Detector Techniques and RHIC
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:

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

$$y \approx \eta \text{ for } p \gg m$$
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)
  ➞ $K^\pm, \pi^\pm, \pi^0, p, \bar{p}, e^\pm$

★ Strangeness
  ➞ $K^0, K^*, \phi, \Lambda, \Xi, \Sigma, \Omega$

★ Real and Virtual Photons
  ➞ $\gamma$
  ➞ $\gamma^* \rightarrow \mu^+\mu^-, \gamma^* \rightarrow e^+e^-$

★ Heavy Flavor
  ➞ $D^0, D^*, D^\pm, B$
  ➞ $\Lambda_c$

★ Quarkonia
  ➞ $J/\psi, \psi', \chi_c, \gamma, \gamma', \gamma''$

★ 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 $4\pi$)?
• All centralities, multiplicities?
• Recording every collision?
THE PERFECT DETECTOR?

★Momentum p
  ⇒ magnetic field × length: \( B \times dl \)
  ⇒ high-\( p_T \) ⇒ large \( B \times dl \) ⇒ small \( p_T \) tracks curl up
  ⇒ low-\( p_T \) ⇒ small \( B \times dl \) ⇒ high \( p_T \) tracks care straight \((p_T \text{ res. lost})\)

★Particle ID
  ⇒ \( \gamma, e \) ⇒ Preshower, hadron blind, little material
  ⇒ hadrons ⇒ PID through interaction with material

★Acceptance
  ⇒ large acceptance ⇒ lots of data ⇒ slow
  ⇒ small acceptance ⇒ few data ⇒ fast

★Energy
  ⇒ \( \gamma, e \) ⇒ E.M. Calorimeter
  ⇒ hadrons ⇒ Hadronic Calorimeter

★Heavy flavor ID
  ⇒ secondary vertices ⇒ high precision Si detectors = material
  ⇒ semileptonic decays \((c, b \rightarrow e + X, \ B \rightarrow J/\psi \ (\rightarrow e e) + X) \Rightarrow\) hadron
blind, little material
A typical high energy detector

Particle types:
- neutrinos (missing energy)
- muons $\mu$
- hadrons $\pi, K, p$
  - quarks, gluons $\rightarrow$ jets
- electrons, photons, $\pi^0$
- charged particles

Rough Classification
- track detectors for charged particles
- “massless” detectors
  - gas detectors
  - solid state detectors
- magnet coil
  (solenoid, field $\parallel$ 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: $\pi$, $K$, $\gamma$, $p$, $n$, ...
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

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

- velocity
- time-of-flight
- or

 Electromagnetic showers

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

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

$v = s/(t_1-t_0)$

Time of flight

Brookhaven Science Associates

NPP SS@MIT, July 2016
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
Examples: $\pi^0$, $\phi$, $\Lambda$, …

Have to be reconstructed from their more stable decay products

Assume you want to measure the $\phi$ 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?

$S = \text{Total} - \text{Background}$

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

**V0**: $\Lambda \rightarrow Kp$

**Kink**: $K \rightarrow \mu \nu$

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

What if $c\tau \sim \text{fm}$?

Works as well but usually more background

NA60

![Graph showing particle identification and decay](image)
PARTICLE IDENTIFICATION - SHORT LIFETIME

Residual background not eliminated. Needs further work to get to final spectra..
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
The RHIC experiments soon get one (STAR) or just got one (PHENIX)

**DCA**: distance of closest approach
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 \( \sim 17^\circ \)

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

≈ stuff in aperture  \quad  ≈ spatial accuracy
RHIC EXPERIMENTS IN A NUTSHELL

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

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

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

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

- Inclusive Particle Production Over Large Rapidity Range

**PHOBOS**

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

- Charged Hadrons in Selected Solid Angle
- Multiplicity in $4\pi$
- 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
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
• An experiment with something for everybody
  - Muons
  - Electrons
  - Photons
  - Hadrons
• Features
  - High resolution
  - High granularity
  - High data taking rate
  - Moderate acceptance
PHENIX (1999)
**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
Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

Tracking in B field: \[ \frac{\delta p}{p} \propto \frac{p_T}{L^2} \]
\[ \Rightarrow \text{resolution degrades with increasing energy (unless } L \propto \sqrt{E}) \]
also: works only for charged particles

Calorimetry: \[ \frac{\delta E}{E} \propto \frac{1}{\sqrt{E}} \]
\[ \Rightarrow \text{for high energy detectors calorimeters are essential components} \]

RHIC: only EMcals
★ EM Shower
- above 10 MeV (γ, e)
- pair production: γ → e⁺e⁻
- bremsstrahlung: e → eγ
- characterized by radiation length X₀
- longitudinal:
  ➡ dE/dt ~ t^α e^{-t} where t = x/X₀
  ➡ shower maximum
- transverse:
  ➡ 95% of shower in cylinder with 2 Rₘ (Moliere radius)
  ➡ Rₘ ~ X₀ typical Rₘ = 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

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

L ≈ 18 X₀

PbSc: σ(E)/E ≈ 8%/√E
PbGl: σ(E)/E ≈ 6%/√E
**ELECTRON IDENTIFICATION**

- **Problem:** They’re rare
- **Solution:** Multiple methods
  - Čerenkov (RICH)
  - $E/(\text{Calorimeter})/p(\text{tracking})$ matching

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![Diagram of PHENIX detector setup](image)

- **South Side**
  - East Arm
  - West Arm
  - DC
  - PC1
  - PC3
  - TEC
  - RICH
  - TOF
  - EMCAL

- **West Arm**
  - 6 PMT RICH ring
  - 2.6 GeV/c track
  - 2.5 GeV EMC hit electron candidate

- **E/p matching for $p>0.5$ GeV/c tracks**
  - All tracks
  - Electron enriched sample (using RICH)

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**Brookhaven National Laboratory**

C. Aschenauer
An other example how to find the hiding electrons $\rightarrow$ 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 $dE/dx$

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).

Too small p lever arm

Impossible to cover full p-range of leptons

Transition Radiation: sensitive to particle $\gamma$ ($\gamma > 1000$)

$$\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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E.C. Aschenauer
THE HERMES TRD

Single Module Response

Count

Plon dE/dx

Electron dE/dx + TR

Energy Deposition (keV)

Single TRD Module

Truncated Mean

combining all 6 modules

Window Frame
Cathode Frame
Wire Frame
Radiator Frame
Radiator
Wires
Window Foll
Gap
Cathode Foll
Detector Volume

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E.C. Aschenauer
Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity
\[ \beta \geq \beta_{\text{thr}} = \frac{1}{n} \quad n: \text{refractive index} \]
may emit light along a conical wave front.

Energy loss by Cherenkov radiation small compared to ionization (≈0.1%). Cherenkov effect is a very weak light source \( \rightarrow \) 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

<table>
<thead>
<tr>
<th>medium</th>
<th>n</th>
<th>( \theta_{\text{max}} ) (deg.)</th>
<th>( N_{ph} ) (eV(^{-1}) cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>air*</td>
<td>1.000283</td>
<td>1.36</td>
<td>0.208</td>
</tr>
<tr>
<td>isobutane*</td>
<td>1.00127</td>
<td>2.89</td>
<td>0.941</td>
</tr>
<tr>
<td>water</td>
<td>1.33</td>
<td>41.2</td>
<td>160.8</td>
</tr>
<tr>
<td>quartz</td>
<td>1.46</td>
<td>46.7</td>
<td>196.4</td>
</tr>
</tbody>
</table>
hadron/positron separation combining signals from: TRD, calorimeter, preshower

hadron separation Dual radiator RICH for π, K, p

Which Hadron (π, K, P) is Which
15 fully functioning detector systems
**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

**Calorimetry:**
- PhotonMultiplicity Detector (PMD)
- Barrel EMC
- Endcap EMC
- Forward Meson Spectrometer
Peripheral Event

color code $\Rightarrow$ energy loss
**DRIFT CHAMBER IN A NUTSHELL**

**Multi Wire Proportional Chamber**

G.Charpak 1968 , nobel prize 1992

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

- Address of fired wire(s) give one dimensional information $\Rightarrow \sigma_x \sim d/\sqrt{12}$
- Improve using drift length time information: typical 100–200 $\mu$m
- Resolution limits: drift and diffusion effects driven by $E \times B$ effects
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 \( R_{\text{in}} \), large \( R_{\text{out}} \))
Want large \( \eta \) 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 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

Gating Grid:
- Designed to reduce charge injection into amplifiers

Slow ions left in volume:
- accumulate, create space charge
- space charge creates distortions

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
Simulation and animation by Gene Van Buren, movie by Jeff Mitchell.
STAR TPC: FROM WEST TO EAST COAST

Berkeley, CA

Long Island, NY

US Air Force
PARTICLE IDENTIFICATION BY $dE/dx$
IN STAR’S TPC

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

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

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

• \(<dE/dx> \sim 1/\beta^2\) region
• MIP: \(\beta \gamma \sim 3-4\)
• relativistic rise:
  \(<dE/dx> \sim \ln \gamma^2 \beta^2\)

Bethe-Bloch Formula

\[
\frac{dE}{dx} = KZ^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]
\]
Simultaneous measurement of $p$ and $dE/dx$ defines mass $m_0 \Rightarrow$ particle ID

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

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

Real detector (limited granularity) can not measure $\langle dE/dx \rangle$!

It measures the energy $\Delta E$ deposited in a layer of finite thickness $\delta x$.

For thin layers or low density materials:

$\Rightarrow$ Few collisions, some with high energy transfer.

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

STAR: 1 track has $\sim 40$ hits = 40 $dE/dx$ values
ELECTRONS VIA $dE/dx$

- Select tracks
  - pre-select electron candidates with EMC ($p/E \sim 1$)
- Plot electron candidates in $p_T$ slices
- Fit $dE/dx(p_T)$ for $K, \pi, e$
- integral of electron fit $\Rightarrow$ yield
- correct yield for efficiency & acceptance $\Rightarrow$ $dN/dp_T$

In real world: more statistics, finer slices. Still at $p_T > 10$ GeV/c $dE/dx$ method fails
• Every experiment has 1-N triggers – can't do without

• Hierarchy:
  - 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 $\sim 2.5 < \eta < 4.5$
Thanks for your attention