Status of the Analysis of $\eta \to \pi^+\pi^-\pi^0$ with the CLAS g12 Data Set - Vol. II

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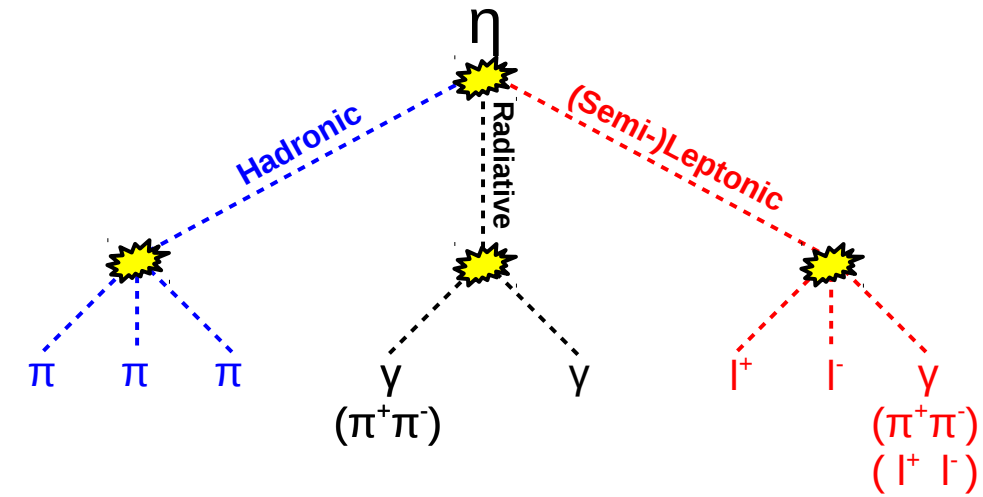
One Meson, many Opportunities

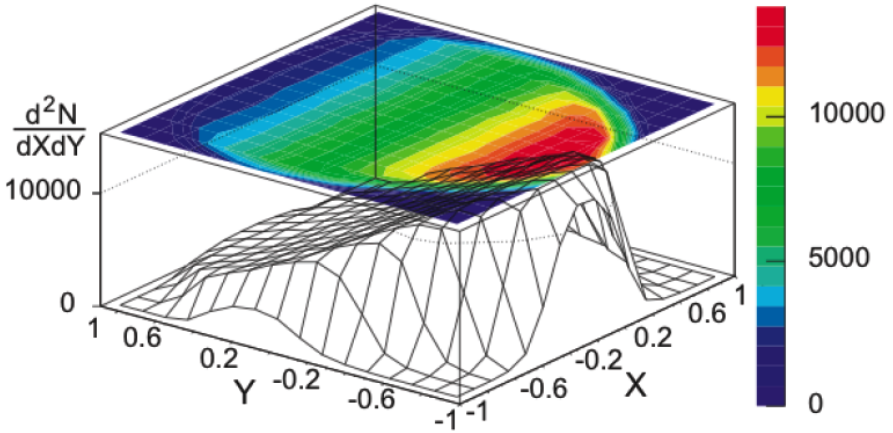
- $m_\eta = 0.5478\,\mathrm{GeV/c^2}$
- $\Gamma_\eta = (1.31 \pm 0.05)\,\mathrm{keV}$
- $\bar{\tau} \approx 5 \cdot 10^{-19}\,\mathrm{s}$
- $J^{PC} = 0^{-+} \Longrightarrow \eta$-meson is: C-, P-, G- and CP- eigenstate
- All strong and electromagnetic decays are forbidden to first order

$\Rightarrow$ **Access to rare decay processes**



Decay mode	Issue
$\eta' \to \pi^+\pi^-\eta$	Dalitz plot analysis
$\eta \to \pi^+\pi^-\pi^0$	Dalitz plot analysis
$\eta^{(\prime)} \to \pi^+\pi^-\gamma$	Box anomaly, $\pi^+\pi^-$ FSI (See talk by G. Mbianda Njenchu, S. Song, T. Roark)
$\eta^{(\prime)} \to e^+e^-\gamma^\star$	Single-off-shell transition form factor
$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$	CP-Violation
$\eta \to e^+e^-e^+e^{-\star}$	Double-off-shell transition form factor
$\eta \to \pi^0 e^+e^-$	C-Violation

The Dalitz Plot



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

Dimensionless Dalitz plot variables:

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

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

- Decay via strong isospin violation: $\Gamma_{meas} \propto Q^{-4}$

  with: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$

  and: $\hat{m} = \frac{1}{2}(m_u + m_d)$

- Dalitz plot analysis: $\frac{d^2\Gamma_{meas}}{dXdY} \propto (1 + aY + bY^2 + dX^2 + fY^3 + gX^2Y + ...)$

  $\rightarrow$ c, e and h would imply C-violation

Current Results

Parameter:		−a	b	d	f
Theor.	ChPT (NNLO)[a]	1.271(75)	0.394(102)	0.055(57)	0.025(160)
	NREFT[b]	1.213(14)	0.308(23)	0.050(3)	0.083(19)
	PWA[c]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
Exp.	KLOE (08)[d]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[e]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE (16)[f]	$1.095(3)(^{3}_{-2})$	0.145(3)(5)	$0.081(3)(^{+6}_{-5})$	$0.141(7)(^{+7}_{-8})$

- Calculation from JPAC* group using the WASA-at-COSY result: $Q = 21.4 \pm 0.4^{(c)}$

  $\star$ **Interactive web page: http://www.indiana.edu/ jpac/index.html**

- **Dalitz Plot Analysis for $\gamma p \to p\eta[\eta \to \pi^+\pi^-\pi^0]$ with CLAS**
  - **i) Extract Dalitz Plot parameter**
  - **ii) Calculate Q via PWA**

(a) J. Bijnens and K. Ghorbani., *JHEP*, 11, (2007)

(b) S- P. Schneider et al., *JHEP*, 028, (2011)

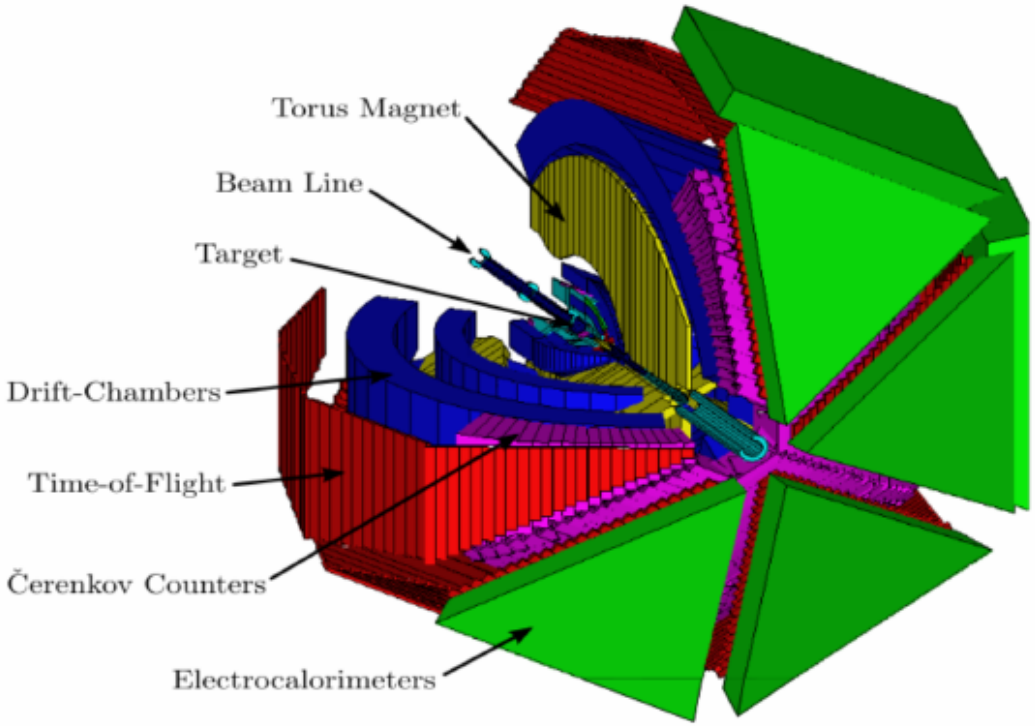
(c) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)

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

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

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

The CLAS g12 Data Set



- $E_{e,beam} = 5.714\,\mathrm{GeV}$
- Photon beam with: $E_{\gamma,\mathrm{beam}} \in [1.1\,\mathrm{GeV}, 5.45\,\mathrm{GeV}]$
- Liquid hydrogen target with $40\,\mathrm{cm}$ length
- Magnetic field $\sim 2\,\mathrm{T}$
- ~ 670 runs in total

- CLAS g12 data set in Jülich:
  - ~ 451 runs $\approx 1\,\mathrm{TB} \longrightarrow$ Corresponds to 2/3 of the total g12 data set
  - Already calibrated and preselected (done by Michael C. Kunkel)
  - Dedicated LMD-group at IKP-1 in Jülich

Reminder: Status at last Collaboration Meeting

- Reconstruction of $\eta \rightarrow \pi^+\pi^-\pi^0$ events:
  - i) Basic steps according to g12 analysis procedure
    - ★ Beam corrections
    - ★ Momentum corrections for charged tracks
    - ★ Fiducial cuts $\Rightarrow$ are particles within detector acceptance?

Reminder: Status at last Collaboration Meeting

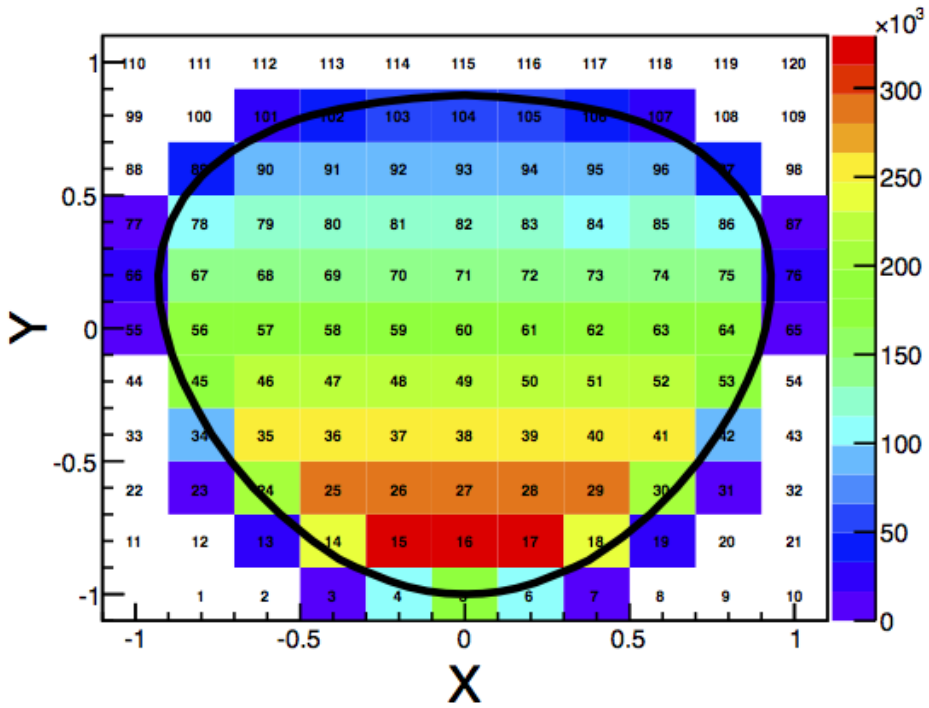
- Reconstruction of $\eta \rightarrow \pi^+\pi^-\pi^0$ events:
  - i) Basic steps according to g12 analysis procedure
  - ii) Kinematic fit
    - ★ Fitter tuned for $\gamma p \rightarrow p\pi^+\pi^-(0)$
    - ★ Tuning parameters are also valid for MC (do not use option "is_mc == true")
    - ★ Reaction hypothesis for analysis: $\gamma p \rightarrow p\pi^+\pi^-(\pi^0)$
    - ★ Accept events with: Prob $\geq$ 10%

Reminder: Status at last Collaboration Meeting

- Reconstruction of $\eta \rightarrow \pi^+\pi^-\pi^0$ events:
  - i) Basic steps according to g12 analysis procedure
  - ii) Kinematic fit
  - iii) Kinematic limit on $M(\pi^+, \pi^-)$
    - ★ Reject contributions from $\omega \rightarrow \pi^+\pi^-\pi^0$
    - ★ Mass constraint: $M(\pi^+, \pi^-) \leq m_\eta + 3\sigma_\eta - m_{\pi^0} = 0.45\,\mathrm{GeV/c^2}$

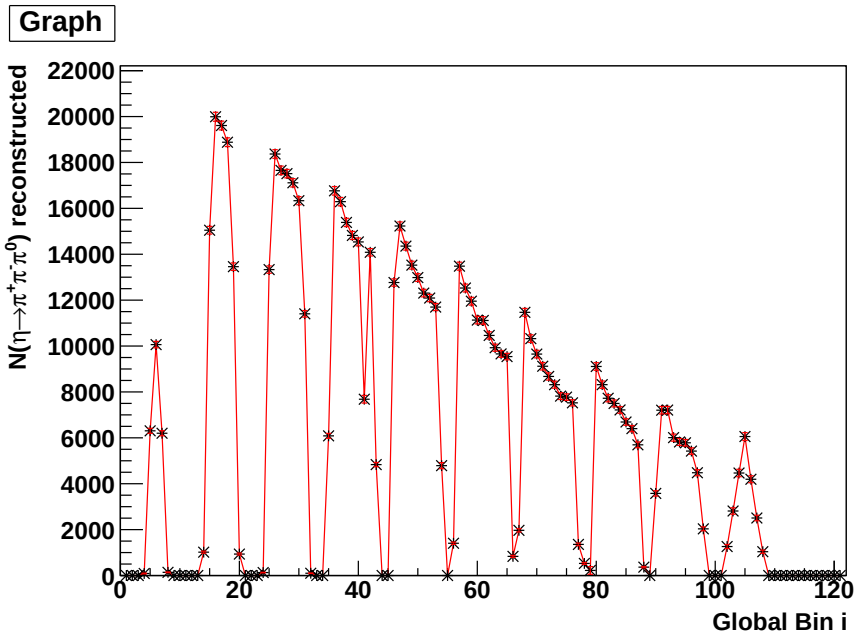
Reminder: Status at last Collaboration Meeting

- Reconstruction of $\eta \rightarrow \pi^+\pi^-\pi^0$ events:
  - i) Basic steps according to g12 analysis procedure
  - ii) Kinematic fit
  - iii) Kinematic limit on $M(\pi^+, \pi^-)$
- One dimensional representation of Dalitz Plot (according to WASA analysis)
  - Define global bin: $i = f(X, Y)$
  - Look at $M_x(p)$ vs i and do bin wise background subtraction

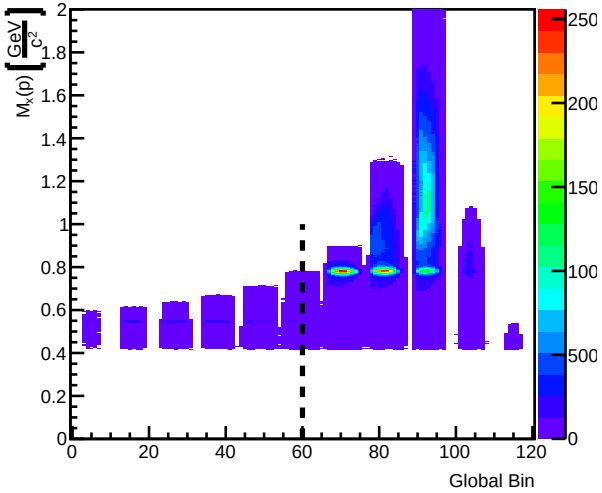


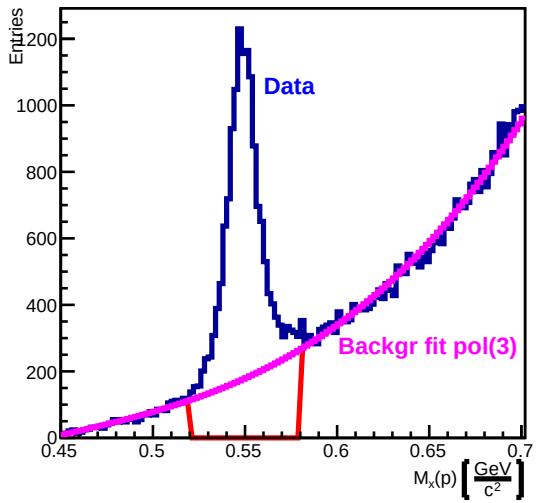
Reminder: Status at last Collaboration Meeting

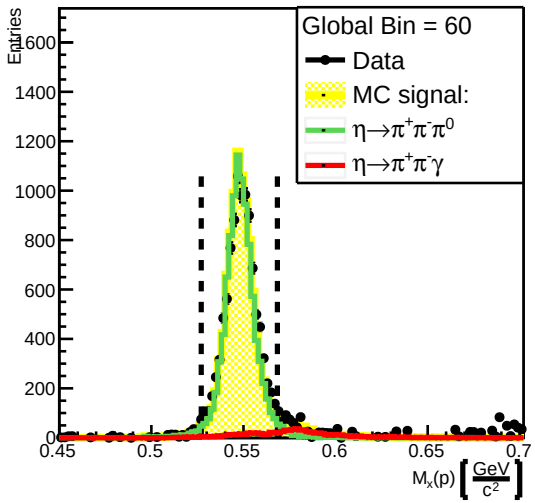
- Reconstruction of $\eta \rightarrow \pi^+\pi^-\pi^0$ events:
  - i) Basic steps according to g12 analysis procedure
  - ii) Kinematic fit
  - iii) Kinematic limit on $M(\pi^+, \pi^-)$
- One dimensional representation of Dalitz Plot (according to WASA analysis)
- Obtained background corrected Dalitz Plot (bottom plot)
- No correction for $\eta \rightarrow \pi^+\pi^-\gamma$ events



Correcting for $\eta \to \pi^+\pi^-\gamma$ events

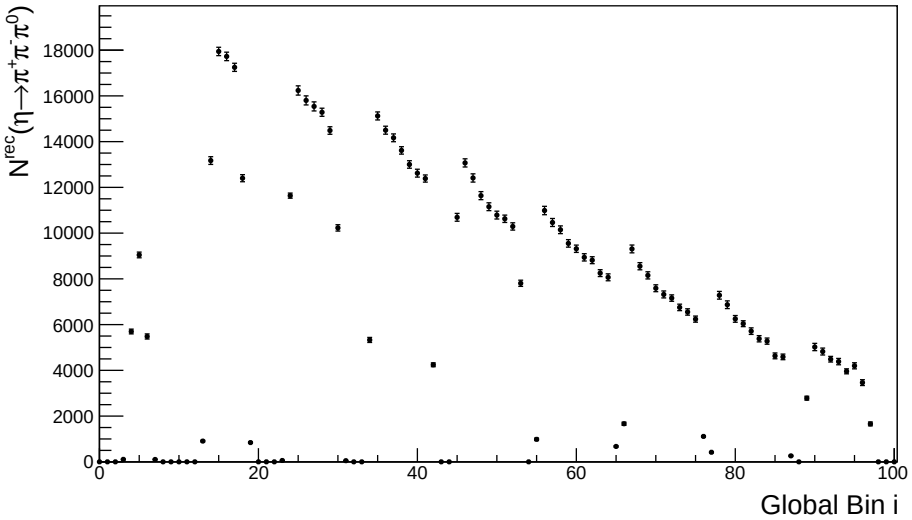


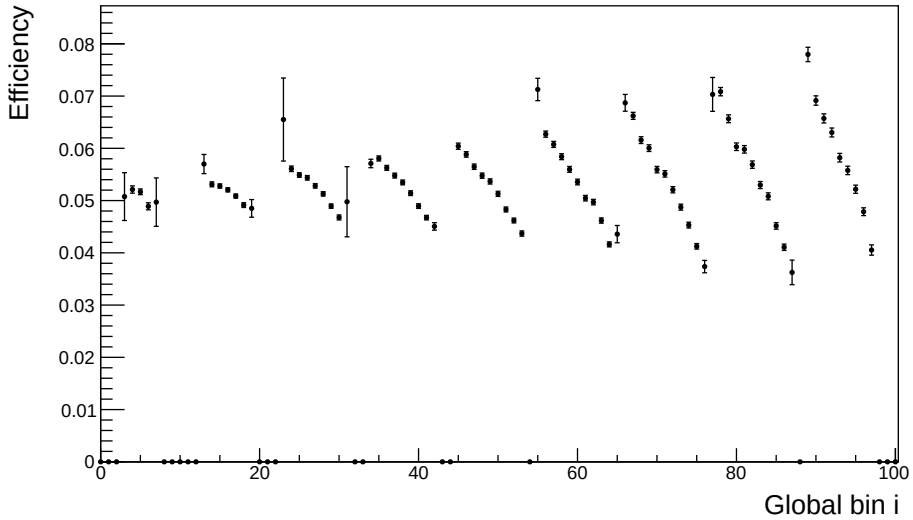




- Look at missing mass $M_x(p)$ spectrum for each global bin and subtract non-resonant background
- Fit background corrected data signal with MC:
  $\eta \to \pi^+\pi^-\pi^0$ + $\eta \to \pi^+\pi^-\gamma$
- Obtain $N^{rec}(\eta \to \pi^+\pi^-\pi^0)$
  (Integral of green distribution in right panel)

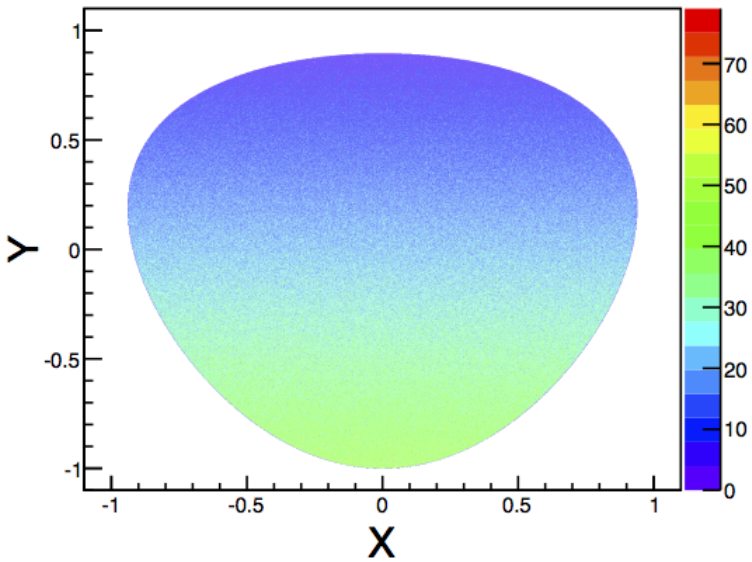
$N^{rec}(\eta \to \pi^+\pi^-\pi^0)$ and Efficiencies

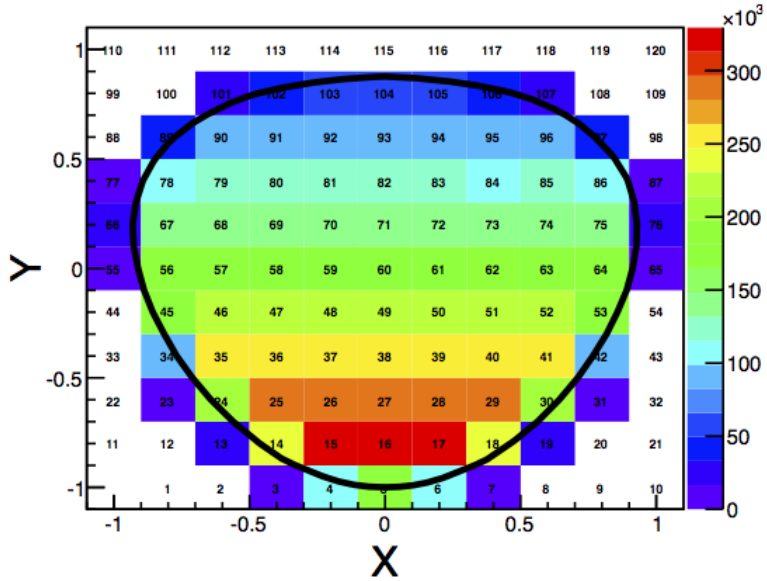


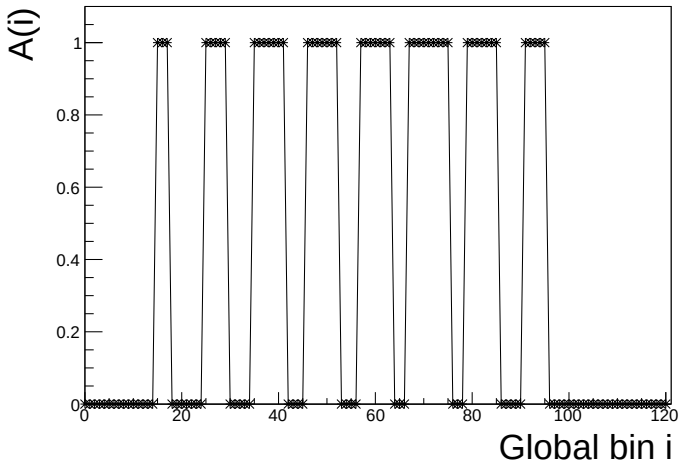


- Use $N^{rec}(\eta \to \pi^+\pi^-\pi^0)$ from fit on previous slide
- $\sim 660\,\mathrm{k}\ \eta \to \pi^+\pi^-\pi^0$ events in the final sample
- Already corrected for contributions from $\eta \to \pi^+\pi^-\gamma$
- Efficiencies with large error bars indicate boarders of the Dalitz Plot (see next slide)

Kinematic Limits - Boarders of the Dalitz Plot



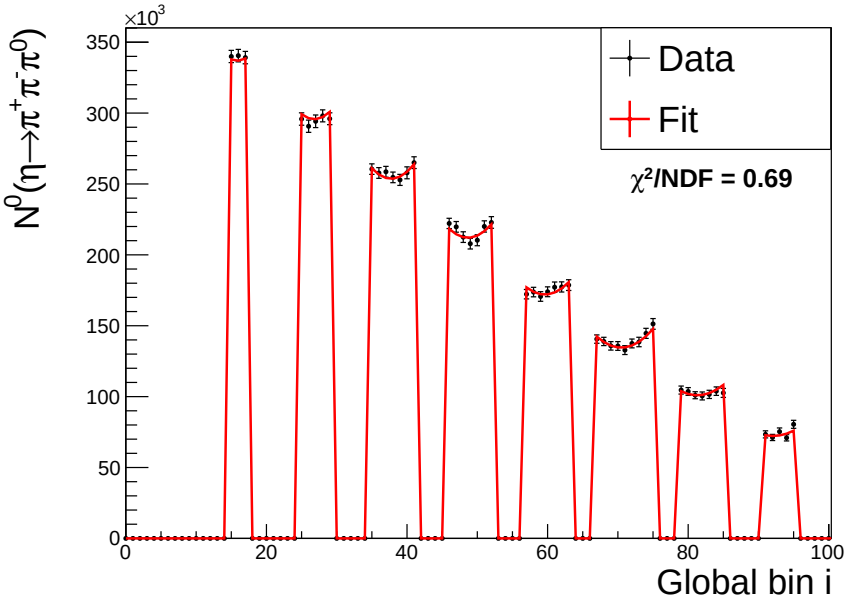


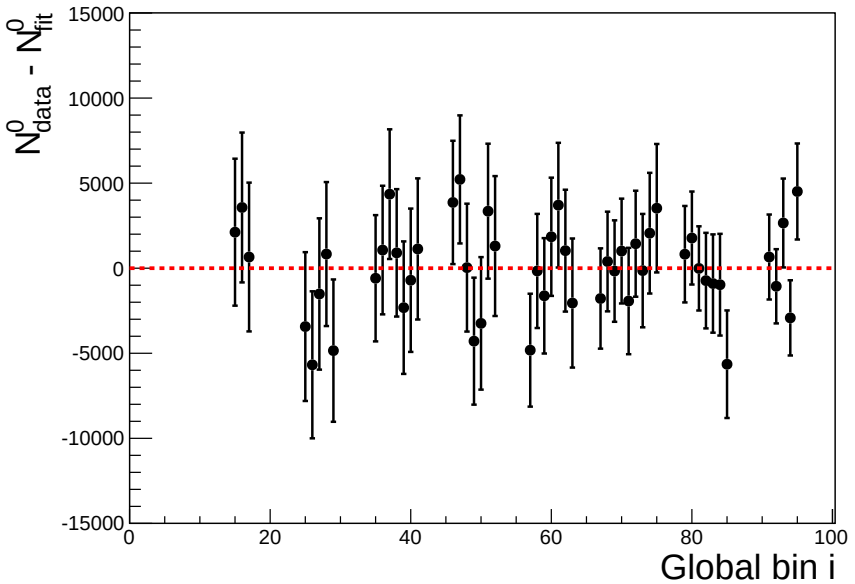


- Effect of dividing the Dalitz Plot into 11×11 bins
- Need to respect kinematic boundaries (see black line in upper right panel)
  $\Rightarrow$ only accept bins which are 100% within the kinematic limits
- $A(i) = \begin{cases} 1, & \text{if bin i(X,Y) is within boarders} \\ 0, & \text{else} \end{cases}$

Calculation of the Dalitz Plot Parameters

- Define: $\chi^2 \equiv \sum_{i=0}^{120} \left(\frac{N_i^{\mathbf{0}}(\eta \to \pi^+\pi^-\pi^{\mathbf{0}}) - N_i^{fit}(a,b,c,d,e,f)}{\Delta N_i^{\mathbf{0}}(\eta \to \pi^+\pi^-\pi^{\mathbf{0}})} \right)^2$
- With:
  - $N_i^0(\eta \to \pi^+\pi^-\pi^0) \equiv N_i^{rec}(\eta \to \pi^+\pi^-\pi^0) \times A(i) \times \frac{1}{\text{Efficiency}(i)}$
  - $\Delta N_i^0(\eta \to \pi^+\pi^-\pi^0) \equiv$ well, the corresponding error
  - $N_i^{fit}(a,b,c,d,e,f) \equiv$
    norm $\times [aY(i) + bY^2(i) + cX(i) + dX^2(i) + eX(i)Y(i) + fY^3(i) + ...]$
- Minimise χ^2 and leave all parameters as free





Results

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	WASA[e]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE (16)[f]	$1.095(3)(^{3}_{-2})$	0.145(3)(5)	$0.081(3)(^{+6}_{-5})$	$0.141(7)(^{+7}_{-8})$
	CLAS G12	1.130(22)	0.195(29)	0.109(21)	0.139(49)

- Calculation from JPAC* group using the WASA-at-COSY result: $Q = 21.4 \pm 0.4^{(c)}$

  $\star$ **Interactive web page: http://www.indiana.edu/ jpac/index.html**

- **Dalitz Plot Analysis for $\gamma p \to p\eta[\eta \to \pi^+\pi^-\pi^0]$ with CLAS**
  - **i) Extract Dalitz Plot parameter** (so close!)
  - **ii) Calculate Q via PWA**
- Results are shown with statistical errors
- Major issue: $c = 0.018 \pm 0.008 \neq 0 \Rightarrow$ Systematic tests

(a) J. Bijnens and K. Ghorbani., *JHEP*, 11, (2007)

(b) S- P. Schneider et al., *JHEP*, 028, (2011)

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

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

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

Systematic Tests done so far

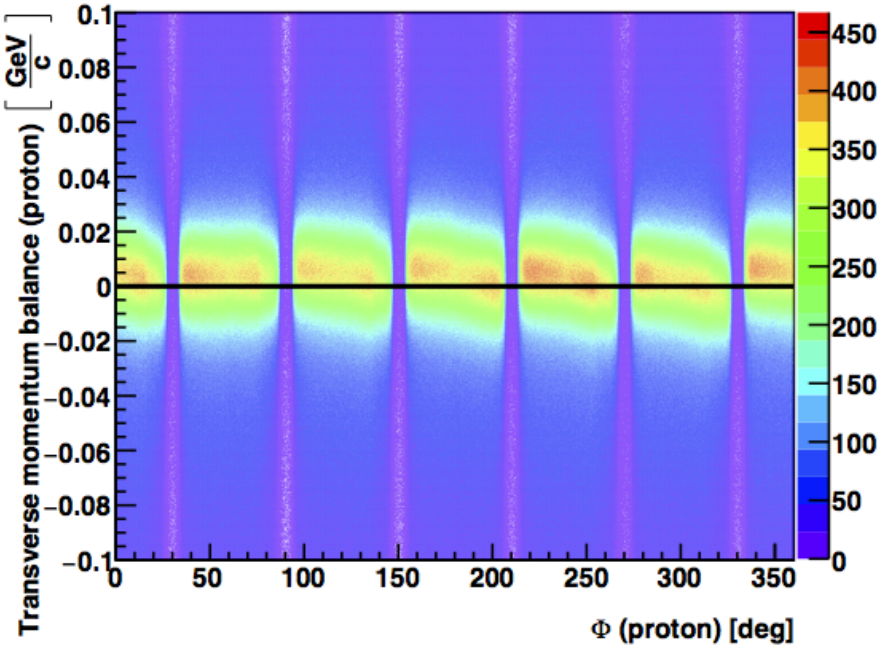
Exp.	$-a$	b	c	d	e	f
WASA	1.144(18)	0.219(66)	−0.007(9)	0.086(33)	−0.020(52)	0.115(37)
KLOE(16)	1.095(6)	0.145(8)	0.0	0.081(9)	0.0	0.141(15)
G12(ref)	1.130(22)	0.195(20)	0.018(8)	0.109(21)	0.010(22)	0.139(49)
G12(fix)	1.130(21)	0.195(20)	0.0	0.105(21)	0.0	0.139(49)
G12(excl1)	1.109(25)	0.152(45)	0.018(8)	0.108(21)	−0.005(25)	0.046(80)
G12(excl2)	1.144(23)	0.171(25)	0.019(7)	0.111(20)	0.003(22)	0.215(71)
G12(excl3)	1.139(30)	0.162(45)	0.018(8)	0.109(21)	−0.006(26)	0.182(126)
G12(E_γ1)	1.226(66)	0.237(66)	0.006(23)	−0.091(59)	−0.063(70)	0.544(146)
G12(E_γ2)	1.104(23)	0.199(21)	0.025(8)	0.088(22)	−0.016(25)	0.086(53)
G12(E_γ3)	1.122(24)	0.216(23)	0.027(8)	0.091(24)	−0.009(25)	0.102(55)
G12(E_γ4)	1.272(135)	0.584(140)	−0.153(49)	−0.004(134)	0.068(139)	−0.112(327)
G12(π^0)	1.166(23)	0.229(22)	0.007(8)	0.097(23)	0.003(23)	0.155(52)

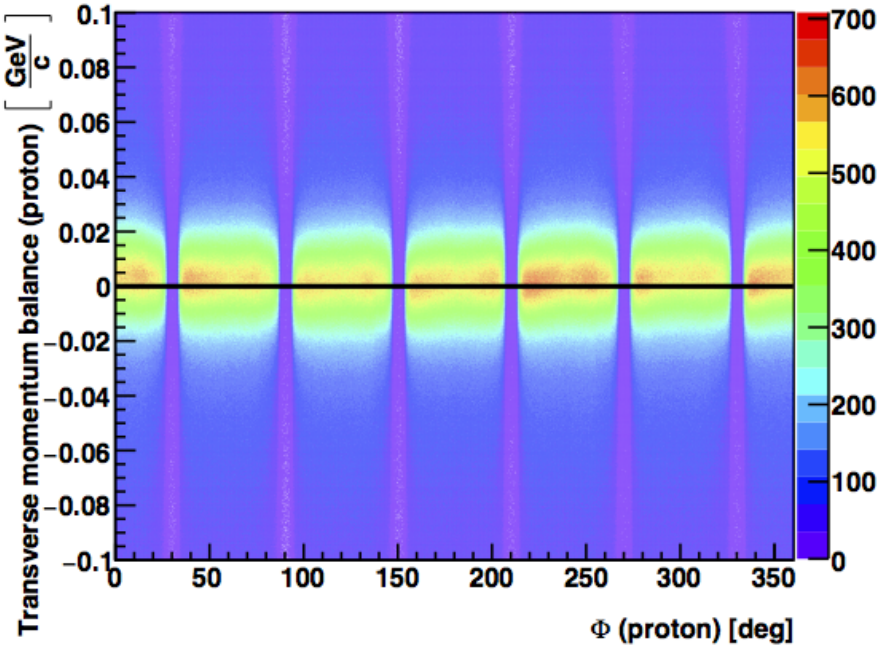
- Legend:
  ref: Reference results
  fix: Fixed c and e to be 0
  excl1: Excluded global bins $>$ 90 from DP-fit
  excl2: Excluded global bins $<$ 20 from DP-fit
  excl3: Excluded global bins $<$ 20 and $>$ 90 from DP-fit
  E_γ1: $E_{\gamma,beam} \leq 1.3\,\mathrm{GeV}$
  E_γ2: $E_{\gamma,beam} > 1.3\,\mathrm{GeV}$
  E_γ3: $E_{\gamma,beam} > 1.3\,\mathrm{GeV}$ & $E_{\gamma,beam} < 3.6\,\mathrm{GeV}$ (also excluded dead paddle region)
  E_γ4: $E_{\gamma,beam} \geq 3.6\,\mathrm{GeV}$
  π^0: 3σ-cut on $M_x^2(p,\pi^+\pi^-)$-distribution
- Further tests and studies ongoing

Summary and Outlook

- ☑ Analysis of the CLAS g12 data set
  - Implemented g12 corrections
  - Tuned kinematic fitter
  - Setup analysis for $\eta \to \pi^+\pi^-\pi^0$
- ☑ Reconstructed $\sim 660\,\mathrm{k}$ $\eta \to \pi^+\pi^-\pi^0$ events
- ☑ Determined Dalitz Plot parameter $\Rightarrow$ Consistent (more or less) with previous experiments
- ☐ Parameter c refuses to be zero
- ☐ Systematic studies (ongoing)
- ☐ Determine Q

Backup: Basic analysis steps

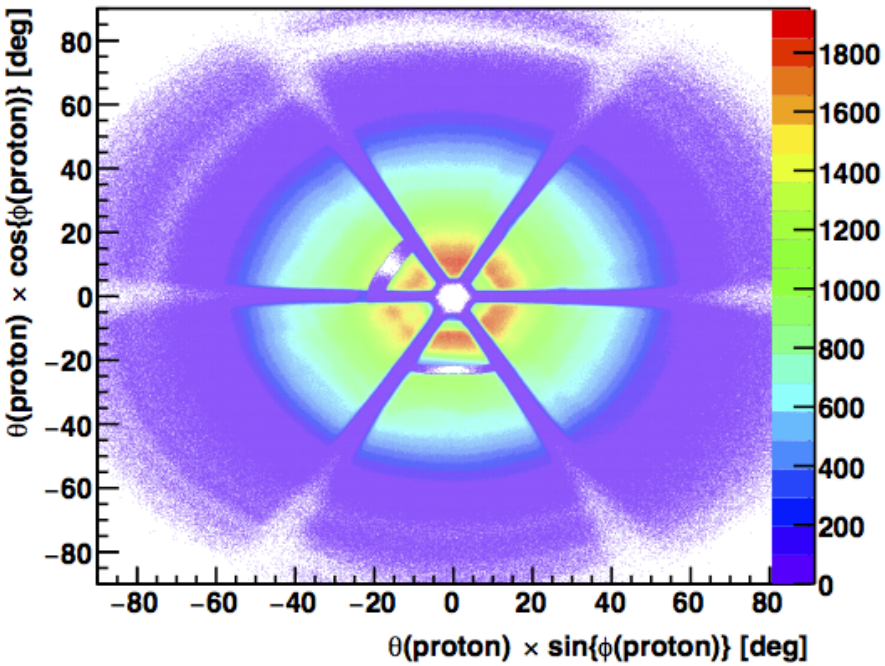


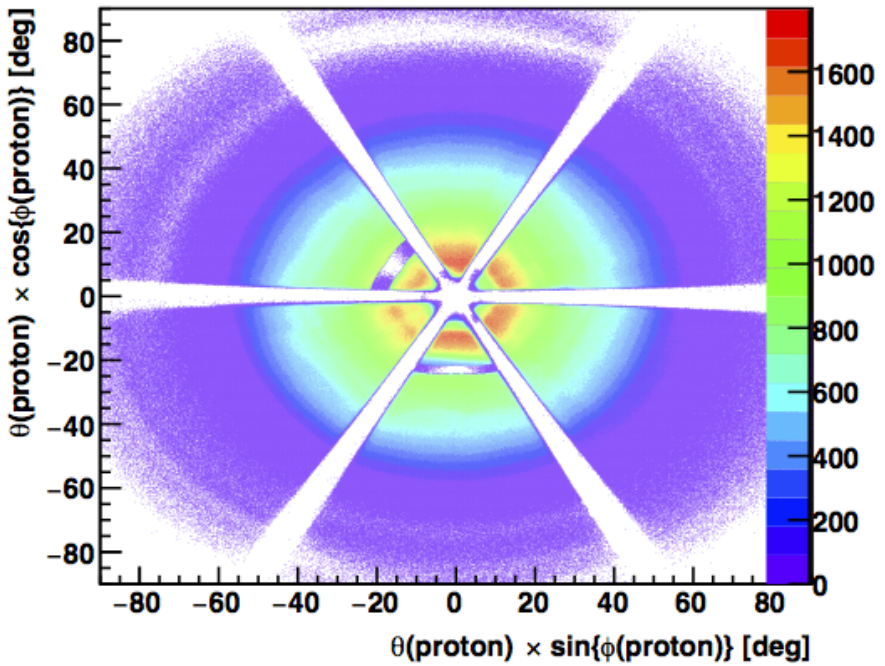


- Transverse momentum balance (proton): $[(\vec{\pi^+} + \vec{\pi^-}) - \vec{p}]_\perp$
- Investigated as function of Φ(proton)
- Left: before Φ-dependent momentum correction / Right: after Φ-dependent momentum correction
- Similar plots for positive/negative pions

Backup: Basic analysis steps

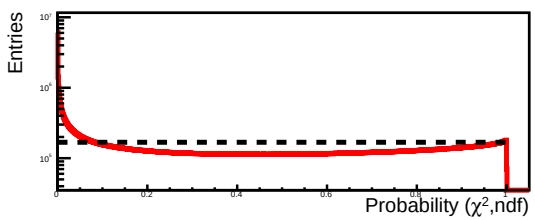
- Fiducial cuts:
  - Geometry based rejection of events outside of detector acceptance
  - In accordance with simulations
- Left: Before fiducial cuts / Right: after fiducial cuts
- Also done for positive/negative pions

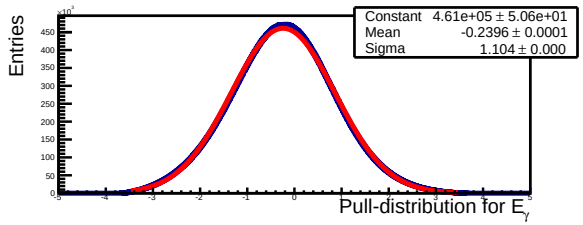


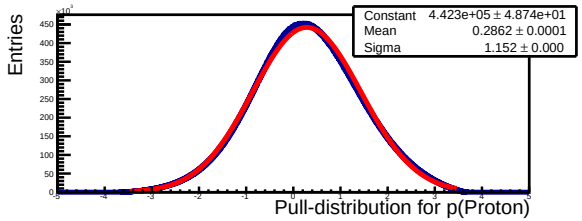


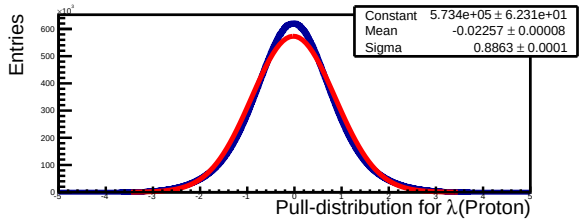
Backup: Tuning of the Kinematic Fit to $\gamma p \to p\pi^+\pi^-$: Pull-Distributions

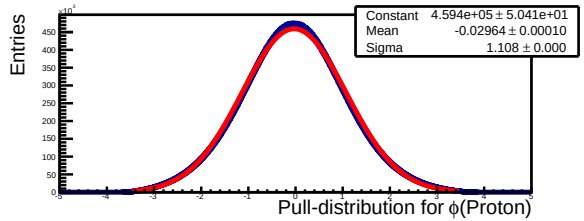
No correction applied

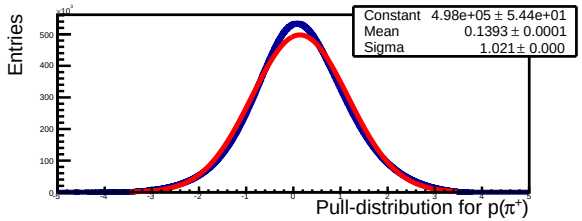


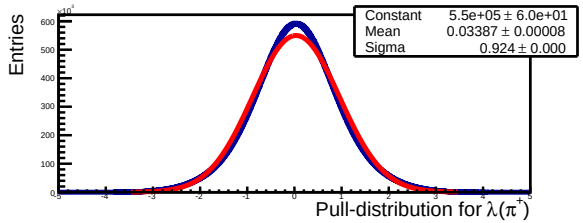


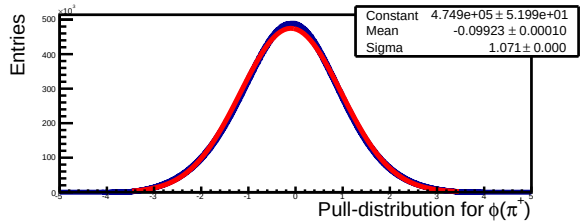


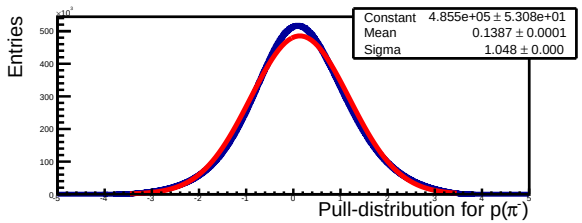


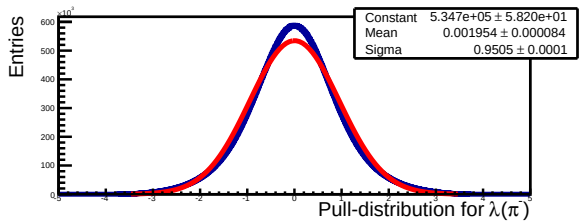


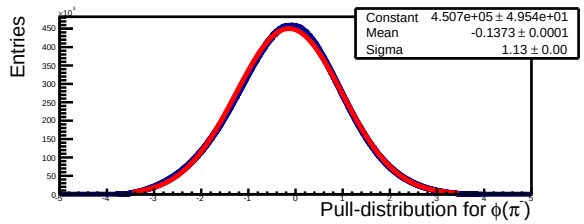






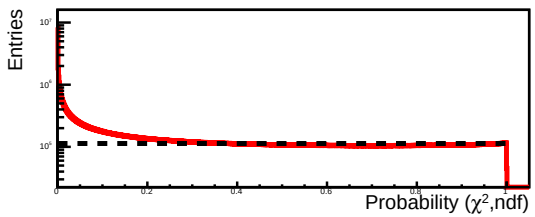


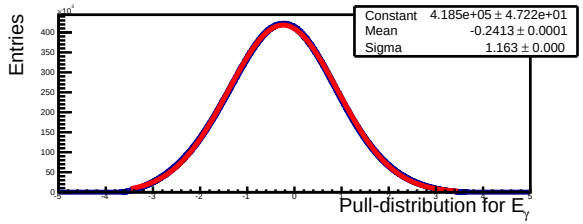


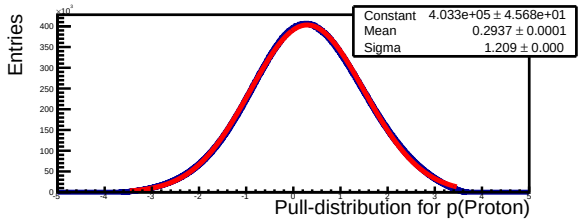


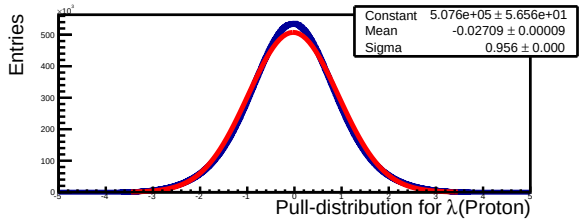
Backup: Tuning of the Kinematic Fit to $\gamma p \to p\pi^+\pi^-$: Pull-Distributions

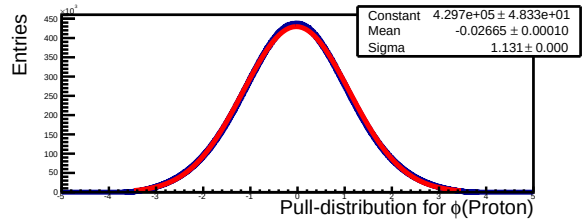
Correction applied

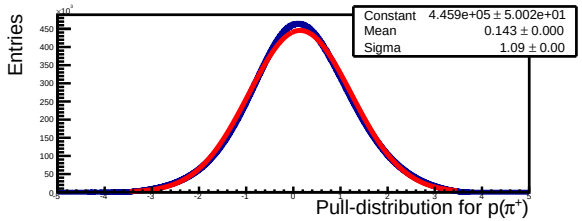


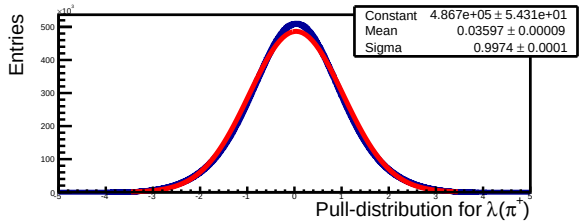


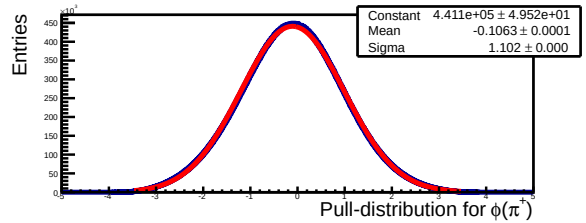


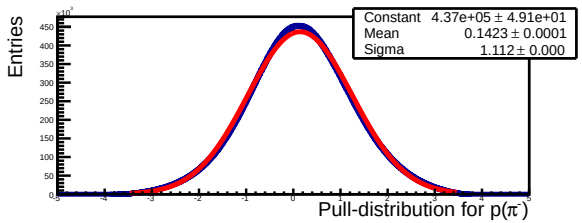


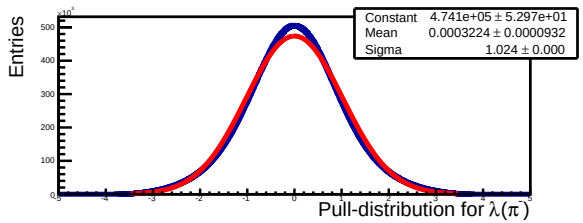


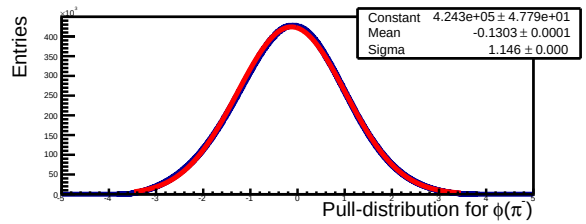






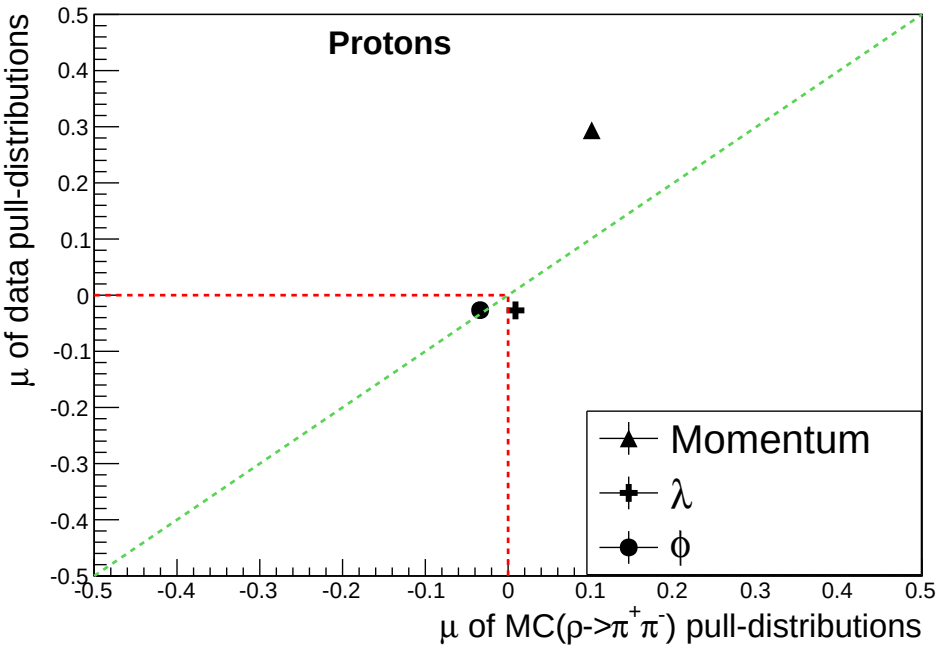


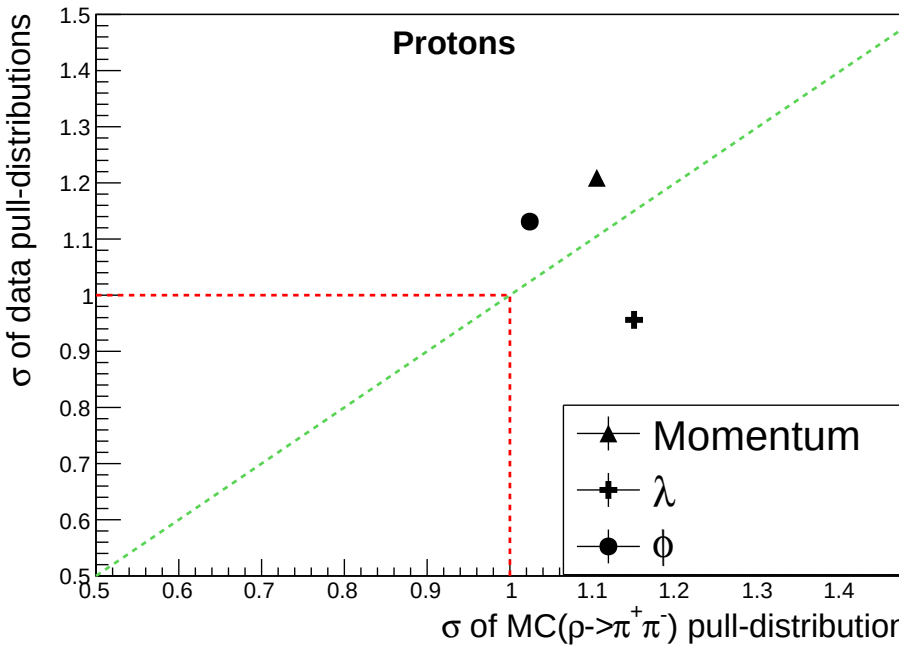




Backup: Comparing Pull-Distributions in Data and MC

Protons

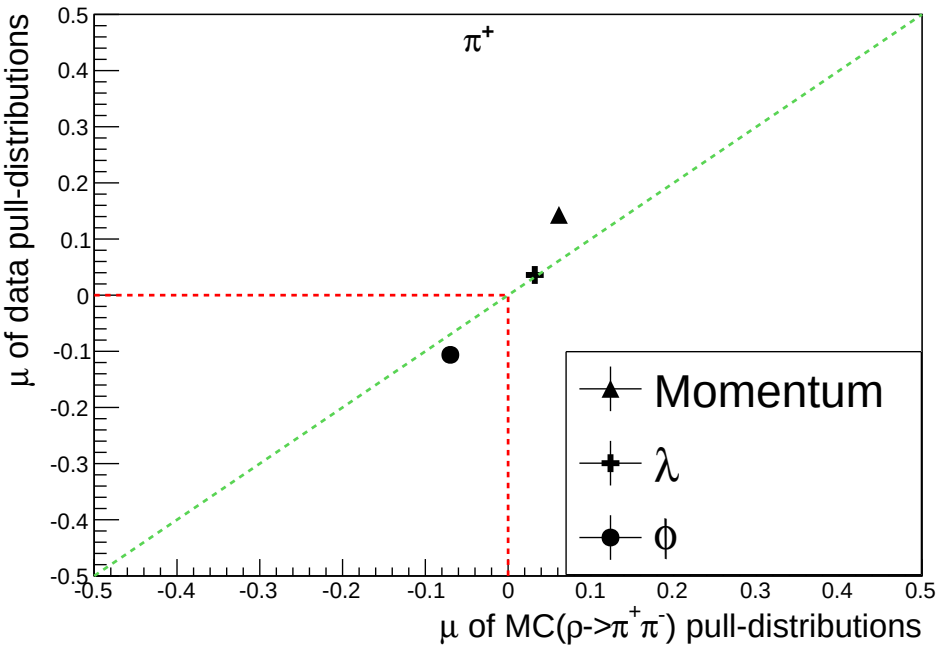


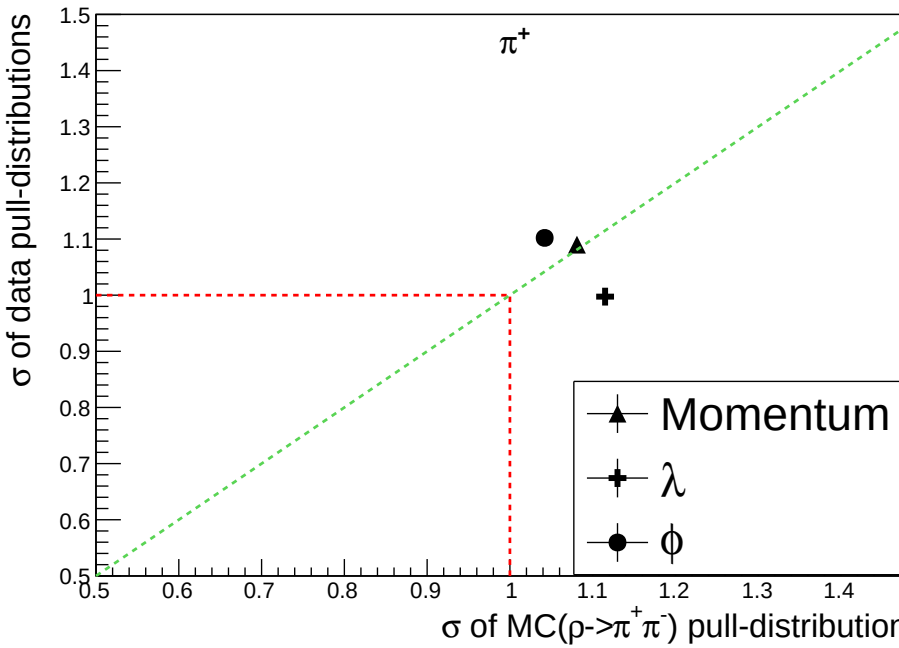


- Performed same analysis for MC as in data
- Used same scaling factors

Backup: Comparing Pull-Distributions in Data and MC

π^+

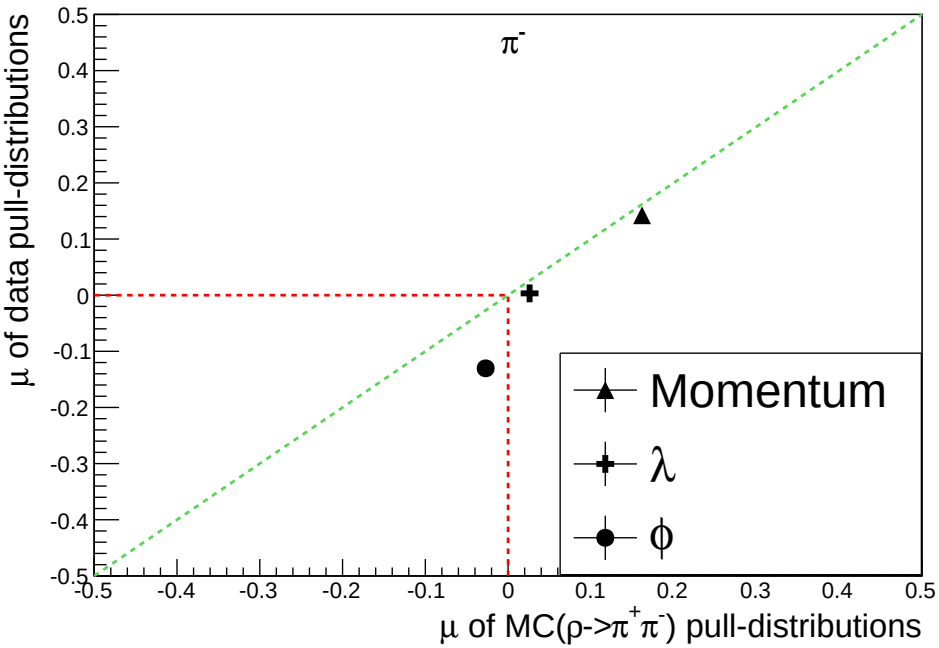


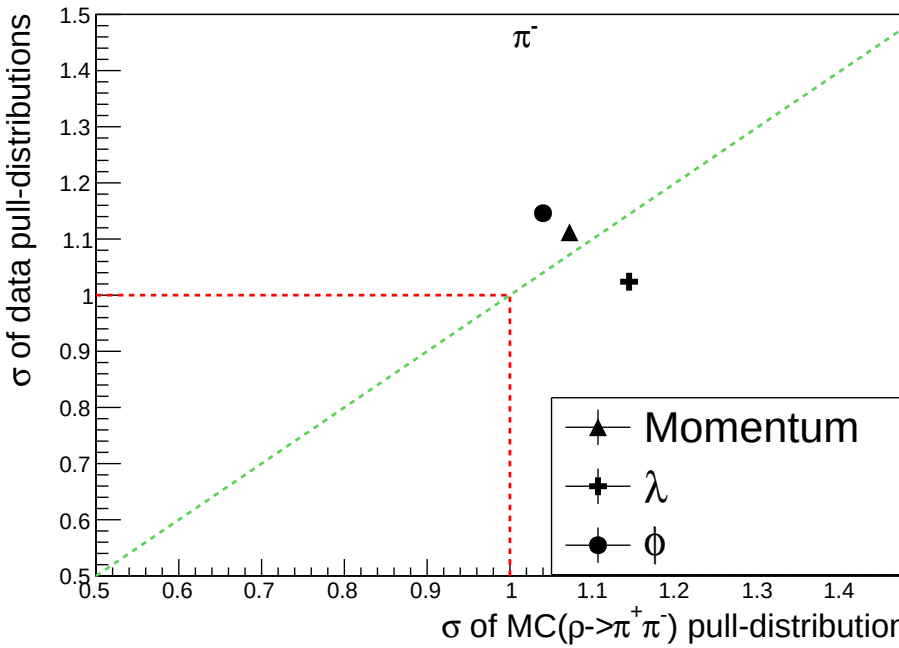


- Performed same analysis for MC as in data
- Used same scaling factors

Backup: Comparing Pull-Distributions in Data and MC

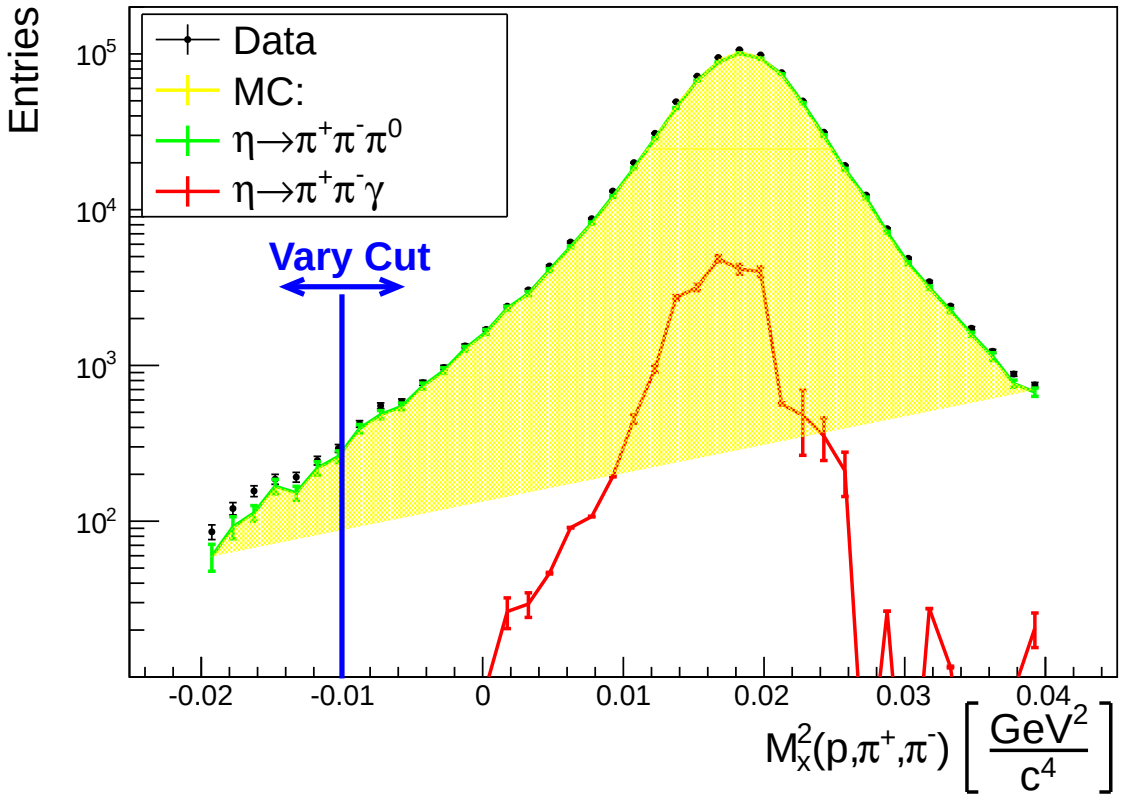
π^-





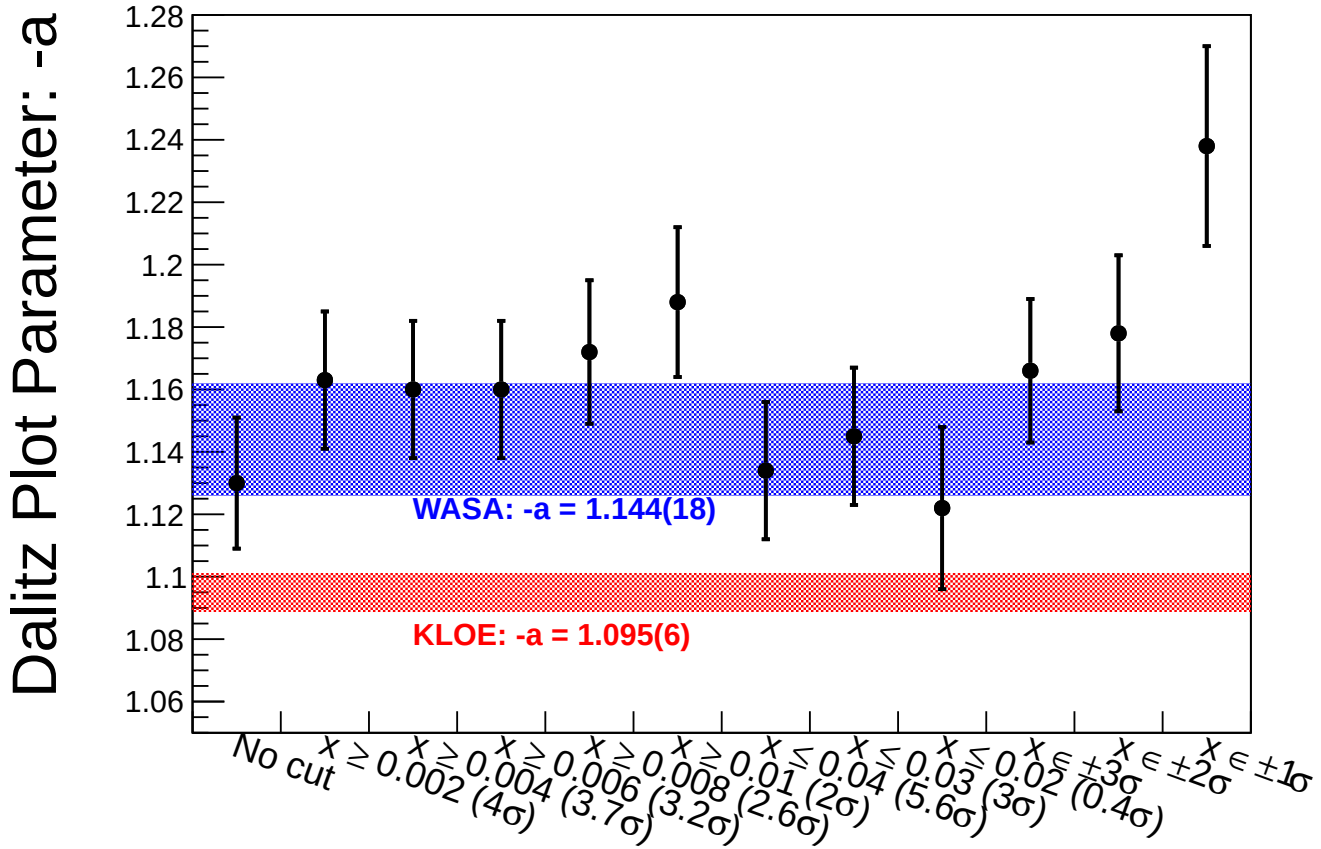
- Performed same analysis for MC as in data
- Used same scaling factors

Backup: The $M_x^2(p, \pi^+, \pi^-)$-distribution



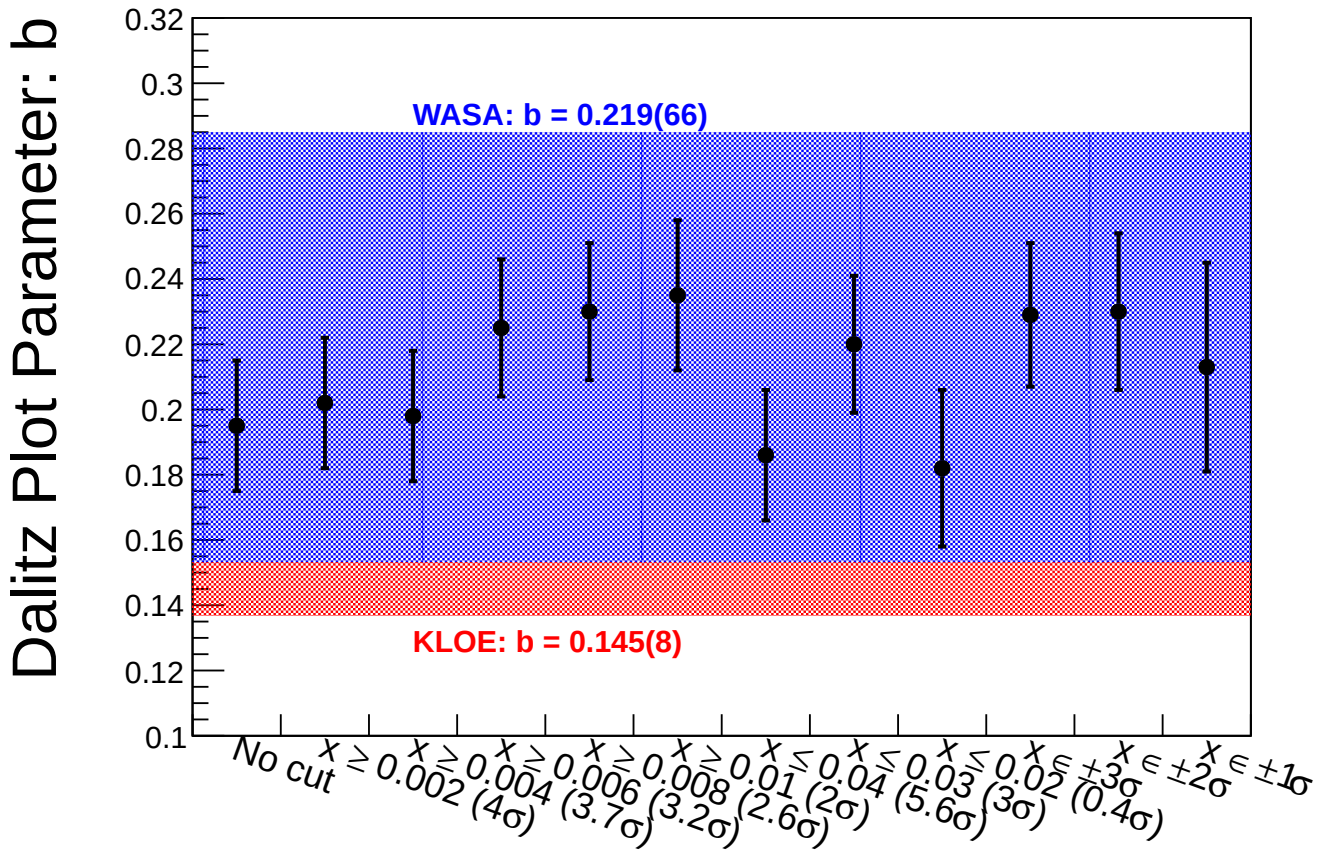
- Background corrected $M_x^2(p, \pi^+, \pi^-)$-distribution for data (black points)
- Yellow area: Sum of corresponding MC distributions
- Next step: Perform different sets of cuts on $M_x^2(p, \pi^+, \pi^-)$ $\leftrightarrow$ How does this effect the DP parameters? $\leftrightarrow$ How sensitive are the DP parameters to (possible) contributions from $\eta \to \pi^+\pi^-\gamma$?

Backup: Cut on $M_x^2(p, \pi^+, \pi^-)$: Parameter a



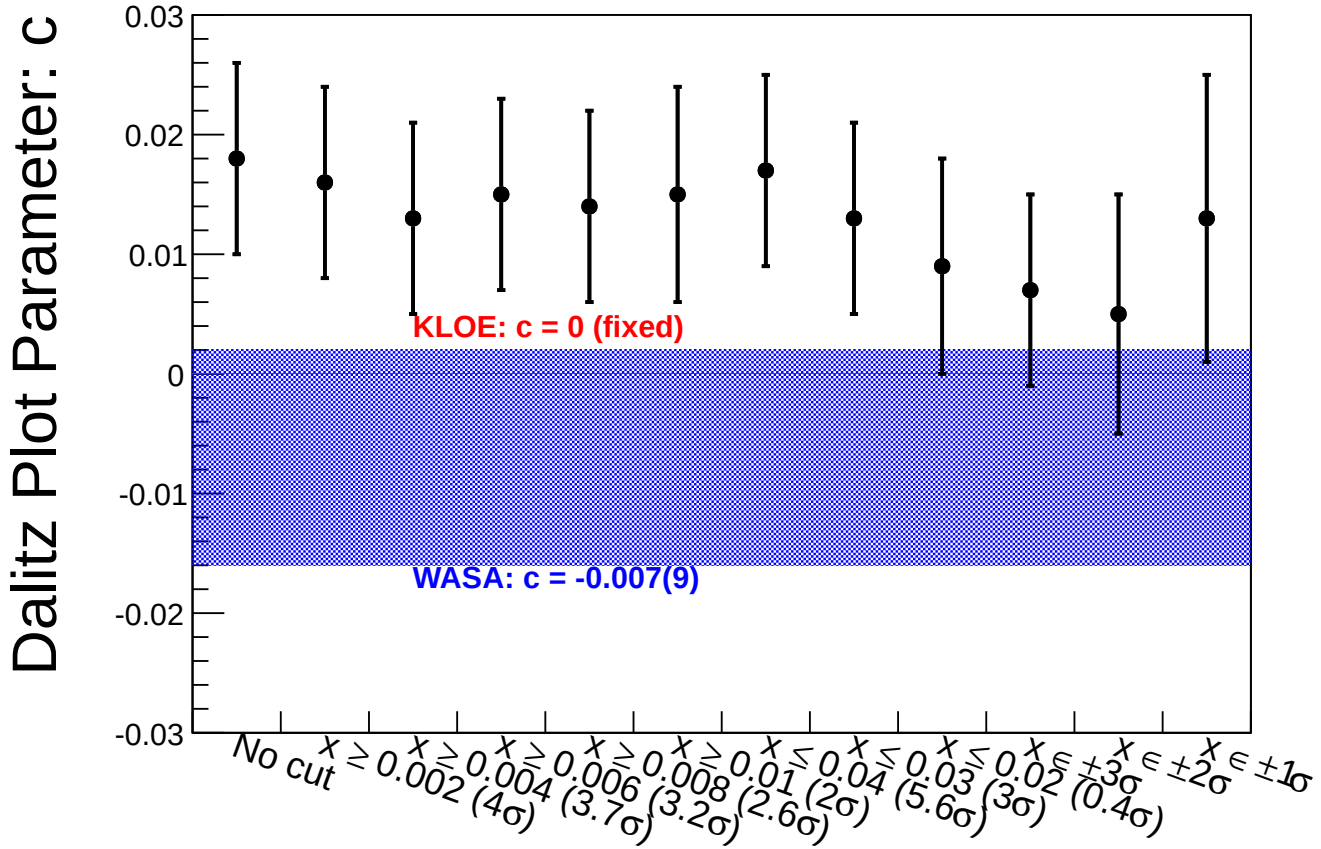
- $x \equiv M_x^2(p, \pi^+, \pi^-)$
- $x \in i\sigma, \;\; i = 1, 2, 3 \equiv 1, 2, 3 \; \sigma$ cut around x
- Unit of X-Axis is GeV^2/c^4

Backup: Cut on $M_x^2(p, \pi^+, \pi^-)$: Parameter b



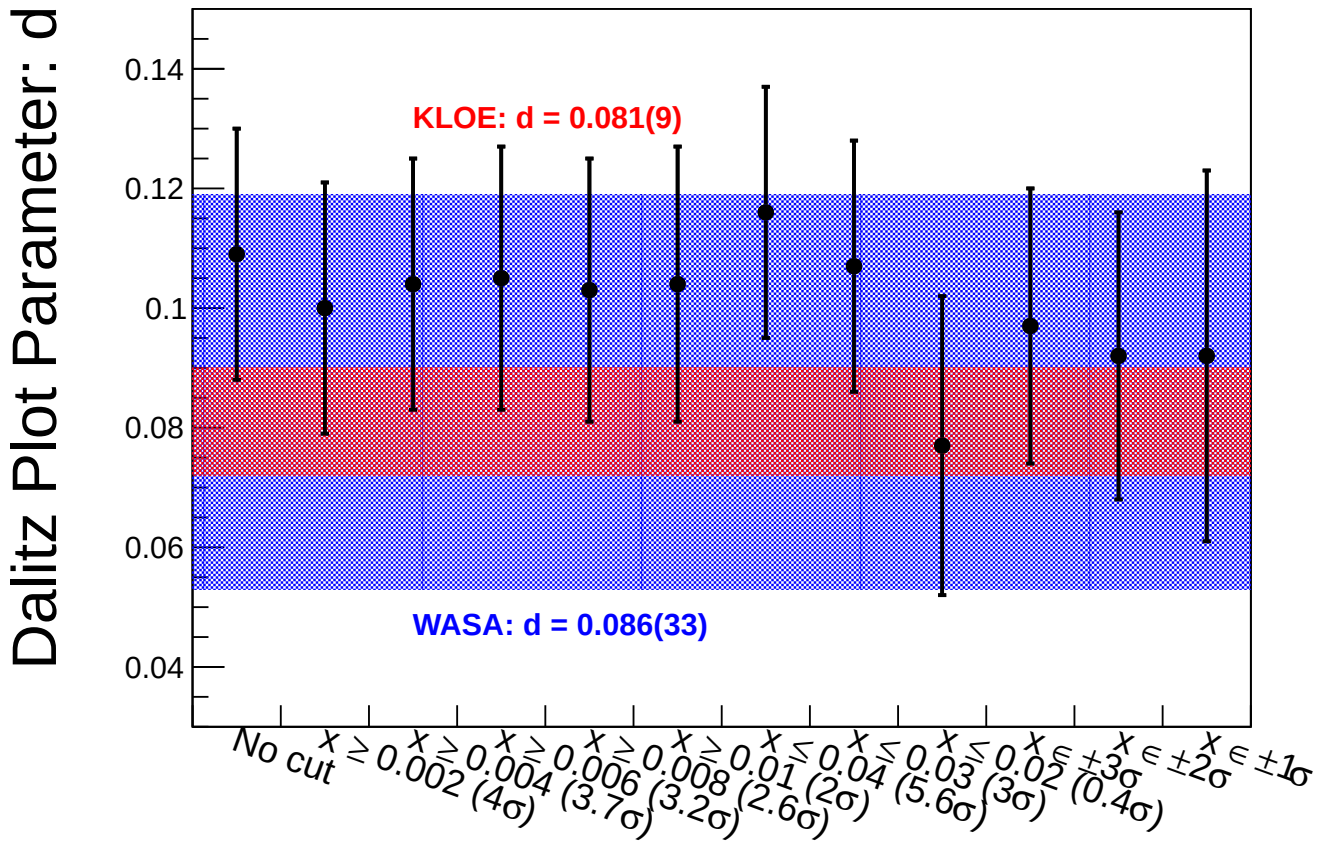
- $x \equiv M_x^2(p, \pi^+, \pi^-)$
- $x \in i\sigma, \;\; i = 1, 2, 3 \equiv 1, 2, 3 \; \sigma$ cut around x
- Unit of X-Axis is GeV^2/c^4

Backup: Cut on $M_x^2(p, \pi^+, \pi^-)$: Parameter c



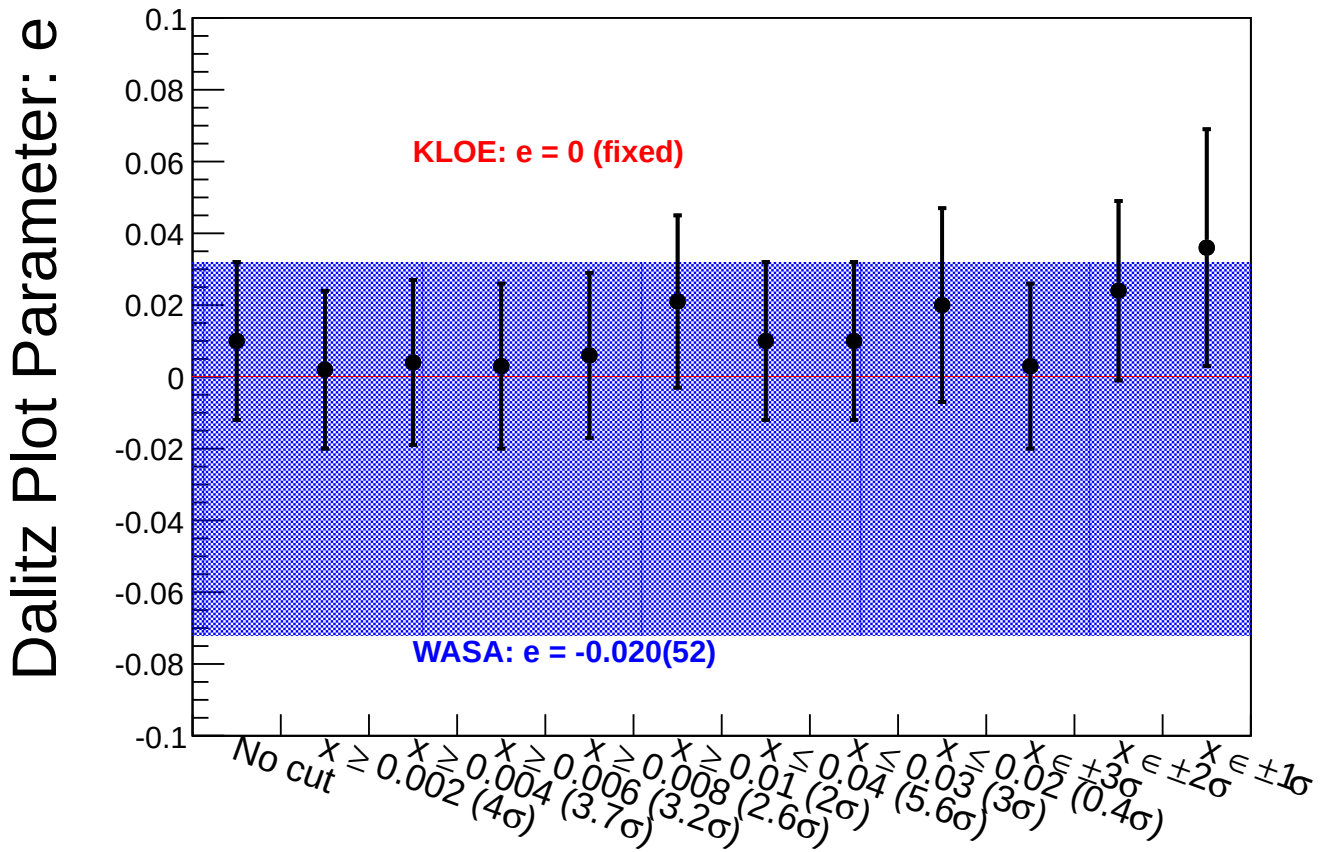
- $x \equiv M_x^2(p, \pi^+, \pi^-)$
- $x \in i\sigma, \;\; i = 1, 2, 3 \equiv 1, 2, 3 \; \sigma$ cut around x
- Unit of X-Axis is GeV^2/c^4

Backup: Cut on $M_x^2(p, \pi^+, \pi^-)$: Parameter d



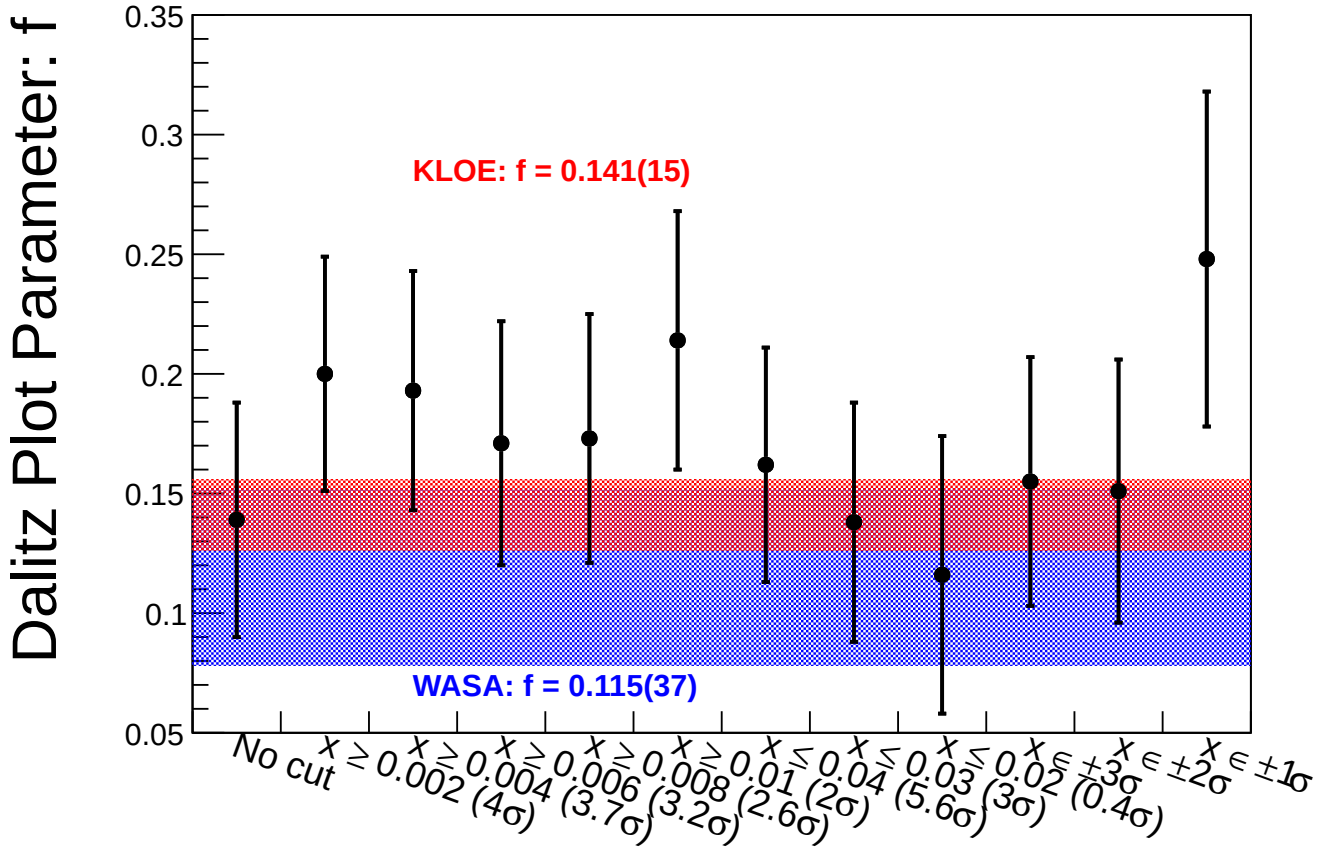
- $x \equiv M_x^2(p, \pi^+, \pi^-)$
- $x \in i\sigma, \;\; i = 1, 2, 3 \equiv 1, 2, 3 \; \sigma$ cut around x
- Unit of X-Axis is GeV^2/c^4

Backup: Cut on $M_x^2(p, \pi^+, \pi^-)$: Parameter e



- $x \equiv M_x^2(p, \pi^+, \pi^-)$
- $x \in i\sigma, \;\; i = 1, 2, 3 \equiv 1, 2, 3 \; \sigma$ cut around x
- Unit of X-Axis is GeV^2/c^4

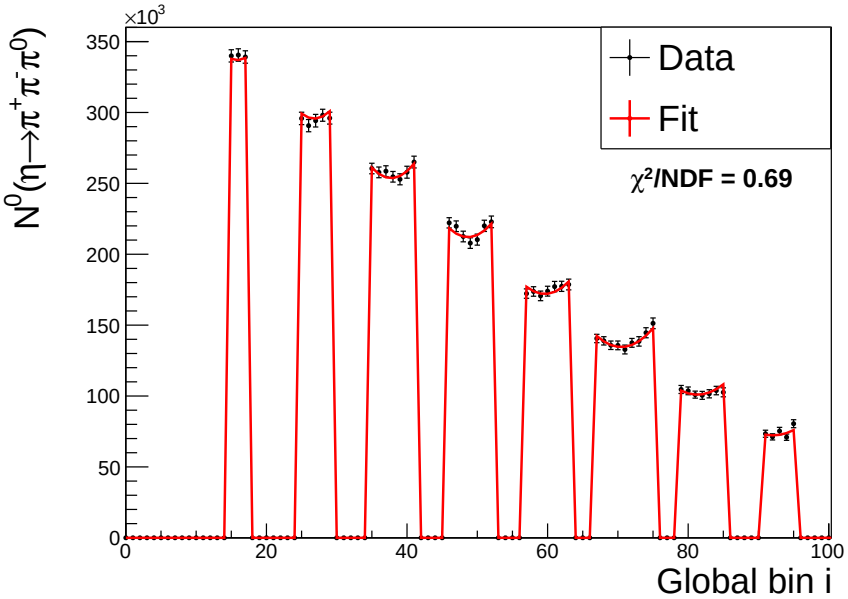
Backup: Cut on $M_x^2(p, \pi^+, \pi^-)$: Parameter f

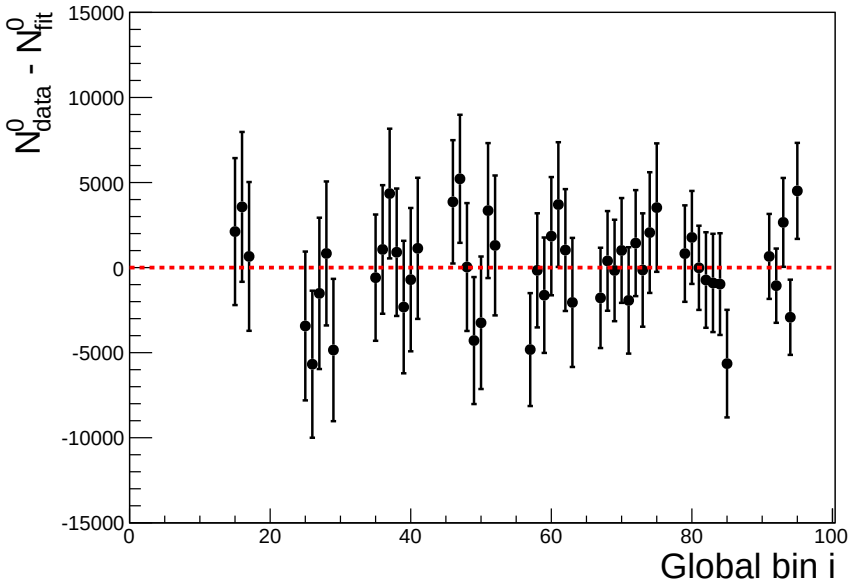


- $x \equiv M_x^2(p, \pi^+, \pi^-)$
- $x \in i\sigma, \;\; i = 1, 2, 3 \equiv 1, 2, 3 \; \sigma$ cut around x
- Unit of X-Axis is GeV^2/c^4

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

All parameters left free

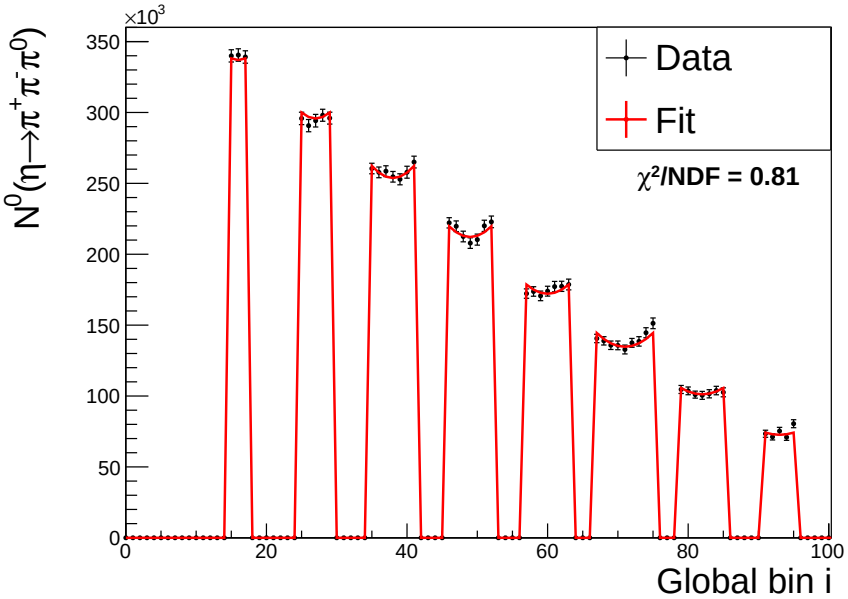


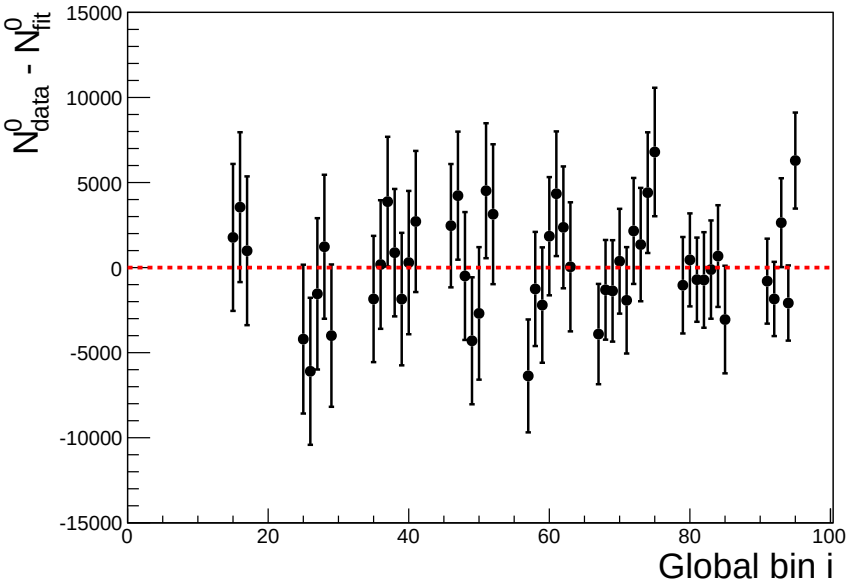


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- c and e are free

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

Fixing c and e

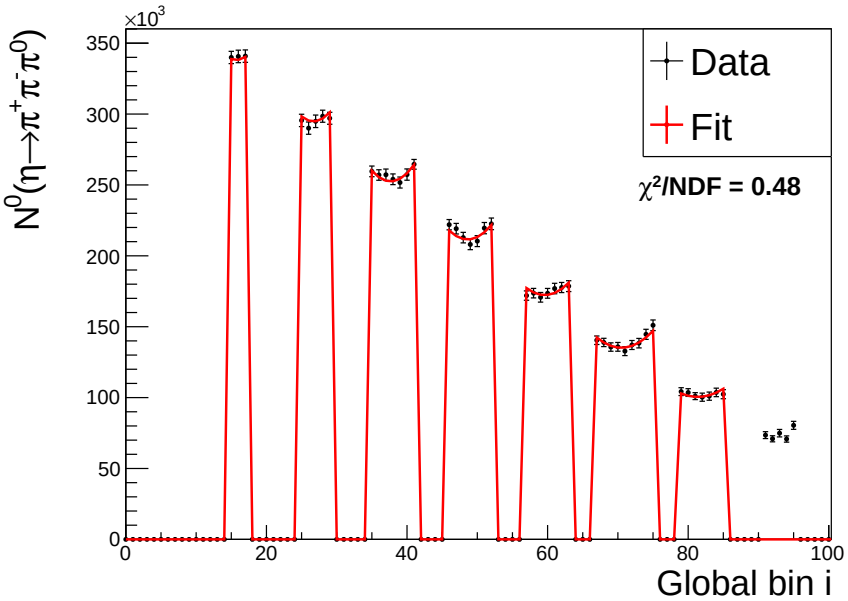


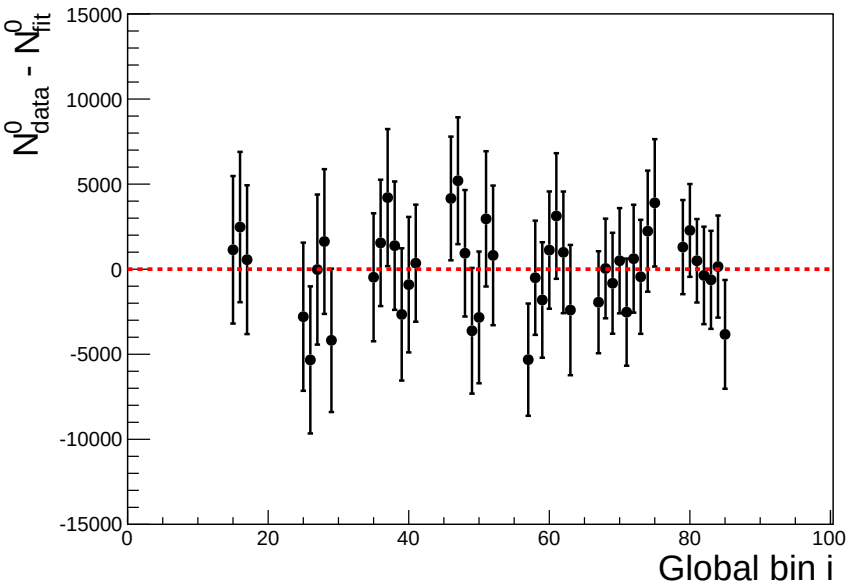


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- Fix: $c = e = 0$

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

Excluding global bins > 90

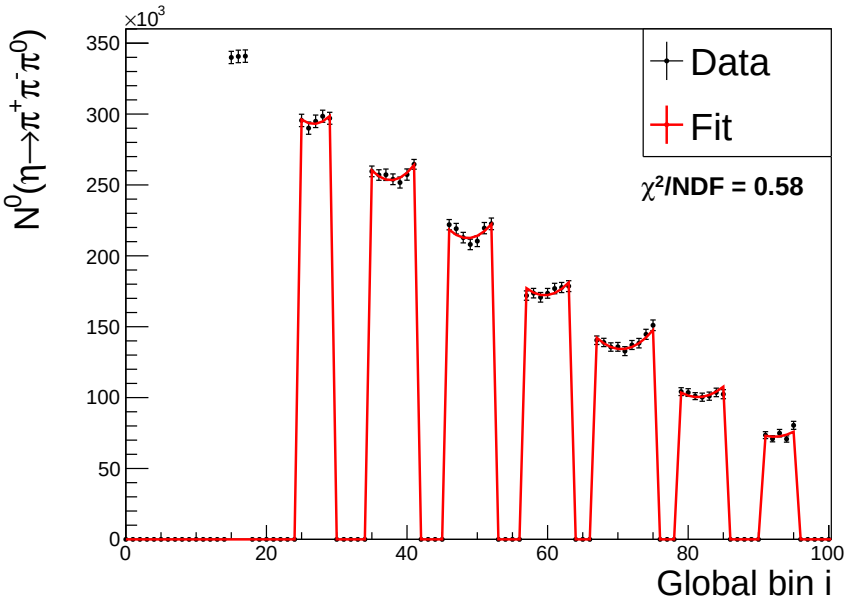


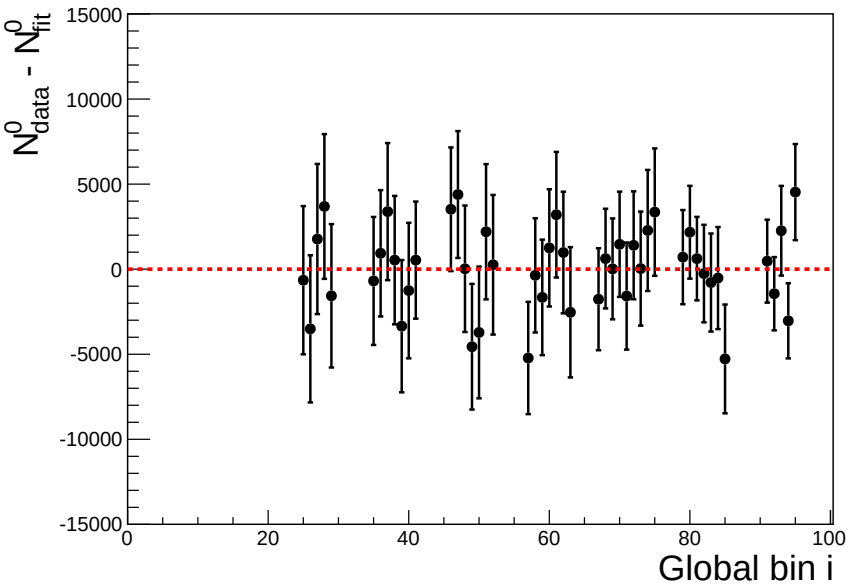


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- All parameters are left as free

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

Excluding global bins < 20

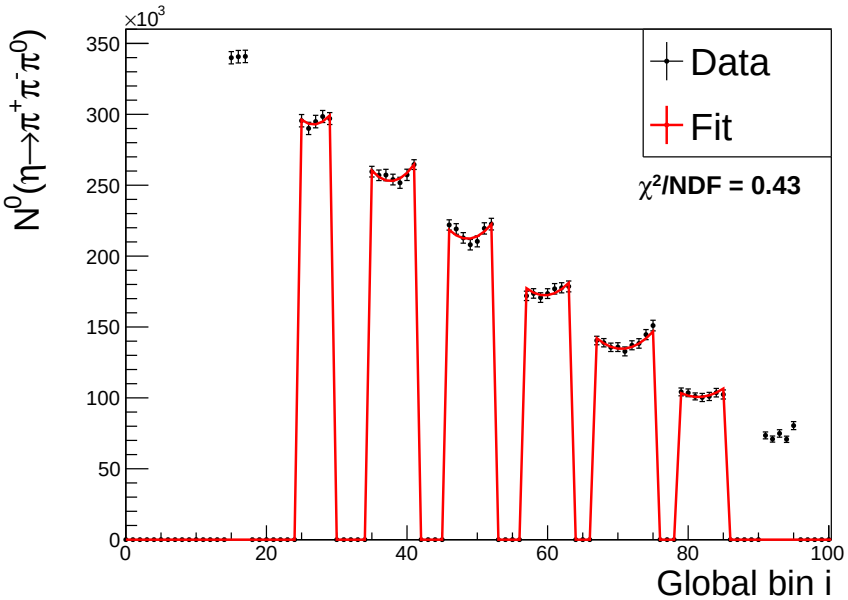


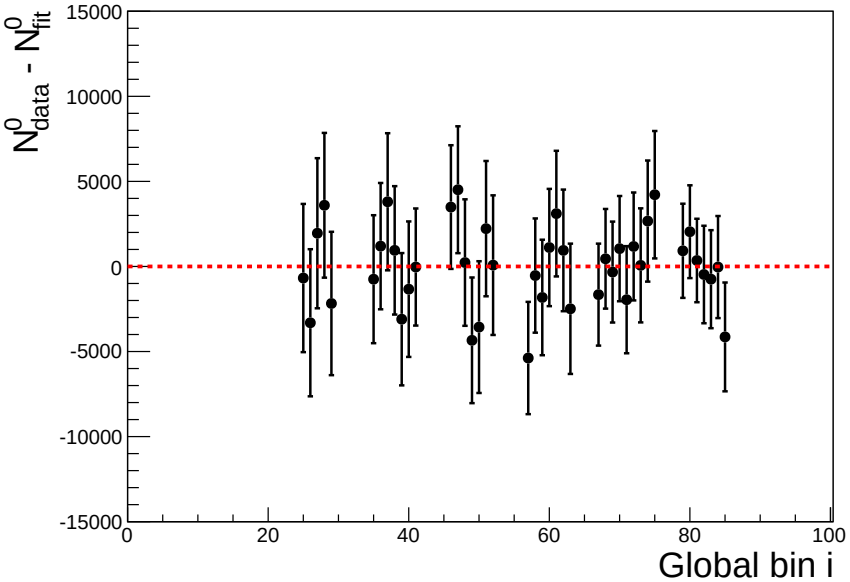


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- All parameters are left as free

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

Excluding global bins < 20 and > 90

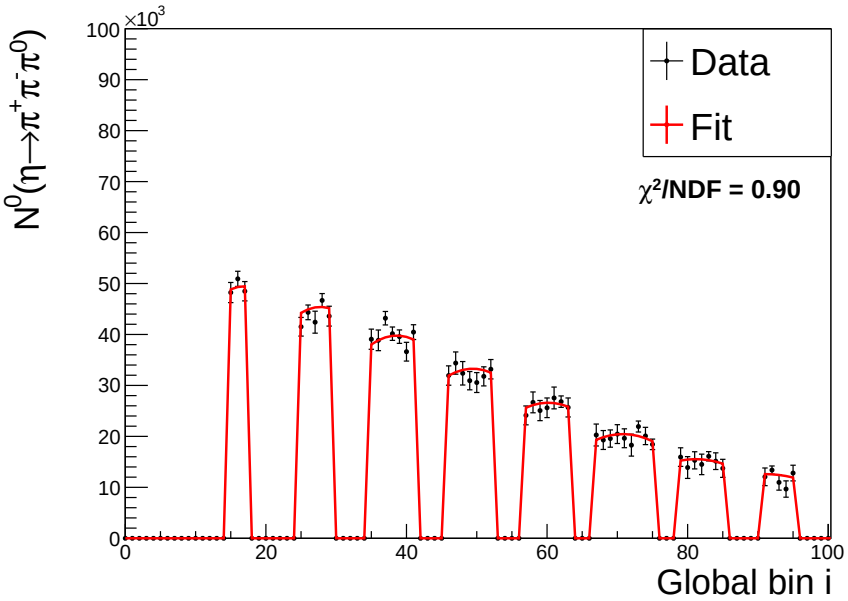


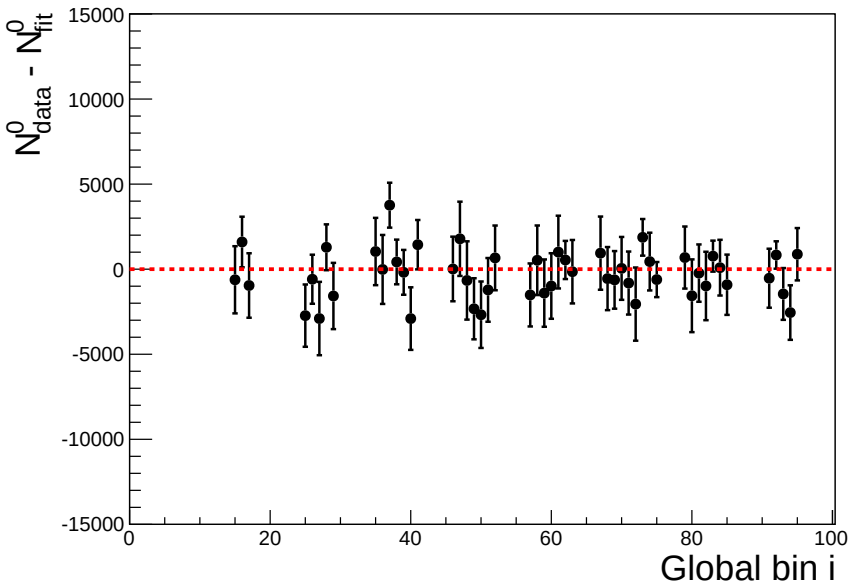


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- All parameters are left as free
- Next test: Select a certain $E_{\gamma,beam}$-range

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

$E_{\gamma,beam} \leq 1.3\,\mathrm{GeV}$

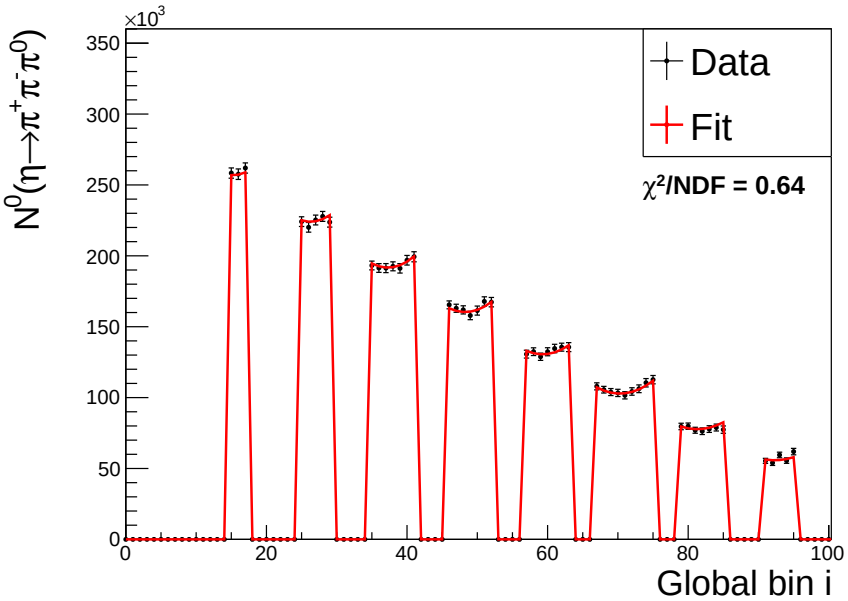


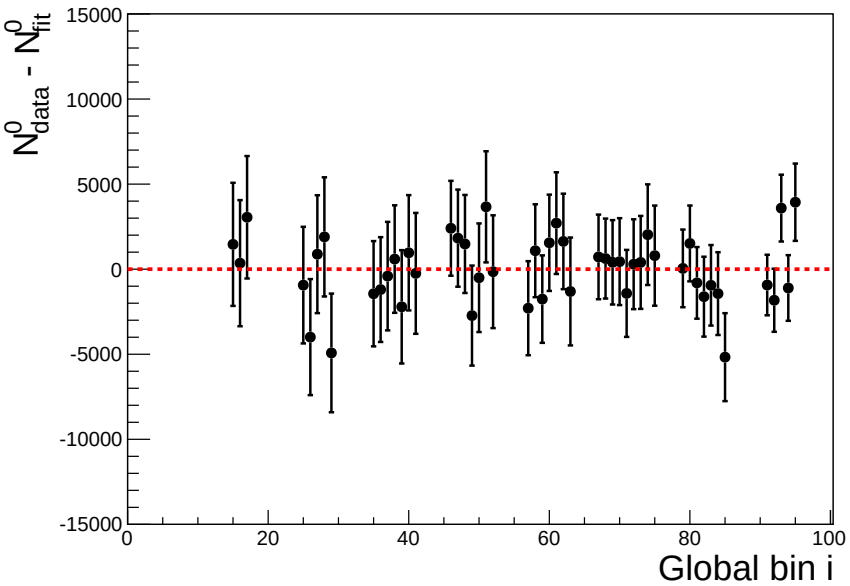


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- All parameters are left as free

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

$E_{\gamma,beam} > 1.3\,\mathrm{GeV}$

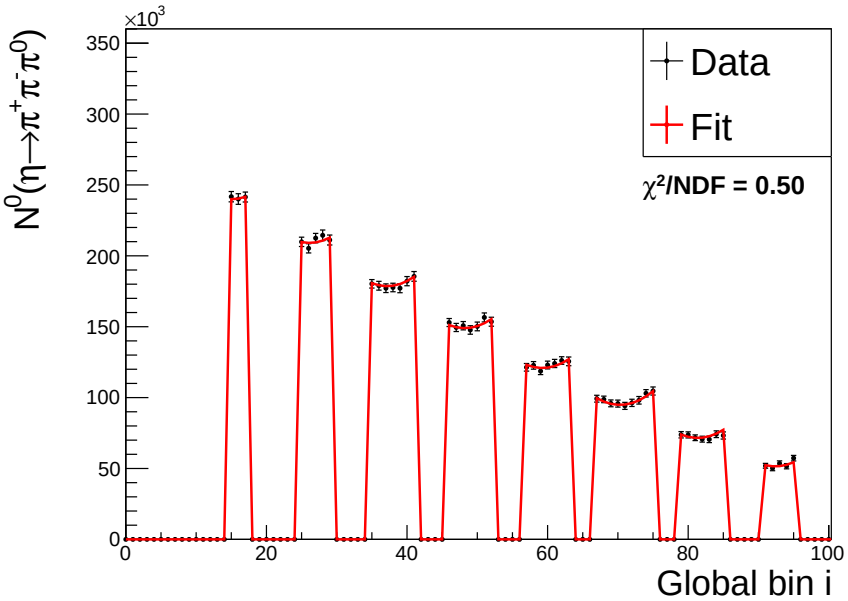


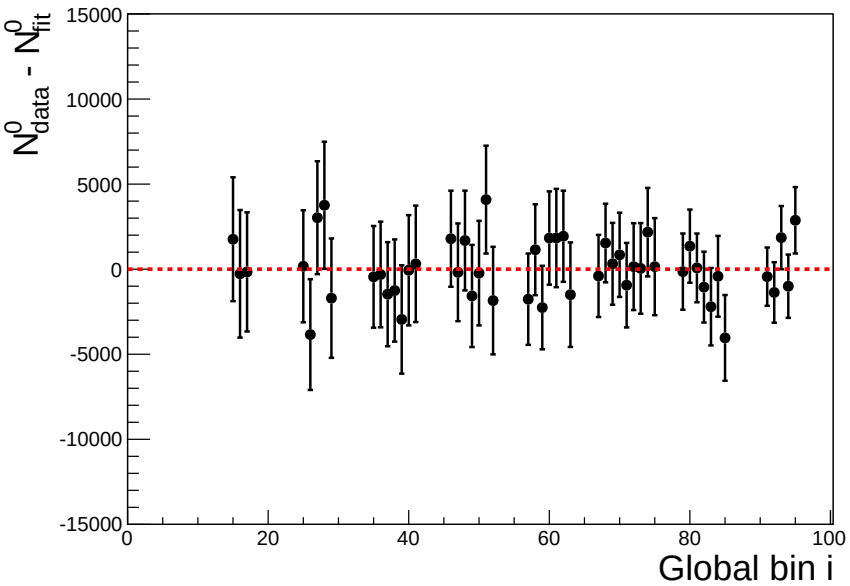


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- All parameters are left as free

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

$E_{\gamma,beam} > 1.3\,\mathrm{GeV}$ & $E_{\gamma,beam} < 3.6\,\mathrm{GeV}$

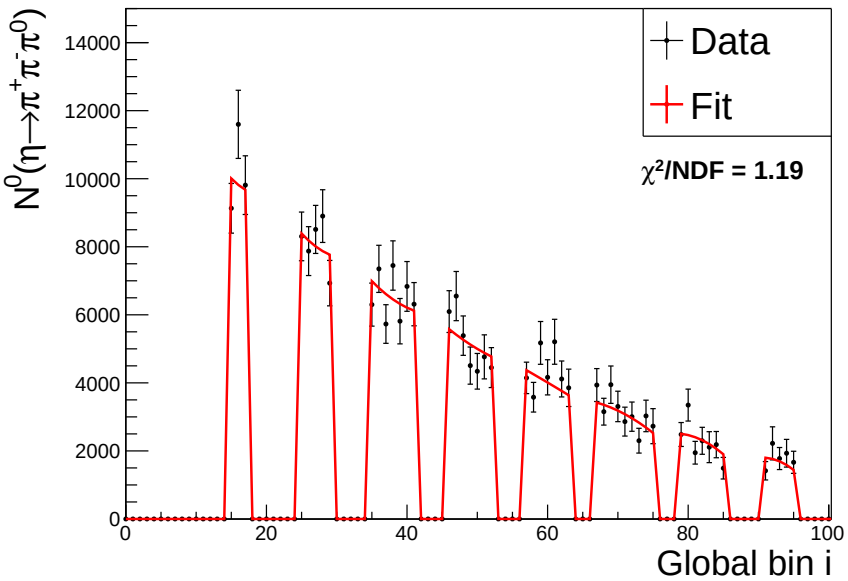


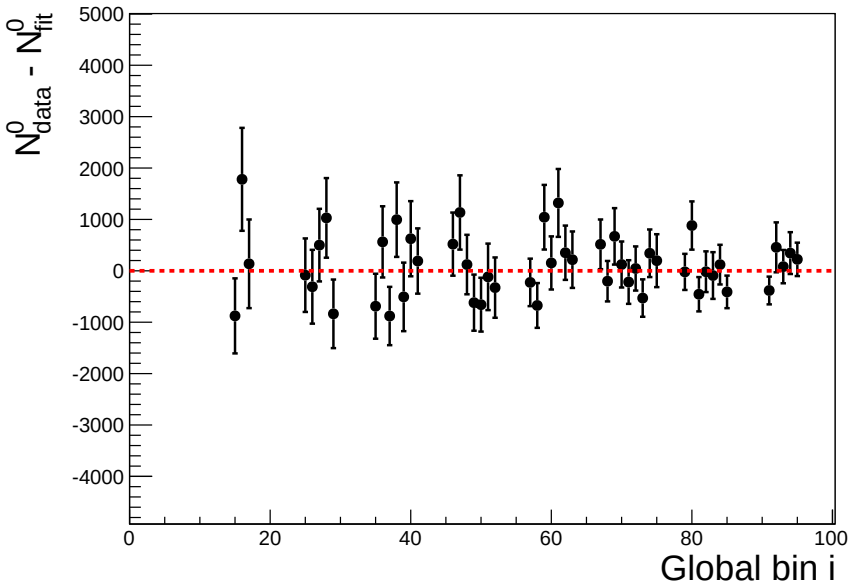


- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + ...)$
- All parameters are left as free

Backup: Fitting the $N^0(\eta \to \pi^+\pi^-\pi^0)$-Distribution

$E_{\gamma,beam} \geq 3.6\,\mathrm{GeV}$





- Fit function: $N^0_{fit} = N \times (aY + bY^2 + cX + dX^2 + eXY^2 + \ldots)$
- All parameters are left as free