Hadronowe rozpady mezonów η i η':
nowe życie detektorów (WASA, Crystal Ball, KLOE)

A. Kupść

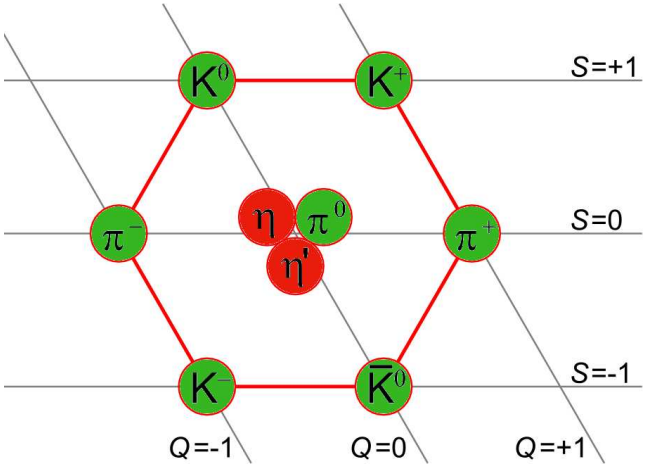
Uniwersytet w Uppsali i Instytut Problemów Jądrowych

- Hadronowe rozpady mezonów η i η'
- Rozpady $\eta, \eta' \to \pi\pi\pi$, $\eta' \to \eta\pi\pi$
- Jak η i η' są produkowane?
- WASA, Crystal Ball, KLOE

Warszawa, 26/10/2007

Who needs η and η'?

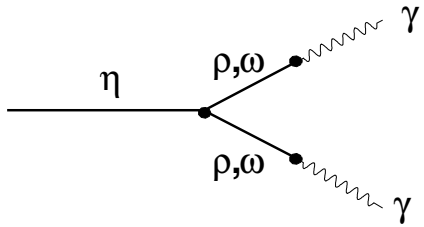
- 1957,1959 Sakata model $\Rightarrow \pi^{'}, \pi^{''}$ (Okun, Ikeda)
- 1961 Spring: Gell-Mann *The Eightfold way*:



... The most clear-cut new prediction for the pseudoscalar mesons is the existence of χ^0, which should decay into 2γ like π^0, unless it is heavy enough to yield $\pi^+\pi^-\gamma$ with appreciable probability... $\chi^0 \to 3\pi$ is forbidden by conservation of I and C. For a sufficiently heavy χ^0 the decay $\chi^0 \to 4\pi$ is possible...

Unexplained η decay modes...

- 1961 Fall: *Apparently unrelated meson was discovered*: Pevsner et al: *Evidence for a Three-Pion Resonance Near 550 Mev*.
- 1962 Gell-Mann et al.,PRL,8,261:
  ... The forbidden decay rates into $3\pi^0$ and $\pi^+\pi^-\pi^\circ$ are difficult to estimate, except that $3\pi^0/(\pi^+ + \pi^- + \pi^\circ) \leq \frac{3}{2}$... The remaining decays may be described roughly on the assumption that the important intermediate steps are $\chi \to 2\rho^0$ and $\chi \to 2\omega$.



$\Rightarrow$ VMD for all η decay modes except for the 3π

η, η' elementary facts

- $M = 547.51 \pm 0.18$ MeV
- $\Gamma = 1.30 \pm 0.07$ keV
- Main decays:

$\eta \to \gamma\gamma$	39%
$\eta \to \pi^0\pi^0\pi^0$	32%
$\eta \to \pi^+\pi^-\pi^0$	23%
$\eta \to \pi^+\pi^-\gamma$	5%

- $\eta \to \pi^0\pi^0, \pi^+\pi^-$ CPV
- $4m_{\pi^0} < m_\eta < 4m_{\pi^+}$
- $\eta \to \pi^0\pi^0\pi^0\pi^0$ CPV

- $M = 957.78 \pm 0.14$ MeV
- $\Gamma = 0.203 \pm 0.016$ MeV
- Main decays:

$\eta' \to \pi^+\pi^-\eta$	44%
$\eta' \to \rho^o\gamma$	29%
$\eta' \to \pi^0\pi^0\eta$	21%
$\eta' \to \omega\gamma$	3%
$\eta' \to \gamma\gamma$	2%

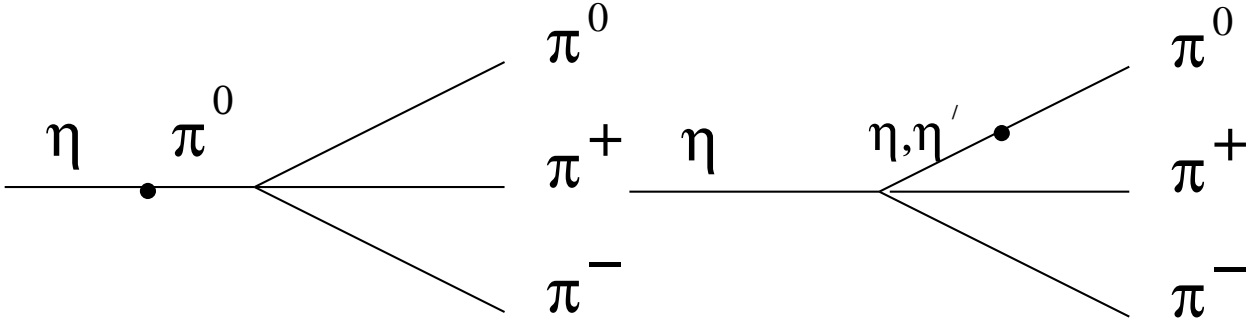
- $\eta' \to \pi^0\pi^0, \pi^+\pi^-$ CPV
- $7m_{\pi^0} < m_{\eta'} < 7m_{\pi^+}$
- $\eta' \to 2[n]\pi^0$ CPV

$\eta(\eta') \to 3\pi$

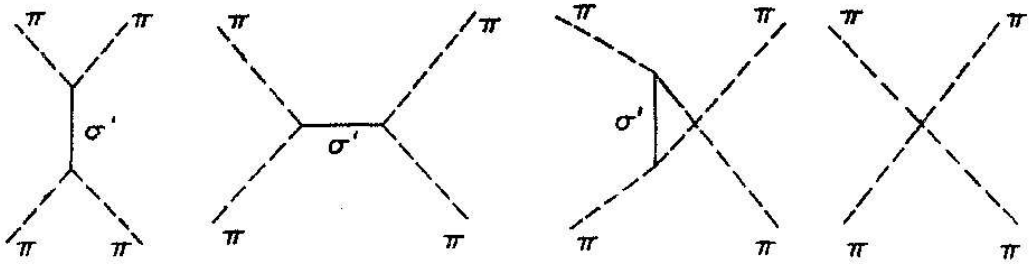
- Isospin violating decay

$\Rightarrow$ Considered to be EM transition for long time

- $\Delta I = 1$ transition due to $\eta - \pi^0$ mixing:



$\Rightarrow$ Reduced to elementary low energy QCD process – $\pi\pi$ scattering:



Chiral Perturbation Theory

Model independent way to study low energy QCD:

- Approximate $SU(3)_L \times SU(3)_R$ chiral symmetry spontaneously broken to $SU(3)_V$

$\Rightarrow$ 8 pseudo-Goldstone mesons (π, K, η)

- Expansion in external momenta and quark masses
- Corrections controlled
- Electroweak interactions included
- Each order more new free parameters...

CHPT: extensions

- Include η' ($\eta' - \eta$ mixing, η' decays):

$\Rightarrow$ Goldstone boson for $N_C \to \infty$

$\Rightarrow$ Can be included as a dynamical degree of freedom

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- Include η' ($\eta' - \eta$ mixing, η' decays):

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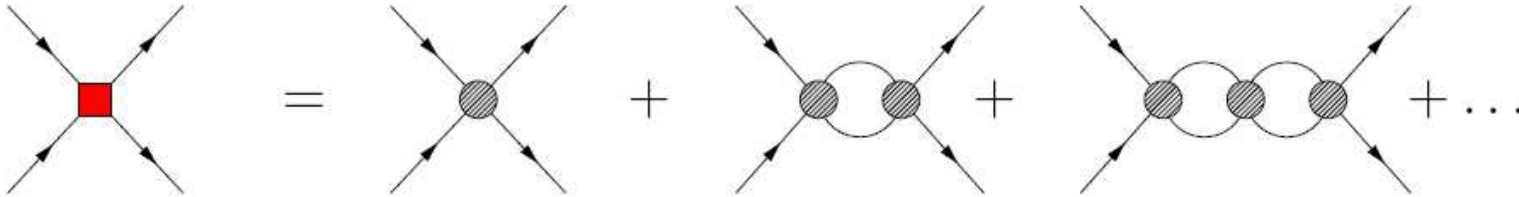
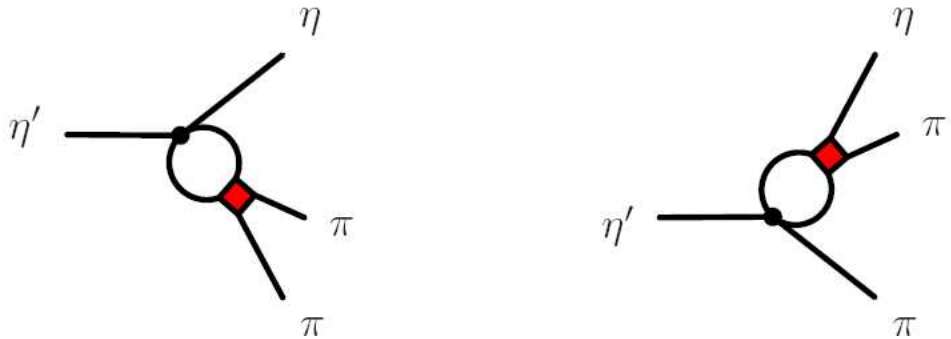
- Final-state interactions:

$\Rightarrow$ Dispersion relations

$\Rightarrow$ Bethe-Salpeter equations (Chiral Unitary Approach)



$\Rightarrow$ Can study contribution of $\pi\pi$, $\pi\eta$ resonances:

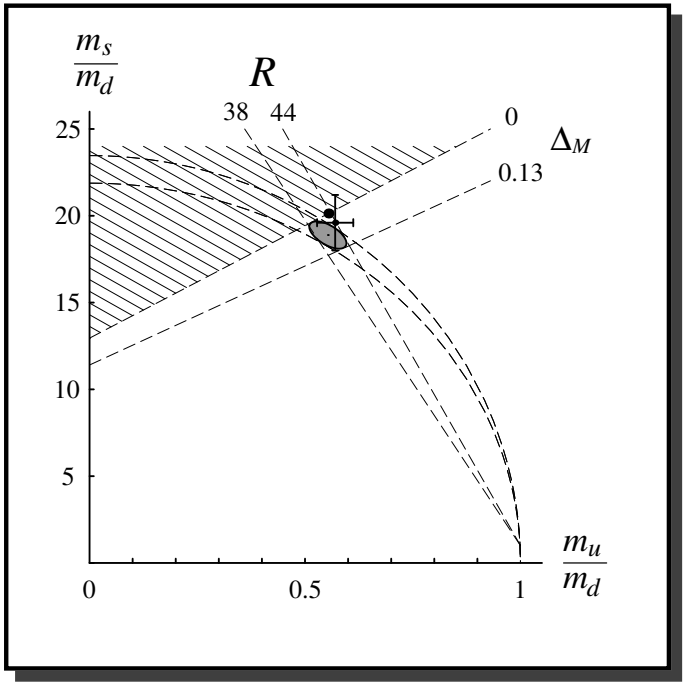


$\eta(\eta') \to 3\pi$ in CHPT

- Isospin violation in strong interactions due to $m_d - m_u$
  $\Gamma_{\eta(\eta')\to 3\pi} \propto \left(\frac{m_d^2 - m_u^2}{m_s^2 - \hat{m}^2}\right)^2 = Q^{-4}$
- 1984 CHPT one loop calculations

  Gasser, Leutwyler NPB250,539
- precise constraint for m_s/m_d, m_u/m_d

  Leutwyler PLB378,313(1996)



- $\Gamma_{exp} = \left(\frac{Q_D}{Q}\right)^4 \Gamma_{th}$
- $Q_D = 24.1$
  $(m_{\pi^+}^2 - m_{\pi^0}^2) = (m_{K^+}^2 - m_{K^0}^2)_{EM}$

$\Rightarrow$ Compare Γ_{exp} and Γ_{th}

$\eta \to 3\pi$

- Can Γ_{th} : be calculated reliably?
- Experimental cross checks:
  - Dalitz plot $\eta \to \pi^\circ\pi^+\pi^-$
  - Dalitz plot $\eta \to \pi^\circ\pi^\circ\pi^\circ$
  - $r = \frac{BR(\eta\to\pi^\circ\pi^+\pi^-)}{BR(\eta\to\pi^\circ\pi^\circ\pi^\circ)}$

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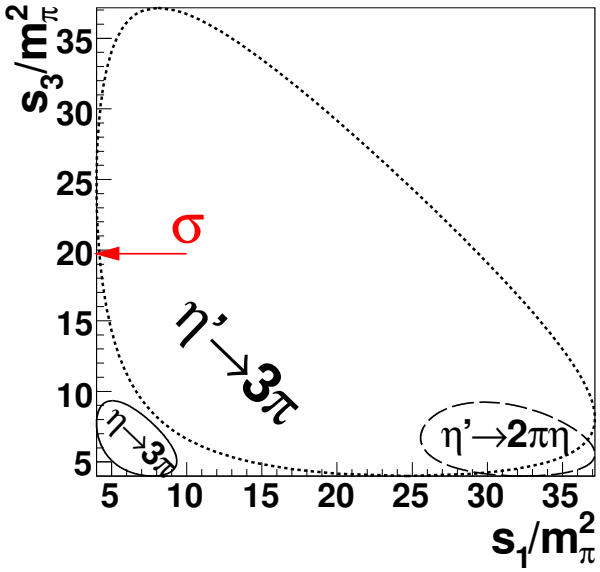
- Q=22.8±0.4 *Dispersion relations + CHPT 1-loop*
  Martemyanov,Sopov PRD71,017501
- Q consistent with Q_D *Chiral Unitary Approach*
  Borasoy,Nißler EPJA26,383

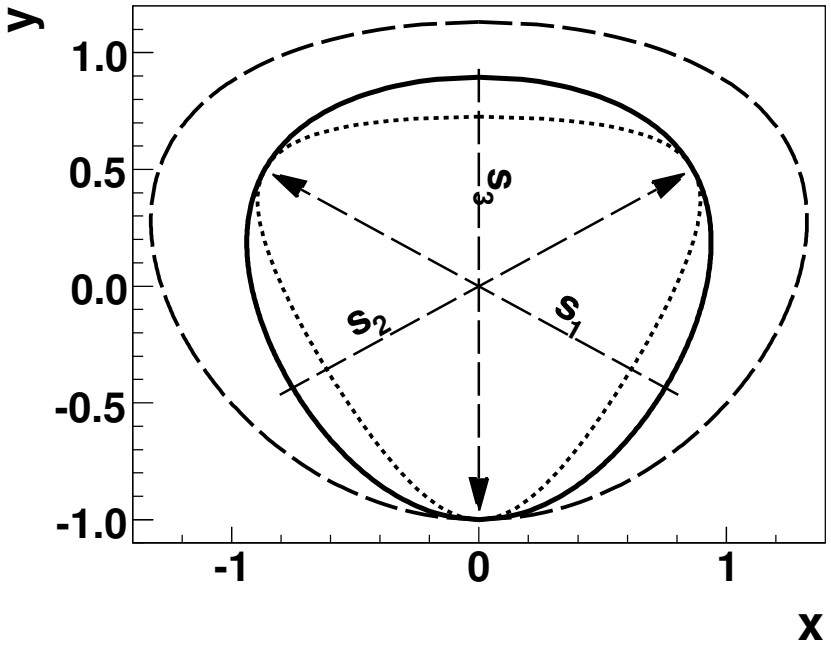
? Convergence? CHPT 2-loop
Bijnens, Ghobani arXiv:0709.0230

Variables

Mandelstam variables:

$$s_i \equiv (p_0 - p_i)^2 = (m_0 - m_i)^2 - 2T_i m_0$$





For $m_1 = m_2$:

$$x \equiv \frac{1}{\sqrt{3}} \frac{T_1 - T_2}{\langle T \rangle}; \quad y \equiv \frac{1}{3}\left(\sum_{i=1}^{3} \frac{m_i}{m}\right) \frac{T_3}{\langle T \rangle} - 1.$$

$\eta \to 3\pi$ – variables

$$|A(x,y)|^2 \propto 1 + ay + by^2 + dx^2 + fy^3 + ...$$

- Current Algebra:

$$A(s_1, s_2, s_3) = A(s_3) \propto \frac{3s_3 - 4m_\pi^2}{m_\eta^2 - m_\pi^2}$$

$\Rightarrow$ linear function

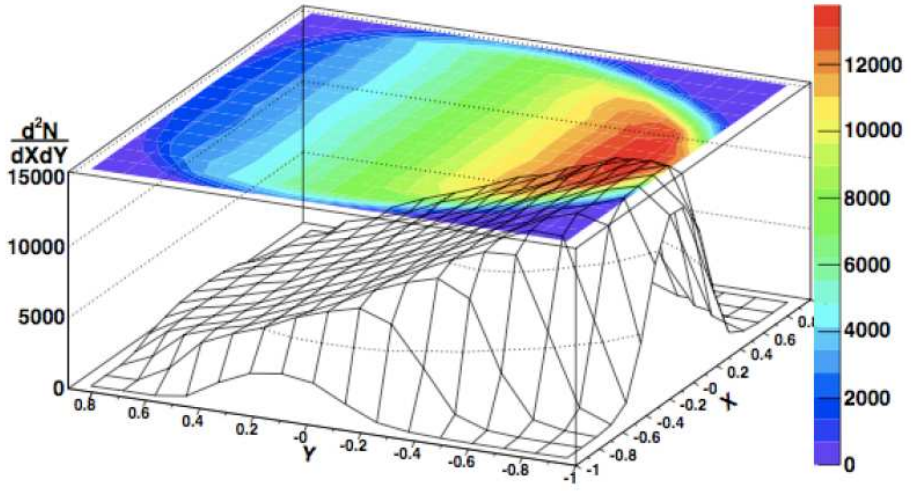
$\Rightarrow$ $a = -1.052$, $b = a^2/4$

- Parameters calculated in CHPT 1,2 loop and Chiral Unitary Approach

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

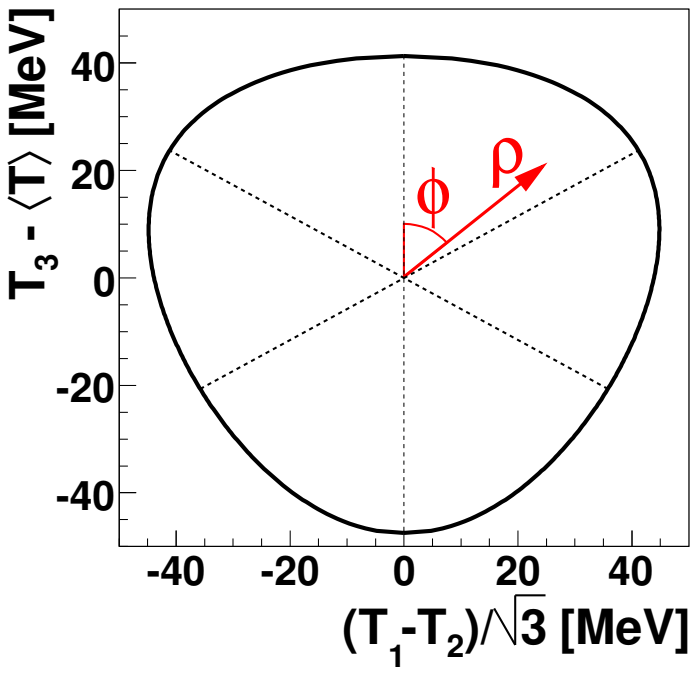
Exp.	KLOE 2007	CBarrel 1998	Layter 1973	Gormley 1970
Ev.	1.3×10^6	3.2×10^3	8.1×10^4	3×10^4
$-a$	$1.090 \pm 0.005^{+0.008}_{-0.019}$	1.22 ± 0.07	1.08 ± 0.014	1.17 ± 0.02
b	$0.124 \pm 0.006 \pm 0.010$	0.22 ± 0.11	0.03 ± 0.03	0.21 ± 0.03
d	$0.057 \pm 0.006^{+0.007}_{-0.016}$	–	0.05 ± 0.03	0.06 ± 0.04
f	$0.14 \pm 0.01 \pm 0.02$	–	–	–

1.34×10^6 events



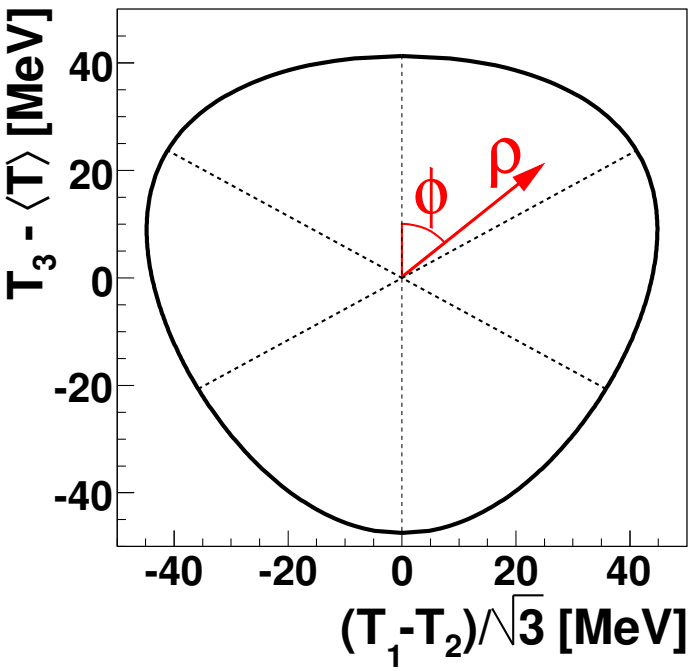
KLOE arXiv:0707.2355:

$\eta \to 3\pi^0$ – variables



- Symetrized Dalitz plot
- $z = \rho^2/\rho^2_{max}$, $0 < \theta < 60^\circ$
- $|\bar{A}(z,\phi)|^2 \propto 1 + 2\,\alpha\, z + \ldots$

$\eta \to 3\pi^0$ – variables



- Symetrized Dalitz plot
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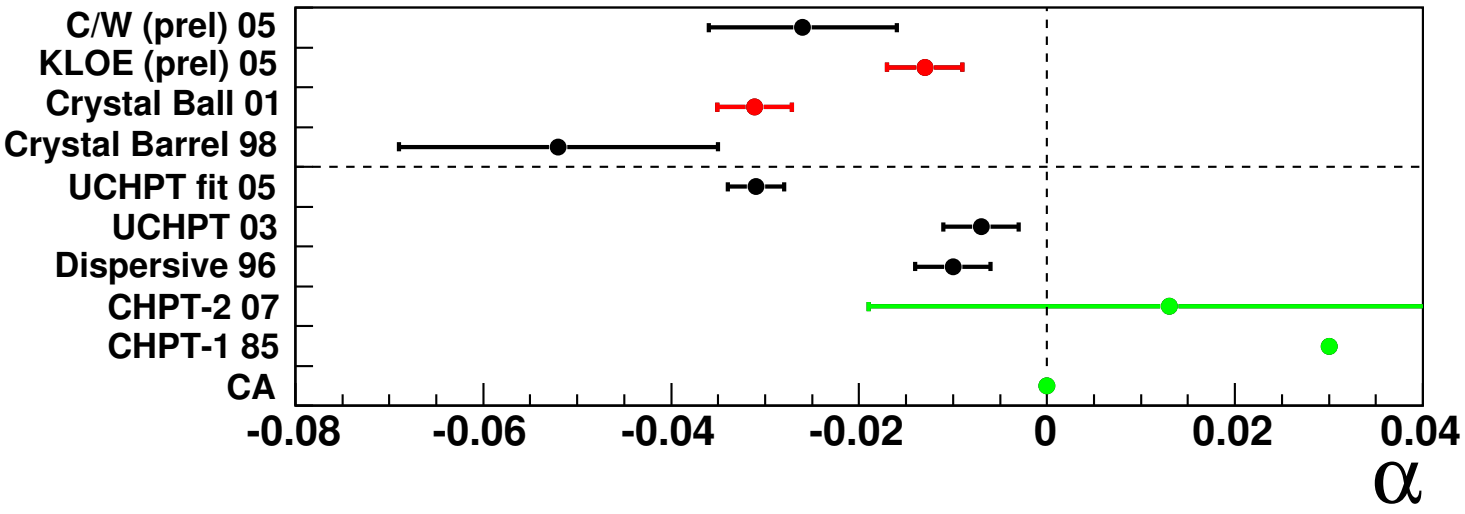
- $|\bar{A}(z,\phi)|^2 \propto 1 + 2\,\alpha\, z + \ldots$

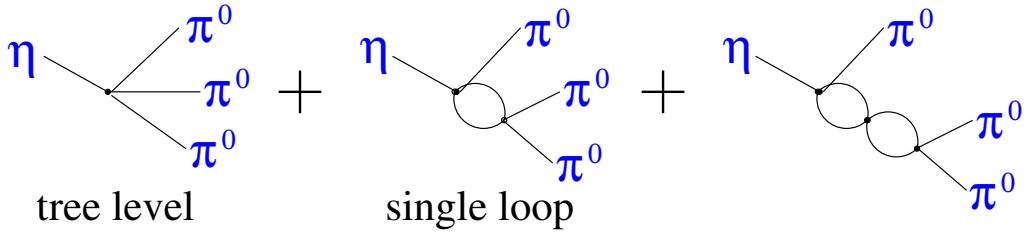
$$\bar{A}(s_1,s_2,s_3) = A(s_1,s_2,s_3) + A(s_2,s_3,s_1) + A(s_3,s_1,s_2)$$

- $r = \frac{BR(\eta,\eta' \to \pi^0\pi^0\pi^0)}{BR(\eta,\eta' \to \pi^+\pi^-\pi^0)} \leq \frac{3}{2}$ for $m_{\pi^0} = m_{\pi^+}$
- For η decays $r_{exp} = 1.44 \pm 0.04$
- e.g. contribution of $\rho^\pm\pi^\mp \Rightarrow r \searrow$

Status of α measurement



- CHPT: In lowest order α=0, $\alpha \neq 0$ due to $\pi - \pi$ FSI:



- Experiment: Crystal Ball not consistent with KLOE

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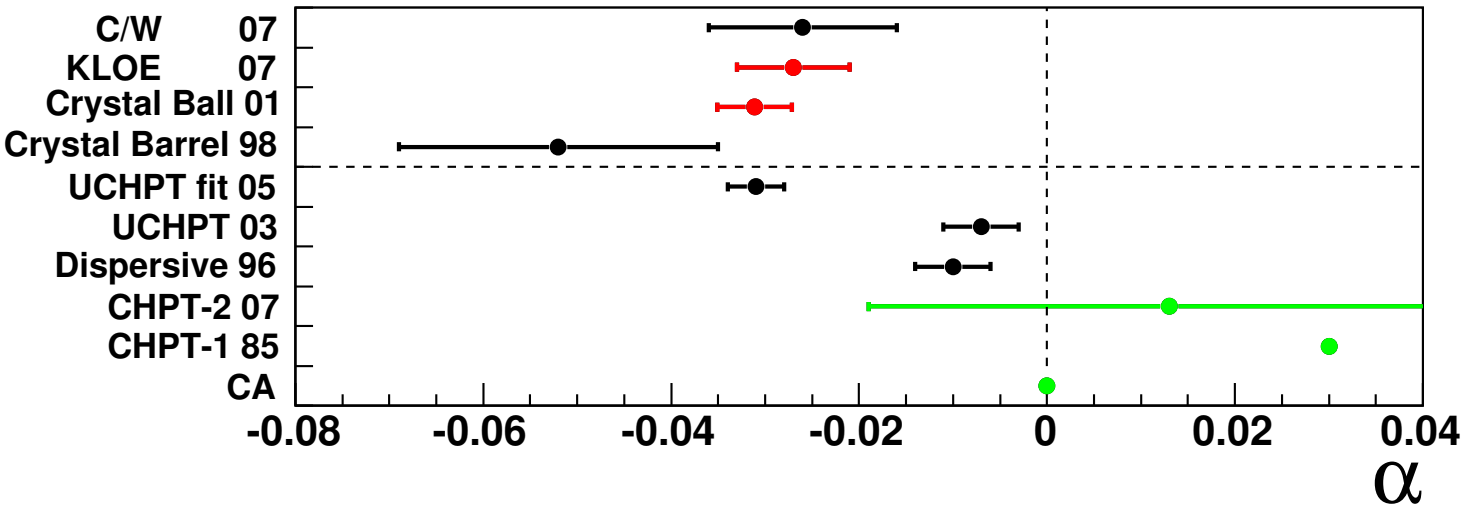

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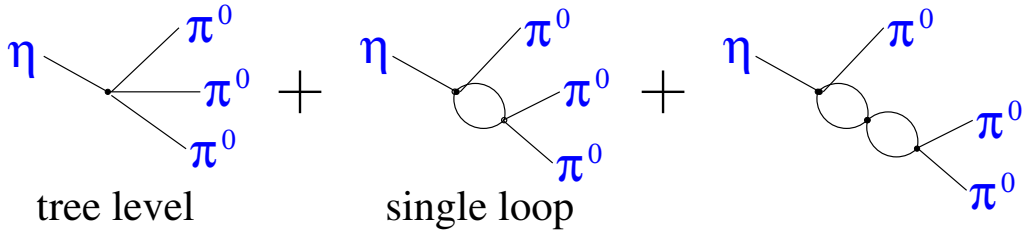
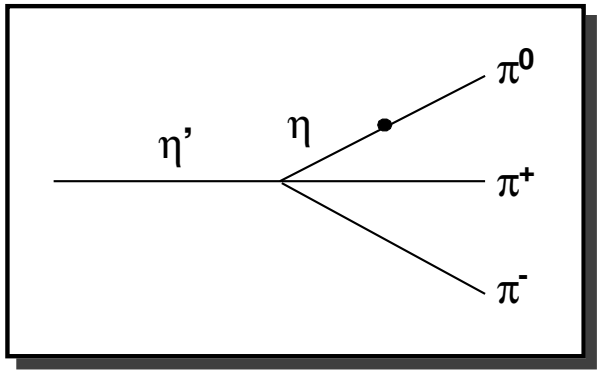


- Experiment: Crystal Ball not consistent with KLOE
- KLOE reanalysis, Data from CB@MAMI, WASA

Quark masses from $\eta' \to 3\pi$

Relate decay $\eta' \to 3\pi$ to $\eta' \to \pi\pi\eta$:



and measure ratios: Gross,Treiman,Wilczek PRD19,2188(1979)

$$\frac{BR(\eta' \to \pi^+\pi^-\pi^0)}{BR(\eta' \to \pi^+\pi^-\eta)} \text{ and } \frac{BR(\eta' \to \pi^0\pi^0\pi^0)}{BR(\eta' \to \pi^0\pi^0\eta)}$$

$\Rightarrow$ do not need Γ

$\Rightarrow$ theory: cancellation of systematics

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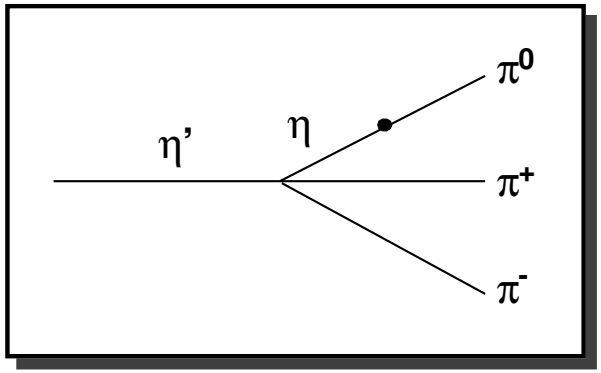

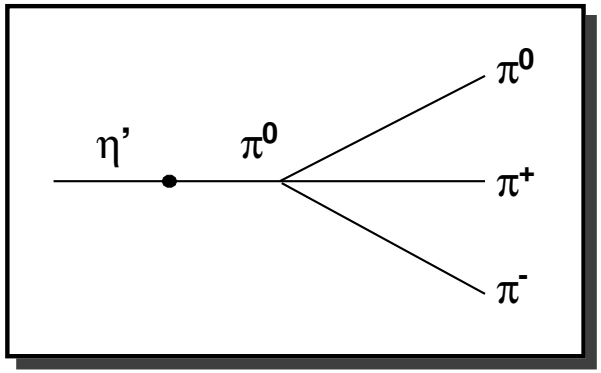

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no! Too simplified assumptions:

Borasoy, Nißler, Meißner PLB643,41(2006)

- Missing important CA diagram
- $A(s_1, s_2, s_3) \neq const$, $\bar{A}(s_1, s_2, s_3) \neq const$

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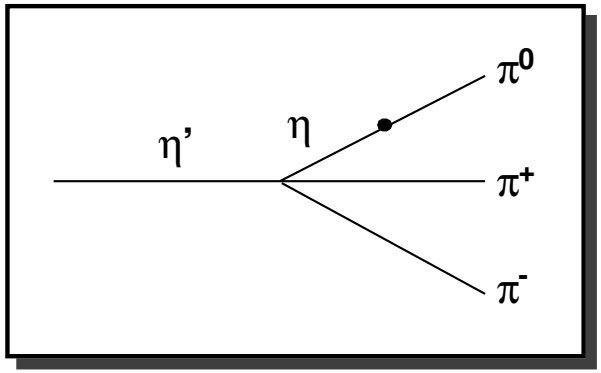

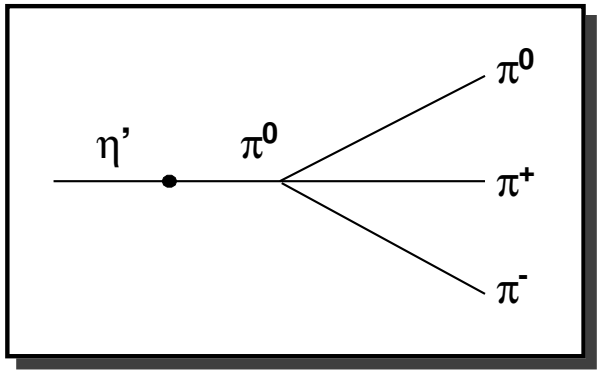

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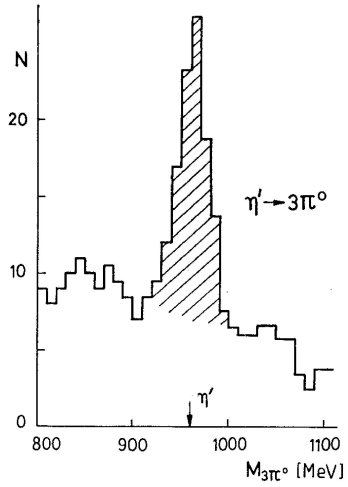
- Missing important CA diagram
- $A(s_1, s_2, s_3) \neq const$, $\bar{A}(s_1, s_2, s_3) \neq const$

$\Rightarrow$ Difficult to extract quark masses

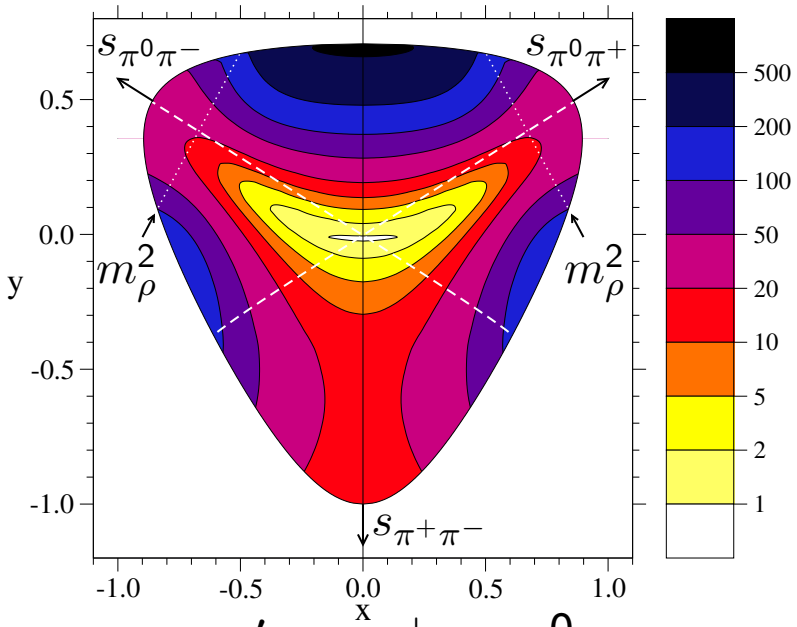
$\eta' \to 3\pi$



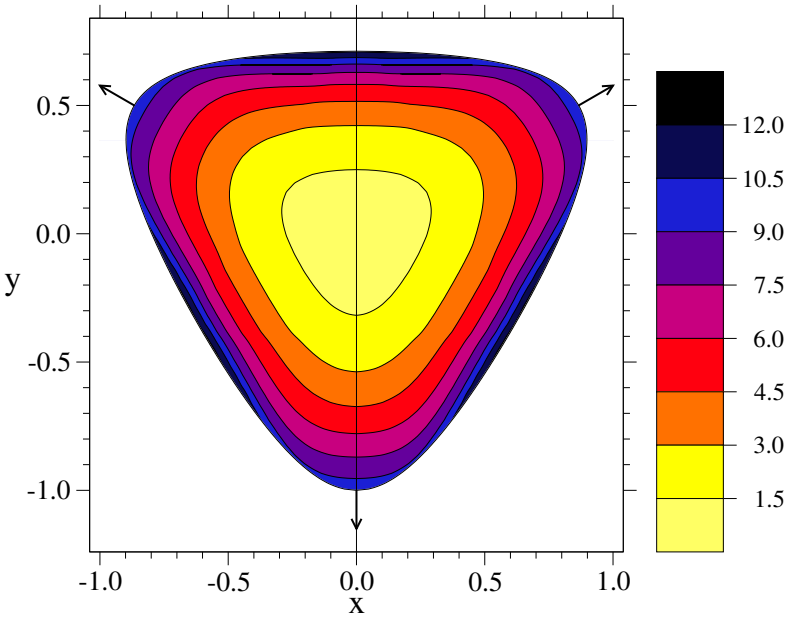
- 65 events GAMS2000 87 ($\eta' \to \pi^0\pi^0\pi^0$):

$\Rightarrow$ $BR(\eta' \to \pi^0\pi^0\pi^0) = (1.5 \pm 0.3) \times 10^{-3}$

- $BR(\eta' \to \pi^+\pi^-\pi^0) < 5\%$ Rittenberg 69
- U(3) CHPT, Borasoy, Nißler 2005:
- $BR(\eta' \to \pi^+\pi^-\pi^0) \approx 1.8\%$ large $\rho^\pm\pi^\mp$

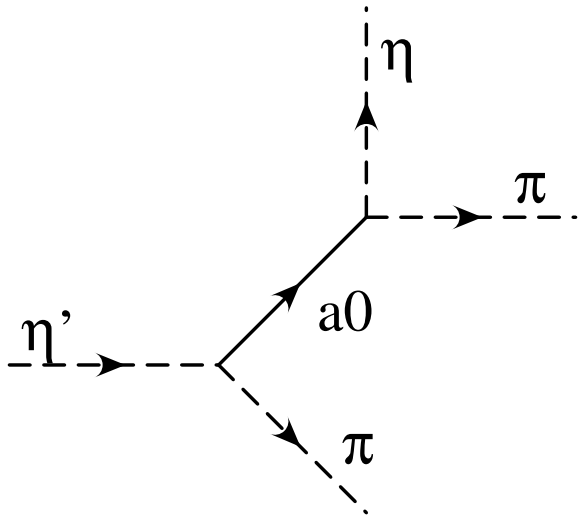


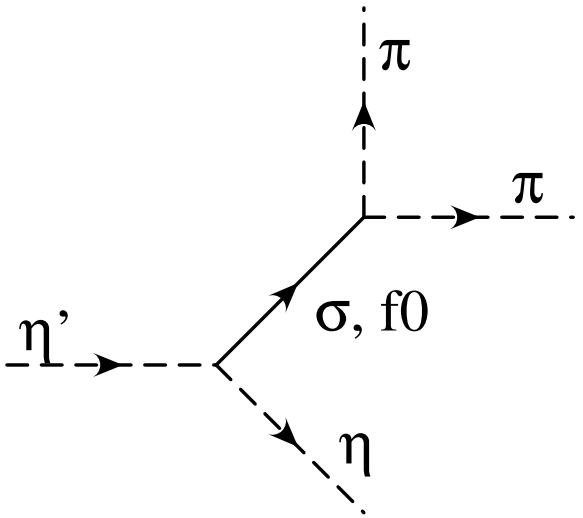
$\eta' \to \pi^+\pi^-\pi^0$

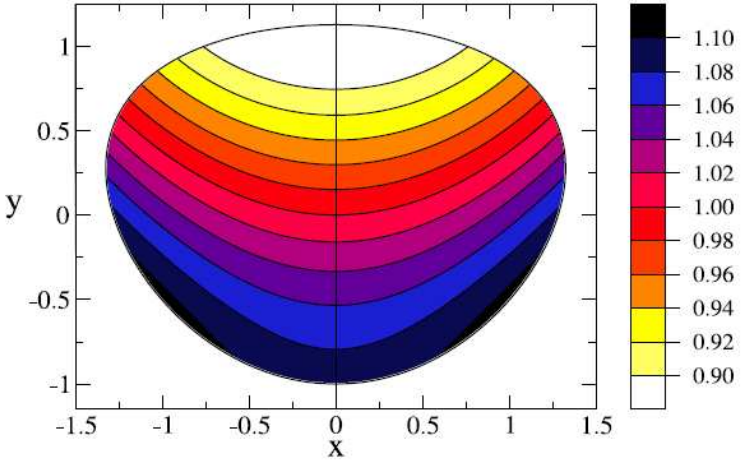


$\eta' \to \pi^0\pi^0\pi^0$

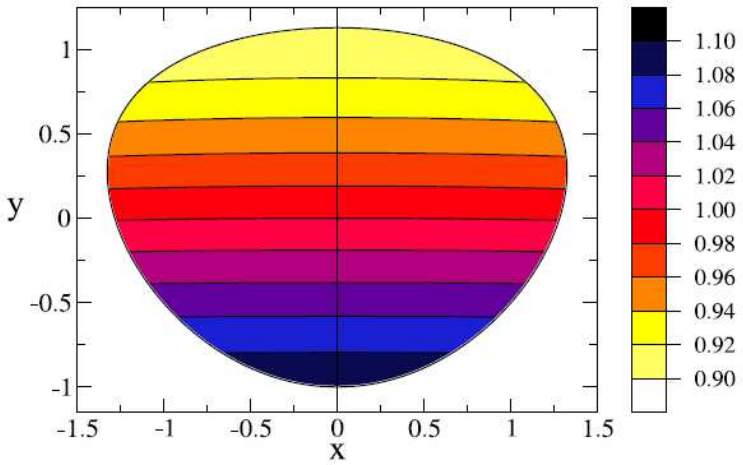
Scalars in $\eta' \to 2\pi\eta$





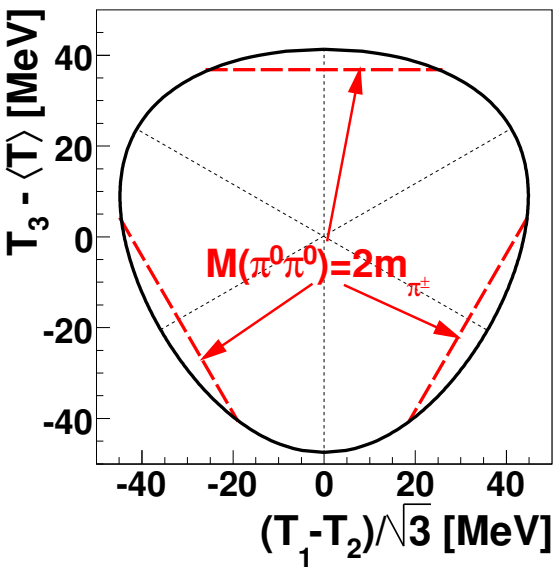


$a_0(980)$

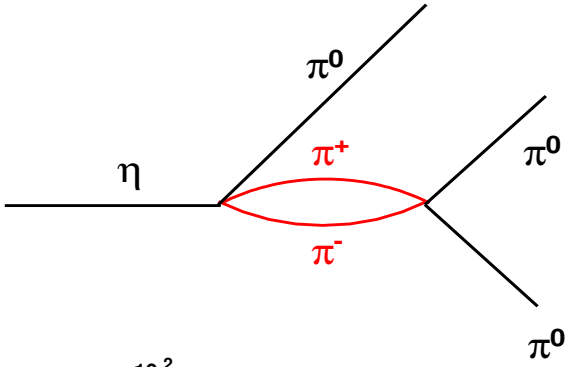


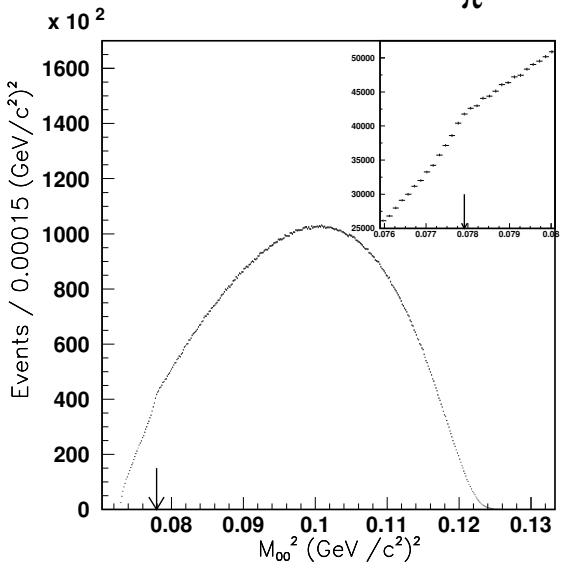
$f_0(980)/\sigma$

What is special in $\eta \to 3\pi^0$ decays?



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





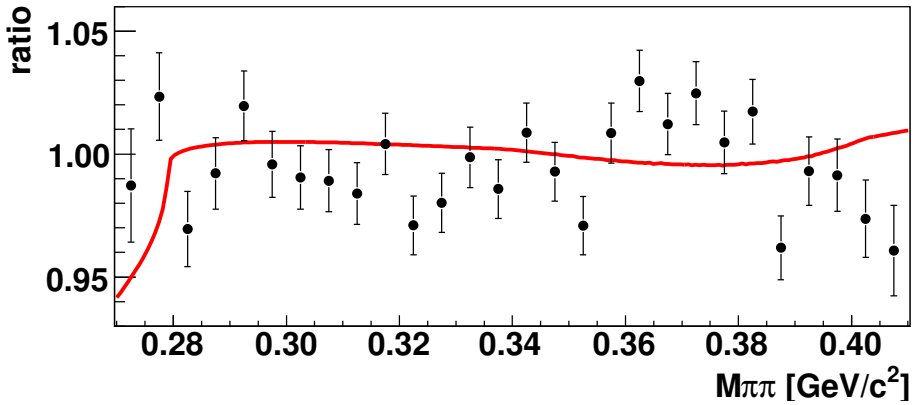
- Cusp in $K^+ \to \pi^+\pi^0\pi^0$
- NA48/2: 10^8 events

$\Rightarrow$ $\pi\pi$ scattering length

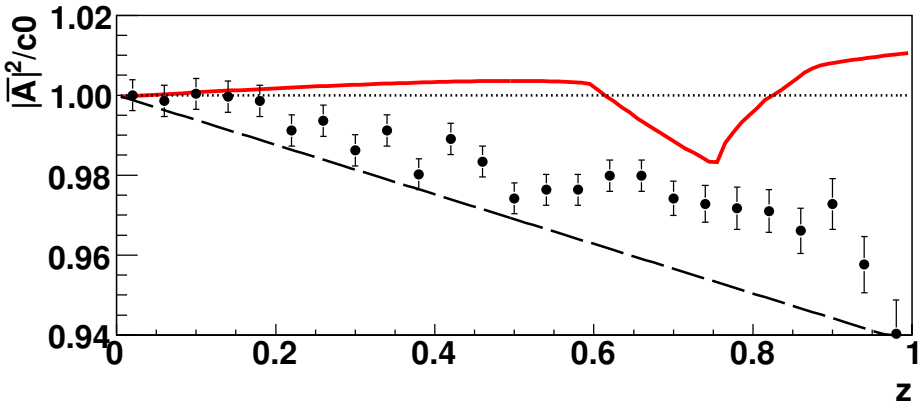
Cusp in $\eta \to \pi^0\pi^0\pi^0$

- Not as large effect as in $K^+ \to \pi^+\pi^0\pi^0$

$\Rightarrow$ Influence on z distribution: $0.6 < z < 0.9$



WASA PRC76:048201



KLOE arxiv:0707.4137

1-loop CHPT

Belina 2006

Pionium

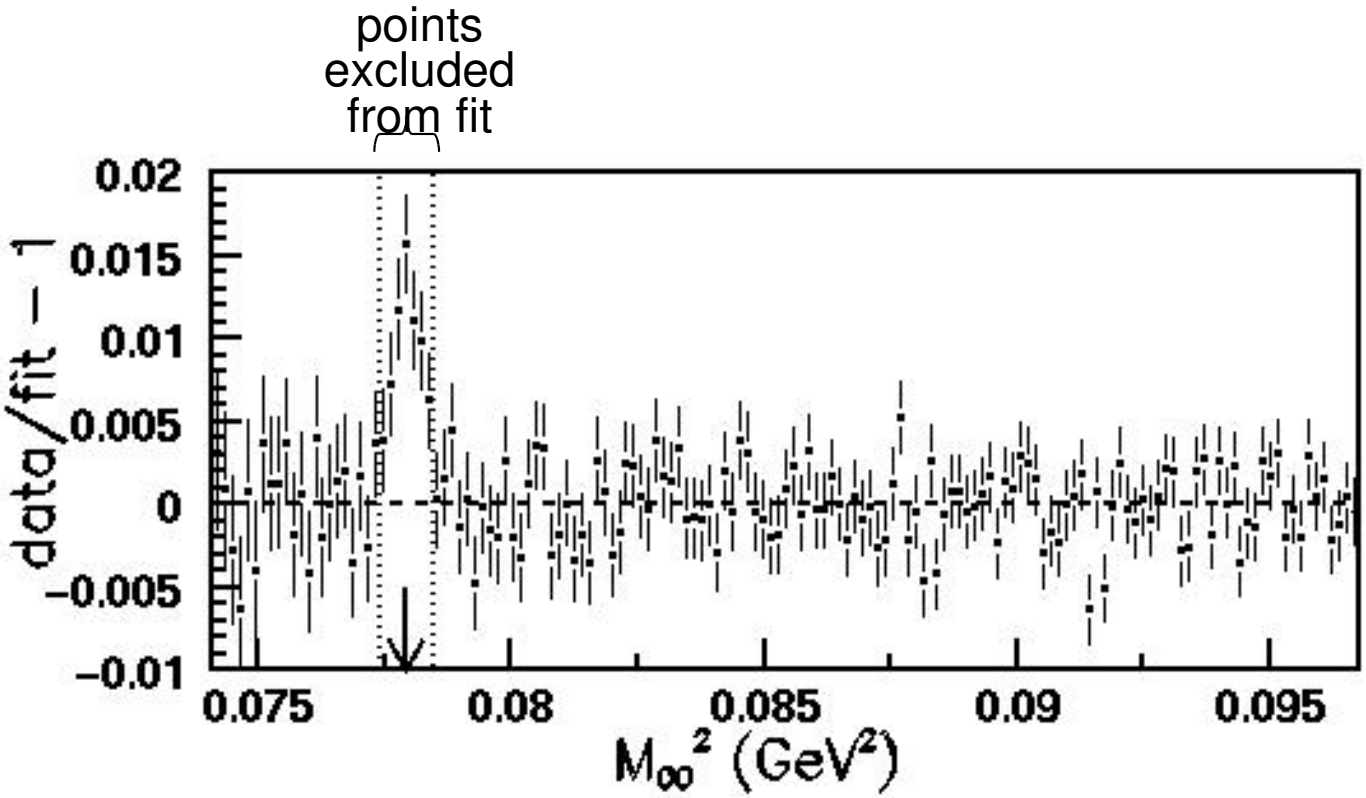
Predictions:

$Br(\eta \to \pi^0 A_{2\pi}) \approx 2 \cdot 10^{-8}$ $\quad$ $Br(\eta' \to \eta A_{2\pi}) \approx 6.2 \cdot 10^{-7}$

$Br(K^+ \to \pi^+ A_{2\pi}) \approx 5.5 \cdot 10^{-7}$ $\quad$ $Br(K_L \to \pi^0 A_{2\pi}) \approx 1.1 \cdot 10^{-7}$

Wycech,Green NPA,562,446, Silagadze JETP,60,689

NA48/2: (DiLella,KAON2007)



2.28± 0.26 times more events than predicted

Experiments & Detectors

Available data

- Crystal Ball (2000): 2×10^7 η AGS $\pi^- p \to n\eta$
- CELSIUS/WASA (2003): 3×10^6 $pp \to pp\eta$ (neutral)
- CELSIUS/WASA (2003): 5×10^5 $pd \to {}^3\mathrm{He}\eta$
- KLOE (2001-2006): 10^8 η, 10^6 η'
- Crystal Ball (2005): 3×10^7 Mainz $\gamma p \to \eta p$
- WASA-at-COSY (2007): 1.5×10^7 η (neutral)

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	ϵ	B/S	Analyzed	Collected
KLOE				
$\eta \to \pi^0\pi^0\pi^0$	0.14	0.08^c	6×10^5	4×10^6
$\eta \to \pi^+\pi^-\pi^0$	0.33	0.003	1.3×10^6	7×10^6
CBall				
$\eta \to \pi^0\pi^0\pi^0$	0.17	0.01^c	10^6	
WASA				
$\eta \to \pi^0\pi^0\pi^0$	0.1	0.05	–	5×10^5

Sources of η, η'

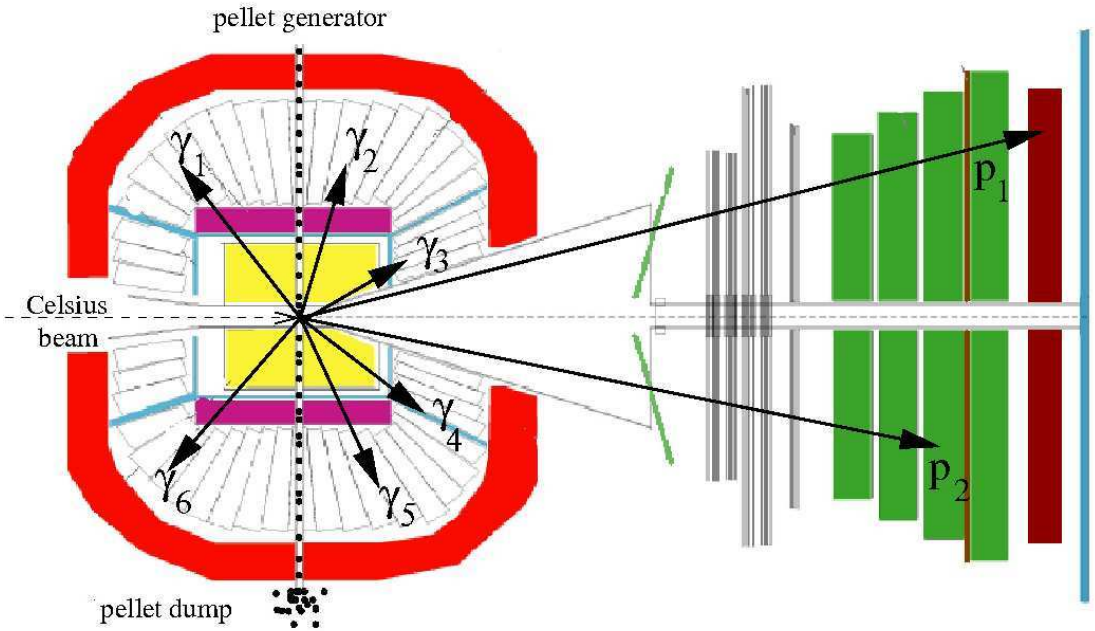
- Close to threshold photo or hadro production (Crystal Ball, WASA)

	T_b	p_b	β	Q	σ (σ_{max})
$pp \to pp\eta$	1.253	1.981	0.63	40	10μb
$pp \to pp\eta'$	2.404	3.208	0.75	45	300nb
$pd \to {}^3\mathrm{He}\eta$	0.891	1.569	0.42	2	400nb
$\pi^- p \to n\eta$	0.559	0.684	0.42		2.8 mb
$\gamma p \to p\eta$	0.706	0.706	0.43	58	16μb
$\gamma p \to p\eta'$	1.447	1.447	0.61	27*	1μb

- e^+e^- ϕ decays (KLOE,KLOE2)
- $\gamma^*\gamma^*$ (KLOE2)

Reaction $pp \to pp\eta$

P_{beam}[GeV/c]	2.1÷2.2
$\sigma[\mu b]$	5÷15
Useful rate @10^{31}: [day^{-1}]	$(2 \div 6)\times 10^6$
MM [MeV] FWHM:	5

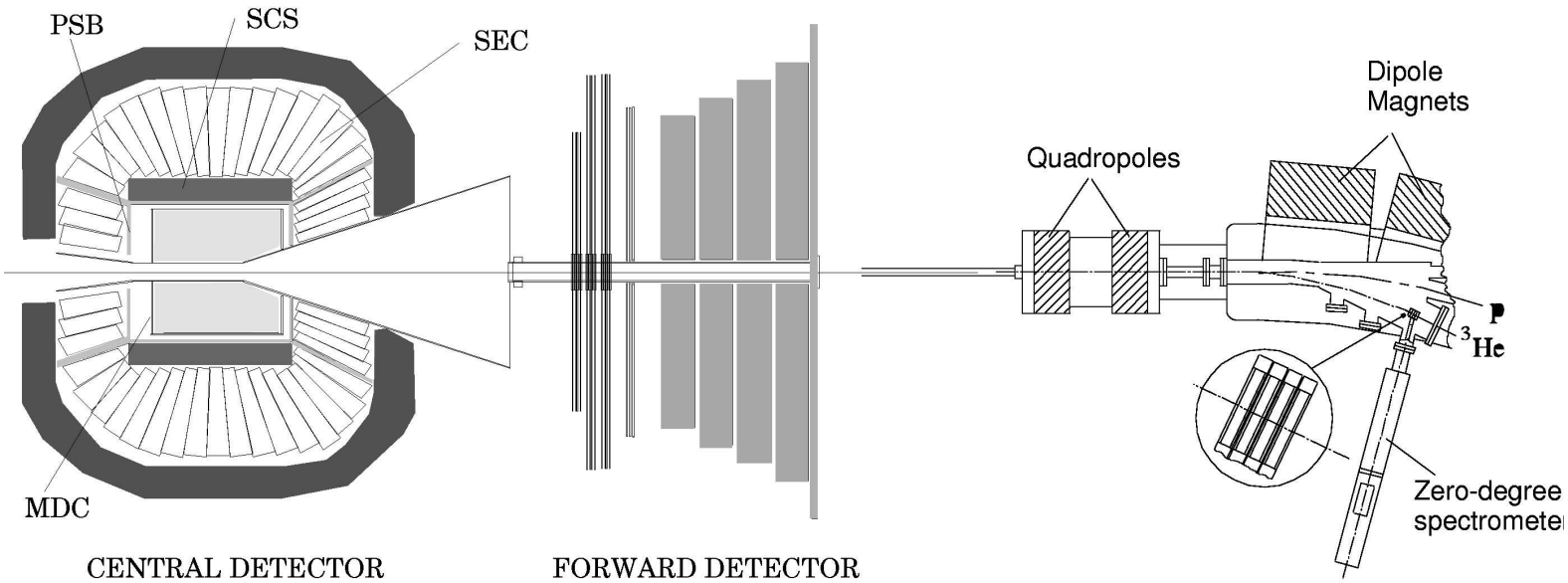


ΔE : $2.5^\circ < \theta < 18^\circ$ $\pi^\pm/p$: 170/300MeV

p : $25^\circ < \theta < 130^\circ$

E : $20^\circ < \theta < 140^\circ$ $16X_0$

$pd \to {}^3\mathrm{He}\eta$

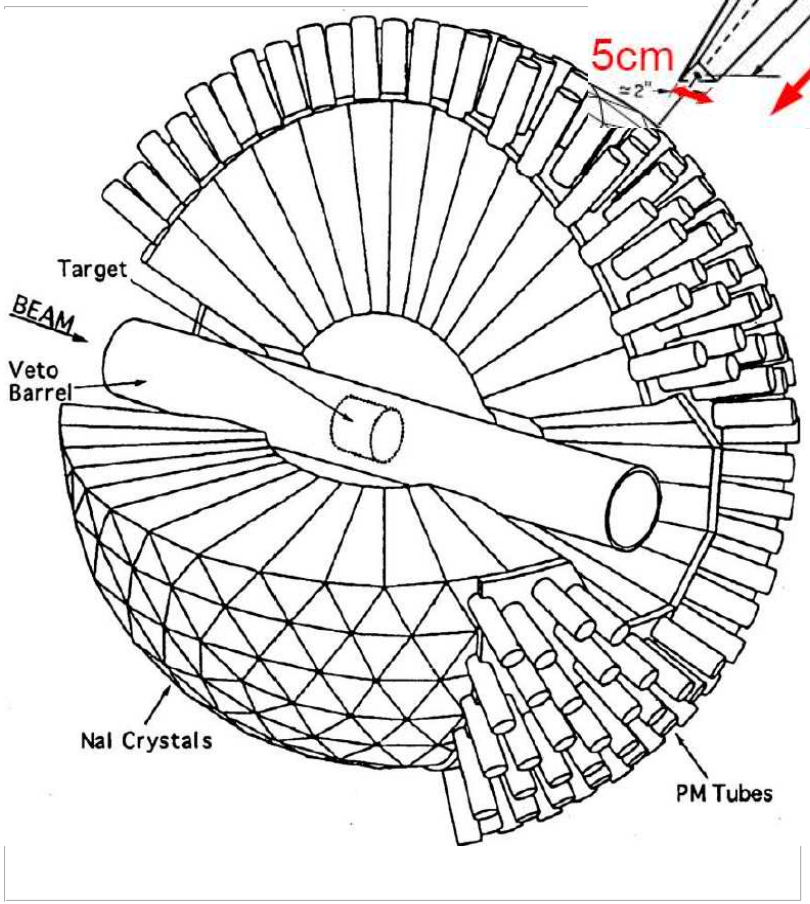


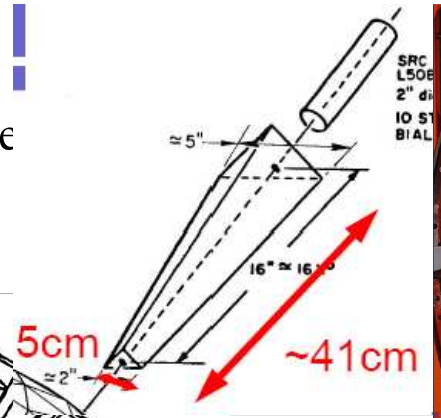
- Tagging: trigger/MM resolution
- Signal/Background
- Separation tagging/decay system
- Cross section only 0.4 μb

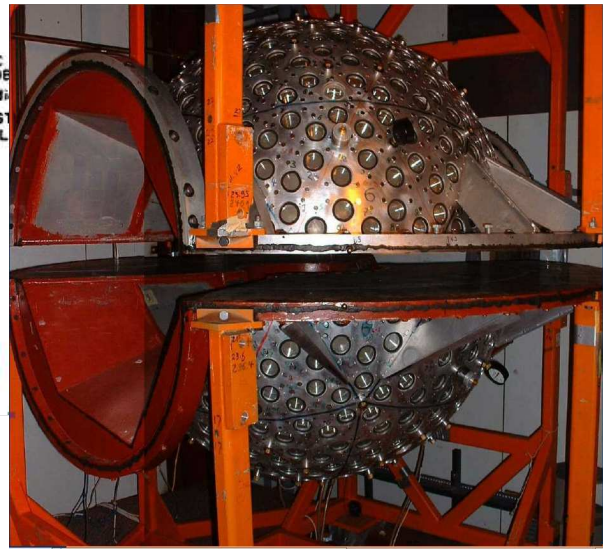
SLAC Crystal Ball

672 NaI(Tl) crystals

Two hermetic hemisphere





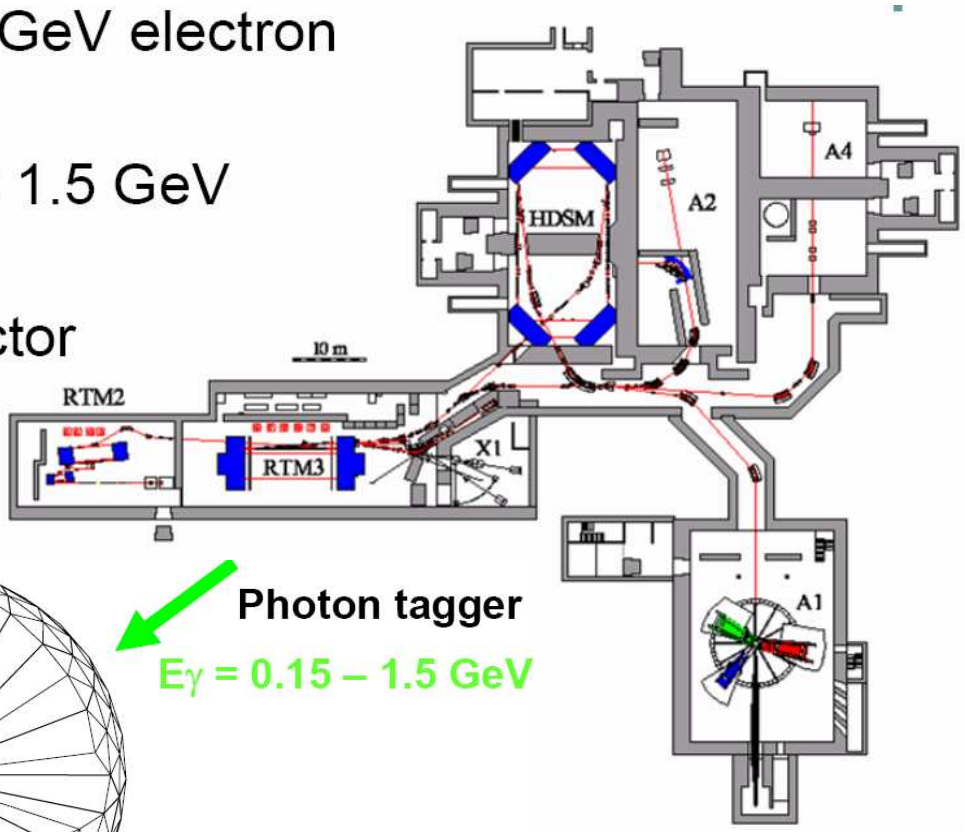


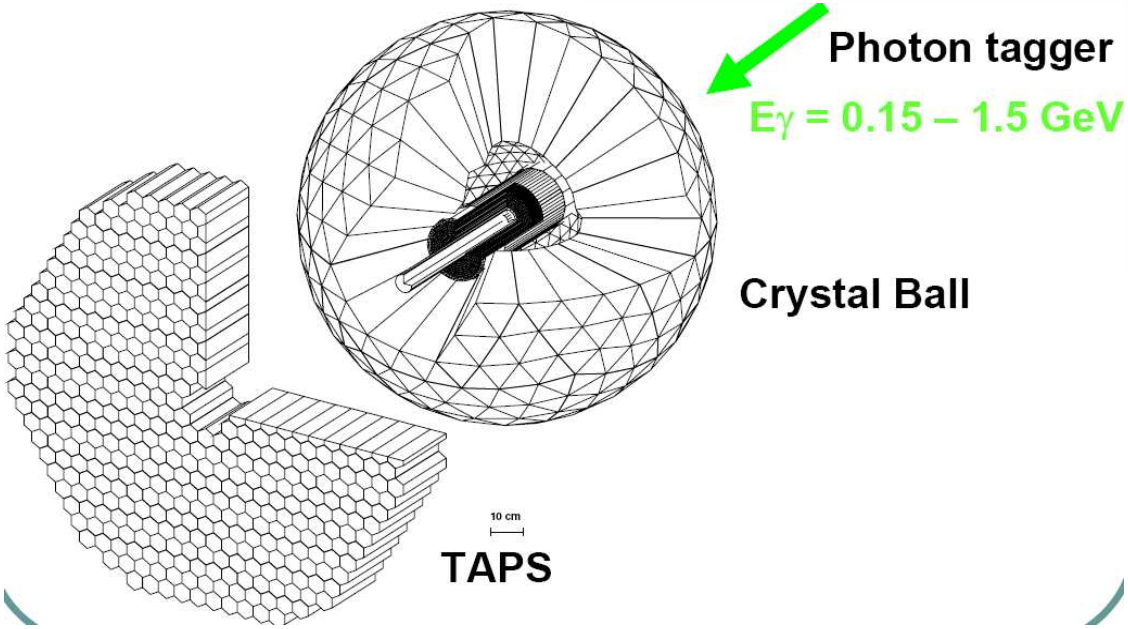
History:

1976	Conceived (e^+e^-)
1978-1981	SPEAR
1982-1986	DORIS
1987-1996	Parked at SLAC
1996-2002	BNL AGS
2003-	MAMI

Crystal Ball at Mainz

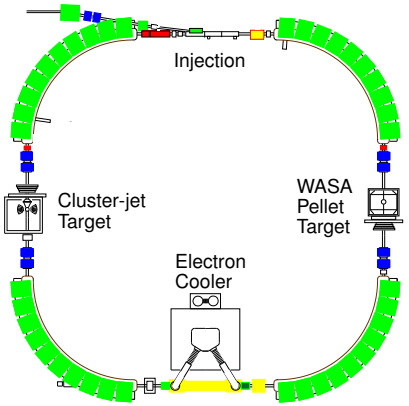
- MAMI-B 0.85 GeV electron microtron
- 2005 MAMI-C 1.5 GeV upgrade
- 100% duty factor



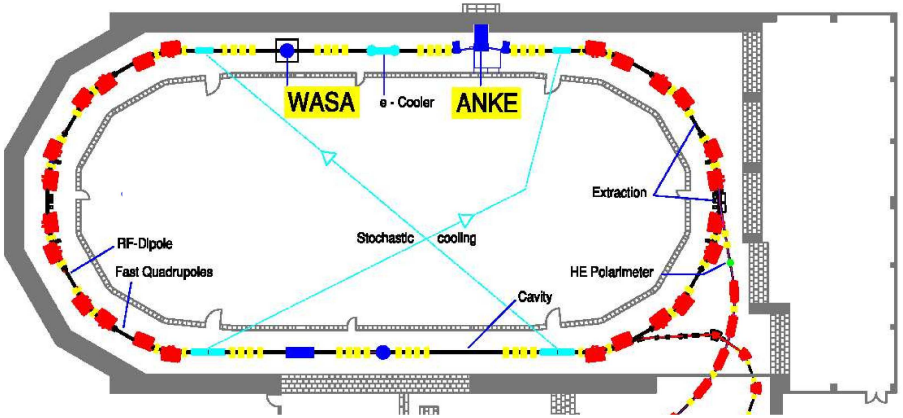


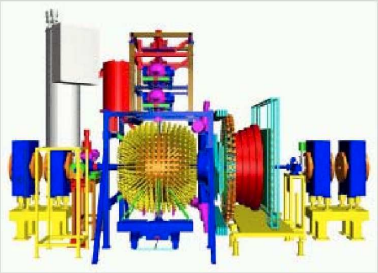
WASA

Uppsala (Sweden), CELSIUS 1989–2005



Jülich (Germany), COSY





WASA at COSY

Key Experiments

Symmetries and Symmetry Breaking

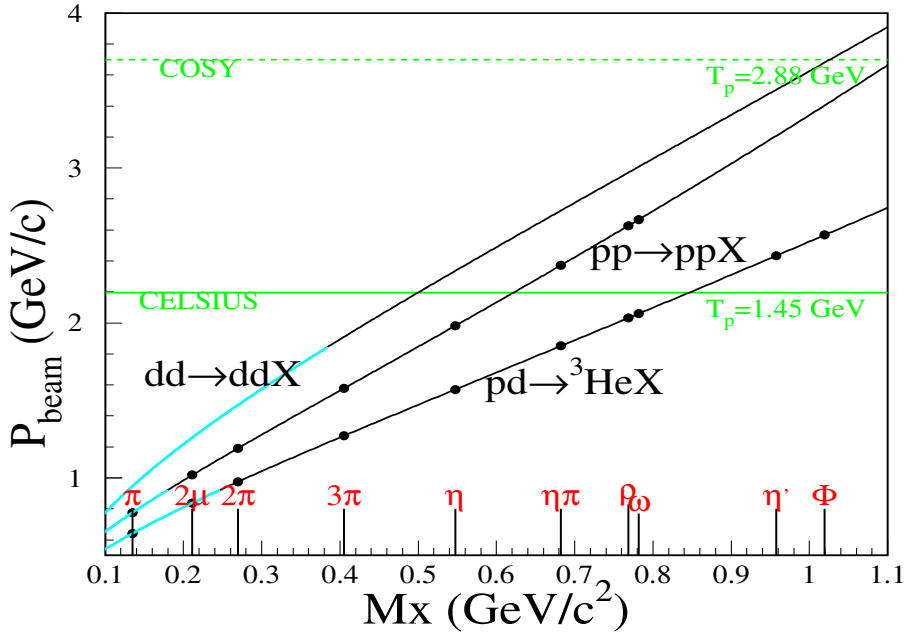
Decays of η and η′ Mesons

Isospin Violation in $\vec{d}d \to \alpha\pi^0$

(Crypto)Exotic Hadron Resonances

$a_0(980)/f_0(980)$ Scalar Meson Mixing

Hyperon Resonances



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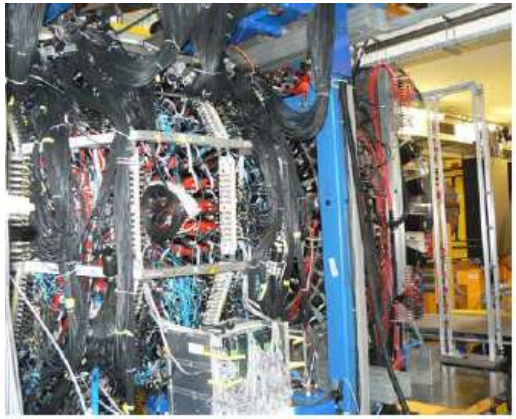
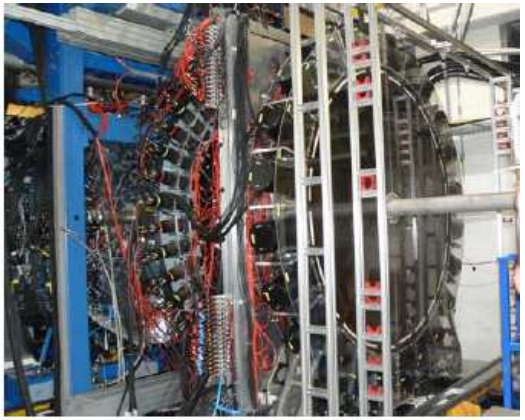
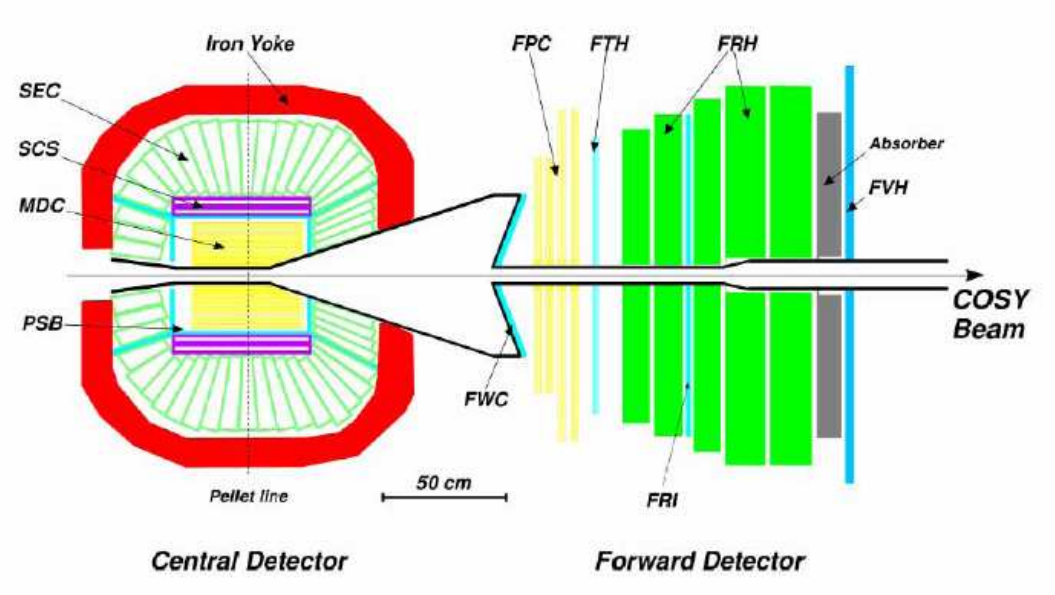
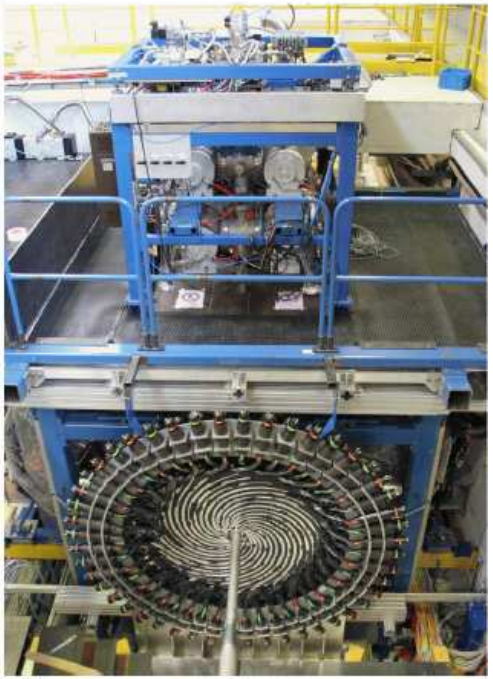
WASA-at-COSY






Iron Yoke
SEC
SCS
MDC
PSB
FPC
FTH
FRH
Absorber
FVH
COSY Beam
FWC
FRI
Pellet line
50 cm
Central Detector
Forward Detector



New DAQ

QDC modules 16ch each
FlashADC with FPGA logic
ZEL FZJ and Uppsala University

sQDC – for CsI, 80MHz 12bit
(70 Modules – 1100 channels)

fQDC – for plastics, 160MHz 12bit
(36 Modules - 580 channels)

QDC

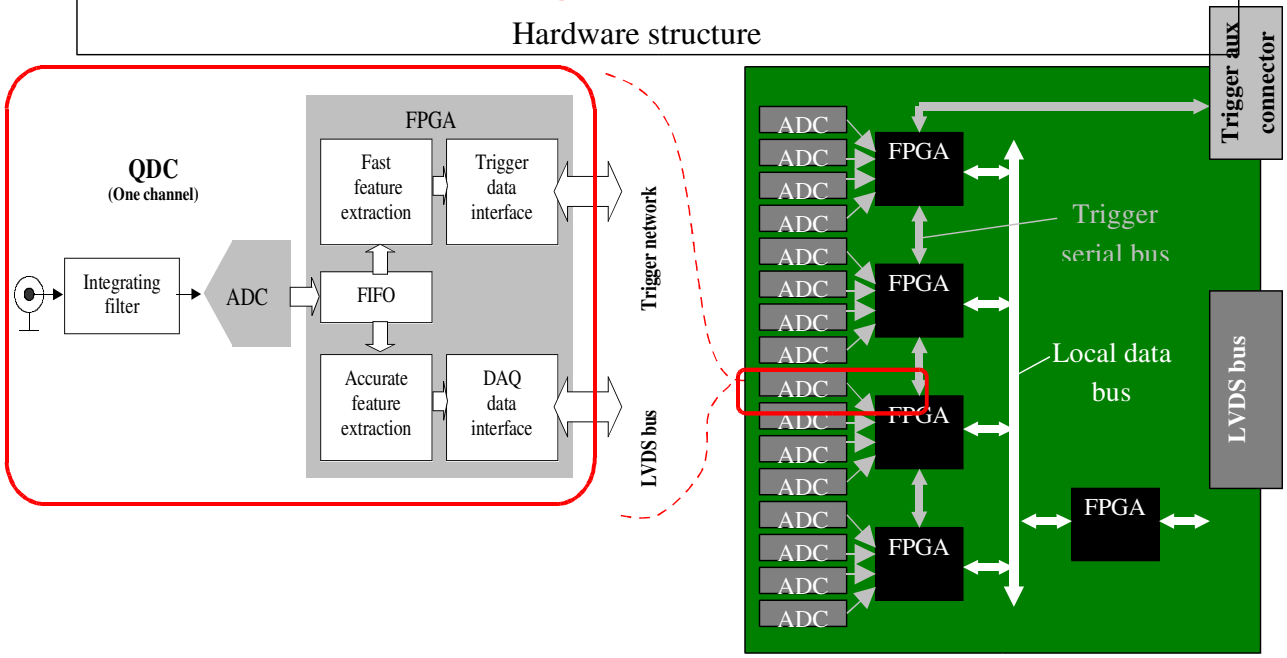
TDC modules (F1,GPX) 64ch each
ZEL FZJ
F1: resol. 120ps, max. rate/ch 500KHz
(F1 - 70 Modules – 3700 channels)

GPX: resol. 90ps, max. rate/ch 10MHz
(GPX - 11 Modules – 708 channels)

TDC

The QDC module

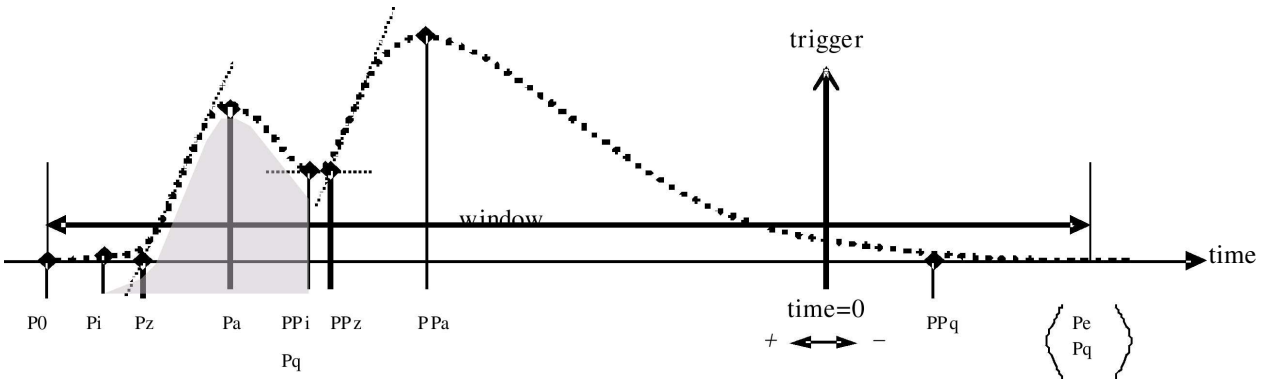
Hardware structure



- 16 ADC channels with symetrizing input amplifiers
- 5 FPGA (4 ADC interfaces, 1 System Bus interface
- 4 ADC channels per FPGA for data retention and feature extraction
- Local bus (LVDS) for data readout
- Trigger bus for high-speed serial trigger link

Paweł Marciniewski & ZEL

Feature extraction



P0 – window beginning

Pi – time for the first non-zero value

Pz – pulse start time calculated from slope crossing the pedestal value

Pa – signal amplitude

Pq – signal integral (charge) *

PPi – minimum value before pileup

PPz – pileup pulse start time calculated from slope crossing the momentary pedestal value Ppi

PPa – pileup pulse amplitude

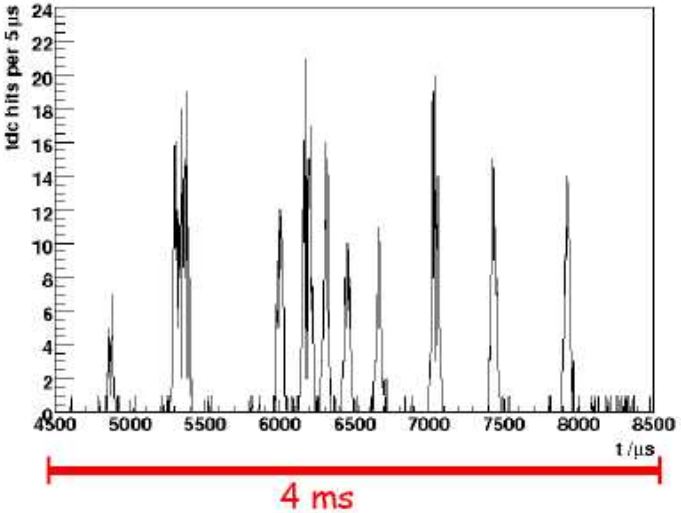
Pe – pileup integral, starting from PPi

* If pileup occurs, the integral **Pq** is only calculated untill PPi time

DAQ and Pellet performance

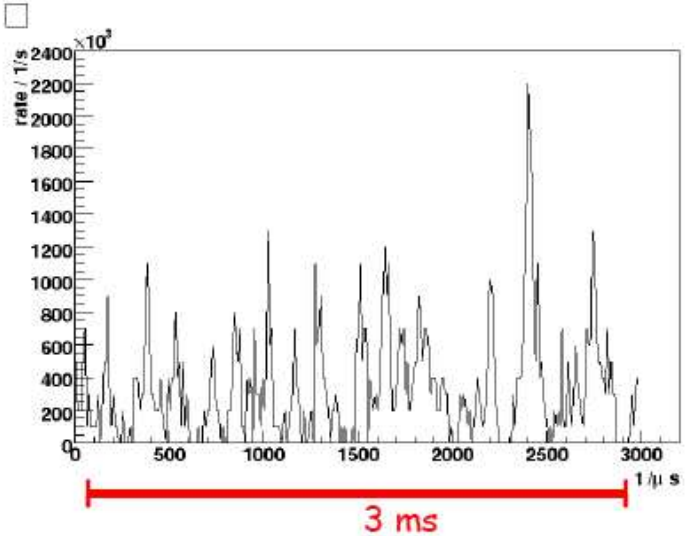
November 06

- only 1000 - 2000 pellets/s
- time „pellet in beam" : 80-100 μs
- DAQ deadtime : 80 μs
- only 1 event per pellet
- ~1500 events/s

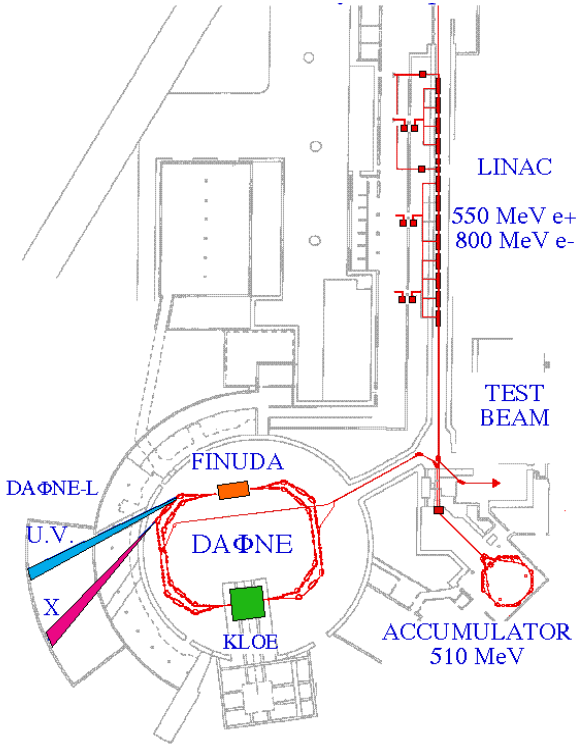


February 07

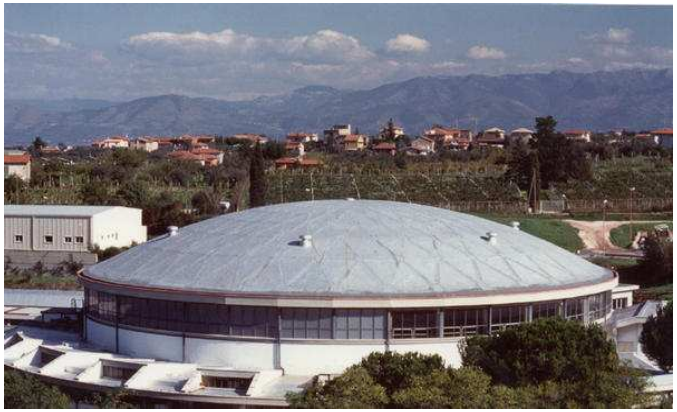
- optimum pellet performance achieved
- 8000 - 10000 pellets /s, as in Uppsala
- first test of final DAQ, „buffered readout"
- will allow to measure 2-4 events per pellet
- above 10.000 events/s



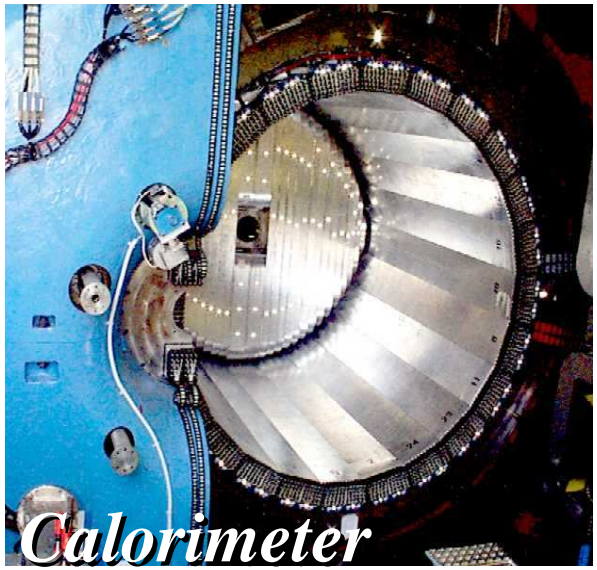
DAΦNE the Frascati Φ factory

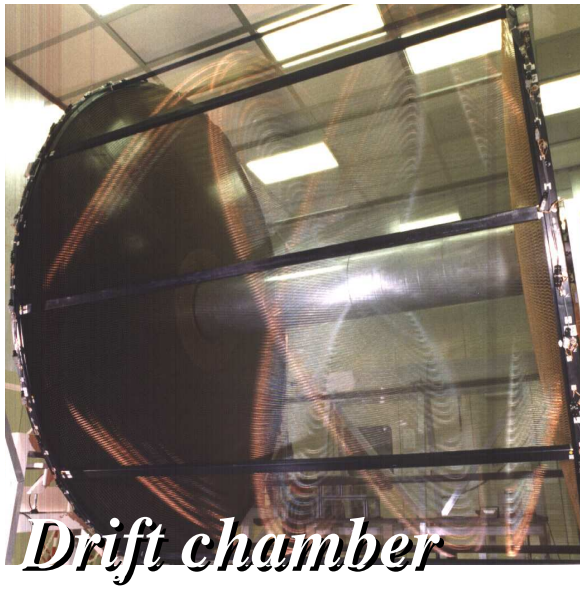


- e^+e^- collider @ $\sqrt{s} = M_\phi = 1019.4$ MeV
- 2 interaction regions (KLOE – DEAR/FINUDA)
- Separate e^+, e^- rings to minimize beam-beam interactions
- Crossing angle: 12.5 mrad ($p_x(\phi) \cong 13$ MeV)



Detector performance



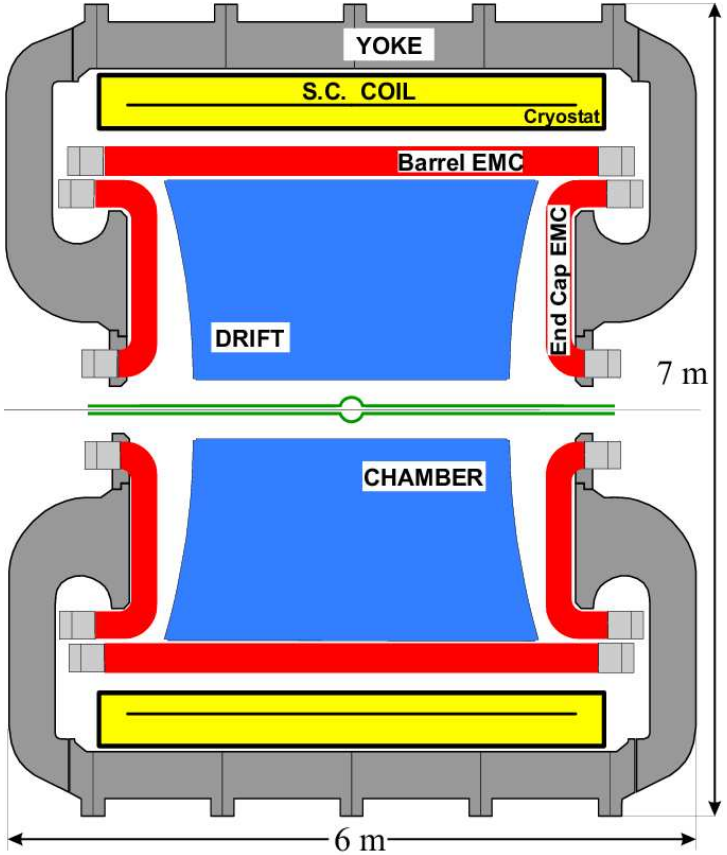


- $\sigma_E/E = 5.7\% / \sqrt{E(\mathrm{GeV})}$
- $\sigma_t = 54\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} \oplus 50\ \mathrm{ps}$

- $\sigma_p/p = 0.4\%$ (tracks with $\theta > 45°$)
- $\sigma_{x/y} = 150\ \mu\mathrm{m}$, $\sigma_z = 2\ \mathrm{mm}$
- $\sigma(M_{\eta \to \pi^+\pi^-}) \sim 3\ \mathrm{MeV}/c^2$

The KLOE detector

Design driven by the measurement of ~~CP~~ via double ratio: $\mathbf{R} = \Gamma(K_L \to \pi^+\pi^-)\,\Gamma(K_S \to \pi^0\pi^0) / \Gamma(K_S \to \pi^+\pi^-)\,\Gamma(K_L \to \pi^0\pi^0)$



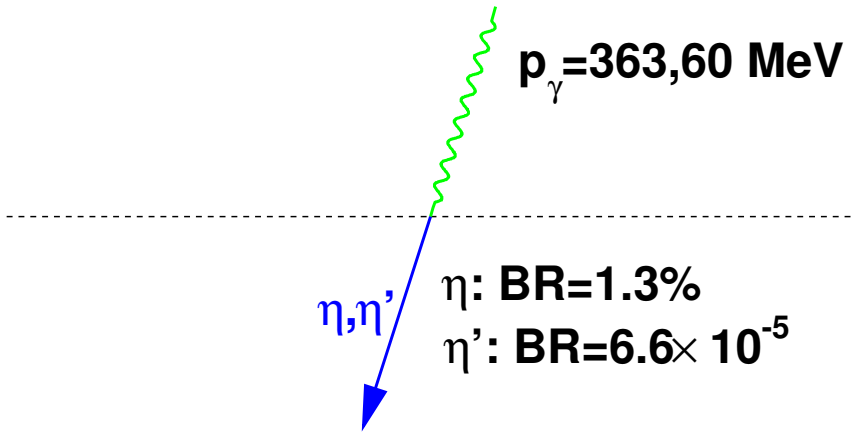
- **Be beam pipe** (spherical, 10 cm ∅, 0.5 mm thick) + **instrumented permanent magnet quadrupoles** (32 PMT's)
- **Drift chamber** (4 m ∅ × 3.3 m, CF frame)
  - Gas mixture: 90% He + 10% C_4H_{10}
  - 12582 stereo–stereo sense wires
  - almost squared cells
- **Electromagnetic calorimeter**
  - lead/scintillating fibers (1 mm ∅), 15 X_0
  - 4880 PMT's
  - 98% solid angle coverage
- **Superconducting coil** (B = 0.52 T)

$\phi \to \gamma\eta(\eta')$ decays

- ϕ produced nearly at rest

$\phi \to \gamma\eta(\eta')$ decays

- ϕ produced nearly at rest
- Signature: monoenergetic photon



$\phi \to \gamma\eta(\eta')$ decays

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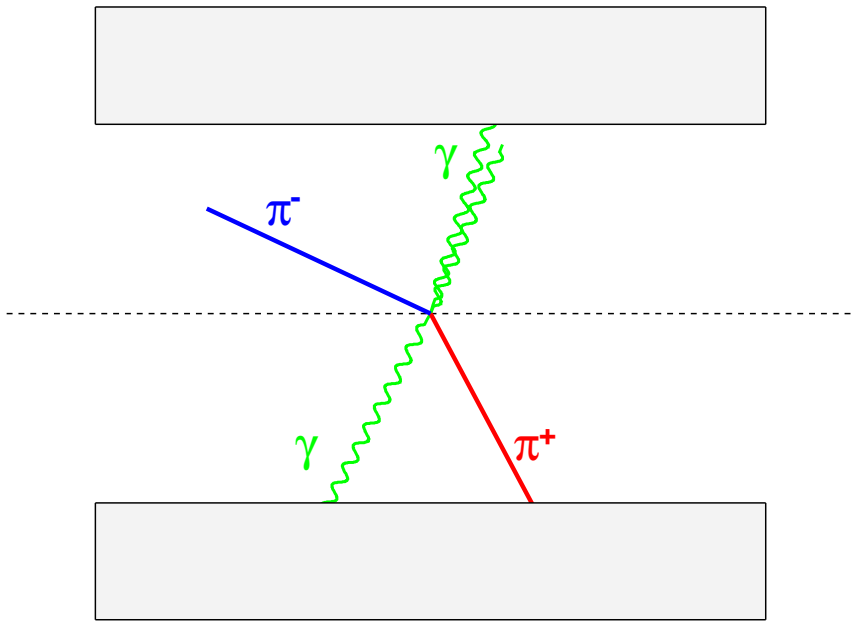
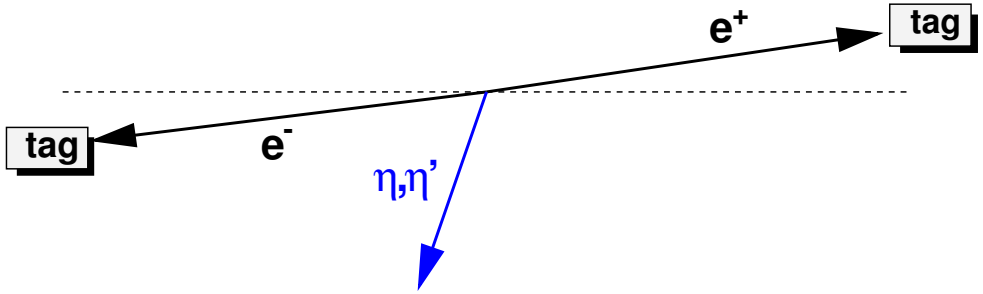


KLOE2

- test *crab waist* scheme fall 2007 (SuperB factory)
- KLOE2 start 2009 aim for $>$20fb^{-1} $\sqrt{s} = m_\phi$
- Inner tracker

KLOE2

- test *crab waist* scheme fall 2007 (SuperB factory)
- KLOE2 start 2009 aim for >20fb^{-1} $\sqrt{s} = m_\phi$
- Inner tracker
- $\gamma^*\gamma^*$ physics at $\sqrt{s} \geq m_\phi$ (taggers):



- $e^+e^- \to e^+e^-\eta(\eta')$:
- Competitive source of η'
- Direct measurement of $\Gamma(\eta(\eta') \to \gamma\gamma)$ (now $\Gamma_{\gamma\gamma} \times \Gamma_i/\Gamma$)

Summary

Outlook: hadronic decays

- High statistics data ($>10^7$ events) for $\eta \to \pi^0\pi^0\pi^0$ (CB, WASA)
- KLOE results on $\eta \to \pi^+\pi^-\pi^0$ will be checked (WASA)
- Data on $\eta' \to \pi\pi\eta$ 10^4–10^5 events (KLOE,CB,WASA)

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Decay $\eta' \to \pi^+\pi^-\pi^0$:

- Not seen
- Predictions $BR = 10 \times BR(\eta' \to \pi^0\pi^0\pi^0)$
- Large phase space
- Huge background:
  - $\Rightarrow$ WASA: $pp \to pp\pi^+\pi^-\pi^0$ 0.4 mb
  - $\Rightarrow$ KLOE: $\phi \to \pi^+\pi^-\pi^0$ 15%
  - $\Rightarrow$ $\eta' \to \omega\gamma$, $\eta' \to \pi^+\pi^-\eta$

? High energy experiments e.g. (VES) $\pi^- p$@40 GeV

Physics of η and η' decays

Laboratory of low energy QDC and SM:

- $\eta, \eta' \to 3\pi$ decays $\Rightarrow m_u/m_s, m_d/m_s$
- $\eta' \to \pi^+\pi^-\gamma$ $\Rightarrow$ QCD anomaly
- η' radiative decays $\Rightarrow \eta'$ quark structure
- Dalitz decays $\Rightarrow$ formfactors
- $\eta \to e^+e^-$ $\Rightarrow$ new interactions
- $\eta \to \pi^\circ e^+e^-,\ \pi^+\pi^-e^+e^-$ $\Rightarrow$ C, CP tests

Conclusions

- Crystal Ball, WASA, KLOE:
  - Better accelerators
  - New electronics
  - Upgraded detectors

Conclusions

- Crystal Ball, WASA, KLOE:
  - Better accelerators
  - New electronics
  - Upgraded detectors
- Extended collaborations
- EtaMesonNet $\Rightarrow$ PrimeNet

Links

- KLOE: www.lnf.infn.it/kloe/
- Crystal Ball BNL: bmkn8.physics.ucla.edu/Crystalball/crystalball.html
- Crystal Ball MAMI: wwwa2.kph.uni-mainz.de/cb/
- CELSIUS/WASA: www.tsl.uu.se/wasa
- WASA-at-COSY: www.fz-juelich.de/ikp/wasa
- EtaMesonNet: www.isv.uu.se/etamesonnet
- ...more references: arXiv:0709.0603