Rediscovering the Standard Model with AI

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Introduction

- The **Standard Model (SM)** explains the fundamental particles and forces of nature.

- It classifies particles into families (baryons, mesons,…) based on their charges

- **In chemistry**, AI has been used to **reconstruct the periodic table** from raw data. [Zhang et al. 2018; Kusaba et al. 2019]

- In particle physics, some work already attempts to recover the **SM Lagrangian** using symbolic regression.

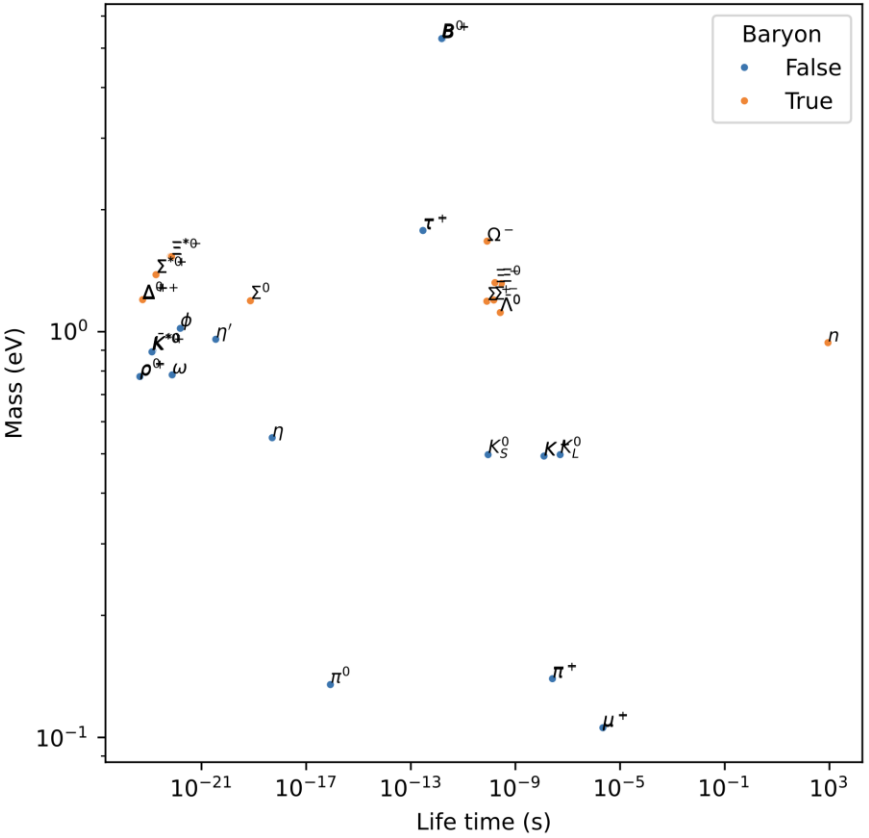
- Can a machine **learn the SM** directly from experimental data?

- Test whether **data alone**—without built-in theory—allows AI to reconstruct the structure and logic of the Standard Model.

Methods:
- Data dimensional reduction (principal component analysis, t-distributed stochastic neighbor embedding).
- Unsupervised Machine Learning : (hierarchical) clustering
- We use only experimental measurements as input – mass, lifetime, spin, decay modes.

Mass vs Lifetime

- **Mass** and **lifetime** are key to understanding particle behavior and interaction type.
- A log-log plot of SM particles shows clear **clustering** based on interaction origin:
- **Clustering reflects the interaction**:
  - **Strong interaction**→ fast decays
  - **Weak interaction**→ slower, rare decays



Baryon-Meson classification

Motivation:

- Particle identification relies on **decay products** detected in collider experiments.
- Decay products encode crucial information: **interaction type**, **mass**, **lifetime**, and **charge** of the parent particle.
- Different families (baryons, mesons, leptons) exhibit **distinct decay signatures** based on the underlying interactions (strong vs. weak).

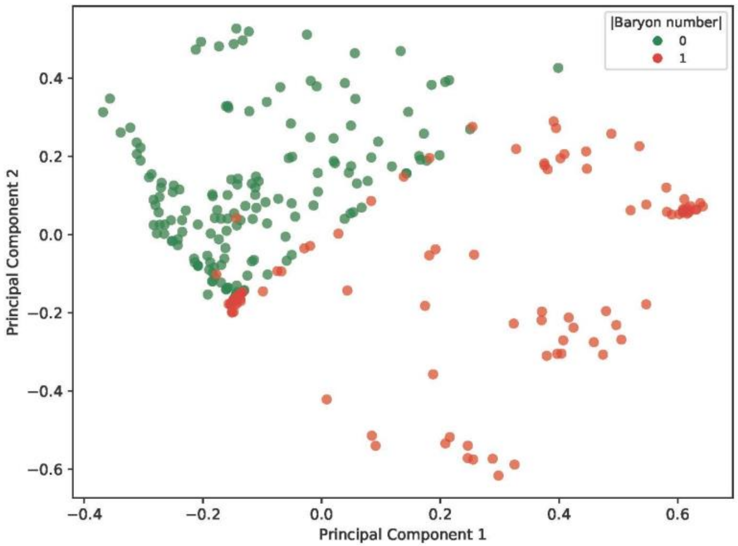
Approach:

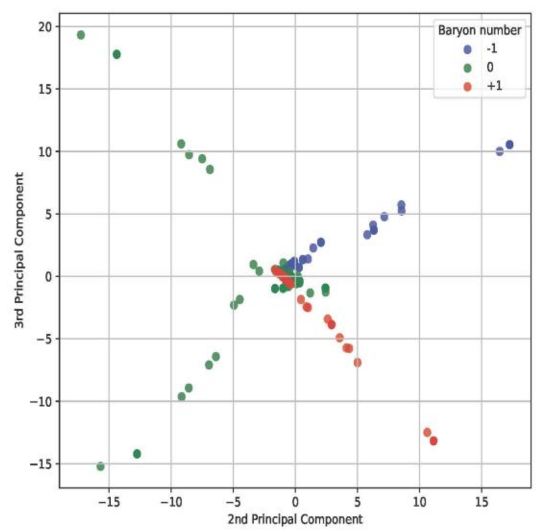
- Use **Principal Component Analysis (PCA)** on decay product features to reduce dimensionality.
- Each particle represented as a **binary vector** of decay products (present/absent in **decay chains**).
- Aim: Identify **latent structure** in decay behavior to classify particles **unsupervised**.

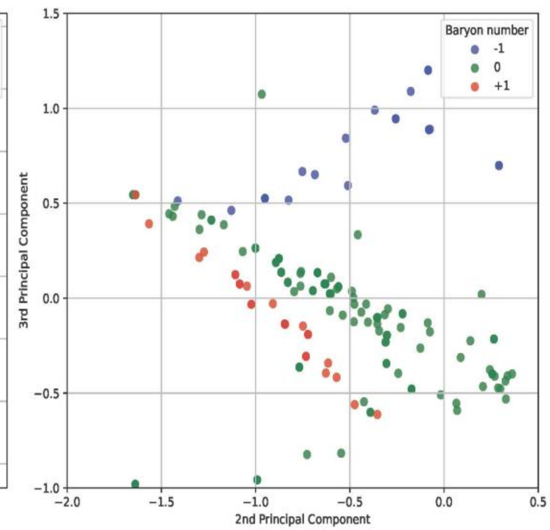
Baryon-Meson classification

PCA on decay mode data clearly **separates baryons and mesons**:

- End-of-chain products like **protons/neutrons** (for baryons) vs. **leptons** (for mesons) drive the separation.







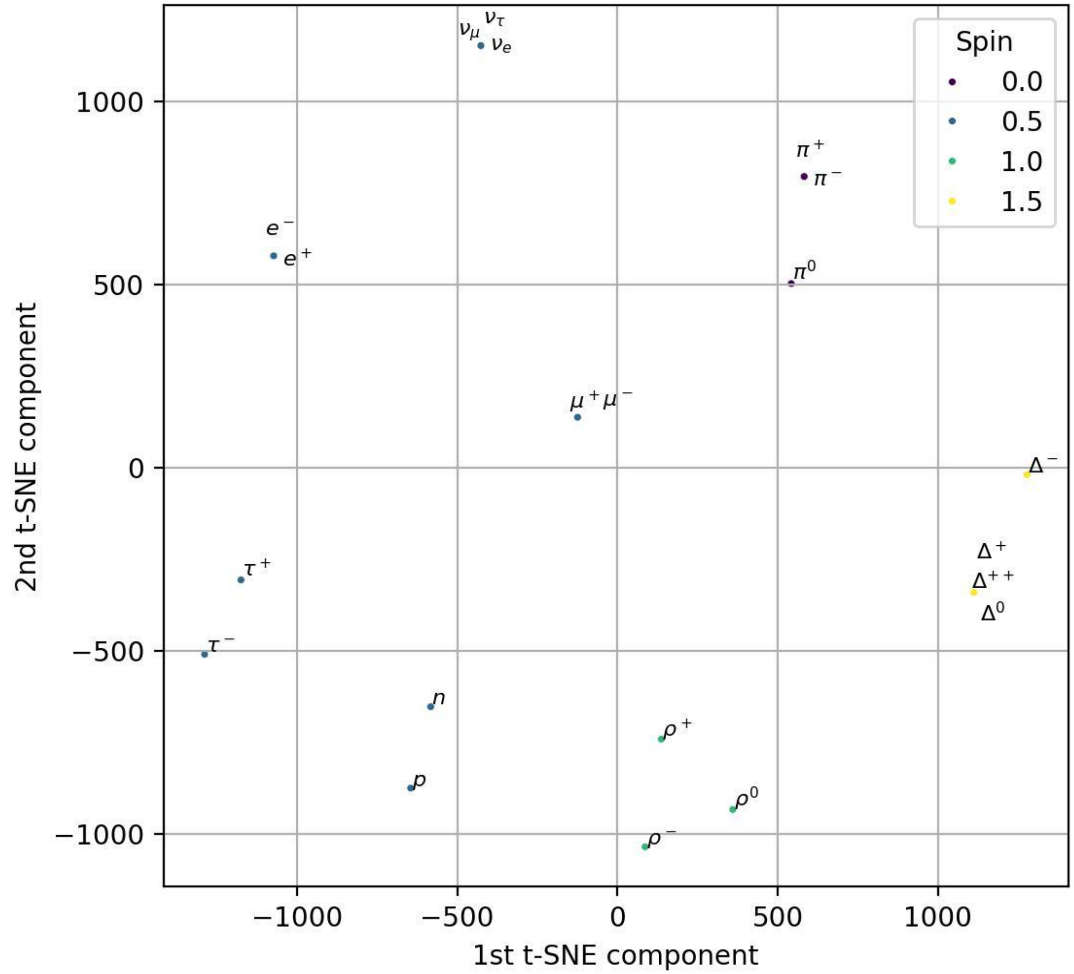
Implication:

Decay data alone—without explicit labeling—encodes sufficient information to recover Standard Model groupings via unsupervised learning.

SU(N) multiplets

- We give mass, lifetime and spin as input.

- Dimensionality reduction (t-SNE) on light hadron particles (u,d quarks) reveals clear clusters aligned with **SU(2) isospin multiplets.**



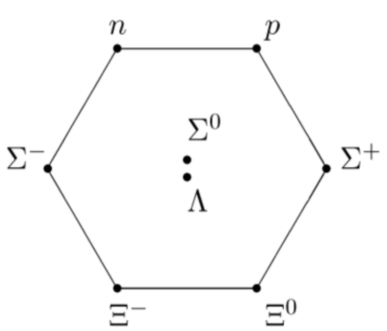
SU(N) multiplets

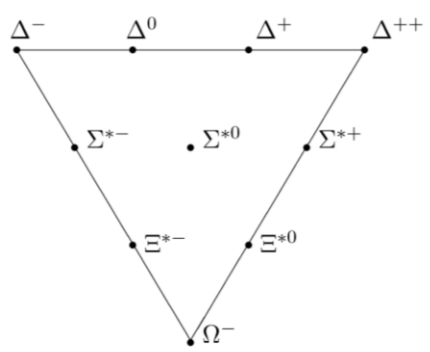
- We give mass, lifetime and spin as inputs

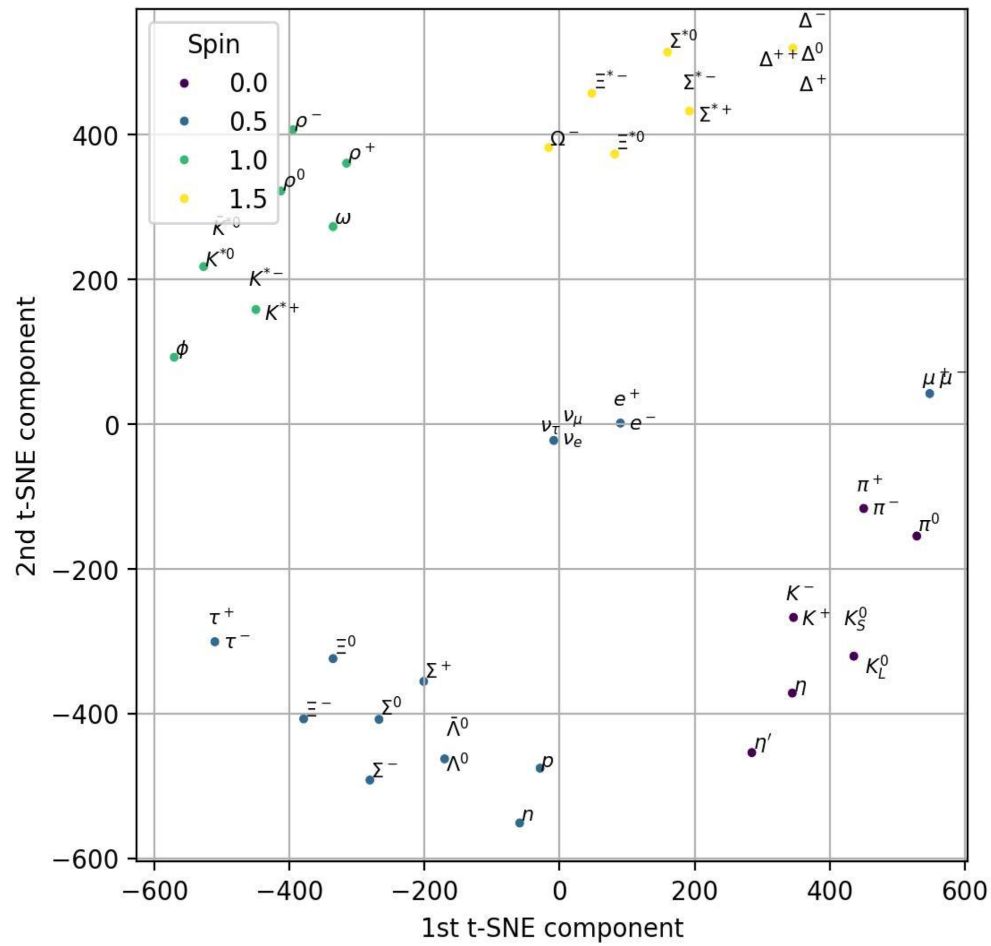
- Dimensionality reduction (t-SNE) on pre-1960 hadron particles reveals clear clusters aligned with **SU(3) flavor multiplets**:

  - Baryon Octet & Decuplet
  (spin-½, spin-3/2)

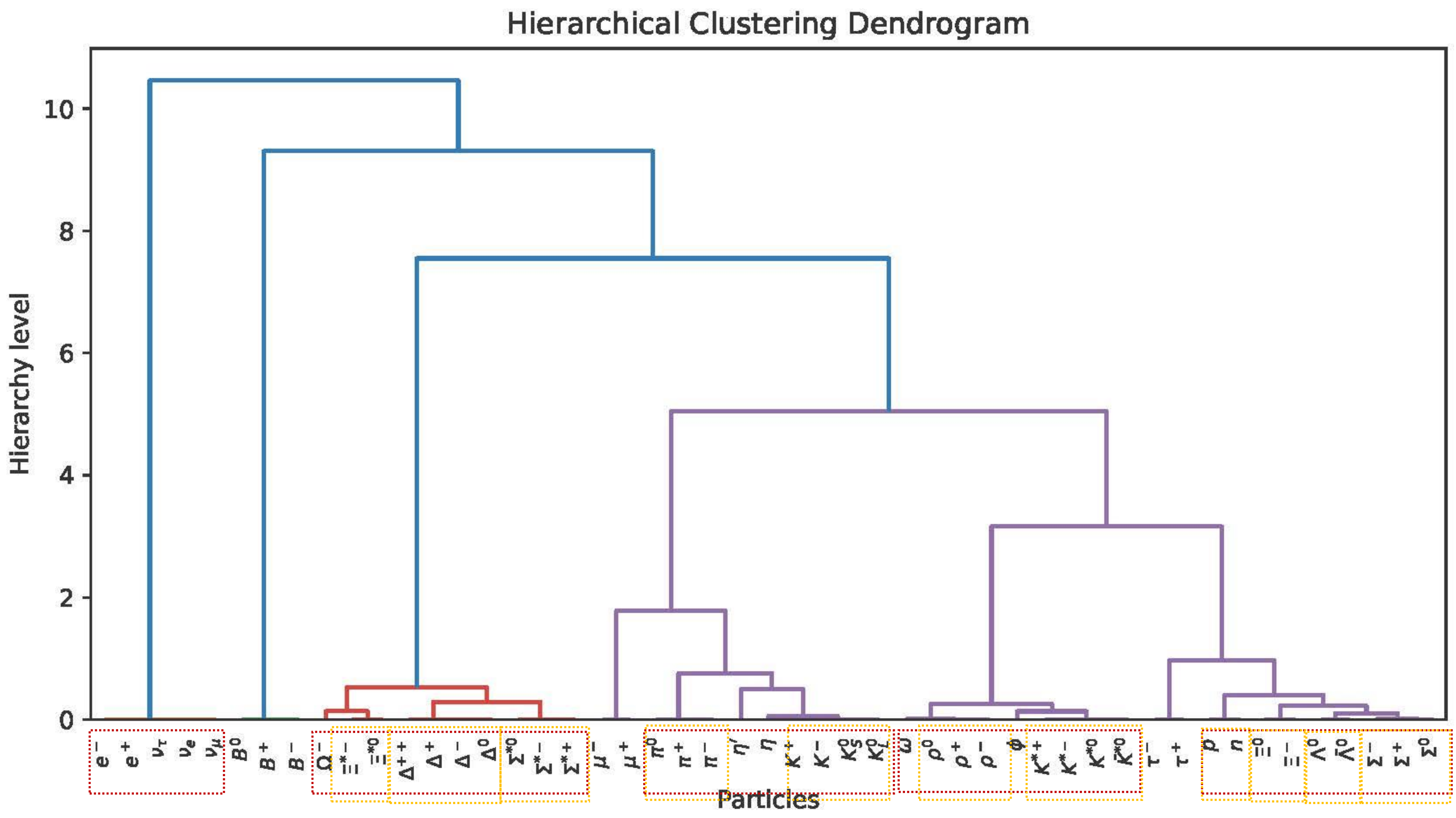
  - Meson Octet/Nonet (spin-0, spin-1)







SU(N) multiplets

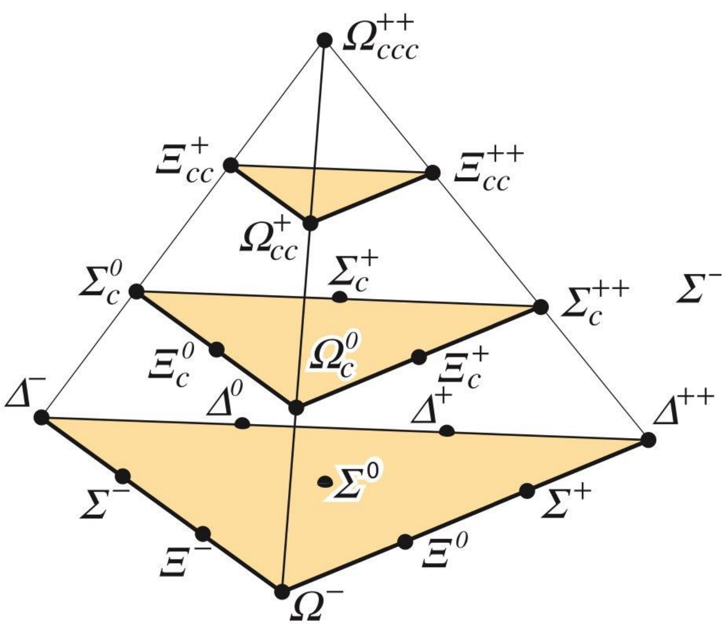


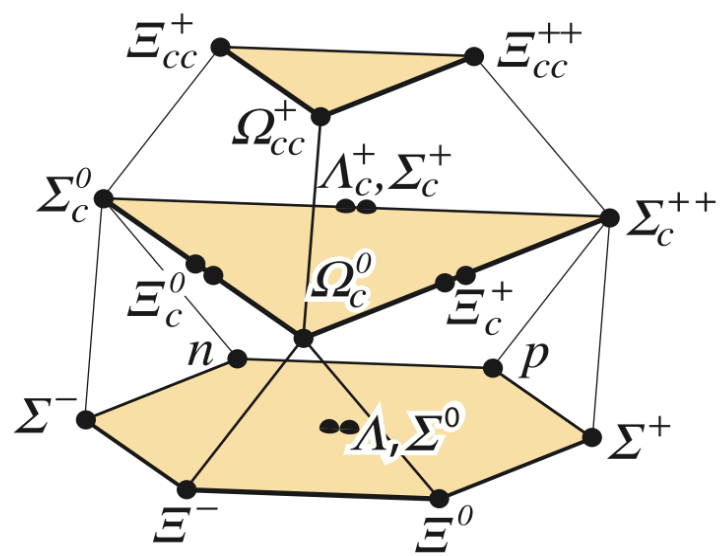
SU(3) symmetry and SU(2) isospin symmetry ----> strange quark

SU(N) multiplets

- Extending analysis to particles containing the **charm** and **bottom quarks**, we examine possible **SU(4) multiplet** structure.

- Expected decomposition [Khan 2019]:
  Baryons: $4 \otimes 4 \otimes 4 \rightarrow 20 \oplus 20 \oplus 20 \oplus 4$
  Mesons: $4 \otimes \bar{4} \rightarrow 15 \oplus 1$



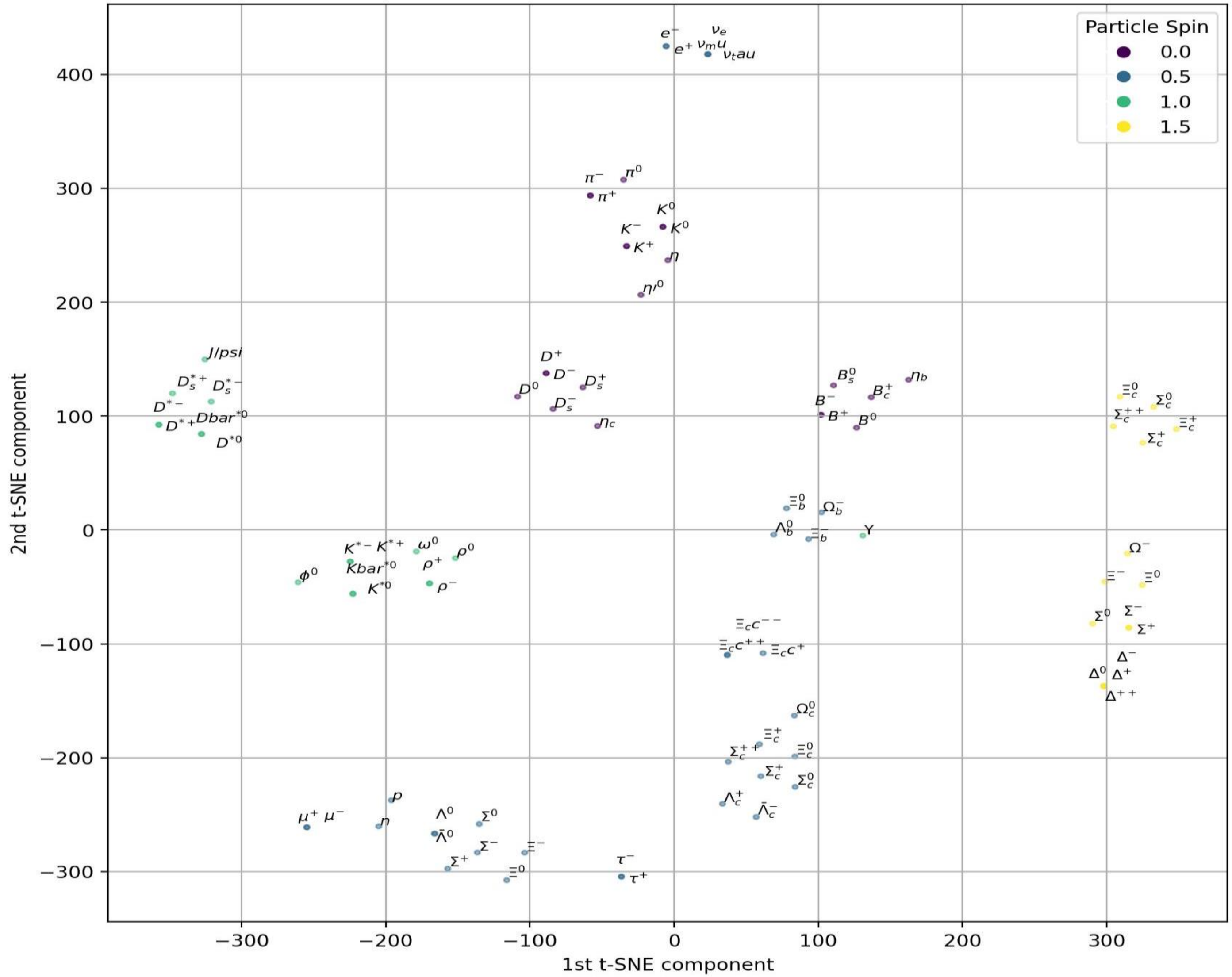


SU(N) multiplets

- Recover **SU(3)** layers within **SU(4)** structure

- Clusters involving charm tend to **group near SU(3) siblings**, reflecting **approxima te SU(4) symmetry**

- SU(4) multiplets are less sharply defined—consistent with **charm's larger mass breaking exact symmetry**.

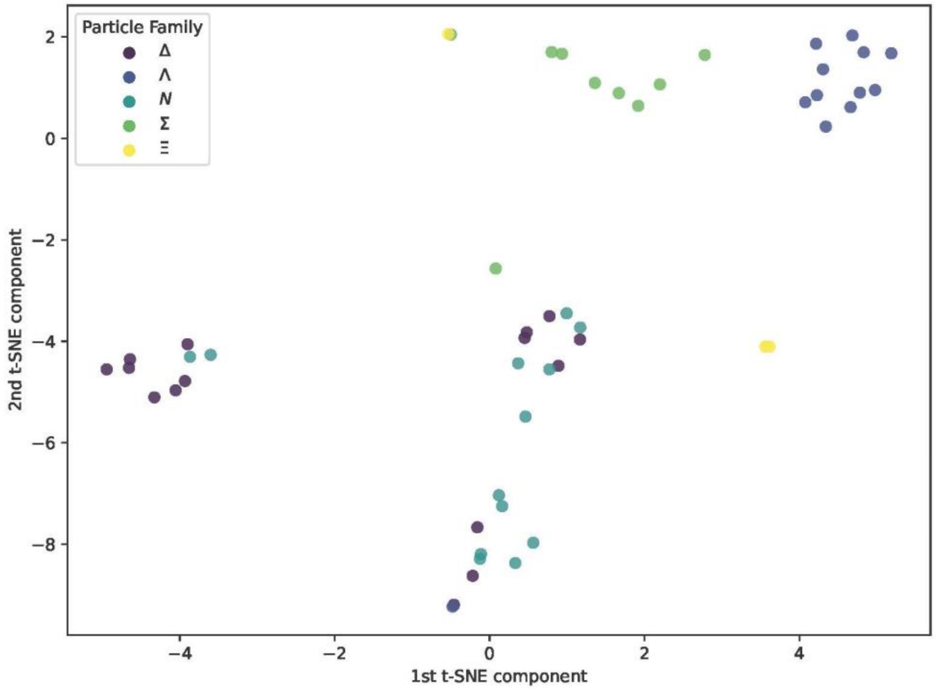


Regge trajectories

We want to study baryons excitations i.e. identify Regge trajectories using only **experimental decay data**.

Approach:
- Focus on baryons with well-measured mass, spin, and decay channels.
- Represent particles by their **decay product vectors**, weighted by branching ratios.
- Apply **unsupervised clustering** to group particles sharing dominant decay patterns.

Observations:
- Clear clustering for Lambda, Σ, and Xi baryons.
- Nucleons and Δ baryons cluster together due to similar decays (N + π) and shared quark structure.
- Ground states often lie outside clusters due to their distinct decay behavior



Regge trajectories

Post-clustering Analysis:

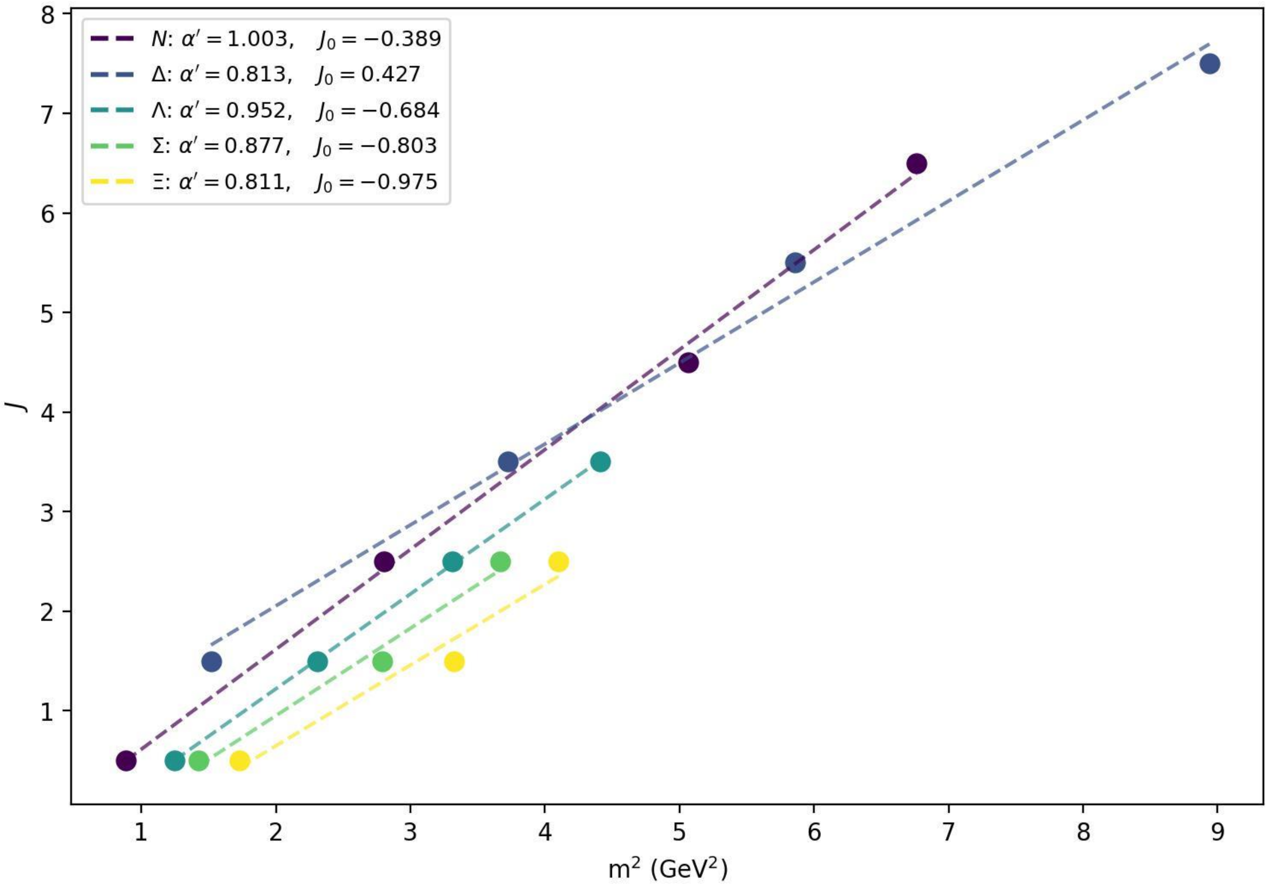
- Plot **total angular momentum J vs m²** for each cluster.
- Particles align along approximate **parabolic curves**, beginning with the ground state.:
- **Trajectory separation** improves classification
- Multiple trajectories for fixed isospin: leading vs daughter trajectories [Klempt, Metschet 2012]

Fitting Result for leading trajectories:

$$J = \alpha' m^2 + J_0$$

• Linear term negligible;

• $\alpha' \approx 0.9$ **universal** across baryon families.



Conclusions

Baryon-Meson Classification:

- Decay products alone encode sufficient structure to classify particles unsupervisedly according to their **baryon numbers**.
- PCA projections highlight the clustering of particle families based on decay similarities.

SU(N) symmetries:

- Clustering on (mass, lifetime, spin) provides the approximate **SU(2), SU(3) and SU(4) flavour** structures of the SM.
- Existence of **strange, charm and bottom quarks (and leptons).**

Regge Trajectories:

- Dimensional reduction of baryonic states via decay modes reveals groupings aligned with known **Regge families**.
- Regge plots and fit show parabolic trajectories starting from the ground state and **universal slope** across different baryon families, consistent with Regge theory expectations.

Outlooks:

- Quark structure.
- Exotic states and anomalies (e.g., tetraquarks, pentaquarks).
- Insights into BSM candidates.

Thank you