Status Update on the Analysis of $\eta \to \pi^+\pi^-(X)$, $X = \pi0/\gamma$ with CLAS

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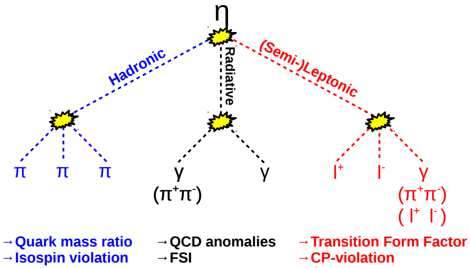
One Meson, many Opportunities

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



Today:

1.) Analysis Status of $\eta \to \pi^+\pi^-\pi^0$

2.) Set up Analysis for $\eta^{(\prime)} \to \pi^+\pi^-\gamma$ (Sorry, no update here)

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

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

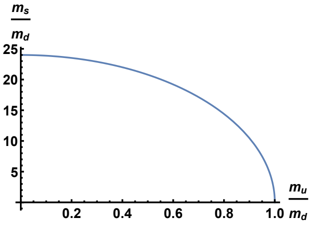
  with: $Q^2 = \left(\frac{m_s}{m_d}\right)^2 \times \left[1 - \left(\frac{m_u}{m_d}\right)^2\right]^{-1}$

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

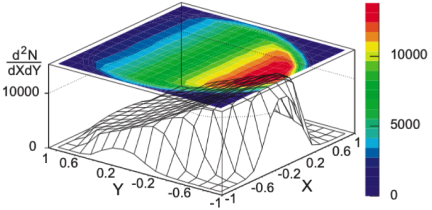
$\Downarrow$

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

b) **Dalitz Plot Analysis**



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



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

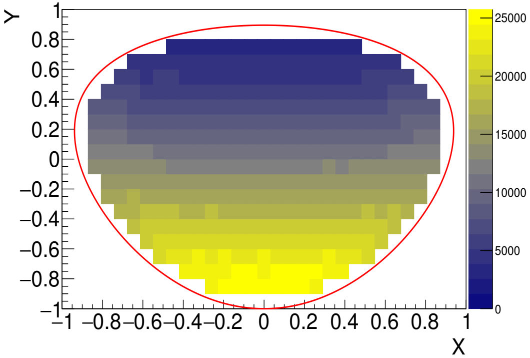
Dimensionless Dalitz Plot Variables:

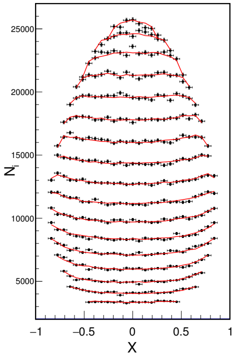
$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}}$$

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

- Describe three body decay by two variables (here: X and Y)
- Complete information about decay dynamics
- Parameterise decay width Γ:
  $\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + ...)$
- $c \neq 0$ 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



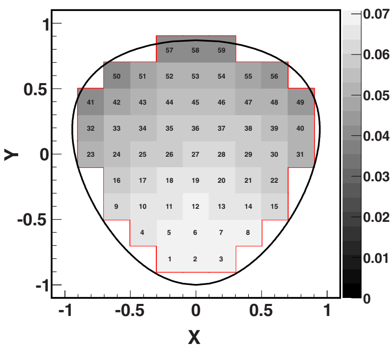


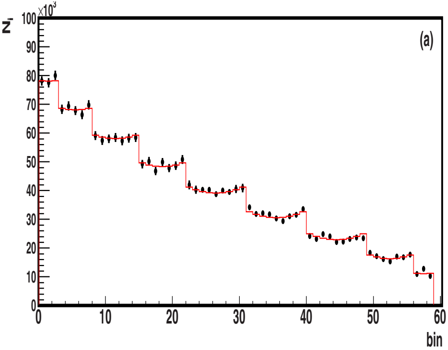
Most recent result from the KLOE-Collaboration:[(f)]

- η-Mesons produced via: $e^+e^- \to \Phi \to \eta\gamma$
- $\approx 4.7 \cdot 10^6$ $\eta \to \pi^+\pi^-\pi^0$ events in the final data sample
- Fit function: $\text{Norm} \times (1 + aY + bY + cX + dX^2 + eXY + fY^3)$
- 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: $pd \to {}^3\mathrm{He}\eta$
- $\approx 120\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events in the final data sample
- Translate each pair (X,Y) into a global bin $i(X, Y)$
  $\to$ Obtain one dimensional Dalitz Plot
- Fit function: $\mathrm{Norm} \times (1 + aY + bY + cX + dX^2 + eXY + fY^3)$

(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)
	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

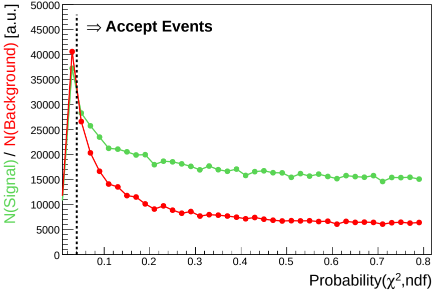
(e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)

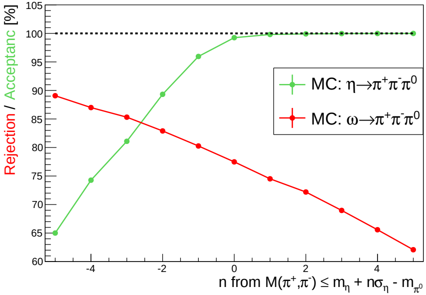
(f) KLOE coll., *JHEP*, 019, (2016)

(g) Peng Guo et al., arXiv: 1608.01447v3, (2017)

- WASA-at-COSY: $Q = 21.4 \pm 1.1$[e]
- KLOE: $Q = 21.7 \pm 1.1$[g]
- **Dalitz Plot Analysis and determination of Q for $\gamma p \rightarrow p\eta[\eta \rightarrow \pi^+\pi^-\pi^0]$ with the CLAS G12 data set**

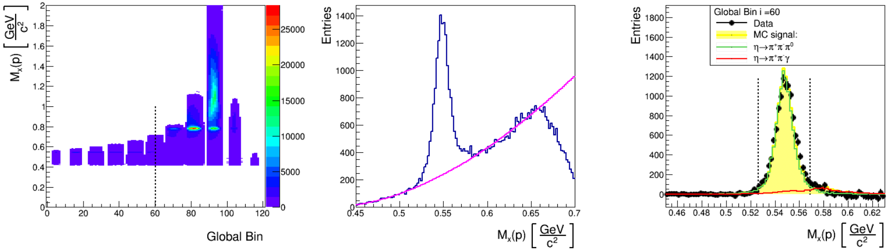
Short Reminder: Status presented at Last Meeting





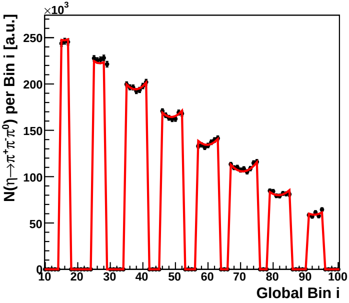
- Problems/Issues:
  - i) Defined analysis parameter for reference data set (see above)
  - ii) Set up machinery for calculation of reconstruction related systematic effects
- Goal of this meeting:
  1. Present recent results
  2. Discuss reconstruction and DP fitting related systematics

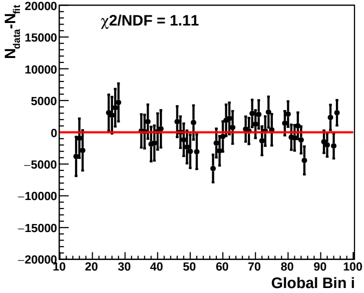
Background Handling and Determination of $N^0(\eta \to \pi^+\pi^-\pi^0)$



- Correct for background for each Global Bin i
- Determination of $N^0(\eta \to \pi^+\pi^-\pi^0)$:
  $N^0(\eta \to \pi^+\pi^-\pi^0)[i] = N^{fit}(\eta \to \pi^+\pi^-\pi^0)[i]/\epsilon[i]$, with: Efficiency $\epsilon[i]$
- Fit resulting distribution with: $\mathrm{Norm} \times (1 + aY + bY + cX + dX^2 + eXY + fY^3)$

Reference Result





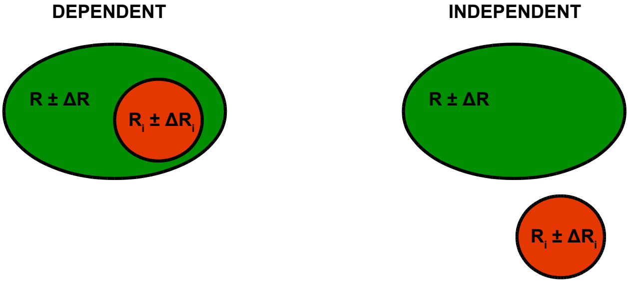
Exp.	$-a$	b	c	d	e	f
WASA	1.144(18)	0.219(66)	−0.007(9)	0.086(33)	−0.020(52)	0.115(37)
KLOE(16)	1.095(6)	0.145(8)	0.0	0.081(9)	0.0	0.141(15)
G12	1.102(20)	0.131(19)	0.013(7)	0.109(19)	0.0	0.247(45)

- Changes since last meeting:
  - Found bug in MC-analysis
  - Re-tuned kinematic fit parameters for MC
  - Re-worked bin-wise background subtraction
  - Re-checked bin wise error estimation (χ^2 of dalitz plot fit was always ~ 0.8)
- Calculated DP Asymmetry: $A = \frac{N^+ - N^-}{N^+ + N^-} = (0.9 \pm 2.9) \cdot 10^{-3}$
- Next step: Look at (analysis related) systematic effects

Determining Systematic Errors: Procedure

1. Do analysis with analysis parameter $p_1, .., p_N$ (e.g. kinematic fit probability)
   $\Rightarrow$ Obtain reference data set with result(s): $R \pm \Delta R$
2. Redo analysis:
   a) Vary parameter p_i (e.g. beam energy) within interval $[p_{i1}, p_{ik}]$
   b) Keep remaining parameters $p_{j \neq i}$ fixed

   $\Rightarrow$ Obtain sub-data sets $i_1, .., i_k$ with result(s): $R_{im} \pm \Delta R_{im}$, $m = 1, .., k$



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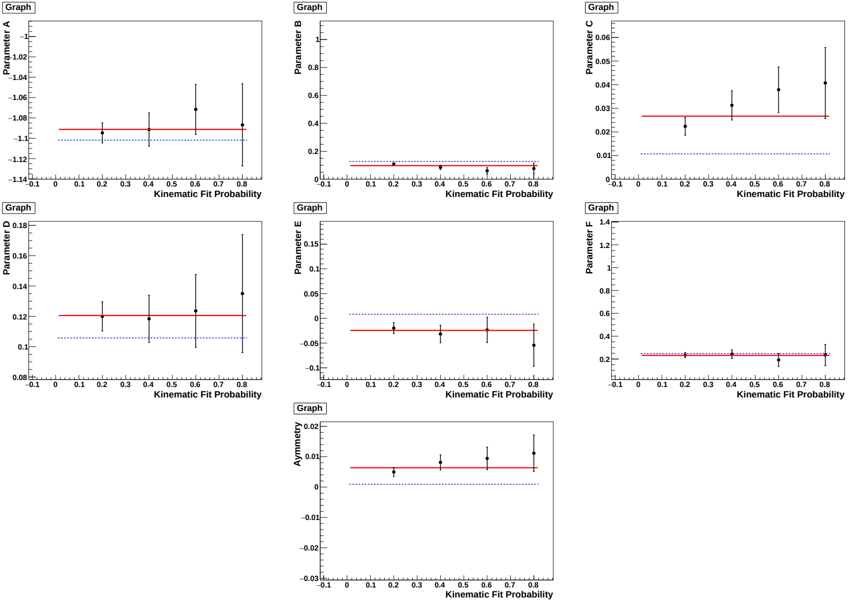
   b) Keep remaining parameters $p_{j \neq i}$ fixed

   $\Rightarrow$ Obtain sub-data sets $i_1, .., i_k$ with result(s): $R_{im} \pm \Delta R_{im},\ m = 1, .., k$
3. Are sub-data sets $i_1, .., i_k$ statistically uncorrelated?

   Yes: Errors ΔR_{im} are (statistically) uncorrelated and can be treated independently
   No: Errors ΔR_{im} are (statistically) correlated and have to be corrected:
   $\Delta R_{im} \mapsto \sqrt{|\Delta R^2 - \Delta R_{im}^2|}$

   $\Rightarrow$ Fit a straight line to $R_{im} \pm \Delta R_{im}$ and determine error σ_i from that fit
4. Repeat steps 1.-3. for remaining parameter

Systematic Effects: The Kinematic Fit



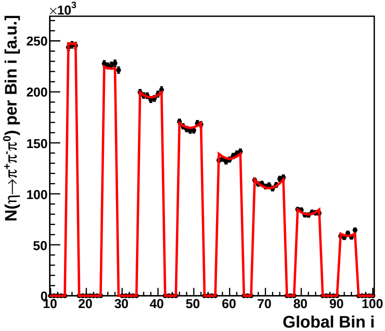
Intermediate Summary

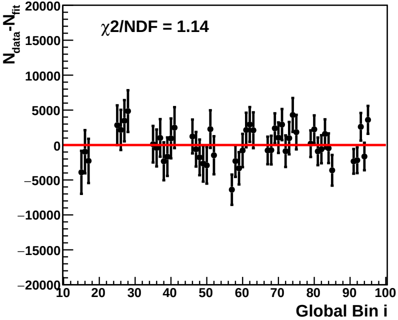
- Systematic dependency on choosing kinematic fit probability:
  i) Parameters a, d, and f seem to be "stable" with respect to reference result
  ii) c, e and asymmetry show largest response
  iii) Parameter b gets < 0.1
- Similar picture for checking effect of invariant mass cut (not shown today)
- Additional tests done:
  - Varied suppression level of $\eta \to \pi^+\pi^-\gamma$ background
  - Checked for leakage/suppression from $\omega \to \pi^+\pi^-\pi^0$
  - Varied bin-wise fitting procedure

$\Rightarrow$ All those tests showed no significant improvement/picture

- Most promising tests: Fitting procedure of the DP itself

Fix DP Parameters c,e and g to 0





Exp.	$-a$	b	c	d	e	f
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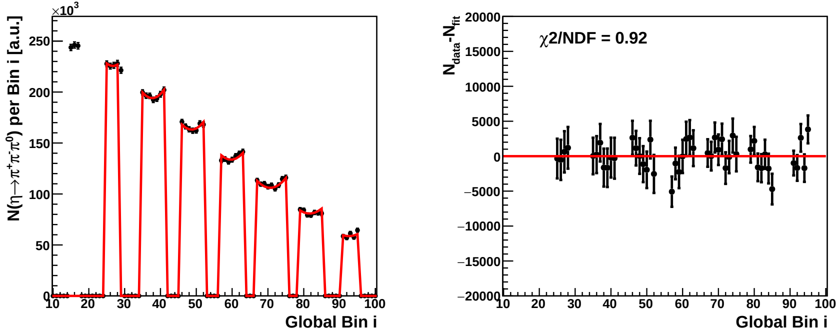
G12	1.102(20)	0.131(19)	0.013(7)	0.109(19)	0.0	0.247(45)
G12(fix)	1.11(16)	0.130(19)	0.0	0.1(16)	0.0	0.261(41)

Reject Points for Bins < 20



Checked many combinations of point groups to reject $\Leftrightarrow$ Those for Bins < 20 show largest effect

Exp.	$-a$	b	c	d	e	f
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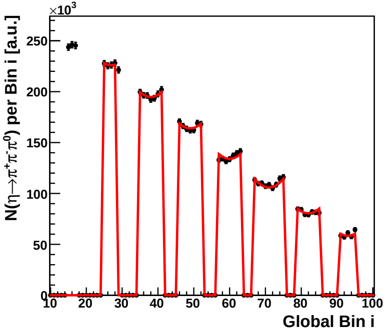
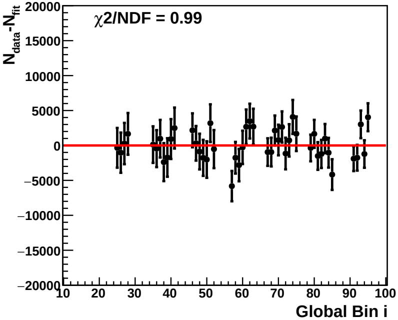
G12(fix)	1.11(16)	0.130(19)	0.0	0.1(16)	0.0	0.261(41)
G12(rp)	1.107(22)	0.176(22)	0.014(7)	0.112(19)	−0.006(22)	0.088(67)

Reject Points for Bins < 20 and fix Parameter c,e and g to 0





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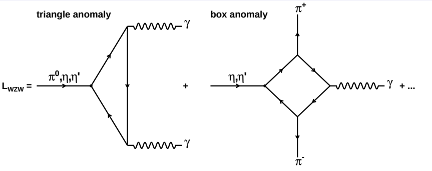
G12(rp)	1.107(22)	0.176(22)	0.014(7)	0.112(19)	−0.006(22)	0.088(67)
G12(rp & fix)	1.109(18)	0.170(23)	0.0	0.099(17)	0.0	0.123(61)

$\eta \to \pi^+\pi^-\gamma$: The Box Anomaly and $\pi^+\pi^-$ FSI

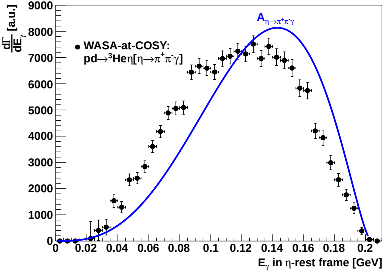
Chiral limit:[(a),(b)]



- Wess-Zumino-Witten Lagrangian
  - (a) Wess, Zumino, *Phys. Lett*, B37(95), 1971
  - (b) Witten, *Nucl. Phys.*, B223:422-432, 1983
- Decay amplitude $A_{\eta\to\pi^+\pi^-\gamma}$ is sensitive to box anomaly[(c)]:

$$A_{\eta\to\pi^+\pi^-\gamma} \propto \frac{e}{4\sqrt{3}\pi^2 F_\pi^3}\left(\frac{F_\pi}{F_8}\cos\theta - \sqrt{2}\frac{F_\pi}{F_0}\sin\theta\right)$$

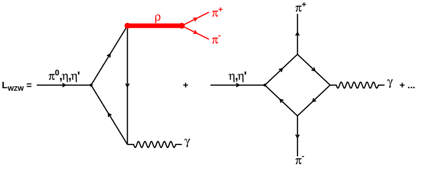
- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}^{(c)}$
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}^{(d)}$
  - (c) B.R. Holstein, *Phys. Scripta*, T99:55-67, 2002
  - (d) PDG, *Chin. Phys.*, 090001, 2014
- Photon energy distribution E_γ:[(e)]
  - (e) WASA-at-COSY coll. *Phys. Lett.*, B707:243-249, 2012



$$E_\gamma(s_{\pi\pi}) = \frac{1}{2}\cdot\left(m_\eta - \frac{s_{\pi\pi}}{m_\eta}\right)$$

$\eta \to \pi^+\pi^-\gamma$: The Box Anomaly and $\pi^+\pi^-$ FSI

Beyond chiral limit:



- Wess-Zumino-Witten Lagrangian & $\pi^+\pi^-$ Final State Interactions
- Modification of decay amplitude:[a]

(a) F.Stollenwerk et al., *Phys. Lett.*, B707:184-190, 2012

$$A_{\eta\to\pi^+\pi^-\gamma} \times [F_{PV}(s_{\pi\pi}) \times (1+\alpha s_{\pi\pi})]$$

$\Rightarrow$

Description of FSI: $\begin{cases} \text{by } F_{PV} & \alpha = 0 \\ \text{reaction specific}^* & \alpha \neq 0 \end{cases}$

*Input from theory

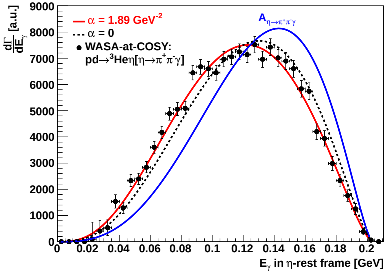
- $\Gamma^{\text{Theory}}(\eta \to \pi^+\pi^-\gamma) = 35.7\,\text{eV}^{(b)}$
- $\Gamma^{\text{Exp.}}(\eta \to \pi^+\pi^-\gamma) = (55.3 \pm 2.4)\,\text{eV}^{(c)}$

(b) B.R. Holstein, *Phys. Scripta*, T99:55-67, 2002

(c) PDG, *Chin. Phys.*, 090001, 2014

- Photon energy distribution E_γ:[d]

(d) WASA-at-COSY coll. *Phys. Lett.*, B707:243-249, 2012



$$E_\gamma(s_{\pi\pi}) = \frac{1}{2} \cdot \left(m_\eta - \frac{s_{\pi\pi}}{m_\eta}\right)$$

Theoretical Predictions and Recent Measurements

		$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	α [GeV^{-2}]
Experiment	Gormley et al.	0.202 ± 0.006	1.8 ± 0.4
	Thaler et al.	0.209 ± 0.004	-
	Layter et al.	-	-0.9 ± 0.1
	GAMS-200*	-	2.7 ± 0.1
	CRYSTAL BARREL*	-	1.8 ± 0.53
	CLEO	0.175 ± 0.013	-
	WASA-at-COSY	Preliminary: 0.206 ± 0.011	1.89 ± 0.86
	KLOE	0.1856 ± 0.003	$1.32^{\star} \pm 0.2$
	CLAS	Analysis ongoing	-
	BESIII	Analysis ongoing for η and η'	-
	WASA-at-COSY	Analysis ongoing for $pp \to pp\eta$	-
Theory	N/D	0.2188 ± 0.0088	0.64 ± 0.02
	HLS	0.1875 ± 0.0094	0.23 ± 0.01
	$(O(p^6) + 1 - \text{loop})$	0.1565 ± 0.0063	-0.7 ± 0.1
	Box anomaly	0.119 ± 0.0048	-1.7 ± 0.02

*Measured $\eta' \to \pi^+\pi^-\gamma$ * Include effects of a_2: Kubis and Plenter, Eur. Phys. J., C75: 283, 2015

Theoretical Predictions and Recent Measurements

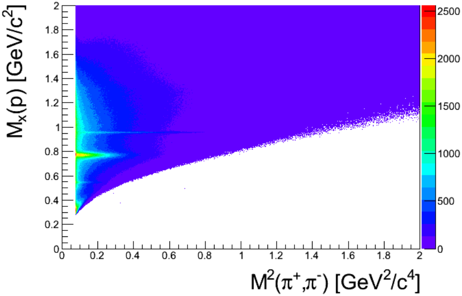
		$\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$	α [GeV^{-2}]
Experiment	*Phys. Rev.,D2:501-505, 1970*	0.202 ± 0.006	1.8 ± 0.4
	Phys. Rev.,D7:2569-2571, 1973	0.209 ± 0.004	-
	Phys. Rev.,D7:2565-2568, 1973	-	-0.9 ± 0.1
	Phys.,C50:451-454, 1991 *	-	2.7 ± 0.1
	Phys. Lett.,B402:195, 1997 *	-	1.8 ± 0.53
	Phys. Rev. Lett.,99(122001), 2007	0.175 ± 0.013	-
	Phys. Rev. Lett.,B707:243-249, 2013	-	1.89 ± 0.86
	Phys. Lett.,B718:910-914, 2013	0.1856 ± 0.003	1.32 ± 0.2
	-	-	-
	-	-	-
Theory	*Phys. Scripta*, T99:55-67, 2002	0.2188 ± 0.0088	0.64 ± 0.02
	Europ. Phys. Journal, C31:525-547, 2003	0.1875 ± 0.0094	0.23 ± 0.01
	Phys. Lett., B237:488-494, 1990	0.1565 ± 0.0063	-0.7 ± 0.1
	Phys. Scripta, T99:55-67, 2002	0.119 ± 0.0048	-1.7 ± 0.02

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

⋆ Include effects of a_2: Kubis and Plenter, Eur. Phys. J., C75: 283, 2015

Current Status in CLAS G12

- Setup analysis:
  - Neural Network to suppress $\pi^+\pi^-(0)$-background
  - Kinematic Fit to hypothesis $\pi^+\pi^-(\gamma)$
- Determine $M(\pi^+, \pi^-)^2$-distributions from plot on the right hand side (Result available at next collaboration meeting)
- Concept for determination of systematic errors already setup
- To Do:
  1. Validation/Justification of analysis steps (currently ongoing)
  2. Determination of α and $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$
  3. Also go for analysis of $\eta' \to \pi^+\pi^-\gamma$ (already visible in right plot)



Summary and Outlook

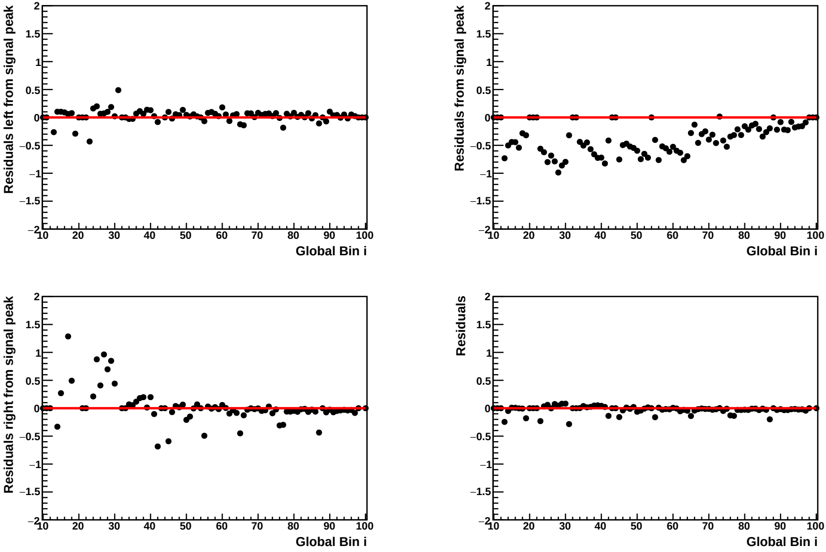
⇒ Analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$:

- Refined analysis and background fitting procedure (not shown here)
- Study of reconstruction-related systematics ⇒ Suspicion on influence of fitting procedure itself:
  i) Fixing Parameters c,e and g to 0
  ii) Neglecting DP bins < 20 show large impact on parameters b and f ⇔ Background handling in this region
- Asymmetry is not affected by i)/ii) ⇔ Hint for other systematic influences
- **Goal:** Have Analysis and systematic studies finished until next collaboration meeting

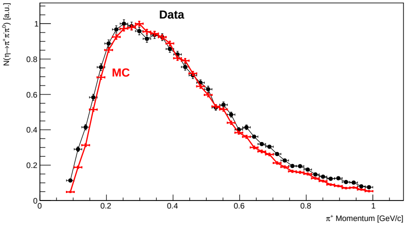
⇒ Analysis of $\eta^{(\prime)} \rightarrow \pi^+\pi^-\gamma$:

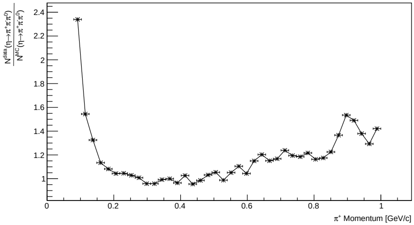
- Set up preliminary reconstruction plan
- Determination of α-parameter ongoing

Backup: Residuals



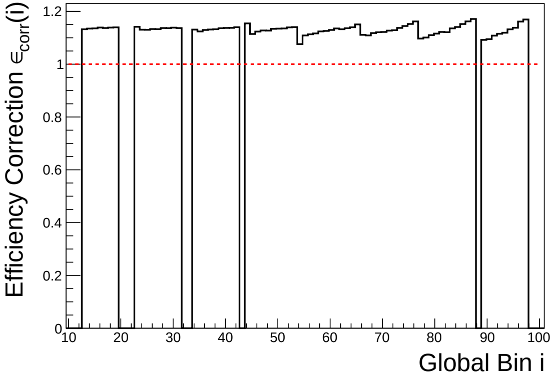
Backup: Momentum and ϕ-dependent Weights





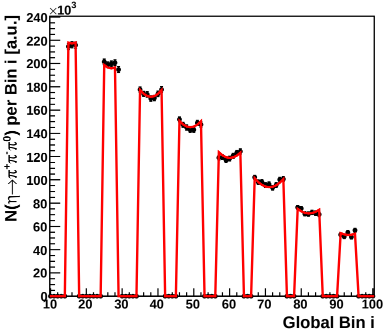
- Look at momenta of: p, π^+ and π^- for different ϕ-ranges (7 ranges in total)
- Example shown here (left hand side): Momentum distribution for π^+ with $\phi \in [-90\,\mathrm{deg}, -30\,\mathrm{deg}]$
- Define ratio (plot on the right hand side): $R(|\vec{p}|_i, \phi_i) \equiv \frac{N^{data}(\eta \to \pi^+\pi^-\pi^{\mathbf{0}})[|\vec{p}|_i, \phi_i]}{N^{MC}(\eta \to \pi^+\pi^-\pi^{\mathbf{0}})[|\vec{p}|_i, \phi_i]}$, $i = p$, π^+, π^-
- Use this ratio to define event weight: $w \equiv R(|\vec{p}|_p, \phi_p) \times R(|\vec{p}|_{\pi^+}, \phi_{\pi^+}) \times R(|\vec{p}|_{\pi^-}, \phi_{\pi^-})$

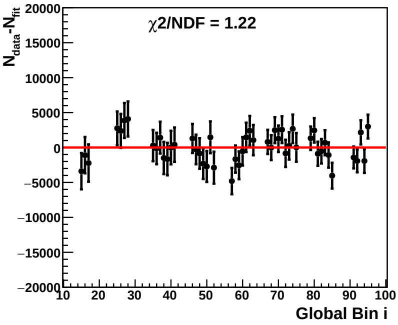
Backup: Efficiency Correction $\epsilon_{corr}(i)$



- Analyse MC: $\eta \to \pi^+\pi^-\pi^0$ with and without momentum dependent weight w
- Ratio of both data sets (per global bin i) defines efficiency correction
- Should ideally be independent of analysis steps (e.g. kinematic fit)

Backup: Effect of the Efficiency Correction



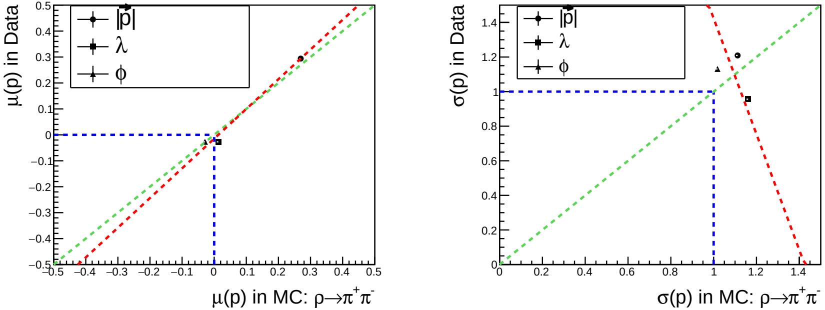


Exp.	$-a$	b	c	d	e	f
WASA	1.144(18)	0.219(66)	−0.007(9)	0.086(33)	−0.020(52)	0.115(37)
KLOE(16)	1.095(6)	0.145(8)	0.0	0.081(9)	0.0	0.141(15)
G12	1.102(20)	0.131(19)	0.013(7)	0.109(19)	0.0	0.247(45)
G12(ϵ)	1.09(19)	0.126(18)	−0.003(6)	0.11(18)	−0.005(20)	0.250(43)

Calculated DP Asymmetry: $A = \frac{N^+ - N^-}{N^+ + N^-} = (-0.5 \pm 0.3) \cdot 10^{-3}$

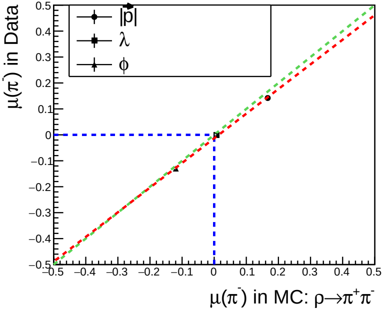
Backup: Comparison of Pull-Distributions

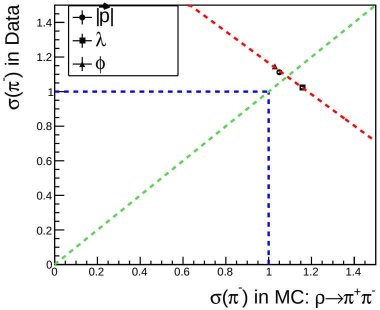
For Protons



Backup: Comparison of Pull-Distributions

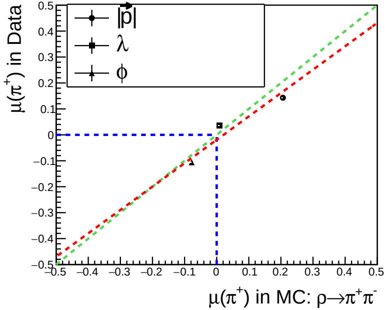
For positive Pions

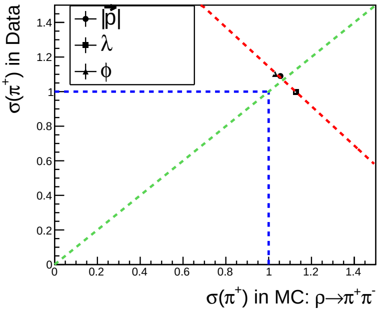




Backup: Comparison of Pull-Distributions

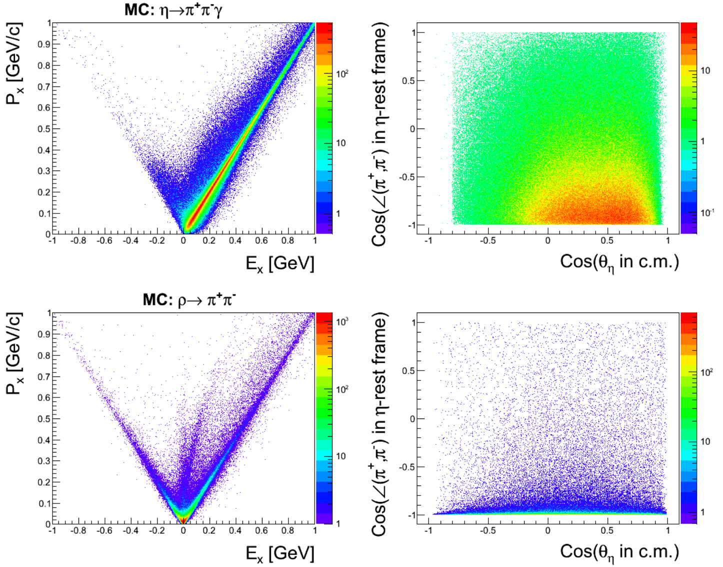
For negative Pions



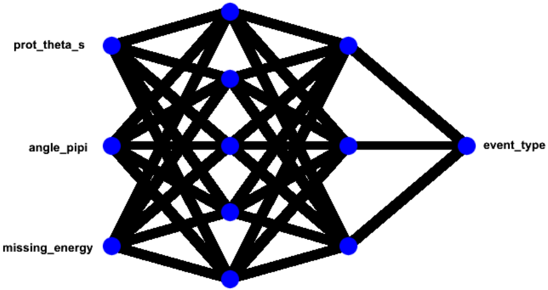


Backup: Reconstruction of $\eta \to \pi^+\pi^-\gamma$-events

Defining discrimination variables

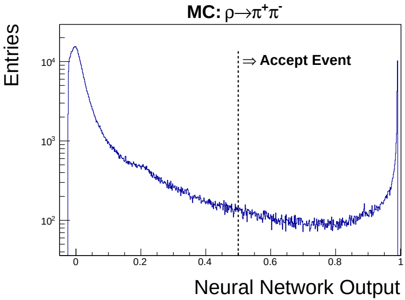


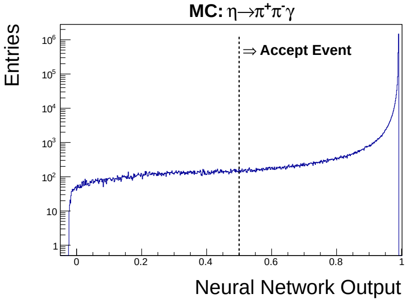
Backup: Multivariable-Analysis: Neural Networks



- One could define separate cuts on the discrimination variables
- But those variables are often correlated $\Rightarrow$ Multivariable-Analysis
- Use an artificial neural network with:
  - prot_theta_s = $\mathrm{Cos}(\theta_\eta(\text{in c.m.}))$
  - angle_pipi = $\mathrm{Cos}(\angle(\pi^+, \pi^-)$in η-rest frame)
  - missing_energy = E_x
  - event_type = 1 for $\eta \rightarrow \pi^+\pi^-\gamma$ and 0 for $\rho \rightarrow \pi^+\pi^-$

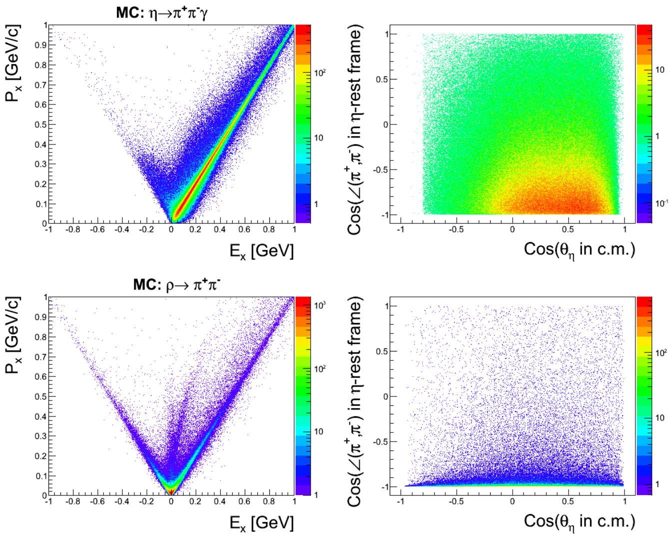
Backup: Neural Network Output





- Network has been trained with MC data where the event type is known
- After training the network, obtain output variable which is a function of the variables defined in the beginning
- Reject events with output less than 50%

Backup: What is cut away?



Before cutting on the neural network output

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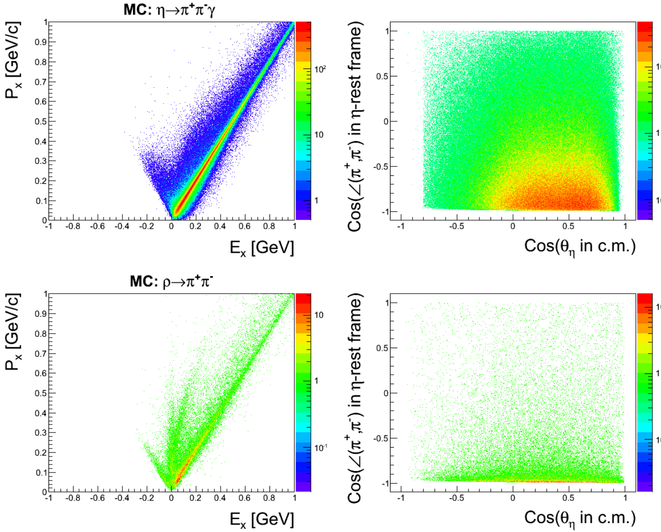
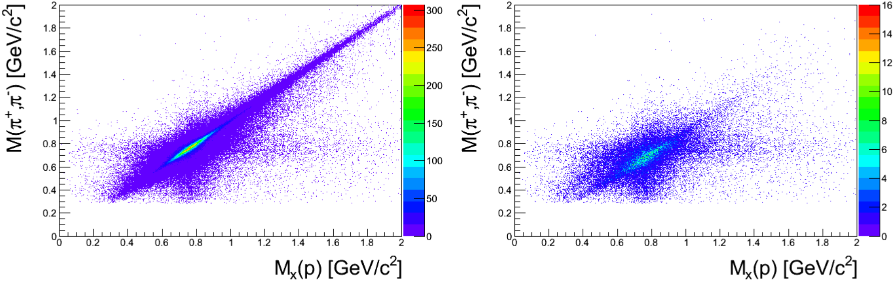


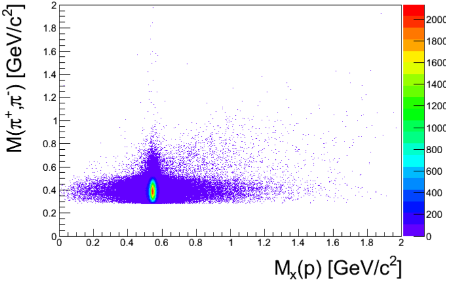
Before cutting on the neural network output

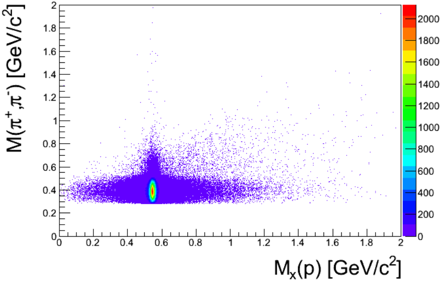
Backup: Masses and Acceptances: MC $\rho \to \pi^+\pi^-$



- Left: wifthout cut / right: with cut
- $\approx 5\%$ events are accepted

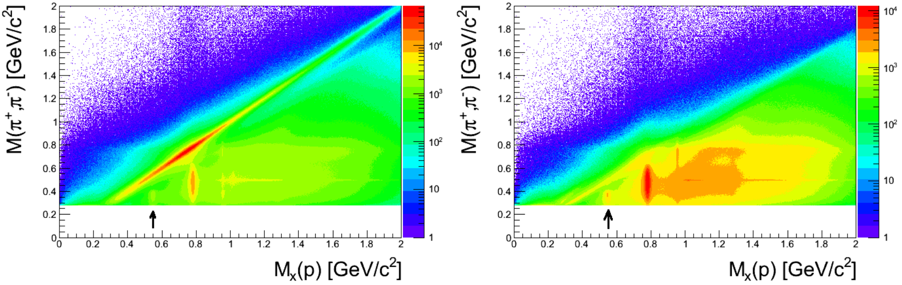
Backup: Masses and Acceptances: MC $\eta \to \pi^+\pi^-\gamma$





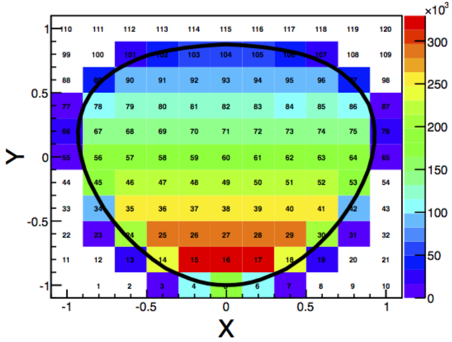
- Left: wifthout cut / right: with cut
- $\approx$ 98% events are accepted

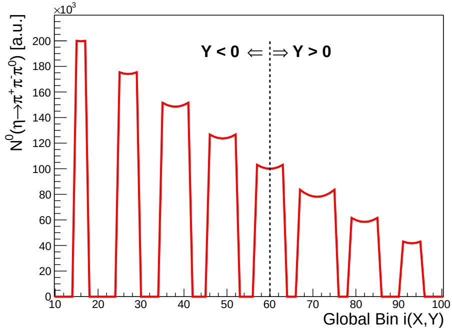
Backup: Application to Data



- Left: wifthout cut / right: with cut
- η-signal clearly visible now
- Reduced $\pi^+\pi^-(0)$-background

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 $i(0,0) = 60$
- $\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3)$

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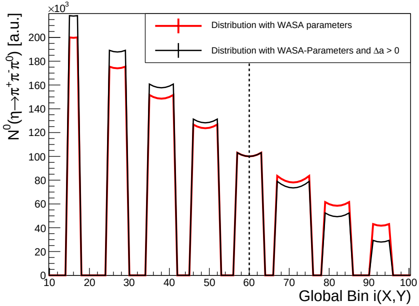

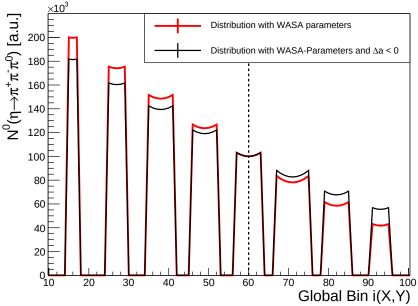

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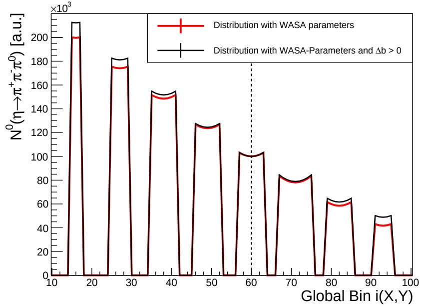

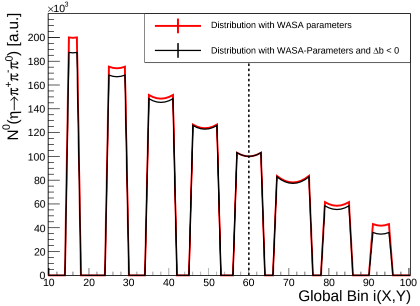

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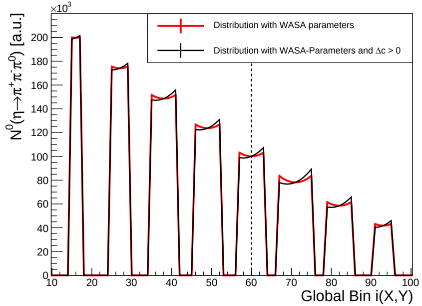

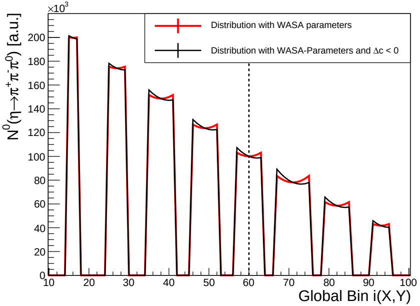

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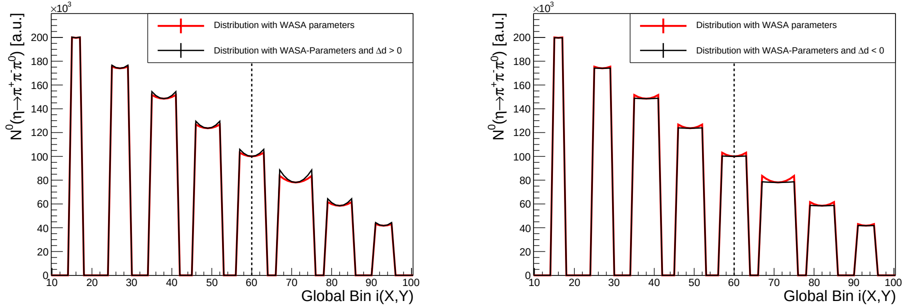

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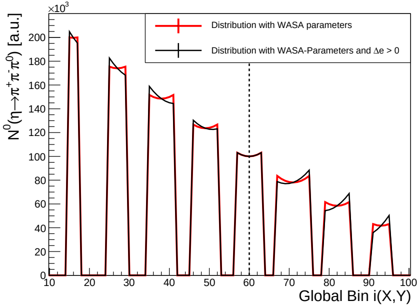

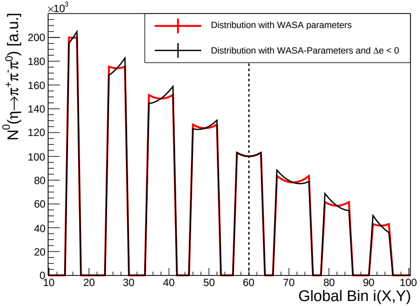

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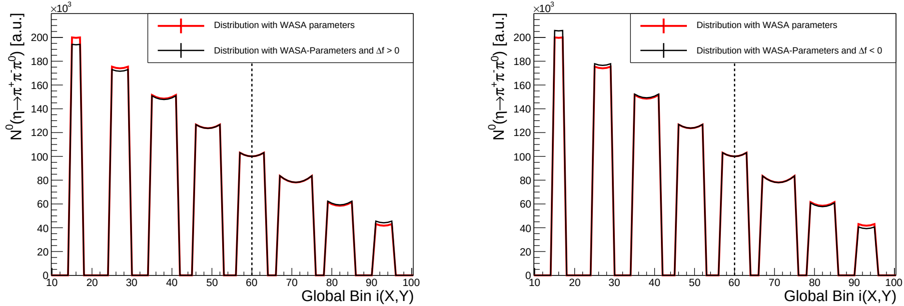

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