Brief Overview of Λ_c Related Physics and Results

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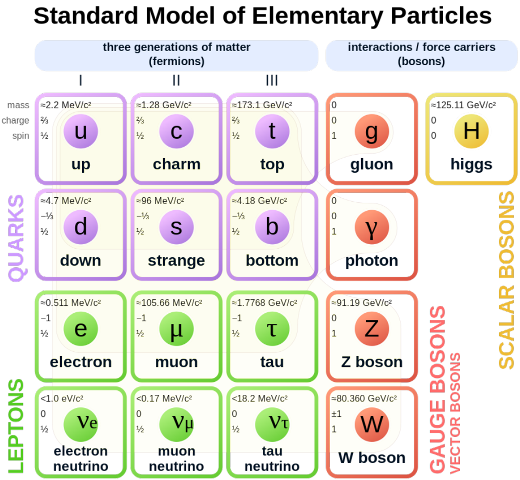
Outline

1. Physics introduction
2. Status of Λ_C analysis in the field
3. Analysis

Standard Model



The standard model of particle physics. Image source: https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

QCD

Overview

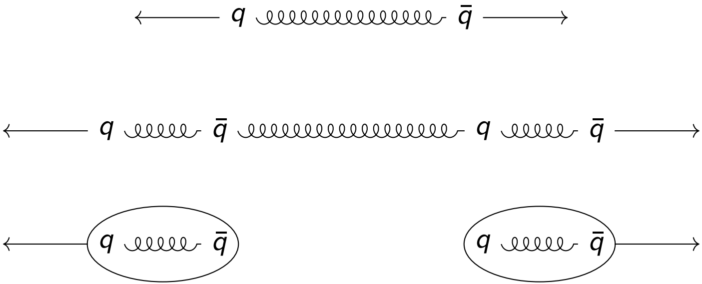
- Proposed in 1964 as a solution to the Λ^{++}'s apparent violation of the Pauli exclusion principle (uuu)
- Needed another degree of freedom to distinguish 3 up quarks
  - 2 of which must have the same spin
- The additional property is color (red, green, blue)

Some takeaways

- No naturally occurring particles that have a non-zero color charge
  - Quarks are bound to color-neutral hadronic states (confinement)
- Gluons are self-interacting and this leads to an approximately distance-independent force ~ 1 GeV/fm
- QCD coupling α_S varies with energy scale
  - This allows perturbation theory to be applied at collider energies

Hadronization/Jets

1. q-$\bar{q}$ pairs are produced at high energy
2. q-$\bar{q}$ energy due to separation is sufficient to produce new q-$\bar{q}$ pairs
    - This repeats until new q-$\bar{q}$ pairs can be produced
3. The now lower energy quarks coalesce to form hadrons



QGP

- The prediction of the QGP state followed the discovery of the asymptotic freedom of the QCD coupling constant (1970s)
- This was first observed at RHIC in 2004
- Motivations for studying QGP:
    - Sate of the universe immediately following the Big Bang
    - Smallest specific viscosity (viscosity to entropy density)

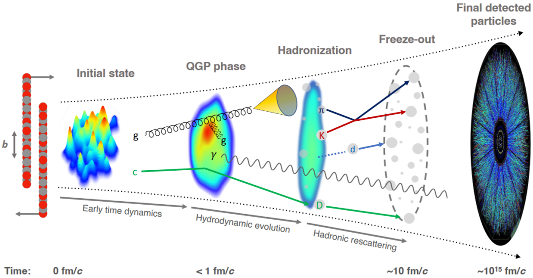


Figure: (Adapted from [14])

QCD Phase space

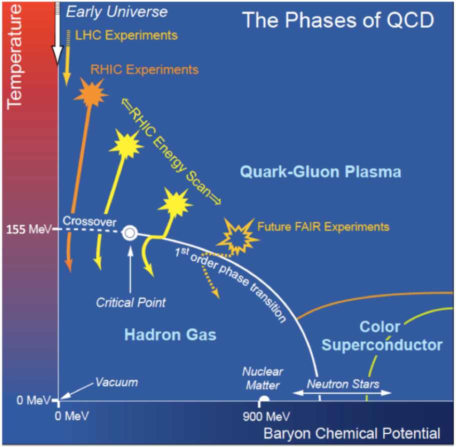


Figure: (Adapted from [16])

1. Collision:
   - $T \sim \sqrt{s_{NN}}$
   - $\mu_B \sim$ q-q separation (small)
2. Hadronization:
   - Energy loss from pair production
   - μ_B decreases (deconfinement)
3. Freeze-out
   - Too “cold” for q-$\bar{q}$ production
   - μ_B increases (now separated, confined hadrons)

Nuclear modification factor

One important quantity is the nuclear modification factor,

$$R_{AB} = \frac{1}{\langle T_{AB} \rangle} \; \frac{dN^{x}_{AB}}{dp_T} \Bigg/ \frac{d\sigma^{x}_{pp}}{dp_T} \tag{1}$$

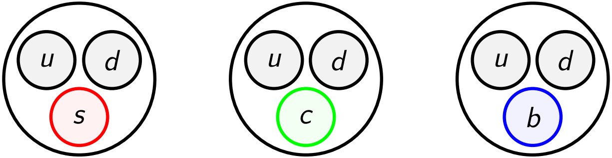
This gives the production of x in collisions between species A, B relative to the yield in proton-proton collisions, where $\langle T_{AB} \rangle$ is the mean nuclear overlap function

$$\frac{1}{N^{inel}_{AB}} \frac{dN^{x}_{AB}}{dp_T} = \langle T_{AB} \rangle \, \frac{d\sigma^{x}_{pp}}{dp_T} \tag{2}$$

It gives the proper normalization for production in AB collisions considering there are more inelastic parton collisions there than in pp.

Λ Baryons

- Spin $\frac{1}{2}$, Isospin 0 family of baryons
  - Each contains one u quark and one d quark
  - (Recall isospin refers the u and d quark content of a hadron)
- A third quark is from a higher generation (s, c, b)



Λ^0, $\tau \sim 10^{-10}$s Λ_c^+, $\tau \sim 10^{-13}$s Λ_b^0, $\tau \sim 10^{-12}$s

- Theoretically, there is also be a Λ_t^+
  - But this will likely decay before it can hadronize

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Λ_C as a QCD probe

Studying hadrons containing heavy quarks is preferable, as

- they are produced in initial hard scatterings on a timescale shorter than QGP formation, $\mathcal{O}(\mathrm{fm}/c)$
- they have a lower annihilation rate than lighter quarks
- their mass is sufficient such that low-p_T hard-scattering processes can be treated perturbatively

Baryon/meson ratios are analyzed to better understand hadronization and coalescence; in this case,

- $\Lambda_c^+ \;\rightarrow\; pK^-\pi^+$
- $D_0 \;\rightarrow\; K^-\pi^+$

Motivations for further study

Many probes are done at CMS (5.02 TeV) or RHIC (200 GeV) energies; we have data for:

- Λ_c/D_0 ratio in CMS and ALICE conditions in *pp*
- Λ_c/D_0 ratio in RHIC conditions in AuAu

Both saw enhancement in this baryon/meson ratio, but RHIC saw this to 2.1σ significance over predictions using PYTHIA8.3 So, another measurement is needed:

- Λ_c/D_0 ratio in RHIC conditions in *pp*

This will help determine if there is further Λ_c/D_0 enhancement which can be attributed to the coalescence process

Motivations for further study (cont'd)

Figures from the STAR and CMS papers showing Λ_c/D_0 enhancement over the PHYIA prediction

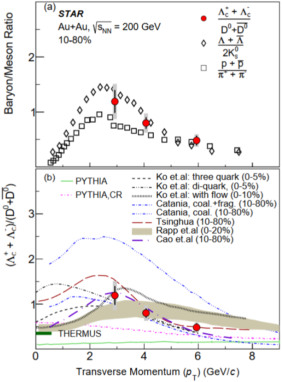

Figure: The STAR result (Figure 2 in [22])

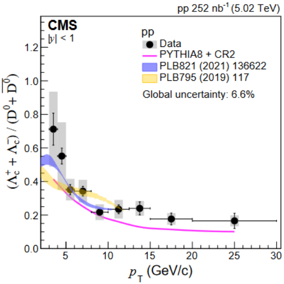

Figure: The CMS result (Figure 7 in [18])

Challenges of studying Λ_c

There are practical difficulties associated with Λ_c reconstruction

- 3-daughter decay (as opposed to 2-daughter decay)
  - The most probable decay branch has three daughter particles $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - The additional daughter candidate means there is an order of magnitude higher background than when reconstructing 2-daughter decays
- Short lifetime
  - Time of flight $\mathcal{O}(10^{-13}\text{ s})$
- Need a high-resolution vertex detector
  - the MVTX (Maps-based VerTeX detector) from sPHENIX
  - the ITS-2 from ALICE

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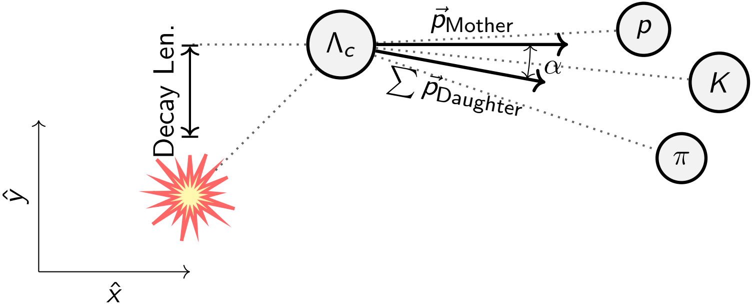
Training

- Methods:
  - ROOT's TMVA package (Multi-Variable Analysis)
  - BDTs (Boosted Decision Trees)
    - Each node of a decision tree evaluates an inequality which depends on a training variable
    - The truth value of the inequality determines which subtree is used for further decisions
    - For boosted trees, additional trees are added to minimize the residuals of the previous training epoch
  - Possibly use DNN (Deep Neural Network)
- Variables:
  - 2D decay length significance
  - 2D pointing angle
  - transverse momentum ratio of daughter tracks (p_T / σ_{p_T})

Kinematic variables

- 2D decay length significance
  - decay length / decay length error
  - "2D" meaning projection in x-y plane
- 2D pointing angle
  - angle between parent momentum and sum of daughter candidate momentums
  - "2D" meaning only the transverse momentums



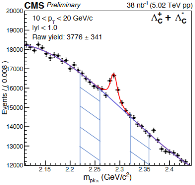
Event Selection

For signal,

- Use Monte-Carlo generated simulation data with truth reconstruction
- Physical parameters of the reconstructed track are used in training when the track is a daughter of a Λ_c.

For background,

- Fit the mass spectrum of reconstructed Λ_c to a Gaussian distribution
- Choose data in the "sidebands" of this distribution ensures that reconstructed mass points from real data are unlikely to contain real Λ_c baryons



Plot showing sidebands from ([15]). The yield of a mass spectrum can be taken as the coefficient of the (normalized) signal probability distribution

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