eta and eta' physics in KLOE

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on behalf of the KLOE-2 Collaboration

Presentation plan

- DAFNE collider, KLOE detector, data collected
- ϕ physics and eta/eta' basic properties

$\eta' \to \eta\pi^+\pi^-$ *[PLB 541 (2002) 45]*

$\eta \to \pi^+\pi^-$ *[PLB 606 (2005) 276]*

$\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$ *[PLB 648 (2007) 267]*

$\eta \to e^+e^-\pi^+\pi^-$ ***[PLB 675 (2009) 283]***

$\eta \to e^+e^-e^+e^-$ ***[PLB 702 (2011) 324]***

$\sigma(e^+e^- \to e^+e^-\eta)$ & $\Gamma(\eta \to \gamma\gamma)$ *[JHEP 01 (2013) 119]*

$\phi \to \eta e^+e^-$ *[PLB 742 (2015) 1]*

$\eta \to \gamma\gamma\gamma$ *[PLB 591 (2004) 49]*

η mass *[JHEP 12 (2007) 073]*

η/η' mixing *[JHEP 07 (2009) 105]*

$\eta \to \pi^\circ\pi^\circ\pi^\circ$ *[PLB 694 (2010) 16]*

$\eta \to \gamma\pi^+\pi^-$ *[PLB 718 (2013) 910]*

$\eta \to \pi^\circ\pi^+\pi^-$ ***[JHEP 1605 (2016) 019]***

- Perspectives/plans for the future
- Summary

DAFNE ϕ factory

- e^+e^- collider @$\sqrt{s} = M_\phi$(1020 MeV)
- Separate e^+e^- rings
- ~100 bunches spaced by 2.7ns
- **KLOE** data taking: 2001–2006
- Best peak/integrated luminosity:

  $L_{peak} = 1.4 \cdot 10^{32}\ cm^{-2}s^{-1}$

  $\int Ldt = 8.5\ pb^{-1}/day$

- **KLOE-2** started in Nov of 2014

  $L_{peak} = 2.2 \cdot 10^{32}\ cm^{-2}s^{-1}$

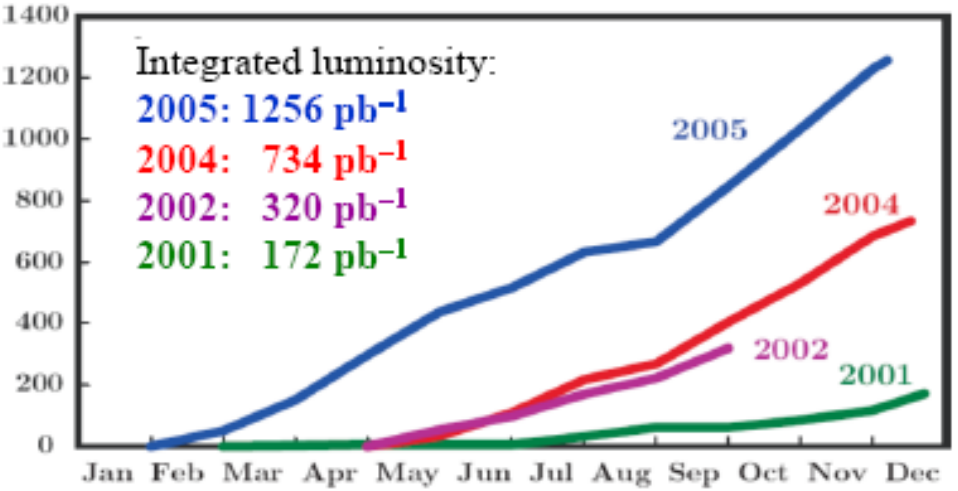
  $\int Ldt = 13.4\ pb^{-1}/day$

- KLOE-2 acquired **~4 fb^{-1}** with a goal of collecting >**5 fb^{-1}** for the end of March 2018

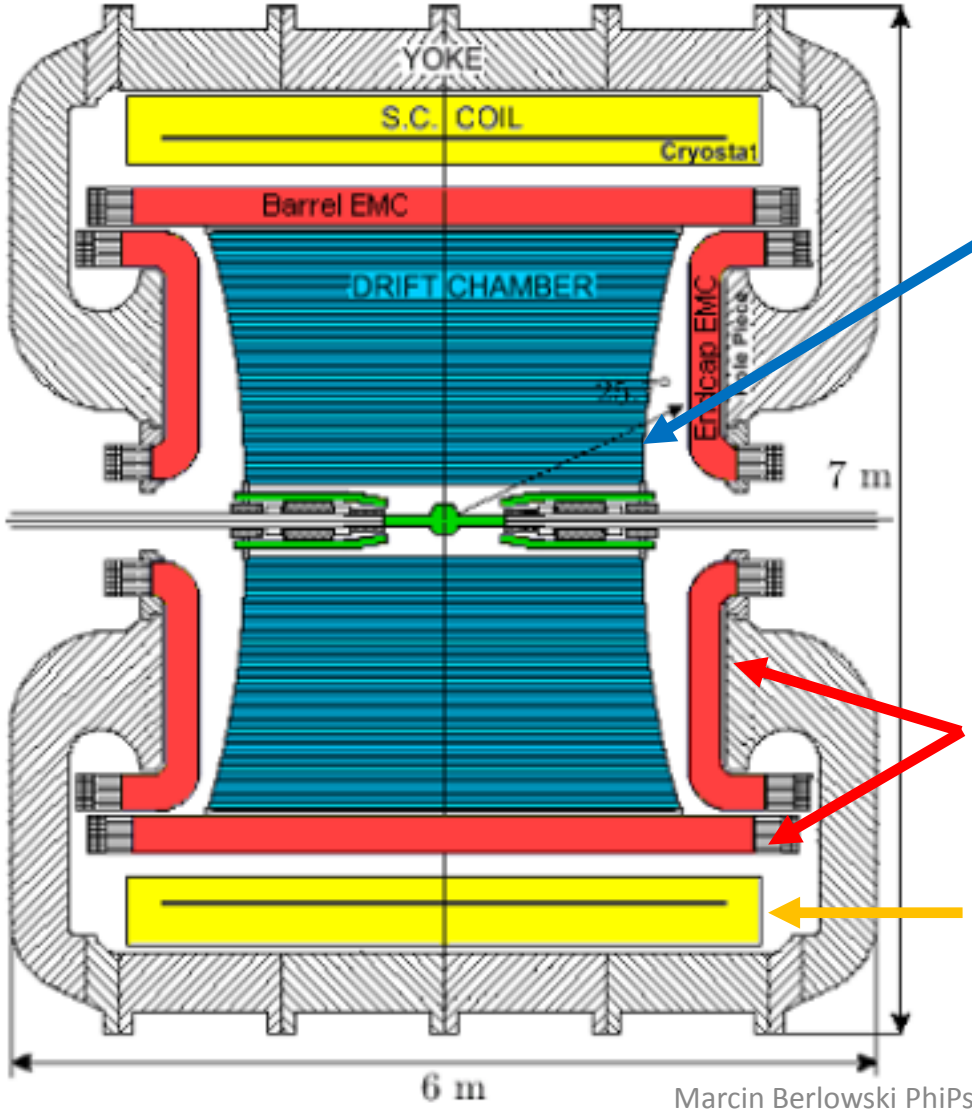
  KLOE-2 [EPJ C68, 619 (2010)]

KLOE data set:

- On peak **2.5 fb^{-1}**
- Off peak ($\sqrt{s} = 1.0GeV$) ~0.26 fb^{-1}



KLOE detector



Drift chamber:

- Gas mixture: 90% He, 10% isobutane
- Resolutions: σ_{xy}=150 μm, σ_z=2 mm, $\frac{\sigma p_t}{p_t} < 0.4\%$ $(45° < \theta < 135°)$

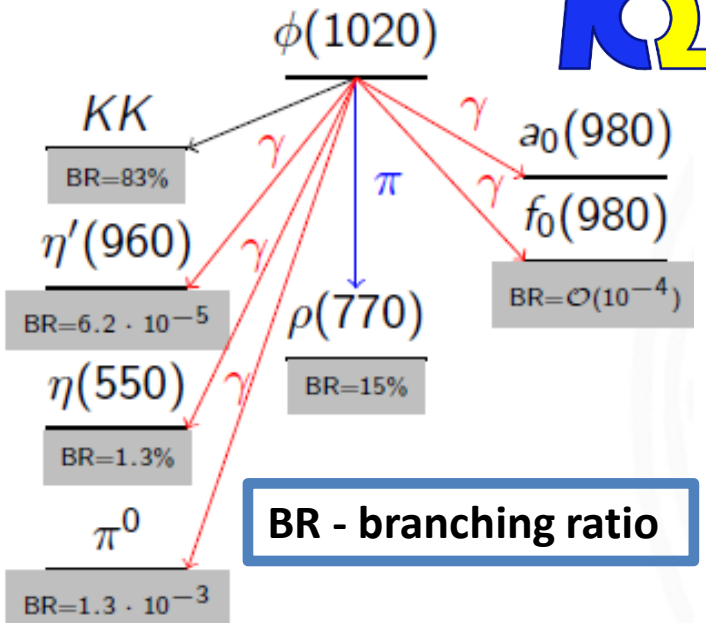
Electromagnetic calorimeter:

- Covers 98% of solid angle
- Made of lead/scintillating fibers
- Resolutions: $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(GeV)}}$,

  $\sigma_T = \frac{57\ ps}{\sqrt{E(GeV)}} \oplus 140$ ps

Both in magnetic field ~0.52 T

η physics with KLOE



- **η meson** ($I^G=0^+$, $J^{PC}=0^{-+}$):
  - Mass m_η= 547.862 ± 0.018 MeV
  - Full width Γ_η= 1.31 ± 0.05 keV

KLOE [JHEP 12 (2007) 073]

- Main **η decay channels**:

$\eta\to\gamma\gamma$ BR~39% $\eta\to\pi^\circ\pi^\circ\pi^\circ$ BR~33%

$\eta\to\pi^\circ\pi^+\pi^-$ BR~23% $\eta\to\gamma\pi^+\pi^-$ BR~4%

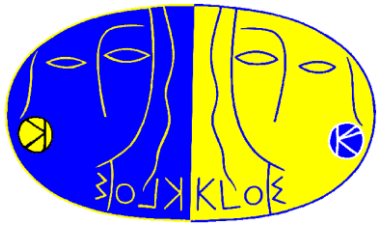
KLOE [PLB 694 (2010) 16]

KLOE [JHEP 1605 (2016) 019]

KLOE [PLB 718 (2013) 910]

- Tagged in KLOE detector with monochromatic photons of 365 MeV
- 2.5 fb^{-1} integrated luminosity with KLOE corresponds to:

~$8\cdot10^9$ ϕ's and ~10^8 η's produced



Motivation

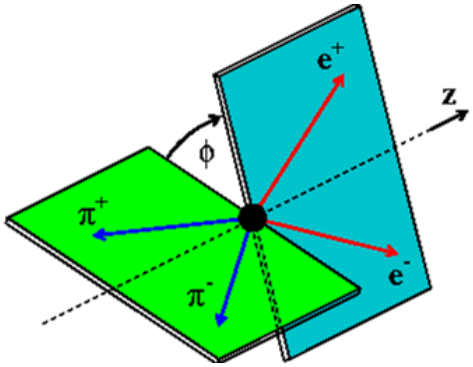
- Spatial structure of the eta meson
- Tests of ChPT and other theories
- Tests of discrete symmetries like: C, P, CP, CPT
- Searches for the effects beyond the SM such as:
  - Flavor conserving violation of CP
  - Dark Matter contribution

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

- **Test of non-CKM CP Violation**

$$\varphi = \angle(\pi^+\pi^-), (e^+e^-)$$

$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$



- CP conservation implies N(ϕ) = N(180°-ϕ)
- Based on sample of ~1.5k events:

$$\mathbf{A_\phi = (-0.6 \pm 2.5_{stat} \pm 1.7_{syst} \pm 0.5_{corr}) \cdot 10^{-2}}$$

$$\mathbf{BR(\eta \to \pi^+\pi^-e^+e^-(\gamma)) = (26.8 \pm 0.9_{stat} \pm 0.7_{syst}) \cdot 10^{-5}}$$

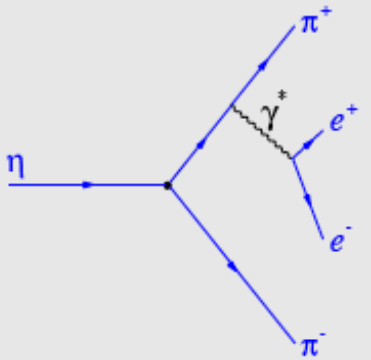
KLOE [PLB 675 (2009) 283]

- Corrected for Final State Radiation
- QED theory gives: BR ~3 ·10^{-5}

BR=(37^{+25}_{-18}±3)·10^{-5} ***CMD-2*** *[PLB 501 (2001) 191]*

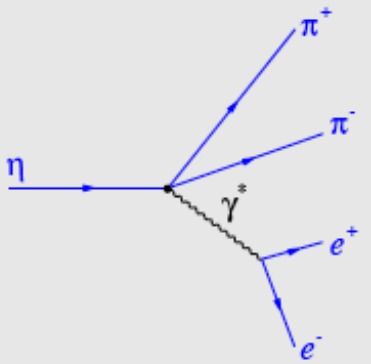
BR=(43^{+20}_{-16}±4)·10^{-5} ***CELSIUS-WASA*** *[PRD 77 (2008) 032004]*

CP violating bremsstrahlung



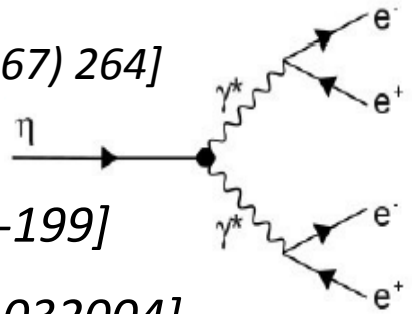
[D. Gao MPL A17 (2002) 1583]

CP conserving M1 γ emission

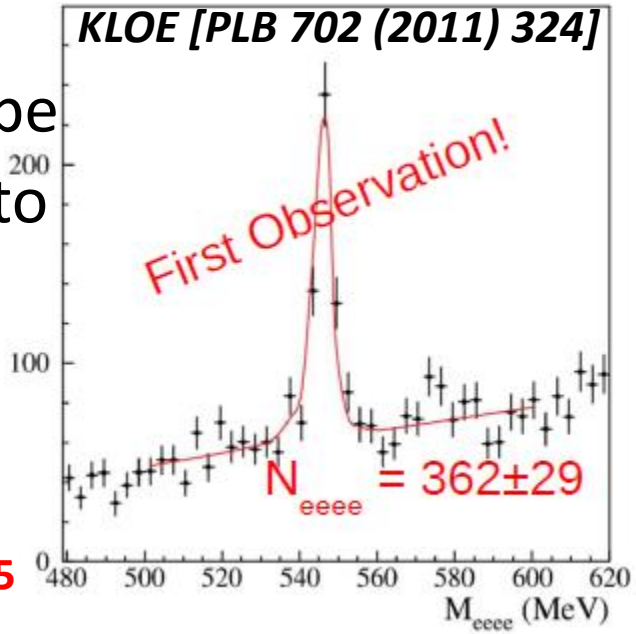


$\eta \to e^+e^-e^+e^-$

- **QED Theory:** BR($\eta \to e^+e^-e^+e^-$) = $2.6 \cdot 10^{-5}$ *[NPB1(1967) 264]*
- **Experimentally only upper limits:**
  - BR < $6.9 \cdot 10^{-5}$ @*CL90%* CMD-2 *[PLB 501 (2001) 191-199]*
  - BR < $9.7 \cdot 10^{-5}$ @*CL90%* CELSIUS/WASA *[PRD 77 (2008) 032004]*



- Based on KLOE data set - 1.7 fb^{-1}
- Rejection of γ conversion on the beam pipe
- Monte Carlo signal simulation according to Bijnens and Persson - *arXiv:hep-ph/0106130*
- Final State Radiation included
- Background from φ decays subtracted



$BR(\eta \to e^+e^-e^+e^-(\gamma)) = (2.4 \pm 0.2_{stat} \pm 0.1_{syst}) \cdot 10^{-5}$

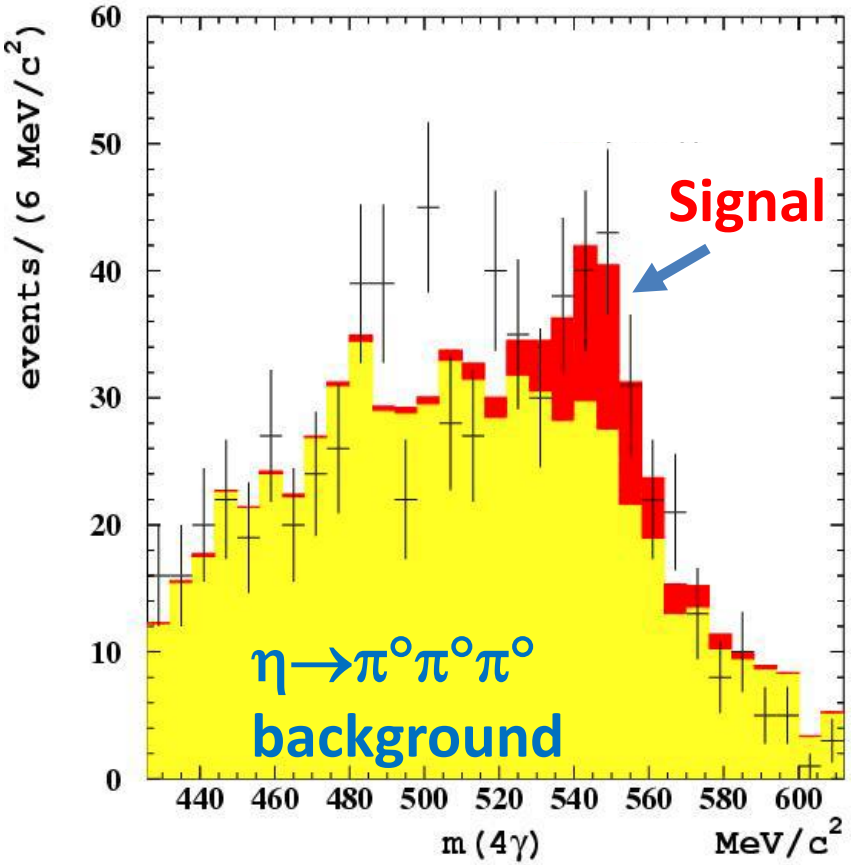
$\eta \to \pi^\circ\gamma\gamma$

- ChPT "golden mode": p^2 null, p^4 suppressed, p^6 dominates

[Ll. Ametller et al. PLB 276(1) (1984) 185-190]

- Mass of two gammas that are not coming from π° can be used as a test of theoretical models
- KLOE 2006 preliminary, based on 450 pb^{-1}; 70 signal events (3σ significance)

$BR(\eta \to \pi^\circ\gamma\gamma) = (8.4 \pm 2.7_{stat} \pm 1.4_{syst}) \cdot 10^{-5}$



- **CB@AGS** (~500 signal events)**:**

  $BR = (22.1 \pm 2.4 \pm 4.7) \cdot 10^{-5}$ *[PRC 78 (2008) 015206]*

- **CB@MAMI** (~1200 signal events)**:**

  $BR = (25.2 \pm 2.5) \cdot 10^{-5}$ *[PRC 90 (2014) 025206]*

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

- $\eta \to \pi^\circ\pi^+\pi^-$ is an isospin violating process which dominantly proceeds via strong interactions
- Sensitive to the light quark masses (in ChPT $\Gamma \sim Q^{-4}$):

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

[G. Colangelo et al. PoS (EPS-HEP2011) 304]

- Provides parameters to describe low energy regime of strong interactions (ChPT)
- Measured Dalitz plot density in the eta rest frame parametrized using Taylor expansion around X=Y=0:

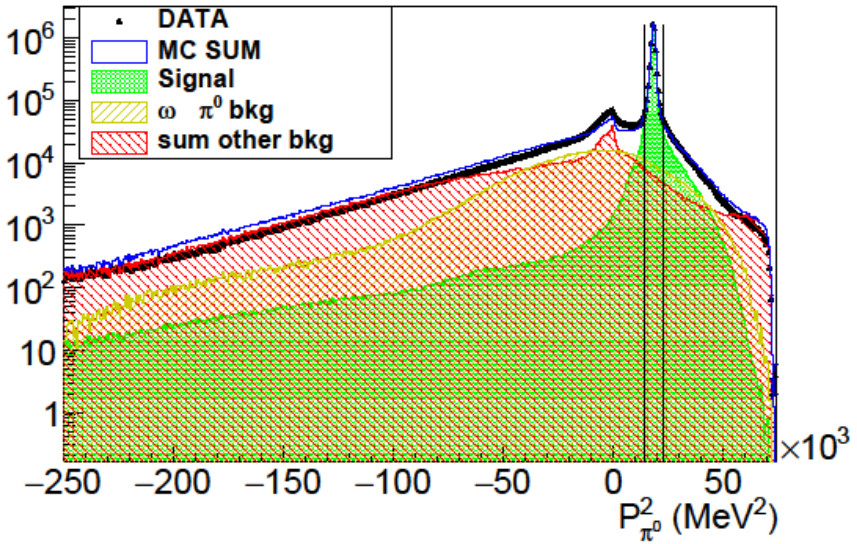
$$|A(X,Y)|^2 \approx 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + \ldots$$

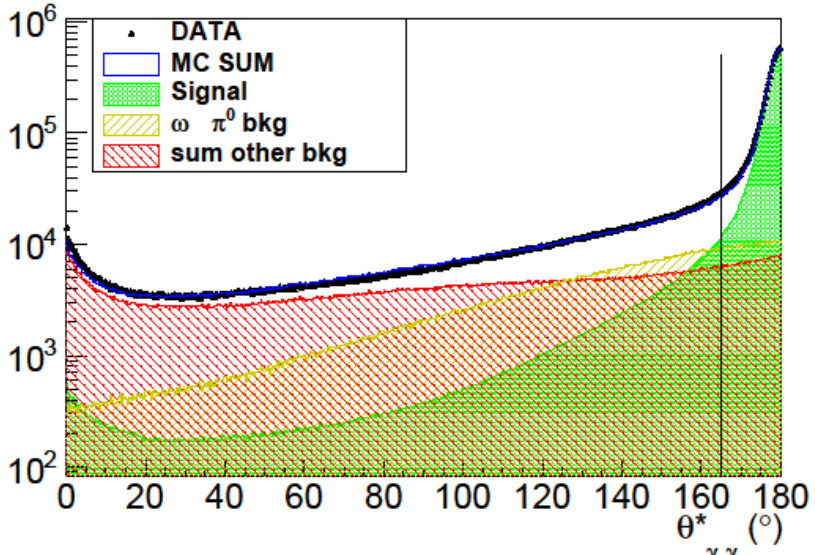
where $X = \sqrt{3}\frac{T_{\pi+} - T_{\pi-}}{Q}$; $Y = \frac{3T_{\pi^\circ}}{Q} - 1$; $Q = T_{\pi+} + T_{\pi-} + T_{\pi^\circ}$

(Odd powers of X in order to conserve C must be equal to 0)

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

- New analysis scheme of KLOE data (*[JHEP05 (2008) 006]*) with almost 4 times better statistics (~1.6 fb^{-1}), using independent data sample
- Systematic errors reduced by a factor of 2
- High overall efficiency - ~38% with only ~1% residual background
- Additional fit including the **g** parameter
- Acceptance corrected, binned data which can be directly used to fit theory
- ~$4.7 \cdot 10^6$ events in 371 bins





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

Dalitz plot parameters

(C viol par. c & e consistent with 0):

$$a = -1.095 \pm 0.003^{+0.003}_{-0.002}$$

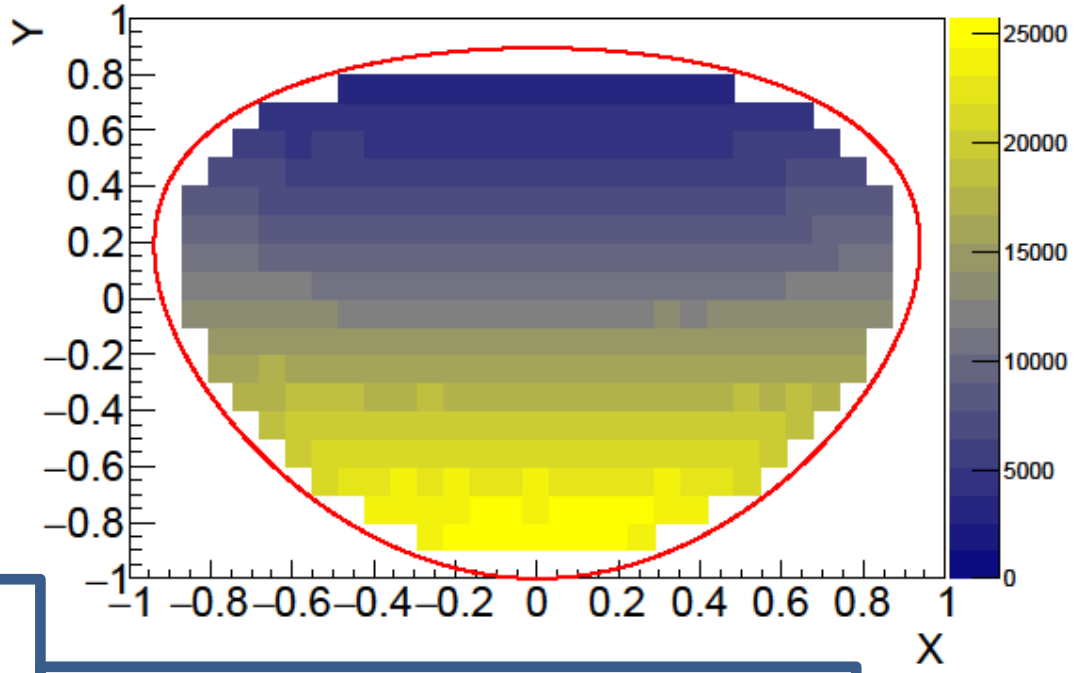
$$b = +0.145 \pm 0.003 \pm 0.005$$

$$d = +0.081 \pm 0.003^{+0.006}_{-0.005}$$

$$f = +0.141 \pm 0.007^{+0.007}_{-0.008}$$

$$g = -0.044 \pm 0.009^{+0.012}_{-0.013}$$

KLOE [JHEP 1605 (2016) 019]



With parameter g=0:

$$a = -1.104 \pm 0.003 \pm 0.002$$

$$b = +0.142 \pm 0.003^{+0.005}_{-0.004}$$

$$d = +0.073 \pm 0.003^{+0.004}_{-0.003}$$

$$f = +0.154 \pm 0.006^{+0.004}_{-0.005}.$$

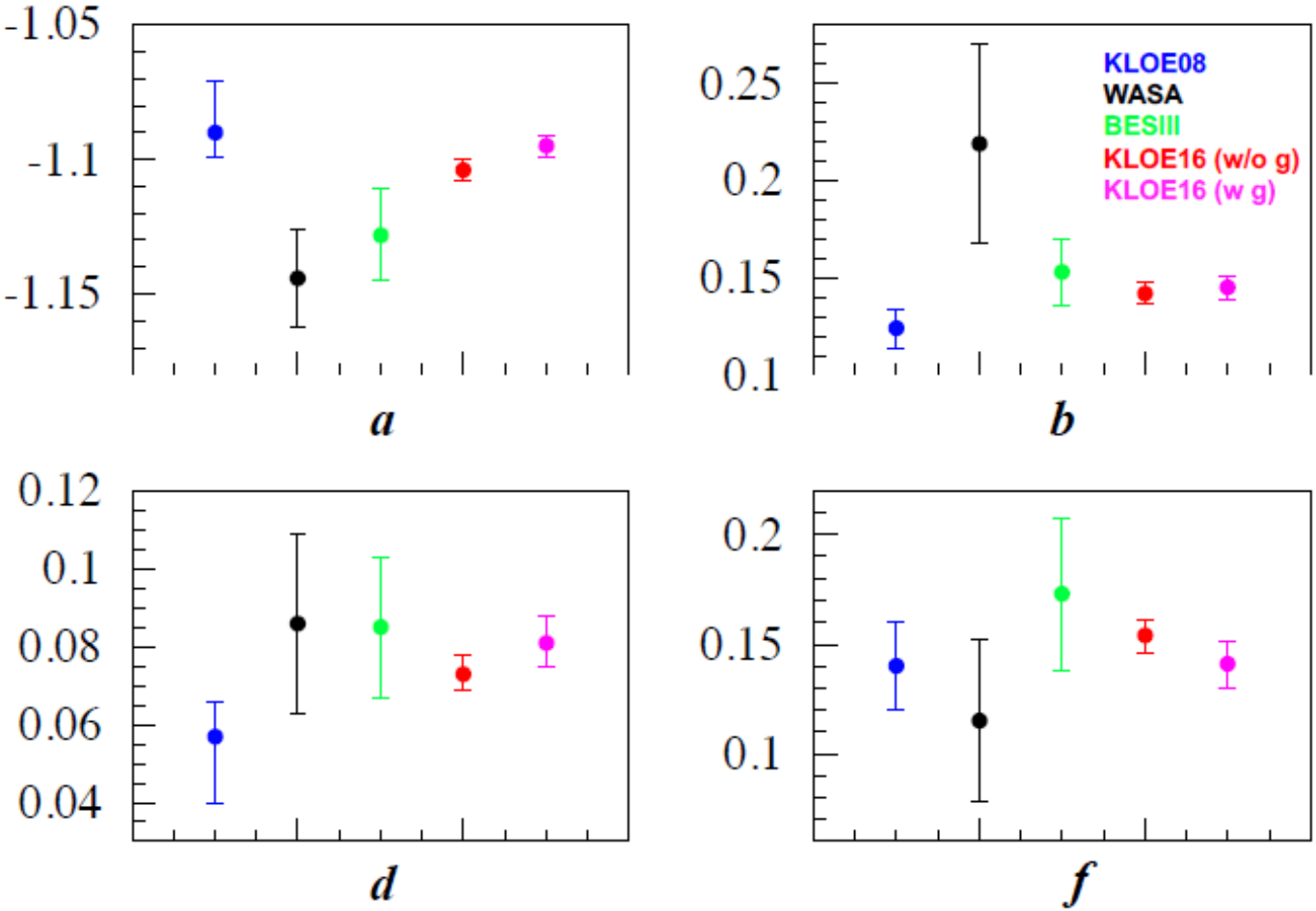
Charge asymmetries:

$$A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}$$

$$A_Q = (+1.8 \pm 4.5^{+4.8}_{-2.3}) \cdot 10^{-4}$$

$$A_S = (-0.4 \pm 4.5^{+3.1}_{-3.5}) \cdot 10^{-4}.$$

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



KLOE08 – *[JHEP05 (2008) 006]*; WASA – *[PRC90 (2014) 045207]*

BESIII – *[PRD92 (2015) 012014]*; KLOE16 – *[JHEP 1605 (2016) 019]*

Perspectives for KLOE-2

- KLOE-2 is not only about **increased statistics**
- **QCALT+CCALT**: will increase acceptance for photons from the interaction point (from 21° to 10°)
- **Inner Tracker**: will improve resolution of tracking and will help to achieve a better vertex reconstruction

Channel	Test	UL (PDG/KLOE)	KLOE Statistics	UL scaled to KLOE+ KLOE-2 (7 fb^{-1})
$\eta \to \gamma\gamma\gamma$	C violation	$1.6 \cdot 10^{-5}$	410 pb^{-1}	$3.9 \cdot 10^{-6}$
$\eta \to \pi^+\pi^-$	P, CP violation	$1.3 \cdot 10^{-5}$	350 pb^{-1}	$2.9 \cdot 10^{-6}$

- $\eta \to \pi^+\pi^- e^+ e^-$ expected BR statistical error of 1.7% (was 3%),
  - asymmetry: statistical sensitivity from $2.5 \cdot 10^{-2}$ to $1.2 \cdot 10^{-2}$
- $\eta \to \pi^\circ\gamma\gamma$ ~1000 events expected at KLOE-2 (was ~70) and better bckg reduction from $\eta \to 3\pi^\circ$ thanks to increased detector's acceptance for γ's

Summary

- KLOE data sample allowed to perform high precision measurements:

$\eta' \to \eta\pi^+\pi^-$ *[PLB 541 (2002) 45]*

$\eta \to \pi^+\pi^-$ *[PLB 606 (2005) 276]*

$\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$ *[PLB 648 (2007) 267]*

$\eta \to e^+e^-\pi^+\pi^-$ *[PLB 675 (2009) 283]*

$\eta \to e^+e^-e^+e^-$ *[PLB 702 (2011) 324]*

$\sigma(e^+e^- \to e^+e^-\eta)$ & $\Gamma(\eta \to \gamma\gamma)$ *[JHEP 01 (2013) 119]*

$\phi \to \eta e^+e^-$ *[PLB 742 (2015) 1]*

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η mass *[JHEP 12 (2007) 073]*

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$\eta \to \gamma\pi^+\pi^-$ *[PLB 718 (2013) 910]*

$\eta \to \pi^\circ\pi^+\pi^-$ *[JHEP 1605 (2016) 019]*

- In KLOE-2 the increased statistics and the new detectors providing better acceptance and resolution, will allow us to improve several results.