# $3\pi$ decays of light vector mesons

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MesonNet Meeting
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# Presentation outline

**Introduction**

Why study $V \to \pi^+\pi^-\pi^0$

**Dalitz plot studies**

$\omega \to \pi^+\pi^-\pi^0$

- WASA
- KLOE
- CLAS

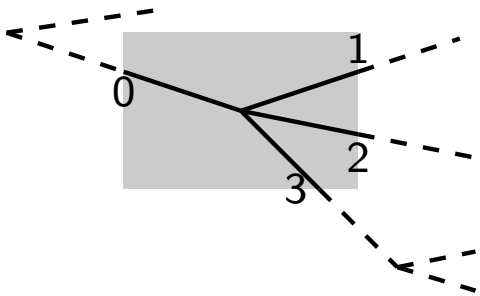
$\phi \to \pi^+\pi^-\pi^0$

- KLOE
- CMD-2

**Experiment $\longleftrightarrow$ Theory**

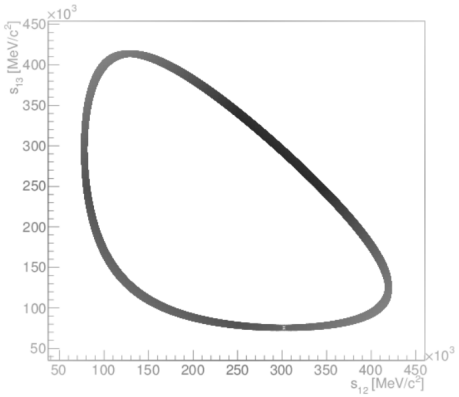
# Dalitz plot

3-body decay



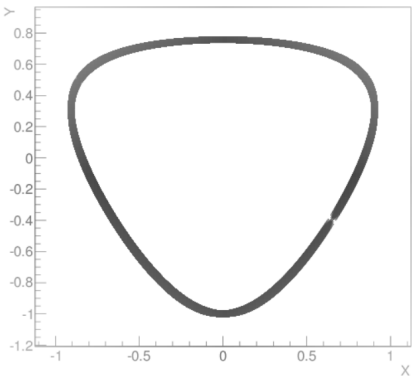

$\mathcal{M}$ given by two independent variables

$\rightarrow$ 2D representation, e.g. $\mathcal{M}(s_{12}, s_{23})$



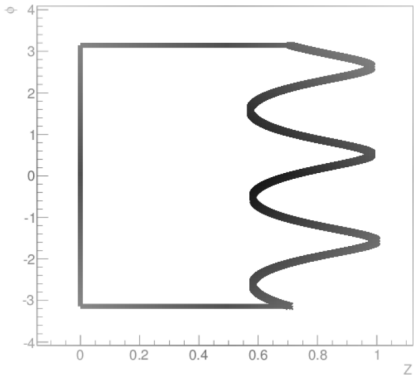

$$s_{ij} = (P_i + P_j)^2$$

Common choice of variables when $m_1 = m_2$




$$X = \sqrt{3}\frac{T_1^* - T_2^*}{Q}$$

$$Y = \frac{(2m_1 + m_3)\,T_3^*}{(m_1 Q)} - 1$$




$$Z = X^2 + Y^2$$

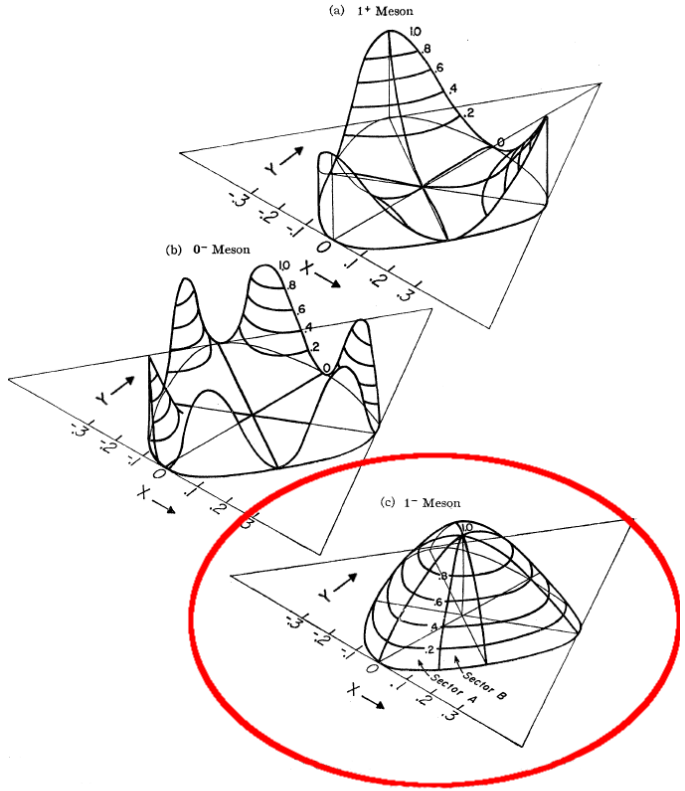
$$\Phi = \tan^{-1}\frac{X}{Y}$$

# Predicted decay dynamic of $\phi/\omega$

$I(J^P)$ conservation

I=0: Any $\pi\pi$ state must be antisymmetric
$\bar{p}_i \times \bar{p}_j = 0 \rightarrow \mathcal{M} = 0$

$J^P=1^-$: $\mathcal{M} \propto \bar{p}_1 \times \bar{p}_2 + \bar{p}_2 \times \bar{p}_3 + \bar{p}_3 \times \bar{p}_1$
$\sum_{ij} \bar{p}_i \times \bar{p}_j = 0 \rightarrow \mathcal{M} = 0$




*Phys.Rev 125, (1962) 687*

# Predicted decay dynamic of $\phi/\omega$

## I($J^P$) conservation

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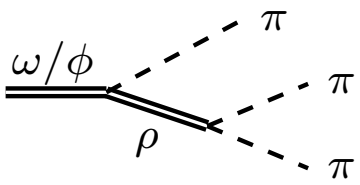
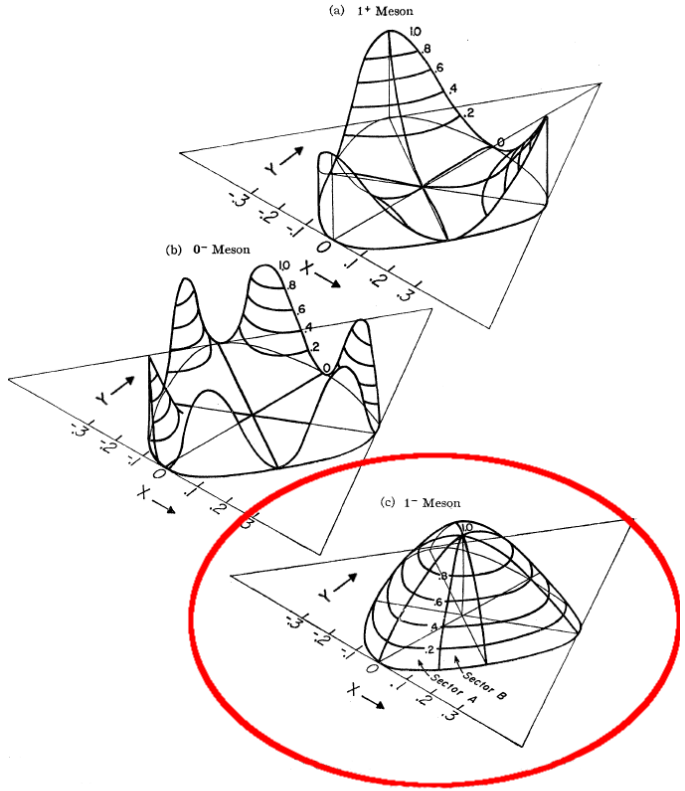
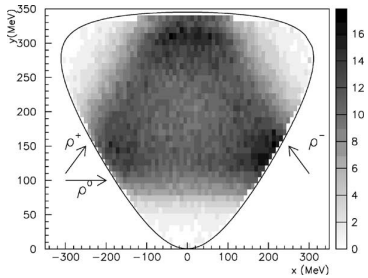



## Intermediate $\rho$



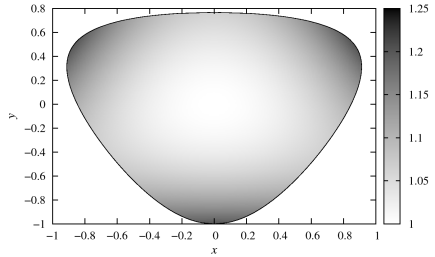

*Phys.Rev 125, (1962) 687*

$\phi$ : $\pi - \pi$ system includes full $\rho$ resonance
*Experimentally established*



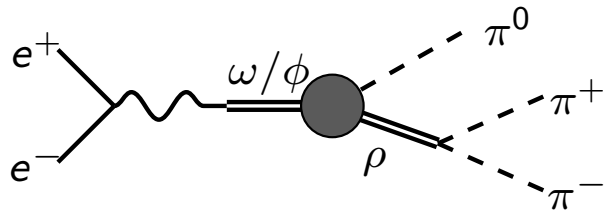

*KLOE data*

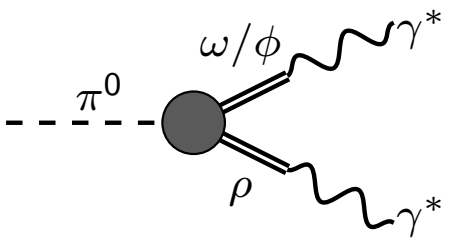
$\omega$ : Onset towards edges of phase space
*Not yet experimentally shown*



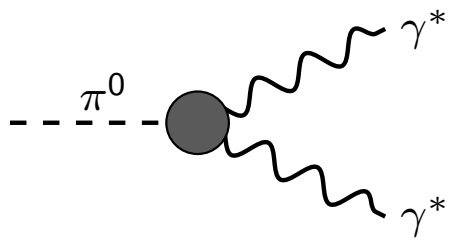

*Prediction by dispersion calculation*

# Dalitz plot distributions as a benchmark for meson transition form factors




a part of

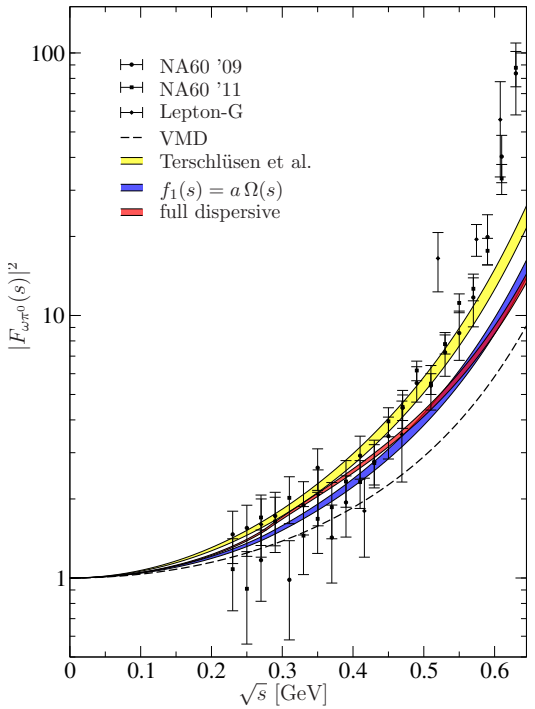



- Probe of hadron structure
- Contribution to HLbL

Meson transition form factors by

1. Dispersion calculation
2. Lagrangian calculation

E.g. $F_{\omega\pi^0}(s)$




*PoS CD12 (2013) 054*

... so why look at $V \to 3\pi$ Dalitz plot?

# Dalitz plot distributions as a benchmark for meson transition form factors

1. Dispersion calculation[1]
2. Lagrangian calculation[2]

full prediction of $\frac{d^2\Gamma_{V\to 3pi}}{ds_{12}\,ds_{23}}$ - to be tested by experimental distribution

$\underline{\phi \to \pi^+\pi^-\pi^0 \text{ Dalitz plot:}}$

Available experimental results used as test by 1

$\underline{\omega \to \pi^+\pi^-\pi^0 \text{ Dalitz plot:}}$

Predictions and parametrisation made by 1 and 2

$F(Z,\Phi) \propto \mathcal{P}\cdot\left\{1 + 2\boldsymbol{\alpha} Z + 2\boldsymbol{\beta} Z^{3/2}\sin 3\Phi + 2\boldsymbol{\gamma} Z^2 + \mathcal{O}(Z^{5/2})\right\}$

$\mathcal{P}$ - p-wave phase space factor

$\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$,... - Dalitz plot parameters.

[1] S.P. Schneider, B. Kubis, F. Niecknig, Eur.Phys.J.C72:2014,2012

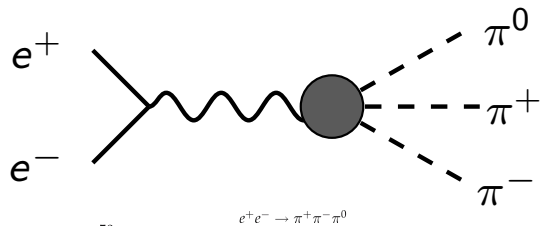
[2] C. Terschlüsen, B. Strandberg, S. Leupold, F. Eichstädt Eur.Phys.J. A49 (2013) 116

# Dalitz plot distributions as a benchmark for meson transition form factors

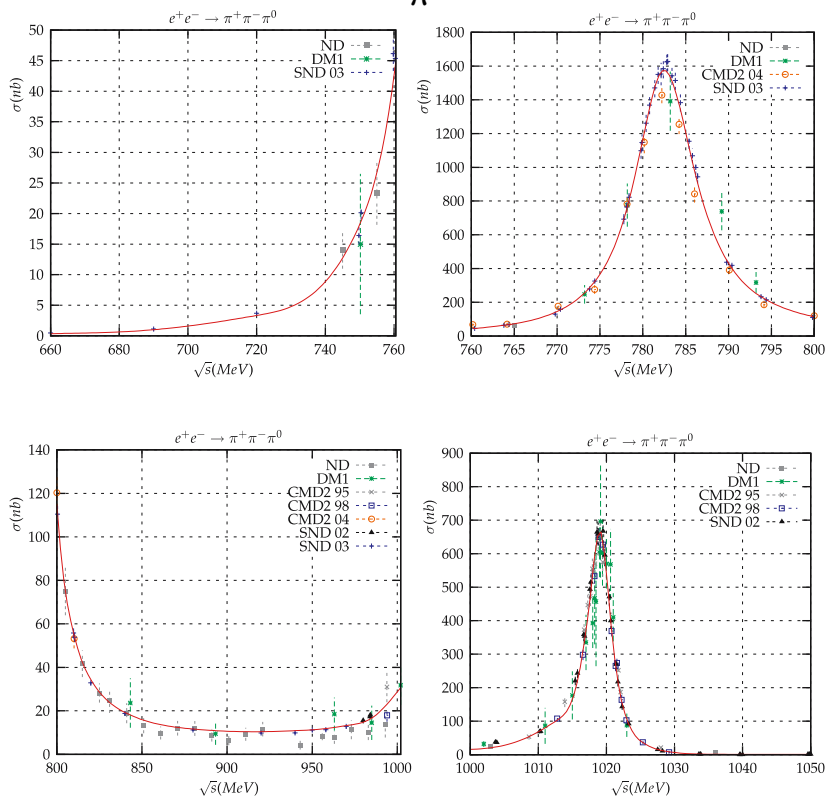
1. Dispersion calculation[1]

Possible extension to

2. Lagrangian calculation[2]




Large $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ data set
from CMD-2, SND, CMD, DM1, DM2 and BaBar




Predictions of $\frac{d^2\Gamma_{V\to 3pi}}{ds_{12}\,ds_{23}}$ from

1. (any $\sqrt{s}$) and 2. ($\sqrt{s}$ <1 GeV)

*Eur.Phys.J. C 47, (2006) 617-624*

[1] S.P. Schneider, B. Kubis, F. Niecknig, Eur.Phys.J.C72:2014,2012

[2] C. Terschlüsen, B. Strandberg, S. Leupold, F. Eichstädt Eur.Phys.J. A49 (2013) 116

# $V \to \pi^+\pi^-\pi^0$ - Ongoing and available experimental studies

$\omega \to \pi^+\pi^-\pi^0$

- WASA
- KLOE
- CLAS

$\phi \to \pi^+\pi^-\pi^0$

- KLOE ✓
- CMD-2✓

# $\omega \to \pi^+\pi^-\pi^0$ - WASA[3]

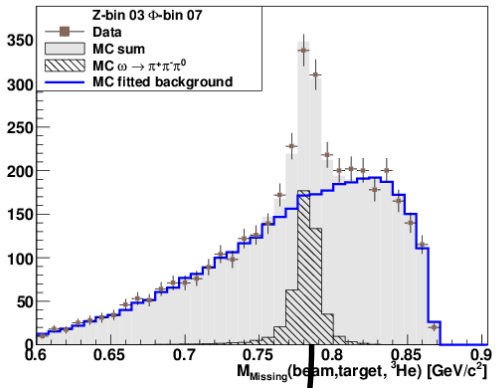
$$p_{beam} + d_{target} \to {}^3He + \omega$$
$$T_{beam} = 1.45,\ 1.5 \text{ GeV}$$

**Data analysis**

Full reconstruction of ${}^3He,\ \pi^+,\ \pi^-,\ 2\gamma$

Selection cuts to reduce
${}^3He\ \pi^+\pi^-\pi^0$ ${}^3He\ \pi^+\pi^-$ ${}^3He\ \omega(\to \pi^+\pi^-)$

Constrained fit of $P_{initial} = P_{final}$



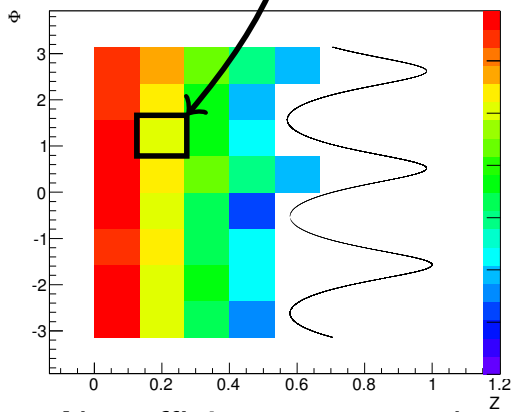

**Dalitz plot analysis**

27 370(380) events in Dalitz plot

Binwise background subtraction

Expected results:

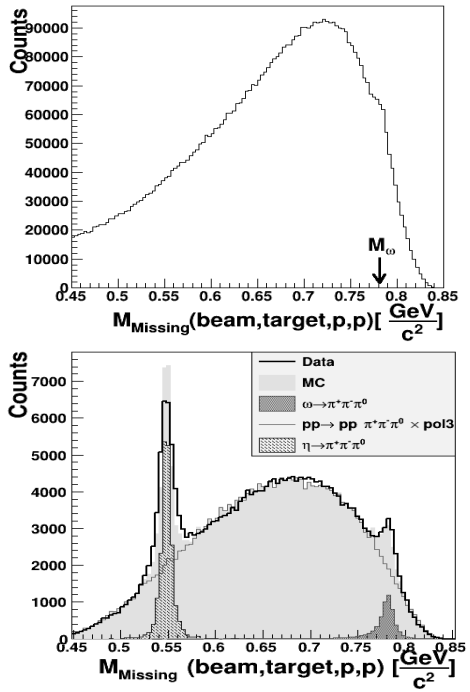
- Efficiency corrected Dalitz plot
- Fitted Dalitz plot parameters $\alpha,\ \beta,\ \gamma, \ldots$




*Not efficiency corrected*

[3] L. Heijkenskjöld, Meson2014, Proceeding in preparation

# $\omega \to \pi^+\pi^-\pi^0$ - WASA[4]




$$p_{beam} + p_{target} \to p + p + \omega$$

$T_{beam} = 2.06$ GeV (also collected $T_{beam} = 2.56$ GeV)

## Data analysis

Full reconstruction of $p,\ p,\ \pi^+,\ \pi^-,\ 2\gamma$

Selection cuts - still large multipion background

Constrained fit on $P_{initial} = P_{final}$ and $P_{\pi^0} = P_\gamma + P_\gamma$

## Dalitz plot analysis

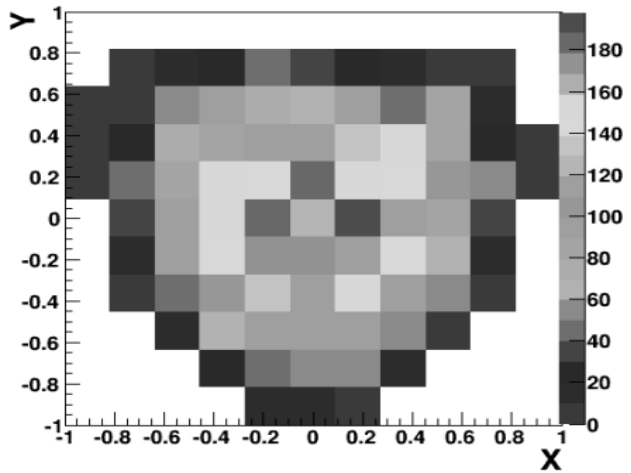
$\sim 5600$ events in $\omega$ peak

Binwise background subtraction

Expected results:

- Efficiency corrected Dalitz plot
- Fitted Dalitz plot parameters $\alpha,\ \beta,\ \gamma, \ldots$

Will analyse second data set as well for more statistics.

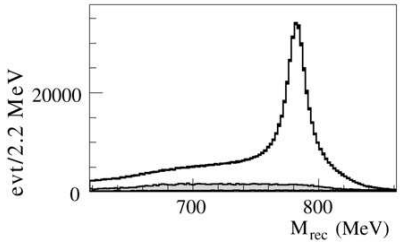



*Not efficiency corrected*

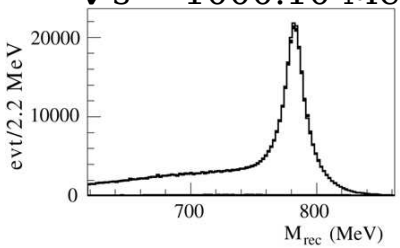
[4] S. Sawant, International Symposium on Nuclear Physics 58, (2013) 644

# $\omega \to \pi^+\pi^-\pi^0$ - KLOE

✓s = 1019.75 MeV




✓s = 1000.10 MeV




$$e^+_{beam} + e^-_{beam} \to \omega + \pi^0$$
$$\sqrt{s} = 1000 - 1030 \text{ MeV}$$

**Data analysis**[5]

Full reconstruction of $\pi^+$, $\pi^-$, $4\gamma$.

Constrained fit on $P_{initial} = P_{final}$ and $T_\gamma - R_\gamma/c = 0$

Background contamination

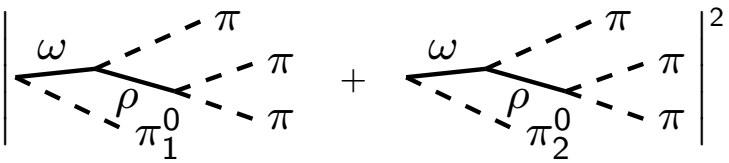
$\Phi$ decays, max $\sim$12% $\qquad$ $a_1(1260)\pi$, $\sim$ 4%

Fit $M_{\pi^0 recoil}$

$\longrightarrow$ $1.3 \times 10^6$ $\omega \to \pi^+\pi^-\pi^0$ events

**$\pi^0 - \pi^0$ interference affecting the Dalitz plot**[6]

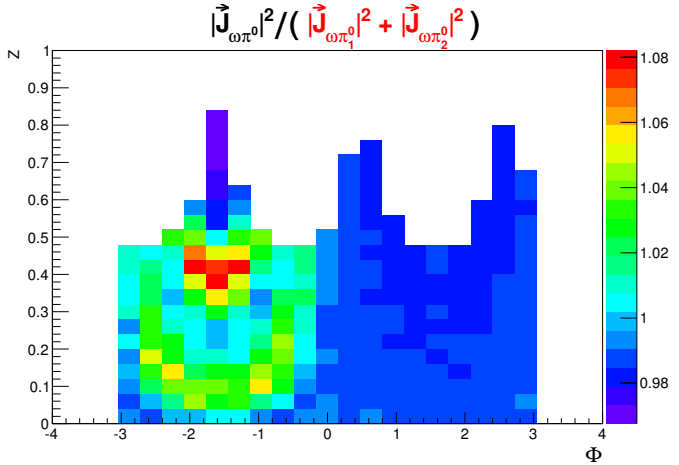
$$\left|\mathbf{J}_{\omega\pi^0}\right|^2 = \left|\mathbf{J}_{\omega\pi^0_1} + \mathbf{J}_{\omega\pi^0_2}\right|^2 =$$




Compare $|\mathbf{J}_{\omega\pi^0}|^2$ to $|\mathbf{J}_{\omega\pi^0_1}|^2 + |\mathbf{J}_{\omega\pi^0_2}|^2$ $\longrightarrow$ $\sim$ 10% effect

Work-around:

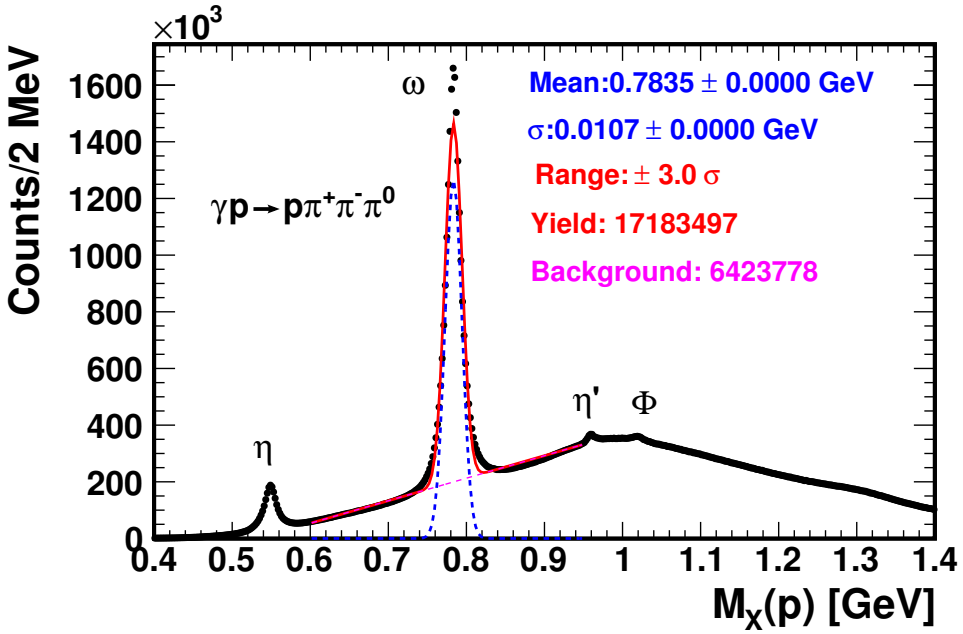
- Only use minimally disturbed part
- Use $e^+e^- \to \omega\gamma_{ISR}$ production channel




[5] Phys.Let. B 669 (2008) 223-228

[6] L. Heijkenskjöld, W. Ikegami Andersson, poster session

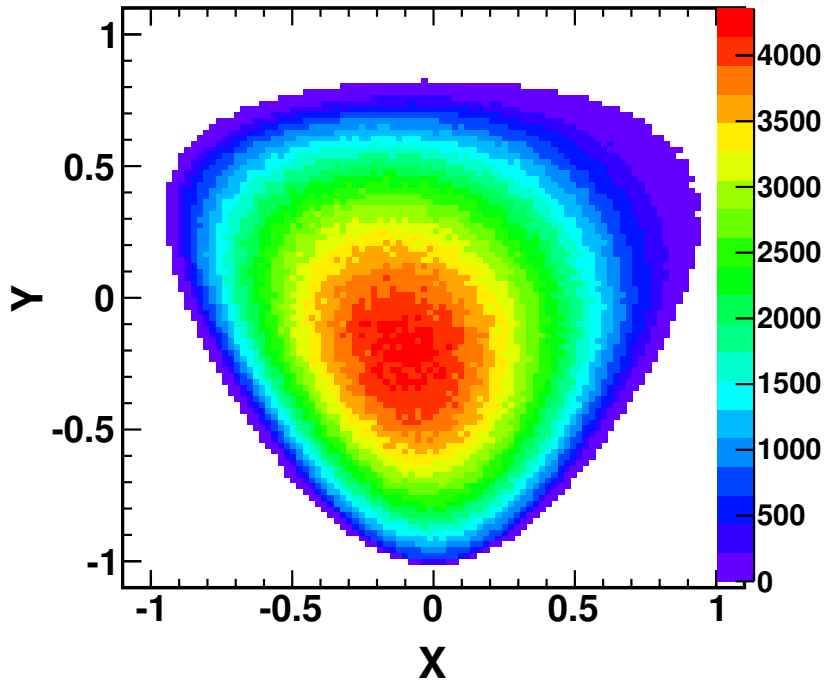
# $\omega \to \pi^+\pi^-\pi^0$ - CLAS[7]




$\sim 17 \times 10^6$ events in peak

$\sim \times 2$ including second data set

$$\gamma_{beam} + p_{target} \to p + \pi^+ + \pi^- + \pi^0$$

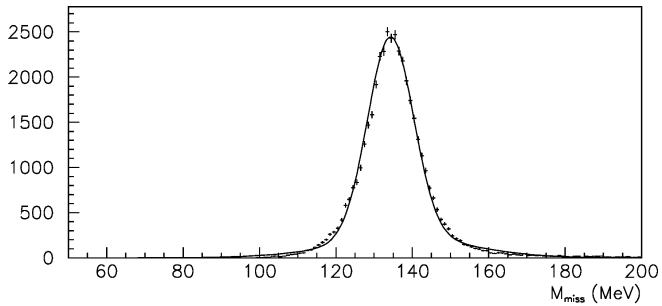



*Not acceptance corrected*

[7] M. Amaryan, MesonNet 2013

# $\Phi \to \pi^+\pi^-\pi^0$ - KLOE[8]

$$e^+_{beam} + e^-_{beam} \to \Phi$$
$$\sqrt{s} =\sim 1019 \text{ MeV}$$




## Data analysis

Full reconstruction of $\pi^+$, $\pi^-$, $\gamma$, $\gamma$

Large $\sigma_\phi \times BR(\phi \to 3\pi)$ & signal selection cuts $\longrightarrow$ very low background $\sim 0.01\%$

$\sim 2 \times 10^6$ events

## Dalitz plot analysis

$X = E^*_+ - E^*_-$ $\quad$ $Y = E^*_\phi - E^*_+ - E^*_- - m_{\pi^0}$

1874 bins, $8.75 \times 8.75$ MeV ($\sigma_{X,Y} \sim 1$ MeV)

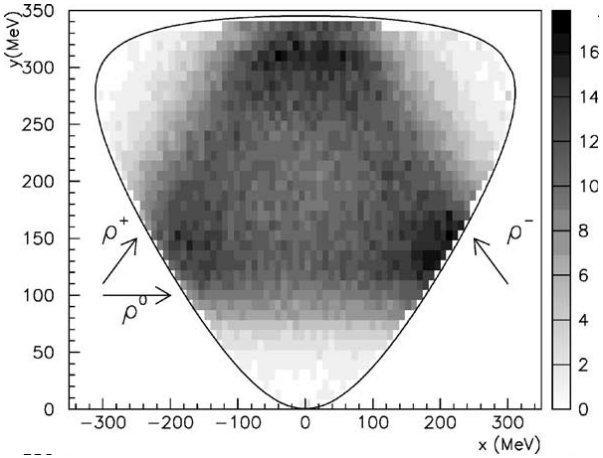
Bin content calculated with:
$D(X, Y) \propto |\bar{p}^*_+ \times \bar{p}^*_-| \times |A_{\rho\pi} + A_{dir} + A_{\omega\pi}|^2$

Fit to efficiency corrected data yield:

| | $\rho^0$ | $\rho^\pm$ |
|---|---|---|
| $m_\rho$(MeV) | 775.9(0.5)(0.5)* | 775.5(0.5)(0.4)* |
| $\Gamma_\rho(MeV)$ | 147.3(1.5)(0.7)* | 143.7(1.3)(1.2) |

* PDG

- Moduli and phase of $A_{dir}$ and $A_{\omega\pi}$




Experimental plot (eff corr) divided by $|\bar{p}^*_+ \times \bar{p}^*_-|$

[8] Phys. Let. B 561 (2003) 55-60

# $\Phi \to \pi^+\pi^-\pi^0$ - CMD-2

$$e^+_{beam} + e^-_{beam} \to \Phi$$
$$\sqrt{s} = 1017 - 1021 \text{ MeV}$$

## Data analysis

Full reconstruction of $\pi^+$, $\pi^-$, $\gamma$, $\gamma$

Background $\sim$1%

Constrained fit of $P_{initial} = P_{final}$

$\longrightarrow \sim 8 \times 10^4$

## Dalitz plot analysis

$X = \frac{E^*_- - E^*_+}{\sqrt{3}}$ $\qquad$ $Y = \sqrt{s} - E^*_- - E^*_+ - m_{\pi^0}$

198 bins, $20 \times 20$MeV

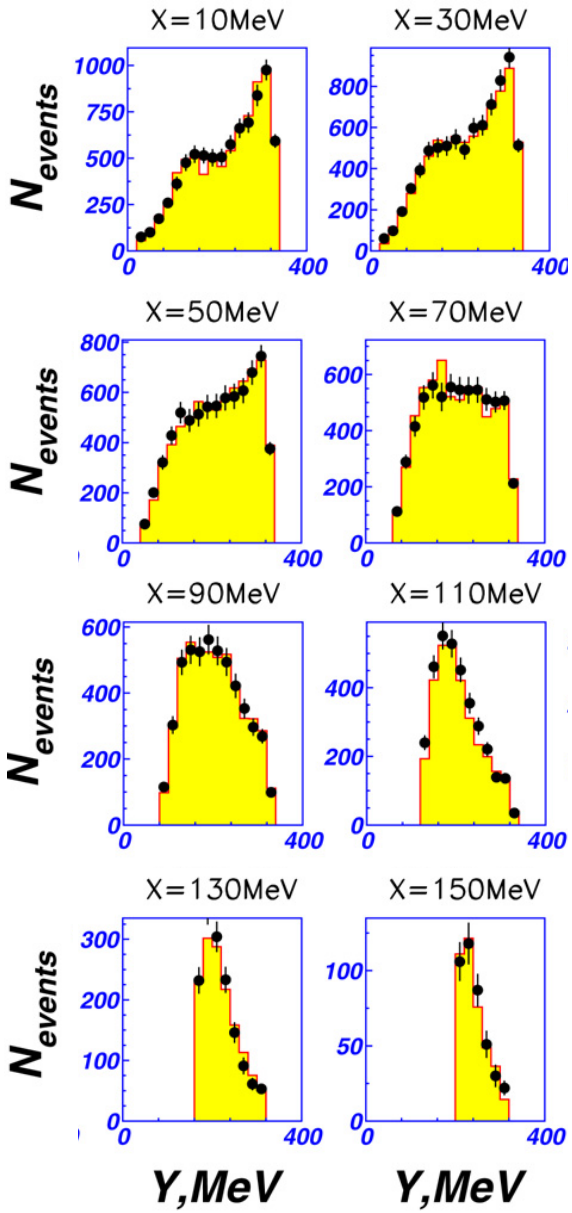
Bin content calculated with:

$N_i^{calc} = \epsilon_{ik} N_o \int_k dXdY |\bar{p}^*_+ \times \bar{p}^*_-|^2 |A_n a e^{i\varphi} + A_{\rho\pi}|$

$\epsilon_{ik}$ - binwise detection efficiency and transition probability.

Result from fit:

- $a$ - in agreement with KLOE.
- $\varphi$ - slightly higher than KLOE



# Experiment ↔ Theory

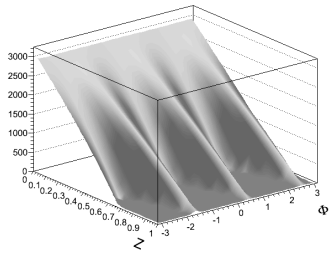
**Two examples**

## Parametrisation of $\omega \to \pi^+\pi^-\pi^0$

$$F(Z,\Phi) \propto \mathcal{P} \cdot \left\{1 + 2\alpha Z + 2\beta Z^{3/2} \sin 3\Phi + 2\gamma Z^2 + \mathcal{O}(Z^{5/2})\right\}$$

$\mathcal{P}$ - p-wave phase space factor

$\alpha$, $\beta$, $\gamma$,... - Dalitz plot parameters.

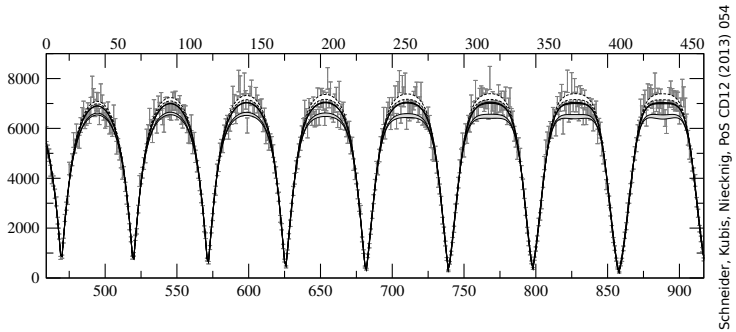


Separate fit to data and theory distributions

+ Includes full uncertainty estimate
- Only for smooth distributions

## Direct theory-data fit of $\phi \to \pi^+\pi^-\pi^0$

Bin content available from KLOE




direct fit possible

+ All dynamic covered
- How to include systematic errors?

- Fit performed by experiment?
  - Continuity issue
- Bin content made available for all systematic checks?

# Summary

**Dalitz plot studies of V $\rightarrow \pi^+\pi^-\pi^0$**

- Benchmark for $\pi^0$ TFF calculations
- Ongoing and available experimental studies
  $\omega$ - WASA, KLOE, CLAS
  $\phi$ - KLOE, CMD-2
- How to best compare experiment - theory?

**Thank you for your attention!**