Studies on decays of light mesons

9th Workshop on Hadron Physics in China and Opportunities Worldwide

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Lena Heijkenskjöld

Institut für Kernphysik, JGU Mainz

24-29 July 2017

Introduction

Light meson decays

Three different but complementary experiments

- WASA-at-COSY
- KLOE/KLOE-2
- A2

Focus on:

- Dalitz plot studies
- Transition form factor measurements

WASA-at-COSY

Wide Angle Shower Apparatus

Operated at Cooler Synchrotron (COSY) 2006-2015.

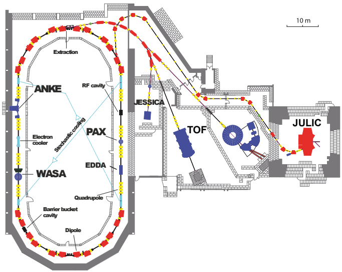
COSY — (un)polarised proton/deutron beam p = 600 - 3700 MeV/c.

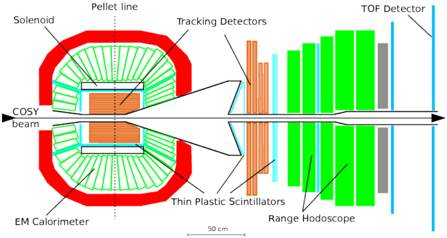
Frozen pellet target — hydrogen/deuterium.

Designed for studies of light mesons.

$$p + p \to p + p + X \quad \text{or} \quad p + d \to {}^{3}\mathrm{He} + X$$

H.-H. Adam et al arXiv:nucl-ex/0411038





Central Detector
$\sim$ 4π coverage of decay particles
Mini drift chamber: 17 cylindrical layers
Calorimeter: 1012 CsI(Na) crystals
Solenoid: B_{max}=1.3T

Forward Detector
Clean tagging of recoil particles
Plastic scintillators
Proportional chamber

KLOE/KLOE-2

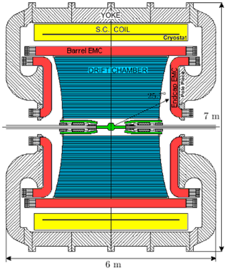
K LOng Experiment

At DAΦNe — e^+e^- collider $\sqrt{s} = M_\Phi = 1019.4$ MeV.

$$e^+ + e^- \to \Phi \to X + Y + ...$$

KLOE operated 2000-2006. collecting 2.5fb^{-1} @ M$_\Phi$ + 250 pb^{-1} off-peak
$\to$ Upgraded to KLOE-2, will collect $>$5 fb^{-1} 2014-2018

F. Bossi, et al. , Nuovo Cimento, 30 (2008) 10
G. Amelino-Camelia et al., Eur. Phys. J. C, 68 (2010) 619



Drift Chamber
4m diameter, 3.3 m long
$\partial p_\perp / p_\perp < 0.4\%$ ($\theta > 45^\circ$)
$\sigma_{xy} = 150\mu$m, σ_z=2mm

Calorimeter
Pb/scintillating fiber
98% coverage of solid angle
$\sigma_T = 57$ ps / $\sqrt{E(GeV)} \oplus 140$ ps

Magnetic field
B=0.52 T

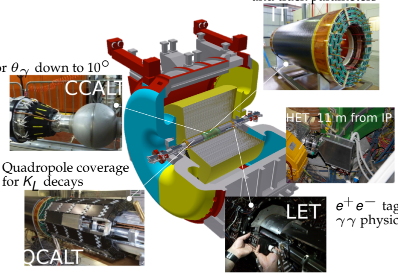


Figure from E. Perez del Rio presentation at International Workshop on e^+e^- collisions from Phi to Psi 2017

A2

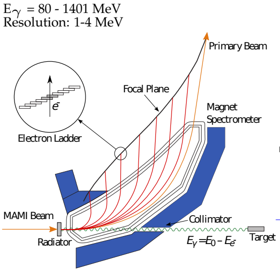
At MAinzer MIkrotron (MAMI) — (un)polarised electron accelerator, $E_{max} = 1.6$ GeV.

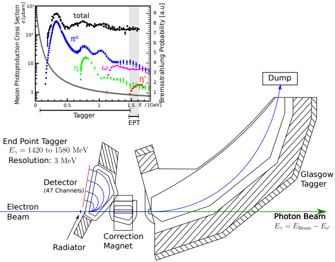
Electrons + radiator $\rightarrow$ tagged bremsstrahlung photons (un/linearly/circularly polarised)

$$\gamma + p \rightarrow p + X$$

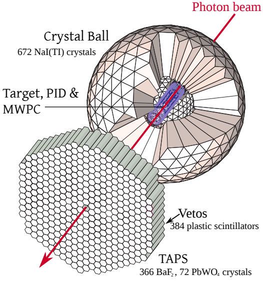
A. Starostin, et al., Phys. Rev. C 64, 055205 (2001)
R. Novotny, IEEE Trans. Nucl. Sci. 38, 379 (1991)
J. C. McGeorge Eur. Phys. J. A (2008) 37: 129-137

The Glasgow photon tagger + The end point tagger





The Crystal Ball + TAPS setup

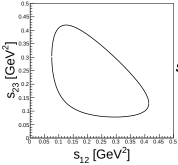


What is a Dalitz plot?

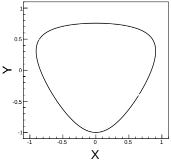
Kinematic variables

3-body decay: $\mathcal{A}$ given by two independent variables $\rightarrow$ 2D representation.

Common choice of variables when $m_1 = m_2$

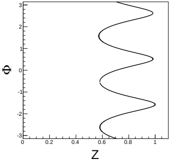


$$s_{ij} = |P_i + P_j|^2$$



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

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



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

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

Parametrisation

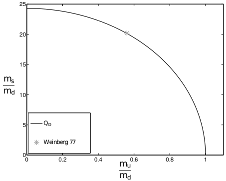
To compare experimental/theory results — only for smooth distributions.

$$|\mathcal{A}(X,Y)|^2 \propto N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots)$$

$$|\mathcal{A}(Z,\Phi)|^2 \propto N(1 + 2\alpha Z + 2\beta Z^{3/2}\sin(3\Phi) + 2\gamma Z^2 + 2\delta Z^{5/2}\sin(3\Phi) + \ldots)$$

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

Study ratio of light m_q



L. Caldeira Balkeståhl, Doctoral dissertation Uppsala U. 2016

$$\mathcal{A}_{\text{LO}}^{\chi\text{PT}} \sim Q^{-2} = \frac{m_d^2 - m_u^2}{m_s^2 - m_{ud}^2}$$

- NNLO χPT calculated[1] — slow convergence
- Dispersive calculations[2,3] — use χPT constraints and exp. results → Q

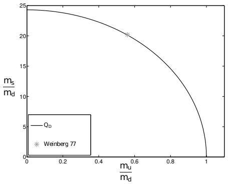
[1] *J. Bijnens, et al., JHEP 11 (2007) 030,* [2] *G. Colangelo, et al.,Phys.Rev.Lett. 118, (2017) 022001,* [3] *P. Guo, et al., arXiv:1608.01447 [hep-ph]*

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

Study ratio of light m_q

$$\mathcal{A}_{\text{LO}}^{\chi\text{PT}} \sim Q^{-2} = \frac{m_d^2 - m_u^2}{m_s^2 - m_{ud}^2}$$

- NNLO χPT calculated[1] — slow convergence
- Dispersive calculations[2,3] — use χPT constraints and exp. results → Q



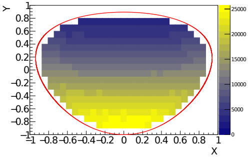
L. Caldeira Balkeståhl, Doctoral dissertation Uppsala U. 2016

[1] *J. Bijnens, et al., JHEP 11 (2007) 030,* [2] *G. Colangelo, et al.,Phys.Rev.Lett. 118, (2017) 022001,* [3] *P. Guo, et al., arXiv:1608.01447 [hep-ph]*

Experimental Dalitz plots

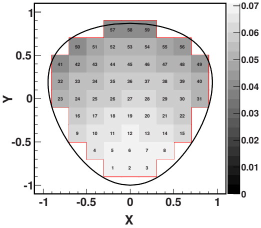
- KLOE $\quad e^+e^- \to \phi \to \gamma\eta$
- WASA $\quad pd \to {}^3He\eta$

KLOE



A. Anastasi, et al., JHEP 1605 (2016) 019

WASA

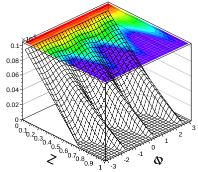


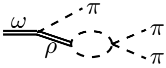
P. Adlarson, et al., Phys.Rev. C90 (2014) no.4, 045207

High statistics Dalitz plot density distribution.
Fit parametrisation → test of theory.
Determination of theory parameters → Q

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

Study decay dynamic





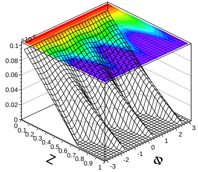
- Final state P-wave
- $\pi - \pi$ interactions — Previously unmeasured

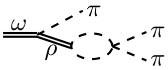
Full predictions by lagrangian approaches[4] and dispersion calculations[5,6].

[4] [Uppsala]C. Terschlüsen, et al., Eur.Phys.J. A49 (2013) 116 [5] [Bonn] S.P. Schneider, et al., Eur.Phys.J. C72 (2014) 2012 [6] [JPAC] I. Danilkin et al., Phys. Rev. D91 (2015) 094029

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

Study decay dynamic





- Final state P-wave
- $\pi - \pi$ interactions — Previously unmeasured

Full predictions by lagrangian approaches[4] and dispersion calculations[5,6].

[4] [Uppsala]C. Terschlüsen, et al., Eur.Phys.J. A49 (2013) 116 [5] [Bonn] S.P. Schneider, et al., Eur.Phys.J. C72 (2014) 2012 [6] [JPAC] I. Danilkin et al., Phys. Rev. D91 (2015) 094029

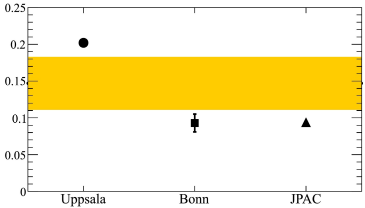
Experimental Dalitz plot

- WASA $pd \to {}^3\mathrm{He}\omega$ and $pp \to pp\omega$
  $(4.408 \pm 0.042) \times 10^4$ events

$$\mathcal{A} \sim [Pwave] \times \left(1 + 2\alpha Z + 2\beta Z^{3/2} \sin 3\phi + \mathcal{O}(Z^2)\right)$$

$\longrightarrow$ First observation of intermediate ρ

$\propto \ \alpha$ parameter



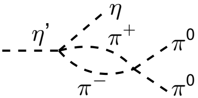
P. Adlarson, et al., Phys.Lett. B770 (2017) 418

$\eta' \to \eta\pi^0\pi^0$

$\eta' \to \eta\pi\pi$: Test for Resonance ChPT[7,9], large-N_C ChPT[8,9] and Dispersive approach[10]

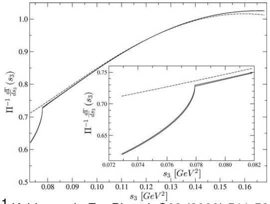
[7] *G. Ecker, et al., Phys. Lett. B 223 (1989) 425,* [8] *R. Kaiser et al., Eur. Phys. J. C 17 (2000) 623,* [9] *Escribano, et al. JHEP 1105 (2011) 094,* [10] *T. Isken et al., arXiv:1705.04339*

Cusp effect



Not yet observed in this channel

NREFT[11] $\to (a_2 - a_0)$: $\pi\pi$ S-wave scat. lengths for I=0,2



[11] *Kubis, et al., Eur.Phys.J. C62 (2009) 511-523*

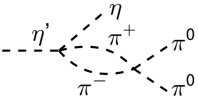
JG|U

$\eta' \to \eta\pi^0\pi^0$

$\eta' \to \eta\pi\pi$: Test for Resonance ChPT[7,9], large-N_C ChPT[8,9] and Dispersive approach[10]

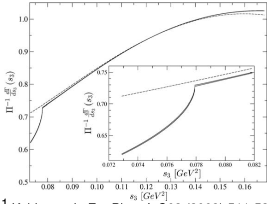
[7]G. Ecker, et al., Phys. Lett. B 223 (1989) 425, [8]R. Kaiser et al., Eur. Phys. J. C 17 (2000) 623, [9]Escribano, et al. JHEP 1105 (2011) 094, [10]T. Isken et al., arXiv:1705.04339

Cusp effect



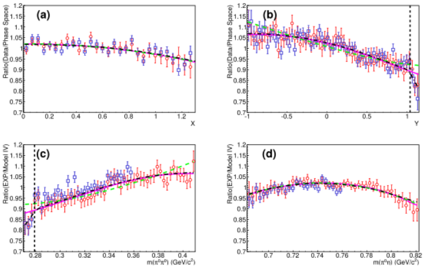
Not yet observed in this channel

NREFT[11] $\to (a_2 - a_0)$: $\pi\pi$ S-wave scat. lengths for I=0,2



[11] Kubis, et al., Eur.Phys.J. C62 (2009) 511-523

A2 Preliminary



P. Adlarson, presentation at International Workshop on e^+e^- collisions from Phi to Psi 2017

Experimental Dalitz plot

- A2 $\gamma p \to \eta' p$
  120 000 events in Dalitz plot

$\longrightarrow$ Fit $1 + aY + bY^2 + cX + dX^2$
$\longrightarrow$ Fit cusp to get $(a_2 - a_0)$

Transition Form Factors

Input to a_μ^{SM}

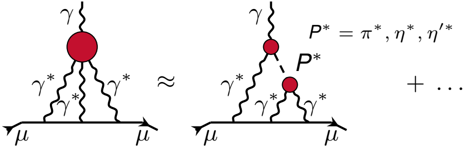
3-4σ discrepancy in $a_\mu^{SM} - a_\mu^{exp}$ — Data driven efforts to reduce theoretical error [12,13].

[12] *G. Colangelo, et al. Phys.Lett. B738 (2014) 6-12* [13] *V. Pauk, et al., Phys.Rev. D90 (2014) no.11, 113012*

Theory contribution	$a_\mu \times 10^{11}$
QED[14]	115965218.178(0.077)
EW[15]	153.6(1.0)
Strong[16]	
HVP	6793.6(41.4)
HLbL	103(29)

[14] *Aoyama, et al., Phys.Rev.Lett. 109 (2012) 111808*
[15] *Gnendiger, et al, Phys.Rev. D88 (2013) 053005*
[16] *Jegerlehner, arXiv:1705.00263 [hep-ph]*

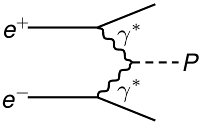
Hadronic light-by-light scattering:



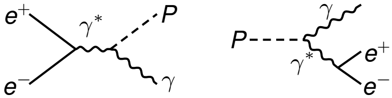
$\rightarrow \quad \mathcal{F}(P^* \rightarrow \gamma^{(*)}\gamma^{(*)})$

Measurable form factors

Space-like



Time-like



Transition Form Factors

Input to a_μ^{SM}

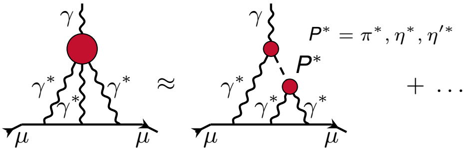
3-4σ discrepancy in $a_\mu^{SM} - a_\mu^{exp}$ — Data driven efforts to reduce theoretical error [12,13].

[12] *G. Colangelo, et al. Phys.Lett. B738 (2014) 6-12* [13] *V. Pauk, et al., Phys.Rev. D90 (2014) no.11, 113012*

Theory contribution	$a_\mu \times 10^{11}$
QED[14]	115965218.178(0.077)
EW[15]	153.6(1.0)
Strong[16]	
HVP	6793.6(41.4)
HLbL	103(29)

[14] *Aoyama, et al., Phys.Rev.Lett. 109 (2012) 111808*
[15] *Gnendiger, et al, Phys.Rev. D88 (2013) 053005*
[16] *Jegerlehner, arXiv:1705.00263 [hep-ph]*

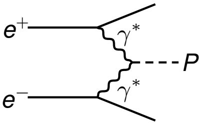
Hadronic light-by-light scattering:



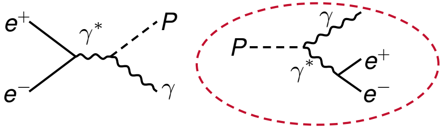
$\rightarrow \quad \mathcal{F}(P^* \rightarrow \gamma^{(*)}\gamma^{(*)})$

Measurable form factors

Space-like

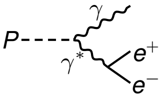


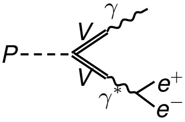
Time-like



Transition Form Factors

Dalitz decays





Study of

- $P \to \gamma l^+ l^-$
- $V \to P l^+ l^-$

Extracting the form factor

- Normalised FF — $F_P(q^2, 0) = \dfrac{\mathcal{F}_P(q^2, 0)}{\mathcal{F}_P(0, 0)}$
- $\dfrac{d\Gamma(P \to \gamma e^+ e^-)}{dq^2 \Gamma(P \to \gamma\gamma)} = [QED]_P \left|F_P(q^2, 0)\right|^2$
- Compare results — VMD-inspired parametrisation $F(q^2, 0) \approx 1 + \Lambda^{-2} q^2$

$P \to \gamma e^+ e^-$

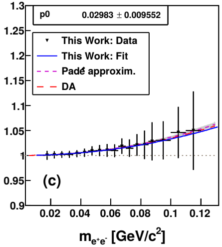
$\pi^0 \to \gamma e^+ e^-$

- A2[17] $\gamma p \to \pi^0 p$ $4 \cdot 10^5$ events

$a_\pi = 0.030(10)$ $\left[\frac{a_\pi}{m^2_{\pi^0}} = \Lambda^{-2} \right]$

$\sim$ factor 2 better precision from NA62.

$\to$ Future plans from A2 to match.



[17] *P. Adlarson, et al., Phys.Rev. C95 (2017) no.2, 025202*

$P \to \gamma e^+ e^-$

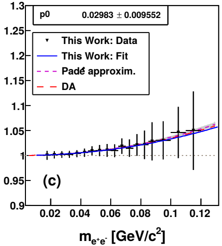
$\pi^0 \to \gamma e^+ e^-$

- A2[17] $\gamma p \to \pi^0 p$ $4 \cdot 10^5$ events

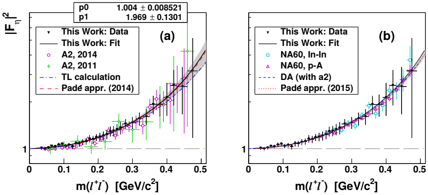
$a_\pi = 0.030(10)$ $\left[\frac{a_\pi}{m^2_{\pi^0}} = \Lambda^{-2}\right]$

$\sim$ factor 2 better precision from NA62.

$\to$ Future plans from A2 to match.



17 P. Adlarson, et al., Phys.Rev. C95 (2017) no.2, 025202



$\eta \to \gamma e^+ e^-$

- A2[18] $\gamma p \to \eta p$ $5.4 \cdot 10^4$ events
  Good experiment - theory agreement.
- Ongoing study with WASA[19] $pp \to pp\eta$

18 P. Adlarson, et al., Phys.Rev. C95 (2017) no.3 035208
19 A. Goswami, JPS Conf.Proc. 13 (2017) 020032

JG|U

$P \to \gamma e^+ e^-$

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

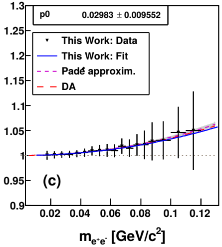
- A2[17] $\gamma p \to \pi^0 p$ $4 \cdot 10^5$ events

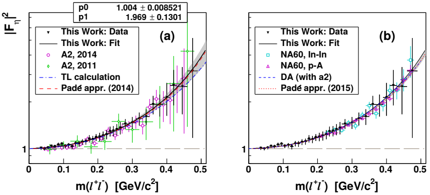
$a_\pi = 0.030(10)$ $\left[\frac{a_\pi}{m^2_{\pi^0}} = \Lambda^{-2} \right]$

$\sim$ factor 2 better precision from NA62.

$\to$ Future plans from A2 to match.

17 P. Adlarson, et al., Phys.Rev. C95 (2017) no.2, 025202





$\eta \to \gamma e^+ e^-$

- A2[18] $\gamma p \to \eta p$ $5.4 \cdot 10^4$ events
  Good experiment - theory agreement.
- Ongoing study with WASA[19] $pp \to pp\eta$

18 P. Adlarson, et al., Phys.Rev. C95 (2017) no.3 035208
19 A. Goswami, JPS Conf.Proc. 13 (2017) 020032

$\eta' \to \gamma e^+ e^-$

- Ongoing study with A2[20] $\gamma p \to \eta' p$
  m_{ee} up to 840 MeV — cover ρ peak

20 O. Steffen, EPJ Web Conf. 142 (2017) 01027

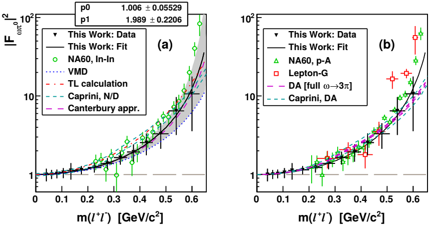
$V \to Pe^+e^-$

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

Significant disagreement between theory – experiment (NA60, Lepton-G)

- A2[21] $\gamma p \to \omega p$ 1100 events
  $\Lambda^{-2}_{\omega\pi^0} = 1.99(22_{tot})$ GeV^{-2}

21 *P. Adlarson et al., Phys.Rev. C95 (2017) no.3, 035208*



$V \to Pe^+e^-$

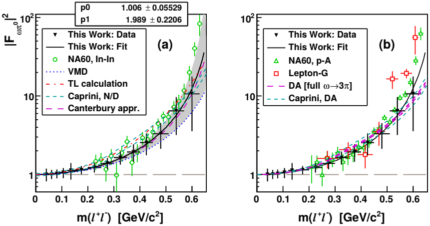
$\omega \to \pi^0 e^+ e^-$

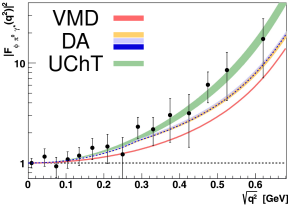
Significant disagreement between theory – experiment (NA60, Lepton-G)

- A2[21] $\gamma p \to \omega p$ 1100 events

  $\Lambda^{-2}_{\omega\pi^0} = 1.99(22_{tot})\ \text{GeV}^{-2}$

21 *P. Adlarson et al., Phys.Rev. C95 (2017) no.3, 035208*





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

- KLOE[22] $e^+e^- \to \phi$ 9500 events (First!)

  Cover higher m_{ee} region — closer look at discrepancy.

  $\Lambda^{-2}_{\Phi\pi^0} = 2.02(11)\ \text{GeV}^{-2}$

22 *A. Anastasi et al., Phys.Lett. B757 (2016) 362-367*

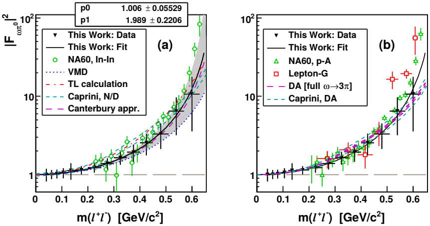
$V \to P e^+ e^-$

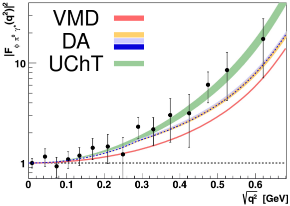
$\omega \to \pi^0 e^+ e^-$

Significant disagreement between theory – experiment (NA60, Lepton-G)

- A2[21] $\gamma p \to \omega p$ 1100 events
  $\Lambda^{-2}_{\omega\pi^0} = 1.99(22_{tot})$ GeV^{-2}

[21] P. Adlarson et al., Phys.Rev. C95 (2017) no.3, 035208





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

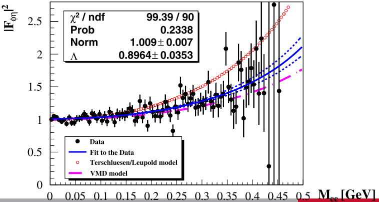
- KLOE[22] $e^+e^- \to \phi$ 9500 events (First!)
  Cover higher m_{ee} region — closer look at discrepancy.
  $\Lambda^{-2}_{\Phi\pi^0} = 2.02(11)$ GeV^{-2}

[22] A. Anastasi et al., Phys.Lett. B757 (2016) 362-367

$\phi \to \eta e^+ e^-$

- KLOE[23] $e^+e^- \to \phi$ $\sim 3 \cdot 10^4$ events
  Better correspondence to VMD.
  $\Lambda^{-2}_{\Phi\eta} = 1.17(10)^{(+7)}_{(-11)}$ GeV^{-2}

[23] D. Babusci et al., Phys.Lett. B742 (2015) 1-6



JG|U

Summary

Studies of light meson decays

- WASA-at-COSY — *pp* / *pd*
- KLOE — e^+e^-
- A2 — $p\gamma$

- Dalitz plot studies

$\eta \to 3\pi$	—	Light quark mass ratio
$\omega \to 3\pi$	—	$\pi\pi$ dynamics
$\eta' \to \eta\pi\pi$	—	$\pi\pi$ S-wave scattering lenghts

- Transition form factors

$P \to \gamma e^+e^-$	—	Good theory accord
$V \to Pe^+e^-$	—	Theory disagreement

JG|U

Summary

Studies of light meson decays

- WASA-at-COSY — *pp* / *pd*
- KLOE — e^+e^-
- A2 — $p\gamma$

- Dalitz plot studies

$\eta \to 3\pi$ — Light quark mass ratio
$\omega \to 3\pi$ — $\pi\pi$ dynamics
$\eta' \to \eta\pi\pi$ — $\pi\pi$ S-wave scattering lenghts

- Transition form factors

$P \to \gamma e^+e^-$ — Good theory accord
$V \to Pe^+e^-$ — Theory disagreement

Thank you for your attention!

Backup — $\eta \to \pi^+\pi^-\pi^0$

TABLE I: Summary of Dalitz plot parameters from experiments and theoretical predictions.

Experiment	$-a$	b	d	f	$-g$
Gormley(70) [16]	1.17 ± 0.02	0.21 ± 0.03	0.06 ± 0.04	–	–
Layter(73) [17]	1.080 ± 0.014	0.03 ± 0.03	0.05 ± 0.03	–	–
CBarrel(98) [18]	1.22 ± 0.07	0.22 ± 0.11	0.06(fixed)	–	–
KLOE(08) [19]	$1.090 \pm 0.005^{+0.019}_{-0.008}$	$0.124 \pm 0.006 \pm 0.010$	$0.057 \pm 0.006^{+0.007}_{-0.016}$	$0.14 \pm 0.01 \pm 0.02$	–
WASA(14) [20]	1.144 ± 0.018	$0.219 \pm 0.019 \pm 0.047$	$0.086 \pm 0.018 \pm 0.015$	0.115 ± 0.037	–
BESIII(15) [21]	$1.128 \pm 0.015 \pm 0.008$	$0.153 \pm 0.017 \pm 0.004$	$0.085 \pm 0.016 \pm 0.009$	$0.173 \pm 0.028 \pm 0.021$	–
Calculations					
ChPT LO [10]	1.039	0.27	0	0	–
ChPT NLO [10]	1.371	0.452	0.053	0.027	–
ChPT NNLO [10]	1.271 ± 0.075	0.394 ± 0.102	0.055 ± 0.057	0.025 ± 0.160	–
dispersive [22]	1.16	0.26	0.10	–	–
simplified disp [5]	1.21	0.33	0.04	–	–
NREFT [12]	1.213 ± 0.014	0.308 ± 0.023	0.050 ± 0.003	0.083 ± 0.019	0.039 ± 0.002
UChPT [11]	1.054 ± 0.025	0.185 ± 0.015	0.079 ± 0.026	0.064 ± 0.012	–

KLOE(16)	$1.095(3)^{+(3)}_{-(2)}$	$0.145(3)(5)$	$0.081(3)^{+(6)}_{-(5)}$	$0.141(7)^{+(7)}_{-(8)}$	$0.044(9)^{+(12)}_{-(13)}$	xFit

A. Anastasi, et al., JHEP 1605 (2016) 019

Backup — $\omega \to \pi^+\pi^-\pi^0$

TABLE I: Dalitz Plot parameters and $\sqrt{\bar{\chi}^2}$ of the polynomial parametrization (40) for $\omega \to 3\pi$. In addition to our results we also show the selected results from Niecknig et al. [37] (dispersive study with incorporated crossed-channel effects) and Terschlusen et al. [19] (Lagrangian based study with the pion-pion rescattering effects).

	$\alpha \times 10^3$	$\beta \times 10^3$	$\gamma \times 10^3$	$\delta \times 10^3$	$\sqrt{\bar{\chi}^2} \times 10^3$
This paper ($\hat{F}=0$)	136	-	-	-	3.5
This paper (full)	94	-	-	-	3.2
Niecknig et al. [37]	84...96	-	-	-	0.9...1.1
Terschlusen et al. [19]	202	-	-	-	6.6
This paper ($\hat{F}=0$)	125	30	-	-	0.74
This paper (full)	84	28	-	-	0.35
Niecknig et al. [37]	74...84	24...28	-	-	0.052...0.078
Terschlusen et al. [19]	190	54	-	-	2.1
This paper ($\hat{F}=0$)	113	27	24	-	0.1
This paper (full)	80	27	8	-	0.24
Niecknig et al. [37]	73...81	24...28	3...6	-	0.038...0.047
Terschlusen et al. [19]	172	43	50	-	0.4
This paper ($\hat{F}=0$)	114	24	20	6	0.005
This paper (full)	83	22	1	14	0.079
Niecknig et al. [37]	74...83	21...24	0...2	7...8	0.012...0.011
Terschlusen et al. [19]	174	35	43	20	0.1

I. Danilkin, et al., Phys.Rev. D91 (2015) no.9, 094029

WASA(17) $\alpha = 147(36) \times 10^3$

P. Adlarson, et al., Phys.Lett. B770 (2017) 418-425

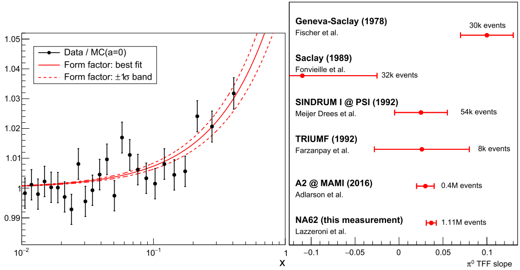
Backup — $V \to \gamma e^+ e^-$

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

- NA62

$a_\pi = 0.0368(57)$ $\left[\frac{a_\pi}{m^2_{\pi^0}} = \Lambda^{-2}\right]$

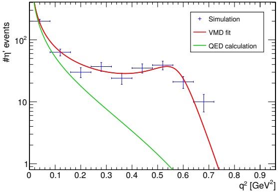
C. Lazzeroni, et al., Phys.Lett. B768 (2017) 38-45



$\eta' \to \gamma e^+ e^-$

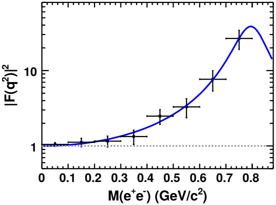
- Ongoing study with A2

A2 - simulation



O. Steffen, EPJ Web Conf. 142 (2017) 01027

- BESIII — $\Lambda^{-2} = 1.60 \pm 0.17_{stat} \pm 0.08_{sys}$ GeV^{-2}
  $\Lambda^{-2}_{VMD} = 1.45$ GeV^{-2} and $\Lambda^{-2}_{\chi PT} = 1.60$ GeV^{-2}



M. Ablikim et al., Phys.Rev. D92 (2015) no.1, 012001