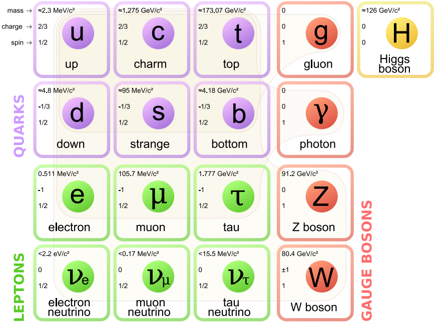
Hadronic Decays of the ω Meson

Lena Heijkenskjöld

Uppsala University

Standard Model



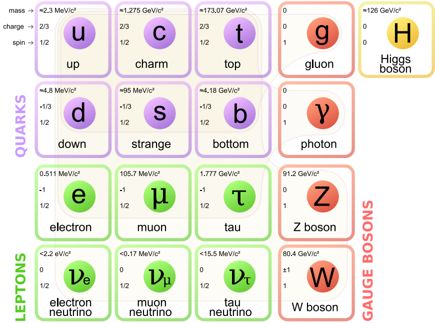
Three fundamental forces

Strong ↓ Quantum Chromo Dynamics

Weak ↘ Electro-Magnetism ↙ Electro-Weak theory

Prevailed a multitude of test

Standard Model



Three fundamental forces

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Prevailed a multitude of test

Hint of physics beyond SM:

anomalous magnetic moment of the muon $a_\mu := \frac{g_\mu - 2}{2}$

$$a_\mu^{exp} = 116592091(54)(33) \times 10^{-11}$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had} = 116591803(1)(42)(26) \times 10^{-11}$$

3.6σ discrepancy → physics beyond the standard model

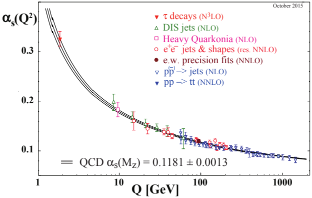
Hadron Physics

Calculations in the lower energy (Q) regime

Q

Elementary particles — Perturbative QCD applicable

Hadrons — Phenomenological models and Effective Field Theories or Lattice QCD



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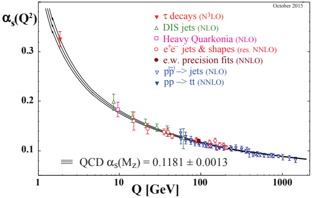


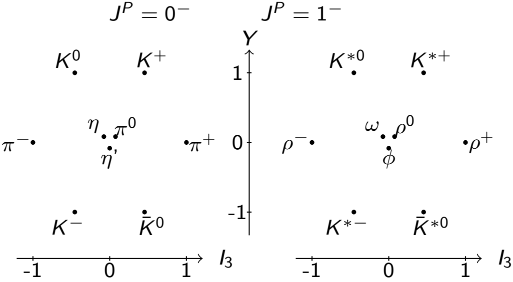
Quark Model

Composite objects:

Baryons - qqq

Mesons - $q\bar{q}$

Classification in Y and I_3



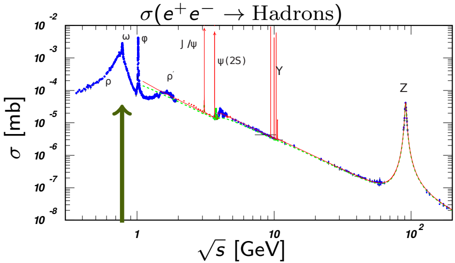
This thesis

The ω meson

$$I^G(J^{PC}) = 0^-(1^{--})$$

$m_\omega = 782.65(12)$ MeV, $\Gamma_\omega = 8.49(8)$ MeV

$\omega \to$	Γ_i/Γ_ω
$\pi^+\pi^-\pi^0$	89.2(7)%
$\pi^0\gamma$	8.28(28)%
$\pi^+\pi^-$	$1.53^{+0.11}_{-0.13}$ %



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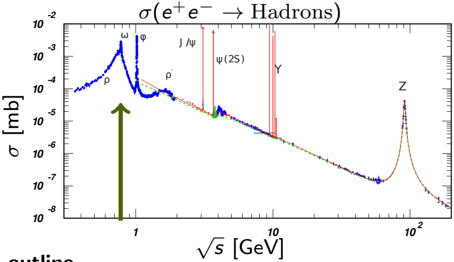


Thesis outline

Part I:

$\omega \to \pi^+\pi^-\pi^0$ Dalitz plot study with WASA-at-COSY

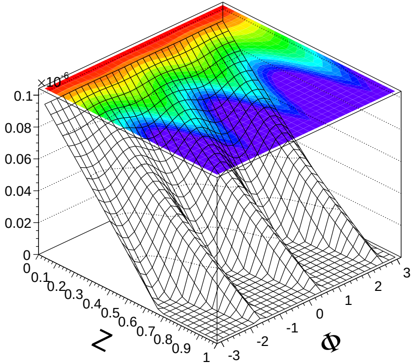
Theory, WASA experiment, Analysis, Results

Part II:

Additional ω studies

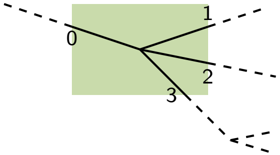
- Search for $\omega \to \pi^+\pi^-$ signal with WASA-at-COSY
- Simulation study of $\pi^0\pi^0$ interference for ω Dalitz plot measurement using KLOE data

Part I: $\omega \to \pi^+\pi^-\pi^0$ Dalitz plot study with WASA-at-COSY



What is a Dalitz plot?

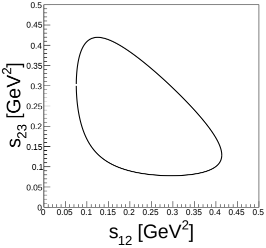
3-body decay



$\mathcal{M}$ given by two independent variables
$\rightarrow$ 2D representation, e.g. $\mathcal{M}(s_{12}, s_{23})$

$$\frac{d^2\Gamma}{ds_{12}ds_{23}} = \frac{1}{(2\pi)^3}\frac{1}{32m^3}|\mathcal{M}|^2$$

$$s_{ij} = |P_i + P_j|^2$$



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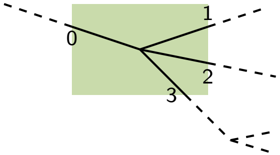

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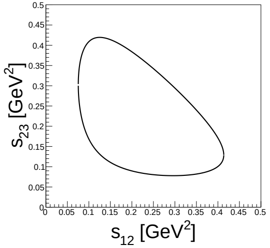
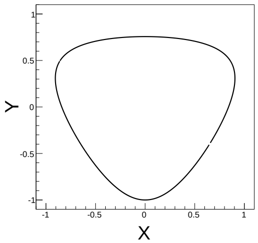
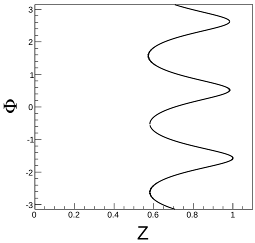


Common choice of variables when $m_1 = m_2$



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

$$Y = \frac{(2m_1 + m_3)T}{(m_1 Q)}$$



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

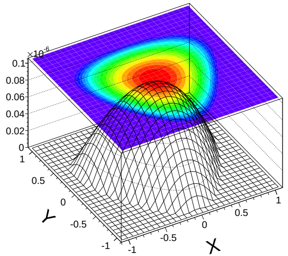
$$\Phi = \tan^{-1}\frac{X}{Y}$$

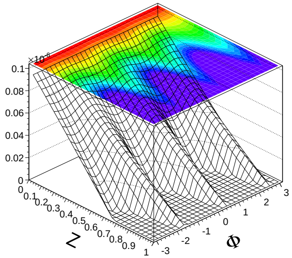
$\omega \to \pi^+\pi^-\pi^0$ dynamics - 1

Dalitz plot density distribution $\sim |\mathcal{M}(s_{12}, s_{23})|^2$, $\quad |\mathcal{M}|^2 = 1 \quad : \quad$ Phase space

Restrictions from quantum numbers

$\omega : I(J^P) = 0(1^-) \longrightarrow J_{3\pi} = 1$ and $J_{2\pi} = 1 \longrightarrow$ P - wave phase space $|\mathcal{M}|^2 = \mathcal{P} \propto |\bar{\mathbf{p}}_i \times \bar{\mathbf{p}}_j|^2$

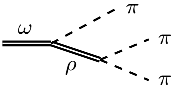




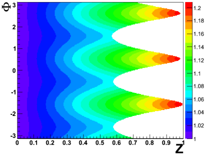
$\omega \rightarrow \pi^+\pi^-\pi^0$ dynamics - 2

$\pi - \pi$ interactions

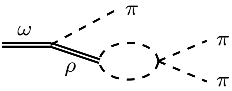
- Intermediate ρ
- $\pi - \pi$ rescattering



$|\mathcal{M}|^2 \ / \ \mathcal{P}$



1. Lagrangian approach[1]



2. Dispersion approach[2]

$$\pi V \rightarrow \pi\pi$$
$$\downarrow$$
$$V \rightarrow \pi\pi\pi$$

Predictions of $\frac{d^2\Gamma}{ds_{12}ds_{23}}$

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

[2] S.P. Schneider, et al., Eur.Phys.J. C72 (2014) 2012 and Danilkin, et al. Phys. Rev. D91 (2015) 094029

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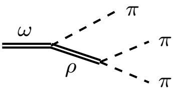
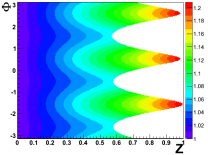


$|\mathcal{M}|^2 \;/\; \mathcal{P}$



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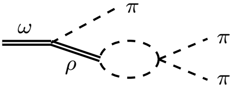

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Predictions of $\frac{d^2\Gamma}{ds_{12}ds_{23}}$

Experiment - Theory comparison

Parametrisation $F(Z, \Phi) \times \mathcal{P}$

$$F(Z, \Phi) = 1 + 2\alpha Z + 2\beta Z^{3/2}\sin(3\Phi) + 2\gamma Z^2 + 2\delta Z^{5/2}\sin(3\Phi) + \mathcal{O}(Z^3)$$

Fits are performed on theory predictions.

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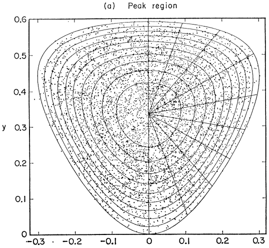
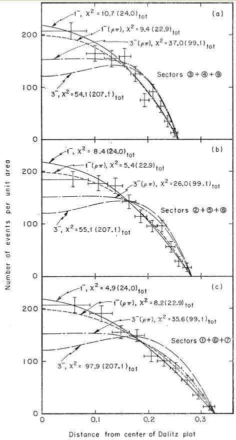
Why study $\omega \to \pi^+\pi^-\pi^0$ dynamics?



Previous measurement

Largest previous statistics for study of the dynamics - 4200 events.

Unable to distinguish ρ onset.



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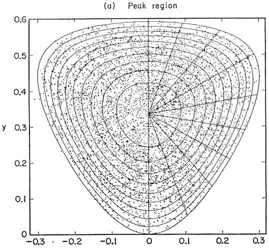

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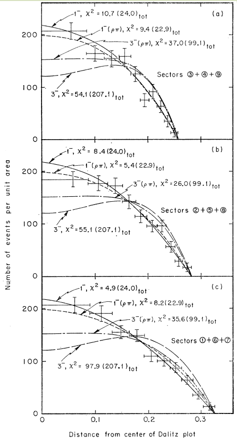
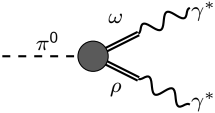
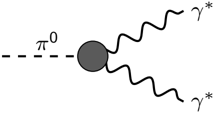


Benchmark for meson transition form factors



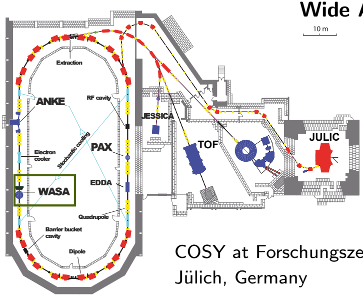
a part of



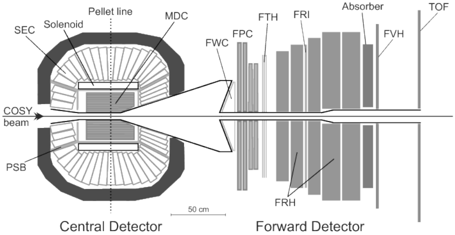
- Probe of hadron structure
- Contribution to HLbL (muon g-2)

Experimental setup

Wide Angle Shower Apparatus



COSY at Forschungszentrum Jülich, Germany



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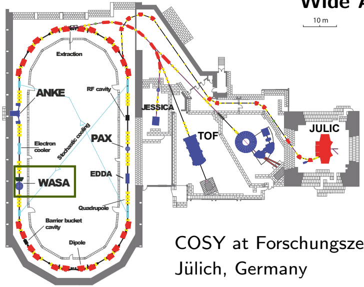

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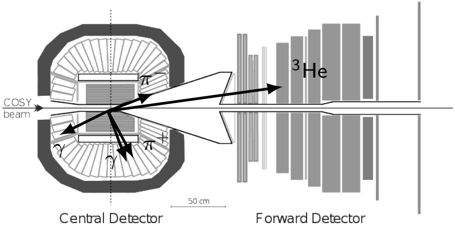


Collected data

$$p + d \to {}^3He + \omega$$

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

$\hookrightarrow \pi^0 + \gamma$

$\hookrightarrow \pi^+ + \pi^-$

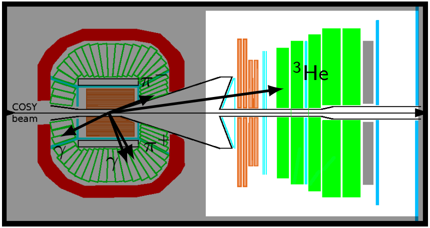
4 weeks beam time in 2011

$T_{beam} = 1.45$ GeV $\to$ 110h

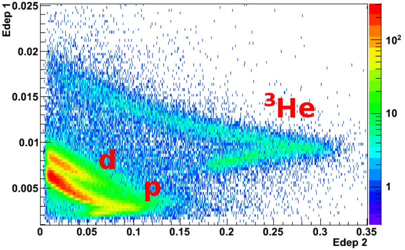
$T_{beam} = 1.50$ GeV $\to$ 100h

Trigger on ^{3}He

Event selection



- ^{3}He candidate



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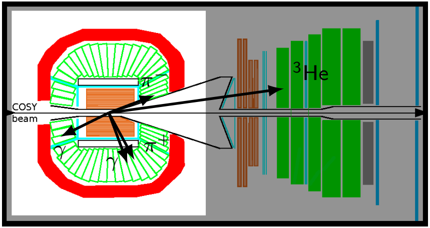
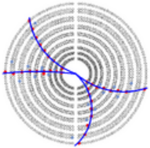
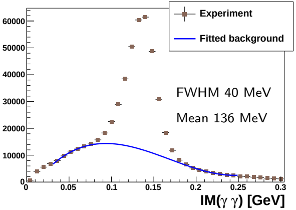


- ^{3}He candidate
- $\pi^+\pi^-\gamma\gamma$ candidates



Charged tracks PID using
drift chamber and solenoid $\sim$ 1 T

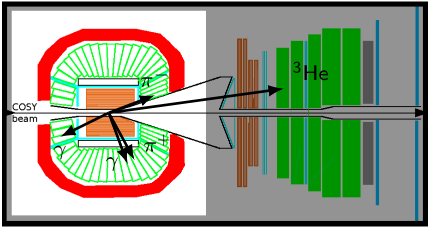
$\geq$ 2 oppositely charged



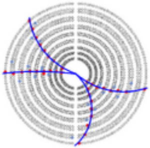
γ reconstruction
in calorimeter

$\geq$ 2 neutral

Event selection



- ^{3}He candidate
- $\pi^+\pi^-\gamma\gamma$ candidates
- π^0 candidates



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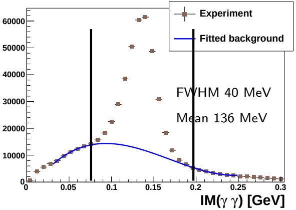

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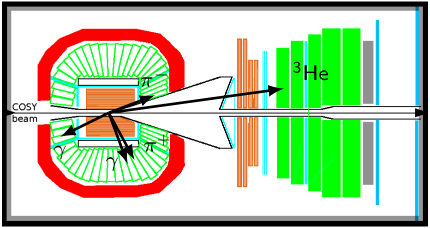
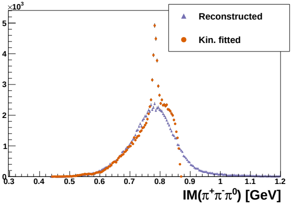


- ^{3}He candidate
- $\pi^+\pi^-\gamma\gamma$ candidates
- π^0 candidates
- Kinematic fit

Constraint: $P_{in} = P_{out}$,
Hypothesis: $pd \to {}^3\mathrm{He}\pi^+\pi^-\gamma\gamma$

- Choose final track candidates
- Test $pd \to {}^3\mathrm{He}\pi^+\pi^-$ hypothesis
- Cut on P(χ^2)>0.05

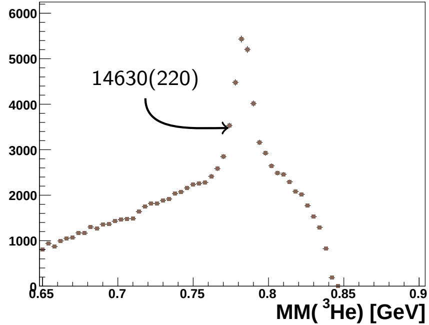
Improve resolution for $X^{Rec} = T,\ \theta,\ \phi$



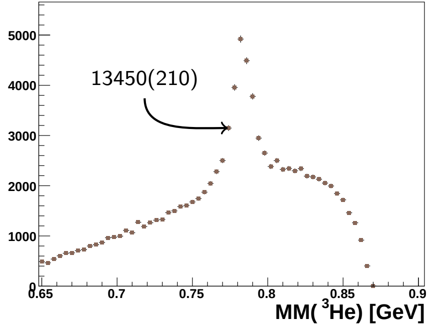
Event selection

Selected sample

$T_{beam} = 1.45$ GeV



$T_{beam} = 1.50$ GeV

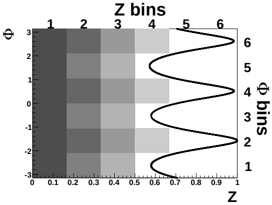


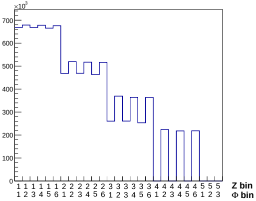
Dalitz plot analysis - Creating the Dalitz plots

Bin size

$Z \in [0,1]$ and $\Phi \in [-\pi, \pi]$
6×6 bins

1D-representation for comparison





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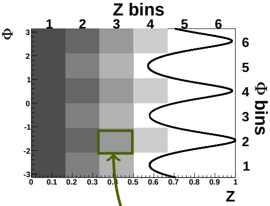
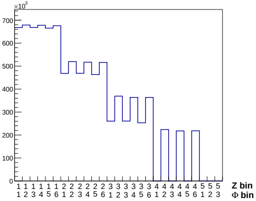


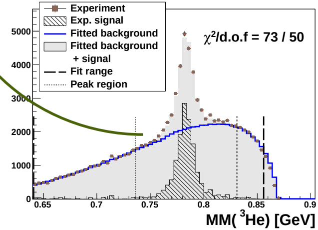


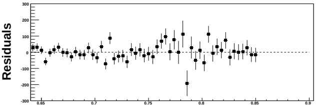
Extracting the ω events

Simulated distributions - $H_{\omega\to3\pi}$ and $H_{3\pi}$

$$\mathbf{F} = \Lambda H_{\omega\to3\pi} + \{a_1 + a_2x + a_3x^2\}H_{3\pi}$$

$$\Lambda = \frac{\lambda}{\int_{I_{min}}^{I_{max}} H_{\omega\to3\pi}} \qquad \lambda = \#\ \text{signal events}$$

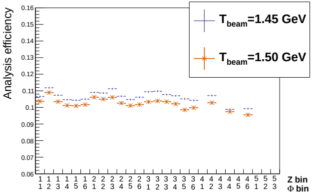




	# events
$T_{beam} = 1.45$ GeV	13790(220)
$T_{beam} = 1.50$ GeV	12830(200)

Dalitz plot analysis - Creating the Dalitz plots

Efficiency correction



Using simulated signal data

$$\epsilon_{ij} = \frac{N_{ij}^{fit}}{N_{ij}^{true}}$$

Bin-wise efficiency correction $\tilde{N}_{ij} = \frac{N_{ij}}{\epsilon_{ij}}$

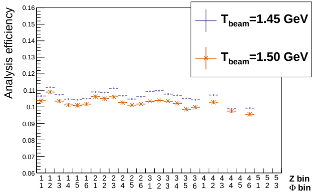
Dalitz plot analysis - Creating the Dalitz plots

Efficiency correction

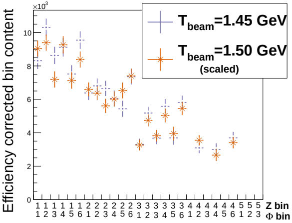
Using simulated signal data

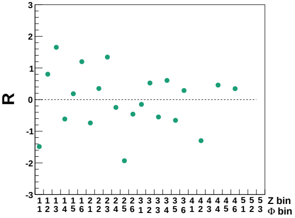
$$\epsilon_{ij} = \frac{N_{ij}^{fit}}{N_{ij}^{true}}$$

Bin-wise efficiency correction $\tilde{N}_{ij} = \frac{N_{ij}}{\epsilon_{ij}}$



Resulting experimental Dalitz plots





Compare the distributions:

$$R_{ij} = \frac{\tilde{N}_{ij} - \tilde{M}_{ij}}{\sqrt{\tilde{\sigma}^2_{N_{ij}} + \tilde{\sigma}^2_{M_{ij}}}}$$

Unbinned ML fit of Gaussian:

$\mu = -0.02$ and $\sigma = 0.93$

Dalitz plot analysis - Parametrisation

Parametrisation $F(Z, \Phi) \times \mathcal{P}$

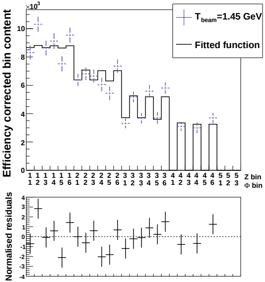
$$F(Z, \Phi) = 1 + 2\alpha Z + 2\beta Z^{3/2} \sin(3\Phi) + 2\gamma Z^2 + 2\delta Z^{5/2} \sin(3\Phi) + \mathcal{O}(Z^3)$$

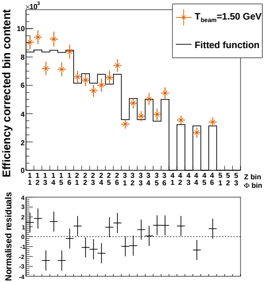
Fit results

Parameters used in fit	$\alpha \times 10^3$	$\beta \times 10^3$	$\gamma \times 10^3$	$\chi^2/d.o.f.$
$\mathcal{N}^1\mathcal{N}^2$	-	-	-	84 / 40
$\mathcal{N}^1\mathcal{N}^2\alpha$	153(42)	-	-	69 / 39
$\mathcal{N}^1\mathcal{N}^2\alpha\beta$	132(48)	55(63)	-	68 / 38
$\mathcal{N}^1\mathcal{N}^2\alpha\gamma$	21(148)	-	232(252)	68 / 38

Sensitive to α parameter:

Onset of ρ state



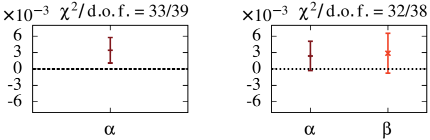


Dalitz plot analysis - Systematical checks

Test of fit procedure

"True" data simulated with P-wave

Fit with $F(Z, \Phi) \times \mathcal{P}$



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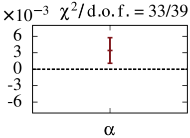
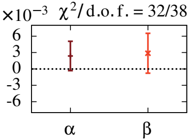


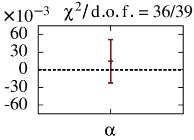


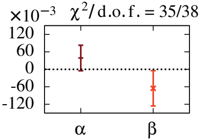
Test of signal extraction method

Simulated dist. - $H_{\omega\to3\pi}$ (P-wave) and $H_{3\pi}$

Generate $H_{Gen} \sim H_{Exp}$

Extract signal events $\to$ Fill Dalitz plot





31/19 37/19

Dalitz plot analysis - Systematical checks

Test of fit procedure

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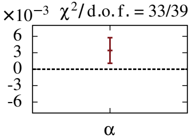
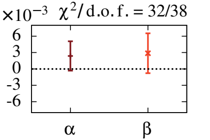
Fit with $F(Z, \Phi) \times \mathcal{P}$





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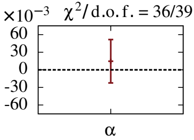
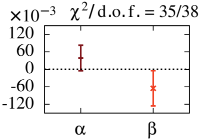
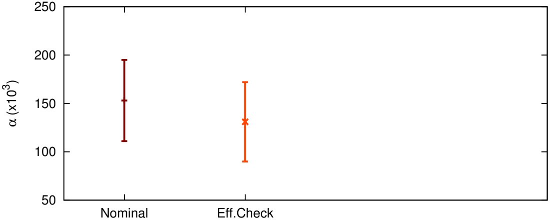




Test of efficiency correction

Fit uncorrected Dalitz plots



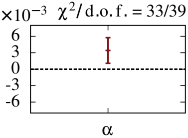
$\chi^2/\mathrm{d.o.f.}$	69/39	79/39	31/19	37/19

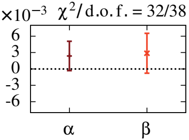
Dalitz plot analysis - Systematical checks

Test of fit procedure

"True" data simulated with P-wave

Fit with $F(Z, \Phi) \times \mathcal{P}$





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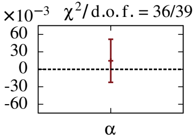
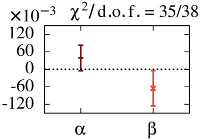


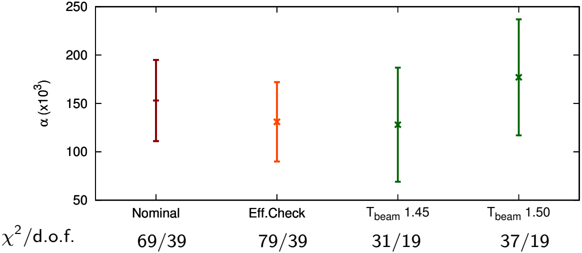


Test of efficiency correction

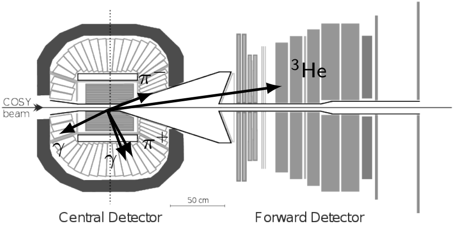
Fit uncorrected Dalitz plots

Test of data set consistency

Individual fits to the two Dalitz plots



$\omega \to \pi^+\pi^-\pi^0$ Dalitz plot - Summary



$$p + d \to {}^3\text{He} + \omega$$

$$T_{beam} = 1.45 \text{ and } 1.50 \text{ GeV}$$

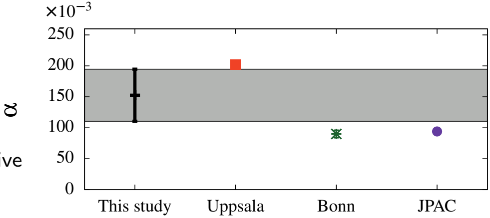
$\to \sim$ 26600(300) events in the Dalitz plots

Fit of parametrisation $(1 + 2\alpha Z) \times \mathcal{P}$

$\to \alpha > 0$ with $\sim 3.5\ \sigma$

Theoretical predictions:

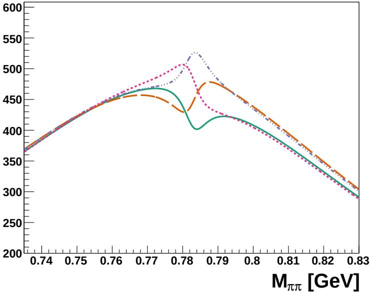
Lagrangian approach (Uppsala) and Dispersive calculations (Bonn,JPAC)



Part II: Additional ω studies

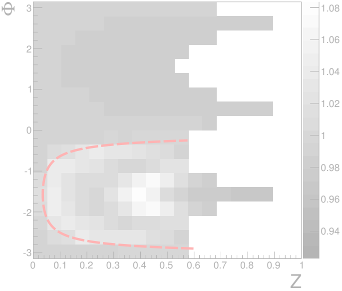
A search for the

$\omega \to \pi^+\pi^-$ signal in WASA



A simulation study of

$\pi^0\pi^0$ interference study with KLOE



Introduction

Why search for $\boldsymbol{\omega \to \pi^+\pi^-}$

$\mathrm{BR}(\omega \to \pi^+\pi^-) = (1.53^{+0.11}_{-0.13})\%$ Isospin violating

$\rho - \omega$ mixing assumed $\to$ Interference pattern in $\mathrm{M}_{\pi\pi}$

In WASA data $\sim$ 28000(300) $\omega \to \pi^+\pi^-\pi^0$ events

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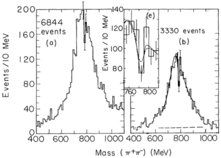
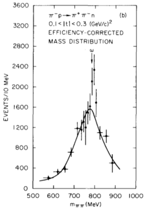
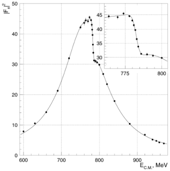
Previous observations

$\pi^+ p/d \to X\pi^+\pi^-$	dip
$\pi^- p \to X\pi^+\pi^-$	peak
$K^- p \to X\pi^+\pi^-$	peak/"shoulder"
$N\gamma \to N\pi^+\pi^-$	"shoulder"
$e^+e^- \to \pi^+\pi^-$	"shoulder"







Introduction

$\rho - \omega$ mixing

Sources of isospin violation: EM interactions, $m_u \neq m_d$, ...

Common approach: $|\rho_I\rangle \equiv |1,0\rangle$ and $|\omega_I\rangle \equiv |0,0\rangle \to$

$$|\rho\rangle = |\rho_I\rangle - \epsilon\,|\omega_I\rangle$$
$$|\omega\rangle = |\omega_I\rangle + \epsilon\,|\rho_I\rangle$$

$|\omega_I\rangle \to \pi^+\pi^-$ often neglected

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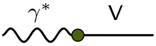
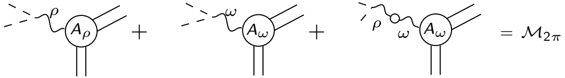
$|\omega_I\rangle \rightarrow \pi^+\pi^-$ often neglected

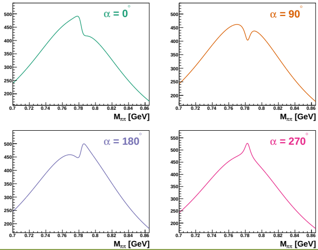
The role of production

e^+e^-: known coupling 

hadronic: not known

$\rightarrow$ mixing info from e^+e^-



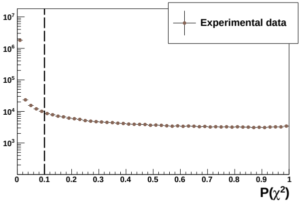


$$|\mathcal{M}_{2\pi}|^2 = |W_2 s_\rho^{-1}|^2 \left\{ |A_\rho|^2 + 2g(1 + \Delta m_0^2 \Re(s_\omega^{-1}))|A_\rho||A_\omega| \cos(\alpha) - 2g\Delta m_0^2 \Im(s_\omega^{-1})|A_\rho||A_\omega| \sin(\alpha) \right\}$$

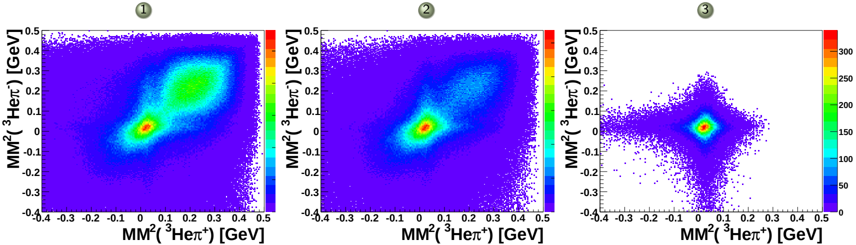
Data analysis

Event selection

1. Selection of ^{3}He, π^+ and π^-
2. Kinematical fit:
   choosing final tracks and suppress $^3\text{He}\pi^+\pi^-\pi^0$
3. Cut on $P(\chi^2) > 0.1$

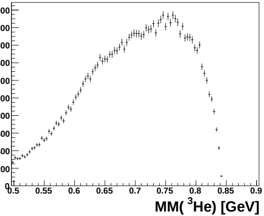


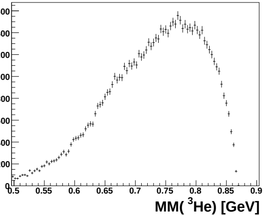
Reduction of non $\pi^+\pi^-$ events



Data analysis

The resulting $\pi^+\pi^-$ mass distribution





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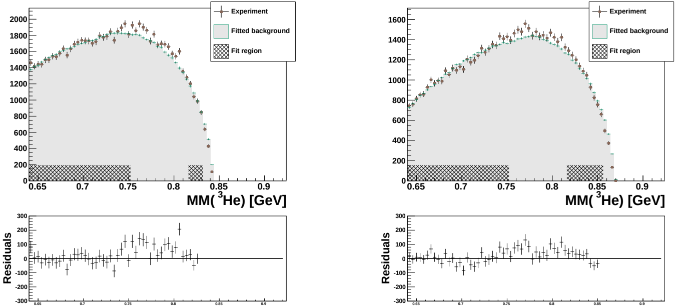


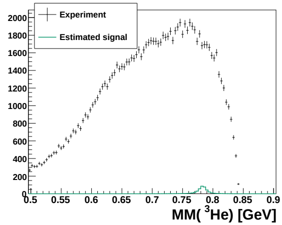
Fit to background using simulated distribution $H_{2\pi}$

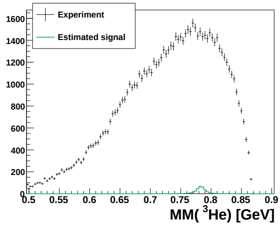
$$\mathbf{F} = \{a_1 + a_2 x + a_3 x^2\} H_{2\pi}$$

No convincing $\rho - \omega$ interference

Data analysis

The resulting $\pi^+\pi^-$ mass distribution





Estimation of # $\omega \to \pi^+\pi^-$ events in final sample

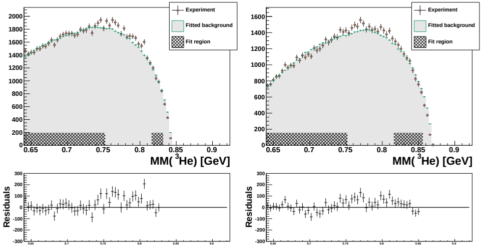
With assumption of no interference

Summary

Data collected by WASA, 28000(300) $\omega \to \pi^+\pi^-\pi^0$ events (BR=89%)

Search for $\omega \to \pi^+\pi^-$ signal (BR=1.53%)

Observe $\rho - \omega$ signal in hadronic production



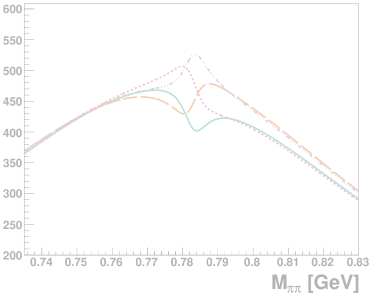
No visible interference

Estimated # $\omega \to \pi^+\pi^-$ small

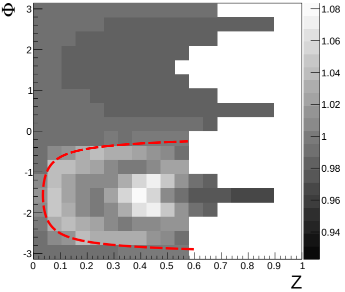
Size of $\rho \to \pi^+\pi^-$ signal unknown

Part II: Additional ω studies

A search for the $\omega \to \pi^+\pi^-$ signal in WASA



A simulation study of $\pi^0\pi^0$ interference study with KLOE



Introduction

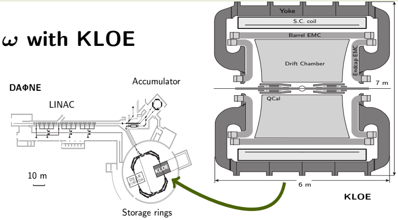
Previous study of $e^+e^- \to \pi^0\omega$ with KLOE

$\sim 600\ {}^{-1}$ pb $\sqrt{s} \in [1000,1030]$ MeV

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

$1349(2)\cdot 10^3$ reconstructed events

Could be used for Dalitz plot study!



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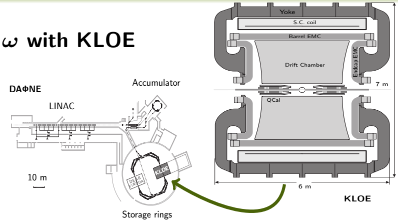


Why care about $\pi^0\pi^0$ interference?

1. Identify primary π^0 in simulation
2. Effect of $\pi^0\pi^0$ interference in Dalitz plot

Needed for $\epsilon = \frac{Reconstructed}{True}$

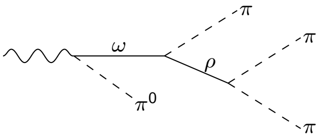
No $\pi^0_{Primary\,/\,Decay}$ in simulation with interference

Can simulation without interference be used?

Effect in simulation $\xrightarrow{?}$ Effect in experiment

Simulation studies

The reaction model



$$
\begin{aligned}
|\mathcal{M}|^2 =& |\mathbf{J}^{+-00}_{\omega\pi^0}|^2 \\
=& \Big| G_\omega [\mathbf{t}_\omega(p_{\pi^0_1}, p_{\pi^-}, p_{\pi^+}, p_{\pi^0_2}) - \mathbf{t}_\omega(p_{\pi^0_1}, p_{\pi^+}, p_{\pi^-}, p_{\pi^0_2}) \\
& -\mathbf{t}_\omega(p_{\pi^0_1}, p_{\pi^0_2}, p_{\pi^+}, p_{\pi^-})] + (p_{\pi^0_1} \longleftrightarrow p_{\pi^0_2}) \Big|^2 \\
=& |\mathbf{J}^{+-00}_{\omega\pi^0_1} + \mathbf{J}^{+-00}_{\omega\pi^0_2}|^2
\end{aligned}
$$

Simulation studies

The reaction model

$$
\begin{aligned}
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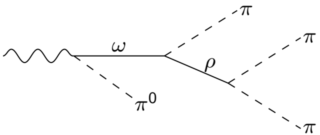
& - \mathbf{t}_\omega(p_{\pi^0_1}, p_{\pi^0_2}, p_{\pi^+}, p_{\pi^-})] + (p_{\pi^0_1} \longleftrightarrow p_{\pi^0_2}) \Big|^2 \\
=& |\mathbf{J}^{+-00}_{\omega\pi^0_1} + \mathbf{J}^{+-00}_{\omega\pi^0_2}|^2
\end{aligned}
$$



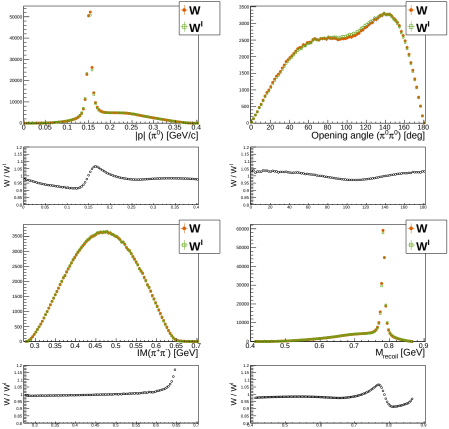
The simulation procedure

1. Generate $\pi^0\pi^+\pi^-\pi^0$ at $\sqrt{s} = 1$ GeV with `GENBOD` $\to \mathcal{W}_{PS}$
2. Calculate $|\mathcal{M}|^2 \to \mathcal{W} = |\mathcal{M}|^2 \cdot \mathcal{W}_{PS}$

Exclude interference $|\mathcal{M}^I|^2 = |\mathbf{J}^{+-00}_{\omega\pi^0_1}|^2 \quad \to \quad \mathcal{W}^I = |\mathcal{M}^I|^2 \cdot \mathcal{W}_{PS}$

Simulation studies - The results

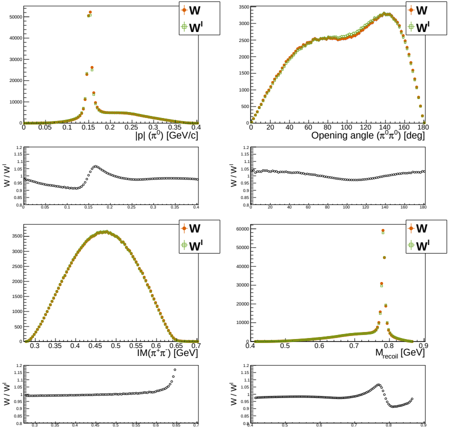
Pion kinematics



No drastic effect on simulation when excluding interference

Simulation studies - The results

Pion kinematics

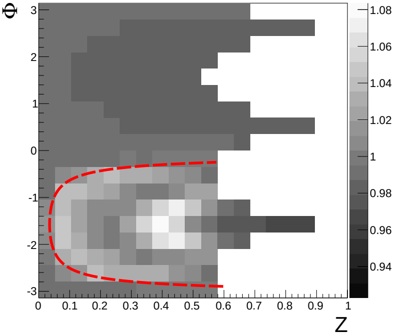


No drastic effect on simulation when excluding interference

Dalitz plot

Select π^0_{Decay} using $|m_\omega - IM(\pi^+\pi^-\pi^0_i)|$

$\mathcal{W}/\mathcal{W}^I$

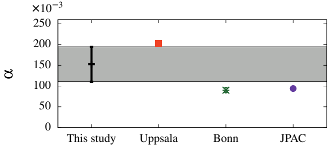


Noticeable effect from interference.

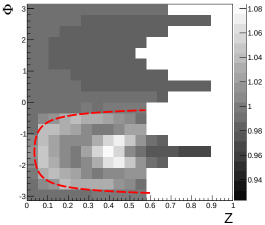
Take care in analysis strategy

Overall Summary

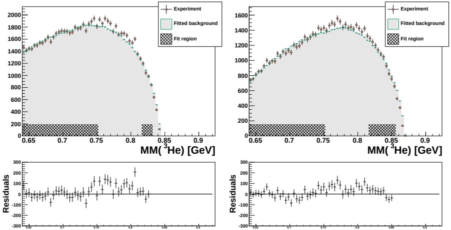
$\omega \to \pi^+\pi^-\pi^0$ Dalitz plot



$\pi^0\pi^0$ simulation study



$\omega \to \pi^+\pi^-$ signal search



Thank you for your attention