Analysis of $f_0(980)$ using Deep Learning Approach

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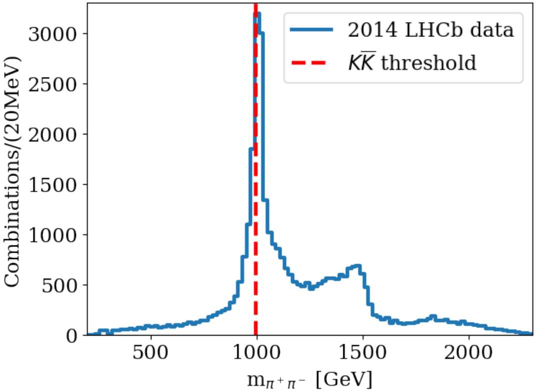
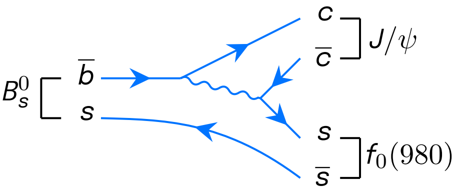
The $f_0(980)$

The appearance of $f_0(980)$ near the $K\bar{K}$ threshold in the $\pi^+\pi^-$ invariant mass distribution from the hadronic decay $B_s^0 \to J/\psi\pi^+\pi^-$ was reported by collaborations such as LHCb [1, 2, 3], Belle [7], D0 [5], and CDF [4].





Exotic Meson

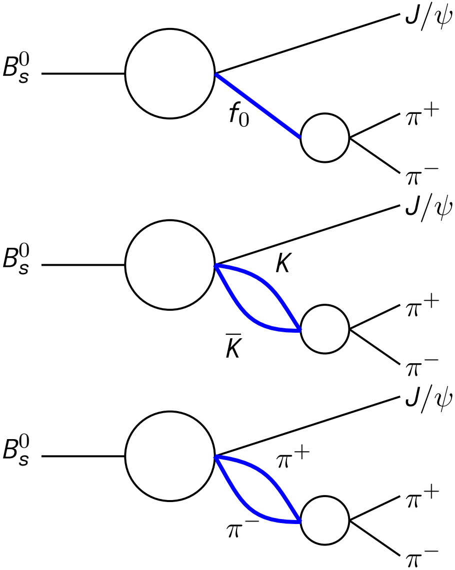
$f_0(980)$

Quantum Numbers: $I(J^P) = 0(0^+)$

Thus,

There must be another set of quark-antiquark (or another standard meson) such that their total parity is the same as the parity of $f_0(980)$

Possible Intermediate states



S-matrix

- The S-matrix maps the initial state particles $(|\psi_{\text{in}}\rangle)$ with the final state particles $(|\psi_{\text{out}}\rangle)$.

$$S = 1 + 2iT \tag{1}$$

$$S = \begin{pmatrix} S_{\pi\pi\to\pi\pi} & S_{\pi\pi\to K\bar{K}} \\ S_{K\bar{K}\to\pi\pi} & S_{K\bar{K}\to K\bar{K}} \end{pmatrix} \tag{2}$$

- Unstable states are associated with the pole singularities in the S-matrix

Morgan's pole-counting argument for weak channel- coupling [8]

Bound state: one pole in the second (II) Riemann sheet
Virtual state: one pole in the fourth (IV) Riemann sheet
Compact state: poles in both the second (II) and third (III) Riemann sheets

Uniformization [6]

Properties of the S-matrix [9]

- Unitary: $S^\dagger S = 1$
- Hermitian below the lowest threshold ($S = S^\dagger$)
- Analytic

$$S_{11} = \frac{D(-q_1, q2)}{D(q_1, q_2)}, \quad S_{22} = \frac{D(q_1, -q2)}{D(q_1, q_2)}, \quad S_{12}^2 = S_{11}S_{22} - \det(S) \tag{3}$$

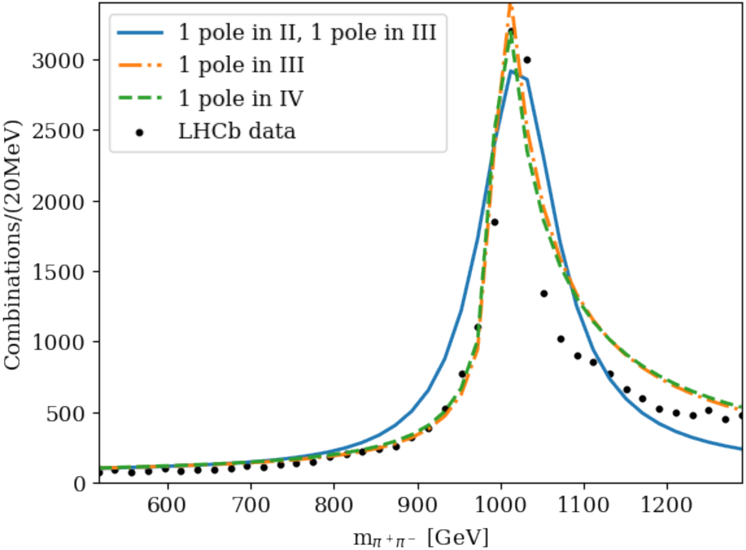
$$D(\omega) \propto \frac{1}{\omega^2}(\omega - \omega_{\text{pole}})(\omega + \omega_{\text{pole}}^*)(\omega - \omega_{\text{reg}})(\omega + \omega_{\text{reg}}^*) \tag{4}$$

$$\omega = \frac{q_1 + q_2}{\sqrt{\epsilon_2^2 - \epsilon_1^2}}, \quad \frac{1}{\omega} = \frac{q_1 - q_2}{\sqrt{\epsilon_2^2 - \epsilon_1^2}} \tag{5}$$

Fitting the experimental data

Fitting function:

$$\frac{dN}{d\sqrt{s}} = \rho(\sqrt{s}) + A|F(\sqrt{s})|^2 + B \quad (6)$$



Deep Neural Networks

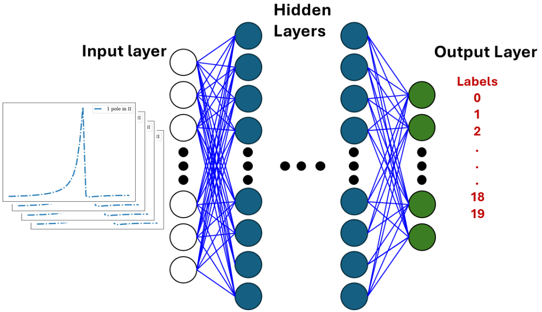


Figure: This is a classification problem where a DNN is an effective tool to use.

Steps

1. Generate training and testing dataset using uniformized S-matrix
2. Designing DNN architectures
3. Training and testing the DNN
4. Validating the DNN using a different dataset
5. Use the trained DNN to classify $f_0(980)$

Generating Datasets

Curriculum					
1	2	3	4	5	6
00: no poles	04: 2 II	07: 2 III	10: 3 III	13: 1 II, 2 III	16: 3 III
01: 1 II	05: 1 II, 1 III	08: 1 III, 1 IV	11: 2 II, 1 III	14: 1 II, 1 III, 1 IV	17: 2 III, 1 IV
02: 1 III	06: 1 II, 1 IV	09: 2IV	12: 2 II, 1 IV	15: 1 III, 2 IV	18: 1 III, 2 IV
03: 1 IV					19: 3 IV

Table: Pole configurations for the dataset

For our preliminary analysis, we generated 500 line shapes per pole configuration resulting in 35,000 line shapes.

Training and Testing DNN (Preliminary Results)

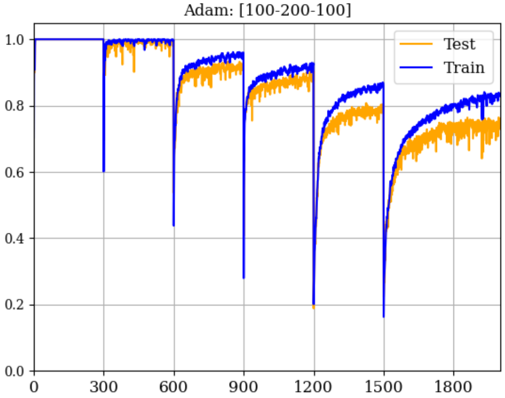


Figure: Optimizer: Adam
Hidden layers: 100-200-100
Training Accuracy: 83.47%
Testing Accuracy: 72.94%

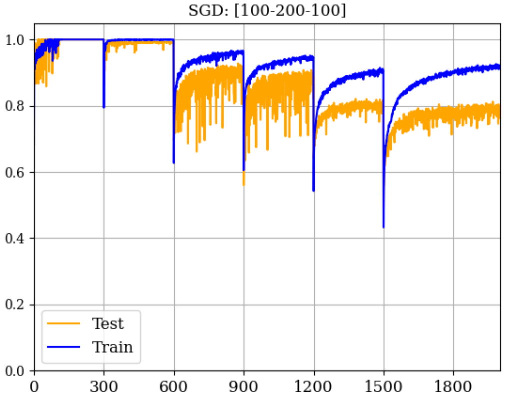


Figure: Optimizer: SGD
Hidden layers: 100-200-100
Training Accuracy: 91.46%
Testing Accuracy: 78.72%

Validation stage

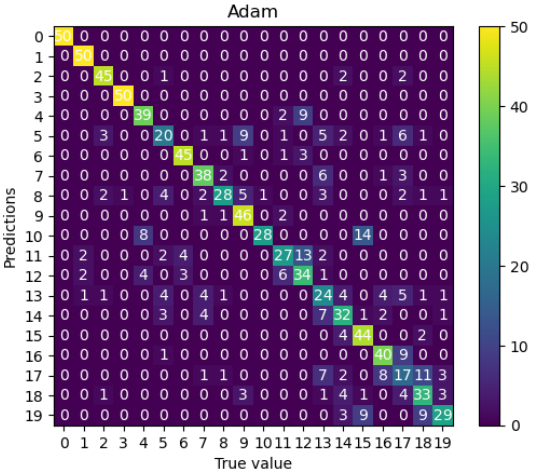


Figure: Confusion Matrix for Adam

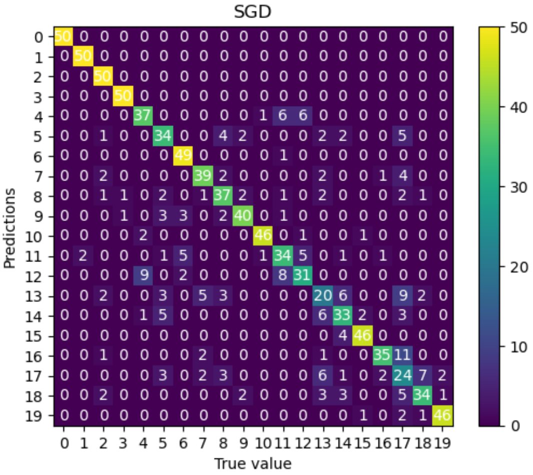


Figure: Confusion Matrix for SGD

Recall-Precision Scores (SGD)

Labels	Precision	Recall	F1-Score
0	1.00	1.00	1.00
1	0.96	1.00	0.98
2	0.85	1.00	0.92
3	0.96	1.00	0.98
4	0.76	0.74	0.75
5	0.67	0.68	0.67
6	0.83	0.98	0.90
7	0.80	0.78	0.79
8	0.73	0.74	0.73
9	0.87	0.80	0.83

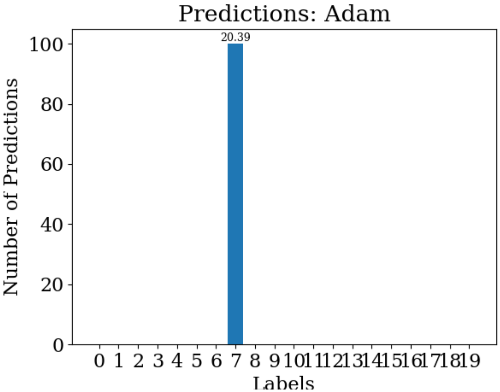
Labels	Precision	Recall	F1-Score
10	0.96	0.92	0.94
11	0.67	0.68	0.67
12	0.72	0.62	0.67
13	0.48	0.40	0.43
14	0.66	0.66	0.66
15	0.92	0.92	0.92
16	0.90	0.70	0.79
17	0.37	0.48	0.42
18	0.76	0.68	0.72
19	0.94	0.92	0.93

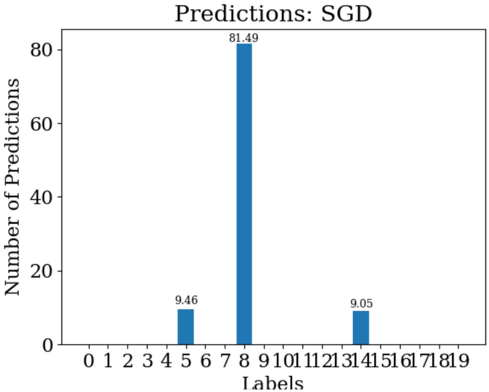
Recall-Precision Scores (Adam)

Labels	Precision	Recall	F1-Score
0	1.00	1.00	1.00
1	0.91	1.00	0.95
2	0.87	0.90	0.88
3	0.98	1.00	0.99
4	0.76	0.78	0.77
5	0.57	0.40	0.47
6	0.87	0.90	0.88
7	0.75	0.76	0.75
8	0.82	0.56	0.67
9	0.72	0.92	0.81

Labels	Precision	Recall	F1-Score
10	0.97	0.56	0.71
11	0.69	0.54	0.61
12	0.58	0.68	0.62
13	0.43	0.48	0.45
14	0.60	0.64	0.62
15	0.64	0.88	0.74
16	0.71	0.80	0.75
17	0.35	0.34	0.35
18	0.57	0.66	0.61
19	0.76	0.58	0.66

Inferencing Stage





05: 1 II, 1 III
07: 2 III

08: 1 III, 1 IV
14: 1 II, 1 III, 1 IV

In summary,

- This work aims to find the nature of $f_0(980)$.
- A deep neural network is an effective tool in classifying line shapes.
- We generated datasets together with their pole configuration using two-channel uniformization.
- For the preliminary results, both the optimizers – Adam and SGD – predicted a two-pole configuration to describe $f_0(980)$.

Outlook

In the future, we will generate more datasets as this will give variations and will help our DNN. We will also explore more effective DNN architectures.

Pentaquark Analysis

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