Hadron Spectroscopy

Lecture 3 – Light Quark Spectroscopy

HUGS - June 2, 2025

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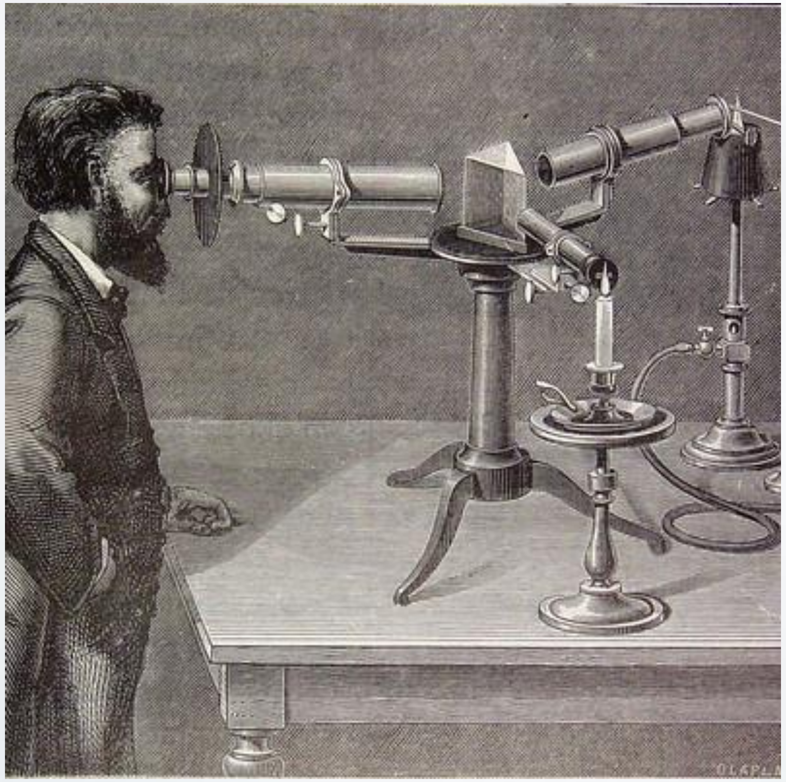
U.S. DEPARTMENT OF ENERGY

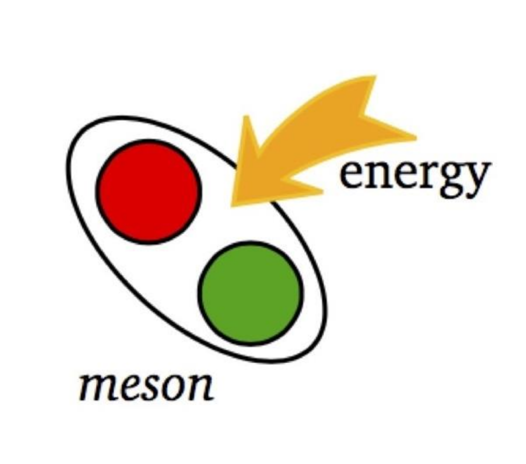
Outline

1. Production and Detection of Excited Hadrons
2. Identification of Excited Hadrons
3. Brief History of Exotic Mesons

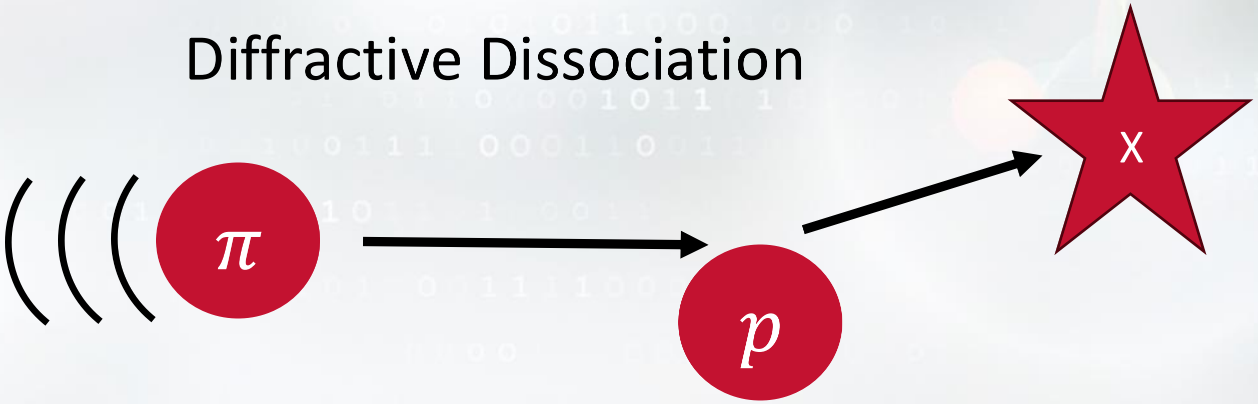
Production and Detection



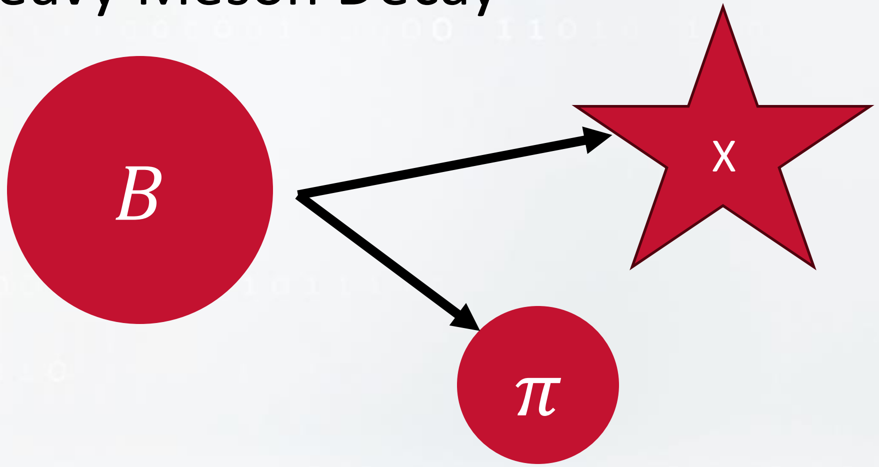
Production Mechanisms for Excited Mesons



Diffractive Dissociation

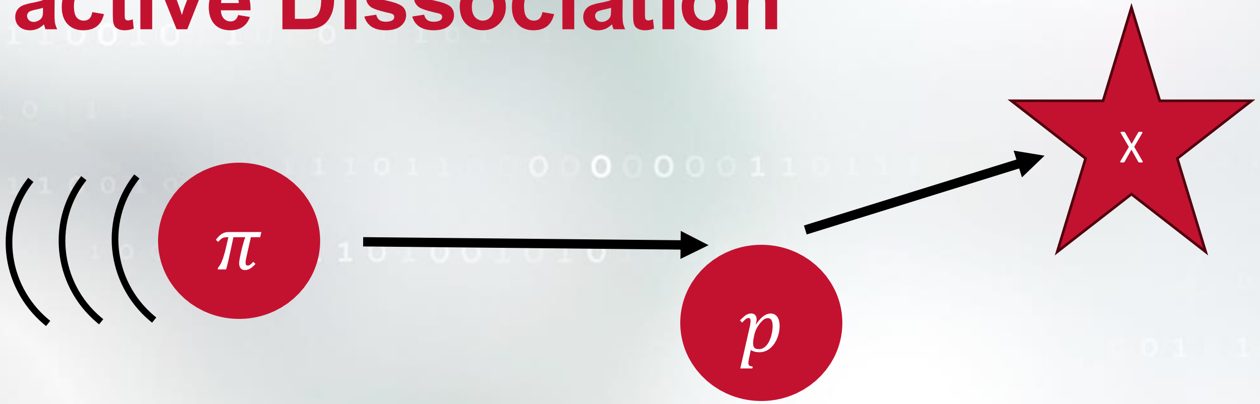


Heavy Meson Decay



Annihilation

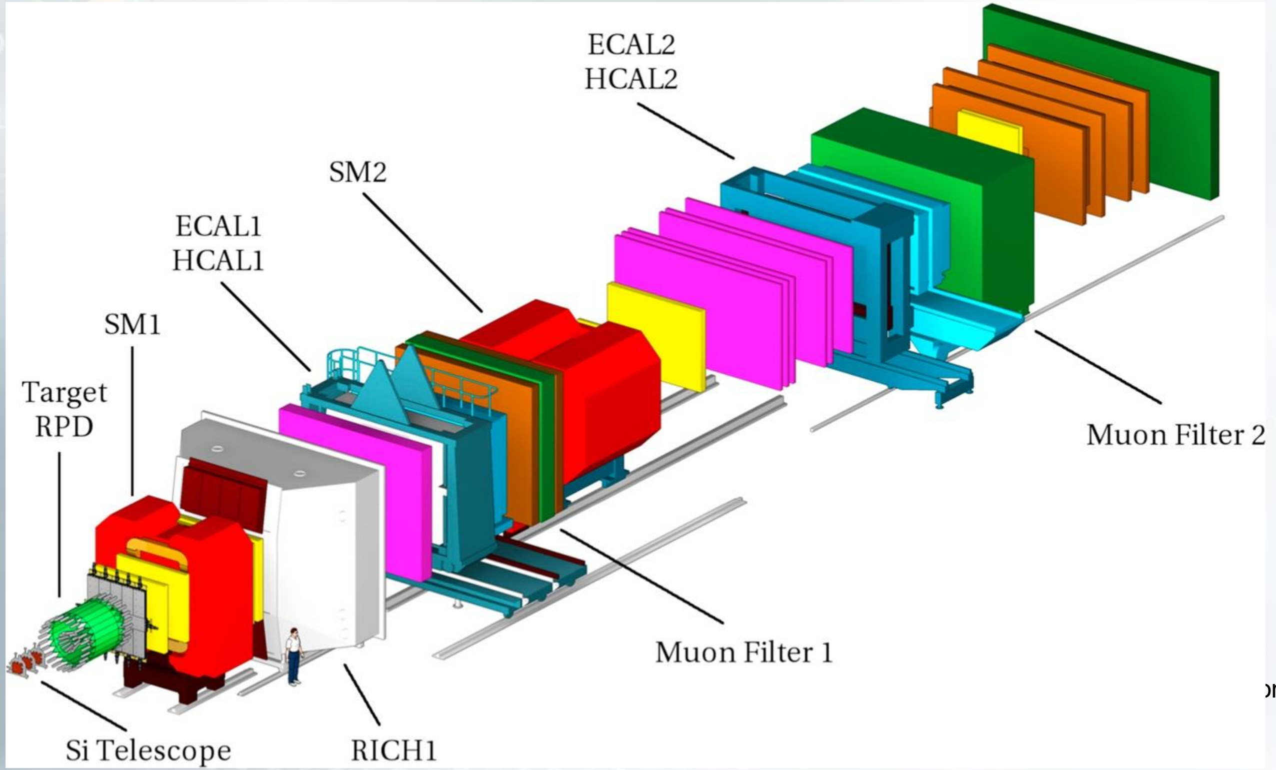
Diffractive Dissociation

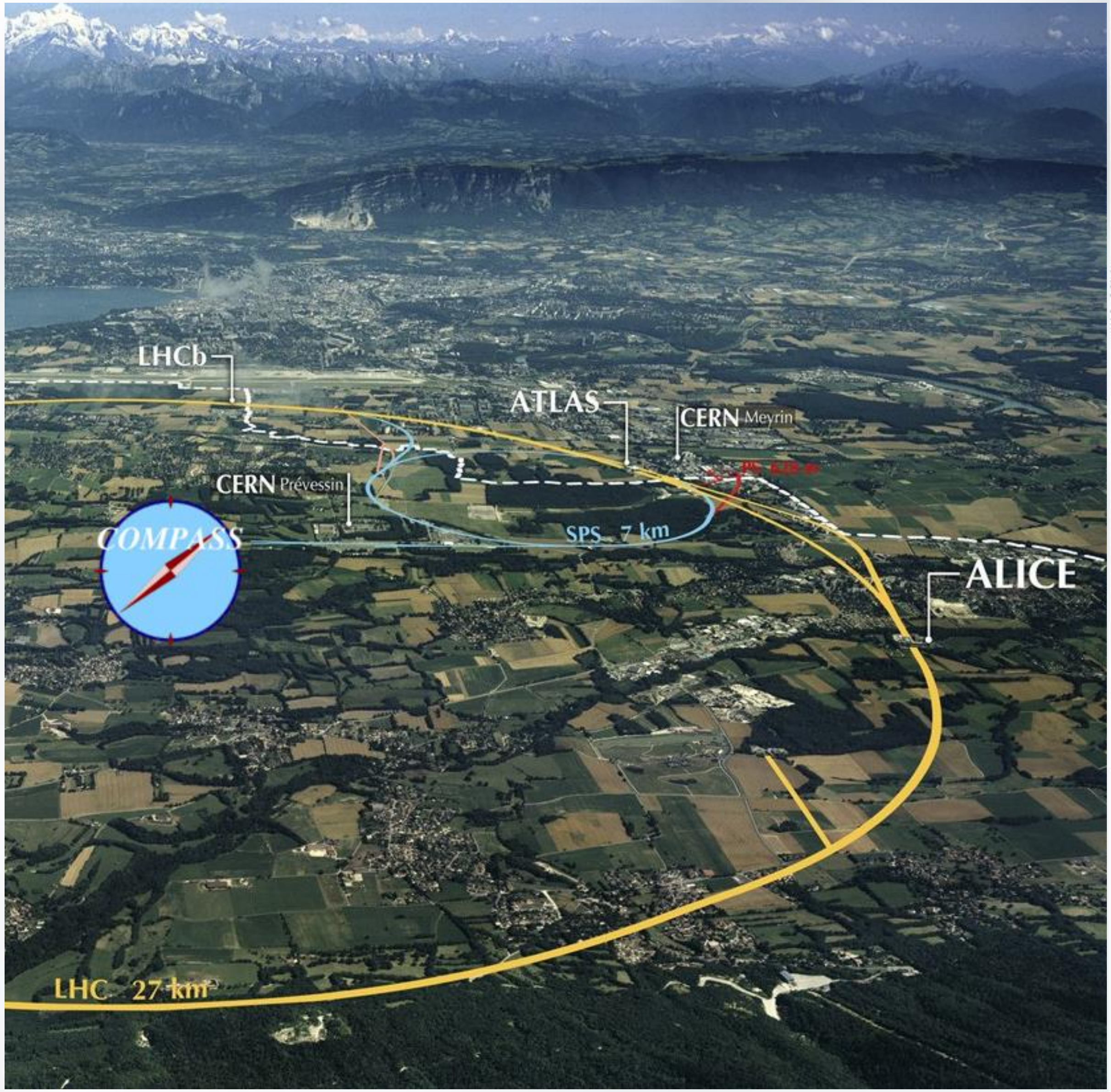


- Historically the most common production mechanism in hadron spectroscopy
- Wide energy range with different particle accelerators:
  E852 experiment at BNL: 18 GeV pion beam
  VES at Protvino: 37 GeV pion beam
  COMPASS experiment at SPS (CERN): 190 GeV hadron beam (pion, kaon, proton)
- Different targets: Hydrogen (p), Solid targets (Be, Pb)
- Target stays intact, beam particle is excited
  → X conserves quantum numbers of beam particle

COMPASS Experiment

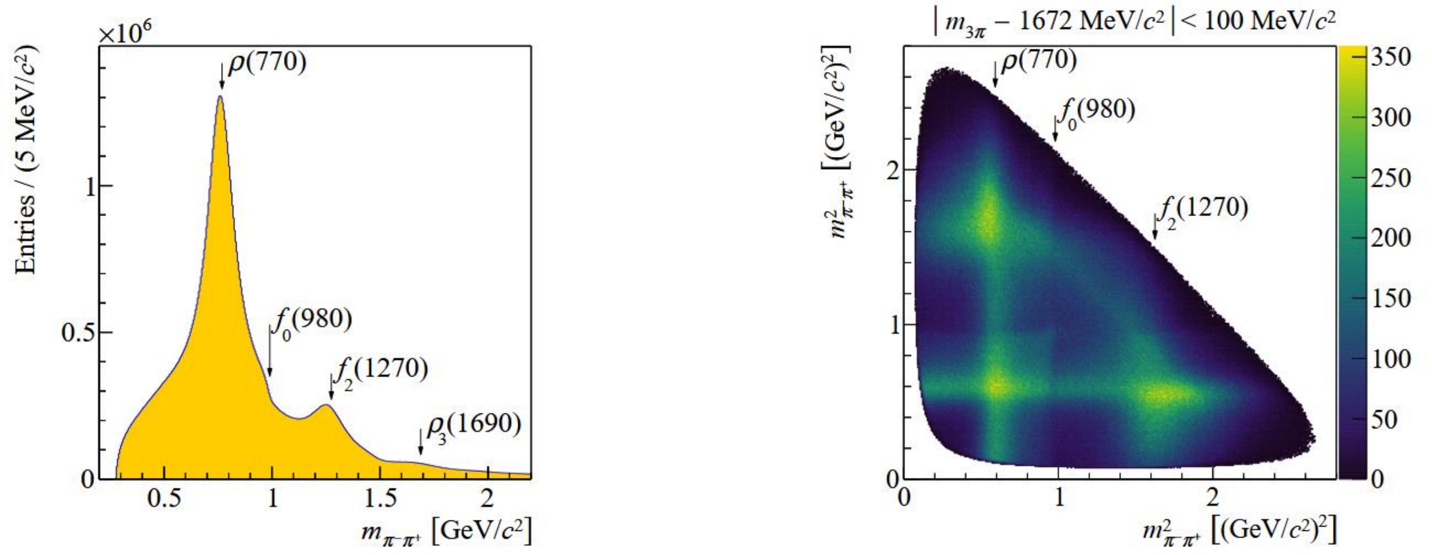
- Data taking between 2004-2022
- Fixed target experiment at CERN SPS
- Hadron beam (190GeV), muon beam (160GeV)
- Continued effort by: AMBER Apparatus for Meson and Baryon Experimental Research

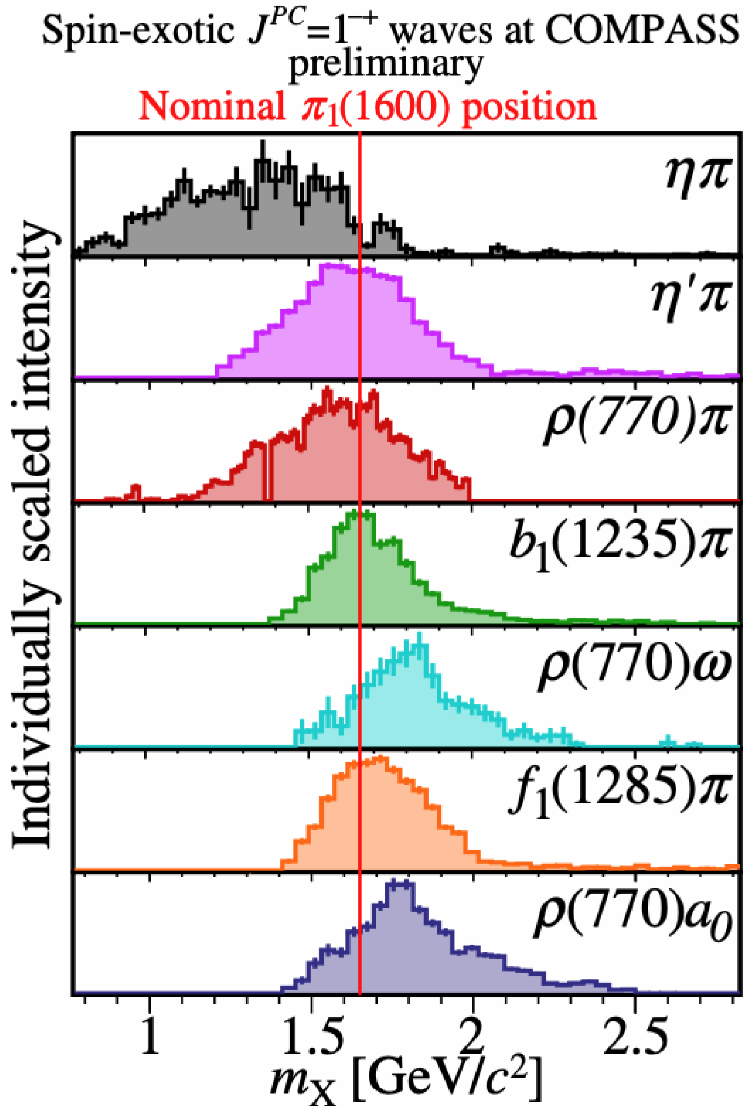




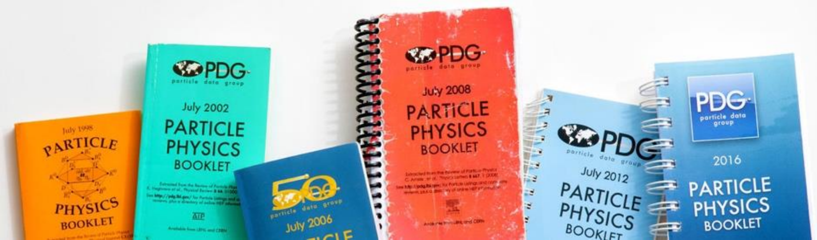
COMPASS Experiment

- Dedicated spectroscopy dataset recorded in 2008/2009
- High statistical precision: development of new analysis methods

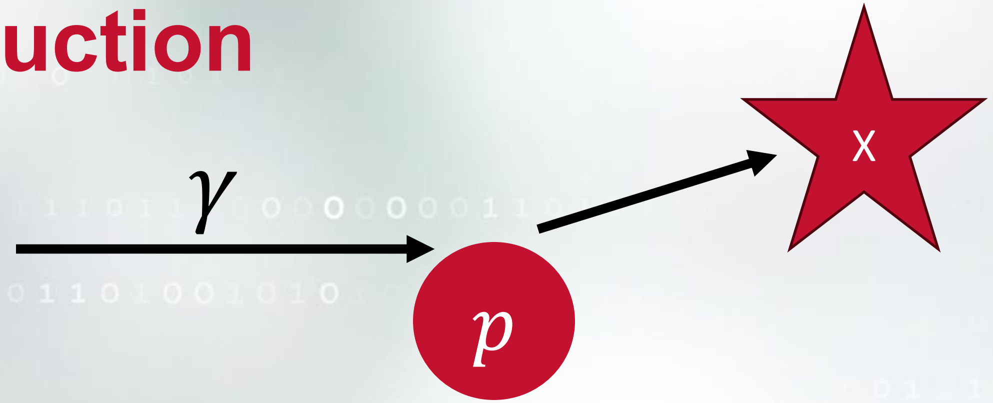




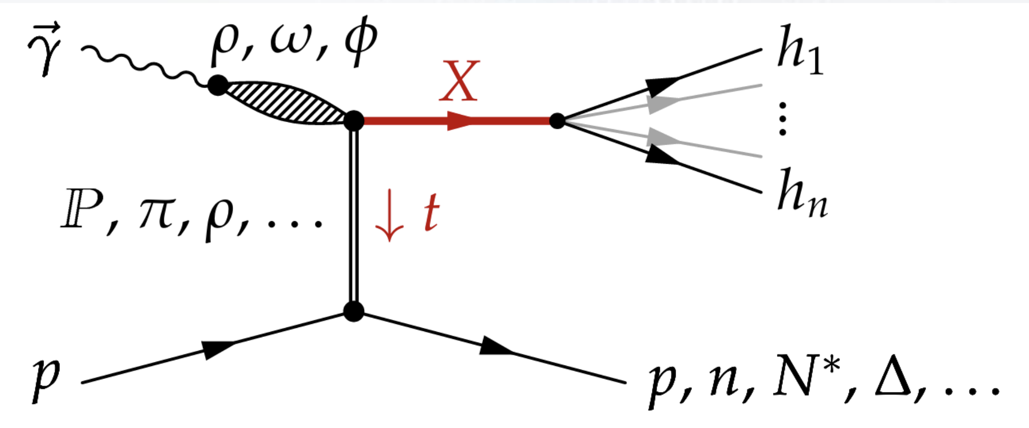
- Access to multiple final states
- Analysis for some final states complete, others still ongoing
- Many new or revised entries in the PDG



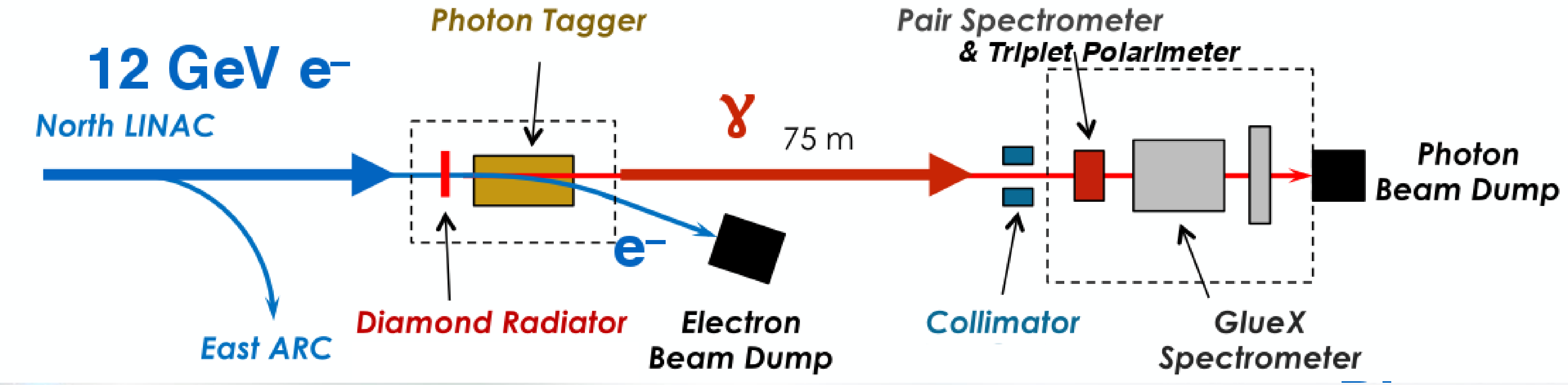
Photoproduction

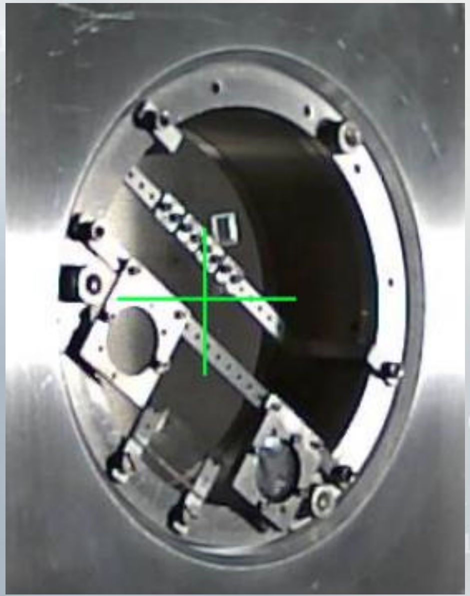


- Production mechanism complementary to diffractive dissociation
- Photon $J^P = 1^-$ acts like a ρ, ω, ϕ meson: "Vector Meson Dominance"
- Linear polarization of photon provides additional constraints
- Very limited photoproduction data existing
- Excited states with wide variety of quantum numbers accessible

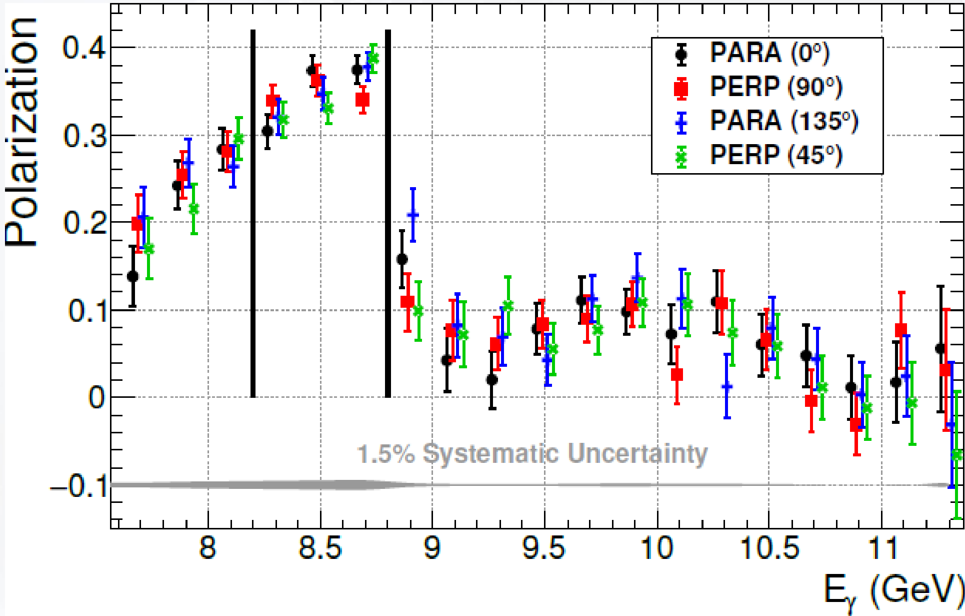


Photon Beam in Hall D at Jefferson Lab





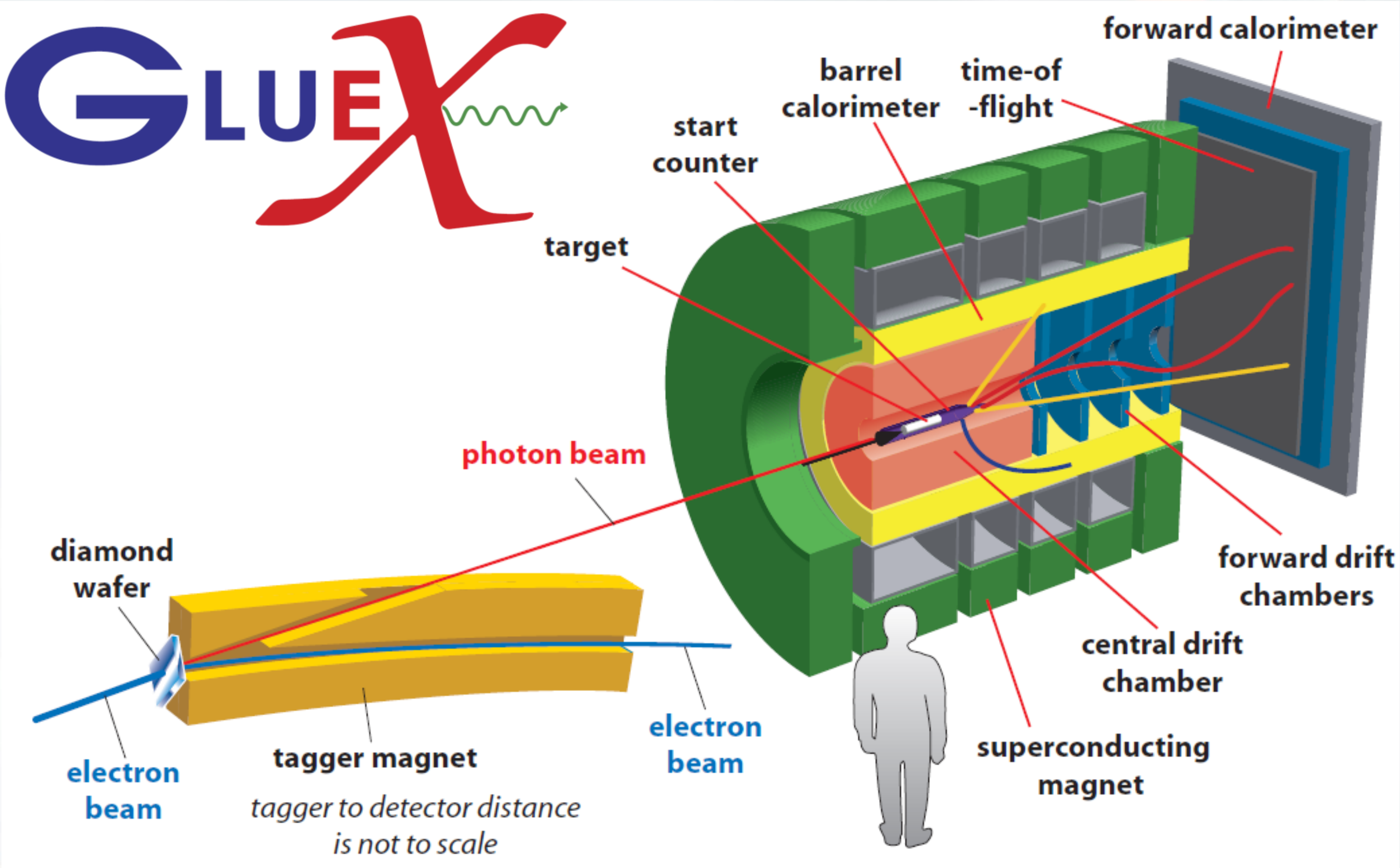
- Coherent Bremsstrahlung on thin diamond radiator
- Collimator suppresses incoherent part
- Linear Polarization up to 40%
- Rotate polarization into 4 orientations
- Beam intensity: up to $5 \times 10^7\ \gamma/\text{s}$ in peak



GlueX Experiment

- Designed for Light Meson Spectroscopy
- Nearly complete acceptance for charged and neutral particles
- Data taking since 2017

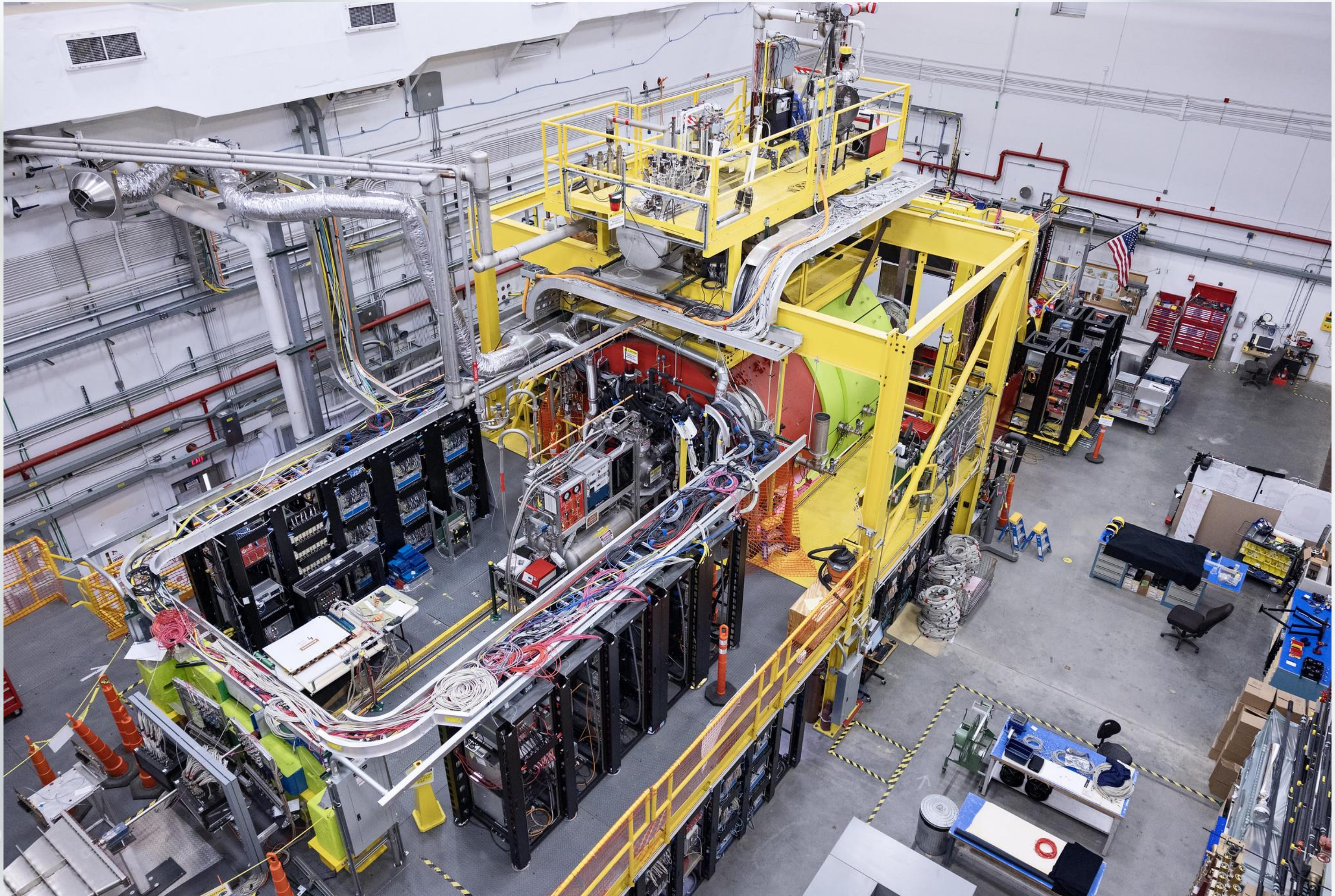
Phase	Years	Luminosity (pb^{-1})	Status
1	2017-2018	125	Results Published Analyzing
2	2020-2026	500?	Data Taking Ongoing
3	?		Proposed



GlueX Experiment

Jefferson Lab

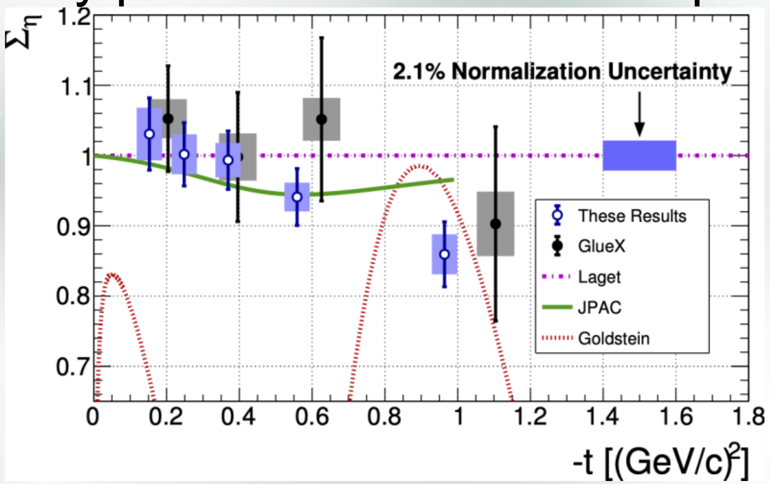
Did you spot our extraterrestrial mascot?

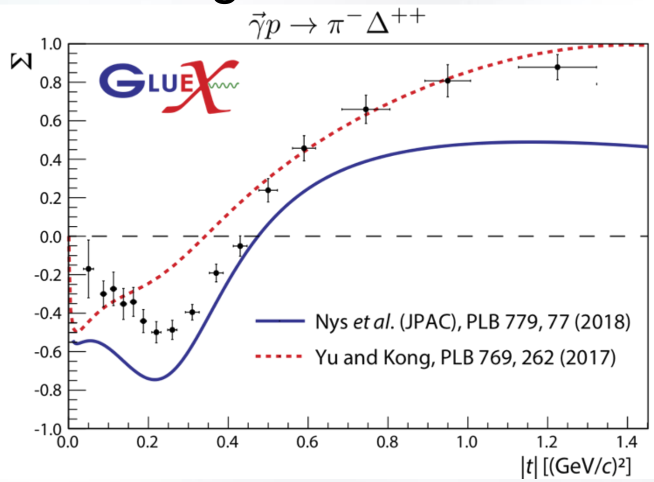


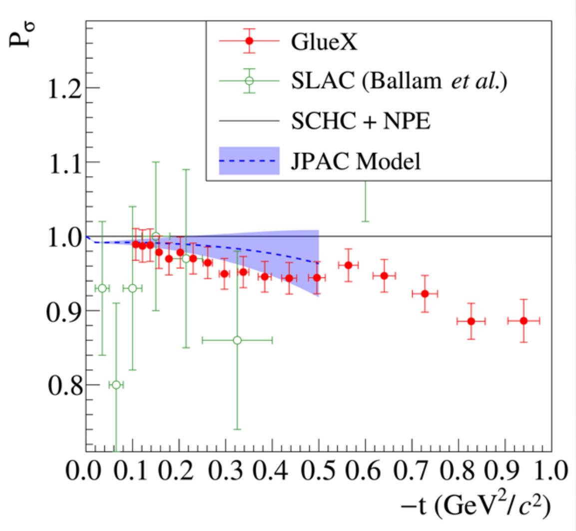
GlueX Experiment

Jefferson Lab

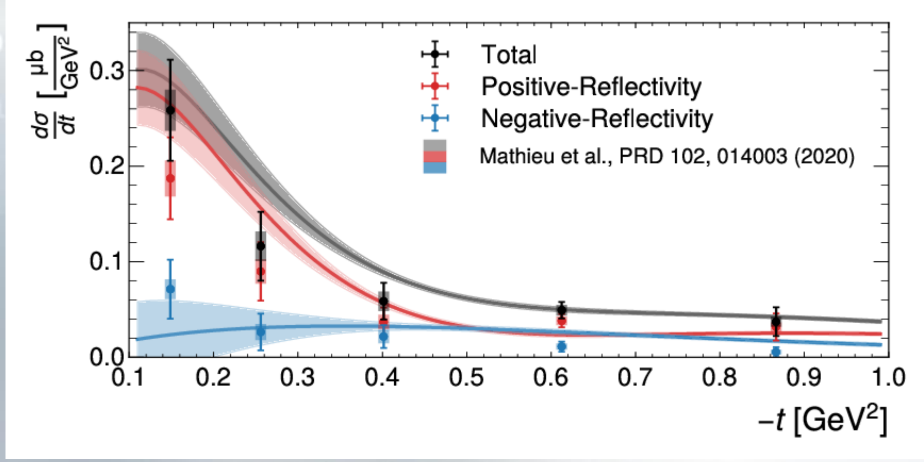
- Many published results on the production of ground state mesons: $\pi, \eta, \eta', \rho^0(770)$, ...

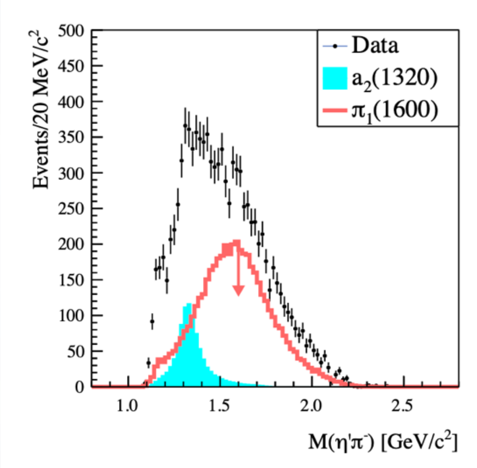


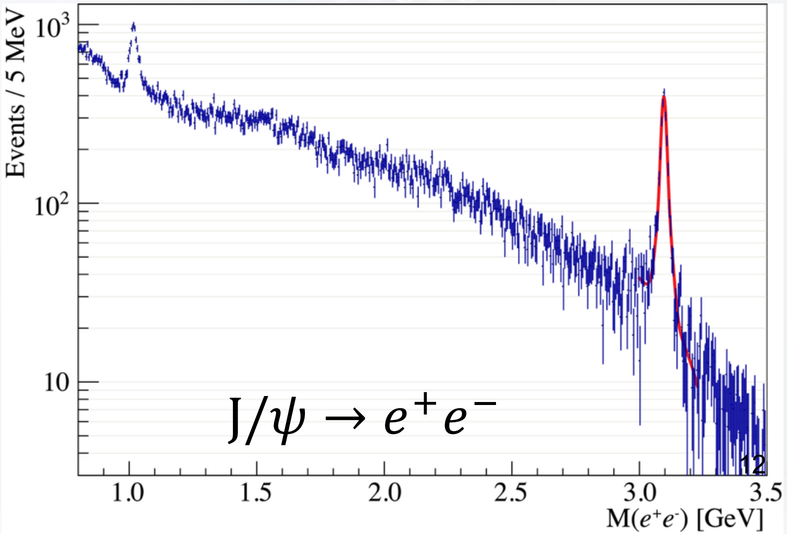




- First results on excited mesons and searches for exotic states:
  $a_2(1320)$ cross section from $\eta\pi$, upper limit on exotic states from $\omega\pi\pi$, ...



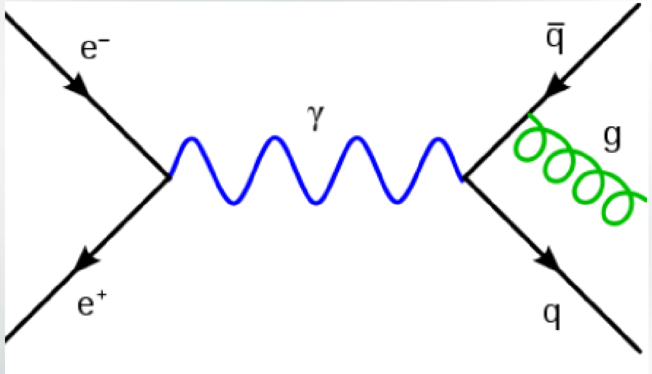




- First detection of charmonium at Jefferson Lab

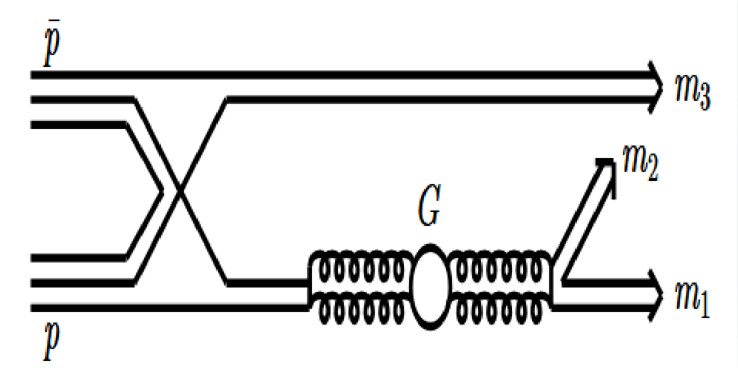
Annihilation

- A wealth of recent data comes from $\boldsymbol{e^+e^-}$ **collider experiments**: BES, Belle, Babar (B-factories)
- Energies of e^+ and e^- do not have to be symmetric
- e^+e^- annihilation is electro-magnetic process: via photon exchange



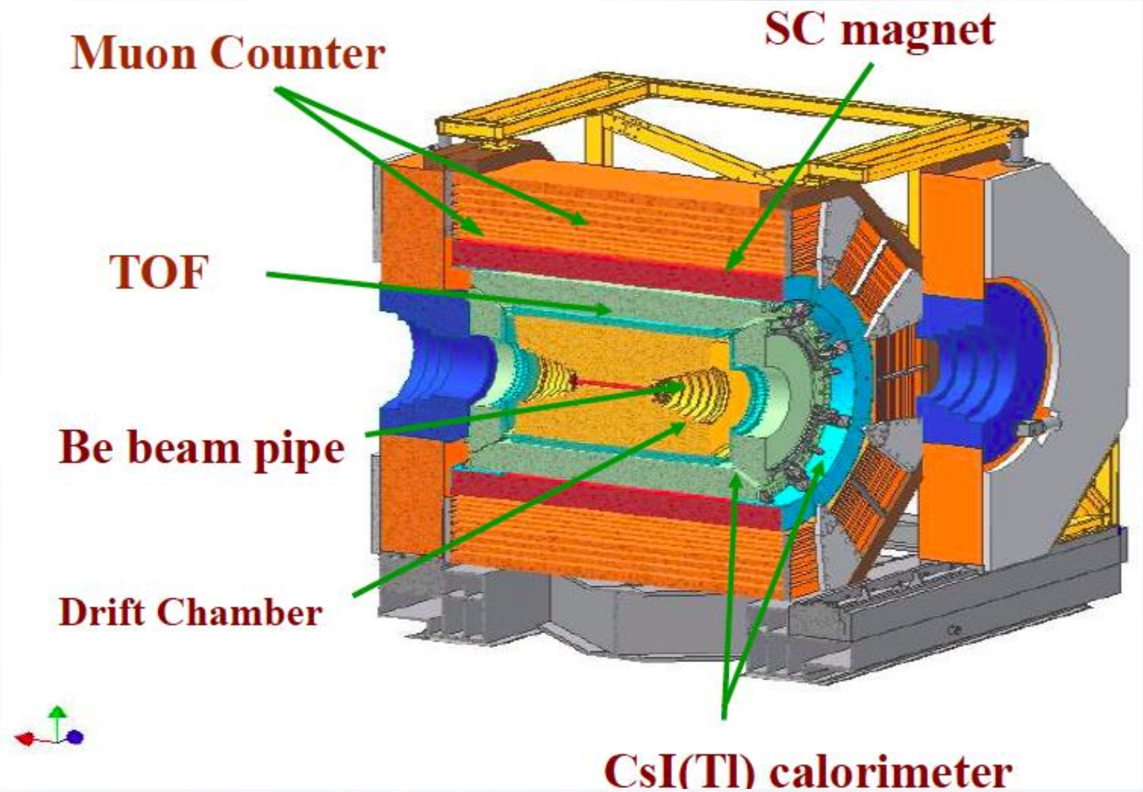
→ Produced system has quantum numbers of photon

- **Antiproton beams** were also used to study hadron spectroscopy: Crystal Barrel at LEAR (CERN), 1989 - 1996
- Will 3 quarks annihilate with 3 antiquarks or are quarks merely rearranged?

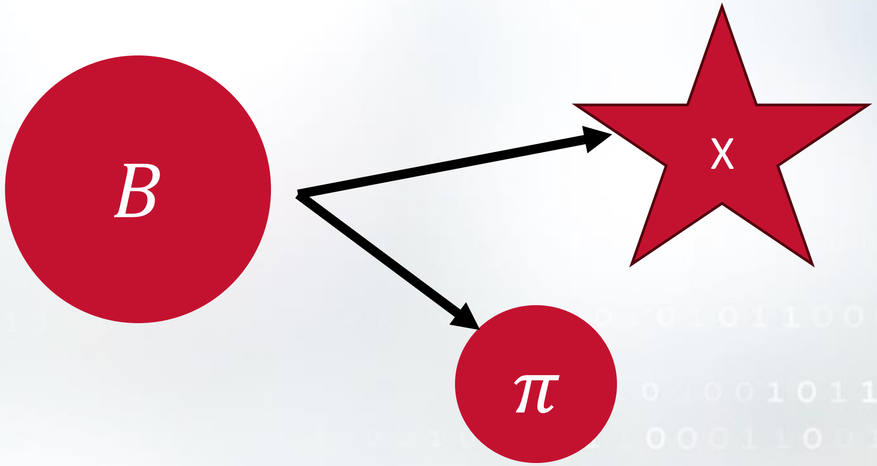


BES-III

- BEPC-II at IHEP (Beijing, China)
- e^+e^- collisions between 2.0 and 4.9 GeV
- Detectors for charged particles, photons and particle identification
- Started taking data in 2008



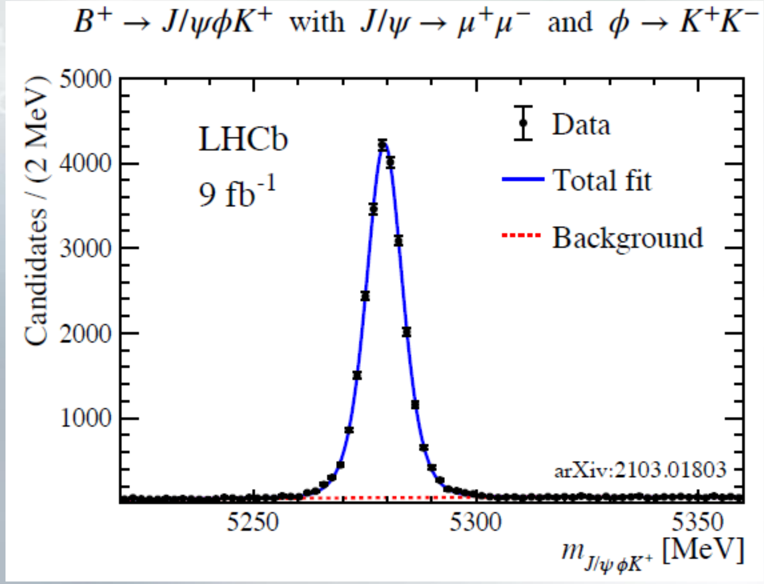
Heavy Meson Decays

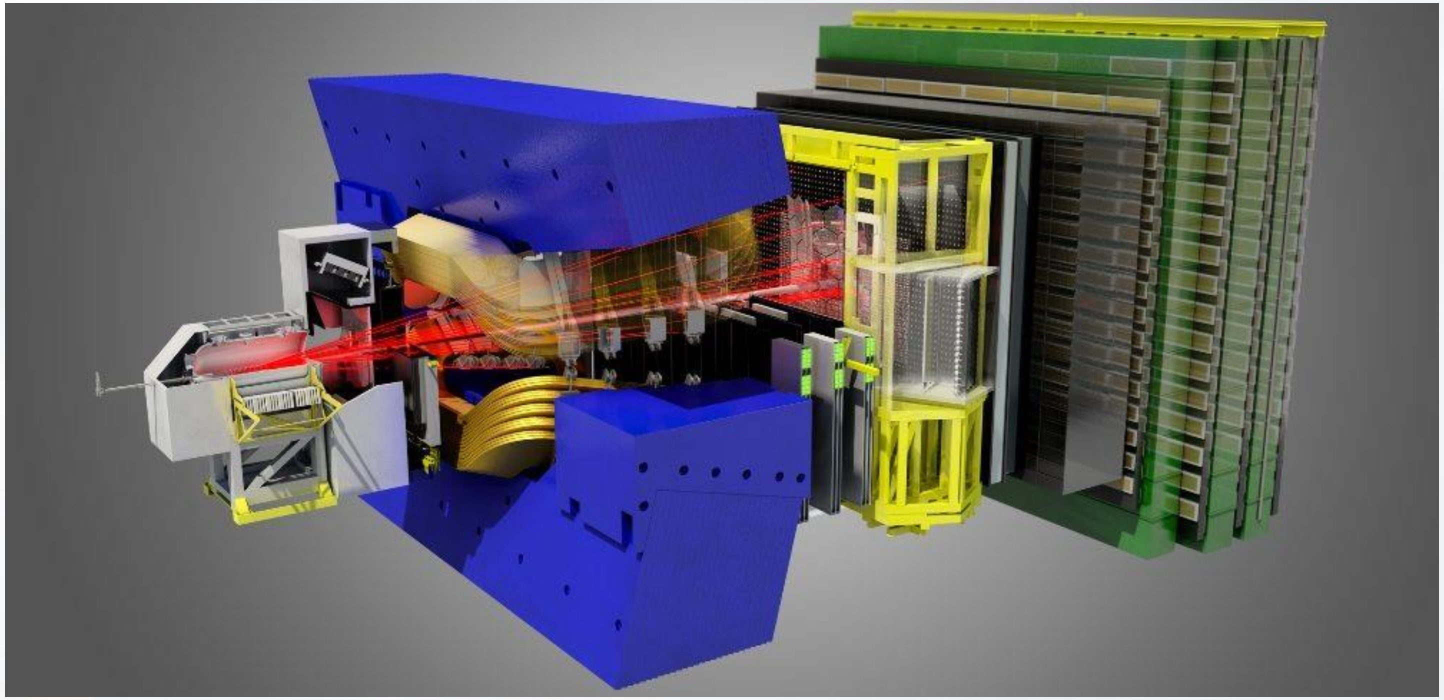


- Production of heavy mesons in e^+e^- annihilation or hadron-hadron collisions
- $D\bar{D}$ or $B\bar{B}$ pairs copiously produced for energies above the $c\bar{c}$ / $b\bar{b}$ threshold
- Tag one meson → clean signal (CP violation experiments)
- Well defined initial state with known quantum numbers
  → study subsystems of decay products
  → multi-particle dynamics

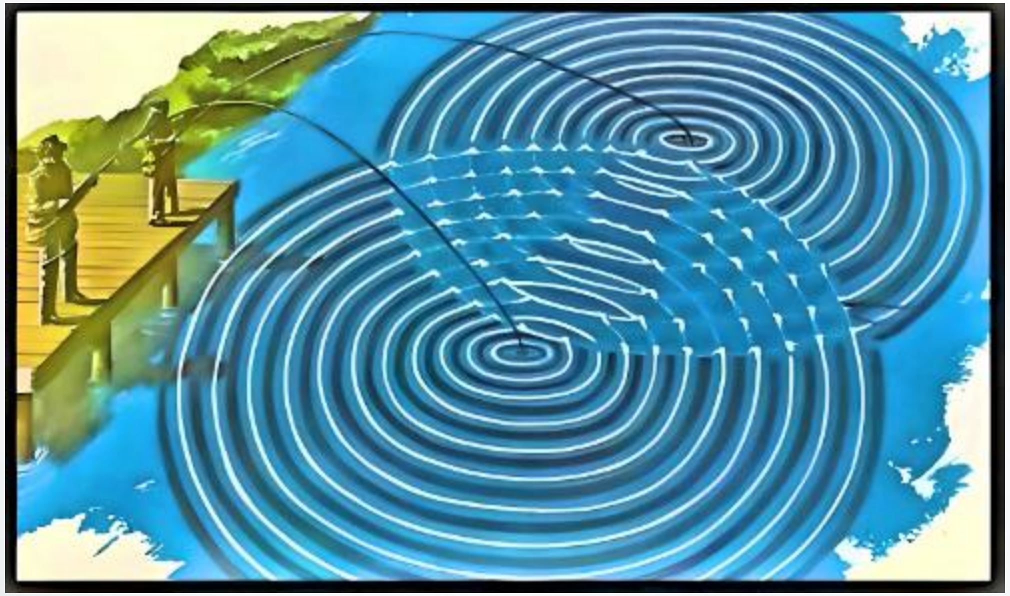
LHCb

- Experiment at Large Hadron Collider at CERN
- Proton-Proton collisions between 7 and 14 TeV
- Clean identification of B decays with displaced vertex
- Reconstruction with light mesons in the final state

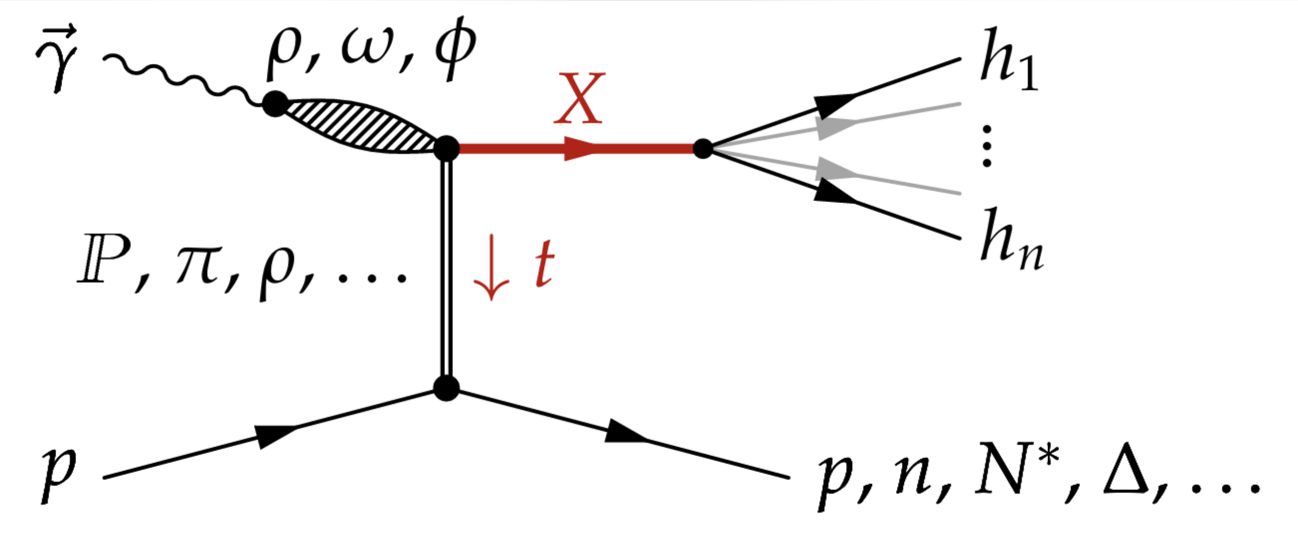




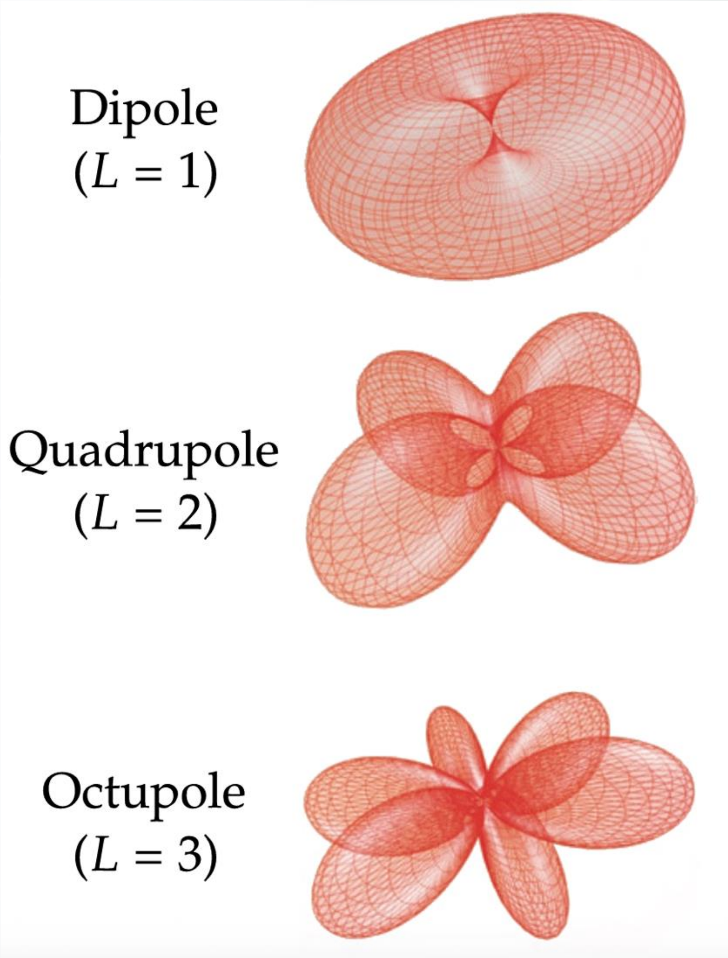
Identification of Excited Hadrons



Amplitude Analysis

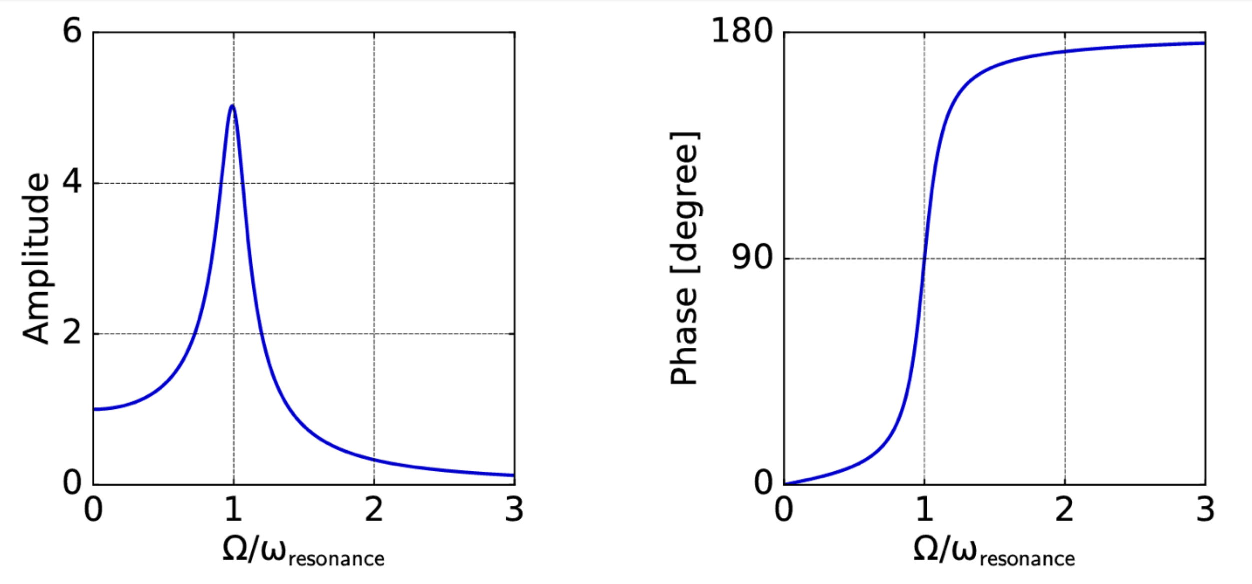


- Use full kinematic information of measured final-state particles
- $|J^P M >$ state of X uniquely determines angular distribution of daughter particles $h_{1\ldots n}$
- Decompose measured distribution into complex-valued, orthogonal amplitudes
- Remember:
  Multipole expansion in classical electro-dynamics

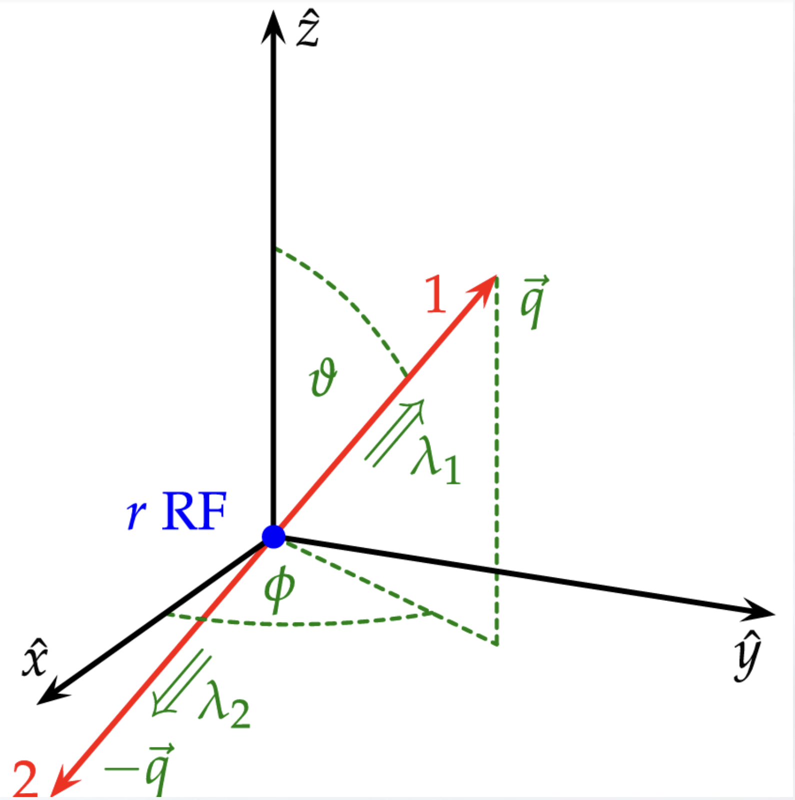


Interference

- Multiple processes with same initial state and same final state
  Intermediate states may interfere
- Simple example: interference of 2 complex-valued amplitudes
  $r_1 = 1$ and $r_2 = 0.1$
  $$P \propto \left| r_1 e^{i\phi_1} + r_2 e^{i\phi_2} \right|^2 = r_1^2 + r_2^2 + 2 r_1 r_2 \cos(\Delta\phi_{12})$$
  $2 r_1 r_2 (= 0.2) \gg r_2^2\ (= 0.01)$
  Increased sensitivity for small signals!
- Interference allows us to measure relative phases $\Delta\phi_{12}$
  additional information in phase shift as a function of mass



Decay Amplitudes

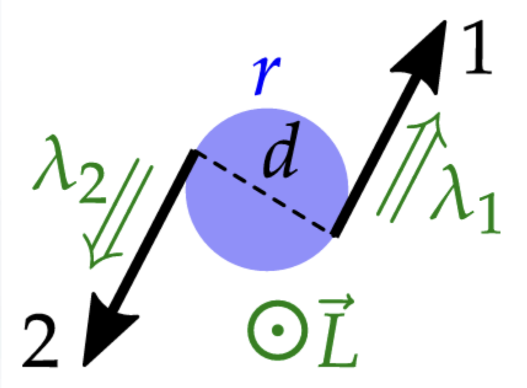


Decay of Particle r into daughters 1 and 2 in its rest frame (RF)

- Spin state of r is $|\, J, M >$ in relevant coordinate system
- Spin states $|\, J_{1,2}, M_{1,2} >$ of daughter particles in helicity basis
- Relative orbital angular momentum L between daughters
- Total spin of decay system: $\vec{S} = \vec{S}_1 \oplus \vec{S}_2$
- Angular distribution defined by decay amplitude:

$$\Psi^{JMLS}_{r\to 1,2}(\vartheta,\phi) \propto \sum_{\lambda_1\lambda_2} \underbrace{< J_1\lambda_1, J_2\, {-\lambda_2} \,|\, S\,\lambda >}_{\text{Spin-Spin coupling}} \underbrace{< L\,0, S\,\lambda \,|\, J\,\lambda >}_{L-S \text{ coupling}} \underbrace{D^{J*}_{M\lambda}(\phi,\vartheta,0)}_{\text{Wigner D function}}$$

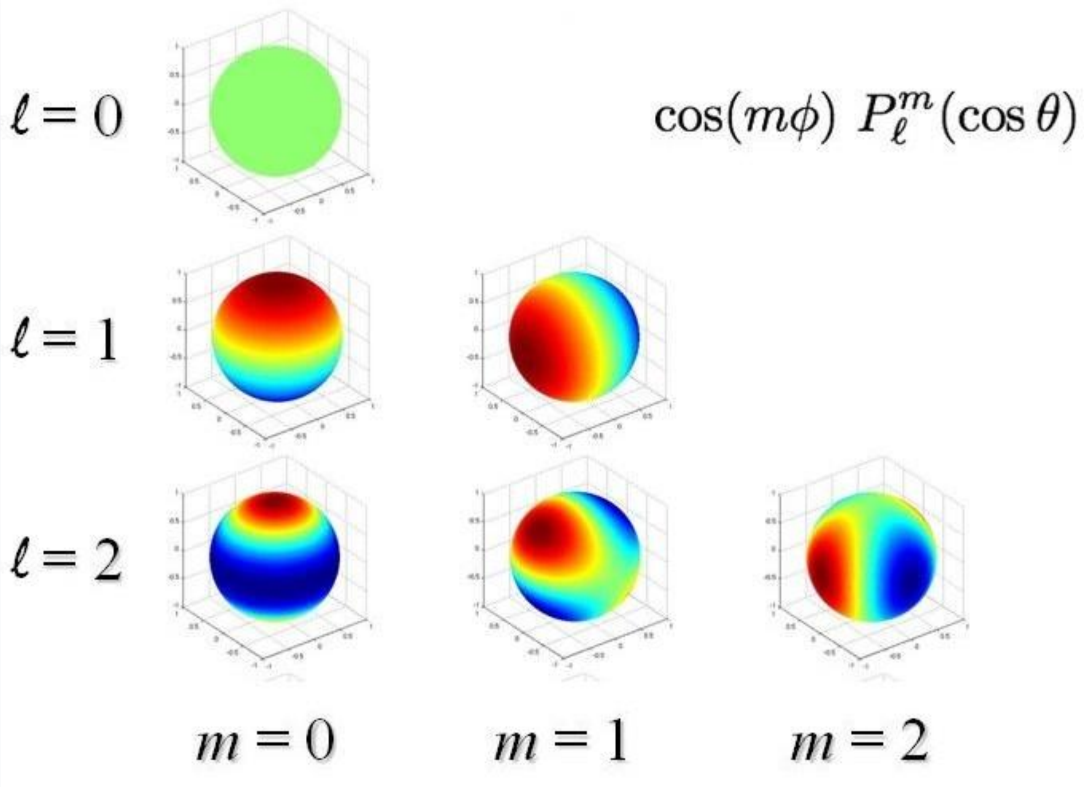
- Decay amplitude completely defined by J, M, L and S



Decay Amplitudes

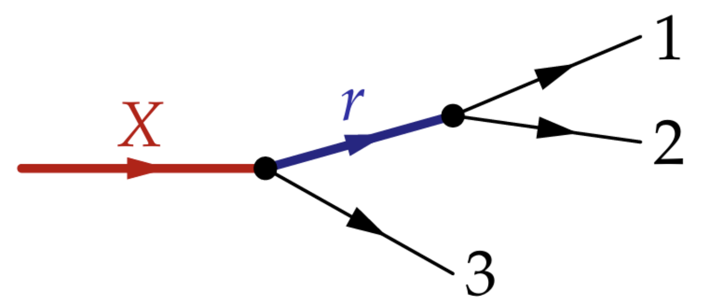
Example: Decay into 2 pseudoscalar mesons (e.g. pions)

- $J_{1,2} = 0$, so $\lambda_{1,2} = 0$
- Simplify Clebsch-Gordon coefficients:
  $< 0\;0, 0\;0 \,|\, S\;\lambda > = \delta_{S0}\delta_{\lambda 0}$, $< L\;0, 0\;0 \,|\, J\;0 > = \delta_{LJ}$
- Wigner D-function: spherical harmonics
  $\delta_{S0}\delta_{\lambda 0}\delta_{LJ}\; D^{J}_{M\lambda}(\phi, \vartheta, 0) = \sqrt{\frac{4\pi}{2L+1}}\; Y^{M}_{L}(\vartheta, \phi)$



Multibody decays:

- Model as cascade of 2-body decays
- Multiply decay amplitudes recursively



How to measure Amplitudes?

- Fermi's Golden Rule: $\gamma + p \to X + p$ and $X \to h_1 + \cdots + h_n$

$$d\sigma = \frac{1}{f} \underbrace{|M(s,t,m_X,\vec{\tau})|^2}_{\text{Matrix Element}} \underbrace{dLIPS_{n+1}(s,t,m_X,\vec{\tau})}_{\text{Lorentz-invariant phase-space element}}$$

- f: flux, s, t: Mandelstam variables, m_X: invariant mass, τ: variables to define the $h_1, \ldots, h_n$ system
- Intensity $I \propto |M|^2$: number density of events that a perfect detector would measure

- Parametrize intensity as coherent sum of amplitudes:

$$I(m_X, t, \vec{\tau}) \propto \left| \sum_a \mathrm{T}_a \Psi_a(\tau) \right|^2$$

- Complex valued decay amplitudes Ψ describe angular distribution of decay
- Complex production coefficient T, constant in narrow kinematic bin (mass, momentum transfer)

Extended Unbinned Maximum Likelihood

- Probability to observe event i with intensity model I in the experiment with acceptance η_i:

$$P_i = \frac{I_i \eta_i}{\int d\Omega\, I\eta} \approx \frac{I_i \eta_i}{\bar{N}}$$

- The total number of observed events N in an experiment of fixed duration follows the Poisson distribution with expectation value $\bar{N}$.
- Extended Likelihood Function

$$L = \frac{e^{-\bar{N}} \bar{N}^N}{N!} \prod_{i=1}^{N} P_i \approx \frac{e^{-\bar{N}}}{N!} \prod_{i=1}^{N} I_i \eta_i$$

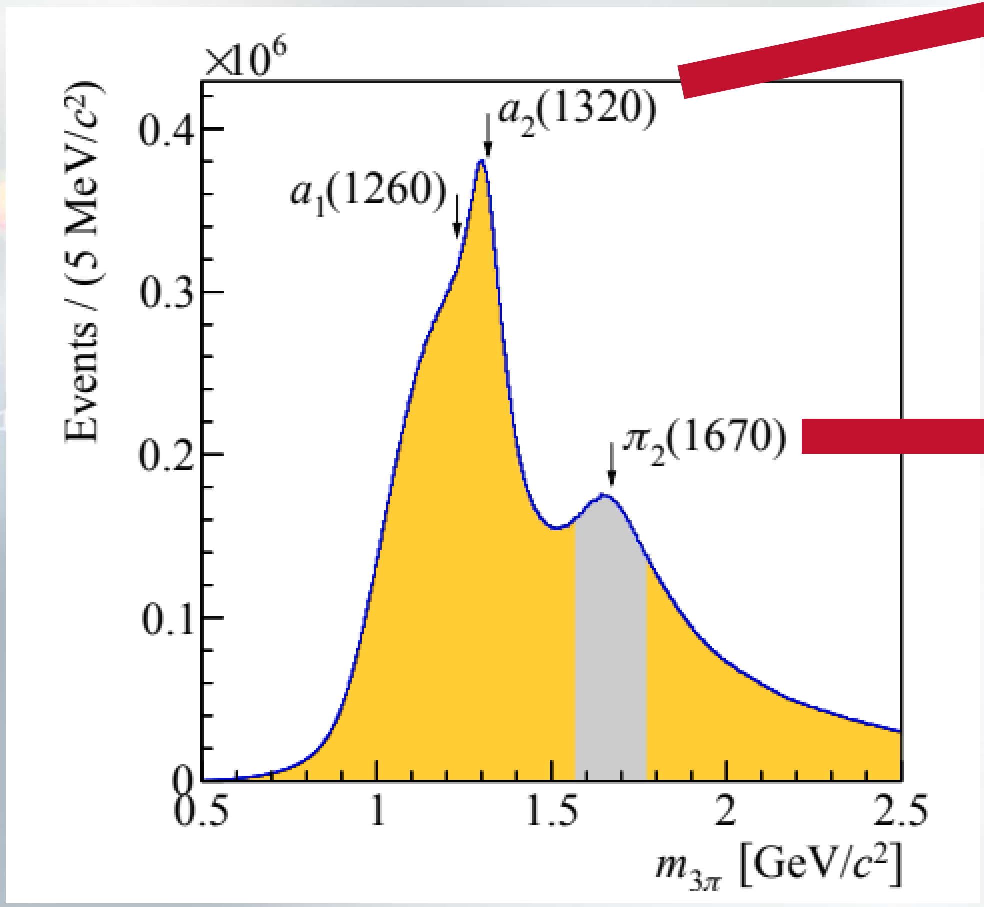
- Take logarithm as sums are computationally easier to handle, omit terms that are independent of the measured events:

$$\ln L = \sum_{i=1}^{N} \ln I_i - \int d\Omega\, I\, \eta$$

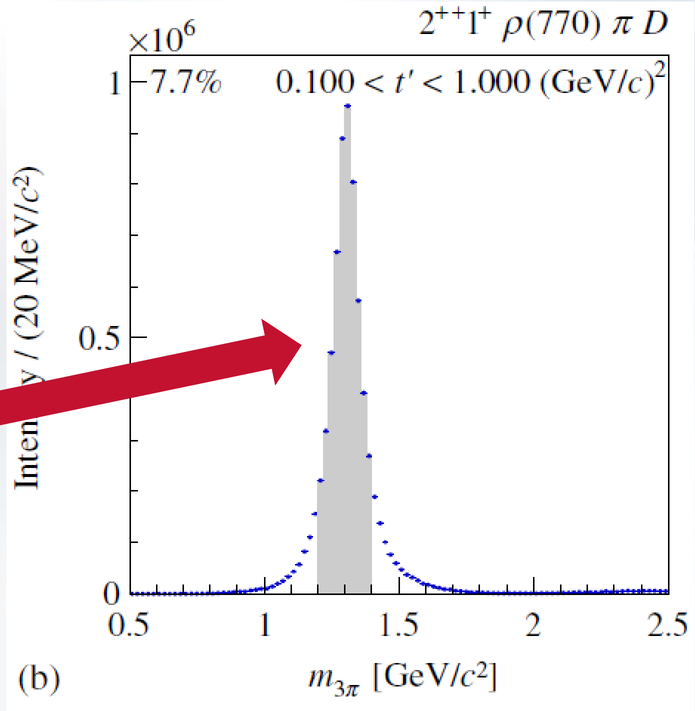
- Normalization integral evaluated by Monte Carlo simulation with unbinned acceptance $\eta = 0/1$
- Maximize by varying complex-valued fit parameters until model fits measured distribution

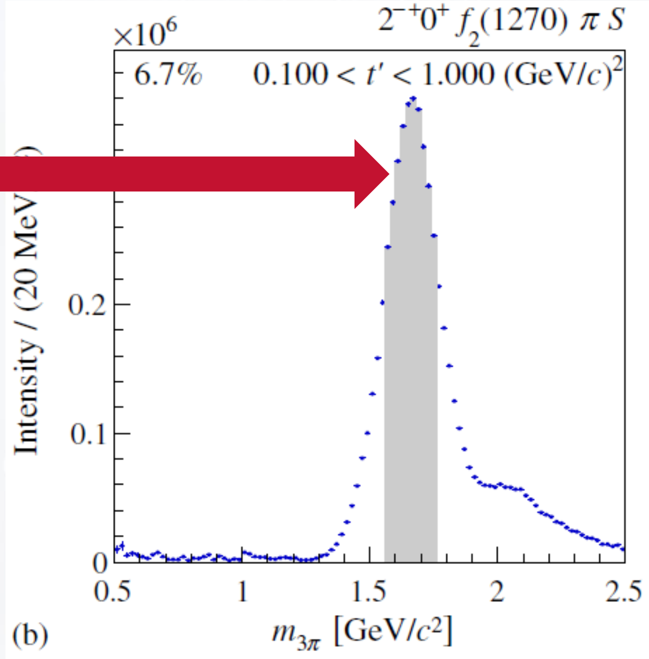
Example:

- Large data set with high precision
- Good understanding of experimental acceptance
- Optimized model



Amplitude Analysis





Example:

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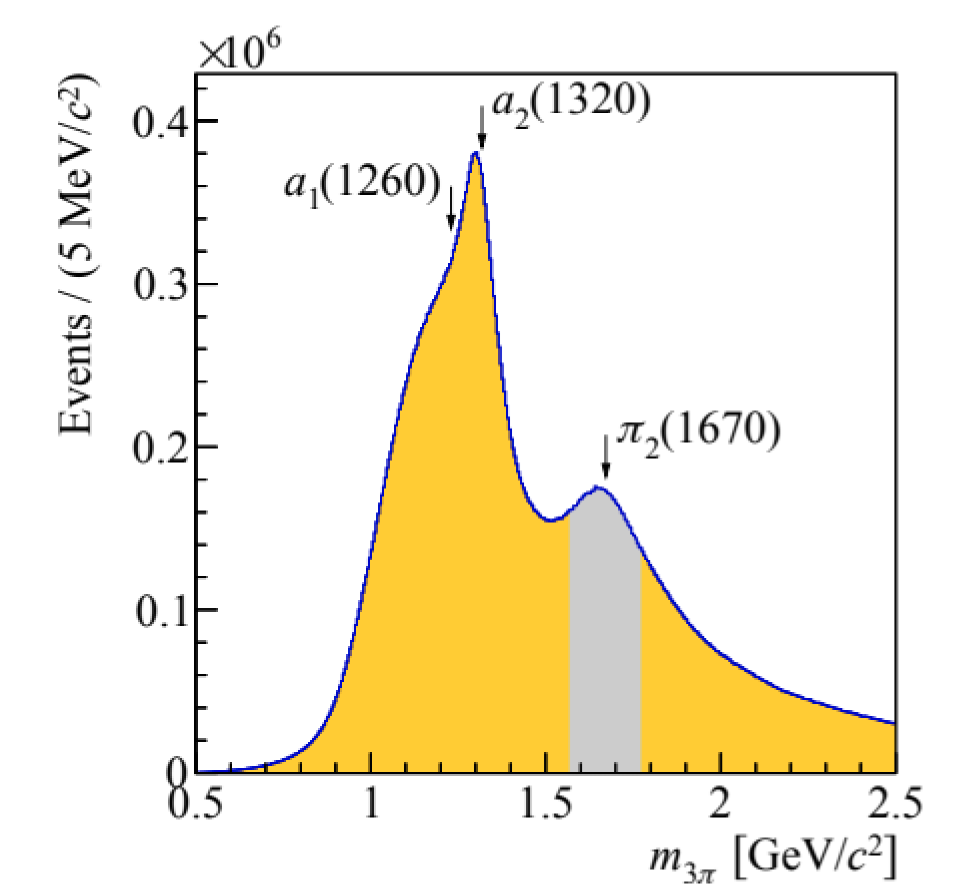
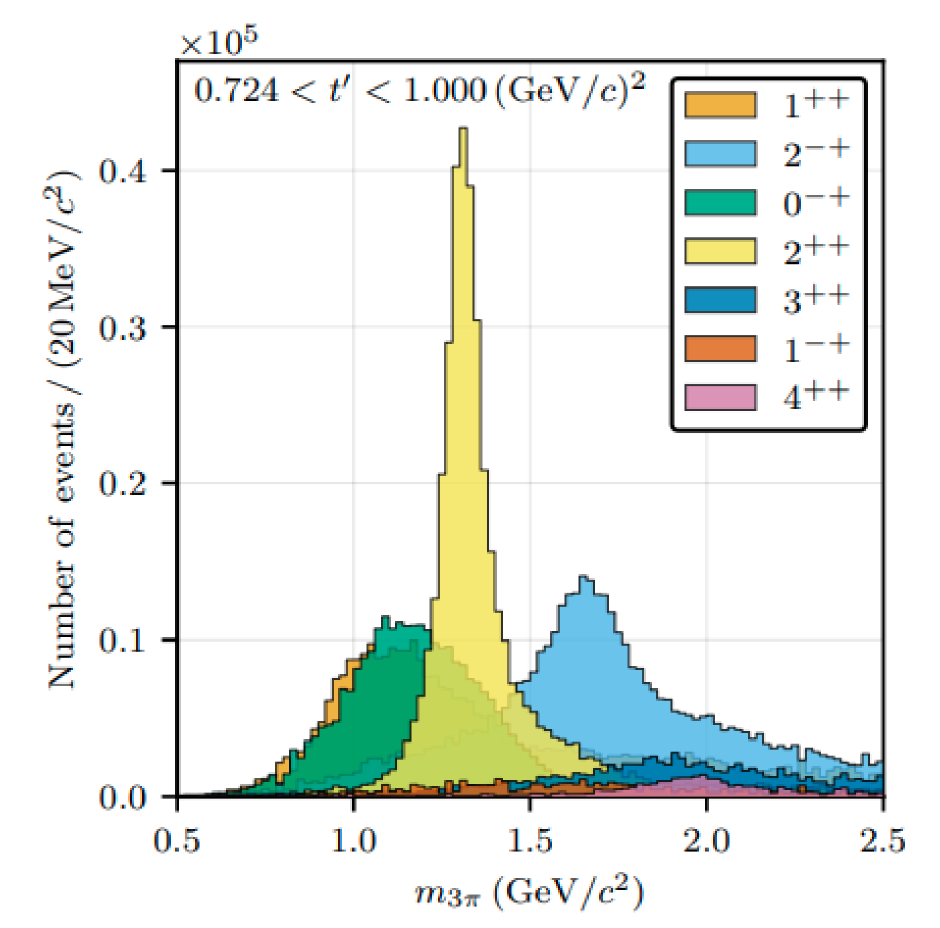


Amplitude Analysis

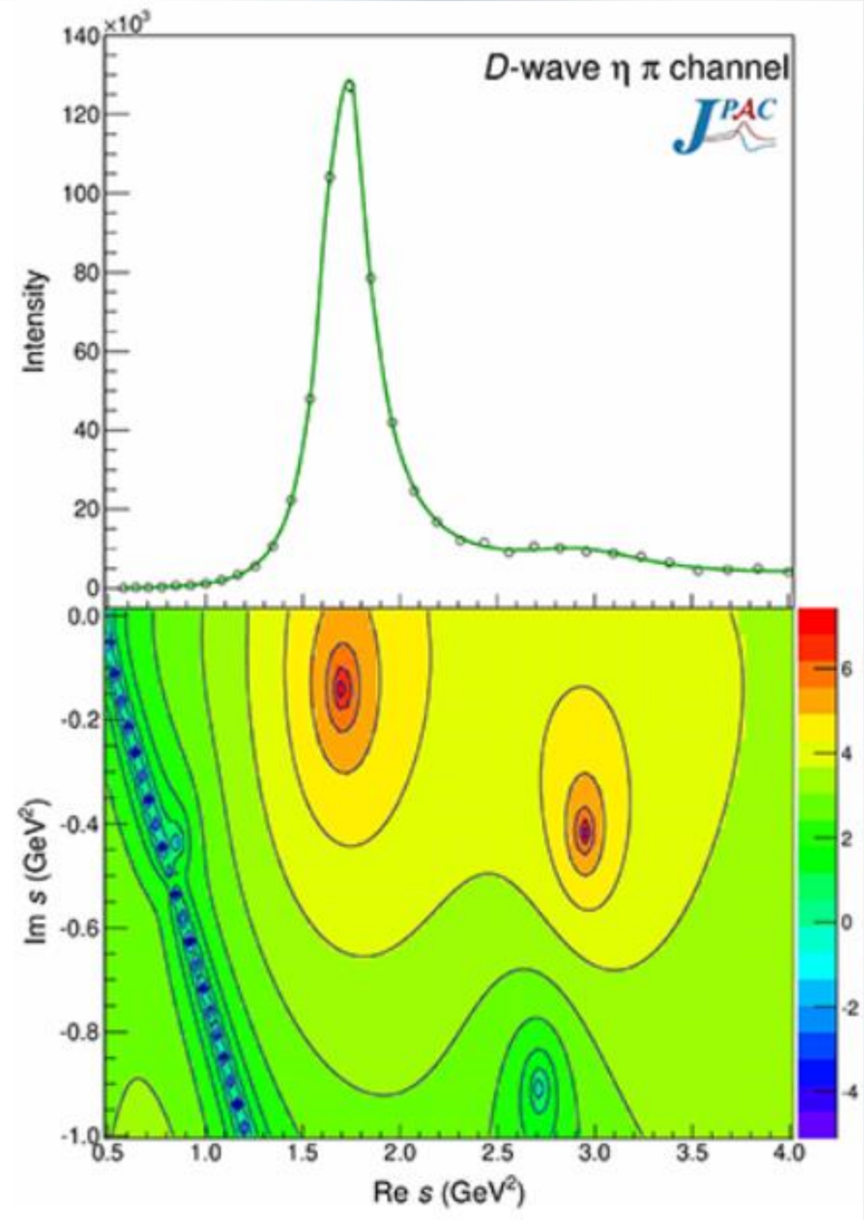


Resonance-Model Fit

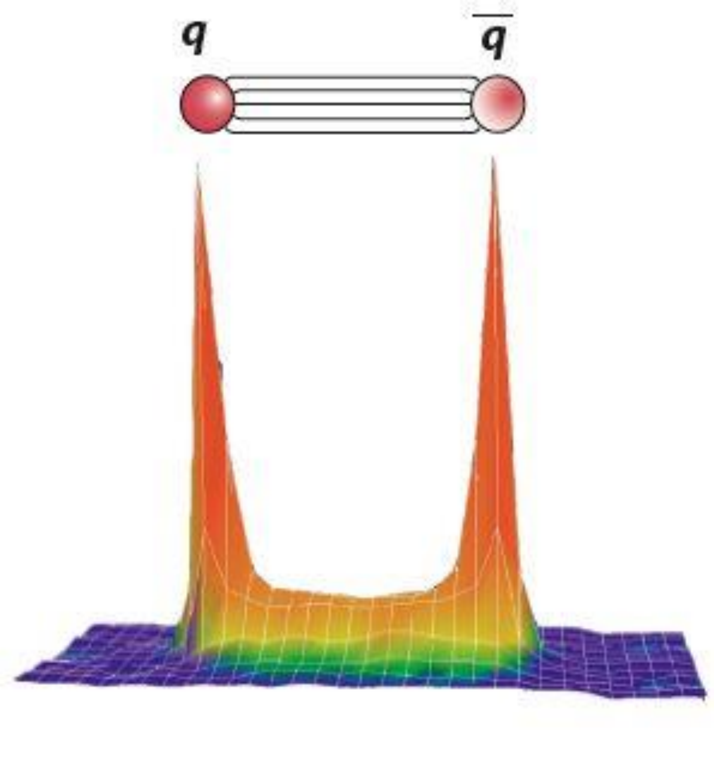
- Fit model to results of partial-wave decomposition
- Extract physical quantities: pole parameters, coupling constants
- Determination on uncertainties: bootstrapping

Model constraints:

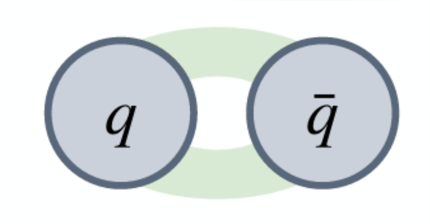
- From scattering theory (remember Lesson 2):
  Analyticity, Unitarity, Crossing Symmetry, …
- Narrow isolated resonances: Breit-Wigner function
- Coupled channels: K-matrix
- May include dynamic effects, background, …



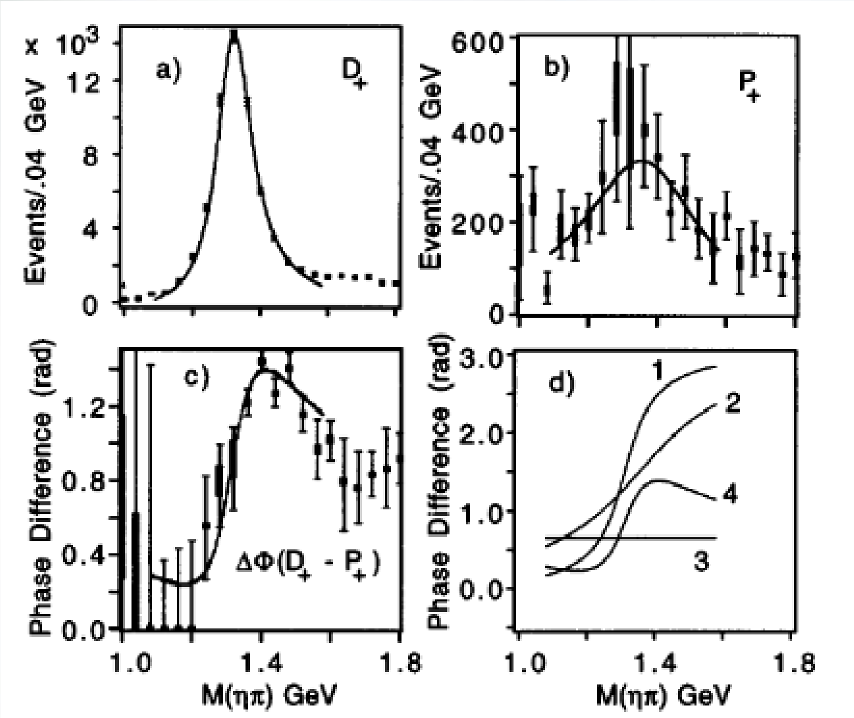
Brief History of Exotic Mesons

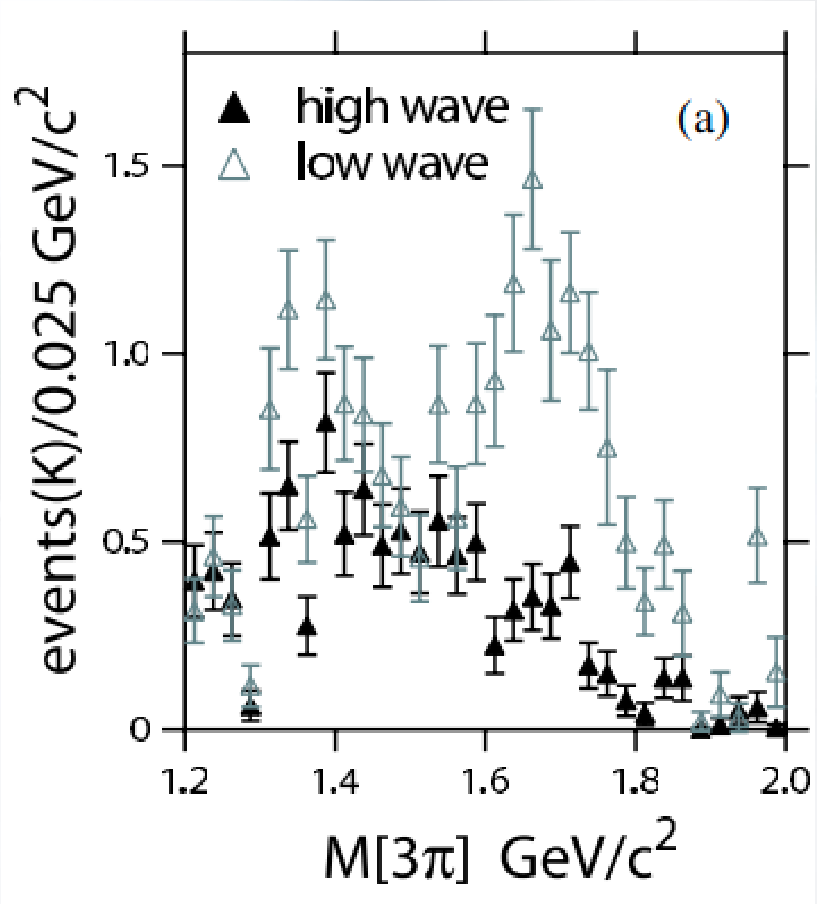


Hybrid Meson Candidate π_1



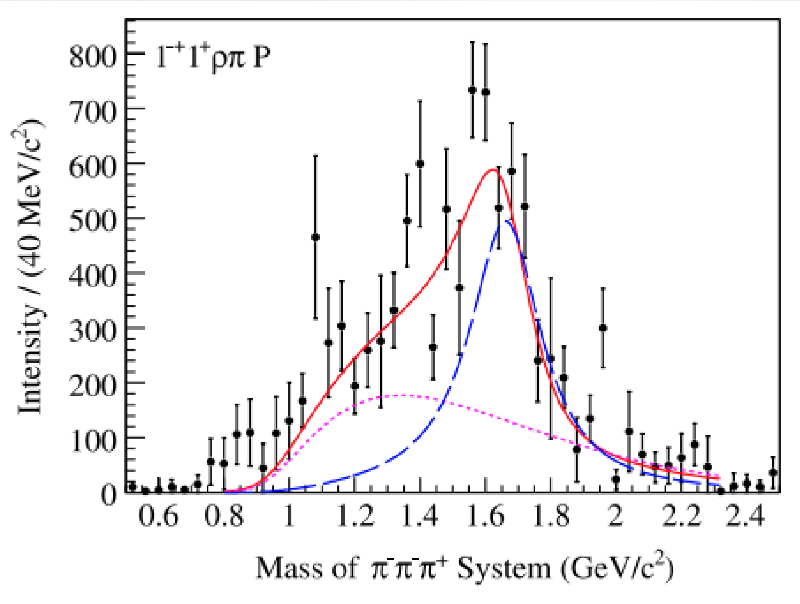
- Hybrid meson: $q\bar{q}g$ with ‘valence’ gluon
- Lightest state with exotic quantum numbers $J^{PC} = 1^{-+}$
  $\rightarrow$ does not mix with $q\bar{q}$ mesons
- Predicted in mass range 1.3-2.2 GeV by various models
- Signal in exotic amplitude seen by E852 (BNL) and VES
- $\pi_1(1400) \rightarrow \eta\pi$ (1997)
- $\pi_1(1600) \rightarrow 3\pi$ (2003)

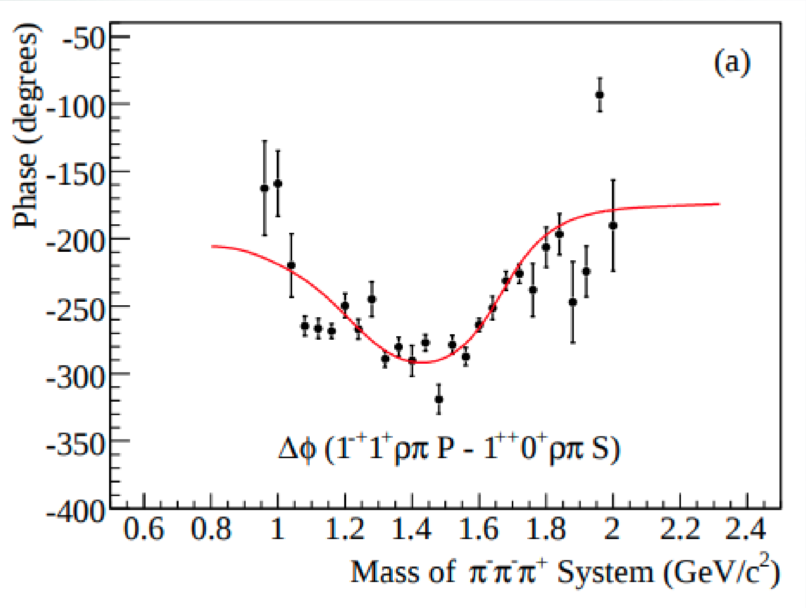




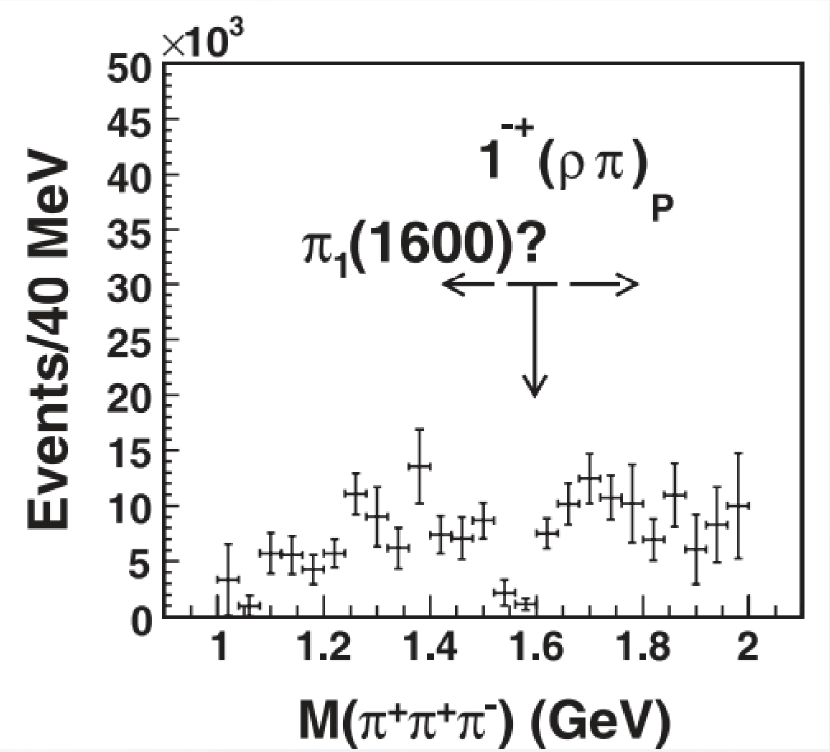
Hybrid Meson Candidate $\pi_1(1600)$

- COMPASS reported signal with phase shift in $\pi_1(1600) \rightarrow \rho\pi$ on Pb target (2009)



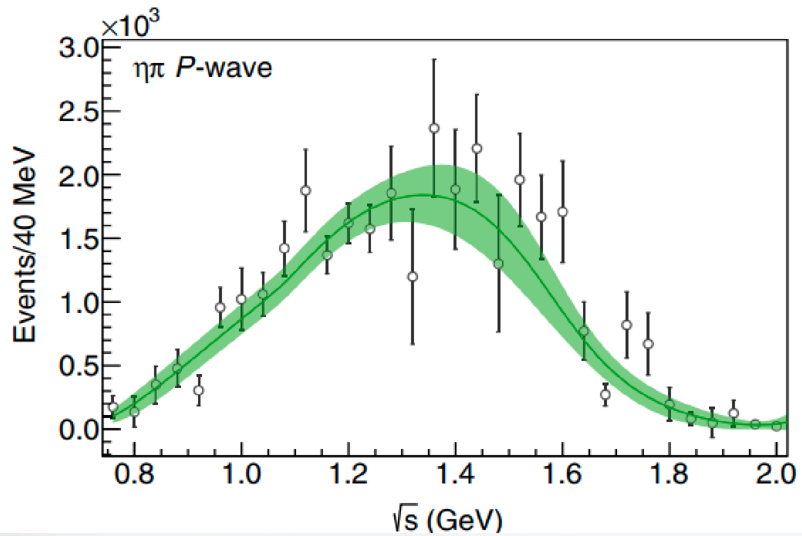


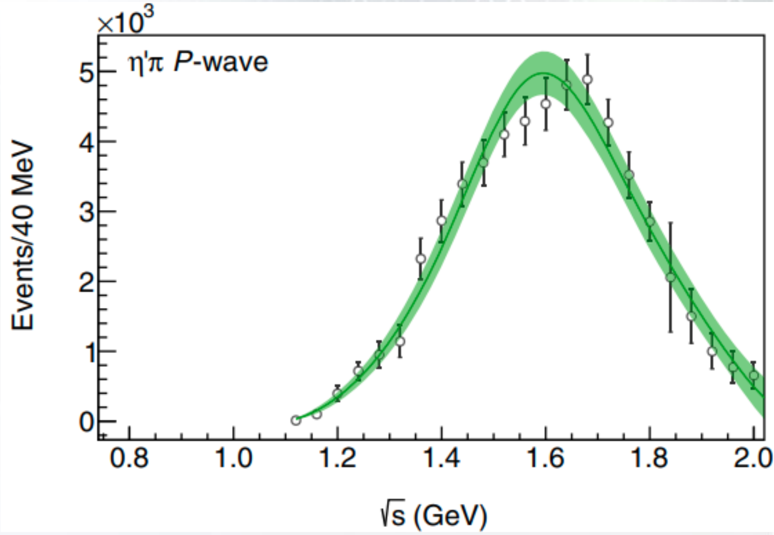
- CLAS at Jefferson Lab studied $\gamma p \rightarrow \pi^+\pi^+\pi^- n$ (2009) :
  No signal in exotic $J^{PC} = 1^{-+}$ wave

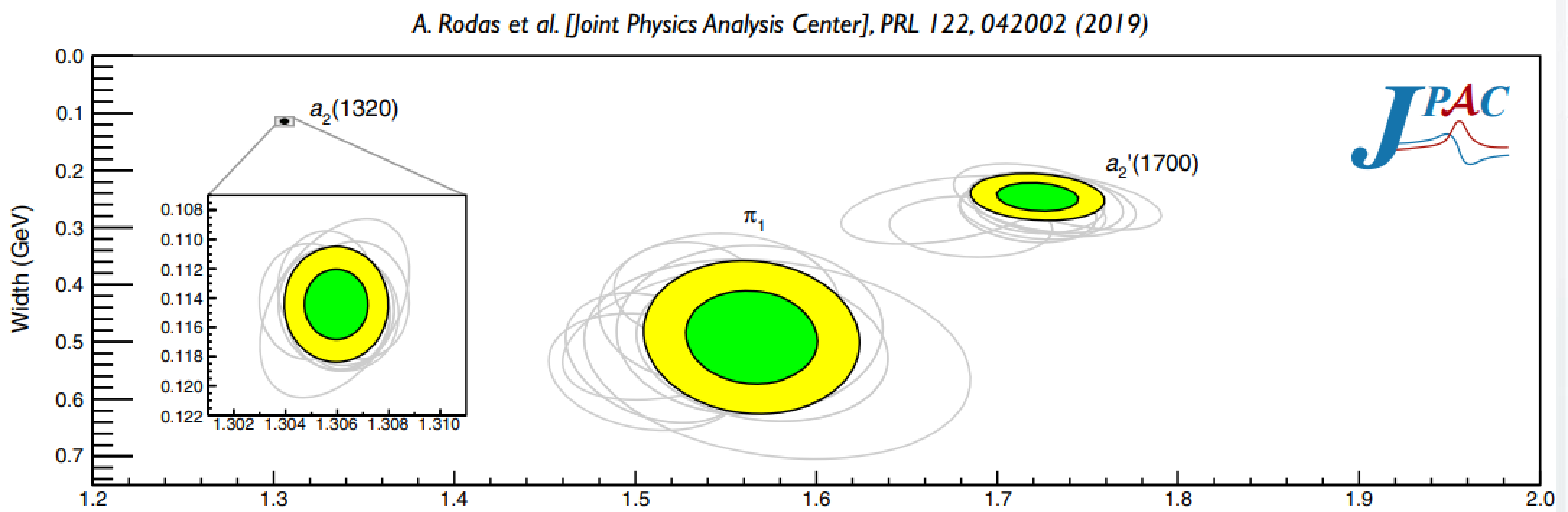


Combined Analyses

- COMPASS reported signals in $J^{PC} = 1^{-+}$ amplitude for both $\eta\pi$ and $\eta'\pi$ final states (2015)
- Analysis of individual channels would lead to 2 separate states
- Combination of data leads to conclusive picture (2019)
- A combined analysis of data from Crystal Barrel ($p\bar{p}$) and COMPASS (πp) confirms this result (2021)



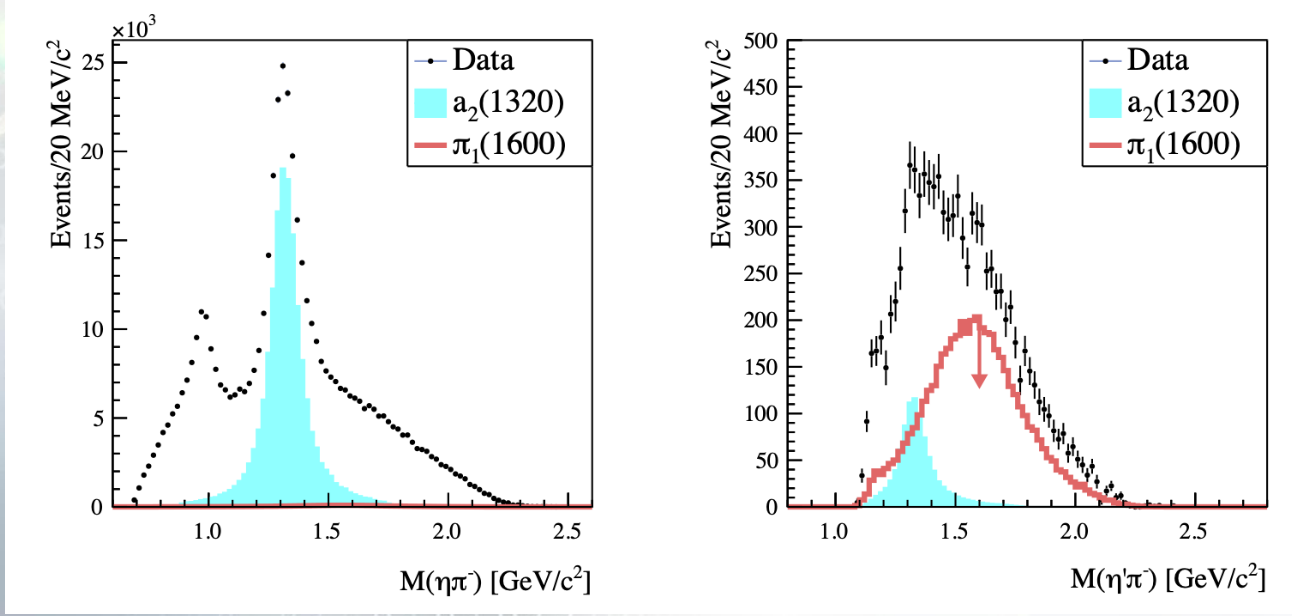




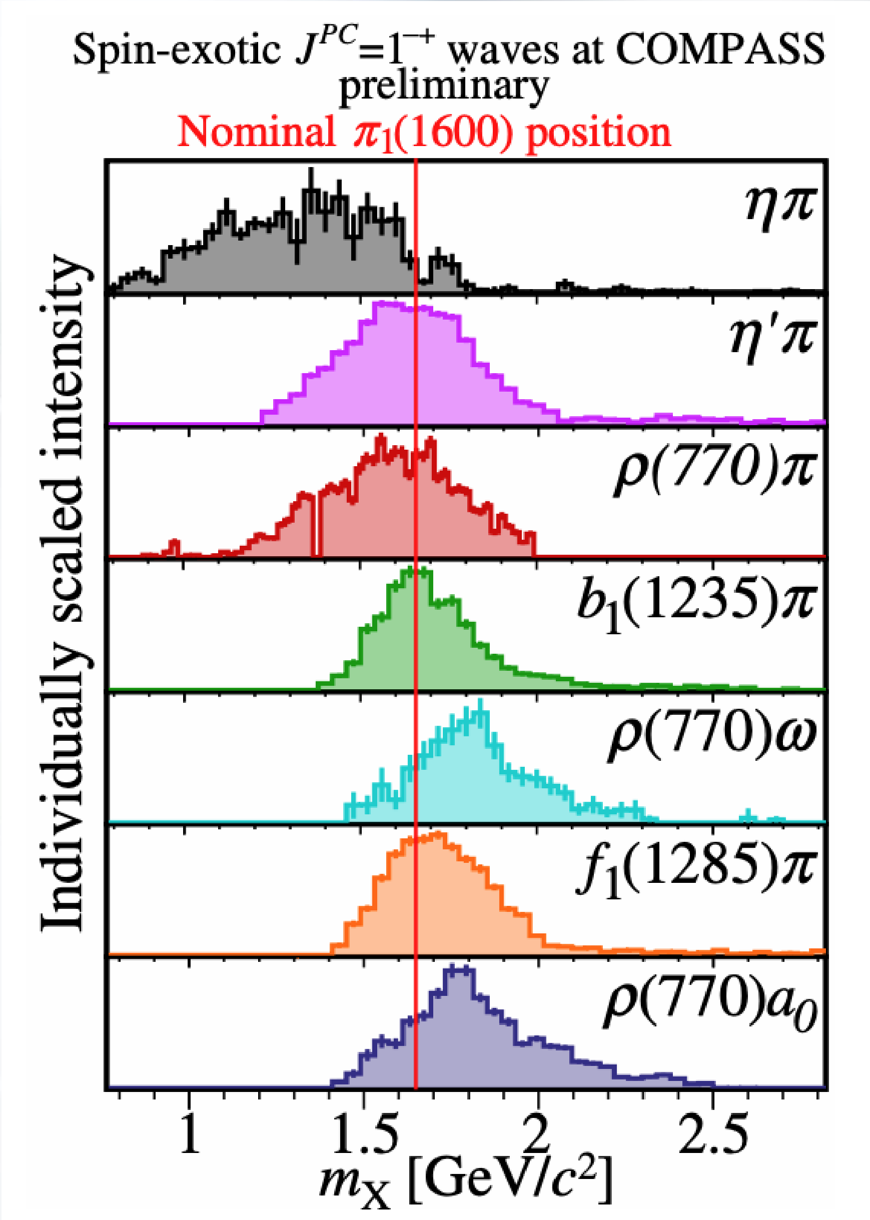
Outlook

- COMPASS is currently studying a large variety of final states (presented at HADRON in March 2025)

- Projection for $\pi_1(1600)$ yield in photoproduction at GlueX



- Continue search for other states with exotic quantum numbers
  → **Find patterns, complete nonets**



Want to know more?

- Light-Meson Spectroscopy with COMPASS
  Bernhard Ketzer, Boris Grube, Dmitry Ryabchikov
  Prog. Part. Nucl. Phys. 113 (2020) 103755
  https://arxiv.org/abs/1909.06366
- Hybrid Mesons
  Curtis A. Meyer, Eric S. Swanson
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  https://arxiv.org/abs/1502.07276
- Glueballs, Hybrids, Multiquarks. Experimental facts versus QCD inspired concepts
  Eberhard Klempt, Alexander Zaitsev
  Physics Reports, Volume 454 1–4 (2007) 1
  https://arxiv.org/abs/0708.4016

QUESTIONS?