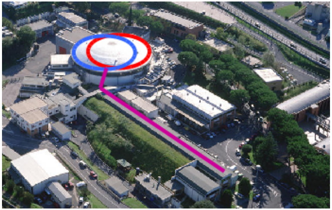
Measurement of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution at KLOE

Li Caldeira Balkeståhl
on behalf of the KLOE-2 collaboration

Department of Physics and Astronomy
Uppsala University

2015-06-26

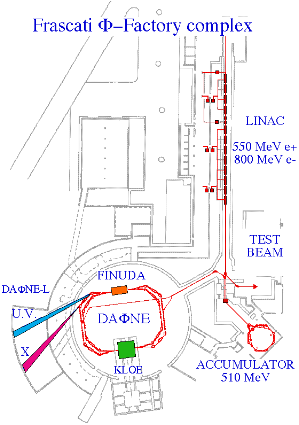
DAϕNE ϕ factory



- e^+e^- collider at $\sqrt{s} = \mathrm{M}_\phi$ (1020 MeV)
- 2 interaction regions
- separate e^+e^- rings
- $\sim$ 100 bunches
- 2.7 ns bunch spacing
- $I^{-/+}_{peak} \sim 2.4/1.5$ A
- $\theta_{cross} = 2 \cdot 12.5$ mrad

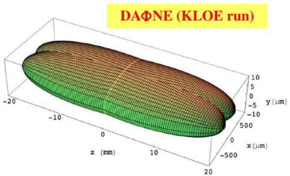
Best performances (1999-2006)

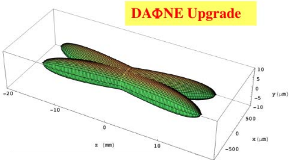
- $\mathrm{L}_{peak} = 1.4 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int \mathrm{L}\ \mathrm{dt} = 8.5\mathrm{pb}^{-1}/\mathrm{day}$

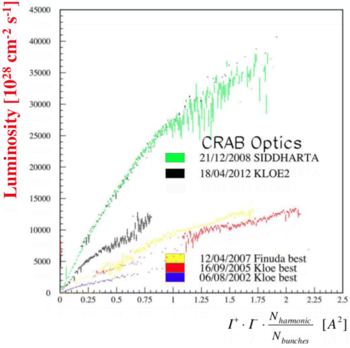


DAϕNE new interaction scheme

- large angle beam crossing
- $\theta_{cross} = 2 \cdot 25$ mrad
- smaller horizontal beam size
- crabbed waist sextupoles



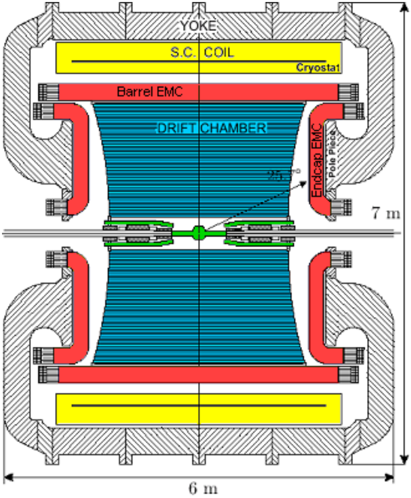




KLOE-2 run

- $L_{peak} = 2.0 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$ (so far)
- higher background levels than in the past

KLOE Experiment



KLOE: DC and EMC in ~ 0.52T

Drift Chamber (4 m diameter, 3.75m long)

- Gas Mixture 90% He +10% C_4H_{10}
- $\sigma_{xy} = 150\ \mu$m; $\sigma_z = 2$ mm
- $\frac{\delta p_t}{p_t} < 0.4\%$ $(\theta > 45^\circ)$

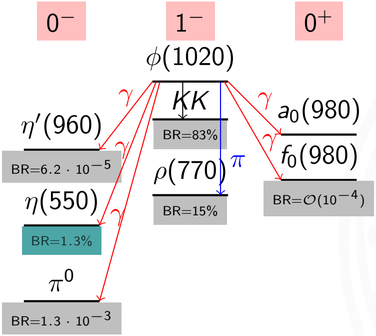
Electromagnetic Calorimeter

- lead/scintillating fibers
- 98% solid angle coverage
- $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(\mathrm{GeV})}}$
- $\sigma_t = \frac{57\ \mathrm{ps}}{\sqrt{E(\mathrm{GeV})}} \oplus 140$ ps
- PID capabilities

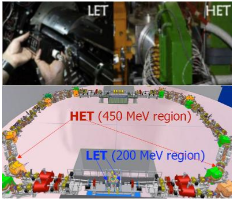
KLOE data taking

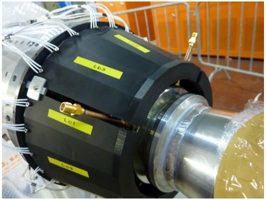
KLOE data taking 2001-2006

- 2.5 fb^{-1} at $\sqrt{s} = M_\phi$ ($\sim 8 \cdot 10^9$ ϕ produced)
- ~ 10 pb^{-1} scan ($1010, 1018, 1023, 1030$ MeV)
- 250 pb^{-1} at 1000 MeV

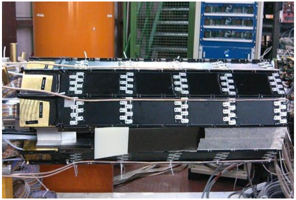


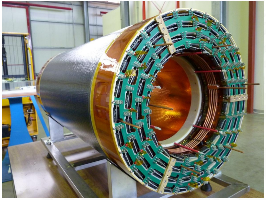
KLOE-2 Upgrade





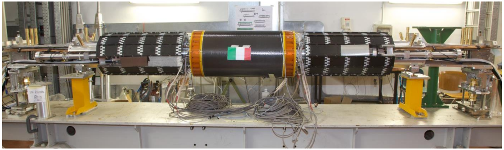
- 2+2 taggers (for $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$)
- 2 new calorimeters (for low angle γs from IR & γs from K_L decays)
- Inner tracker (cylindrical GEM, for better vertex reconstruction and larger low p_t track acceptance)

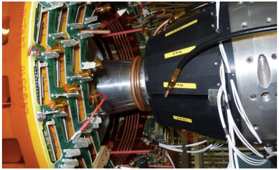


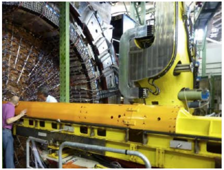


KLOE-2 Upgrade

- New detectors installed
- KLOE-2 runs since November 2014
  fully operational detectors

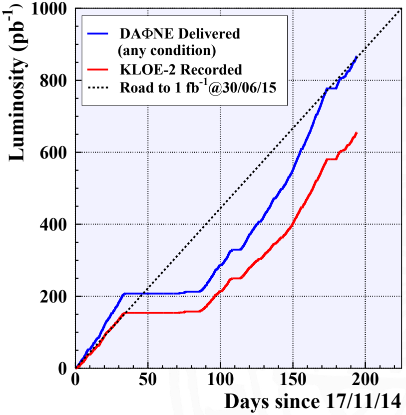






KLOE-2 Upgrade

- Milestone:
  1 fb^{-1} until end of June
- Goal:
  $\geq 5\ \mathrm{fb}^{-1}$ in next 2-3 years



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

η meson:

- quark composition $\sim \frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$
- mass $m = 547.862(18)$ MeV
- full width $\Gamma = 1.31(5)$ keV
- $I^G = 0^+$, $J^{PC} = 0^{-+}$

π^0 meson:

- mass $m = 134.9766(6)$ MeV
- $I^G = 1^-$, $J^{PC} = 0^{-+}$
- $\pi^0 \to \gamma\gamma$ BR$\sim$ 99%
- $\pi^0 \to e^+e^-\gamma$ BR$\sim$ 1%

Main decays:
(BR - branching ratio)

- $\eta \to \gamma\gamma$ BR$\sim$ 39%
- $\eta \to 3\pi^0$ BR$\sim$ 33%
- $\eta \to \pi^+\pi^-\pi^0$ BR$\sim$ 23%
- $\eta \to \pi^+\pi^-\gamma$ BR$\sim$ 4%

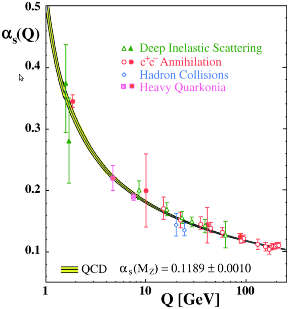
$\pi^{+/-}$ mesons:

- mass $m = 139.57018(35)$ MeV
- $I^G = 1^-$, $J^P = 0^-$

Theory: QCD to ChPT

Quantum Chromodynamics (QCD)

- theory of the strong interaction
- α_s strong interaction coupling



(figure from Prog.Part.Nucl.Phys. 58 (2013) 351-386)

At high energies

- perturbative QCD
- very successful

At low energies

- lattice QCD
- effective field theory: ChPT

Chiral Perturbation Theory (ChPT)

- (approximate) chiral symmetry of QCD
- other symmetries of QCD
- degrees of freedom: π, K, η
- perturbative expansion in powers of momenta

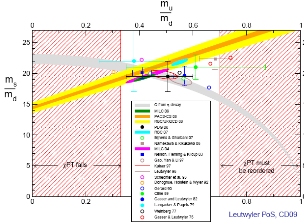
Theory: $\eta \to \pi^+\pi^-\pi^0$

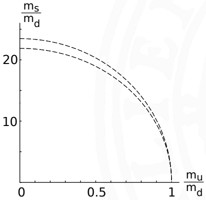
Slow convergence of ChPT for calculations of $\Gamma(\eta \to \pi^+\pi^-\pi^0)$:

- $\Gamma_{LO} \sim 70$ eV
- $\Gamma_{LO+NLO} = 160 \pm 50$ eV
- $\Gamma_{LO+NLO+NNLO} = 298$ eV
- $\Gamma_{exp} = 300 \pm 11$ eV

$$\text{In ChPT} \quad \Gamma(\eta \to \pi^+\pi^-\pi^0) \propto Q^{-4}$$

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \qquad \hat{m} = \frac{1}{2}(m_d + m_u)$$

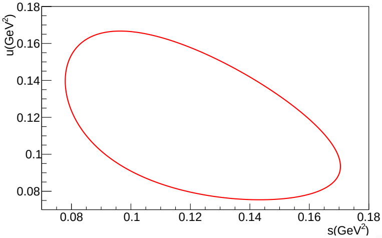




Dalitz plot

$2 \to 2$ scattering or $1 \to 3$ decay

- amplitude (A) depends on 2 variables
- usually 2 of the Mandelstam variables
  ($e.g.$ $s = (P_\eta - P_{\pi^0})^2$, $u = (P_\eta - P_{\pi^-})^2$)
- $\Gamma(\eta \to \pi^+\pi^-\pi^0) = \int |A(s,u)|^2 dsdu$ (over the physical region)



$|A(s,u)|^2$: Dalitz plot distribution

$\eta \to \pi^+\pi^-\pi^0$ Dalitz plot variables

In the η-rest frame:

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

$$Y = \frac{3T_0}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta}\left[(m_\eta - m_{\pi^0})^2 - s\right] - 1$$

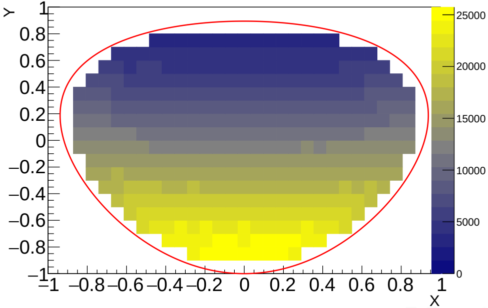
where

$Q_\eta = T_+ + T_- + T_0 = m_\eta - 2m_{\pi^+} - m_{\pi^0}$

T_+, T_-, T_0 kinetic energies of the π^+, π^-, π^0

s, u, t are the Mandelstam variables

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



Compare theory and experiment

Dalitz plot parameters

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

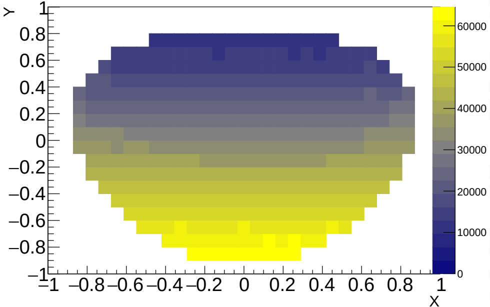
Previous results

Experiment	$-a$	b	d	f	g
Gormley(70)	1.17(2)	0.21(3)	0.06(4)	-	-
Layter (73)	1.080(14)	0.03(3)	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)	-
WASA (14)	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)	-
BESIII(15)	1.128(15)(8)	0.153(17)(4)	0.085(16)(9)	0.173(28)(21)	-

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

New KLOE analysis

- More data ($\sim 1.6\ \mathrm{fb}^{-1}$), different data set (2004-2005 period)
- Reduction of systematic errors
  - Monte Carlo description has been improved
  - Event classification effect cross-checked directly on prescaled data sample
- Provide Dalitz plot parameters
- Provide acceptance corrected, binned data

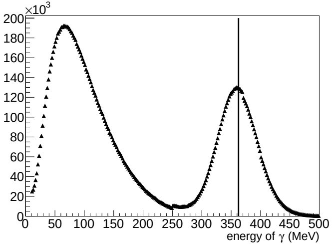


Signal Selection and Reconstruction

Signal reaction: $\eta \to \pi^+\pi^-\pi^0$

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

Data:
energy of 3 selected photons



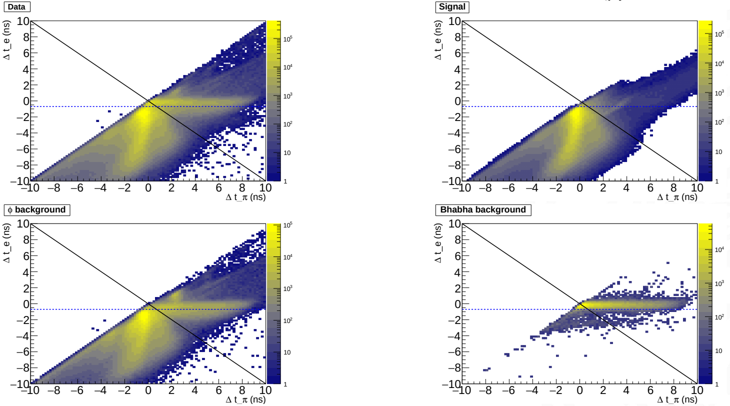
Selection steps

- ≥ 3 photons in EMC
- most energetic photon ($E_\gamma > 250$ MeV) assumed γ_ϕ
- P_{π^-} and P_{π^+}: measured tracks in DC (assume m_π)
- $P_\eta = P_\phi - P_{\gamma_\phi}$ decay
- $P_{\pi^0} = P_\eta - P_{\pi^-} - P_{\pi^+}$
- select γ's from π^0 decay by opening angle

Background rejection

Cuts to reject Bhabha scattering events:

- a graphical cut on the angle between the γ's and charged π's momenta
- particle identification with time-of-flight
  Δt between DC track and EMC cluster for π and e hypothesis

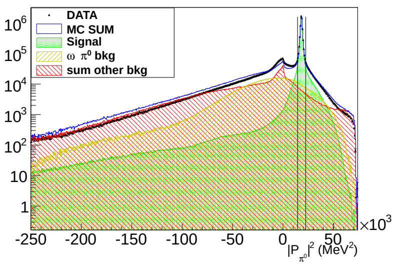


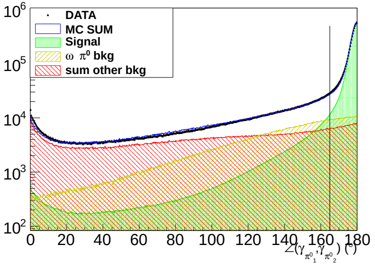
Background rejection

Cuts

- $||P_{\pi^0}| - m_{\pi^0}| < 15$ MeV (figure of $P^2_{\pi^0}$)
- Opening angle between π^0-decay γ's in the π^0 rest frame ($> 165°$)

Signal efficiency $\epsilon_{sig} = 38\%$

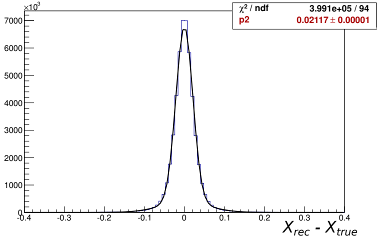


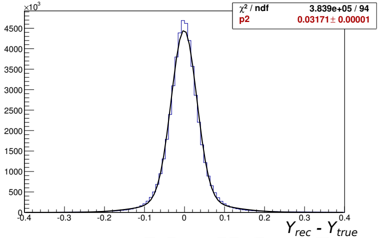


- Fit of MC to data to get scaling factors for background
- Scaling factor from opening angle, difference to missing mass as error

Dalitz plot variables - resolution

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



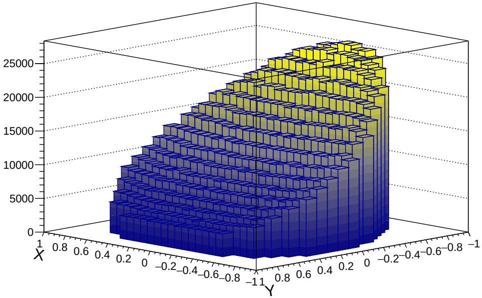


Taking the width of the "core" Gaussian as an estimate of the resolution:

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

31 x 20 bins, $\Delta X = 3.07\delta X \quad \Delta Y = 3.12\delta Y$

Dalitz plot



$(4.699 \pm 0.007) \cdot 10^6$ events

Fit distribution to get $a, b, \ldots$

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

Dalitz plot parameter fit

Minimize

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

with:

- $N_{theory} = \int |A(X,Y)|^2 dPh(X,Y)$
- $N_i = N_{data,i} - s_1 B_{i1} - s_2 B_{i2}$ background subtracted data content in bin i
- $\tilde{\epsilon}_j$ acceptance of bin j
- S_{ij} smearing matrix from bin j to bin i in the Dalitz plot
- Use $\hat{s}_{ij} = S_{ij} \cdot \tilde{\epsilon}_j = \frac{N_{rec,i;gen,j}}{N_{gen,j}}$
- $\sigma_i^2 = \sigma_{N_i}^2 + \sigma_{\hat{s}_{ij}}^2$, error in bin i
  $\sigma_{N_i}^2 = N_{data,i} + s_1^2 \cdot B_{i1} + \sigma_{s_1}^2 \cdot B_{i1}^2 + s_2^2 \cdot B_{i2} + \sigma_{s_2}^2 \cdot B_{i2}^2$
  $\sigma_{\hat{s}_{ij}}^2 = \sum_{j=1}^{Nbins} N_{theory,j}^2 \cdot \frac{\hat{s}_{ij} \cdot (1-\hat{s}_{ij})}{N_{gen,j}}$

Fit Results

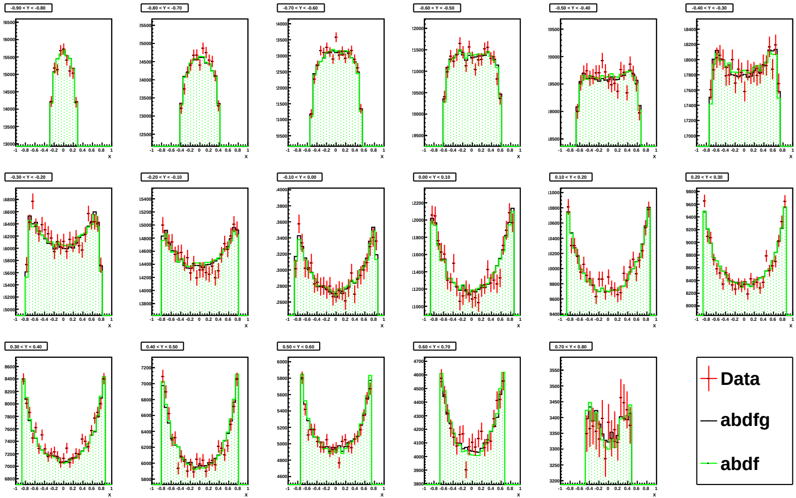
Number of bins: 371

a	$b{\cdot}10^1$	$d{\cdot}10^2$	$f{\cdot}10^1$	$g{\cdot}10^2$	χ^2	Prob
-1.104 ± 0.002	1.533 ± 0.028	6.75 ± 0.27	-	-	1007	10^{-60}
-1.104 ± 0.003	1.420 ± 0.029	7.26 ± 0.27	1.54 ± 0.06	-	385	0.24
-1.095 ± 0.003	1.454 ± 0.030	8.11 ± 0.33	1.41 ± 0.07	-4.37 ± 0.89	360	0.56
-1.095 ± 0.003	1.454 ± 0.030	8.11 ± 0.32	1.41 ± 0.07	-4.37 ± 0.89	354	0.60

Last row also:

$$c \cdot 10^3 = 4.34 \pm 3.39, \qquad e \cdot 10^3 = 2.52 \pm 3.20,$$
$$h \cdot 10^2 = 1.07 \pm 0.90, \qquad l \cdot 10^3 = 1.08 \pm 6.54$$

Fit and data comparison



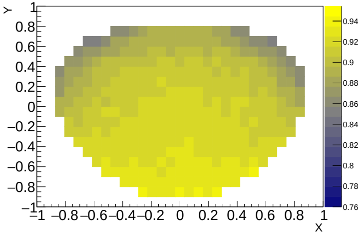
Systematic checks

- Minimum photon energy cut: standard cut 10 MeV, varied to 15 MeV and 20 MeV
- Background subtraction: scaling factors for each bin separately
- Choice of binning: varied the number of bins $\sim 2\delta_{X,Y}$ to $\sim 5\delta_{X,Y}$ (10 configurations)
- Track-photon angle cut: area of graphical cut varied by $\pm 10\%$
- Time of flight: two cuts varied separately
- Photon opening angle cut: varying the cut in steps of $3^\circ \sim 1\sigma$
- Missing mass cut: varying the cut in steps of 2.0 MeV$\sim 1\sigma$
- Event classification procedure: checked with a prescaled data sample without the event classification constraints, evaluated from MC

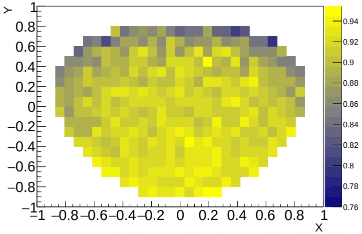
Event classification procedure

Ratio of Dalitz plot distribution with and without event classification

- in signal MC: $91.490 \pm 0.004\%$
- in prescaled (1/20) data: $91.45 \pm 0.05\%$



Signal



Prescaled data

Effect of the event classification on signal MC as systematic effect

Summary of systematic errors

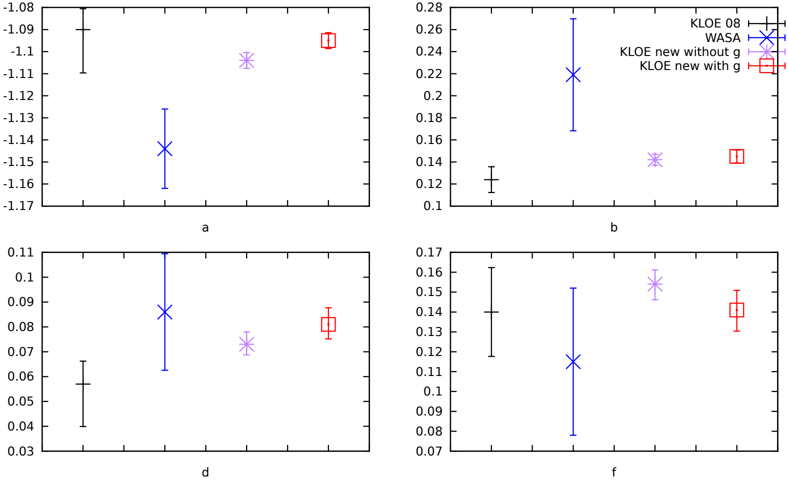
	-a	b	d	f	g
prel result	$1.095(3)(^{+3}_{-2})$	$0.145(3)(5)$	$0.081(3)(^{+6}_{-5})$	$0.141(7)(^{+7}_{-8})$	$-0.044(9)(^{+12}_{-13})$
syst err	Δa	Δb	Δd	Δf	Δg
E_γ min	± 0.0006	± 0.0012	± 0.0010	± 0.0005	± 0.0016
bkg sub	± 0.0008	± 0.0007	± 0.0011	± 0.0006	± 0.0038
binning	± 0.0017	± 0.0013	± 0.0009	± 0.0036	± 0.0044
track-photon	$^{+0}_{-0.0001}$	$^{+0}_{-0.0002}$	$^{+0.0002}_{-0.0002}$	$^{+0.0003}_{-0}$	$^{+0.0003}_{-0.0002}$
TOF hor	$^{+0.0006}_{-0.0011}$	$^{+0.0012}_{-0.0001}$	$^{+0.0018}_{-0.0001}$	$^{+0.0003}_{-0.0008}$	$^{+0.0026}_{-0.0054}$
TOF diag	$^{+0}_{-0}$	$^{+0}_{-0.0001}$	$^{+0.0003}_{-0.0001}$	$^{+0}_{-0}$	$^{+0.0002}_{-0.0001}$
γ angle	$^{+0.0014}_{-0.0005}$	$^{+0.0002}_{-0.0001}$	$^{+0.0021}_{-0.0012}$	$^{+0.0005}_{-0.0025}$	$^{+0.0026}_{-0.0038}$
miss mass	$^{+0.0008}_{-0.0010}$	$^{+0.0046}_{-0.0043}$	$^{+0.0049}_{-0.0045}$	$^{+0.0057}_{-0.0062}$	$^{+0.0100}_{-0.0092}$
event class	± 0.0000	± 0.0008	± 0.0006	± 0.0009	± 0.0012
sum	$^{+0.0026}_{-0.0025}$	$^{+0.0052}_{-0.0048}$	$^{+0.0059}_{-0.0050}$	$^{+0.0069}_{-0.0077}$	$^{+0.0123}_{-0.0129}$

Experimental results

Experiment	$-a$	b	d	f	g
Gormley(70)	1.17(2)	0.21(3)	0.06(4)	-	-
Layter(73)	1.080(14)	0.03(3)	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)	-
WASA(14)	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)	-
BESIII(15)	1.128(15)(8)	0.153(17)(4)	0.085(16)(9)	0.173(28)(21)	-
this work	$1.095(3)(^{+3}_{-2})$	0.145(3)(5)	$0.081(3)(^{+6}_{-5})$	$0.141(7)(^{+7}_{-8})$	$-0.044(9)(^{+12}_{-13})$
this work	1.104(3)(2)	$0.142(3)(^{+5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$	-

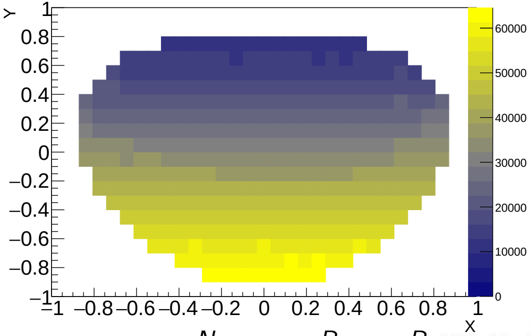
Preliminary

Experimental results



Systematic and statistical errors added in quadrature

Acceptance corrected data



$$N_i = \frac{N_{data,i} - s_1 B_{i1} - s_2 B_{i2}}{\epsilon_i}$$

$$\text{with } \epsilon_i = \frac{N_{rec,i}}{N_{gen,i}}$$

Agreement with full results

Full smearing matrix (preliminary)	Acceptance corrected data
$a = -1.095(3)(^{+3}_{-2})$	$a = -1.092(3)$
$b = 0.145(3)(5)$	$b = 0.145(3)$
$d = 0.081(3)(^{+6}_{-5})$	$d = 0.081(3)$
$f = 0.141(7)(^{+7}_{-8})$	$f = 0.137(6)$
$g = -0.044(9)(^{+12}_{-13})$	$g = -0.044(8)$
$a = -1.104(3)(2)$	$a = -1.101(3)$
$b = 0.142(3)(^{+5}_{-4})$	$b = 0.142(3)$
$d = 0.073(3)(^{+4}_{-3})$	$d = 0.072(3)$
$f = 0.154(6)(^{+4}_{-5})$	$f = 0.150(6)$

Acceptance corrected data: simpler, approximate way to compare experimental distribution to theory

Summary

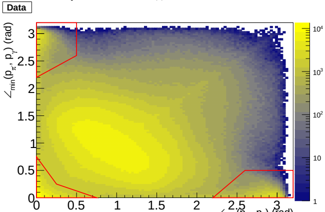
- New high statistics, precision measurement of $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution
  - Dalitz plot parameters and acceptance corrected distribution
  - first measurement of g parameter ($\sim 3\sigma$ level)
  - paper in preparation
  - work in progress: extract Q^2 in collaboration with Emilie Passemar

- KLOE-2 data taking campaign ongoing
  - New detectors installed and working
  - Goal ≥ 5 fb^{-1} in 2-3 years

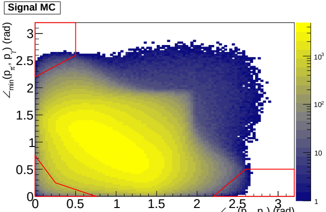
Thanks for your attention!

Cut to reject Bhabha events

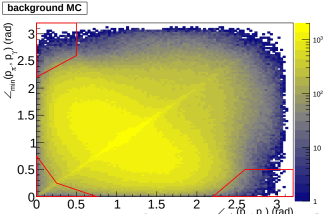
Smallest angle between γ (from π^0) and P_{π^+} *vs* smallest angle between γ (from π^0) and P_{π^-}



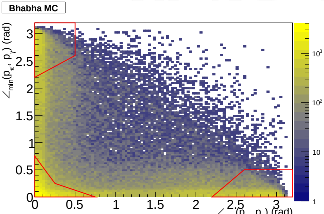
data



signal from allphys MC

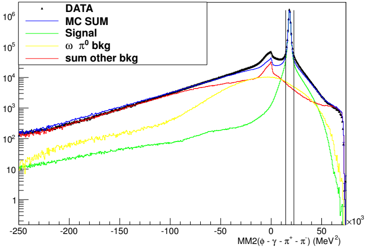


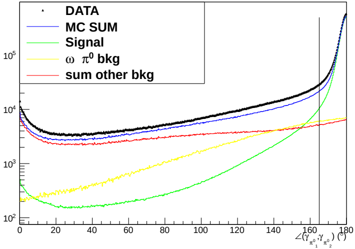
background from allphys MC



eeg background

Background scaling factors





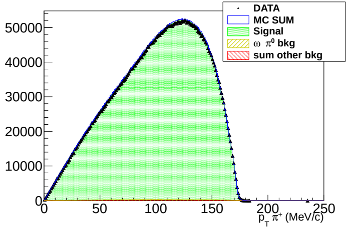
Fit of Monte Carlo to data to get scaling factors for background

Scaling factors	Signal	$\omega\pi^0$ background	rest background	χ^2
Opening angle	0.1109(1)	1.530(6)	1.222(3)	$7.2 \cdot 10^3$
Missing mass squared	0.1131(1)	1.839(5)	0.973(3)	$7.8 \cdot 10^4$

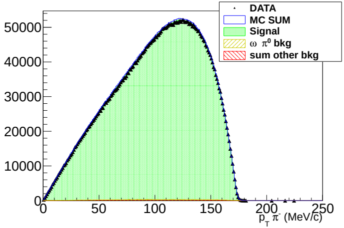
Scaling factor from opening angle, difference to missing mass as error

Data-MC comparison

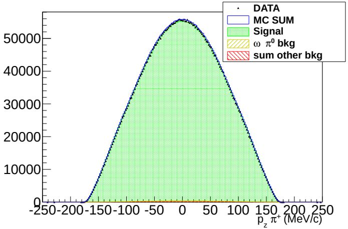
In the η rest frame



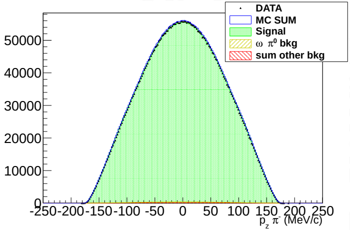
transverse momentum of π^+



transverse momentum of π^-

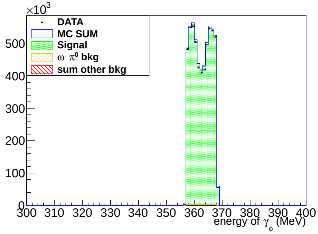


longitudinal momentum of π^+

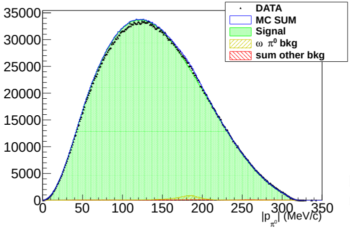


longitudinal momentum of π^-

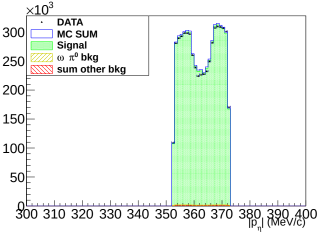
Comparison data-MC



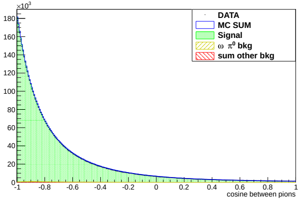
Energy of radiative photon



$|\vec{p_{\pi^0}}|$



$|\vec{p_\eta}|$



Cosine of angle between the charged π in the η rest frame

Fit Results

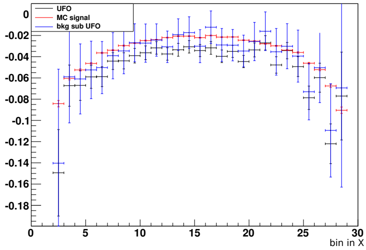
31 bins in $X \Leftrightarrow \Delta X = 3.07\sigma_x$,
20 bins in $Y \Leftrightarrow \Delta Y = 3.12\sigma_Y$
Number of bins: 371

a	$b \cdot 10^1$	$c \cdot 10^3$	$d \cdot 10^2$	$e \cdot 10^3$	$f \cdot 10^1$	$g \cdot 10^2$	$h \cdot 10^2$	$l \cdot 10^3$	χ^2	Prob
-1.095 ± 0.003	1.454 ± 0.030	-4.34 ± 3.39	8.11 ± 0.32	2.52 ± 3.20	1.41 ± 0.07	-4.37 ± 0.89	1.07 ± 0.90	1.08 ± 6.54	354	0.60
-1.095 ± 0.003	1.454 ± 0.031	-	8.12 ± 0.33	3.20 ± 3.71	1.41 ± 0.07	-4.37 ± 0.89	0.33 ± 0.68	-6.22 ± 3.03	356	0.58
-1.095 ± 0.003	1.454 ± 0.031	-4.68 ± 3.44	8.11 ± 0.33	-	1.41 ± 0.07	-4.37 ± 0.89	1.37 ± 0.84	1.96 ± 6.61	354	0.60
-1.035 ± 0.002	1.598 ± 0.029	-4.29 ± 3.45	9.14 ± 0.33	2.45 ± 3.62	-	-11.66 ± 0.84	1.06 ± 0.90	1.03 ± 6.72	792	10^{-34}
-1.104 ± 0.003	1.419 ± 0.031	-4.33 ± 3.39	7.26 ± 0.28	2.46 ± 3.67	1.54 ± 0.06	-	1.07 ± 0.89	1.09 ± 6.46	379	0.26
-1.095 ± 0.004	1.454 ± 0.030	-1.66 ± 2.54	8.11 ± 0.34	4.69 ± 3.25	1.41 ± 0.08	-4.37 ± 1.10	-	-2.43 ± 5.72	355	0.59
-1.095 ± 0.003	1.454 ± 0.030	-3.84 ± 1.66	8.11 ± 0.32	2.64 ± 3.55	1.41 ± 0.07	-4.37 ± 0.90	1.00 ± 0.82	-	354	0.61
-1.104 ± 0.002	1.533 ± 0.028	-	6.75 ± 0.27	-	-	-	-	-	1007	10^{-60}
-1.104 ± 0.003	1.420 ± 0.029	-	7.26 ± 0.27	-	1.54 ± 0.06	-	-	-	385	0.24
-1.104 ± 0.003	1.420 ± 0.029	-1.66 ± 1.08	7.26 ± 0.27	-	1.54 ± 0.06	-	-	-	383	0.25
-1.104 ± 0.003	1.420 ± 0.029	-	7.26 ± 0.27	1.49 ± 2.70	1.54 ± 0.06	-	-	-	385	0.28
-1.095 ± 0.003	1.454 ± 0.030	-	8.11 ± 0.33	-	1.41 ± 0.07	-4.37 ± 0.89	-	-	360	0.56
-1.104 ± 0.003	1.420 ± 0.028	-	7.26 ± 0.27	-	1.54 ± 0.06	-	0.07 ± 0.48	-	385	0.23
-1.104 ± 0.003	1.420 ± 0.029	-	7.26 ± 0.27	-	1.54 ± 0.06	-	-	-4.00 ± 2.59	383	0.25
-1.095 ± 0.003	1.454 ± 0.030	-	8.11 ± 0.33	-	1.41 ± 0.07	-4.37 ± 0.89	-	-	360	0.56
-1.095 ± 0.003	1.454 ± 0.030	-1.66 ± 1.09	8.11 ± 0.32	-	1.41 ± 0.07	-4.37 ± 0.88	-	-	358	0.58
-1.095 ± 0.003	1.454 ± 0.030	-	8.11 ± 0.32	1.53 ± 2.77	1.41 ± 0.07	-4.37 ± 0.88	-	-	360	0.55
-1.095 ± 0.003	1.454 ± 0.032	-	8.11 ± 0.36	-	1.41 ± 0.07	-4.37 ± 0.88	0.07 ± 0.49	-	360	0.55
-1.095 ± 0.003	1.454 ± 0.030	-	8.11 ± 0.32	-	1.41 ± 0.07	-4.37 ± 0.88	-	-4.02 ± 2.57	358	0.58

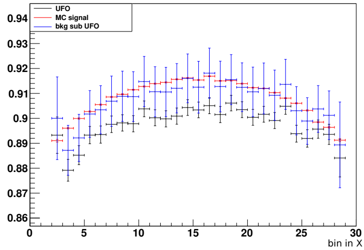
Event classification procedure

Fit the ratios with straight lines in X slices

Black - UFO, Red - MC signal, Blue - background subtracted UFO



slope



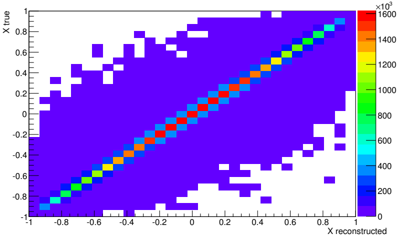
intersect

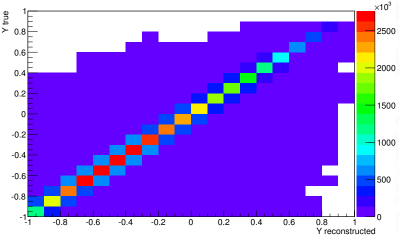
Good agreement

Close to diagonal smearing matrix

Percentage of reconstructed events in ___ that were generated in bin *I* to the total number of reconstructed events generated in bin *I*

- the same bin: 51.3 %
- in 9 closest bins (1 bin ring): 96.5%
- in 25 closest bins (2 bin ring): 98.6%





Percentage of events in

- *X* diagonal: 68.9 %
- *X* diagonal ±1 bin: 97.8%

- *Y* diagonal: 68.9 %
- *Y* diagonal ±1 bin: 97.1%

Summary of systematic errors

	-a	b	d	f
result	1.104(3)(2)	$0.142(3)(^{+5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
syst	Δa	Δb	Δd	Δf
E_γ min	± 0.0009	± 0.0010	± 0.0006	± 0.0000
bkg sub	± 0.0001	± 0.0005	± 0.0006	± 0.0008
γ-track	$+0$ -0.0001	$+0.0000$ -0.0002	$+0.0001$ -0.0001	$+0.0004$ -0
bin	± 0.0009	± 0.0014	± 0.0009	± 0.0026
TOF hor	$+0$ -0.0006	$+0.0014$ -0.0006	$+0.0007$ -0	$+0.0019$ -0.0015
TOF diag	$+0.0000$ -0.0000	$+0.0000$ -0.0001	$+0.0003$ -0.0000	$+0.0000$ -0.0000
γ angle	0.0006 -0.0000	0.0001 -0.0001	0.0014 -0.0008	0 -0.0013
$m\pi^0$	0.0010 -0.0010	0.0039 -0.0036	0.0031 -0.0026	0.0028 -0.0035
EVCL	± 0.0002	± 0.0009	± 0.0009	± 0.0013
sum	0.0018 -0.0018	0.0046 -0.0041	0.0038 -0.0031	0.0045 -0.0051

Previous results

Experiment	$-a$	b	d	f	g
Gormley(70)	1.17(2)	0.21(3)	0.06(4)	-	-
Layter (73)	1.080(14)	0.03(3)	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)	-
WASA (14)	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)	-

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

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**, page 006 (2008)
P. Adlarson *et al.* (WASA-at-COSY Collaboration), *Phys.Rev.* **C90**, 045207 (2014).

ChPT (LO, NLO, NNLO): J. Bijnens and K. Ghorbani, *JHEP* **0711**, 030 (2007).
dispersive: J. Kambor, C. Wiesendanger and D. Wyler, *Nucl.Phys.* **B465**, 215 (1996).
simplified disp: J. Bijnens and J. Gasser, *Phys.Scripta* **T99**, 34 (2002).
NREFT: S. P. Schneider, B. Kubis and C. Ditsche, *JHEP* **1102**, 028 (2011).
U ChPT: B. Borasoy and R. Nissler, *Eur.Phys.J.* **A26**, 383 (2005).