Update on the Dalitz Plot Analysis of: $\eta \rightarrow \pi^+\pi^-\pi^0$ with the CLAS6 g12 Data Set

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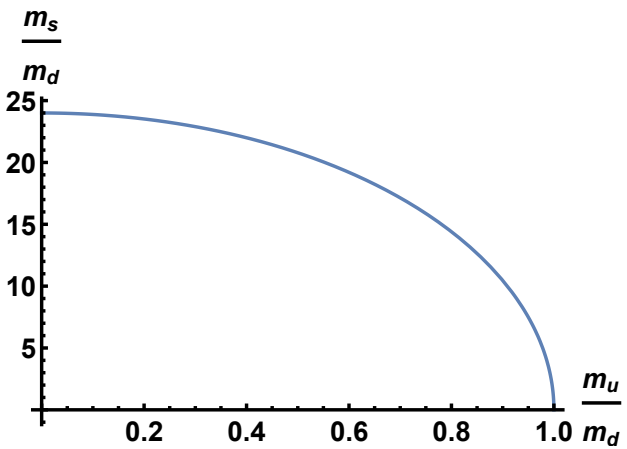
Decay Dynamics of $\eta \to \pi^+\pi^-\pi^0$

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
- 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**

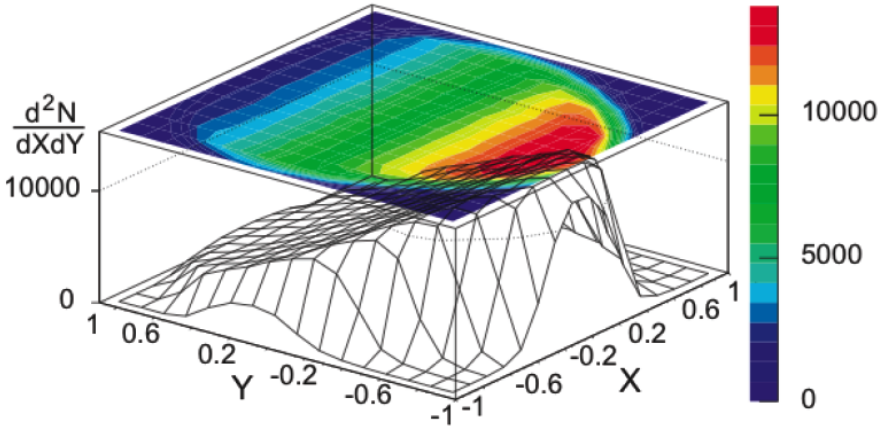


$\Downarrow$

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**

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



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

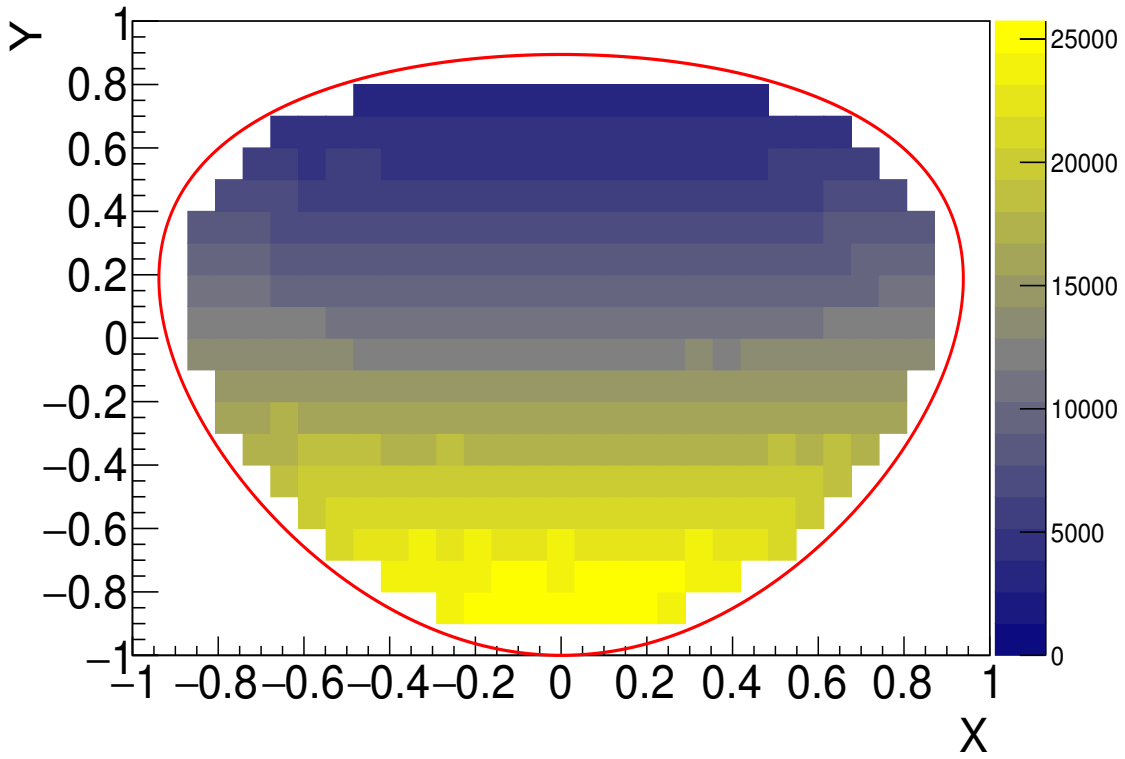
Dimensionless Dalitz Plot Variables:

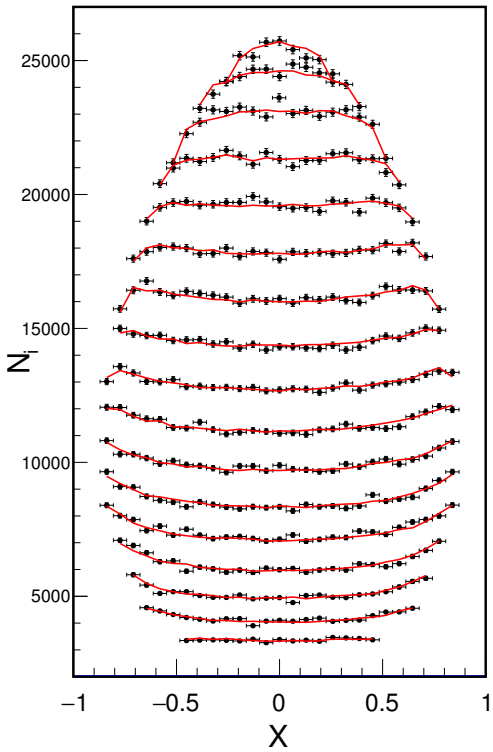
$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}}$$

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

- 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



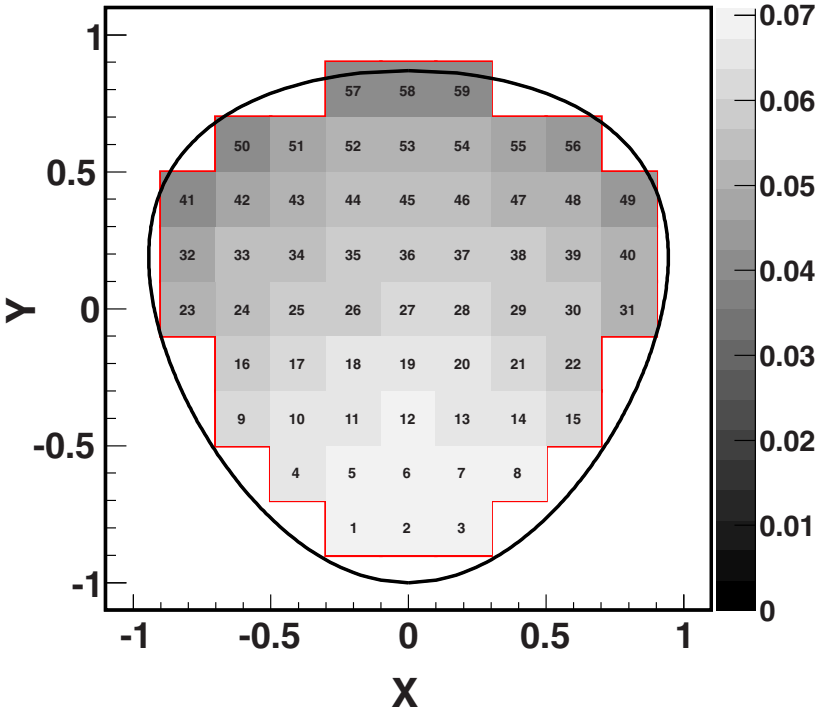


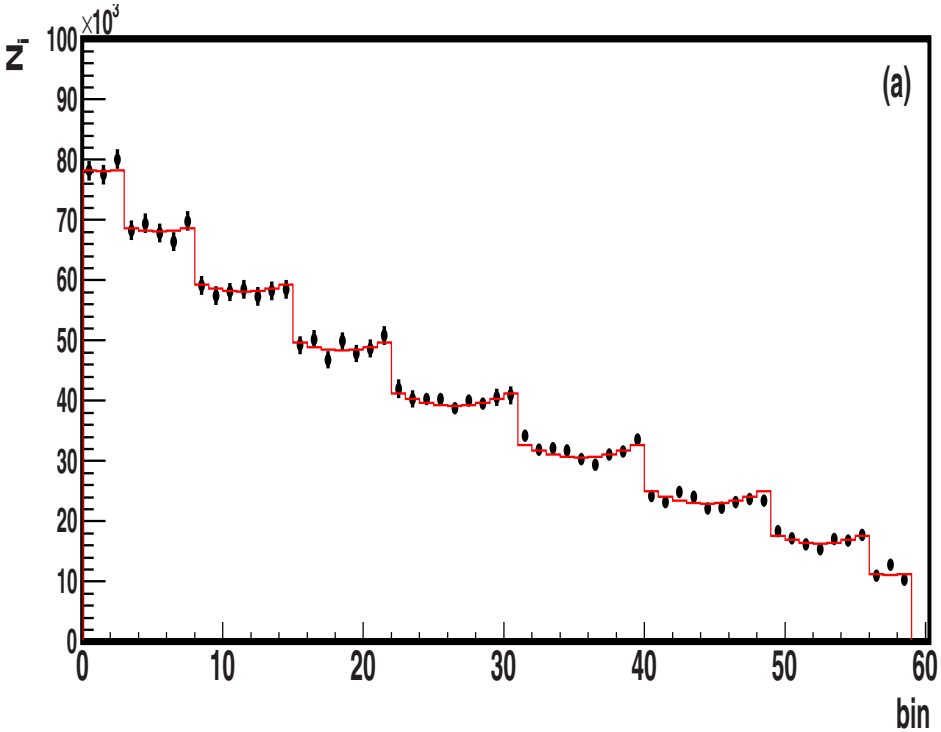
Most recent result from the KLOE-Collaboration:[(f)]

- 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: 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)
	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

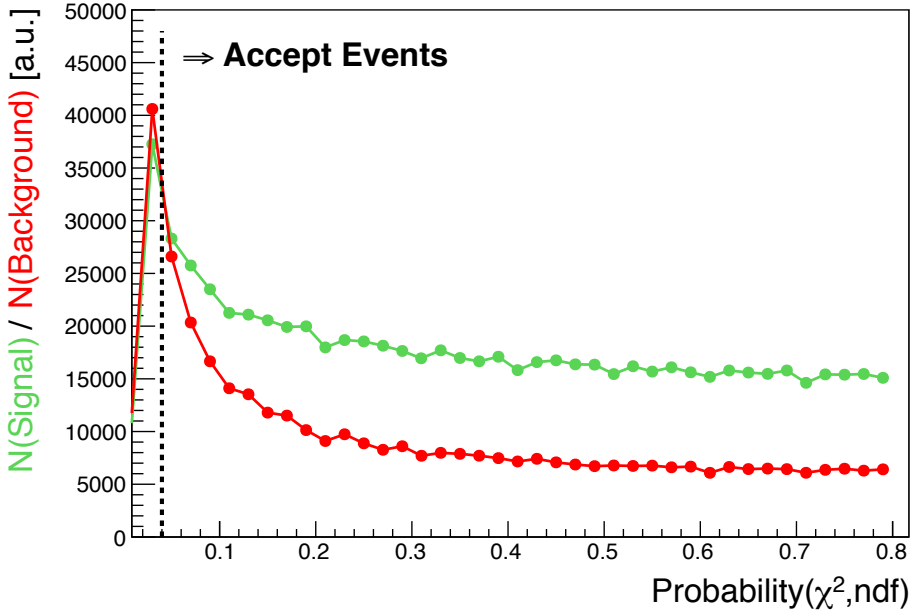
(e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)

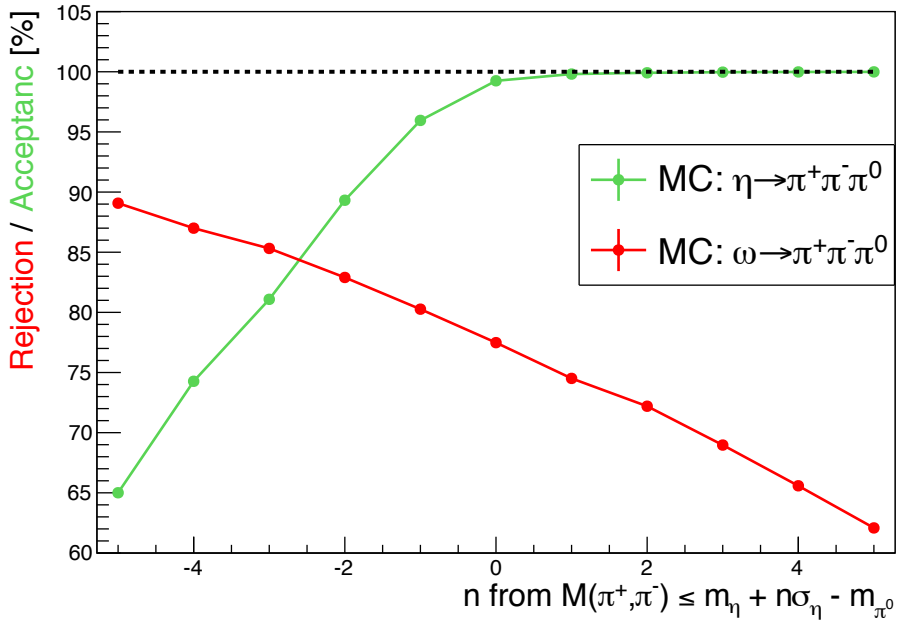
(f) KLOE coll., *JHEP*, 019, (2016)

(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 $\gamma p \to p\eta[\eta \to \pi^+\pi^-\pi^0]$ with the CLAS G12 data set**

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

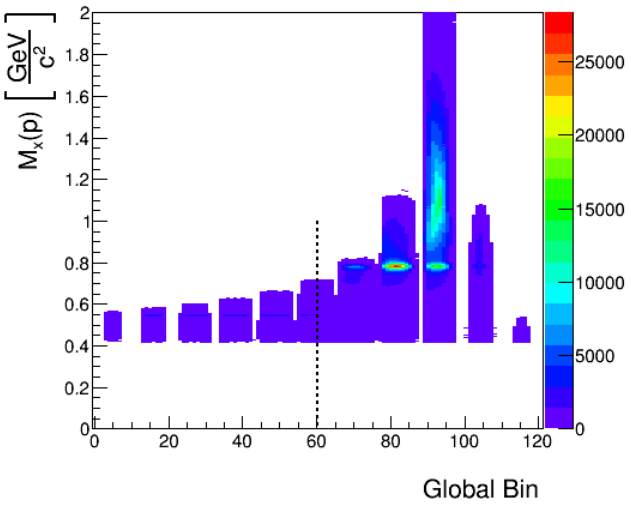


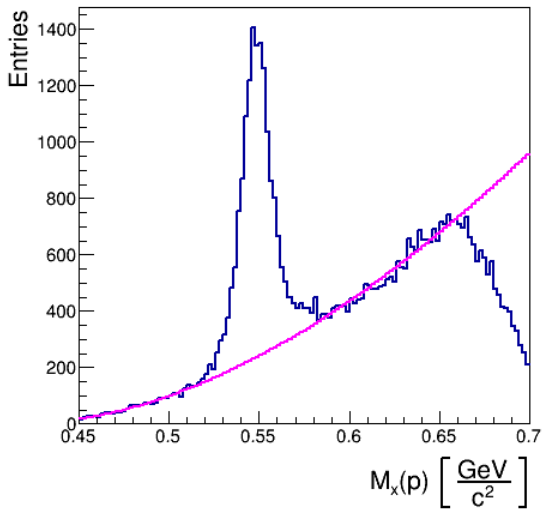


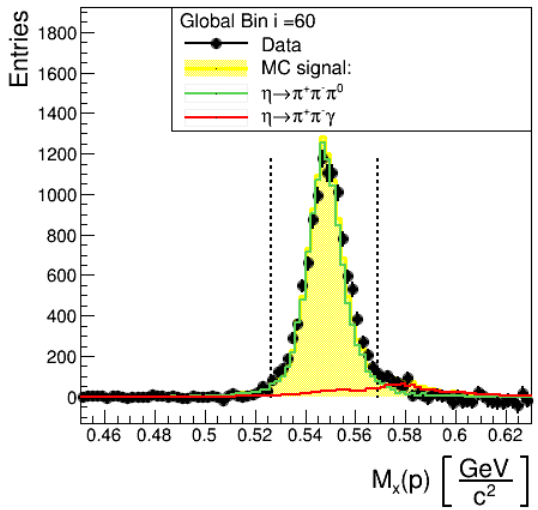
i) **Kinematic Fit:**
Prob. $\geq 4\%$ $\Rightarrow$ Chosen according to best ratio: $S/(S+B)$

ii) **Rejection of $\omega \to \pi^+\pi^-\pi^0$:**
$M(\pi^+,\pi^-) \leq m_\eta + 2\sigma_\eta - m_{\pi^0}$ $\Rightarrow$ Chosen according to 100% acceptance for $\eta \to \pi^+\pi^-\pi^0$ and 70% rejection of $\omega \to \pi^+\pi^-\pi^0$

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

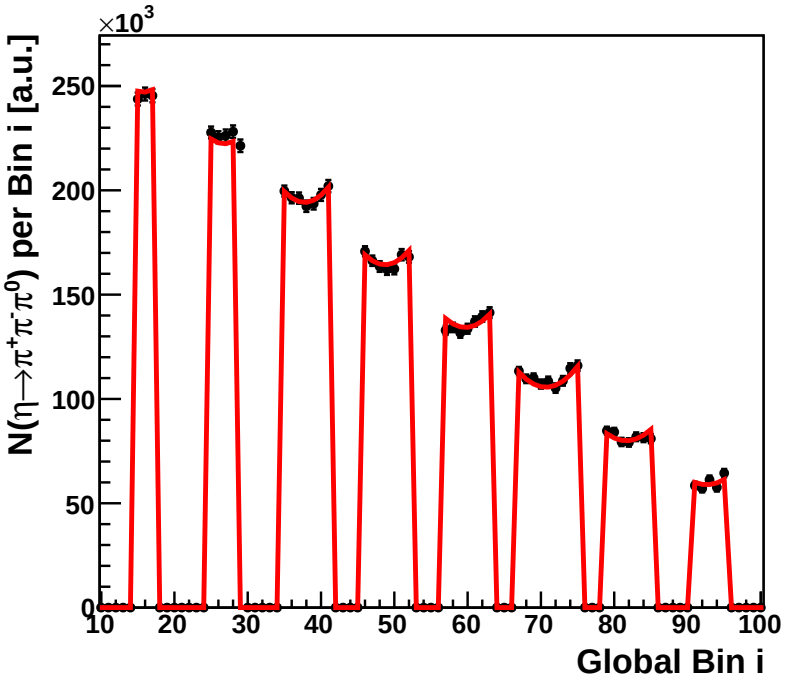


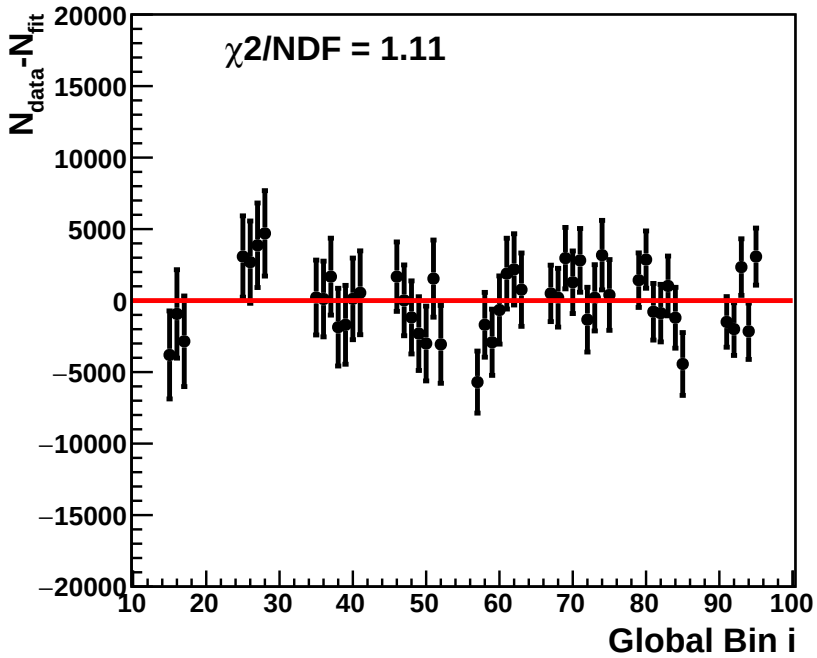




- Correct for background for each Global Bin i
- Determination of $N^0(\eta \to \pi^+\pi^-\pi^0)$:
  $N^0(\eta \to \pi^+\pi^-\pi^0)[i] = N^{fit}(\eta \to \pi^+\pi^-\pi^0)[i]/\epsilon[i]$, with: Efficiency $\epsilon[i]$
- Fit resulting distribution with: Norm $\times (1 + aY + bY + cX + dX^2 + eXY + fY^3)$

Dalitz Plot Parameter for $\eta \to \pi^+\pi^-\pi^0$





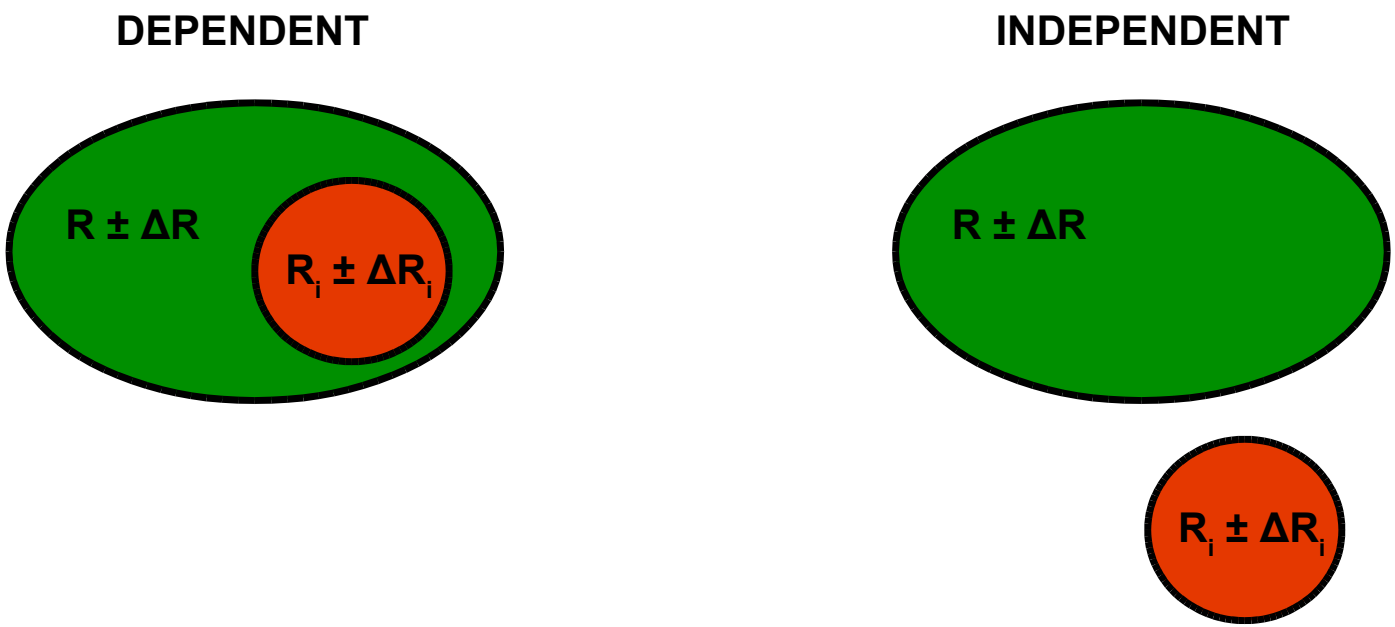
Exp.	-a	b	c	d	f
KLOE(08)	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	0.0	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
WASA	1.144(18)	0.219(19)(47)	0.0	0.086(18)(15)	0.115(37)
KLOE(16)	1.104(5)(2)	$0.142(3)(^{+5}_{-4})$	0.0	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
G12	1.102(20)(?)	0.127(18)(?)	0.011(7)(?)	0.106(19)(?)	0.248(45)(?)

- Parameter e is 0
- Dalitz Plot Asymmetry $A = \frac{N^+ - N^-}{N^+ + N^-} = (0.9 \pm 2.9) \cdot 10^{-3}$
- Biggest issue: Determine systematics

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): $R_{im} \pm \Delta R_{im},\ m = 1, .., k$



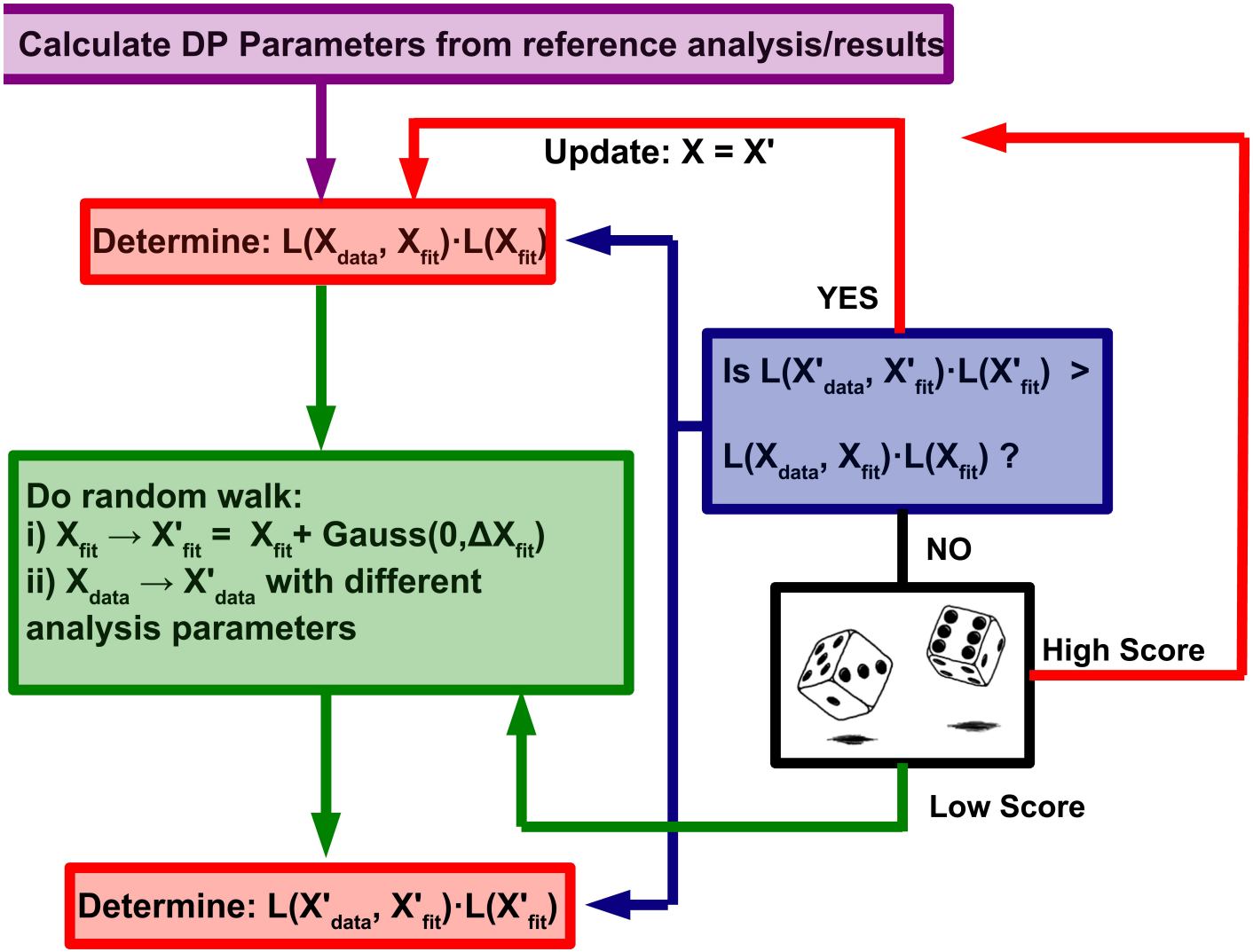
Reminder: Status at Collaboration Meeting in March 2017

Parameter	σ_{stat}	σ_{beam}	σ_{fit}	σ_{im}	σ_{π^0}	σ_{tot}
$a = -1.135$	± 0.021	$^{+0.042}_{-0.039}$	$^{+0.274}_{-0.159}$	$^{+0.046}_{-0.042}$	$^{0.016}_{0.060}$	$^{+0.281}_{-0.179}$
$b = 0.149$	± 0.020	$^{+0.3}_{-0.281}$	$^{+0.289}_{-0.322}$	$^{+0.118}_{-0.136}$	$^{0.045}_{-0.012}$	$^{+0.435}_{-0.449}$
$c = 0.013$	± 0.008	$^{+0.103}_{-0.115}$	$^{+0.008}_{0.007}$	$^{+0.004}_{-0.001}$	$^{+0.003}_{-0.018}$	$^{+0.103}_{-0.117}$
$d = 0.120$	± 0.020	$^{+0.004}_{-0.037}$	$^{+0.007}_{-0.032}$	$^{+0.008}_{-0.019}$	$^{+0.002}_{-0.003}$	$^{+0.011}_{-0.053}$
$e = 0.014$	± 0.021	$^{+0.004}_{-0.038}$	$^{+0.006}_{-0.040}$	$^{+0.019}_{-0.026}$	$^{+0.003}_{-0.002}$	$^{+0.021}_{-0.061}$
$f = 0.269$	± 0.048	$^{+0.057}_{-0.337}$	$^{+0.074}_{-0.030}$	$^{+0.095}_{-0.228}$	$^{+0.087}_{-0.052}$	$^{+0.159}_{-0.411}$
$g = -0.055$	± 0.068	$^{+0.038}_{-0.099}$	$^{+0.021}_{-0.118}$	$^{0.066}_{-0.004}$	$^{0.014}_{-0.006}$	$^{+0.038}_{-0.154}$

- Errors shown above are far too large
- Correlation between various analysis steps?
- Dalitz Plot Parameters changed due to improved error propagation
- Change of strategy:
  - i) De-correlate errors, or get reasonable upper limit for the error
  - ii) Avoid bias in fitting
  - iii) How to compare results to other experiments?

Towards Systematic Uncertainties: Random Walk Analysis

- Spend a lot of time in understanding systematics
- Had problems with estimating errors properly
- Try different approach: Random walk around reference result



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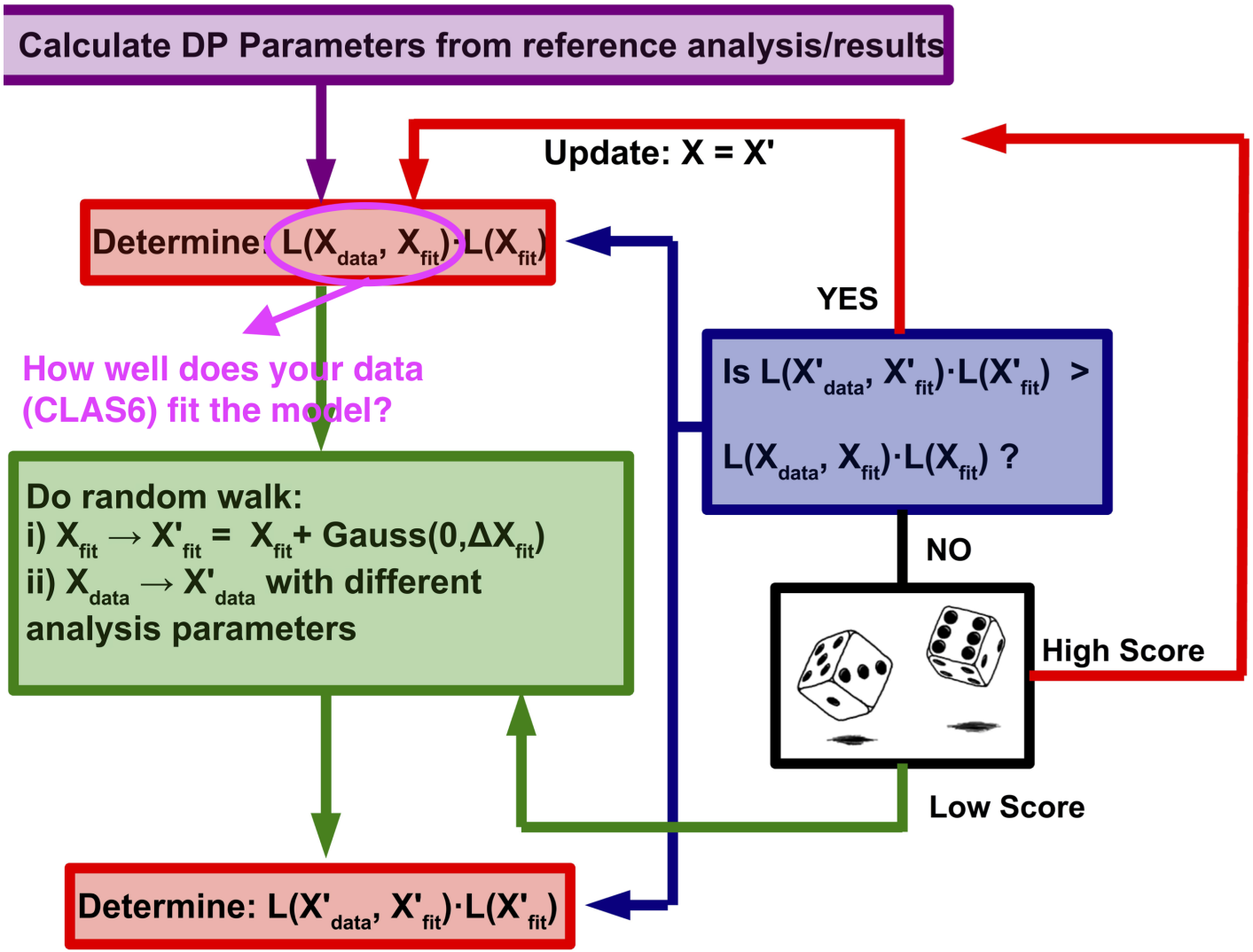

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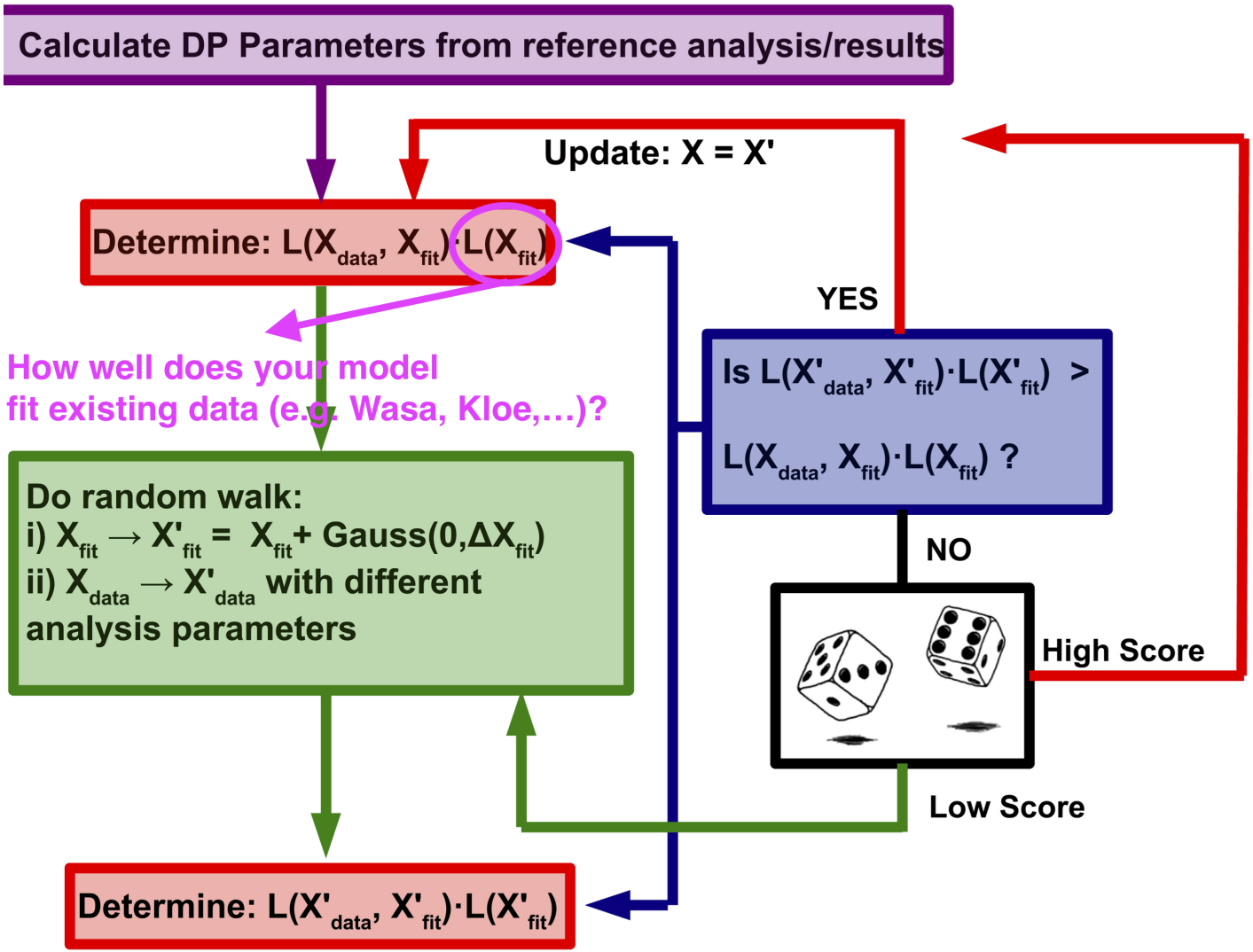
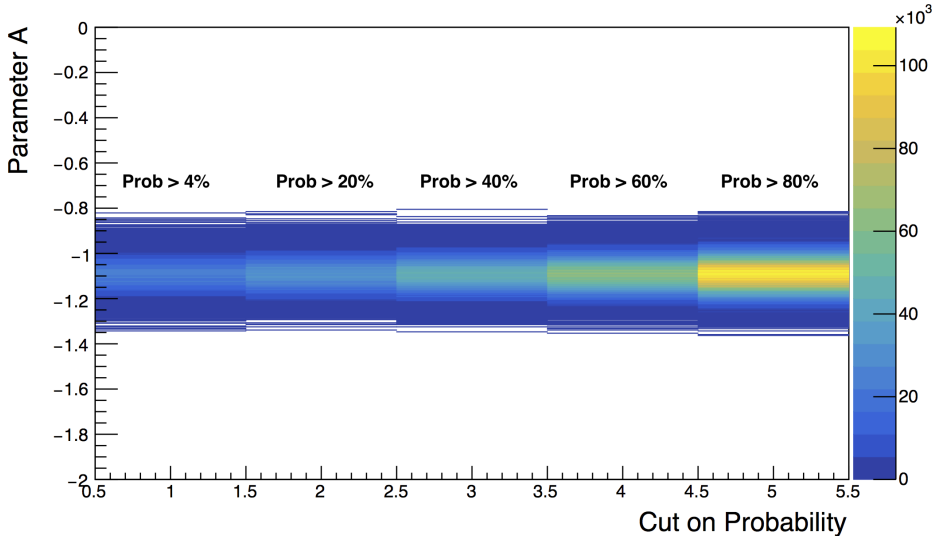
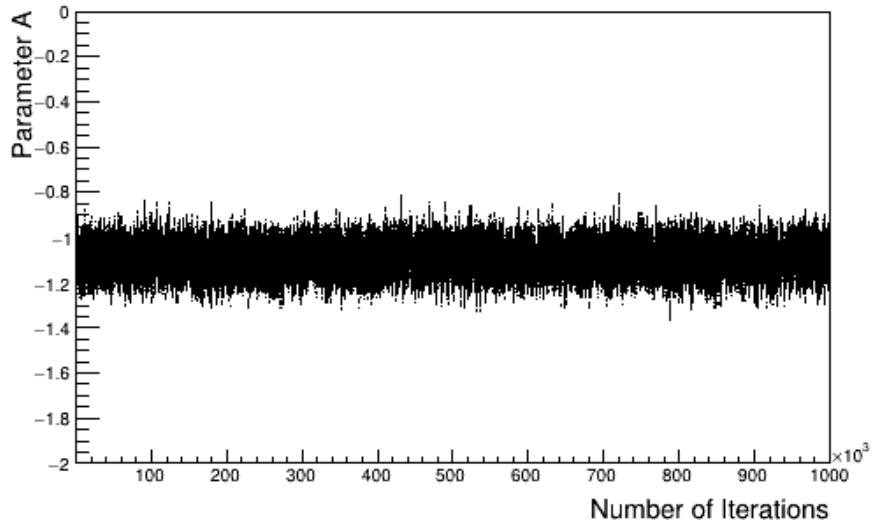
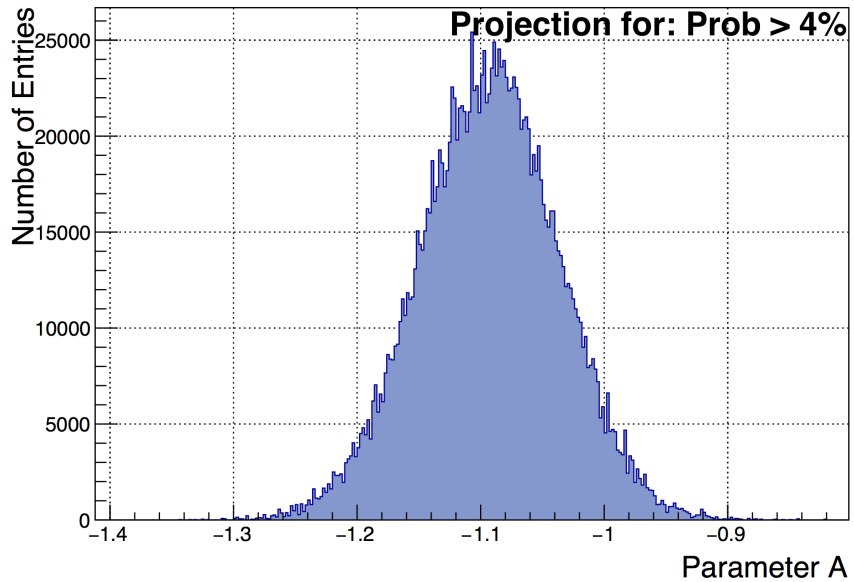
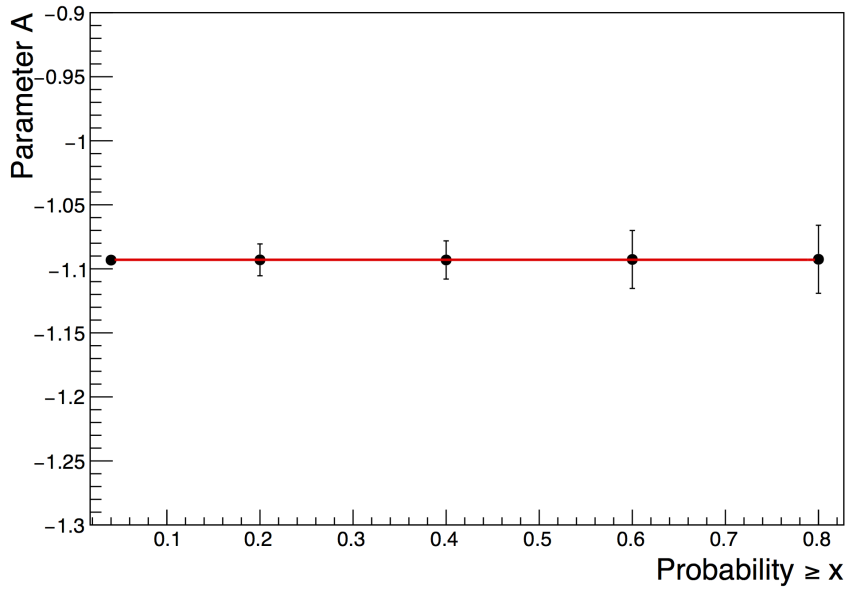


Results after the Random Walk









Current Status

Parameter	$\sigma_{stat}[10^{-3}]$	$\sigma_{kFit}[10^{-3}]$	$\sigma_{\omega}[10^{-3}]$	$\sigma_{sys,tot}[10^{-3}]$
a = -1.102	20	0.4	13	13
b = 0.127	18	5	5	5
c = 0.011	7	7	2	7
d = 0.106	19	2	4	5
f = 0.248	45	3	10	10

- Total systematic error from March 2017: $\lesssim 40\%$
  (Just including σ_{kFit} and σ_{ω})
- Total systematic error now: $\lesssim 5\%$
- Still missing in table above: Check / Correction for correlations (ongoing)
- Effects of choosing a photon beam energy range will be included soon
  (1D Dalitz Plots already calculated)

Summary and Outlook

- Refined error estimation $\Rightarrow$ Errors are in a more "reasonable" range
- Need to include into error-estimation:
  - Variation of photon beam energy range
  - Leaving out "sensitive" data points $\rightarrow$ Turned out to have an effect on f
  - Correlation of errors
- Statistical error depends on number of Dalitz Plot bins
  $\Leftrightarrow$ Finer binning?

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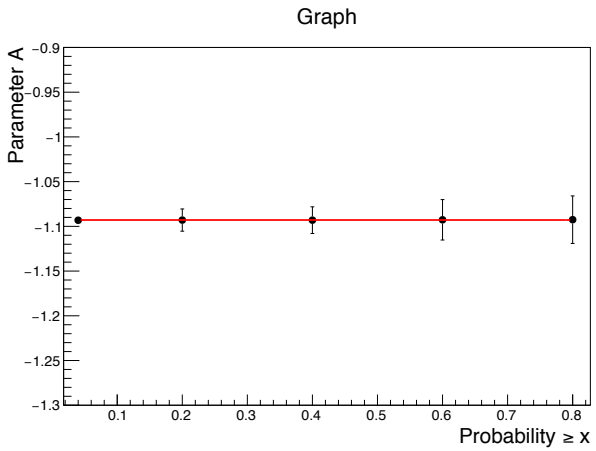
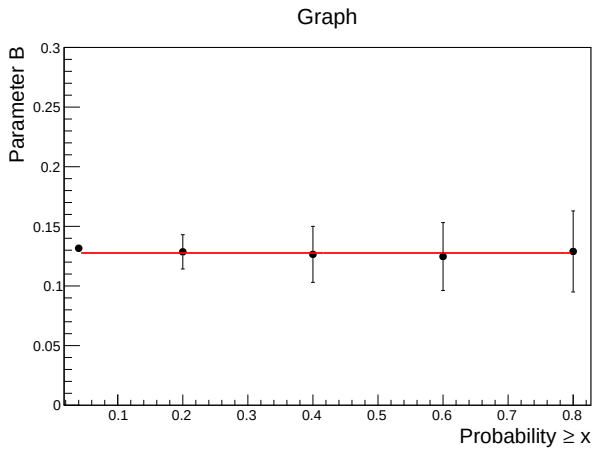
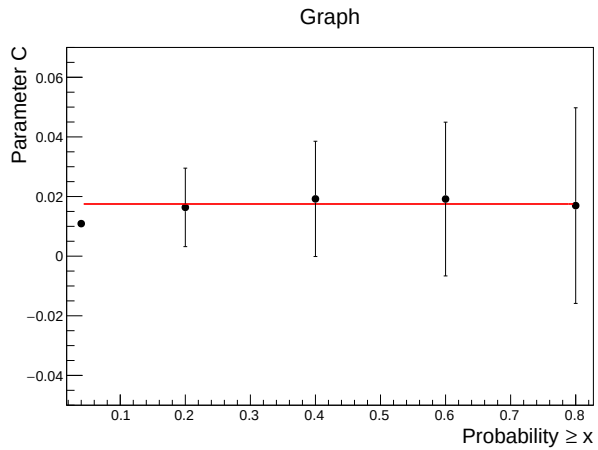
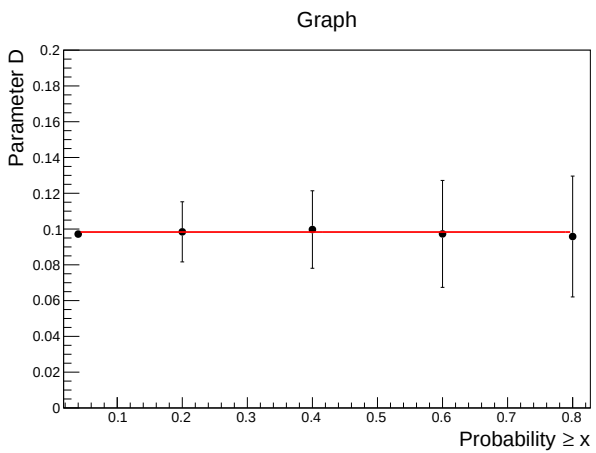
WASA	1.144(18)	0.219(19)(47)	0.0	0.086(18)(15)	0.115(37)
KLOE(16)	1.104(5)(2)	$0.142(3)(^{+5}_{-4})$	0.0	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
G12	1.102(20)(13)	0.127(18)(5)	0.011(7)(7)	0.106(19)(5)	0.248(45)(10)

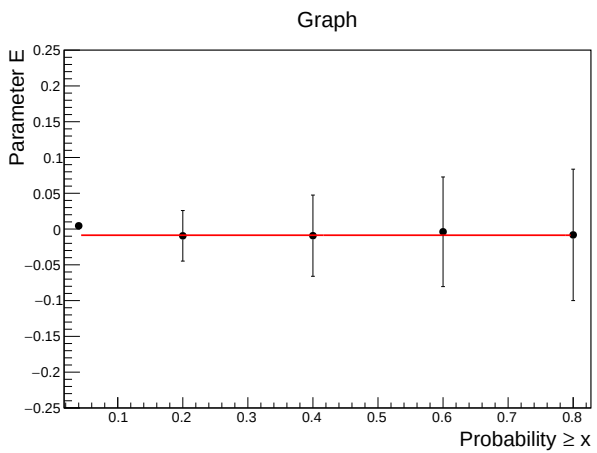
Backup: Influence of choosing the Kinematic Fit Probability

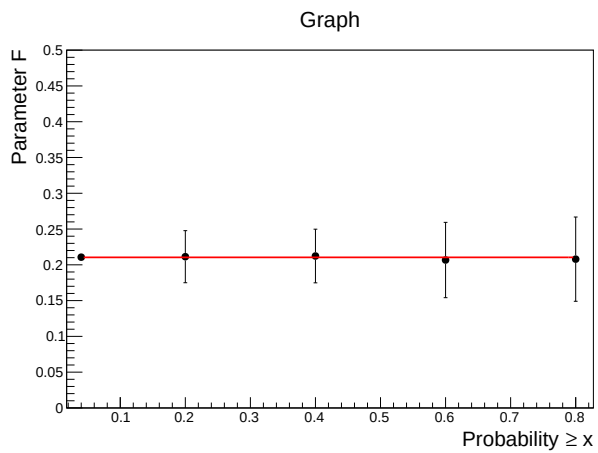




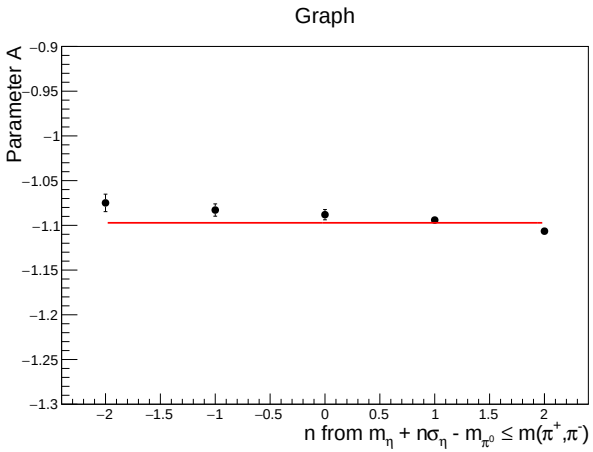


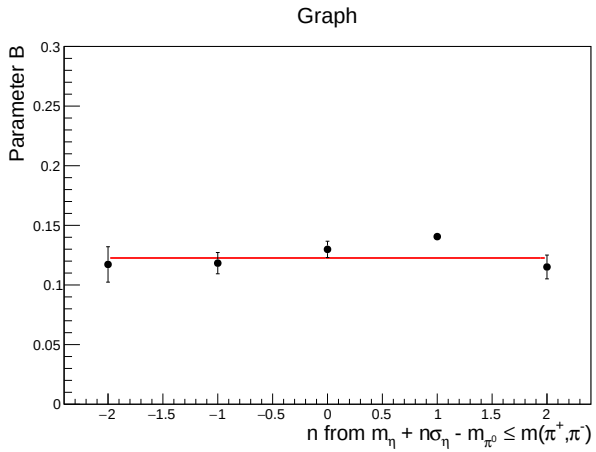


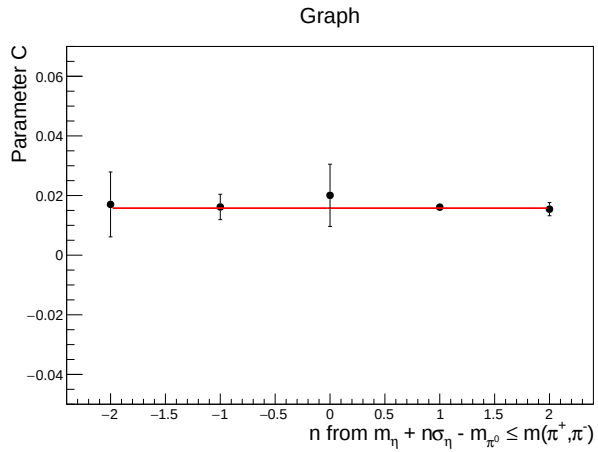


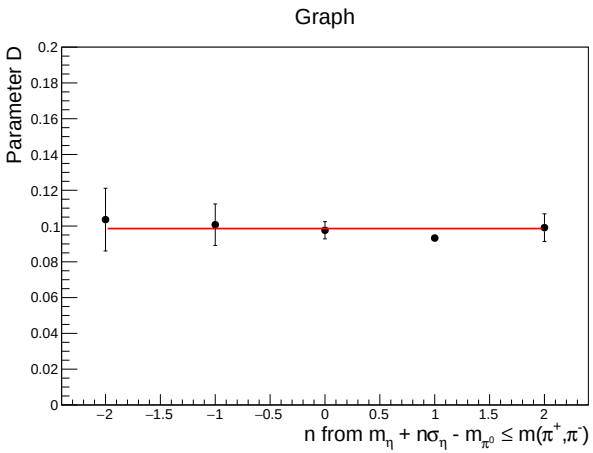


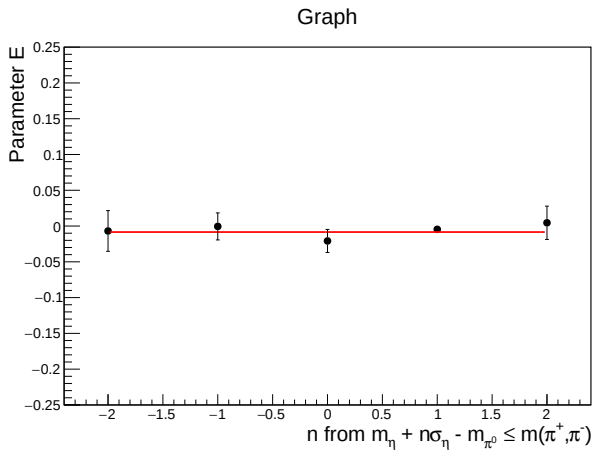
Backup: Influence of the ω-Rejection

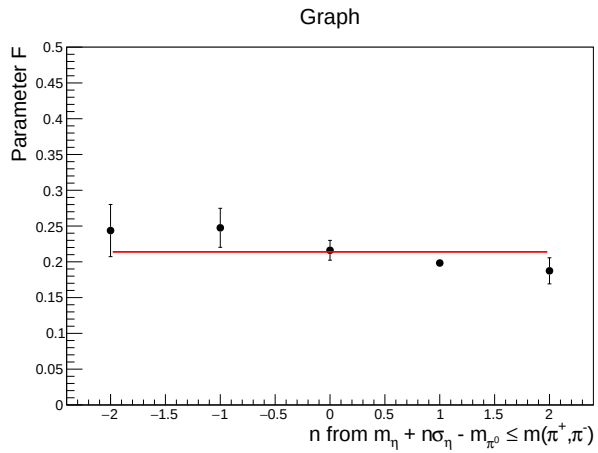




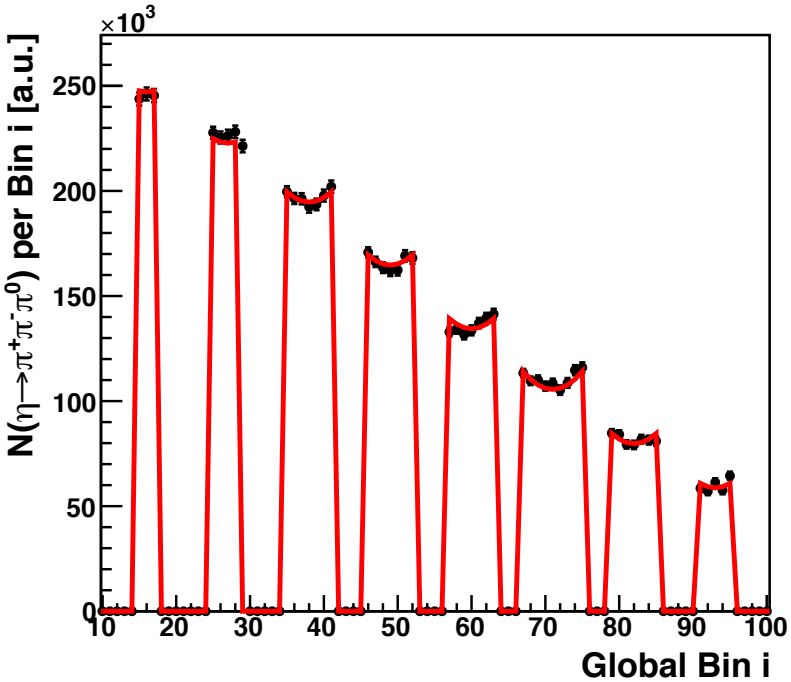


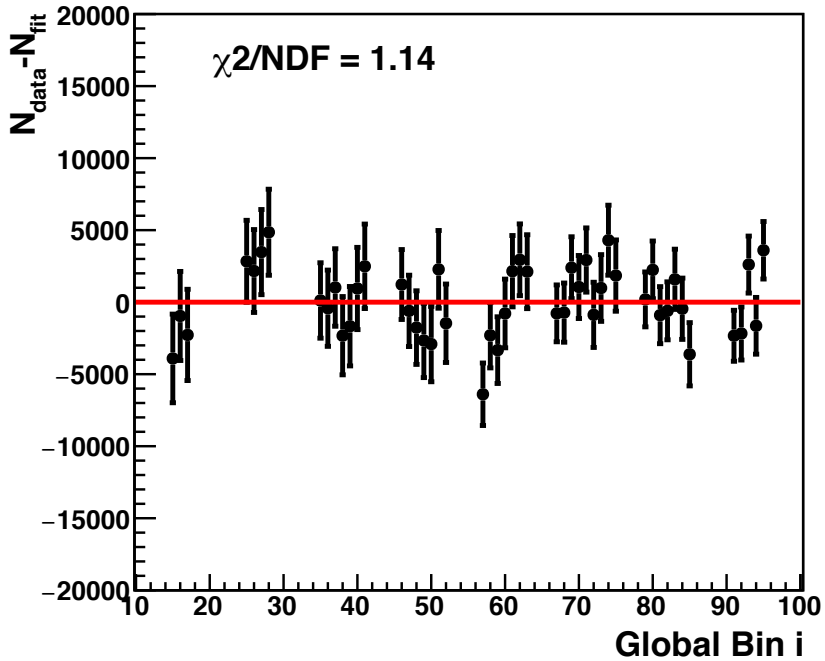






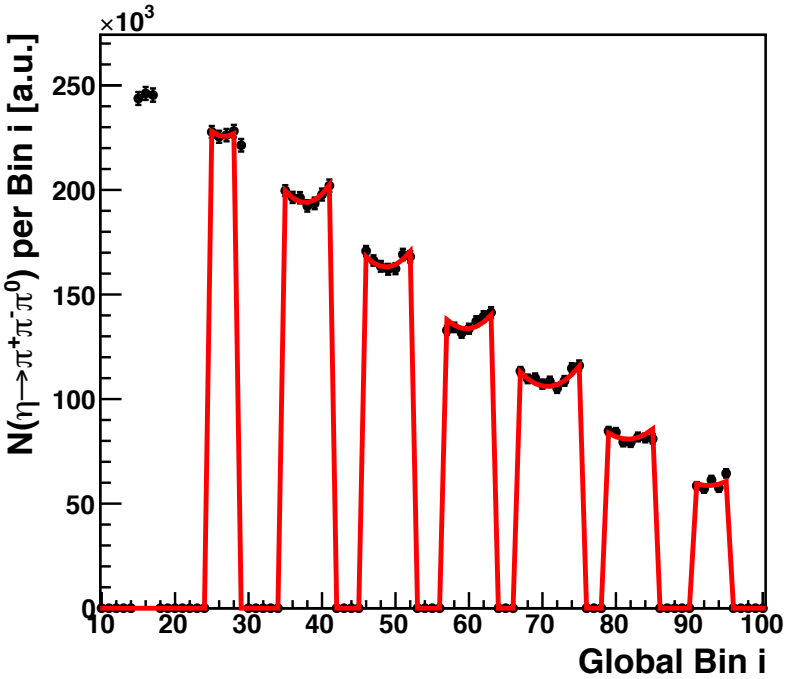
Backup: Fixing Parameters c,e and g = 0

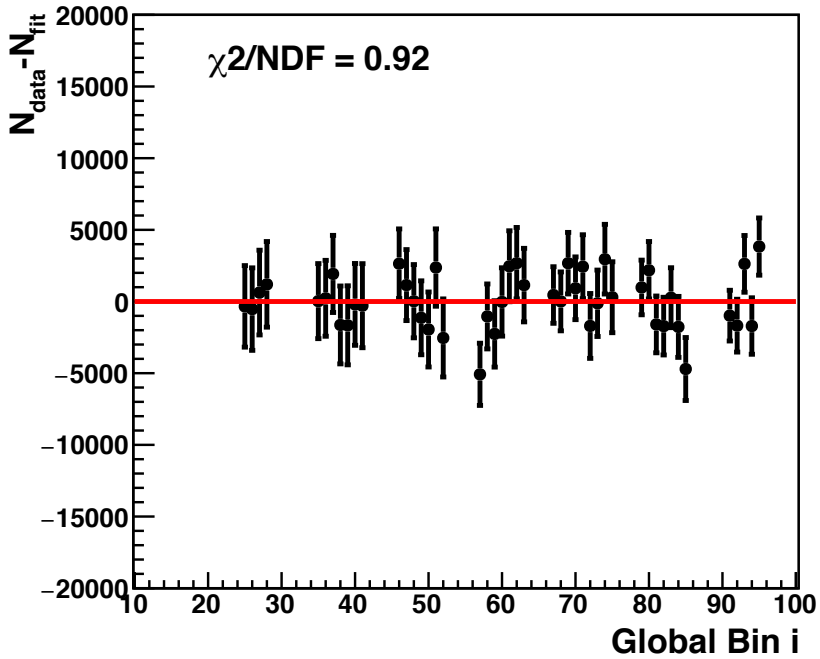




Exp.	$-a$	b	c	d	e	f
WASA	1.144(18)	0.219(66)	−0.007(9)	0.086(33)	−0.020(52)	0.115(37)
KLOE(16)	1.095(6)	0.145(8)	0.0	0.081(9)	0.0	0.141(15)
G12	1.102(20)	0.131(19)	0.013(7)	0.109(19)	0.0	0.247(45)
G12(fix)	1.11(16)	0.130(19)	0.0	0.1(16)	0.0	0.261(41)

Backup: Reject Bins < 20

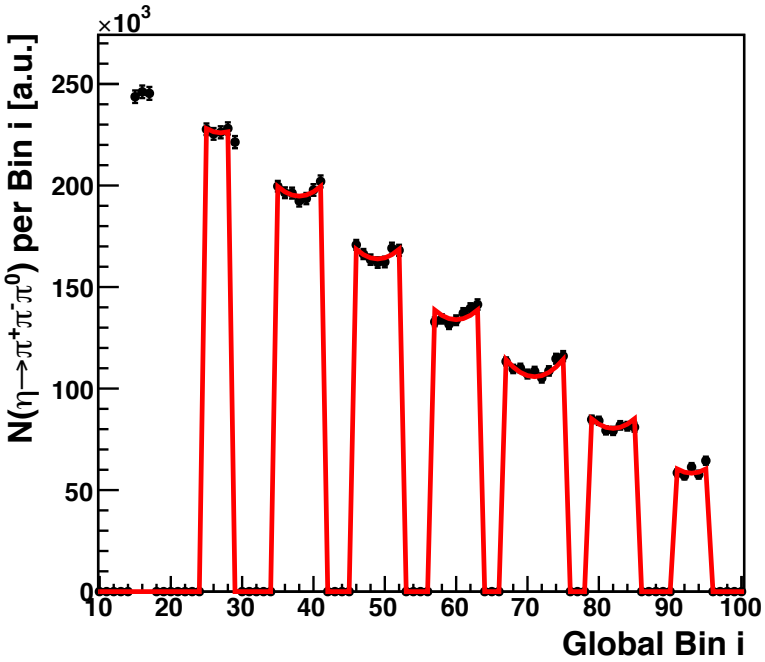


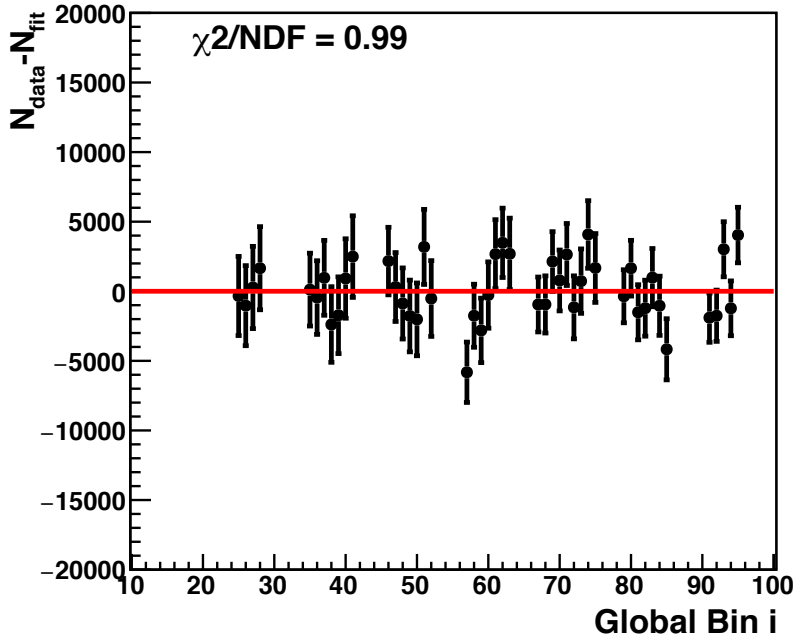


Checked many combinations of point groups to reject $\Leftrightarrow$ Those for Bins < 20 show largest effect

Exp.	$-a$	b	c	d	e	f
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(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)

Backup: Fixing Parameters c,e and g = 0 and Reject Bins < 20





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(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)
G12(rp & fix)	1.109(18)	0.170(23)	0.0	0.099(17)	0.0	0.123(61)