# Experimental overview of $\eta \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot

Li Caldeira Balkeståhl
on behalf of KLOE-2 Collaboration
on behalf of WASA-at-COSY

Department of Physics and Astronomy
Uppsala University

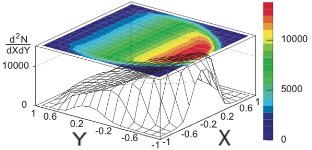
2014-09-29
MesonNet Meeting

# Dalitz plot variables

In the $\eta$-rest frame:

$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta} = \frac{\sqrt{3}}{2m_\eta Q_\eta}(u - t)$$

$$Y = \frac{3T_{\pi^0}}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta}\left[(m_\eta - m_{\pi^0})^2 - s\right] - 1$$




$$Q_\eta = T_{\pi^+} + T_{\pi^-} + T_{\pi^0} = m_\eta - 2m_{\pi^+} - m_{\pi^0}$$

$T_{\pi^+}, T_{\pi^-}$, $T_{\pi^0}$ kinetic energies of the $\pi^+$, $\pi^-$, $\pi^0$

$s$, $u$, $t$ are the Mandelstam variables.

# Dalitz plot parameters

Fit the data to

$$N = \int |A(X,Y)|^2 dPh(X,Y)$$

$$|A(X,Y)|^2 \simeq N(1+aY+bY^2+cX+dX^2+eXY+fY^3+gX^2Y+hXY^2+lX^3+\ldots)$$

$c$, $e$, $h$ and $l$ must be zero because of C-invariance

Better way of comparing data and theory?

- Acceptance corrected data binned in $X$ and $Y$

# Experimental and theoretical status

| **Experiment** | -a | b | d | f | g |
|---|---|---|---|---|---|
| Gormley (70) | 1.17(2) | 0.21(3) | 0.06(4) | - | - |
| Layter *et al* (73) | 1.080(14) | 0.034(27) | 0.05(3) | - | - |
| CBarrel (98) | 1.22(7) | 0.22(11) | 0.06(fixed) | - | - |
| KLOE (08) | $1.090(5)(^{+19}_{-8})$ | 0.124(6)(10) | $0.057(6)(^{+7}_{-16})$ | 0.14(1)(2) | - |

| **Calculations** | -a | b | d | f | g |
|---|---|---|---|---|---|
| $\chi$PT LO[1] | 1.039 | 0.27 | 0 | 0 | - |
| $\chi$PT NLO[1] | 1.371 | 0.452 | 0.053 | 0.027 | - |
| $\chi$PT NNLO[1] | 1.271(75) | 0.394(102) | 0.055(57) | 0.025 (160) | - |
| dispersive[2] | 1.16 | 0.26 | 0.10 | - | - |
| simplified disp[3] | 1.21 | 0.33 | 0.04 | - | - |
| NREFT[4] | 1.213(14) | 0.308(23) | 0.050(3) | 0.083(19) | -0.039(2) |
| BSE[5] | 1.054(25) | 0.185(15) | 0.079(26) | 0.064(12) | - |

KLOE (08) $1.337 \pm 0.001$ Mevts in Dalitz plot

M. Gormley *et al.*, *Phys. Rev.* **D2**, 501 (1970)
J. Layter *et al.*, *Phys. Rev.* **D7**, 2565 (1973)
A. Abele *et al.* (Crystal Barrel Collaboration),*Phys. Lett.* **B417**, 197 (1998)
F. Ambrosino *et al.* (The KLOE collaboration), *JHEP*, **Vol 5**, 006, (2008)

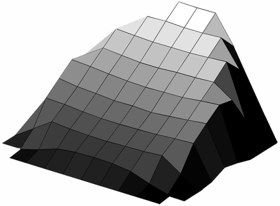
[1] J. Bijnens and K. Ghorbani, *JHEP*, **0711**, 030, (2007)
[2] J. Kambor, C. Wiesendanger and D. Wyler, *Nucl. Phys*, **B465**, 215 (1996)
[3] J. Bijnens and J. Gasser, *Phys. Scripta*, **T99**, 34 (2002)
[4] S. P. Schneider, B. Kubis and C. Ditsche, *JHEP*, **1102**, 028 (2011)
[5] B. Borasoy and R. Nißler, *Eur. Phys. J.*, **A26**, 383 (2005)

# Motivation for new measurements

More high statistics results needed

With WASA-at-COSY

- Independent measurement
- Different detector, different $\eta$ production mechanism
- Different systematic errors

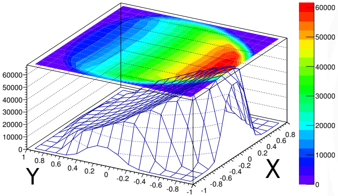


# Motivation for new measurements

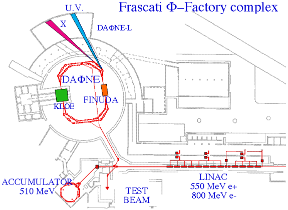
More high statistics results needed

With KLOE

- More data ($\sim 1.6\ \mathrm{fb}^{-1}$), independent data set
- Monte Carlo description has been improved
- Reduce systematic errors
  - event classification efficiency from prescaled events without event classification (biggest source of systematic error before)



# Da$\phi$ne and KLOE




DA$\phi$NE

- $e^+e^-$ collider
- $\sqrt{s} = M_\phi$
- $e^+e^- \to \phi \to \eta\gamma$
- separate $e^+e^-$ rings
- crossing angle 25 mrad

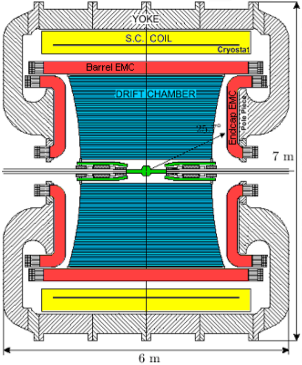
KLOE: DC and EMC in $\sim 0.52$T

Drift Chamber (4 m diameter, 3.75m long)

- $\sigma_{xy} = 150\ \mu$m; $\sigma_z = 2$ mm
- $\frac{\delta p_t}{p_t} < 0.4\%\ (\theta > 45^\circ)$

Electromagnetic Calorimeter

- lead/scintillating fibers
- 98% solid angle coverage
- $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(\mathrm{GeV})}}$
- $\sigma_t = \frac{57\ \mathrm{ps}}{\sqrt{E(\mathrm{GeV})}} \oplus 100$ ps

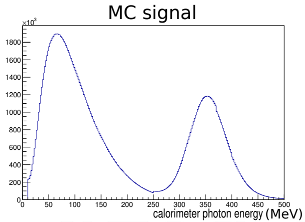


# $\eta \to \pi^+\pi^-\pi^0$ Event Reconstruction

$$e^+e^- \to \phi \to \eta\gamma_\phi$$
$$\eta \to \pi^+\pi^-\pi^0, \quad \pi^0 \to \gamma\gamma$$

final state $\pi^+\pi^-\gamma_\phi\gamma\gamma$

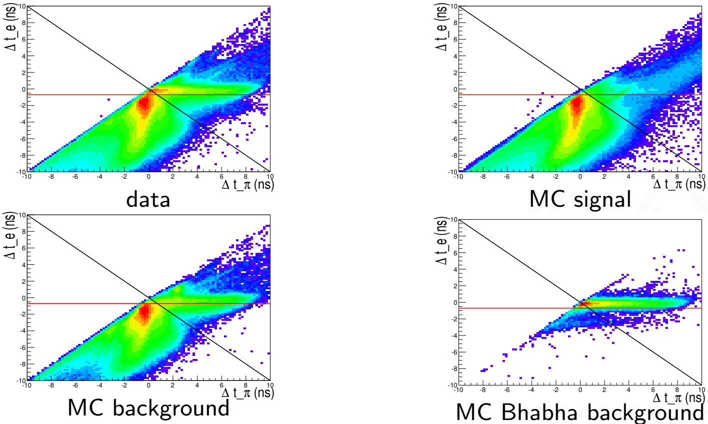
- $\geq$ 3 photons in EMC
- most energetic photon with $E_\gamma > 250$ MeV from $\phi \to \eta\gamma_\phi$
- $E_{\gamma_\phi}$ from 2-body $\phi$ decay kinematics
- Calculate $P_\eta = P_\phi - P_{\gamma_\phi}$
- Calculate $P_{\pi^0} = P_\eta - P_{\pi^+} - P_{\pi^+}$
- Background rejection cuts



# Background rejection

Cuts - Reject Bhabha scattering events:

- angle between tracks and photons
- particle identification with time-of-flight - tracks with calorimeter info: calculate $\Delta t$ between track and cluster for $\pi$ and $e$ hypothesis

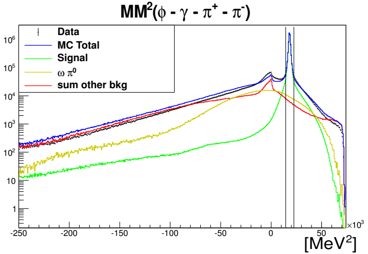


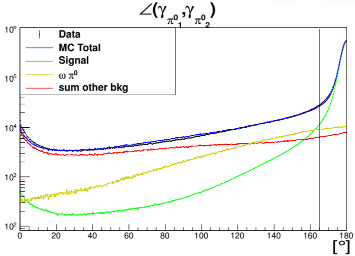
# Data-MC comparison

Cuts

- $|\text{Missing mass}(\phi - \gamma_\phi - \pi^+ - \pi^-) - m_{\pi^0}| < 15$ MeV - plot MM$^2$
- Opening angle between $\pi^0$-decay $\gamma$'s in the $\pi^0$ rest frame ($> 165°$)

Fit of Monte Carlo to data to get scaling factors for background



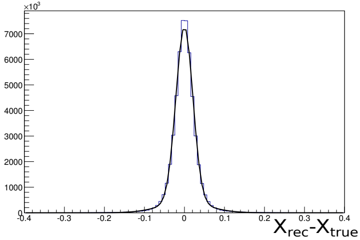



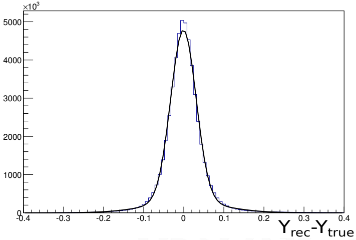

After event reconstruction and cuts for backround suppression:

- Signal efficiency $\epsilon_{sig} = 37.6\%$
- Background contamination 1%

# Dalitz plot variables - resolution

Evaluated with Monte Carlo:
Look at $X_{rec} - X_{gen}$ and $Y_{rec} - Y_{gen}$, fit with 2 gaussians.




Taking the width of the "core" Gaussian as an estimate of the resolution:

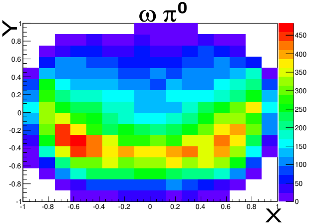
$$\delta X = 0.021 \qquad \delta Y = 0.032$$

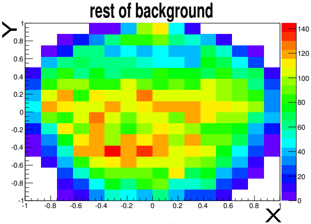
Dalitz plots made with 16 bins, $\Delta X = 0.125 \quad \Delta Y = 0.125$

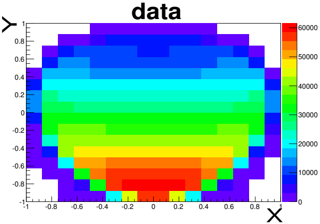
# Background subtraction

Using Monte Carlo and scaling factors

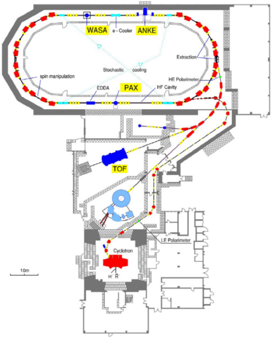
- subtract $\omega\pi^0$ background
- subtract rest of background



# COSY and WASA-at-COSY

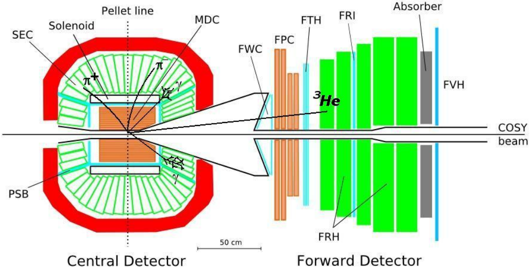



## COSY

- proton and deuteron accelerator
- in Jülich, Germany

## WASA

- Central Detector - measure decay products
- Forward Detector - measure recoil particles
- deuterium or hydrogen pellet target
- $pd \rightarrow {}^3He\eta$ at 1.0 GeV



# $\eta \to \pi^+\pi^-\pi^0$ Event Reconstruction

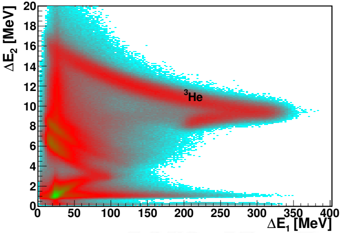
$pd \to {}^3He\eta$

$\quad\quad \hookrightarrow \pi^+\pi^-\pi^0$

$\quad\quad\quad\quad \hookrightarrow \gamma\gamma$

final state ${}^3He\pi^+\pi^-\gamma\gamma$

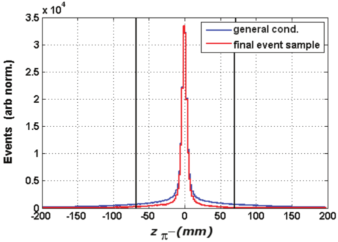
- Identify ${}^3He$ from energy deposit in different forward detector layers
- Background rejection cuts
- Kinematical fit
  - improve resolution
  - reject background
- Calculate $P_{\pi^0} = P_{\gamma,kfit} + P_{\gamma,kfit}$
- Calculate $P_\eta$




P. Adlarson *et al.* (WASA-at-COSY collaboration), arXiv:1406.2505 (2014)

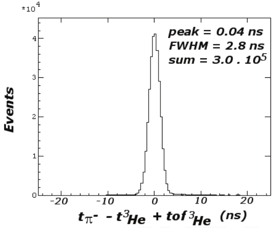
# Background rejection cuts

- Cut around the interaction point

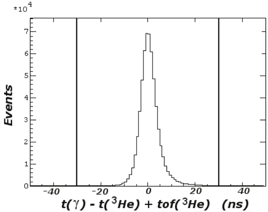



P. Adlarson, PhD thesis Uppsala University 2012

- Charged track timing




- Photon timing

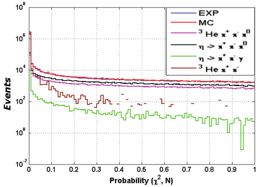


# Kinematic fit

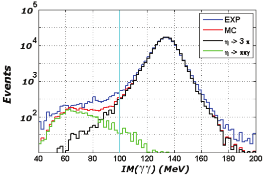
Fit final state $T$, $\theta$, $\phi$ to $pd \rightarrow {}^3He\pi^+\pi^-\gamma\gamma$

- uncertainties from MC as $F(T,\theta)$ ( $F(E,\text{crystal plane})$ for $\gamma$s)

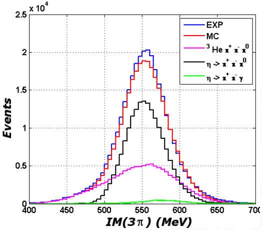
Cut $P(\chi^2) > 0.01$

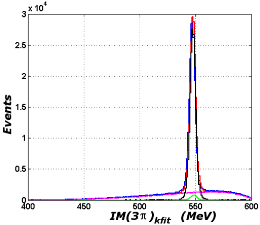



Cut $IM(\gamma\gamma) > 100$ MeV




Improved resolution $IM(3\pi)$

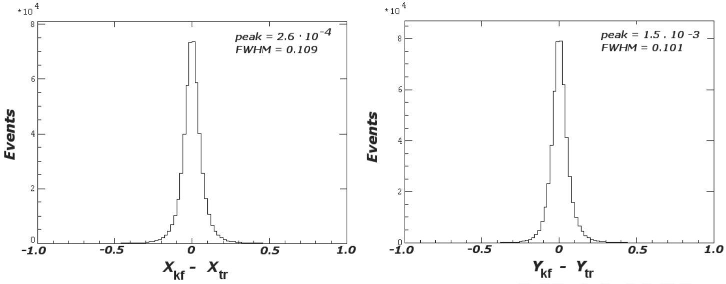



P. Adlarson, PhD thesis Uppsala University 2012

# Dalitz plot variables - resolution

Evaluated with Monte Carlo:
Look at $X_{rec} - X_{gen}$ and $Y_{rec} - Y_{gen}$ FWHM




Taking the FWHM as resolution, $\delta X \sim \delta Y \sim 0.10$

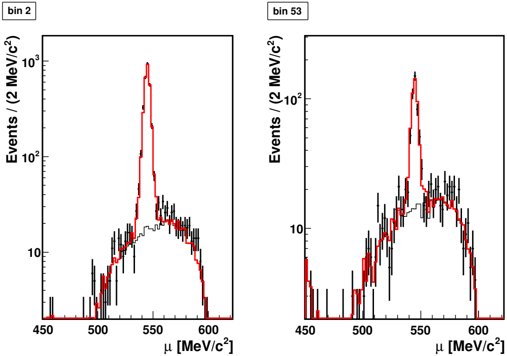
Dalitz plot made with $\Delta X = 0.20 \quad \Delta Y = 0.20$
Limiting factor is statistics

P. Adlarson, PhD thesis Uppsala University 2012

# Background subtraction

For each Dalitz Plot bin, look at $\mu = MM(^3He)$

- simulated $pd \to {}^3He\eta$ (denoted $s(\mu)$) and phase space simulated $pd \to {}^3He\pi^+\pi^-\pi^0$ (denoted $b(\mu)$)
- fit of $N_s s(\mu) + N_b(1+\alpha\mu)b(\mu)$ to data to get $N_s$, $N_b$ and $\alpha$
- subtract simulated $\eta \to \pi^+\pi^-\gamma$




P. Adlarson *et al.* (WASA-at-COSY collaboration), arXiv:1406.2505 (2014)

# Fit procedure

$$N_{theory} = \int N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y)dPh(X,Y)$$

KLOE

$$\chi^2 = \sum_{i=1}^{Nbins} \left( \frac{N_i - \sum_{j=1}^{Nbins} \epsilon_j S_{ij} N_{theory,j}}{\sigma_i} \right)^2$$

with

- $N_i$ background subtracted data
- $\epsilon_j$ efficiency
- $S_{ij}$ smearing matrix
- $\int YdPh(X,Y)$, $\int Y^2dPh(X,Y)$, etc. by MC integration

WASA

$$\chi^2 = \sum_{i=1}^{Nbins} \left( \frac{\frac{N_i}{\epsilon_i} - N_{theory,i}}{\sigma_i} \right)^2$$

with

- $N_i$ background subtracted data
- $\epsilon_i$ efficiency
- $\int NaYdPh(X,Y) \simeq NaY_i^C \Delta Y \Delta X$, $\int NcXdPh(X,Y) \simeq NcX_i^C \Delta Y \Delta X$, etc

# Preliminary results

$$N_{theory} = \int N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y)dPh(X, Y)$$

$c$ and $e$ consistent with zero

| **Experiment** | $-a$ | $b$ | $d$ | $f$ |
|---|---|---|---|---|
| KLOE 08 | $1.090(5)(^{+8}_{-19})$ | 0.124(6)(10) | $0.057(6)(^{+7}_{-16})$ | 0.14(1)(2) |
| WASA prel. | 1.144(18) | 0.219(19)(37) | 0.086(18)(18) | 0.115(37) |
| KLOE prel. | 1.104(3) | 0.144(3) | 0.073(3) | 0.155(6) |

New KLOE analysis only statistical errors!

New KLOE: Sensitive to $g$ parameter, but still investigating

F. Ambrosino *et al.* (The KLOE collaboration), *JHEP*, **Vol 5**, page 006, (2008)
P. Adlarson *et al.* (WASA-at-COSY collaboration), arXiv:1406.2505 (2014)

# Summary

- Two independent high statistics measurements of $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot

KLOE

- Full systematic checks to be done

WASA

- Systematic checks (magnetic field, beam accelerator mode, background fitting)
- Acceptance corrected data provided
- Final paper coming soon (arXiv:1406.2505)
- Larger statistics available