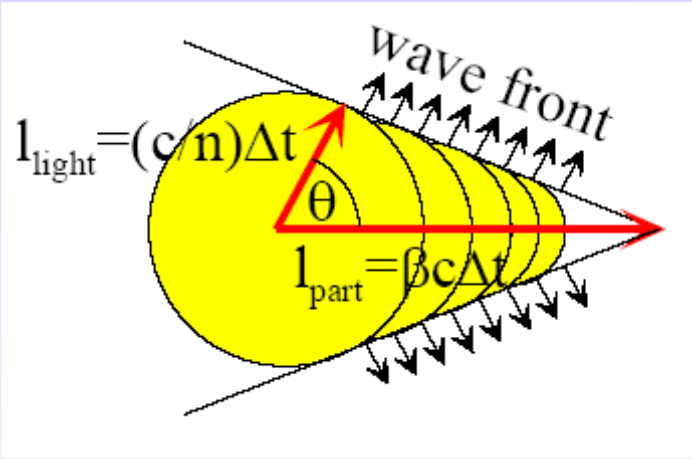
- Problem: They're rare
- Solution: Multiple methods
  - Čerenkov (RHIC)
  - E(Calorimeter)/p(tracking) matching







Cherenkov (Čerenkov) detectors

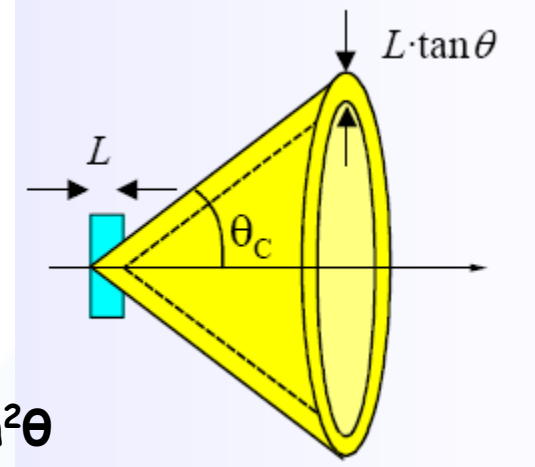


Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity

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

may emit light along a conical wave front.

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



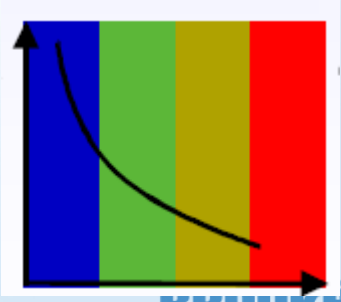
Energy loss by Cherenkov radiation small compared to ionization (≈0.1%). Cherenkov effect is a very weak light source → need highly sensitive photodetectors.

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

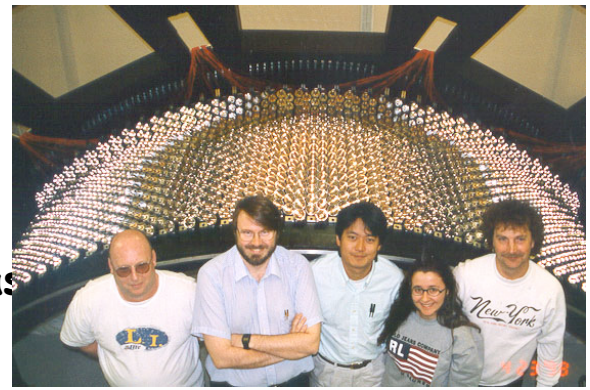
N_0: number of merit for a Cherenkov detector

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

dn/dλ

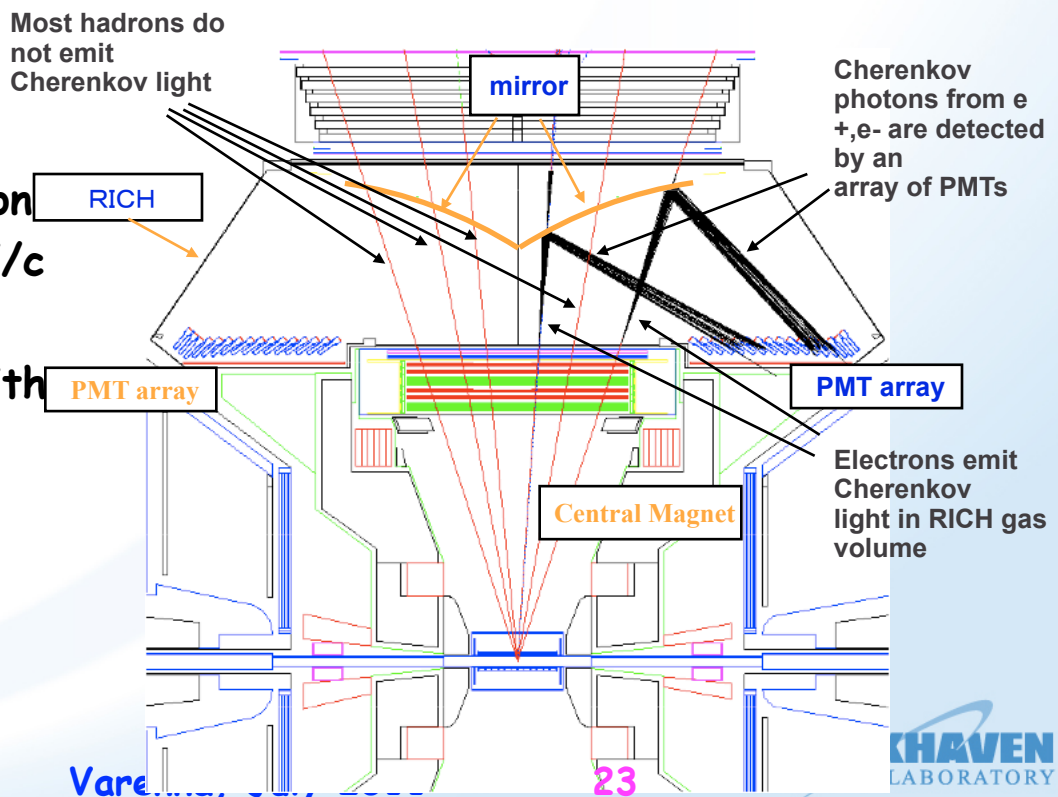


PHENIX PID via Cherenkov



Key features

- ★ Ring imaging Cherenkov with gas 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 less than ~ 4 GeV/c
- ★ Limit: 5 GeV/c ⇒ $R_e \cong R_\pi$
- ★ Two ring separation:
  ~ few degrees in both θ and φ



Calorimeter in a nutshell

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

Tracking in B field: $\delta p/p \propto p_T/L^2$

$\Rightarrow$ resolution degrades with increasing energy (unless $L \propto \sqrt{E}$)

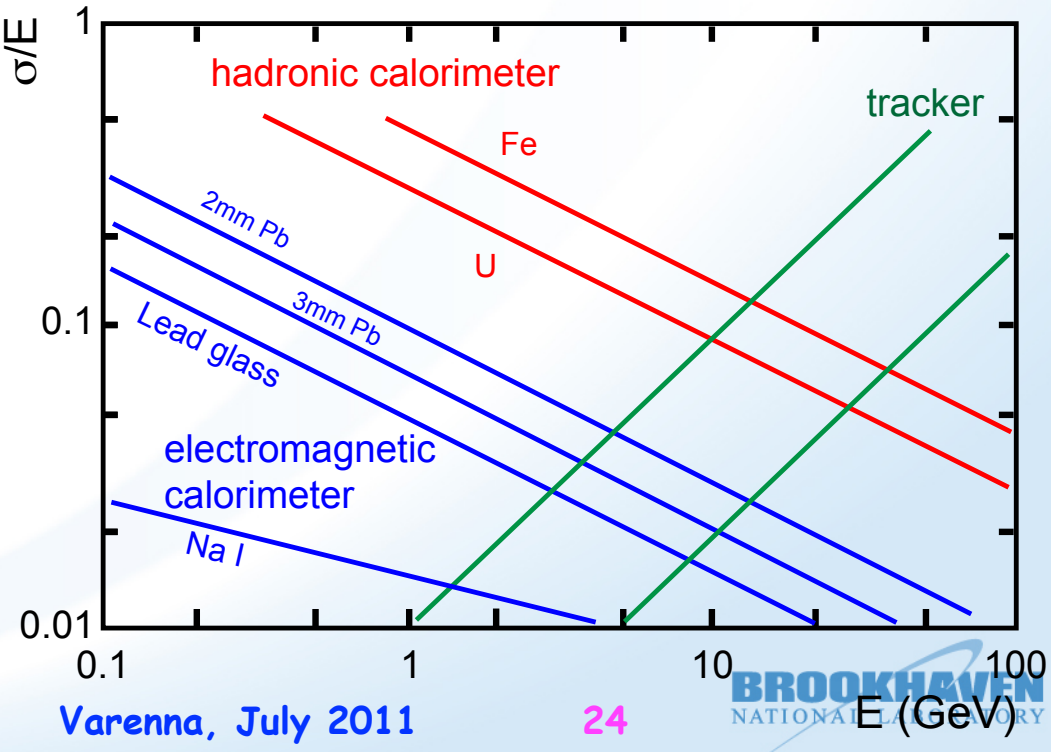
also: works only for charged particles

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

$\Rightarrow$ for high energy

detectors calorimeters are essential components

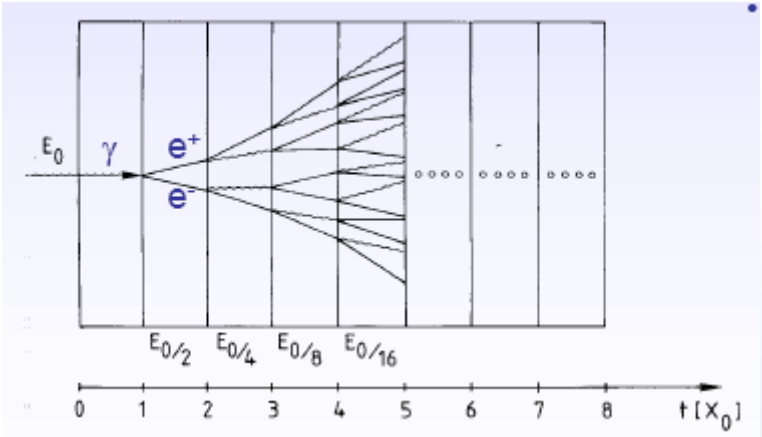
RHIC: only EMcals



Calorimeters in a nutshell

★ EM Shower

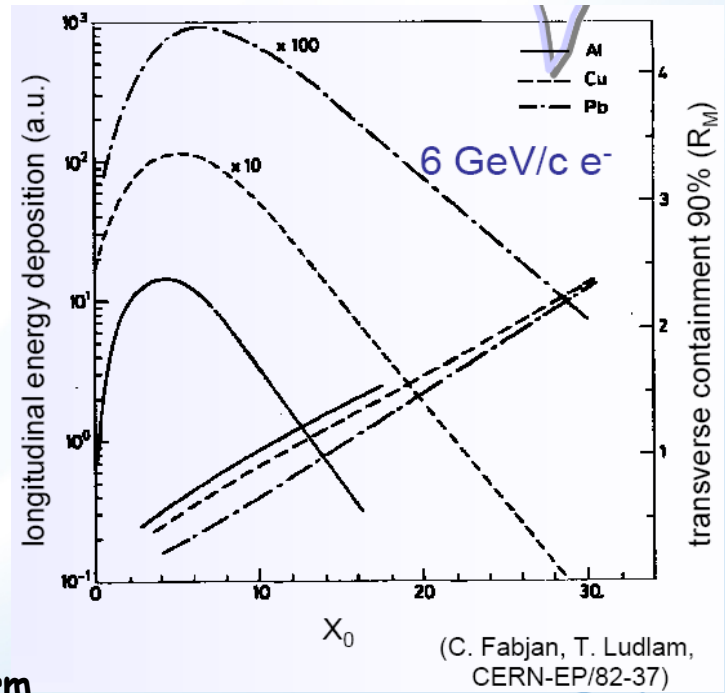
- above 10 MeV (γ, e)
- pair production: $\gamma \rightarrow e^+e^-$
- bremsstrahlung: $e \rightarrow e\,\gamma$
- characterized by radiation length X_0
- longitudinal:
  - ➡ $dE/dt \sim t^{\alpha} e^{-t}$ where $t = x/X_0$
  - ➡ shower maximum
- transverse:
  - ➡ 95% of shower in cylinder with 2 R_M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



★ Resolution

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

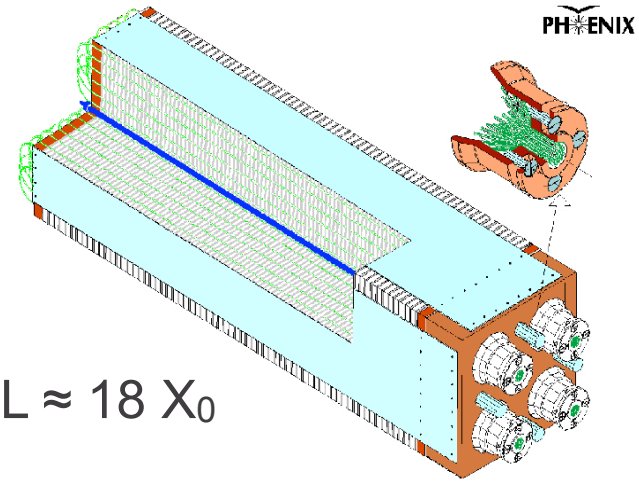
stochastic term — constant term — noise term



Two PHENIX Calorimeters

PbSc Calorimeter

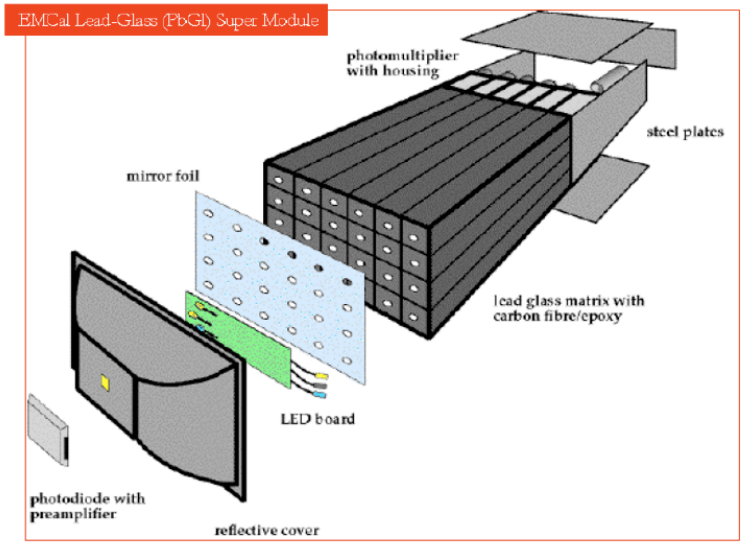
Lead-scintillator sandwich (sampling)
Wavelength-shifting fiber light transport
Photomultiplier readout



$L \approx 18\ X_0$

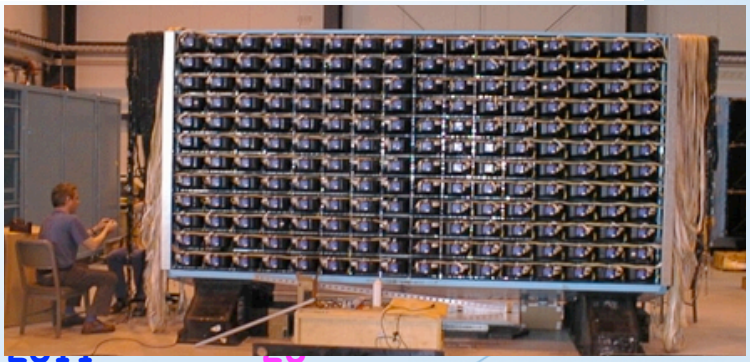
PbGl Calorimeter

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



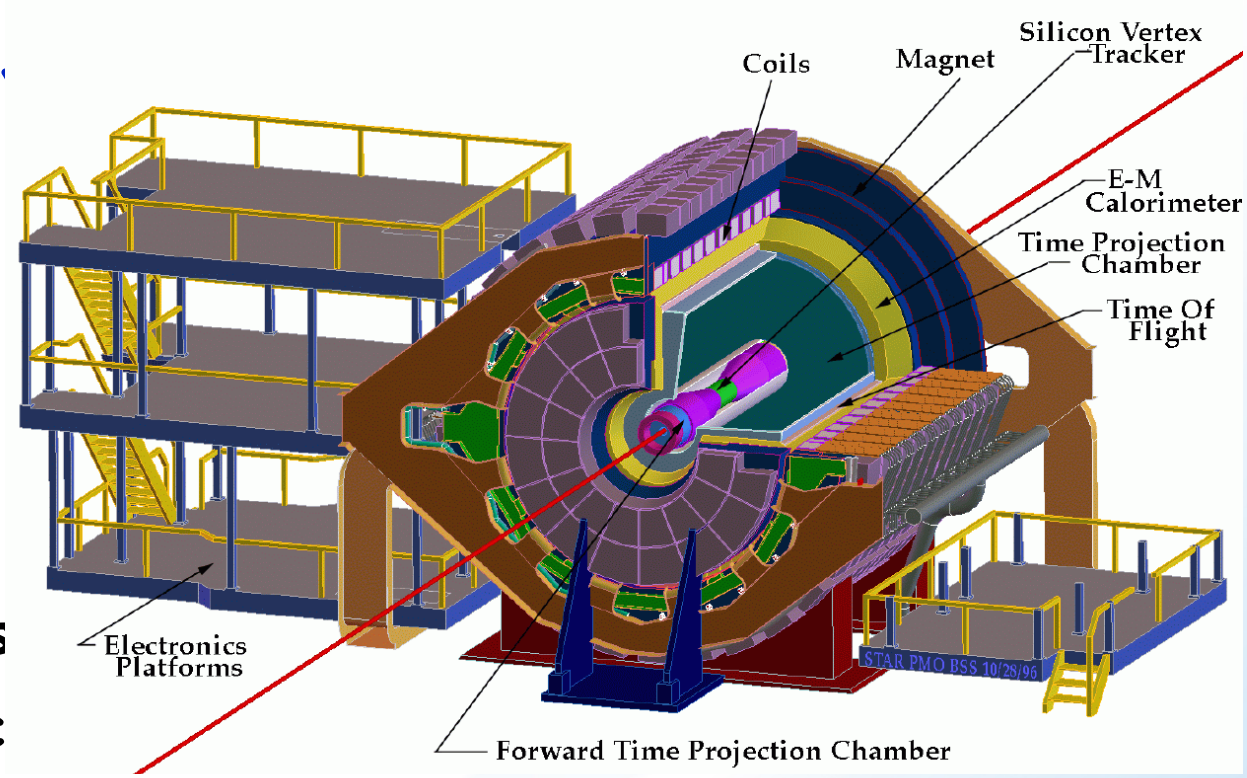
PbSc: $\sigma(E)/E \approx 8\%/\sqrt{E}$

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

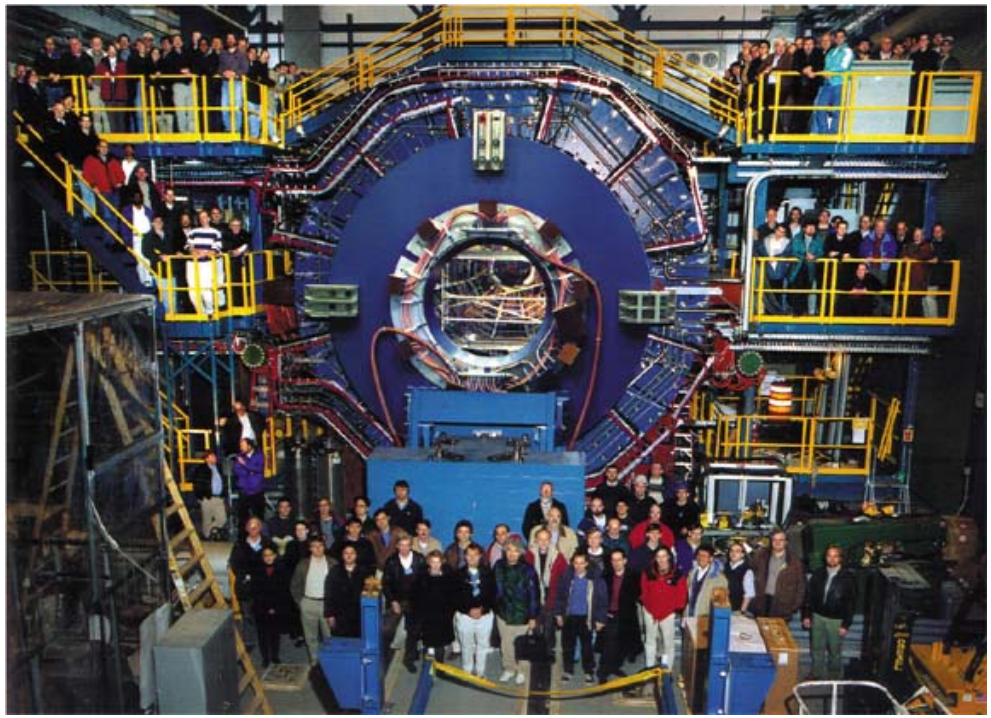


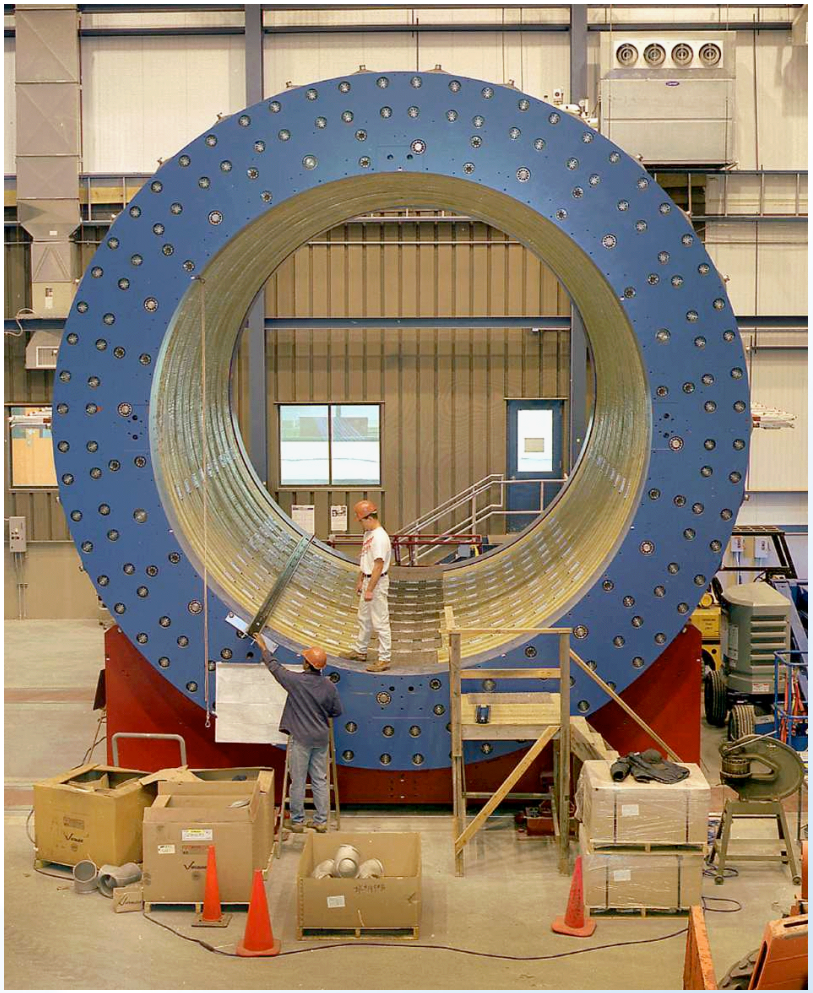
STAR

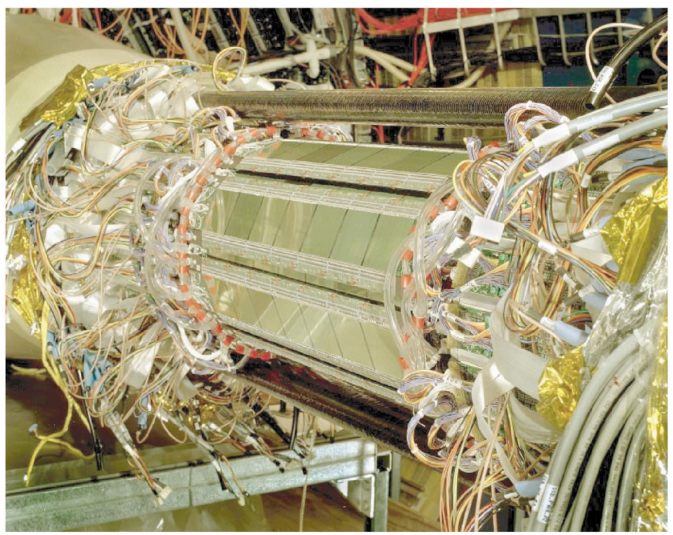
- ★ An experiment with something for ever
  - ✦ Hadrons
  - ✦ Jets
  - ✦ Electrons
  - ✦ Photons
- ★ Features
  - ✦ Typical HEP Des
  - ✦ Large acceptanc
  - ✦ Solenoidal field
  - ✦ Main detector: TPC
  - ✦ E.M. Calorimetry (central + forward)



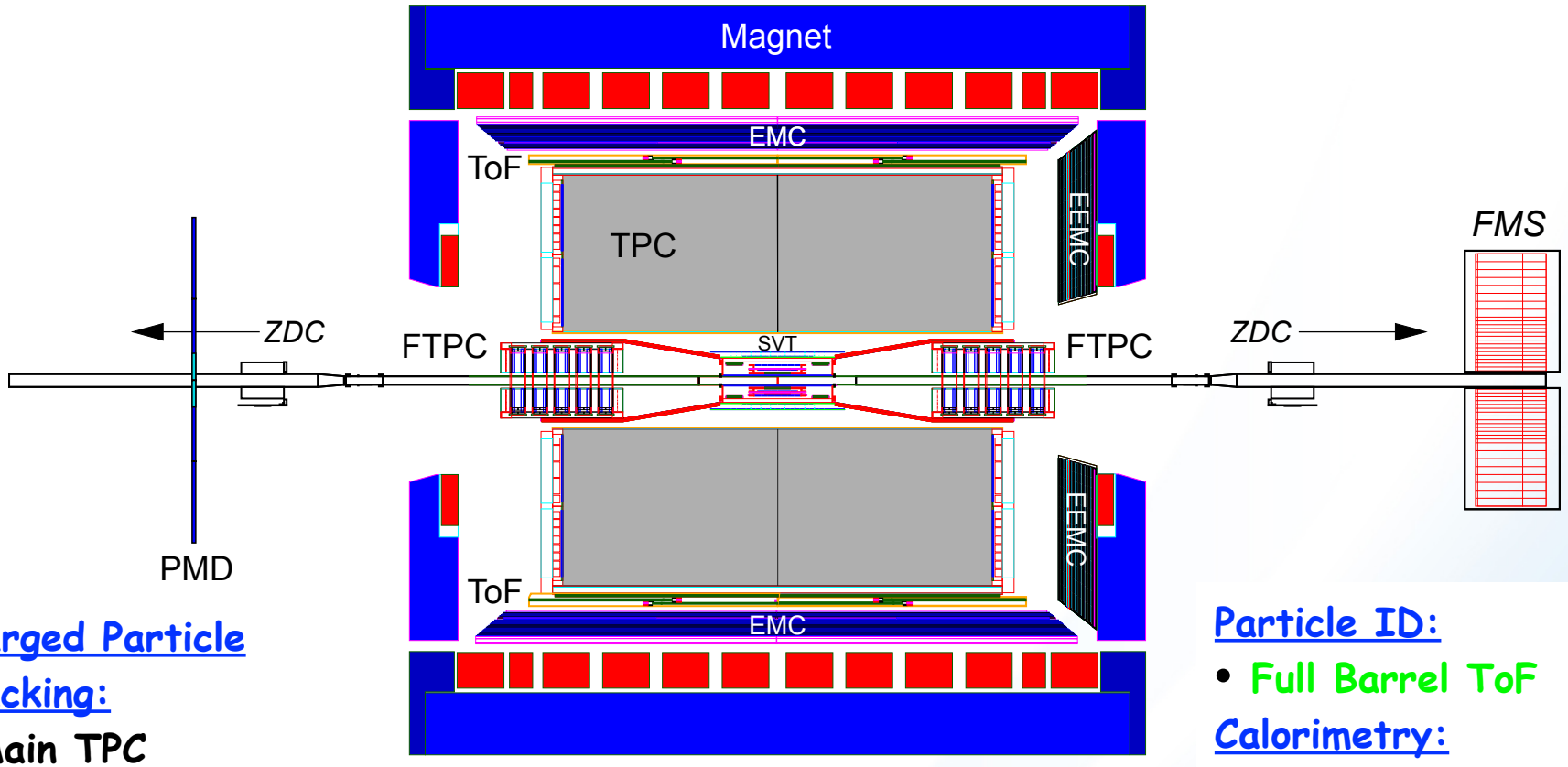
STAR (2001)







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:

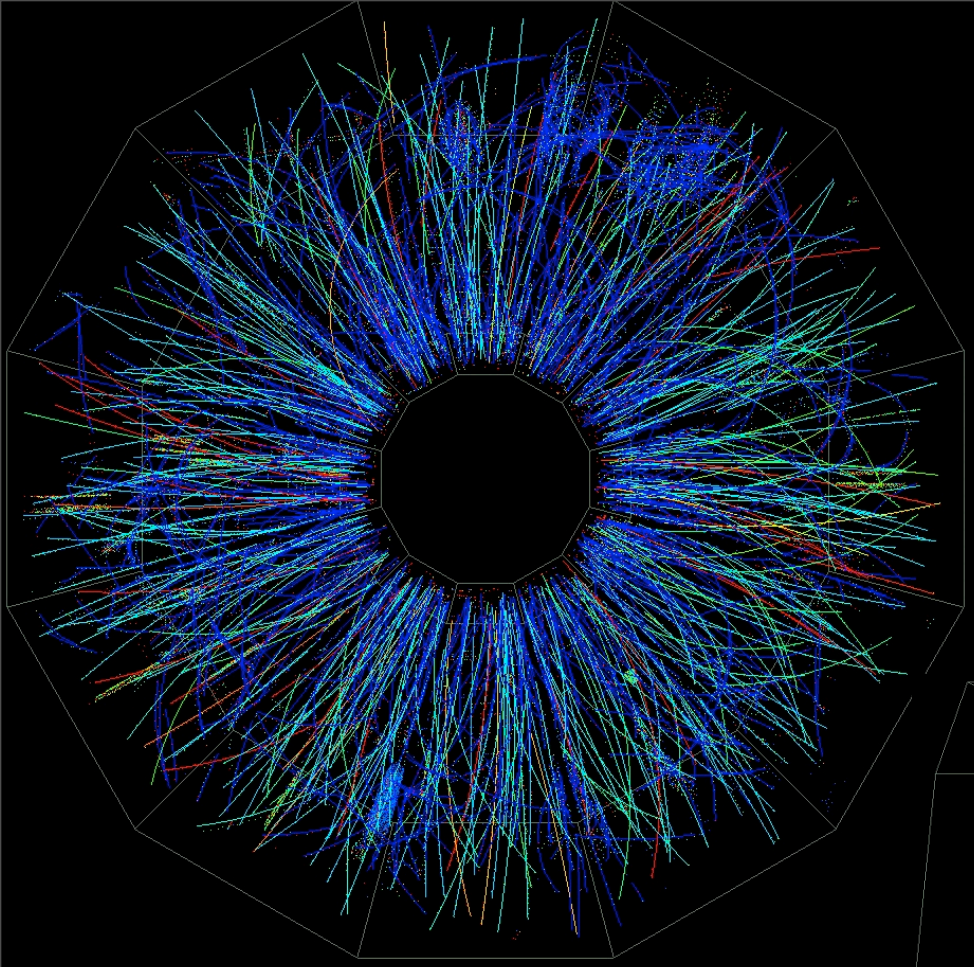
- Beam-Beam Counter (BBC)
- Zero Degree Calorimeter (ZDC)
- Forward Pion Detectors (FPD)

Particle ID:

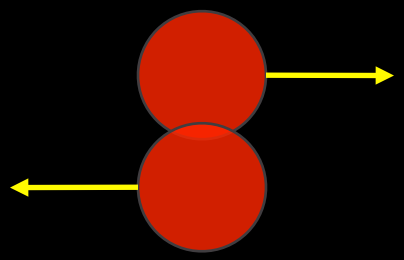
- Full Barrel ToF

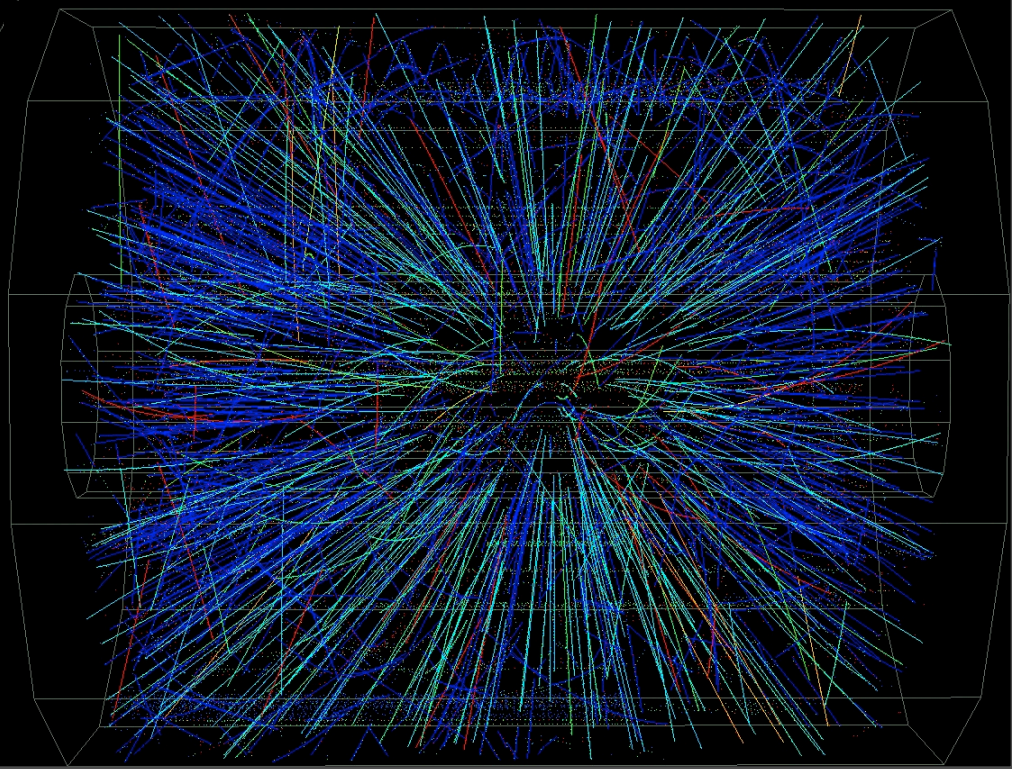
Calorimetry:

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



Peripheral Event





color code ⇒ energy loss

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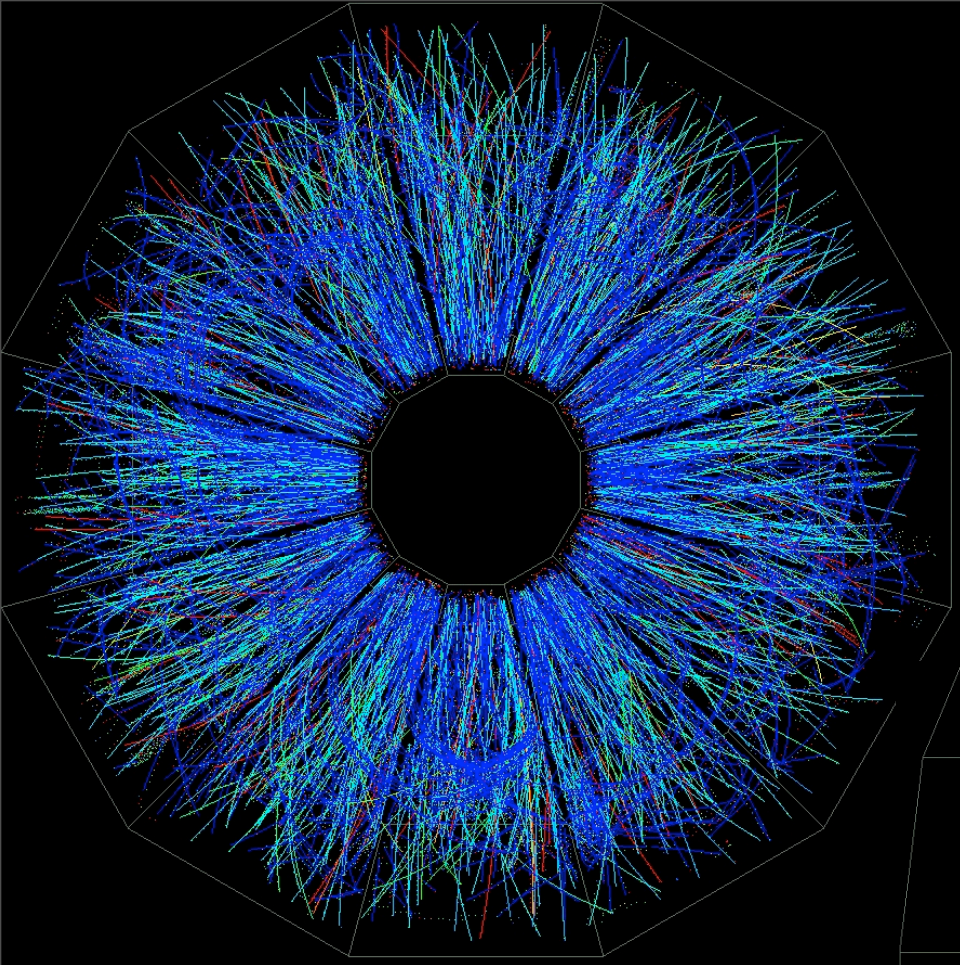
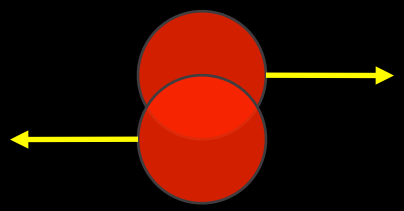
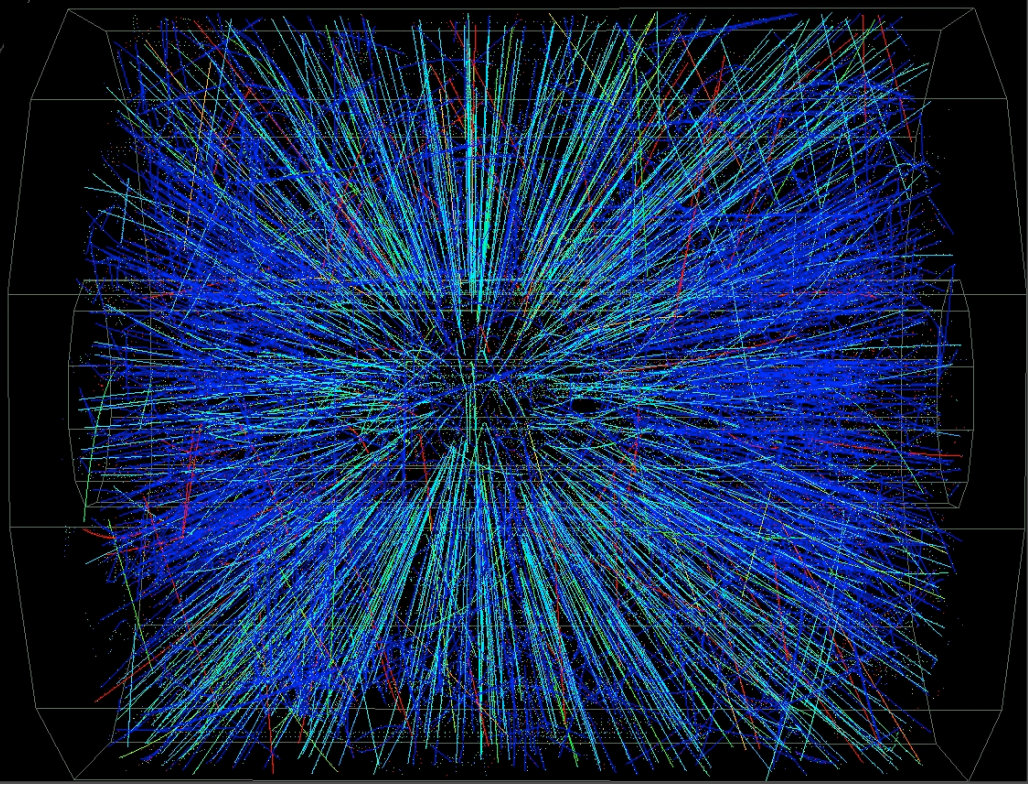


Mid-Central Event





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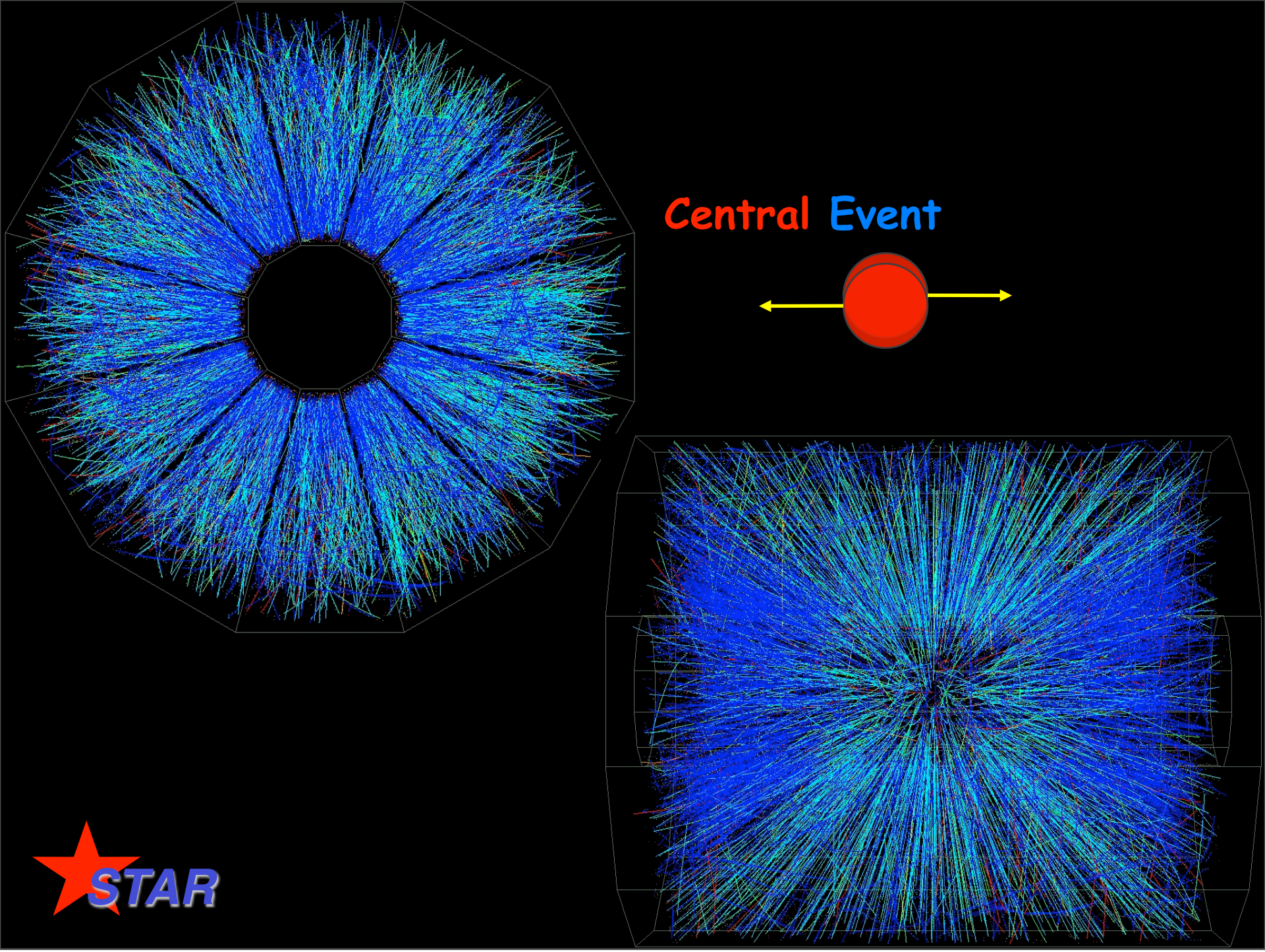
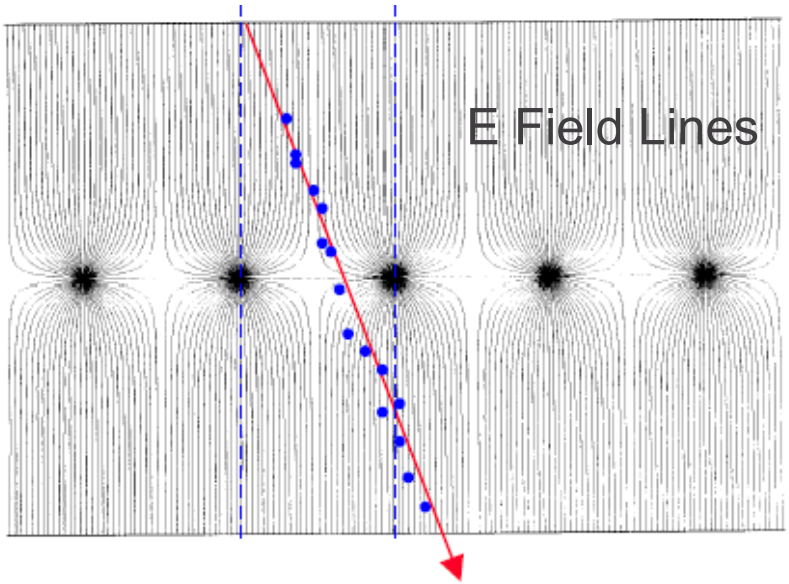
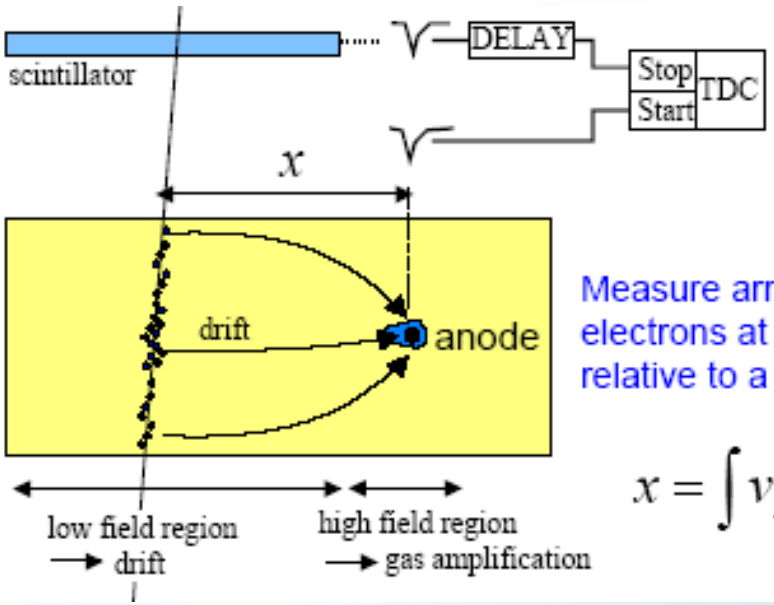

Central Event
STAR

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 ⇒ σ_x~d/√12
- Improve using drift length time information: typical 100-200 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:

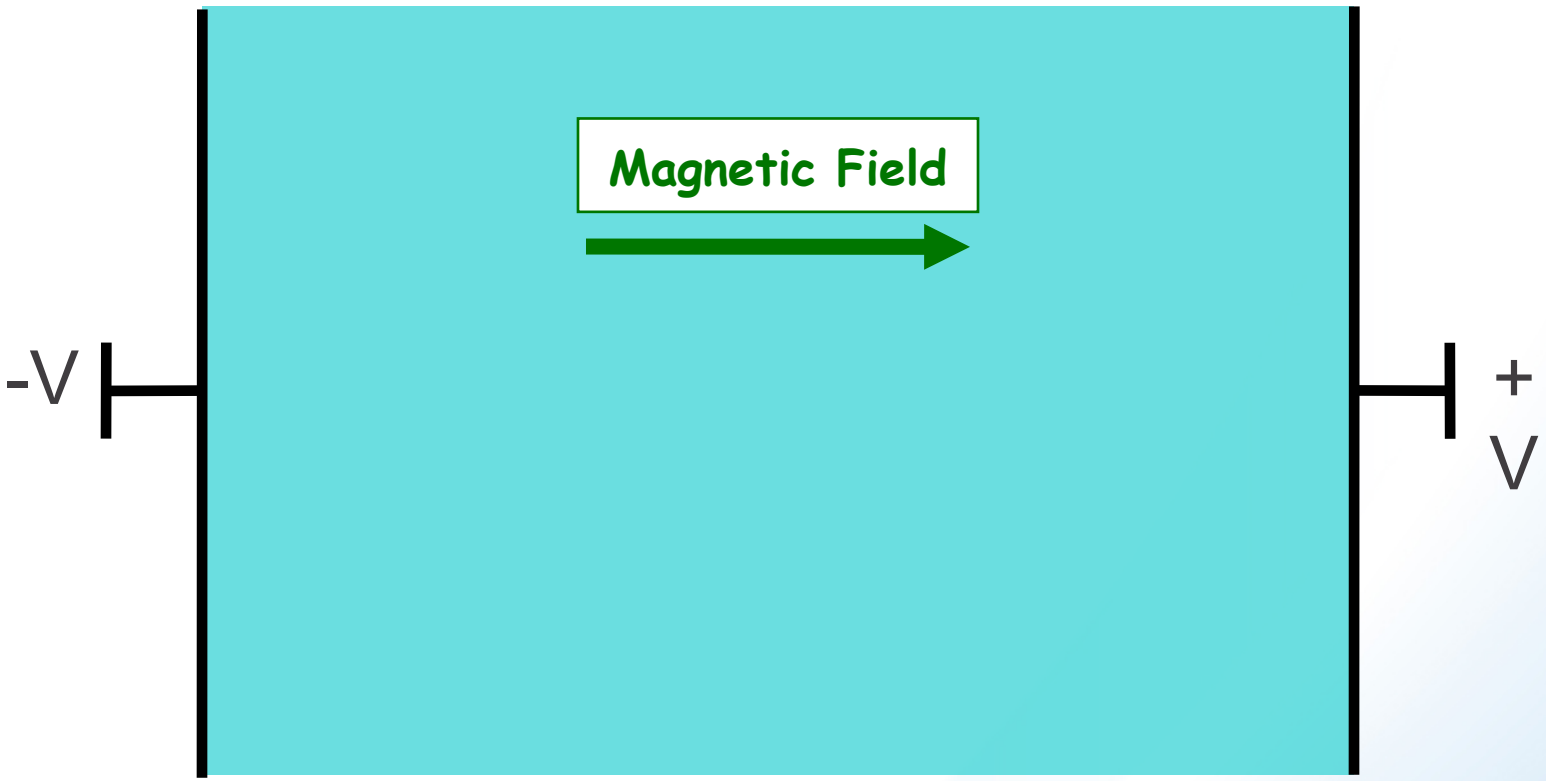
- thousands of wires
- long wires
- complex construction (dead zones)

Solution: let the electrons drift over long distances

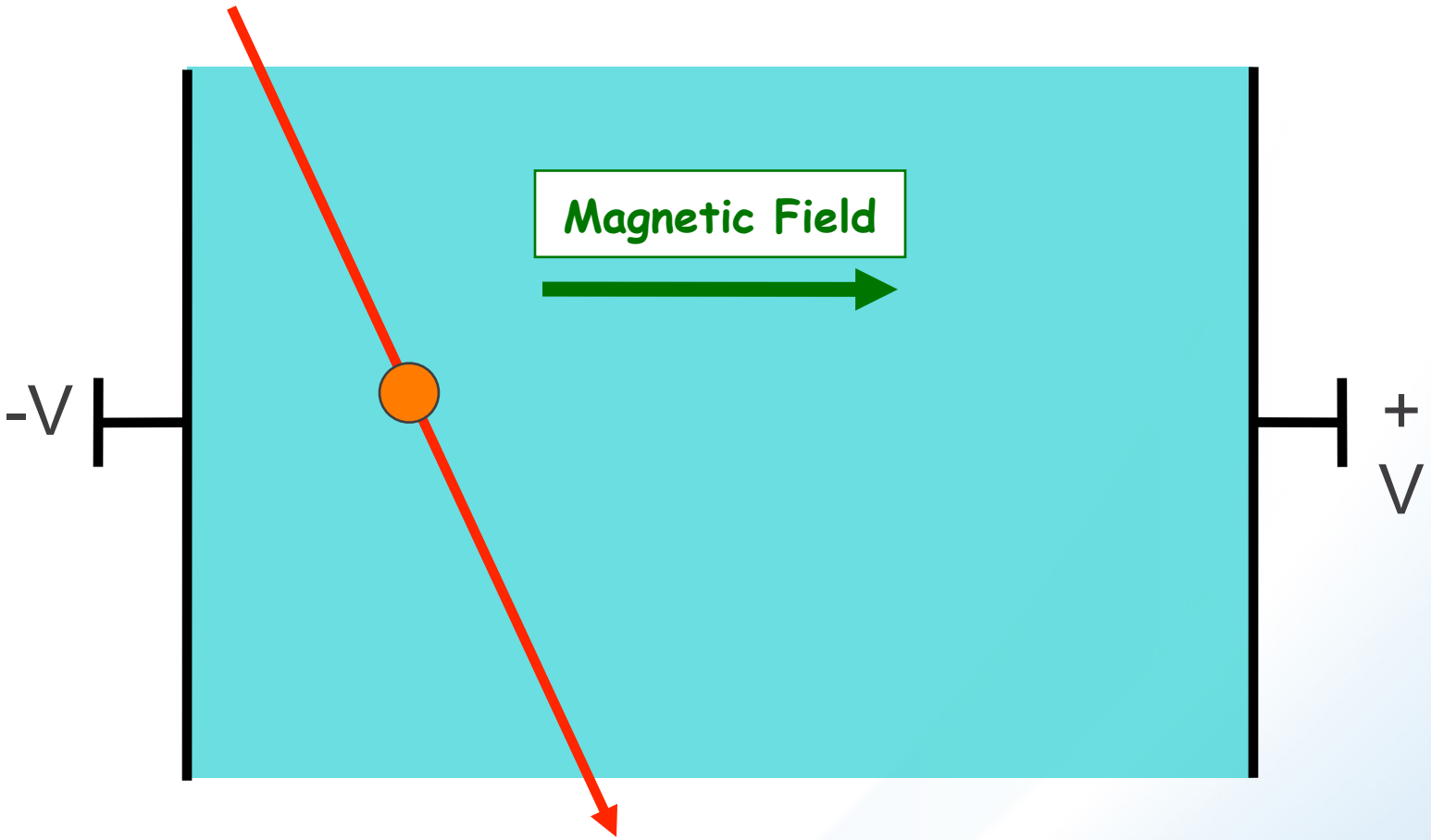
➡ TPC: essentially a huge gas filled box

Think of a TPC as a 3D CCD camera

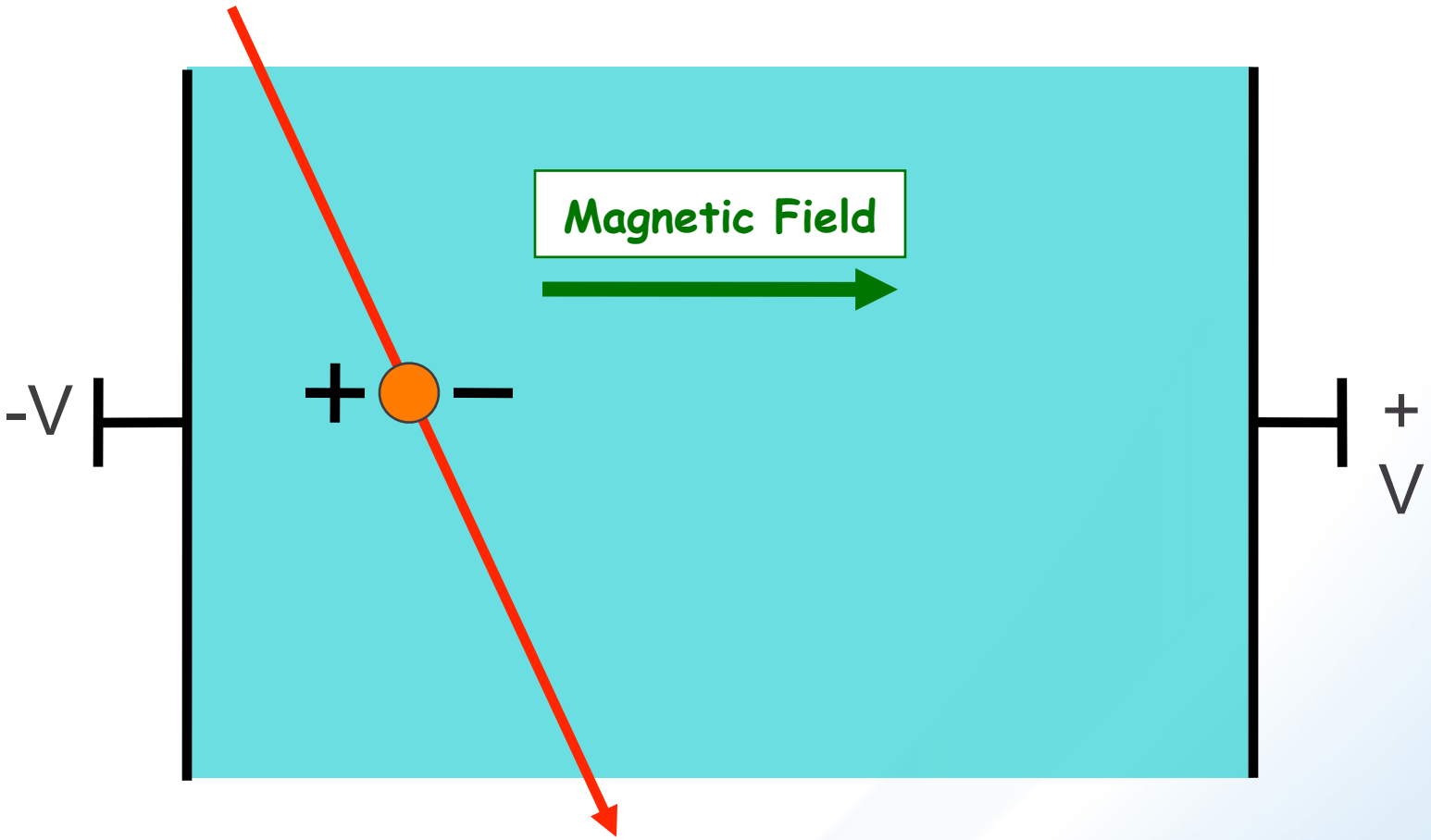
The basic concept of a TPC



The basic concept of a TPC



The basic concept of a TPC



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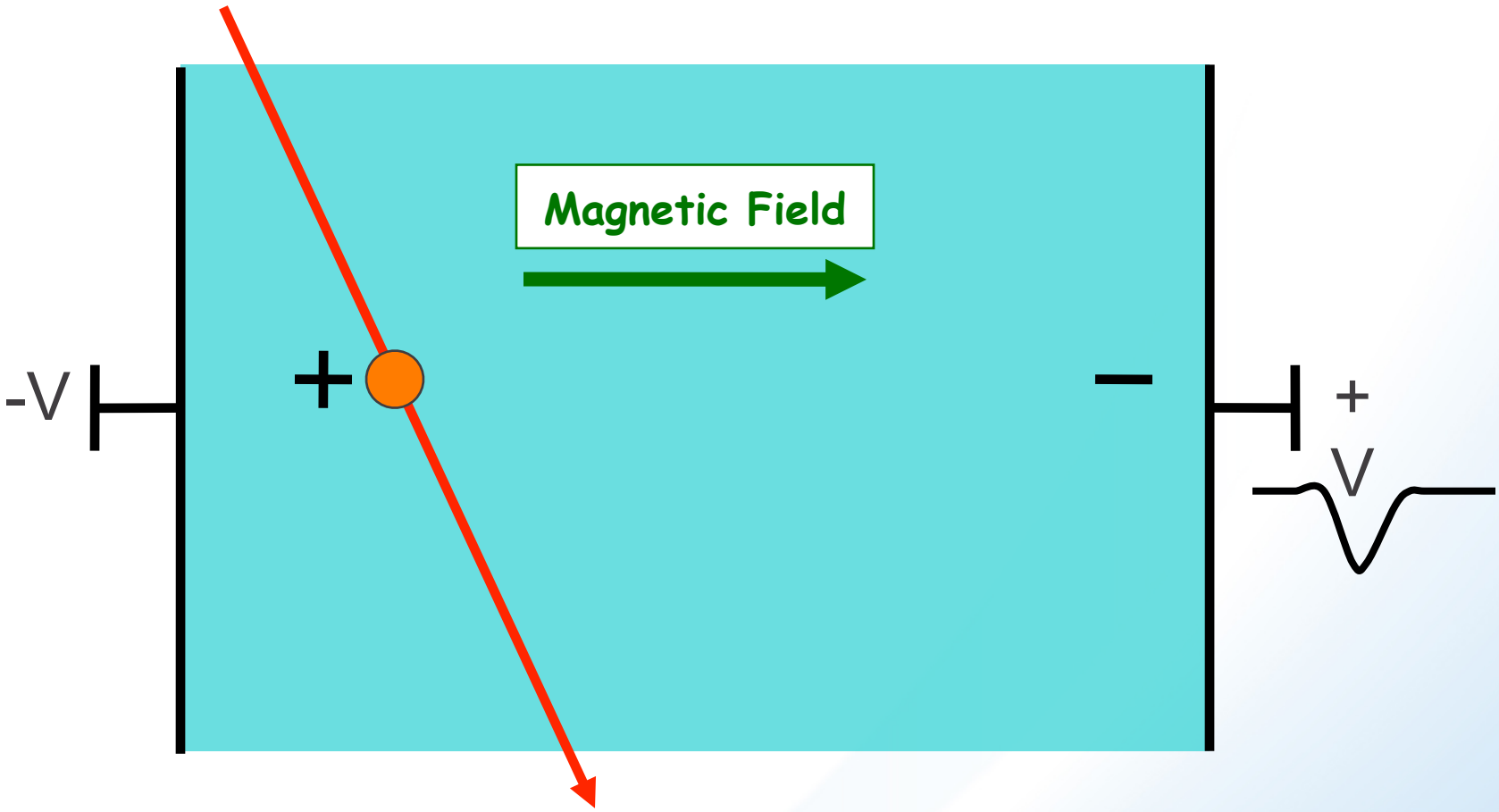
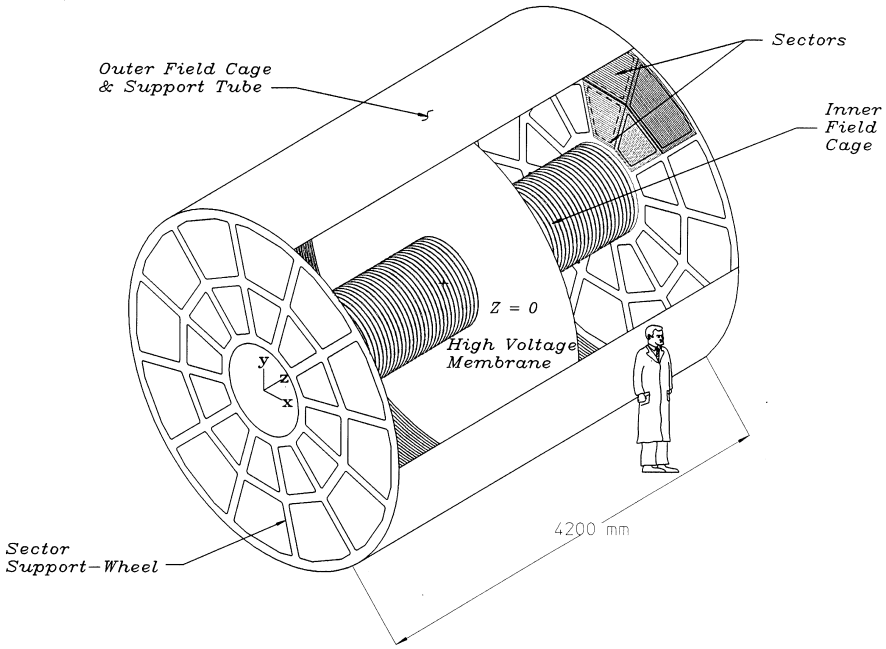
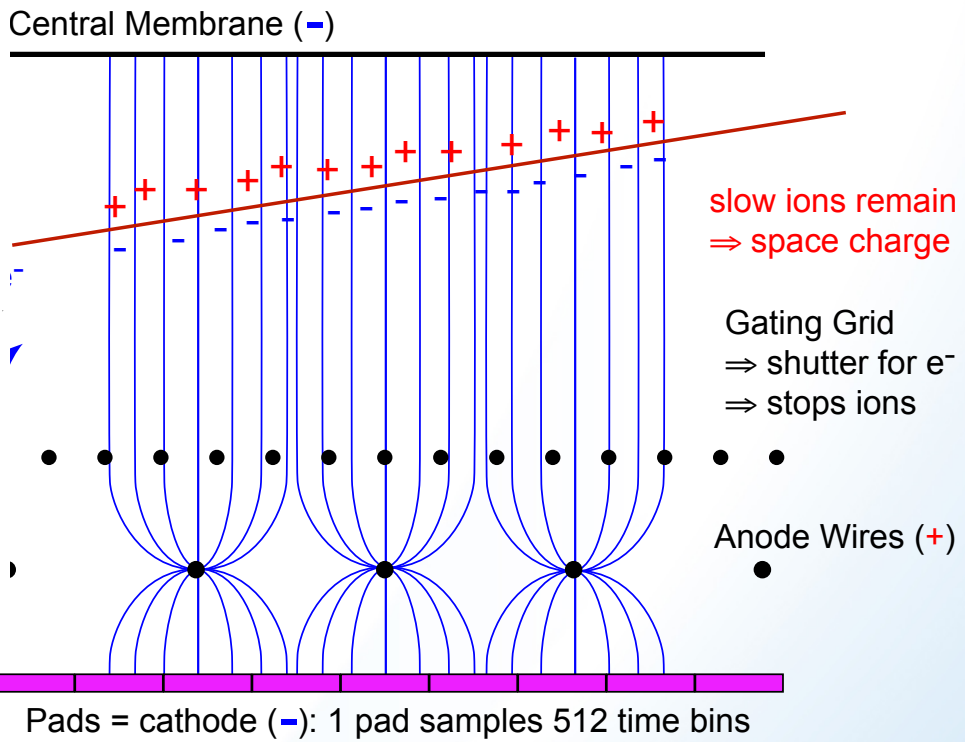


The time to reach the end of the TPC determines the distance drifted in the gas.

A 3-D camera to measure particle positions.

TPC Details





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

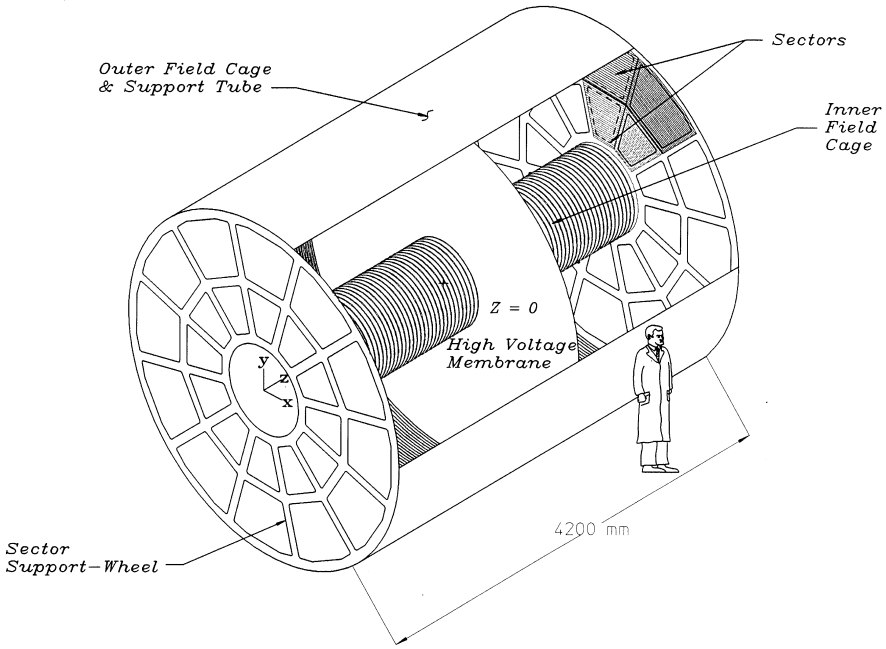
Gating Grid:

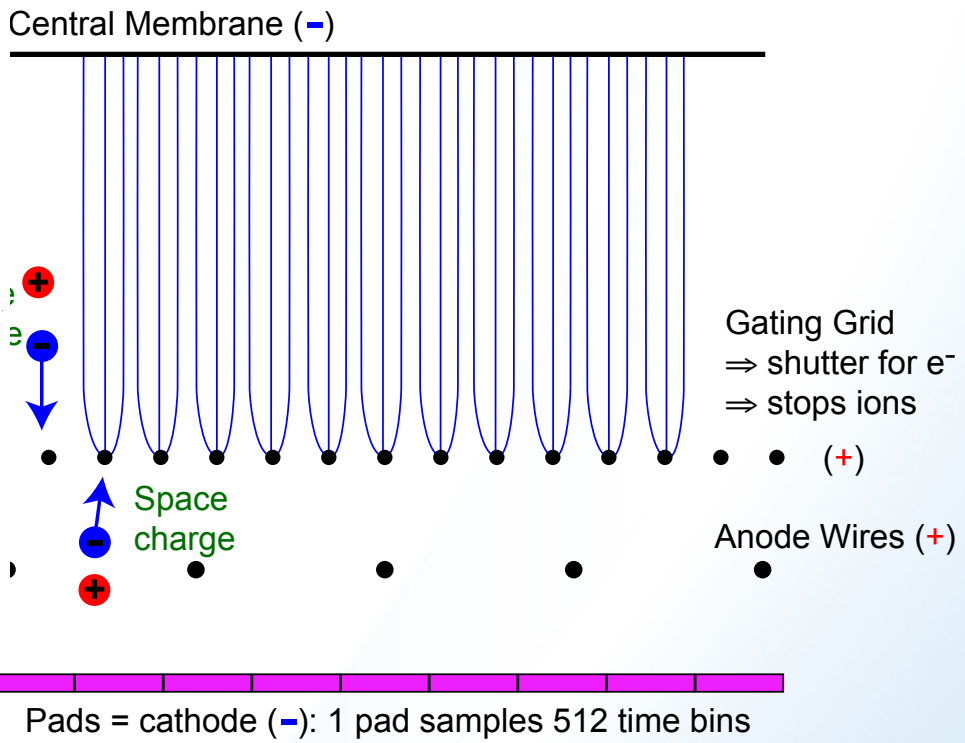
- Designed to reduce charge injection into amplifiers

Slow ions left in volume:

- accumulate, create space charge
- space charge creates distortions

TPC Details





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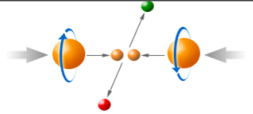
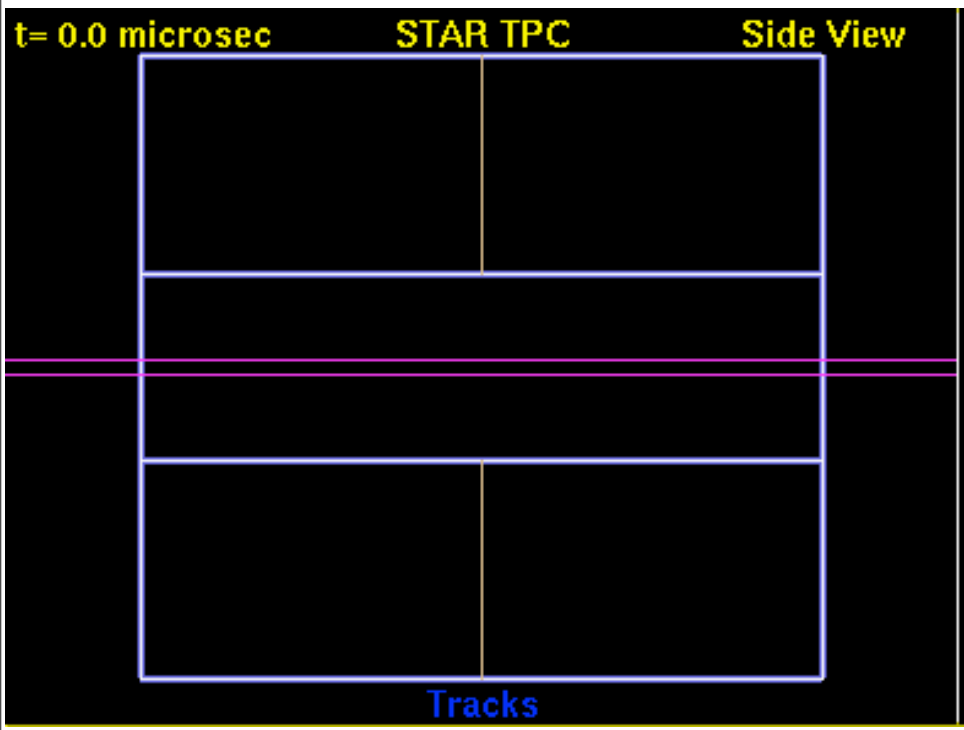
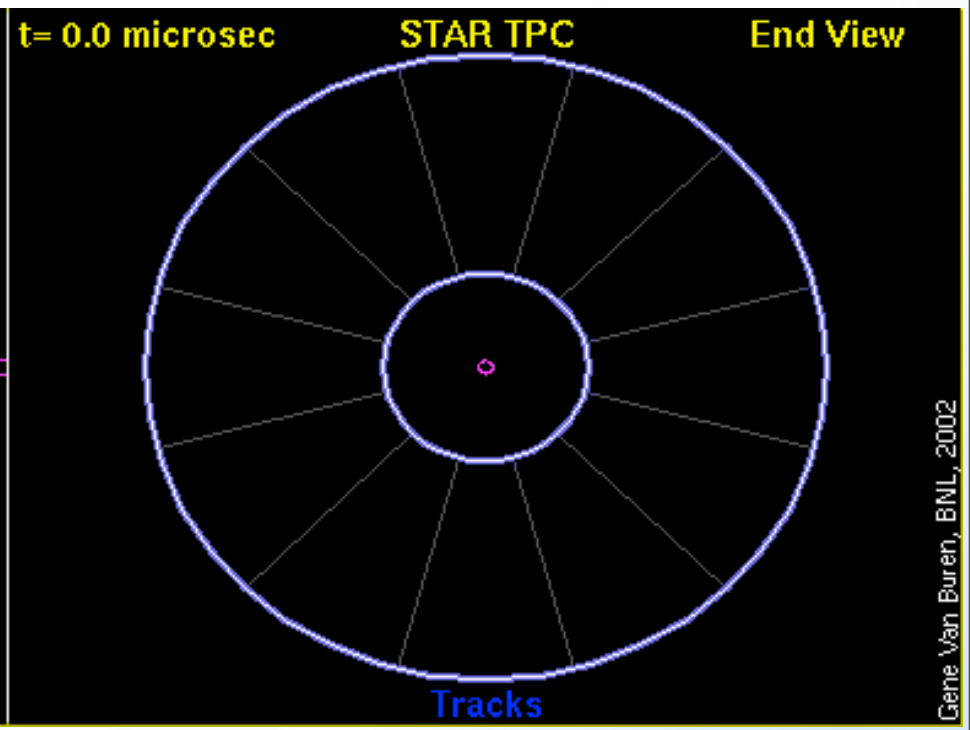


The STAR TPC

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

The STAR TPC



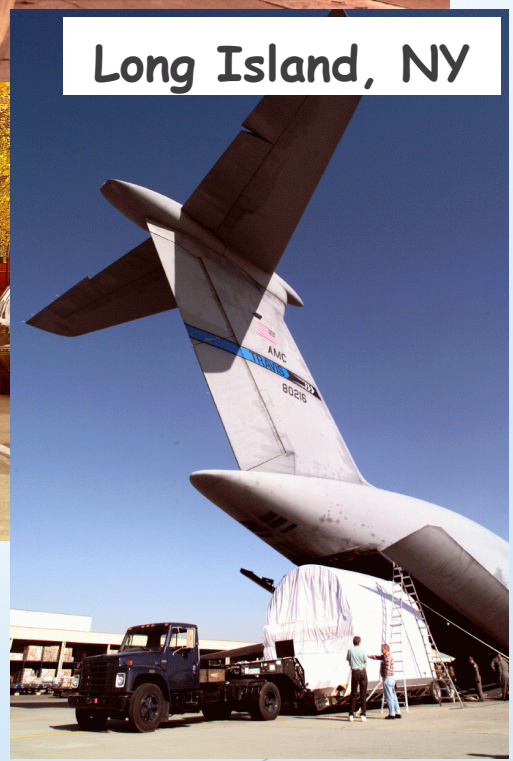


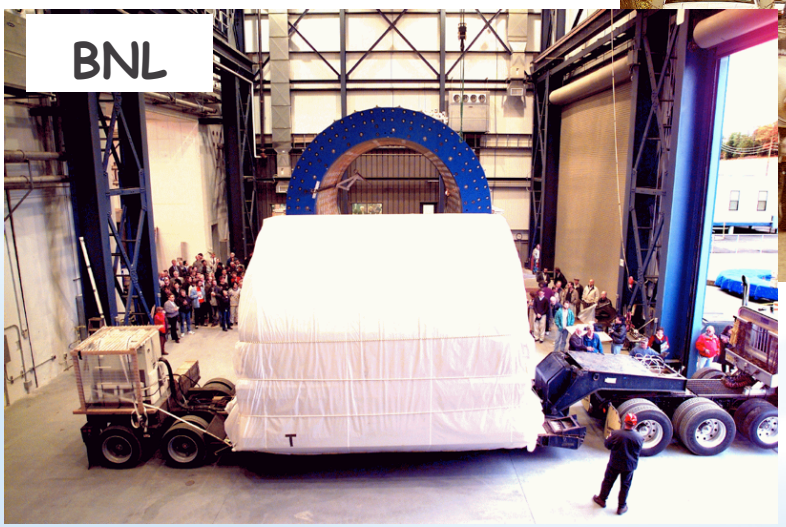
Simulation and animation by Gene Van Buren, movie by Jeff Mitchell.

STAR TPC: from West to East Coast

Berkeley, CA


US Air


Long Island, NY

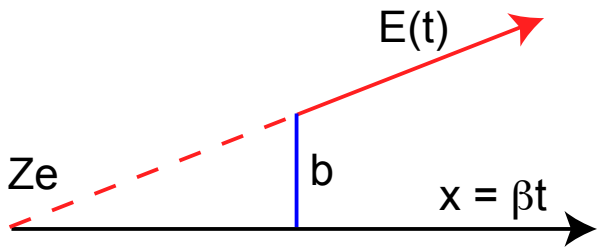

BNL

Varenna, July 2011

Particle Identification by dE/dx in

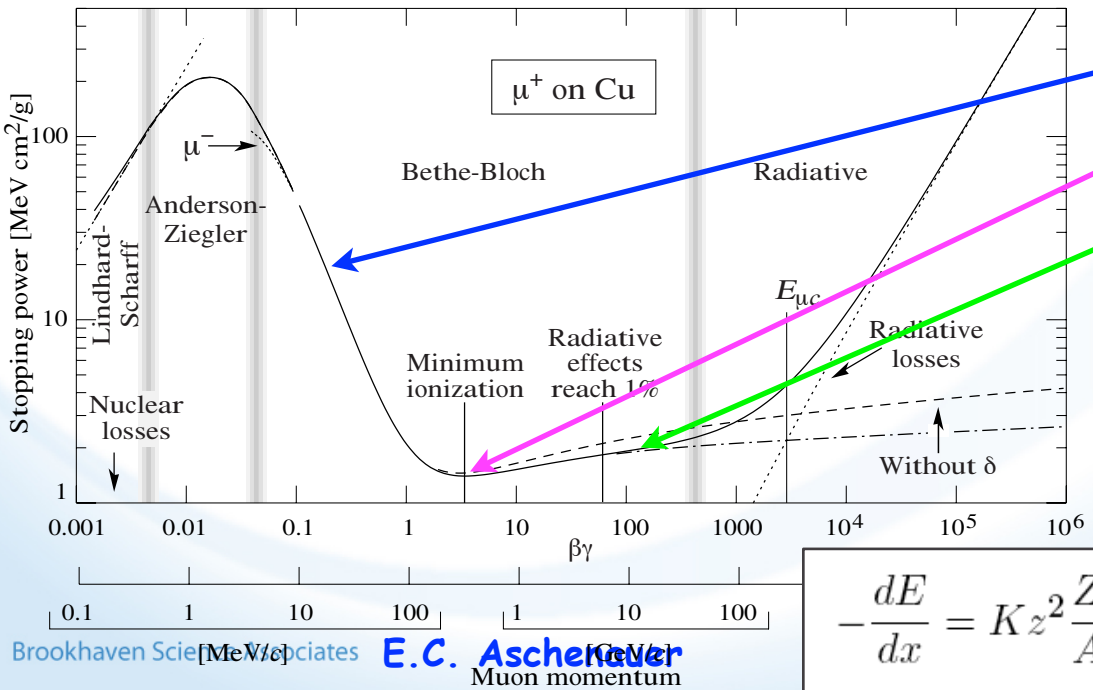
- **Elementary calculation of energy loss:**

– **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/β² region**
- **MIP: βγ ~ 3-4**
- **relativistic rise: <dE/dx> ~ lnγ²β²**

Bethe-Bloch Formula

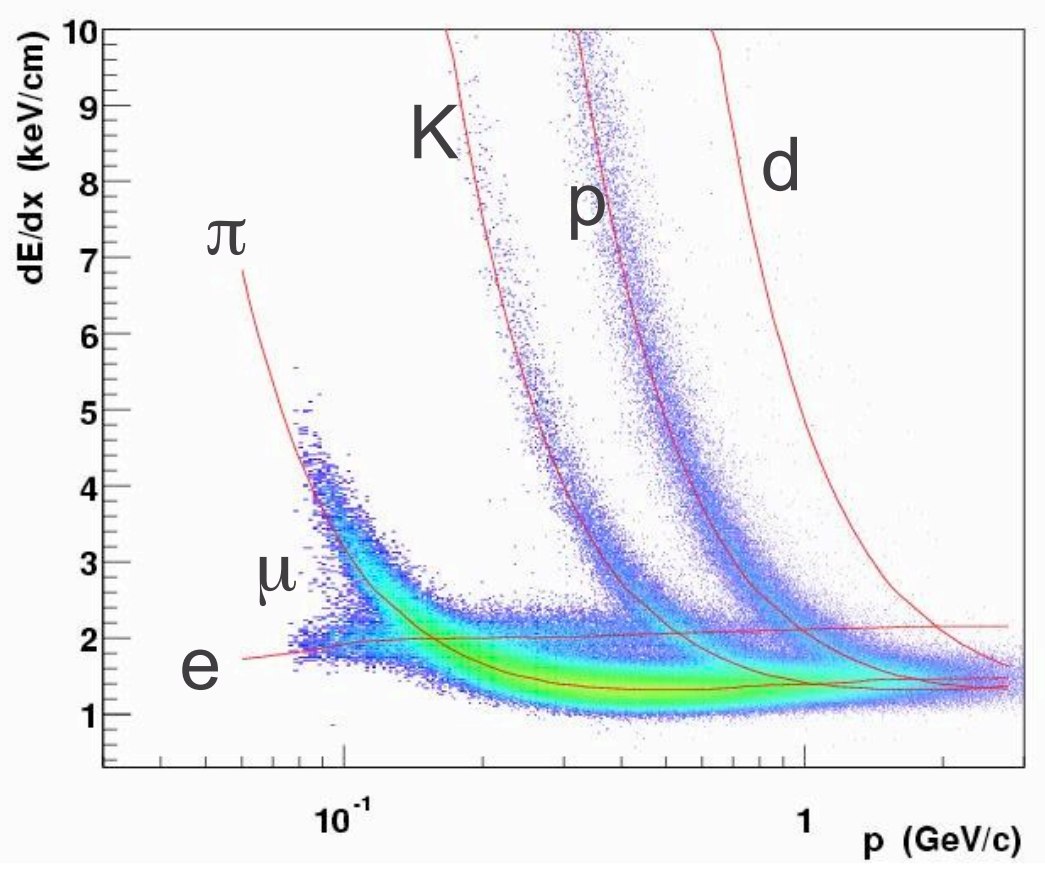
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Particle Identification by dE/dx in

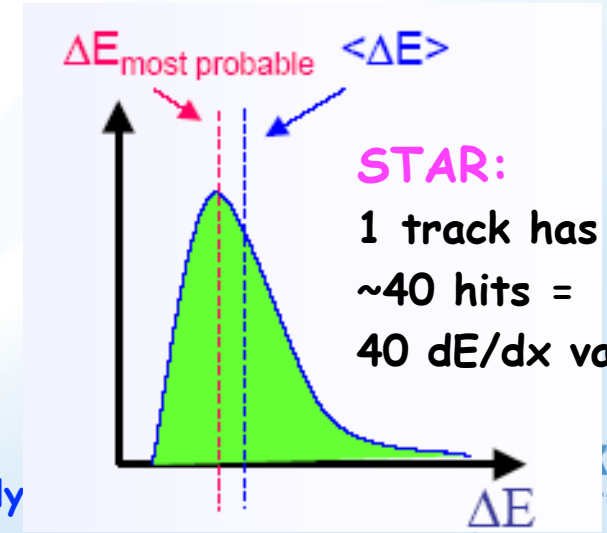
$$p = mv = m_0 \beta\gamma c$$

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

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"



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
- L2 and higher: online processor farms all RHIC experiments use:
  - ZDC (Zero Degree Calorimeter)
  - BBC (Beam-Beam Counter)

- What does a L0 trigger do at RHIC:

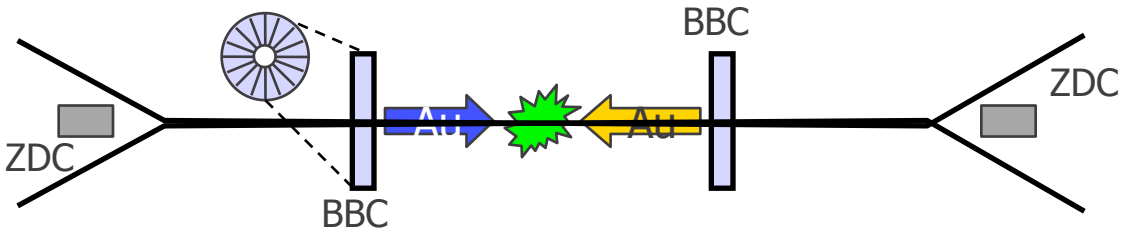
- tell that there was an interaction (not trivial)
- select interaction according to centrality
- select a range of allowed event vertices
- select rare processes (jets, high-pt particles)

- What do higher level trigger do:

- the rest ...
- examples: trigger on quarkonia, complicated event topology, correlations

What all RHIC experiments have:

Trigger always on ZDC (BBC) coincidence

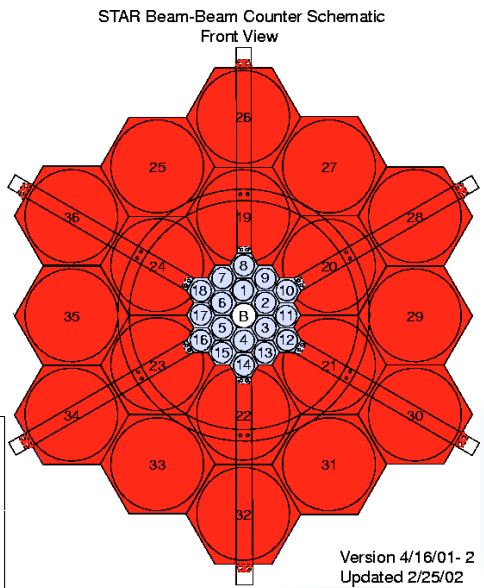


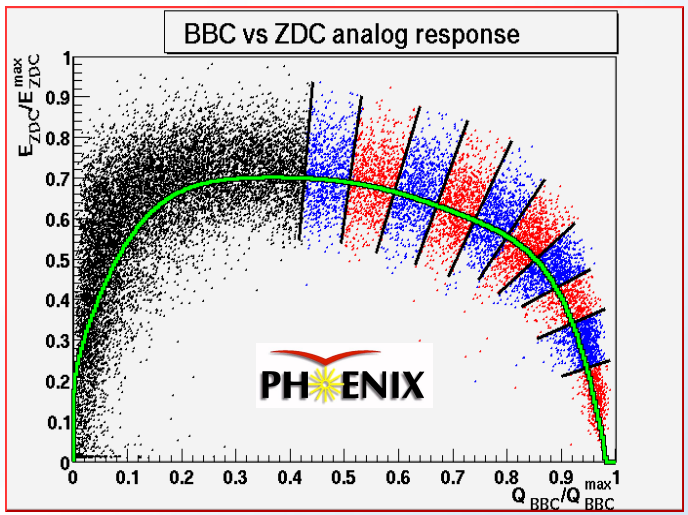
Only free neutrons hit ZDC

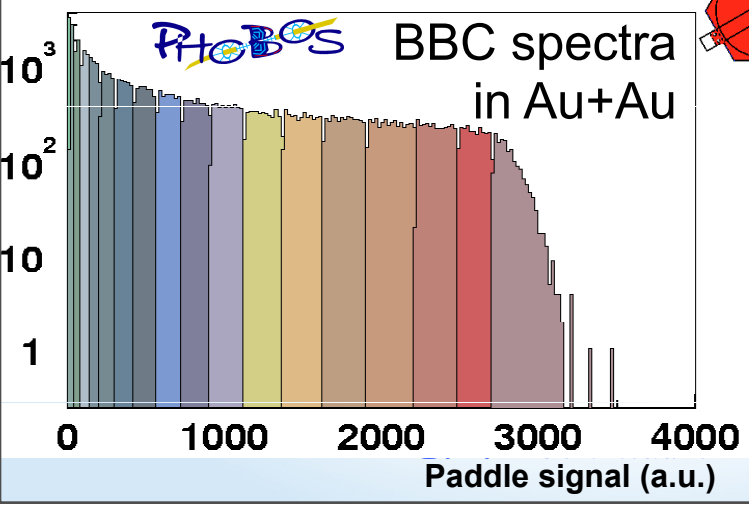
central: few hits

peripheral: few hits

ZDC alone is ambiguous







ZDC: simple calorimeter, low granularity optimized for 200 GeV

BBC: scintillator paddles ~ 2.5 < η < 4.5

Now we have everything to measure something
Lecture IV

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