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JÜLICH FORSCHUNGSZENTRUM

Investigation of the Hadronic Decay $\eta \to \pi^+\pi^-\pi^0$ with CLAS

01.02.2017 | 7th Workshop of the APS Topical Group Hadronic Physics 2017

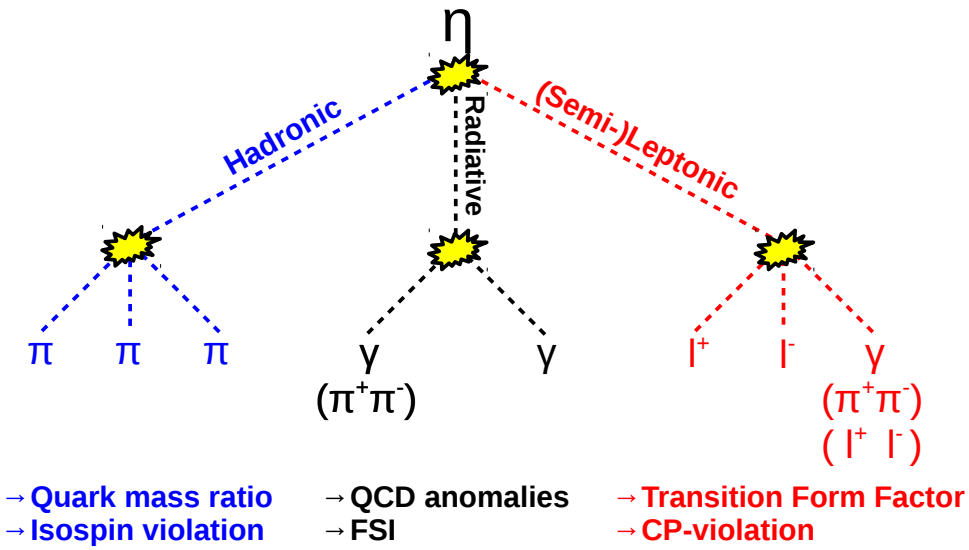
Institute for Nuclear Physics - Jülich Research Center

One Meson, many Opportunities

Properties of the η-meson

m_η [GeV/c^2]	0.5478
Γ_η [keV]	(1.31 ± 0.05)
$\bar{\tau}$ [s]	$5 \cdot 10^{-19}$
J^{PC}	0^{-+}

- The η-meson is a *C*-, *P*-, *G*- and *CP*- eigenstate
- All strong and electromagnetic decays are forbidden to first order
- Access to rare decay processes



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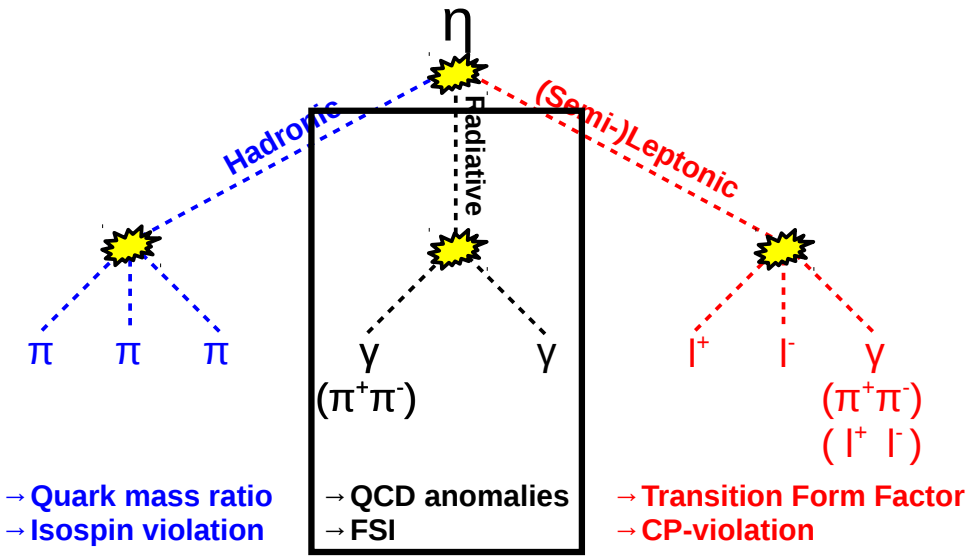

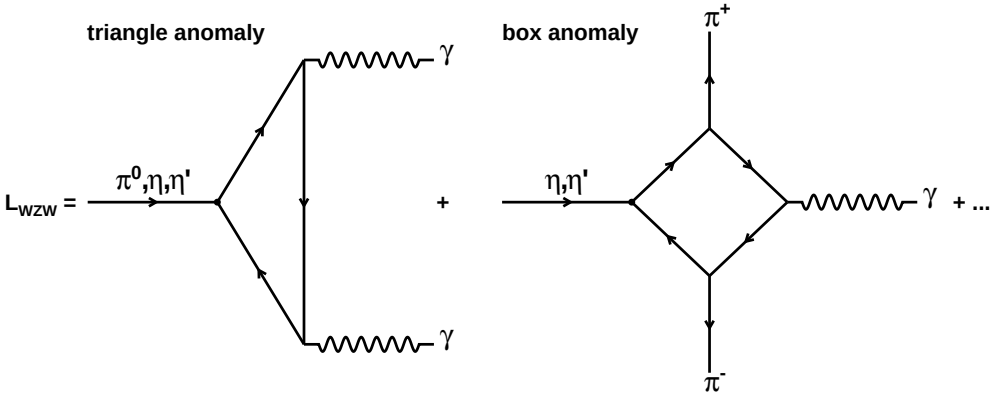

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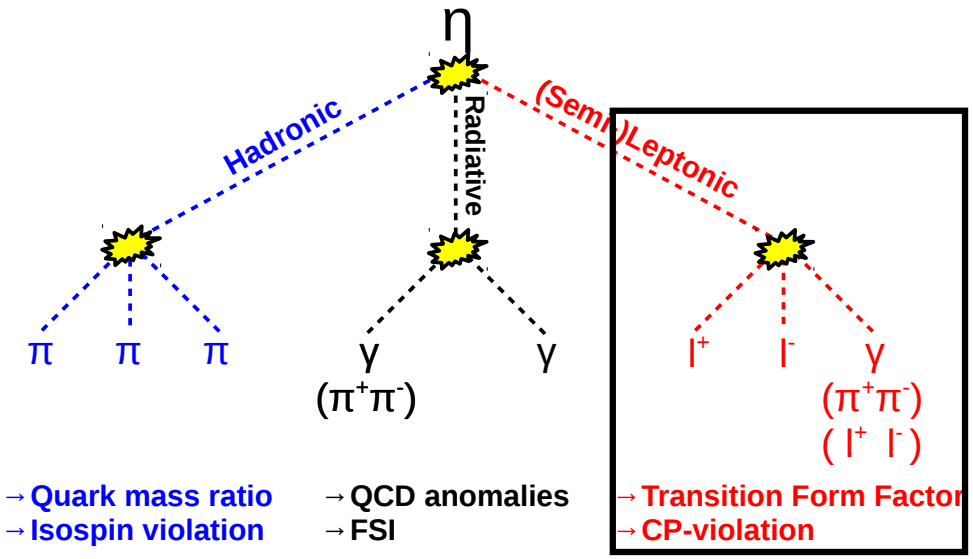

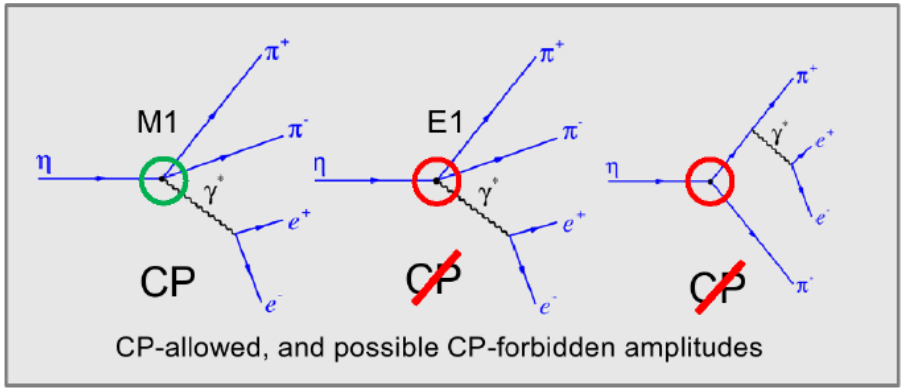

CP-allowed, and possible CP-forbidden amplitudes

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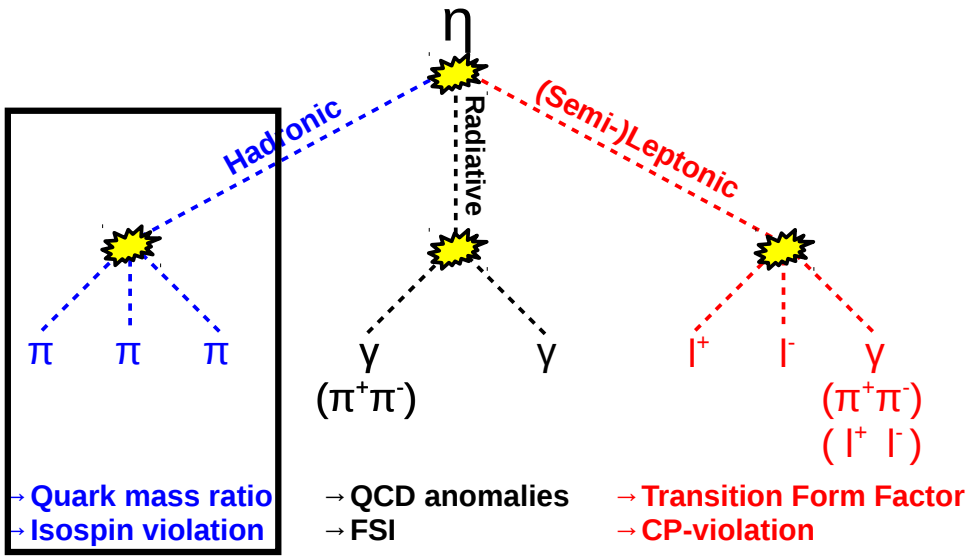


Focus of this Talk

Decay Dynamics of $\eta \to \pi^+\pi^-\pi^0$

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

- Decay $\eta \to \pi^+\pi^-\pi^0$ is G-violating $\Rightarrow$ Forbidden to first order
- Electromagnetic contributions found to be small
  $\Rightarrow$ Isospin-violation $\Rightarrow$ C-conservation
- Decay width: $\boldsymbol{\Gamma \propto Q^{-4}}$

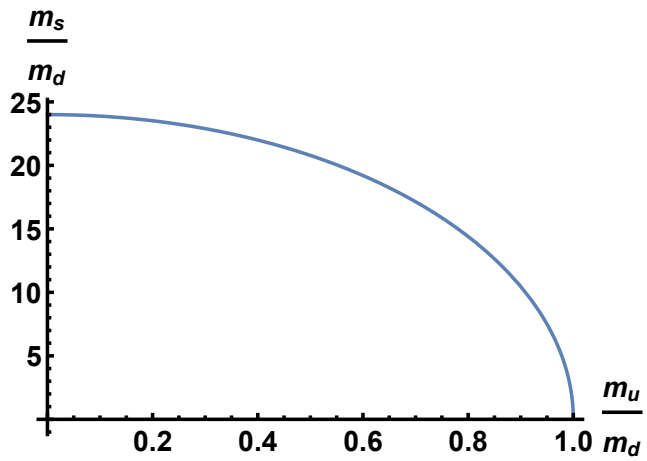
  with: $Q^2 = \left(\frac{m_s}{m_d}\right)^2 \times \left[1 - \left(\frac{m_u}{m_d}\right)^2\right]^{-1}$

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

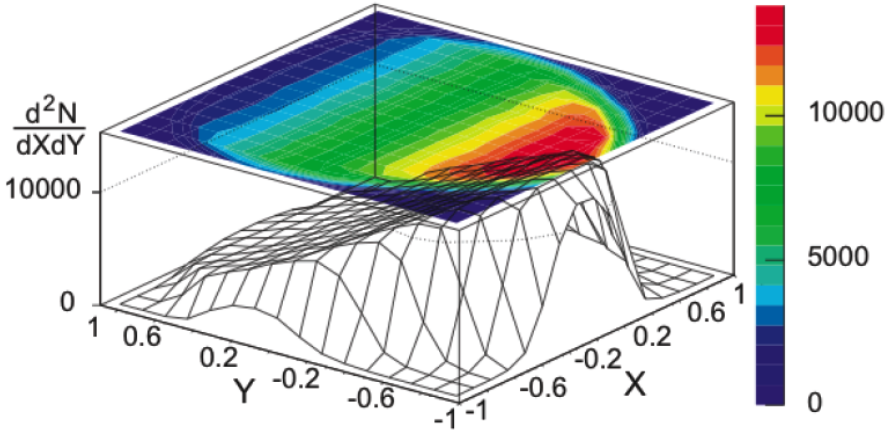
$\Downarrow$

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



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



(a) KLOE coll., *JHEP*, 05, (2008)

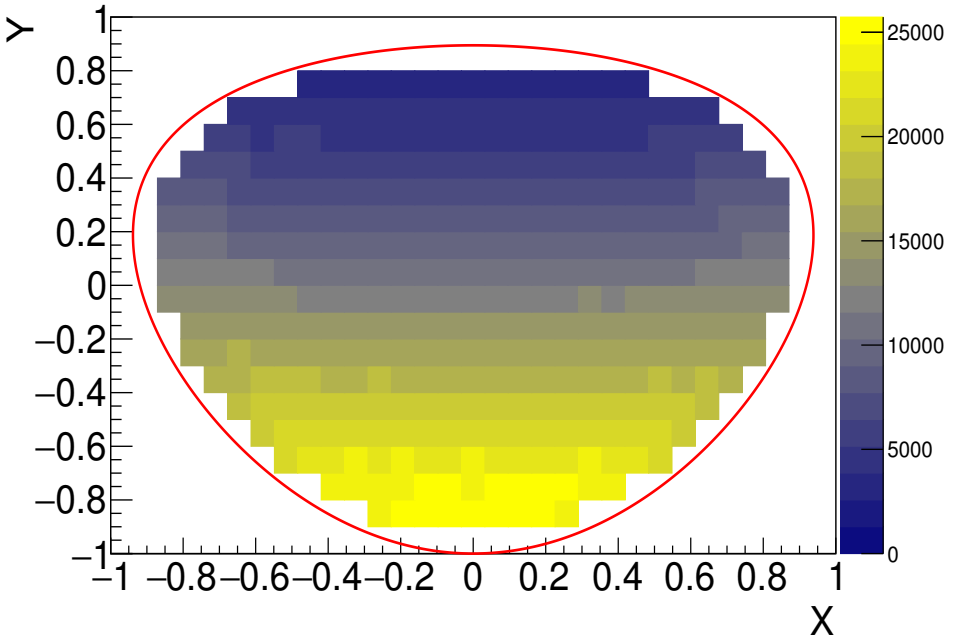
Dimensionless Dalitz Plot Variables:

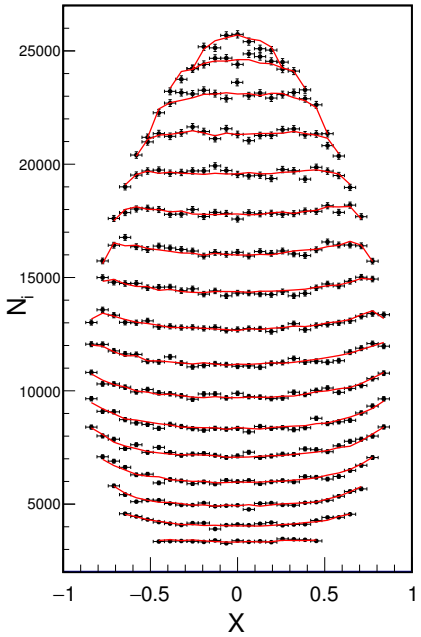
$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}}$$

$$Y = 3\frac{T_{\pi^0}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}} - 1$$

- Describe three body decay by two variables (here: X and Y)
- Complete information about decay dynamics
- Parameterise decay width Γ:
  $$\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots)$$
- $c \neq 0$ and $e \neq 0$:
  i) Imply C-violation
  ii) Cause asymmetries within the Dalitz Plot
- Compare Dalitz Plot parameters a,b,d,f from experiment and theory

Recent Measurements I



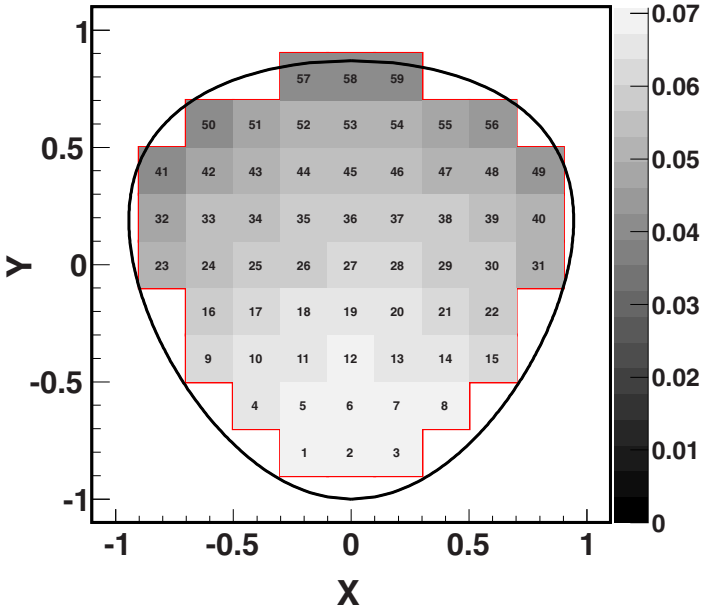


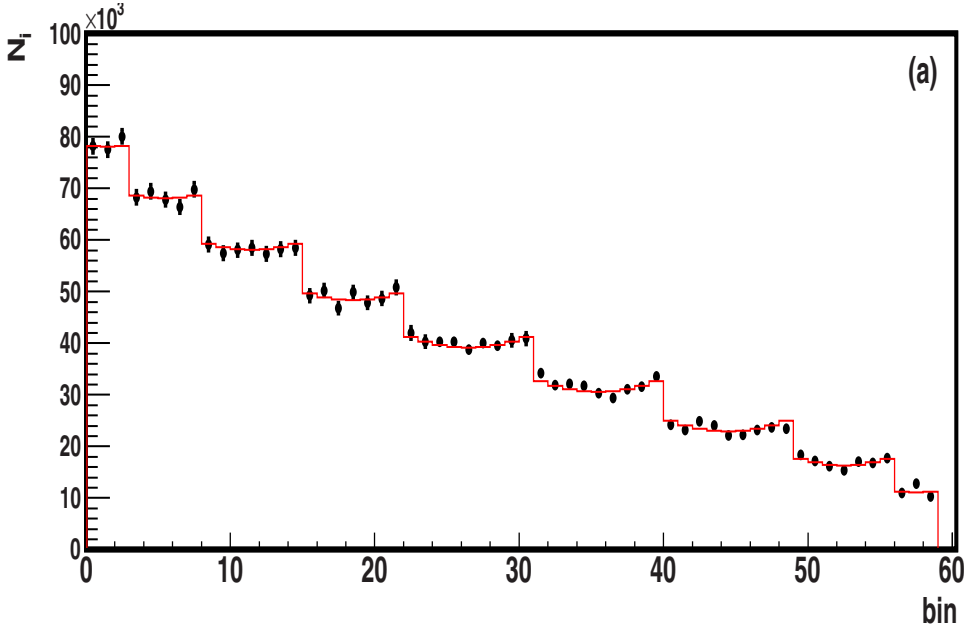
Most recent result from the KLOE-Collaboration:[f]

- η-Mesons produced via: $e^+e^- \rightarrow \Phi \rightarrow \eta\gamma$
- $\approx 4.7 \cdot 10^6$ $\eta \rightarrow \pi^+\pi^-\pi^0$ events in the final data sample
- Fit function: Norm $\times$ $(1 + aY + bY + cX + dX^2 + eXY + fY^3)$
- Determined asymmetries of the Dalitz Plot $\Rightarrow$ Consistent with zero
  $\Rightarrow$ No C-violation

(f) KLOE coll., *JHEP*, 019, (2016)

Recent Measurements II





Result from the WASA-at-COSY Collaboration:[(d)]

- η-Mesons produced via: $pd \rightarrow {}^3\mathrm{He}\eta$
- $\approx 120\,\mathrm{k}\ \eta \rightarrow \pi^+\pi^-\pi^0$ events in the final data sample
- Translate each pair (X,Y) into a global bin $i(X, Y)$
  $\rightarrow$ Obtain one dimensional Dalitz Plot
- Fit function: Norm $\times\ (1 + aY + bY + cX + dX^2 + eXY + fY^3)$

(d) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), 2014

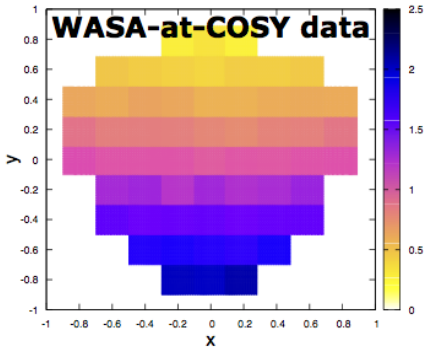
Recent Measurements and Theoretical Predictions

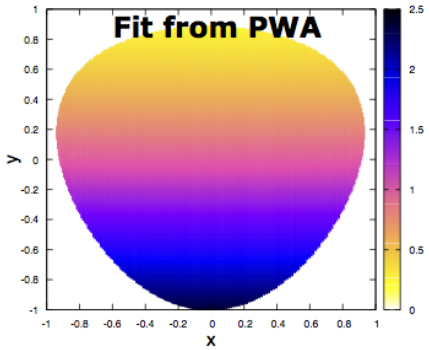
	Parameter:	$-a$	b	d	f
Exp.	KLOE (08)[a]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[d]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE (16)[f]	1.104(3)(2)	$0.142(3)(^{5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
Theor.	ChPT (NNLO)[b]	1.271(75)	0.394(102)	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)

(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)

- WASA-at-COSY results used for Partial Wave Analysis (PWA) from JPAC* group
  $\Rightarrow$ Direct calculation of: $Q = 21.4 \pm 0.4_{\text{stat}}$ [e]
- **Dalitz Plot Analysis and determination of Q for $\gamma p \to p\eta[\eta \to \pi^+\pi^-\pi^0]$ with CLAS**

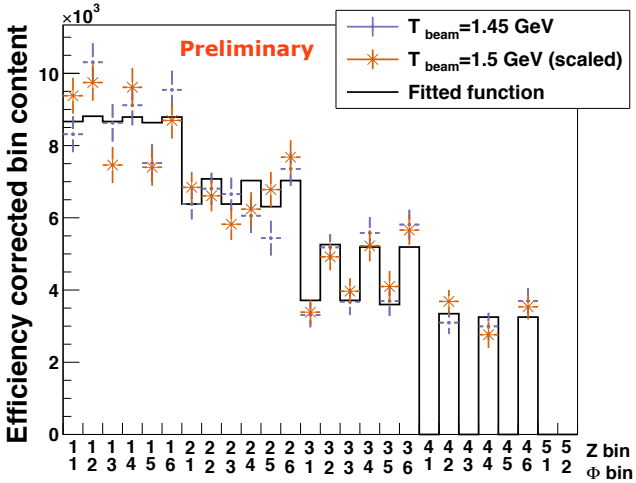


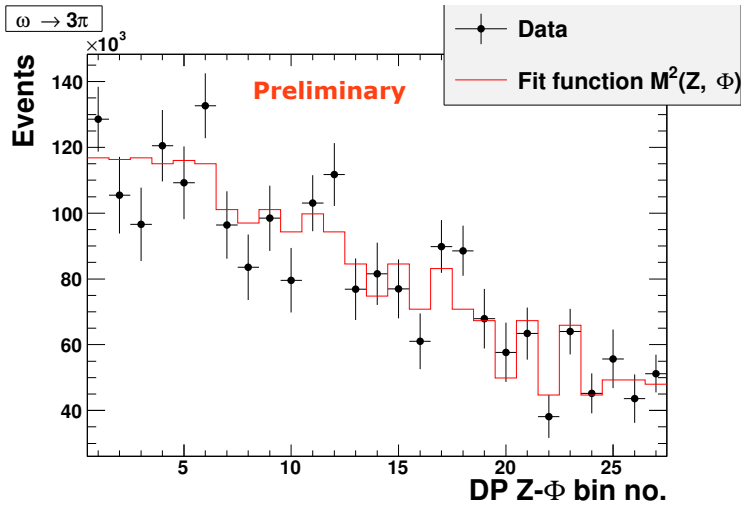


* See plenary talk "Hadron Spectroscopy at JPAC" by Alessandro Pilloni at 4.40 p.m.

Small Outlook: Dalitz Plot Analysis for $\omega \to \pi^+\pi^-\pi^0$ with WASA-at-COSY

- Theoretical description of this decay:
  VMD Model, Lagrangian Approach[(a)], Dispersive Analysis[(b),(c)]
  $\to$ Input from experiment needed
- Look at: $\frac{d^2\Gamma}{dZd\Phi} \propto (1 + 2\alpha Z + 2\beta Z^{3/2}\sin^3\Phi + \mathcal{O}(Z^2) + ...)$
- Analysis ongoing[(d),(e)] for the reaction:
  $pd \to {}^3\mathrm{He}\omega[\omega \to \pi^+\pi^-\pi^0]$ and $pp \to pp\omega[\omega \to \pi^+\pi^-\pi^0]$



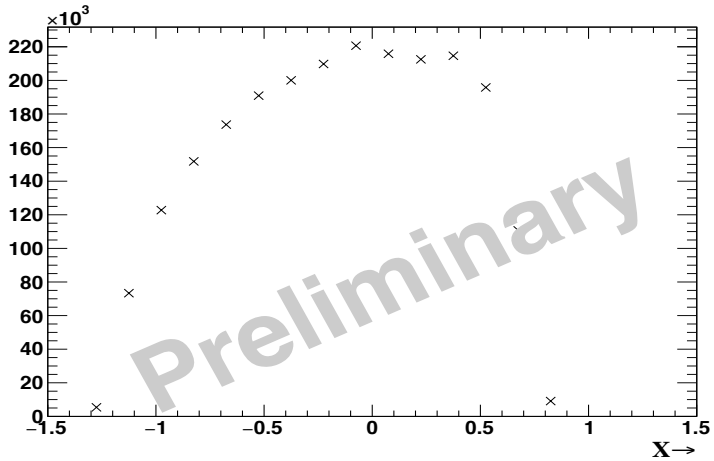


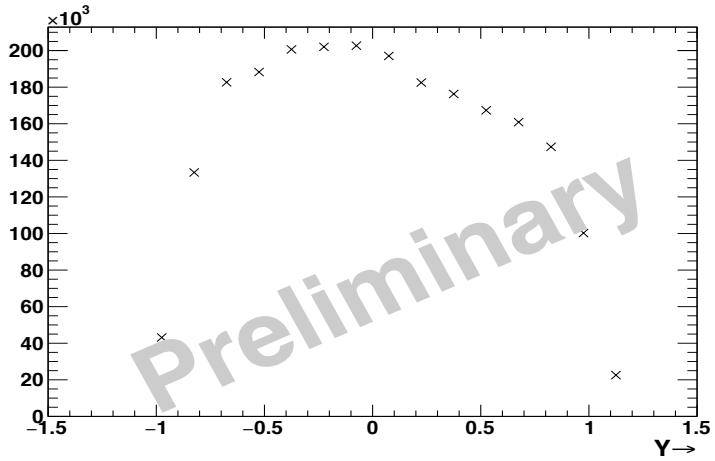
(a) S. Leupold et al., Eur. Phy. J. **A 39**, 205-212, (2009) (b) N. Niiecknig et al., Eur. Phy. J. **C 39**, 2014, (2012)

(c) I.V:Danilkin et al., Phys. Rev. **D91**, 094029, (2015) (d) PhD.-Project of Lena Heijkenskjöld (e) PhD.-Project of Siddhesh Sawant

Small Outlook: Dalitz Plot Analysis for $\eta' \to \pi^+\pi^-\eta$ with CLAS

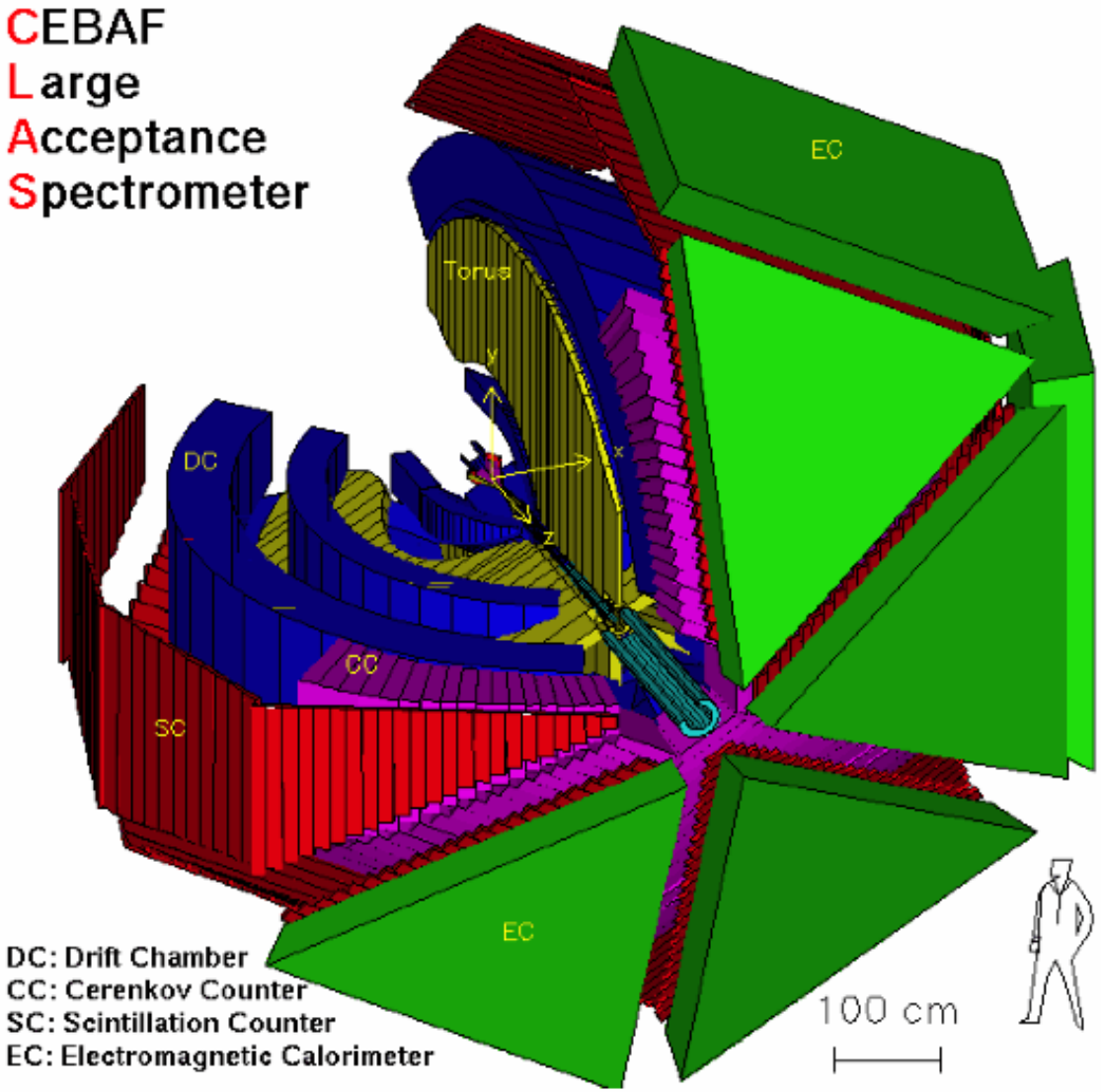
- The decay $\eta' \to \pi^+\pi^-\eta$ allows to probe the low energy regime of QCD
  $\Rightarrow$ Test ChPT
- Compare theory and experiment by checking decay kinematics
  $\Rightarrow$ Dalitz Plot
- Analysis* performed using the CLAS g12 data set
- $\approx 87\,\mathrm{k}$ events reconstructed



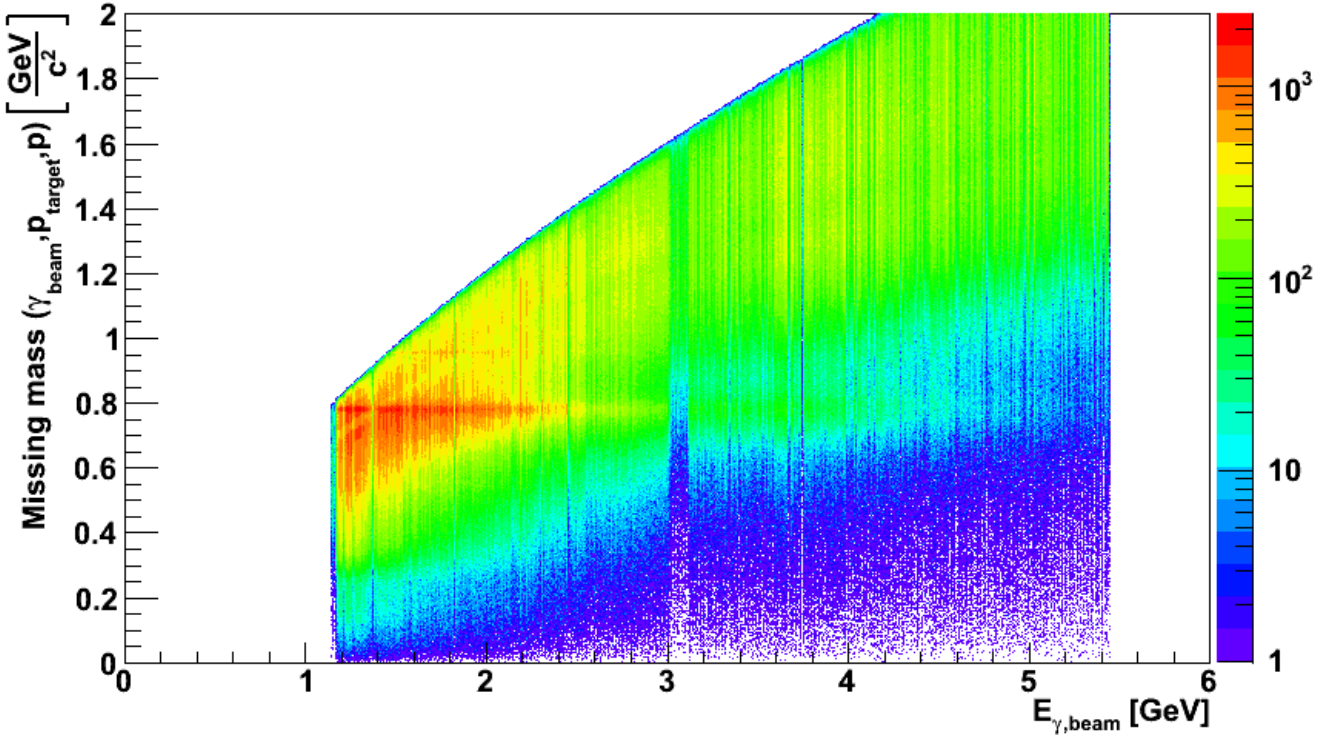


* PhD-Project of S. Ghosh

CEBAF Large Acceptance Spectrometer - CLAS

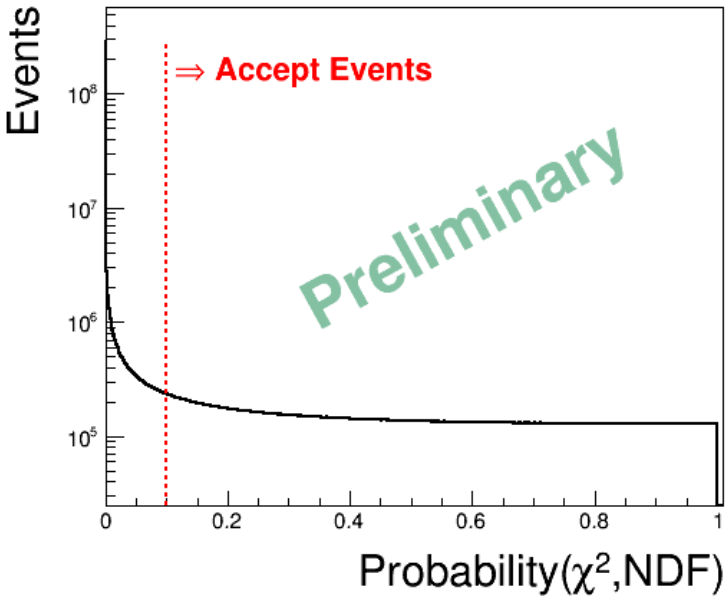


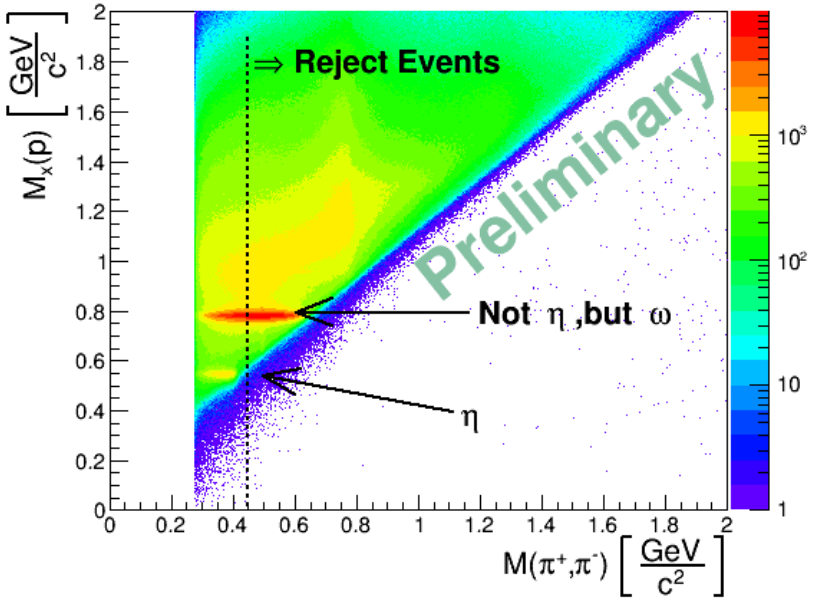
The CLAS g12 $\gamma p \to pX$ Data Set



- Photon beam: $E_{\gamma,\text{beam}} \in [1.1\,\text{GeV}, 5.45\,\text{GeV}]$
- (Main) Contributions from:
  - Direct pion production (e.g. $\gamma p \to p\pi^+\pi^-\pi^0$)
  - π^0, η, ω and ρ decays

Reconstruction of $\eta \to \pi^+\pi^-\pi^0$ Events





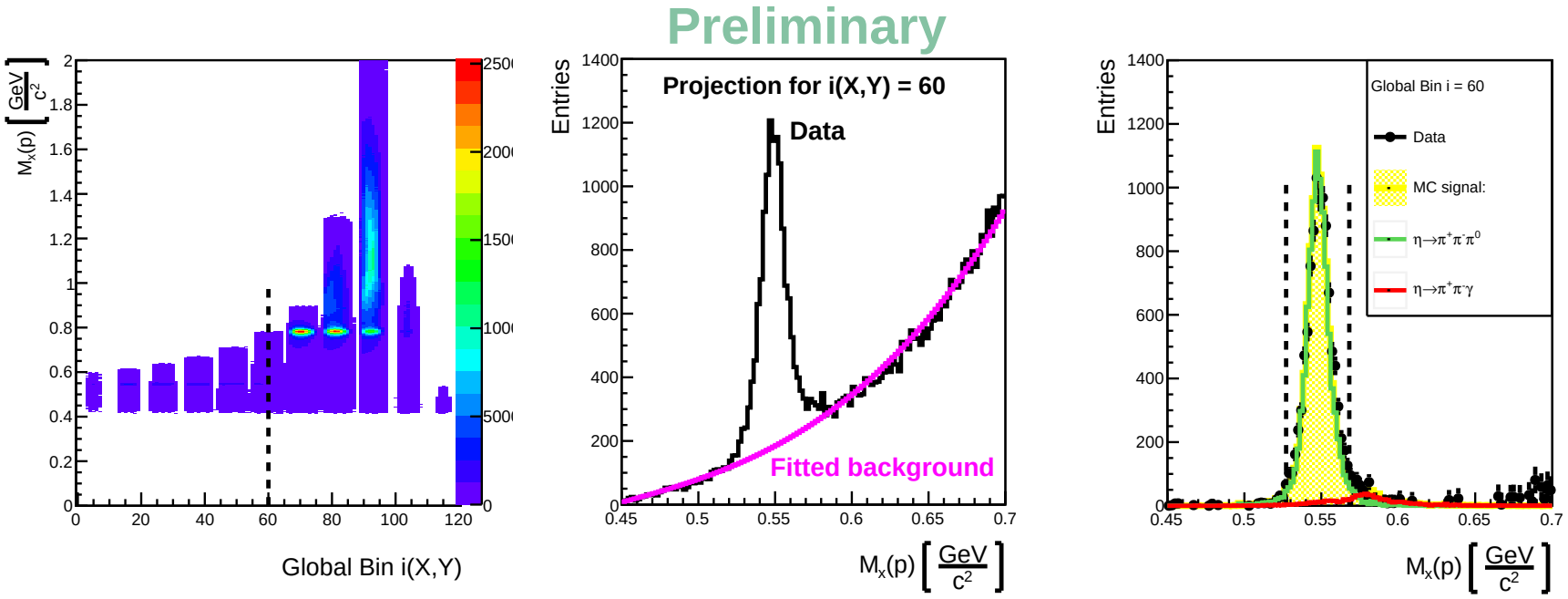
Decay Specific Analysis Steps

i) Kinematic fit with reaction hypothesis: $\gamma p \to p\pi^+\pi^-(\pi^0)$

ii) Kinematic Limit: $M(\pi^+, \pi^-) \leq m_\eta + 3\sigma_{\eta,res} - m_{\pi^0}$

$\approx 700\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events reconstructed so far

Towards the Dalitz Plot

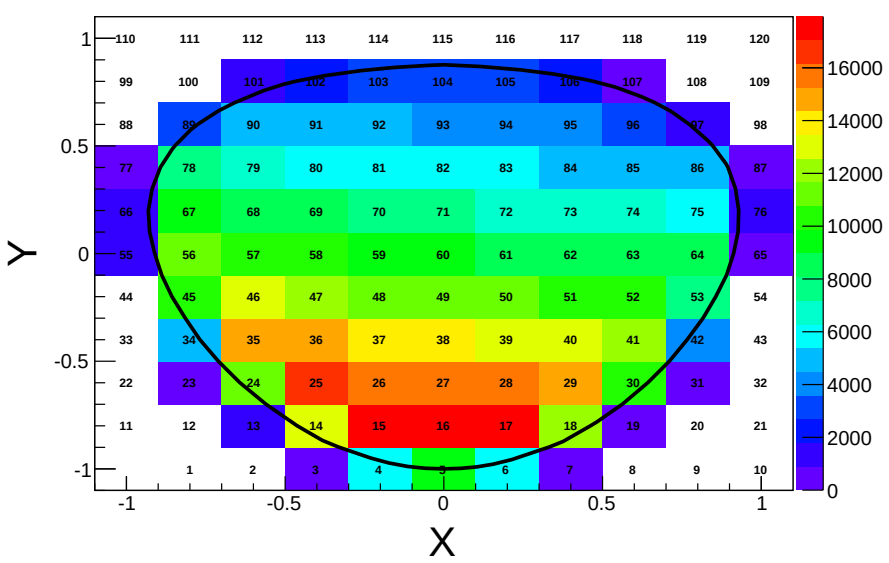


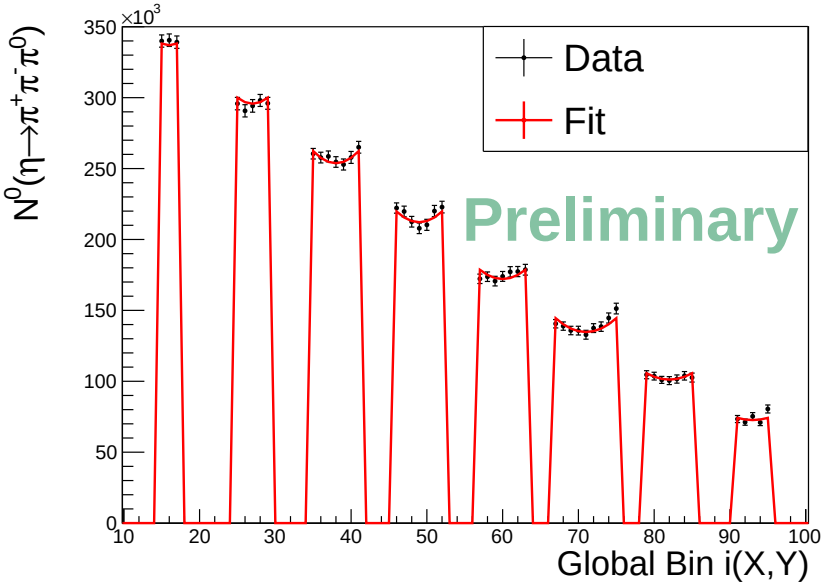
i) Look at $M_x(p)$-spectrum as a function of the global bin $i(X, Y)$

ii) Subtract non-resonant background

iii) Correct for contributions from $\eta \to \pi^+\pi^-\gamma$

Current Status



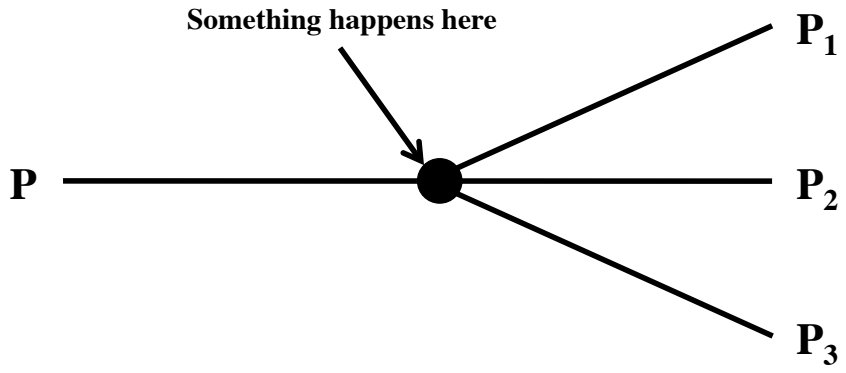


- **Left:** Dalitz Plot after background subtraction and correction for $\eta \to \pi^+\pi^-\gamma$ events (see previous slide)
- **Right:** One Dimensional Dalitz Plot after applying efficiency correction
- Fit function: Norm $\times (1 + aY + bY + dX^2 + fY^3)$
- Systematic checks and validation of current results ongoing

Summary and Outlook

1. Features of the hadronic decay: $\eta \to \pi^+\pi^-\pi^0$
   - C-conserving
   - Isospin-violating
   - Decay amplitude driven by quark mass ratio
2. Determine decay amplitude via Dalitz Plot Analysis
   - Kinematics of a three body decay described by two variables
   - Dalitz Plot Parameters: a,b,c,d,e and f
   - Asymmetries in Dalitz Plot $\leftrightarrow$ c and e are non-zero $\leftrightarrow$ C-Violation
3. Several experimental and theoretical efforts to determine Dalitz Plot
   - $c = e = 0$ confirmed by experiments
   - Latest measurements done by WASA-at-COSY and KLOE:
     i) KLOE confirmed Dalitz Plot asymmetries to be consistent with zero
     ii) WASA-at-COSY results used in PWA (JPAC-group) to determine the quark mass ratio
   - JPAC: Partial Wave Analysis as a tool to fit experimental Dalitz Plot distributions
4. Dalitz Plot Analysis of $\eta \to \pi^+\pi^-\pi^0$ with CLAS
   - $\approx 700\,\mathrm{k}$ events reconstructed so far
   - Final (one dimensional) Dalitz Plot distribution
   - To do:
     i) Systematics checks (ongoing)
     ii) Determination of quark mass ratio

Backup: Three Body Decays and the Dalitz Plot



Kinematic Constraints	NDF
3 Lorentz-Vectors	12
Momentum Conservation	−3
Energy Conservation	−1
3 Masses	−3
3 Euler Angles	−3
Total*	**2**

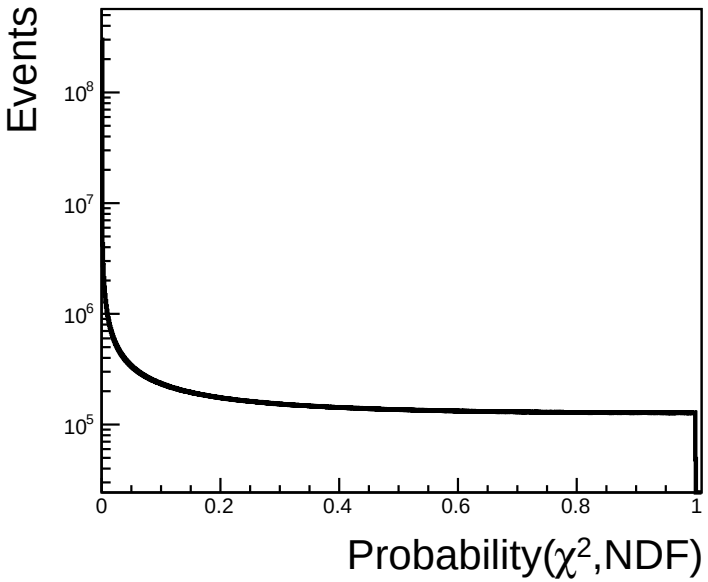
* Valid for all particles being scalars

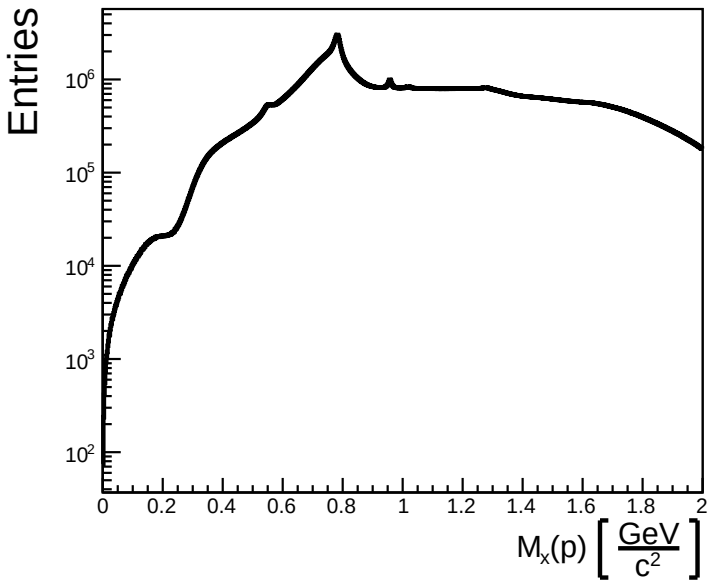
Dalitz Plot

- Two* variables sufficient to describe three body decay
- Display decay kinematics
- Show possible resonances

Backup: Reconstruction of $\eta \to \pi^+\pi^-\pi^0$

I) The Kinematic Fit

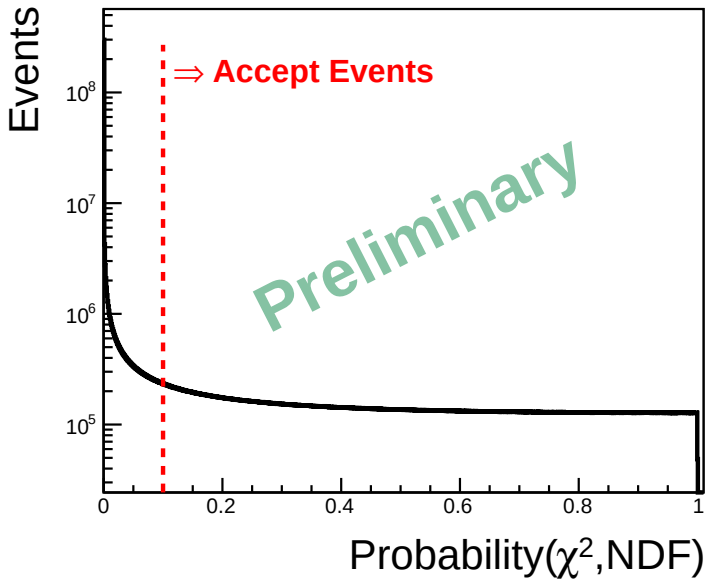


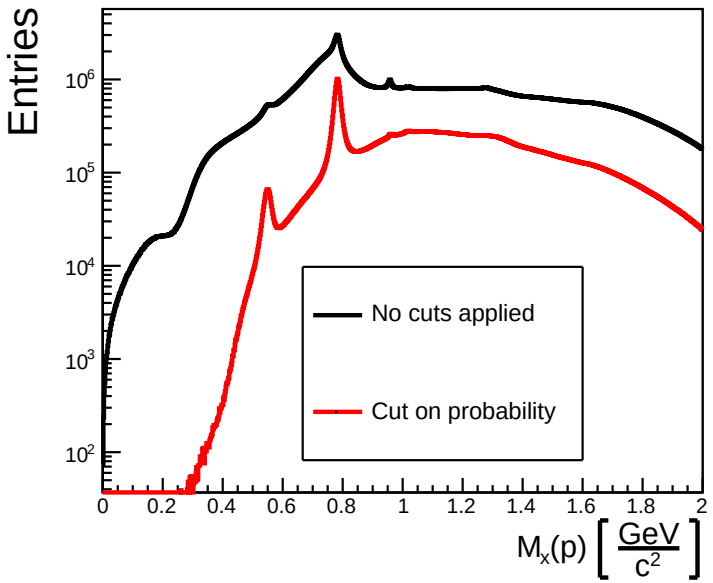


- $\sim 2/3$ of the available CLAS g12 data set analysed so far
- Use least squares kinematic fit
  - Reaction hypothesis: $\gamma p \to p\pi^+\pi^-(\pi^0)$
  - Reject events with a probability $< 10\%$

Backup: Reconstruction of $\eta \to \pi^+\pi^-\pi^0$

I) The Kinematic Fit





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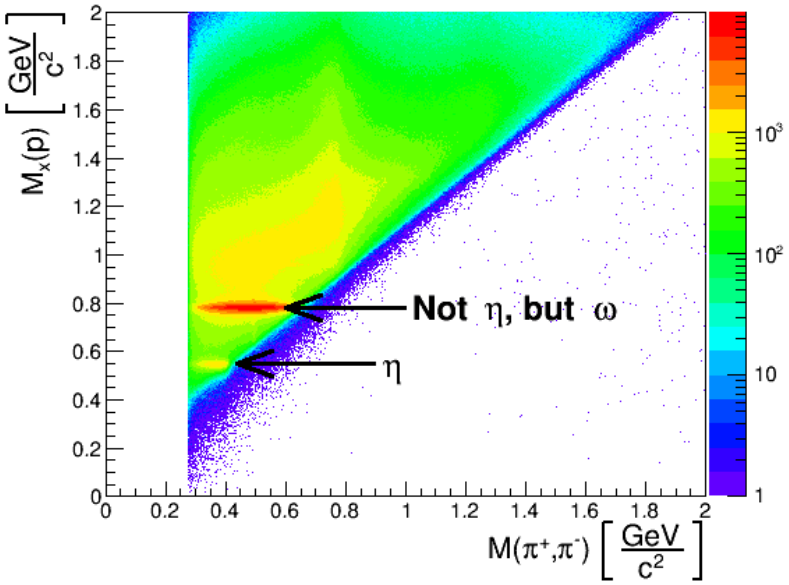
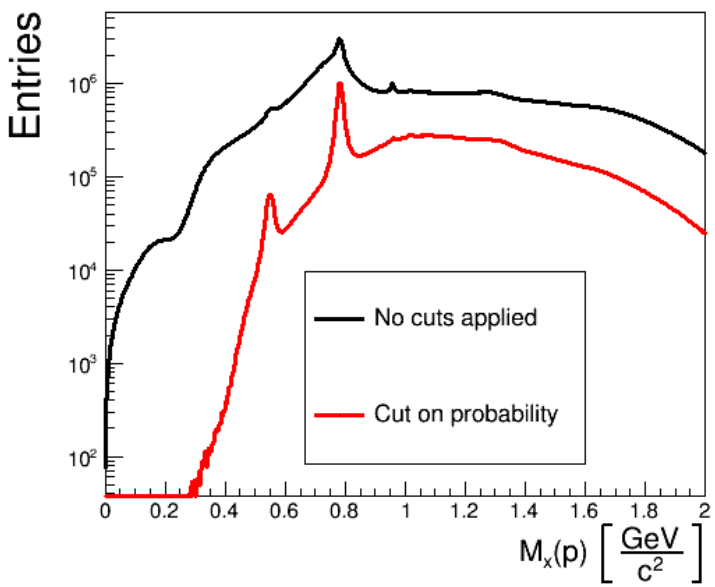
Backup: Reconstruction of $\eta \to \pi^+\pi^-\pi^0$

II) Reject Contributions from $\omega \to \pi^+\pi^-\pi^0$

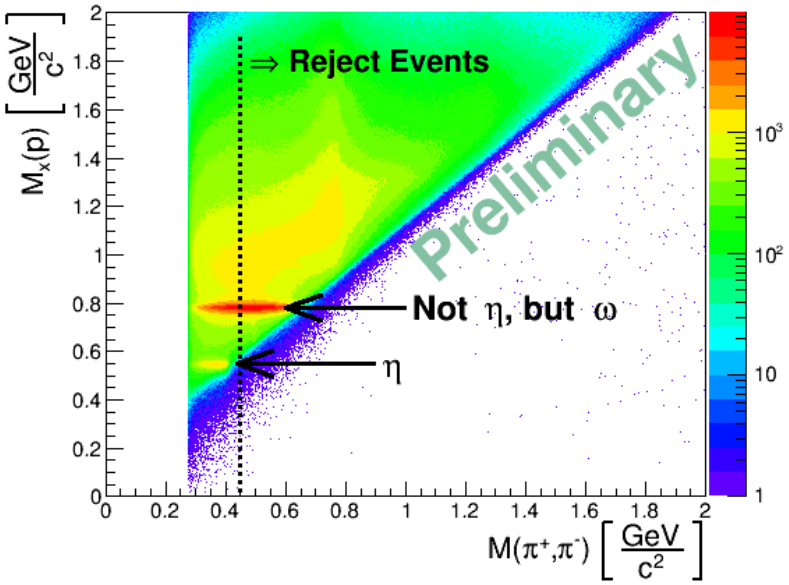


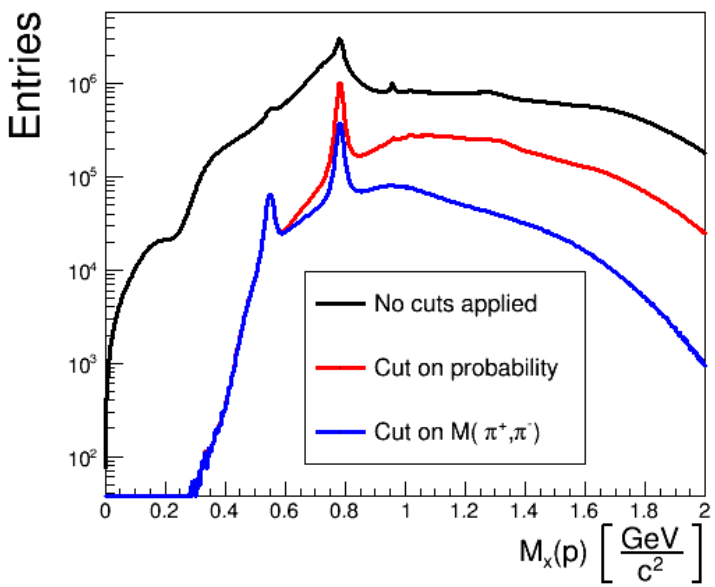


- $\sim 2/3$ of the available CLAS g12 data set analysed so far
- Use least squares kinematic fit
- Use kinematic limit: $M(\pi^+, \pi^-) \leq m_\eta + 3\sigma_{\eta,rec} - m_{\pi^0}$

Backup: Reconstruction of $\eta \to \pi^+\pi^-\pi^0$

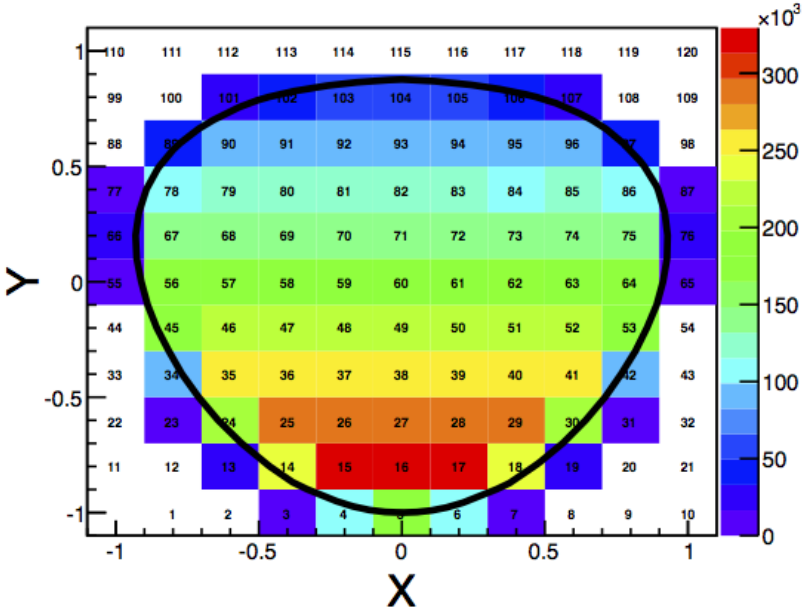
II) Reject Contributions from $\omega \to \pi^+\pi^-\pi^0$

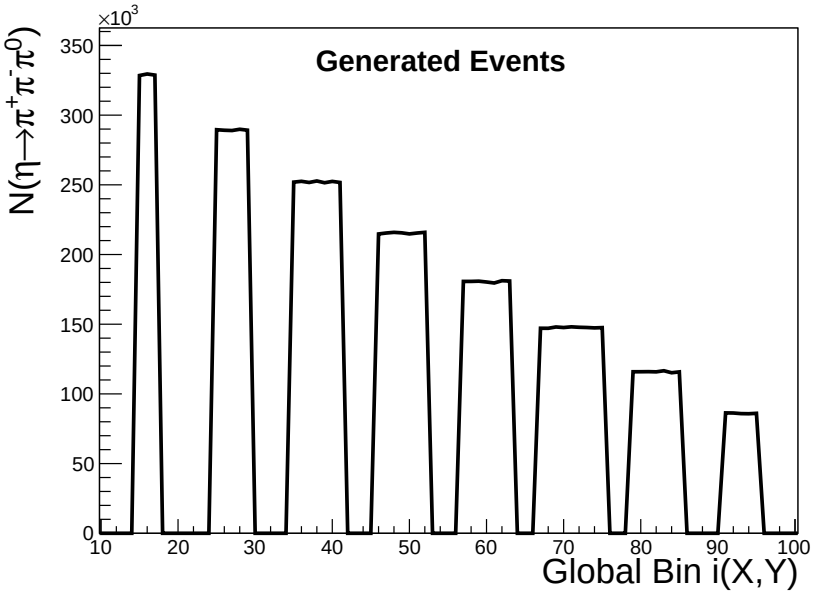




- $\sim 2/3$ of the available CLAS g12 data set analysed so far
- Use least squares kinematic fit
- Use kinematic limit: $M(\pi^+, \pi^-) \leq m_\eta + 3\sigma_{\eta,rec} - m_{\pi^0}$

Backup: The Dalitz Plot in one Dimension



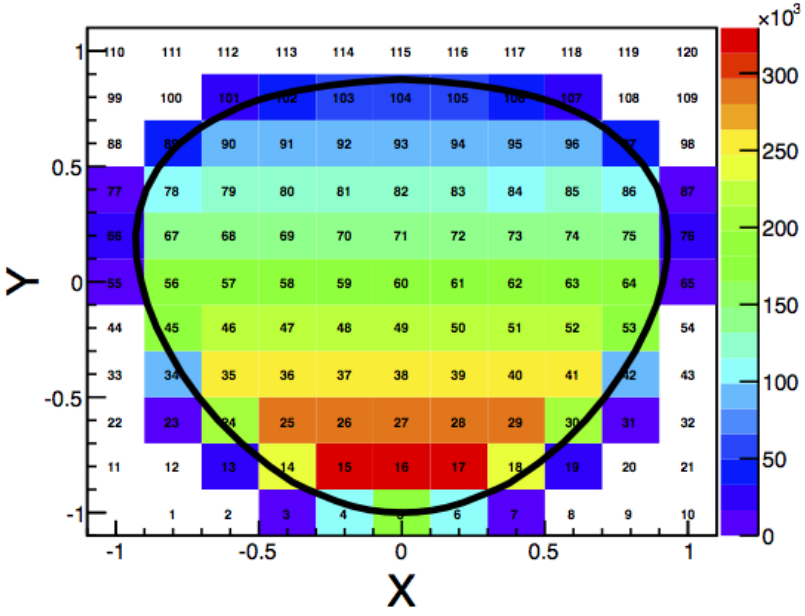


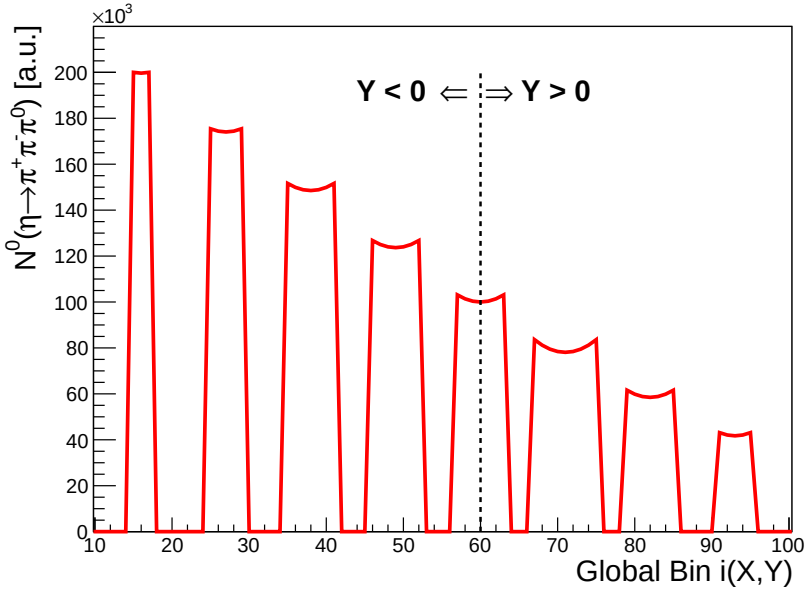
Follow WASA-at-COSY analysis[(a)]:

- Divide Dalitz Plot in $N \times N$ bins
- Translate each pair (X,Y) into a global bin number $i \in [0, N^2 - 1]$ (e.g. $X = Y = 0 \equiv i = 60$)
- Take kinematic boundaries (see black line in left plot) into account

(a) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), 2014

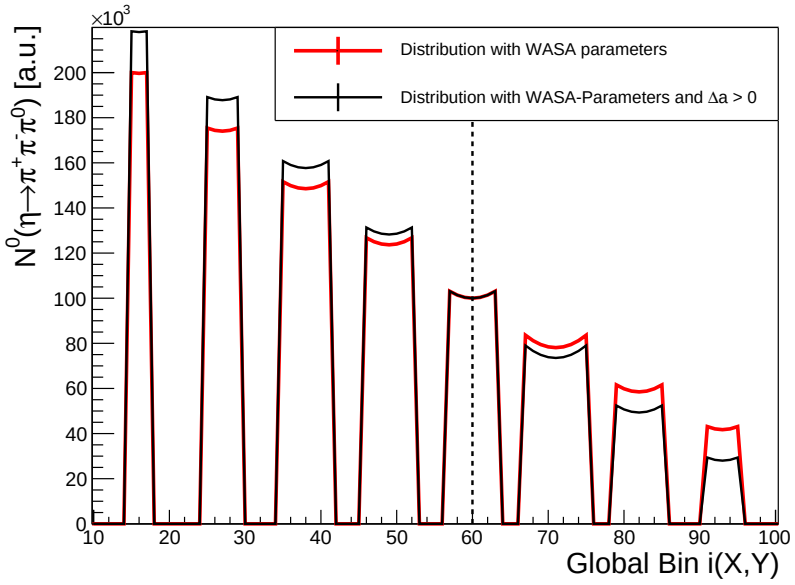
Backup: Features of the 1D Dalitz Plot

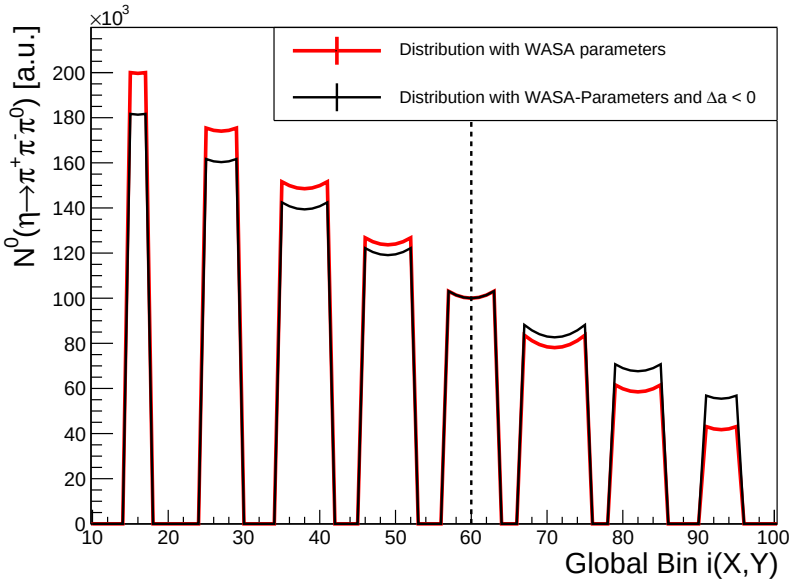




- Look at 1D Dalitz Plot with WASA-at-COSY values for a,b,d and f
- Center of Dalitz Plot is at $i(0,0) = 60$
- $\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3)$

Backup: Features of the 1D Dalitz Plot





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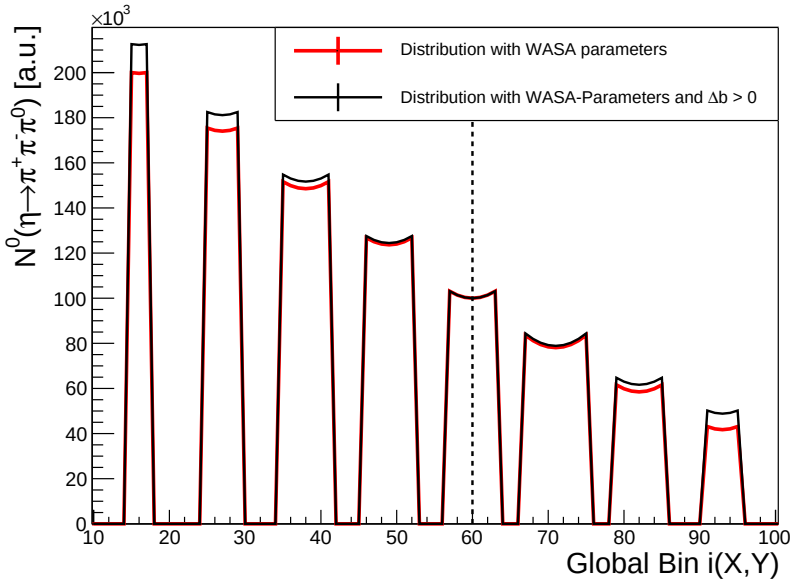

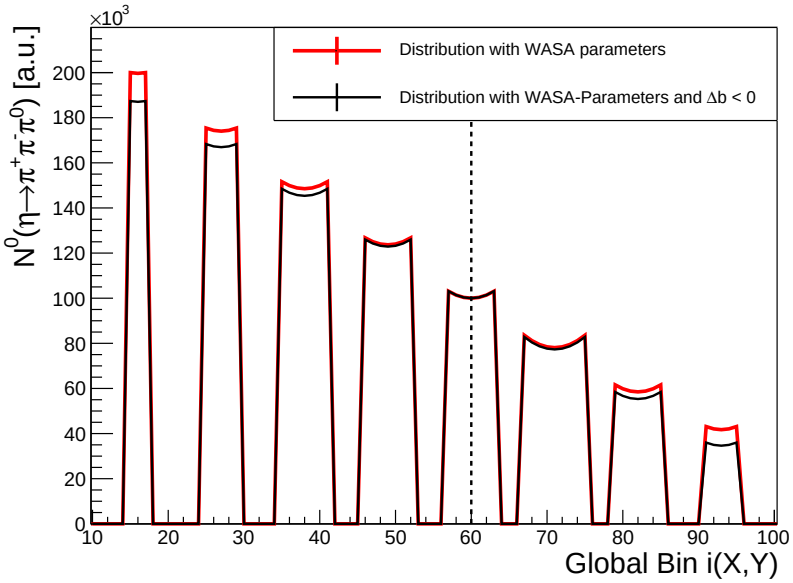

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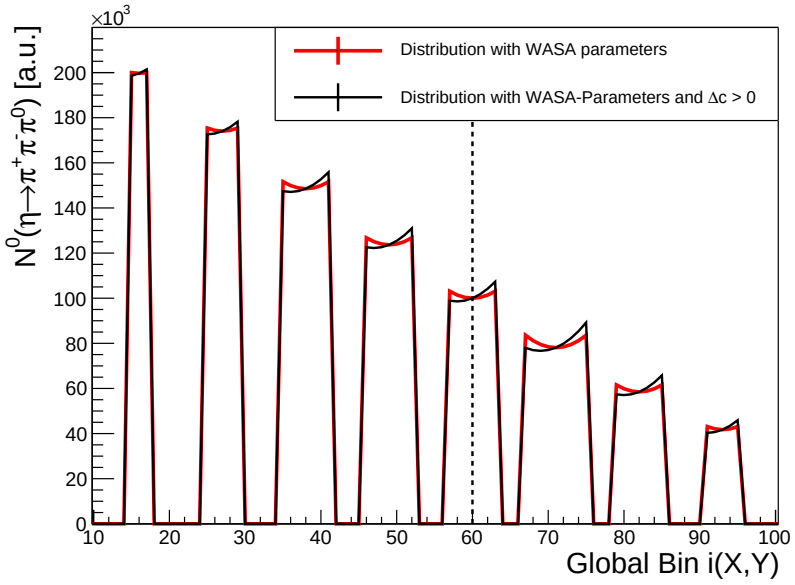

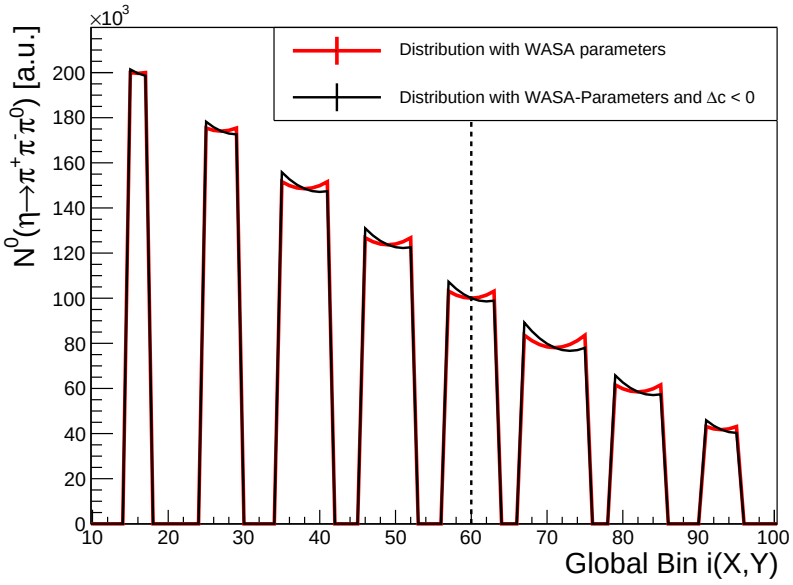

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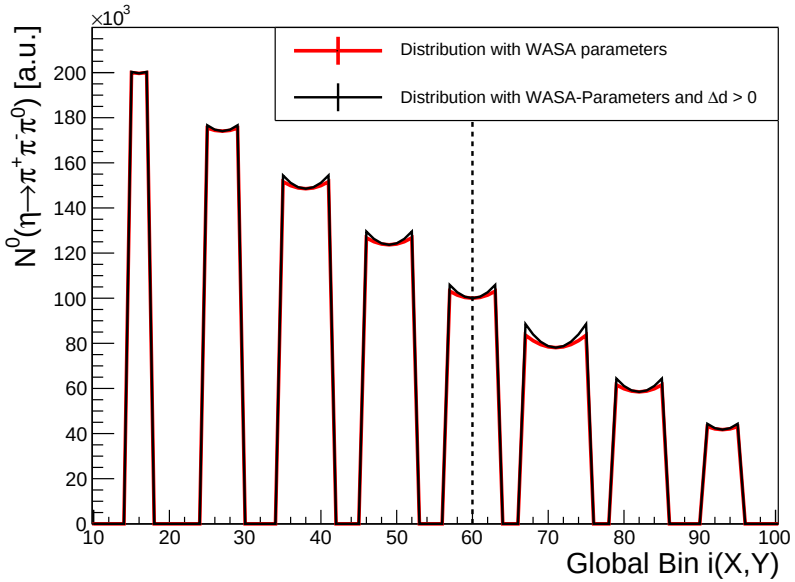

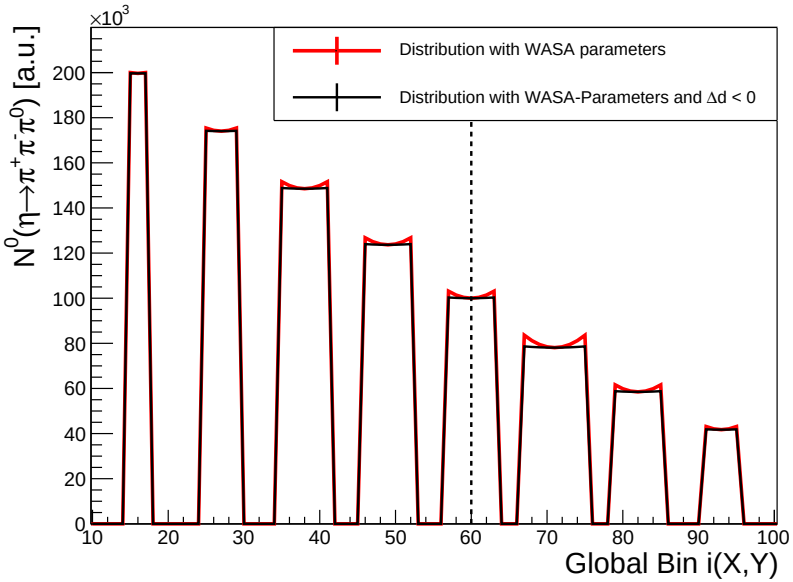

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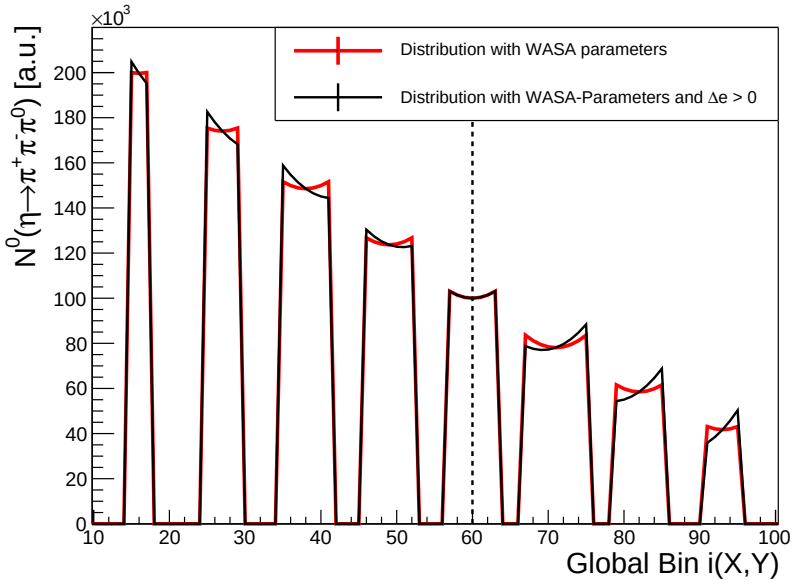

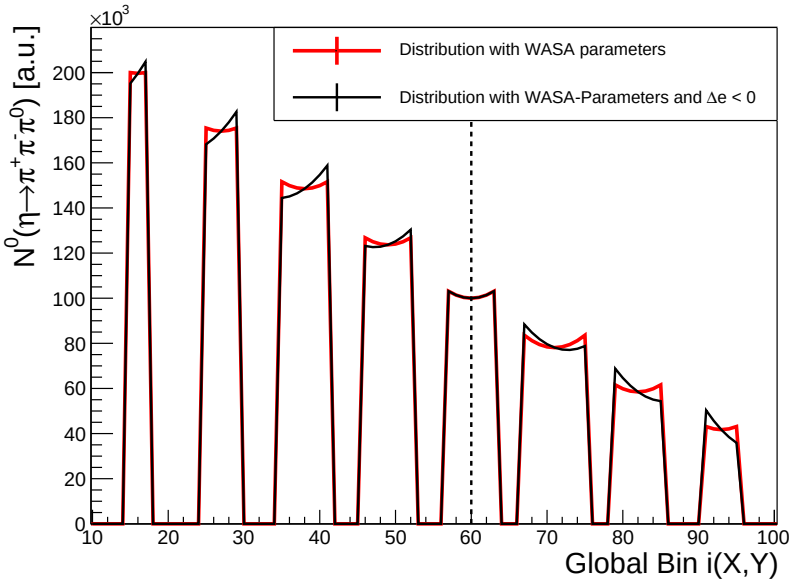

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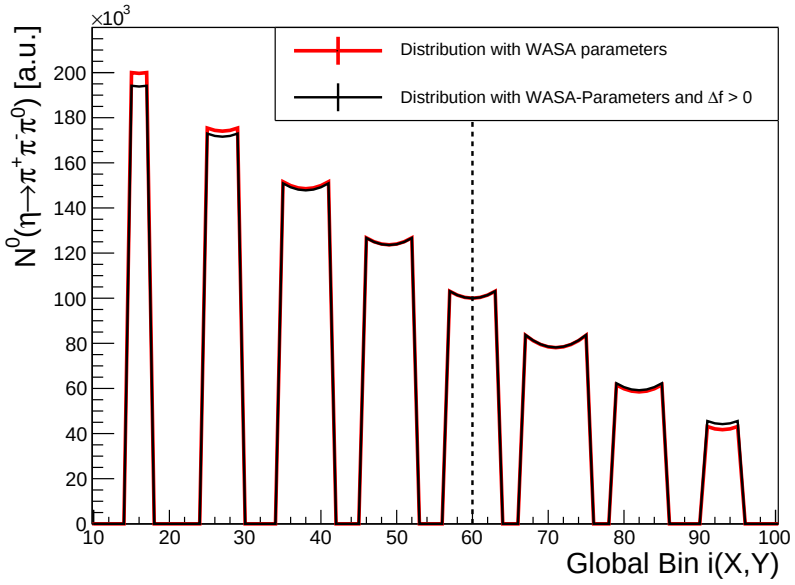

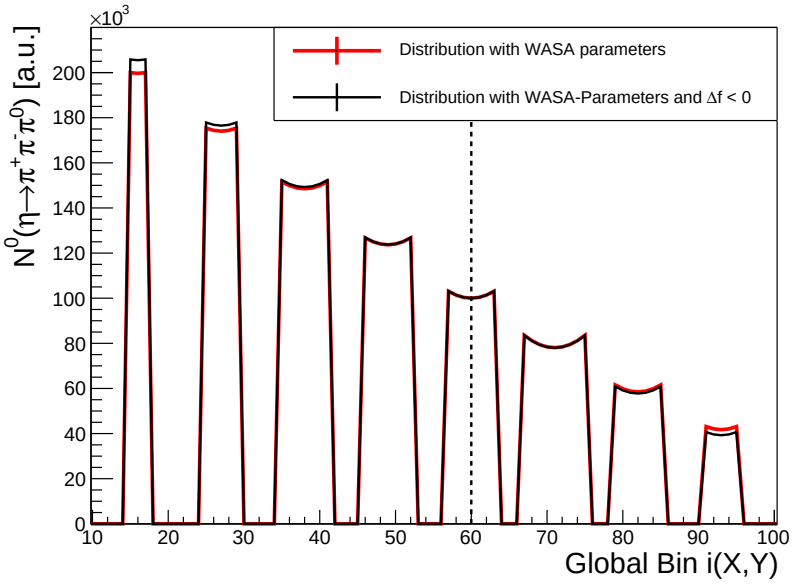

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