PC4521 - Frontiers of Particle Physics - Lectures 7 & 8

CP Violation & BaBar
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Everyone now thinks that the universe started with a Big Bang, which created equal amounts of matter and antimatter. Now we just have a universe full of matter – so where did the antimatter go? If there were areas with antimatter, then we'd see radiation from their annihilations – we don't see this.

Sakhanov conditions:

- Baryon number violation
- Universe must have been out of thermal equilibrium at some point in its history – accounted for in inflationary theories
- There must be processes which violate CP theory

Standard model does allow a small amount of CP violation, which comes in in the quark mixing matrix – too small by a factor of circa 1 billion to account for matter/antimatter asymmetry observed. It's one of the least well-tested parts of the standard model.

What is CP symmetry?
Operator $\hat{C}$, which is the charge conjugator – changes particles to antiparticles and vice-versa. E.g.: $\hat{C}|\pi^+\rangle = |\pi^-\rangle$, $\hat{C}|\pi^0\rangle = |\pi^0\rangle$, $\hat{C}|\gamma\rangle = -|\gamma\rangle$.
Operator $\hat{P}$, which is the parity conjugator – reflects spatial directions. Leaves spin unchanged. Reverses helicity. E.g. $\hat{P}|e_L^-\rangle = |e_R^-\rangle$, $\hat{P}|\pi^+\rangle = -|\pi^+\rangle$ (L and R on the bottom denotes handedness)

CP (also written CP with a hat on it) is both combined.
Weak interaction violates C and P, but was though to conserve CP symmetry until 1964. $K_L^0 \to 2\pi$ → CP violation. This is a very small effect – kaons are light, so there aren't many decay methods available. It is also difficult to relate this to standard model parameters.

It is expected that in the $B_d - meson$ system the effects will be larger, and some decays will be theoretically clean – it will be easy to relate them to SM parameters.

Two experiments: BABAR (Stanford) and Belle (Japan), which aim to take precise measurements of CP violation in B-mesons.

PEPII and BABAR
At Stanford Linear Accelerator Centre, California. It is a e^+e^- collider – clean environment, no particle remnants as you would get with protons etc. It is fairly low energy, and has asymmetric beam energies - $9GeV$ beam of electrons and $3.1GeV$ beam of positrons. Total CM is $\sqrt{(9+3.1)^2-(9-3.1)^2} \approx 10.58GeV$ - which is the mass of the resonance $\Upsilon(4S)$ $\left[M(\Upsilon(4S))\right]$.

$\Upsilon(4S)$ is the lightest $b\bar{b}$ states which can decay into a pair of B mesons $m_B \sim 5.28GeV$. 50% of the time, it decays into B^+B^-, and 50% into $B^0\bar{B}^0$

$$e^+e^- \to \gamma \to b\bar{b} \to B^0\left(\bar{b}d\right)+\bar{B}^0\left(b\bar{d}\right)$$

Due to asymmetric beam energies, $\Upsilon(4S)$ is moving with Lorentz boost $\beta\gamma = 0.56$ - this lengthens the decay, so the vertices of the two B-mesons are separated by a measurable distance.

Rate of process = Cross section x luminosity$= \sigma L$. σ is measured in barns $\left(10^{-22}m^2\right)$, and luminosity is measured in $cm^{-2}s^{-1}$.

Peak luminosity is currently $\sim 10^{34}cm^{-2}s^{-1}$.
Cross-section for $\Upsilon(4S)$ at CM energy of $10.58GeV$ is $\sim 1nb$.
Therefore at peak luminosity, there are about 10 $B\bar{B}$ pairs per second.
The more important quantity is the integrated luminosity – the luminosity integrated over time (it can't always be at full intensity, due to technical reasons). It is measured in fb^{-1}. Since 1999, BABAR has recorded ~ $300fb^{-1}$, which corresponds to ~ 300 million $B\bar{B}$ pairs.

The BABAR detector
5 layers of subdetectors arranged around the Interaction Point. It is slightly asymmetric; there are more coverage in the forward direction.

Silicon Vertex Tracker (SVT).
- Innermost detector
- It tracks charged particles close to the interaction point. Want to locate the decay vertices of short-lived particles.
- It has 5 layers of silicon strip detectors – this many layers means that you get a 3D position, plus the amount of curvature of the particle track.
- A charged particle will ionize the silicon, which generates e^- and holes, which can be detected by HV (High Voltage?) sensors.

Drift Chamber (DCH)
- Second detector.
- Also tracks charged particles.
- Measures the momentum via curvature in IST longitudinal B-field.
- $p_{transverse}[GeV] = 0.3B[T]r[m]$
- Also need angle with respect to the longitudinal axis to measure p.
- Contains a low pressure gas, which is ionized when charged particles travel through it.
- 20 thousand wires strung longitudinally through the chamber, at $1930V$ attract e^-, and detect the charge.
- Wires are slightly angled, so a 3D track position can be obtained.

DIRC
- Third detector out
- Does particle identification.
- More shortly…

Electromagnetic Calorimeter (EMC)
- Fourth detector out.
- Detects and measures the energy of neutral particles – normally γ . Can detect $\pi^0 \to \gamma\gamma$.
- Compare energy deposited in the EMC $(\to E)$ with the momentum measured in the DCH $(\to p)$.

  $\frac{E}{p} \sim 1$ for $e^{\pm}$.

  $\frac{E}{p}$ is small for $\mu^{\pm}$.

Magnets
- 1.5T solenoidal superconducting magnets.

Instrumented Flux Return (IFR)
- Final detector
- Layers of iron interspersed with layers of muon detection chambers.
- Iron slows things down – only muons will penetrate more than a few layers.

Trigger system
- Can't measure all the detectors all the time. Need to pick and choose.
- Level 1 trigger – L1T
  - Hardware – specialized fast circuit boards.
  - One part looks at DCH tracks
  - One part looks at energy clusters within the EMC.
- Level 2 trigger doesn't exist…
- Level 3 trigger
  - Software – farm of linux servers.
  - Performs some event reconstruction.
  - Reduces the event rate to a loggable level (~250Hz – 250 events per second, of which around 10 are BB events). [Limited disk space]

<u>The DIRC</u>
Detector of Internally Reflected Cerenkov light.

There are 5 different long-lived particles for which the track can be detected - $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p^{\pm}$.
EMC detects electrons
IFR detects muons
They are not much good at identifying the charged hadrons, though.

The DIRC detects and identifies charged hadrons – in particular, telling between $\pi^\pm$ and $K^\pm$ (there aren't many $p^\pm$ in BABAR).

Important for:

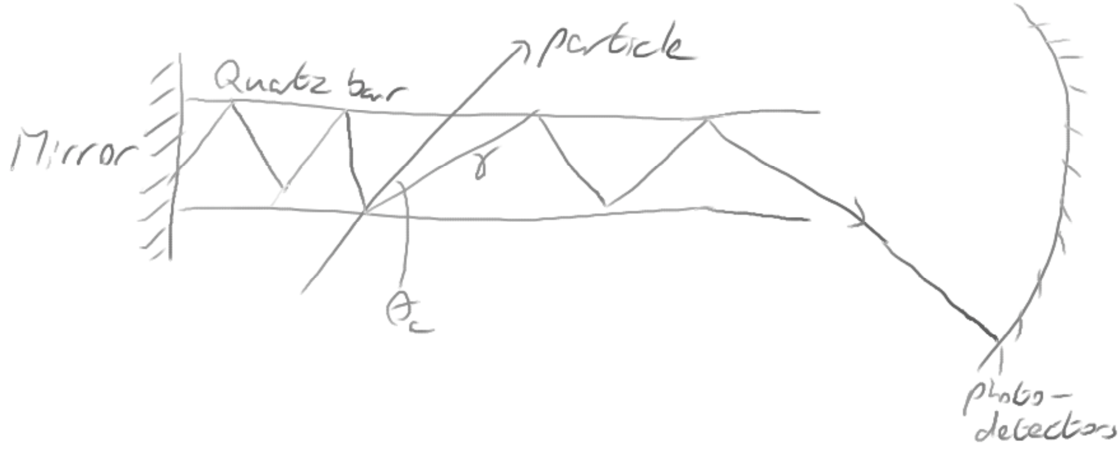
- "Flavour tagging" of the $B-$meson. (more next week)
- Analysis of $B \to K\pi$ decays.
  $N\left(B^0 \to K^+\pi^-\right) \neq N\left(\bar{B}^0 \to K^-\pi^+\right)$
  N is the number of detections.
  This is a measure of "direct" CP violation.
  Assymetry - $\dfrac{N\left(K^-\pi^+\right) - N\left(K^+\pi^-\right)}{N\left(K^-\pi^+\right) + N\left(K^+\pi^-\right)} = -0.133 \pm 0.030 \pm 0.009$ (BABAR 2004).
  This is 4.2σ observation of direct CP violation.
- … and more.

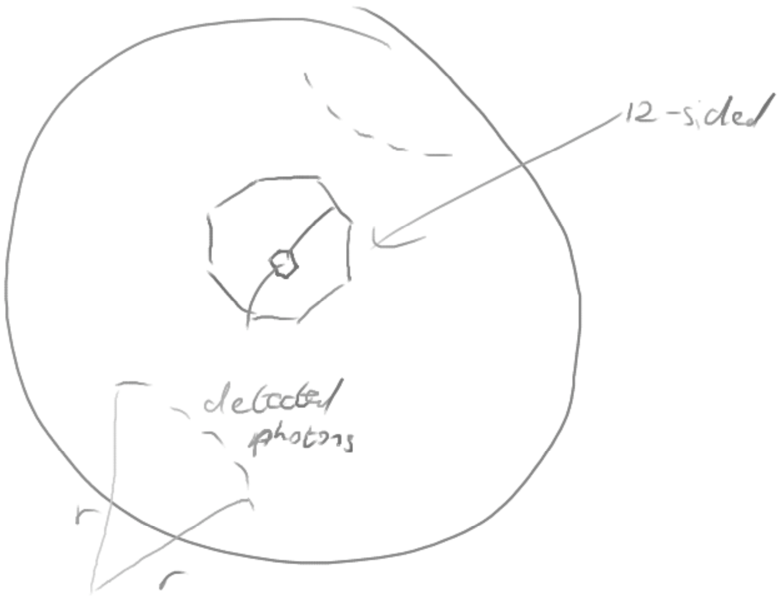
DIRC works off Cerenkov radiation.
Particle moving with velocity v in a medium with refractive index $n > 1$. If the particle is emitting photons, then you get a wavefront. Angle between particle path and the perpendicular to the wavefront is θ_c. Particle path is vt. Perpendicular path is $\frac{c}{n}t$. Hence:

$$\cos\theta_c = \frac{\frac{c}{n}t}{vt} = \frac{1}{n\beta}.$$

Hence there will be no light emitted unless the particle is traveling faster than the speed of light in that medium.
This is analogous to the shock wave obtained from "breaking the sound barrier".
If you can measure θ_c, then you can get the velocity of the particle. Combine this with the momentum, $p = \beta\gamma m$, to get the rest mass m of the particle, which tells you what type of particle it is.

BABAR DIRC is a 12-sided polygon made of quartz $(n = 1.473)$ bars with a mirror at the front end, which his the direction that the high energy beam is going. There is a large hemispherical water-filled "Stand-Off Box" (SOB) at the back, which is covered by (circa 100,000) photomultiplier tubes.





Measure radius of arc. Also need to know (from the drift chamber) the position and angle at which the track enters the quartz bar. → get a measurement of θ_c the Cerenkov angle.
Combine this with the measurement of p from the drift chamber to get the mass m of the particle.

Design considerations:

- Most expensive part of BABAR is the EMC – so you want to make the EMC as small as possible to cut down on the cost.
- Also want to maximize the performance of the EMC – if you have thick, non-uniform material in front of it then it will degrade its performance.
- Having just a thin layer of quartz, with the detection gear off to one side, is good.

Output of DIRC is a likelihood function for each track to be $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p^{\pm}$.