Photoproduction of K_S Pairs at GlueX

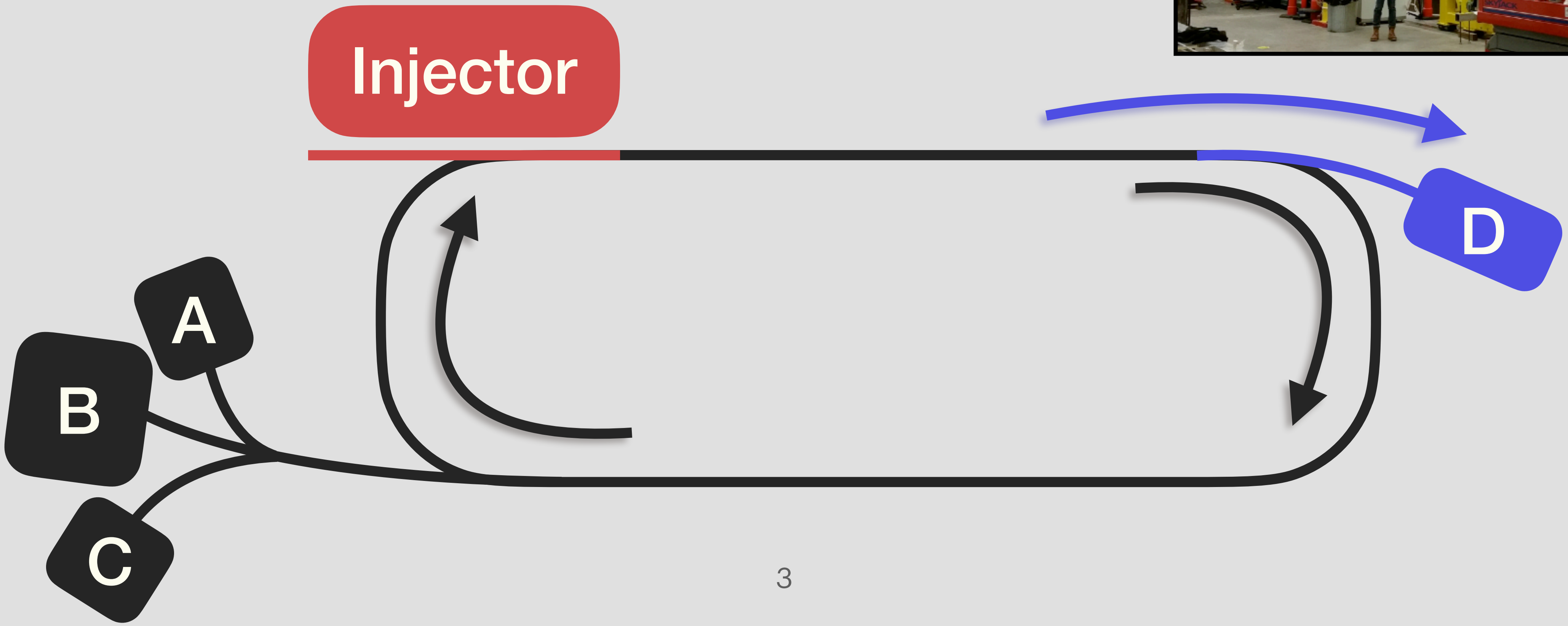
N. Dene Hoffman — 28 May 2024

Overview

- What is GlueX?
- Introduction to $K_S K_S$
- Event reconstruction
  - Background subtraction with sPlot
- Partial-wave analysis
  - Choice of waveset
  - Mass-independent fits (Y_L^M + Reflectivity)
  - Mass-dependent fits (K-Matrix)
- Results and Conclusions

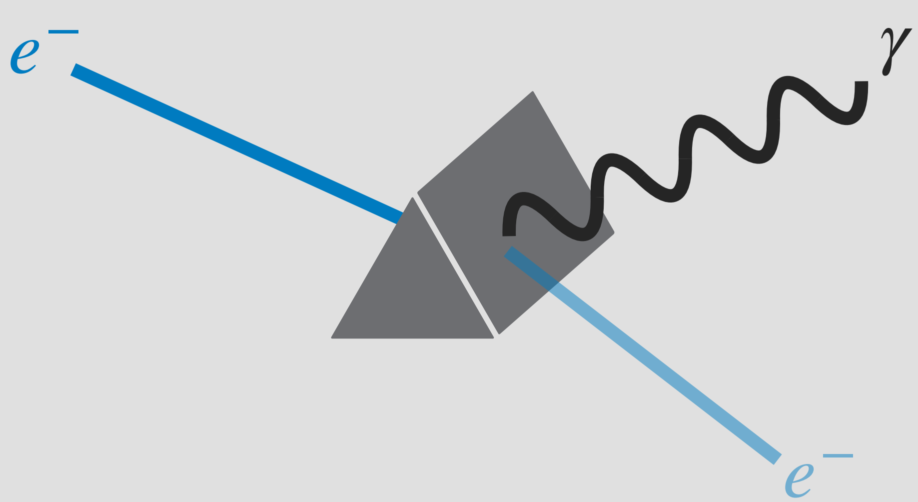
What is GlueX?

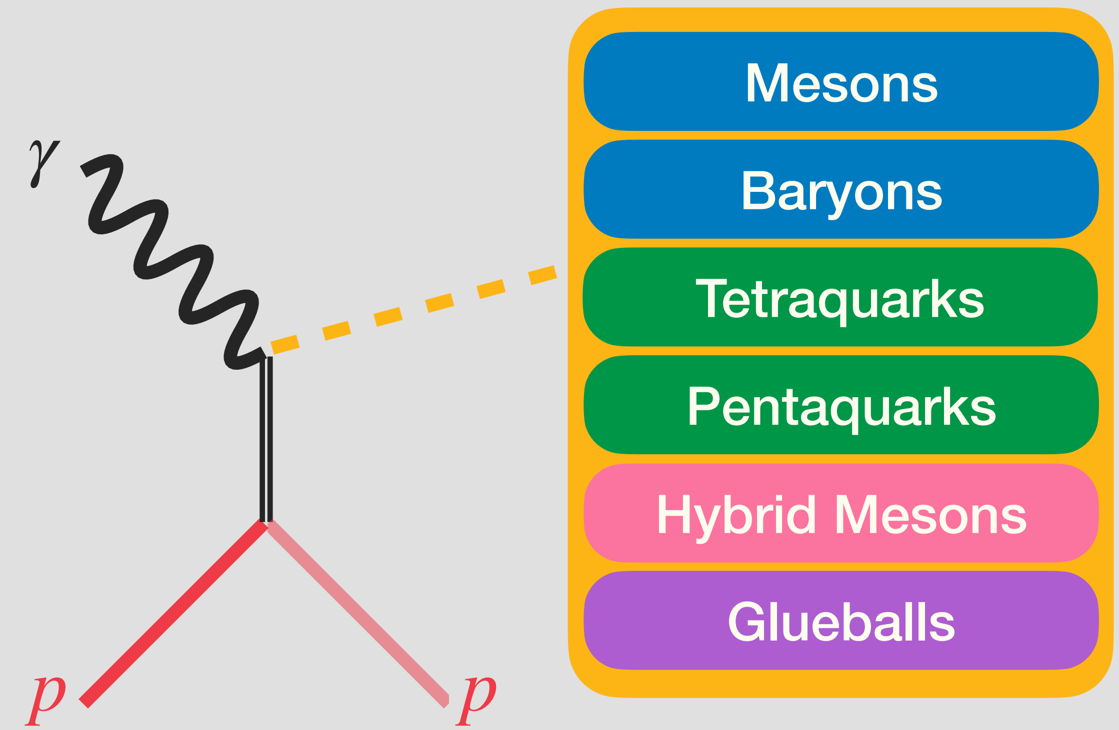
- The GlueX experiment is located in Hall-D at Jefferson Lab in Newport News, VA



What is GlueX?

- The GlueX experiment is located in Hall-D at Jefferson Lab in Newport News, VA
- 12 GeV electron beam is converted into polarized photons via diamond radiator
- Photon beam hits proton target (LH_2) and hadronizes, producing mesons, baryons, and possibly non-$q\bar{q}$ hadrons





Introduction to $K_S K_S$

- K_S^0 particles and their longer-lived partner K_L^0 are the weak eigenstates of the neutral kaon system

$$K^0 = d\bar{s}$$

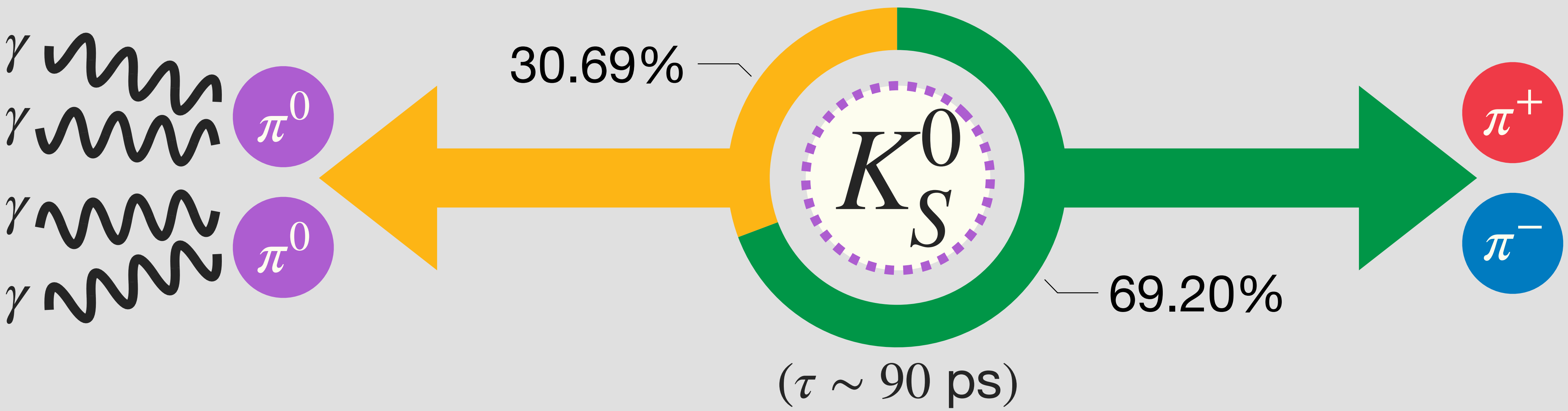
$$\bar{K}^0 = \bar{d}s$$

$$K_S^0 = \frac{K^0 + \bar{K}^0}{\sqrt{2}}$$

$$K_L^0 = \frac{K^0 - \bar{K}^0}{\sqrt{2}}$$

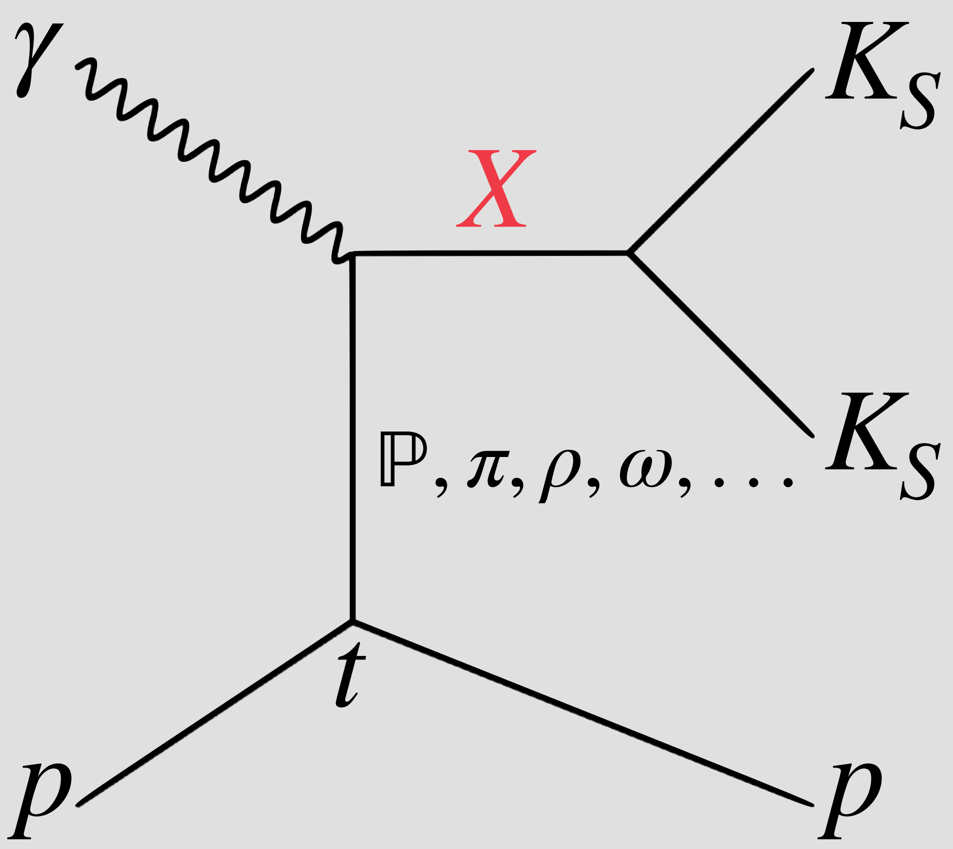
Introduction to $K_S K_S$

- K_S^0 particles and their longer-lived partner K_L^0 are the weak eigenstates of the neutral kaon system
- They decay via the weak force to $\pi^+\pi^-$ (70%) or $\pi^0\pi^0$ (30%)



Introduction to $K_S K_S$

- K_S^0 particles and their longer-lived partner K_L^0 are the weak eigenstates of the neutral kaon system
- They decay via the weak force to $\pi^+\pi^-$ (70%) or $\pi^0\pi^0$ (30%)
- We are interested in $\gamma p \to Xp \to K_S K_S p$



Introduction to $K_S K_S$

Resonances in $K_S K_S$

- We want to determine the intermediate resonance $X \to K_S K_S$
- X must have $J^{PC} = (0,2,\ldots)^{++}$

(too light to decay to $K_S K_S$)

$f_0(500)$

$f_0(980)$ $f_0(1370)$ $f_0(1500)$ $f_0(1710)$

$a_0(980)$ $a_0(1450)$ 0^{++}

$f_2(1270)$ $f_2'(1525)$ $f_2(1810)$ $f_2(1950)$

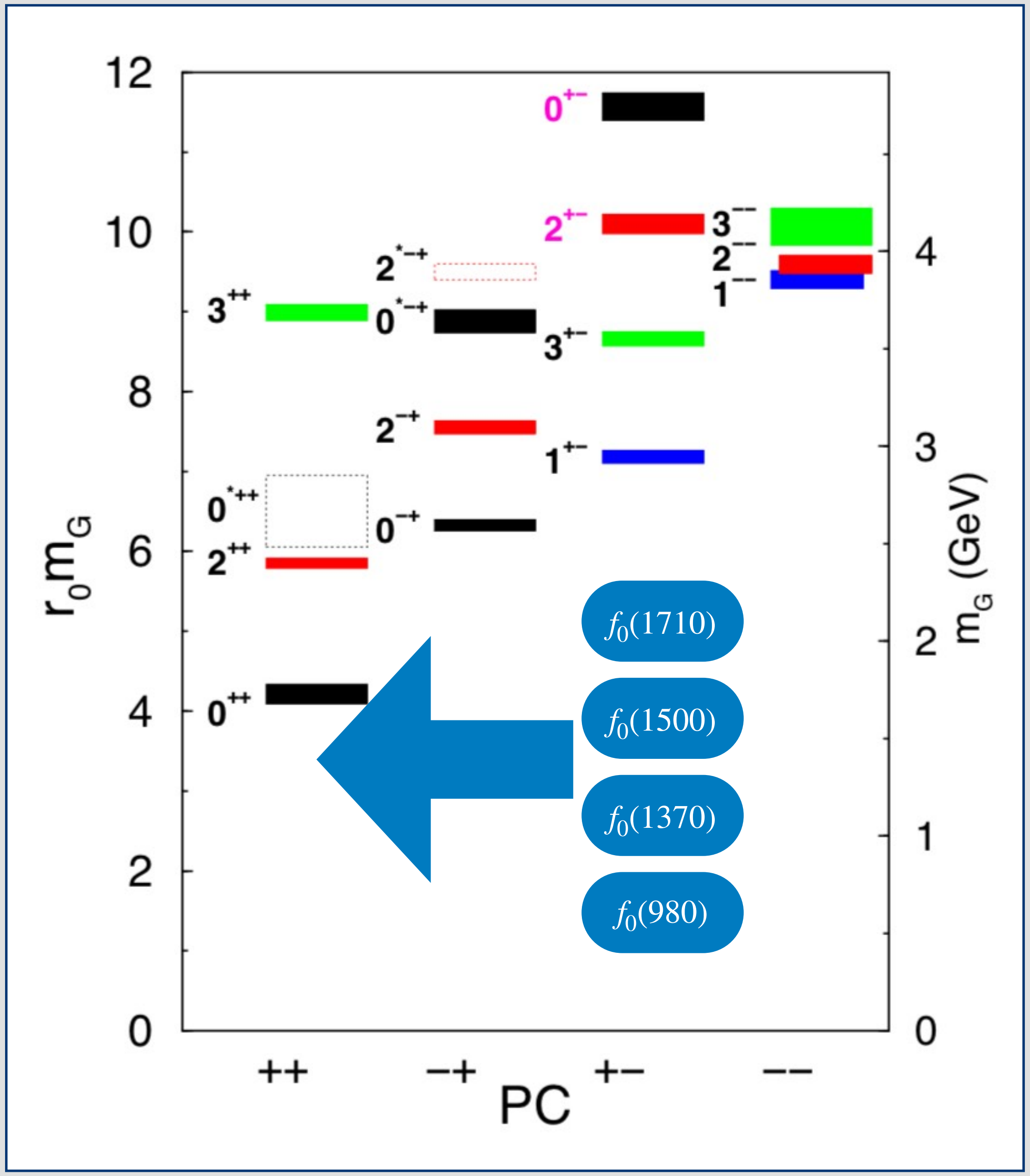
$a_2(1320)$ $a_2(1700)$ 2^{++}

Introduction to $K_S K_S$

- f_0 states overlap with the lightest scalar glueball (0^{++})
- Including the $f_0(500)$, there are too many f_0 states with respect to a_0 states
- Possible explanations include glueball mixing and even light tetraquarks

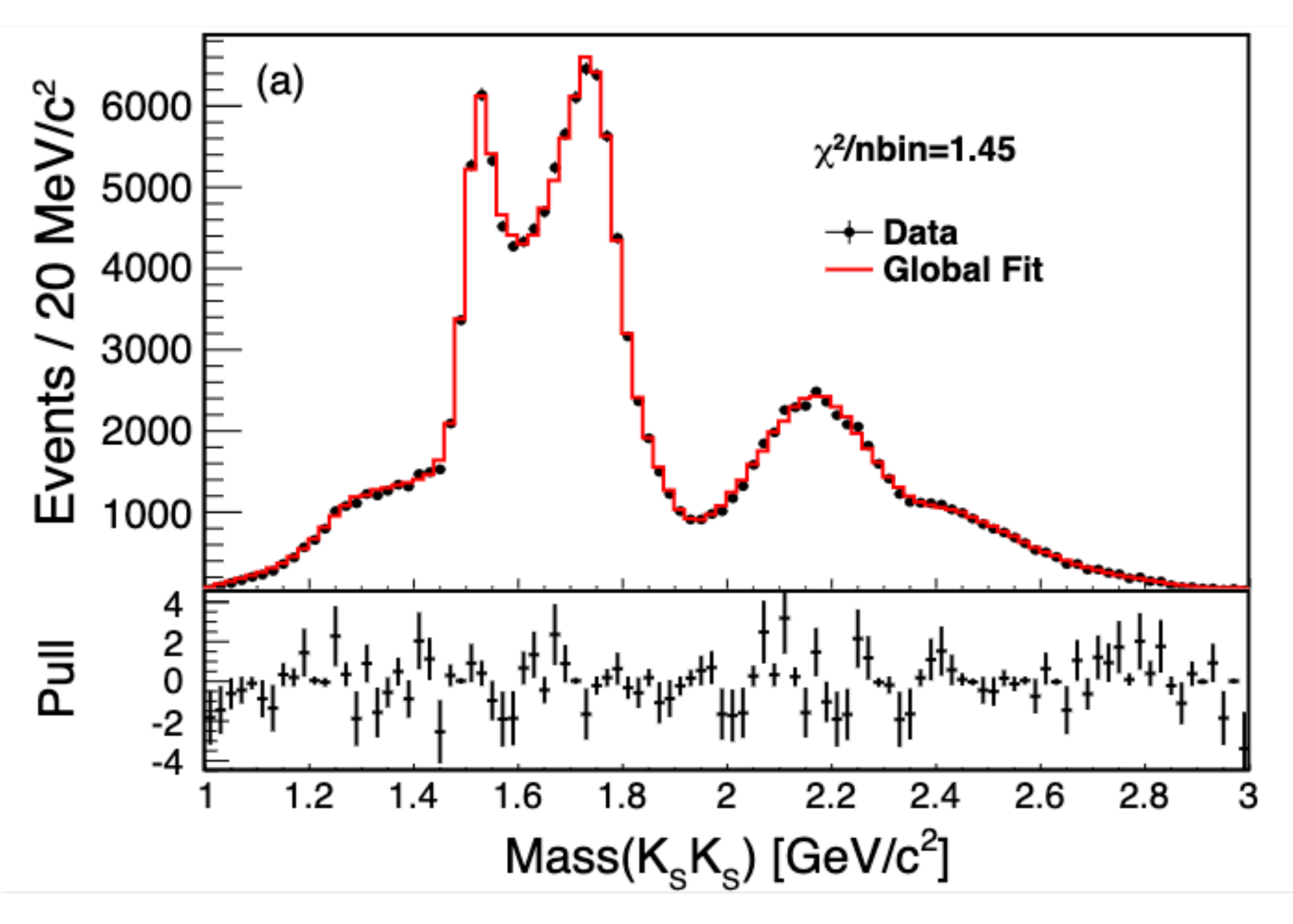
Morningstar, C. J. and Peardon, M. Glueball spectrum from an anisotropic lattice study, Phys. Rev. D 60, 034509 (1999)

Quenched LQCD Glueball Spectrum



Introduction to $K_S K_S$

- This channel has been studied in some other experiments, most recently by BESIII
- Their result will look different from ours because they were looking at J/ψ radiative decays rather than photoproduction

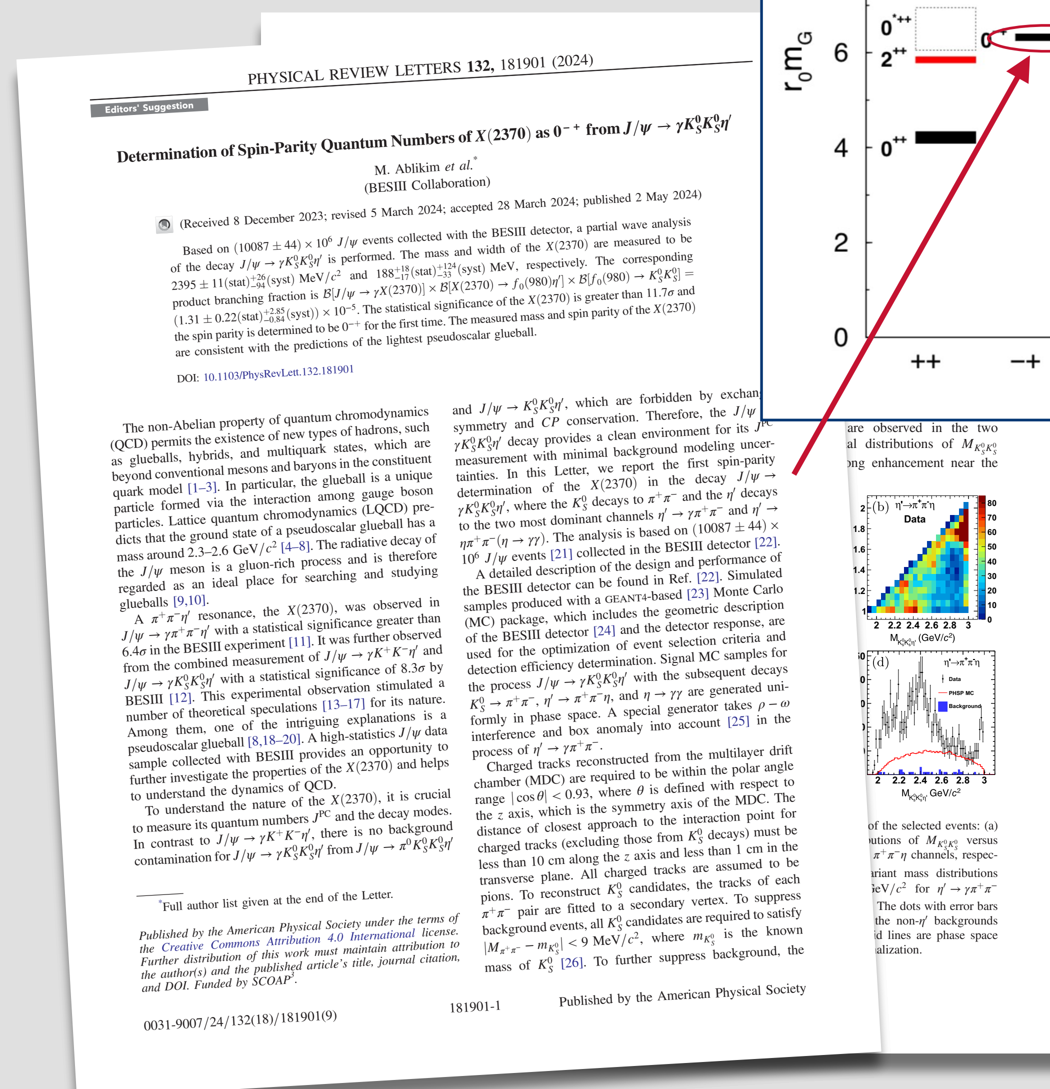


Recent result from BESIII ($J/\psi \rightarrow \gamma K_S K_S$)

M. Ablikim *et al.* (BESIII Collaboration). Amplitude analysis of the $K_S K_S$ system produced in radiative J/ψ decays, Phys. Rev. D 98, 072003 (2018)

Introduction to $K_S K_S$

- BESIII has recently published evidence that the $X(2370)$ is the pseudoscalar glueball (0^{-+}) using $J/\psi \to \gamma K_S K_S \eta'$
- Doesn't show up in this channel (wrong parity, too heavy to produce many anyway)


PHYSICAL REVIEW LETTERS **132,** 181901 (2024)

Editors' Suggestion

Determination of Spin-Parity Quantum Numbers of $X(2370)$ as 0^{-+} from $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

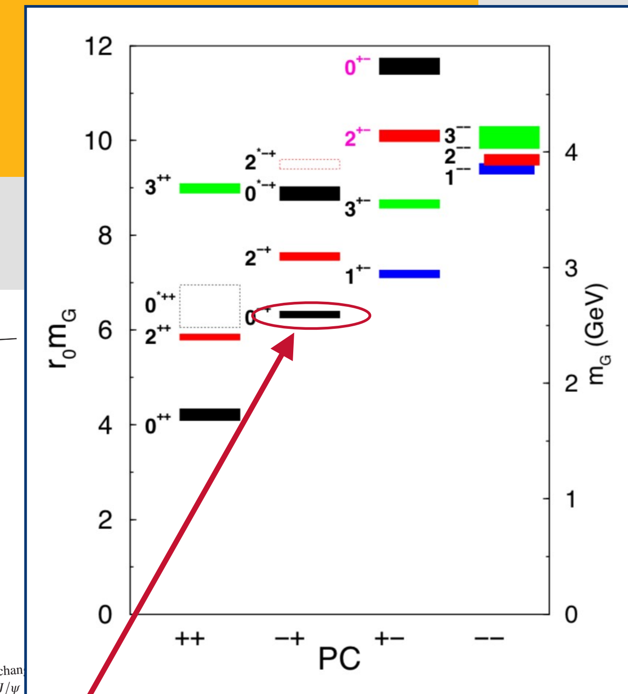
M. Ablikim *et al.**
(BESIII Collaboration)

(Received 8 December 2023; revised 5 March 2024; accepted 28 March 2024; published 2 May 2024)

Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, a partial wave analysis of the decay $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is performed. The mass and width of the $X(2370)$ are measured to be $2395 \pm 11(\mathrm{stat})^{+26}_{-94}(\mathrm{syst})$ MeV/c^2 and $188^{+18}_{-17}(\mathrm{stat})^{+124}_{-33}(\mathrm{syst})$ MeV, respectively. The corresponding product branching fraction is $\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}[X(2370) \to f_0(980)\eta'] \times \mathcal{B}[f_0(980) \to K_S^0 K_S^0] = (1.31 \pm 0.22(\mathrm{stat})^{+2.85}_{-0.84}(\mathrm{syst})) \times 10^{-5}$. The statistical significance of the $X(2370)$ is greater than 11.7σ and the spin parity is determined to be 0^{-+} for the first time. The measured mass and spin parity of the $X(2370)$ are consistent with the predictions of the lightest pseudoscalar glueball.

DOI: 10.1103/PhysRevLett.132.181901

0031-9007/24/132(18)/181901(9) 181901-1 Published by the American Physical Society



M. Ablikim *et al.* (BESIII Collaboration). Determination of Spin-Parity Quantum Numbers of $X(2370)$ as 0^{-+} from $J/\psi \to \gamma K_S^0 K_S^0 \eta'$, Phys. Rev. Lett. 132, 181901 (2024)

Event Reconstruction

- Kinematic fit of kaon masses, decay vertices, and four-momenta in exclusive reconstruction with tight constraint on χ^2_ν
- Select photons in the most polarized energy range
- Select protons with a z-vertex inside the GlueX target
- $K_S \rightarrow \pi^+\pi^-$ is a weak decay, so we can distinguish it from non-strange production using the kaon lifetime

Signal Channel

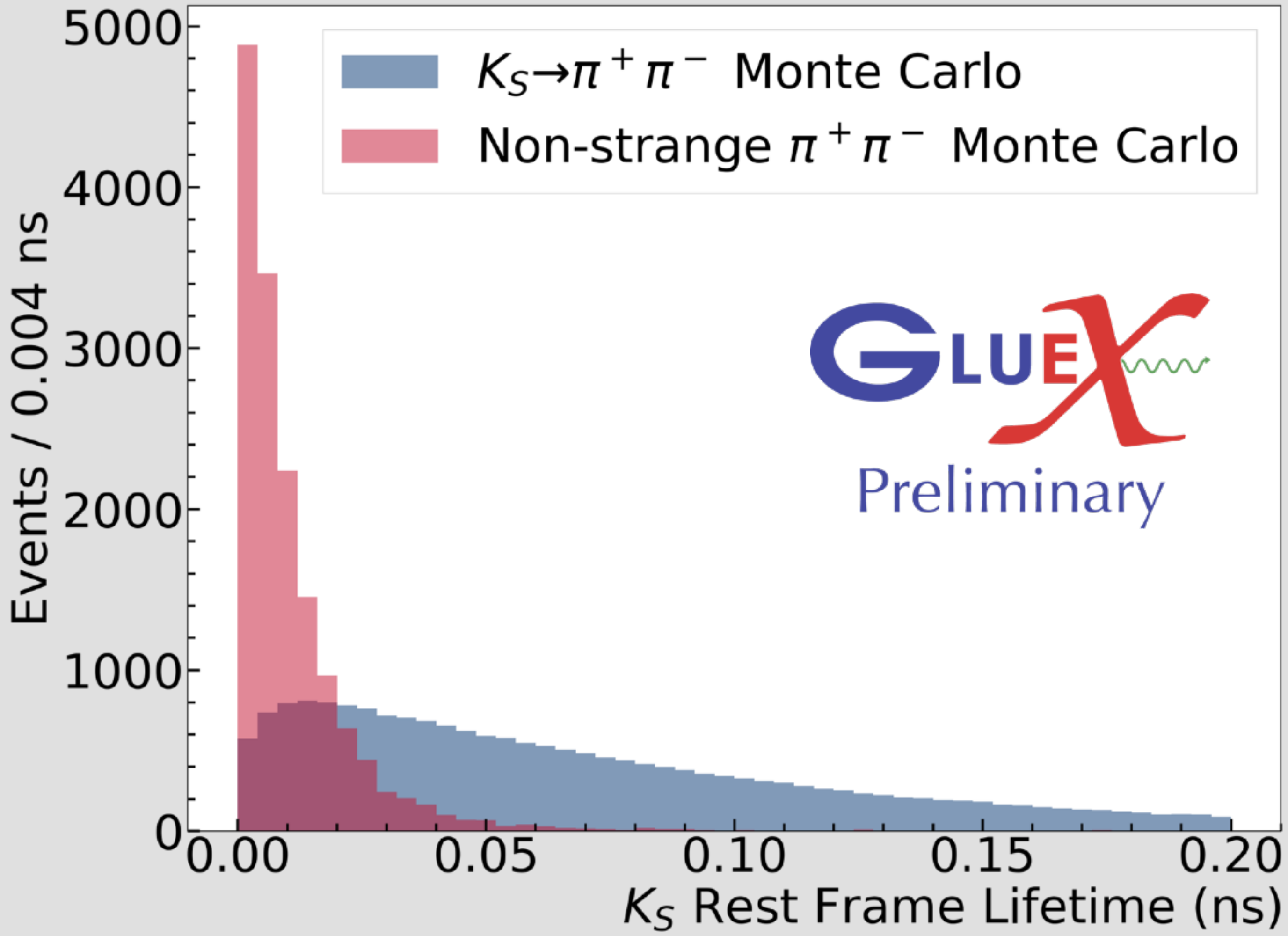
$$\gamma p \rightarrow K_S K_S p \xrightarrow{\text{weak}} \pi^+\pi^-\pi^+\pi^- p$$

Non-Strange Background

$$\gamma p \xrightarrow{\text{strong}} \pi^+\pi^-\pi^+\pi^- p$$

Event Reconstruction

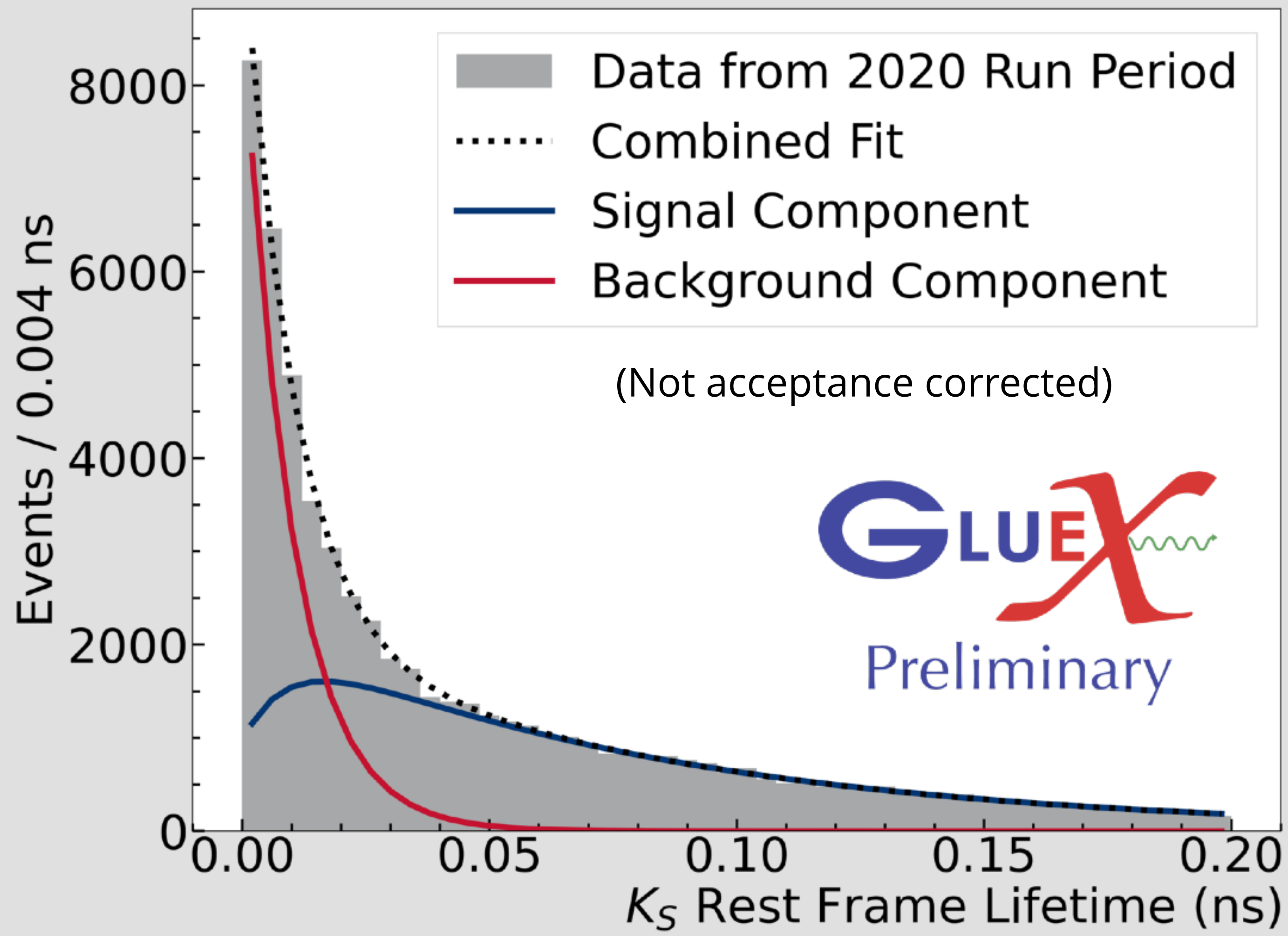
- Model both signal and non-strange background, in Monte Carlo



Monte Carlo simulations of signal and non-strange background

Event Reconstruction

- Model both signal and non-strange background, in Monte Carlo
- Use sPlot to assign weights to each event based on the probability of the pions coming from a K_S or from some non-strange production

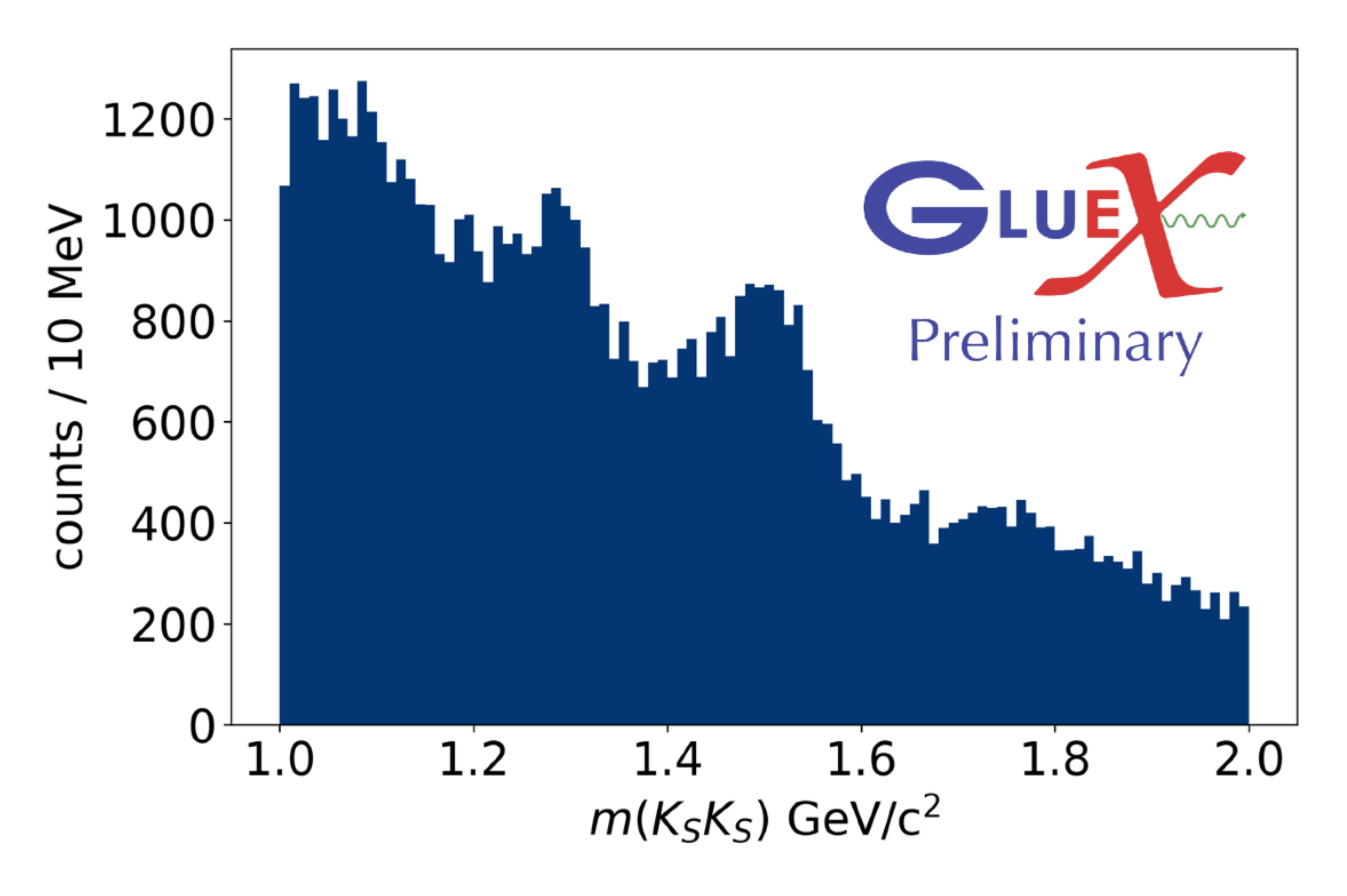


Fit of signal and background distributions to data

M. Pivk & F. Le Diberder. sPlot: A statistical tool to unfold data distributions, NIM A, 555 1-2, p.356-369 (2005)

Event Reconstruction

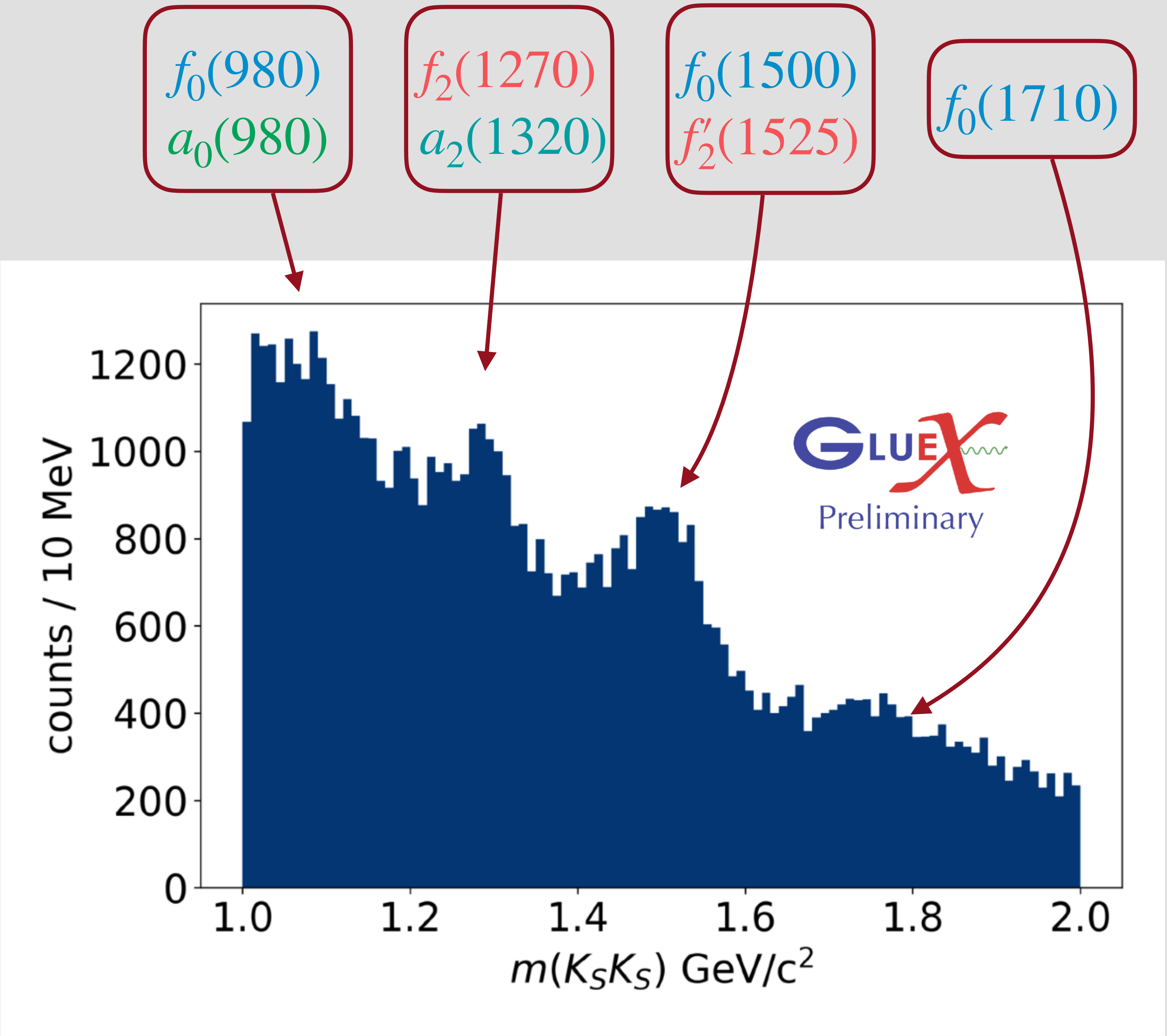
- After all selections/cuts
  with sPlot weights



Event Reconstruction

- After all selections/cuts with sPlot weights
- Most peaks correspond to more than one expected resonance
- With this channel alone, we can separate different spin states (but not isospin)

(Some of the most likely narrow resonances)

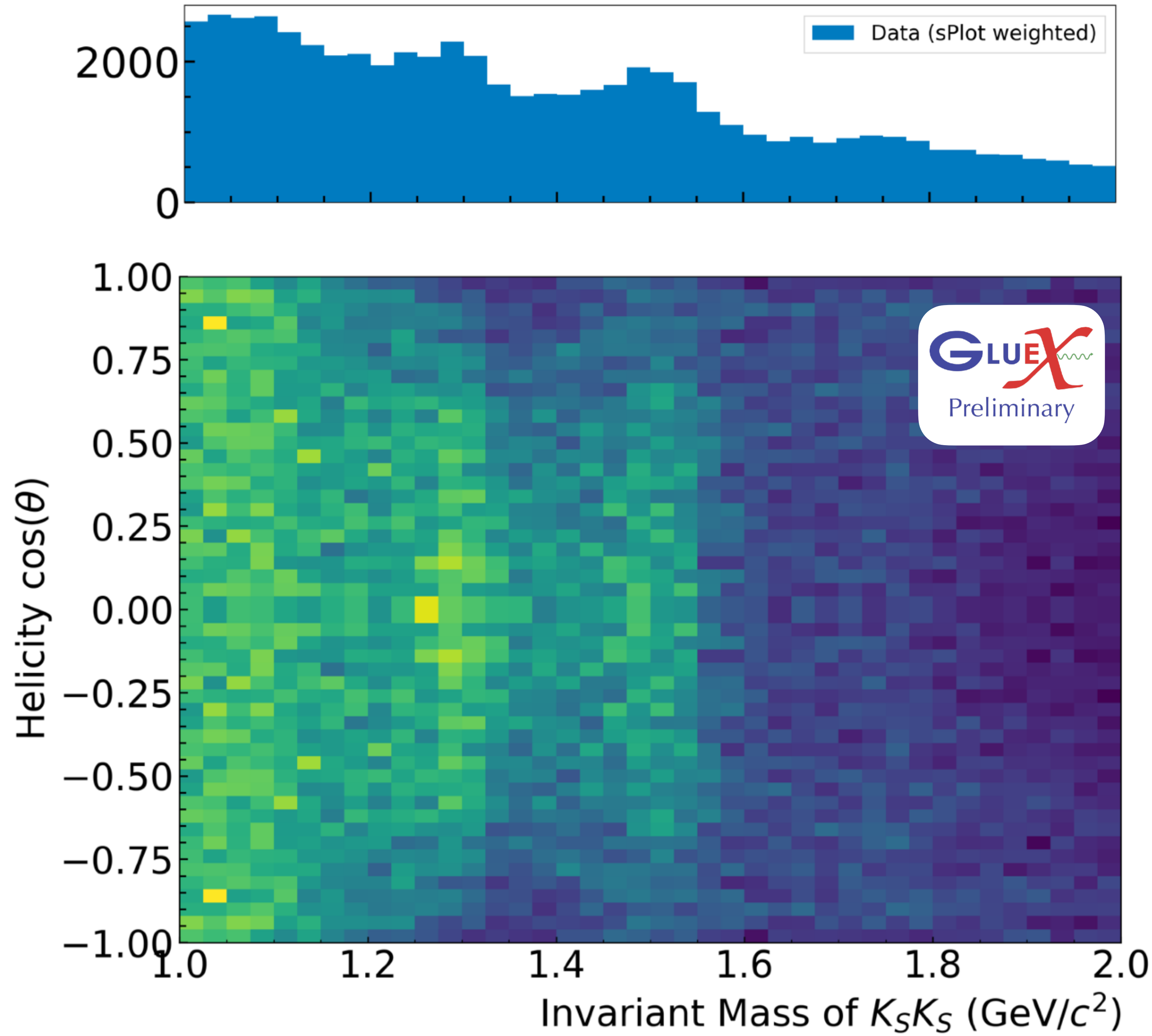


Partial-Wave Analysis

Main Idea:

Fit the decay angles of $X \rightarrow K_S K_S$ to spherical harmonics to separate spin-0 and spin-2 resonances

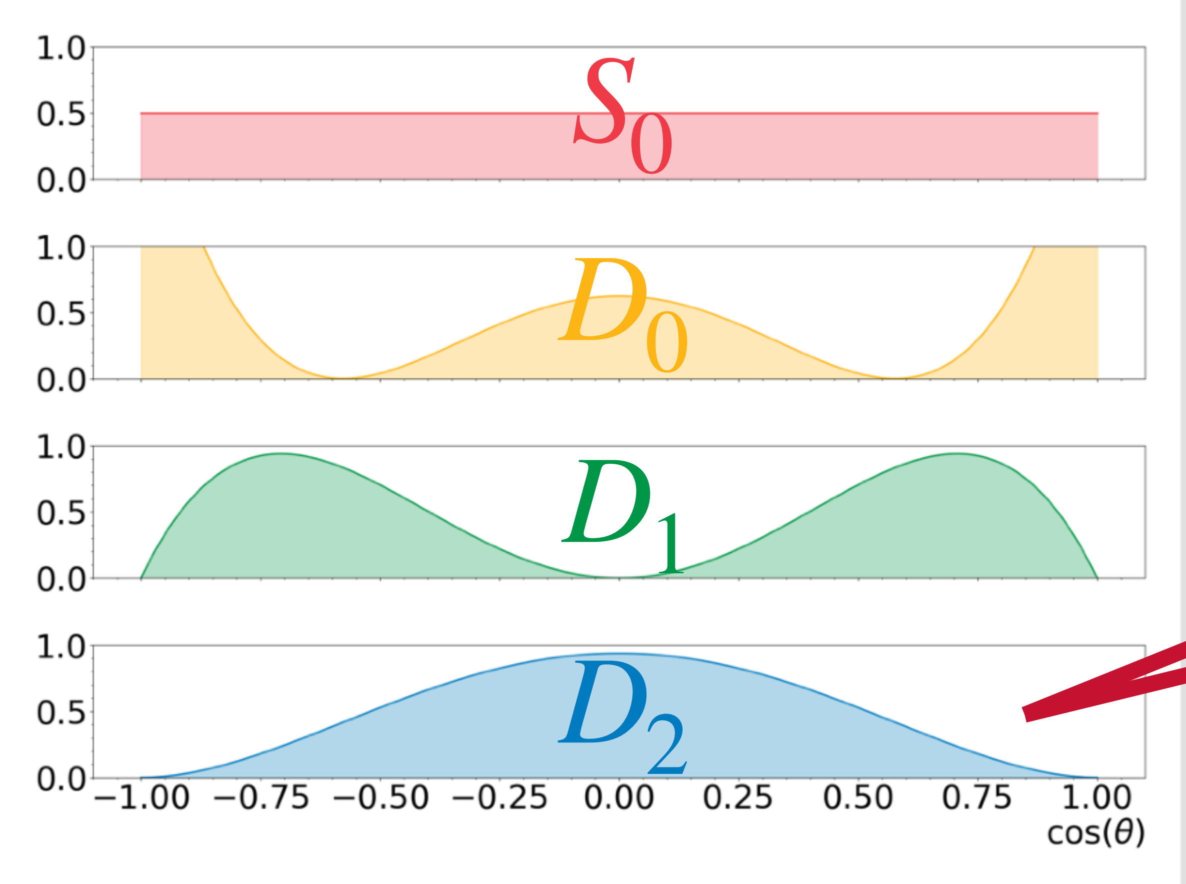
Note: Helicity angles are measured in the rest frame of the resonance—the z-axis is the boost direction

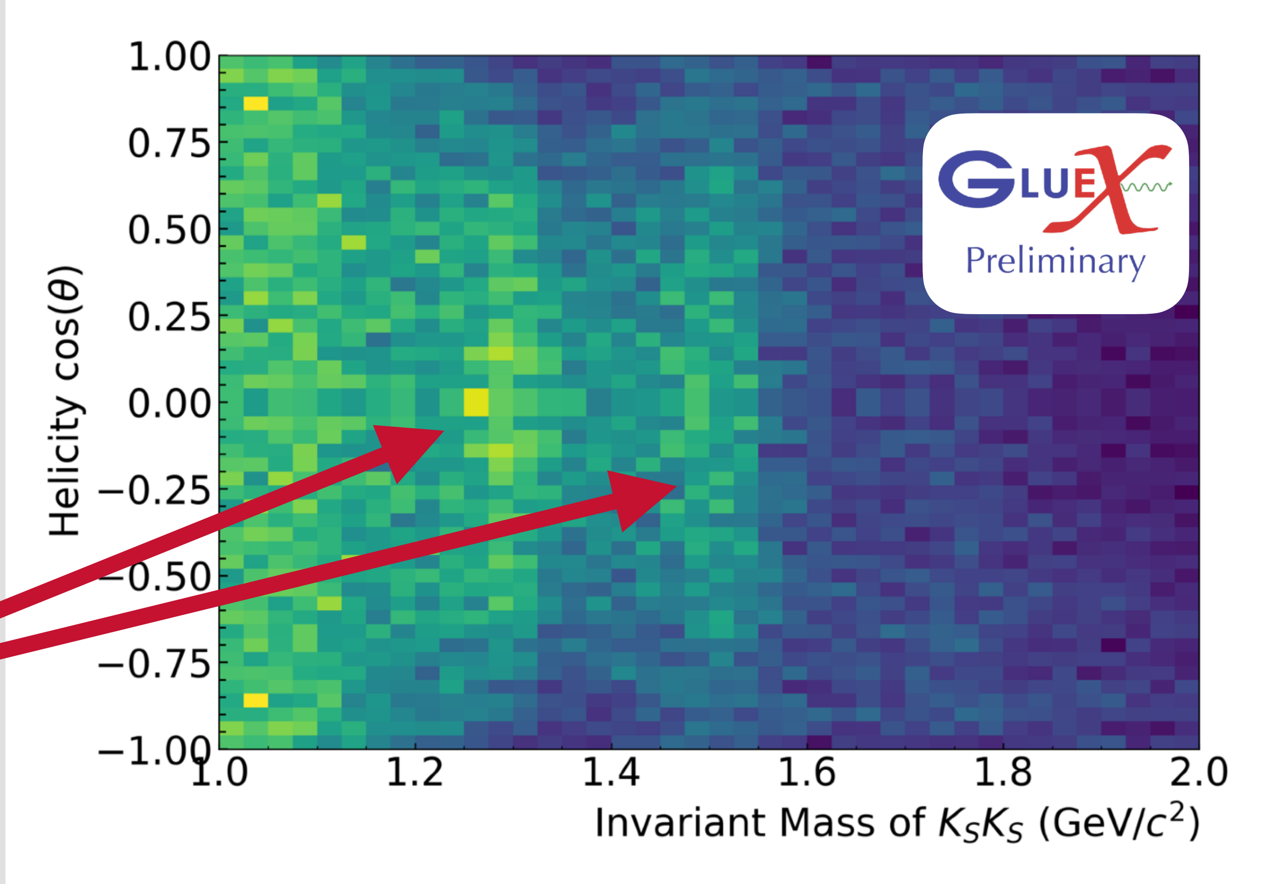


Note: not acceptance corrected

Partial-Wave Analysis

D-wave-like structures visually appear to be D_2





For now, we will use this wave as the dominant spin-2 signal, although this maybe be adjusted in the future

Choice of Wave Set

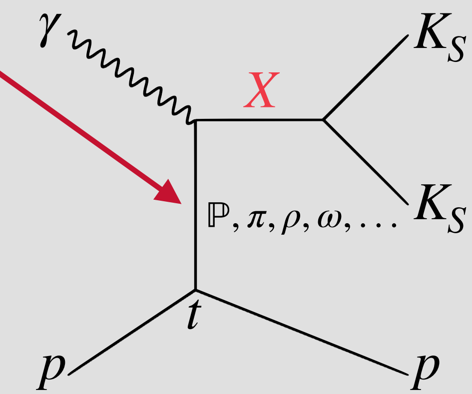
J^{PC}	0^{++}	2^{++}
$[\ell]_m$	S_0	D_2

Types of Fits

Mass-Independent	Bin by mass and fit each bin independently (no mass model)
Mass-Dependent	Model mass with K-matrix amplitude and fit all data together

Mass-Independent Fit

- With a linearly polarized beam, we can write amplitudes in the reflectivity basis, $\varepsilon = -1$ or $+1$ (positive reflectivity means natural parity exchange in t-channel here)
- $[\ell]_m^{(+)}$ and $[\ell]_m^{(-)}$ are complex free parameters in the fit
- $\Omega = \{\cos(\theta), \phi\}$



$$I(\Omega, \Phi) \propto (1-P_\gamma)\left|\sum_{\ell,m} [\ell]_m^{(-)} \Re[Z_\ell^m(\Omega, \Phi)]\right|^2 + (1-P_\gamma)\left|\sum_{\ell,m} [\ell]_m^{(+)} \Im[Z_\ell^m(\Omega, \Phi)]\right|^2 +$$

$$(1+P_\gamma)\left|\sum_{\ell,m} [\ell]_m^{(+)} \Re[Z_\ell^m(\Omega, \Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{\ell,m} [\ell]_m^{(-)} \Im[Z_\ell^m(\Omega, \Phi)]\right|^2$$

$$Z_\ell^m(\Omega, \Phi) \equiv Y_\ell^m(\Omega) e^{-\iota\Phi}$$

V. Mathieu et al. Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX, Phys Rev D 100, 054017 (2019)

Mass-Dependent Fit

The K-Matrix Amplitude

- Fix most free parameters (including entire K-matrix) to results from Kopf et al.
  - $\alpha \rightarrow$ Resonances
  - $B \rightarrow$ Blatt-Weisskopf barrier factors
  - $g \rightarrow$ Final-state couplings
  - $m_\alpha \rightarrow$ Resonance mass
  - $c \rightarrow$ Backgrounds in K-matrix
  - $C \rightarrow$ Chew-Mandelstam function (matrix)
- Fit the coupling to $p\gamma$
  - $\beta_\alpha \rightarrow$ Photocoupling (complex)

$$K_{ij}(m) = \sum_\alpha B_{i,\alpha}\left(\frac{g_{i,\alpha}g_{j,\alpha}}{m_\alpha^2 - m^2} + c_{ij}\right)B_{j,\alpha}$$

$$P_j(m) = \sum_\alpha \left(\frac{\beta_\alpha g_{j,\alpha}}{m_\alpha^2 - m^2}\right)B_{j,\alpha}$$

$$F(m) = (1 + K(m)C(m))^{-1} \cdot P(m)$$

K-Matrix Parameterization

Kopf, B., Albrecht, M., Koch, H. et al. Investigation of the lightest hybrid meson candidate with a coupled-channel analysis of $\bar{p}p$-, π^-p-, and $\pi\pi$-Data, Eur. Phys. J. C81, 1056 (2021)

Mass-Dependent Fit

The K-Matrix Amplitude + Z_ℓ^m

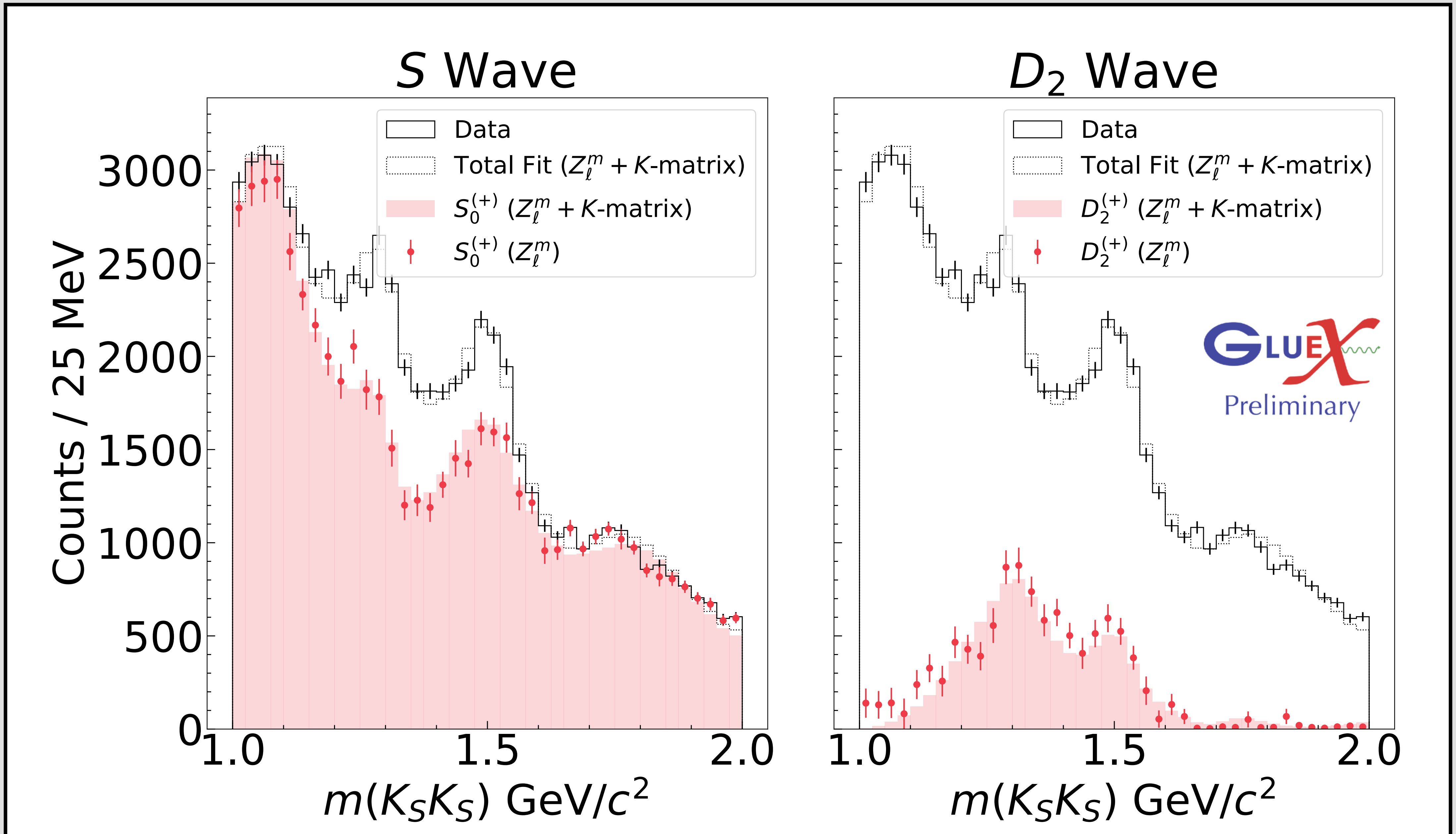
$$I(\Omega, m, \Phi) \propto (1+P_\gamma)\left| \left(F_{f_0}^{(+)}(\vec{\beta}_{f_0^{(+)}}, m) + F_{a_0}^{(+)}(\vec{\beta}_{a_0^{(+)}}, m)\right) \Re[Z_0^0(\Omega, \Phi)] + \left(F_{f_2}^{(+)}(\vec{\beta}_{f_2^{(+)}}, m) + F_{a_2}^{(+)}(\vec{\beta}_{a_2^{(+)}}, m)\right) \Re[Z_2^2(\Omega, \Phi)] \right|^2 + (1-P_\gamma)\left| \left(F_{f_0}^{(+)}(\vec{\beta}_{f_0^{(+)}}, m) + F_{a_0}^{(+)}(\vec{\beta}_{a_0^{(+)}}, m)\right) \Im[Z_0^0(\Omega, \Phi)] + \left(F_{f_2}^{(+)}(\vec{\beta}_{f_2^{(+)}}, m) + F_{a_2}^{(+)}(\vec{\beta}_{a_2^{(+)}}, m)\right) \Im[Z_2^2(\Omega, \Phi)] \right|^2$$

$$F_{I\ell}^{(\epsilon)}(\vec{\beta}, m) \equiv (1 + K_{I\ell}(m)C_{I\ell}(m))^{-1} \cdot P_{I\ell}(\vec{\beta}_{I\ell}^{(\epsilon)}, m)$$

$$Z_\ell^m(\Omega, \Phi) \equiv Y_\ell^m(\Omega)e^{-\imath\Phi}$$

Fits with Positive Reflectivity Only

- Sub-waves (f_0, f_2, a_0, and a_2) are summed up into S/D-waves
- Binned fits appear to match K-matrix very well (binned results are bootstrapped for better error bars)
- Can we include negative reflectivity?



Choice of Wave Set

J^{PC}	0^{++}	2^{++}
$[\ell]_m^{(+)}$	S_0^+	D_2^+
$[\ell]_m^{(-)}$	S_0^-	

Mass-Dependent Fit with Both Reflectivities

The K-Matrix Amplitude + Z_ℓ^m

$$I(\Omega, m, \Phi) \propto (1-P_\gamma)\left|\sum_{\ell,m}\left(F_{f_0}^{(-)}(\vec{\beta}_{f_0^{(-)}}, m) + F_{a_0}^{(-)}(\vec{\beta}_{a_0^{(-)}}, m)\right)\Re[Z_0^0(\Omega, \Phi)]\right|^2 +$$

$$(1+P_\gamma)\left|\sum_{\ell,m}\left(F_{f_0}^{(-)}(\vec{\beta}_{f_0^{(-)}}, m) + F_{a_0}^{(-)}(\vec{\beta}_{a_0^{(-)}}, m)\right)\Im[Z_0^0(\Omega, \Phi)]\right|^2 +$$

$$(1+P_\gamma)\left|\left(F_{f_0}^{(+)}(\vec{\beta}_{f_0^{(+)}}, m) + F_{a_0}^{(+)}(\vec{\beta}_{a_0^{(+)}}, m)\right)\Re[Z_0^0(\Omega, \Phi)] + \left(F_{f_2}^{(+)}(\vec{\beta}_{f_2^{(+)}}, m) + F_{a_2}^{(+)}(\vec{\beta}_{a_2^{(+)}}, m)\right)\Re[Z_2^2(\Omega, \Phi)]\right|^2 +$$

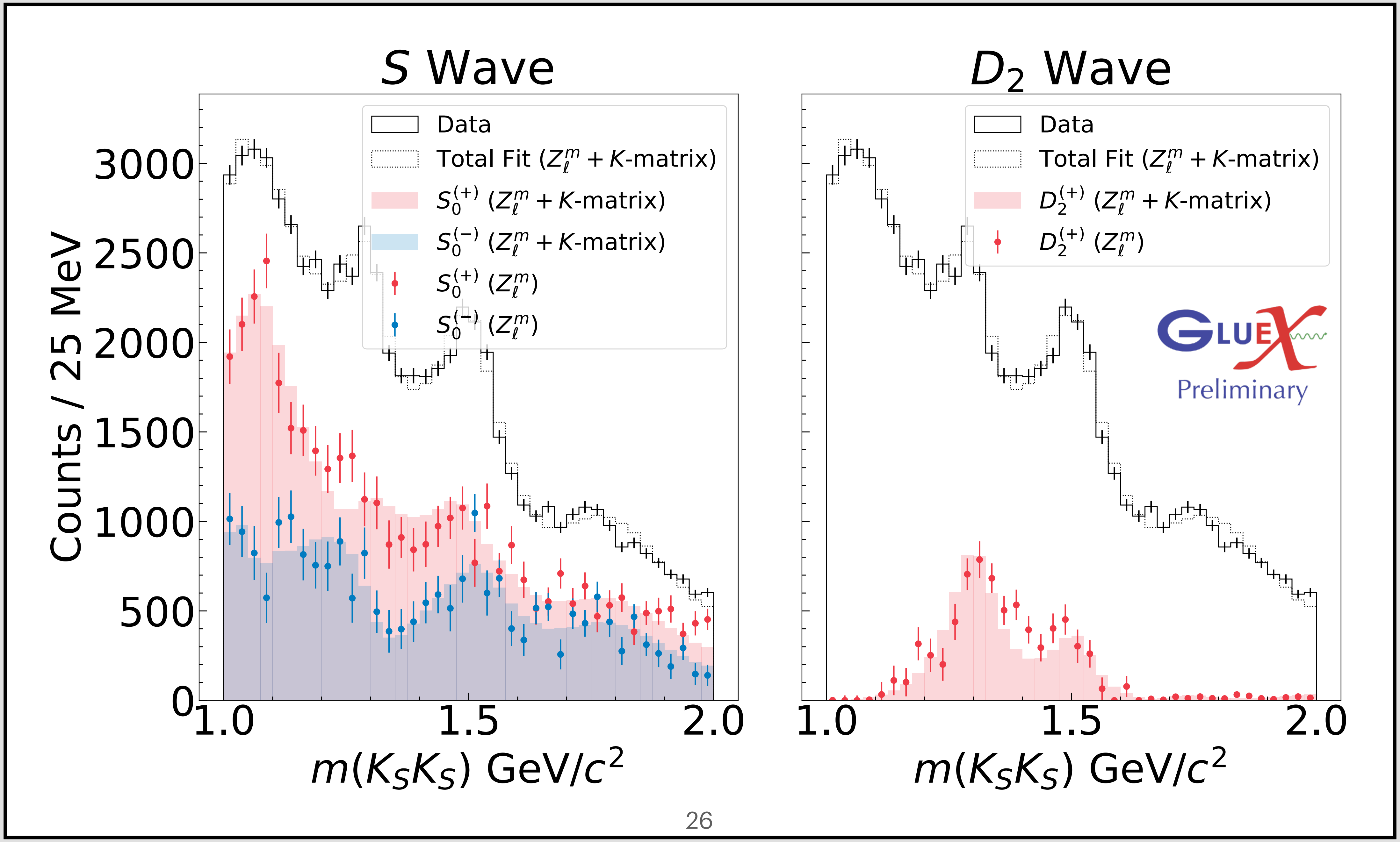
$$(1-P_\gamma)\left|\left(F_{f_0}^{(+)}(\vec{\beta}_{f_0^{(+)}}, m) + F_{a_0}^{(+)}(\vec{\beta}_{a_0^{(+)}}, m)\right)\Im[Z_0^0(\Omega, \Phi)] + \left(F_{f_2}^{(+)}(\vec{\beta}_{f_2^{(+)}}, m) + F_{a_2}^{(+)}(\vec{\beta}_{a_2^{(+)}}, m)\right)\Im[Z_2^2(\Omega, \Phi)]\right|^2$$

$$F_{I\ell}^{(\epsilon)}(\vec{\beta}, m) \equiv (1 + K_{I\ell}(m)C_{I\ell}(m))^{-1} \cdot P_{I\ell}(\vec{\beta}_{I\ell}^{(\epsilon)}, m)$$

$$Z_\ell^m(\Omega, \Phi) \equiv Y_\ell^m(\Omega)e^{-\imath\Phi}$$

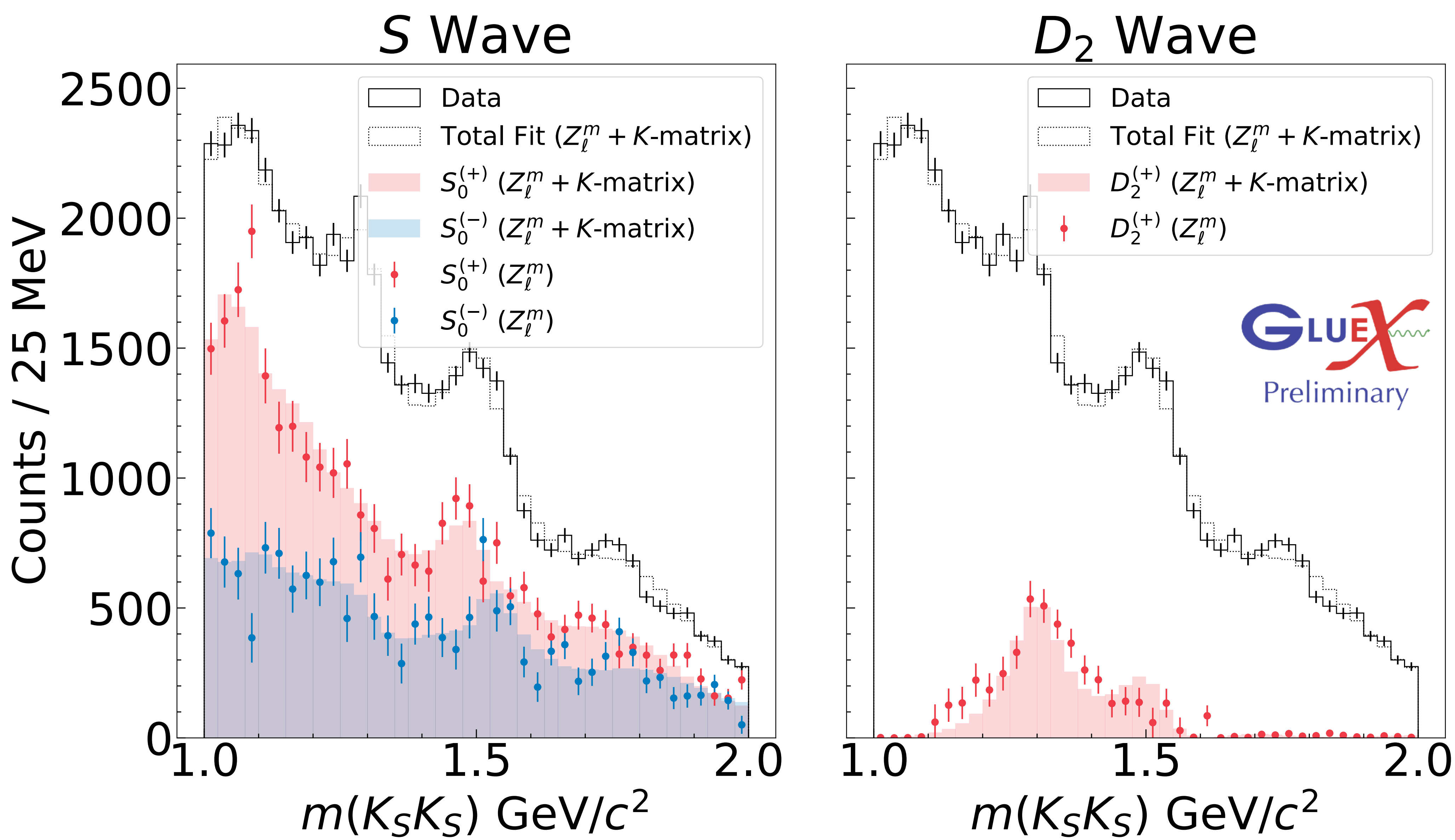
Fits with Both Reflectivities

- To add a negative-reflectivity S-wave, we have to add 11 new free parameters to the fit, 7 from the f_0 K-matrix and 4 from the a_0 K-matrix
- Can we do even more?



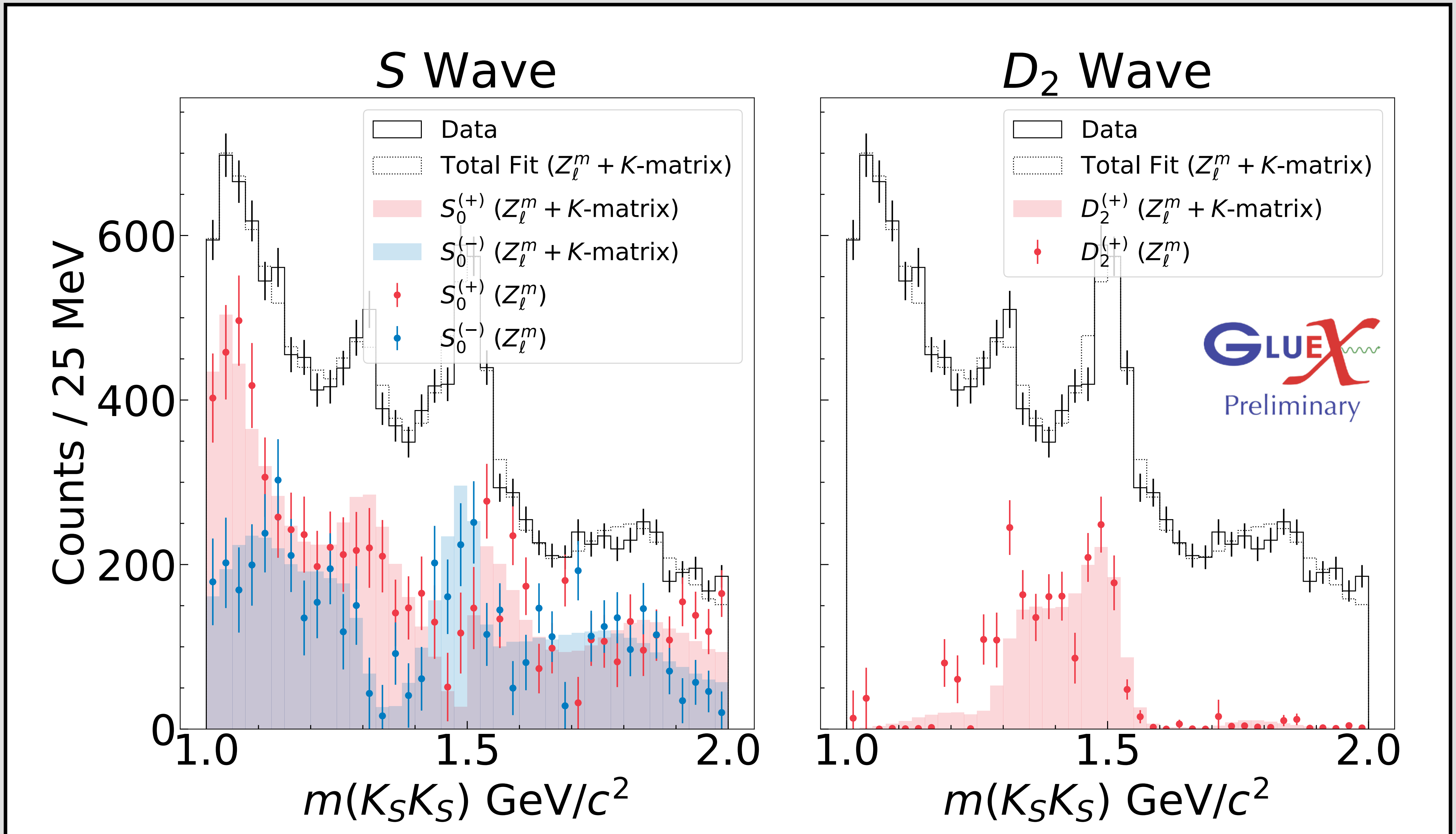
Fit Results Binned by t

- Let's examine the Mandelstam-t dependence
- First, let's look at $-t < 0.5$ GeV^2



Fit Results Binned by t

- Next, let's look at $-t > 0.5$ GeV^2
- A bit chaotic, but it actually still seems to match up nicely



Closing Remarks

- We have presented the latest data from **all current** GlueX analysis runs (2017-2020) — More data is being collected!
- A mass-independent partial-wave analysis shows the preliminary separation of spin-0 and spin-2 resonances in this channel
  - Strong indication of $f_2(1270)/a_2(1320)$ and $f_2'(1525)$
- A mass-dependent partial-wave analysis using a K-matrix parameterization shows similar results
- We can further divide both of these fits using the reflectivity basis and study Mandelstam t-dependence
- **Next Steps**:
  - We know there could (and should) be other D-wave projections in this channel, so we want to try increasing the number of waves to accommodate results from other GlueX channels
  - A coupled channel analysis with $\pi\pi$, $\pi\eta$, $\pi\eta'$, $\eta\eta$, and $\eta\eta'$ could isolate f_0 states in photoproduction

(Currently under investigation at GlueX)

Carnegie Mellon University

GlueX

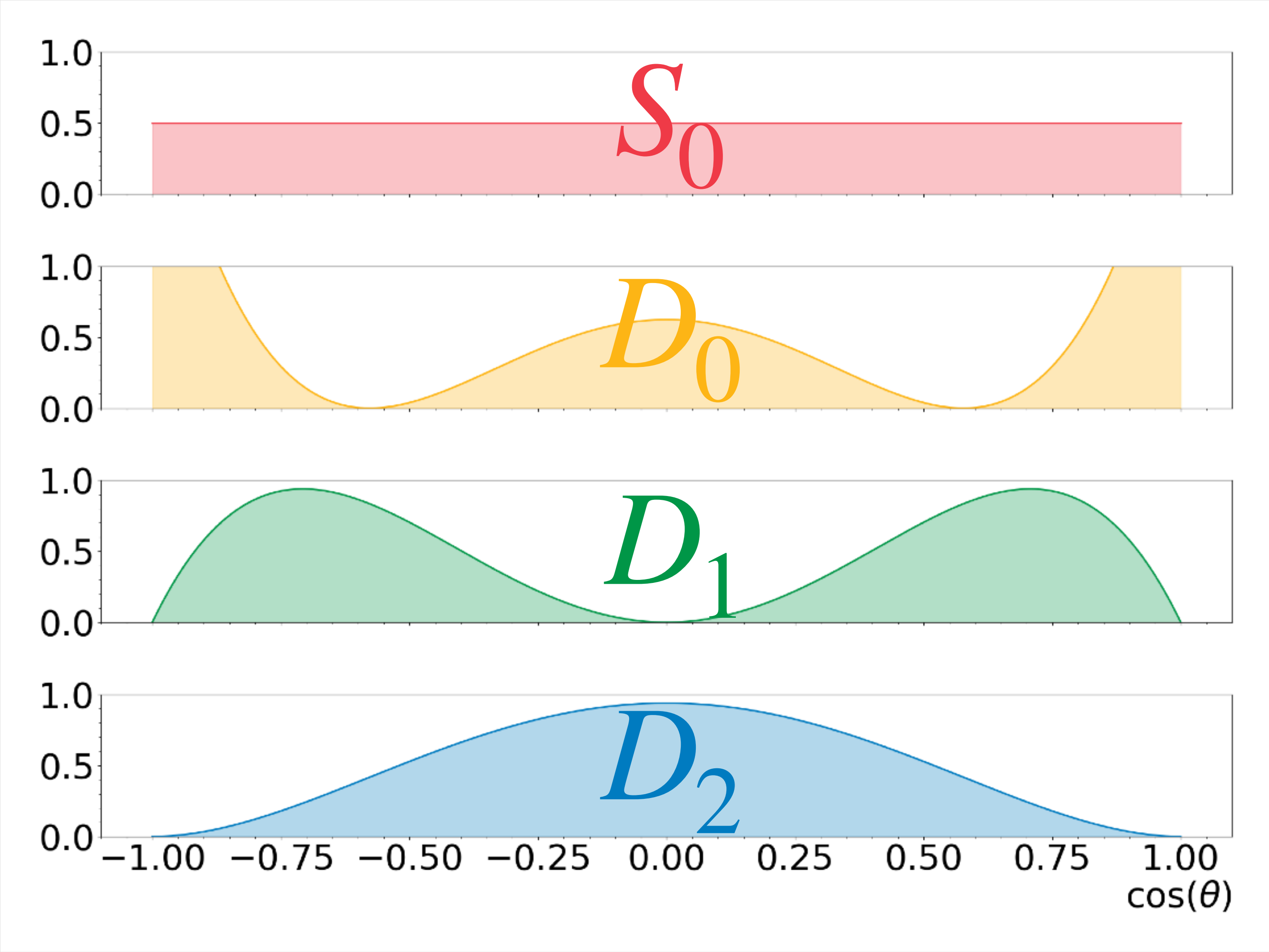
Thank you, GlueX Collaboration!
http://www.gluex.org/thanks.html

Backup

Partial-Wave Analysis

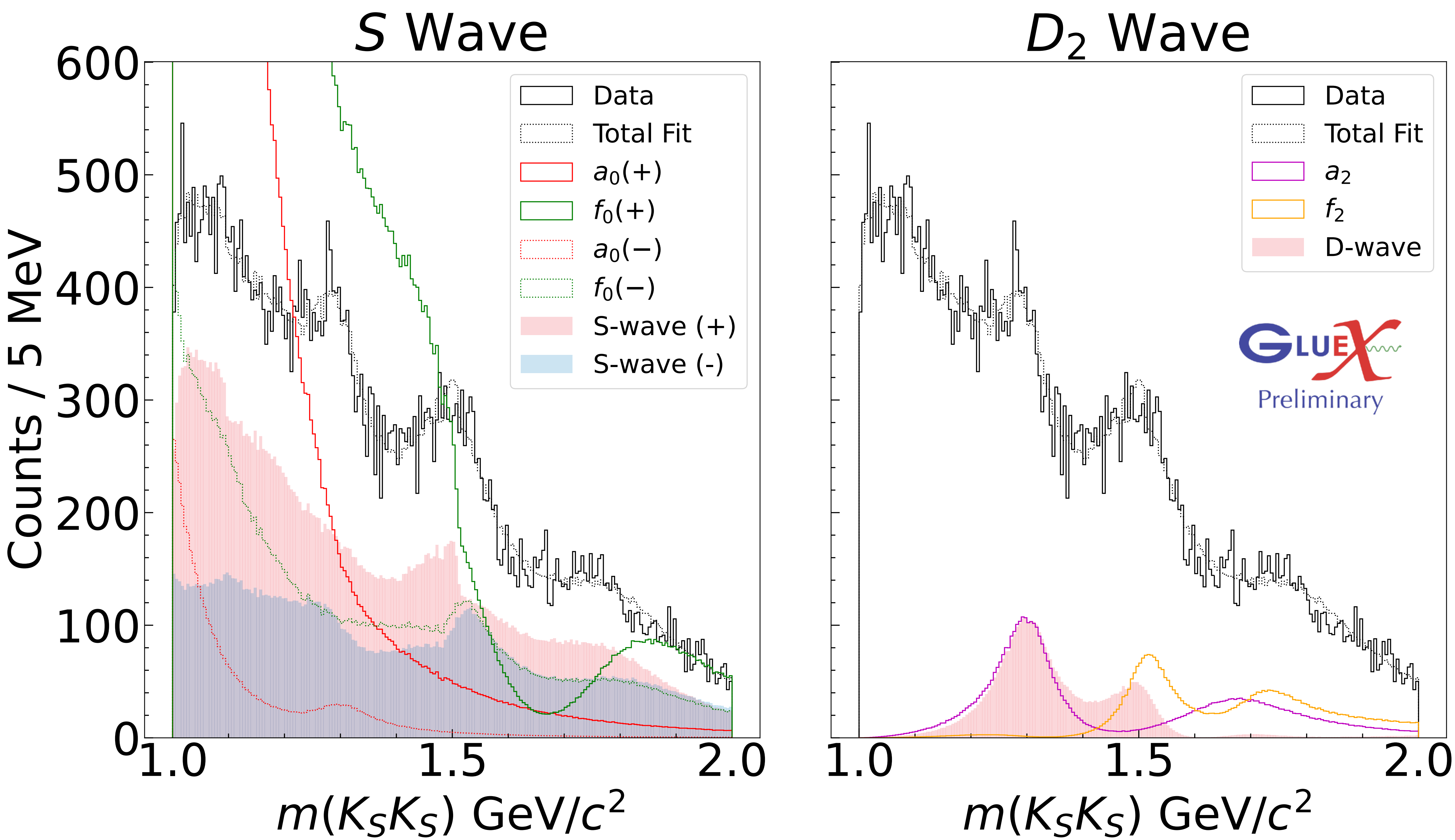
- Looking at the decay angles in the helicity frame, we should be able to distinguish spin:
  - f_0, a_0— flat in $\cos(\theta)$
  - f_2, a_2— <u>not</u> flat in $\cos(\theta)$

Note: Helicity angles are measured in the rest frame of the resonance—the z-axis is the boost direction



Projections of Y_ℓ^m Spherical Harmonics

Finer-binned K-Matrix for $-t < 0.5$



Finer-binned K-Matrix for $-t > 0.5$