Study on the $\phi\pi^0$ system in search for exotic mesons at GlueX

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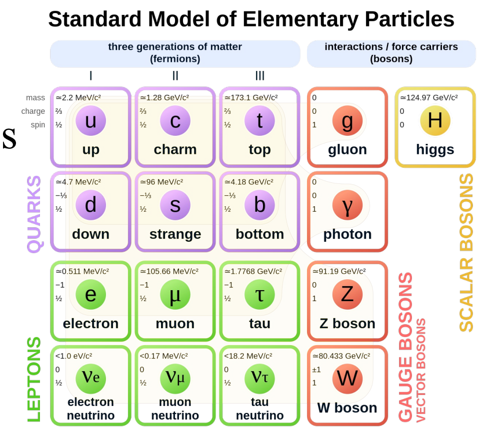
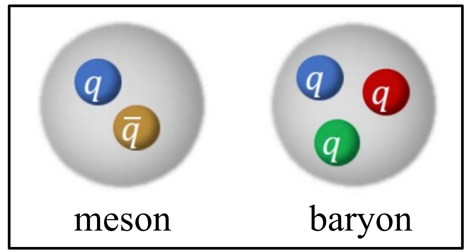
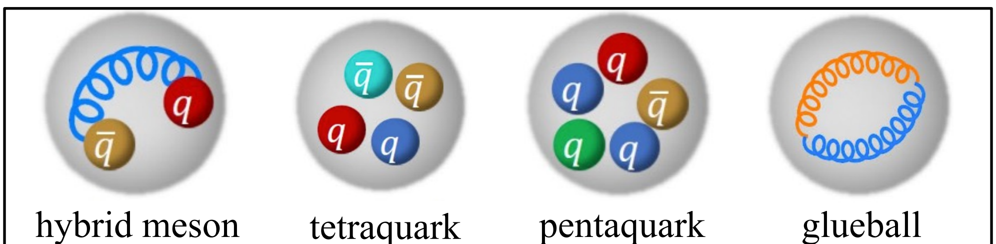
Introduction

—— Quantum Chromodynamics



- In the Standard Model, Quantum Chromodynamics (QCD) describes the strong interactions of quarks mediated by gluons.
- The bound state of quarks is called **"hadron"**
- In nature, hadrons appear to have 2 configurations according to the **Quark Model**
  - **Meson:** quark-antiquark state($q\bar{q}$)
  - **Baryon:** three-quark state(qqq)
- However, QCD allows other **"exotic"** configurations, for example:





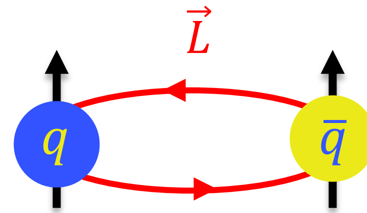
Introduction

—— Mesons in the Quark Model

- Mesons: quark-antiquark state($q\bar{q}$)
- Total spin $J = L \oplus S$
  - Spin $S = S_1 + S_2 = 0, 1$
  - The orbital angular momentum $L = 0, 1, 2, \ldots$
- Parity P
  - $\vec{r} \rightarrow -\vec{r}$
  - $P = (-1)^{L+1}$
- Charge conjugation C
  - Particle → Antiparticle, $q\bar{q} \rightarrow \bar{q}q$
  - $C = (-1)^{L+S}$
- Notation

$^{(2S+1)}L_J$ $\quad {}^1S_0,\ {}^3S_1,\ {}^1P_1,\ {}^3P_0,\ {}^3P_1,\ {}^3P_2, \ldots$

J^{PC} $\quad 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}, \ldots$



❖ Allowed J^{PC} for $q\bar{q}$

❖ Exotic J^{PC}

0^{--} 0^{++} 0^{-+} 0^{+-}

1^{--} 1^{++} 1^{-+} 1^{+-}

2^{--} 2^{++} 2^{-+} 2^{+-}

3^{--} 3^{++} 3^{-+} 3^{+-}

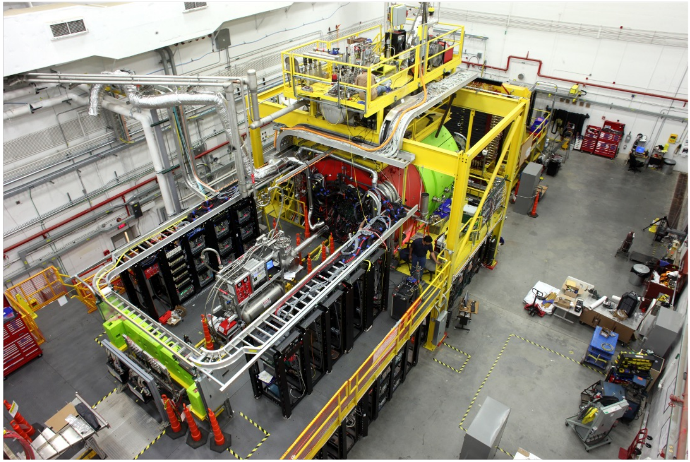
4^{--} 4^{++} 4^{-+} 4^{+-}

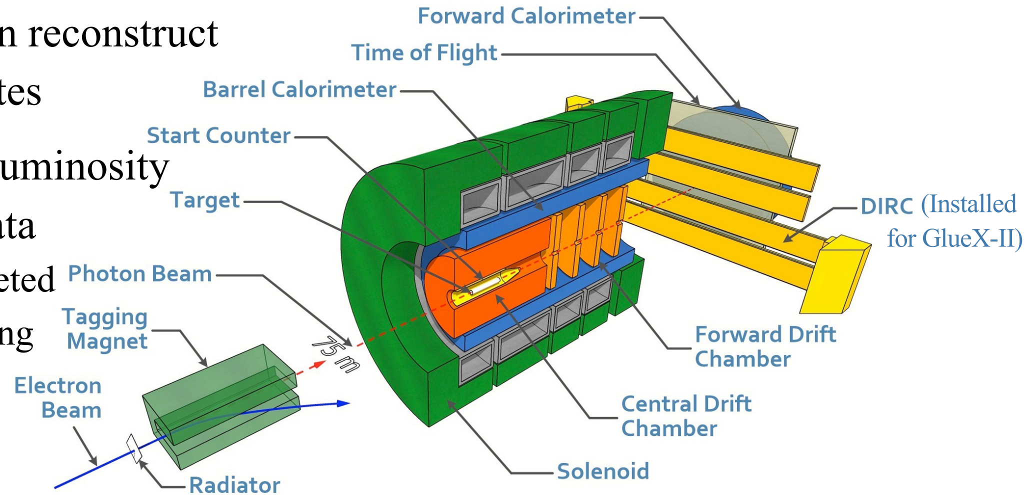
5^{--} 5^{++} 5^{-+} 5^{+-}

…

Introduction
—— GlueX Experiment

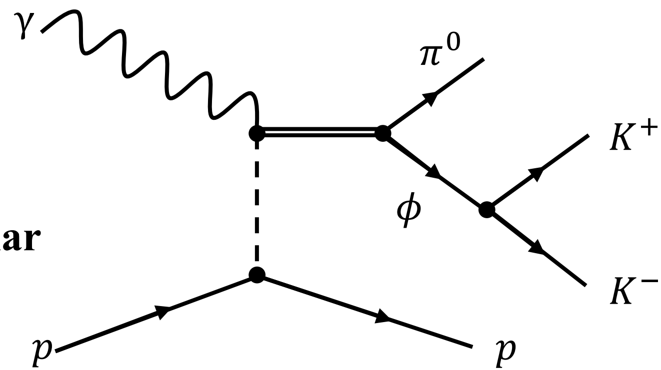
- GlueX's primary goal is to search for **exotic hybrid mesons**
- 12 GeV electron beam
- 9 GeV polarized photon beam
- Liquid hydrogen target(proton)
- GlueX detector can reconstruct exclusive final states
- $257.4\ pb^{-1}$ total luminosity from all current data
    - GlueX-I completed
    - GlueX-II ongoing





Introduction

—— $\phi\pi^0$ system



- Reaction: $\gamma p \rightarrow \phi\pi^0 p$
  with $\phi \rightarrow K^+K^-$, $\pi^0 \rightarrow \gamma\gamma$
- $\phi\pi^0$ is one of the **Vector-Pseudoscalar** systems
  J^{PC}: $\phi\ 1^{--}$, $\pi^0\ 0^{-+}$
- May find strange-quark counterparts to Z states in the charm and bottom sectors
- Possible J^{PC} for $\phi\pi^0$ system

L	J^{PC}			
0		1^{+-}		
1	0^{--}	1^{--}	2^{--}	
2		1^{+-}	2^{+-}	3^{+-}

- The 0^{--} and 2^{+-} are exotic quantum numbers, which are forbidden by quark model
- The 2^{--} is a state never seen before in light quark systems

Event Selection

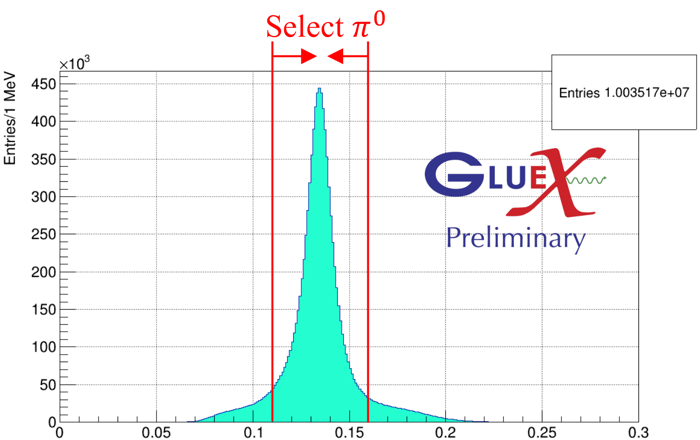
- GlueX Phase-I & Phase-II data
  - GlueX-II is ongoing. Only use the 2020 dataset
- Select exclusive reaction:

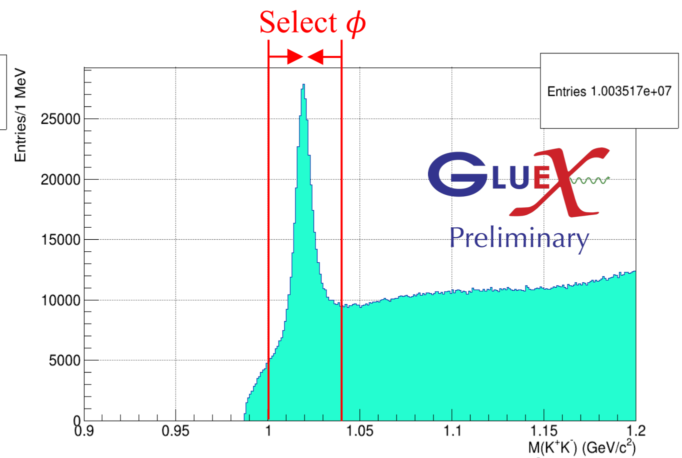
$$\gamma p \rightarrow K^+K^-\pi^0 p$$

  - A kinematic fit is performed on each event.

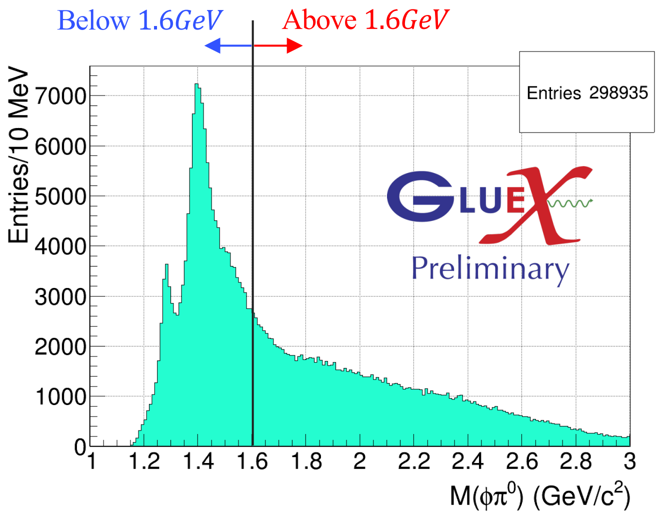
Basic selections and cuts:

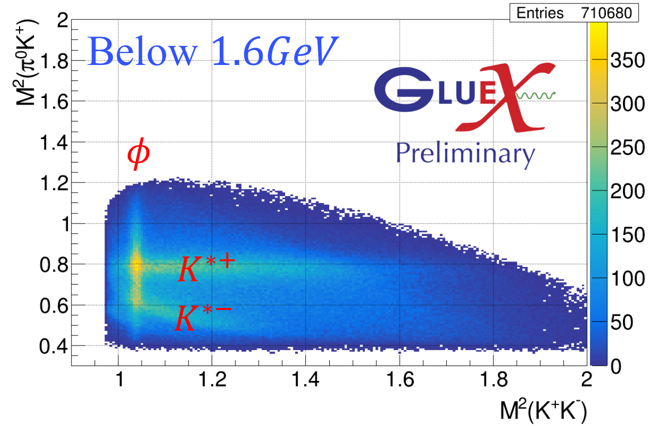
1. $\chi^2/ndf < 3.5$
2. $8.2GeV < E_{Beam} < 8.8GeV$
3. $-0.01 < MM^2 < 0.01$
4. $0.11GeV < M_{\pi^0} < 0.16GeV$
5. $1.00GeV < M_{\phi} < 1.04GeV$
6. Cut $1.4GeV < M_{\pi^0 p} < 1.8GeV$

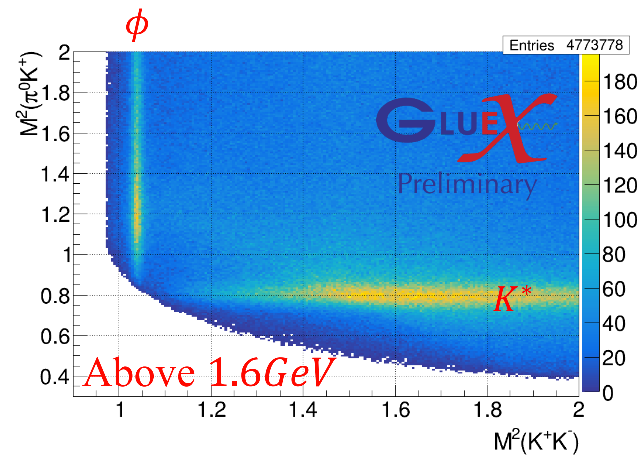




Event Selection



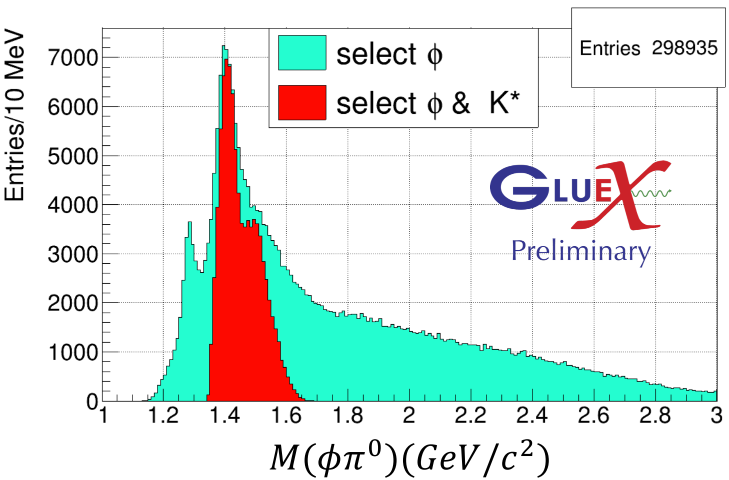




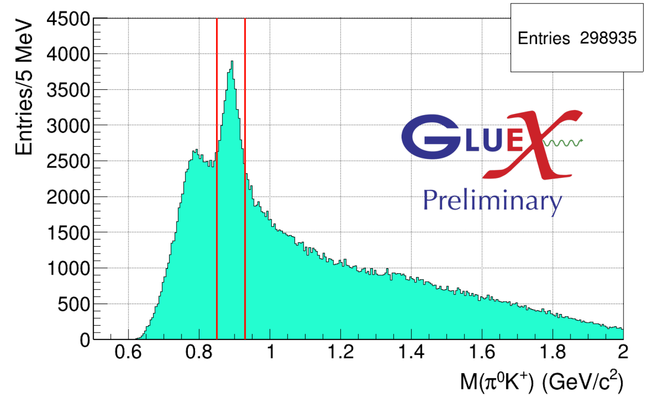
- One peak at 1.3GeV, the other at 1.4GeV
  - $f_1(1285) \rightarrow a_0(980)\pi^0 \rightarrow K^+K^-\pi^0$
  - $\eta(1405)/f_1(1420) \rightarrow K^*\overline{K} \rightarrow K^+K^-\pi^0$
- With Dalitz plot $M^2(\pi^0K^+)$ vs $M^2(K^+K^-)$
  - $M(\phi\pi^0) < 1.6GeV$, K^* leaks into ϕ selection
  - $M(\phi\pi^0) > 1.6GeV$, K^* and ϕ separate

$\eta(1405)/f_1(1420)$

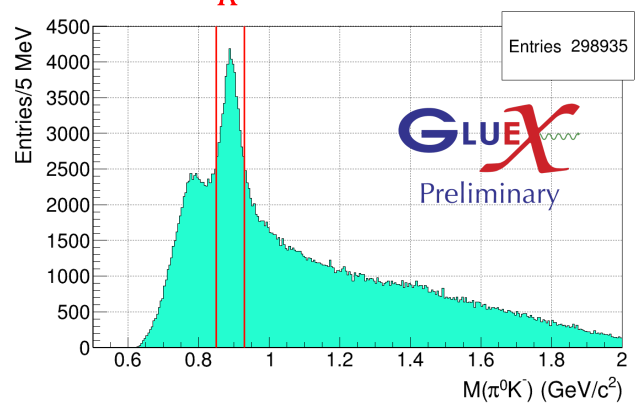
- Select K^{*+} or K^{*-}
- In the $\phi\pi^0$ spectrum, the peak around 1400 is $K^*\bar{K}$ resonance
  - $\eta(1405) \rightarrow K^*\bar{K} \rightarrow K^+K^-\pi^0$
  - $f_1(1420) \rightarrow K^*\bar{K} \rightarrow K^+K^-\pi^0$



K^{*+}

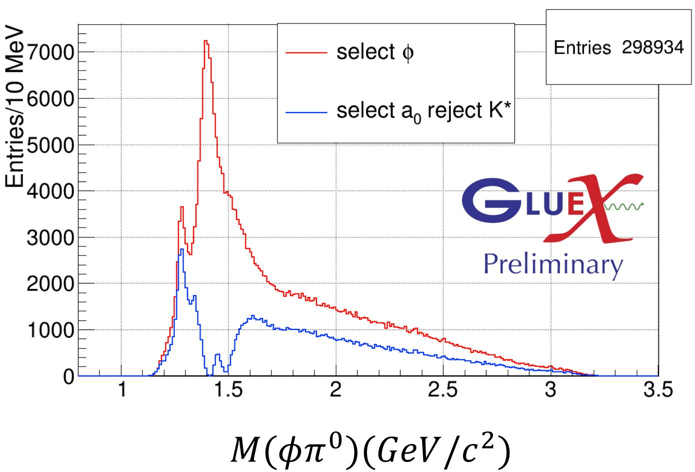


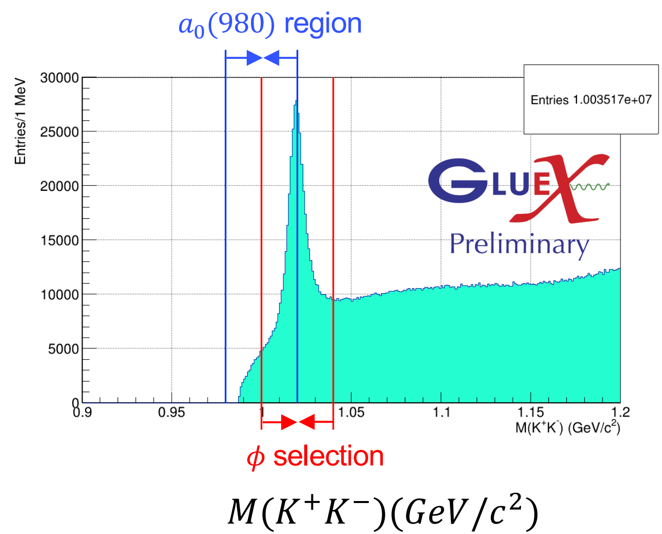
K^{*-}



$f_1(1285)$

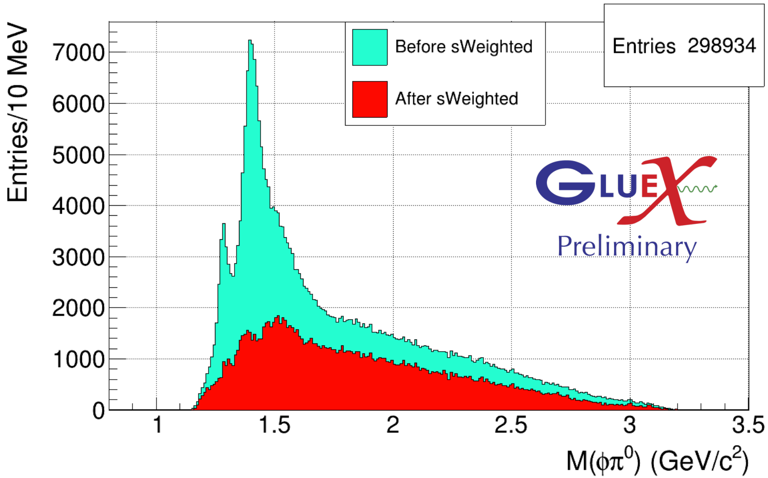
- $f_1(1285) \rightarrow a_0(980)\pi^0 \rightarrow K^+K^-\pi^0$
- $a_0(980)$ can decay to K^+K^- with a tail leaking into the ϕ mass region
- Select $a_0(980)$ from 0.98GeV to 1.02GeV and reject K^*
- The peak around 1280 is $f_1(1285)$ resonance





Background Subtraction

- With the *sPlot* formalism, we can assign weights to each events to statistically subtract the background
  - M. Pivk & F. Le Diberder. sPlot: A statistical tool to unfold data distributions, NIM A, 555 1-2, p.356-369 (2005)
  - Main idea: calculate weights by fitting with known probability distribution functions on a discriminating variable - $M(K^+K^-)$
- Compare $M(\phi\pi^0)$ for sWeighted data with unweighted data
  - Most of the 2 background peaks are suppressed



Partial Wave Analysis

1. The **angular distributions** of the final-state particles provide information about **spin** and **parity** of resonances
2. Extract different resonance amplitudes with **maximum likelihood fitting**

- Amplitudes and Intensity:

$$I(\Phi,\Omega,\Omega_H) = 2\kappa \sum_k$$

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$$\Bigg\{(1-P_\gamma)\left[\left|\sum_{i,m}[J_i]^{(-)}_{m,k} Im(Z)\right|^2 + \left|\sum_{i,m}[J_i]^{(+)}_{m,k} Re(Z)\right|^2\right] +$$

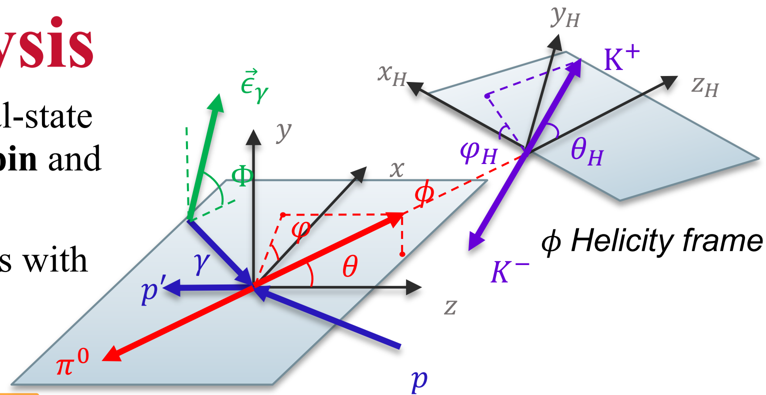
$$(1+P_\gamma)\left[\left|\sum_{i,m}[J_i]^{(+)}_{m,k} Im(Z)\right|^2 + \left|\sum_{i,m}[J_i]^{(-)}_{m,k} Re(Z)\right|^2\right]\Bigg\}$$

$$Z^i_m(\Phi,\Omega,\Omega_H) = e^{-i\Phi} X^i_m(\Omega,\Omega_H)$$

$$X^i_m(\Omega,\Omega_H) = \sum_{\lambda=-1,0,1} D^{J_i *}_{m,\lambda}(\Omega) F^i_\lambda D^{1*}_{\lambda,0}(\Omega_H) G$$

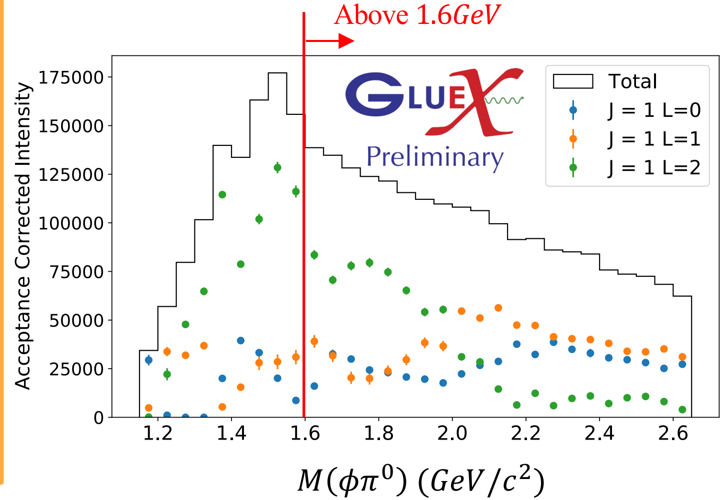
super script (+/−): reflectivity $\epsilon = \tau_i \tau_e$

- τ_i : Naturality of the produced system($\phi\pi^0$)
- τ_e : Naturality of the exchanged particle
- Naturality $\tau = P(-1)^J$



Helicity frame of $\phi\pi^0$

Fit with 3 amplitudes: $1^+[S]$ $1^-[P]$ $1^+[D]$



Summary

- GlueX Phase-I & Phase-II data
- 2 peaks on the $\phi\pi^0$ invariant mass spectrum are from background
  - $f_1(1285) \to a_0(980)\pi^0 \to K^+K^-\pi^0$
  - $\eta(1405)/f_1(1420) \to K^*\overline{K} \to K^+K^-\pi^0$
- *sPlot* can remove most of the $K^+K^-\pi^0$ background
  - Some background events are left for $M(\phi\pi^0) < 1.6GeV$
- Partial Wave Analysis
  - Fit with $1^+[S,D], 1^-[P]$ amplitudes
  - $1^+[D]$ amplitude is dominant with a bump around $1.8GeV$
  - $1^+[S]$ and $1^-[P]$ amplitudes are relatively flat

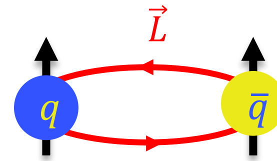
- GlueX acknowledges the support of several funding agencies and computing facilities: www.gluex.org/thanks

Backup slides

Introduction

Mesons in the Quark Model

- Quarks are fermions with ½ spin.
- Total spin $J = L \oplus S$
  - Spin $S = S_1 + S_2 = 0, 1$
  - The orbital angular momentum
    $L = 0, 1, 2, \ldots$
  - Notation: $^{(2S+1)}L_J$
    $^1S_0, {}^3S_1, {}^1P_1, {}^3P_0, {}^3P_1, {}^3P_2, \ldots$
- Parity P
  - $\vec{r} \to -\vec{r}$
  - Spin is invariant under parity operator
  - $P[\psi(\vec{r})] = \psi(-\vec{r}) = \eta_P \psi(\vec{r})$
  - With $Y_{LM}(\pi - \theta, \pi + \varphi) = (-1)^L Y_{LM}(\theta, \varphi)$
  - Intrinsic parity of fermion-antifermion: -1
  - $P = (-1)^{L+1}$



J	$L = 0$	$L = 1$	...
$S = 0$	0	1	...
$S = 1$	1	0, 1, 2	...

Wavefunctions:

$$\Psi(\vec{r}, \vec{S}) = \psi(\vec{r})\, \chi(\vec{S})$$

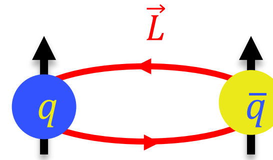
$$\psi(\vec{r}) = R_{NL}(r)\, Y_{LM}(\theta, \varphi)$$

Under parity operator:

$$\psi(-\vec{r}) = R_{NL}(r)\, Y_{LM}(\pi - \theta, \pi + \varphi)$$

Introduction

Mesons in the Quark Model



- Charge conjugation C
  - Particle → Antiparticle, $q\bar{q} \to \bar{q}q$
  - Effectively take $\vec{r} \to -\vec{r}$ like parity. We first get a factor $(-1)^{L+1}$.
  - The spin function is exchanged, $|\alpha, \beta > \to |\beta, \alpha >$
    - For $S = 1$, symmetric spin function $\Longrightarrow (+1)$.
    - For $S = 0$, antisymmetric spin function $\Longrightarrow (-1)$.
  - $C = (-1)^{L+S}$

➢ $S = 1$

$$|1,+1\rangle = |+,+\rangle$$

$$|1,0\rangle = \frac{1}{\sqrt{2}}(|+,-\rangle + |-,+\rangle)$$

$$|1,-1\rangle = |-,-\rangle$$

➢ $S = 0$

$$|0,0\rangle = \frac{1}{\sqrt{2}}(|+,-\rangle - |-,+\rangle)$$

- Notation ${}^{(2S+1)}L_J$ ${}^1S_0,\ {}^3S_1,\ {}^1P_1,\ {}^3P_0,\ {}^3P_1,\ {}^3P_2, \ldots$

  J^{PC} $0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}, \ldots$

❖ Allowed J^{PC} for $q\bar{q}$

❖ Exotic J^{PC}

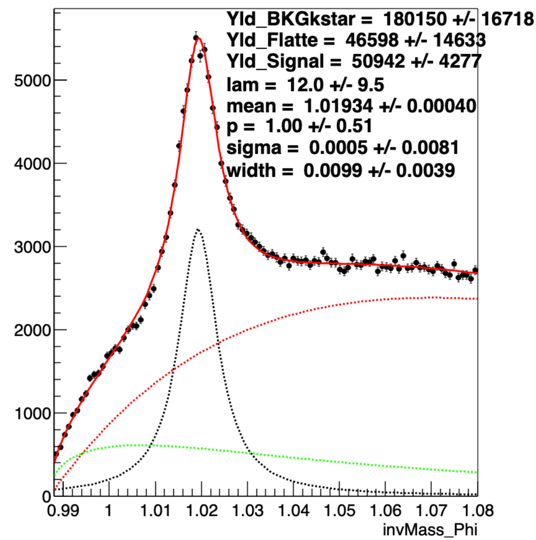
0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

...

sPlot

- *sPlot* method can separate different sources of events (signal, bkg)
  - Need a discriminating variable for which the distributions of different sources of events are known
  - Perform fits to probability distribution functions (PDF)
  - Calculate the weight
- Use the $M(K^+K^-)$ as the discriminating variable
- Fit to different PDF sets for events in different $M(\phi\pi^0)$ regions:
  1. For $M(\phi\pi^0) < 1.6GeV$
     - ---- signal: Voigtian distribution
     - ---- K^*K bkg: $(m - m_0)^p e^{-\lambda m}$
     - ---- $a_0(980)$ bkg: Flatte distribution

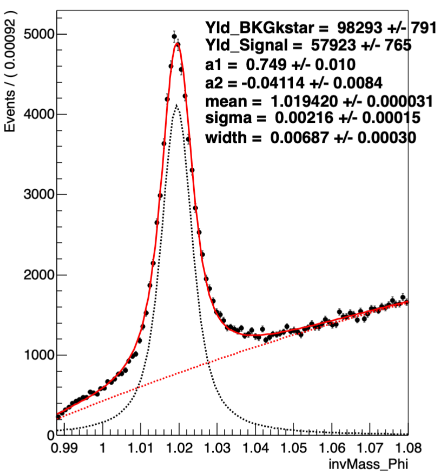
$Fit\ for\ M(\phi\pi^0) < 1.6GeV$



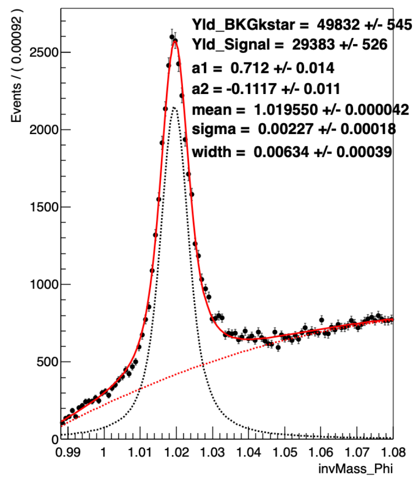
sPlot

2. For $M(\phi\pi^0) > 1.6GeV$
   - Slice $M(\phi\pi^0)$ to 3 bins, fit each bin separately
   - ---- signal: Voigtian distribution
   - ---- bkg, 2nd Chebyshev polynomial $a_2T_2(x) + a_1T_1(x) + 1$

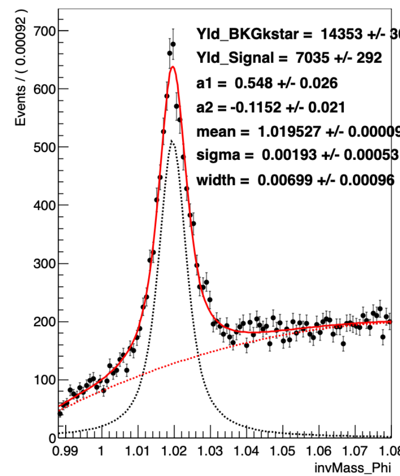
Fit for $M(\phi\pi^0) \in [1.6,2.13]$



Fit for $M(\phi\pi^0) \in [2.13,2.66]$

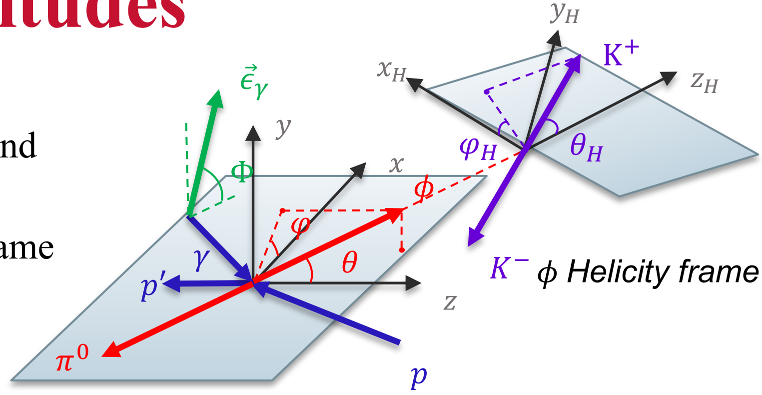


Fit for $M(\phi\pi^0) \in [2.66,3.2]$



Definition of Amplitudes

- Described by 5 angles:
  - **Φ** between polarization vector and the production plane
  - $\boldsymbol{cos\theta, \varphi}$ in the resonance rest frame
  - $\boldsymbol{cos\theta_H, \varphi_H}$ in the ϕ rest frame
- Reflectivity basis:
  - Amplitudes can be decomposed to reflectivity basis $\epsilon = \pm$
  - Reflectivity is correlated with naturality of the exchange particle
- Naturality: $\tau = P(-1)^J$
  - The produced resonance can be natural or unnatural



Helicity frame of $\phi\pi^0$

Possible Produced Resonances

L	J^{PC}(Naturality)			
0		$1^{+-}(-1)$		
1	$0^{--}(-1)$	$1^{--}(+1)$	$2^{--}(-1)$	
2		$1^{+-}(-1)$	$2^{+-}(+1)$	$3^{+-}(-1)$

- Reflectivity $\epsilon = \tau_i \tau_e$
  - τ_i : Naturality of the produced system($\phi\pi^0$)
  - τ_e : Naturality of the exchanged particle

Definition of Amplitude

- Amplitudes and Intensity:

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$$I(\Phi,\Omega,\Omega_H) = 2\kappa \sum_k$$

$$\left\{(1-P_\gamma)\left[\left|\sum_{i,m}[J_i]^{(-)}_{m,k} Im(Z)\right|^2 + \left|\sum_{i,m}[J_i]^{(+)}_{m,k} Re(Z)\right|^2\right] + \right.$$

$$\left.(1+P_\gamma)\left[\left|\sum_{i,m}[J_i]^{(+)}_{m,k} Im(Z)\right|^2 + \left|\sum_{i,m}[J_i]^{(-)}_{m,k} Re(Z)\right|^2\right]\right\}$$

$$Z^i_m(\Phi,\Omega,\Omega_H) = e^{-i\Phi} X^i_m(\Omega,\Omega_H)$$

$$X^i_m(\Omega,\Omega_H) = \sum_{\lambda=-1,0,1} D^{J_i *}_{m,\lambda}(\Omega) F^i_\lambda D^{1*}_{\lambda,0}(\Omega_H) G$$

- Wigner D Matrix: JM frame → Helicity frame
  - λ: helicity of ϕ
- F describes $X \to \phi\pi$
  - $F^i_\lambda = \sum_L \langle J_i;\lambda | LS;0\lambda\rangle\, C^i_L$
- G describes $\phi \to K^+K^-$
- D-wave/S-wave ratio $D/S = C^i_D / C^i_S$

L	J^{PC}(Naturality)			
0		$1^{+-}(-1)$		
1	$0^{--}(-1)$	$1^{--}(+1)$	$2^{--}(-1)$	
2		$1^{+-}(-1)$	$2^{+-}(+1)$	$3^{+-}(-1)$

- Fit from 1.15GeV to 2.65GeV
  - 30 bins, 50MeV binwidth
- $\mathbf{1^+[S,D], 1^-[P]}$
- Reflectivity $\epsilon = \pm$,
- All spin projection
- All polarization orientation
- D/S as a **Real** number

- k = 0/1: nucleon spin non-flip/flip (experimentally indistinguishable)

Possible particle states

- $\mathbf{1^+[S,D]}$, b-like
- $\mathbf{1^-[P]}$, ρ-like

- Entries without the black dot "•" are not established.

- b_1 is too close to the threshold
- $\rho(1450)$ is affected by the K^* bkg
- $\rho(1700)$ may be the only possible one

• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$X(1750)$	$?^-(1^{--})$
• $f_0(980)$	$0^+(0^{++})$	$\eta(1760)$	$0^+(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	$f_2(1810)$	$0^+(2^{++})$
• $h_1(1170)$	$0^-(1^{+-})$	$X(1835)$	$?^?(0^{-+})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $a_1(1260)$	$1^-(1^{++})$	• $\eta_2(1870)$	$0^+(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_1(1285)$	$0^+(1^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $\eta(1295)$	$0^+(0^{-+})$	$f_2(1910)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$a_0(1950)$	$1^-(0^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $a_4(1970)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2005)$	$1^-(2^{-+})$
• $h_1(1415)$	$0^-(1^{+-})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2020)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	• $f_4(2050)$	$0^+(4^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $a_0(1450)$	$1^-(0^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$\rho(2150)$	$1^+(1^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $\phi(2170)$	$0^-(1^{--})$
$f_1(1510)$	$0^+(1^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$\rho(1570)$	$1^+(1^{--})$	$\rho_3(2250)$	$1^+(3^{--})$
$h_1(1595)$	$0^-(1^{+-})$	• $f_2(2300)$	$0^+(2^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_4(2300)$	$0^+(4^{++})$
• $a_1(1640)$	$1^-(1^{++})$	$f_0(2330)$	$0^+(0^{++})$
$f_2(1640)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$\rho_5(2350)$	$1^+(5^{--})$
• $\omega(1650)$	$0^-(1^{--})$	$X(2370)$	$?^?(?^{??})$
• $\omega_3(1670)$	$0^-(3^{--})$	$f_6(2510)$	$0^+(6^{++})$