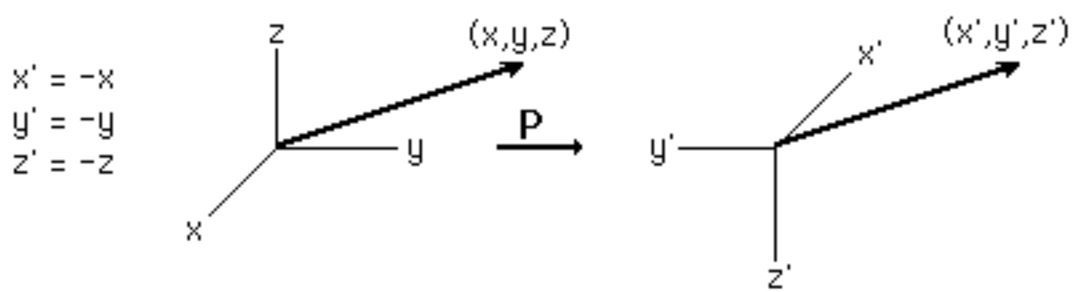
Basics of CP violation

Summary from previous class

- pp results of heavy flavor mesons.
- Charm meson measurements in the decay channel
  - D^0, D^+, D^{*+}, D_s
- Fragmentation fraction measured at LHC consistent with previous measurements.
- Beauty meson measurements.
  - New beaty baryon resonance discovered at CMS.
- Quarkonia measurements at LHC
  - Discovery of new states.
- Exotic state of 4 quark mesons (XYZ) observed.
- Top measurement technique at LHC

Charge parity transformation

- Charge transformation
  - a mathematical operation that transforms a particle into an antiparticle
- Parity transformation
  - reflection through the origin of the space coordinates of a particle or particle system; i.e., the three space dimensions x, y, and z become, respectively, −x, −y, and −z.
  - parity conservation means that left and right and up and down are indistinguishable in the sense that an atomic nucleus emits decay products up as often as down and left as often as right.



Charge parity transformation

- It was assumed that elementary processes involving the electromagnetic force and the strong and weak forces exhibited symmetry with respect to both charge conjugation and parity
  —namely, that these two properties were always conserved in particle interactions.

- The τ–θ puzzle
  $\tau^+ \rightarrow \pi^+ \pi^- \pi^+$
  $\theta^+ \rightarrow \pi^0 \pi^+$ (π : P = -1)

  - No difference was found between the masses and lifetimes, indicating that they are the same particle.
  - But parity violated if same particle.
  - Question : Is parity conserved always??
  - Tsung-Dao Lee and Chen-Ning Yang checked literature to question of parity conservation in all fundamental interactions → No experimental data for weak interaction.
  - Wu experiment.

Wu experiment

- Experiment monitored decay of cobalt-60 atoms.
- Cooled atoms to absolute zero and aligned in a uniform magnetic field.
- Cobalt-60 is an unstable isotope of cobalt that decays by beta decay to the stable isotope nickel-60.
  $${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$
- Gamma rays emitted by electromagnetic process.
- If P conserved : electrons should be emmtted in both direction equally
- Observed : electrons emitted opposite to magnetic field → **parity not conserved**
- **Answer to τ–θ puzzle : same particle K^+**

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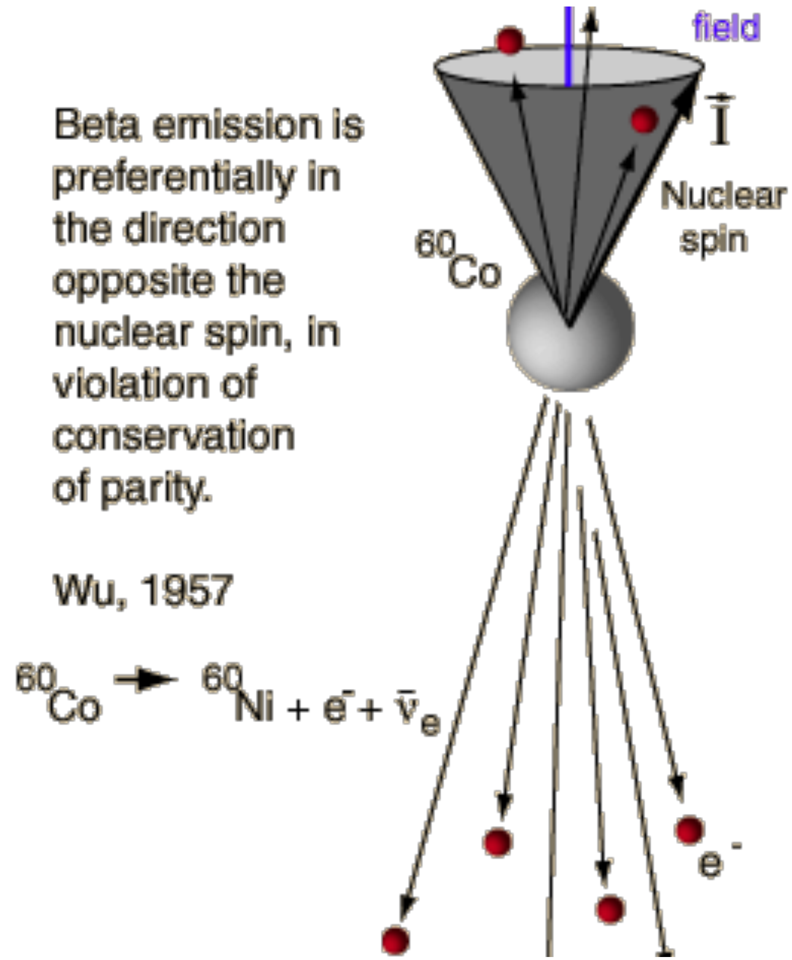


Neutral Kaons

K^0 : d – sbar

$$K_S^0 \quad \frac{\psi(d\bar{s}) + \psi(\bar{d}s)}{\sqrt{2}} \quad \text{Lifetime} \quad 9 \times 10^{-11}\ \text{s}$$

$$K_L^0 \quad \frac{\psi(d\bar{s}) - \psi(\bar{d}s)}{\sqrt{2}} \quad \text{Lifetime} \quad 5 \times 10^{-8}\ \text{s}$$

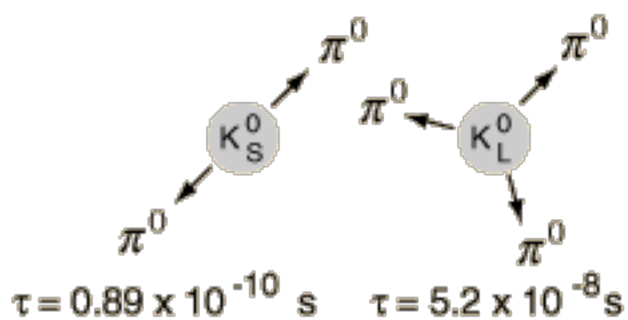
K^0 and K^0bar are superposition of two weak eigenstates which have vastly different lifetimes:

The long-lived neutral kaon is called the K_L ("K-long"), decays primarily into three pions, and has a mean lifetime of 5.18×10−8 s.

The short-lived neutral kaon is called the K_S ("K-short"), decays primarily into two pions, and has a mean lifetime 8.958×10−11 s.

$$K_S^0 \rightarrow \pi^+ + \pi^- \qquad K_S^0 \rightarrow \pi^0 + \pi^0$$

$$K_L^0 \rightarrow \pi^+ + \pi^- + \pi^0 \qquad K_L^0 \rightarrow \pi^0 + \pi^0 + \pi^0$$

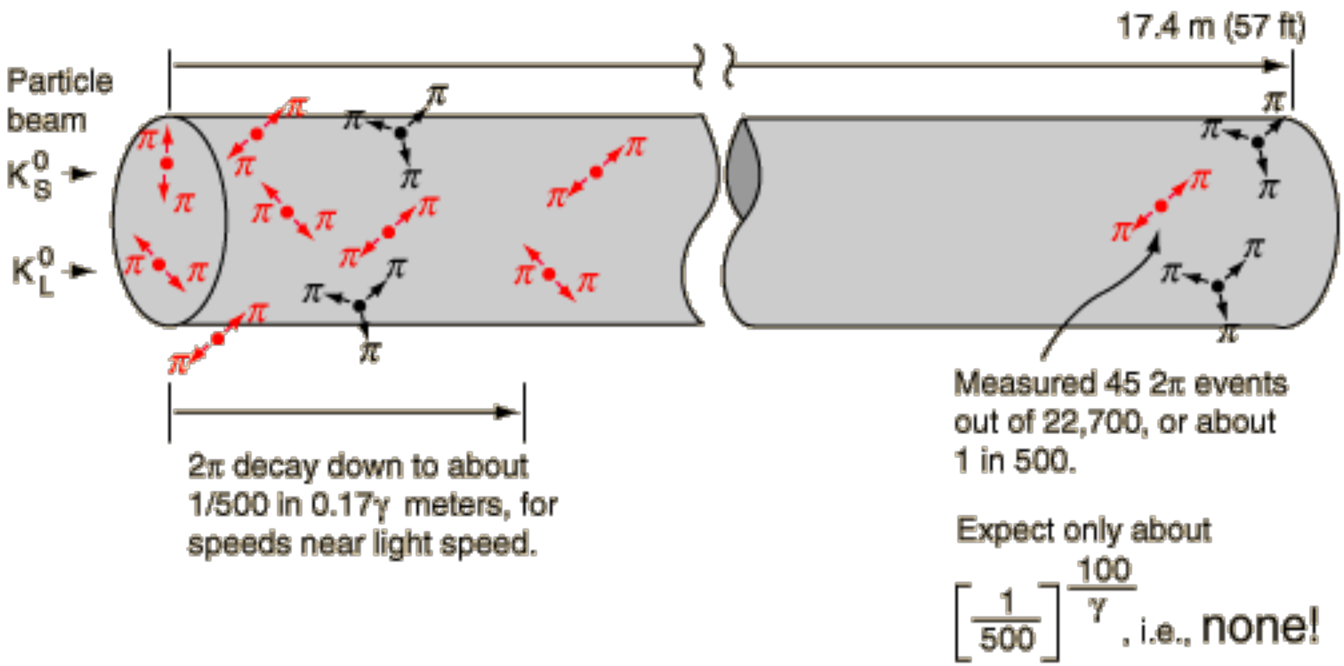


$$K_S^0 = \frac{K^0 - \bar{K}^0}{\sqrt{2}}$$

$$K_L^0 = \frac{K^0 + \bar{K}^0}{\sqrt{2}}$$

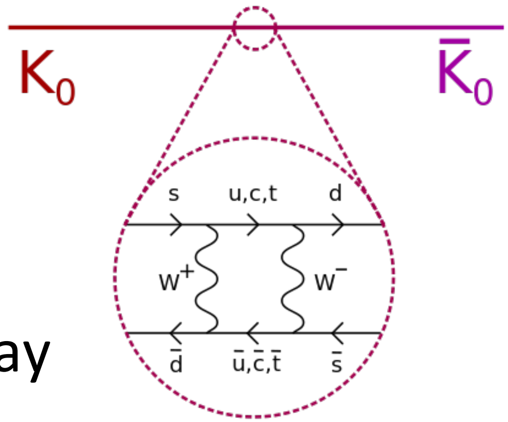
Cronin and Fitch experiment

- Though parity is not conserved, Charge + parity was thought to be conserved.
- In 1964 Cronin and Fitch performed a beam experiment in which they measured the decay of pions at the end of a 57 foot beamline.
- Given the disparity of the lifetimes of the two kaon species, you expect to see only the long-lived version at the end of the beam tube, but they found about 1 in 500 decays to be 2-pion decays, characteristic of the short-lived species.



CP violation

- Kaon : K^0 (d-sbar)



- On observing the weak decay into leptons
  - K^0 always decayed into electron.
  - Anti K^0 decayed to positron.
  - Analysis of the time dependence of this decay
    - Showed that few K^0 decayed to positron.

Explanation :

An initially pure beam of K^0 will turn into its antiparticle while propagating, which will turn back into the original particle and so on. This is called particle oscillation…

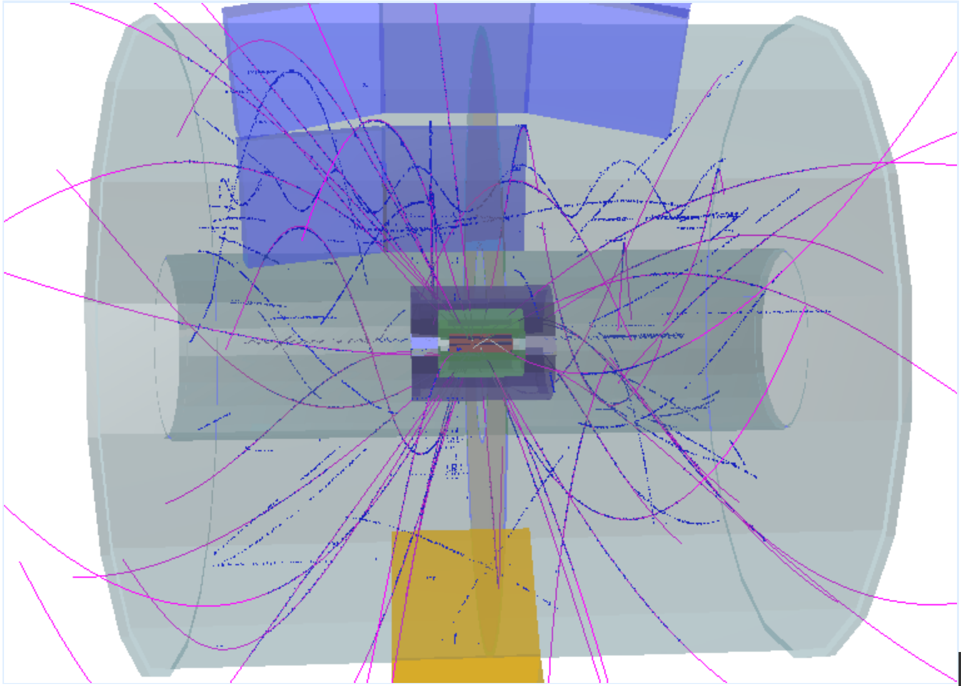
CP violation

- Standard model contains an explanation for CP violation.
- But as the effect of the phenomenon is small, its difficult to show conclusively that the explanation is correct.
- Kaons are very difficult objects to model in the theory.
- Theoretical calculations becomes easier with heavy quarks, such as beauty quark.
- They are best for measurements of CP violations.
- Read for more details on CP violation in B mesons.

CP violation

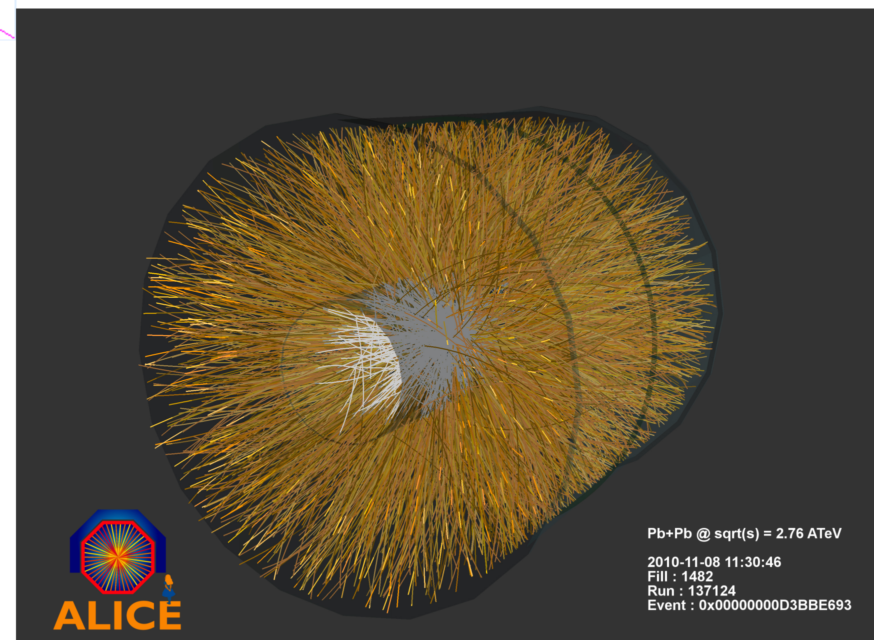
- CP violation has important theoretical consequences.
- The violation of CP symmetry enables to make an absolute distinction between matter and antimatter.
- Rare decays could show physics beyond Standard model

Heavy Flavors in heavy ion collisions

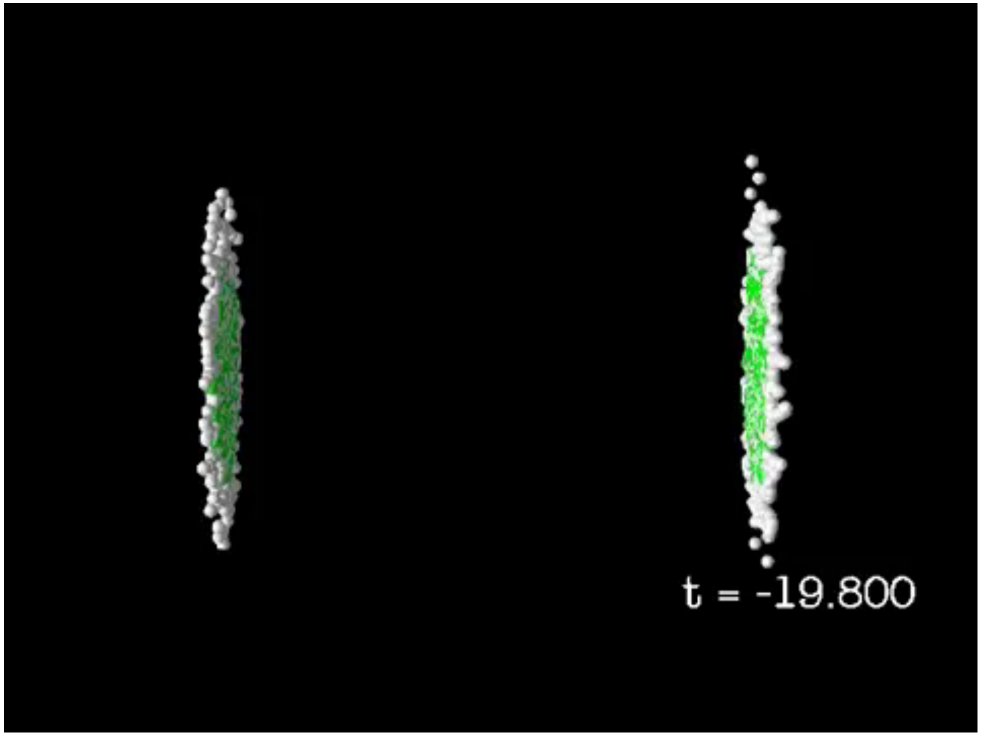


pp collision

Pb-Pb collision

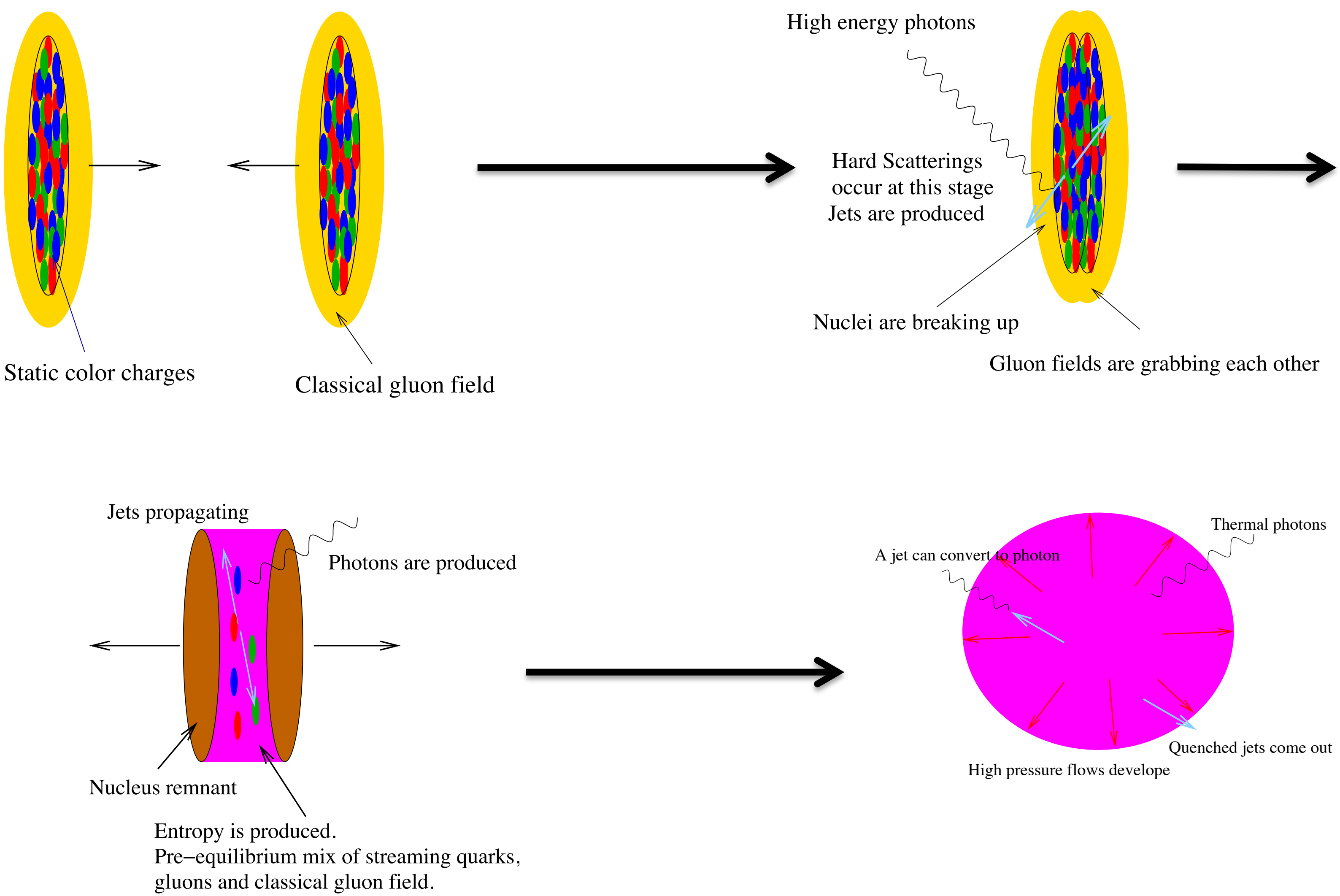


Heavy-ion collisions

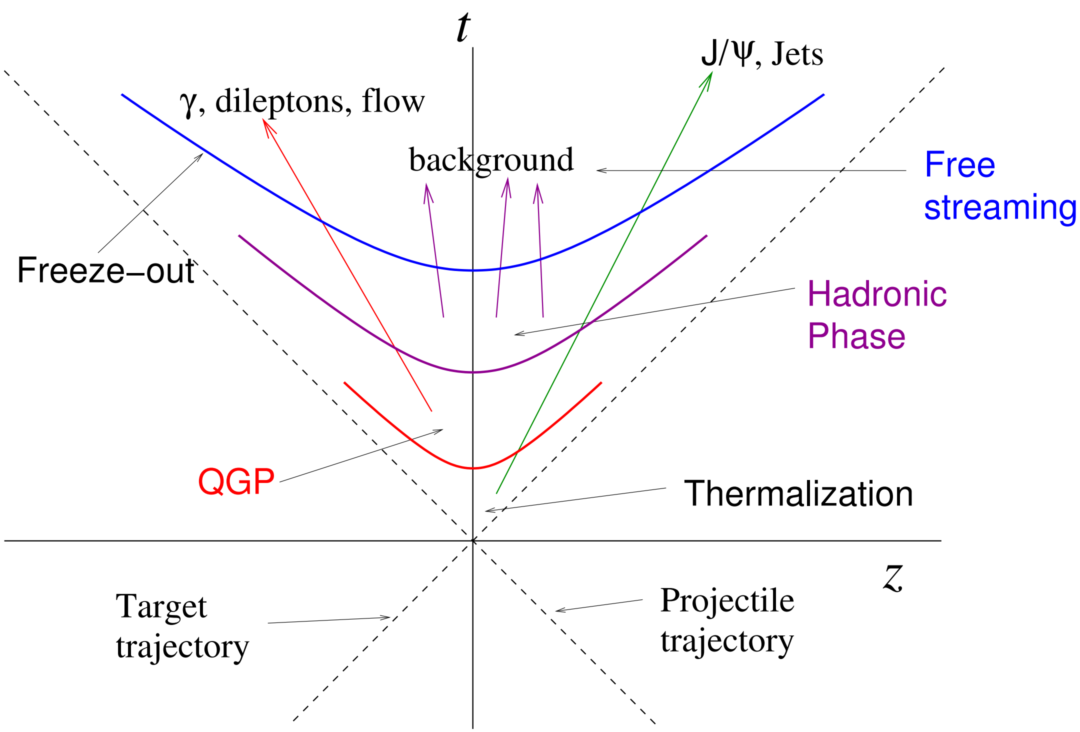


- The particles produced inside the volume → interact with each other.
- Undergo elastic and inelastic collisions.
- The system will undergo a dramatic expansion.
- Formation of hadrons.
- Produce stable particles.

Schematic view of Heavy ion collision



Schematic view of Heavy ion collision



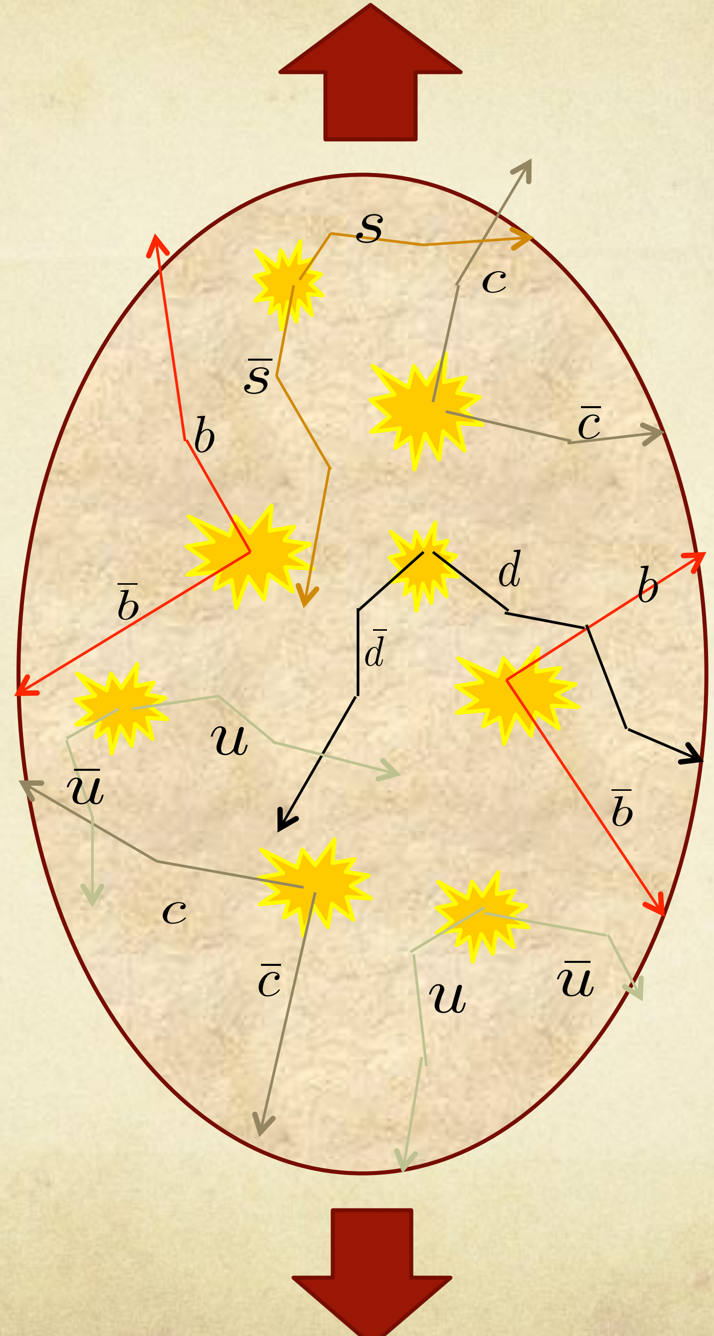
- The large pressure gradient between QCD matter and the surrounding vacuum
  → dramatic expansion
- Hadronic phase (chemical freezout)
  →Inelastic cross-section are typically smaller than elastic
  → Fixed particle ratios
- Thermal freezout
  → Final state interactions between particles become negligible.
- Use different probes to obtain thermodynamic and transport properties of QGP.

Heavy quarks

Quark	Mass
Up	2.3 MeV/c^2
Down	4.8 MeV/c^2
Strange	95 MeV/c^2
Charm	1275 MeV/c^2
Beauty	4018 MeV/c^2

- Heavy quarks are produced early in the collision.
- They decay weakly so their lifetime is greater than that of the QGP (few fm).
- When traversing the medium they undergo elastic and inelastic scattering with the partons in the plasma.
- So they experience the full evolution of QGP.

The created quarks (antiquarks) gets scattered inside the fireball medium.

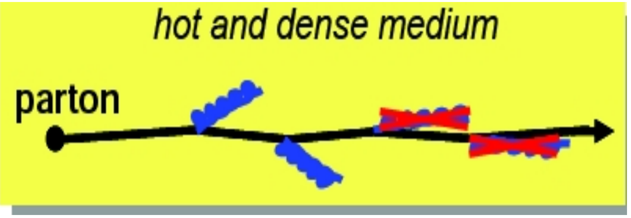


Lighter quarks (u, d, s) undergo more scattering than heavy quarks (c, b)

Heavy quarks loose less energy due to their mass and hence carry important information about the medium.

Heavy quarks

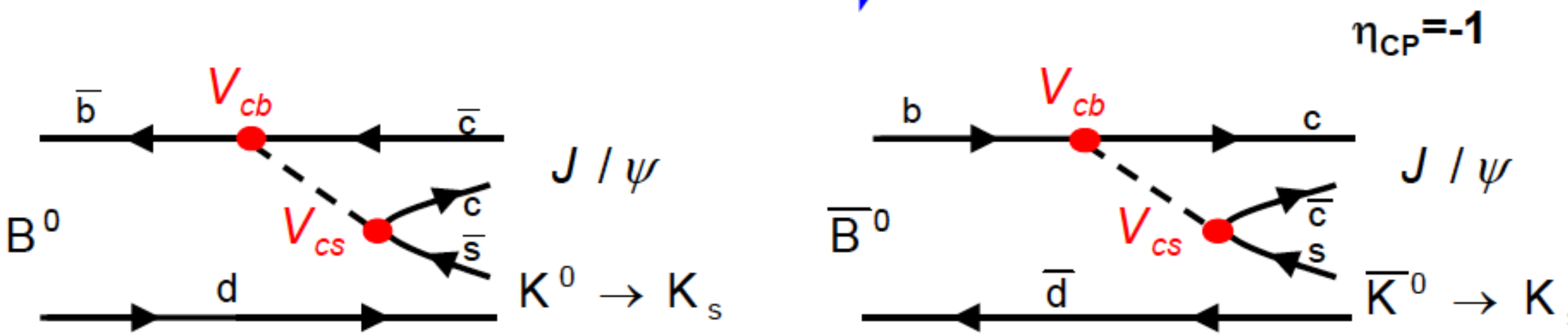
- Dead cone effect
  - Heavy quarks loose less energy compared to light quarks.
- Light quarks and gluons can be produced or annihilated during the entire partonic phase of the medium.
- Heavy quarks preserve their flavour and mass identity while traversing the medium.

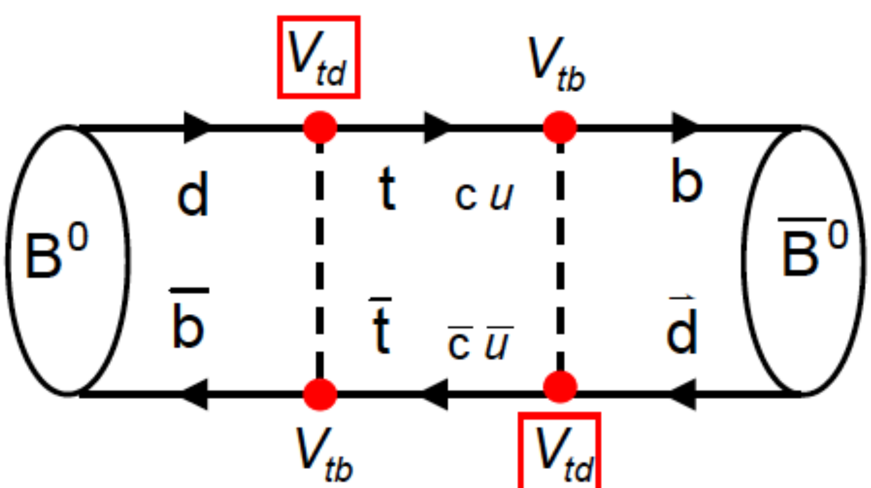


Back up

Golden decay channel

$B^0 \to J/\psi\ K_s$ CP **$\overline{B}^0 \to J/\psi\ K_s$**



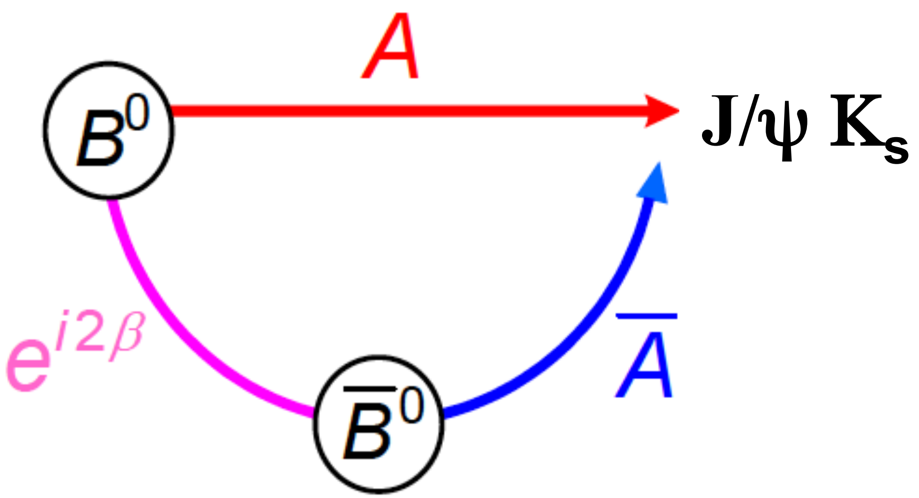


Mixing Phase:

$$e^{i\phi_d} = e^{i2\beta}$$

$B^0 \rightarrow J/\psi\ K_s$ CP $\overline{B}^0 \rightarrow J/\psi\ K_s$

$\eta_{CP} = -1$



$$\Gamma(B^0 \rightarrow J/\psi K_s)(t) \neq \Gamma(\overline{B}^0 \rightarrow J/\psi K_s)(t)$$

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \rightarrow J/\psi K_S) - \Gamma(B^0 \rightarrow J/\psi K_S)}{\Gamma(\overline{B^0} \rightarrow J/\psi K_S) + \Gamma(B^0 \rightarrow J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$