Detector Techniques and RHIC

BROOKHAVEN
NATIONAL LABORATORY

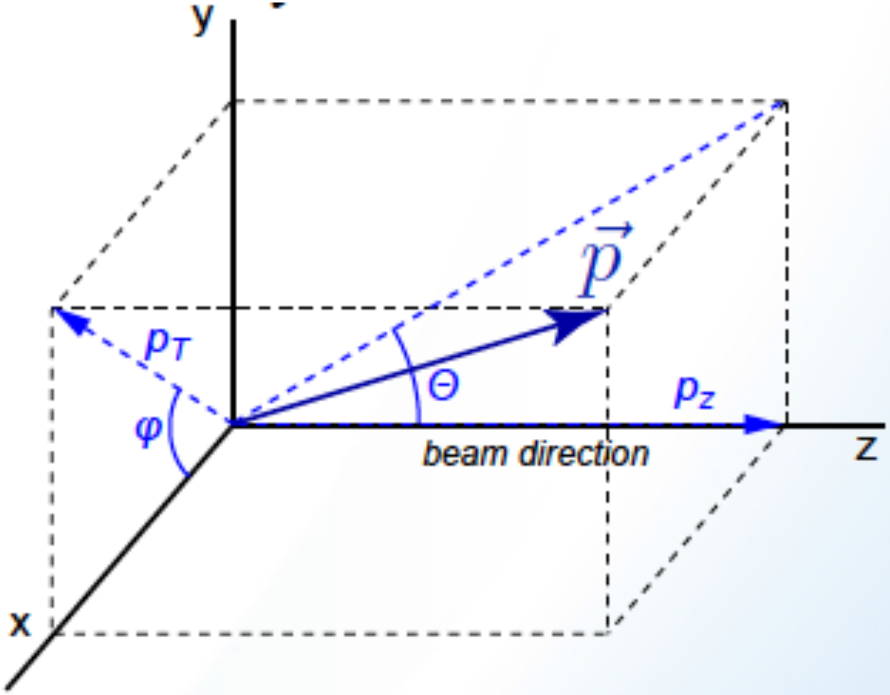
a passion for discovery

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

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

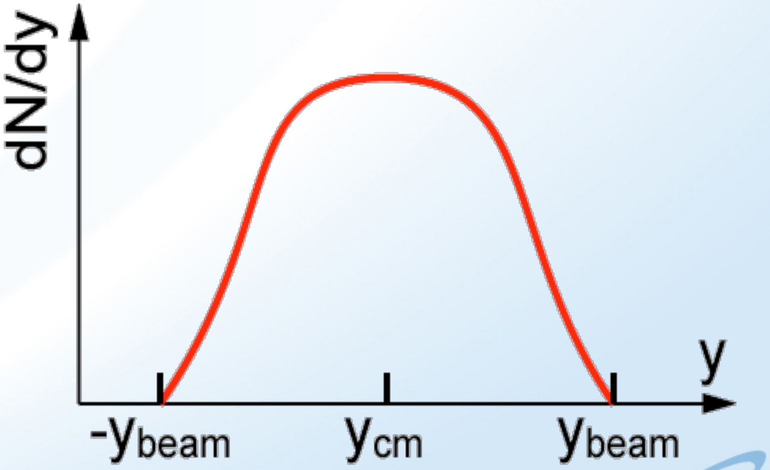
Boost in z:

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

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:

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

Lorentz invariant cross-section:

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

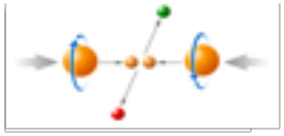
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi}\frac{d^2\sigma}{p_T dp_T dy}$$

in terms of variables we know and love

THE PROBES WE WANT TO MEASURE …

- ★ **Baseline (majority of produced particles)**
  - ➡ $K^\pm$, $\pi^\pm$, π^0, p, p,$e^\pm$
- ★ **Strangeness**
  - ➡ K^0_σ, 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 ⇒ Preshower, 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

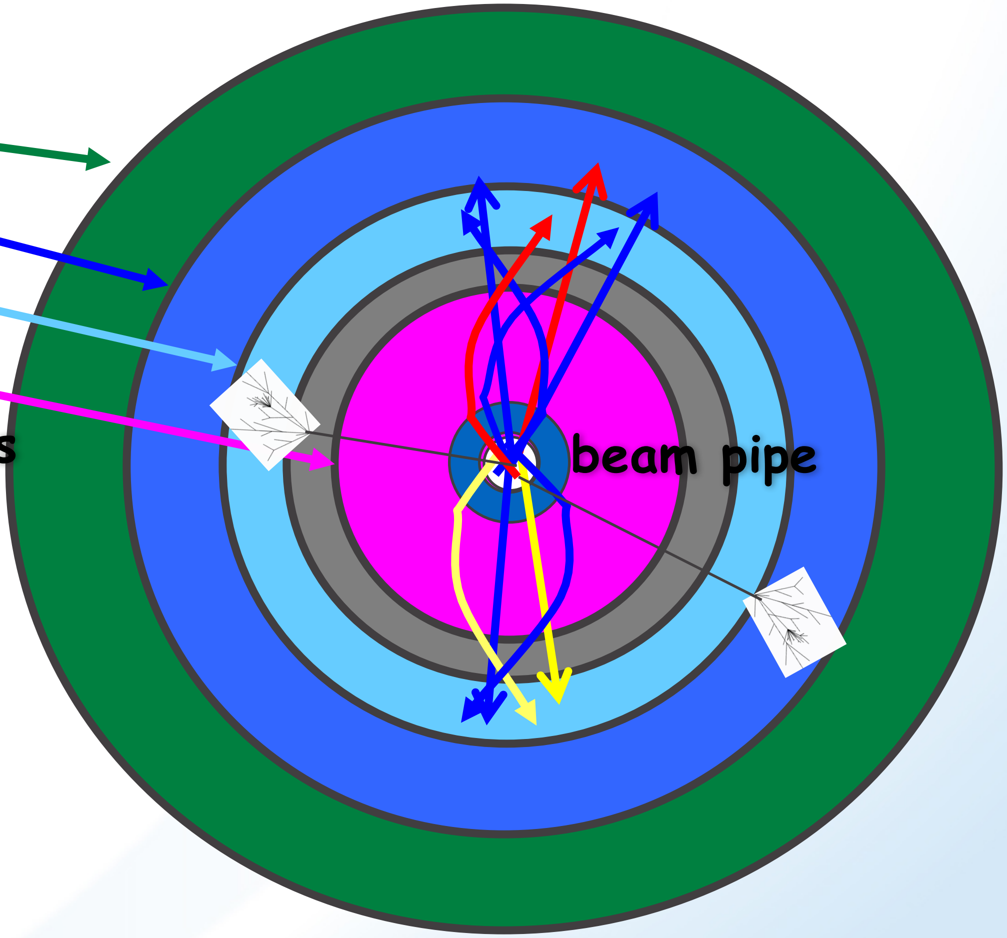
★Heavy flavor ID

- ➡secondary vertices ⇒ high precision Si detectors = material
- ➡semileptonic decays (c, b → e + X, B → J/ψ (→ e e) + X) ⇒ hadron blind, little material

A TYPICAL HIGH ENERGY DETECTOR

Particle types:

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



Rough Classification

- track detectors for charged particles
  - "massless" detectors
    - gas detectors
    - solid state detectors
- magnet coil
  (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

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 + pathlength

↓

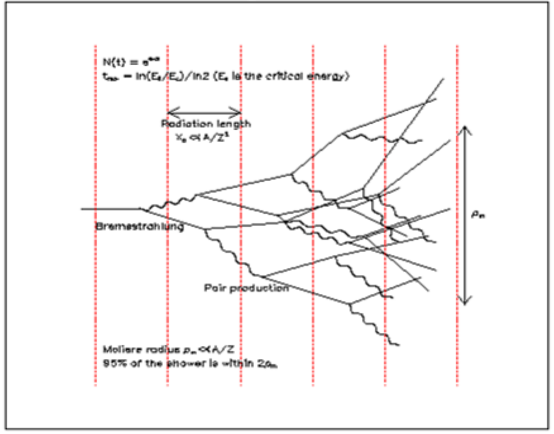
Fully stop the particle

Convert its energy to

- light, charge…

Collect and read out

Cherenkov effect


Electromagnetic showers

3-momentum

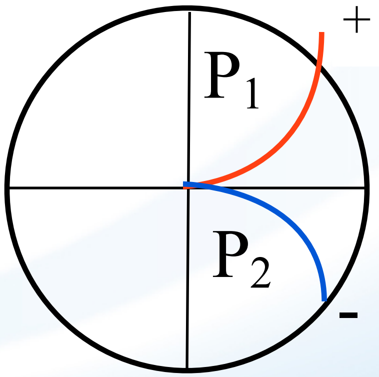
↓

tracking

↓

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

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



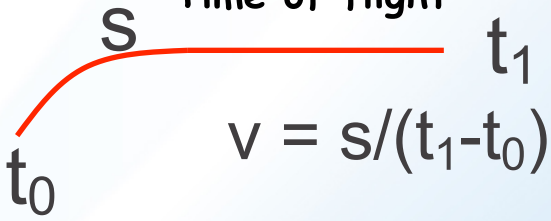
veloc

↓

time-of-flight

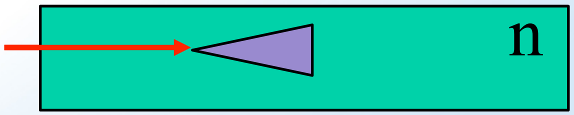
or

Time of flight



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

Cherenkov



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

PARTICLE IDENTIFICATION – LONG LIFETIME

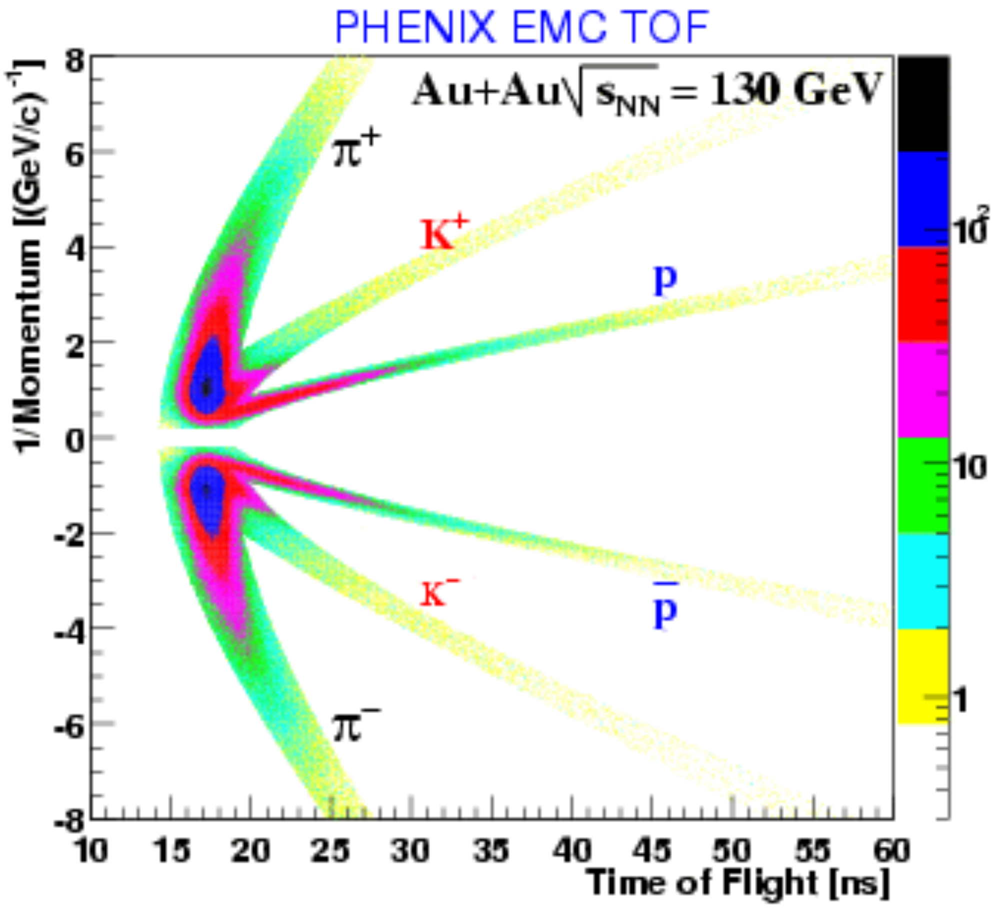
Why do I emphasize long lifetime? Because the detectors are fairly large, and the particle produced at the vertex has to survive until it reaches the detector!

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

Examples: π^0, ϕ, Λ, …

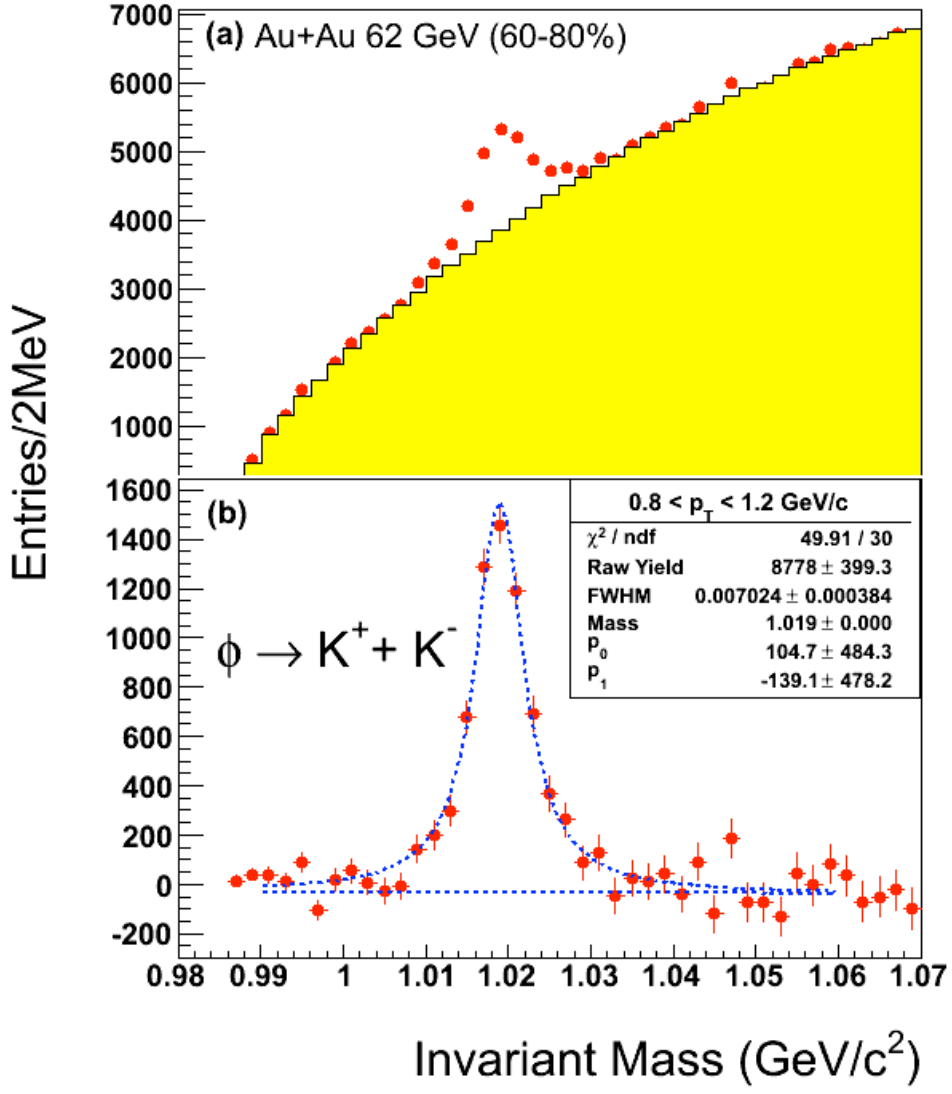
Have to be reconstructed from their more stable decay products

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

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

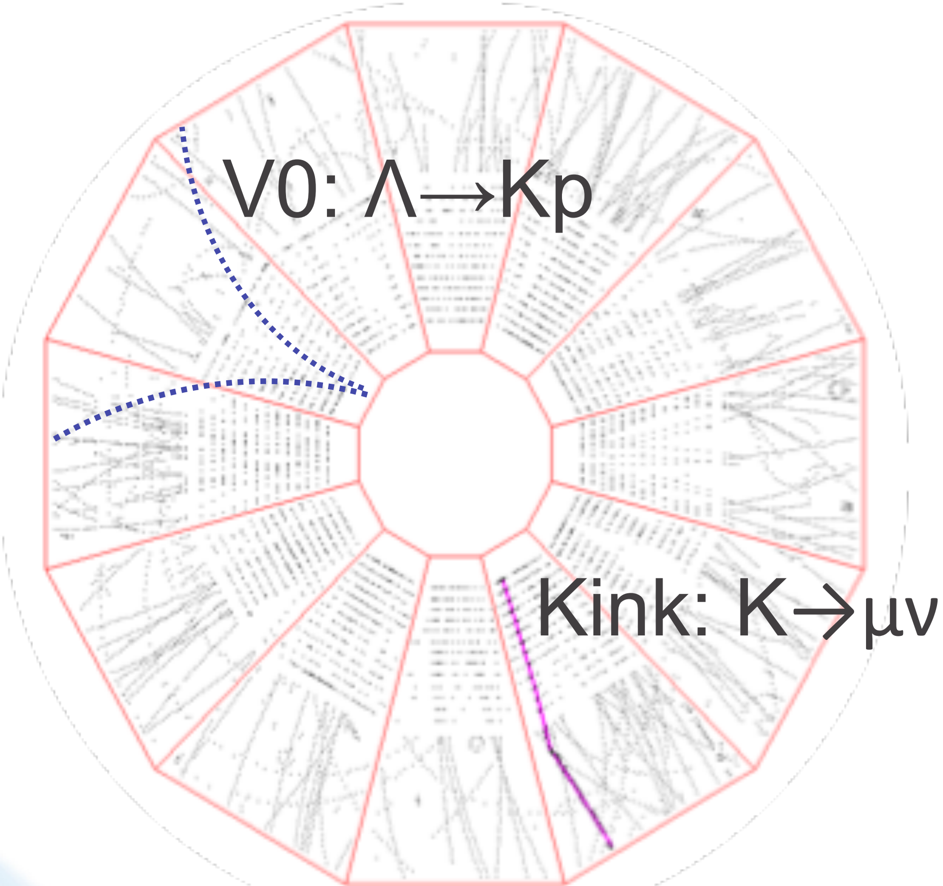
S = Total - Background

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



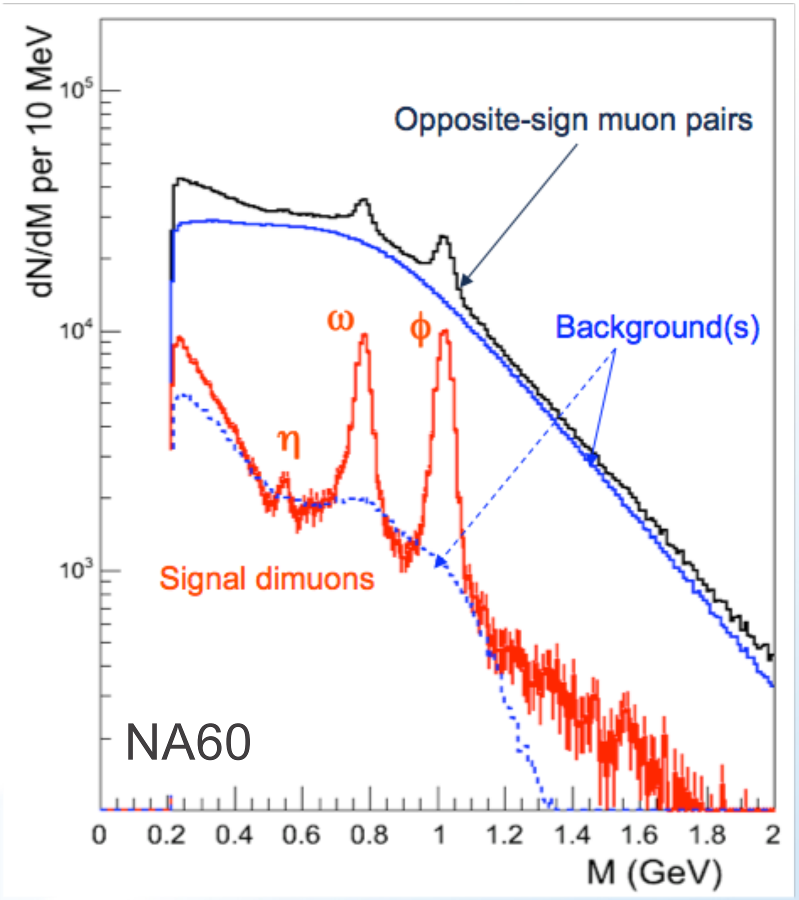
PARTICLE IDENTIFICATION – SHORT LIFETIME

Different topologies



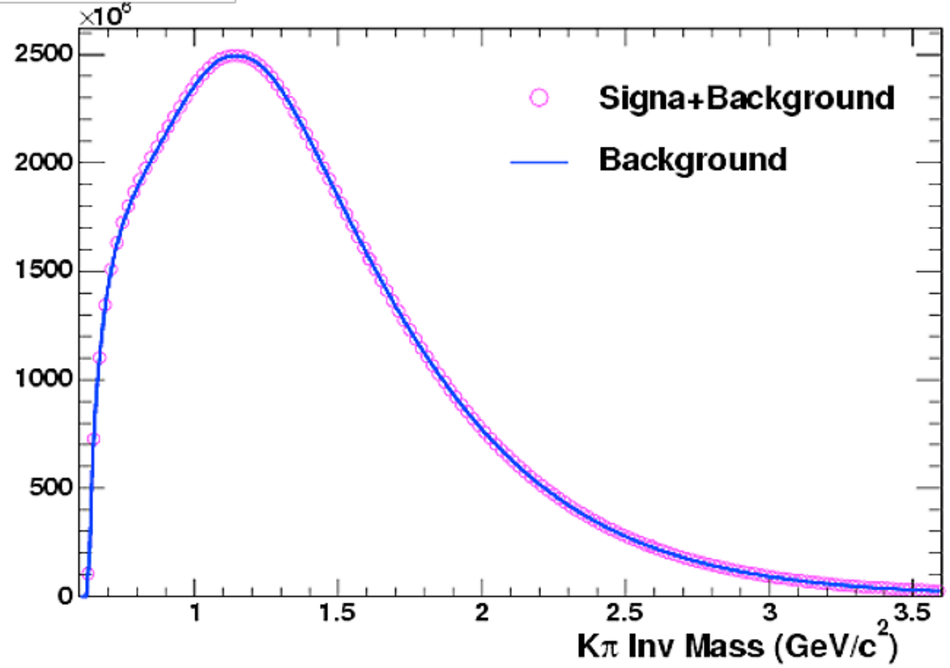
Note weak decaying particle (like Λ, Ω, K^0_s) decay cm away from the interaction vertex – **cm are easy to deal with**

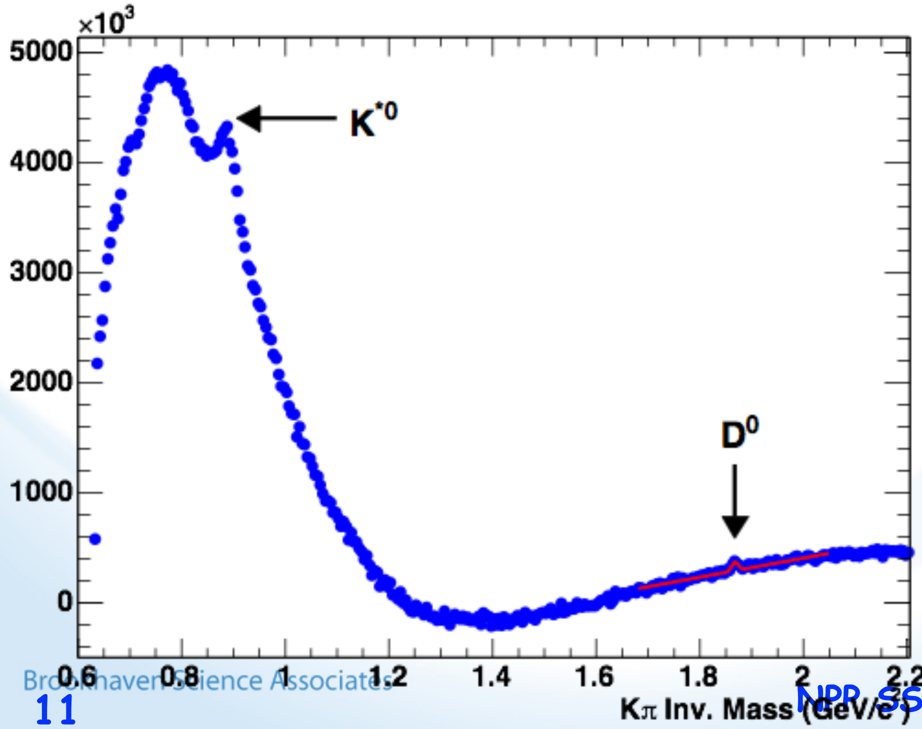
What if cτ ~ fm ?



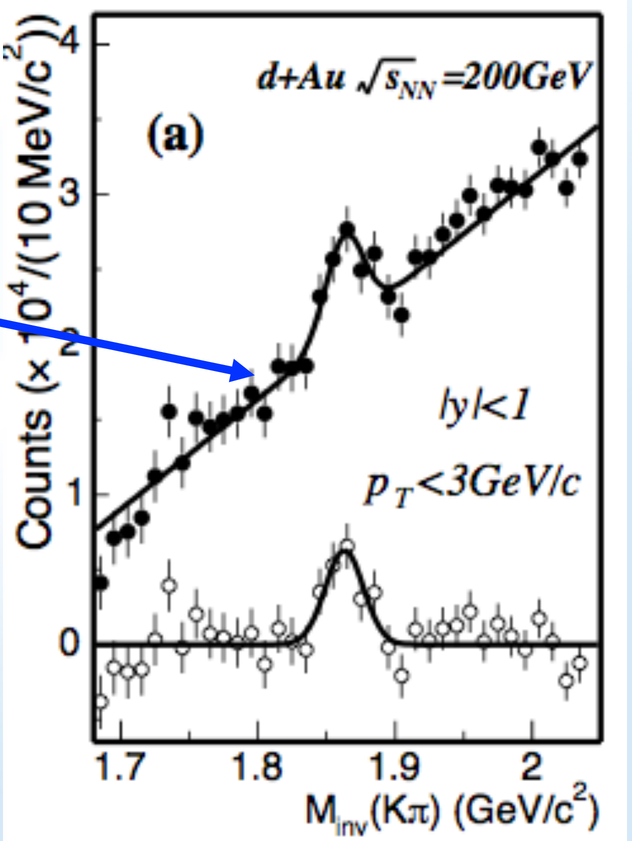
Works as well but usually more background

PARTICLE IDENTIFICATION – SHORT LIFETIME



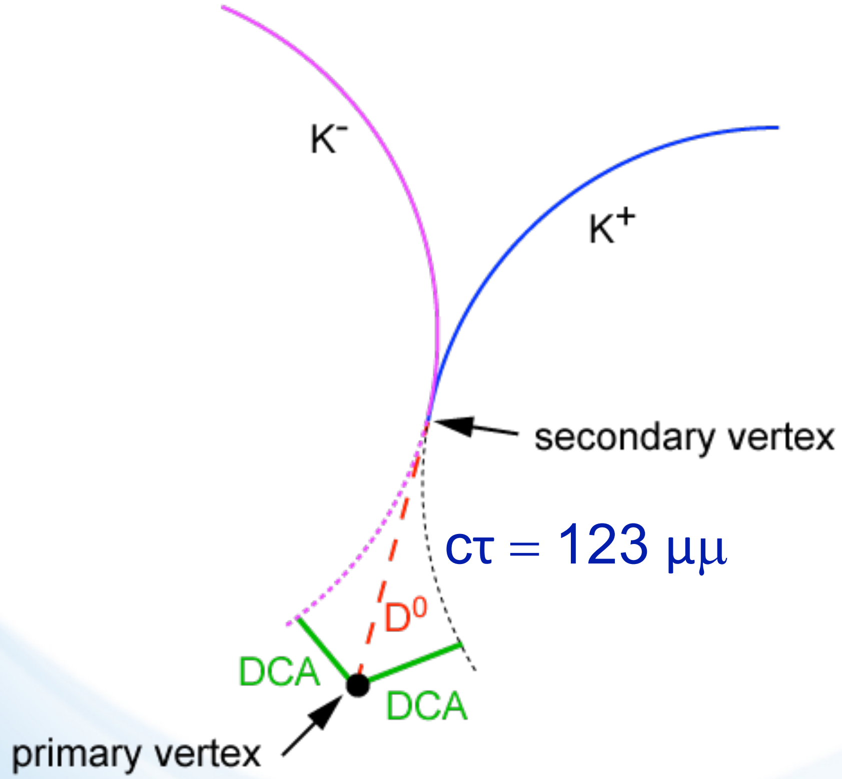


Residual background not eliminated. Needs further work to get to final spectra..



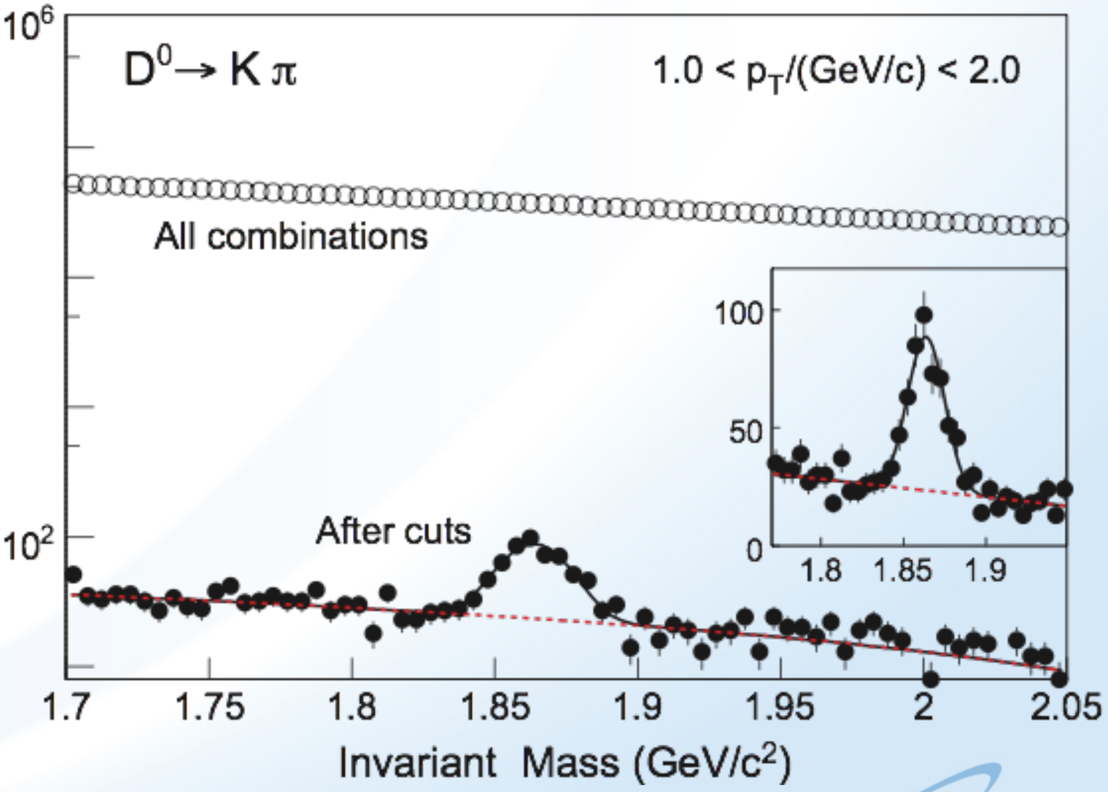
PARTICLE IDENTIFICATION – VERY SHORT LIFETIME

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)



DCA: distance of closest approach

Simulation of STAR Heavy Flavor Tracker

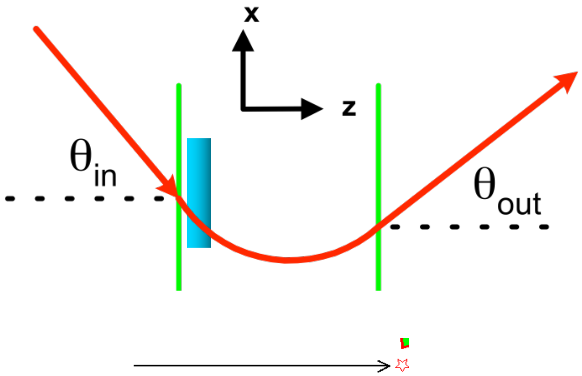


MAGNETIC FIELDS AT RHIC

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

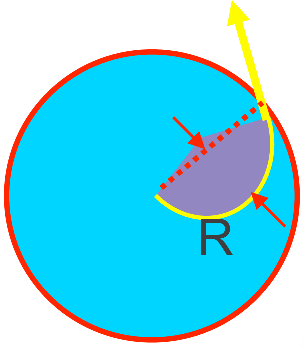
More useful: $p_T = 0.3 \cdot B \cdot R \; \frac{GeV/c}{T \cdot m}$

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

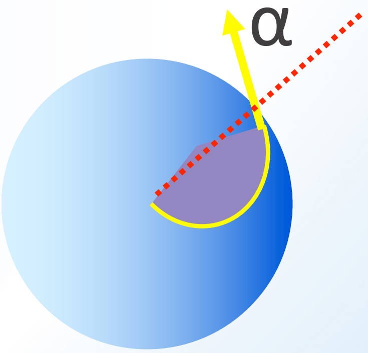


BRAHMS

PHOBOS



STAR



PHENIX

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

~stuff in aperture

~spatial accuracy

RHIC EXPERIMENTS IN A NUTSHELL

BRAHMS Decommissioned

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

PHOBOS Decommissioned

small experiment - "tabletop"
(i) huge acceptance $\Delta\phi$, $\Delta\eta$, 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: $\Delta\phi = \pi$, $\Delta\eta = \pm 0.35$
leptons (muons in forward arms), photons, hadrons

STAR

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

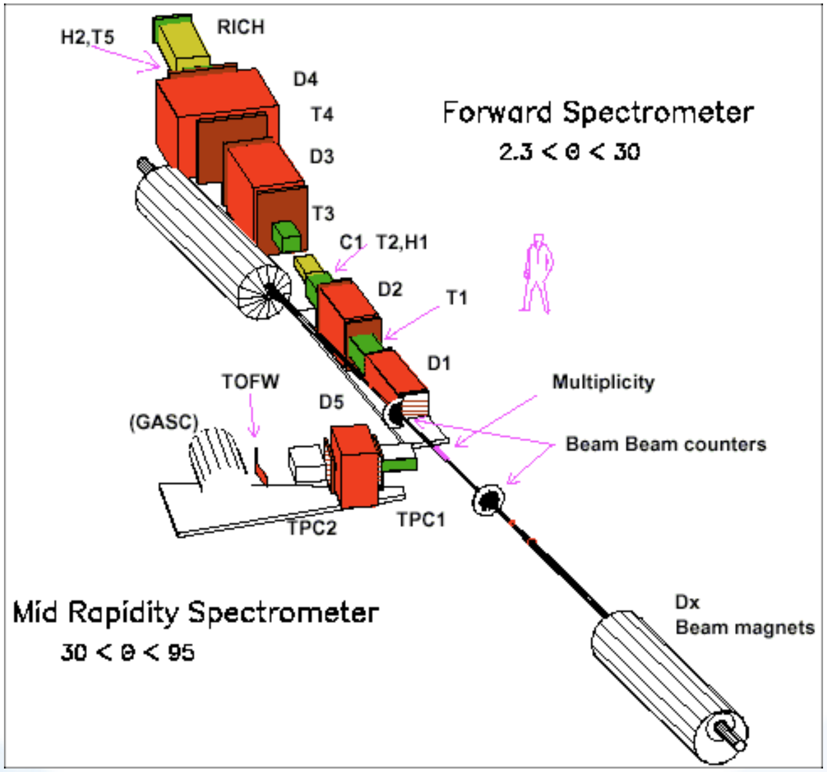
THE TWO "SMALL" EXPERIMENTS AT RHIC

BRAHMS

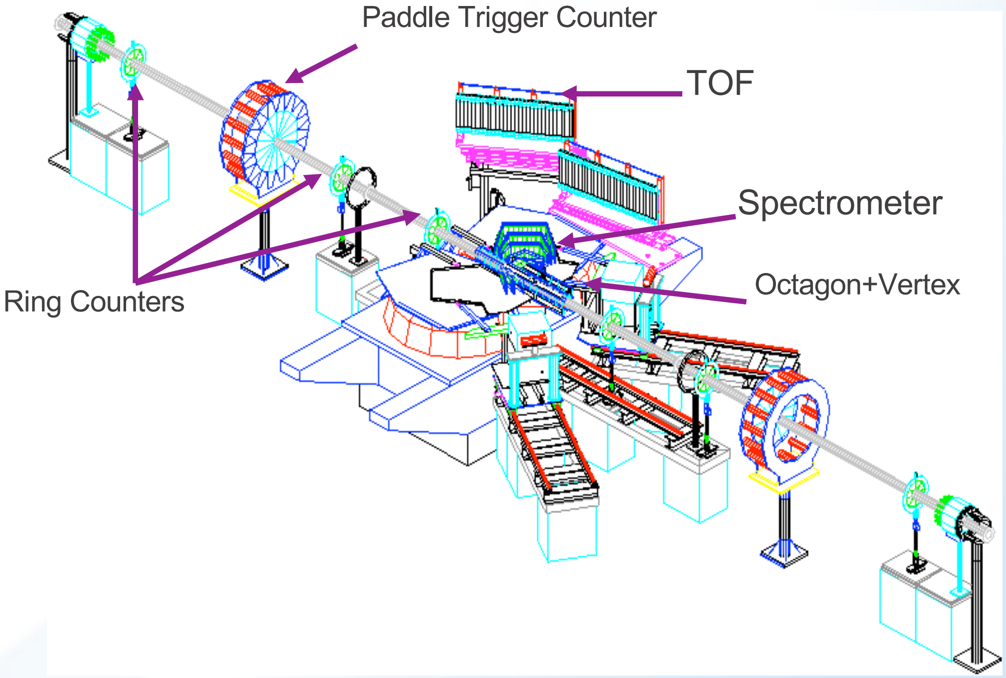
2 "Conventional" Spectrometers
Magnets, Tracking Chambers,
TOF, RICH, ~40 Participants

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 Selected Solid Angle
- Multiplicity in 4π
- Particle Correlations

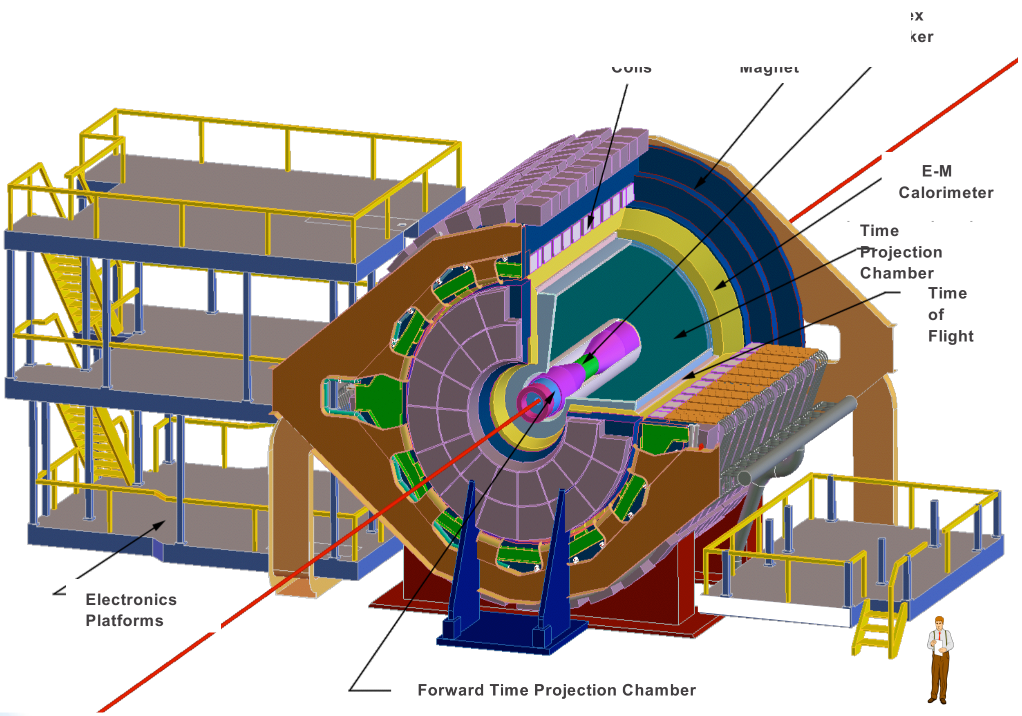
THE TWO "LARGE" DETECTORS AT RHIC

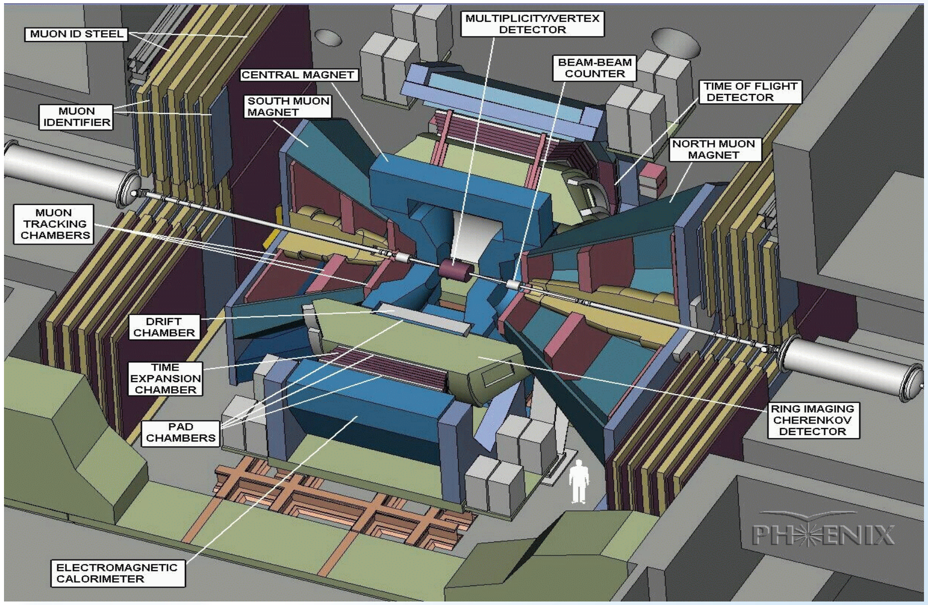
STAR

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

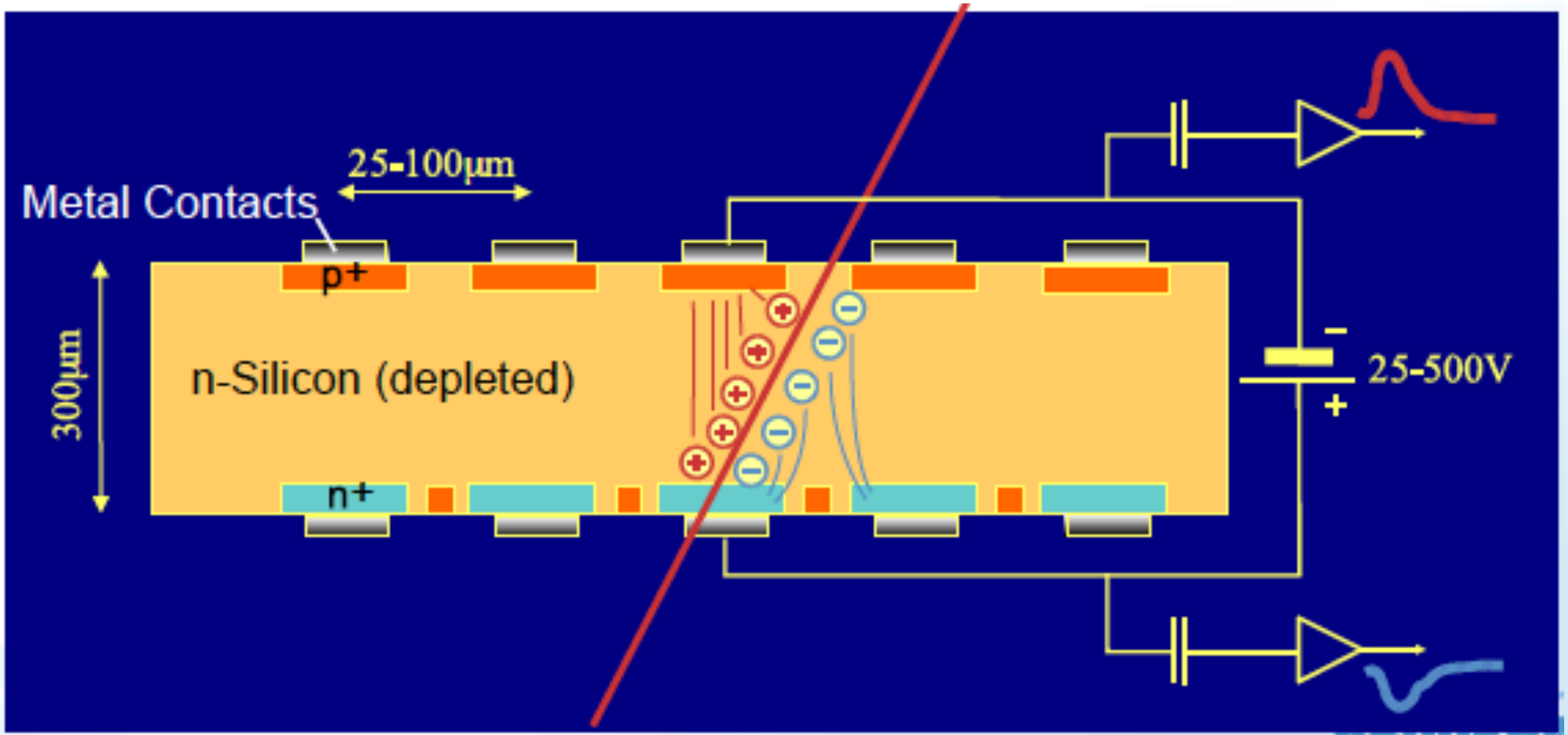
- ✓ Leptons, Photons, and Hadrons in Selected Solid Angles
- ✓ Simultaneous Detection of Various Phase Transition Phenomena

SILICON DETECTORS IN A NUTSHELL

Basic motivation: charged particle position measurement

Use ionization signal left behind by charged particle passage

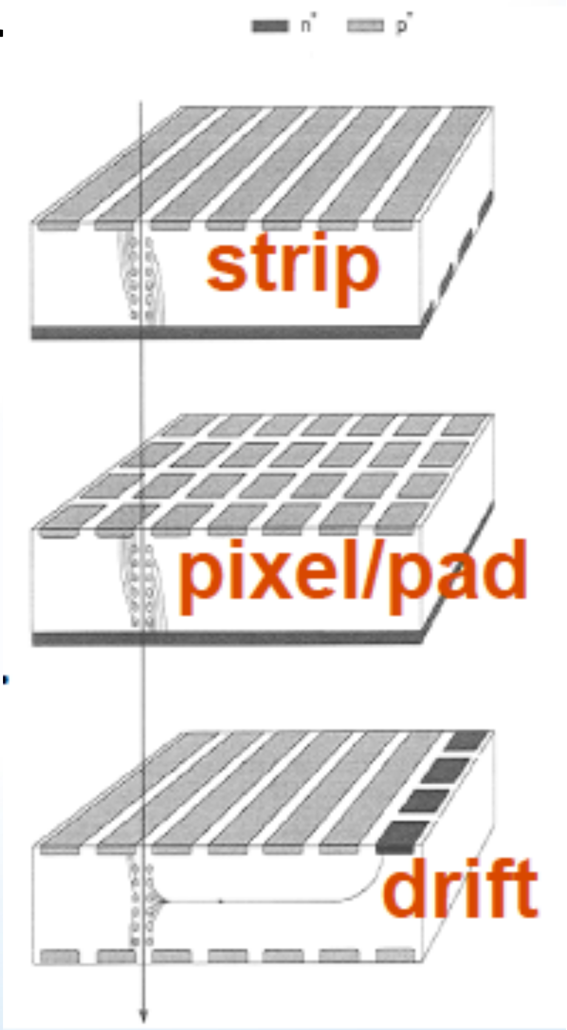
- Ionization produces electron-ion pairs, use an electric field to drift the electrons and ions to the oppositely charged electrodes.
- In a solid semiconductor, ionization produces electron-hole pairs. For Si need 3.6 eV to produce one e-h pair. In pure Si, e-h pairs quickly recombine ⇒ n-doped (e carriers/donors) 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
- 2^{nd} 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

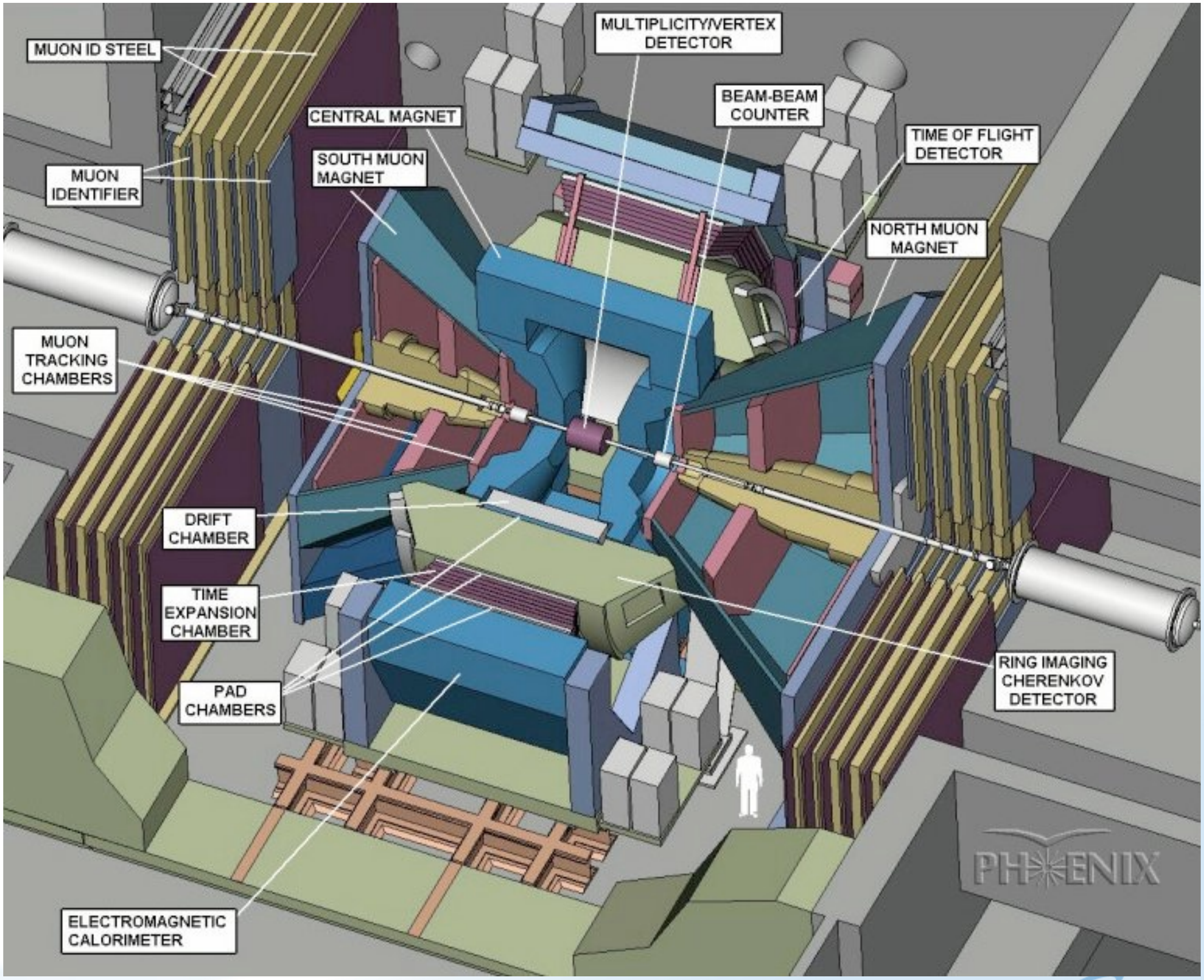
➡ Pad devices ("big pixels or wide strips")

- 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:

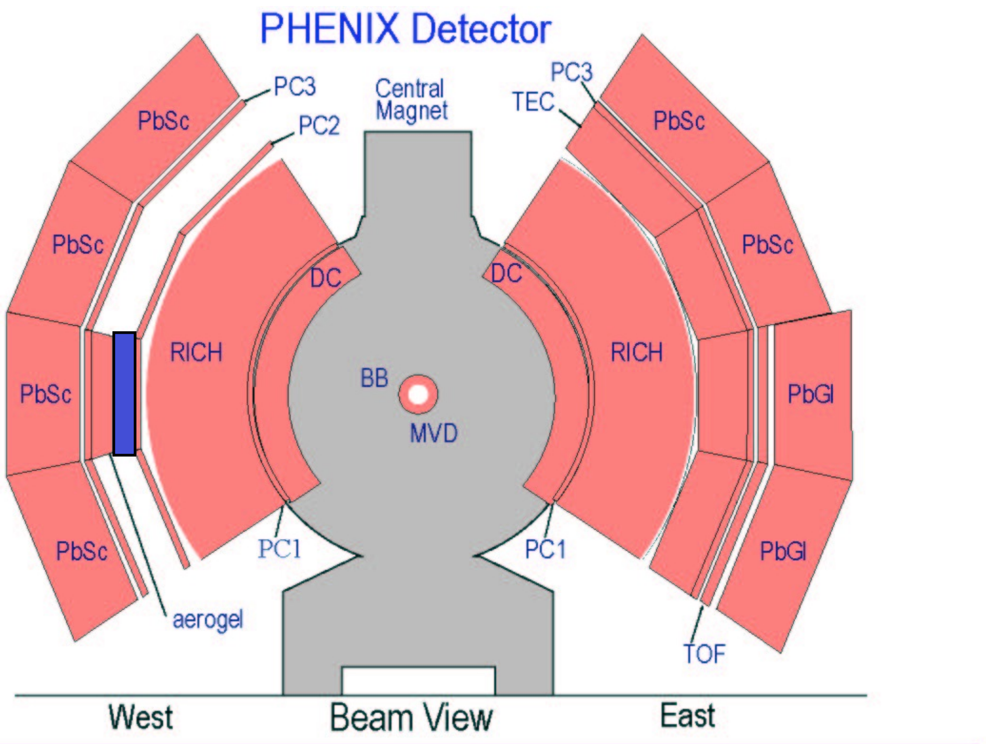
- Time of Flight
- Ring Imaging Cerenkov Counter
- TEC/TRD
- Muon ID (PDT's)
- Aerogel Cerenkov Counter
- Multi-Gap Resistive Plate Chamber ToF
- Hadron Blind Detector

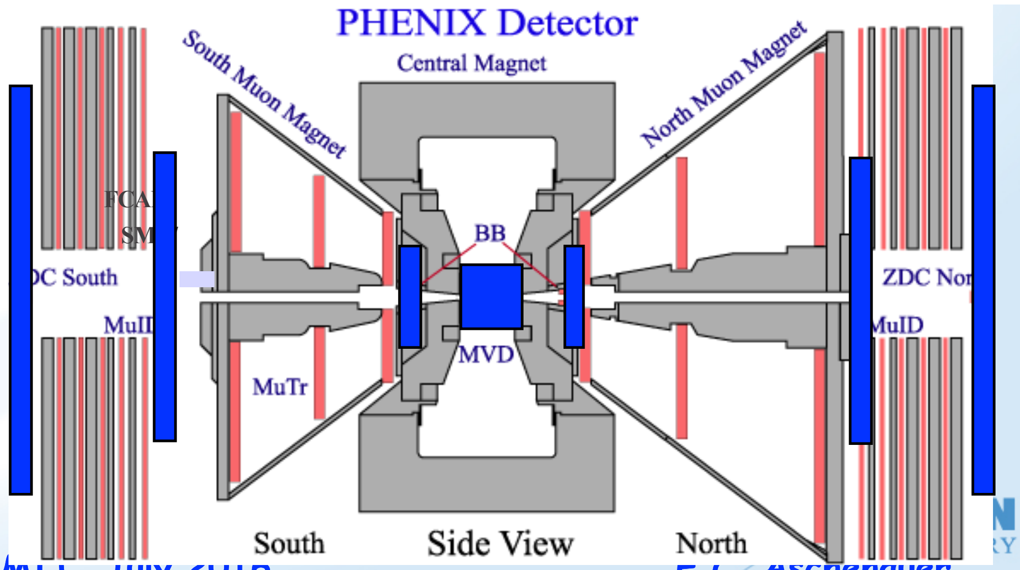
Calorimetry:

- Pb Scintillator
- Pb Glass
- Muon Piston Calorimeter

Event Characterization:

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





CALORIMETER IN A NUTSHELL

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

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

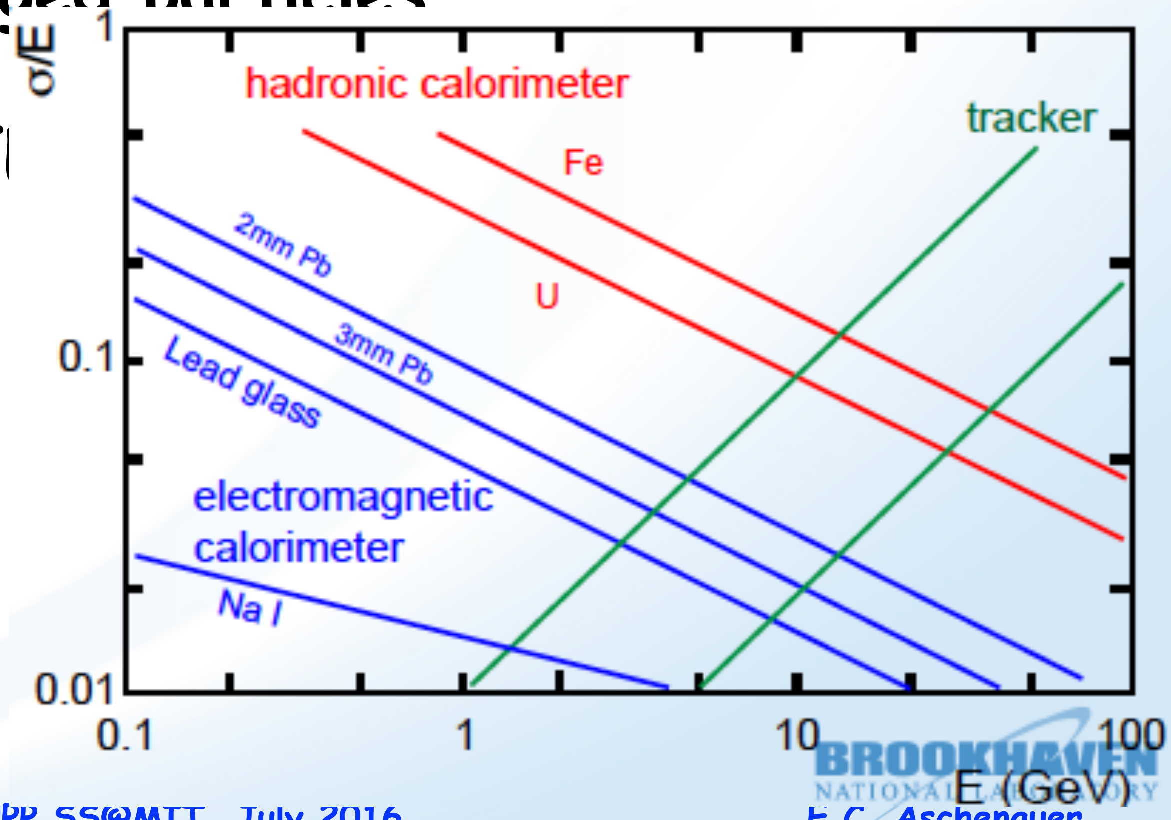
$\Rightarrow$ resolution degrades with increasing energy (unless $L \propto \sqrt{E}$)

also: works only for charged particles

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

$\Rightarrow$ for high energy detectors calorimeters are essential components

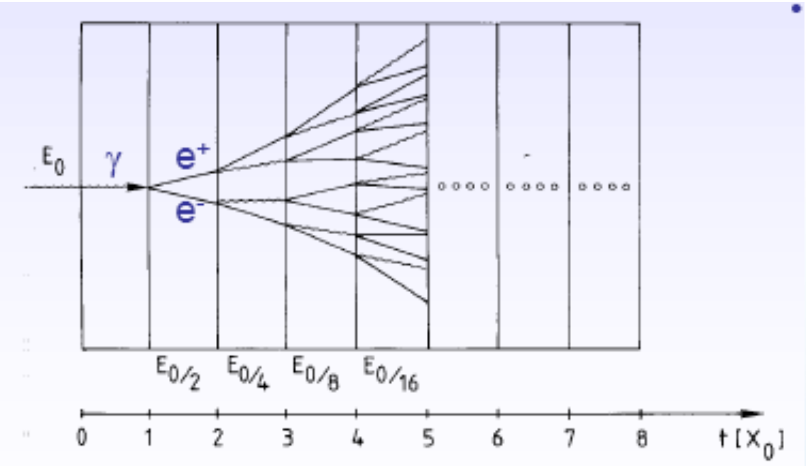
RHIC: only EMcals

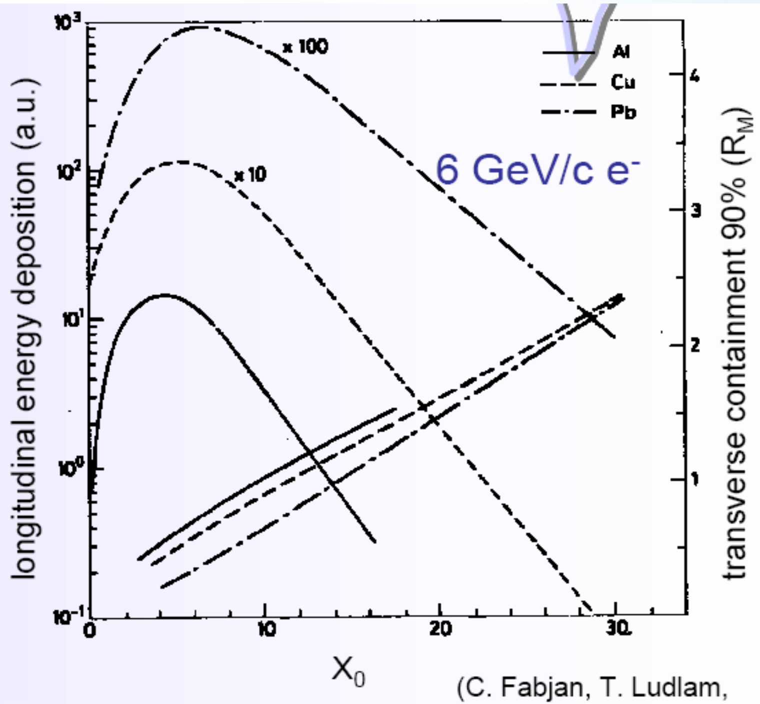


CALORIMETERS IN A NUTSHELL

★ 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





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

★ Resolution

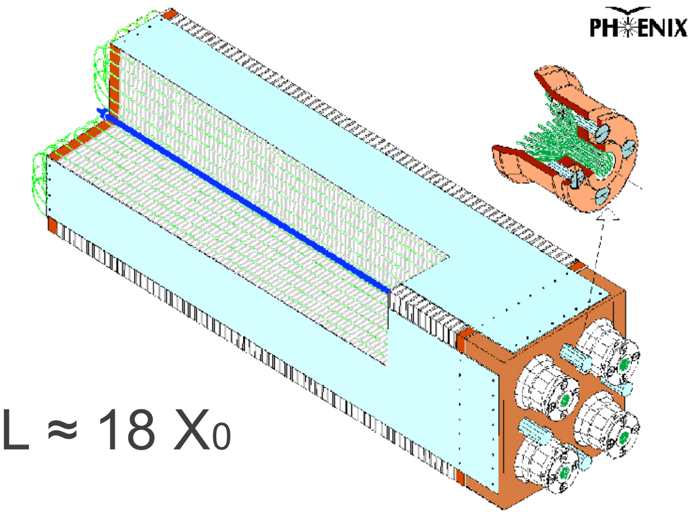
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

stochastic term   constant term   noise term

TWO PHENIX CALORIMETERS

PbSc Calorimeter

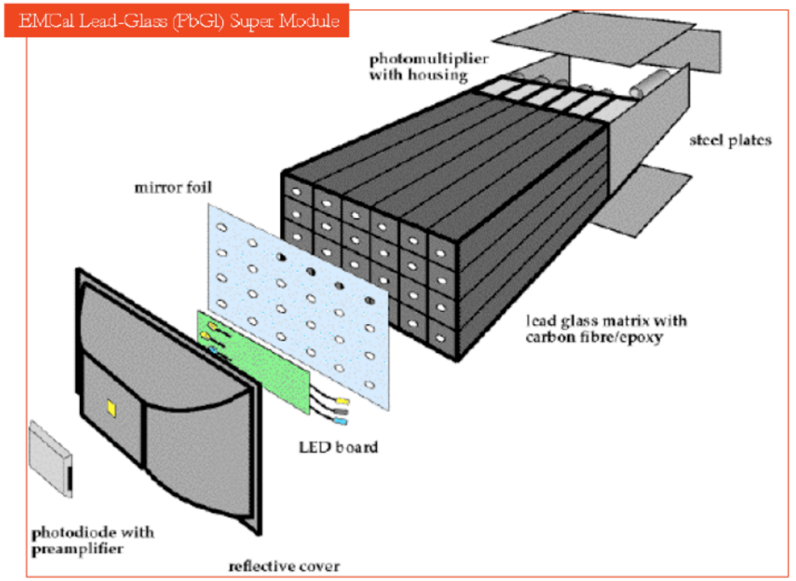
Lead-scintillator sandwich (sampling)
Wavelength-shifting fiber light transport
Photomultiplier readout



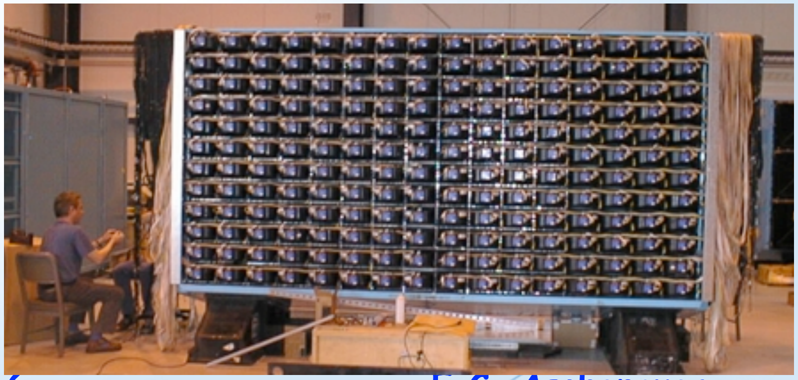
$L \approx 18\ X_0$

PbGl Calorimeter

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

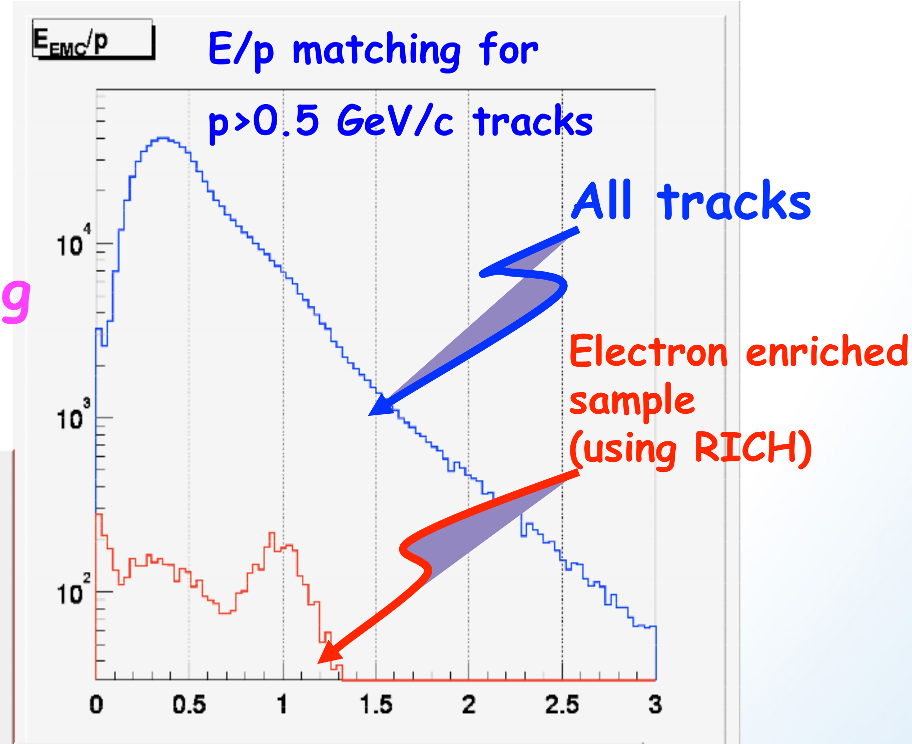


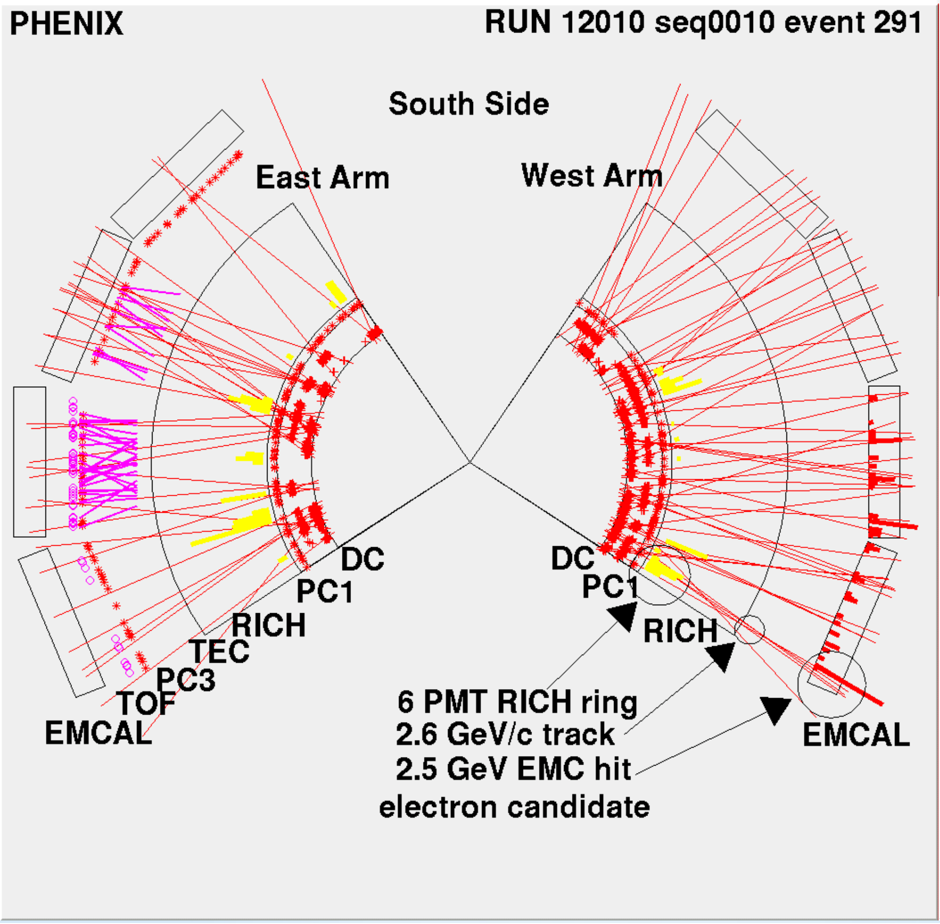
PbSc: $\sigma(E)/E \approx 8\%/\sqrt{E}$
PbGl: $\sigma(E)/E \approx 6\%/\sqrt{E}$

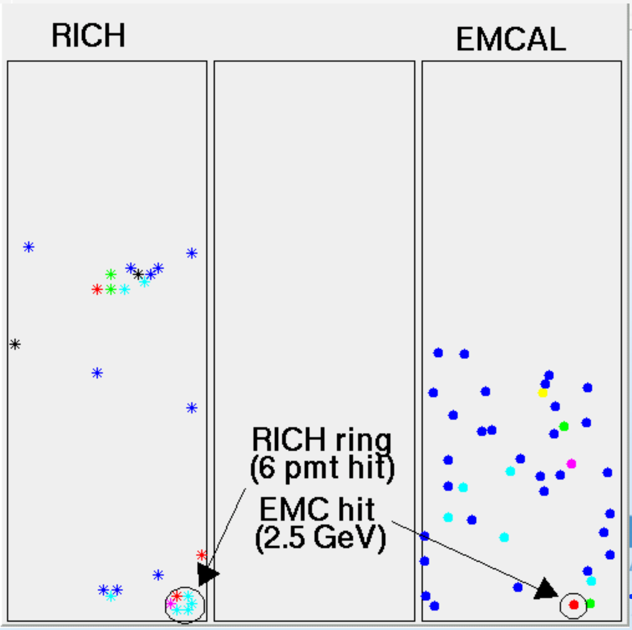


ELECTRON IDENTIFICATION

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



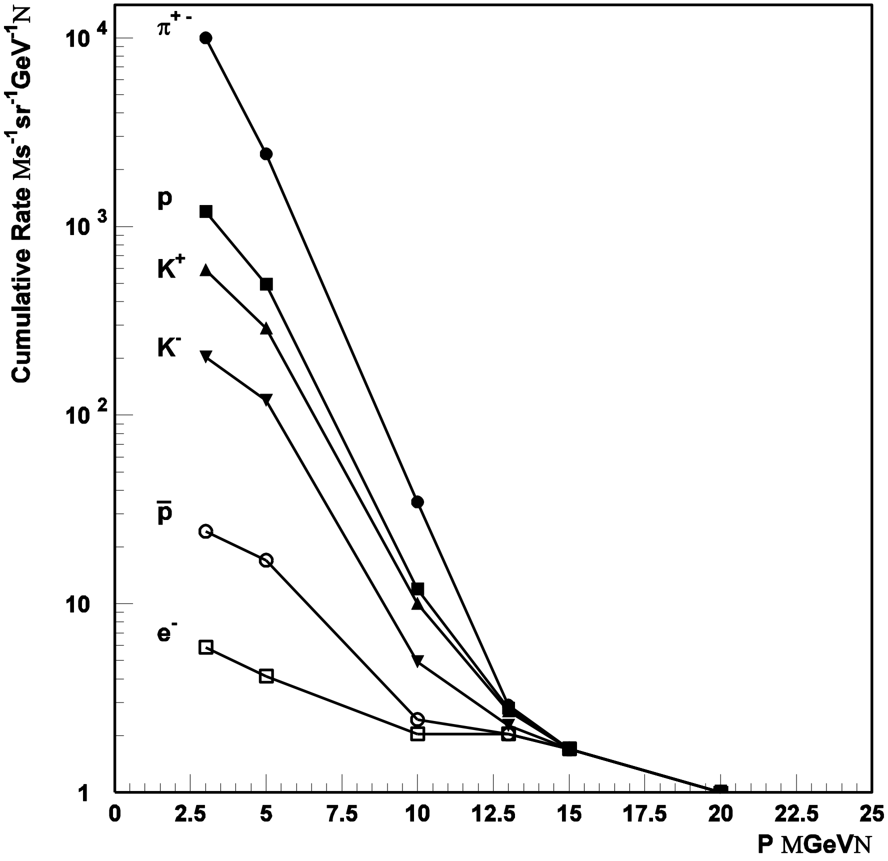


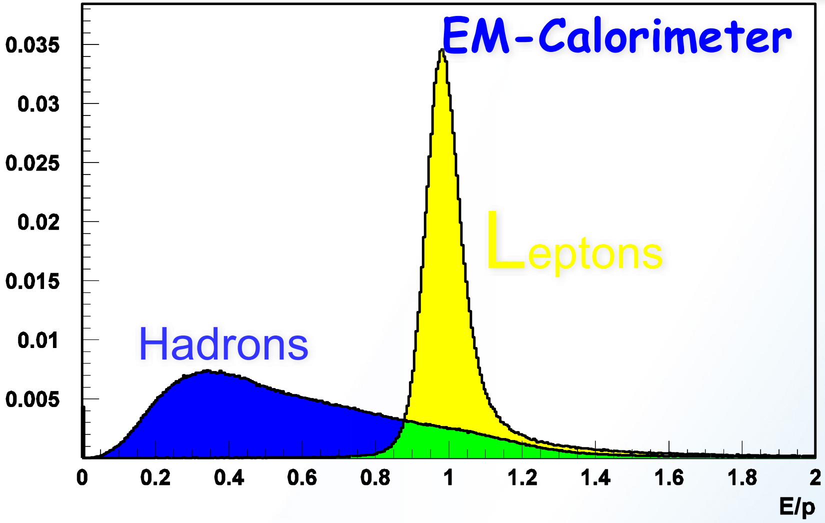


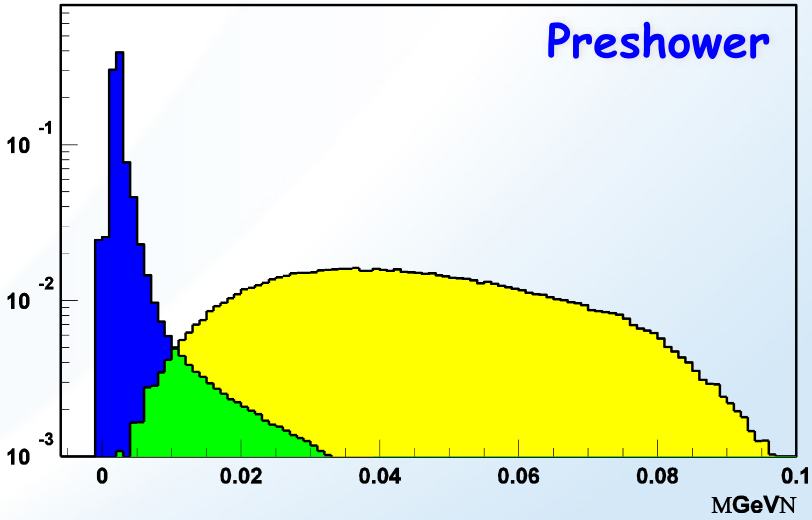
WHICH PARTICLE IS WHICH

An other example how to find the hidding electrons → HERMES@DESY

Physics requirement: Need lepton hadron separation over wide momentum range





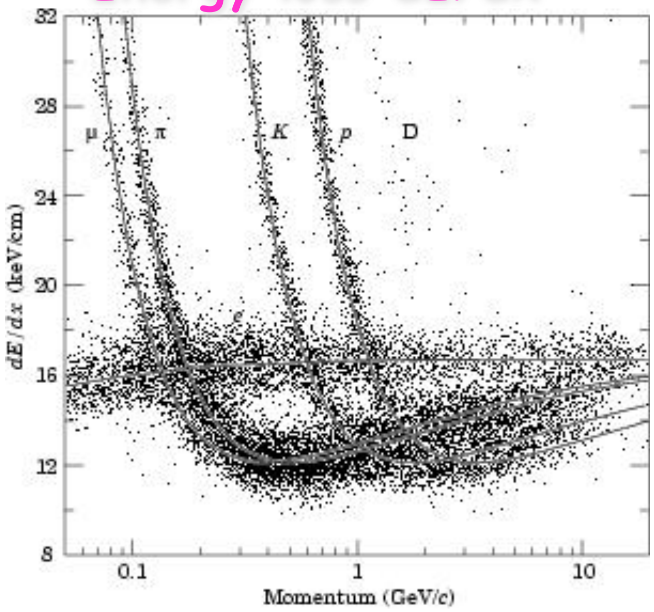


In worst case factor 10^5 hadron suppression is needed

combined suppression 10^3
Factor 100 still needed

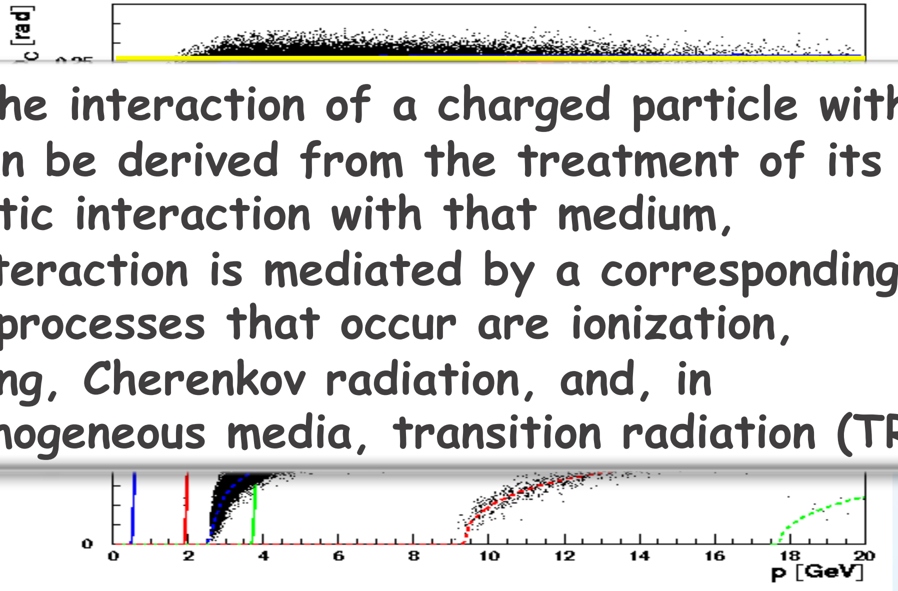
WHAT IS THE BEST DETECTOR CONCEPT

Energy loss dE/dx



Too small p lever arm

Cerenkov Radiation

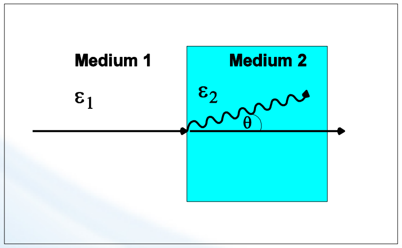


In general, the interaction of a charged particle with a medium can be derived from the treatment of its electromagnetic interaction with that medium, where the interaction is mediated by a corresponding photon. The processes that occur are ionization, Bremsstrahlung, Cherenkov radiation, and, in case of inhomogeneous media, transition radiation (TR).

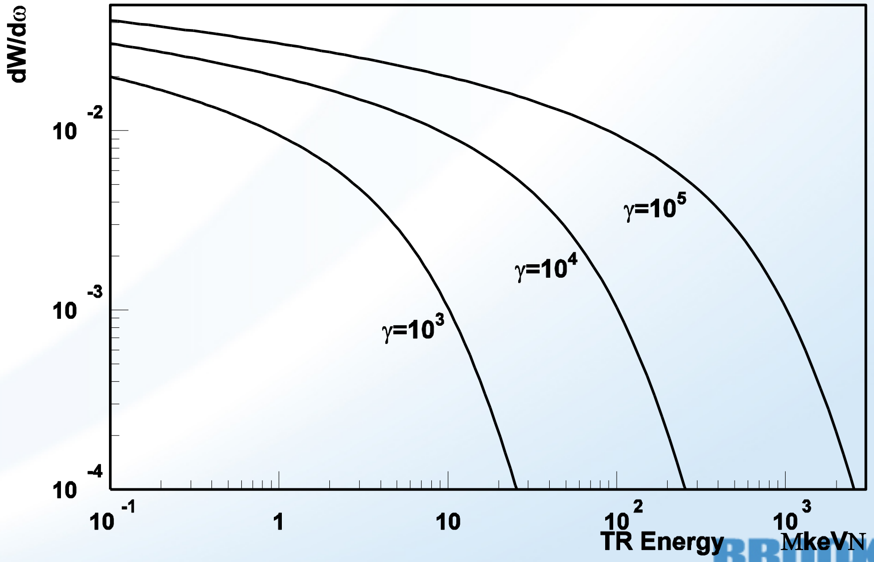
Impossible to cover full p-range of leptons

Transition Radiation:

sensitive to particle γ (γ>1000)

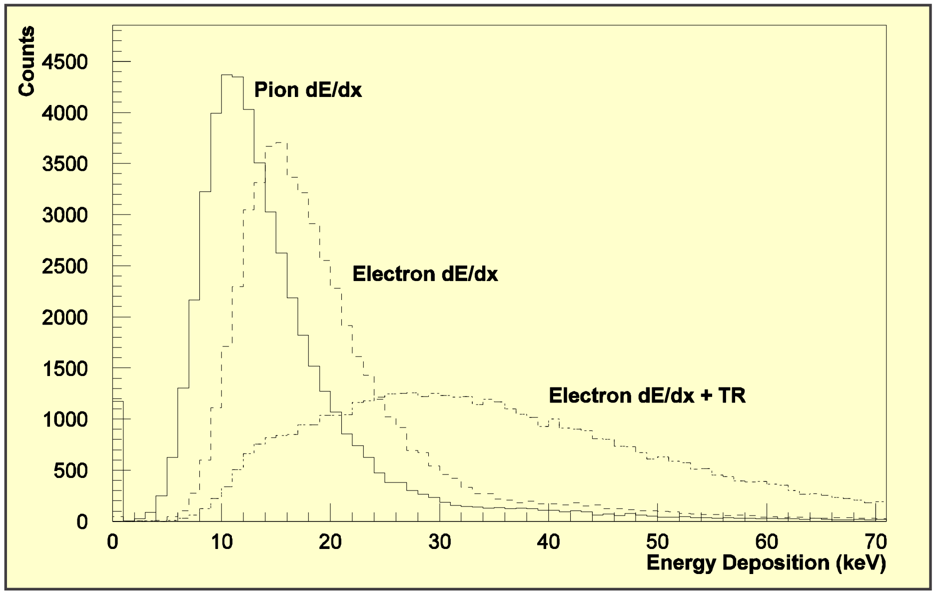


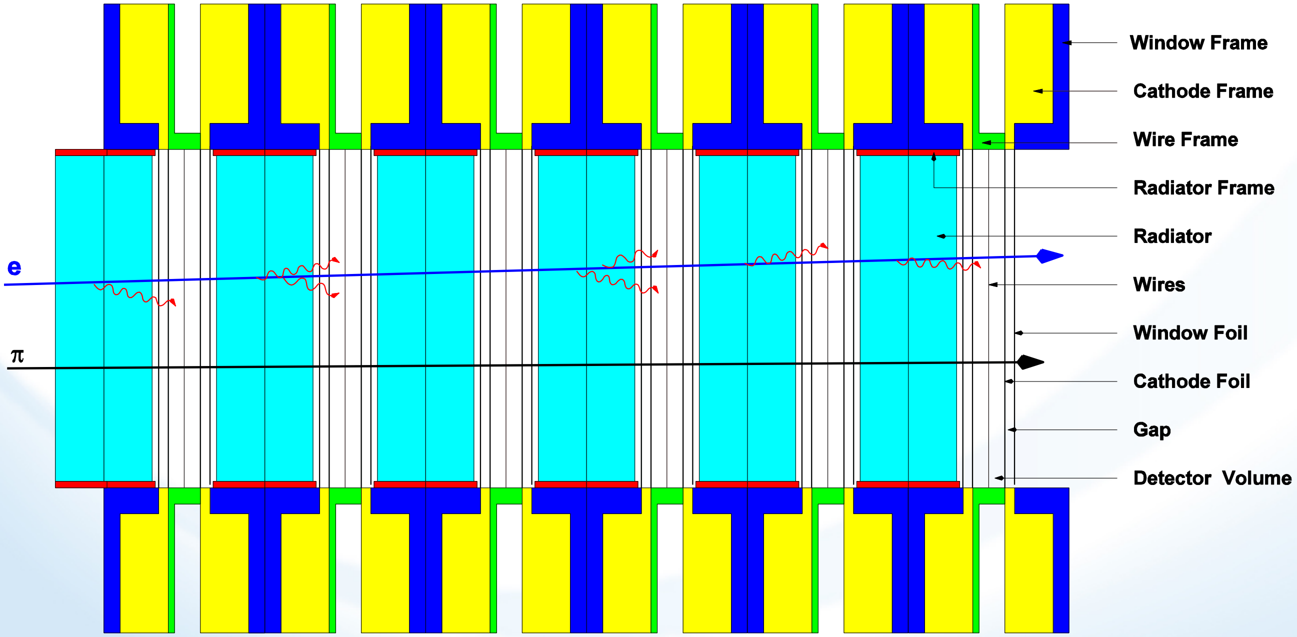
$$= \frac{1}{\sqrt{1 \quad \frac{v^2}{c^2}}}$$

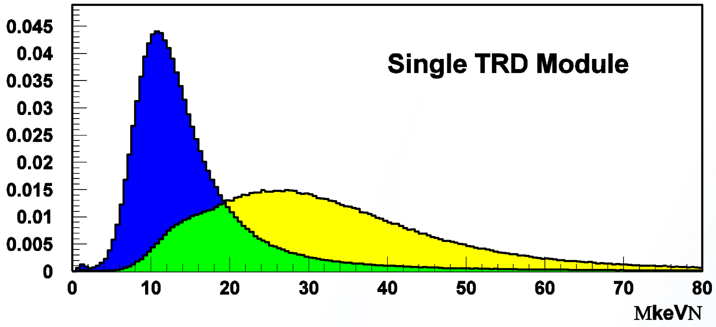


THE HERMES TRD

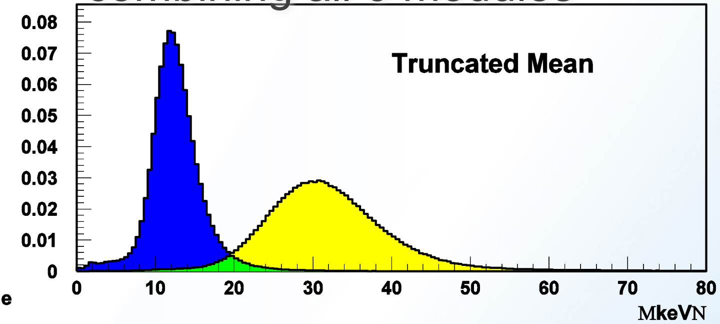
Single Module Response

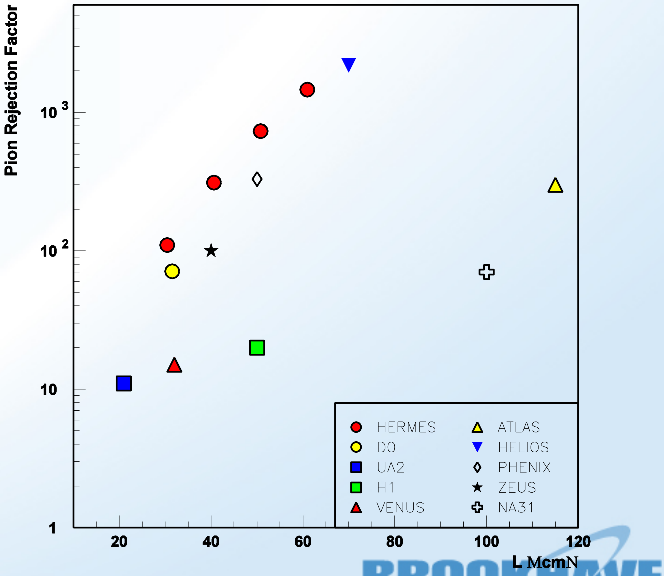




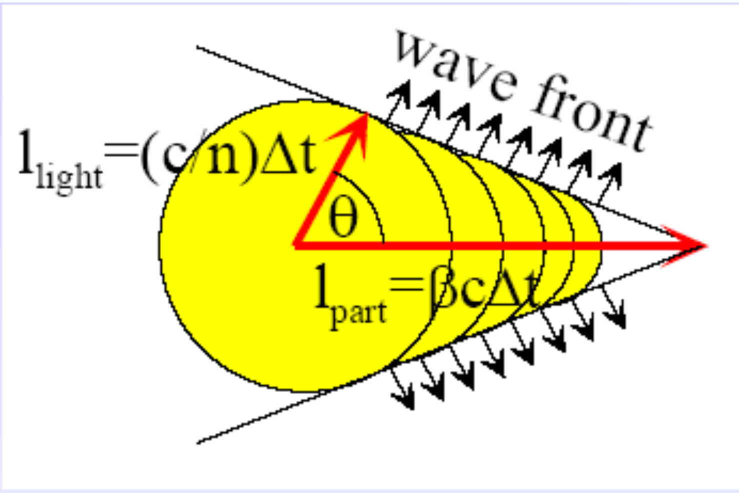


combining all 6 modules





CHERENKOV DETECTORS

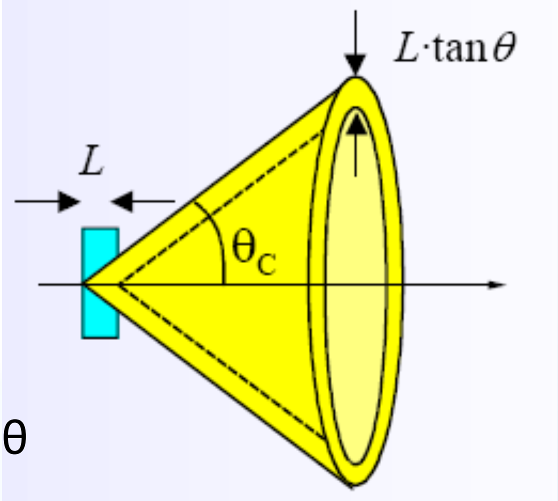


Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity

$\beta \geq \beta_{thr}=1/n$ 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.

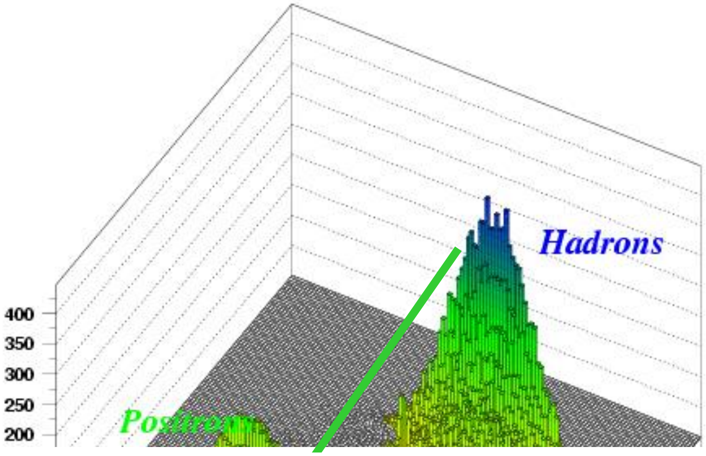
Number of detected photo electrons: $N_{pe}= N_0 L \sin^2\theta$

N_0: number of merit for a Cherenkov detector

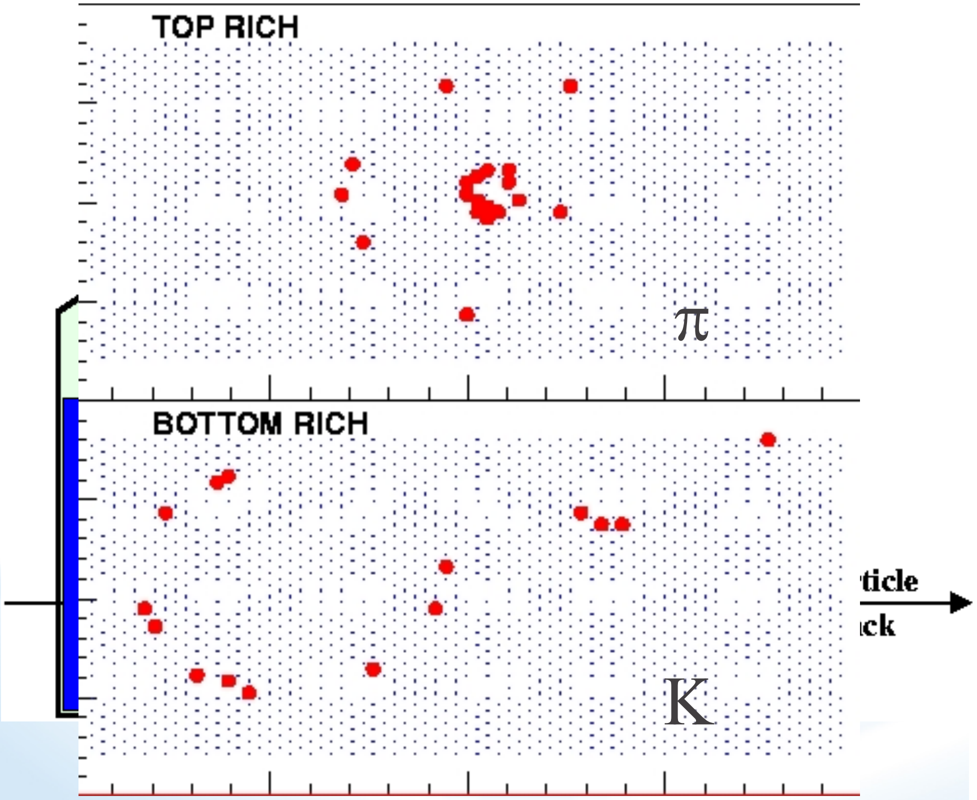
medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

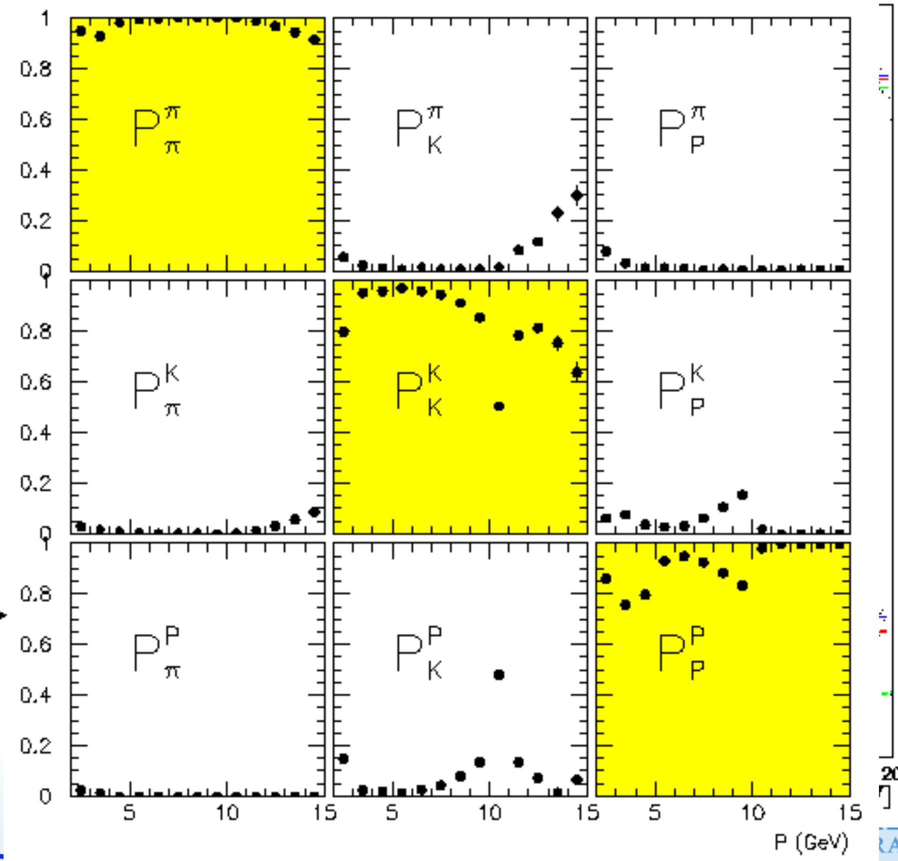
WHICH HADRON (Π,K,P) IS WHICH

hadron/positron separation
combining signals from:
TRD, calorimeter, preshower



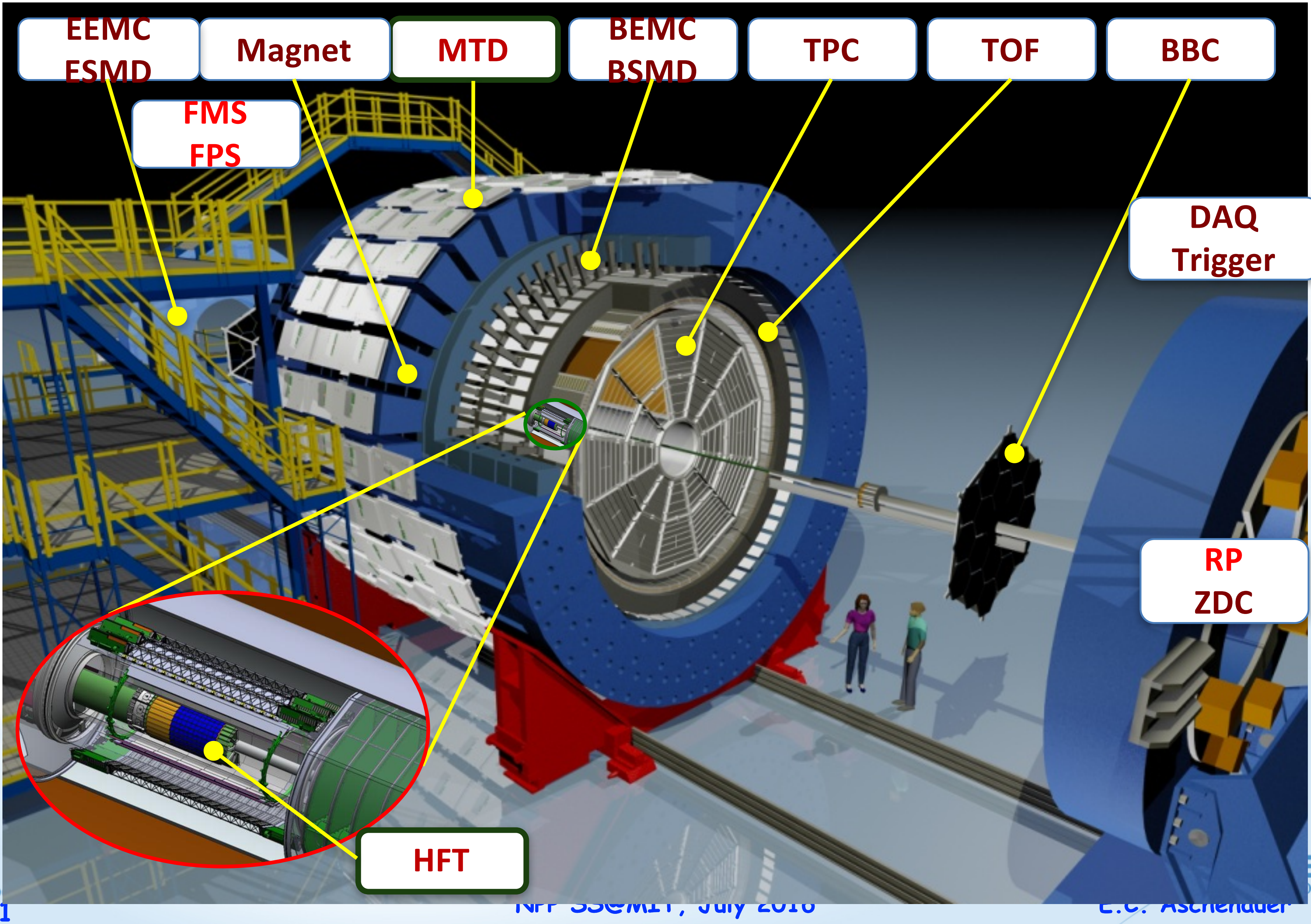
hadron separation
Dual radiator RICH for π, K, p



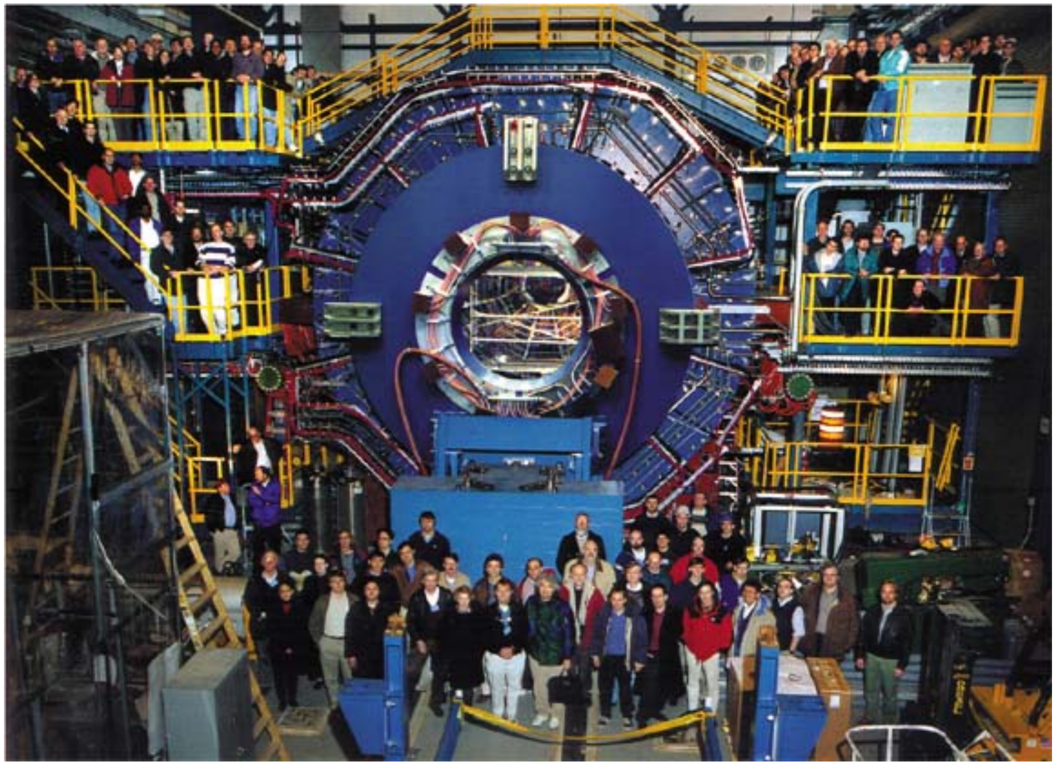


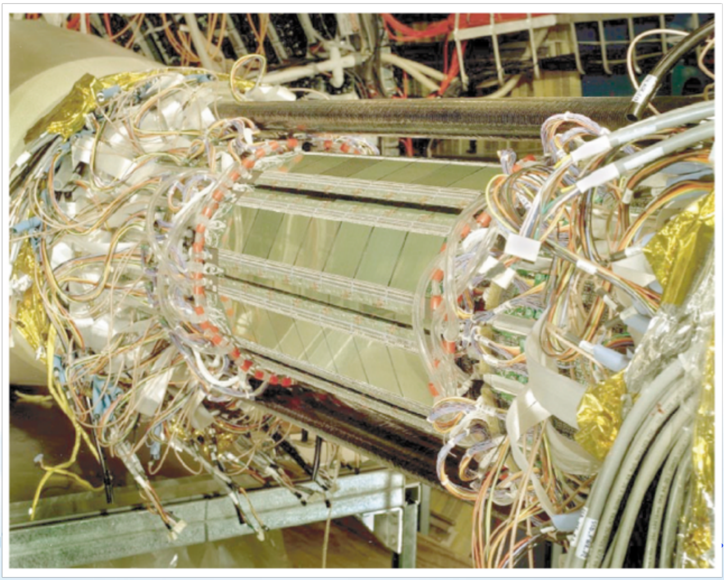
STAR

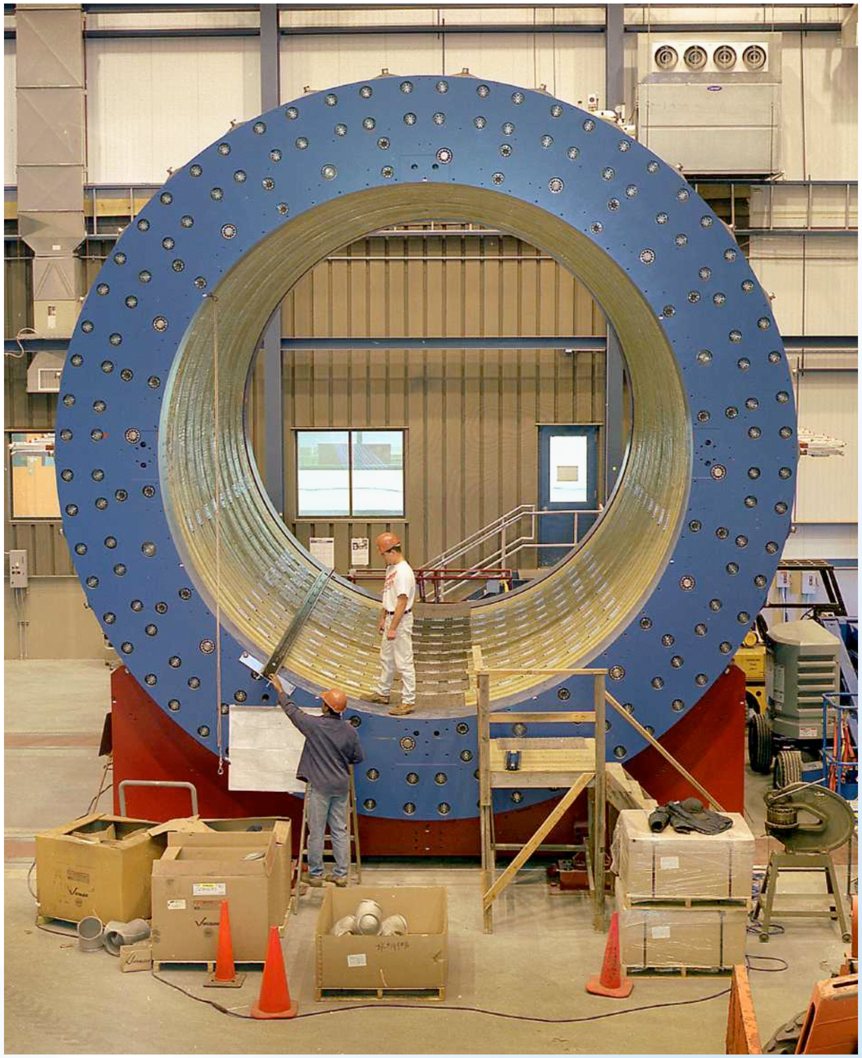
15 fully functioning detector systems



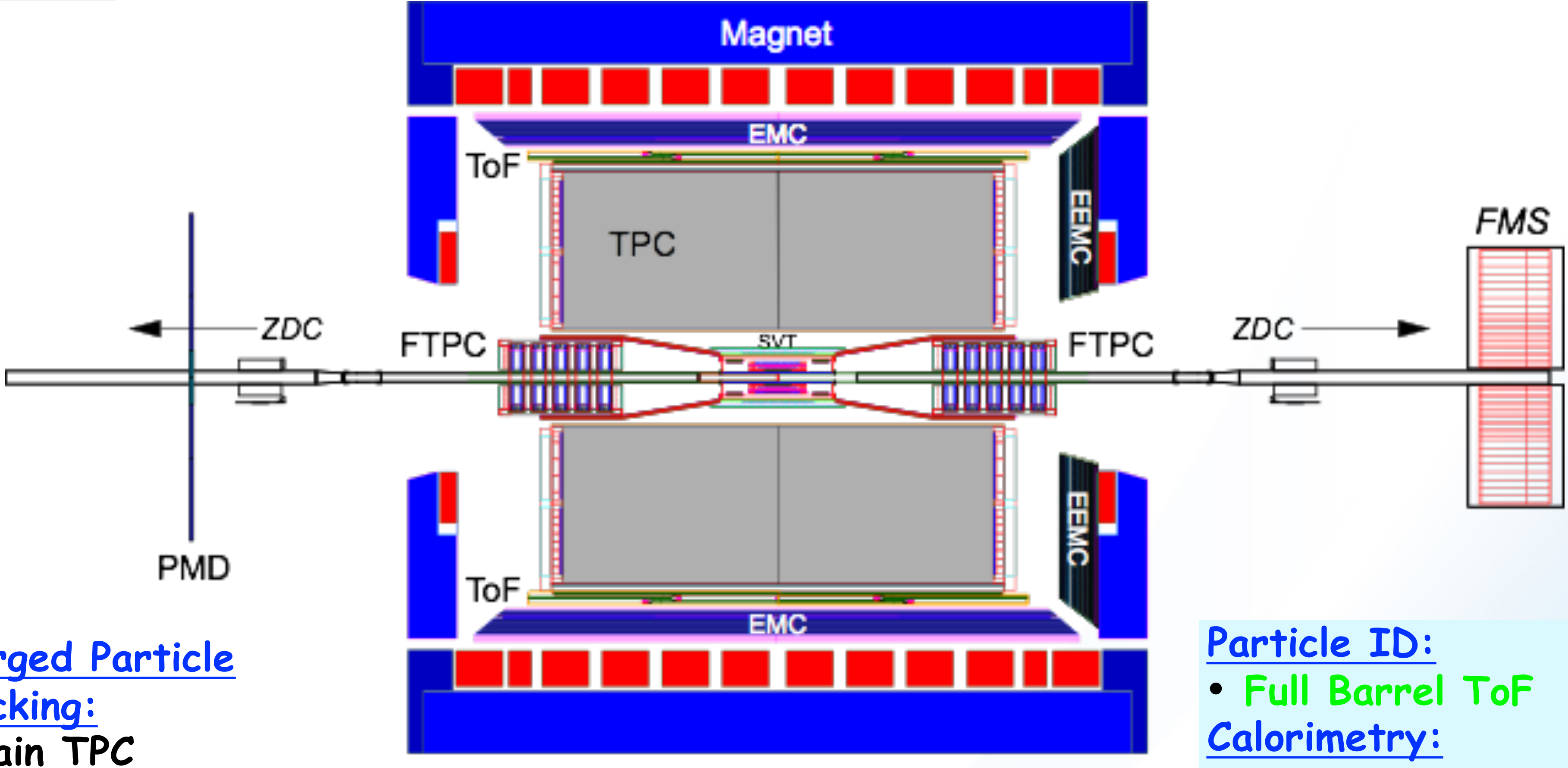
STAR (2001)







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)

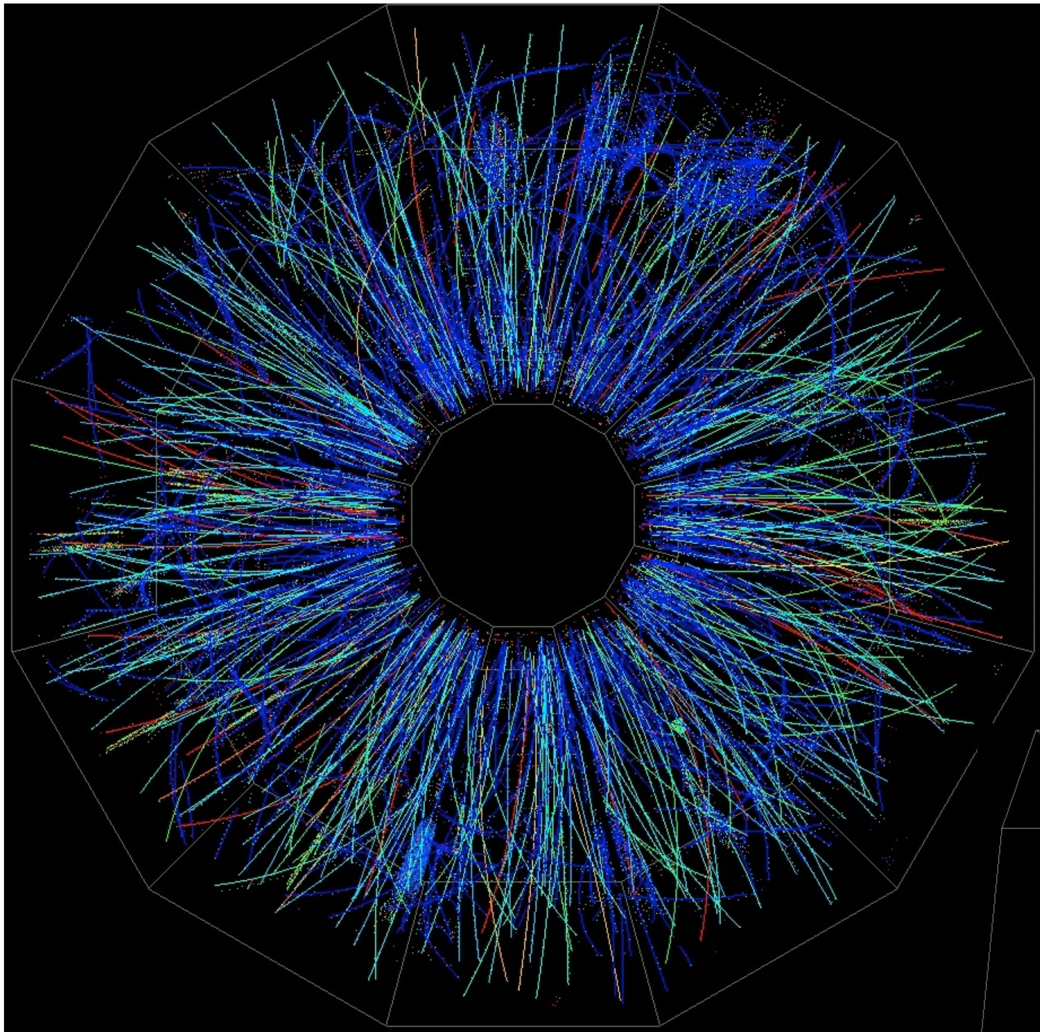
Particle ID:

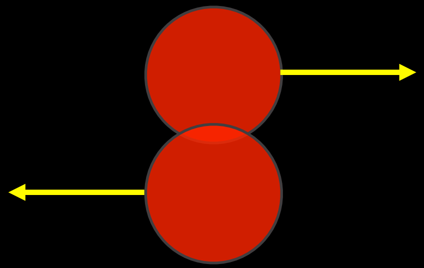
- Full Barrel ToF

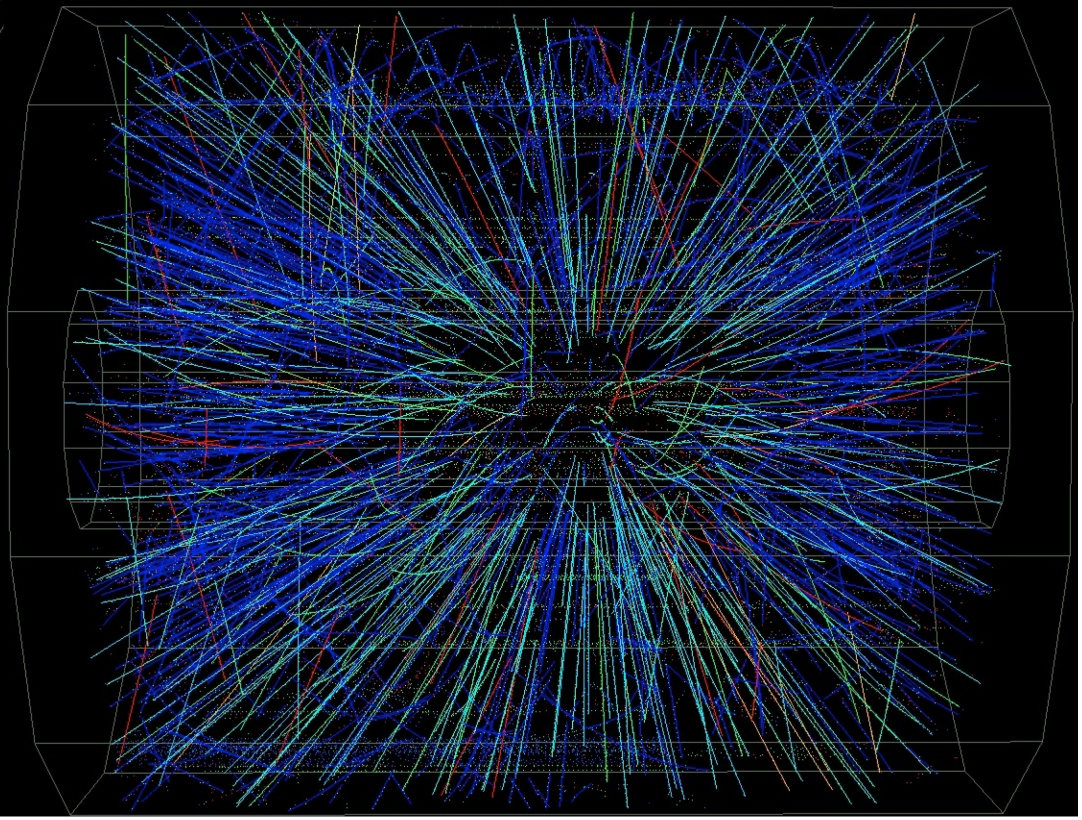
Calorimetry:

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

Peripheral Event



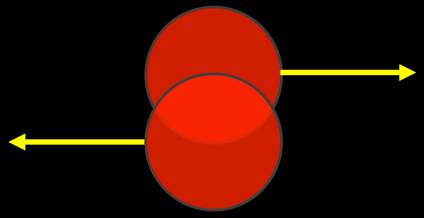


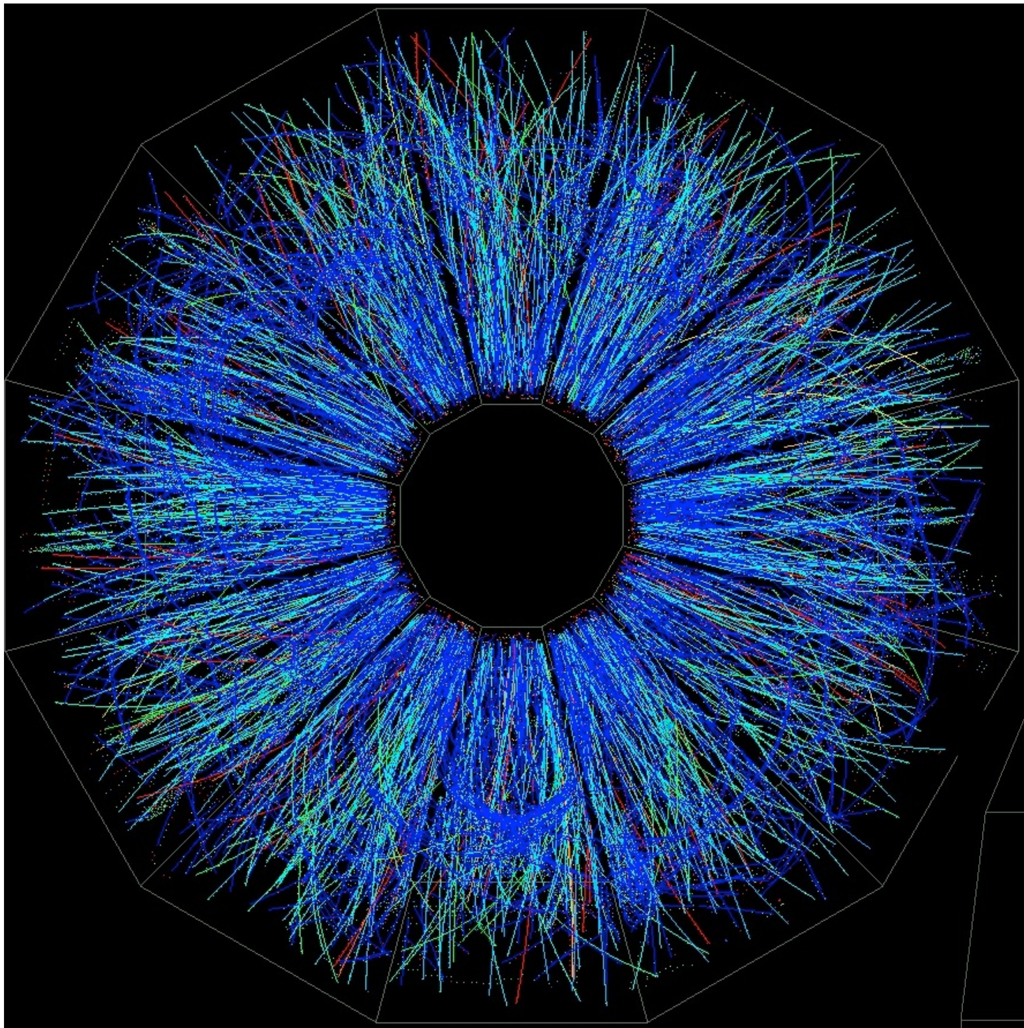


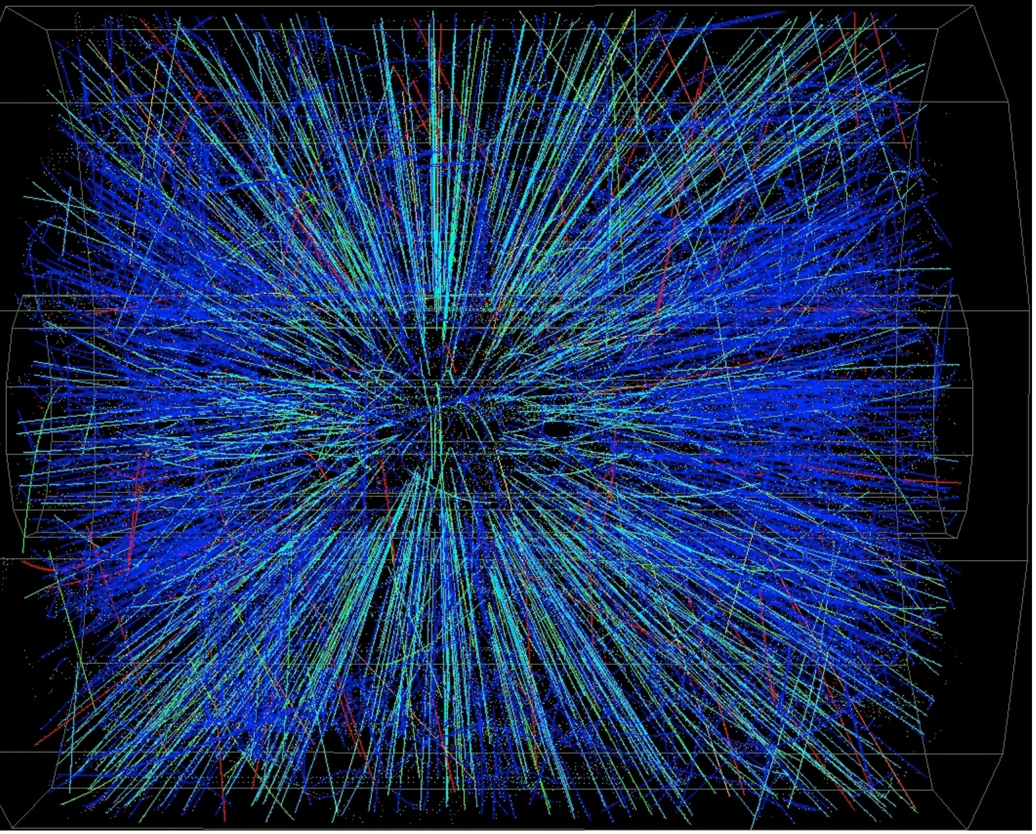
color code ⇒ energy loss

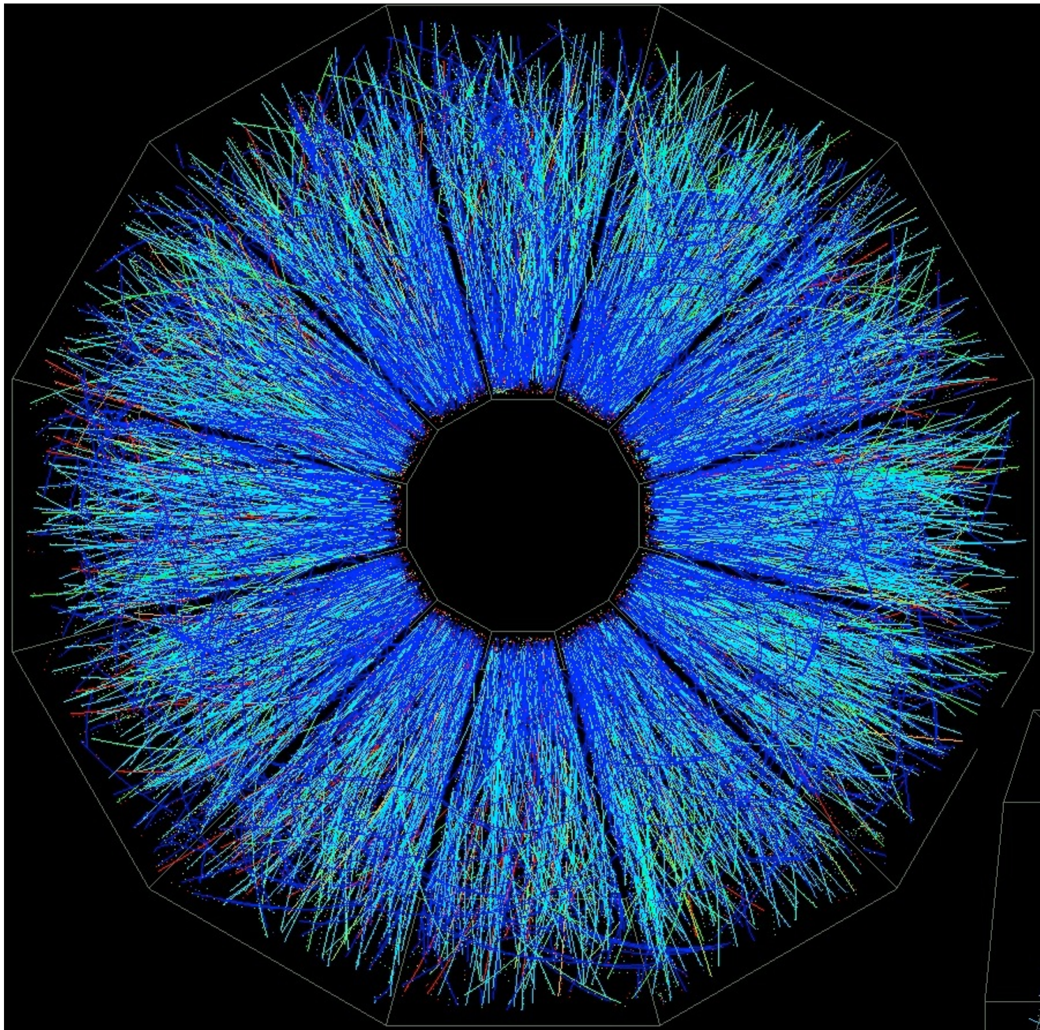
STAR

Mid-Central Event

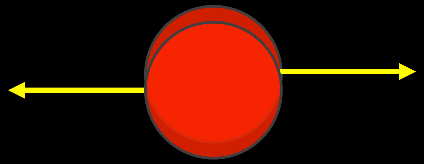


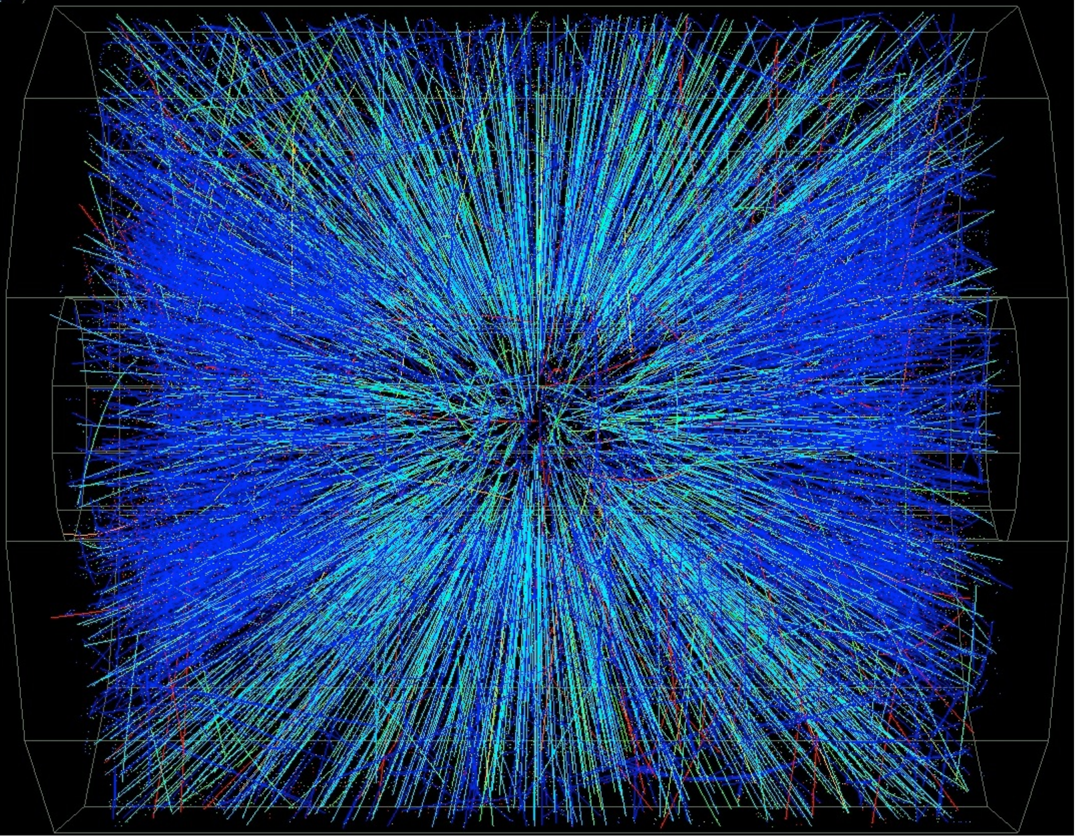






Central Event



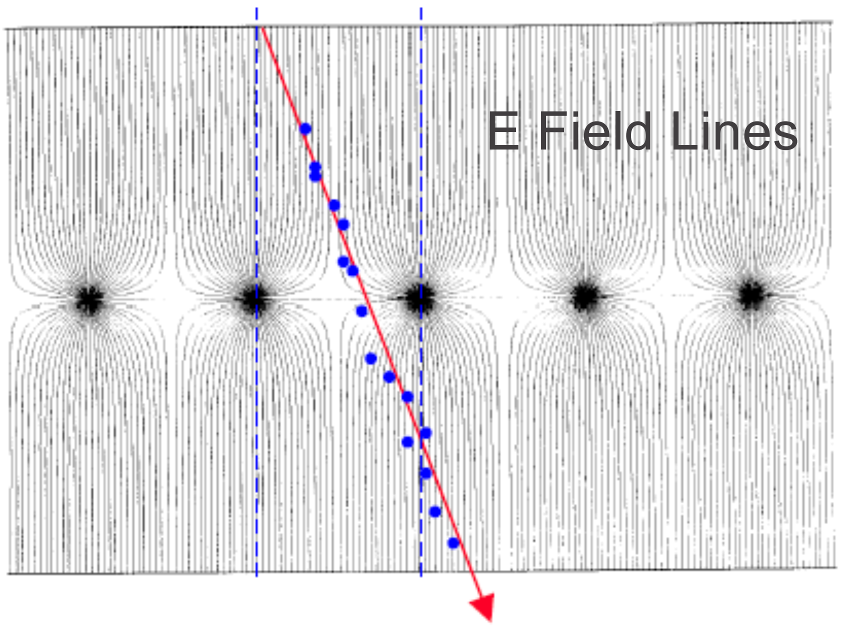


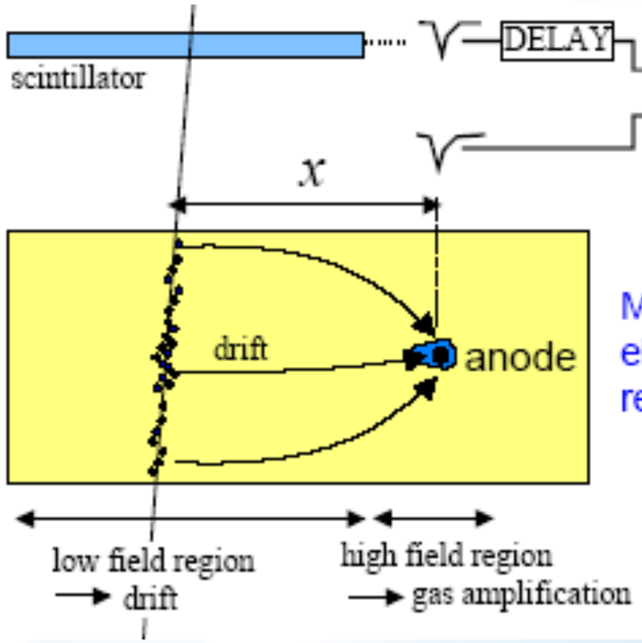
STAR

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 ⇒ $\sigma_x \sim d/\sqrt{12}$
- 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)

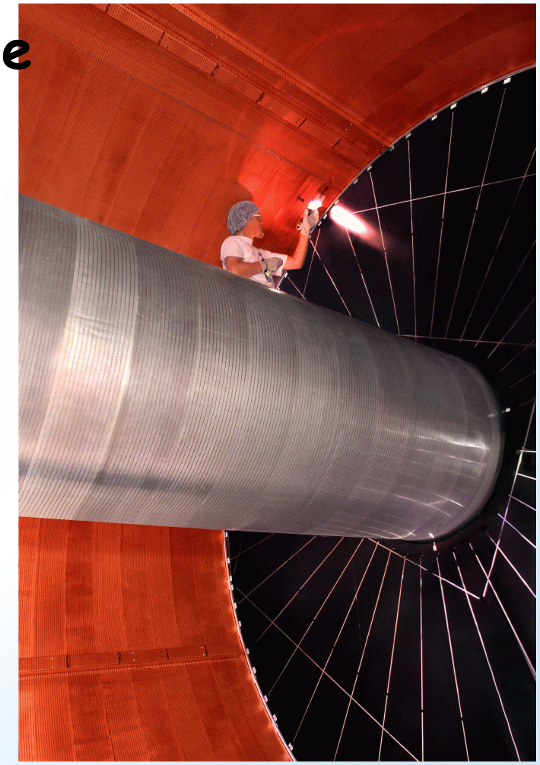
Error of momentum measurement: $$\frac{\sigma(p_T)}{p_T} \propto \frac{\sigma(x)\cdot p_T}{B\cdot L^2}$$

➡ 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)

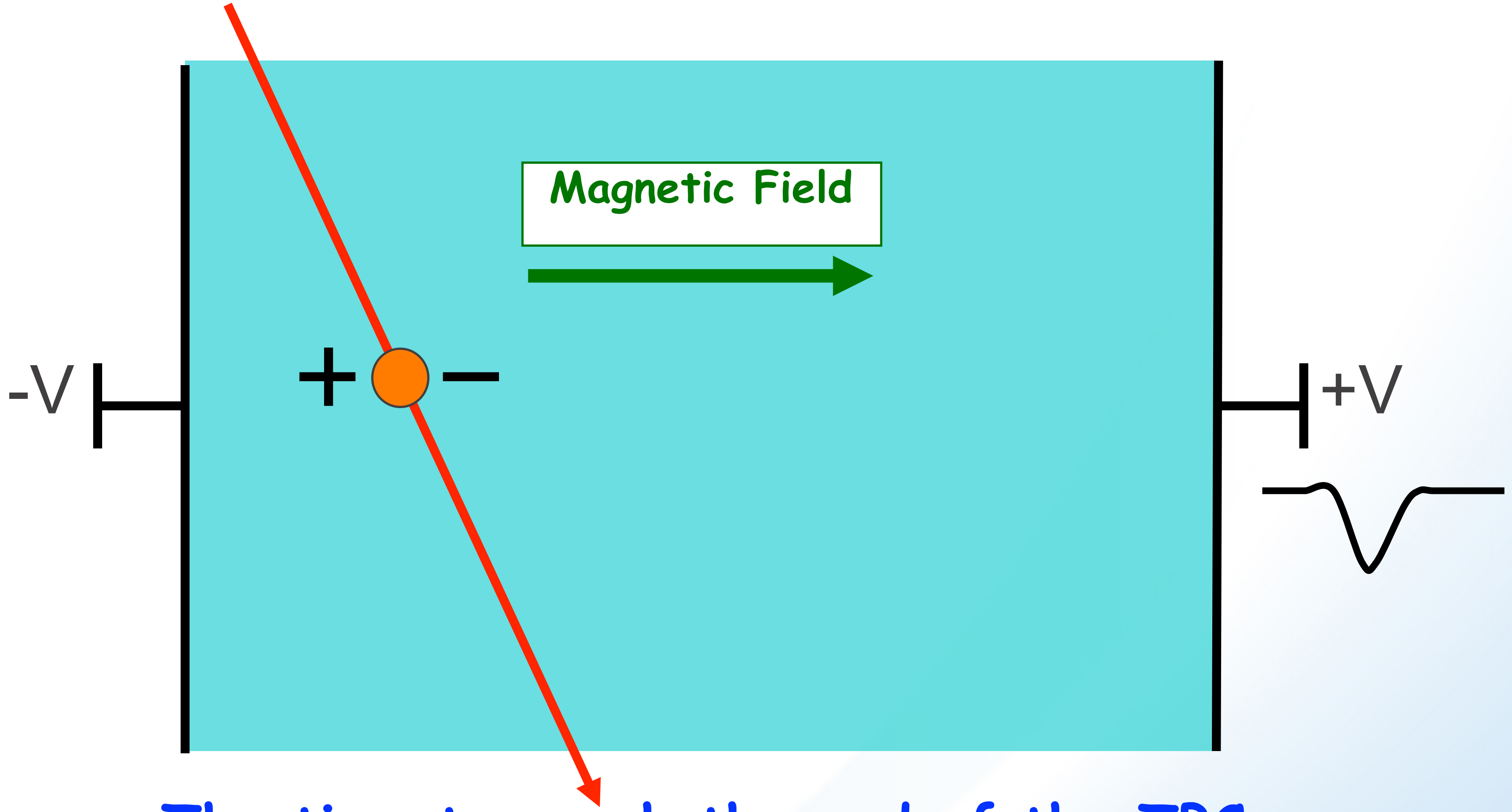
Solution:

let the electrons drift over long distances

➡ TPC: essentially a huge gas filled box

Think of a TPC as a 3D CCD camera

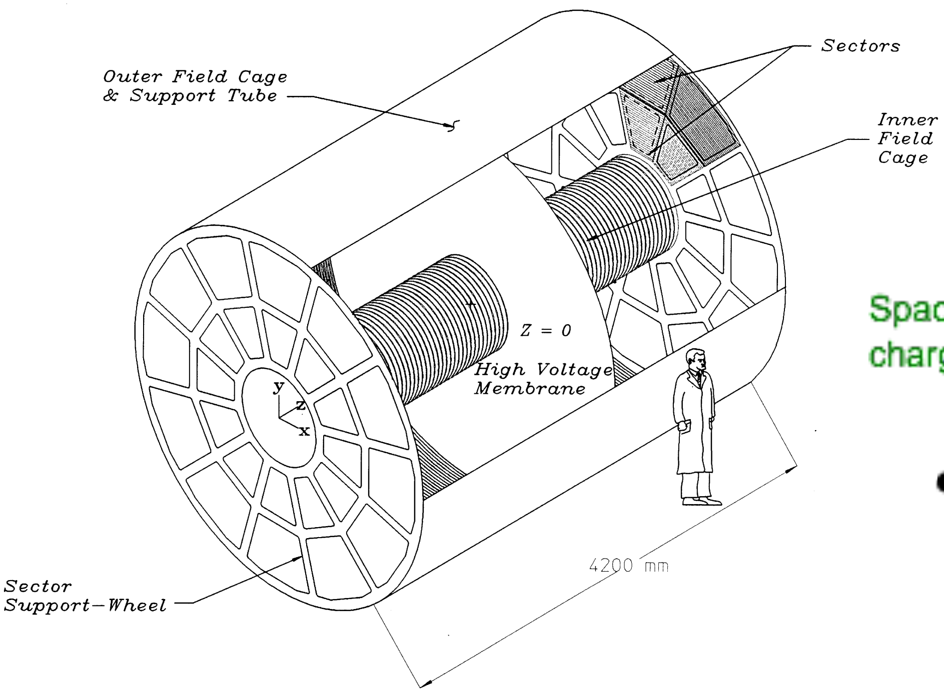
THE BASIC CONCEPT OF A TPC

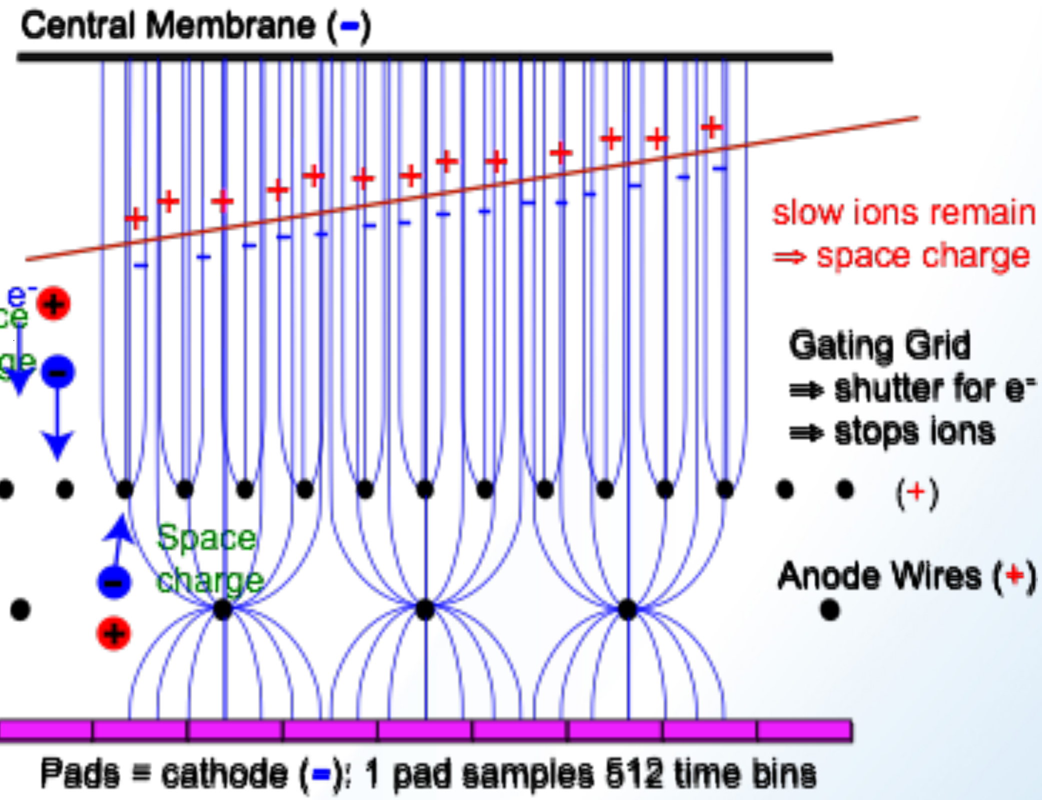


The time to reach the end of the TPC determines the distance drifted in the gas.

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

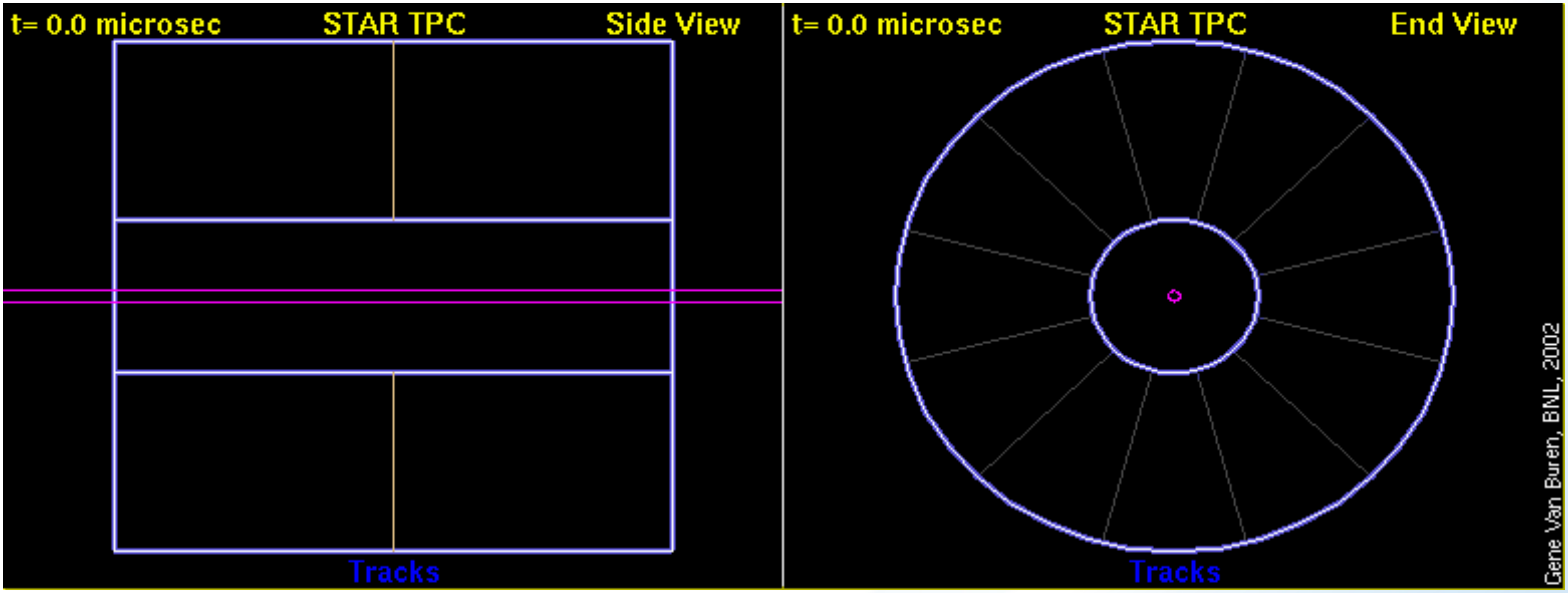
Gating Grid:

- Designed to reduce charge injection into amplifiers

Slow ions left in volume:

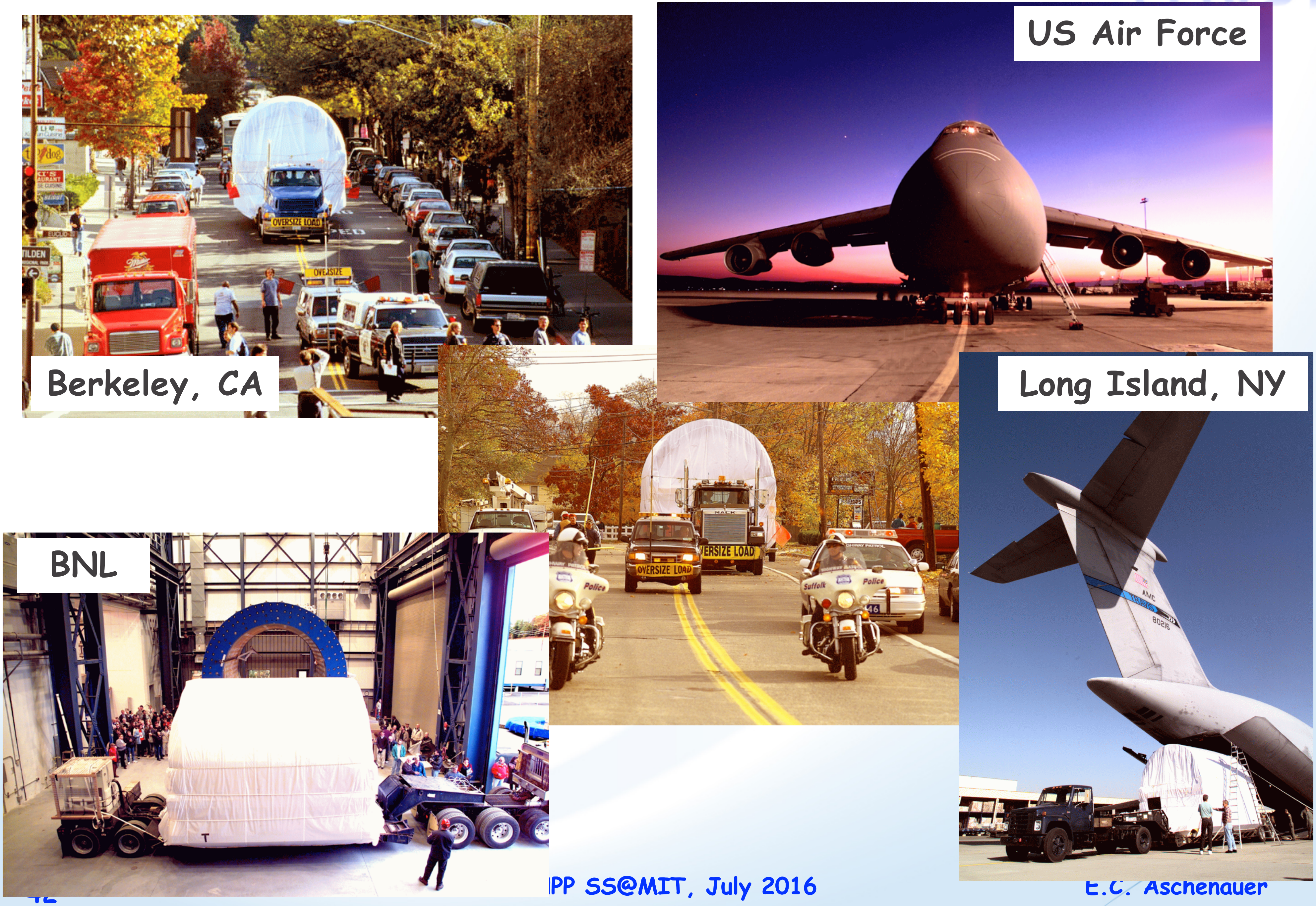
- accumulate, create space charge
- space charge creates distortions

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

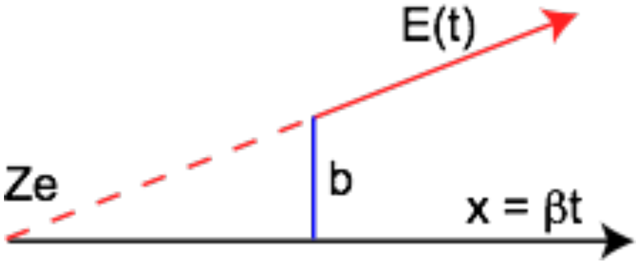
Long Island, NY

BNL

PARTICLE IDENTIFICATION BY dE/dx IN STAR'S TPC

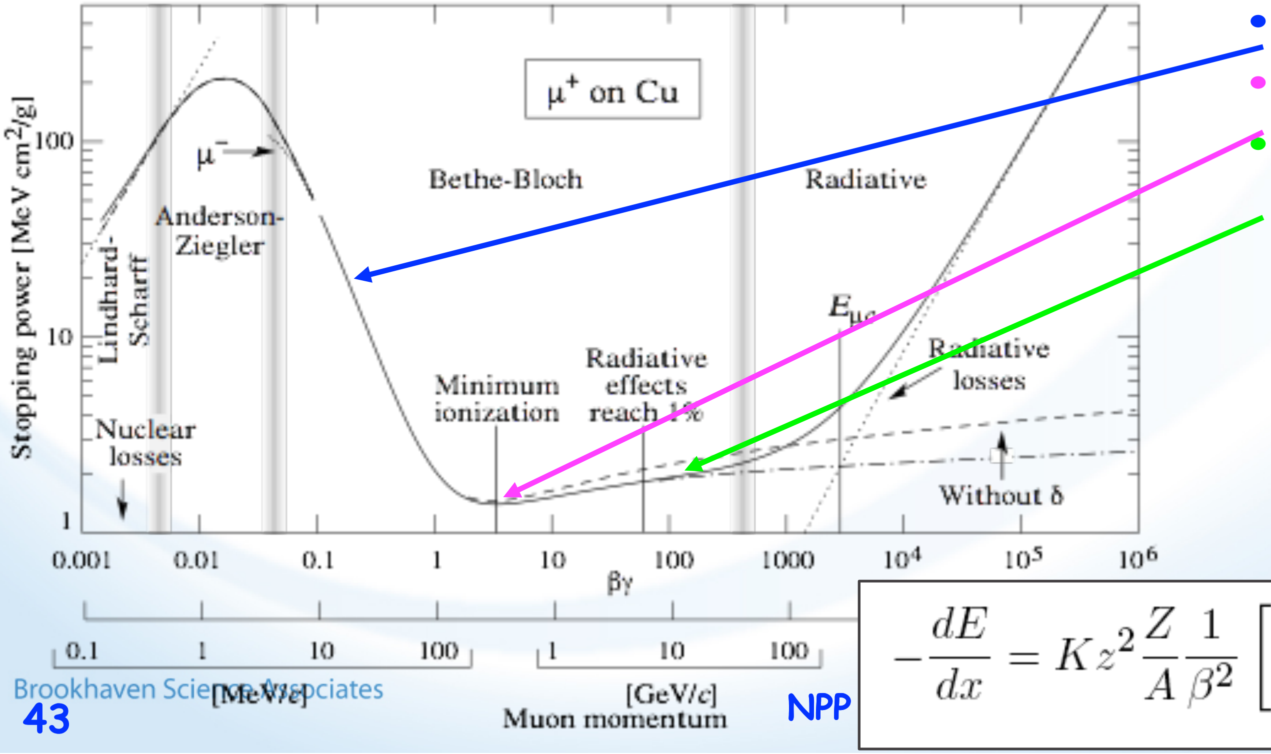
- Elementary calculation of energy loss:

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

Bethe-Bloch Formula

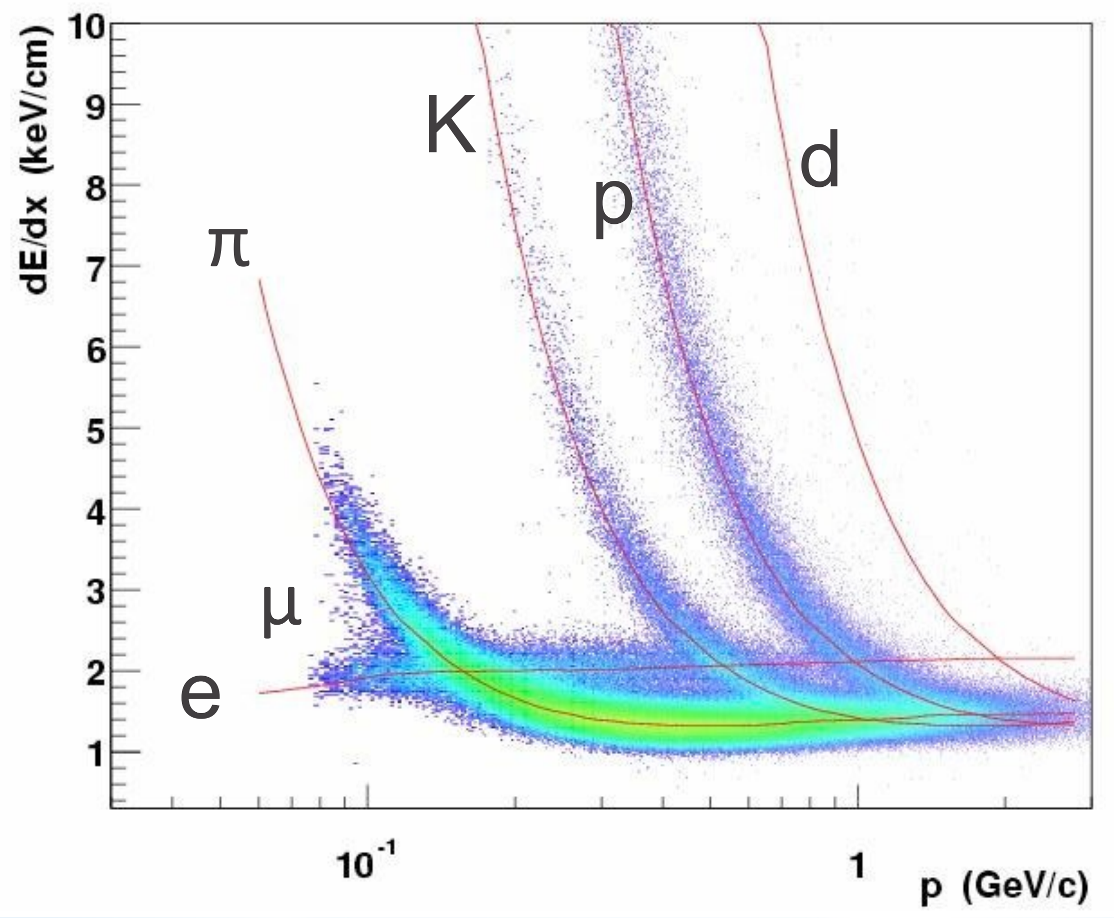
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

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



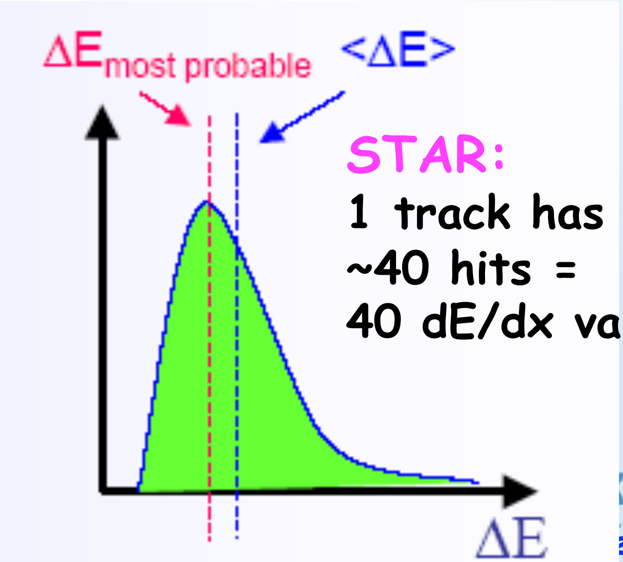
Real detector (limited granularity) can not measure <dE/dx> !

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.

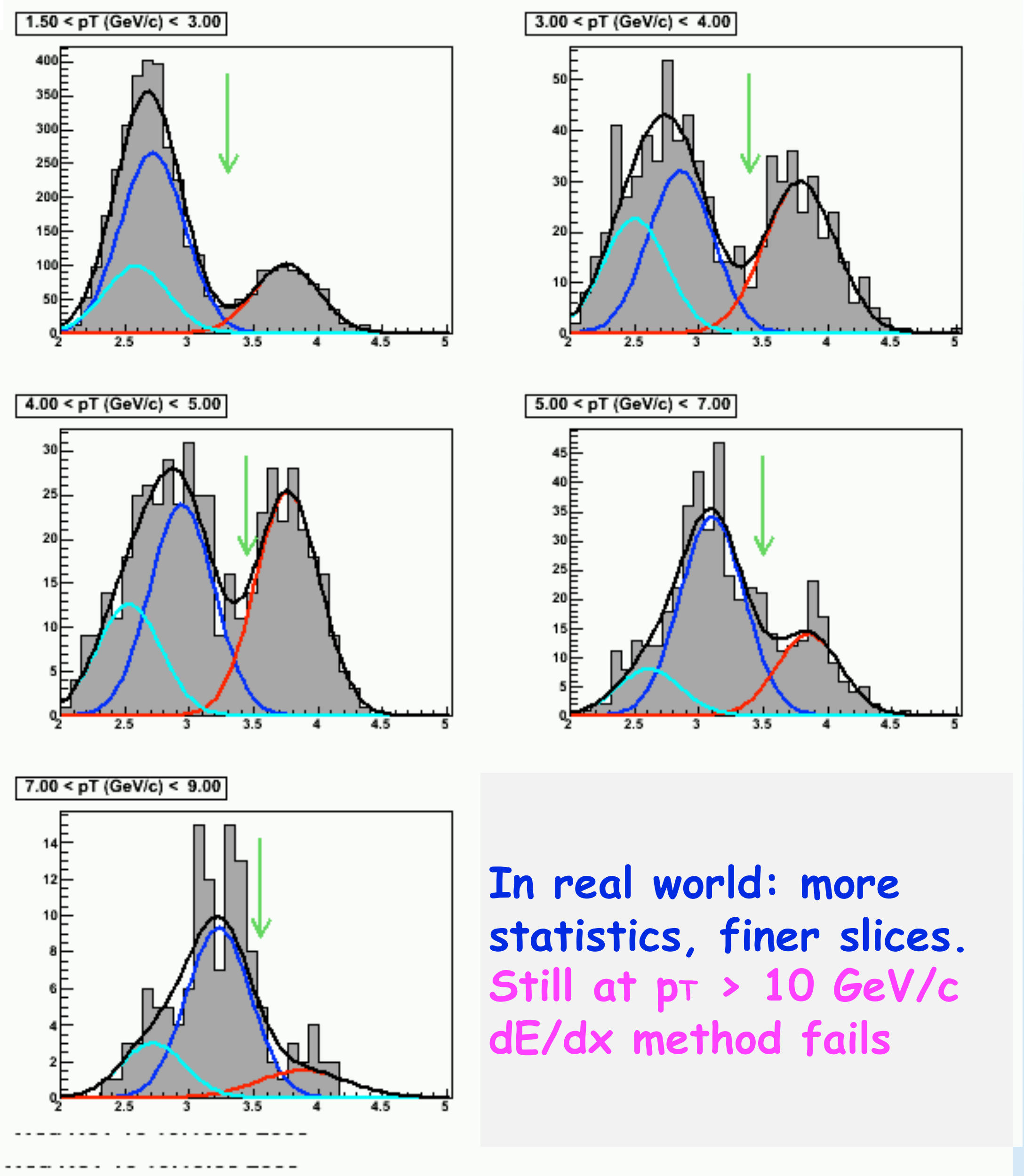
Energy loss distributions show large fluctuations towards high losses: "Landau tails"



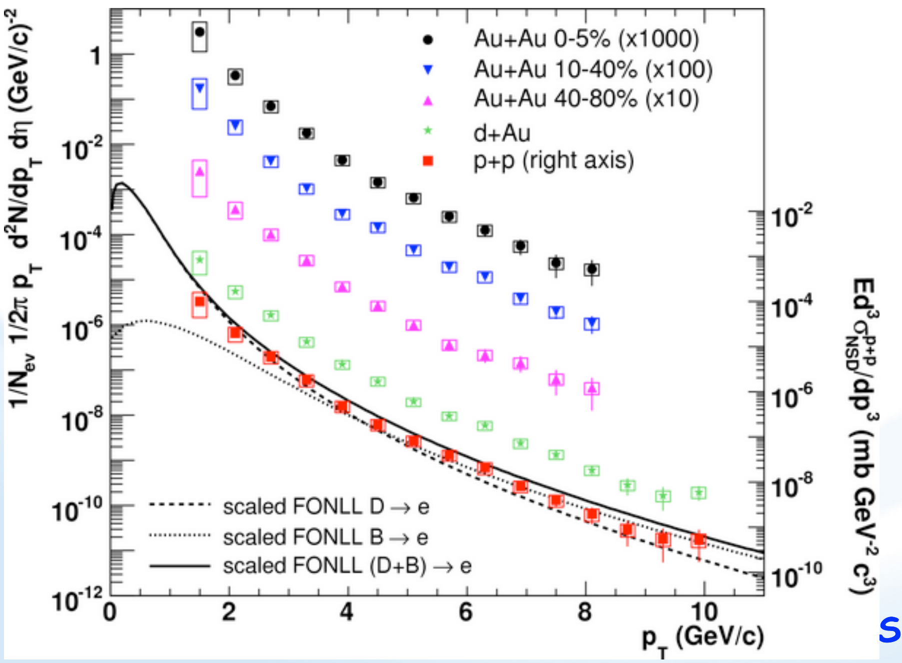
STAR:
1 track has
~40 hits =
40 dE/dx values

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

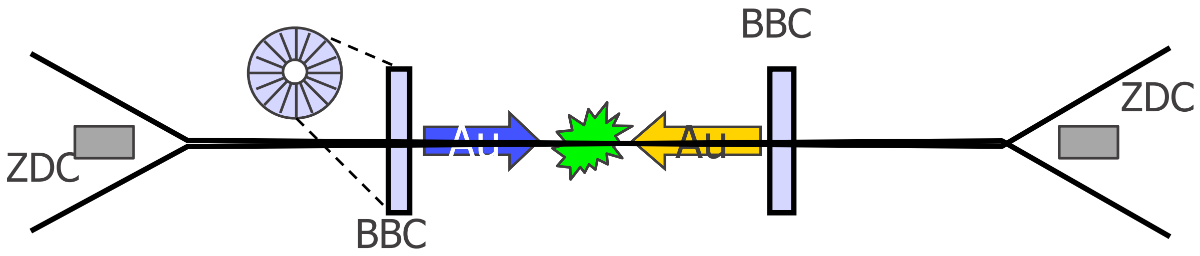


TRIGGER

- 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: ZDC, BBC

Trigger always on ZDC (BBC) coincidence

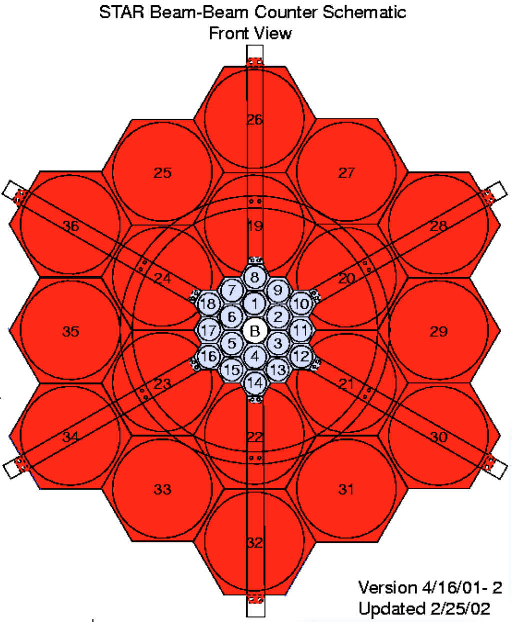


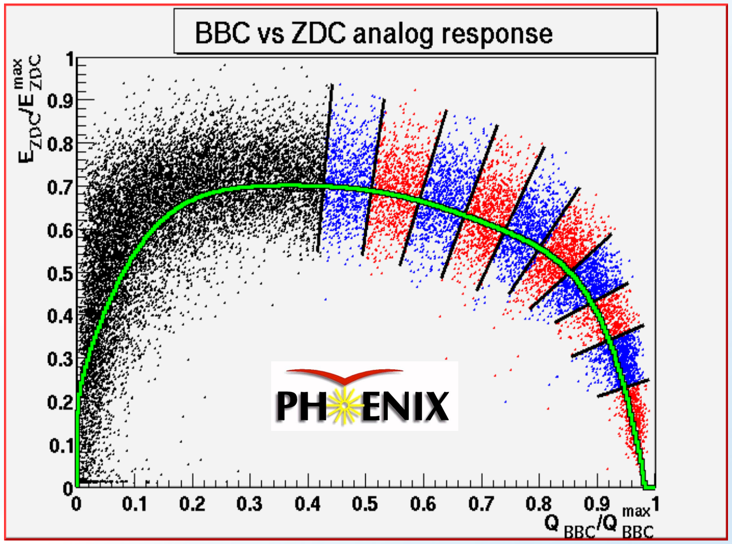
Only free neutrons hit ZDC

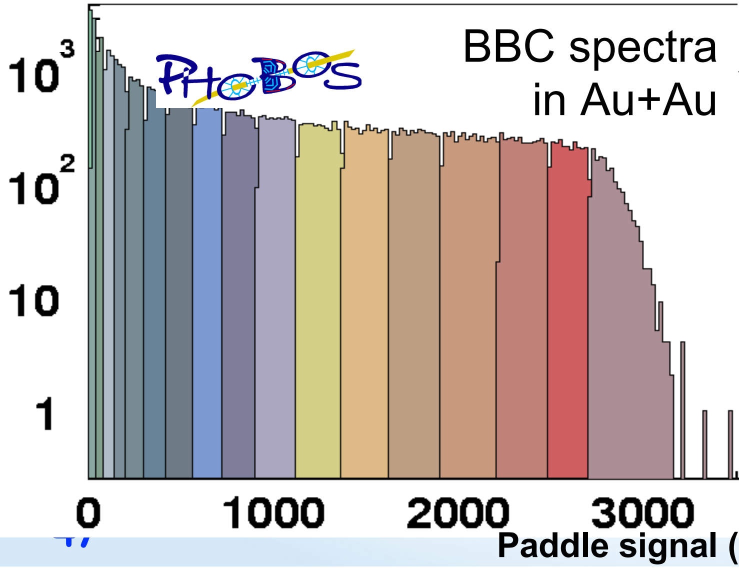
central: few hits

peripheral: few hits

ZDC alone is ambiguous







ZDC: simple calorimeter, low granularity optimized for 200 GeV

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

SUMMARY

Thanks for your attention


BACK UP