Analysis of hidden-charm pentaquarks as triangle singularities via deep learning

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Our Work

A Deep Learning Framework for Disentangling Triangle Singularity and Pole-Based Enhancements

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Enhancements in the invariant mass distribution or scattering cross-section are usually associated with resonances. However, the nature of exotic signals found near hadron-hadron thresholds remain a puzzle today. In fact, a purely kinematic triangle mechanism is also capable of producing similar structures, but do not correspond to any unstable quantum state. In this paper, we report for the first time, that a deep neural network can be trained to distinguish triangle singularity from pole-based enhancements. We also identify the type of dynamic pole structure that can be misidentified as triangle enhancement. We apply our method to confirm that the $P_\psi^N(4312)^+$ state is not due to a single triangle singularity, and is more favored towards a pole-based interpretation based solely on pure line-shape analysis. Lastly, we argue how our method can be used as a model-selection framework to help in classifying other exotic hadron candidates.

Keywords: triangle singularity, uniformization, deep learning, exotic hadrons, model selection

arxiv.org/abs/2403.18265

- Developed a deep neural network model able to distinguishing between triangle singularity and pole-based enhancements
- Confirmed via pure line-shape analysis that the triangle interpretation can be ruled out for $P_\psi^N(4312)^+$

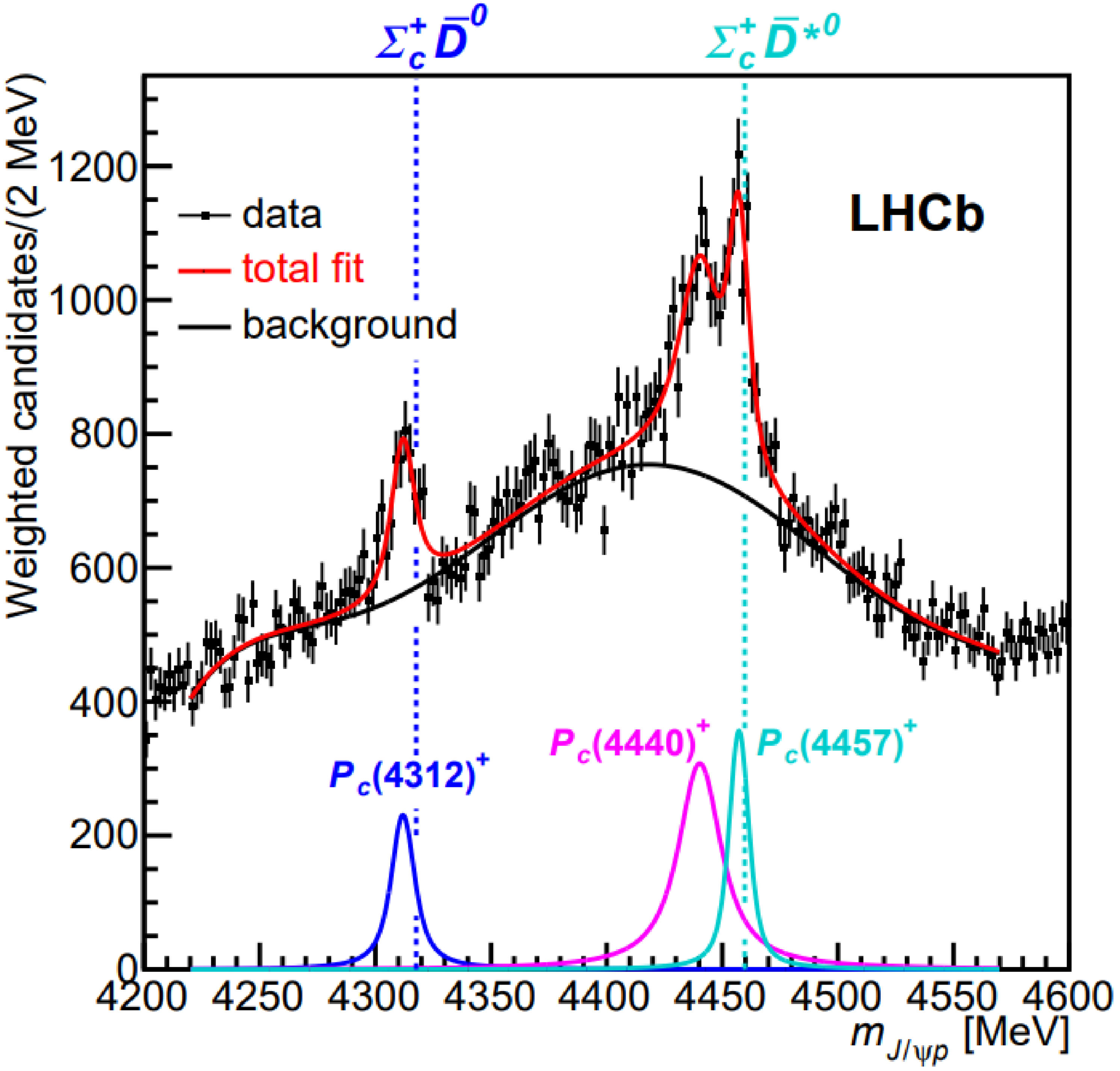
LHCb Pentaquarks

Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$

LHCb collaboration†

Abstract

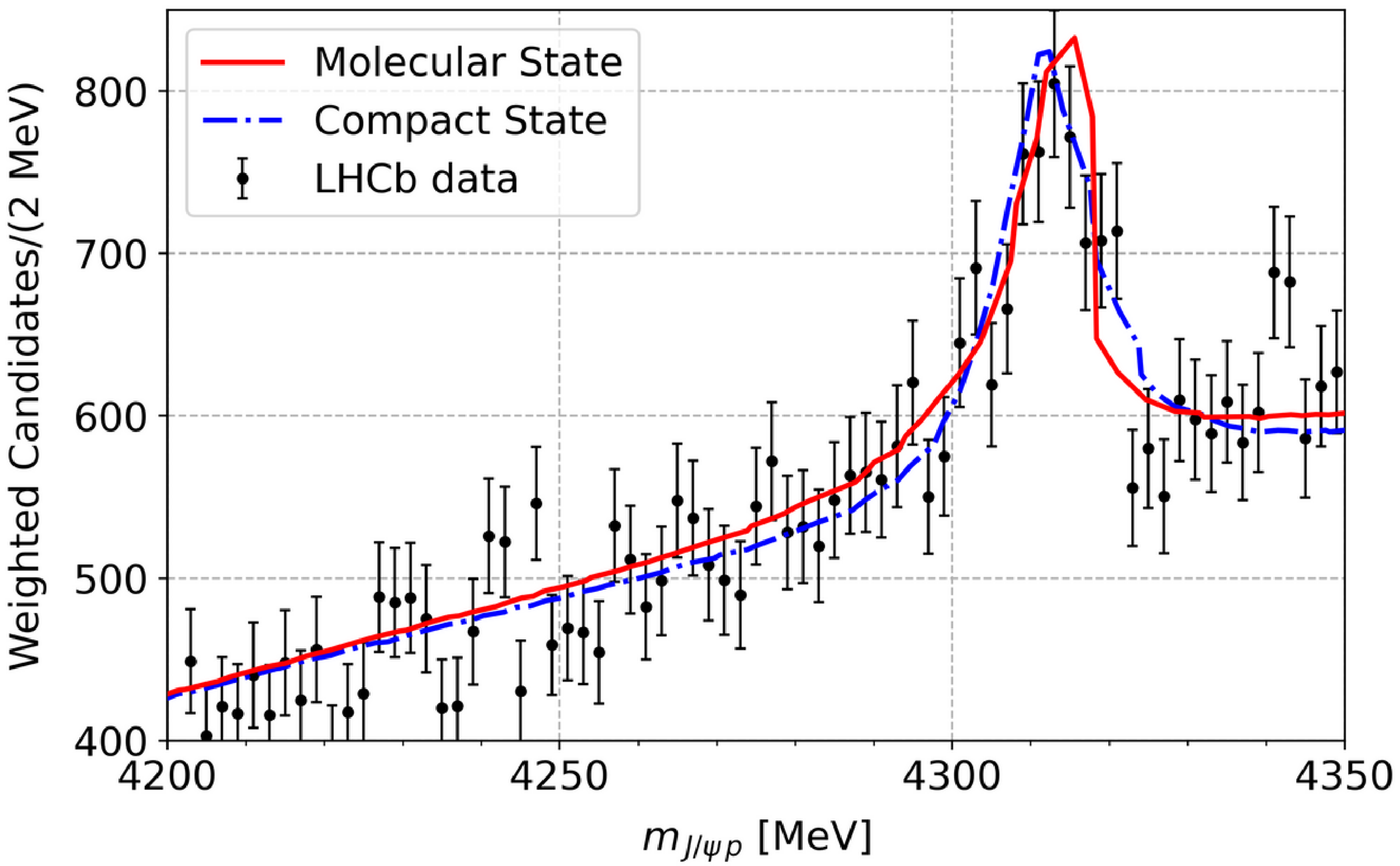
A narrow pentaquark state, $P_c(4312)^+$, decaying to $J/\psi p$ is discovered with a statistical significance of 7.3σ in a data sample of $\Lambda_b^0 \to J/\psi p K^-$ decays which is an order of magnitude larger than that previously analyzed by the LHCb collaboration. The $P_c(4450)^+$ pentaquark structure formerly reported by LHCb is confirmed and observed to consist of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$, where the statistical significance of this two-peak interpretation is 5.4σ. Proximity of the $\Sigma_c^+ \overline{D}^0$ and $\Sigma_c^+ \overline{D}^{*0}$ thresholds to the observed narrow peaks suggests that they play an important role in the dynamics of these states.



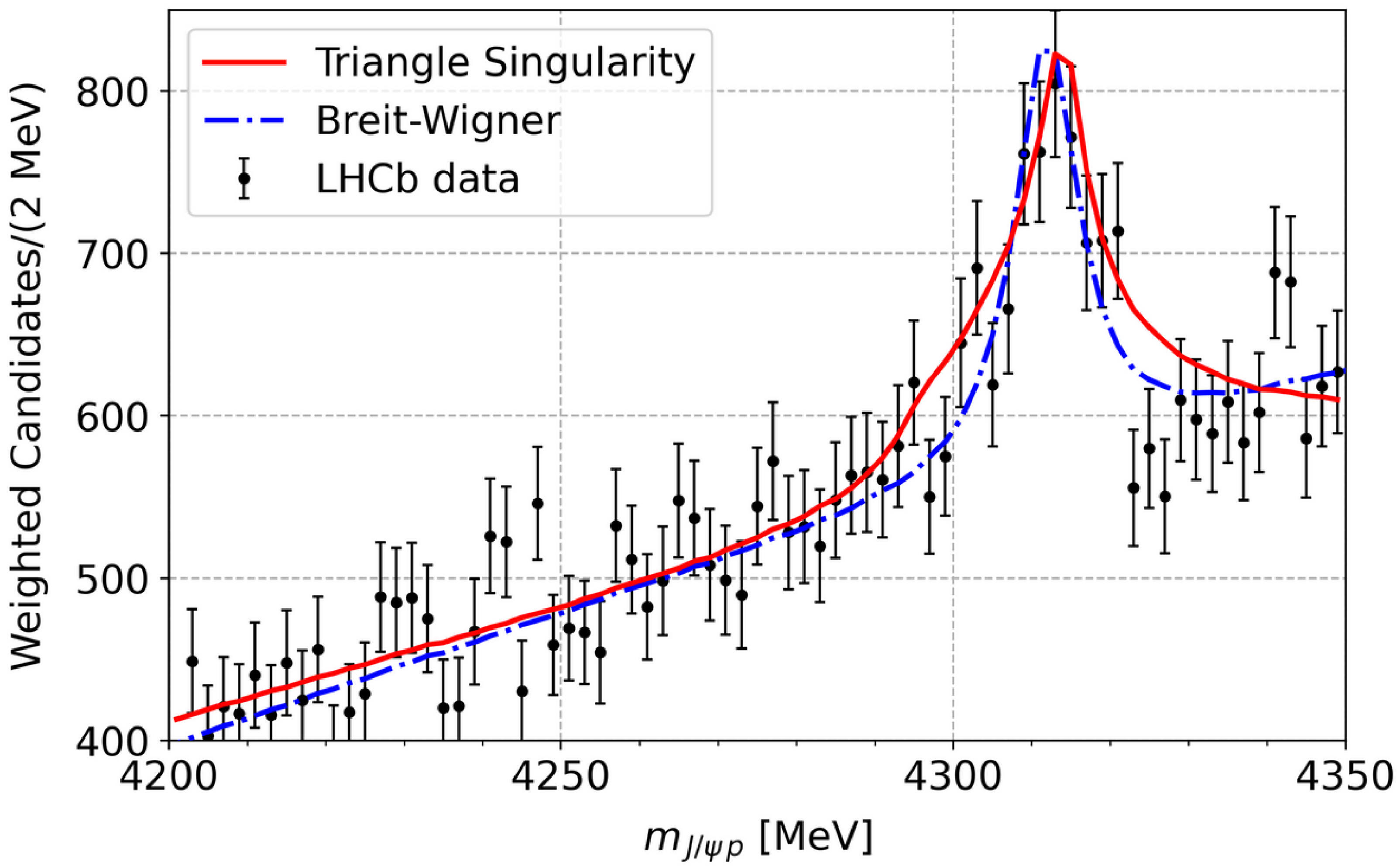
LHCb, Phys. Rev. Lett. 122, 222001 (2019)

$P_{\psi}^{N}(4312)^{+}$

POLES OF THE S-MATRIX

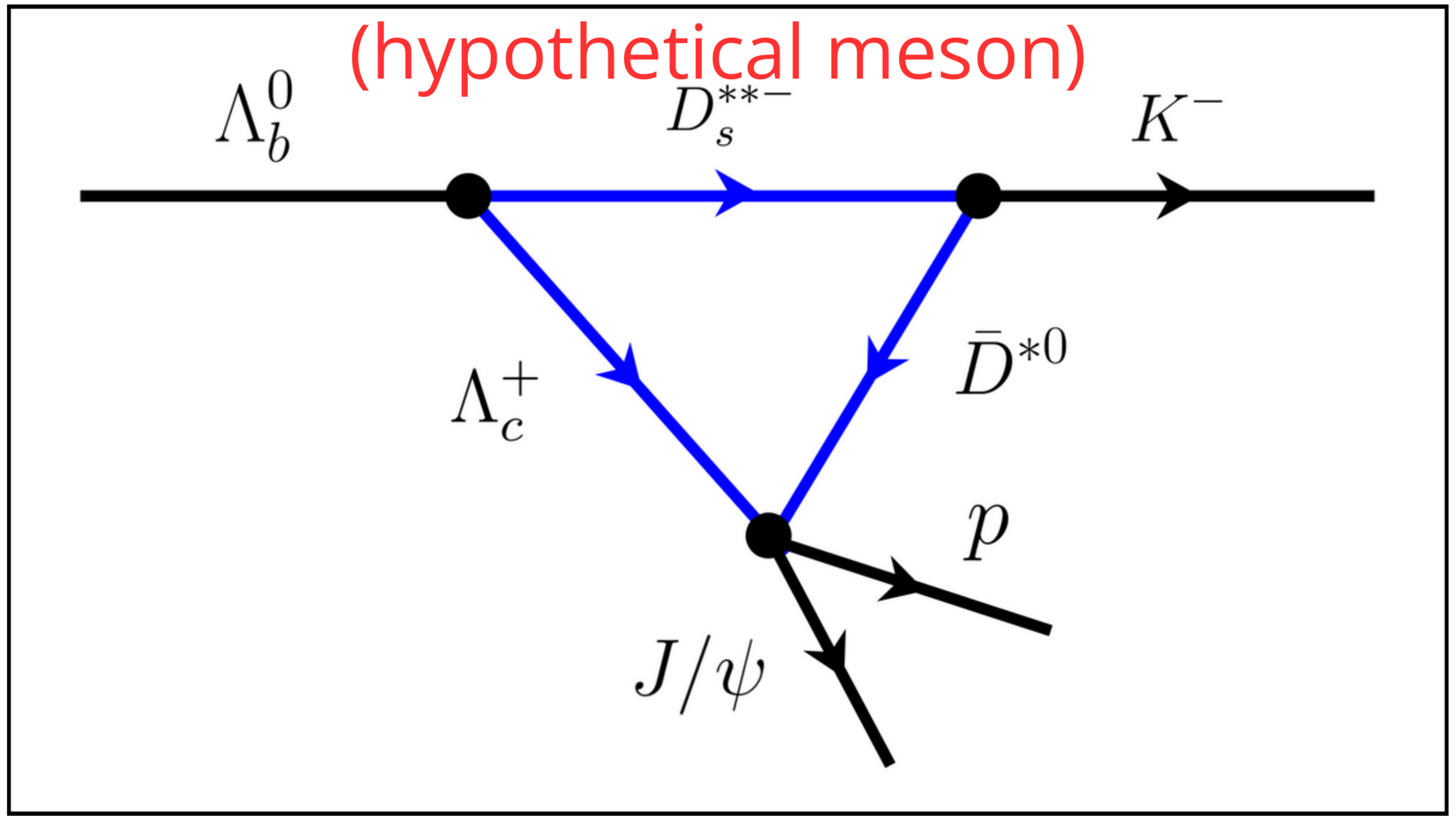


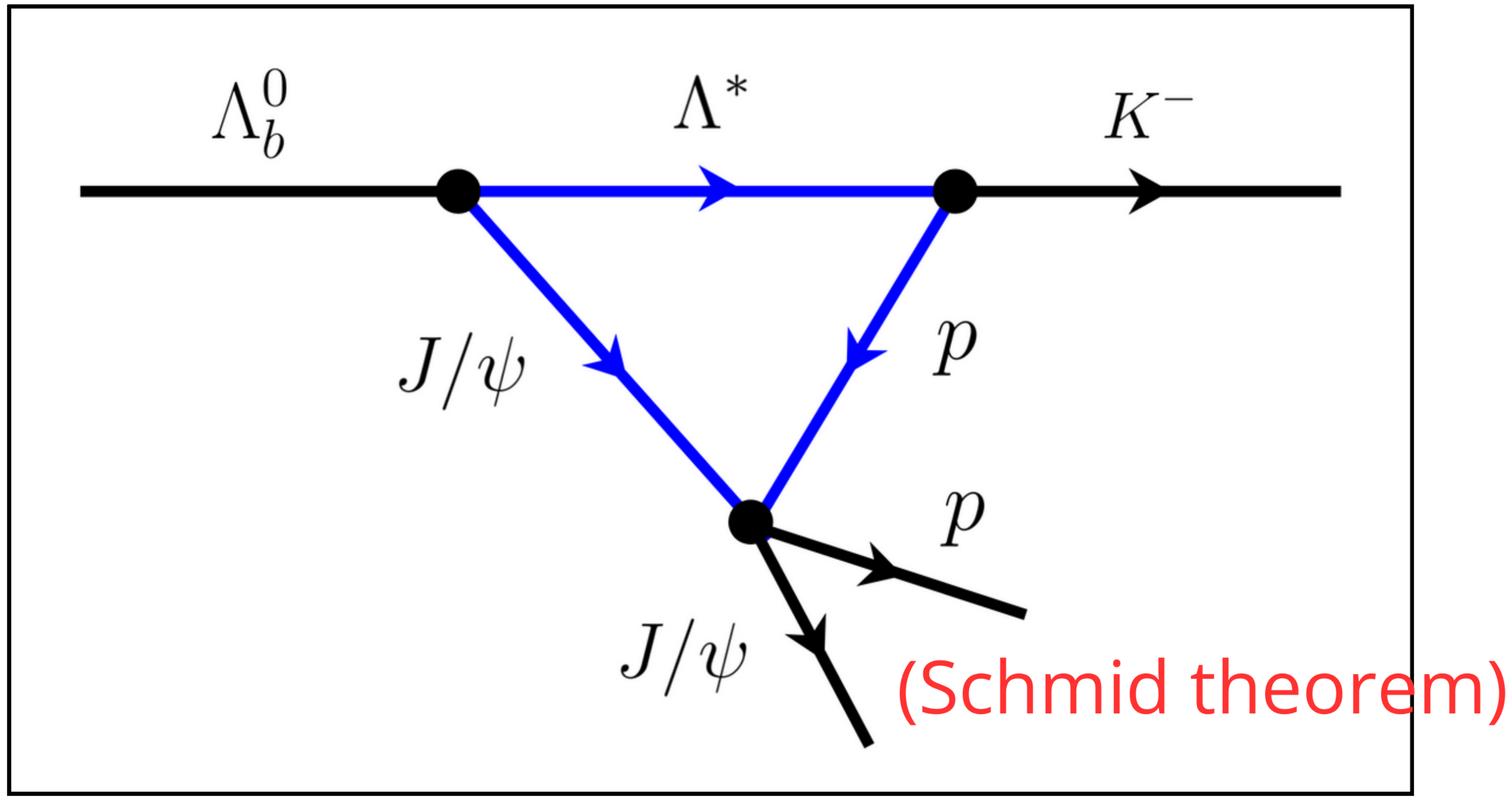
TRIANGLE SINGULARITY



Various models can produce **similar line shapes** that fit the experimental data, despite describing **very different physics**.

Triangle of $P_{\psi}^{N}(4312)^{+}$

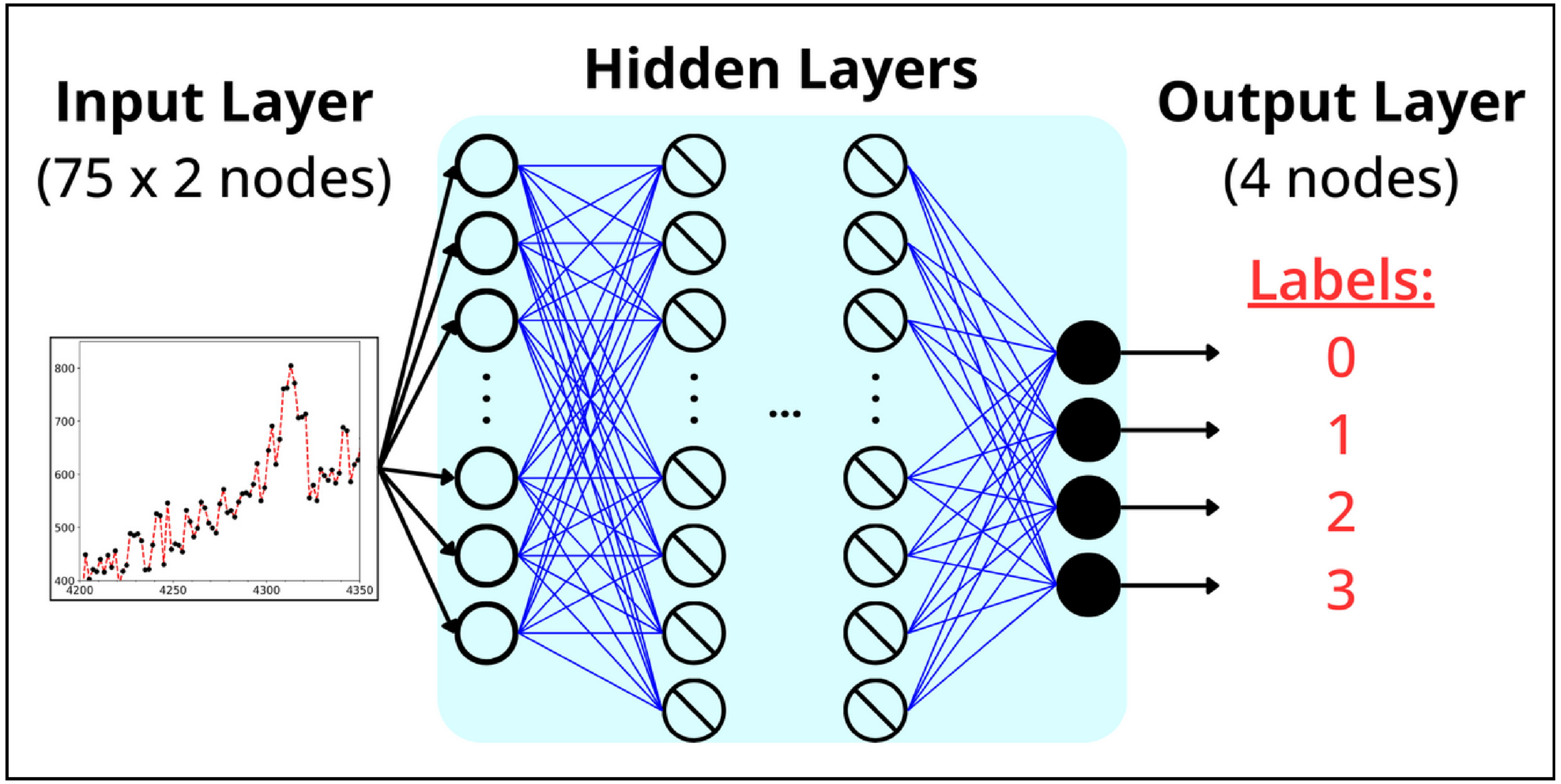




Theoretical analysis already suggests that the triangle sigularity is an **unlikely** origin of the 4312 pentaquark state based on **physical constraints**.

LHCb, Phys. Rev. Lett. 122, 222001 (2019)

Deep Learning Framework



We use machine learning, specifically a **Deep Neural Network**, to solve this **classification problem**.

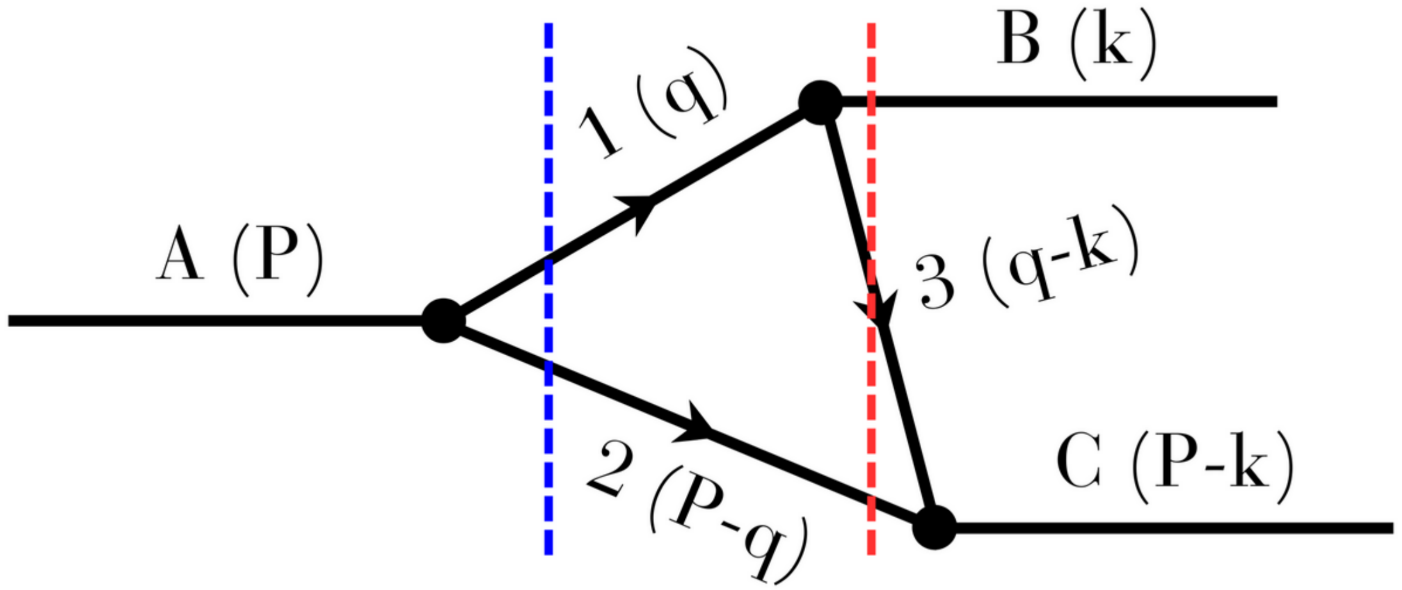
STEPS:

1. Generate the Training Dataset
2. Design the DNN Architecture
3. Train, Test, and Validate the DNN
4. Use DNN for Inference

D.L.B. Sombillo et al., Phys. Rev. D 104, 3, 036001 (2021)

Formalism

Triangle Singularity



$$I(k) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{(q^2 - m_1^2 + i\epsilon)\left[(P-q)^2 - m_2^2 + i\epsilon\right]\left[(q-k)^2 - m_3^2 + i\epsilon\right]} \quad (1)$$

$$I(k) \propto \int_0^\infty \frac{q^2 f(q)\, dq}{P^0 - \sqrt{m_1^2 + q^2} - \sqrt{m_2^2 + q^2} + i\epsilon} \qquad f(q) = \int_{-1}^{1} \frac{dz}{E_C - \omega(q) - \sqrt{m_3^2 + q^2 + k^2 + 2qkz} + i\epsilon} \quad (2)$$

$$m_{23}^2 \in \left[(m_2 + m_3)^2,\ \frac{M_a m_3^2 - M_b^2 m_2}{M_a - m_2} + M_a m_2\right], \qquad m_1^2 \in \left[\frac{M_a^2 m_3 + M_b^2 m_2}{m_2 + m_3} - m_2 m_3,\ (M_a - m_2)^2\right] \quad (3)$$

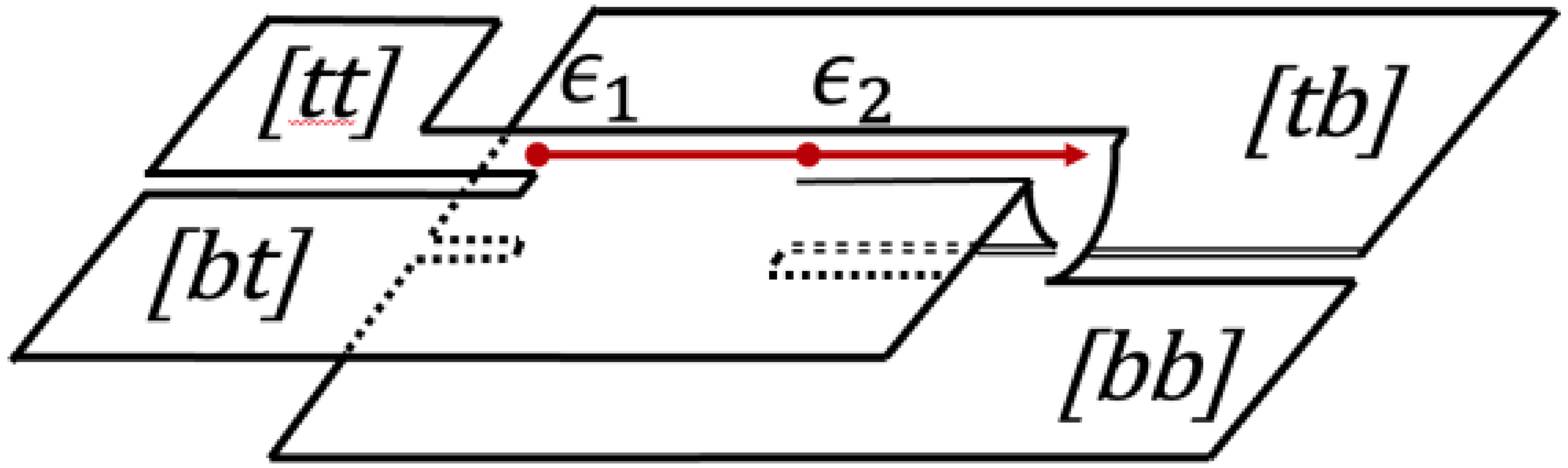
F.-K. Guo et al., Prog. Part. Nucl. Phys. 112, 103757 (2020)

Follow mass condition to generate multiple line shapes for the training dataset.

Formalism

Reimann sheets in a two-channel scattering

Uniformization of the S-matrix (Poles)



L. M. Santos & D. L. B. Sombillo, Phys. Rev. C 108, 045204 (2023).

$$S_{11}(q_1,q_2)=\frac{D(-q_1,q_2)}{D(q_1,q_2)};\qquad S_{22}(q_1,q_2)=\frac{D(q_1,-q_2)}{D(q_1,q_2)} \quad (4)$$

$$\omega=\frac{q_1+q_2}{\sqrt{\epsilon_2^2-\epsilon_1^2}};\quad \frac{1}{\omega}=\frac{q_1-q_2}{\sqrt{\epsilon_2^2-\epsilon_1^2}} \quad (5)$$

M. Kato, Annals of Physics 31, 130 (1965).

$$D(\omega)\propto\frac{1}{\omega^2}(\omega-\omega_{\rm pole})(\omega+\omega^*_{\rm pole})(\omega-\omega_{\rm reg})(\omega+\omega^*_{\rm reg}) \quad (6)$$

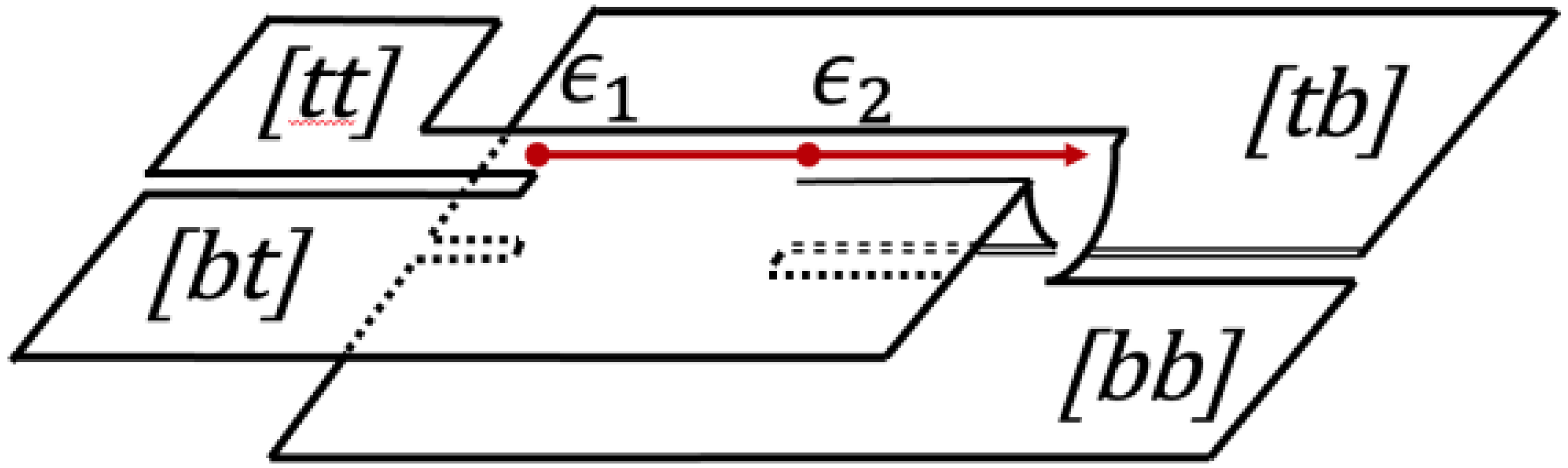
$$\frac{dN}{d\sqrt{s}}=\rho(\sqrt{s})\left[|F(\sqrt{s})|^2+B(\sqrt{s})\right] \quad (7)$$

JPAC, Phys. Rev. Lett. 123, 092001 (2019).

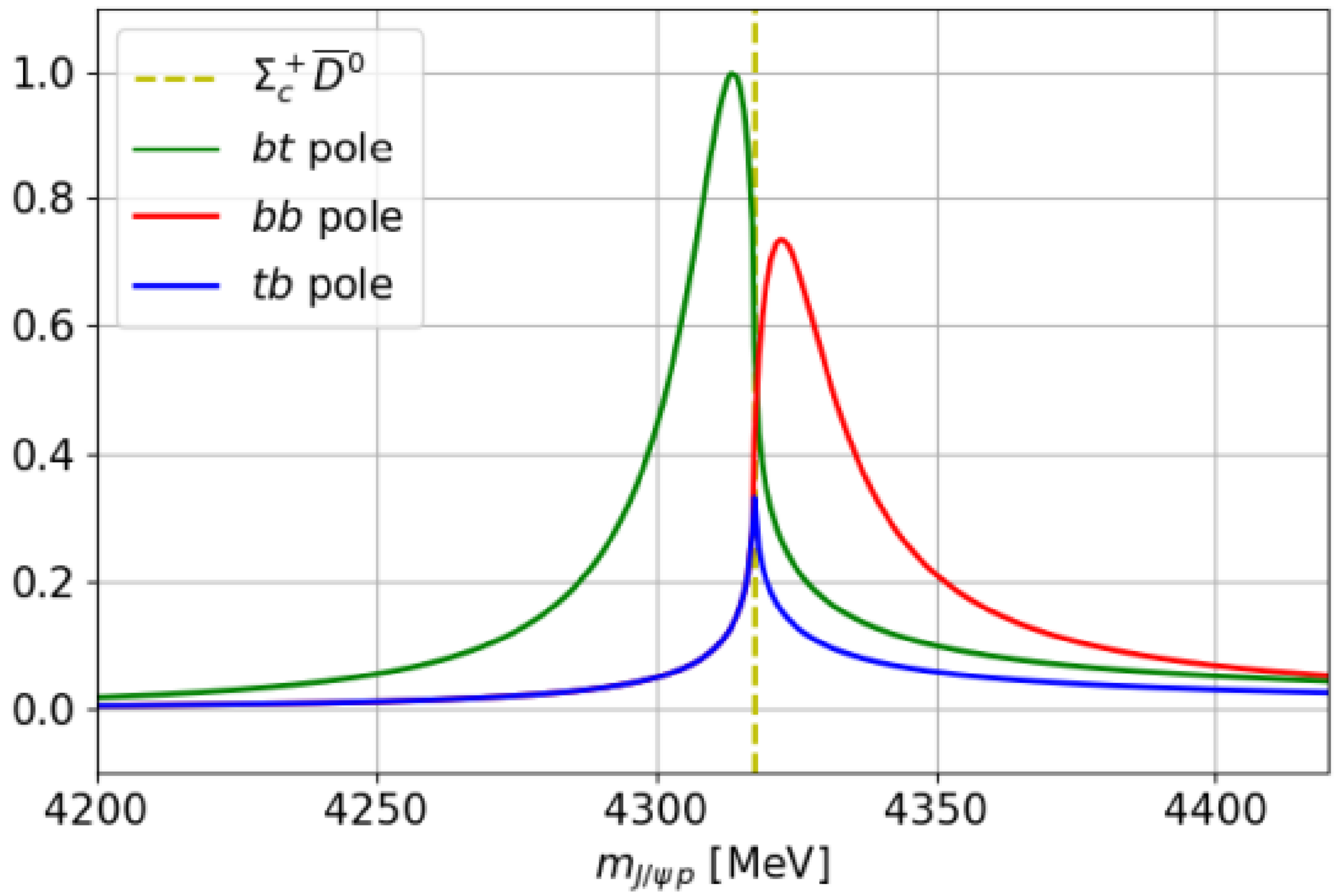
Formalism

Uniformization of the S-matrix (Poles)

Reimann sheets in a two-channel scattering



L. M. Santos & D. L. B. Sombillo, Phys. Rev. C 108, 045204 (2023).

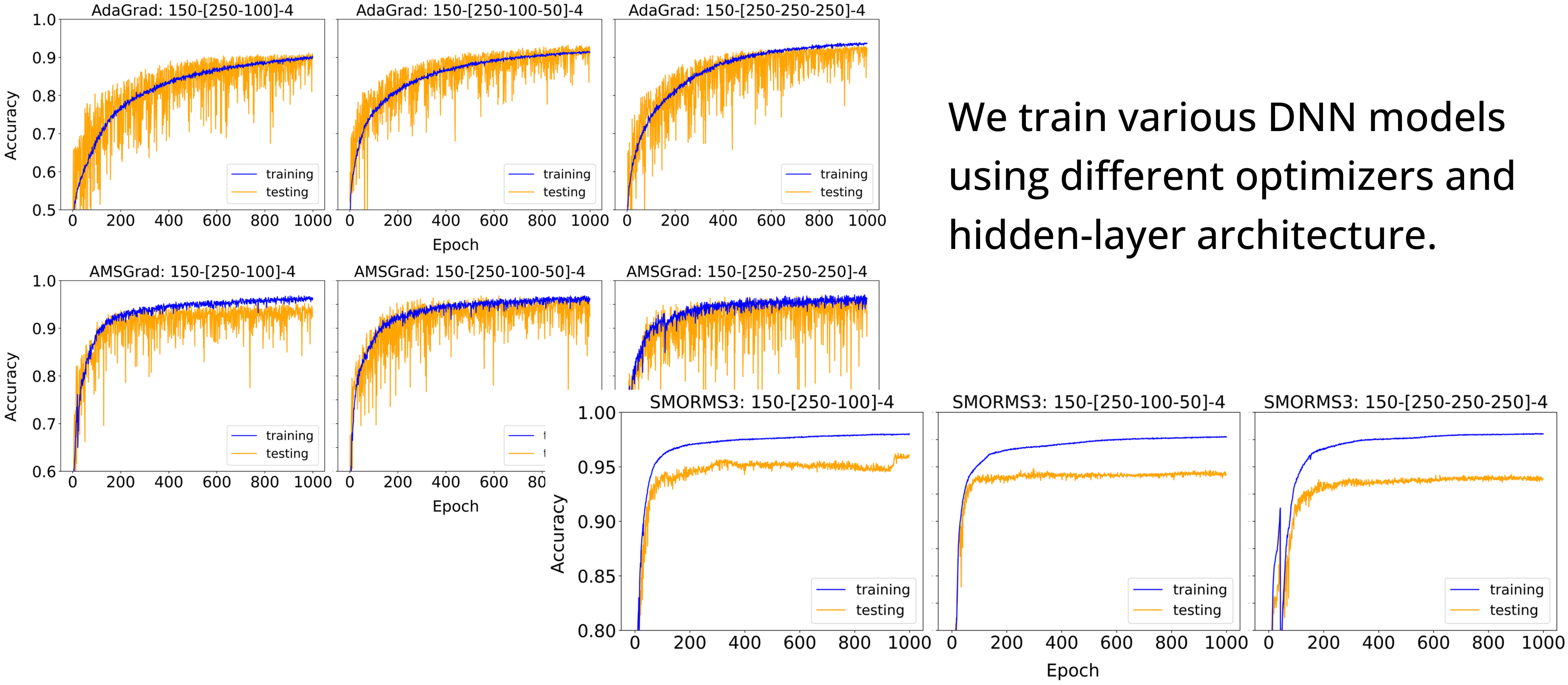


Pole Counting

- 1 pole in *[bt]*: bound state
- 1 pole in *[tb]*: virtual state
- 1 pole each in *[bt]* + *[bb]*: nearly compact state

D. Morgan, Nucl. Phys. A 543, 632 (1992).

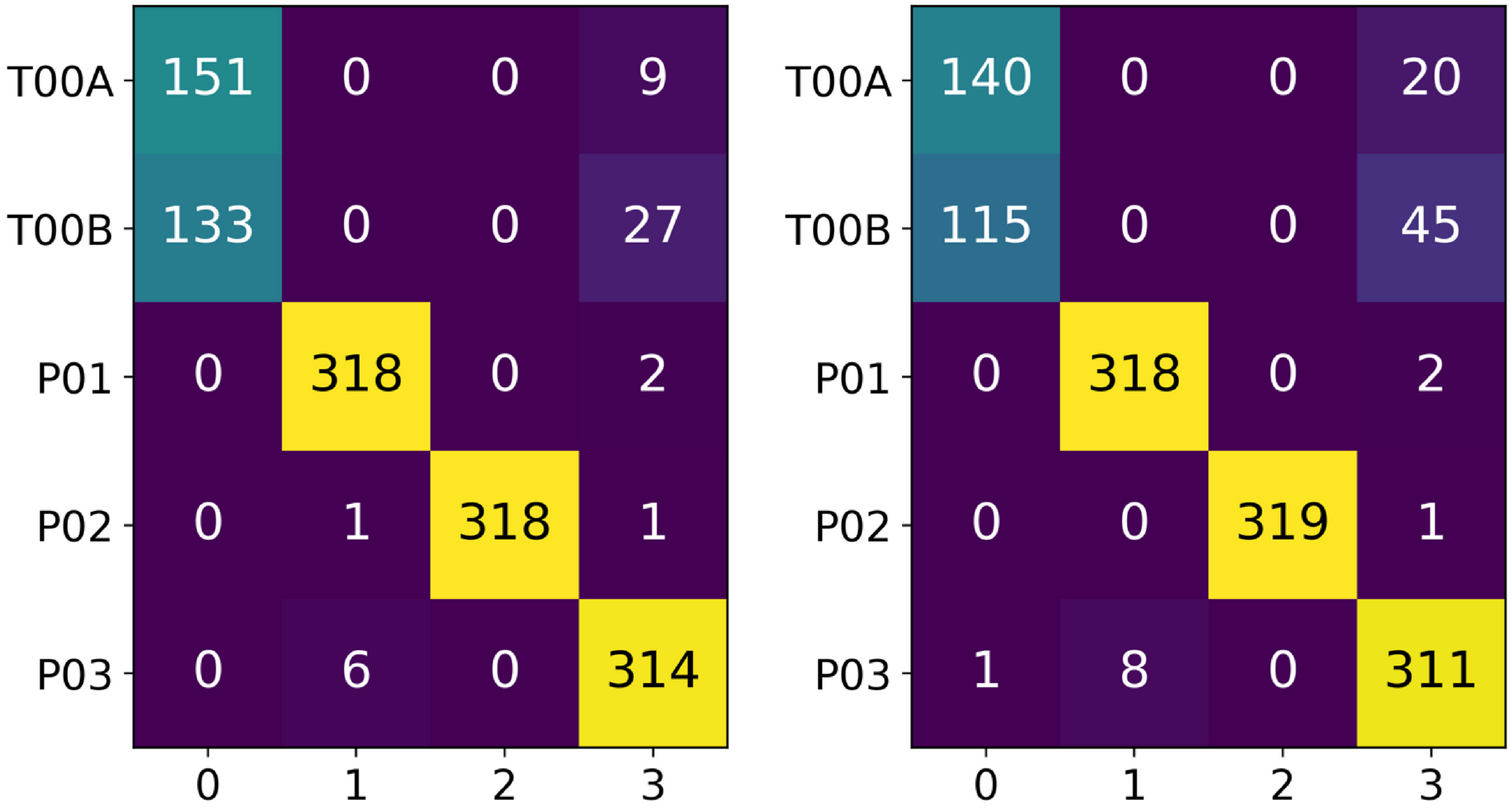
DNN Training & Testing



We train various DNN models using different optimizers and hidden-layer architecture.

DNN Validation

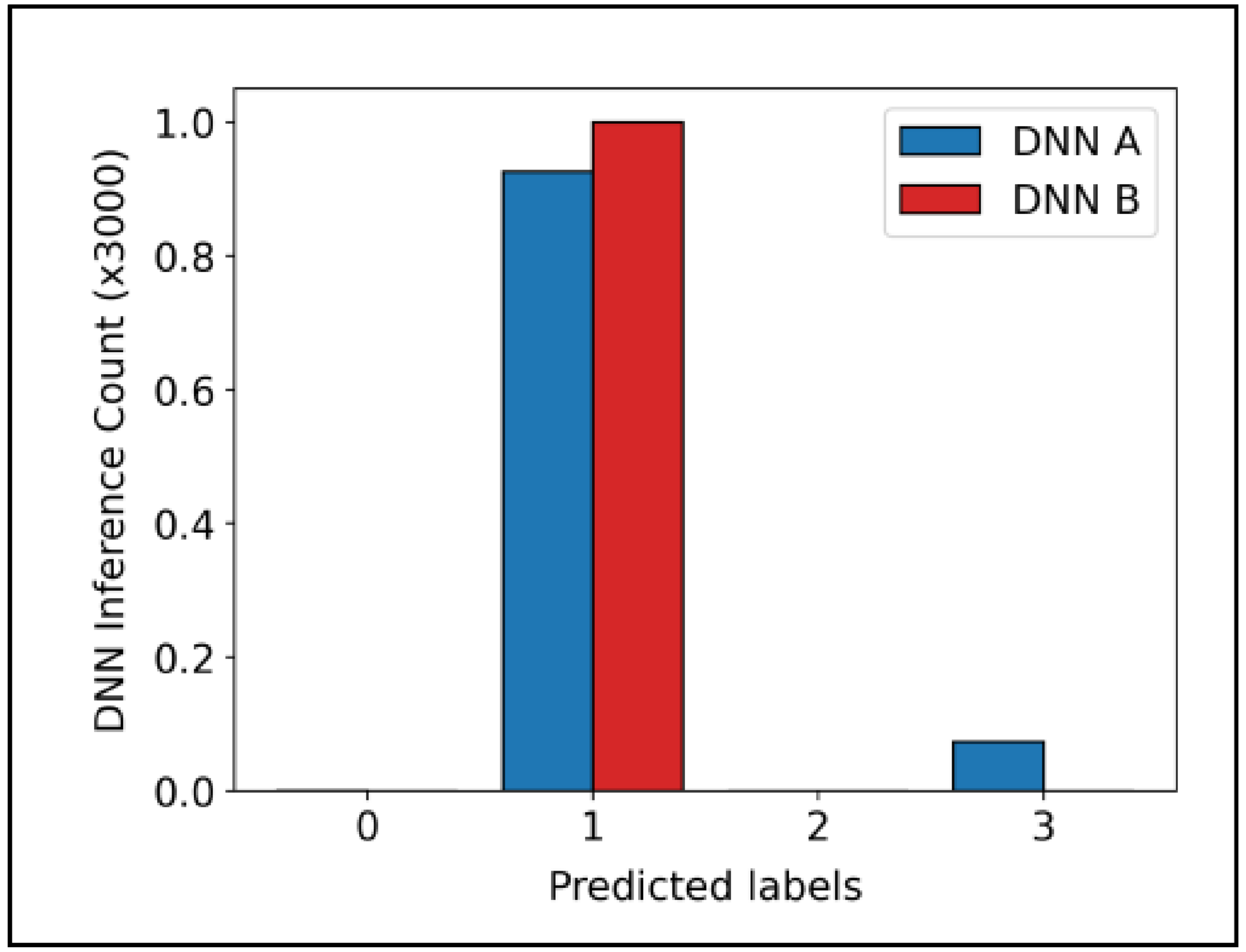
Confusion Matrix



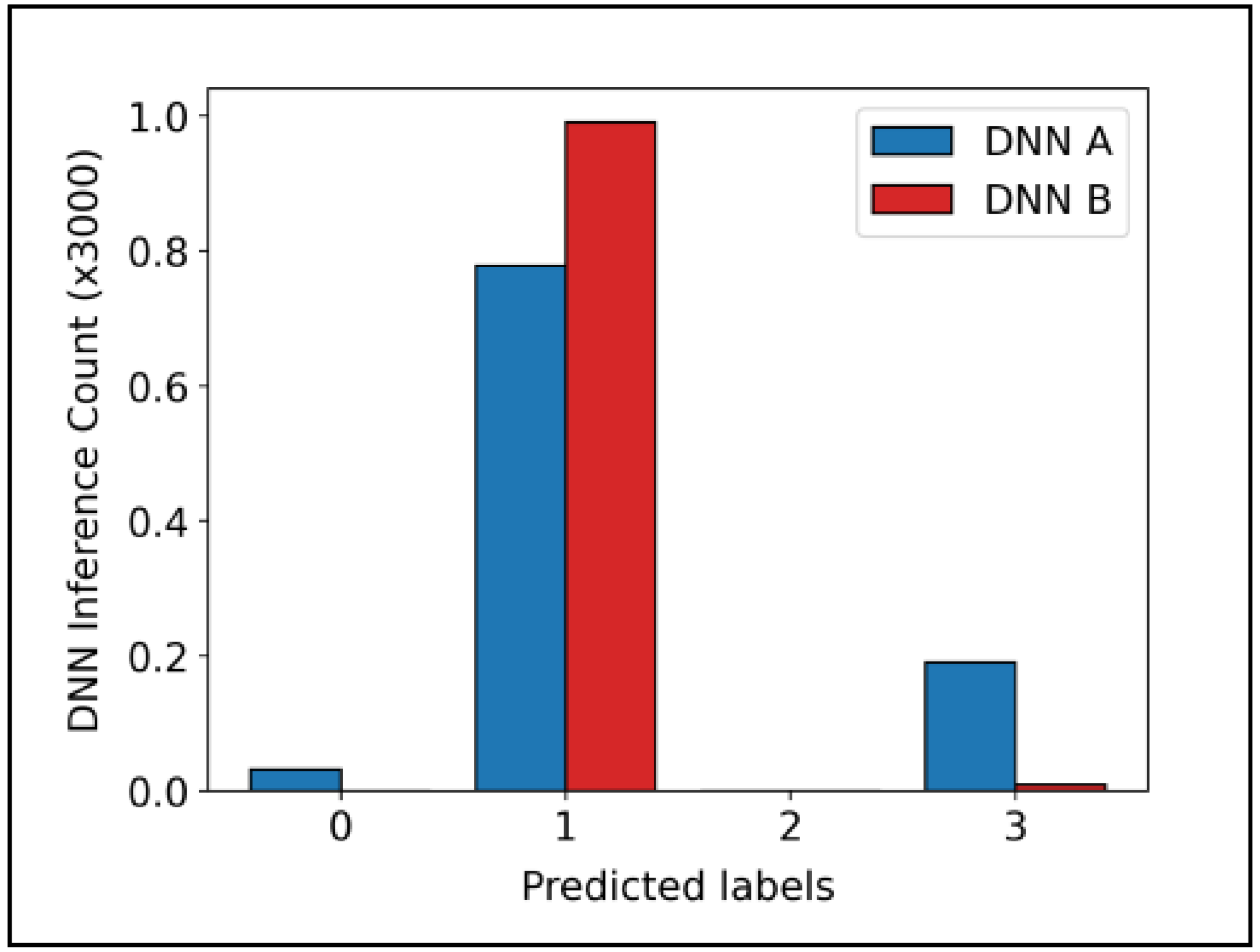
Output Label	Interpretation
0	Triangle Singularity
1	Bound state
2	Virtual state
3	Compact state

DNN prediction capability is clear and generally satisfactory.

Interpretation of $P_\psi^N(4312)^+$



(a) Uniform distribution



(b) Normal distribution

Output Label	Interpretation
0	Triangle Singularity
1	Bound state
2	Virtual state
3	Compact state

DNN models consistently rule out traingle singularity, and favor the dynamic pole structure.

Model Selection Framework

- Our trained model was able to **select the most favorable mechanism** to be used to interpret/explain a measured enhancement, while eliminating the misleading ones.

- Note that this is only suggestive in nature and NOT confirmatory. It only serves to **provide stronger intuition** on the true nature of the measured signals.

- This can be used to study the two other pentaquark states and various other exotic candidates.

Analysis of hidden-charm pentaquarks as triangle singularities via deep learning

Summary:

We developed a **model-selection framework** using a Deep Neural Network to **distinguish triangle singularity from pole-based enhancements** and confirmed that the **single triangle kinematic interpretation can be consistently ruled** out for the $P_{\psi}^{N}(4312)^{+}$.

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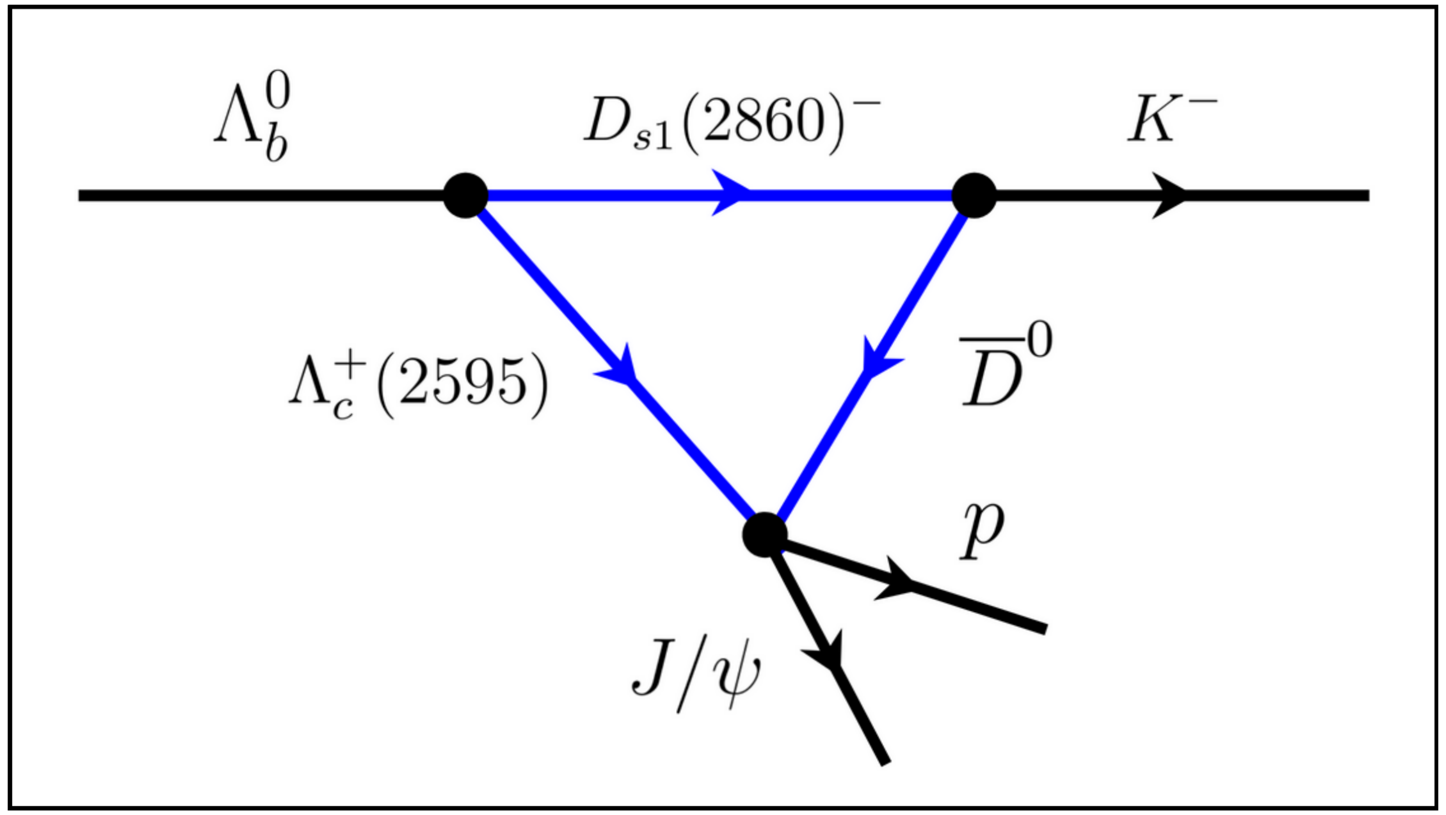
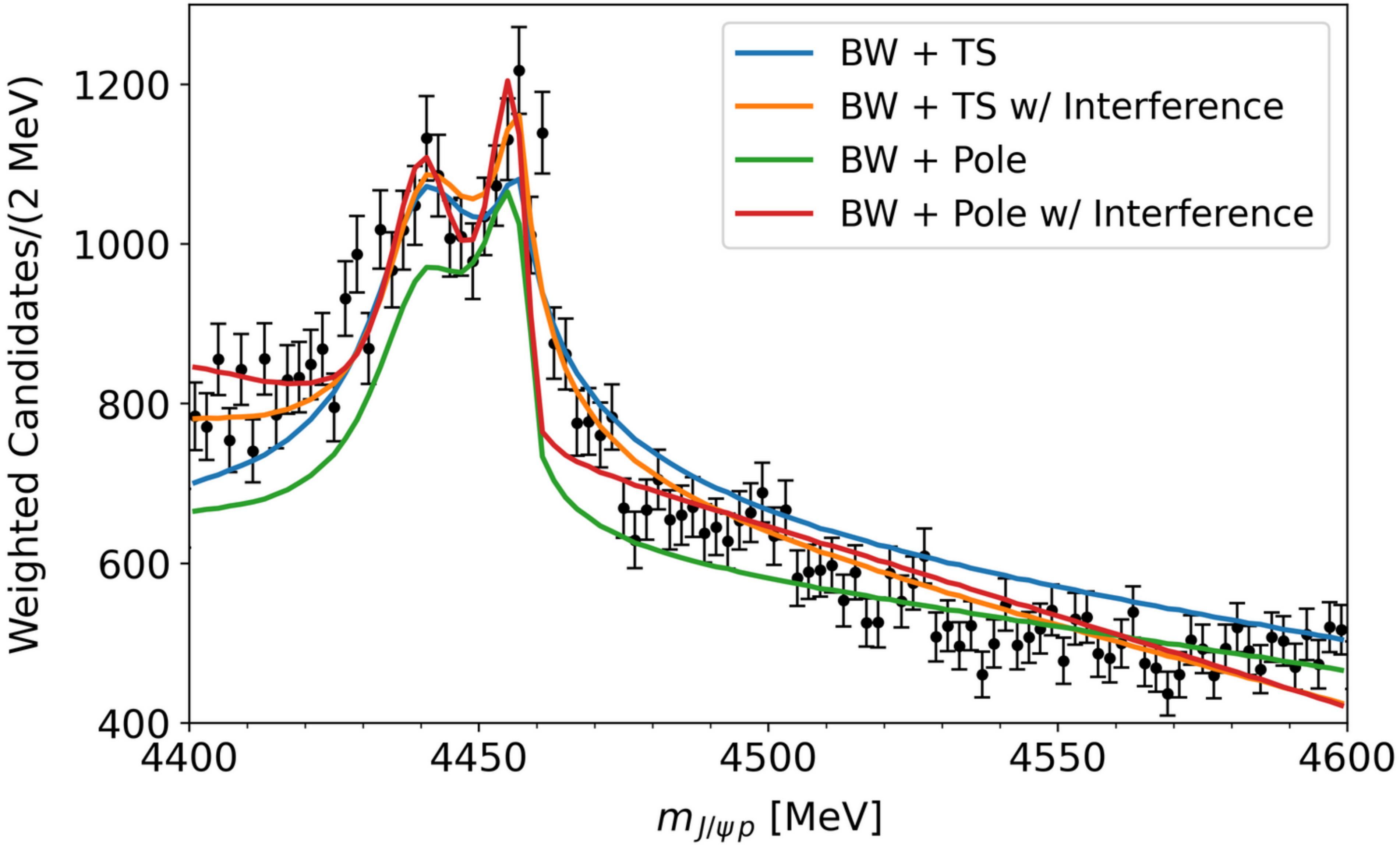
Backup: The two-peak structure

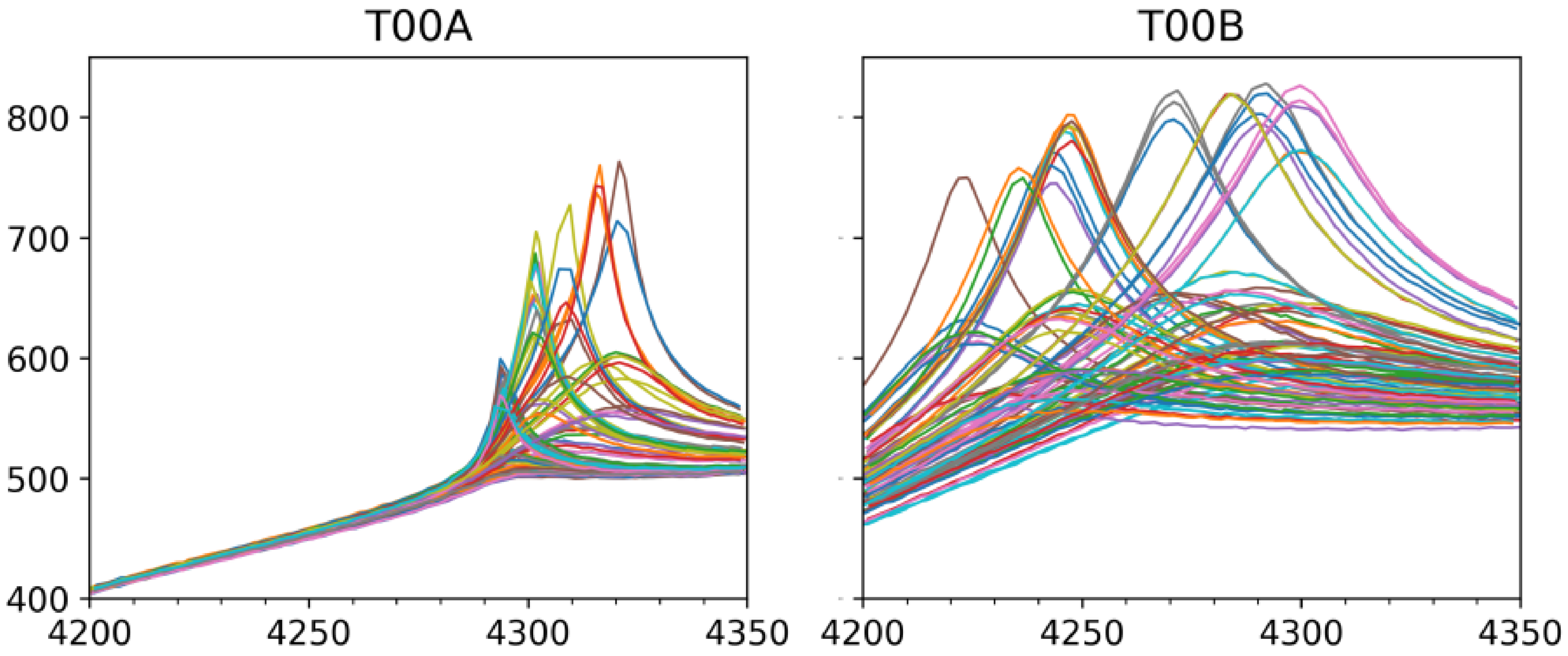
Triangle of $P_\psi^N(4457)^+$



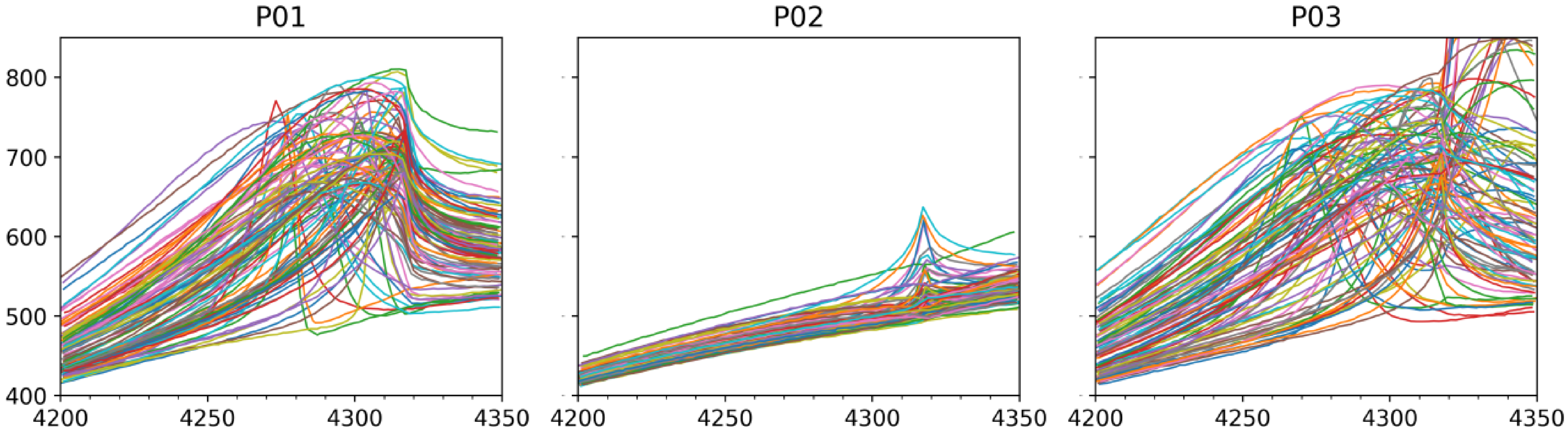


We may use a Breit-Wigner for the 4440 state and Pole/TS for the 4457 state.

Backup: Sample datasets (TS)



Backup: Sample datasets (Poles)



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