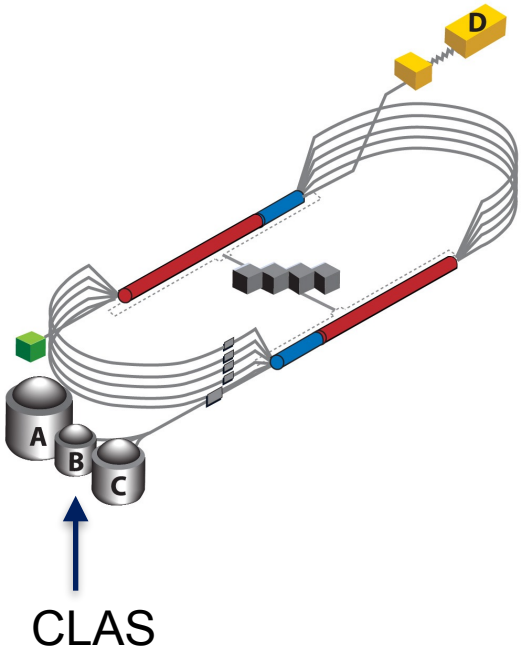
Jefferson Lab
Thomas Jefferson National Accelerator Facility

JÜLICH
FORSCHUNGSZENTRUM

Light Meson Decays from Photon-Induced Reactions with CLAS

24 March 2015 | HK 38.1 | Michael C. Kunkel | IKP-1 | on behalf of the CLAS Collaboration and LMD group

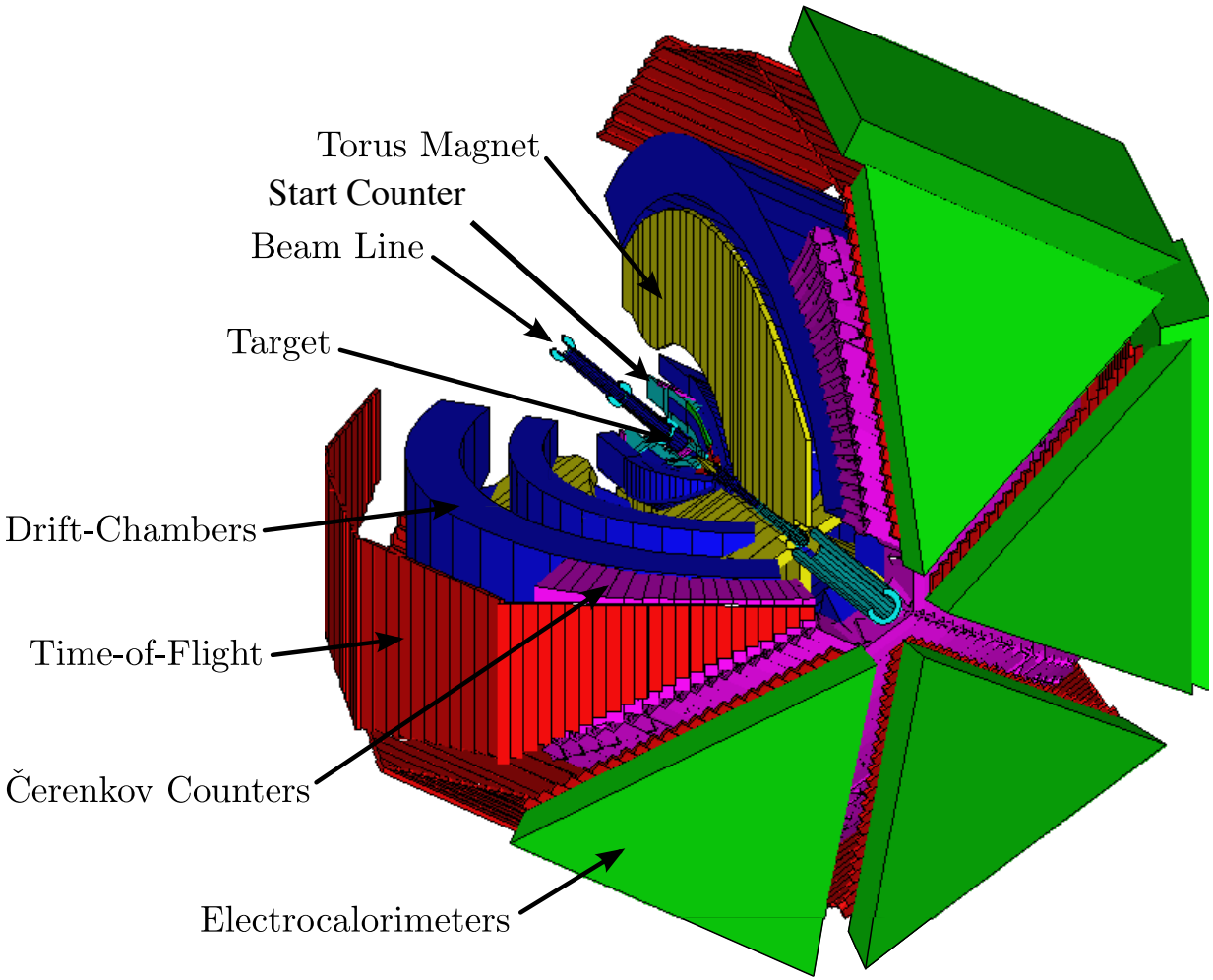
Thomas Jefferson National Laboratory



Continous Electron Beam Accelerator Facility (CEBAF) at 12 GeV

Aerial View

CEBAF Large Acceptance Spectrometer (CLAS)



The g11 and g12 experiments

g11 $\gamma p \rightarrow pX$	g12 $\gamma p \rightarrow pX$
60 - 65 nA 4.023 GeV e^- beam $0.803 < E\gamma < 3.815$	60 - 65 nA 5.714 GeV e^- beam $1.142 < E\gamma < 5.425$
40 cm (2 cm radius) liquid H_2 target placed at CLAS center	40 cm (2 cm radius) liquid H_2 target placed -90cm from CLAS center
Trigger required at least two charged tracks in different sectors	Trigger required at least two charged tracks in different sectors for $E\gamma > 3.6$
20×10^9 productions triggers as 21 TB of raw data	26×10^9 productions triggers as 128 TB of raw data
	Cherenkov Counters and Electromagnetic Calorimeter in trigger for entire $E\gamma$ range

Light Meson Decays in CLAS

CLAS Light Meson Decay (LMD) Program Institutional Contributors

- Old Dominion University, Norfolk, Virginia 23529
- Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188300, Russia
- INFN, Sezione di Genova, 16146 Genova, Italy
- The George Washington University, Washington, DC 20052
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- University of South Carolina, Columbia, South Carolina 29208
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- Indian Institute of Technology Indore, Khandwa Road, Indore-452017, Madhya Pradesh, India
- Institut fu¨r Kernphysik, Forschungszentrum, Jülich, Germany
- Jülich Center for Hadron Physics, Forschungszentrum Jülich, 52425 Jülich, Germany
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- Institut für Theoretische Physik II, Ruhr–Universität Bochum, D–44780 Bochum, Germany
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Light Meson Decays in CLAS

CLAS Light Meson Decay (LMD) Program was established to investigate

Meson Decay	Physics	Meson Decay	Physics
$\pi^0 \rightarrow e^+e^-\gamma$	Heavy photon upper limit	$\eta(') \rightarrow \pi^-\pi^+\gamma$	Box anomaly
$\eta(') \rightarrow e^+e^-\gamma$	Transition Form Factor	$\omega \rightarrow \pi^-\pi^+\gamma$	Upper limit branching ratio $<3.6\times10^{-3}$
$\omega \rightarrow \pi^0e^+e^-$	Transition Form Factor	$\eta, \omega, \Phi \rightarrow \pi^-\pi^+\pi^0$	Dalitz plot analysis
$\eta(') \rightarrow \pi^0e^+e^-$	C violation	$\eta' \rightarrow \pi^-\pi^+\eta$	Dalitz plot analysis/meson mixing
$\eta(') \rightarrow \pi^-\pi^+e^+e^-$	CP violation	$\Phi \rightarrow \pi^-\pi^+\eta$	G-parity violation

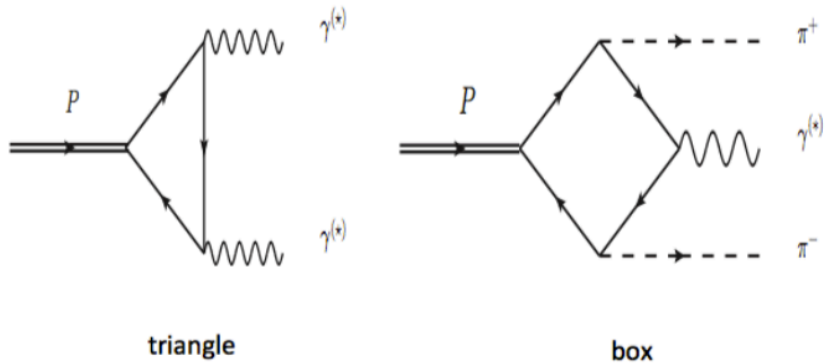
Box Anomaly of η(')→$\pi^-\pi^+\gamma$

Njencheu Georgie Mbianda, Moskov Amaryan;

Old Dominion University

Motivation:

- The 2 photon decay of π^0, η, η' →γγ proceed from the understood triangle or axial anomaly. While radiative decays of η, η' →$\pi^-\pi^+\gamma$ are related to a less understood box anomaly.



- With an analysis of the photon energy distribution of the radiative decays of η and η', the decay widths are determined by the box anomaly in the chiral limit.
- Radiative decays from CLAS will test the box anomaly, including FSI of the pions. FSI occur because beyond the chiral limit, quarks have mass.

Box Anomaly

$$\frac{d\Gamma(\eta \to \pi^+\pi^-\gamma)}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2\,\Gamma_0(s_{\pi\pi})$$

$$\Gamma_0(s_{\pi\pi}) = \frac{1}{3\cdot 2^{11}\cdot \pi^3 M_\eta^3}\left(M_\eta^2 - s_{\pi\pi}\right)^3 s_{\pi\pi}\cdot\beta_\pi^3$$

$$\text{with } \beta_\pi = \sqrt{1-4M_\pi^2/s_{\pi\pi}}.$$

- the pion vector form factor can be approximated by the polynomial

$$|F_V(s_{\pi\pi})| \approx 1 + (2.12\pm0.01)s_{\pi\pi} + (2.13\pm0.01)s_{\pi\pi}^2 + (13.80\pm0.14)s_{\pi\pi}^3$$

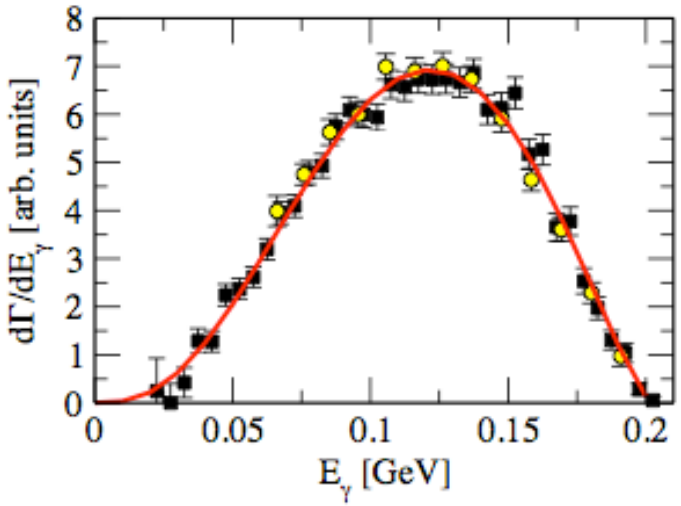
- Expansion around $s_{\pi\pi} = 0$ gives the process specific function

$$P(s_{\pi\pi}) = 1 + \alpha\cdot s_{\pi\pi} + \mathcal{O}(s_{\pi\pi}^2)$$

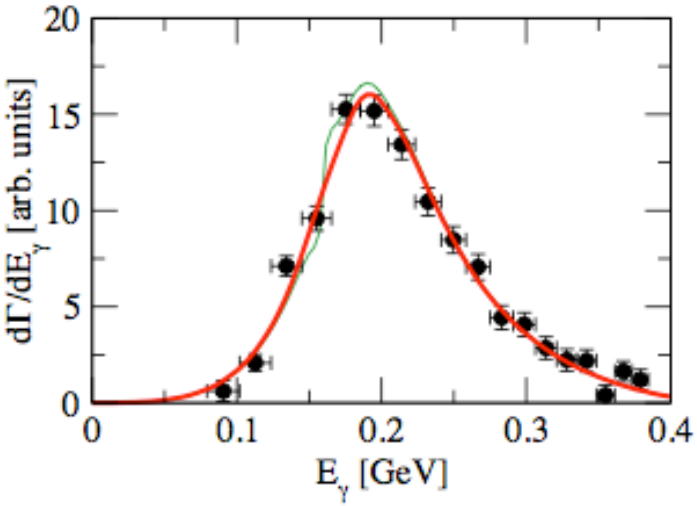
- from which α can be measured.

Experimental data from WASA-at-COSY(η) and CRYSTAL BARREL(η')

$\eta \to \pi^+\pi^-\gamma$



$\eta' \to \pi^+\pi^-\gamma$



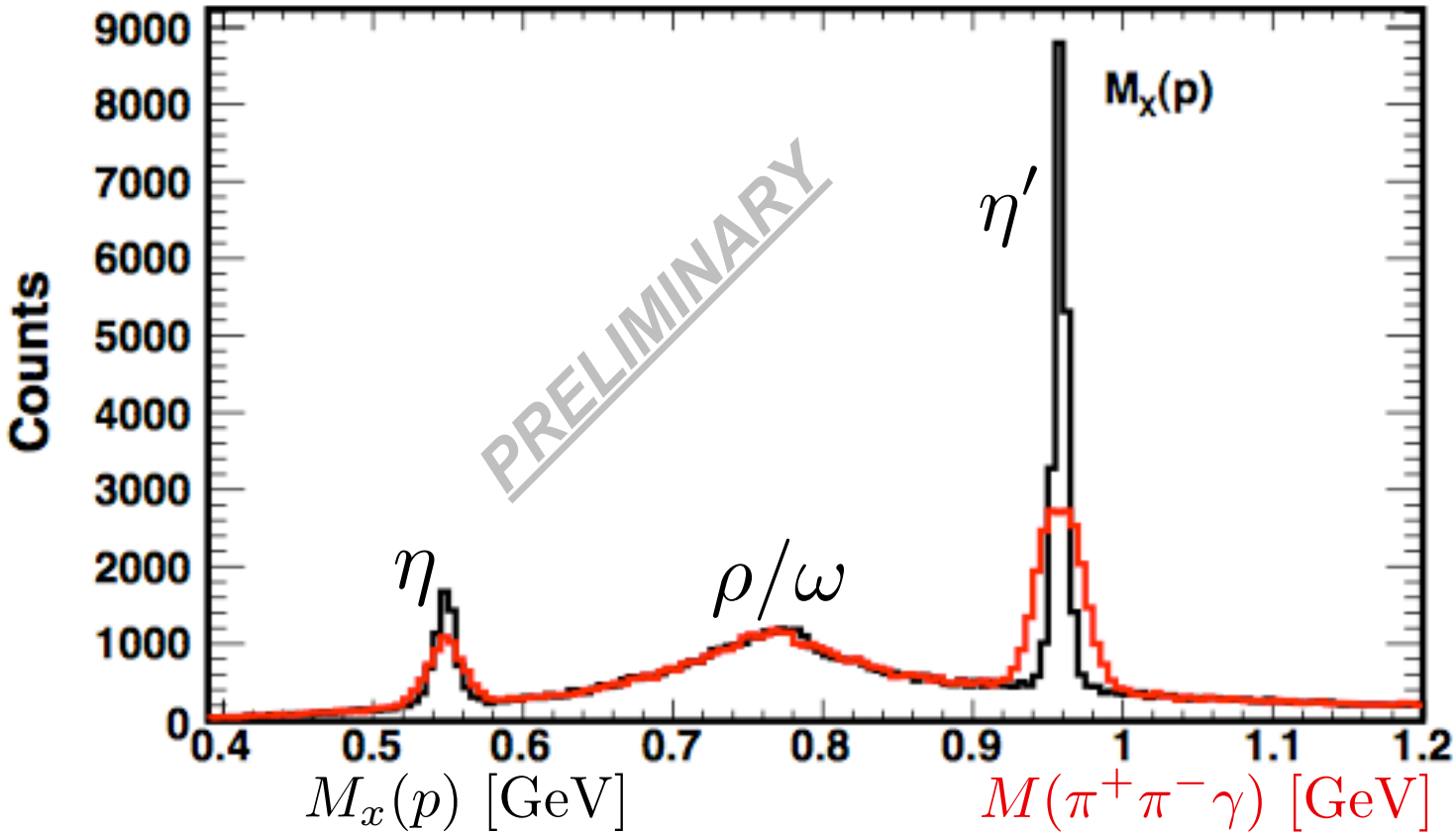
$\alpha = (1.89 \pm 0.25 \pm 0.59)\ \mathrm{GeV}^{-2}$ [1]

$\alpha' = (1.8 \pm 0.49 \pm 0.04)\ \mathrm{GeV}^{-2}$ [2]

$$s_{\pi\pi} = m^2 - 2E_\gamma m$$

[1]F.Stollenwerk et al., Phys. Lett. B707:184-190, 2012
[2]A. Abele et al. Phys.Lett. B402, 195 (1997).

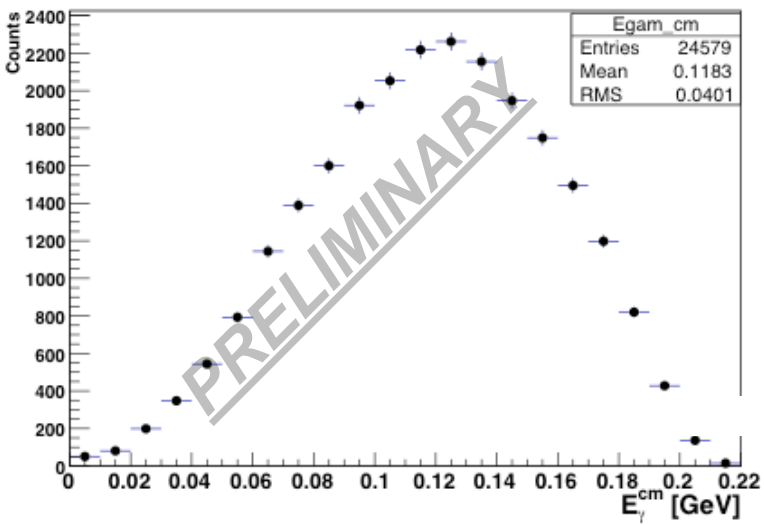
Radiative Decay



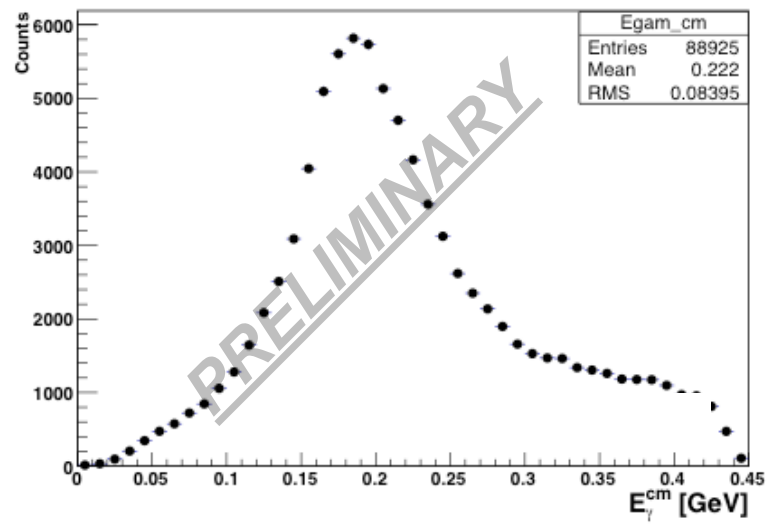
CLAS data yield for γp→p{η,η'→π+ π- γ} *from g11 data set*

CLAS Uncorrected Data

$$\eta \to \pi^+\pi^-\gamma$$



$$\eta' \to \pi^+\pi^-\gamma$$



Dalitz Plot of $\eta' \to \pi^- \pi^+ \eta$

Sudeep Ghosh, Anki Roy;

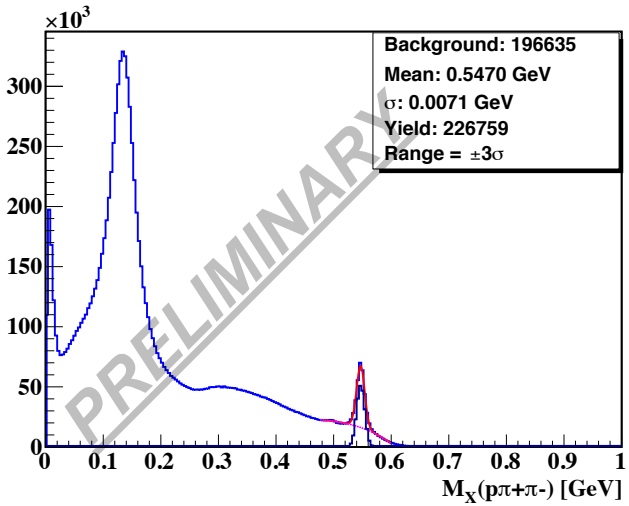
IIT

Motivation:

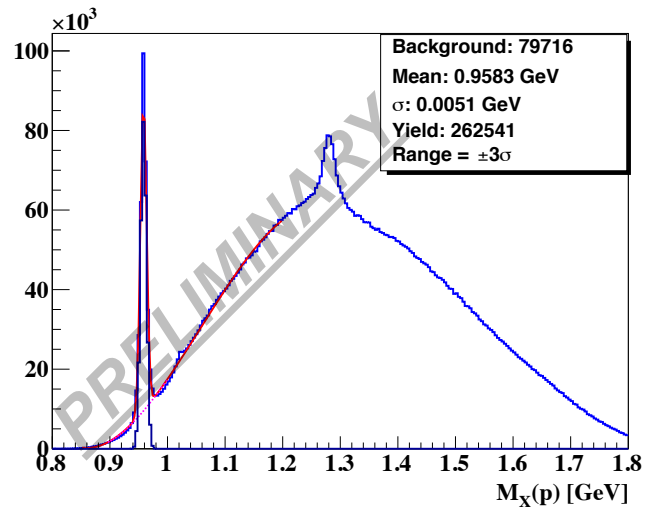
- Dalitz plot of $\eta' \to \pi^- \pi^+ \eta$ provides kinematic information of the decay, enabling the studying of low energy dynamics of QCD and heavier mass pseudoscalar mesons.
- The $\eta' \to \pi^- \pi^+ \eta$ decay has a low Q-value due to relatively heavier decay products, thus helping us to test and limit the effective chiral Lagrangian theory
- $f(X,Y)=N \cdot (1+a(Y)+b(Y)^2 +c(X)+d(X)^2)$

Parameters	*VES*	*Theory*	*BESIII*	*Stat. err. in BESIII*	*Stat. err. in CLAS*
a	*-0.127±0.018*	*-0.116±0.011*	*-0.047±0.012*	*±0.011*	*±0.004*
b	*-0.106±0.032*	*-0.042±0.034*	*-0.069±0.021*	*±0.019*	*±0.006*
c	*+0.015*	*...*	*+0.019±0.012*	*±0.011*	*±0.004*
d	*-0.082±0.019*	*+0.010±0.019*	*-0.073±0.013*	*±0.012*	*±0.004*

Dalitz Plot of γp→pη'→pπ⁻π⁺η



Missing mass of $p\pi^-\pi^+$ for events where $M_x(p)=0.958\pm0.015$ GeV



Missing mass of p for events where $M_x(p\pi^-\pi^+)=0.5\pm0.015$ GeV

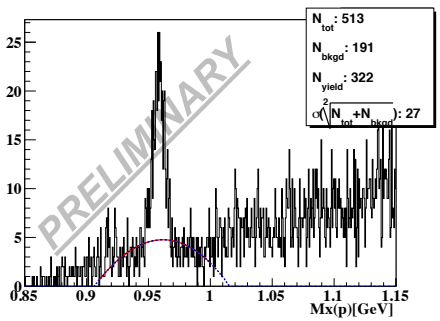
Dalitz variables for $\pi^-\pi^+\eta$

$$X = \frac{\sqrt{3}(T_{\pi^+} - T_{\pi^-})}{Q} \qquad Y = \frac{(m_\eta + 2m_\pi)}{m_\pi} \cdot \frac{T_\eta}{Q} - 1$$

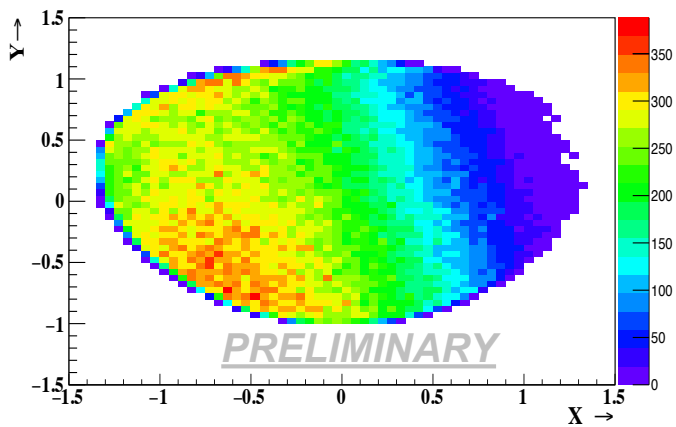
where $T_i(i = \pi^+, \pi^-, \eta)$ is the kinetic energy of a given particle in the rest frame of η' and $Q = T_{\pi^+} + T_{\pi^-} + T_\eta$

Data Analysis

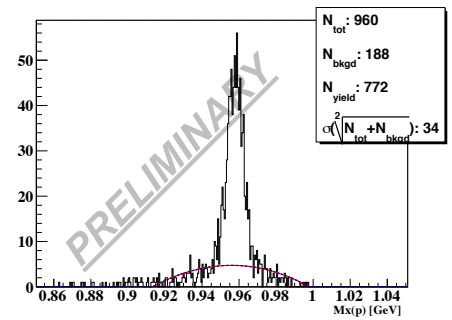
Data satisfying the cross-section is fed to the Dalitz plot of 30x30 (X(-1.5,1.5) x Y(-1.5,1.5)) and then a pol-3 background subtraction performed in the 3σ(0.946-0.97 GeV) region of every Dalitz bin



Dalitz plot bin with lower statistics



Dalitz plot for $\eta' \rightarrow \pi^- \pi^+ \eta$ from CLAS g11



Dalitz plot bin with higher statistics

Dalitz Plot of $\eta \to \pi^- \pi^+ \pi^0$

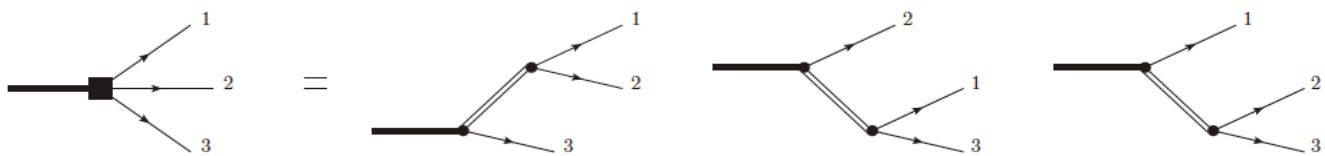
JPAC: Adam Szczepaniak, Diane Schott, Peng Guo et. al.

Jlab

Motivation:

- $\eta \to \pi^- \pi^+ \pi^0$ is sensitive to isospin breaking, which in QCD originates from the mass difference between the up and down quarks.

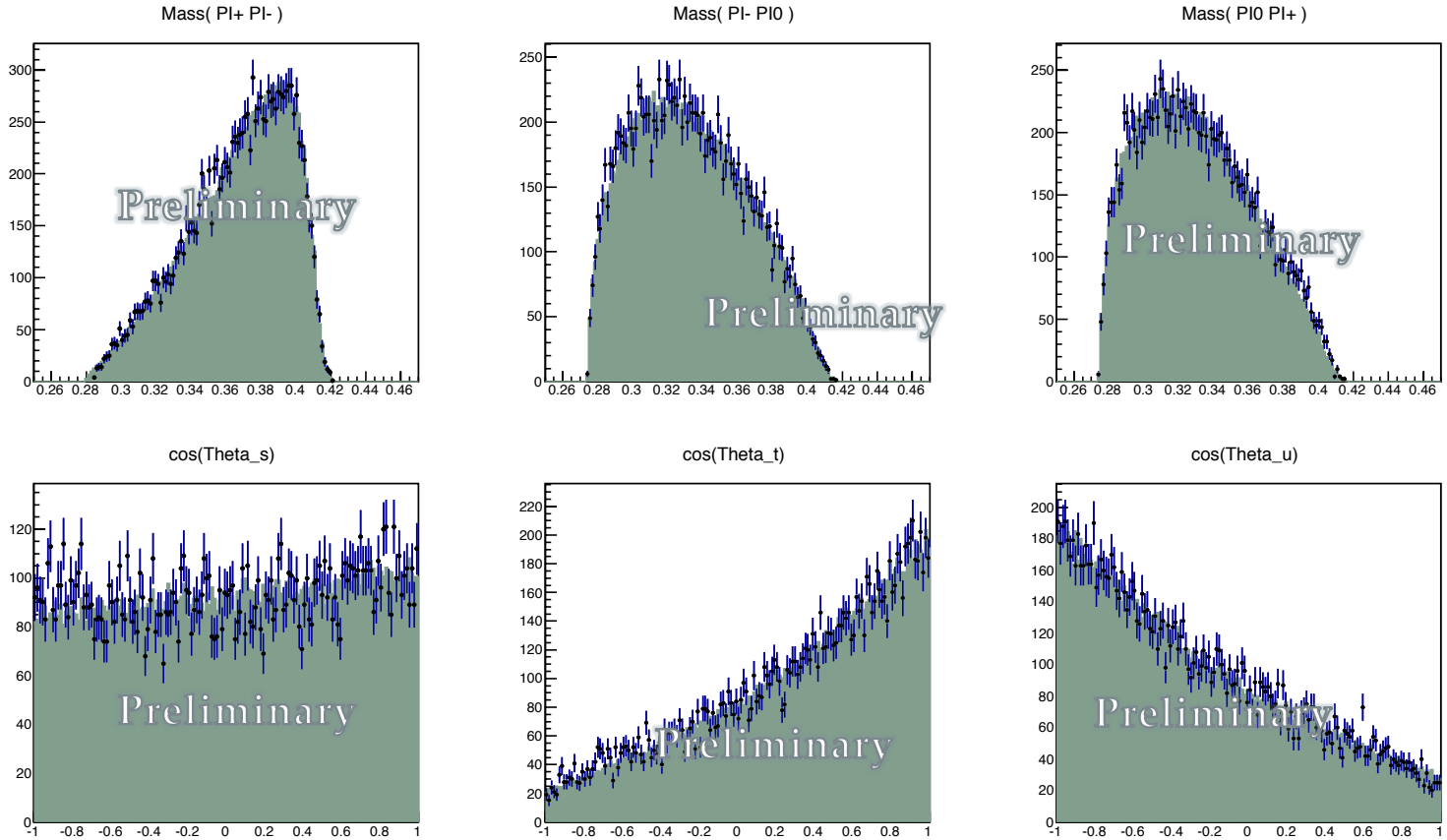
$$A(s,t) = \sum_J^{J_{max}} (2J+1)\, d^J_{1,0}(\theta_s)\, f_J(s) + \sum_J^{J_{max}} (2J+1)\, d^J_{1,0}(\theta_t)\, f_J(t) + \sum_J^{J_{max}} (2J+1)\, d^J_{1,0}(\theta_u)\, f_J(u)$$



- The isobar model assumes quasi 2-body decay and is insufficient for some channels
- It is important to construct amplitudes which contain all the known physics such as 3-body interactions, coupled channel, unitarity, analyticity, etc.
- The $\eta \to \pi^- \pi^+ \pi^0$ analysis is building in the three-body interaction (unitarity and analyticity) as a first step for future experimental analysis tools.

Dalitz Plot

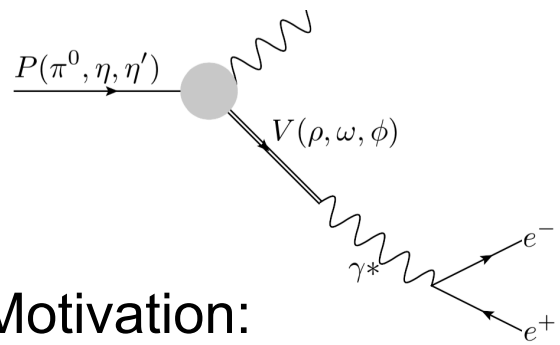
Fit after background subtraction

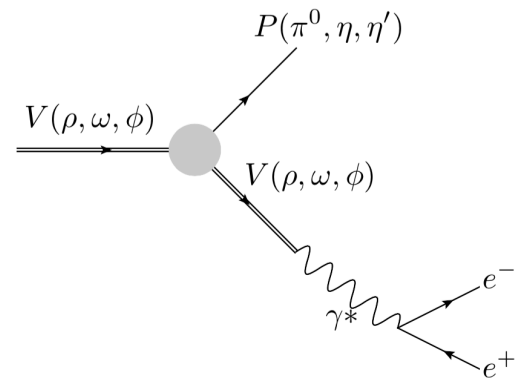


Transition Form Factors

Susan Schamand, Michaela Schever, Michael C. Kunkel;

Institut für Kernphysik, Forschungszentrum Jülich





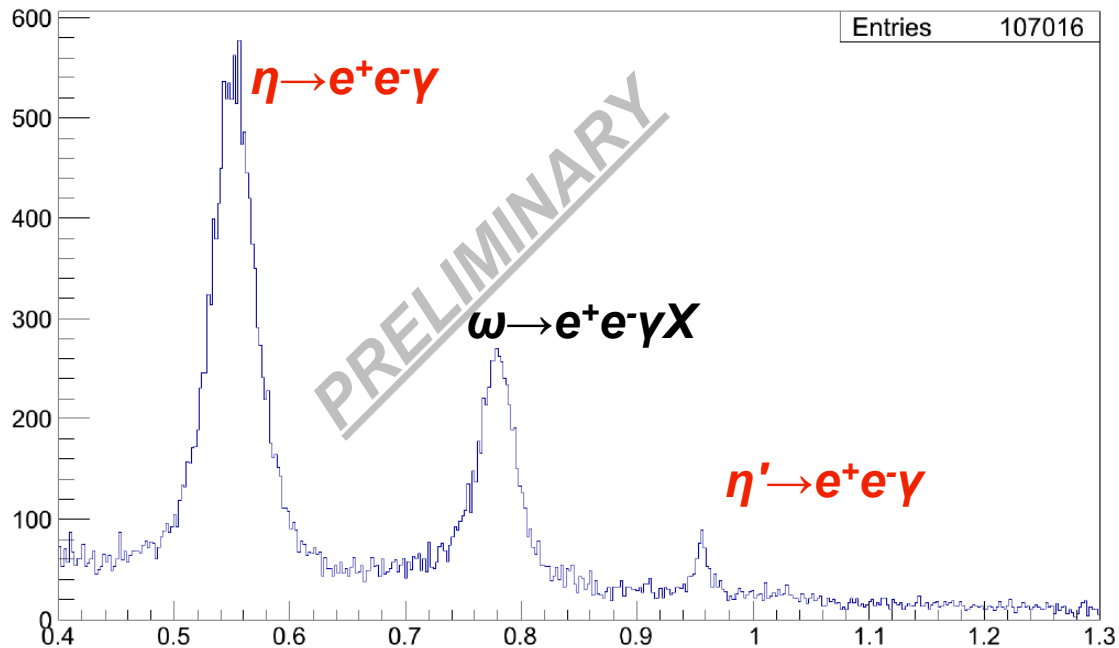
Motivation:

- In the VMD model the transition form factors provides insight into the meson charge radius.
- For pseudoscalar mesons η and η', ratio of form factors provides information on missing angle.
- For vector meson ω there currently exist discrepancy in the measurement of the form factor with VMD model.
- The knowledge of the η form factor is also needed for the interpretation of the g-2 experiment.
- g12 experiment collected world breaking data samples of the pe^+e^-X reaction using Cherenkov Counters and an Electromagnetic Calorimeter

Transition Form Factors

$$\frac{d\Gamma_{P\to l^+l^-\gamma}}{dq^2 d\Gamma_{P\to\gamma\gamma}} = \frac{2\alpha}{3\pi q^2}\left(1-\frac{q^2}{m_P^2}\right)^3\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}\left(1+\frac{2m_l^2}{q^2}\right)|_{\mathrm{Q.E.D}}$$

$$\frac{d\Gamma_{P_{P\to l^+l^-\gamma}}}{dq^2 d\Gamma_{P_{P\to\gamma\gamma}}}|_{\mathrm{measured}} = \frac{d\Gamma_{P_{P\to l^+l^-\gamma}}}{dq^2\Gamma_{P\to\gamma\gamma}}|_{\mathrm{Q.E.D}}\left|F(q^2)\right|^2$$



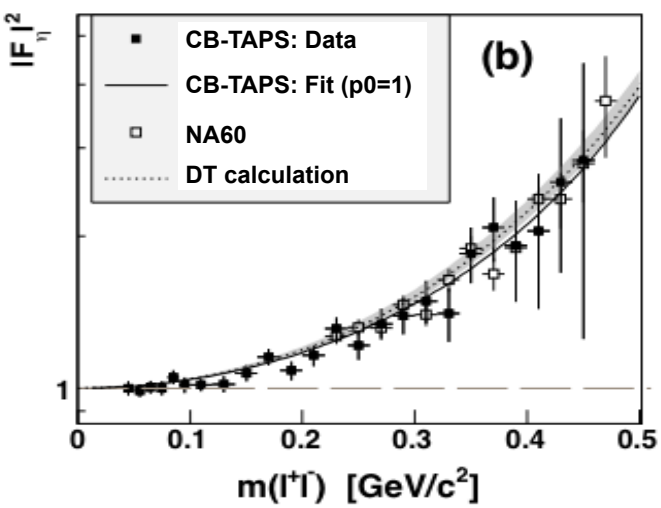
CLAS data yield from γp→pX with $M^2_x(pe^+e^-)<0.018$ GeV^2
$M_E(pe^+e^-)>0.075$ GeV and electron/positron ID

For η' please see poster by Michaela Schever

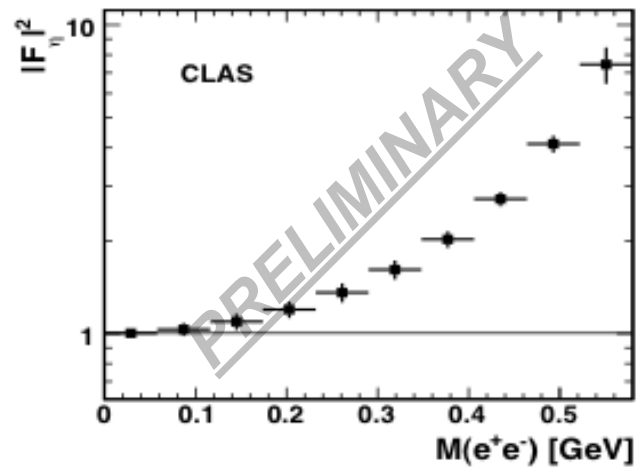
η Transition Form Factors

$$\frac{d\Gamma_{P\to l^+l^-\gamma}}{dq^2 d\Gamma_{P\to\gamma\gamma}} = \frac{2\alpha}{3\pi q^2}\left(1-\frac{q^2}{m_P^2}\right)^3\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}\left(1+\frac{2m_l^2}{q^2}\right)|_{\mathrm{Q.E.D}}$$

$$\frac{d\Gamma_{P_{P\to l^+l^-\gamma}}}{dq^2 d\Gamma_{P_{P\to\gamma\gamma}}}|_{\mathrm{measured}} = \frac{d\Gamma_{P_{P\to l^+l^-\gamma}}}{dq^2\Gamma_{P\to\gamma\gamma}}|_{\mathrm{Q.E.D}}\left|F(q^2)\right|^2$$



Recent results the η transition form factor with errors. Image Source: Phys. Rev. C 89, 044608



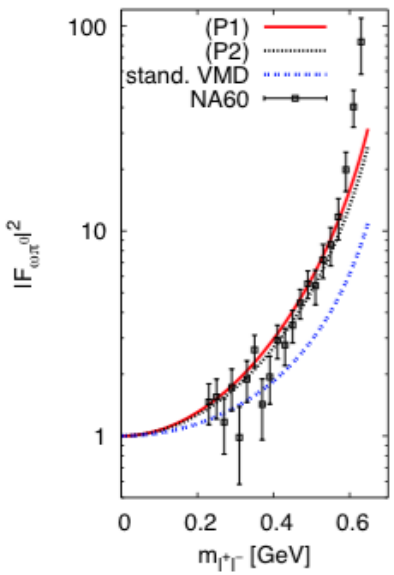
CLAS projected errors on η transition form factor

Currently seeking applicant for analysis

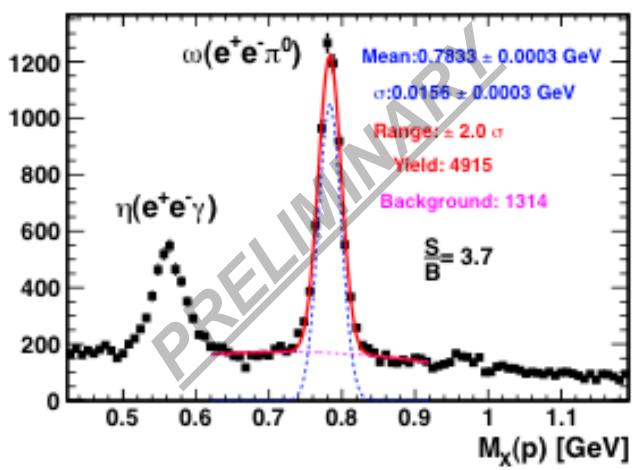
ω Transition Form Factor

$$\frac{d\Gamma_{\omega\to l^+l^-\pi^0}}{dq^2 d\Gamma_{\omega\to\pi^0\gamma}} = \frac{\alpha}{3\pi q^2}\left(\left(1+\frac{q^2}{m_\omega^2-m_{\pi^0}^2}\right)^2 - \frac{4m_\omega^2 q^2}{m_\omega^2-m_{\pi^0}^2}\right)^{\frac{3}{2}}\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}\left(1+\frac{2m_l^2}{q^2}\right)|\text{Q.E.D}$$

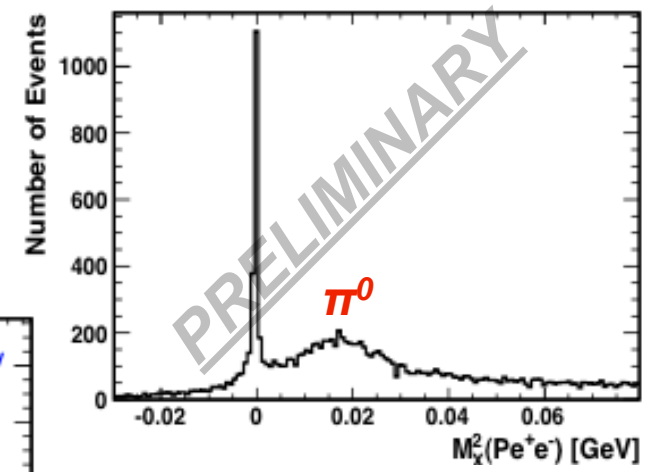
$$\frac{d\Gamma_{\omega\to l^+l^-\pi^0}}{dq^2 d\Gamma_{\omega\to\pi^0\gamma}}\Big|_{\text{measured}} = \frac{d\Gamma_{\omega\to l^+l^-\pi^0}}{dq^2 d\Gamma_{\omega\to\pi^0\gamma}}\Big|_{\text{Q.E.D}}\left|F(q^2)\right|^2$$



Recent results the ω transition form factor with errors. Image Source: Conference Proceedings



CLAS data yield from γp→pX with $M^2_X(pe^+e^-) = M^2_{\pi 0} \pm 0.01$ GeV^2



CLAS data yield from γp→pe⁺e⁻X with $M_X(p) = M_\omega \pm 0.031$ GeV

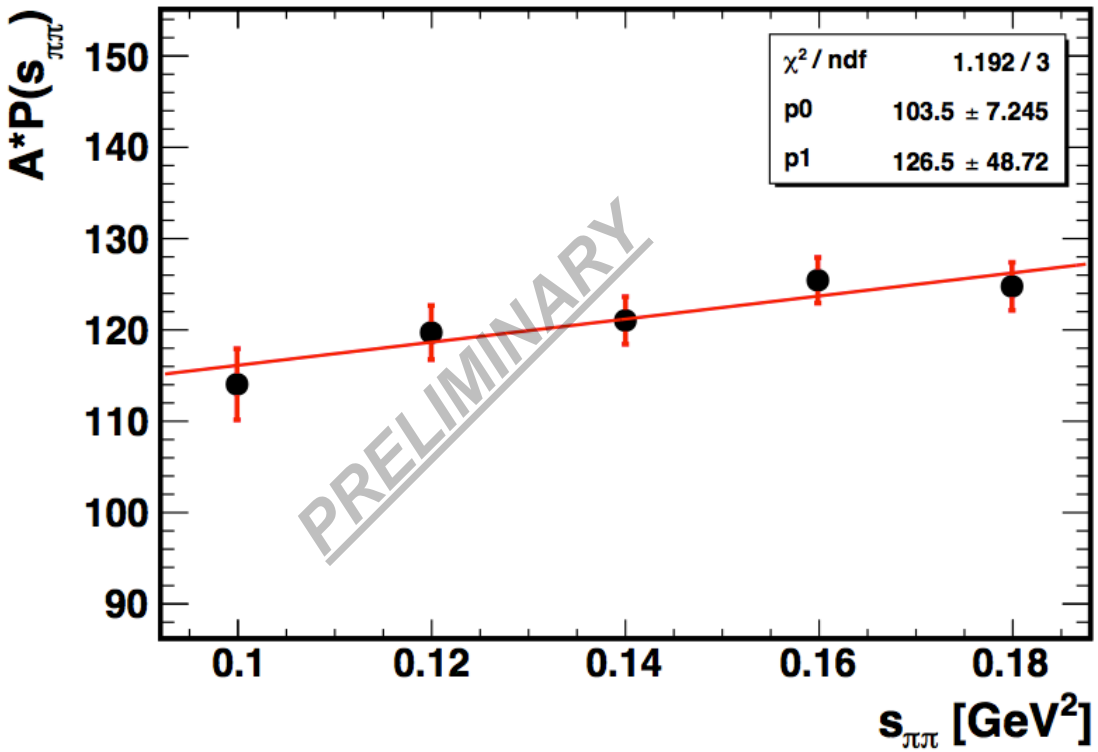
Summary

- CLAS LMD program has established a wide range of physics topics related to meson decays
- CLAS LMD program has global participation
- Statistics of CLAS data will enable precise measurements for the LMD physics program including but not limited to
  - Study $\pi^-\pi^+$ FSI within the anomalous decay $\eta(')\rightarrow\pi^-\pi^+\gamma$
  - Dalitz plot variable measurements
  - Transition form factors of pseudoscalar and vector mesons

BACKUP START HERE

CLAS Uncorrected Data

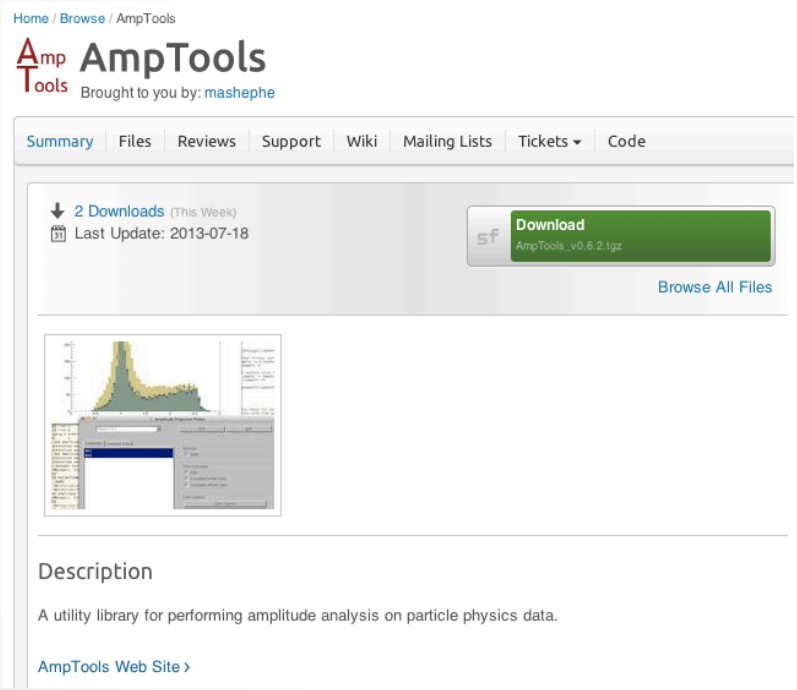
$$\eta \to \pi^+\pi^-\gamma$$



$$\alpha = (1.22 \pm 0.47) GeV^{-2}$$

- Need to work on MC to improve statistical precision

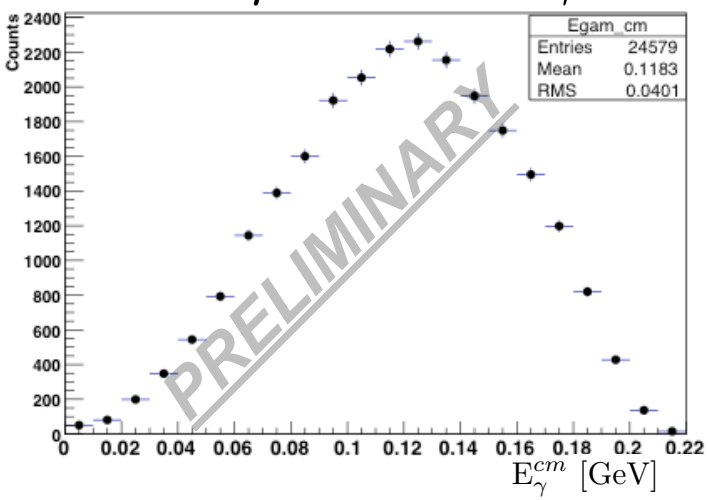
Tools



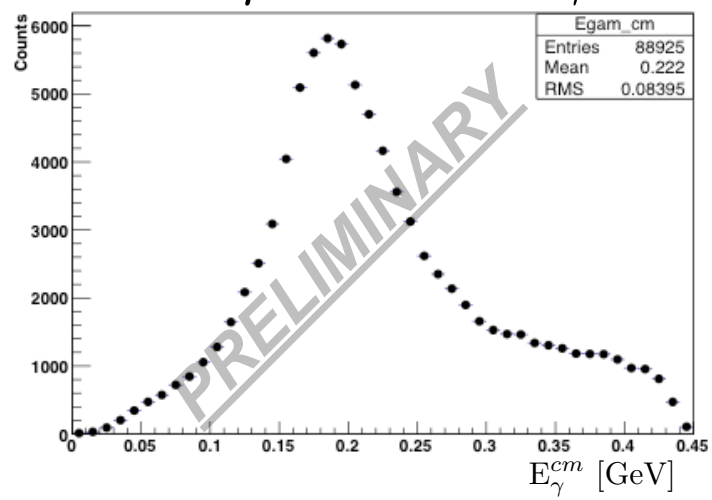
- **AmpTools framework:**
- It contains directories:
  - AmpTools/ :includes fitter and plotter
  - Tutorials/ : includes amplitudes, data
- User defined configuration files lets you define:
  - Initial fit parameters
  - Step size
  - Fix parameters
  - Real or imaginary parameters
  - Can call different amplitudes without changing or recompiling code

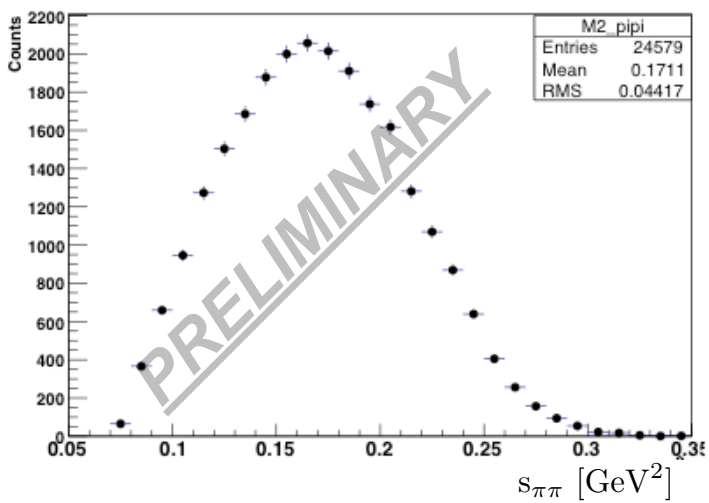
CLAS Uncorrected Data

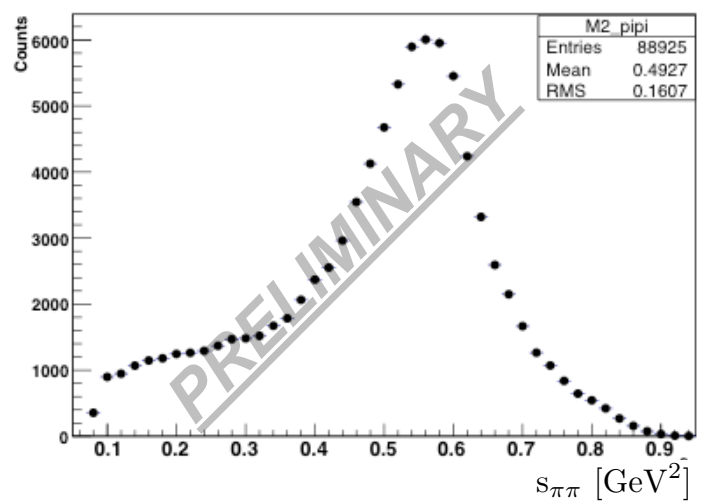
$\eta \to \pi^+\pi^-\gamma$



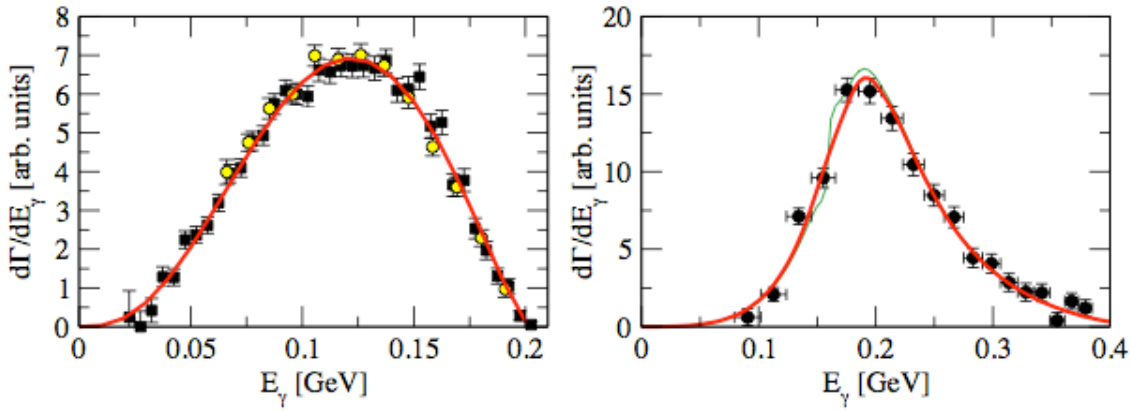
$\eta' \to \pi^+\pi^-\gamma$



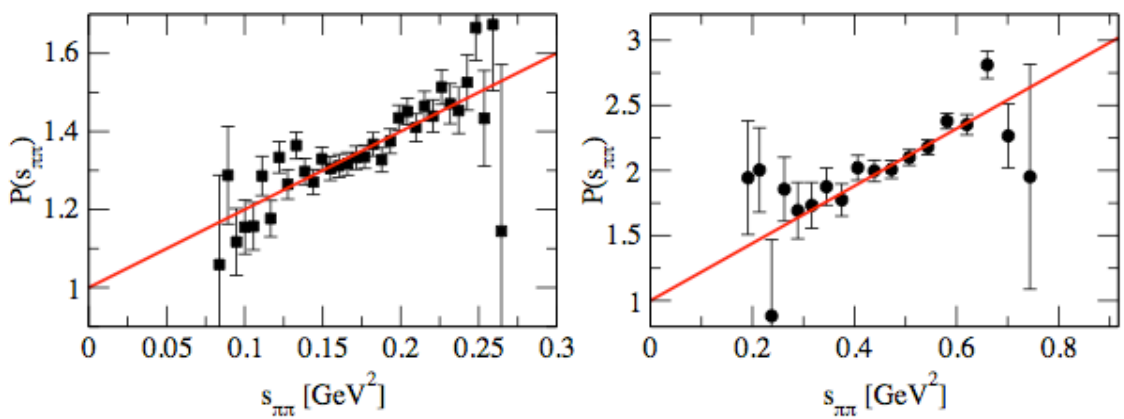




Experimental data from WASA-at-COSY(η) and CRSTAL BARREL(η') with error weighted fits.

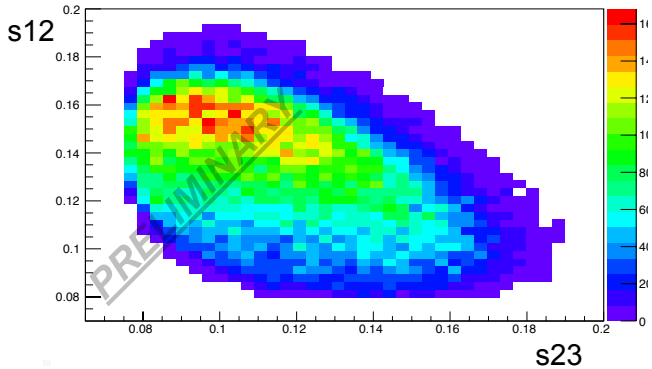


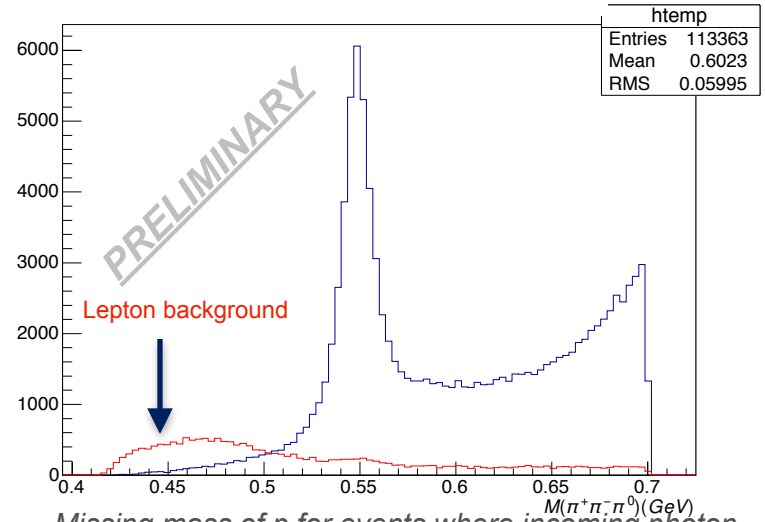
$$s_{\pi\pi} = m^2 - 2E_\gamma m$$



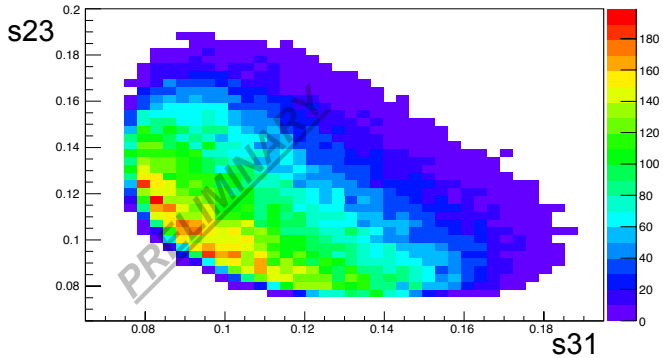
$$\alpha = (1.96 \pm 0.27 \pm 0.02)\ \mathrm{GeV}^{-2}\ ; \quad \alpha' = (1.80 \pm 0.49 \pm 0.04)\ \mathrm{GeV}^{-2}$$

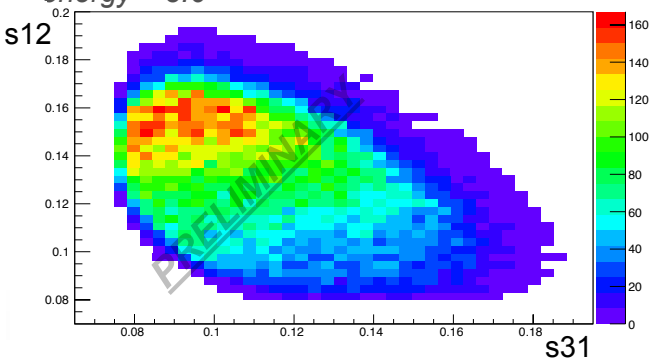
Dalitz Plot





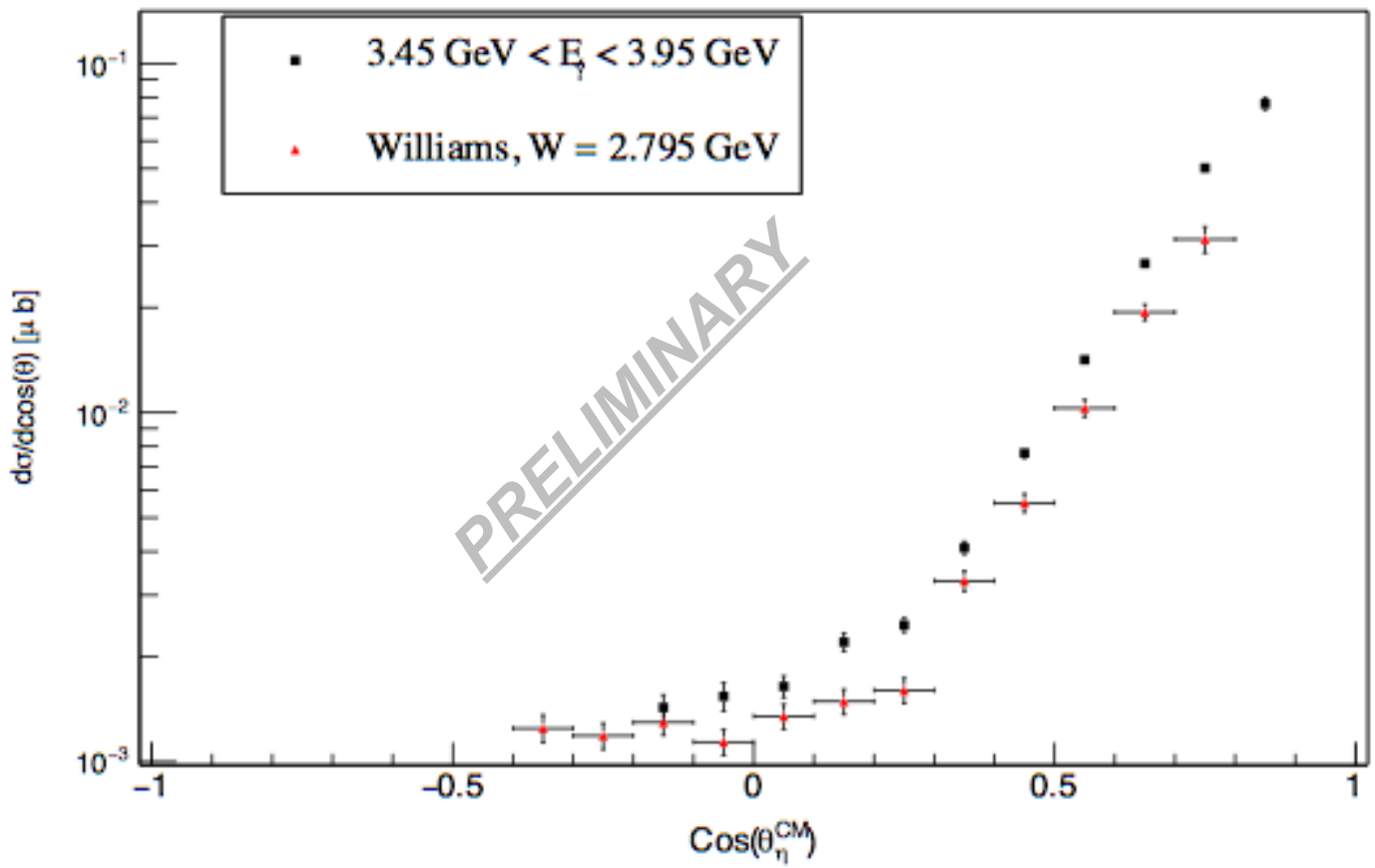
Missing mass of p for events where incoming photon energy > 3.6





Extraction Cross-Sections

Comparing g11 $\eta \rightarrow \pi^- \pi^+ \pi^0$ to g12 $\eta \rightarrow \pi^- \pi^+ \pi^0$ using AmpTools



Light Meson Decays in CLAS

CLAS Light Meson Decay (LMD) Program was established to investigate

Meson Decay	Physics	Data Set
$\eta(') \rightarrow \pi^- \pi^+ \gamma$	Box anomaly	g11, g12
$\omega \rightarrow \pi^- \pi^+ \gamma$	Upper limit branching ratio	g11, g12
$\eta, \omega, \Phi \rightarrow \pi^- \pi^+ \pi^0$	Dalitz plot analysis	g11, g12
$\eta' \rightarrow \pi^- \pi^+ \eta$	Dalitz plot analysis/meson mixing	g11, g12
$\Phi \rightarrow \pi^- \pi^+ \eta$	G-parity violation	g11, g12
$\Phi \rightarrow \omega \gamma$	C violation, rare decay	g11, g12
NULL	Invisible decay	g11, g12
f_1	isospin symmetry breaking, f1	g11, g12