Studying Isospin breaking and anomalous η/η'-Decay Modes in Photoproduction with GlueX

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(For the GlueX Collaboration)

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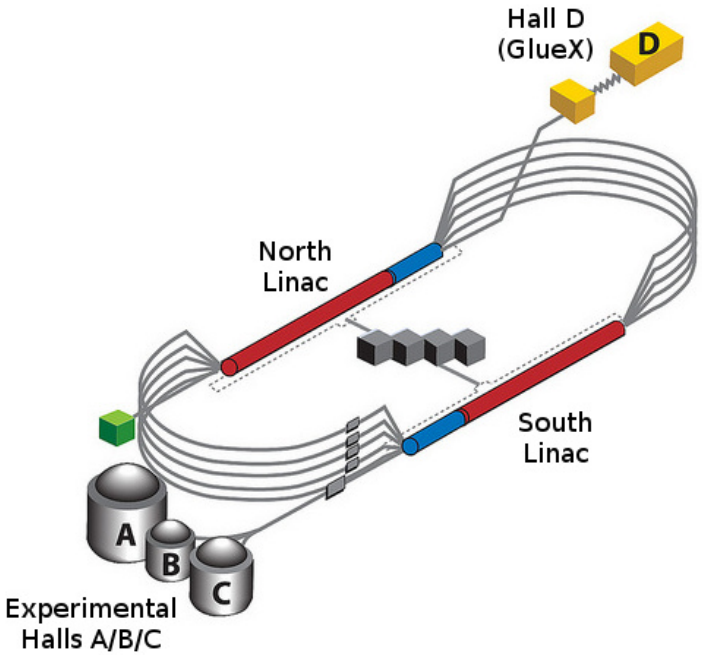
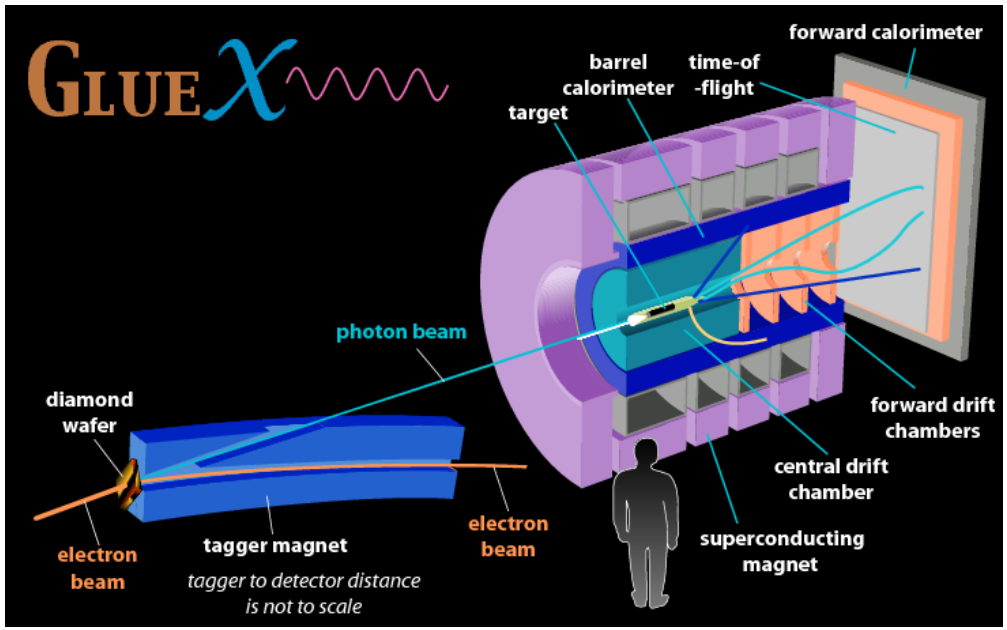
The **Gl**uonic **eX**citations (**GlueX**) Experiment at Thomas Jefferson National Laboratory





Experimental Hall D:

- Over 125 scientists from:
  - 28 Institutions
  - 10 Countries
- Experiments with polarized photon beam

☑ **Phase I:** Low intensity $\sim 5\,\mathrm{PB}$ of data taken

Run Period	Luminosity $[\mathrm{pb}^{-1}]$
2016	2
2017	21
2018	80

☐ **Phase II:** High intensity + DIRC upgrade → Start in fall this year

Physics Roadmap

Diagram taken from Sean Dobbs

Physics Roadmap

Diagram taken from Sean Dobbs

Collect Data

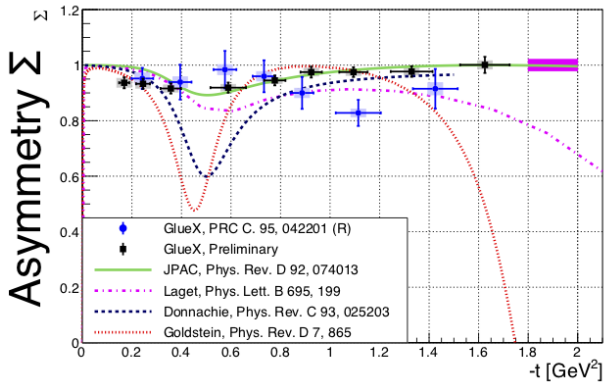
Understand production mechanisms

$\gamma p \rightarrow (\pi 0, \eta, \eta') p$

$\gamma p \rightarrow (\rho, \omega, \phi) p$

$\gamma p \rightarrow (\Lambda, \Sigma) K^+$

$\gamma p \rightarrow \pi^0 p$



Physics Roadmap

Diagram taken from Sean Dobbs

Collect Data

Understand production mechanisms

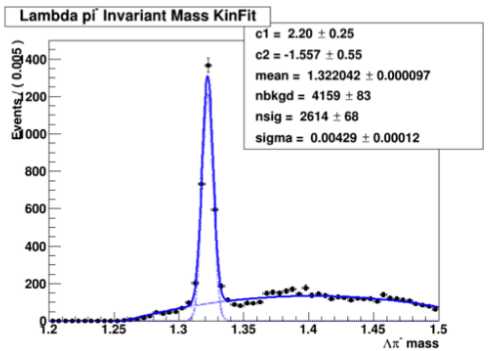
Measure cross sections

$\gamma p \rightarrow (\pi 0, \eta, \eta') p$

$\gamma p \rightarrow (\rho, \omega, \phi) p$

$\gamma p \rightarrow (\Lambda, \Sigma) K^+$

$\gamma p \rightarrow K^+ K^+ \Xi^-$



Physics Roadmap

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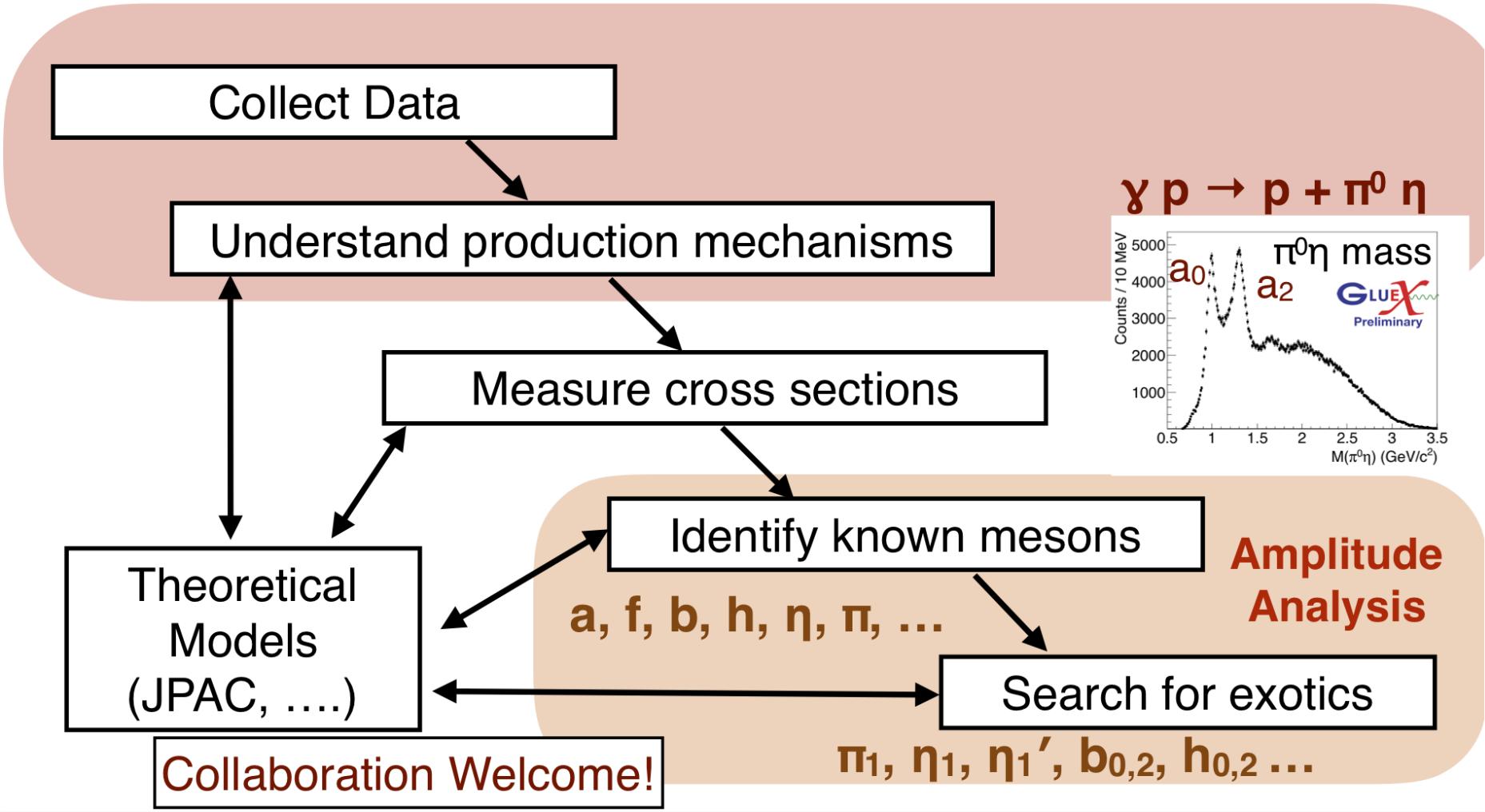

Physics Roadmap

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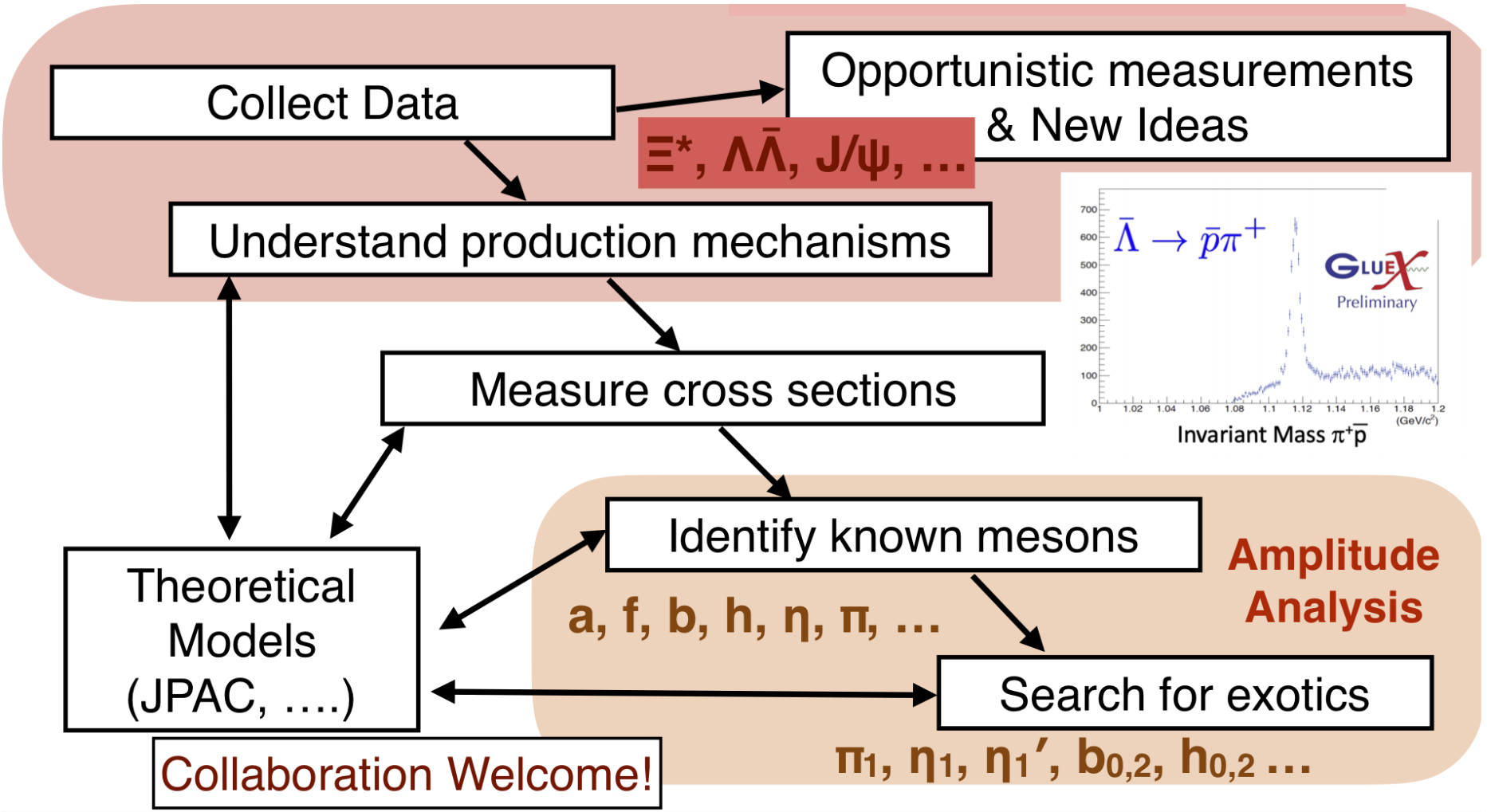
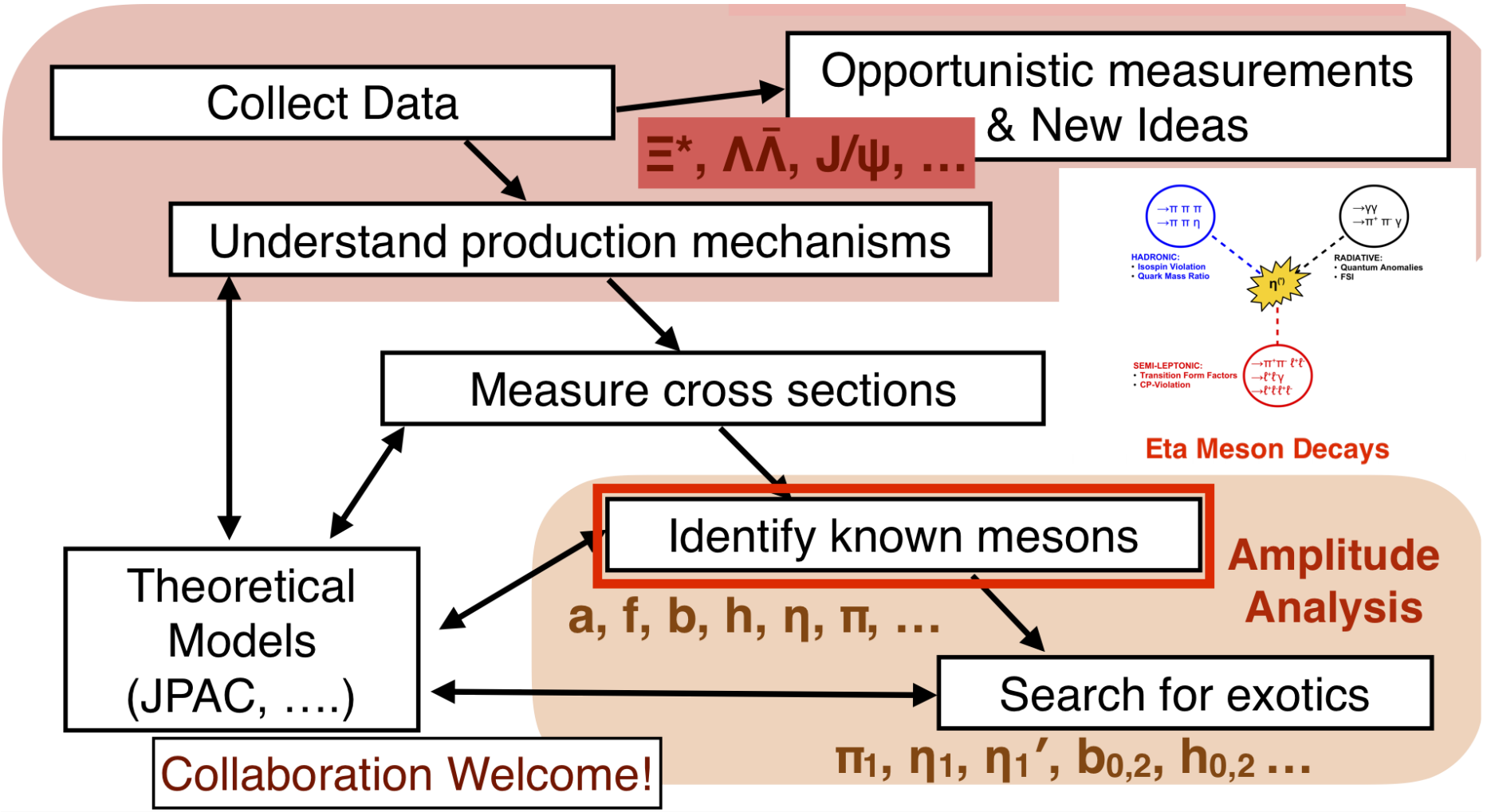
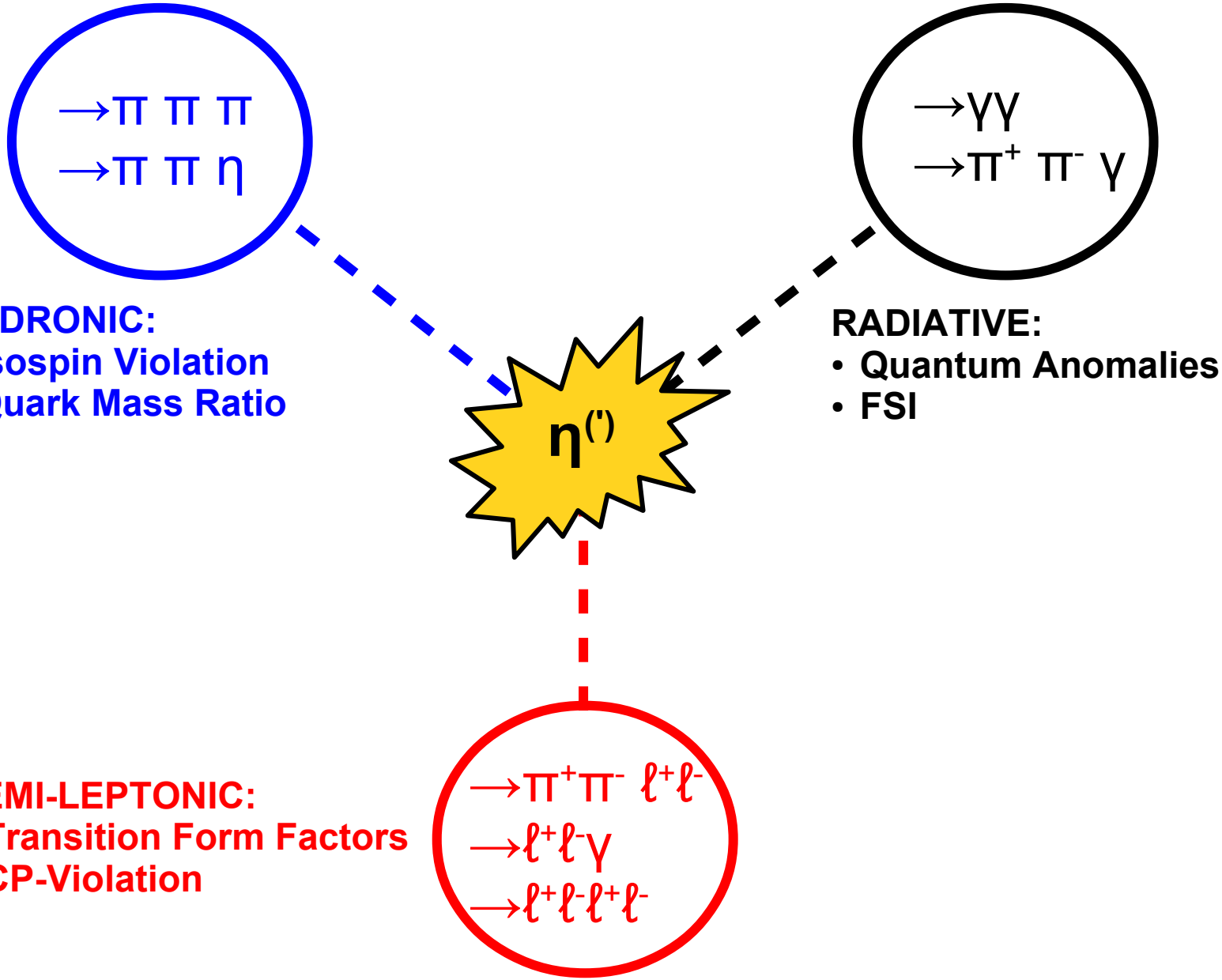


Physics Roadmap

Diagram taken from Sean Dobbs



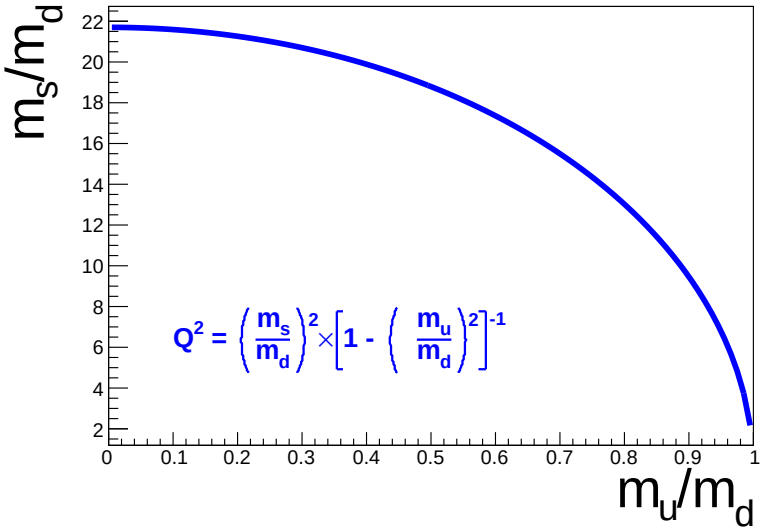
$\eta/\eta^{(\prime)}$ Decays



$\eta \to \pi^+\pi^-\pi^0$ Decay Properties

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

- Decay $\eta \to \pi^+\pi^-\pi^0$ is...
  - ... G-violating
  - ... C-conserving $\Leftrightarrow$ Isospin breaking
- Determine quark mass ratio by measuring decay width: $\Gamma(\eta \to \pi^+\pi^-\pi^0) \propto Q^{-4}$



$\Rightarrow$ Experimental access to Γ:

i) Relative branching fraction: e.g. $\Gamma(\eta \to \pi^+\pi^-\pi^0)/\Gamma(\eta \to \gamma\gamma)$

ii) Dalitz Plot analysis

$\eta \to \pi^+\pi^-\pi^0$ 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:

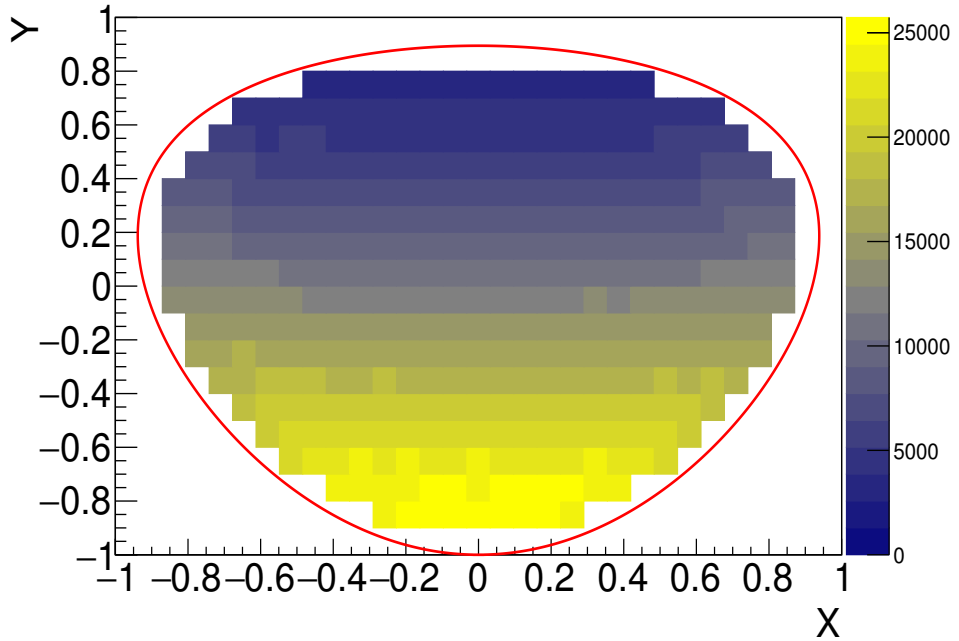
  $X = \sqrt{3}(T_{\pi^+} - T_{\pi^-})/\Sigma_T \to$ Sensitive to charge conjugation

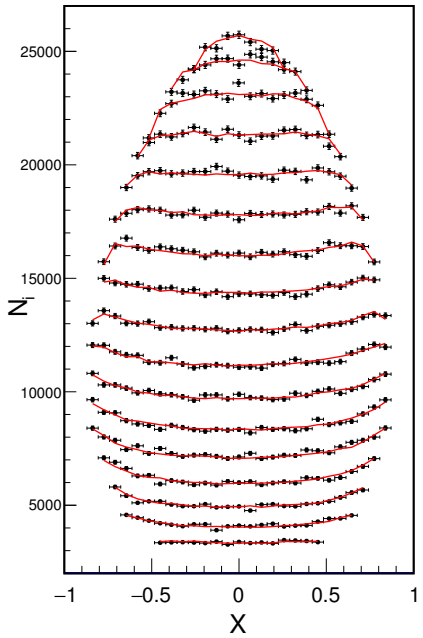
  $Y = 3T_{\pi^0}/\Sigma_T - 1$

- 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





$\eta \to \pi^+\pi^-\pi^0$ 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:

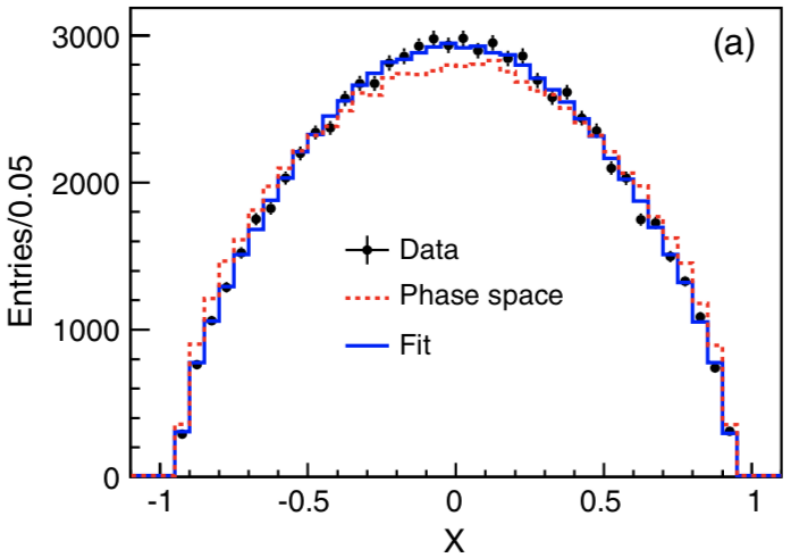
  $X = \sqrt{3}(T_{\pi^+} - T_{\pi^-})/\Sigma_T$ → Sensitive to charge conjugation

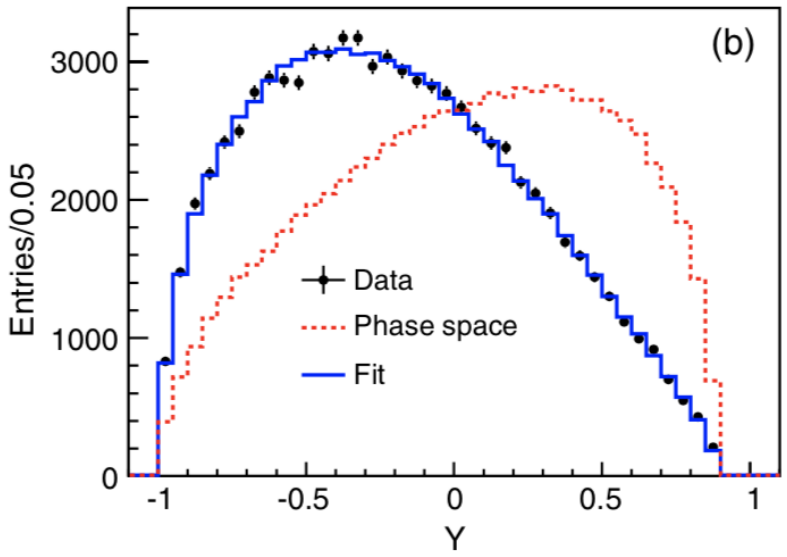
  $Y = 3T_{\pi^0}/\Sigma_T - 1$

- Results from BESIII: BESIII, *Phys. Rev.*, D92(012014), (2015)

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

ii) $\approx 80\,\mathrm{k}$ $\eta \to \pi^+\pi^-\pi^0$ events





$\eta \to \pi^+\pi^-\pi^0$ 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:

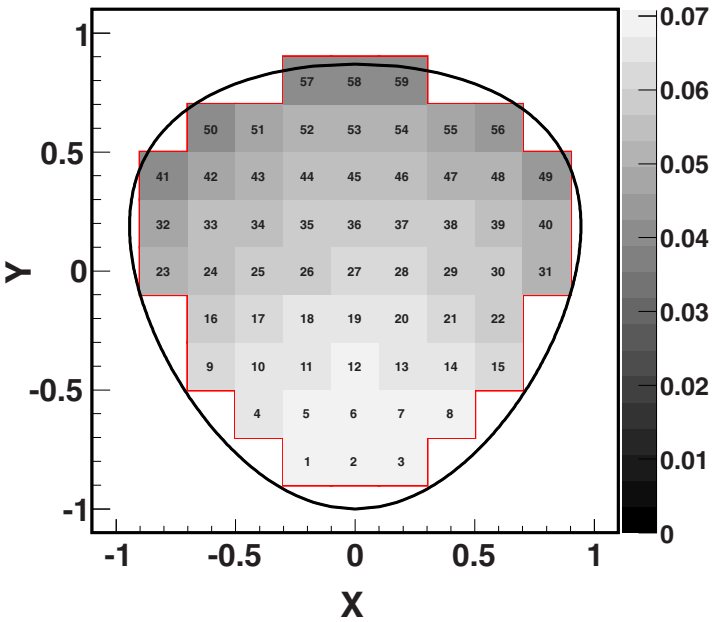
  $X = \sqrt{3}(T_{\pi^+} - T_{\pi^-})/\Sigma_T \to$ Sensitive to charge conjugation

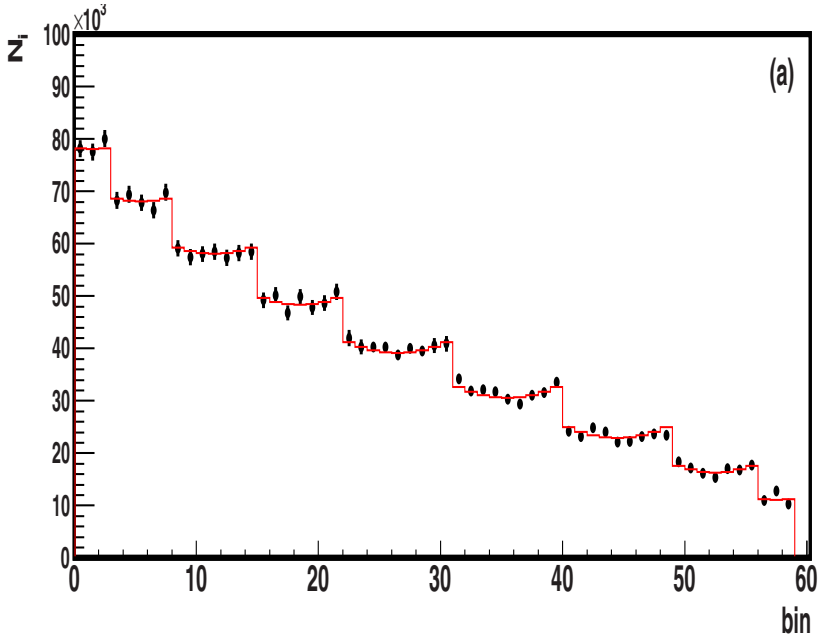
  $Y = 3T_{\pi^0}/\Sigma_T - 1$

- 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) $\approx 170\,\mathrm{k}$ $\eta \to \pi^+\pi^-\pi^0$ events





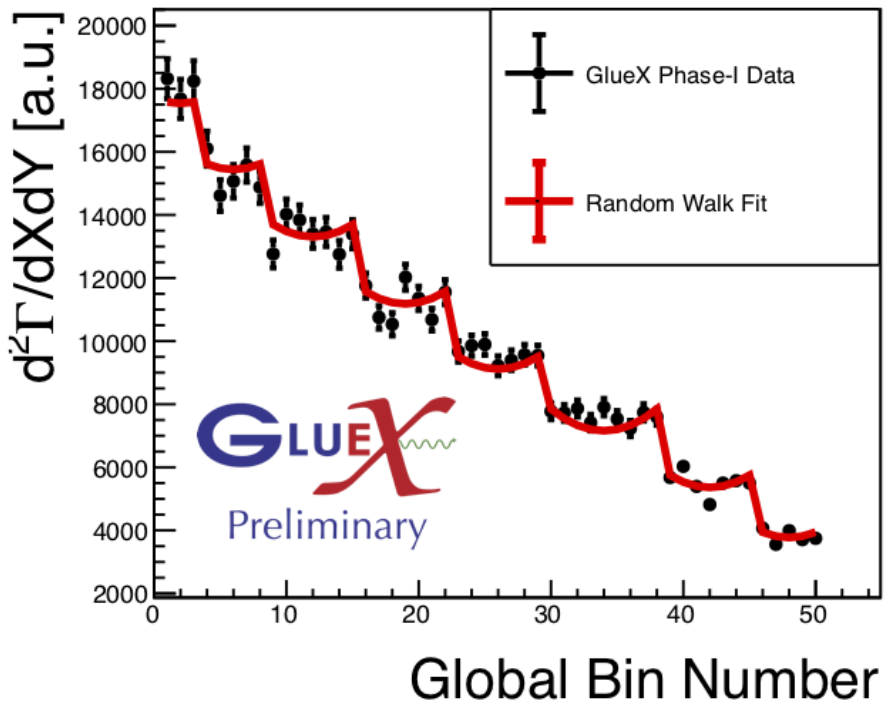
$\eta \to \pi^+\pi^-\pi^0$ Recent Results

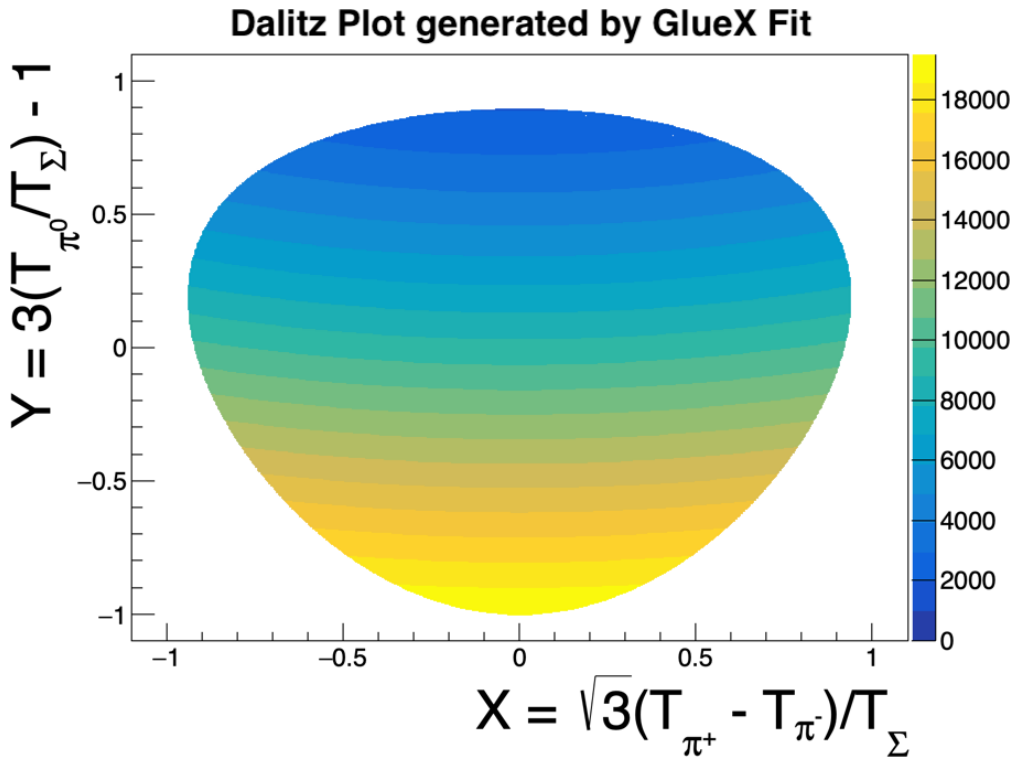
Parameter:		– a	b	d	f
Exp.	KLOE(08)[a]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[b]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	BESIII[c]	1.128(15)(8)	0.153(17)(4)	0.085(16)(9)	0.173(28)(21)
	KLOE(16)[d]	$1.104(3)(2)$	$0.142(6)(^{5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
Theo.	PWA[e]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
	PWA[f]	1.077(29)	0.170(8)	0.060(2)	0.091(3)
	KT[g]	1.142(45)	0.172(16)	0.097(13)	0.122(16)

(a) KLOE coll., *JHEP*, 05, (2008)
(b) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), (2014)
(c) BESIII, *Phys. Rev.*, D92(012014), (2015)
(d) KLOE coll., *JHEP*, 019, (2016)
(e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)
(f) Peng Guo et al., *Phys. Lett.*, B771(497-502), (2017)
(g) M.Albaladejo and B. Moussallam, *Eur. Phys. J.*, C, (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.) $\eta' \to \pi^+\pi^-\eta$

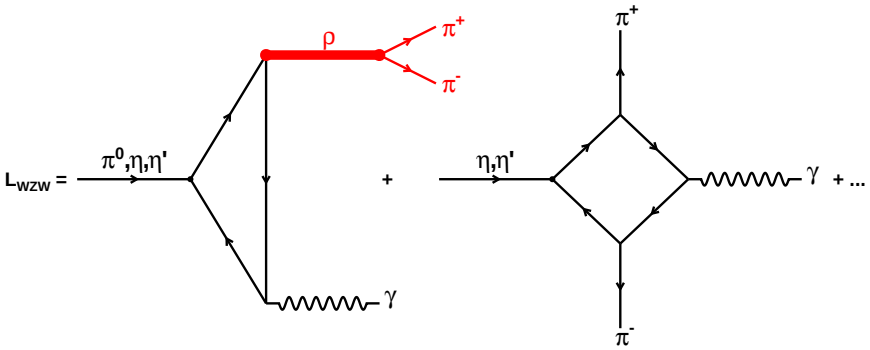
$\eta \to \pi^+\pi^-\pi^0$ Status GlueX-I Data Analysis





- $\approx 300\,\mathrm{k}$ $\eta \to \pi^+\pi^-\pi^0$ events reconstructed in 20% of GlueX Phase-I data
  - Found consistency with previous measurements
  - No asymmetries in Dalitz Plot observed
  - Checks for systematic uncertainties ongoing
- Dalitz Plot analysis for remaining GlueX Phase-I data ongoing

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



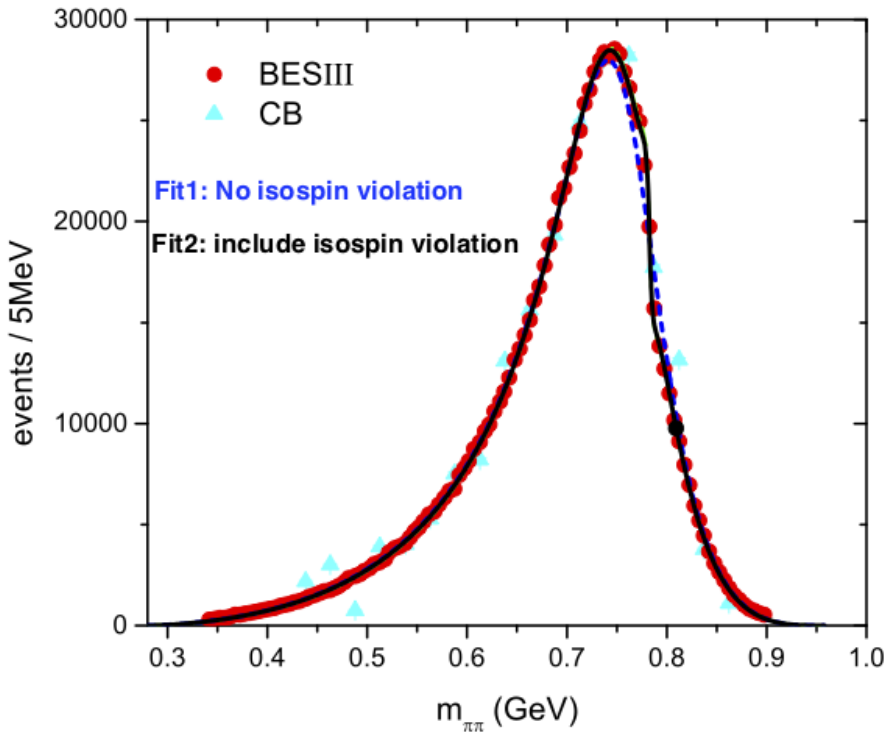
Underlying decay: $\eta^{(\prime)} \to \pi^+\pi^-\gamma$

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

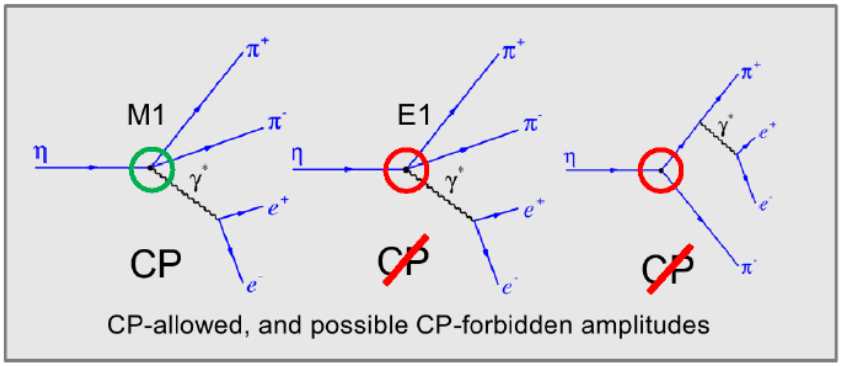
- Study $M(\pi^+,\pi^-)$-Distribution:
  - i) Determine contributions from box anomaly term
  - ii) Insights into $\pi\pi$-FSI
- Amplitude analysis for decay: $\eta' \to \pi^+\pi^-\gamma$

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

Amplitude/Resonance	[keV]
$\eta' \to \rho\gamma \to \pi^+\pi^-\gamma$	56.6 ± 5.3
Box Anomaly	3.34 ± 0.35
$\eta' \to \omega\gamma \to \pi^+\pi^-\gamma$	$(67.5 \pm 16.0)10^{-3}$



$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$ 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 $\to$ 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 pion-lepton decay planes

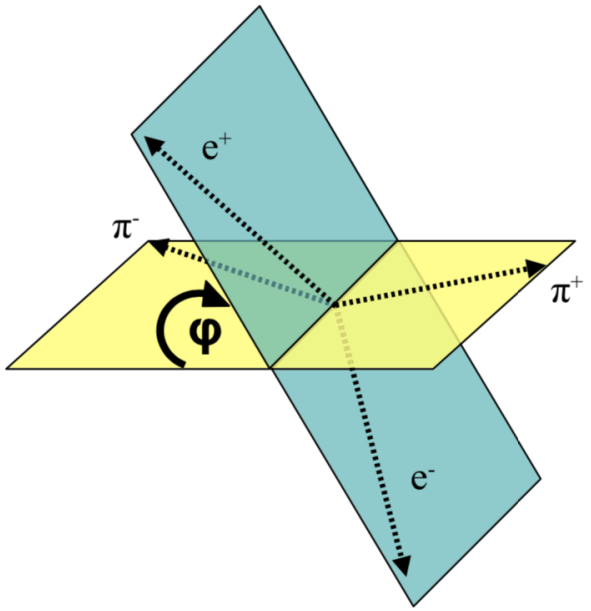


Illustration on the bottom right taken from:

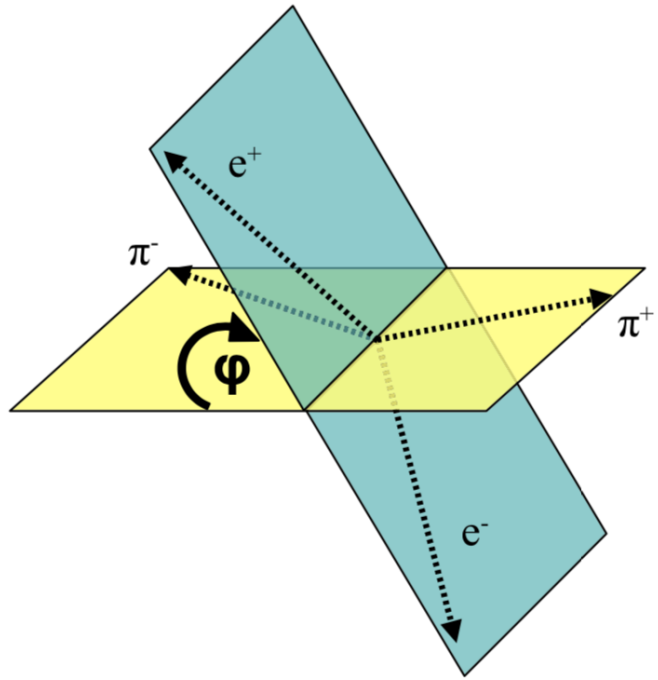
WASA-at-COSY coll. *Phys. Rev.C*,94 ,065206 (2016)

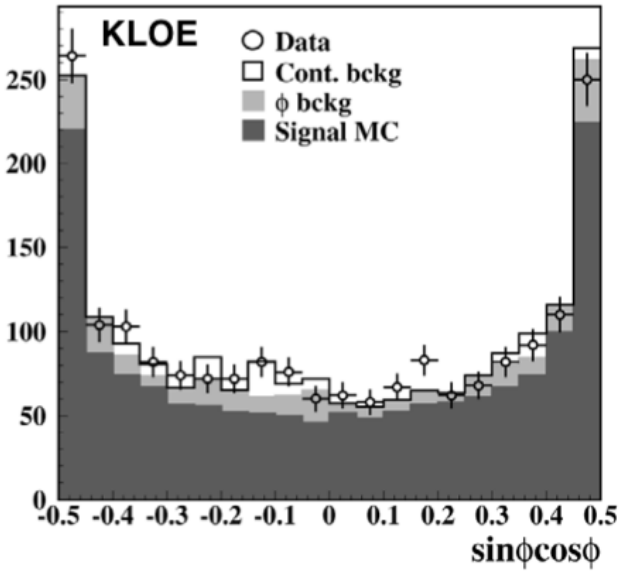
$\eta \to \pi^+\pi^-e^+e^-$ Asymmetry

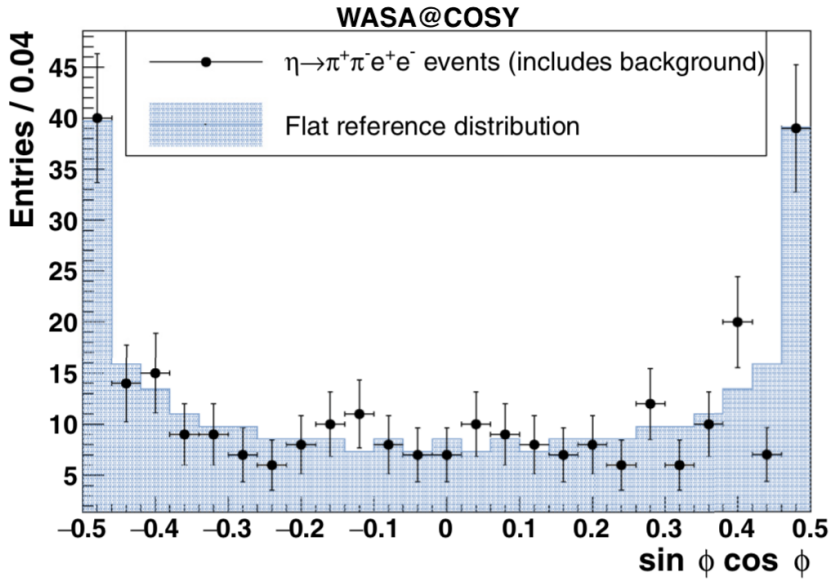
- $A_\Phi = \frac{N(\sin[\Phi]\cos[\Phi]>0) - N(\sin[\Phi]\cos[\Phi]<0)}{N(\sin[\Phi]\cos[\Phi]>0) + N(\sin[\Phi]\cos[\Phi]<0)}$
- Measuring A_Φ reveals information about CP-violating transitions
- Upper limit predicted by theory[(a)]: $\sim 1\%$

(a) D. Gao. *Mod. Phys. Lett.*, A17:1583-1588,(2002)

- Measurements of A_Φ performed by WASA-at-COSY and KLOE







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

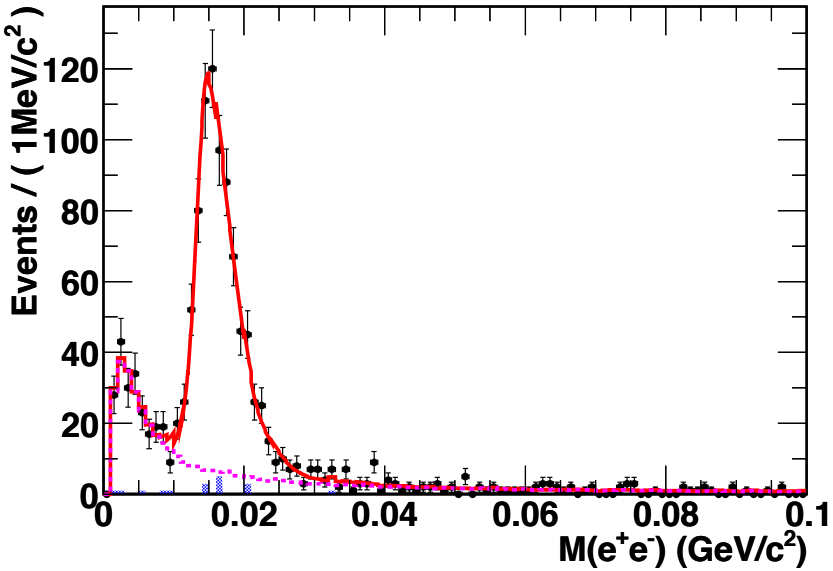
Experiment	X	$\frac{\Gamma(X\to\pi^+\pi^- e^+ e^-)}{\Gamma_X}$ $[10^{-4}]$	A_Φ $[10^{-2}]$	#Events $[k]$
WASA [b]	η	$2.7 \pm 0.2_{stat} \pm 0.2_{sys}$	$-1.1 \pm 6.6_{stat} \pm 0.2_{sys}$	0.215
KLOE [c]	η	$2.68 \pm 0.09_{stat} \pm 0.07_{sys}$	$-0.6 \pm 2.5_{stat} \pm 1.8_{sys}$	1.6
BESIII [d]	η'	$21.1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

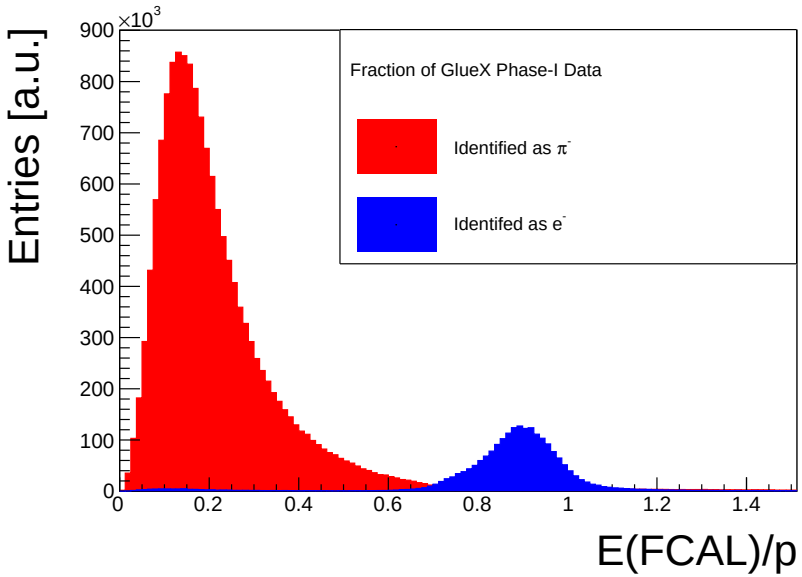
(d) BESIII coll. *Chinese Phys. C* 42, 04202 (2108)

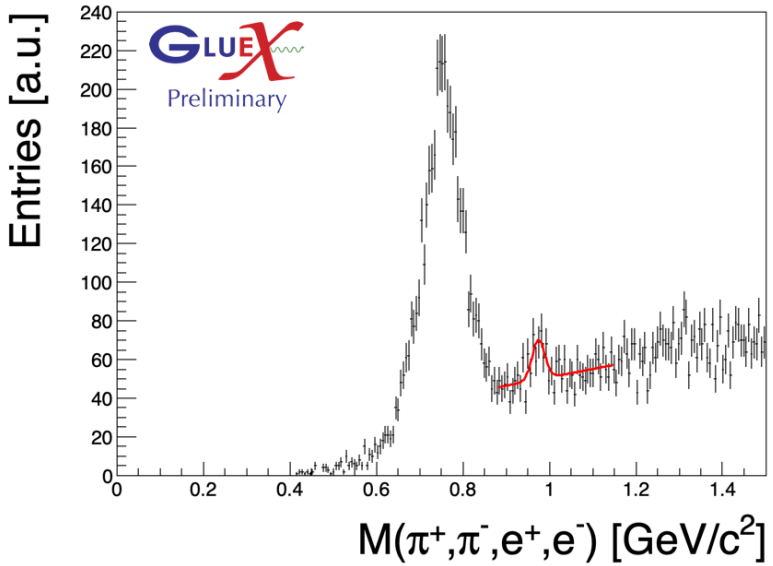
- Shown on the right:
  BESIII[d] analysis of $\eta' \to \pi^+\pi^- e^+ e^-$
- Main background contribution:
  $\eta' \to \pi^+\pi^-\gamma$ at $M(e^+, e^-) \approx 0.015\,\mathrm{GeV}$



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

- Want to measure/study:
  - 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 subsample of the GlueX Phase-I data:
  - Reconstructed ~ 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 $\eta \to \pi^+\pi^-\pi^0$:**
   - Reconstructed $\sim 300\,\mathrm{k}$ events in 20% of GlueX Phase-I data
   - Dalitz Plot distribution shows no C-violating asymmetries
     $\Rightarrow$ Uniform reconstruction efficiency
   - Analysis of remaining data ongoing
   - Estimation of systematic uncertainties and parameter extraction on the way
   - Expected statistics after analyzing total GlueX Phase-I data comparable with KLOE
2. **Anomalous Decay $\eta^{(\prime)} \to \pi^+\pi^- e^+ e^-$:**
   - Reconstructed ~ 120 η' event candidates in subsample of GlueX Phase-I data
   - Electron identification important 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