Studying the hadronic and semi-leptonic Decay Modes of the $\eta^{(\prime)}$-Meson with GlueX-I

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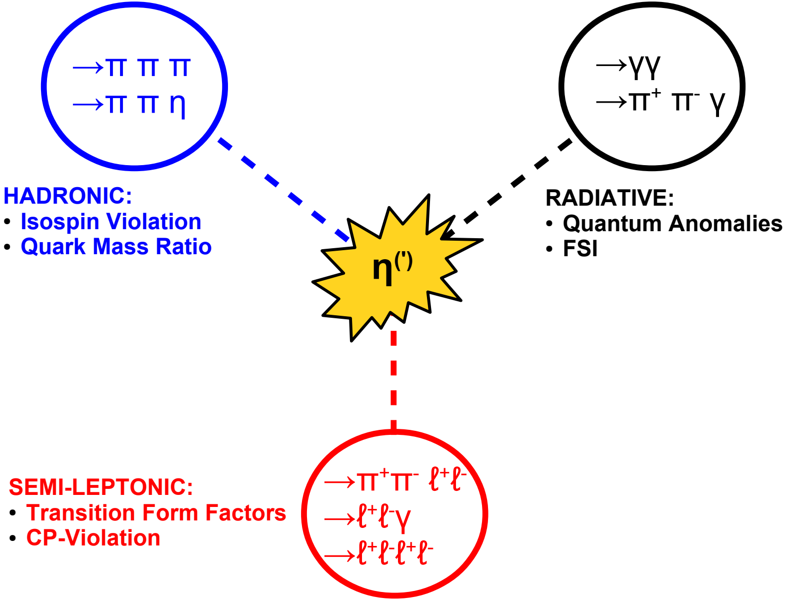
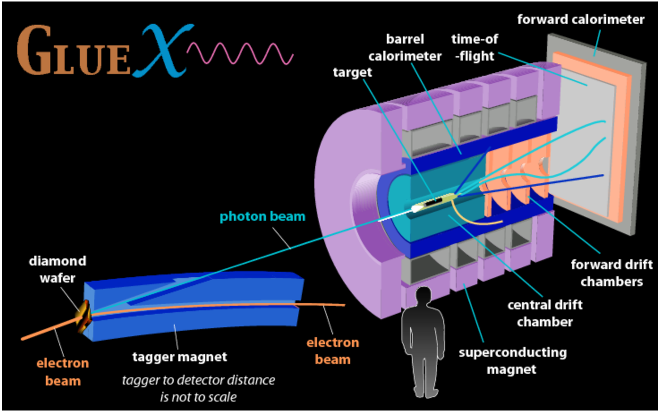
The $\eta^{(\prime)}$-Trinity



The GlueX Experiment



- Completed data taking phase I in fall 2018:

Run Period	Luminosity $[\mathrm{pb}^{-1}]$
2016	10
2017	45
2018	150

- Continue data taking with DIRC upgrade and high intensity beam in fall 2019

$\boxed{\eta \to \pi^+\pi^-\pi^0}$ Decay Dynamics

System	Isospin State $\|I, I_z\rangle$	C-Eigenvalue	G-Eigenvalue
η	$\|0,0\rangle$	$+1$	$+1$
$(\pi^+\pi^-\pi^0)$	$\|0,0\rangle$	-1	-1
$(\pi^+\pi^-\pi^0)$	$\|1,0\rangle$	$+1$	-1

- Decay $\eta \to \pi^+\pi^-\pi^0$ is G-violating $\Rightarrow$ Forbidden to first order
- Decay is driven by isospin breaking part of strong interaction
  $\Rightarrow$ C is conserved
- Decay width: $\Gamma \propto Q^{-4}$

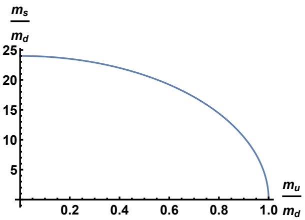
  with: $Q^2 = \left(\frac{m_s}{m_d}\right)^2 \times \left[1 - \left(\frac{m_u}{m_d}\right)^2\right]^{-1}$

$\Rightarrow$ **Determine decay width Γ $\Rightarrow$ Access to quark mass ratio**

$\Downarrow$

a) Measure $\Gamma(\eta \to \pi^+\pi^-\pi^0)$, e.g. via $\frac{\Gamma(\eta \to \pi^+\pi^-\pi^0)}{\Gamma(\eta \to \gamma\gamma)}$

b) Dalitz Plot Analysis



$\boxed{\eta \to \pi^+\pi^-\pi^0}$ Dalitz Plot Analysis

- Parameterize decay width Γ:

$$\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \cdots)$$

- With dimensionless variables:

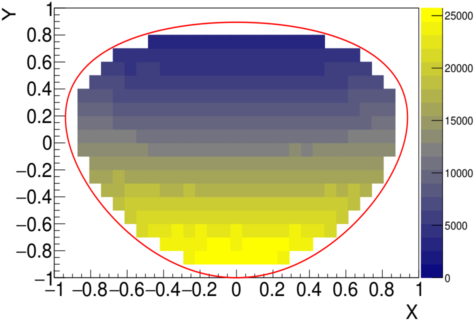
$$X = \sqrt{3}(T_{\pi^+} - T_{\pi^-})/\Sigma_T \to \text{Sensitive to charge conjugation}$$

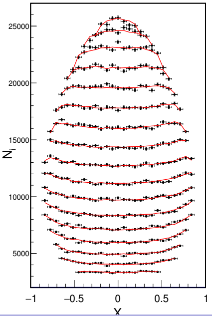
$$Y = 3T_{\pi^0}/\Sigma_T - 1$$

- Results from KLOE: KLOE coll., *JHEP*, 019, (2016)

i) η-Mesons produced via: $e^+e^- \to \Phi \to \eta\gamma$

ii) $\approx 4.7\,\mathrm{M}$ $\eta \to \pi^+\pi^-\pi^0$ events





$\boxed{\eta \to \pi^+\pi^-\pi^0}$ Dalitz Plot Analysis

- Parameterize decay width Γ:

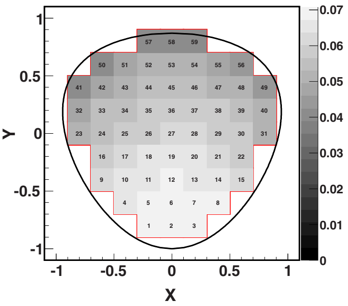
  $\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \cdots)$
- With dimensionless variables:

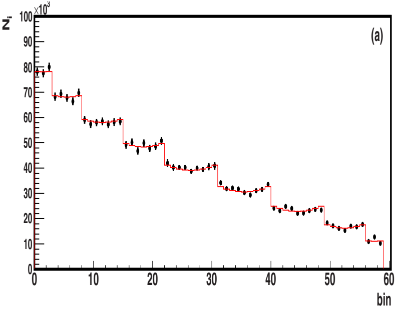
  $X = \sqrt{3}(T_{\pi^+} - T_{\pi^-})/\Sigma_T$ → Sensitive to charge conjugation

  $Y = 3T_{\pi^0}/\Sigma_T - 1$
- Results from WASA-at-COSY: WASA-at-COSY coll., *Phys. Rev.*, C90(045207), (2014)

i) η-Mesons produced via: $pd \to {}^3\mathrm{He}\eta$

ii) $\approx 120\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events





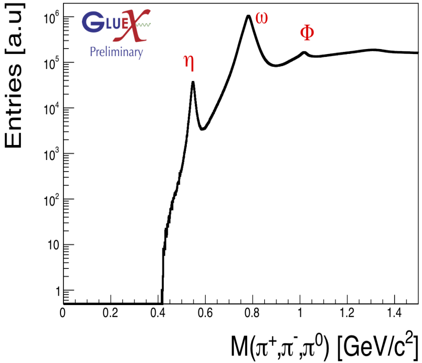
$\eta \to \pi^+\pi^-\pi^0$ Recent Results

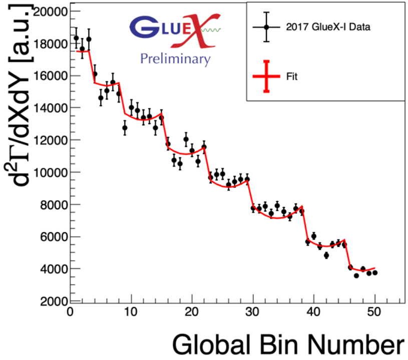
	Parameter:	$-$ a	b	d	f
Exp.	KLOE(08)[a]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[d]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE(16)[f]	1.104(3)(2)	$0.142(6)(^{5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
Theo.	ChPT (NNLO)[b]	1.271(75)	0.394(102)	0.055(57)	0.025(160)
	NREFT[c]	1.213(14)	0.308(23)	0.050(3)	0.083(19)
	PWA[e]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
	PWA[g]	1.077(29)	0.170(8)	0.060(2)	0.091(3)

(a) KLOE coll., *JHEP*, 05, (2008)
(b) J. Bijnens and K. Ghorbani., *JHEP*, 11, (2007)
(c) S- P. Schneider et al., *JHEP*, 028, (2011)
(d) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), (2014)
(e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)
(f) KLOE coll., *JHEP*, 019, (2016)
(g) Peng Guo et al., *Phys. Lett.*, B771(497-502), (2017)

- Partial wave analysis performed by JPAC:
  WASA-at-COSY: $Q = 21.4 \pm 1.1$[e] ($\sim 120\,\mathrm{k}$ events)
  KLOE: $Q = 21.7 \pm 1.1$[g] ($\sim 4.7 \cdot 10^6$ events)
- CLAS6 Dalitz Plot analysis on g12 data ongoing
- **Perform Dalitz Plot Analysis with GlueX-I Data**
  1.) $\boldsymbol{\eta \to \pi^+\pi^-\pi^0}$
  2.) $\eta' \to \pi^+\pi^-\eta$

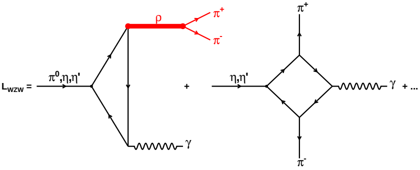
$\boxed{\eta \to \pi^+\pi^-\pi^0}$ Status GlueX-I Data Analysis





- $\approx 300\,\mathrm{k}$ $\eta \to \pi^+\pi^-\pi^0$ events reconstructed in 2017 data set
- No asymmetry observed: c, e (and h) are consistent with 0
- Dalitz Plot analysis for GlueX-I 2018 data set ongoing

$\boxed{\eta^{(\prime)} \to \pi^+\pi^- e^+ e^-}$ **Box Anomaly, FSI** and CP-Violation

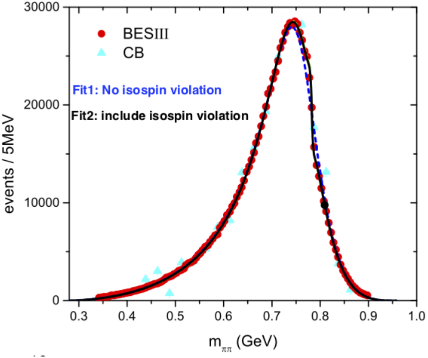


Underlying decay: $\eta^{(\prime)} \to \pi^+\pi^-\gamma$

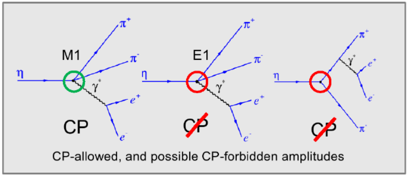
- Wess-Zumino-Witten-Lagrangian
  $+\ \pi\pi$-FSI
- CP-Conserving for M_1 and E_2 photon transitions

- Study $M(\pi^+,\pi^-)$-Distribution:
  - i) Determine contributions from box anomaly term
  - ii) Insights into $\pi\pi$-FSI
    $\Rightarrow$ mainly ρ-Resonance for η'
- Amplitude analysis for decay:
  $\eta' \to \pi^+\pi^-\gamma$

Ling-Yun Dai et al., Phys. Rev. D97(036012),(2018)



$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$ Box Anomaly, FSI and **CP-Violation**



Underlying decay: $\eta^{(\prime)} \to \pi^+\pi^-\gamma$

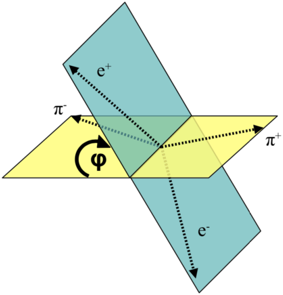
- Wess-Zumino-Witten-Lagrangian $+\ \pi\pi$-FSI
- CP-Conserving for M_1 and E_2 photon transitions
- Access to CP-violation $\to$ Measure E_1 γ transition $\to$ Need information about γ polarization

Virtual case: $\eta^{(\prime)} \to \pi^+\pi^-\gamma^*$

- Where: $\gamma^* \to e^+e^-$
  $\Rightarrow$ suppressed by $\approx \alpha$
- Polarization encoded in $(\pi^+\pi^-)$-(e^+e^-) decay planes

Illustration on the bottom right taken from:

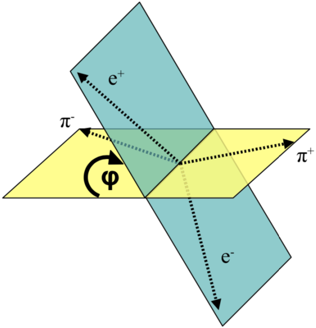
WASA-at-COSY coll. *Phys. Rev.C*,94 ,065206 (2016)

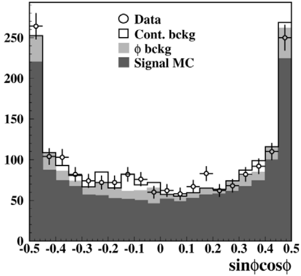


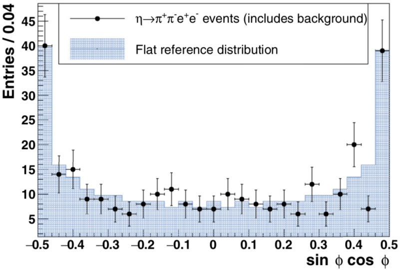
$\eta \to \pi^+\pi^-e^+e^-$ Asymmetry

- $A_\Phi = \frac{N(\sin[\Phi]\cos[\Phi]>0) - N(\sin[\Phi]\cos[\Phi]<0)}{N(\sin[\Phi]\cos[\Phi]>0) + N(\sin[\Phi]\cos[\Phi]<0)}$
- Measuring A_Φ reveals information about CP-violating transitions
- Upper limit predicted by theory[a]: $\sim 1\%$

  (a) D. Gao. *Mod. Phys. Lett.*, A17:1583-1588,(2002)
- Measurements of A_Φ performed by:
  i) KLOE (bottom left)
  ii) WASA-at-COSY (bottom right)







$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$ Asymmetry and Branching Fraction

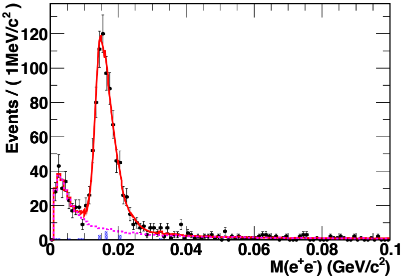
Experiment	X	$\frac{\Gamma(X\to\pi^+\pi^-e^+e^-)}{\Gamma_X}$ $[10^{-4}]$	A_Φ $[10^{-2}]$	#Events $[k]$
WASA $^{(b)}$	η	$2.7 \pm 0.2_{stat} \pm 0.2_{sys}$	$-1.1 \pm 6.6_{stat} \pm 0.2_{sys}$	0.215
KLOE $^{(c)}$	η	$2.68 \pm 0.09_{stat} \pm 0.07_{sys}$	$-0.6 \pm 2.5_{stat} \pm 1.8_{sys}$	1.6
BESIII $^{(d)}$	η'	$21.1 \pm 1.2_{stat} \pm 1.5_{sys}$	n/a	0.429

(b) WASA-at-COSY coll. *Phys. Rev.C*,94 ,065206 (2016)

(c) KLOE coll. *Phys. Lett.B*,675 ,283-288 (2009)

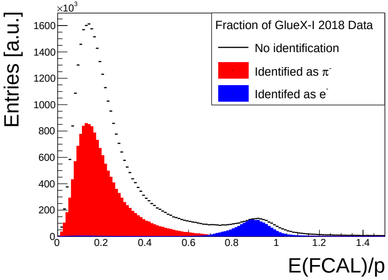
(d) BESIII coll. *Chinese Phys. C* 42, 04202 (2108)

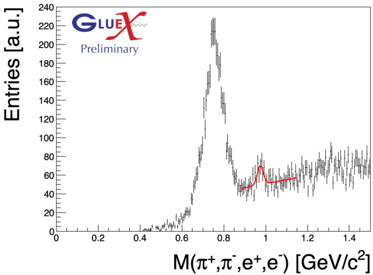
- Shown on the right: BESIII$^{(d)}$ analysis of $\eta' \to \pi^+\pi^-e^+e^-$
- Main background contribution: $\eta' \to \pi^+\pi^-\gamma$ at $M(e^+, e^-) \approx 0.015\,\mathrm{GeV}$



$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$ Plans and Analysis Strategy for GlueX-I

- Physics Observables:
  - i) Branching fraction
  - ii) $M(\pi^+,\pi^-)$ and $M(e^+,e^-)$
  - iii) A_Φ
- PID is crucial part of analysis:
  - Utilize machine learning to identify particles within detector
  - Combine information into Bayesian probability
- Analyzed 5% of the GlueX-I 2018 data so far:
  - Reconstructed $\sim 120\ \eta' \to \pi^+\pi^-e^+e^-$ event candidates
  - Main background contributions from: ρ^0, ω, K_S and $\eta' \to \pi^+\pi^-\gamma$





Summary and Outlook

1. **Dalitz Plot Analysis for $\boldsymbol{\eta \to \pi^+\pi^-\pi^0}$:**
    - Reconstructed $\sim 300\,\mathrm{k}$ events in GlueX-I 2017 data
    - Dalitz Plot distribution shows no C-violating asymmetries
      $\Rightarrow$ Uniform reconstruction efficiency
    - Analysis of GlueX-I 2018 data ongoing
    - Systematic studies and parameter extraction on the way
    - Expected statistics after analyzing total GlueX-I data comparable with KLOE
2. **Anomalous Decay $\boldsymbol{\eta^{(\prime)} \to \pi^+\pi^-e^+e^-}$:**
    - Reconstructed ~ 120 η' event candidates in 5% of GlueX-I 2018 data
    - Electron identification crucial for analysis:
        i) Suppression of $\pi^\pm$ background
        ii) Calculation of asymmetry A_Φ
    - Analysis of remaining data set is ongoing
    - Expected to have at least statistics as current BESIII result

Content