Recent results from KLOE-2

The 21st Particles and Nuclei International Conference

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Wojciech Krzemień

On behalf of the KLOE-2 collaboration

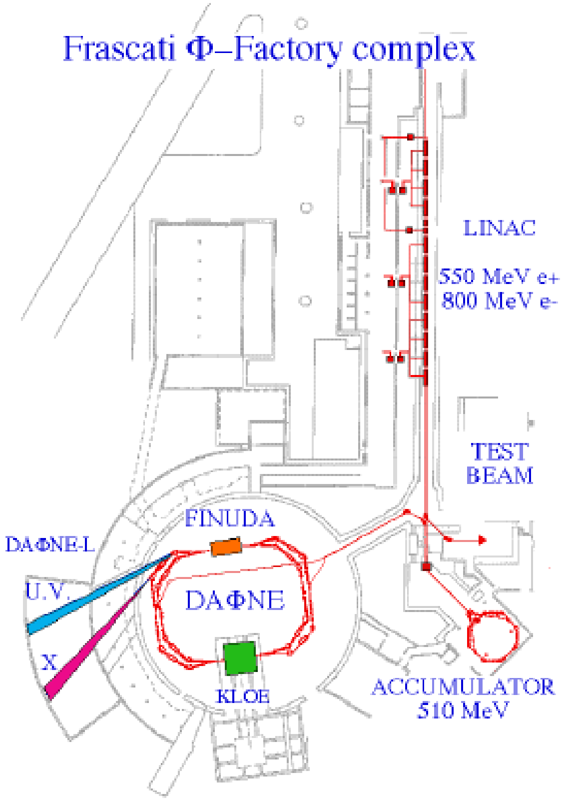
NATIONAL SCIENCE CENTRE
POLAND

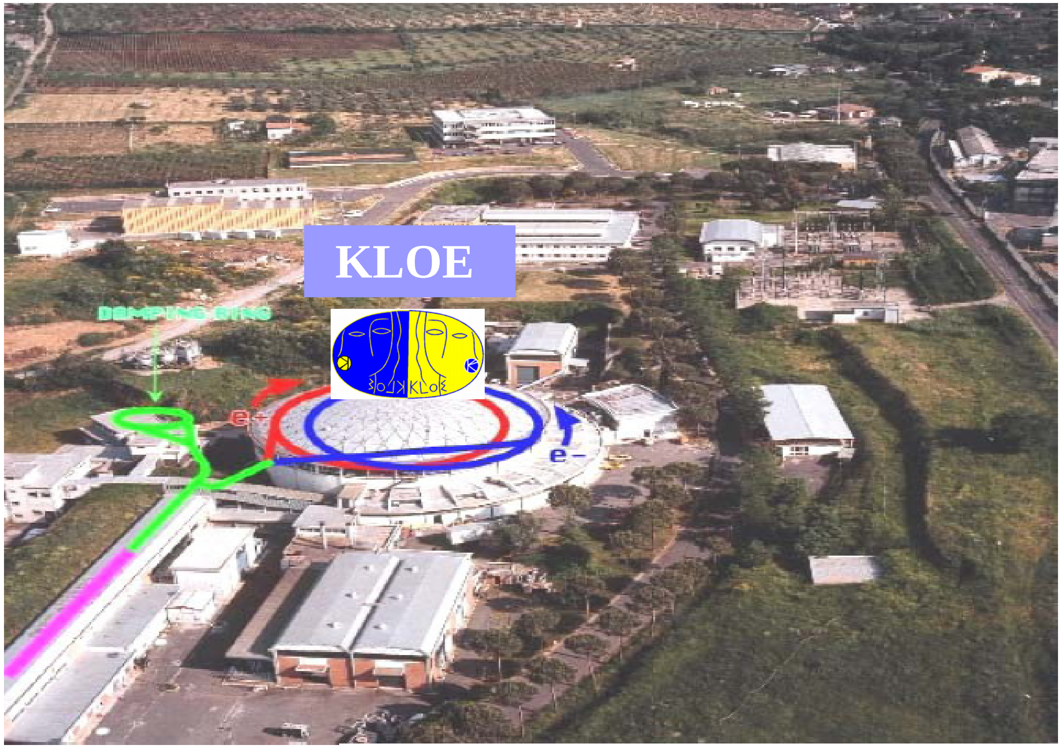
Outline

- KLOE-2 detector and the DAΦNE Φ-factory,
- Measurement of the running coupling constant $\alpha_{QED}(s)$,
- Dalitz plot analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$,
- Searches for dark forces,
- Tests of discrete symmetries with entangled kaons,
- Summary

KLOE-2 detector and DAΦNE Φ-factory

DAΦNE
(Double Annular Φ Factory for Nice Experiments)

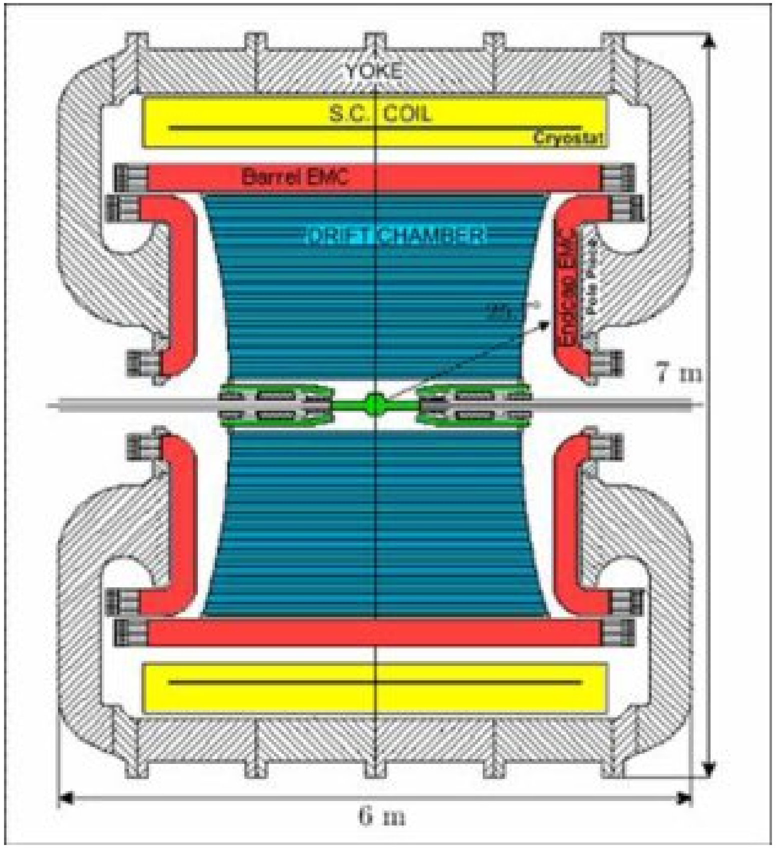




- $e^+ e^-$ collider $\sqrt{s} = M_\Phi = 1019.4$ MeV
  - 2 interaction regions
  - $e^+ e^-$ separated rings
  - 105 + 105 bunches spaced by 2.7 ns
- DAΦNE upgrade (2008): new interaction scheme
  - Large beam crossing angle
  - Crab waist sextupoles

KLOE detector

- **Calorimeter**
- 98% coverage full solid angle
- $\sigma_E/E = 5.7\% / \sqrt{E(\mathrm{GeV})}$
- $\sigma_T = 57\ \mathrm{ps} / \sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$
- Barrel + 2 end-caps:
  - Pb/scintillating fiber readout by 4880 PMTs



Magnetic field B = 0.52 T

- **Drift Chamber**
- Low-mass gas mixture: 90% Helium + 10% isobutane
- $\delta p_\perp / p_\perp < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} = 150\ \mu\mathrm{m}$; $\sigma_z = 2\ \mathrm{mm}$
- 12582 cells
- Stereo geometry
- 4m diameter, 3.3m long

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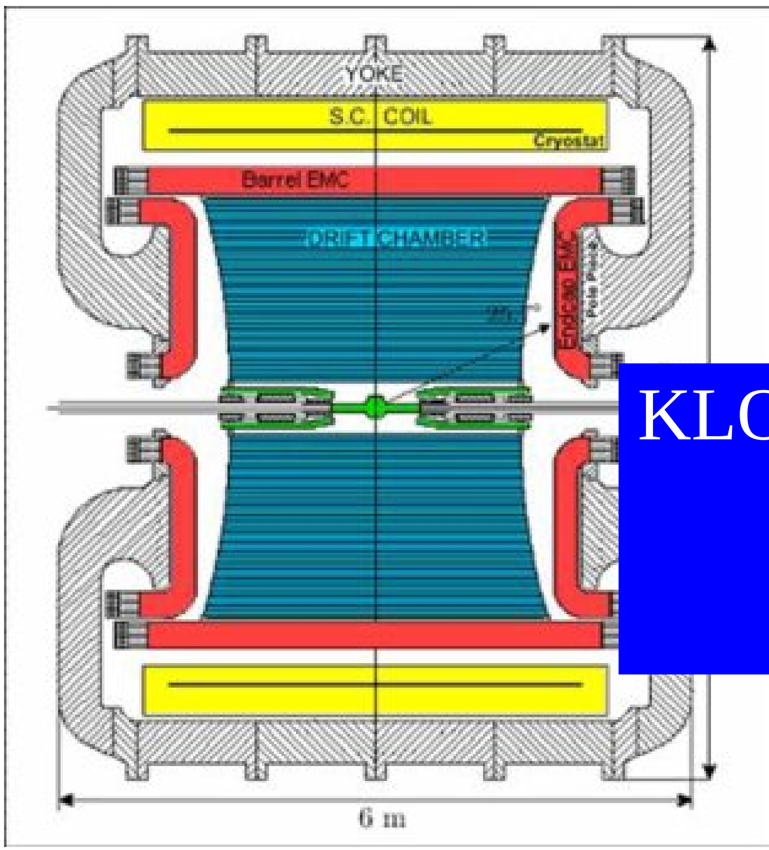
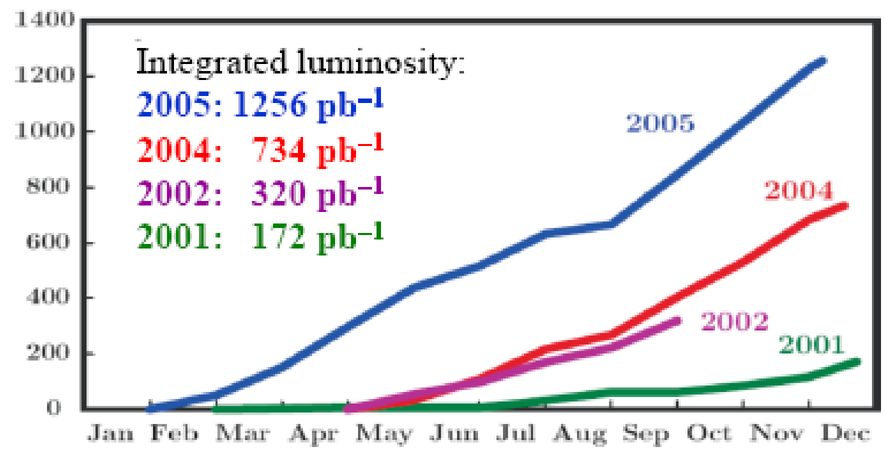


Magnetic field B = 0.52 T

- **KLOE data taking campaign 1999- 2005**
  - ~ 2.5 fb^{-1}
  - ~ 260 pb^{-1} off-peak

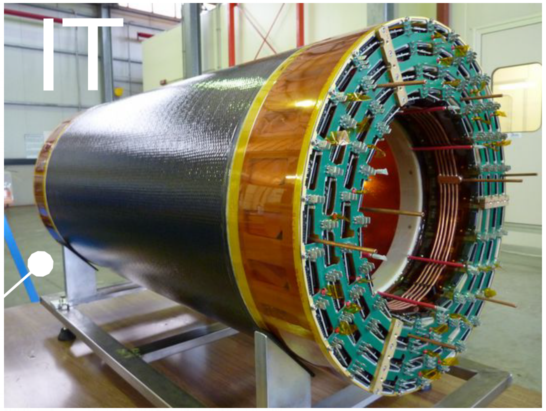


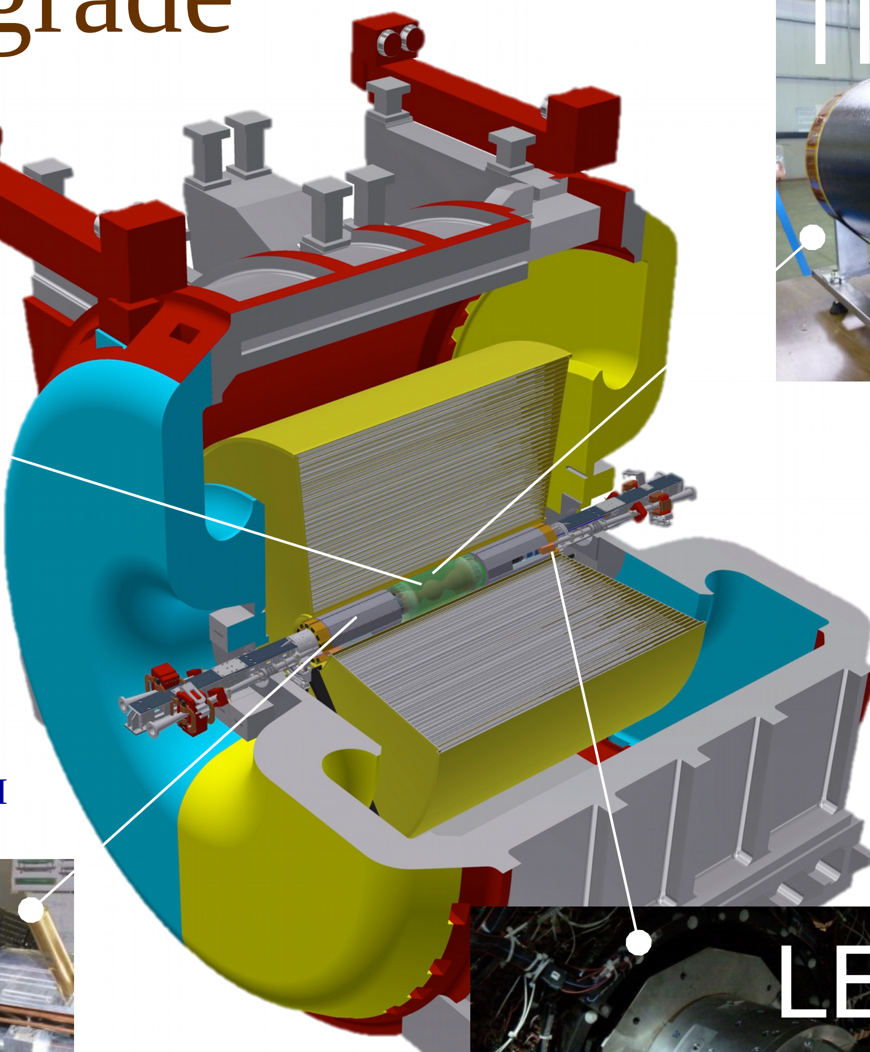
KLOE data sample (2.5 fb^{-1}): ~ 8 x 10^9 Φ
~ 10^8 η
~ 5 x 10^5 η'

- Stereo geometry
- 4m diameter, 3.3m long

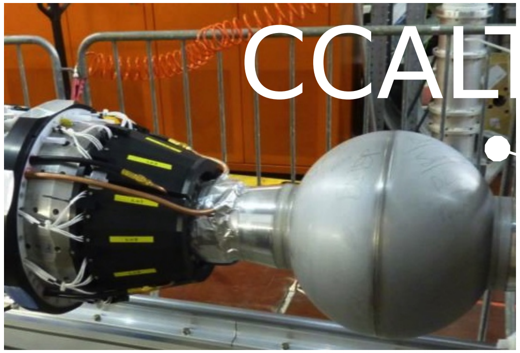
KLOE-2 Upgrade

- 4 layers of C-GEM
- better vertex reconstruction and track parameters



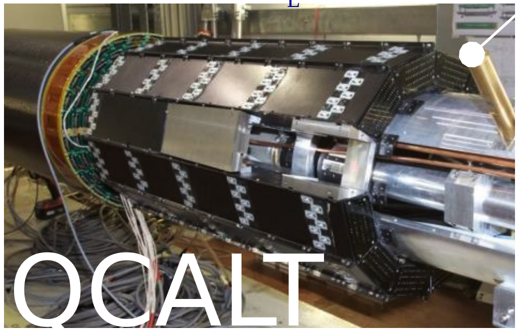


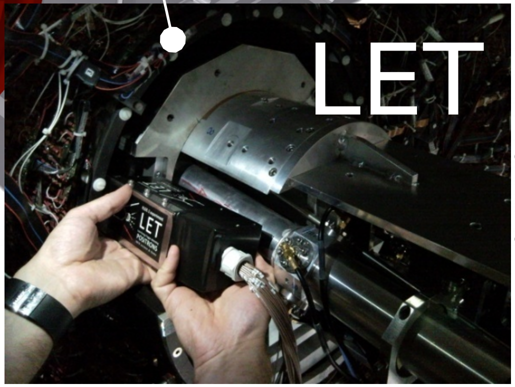
- LYSO Crystal w SiPM
- low angle γ's (down to 10°)



- Scintillator hodoscope +PMTs
- e+e--taggers for γγ-physics

- Tungsten / Scintillating Tiles w SiPM
- Quadrupole coverage for K_L decays

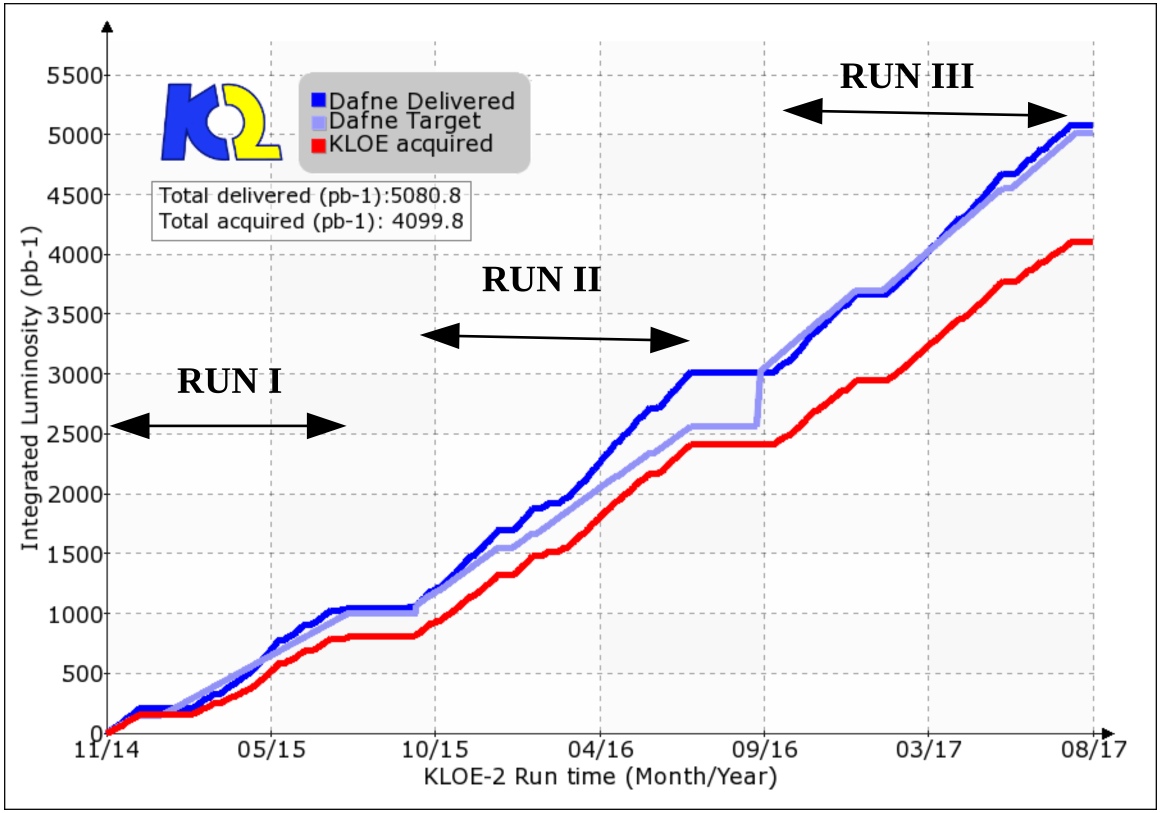




- calorimeters LYSO+SiPMs
- at ~ 1 m from IPe+e--taggers for γγ-physics

KLOE-2 data taking

- KLOE-2 has started a new data campaign in November 2014
- All KLOE-2 detectors operational
- DAΦNE luminosity: peak = $2.2\text{x}10^{32}$ & daily delivered >10 pb^{-1}



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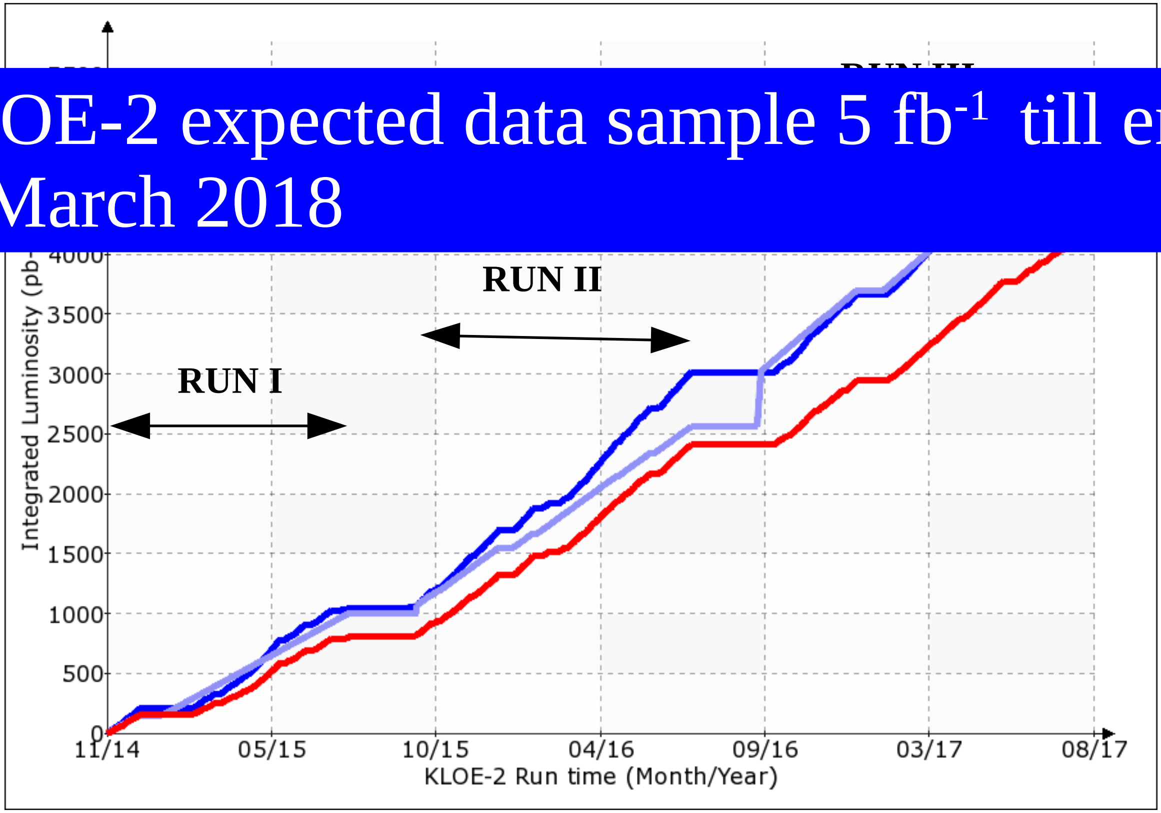


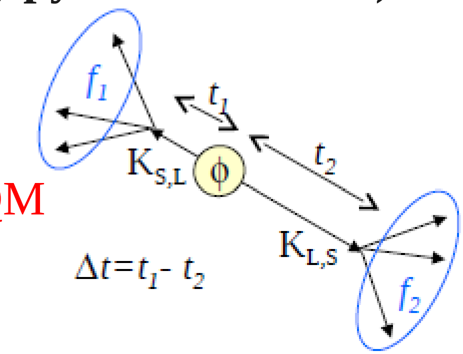
KLOE-2 expected data sample 5 fb^{-1} till end of March 2018

Physics with KLOE-2

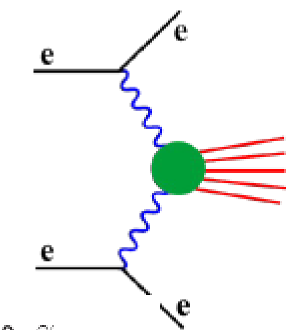
KLOE-2 rich physics program

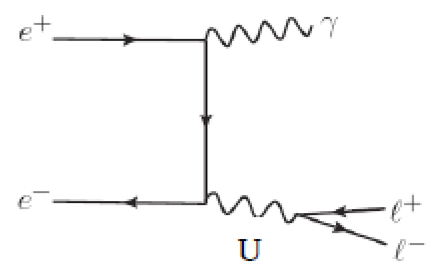
Eur. Phys. J C68 (2010) 619 **+**

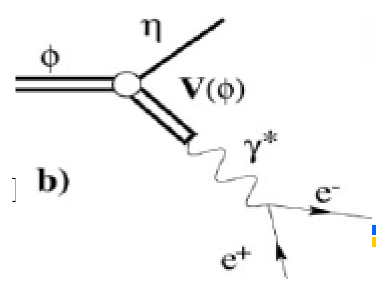
KLOE-2 WORKSHOP @1GeV (https://agenda.infn.it/conferenceDisplay.py?confId=11722)

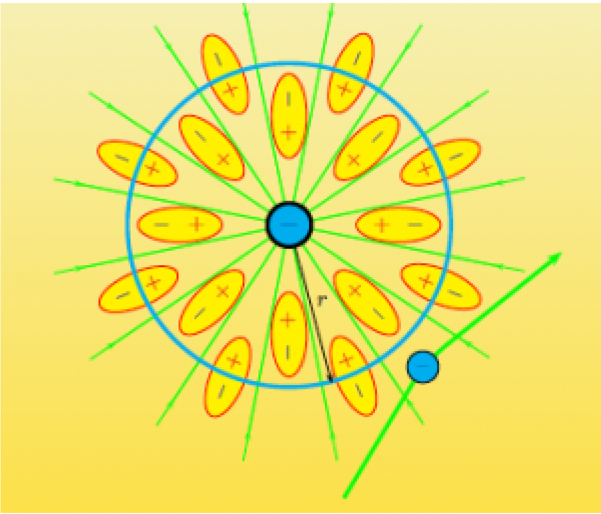


- Kaon physics
  - Discrete symmetries test
  - High precision tests of CPT and QM
- γγ physics
  - $\gamma\gamma \rightarrow \pi^0$
  - Study of $\Gamma(S/P \rightarrow \gamma\gamma)$
  - P transition form factor
- Light meson spectroscopy
  - Properties of scalar/vector mesons
  - Rare η decays
  - η' physics
- Dark matter searches
  - Light bosons
  - Leptophobic searches
  - ALPs
- Hadronic Physics below 1 GeV







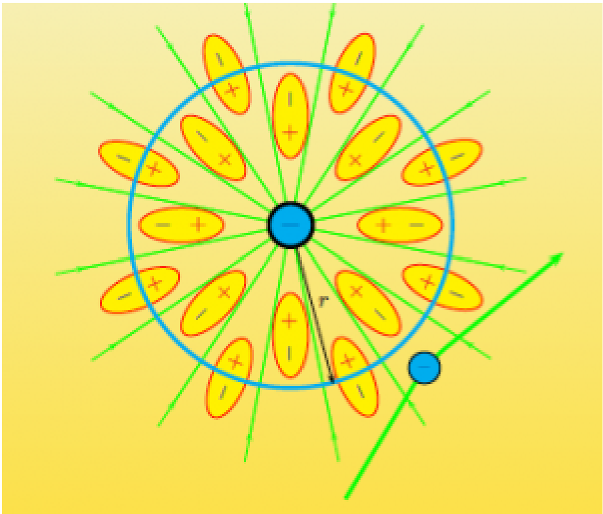


Measurement of the QED coupling constant $\alpha(s)_{QED}$

Figure from http://w3.lnf.infn.it/the-variable-constant/?lang=en

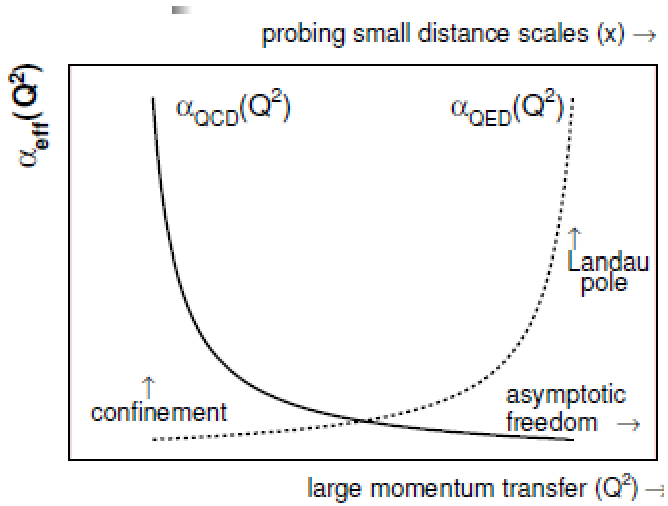
$\alpha(s)_{QED}$ below 1 GeV

- α_{QED} is a running parameters due to Vacuum Polarization
- "Vacuum Polarization" function $\Pi(q^2)$ can be absorbed by redefinition of an effective charge



$$e^2 \rightarrow e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))} \qquad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$

$$\boxed{\alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha}}$$



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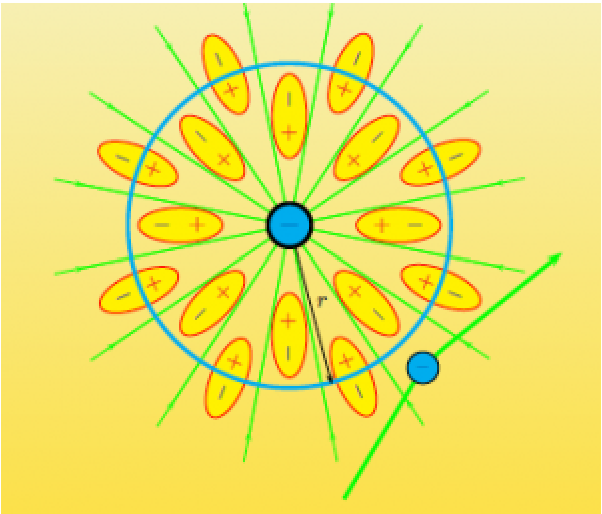

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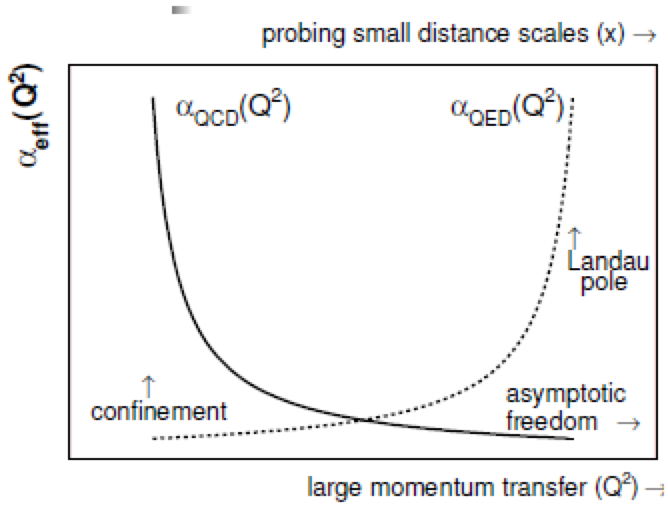
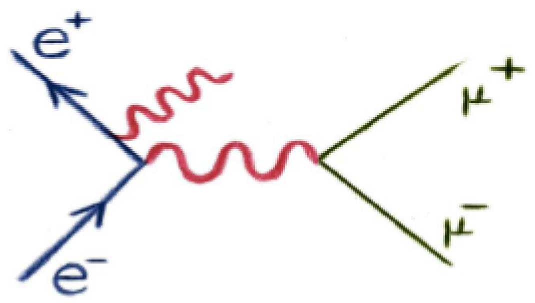


$$\boxed{\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}{}_{had} + \cancel{\Delta\alpha_{top}}}$$

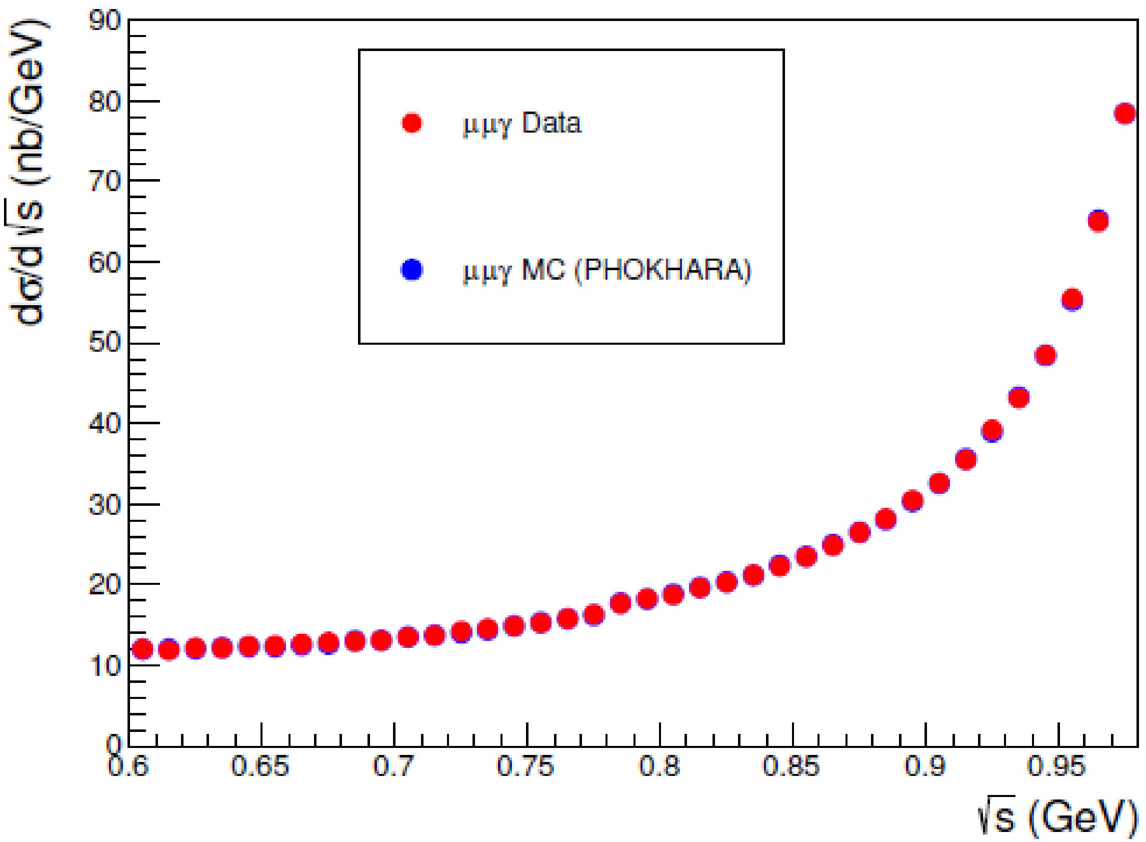
QED | non-perturbative QCD | negligible at lower energies

Phys. Lett. B 767 (2017) 485-492

$\alpha(s)_{QED}$ from 0.6 to 0.975 GeV



- time-like measurement
- L = 1.7 fb^{-1} (KLOE data)
- Total systematic error ~ 1%



- Excellent agreement with NLO theory (PHOKARA MC) with VP inside (H. Czyz, A. Grzelinska, J.H. Kuhn, G. Rodrigo, Eur. Phys. J. C 39 (2005) 411.)

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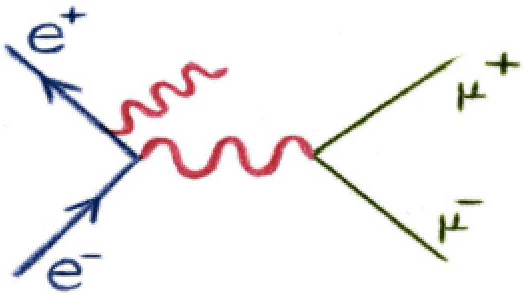
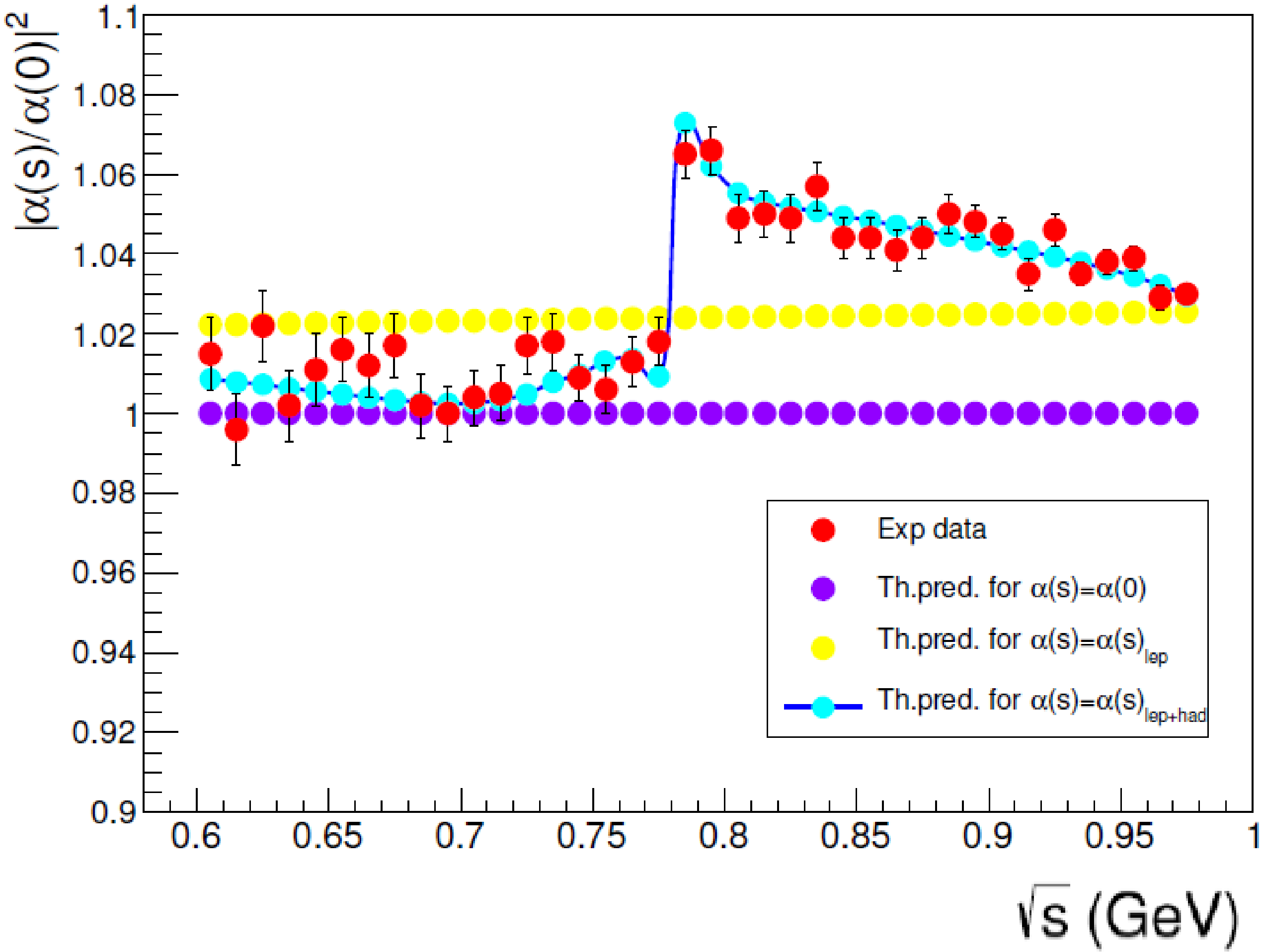
Hadronic contribution



- time-like measurement
- L = 1.7 fb^{-1} (KLOE data)
- Total systematic error ~ 1%

$$\boxed{\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}}$$



$\Delta\alpha_{had}$ obtained by dispersive approach with 0.1% accuracy (F. Jegerlerhner):

$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$$

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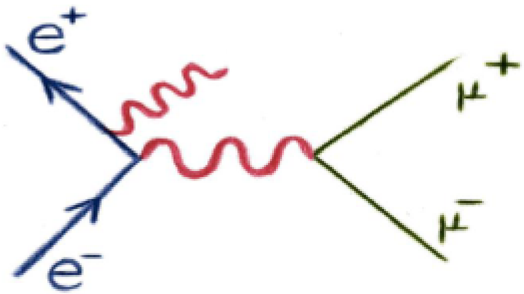

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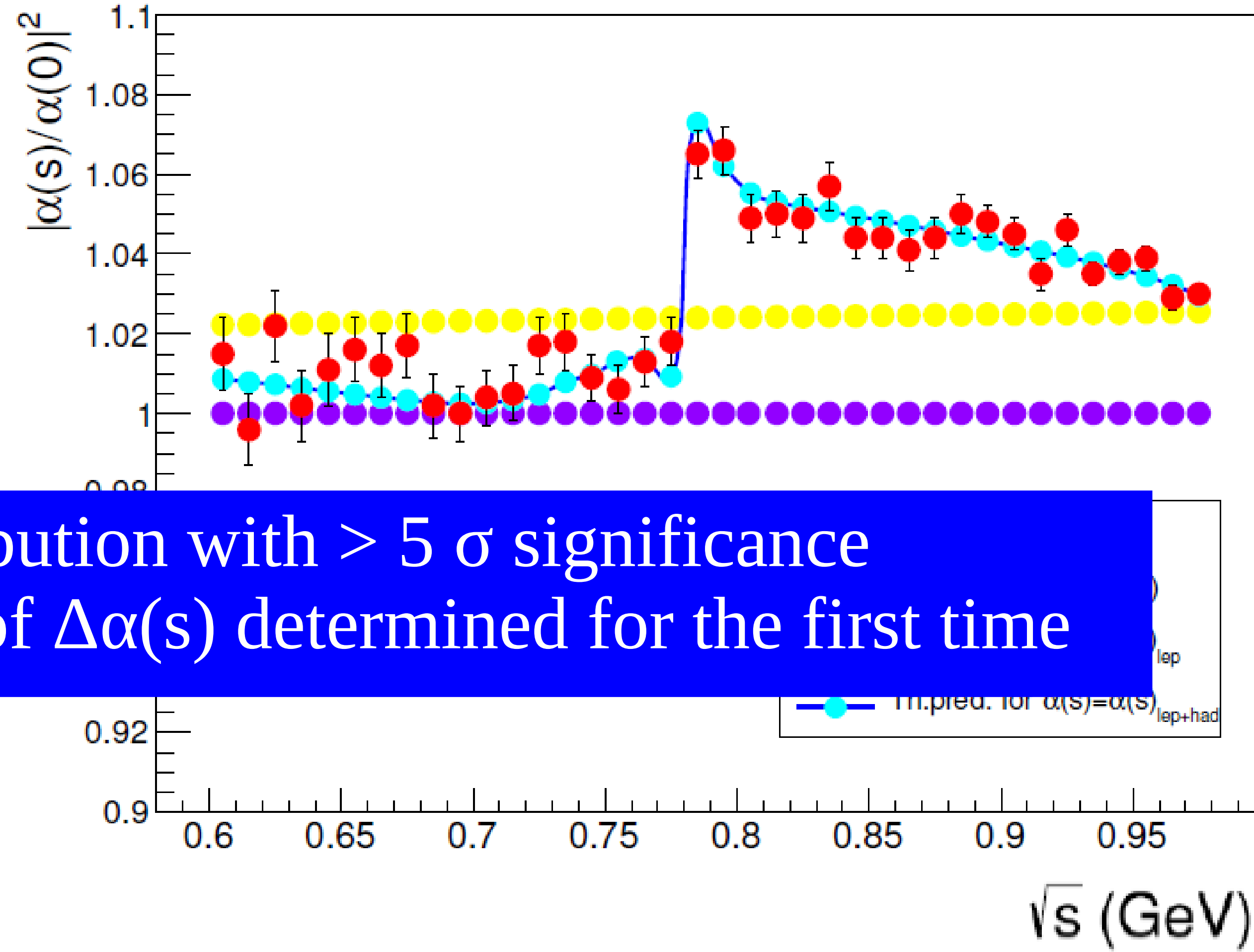

Hadronic contribution with > 5 σ significance
Re and Im part of Δα(s) determined for the first time

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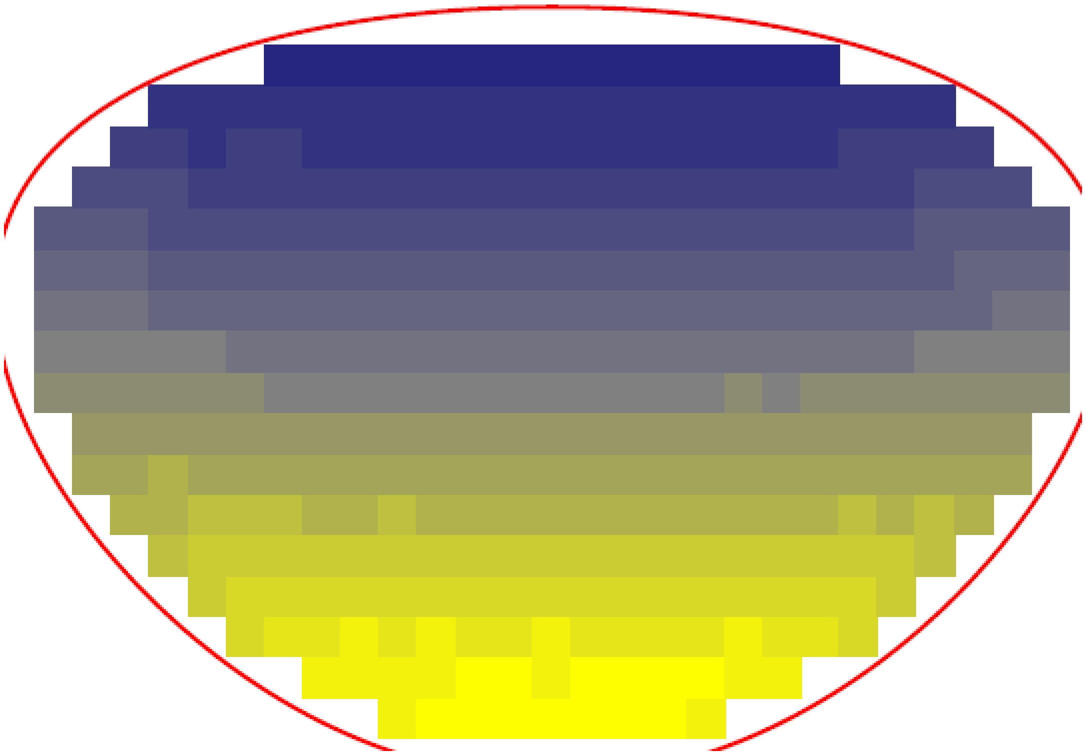


Dalitz plot analysis of $\eta \rightarrow \pi^{+}\pi^{-}\pi^{0}$

The $\eta \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot distribution

- $\eta \rightarrow \pi^+\pi^-\pi^0$ isospin violating process (mainly via strong interaction)
- Constraint in the light quark masses

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

- Description of the low energy strong interactions (ChPT)
- Dalitz density distribution in η-rest frame parametrized as a polynomial expansion around X = Y = 0:

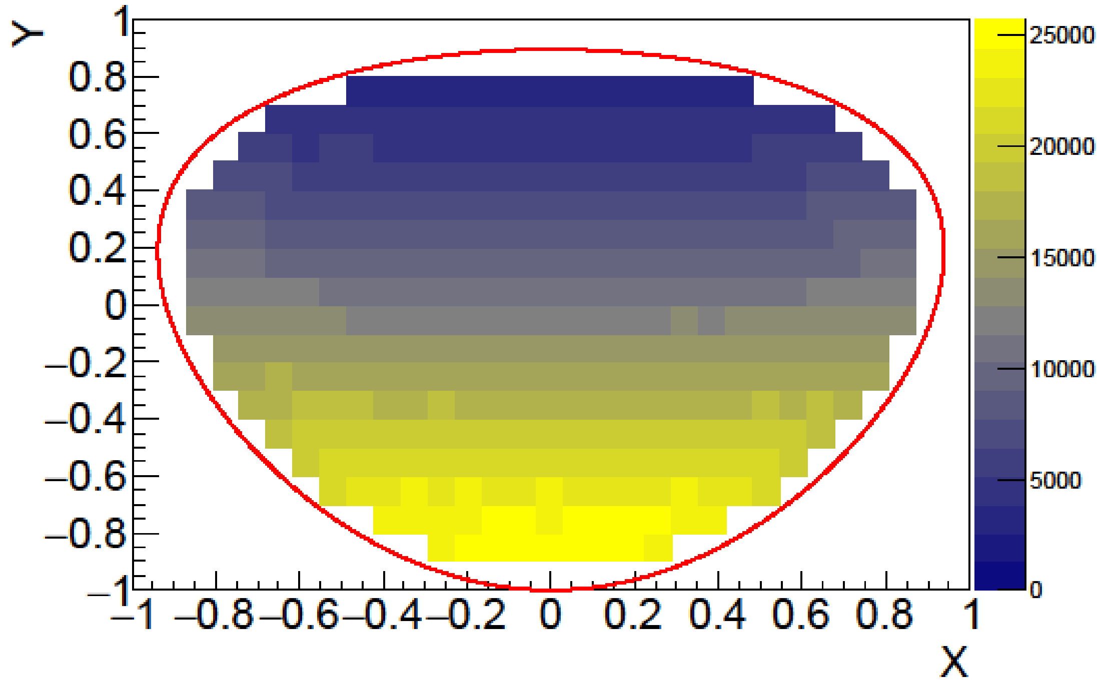
$$|A(X,Y)|^2 \approx 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots$$

- where: $X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta}$; $Y = \frac{3T_{\pi^0}}{Q_\eta} - 1$; $Q_\eta = T_{\pi^+} + T_{\pi^-} + T_{\pi^0} = m_\eta - 2m_{\pi^+} - m_{\pi^0}$
  (odd powers of X must be zero for C-invariance)

- Previous precision measurement KLOE *(JHEP05 (2008) 006)*
  L= 450 pb^{-1} ==> 1.34×10^6 events

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

Data sample L = 1.7 fb^{-1}
e+e- $\to \eta\gamma$



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a	$b \cdot 10$	$d \cdot 10^2$	$f \cdot 10$	$g \cdot 10^2$	c, e, h, l	χ^2/dof	Prob
-1.104 ± 0.003	1.420 ± 0.029	7.26 ± 0.27	1.54 ± 0.06	0	0	385/366	0.24
-1.095 ± 0.003	1.454 ± 0.030	8.11 ± 0.33	1.41 ± 0.07	-4.4 ± 0.9	0	360/365	0.56

syst. error ($\times 10^4$)	Δa	Δb	Δd	Δf	Δg
TOTAL	$^{+26}_{-25}$	$^{+52}_{-48}$	$^{+59}_{-50}$	$^{+69}_{-77}$	$^{+123}_{-129}$

JHEP 1605 (2016) 019

The η → $\pi^+\pi^-\pi^0$ Dalitz plot distribution

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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]	$1.128 \pm 0.015 \pm 0.008$	$0.153 \pm 0.017 \pm 0.004$	$0.085 \pm 0.016 \pm 0.009$	$0.173 \pm 0.028 \pm 0.021$	–

Charge asymmetries:

$$A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}$$
$$A_Q = (+1.8 \pm 4.5^{+4.8}_{-2.3}) \cdot 10^{-4}$$
$$A_S = (-0.4 \pm 4.5^{+3.1}_{-3.5}) \cdot 10^{-4}.$$

C-violating parameters consistent with zero → sensitive test using integrated charge asymmetries

JHEP 1605 (2016) 019

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

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- Statistic uncertainties improved by a factor of ~2
- Systematic uncertainties improved up to a factor of three with respect to KLOE08
- g parameter extracted for the first time

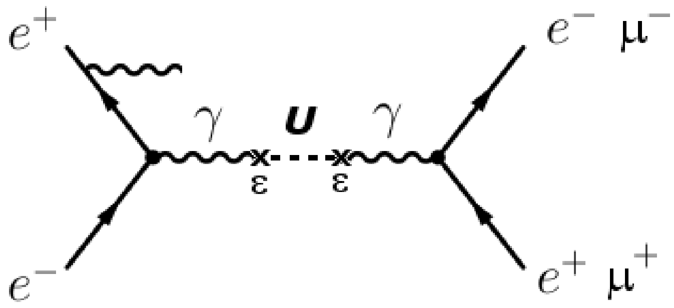
C-violating parameters consistent with zero → sensitive test using integrated charge asymmetries

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{dark}^{\mu\nu}$$

Searches for dark forces

Dark Forces searches with KLOE

- A new low energy gauge interaction mediated by a neutral light mass vector particle, usually named the U boson, with a small kinetic mixing ε ($<10^{-3}$) with SM



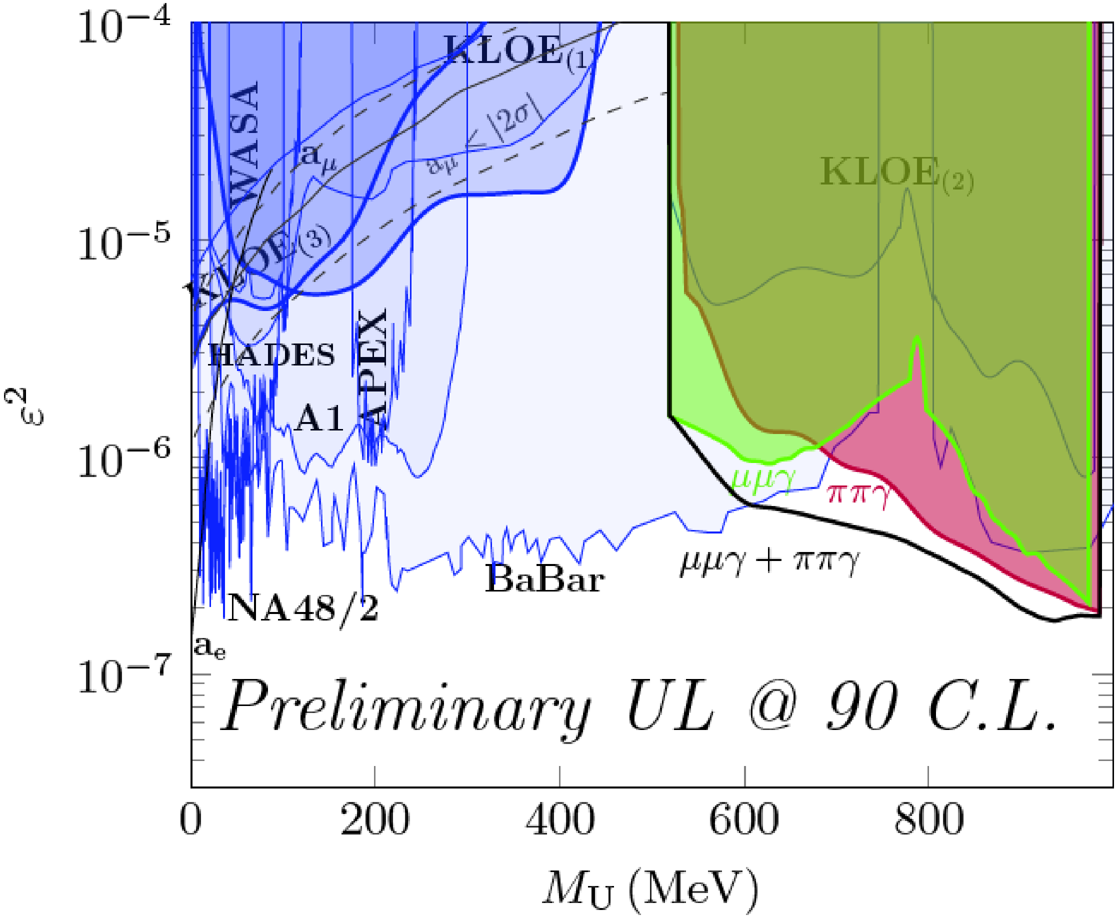
- Dark vector boson U which mixes with photon:

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

- Many searches in the recent years
- KLOE measurements in the mass range 5 MeV < m_U < 980 MeV
  - $\Phi \to \eta U$ with $U \to e^+ e^-$ — Phys. Lett B 706 (2012) 251-255; Phys. Lett B 720 (2013) 111-115
  - $e^+ e^- \to U\gamma$ with $U \to \mu^+ \mu^-$ — Phys. Lett B 736 (2014) 459-464
  - $e^+ e^- \to Uh'$ with $h' \to$ invisible — Phys.Lett. B747 (2015) 365-372
  - $e^+ e^- \to U\gamma$ with $U \to e^+ e^-$ — Phys.Lett. B750 (2015) 633-637
  - $e^+ e^- \to U\gamma$ with $U \to \pi^+ \pi^-$ — Phys.Lett. B757 (2016) 356-361
- Search for dilepton resonances

Dark Forces searches with KLOE

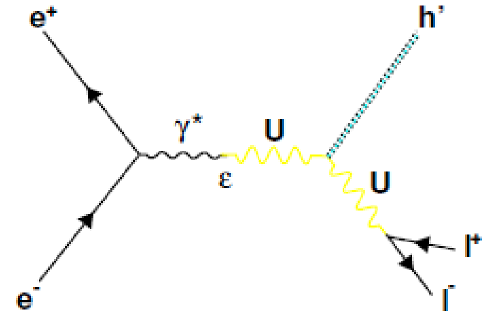
- KLOE
  - (1) Dalitz decay *PLB 720 (2013)*
  - (2) U → $\mu^+\mu^-$ *PLB 736 (2014)*
  - (3) U → e^+e^- *PLB 750 (2015)*
  - U → $\pi^+\pi^-$ *PLB 757 (2016)*
  - *U → $\mu^+\mu^-$ full statistics- Preliminary*
  - *U → $\mu^+\mu^-$ combined with U → $\pi^+\pi^-$ Preliminary*
- BABAR *PRL 113 201801 (2014)*
- WASA *PLB 726 (2013)*
- HADES *PLB 731 (2014)*
- APEX *PRL 107 (2011)*
- A1/MAMI *PRL 112 (2014)*
- NA48/2 *PLB 746 (2015)*



- The current limits exclude g-2 favoured regions
- A further factor of 2 in sensitivity expected from KLOE-2 experiment with respect to full KLOE data

Phys.Lett. B747 (2015) 365-372

Higgsstrahlung process



- $m_{h'} > 2m_U$

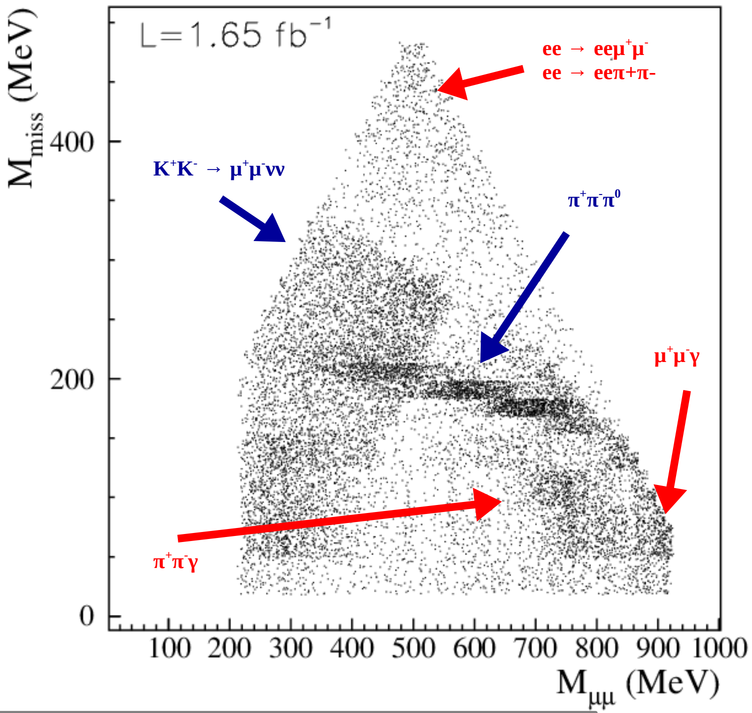
with decays: $e^+e^- \rightarrow Uh'$ with $h' \rightarrow UU$
thus 6l, 2π+4l, 6π in the final state

- $m_{h'} < 2m_U$

where h' is "invisible":

  - Life time of the dark Higgs boson
  - $\varepsilon = 10^{-3}$
  - $\alpha_D = \alpha_{em}$
  - $m_{h',U} \sim 100$ MeV

  - $\tau > 5\ \mu s \rightarrow \beta\gamma c\tau > 100$ m $\rightarrow$ h' would be invisible up to $\varepsilon \sim 10^{-2}$ to 10^{-1} depending on $m_{h'}$



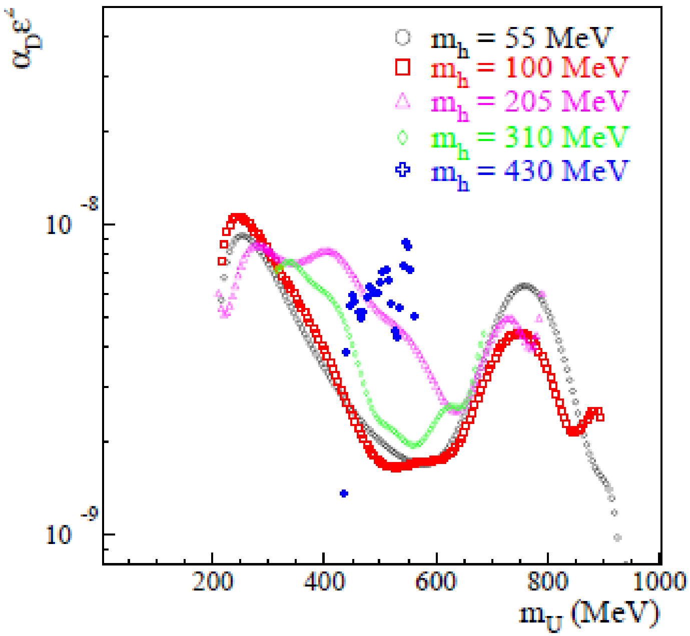
Final state: 2 muons + missing energy → peak in the M_{miss} vs $M_{\mu\mu}$ distribution

Phys.Lett. B747 (2015) 365-372

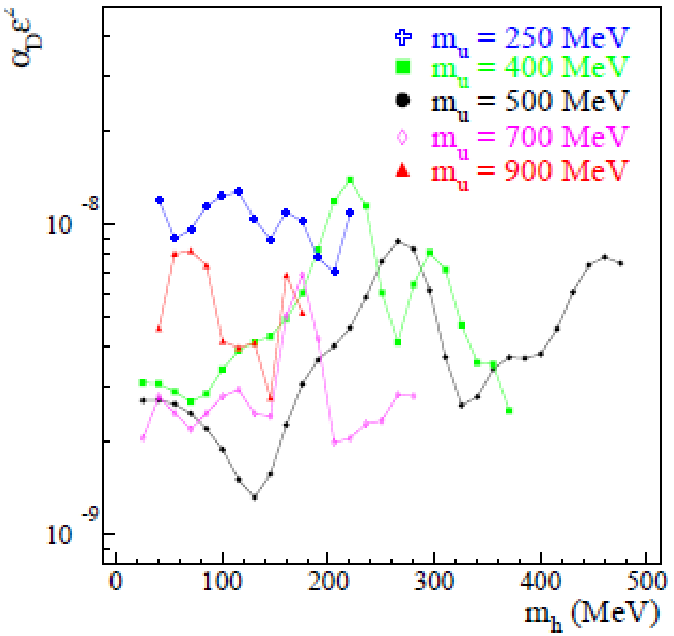
Higgsstrahlung process

Combined results on- and off- peak data:

$$\alpha_D \epsilon^2 = \frac{N_{90}}{\epsilon_{eff}} \frac{1}{L_{integrated} \cdot \sigma(\alpha_D \epsilon^2 = 1)}$$

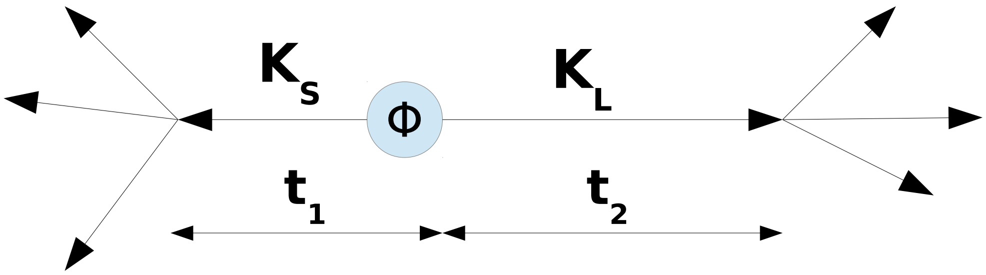


Limit on $\alpha_D\epsilon^2$ vs m_U at 90% CL



Limit on $\alpha_D\epsilon^2$ vs $m_{h'}$ at 90% CL

Limits ~ 10^{-8} - 10^{-9} in $\alpha_D\epsilon^2$ (translate in 10^{-3} to ~ 10^{-4} in ϵ if $\alpha_D = \alpha_{em}$)



Discrete symmetry tests with kaon pairs

K_S semileptonic charge asymmetry

K_S and K_L semileptonic charge asymmetry

T CPT viol. in mixing

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} = 2\Re\varepsilon \pm 2\Re\delta - 2\Re y \pm 2\Re x_-$$

CPTV in $\Delta S=\Delta Q$ $\Delta S\neq\Delta Q$ decays

$A_{S,L}\neq 0$ signals CP violation

$A_S\neq A_L$ signals CPT violation

$\boxed{A_L = (3.322 \pm 0.058 \pm 0.047) \times 10^{-3}}$

KTEV PRL88,181601(2002)

$\boxed{A_S = (1.5 \pm 9.6 \pm 2.9) \times 10^{-3}}$

KLOE PLB 636(2006) 173

Data sample: L=410 pb^{-1}

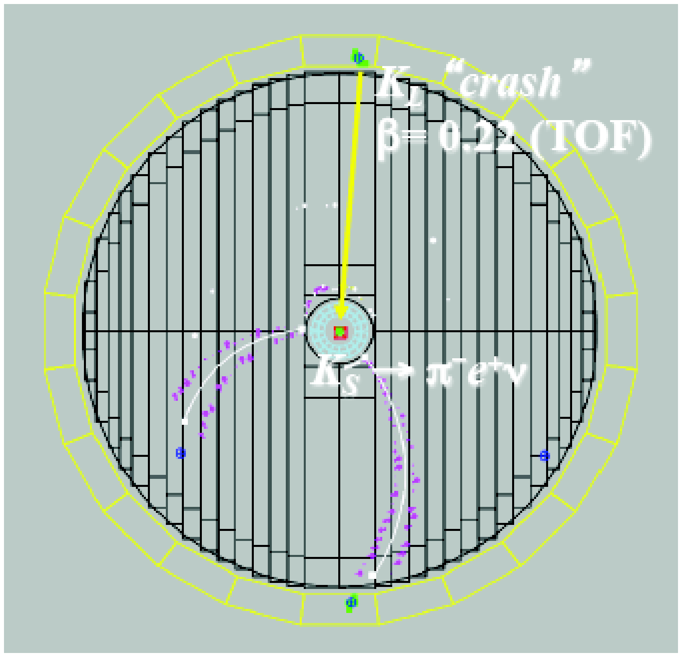
$\boxed{A_S - A_L = 4(\Re\delta + \Re x_-)}$ $\longrightarrow$ $\boxed{\Re x_- = (-0.8 \pm 2.5) \times 10^{-3}}$ **CPT & $\Delta S=\Delta Q$ viol.**

$\boxed{A_S + A_L = 4(\Re\varepsilon - \Re y)}$ $\longrightarrow$ $\boxed{\Re y = (0.4 \pm 2.5) \times 10^{-3}}$ **CPT viol.**

input from other experiments

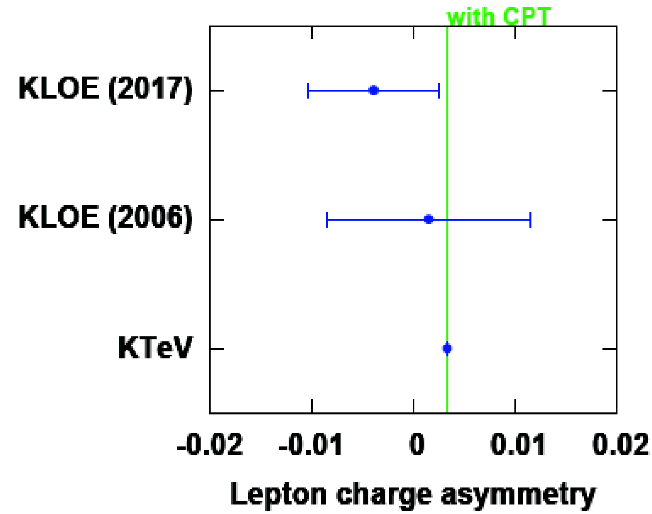
KLOE PLB 636(2006) 173

K_S semileptonic charge asymmetry



K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)

Data sample:
L =1.7 fb^{-1}



preliminary

KLOE (2017)

$$\boxed{A_S = (-3.9 \pm 5.7\,^{+3.3}_{-2.4}) \times 10^{-3}}$$

It will improve the CPT test (Imδ)
using Bell-Steinberger relationship

$\boxed{\text{with KLOE-2 data: } \delta A_S(\text{stat}) \to \sim 3\times10^{-3}}$

$$\boxed{A_S - A_L = 4(\Re\delta + \Re x_-)} \longrightarrow \boxed{\Re x_- = (-2.1 \pm 1.6) \times 10^{-3}} \quad \textbf{CPT \& } \Delta S{=}\Delta Q \textbf{ viol.}$$

$$\boxed{A_S + A_L = 4(\Re\varepsilon - \Re y)} \longrightarrow \boxed{\Re y = (1.8 \pm 1.6) \times 10^{-3}} \quad \textbf{CPT viol.}$$

input from other experiments

T and CPT tests in transition

Reference	T-conjug.	CP-conjug.	CPT-conjug.
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$

K_+ K_- pure CP + and - states

Neglecting direct CP/CPT violation:

$$\langle K_- | K_+ \rangle = 0$$

$$\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]
\end{aligned}$$

T

$$\begin{aligned}
R_{1,\mathcal{CPT}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right] \\
R_{2,\mathcal{CPT}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \\
R_{3,\mathcal{CPT}}(\Delta t) &= P\left[K_+(0) \to K^0(\Delta t)\right] / P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] \\
R_{4,\mathcal{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]
\end{aligned}$$

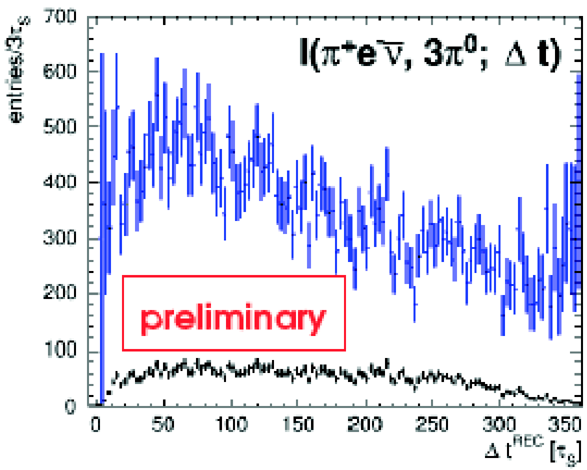
CPT

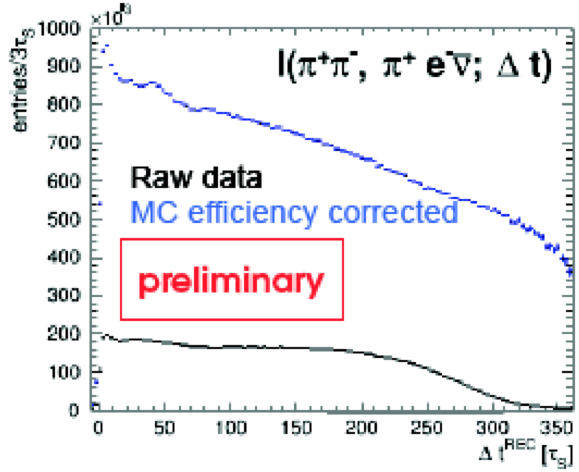
Any deviation from R =1 violation of T/CPT symmetry

J. Bernabeu, A.D.D., P. Villanueva JHEP 10 (2015) 139, NPB 868 (2013) 102

Data sample:
L =1.7 fb^{-1}

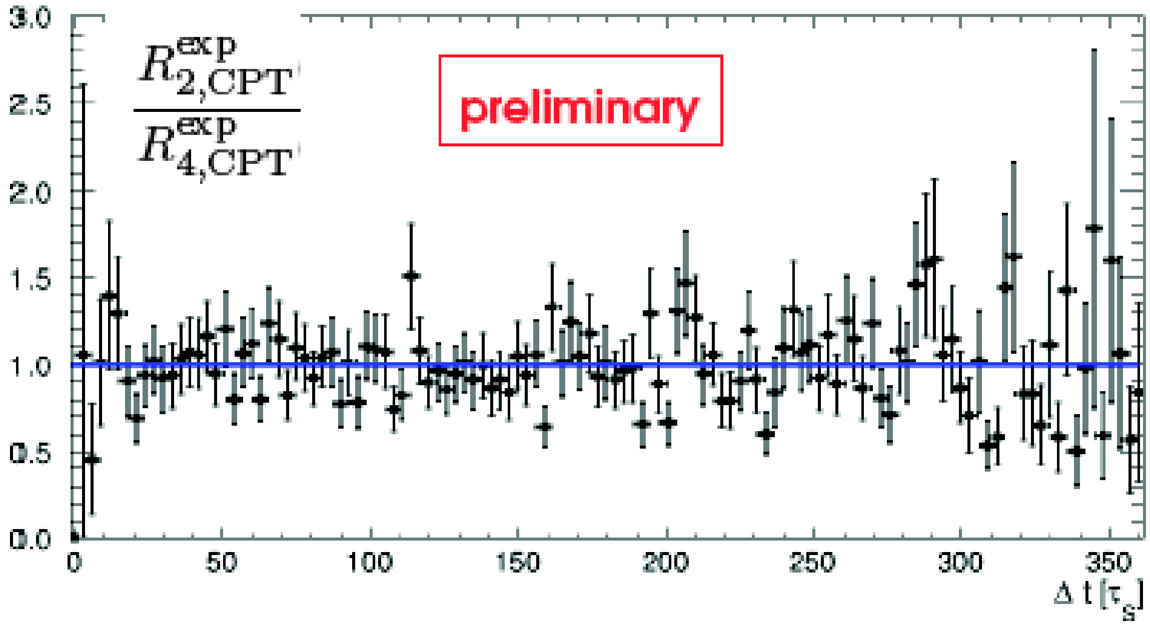
T and CPT tests in transition





$$R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

$$R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

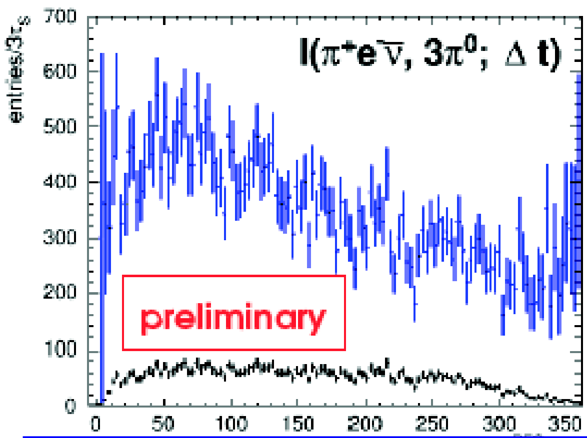


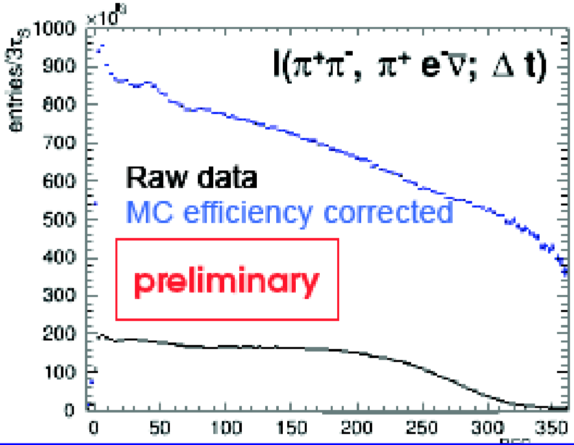
CPT test with the double ratio:

$$\frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

Data sample:
L =1.7 fb^{-1}

T and CPT tests in transition



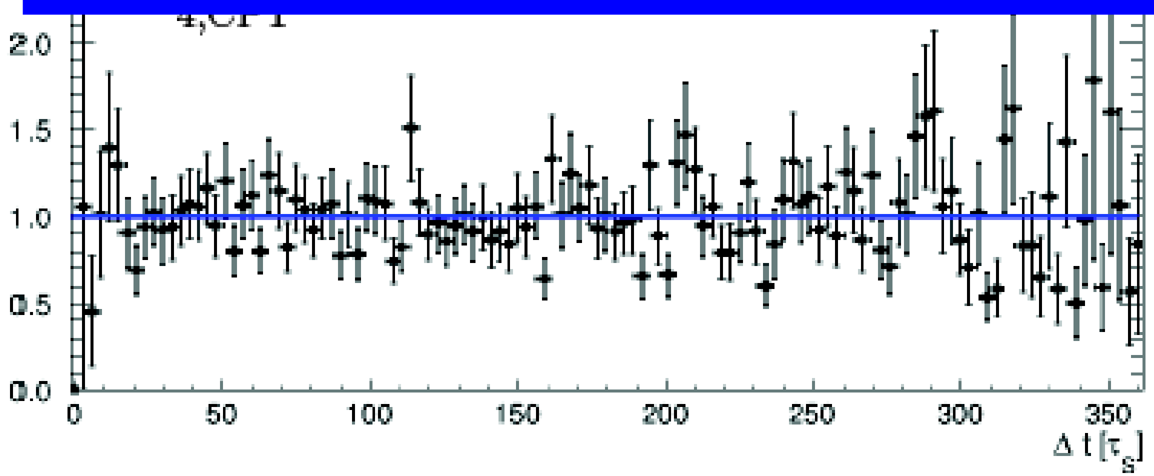


$$R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

$$R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

- Analysis in progress
- With all KLOE-2 statistics expected sensitivity of R$_2$/R$_4$<= 10^{-3}

$$\frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

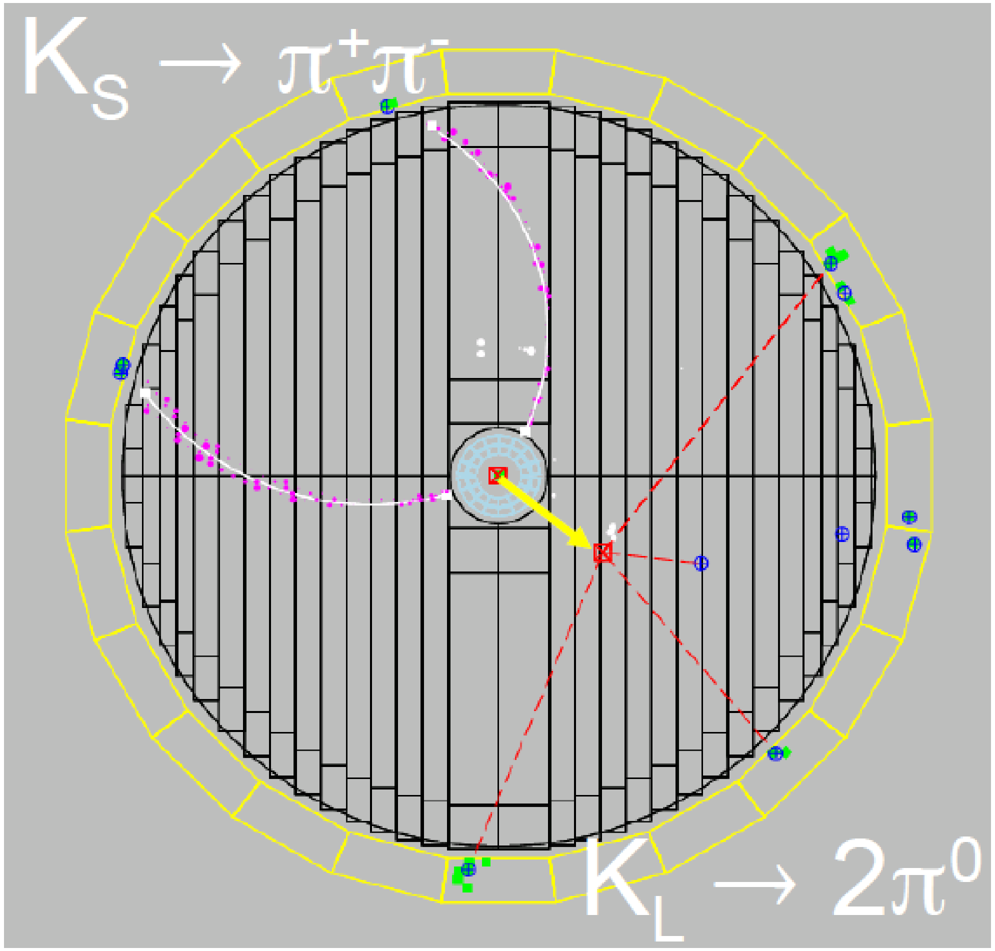


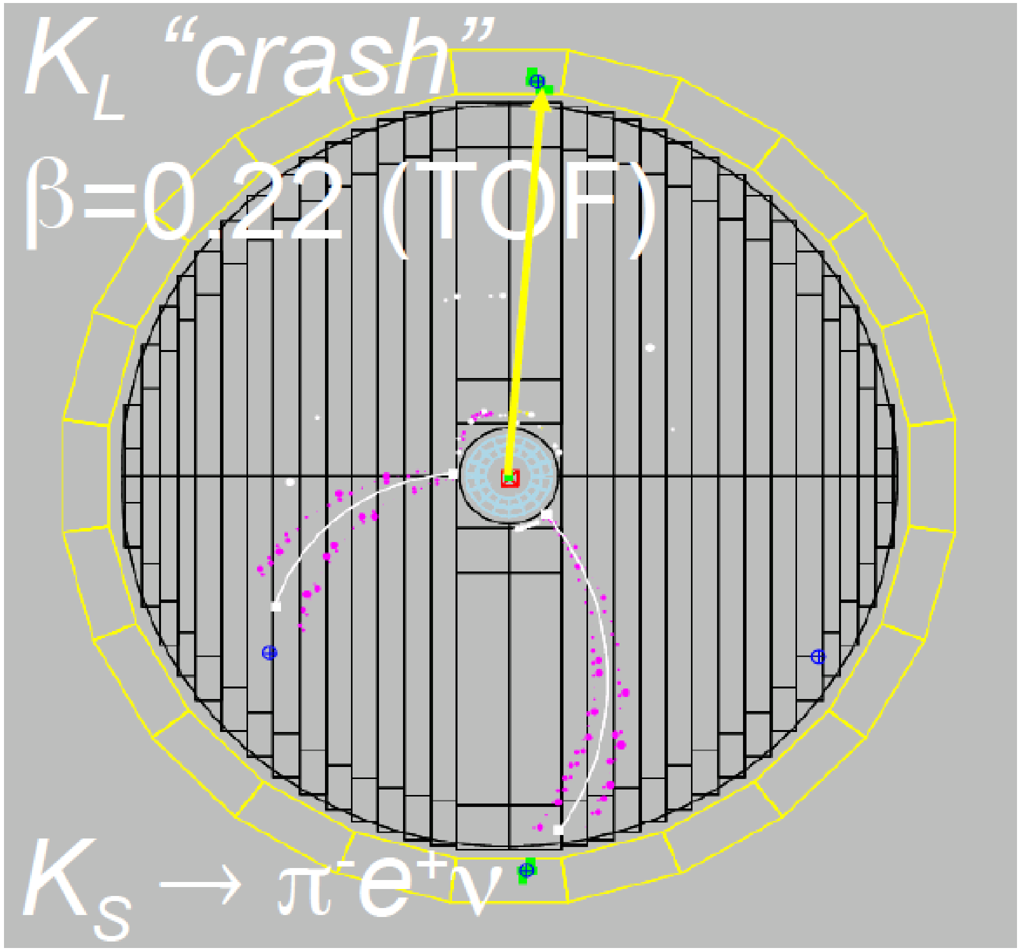
Summary

- **The KLOE experiment has provided among others results on:**
  - Measurement of the QED coupling constant $\alpha_{QED}(s)$,
  - Dalitz plot analysis of $\eta \to \pi^+\pi^-\pi^0$,
  - Searches for dark forces,
  - Tests of discrete symmetries
- **Several analyses with the KLOE and KLOE-2 data sets are in progress**
- **New data taking period is ongoing:**
  - expected data sample of at least **5 fb^{-1}** (by the end of March 2018)
  - Upgraded detector → **improved sensitivity**

Thank you for your attention

Backup slides

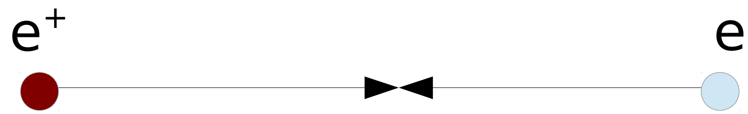




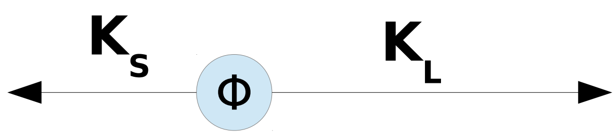
K_L tagged by
$K_S \to \pi^+\pi^-$ vertex at IP

K_S tagged by
K_L interaction in EmC

Neutral kaon interferometry



$e^+ e^- \rightarrow \Phi$

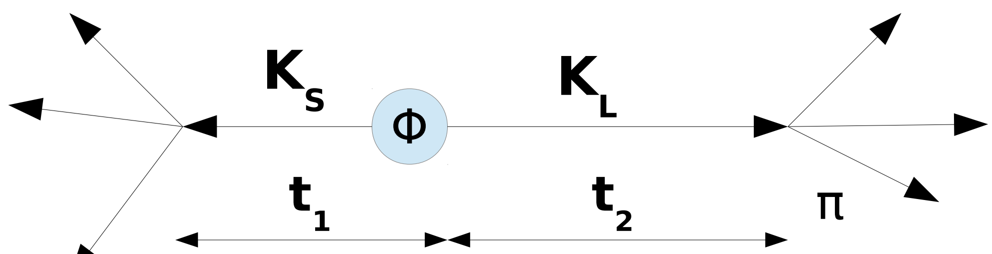


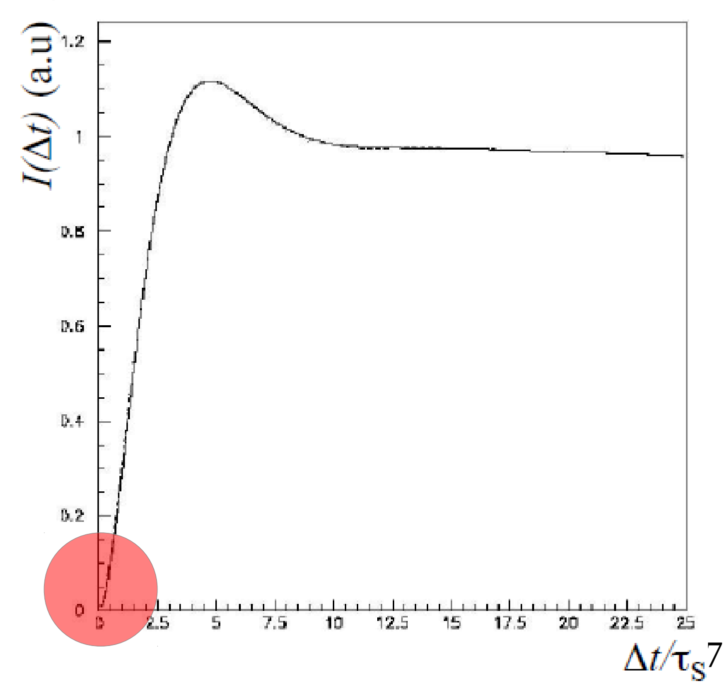
$\Phi \rightarrow K_S K_L$

Antisymmetric quantum state

$J^{PC} = 1^{--}$

Quantum entanglement (EPR)

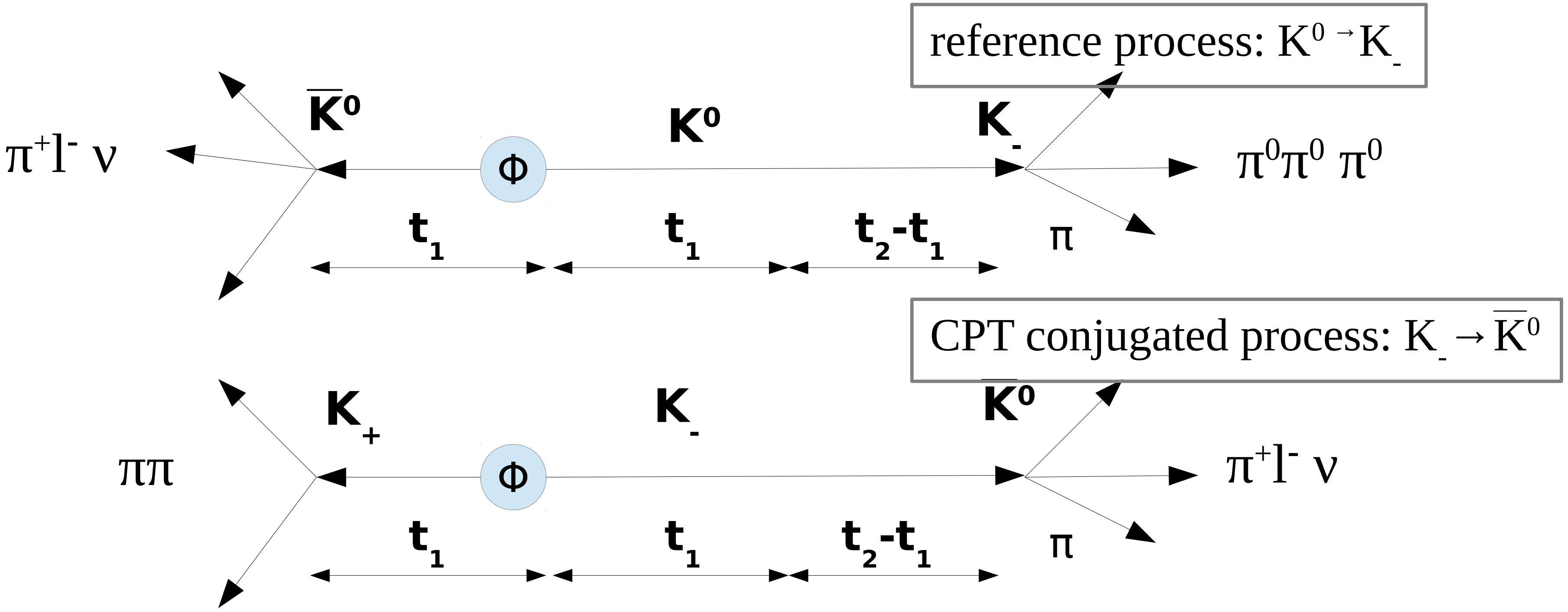




Destructive interference

T and CPT tests in transition

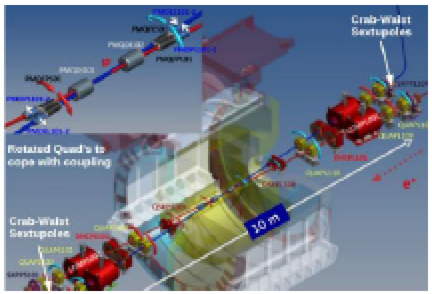
- Entanglement to prepare the state
- Decay of orthogonal “CP” states for filtering:
- CP and T conjugated Processes: $K_- \rightarrow K^0$ and $\bar{K}^0 \rightarrow K_-$



One can separate the tests of CPT and T

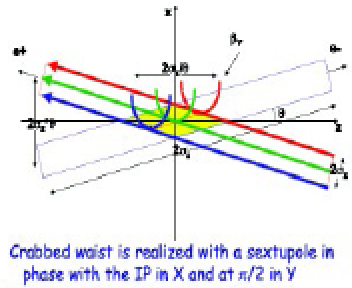
J. Bernabeu, A.D.D., P. Villanueva JHEP 10 (2015) 139, NPB 868 (2013) 102

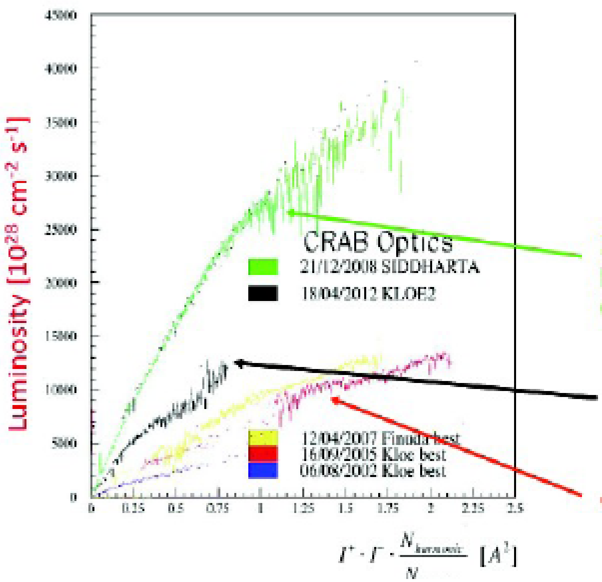
DAFNE upgrade



Crab Waist Scheme: beam crossing at large angle, sextuple correction

Crabbed waist scheme at DAΦNE





Implemented in DAFNE and tested in 2008 on SIDDARTHA experiment (no magnetic field)

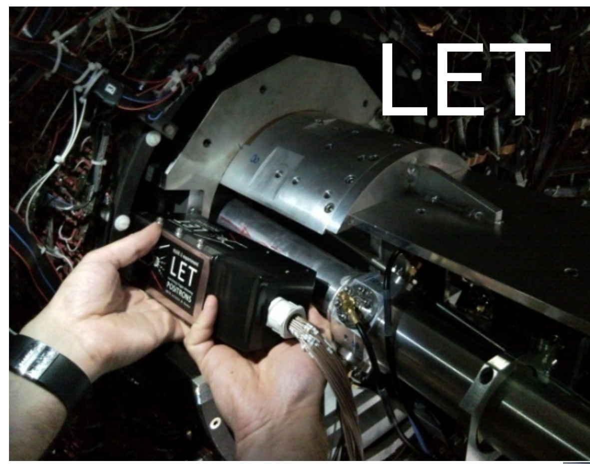
In KLOE B=0.52T require specific tuning and background control

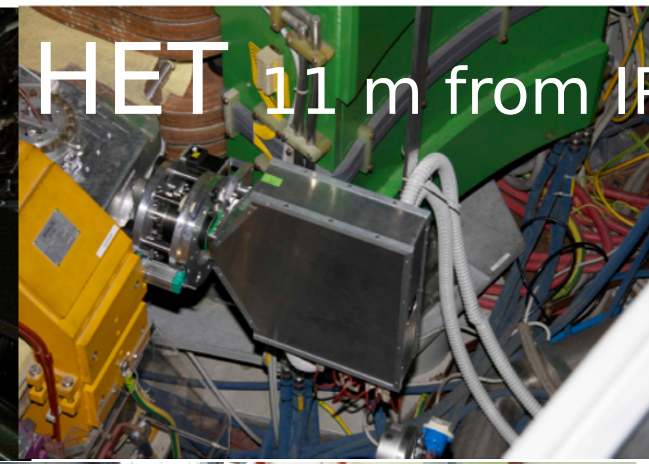
Taken from A. Selce's talk SIF 2016

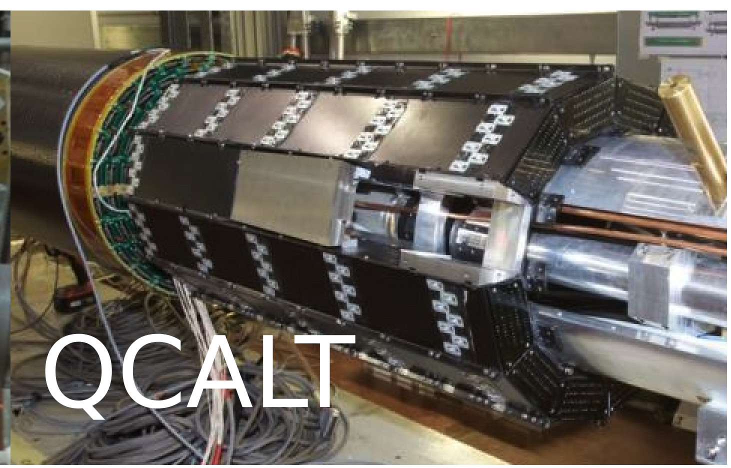
KLOE-2 Upgrade

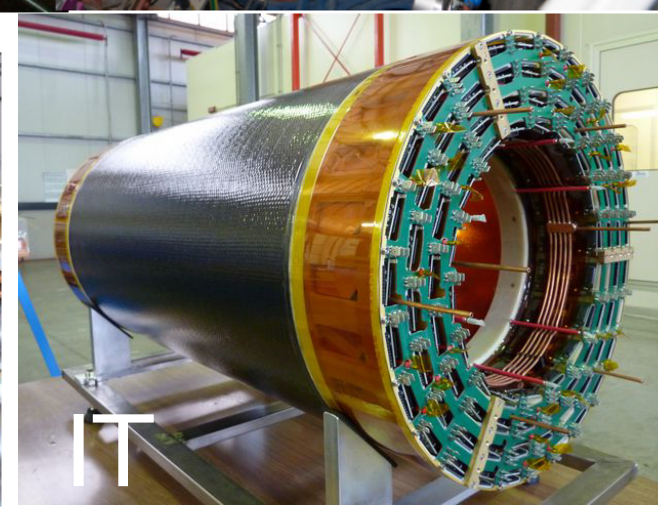
- KLOE-2 new data taking campaign started in November 2014
- It will collect more than 5 fb^{-1} up to March 2018
- New detectors fully operational

- Tagging system LET & HET
  - e+e--taggers for γγ-physics
- CCALT & QCALT
  - 2 new calorimeters
  - CCALT for low angle γ's (down to 10°)
  - Quadrupole coverage for K_L decays
- Inner Tracker
  - 4 layers of C-GEM
  - better vertex reconstruction and track parameters



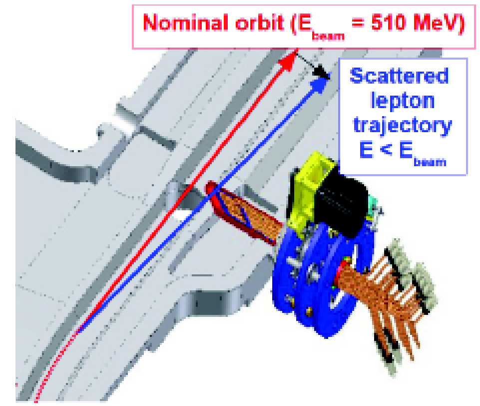


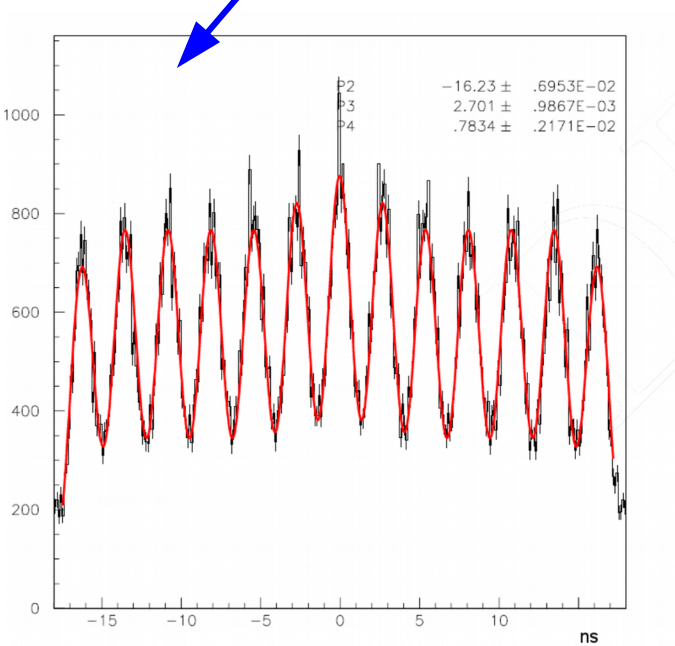




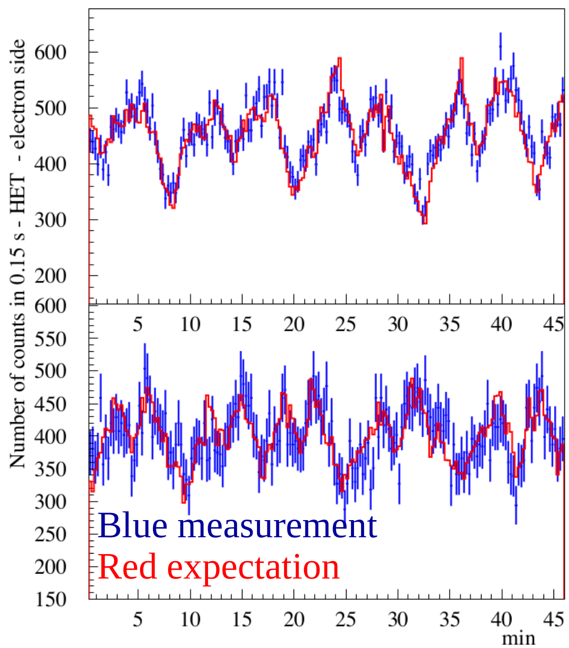
High Energy Tagger (HET)

- HET stations located approximately at 11m from IP after bending dipoles
- Strong energy-trajectory correlation
    - Scintillating hodoscope + PMTs
- **σ_t = 550(1)ps**





Tdiff between stations

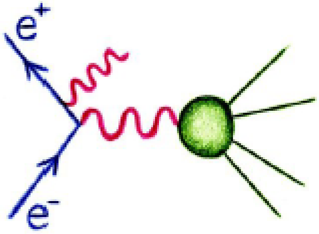


Scattered $e^{\pm}$ of E > 400 MeV escape beam pipe after first bending dipole of DAΦNE → spectrometer

- fast feedback on machine operation
- Rates dominated by single arm Bhabha's

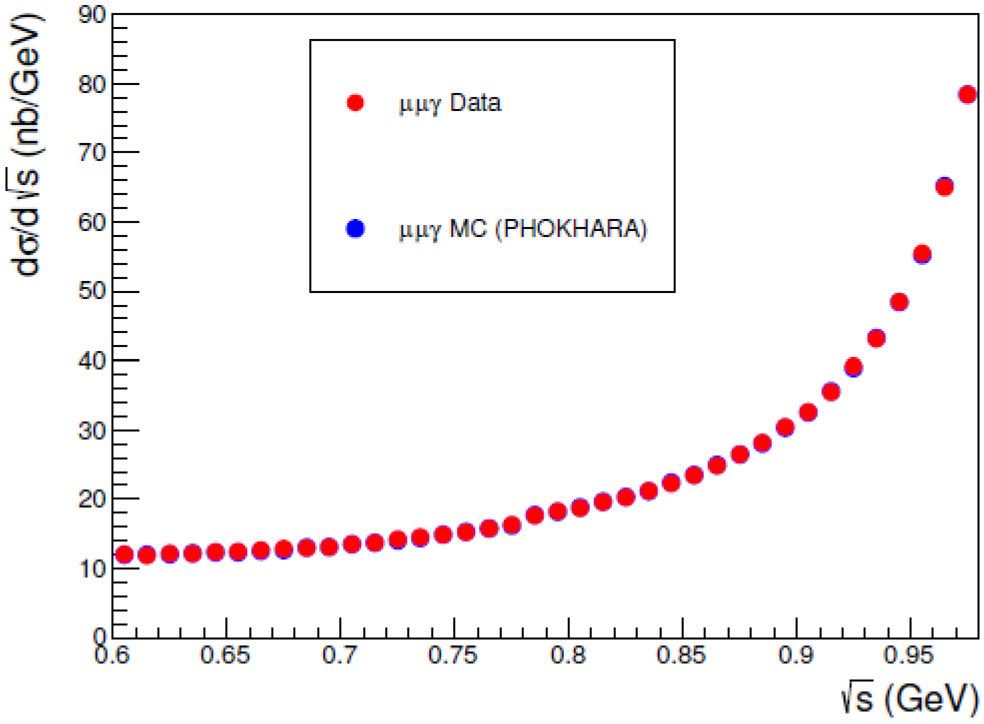
$$R_{HET} \sim R_{trig}(\alpha L + \beta I^2)$$

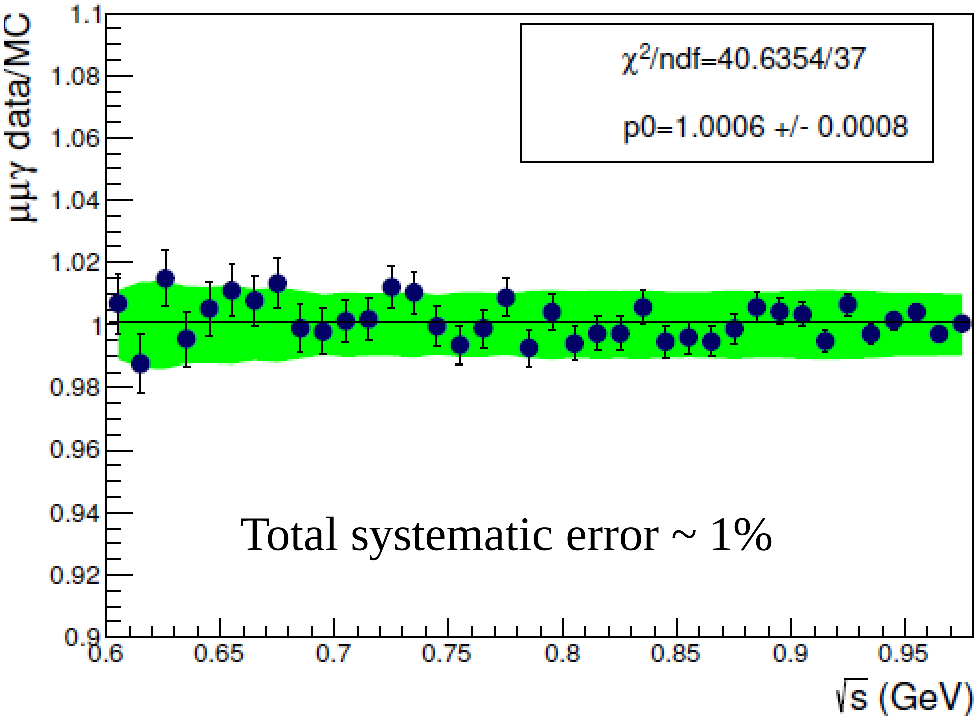
$\alpha(s)_{QED}$ between 600 MeV and 975 MeV



Phys. Lett. B 767 (2017) 485-492

- Analysis performed with data sample of $L = 1.7\ fb^{-1}$
- Event selection: 2 opposite charge tracks + undetected photons (small angle)
- Excellent agreement with NLO theory (PHOKARA MC) with VP inside
(H. Czyz, A. Grzelinska, J.H. Kuhn, G. Rodrigo, Eur. Phys. J. C 39 (2005) 411.)





$\alpha(s)_{QED}$ between 600 MeV and 975 MeV

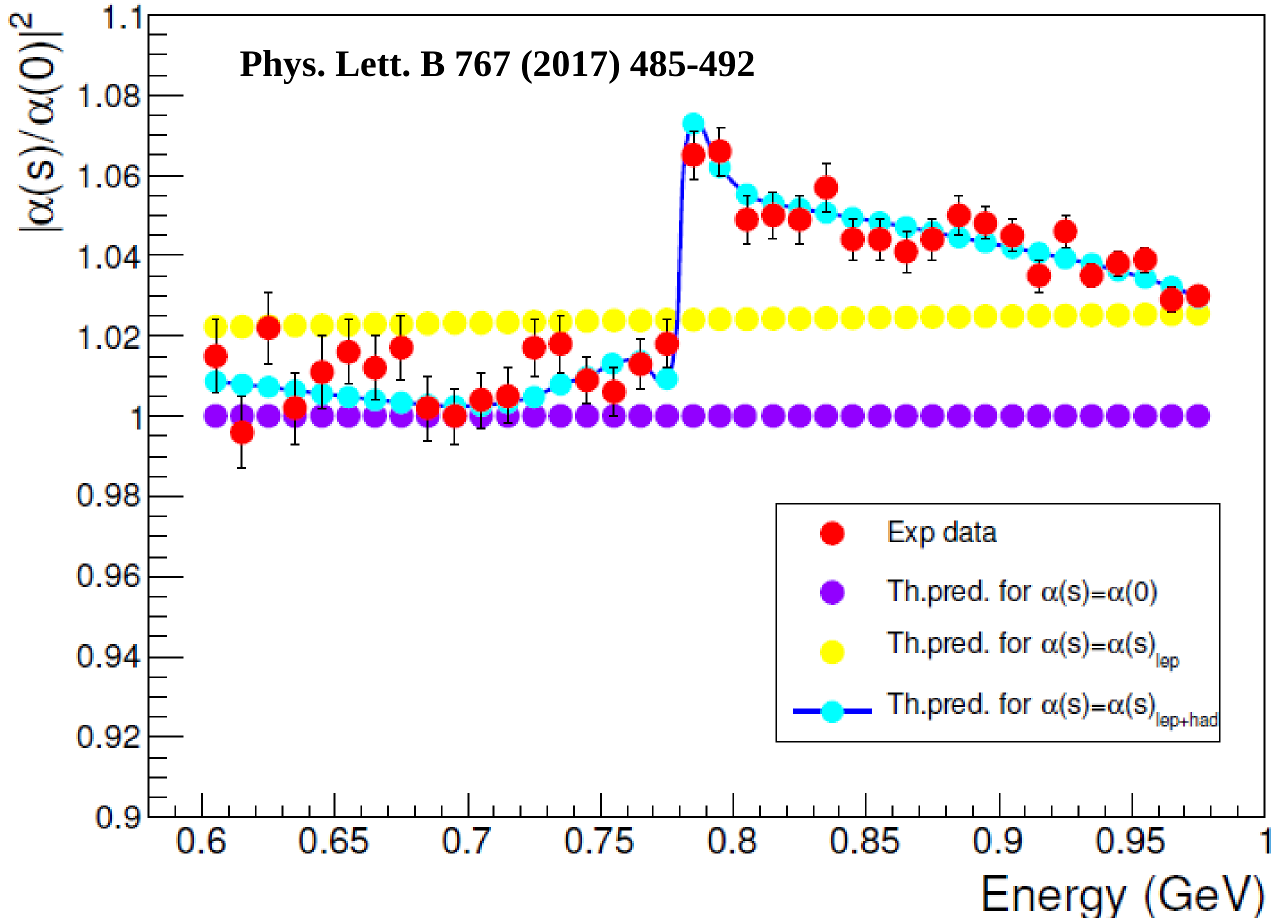
$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

$\frac{d\sigma^{MC}}{dM_{\mu\mu}}$ with the VP contribution removed.

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = |1/(1-\Delta\alpha(s))|^2$$

$$\Delta\alpha(s) = \Delta\alpha_{lep}(s) + \Delta\alpha_{had}(s)$$

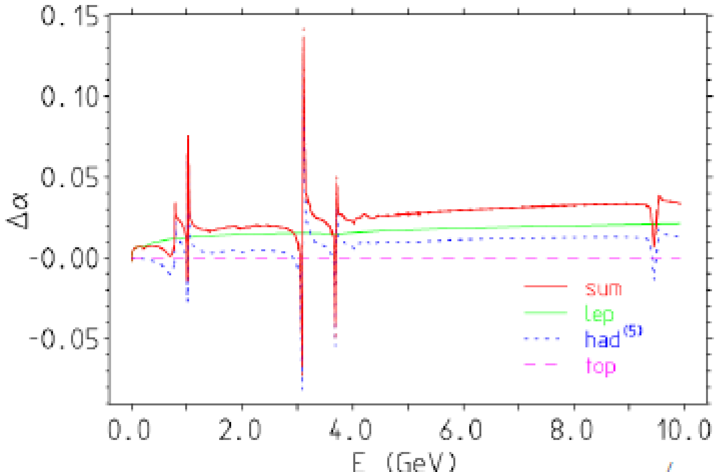
(we neglect the top contribution)

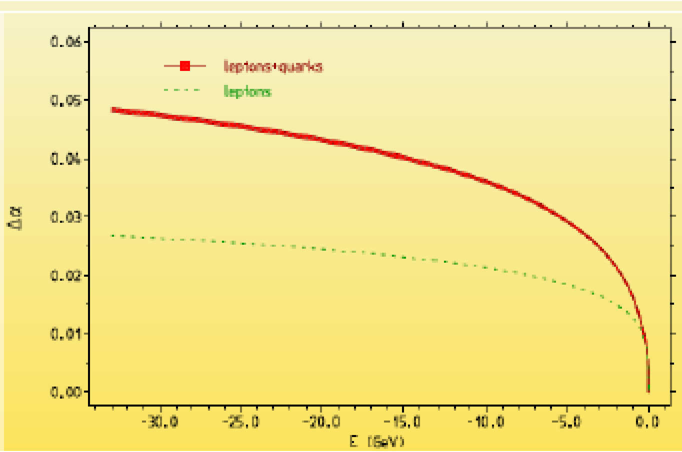


$\Delta\alpha_{had}$ obtained by dispersive approach using data in time-like region provided by F. Jegerlehner (with 0.1% accuracy)

$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$$

$\alpha(s)_{QED}$ hadronic component behaviour

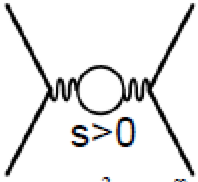




E=√s

Time-like

Behaviour characterized by the opening of resonances

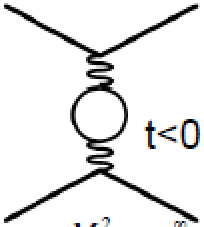


$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$

E=-√-t

Space-like

Very smooth behaviour



$$\Delta\alpha^{(5)}_{had}(-q_0^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s+q_0^2)}$$

Taken from G.Venanzoni's Phi2Psi 2017

Event selection

Event Selection: Small Angle (SA)

Muon tracks at large angles

$50^o < \theta_\mu < 130^o$

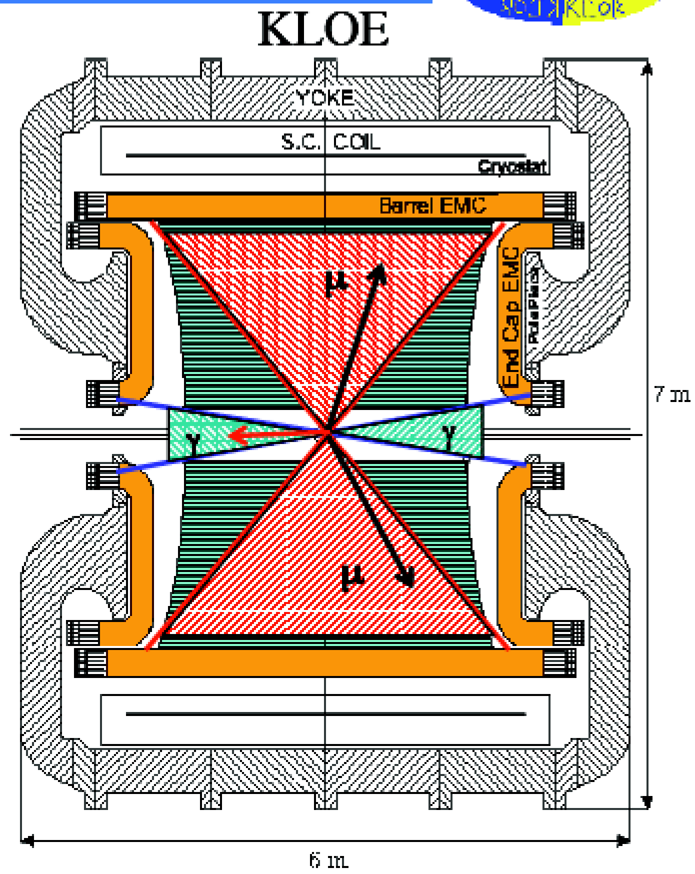
Photons at small angles

$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

➔ Photon momentum from kinematics:

$$\boxed{\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)}$$

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination



Taken from G.Venanzoni’s Phi2Psi 2017

The $\eta \rightarrow \pi^{+}\pi^{-}\pi^{0}$ Dalitz plot distribution

- Dalitz plot parameters:

JHEP 1605 (2016) 019

Fit/set#	a	$b \cdot 10$	$d \cdot 10^2$	$f \cdot 10$	$g \cdot 10^2$	c, e, h, l	χ^2/dof	Prob
(1)	-1.095 ± 0.003	1.454 ± 0.030	8.11 ± 0.32	1.41 ± 0.07	-4.4 ± 0.9	free	354/361	0.60
(2)	-1.104 ± 0.002	1.533 ± 0.028	6.75 ± 0.27	0	0	0	1007/367	0
(3)	-1.104 ± 0.003	1.420 ± 0.029	7.26 ± 0.27	1.54 ± 0.06	0	0	385/366	0.24
(4)	-1.095 ± 0.003	1.454 ± 0.030	8.11 ± 0.33	1.41 ± 0.07	-4.4 ± 0.9	0	360/365	0.56
(5)	-1.092 ± 0.003	1.45 ± 0.03	8.1 ± 0.3	1.37 ± 0.06	-4.4 ± 0.9	0	369/365	0.43
(6)	-1.101 ± 0.003	1.41 ± 0.03	7.2 ± 0.3	1.50 ± 0.06	0	0	397/366	0.13

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]	$1.128 \pm 0.015 \pm 0.008$	$0.153 \pm 0.017 \pm 0.004$	$0.085 \pm 0.016 \pm 0.009$	$0.173 \pm 0.028 \pm 0.021$	–

The $\eta \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot distribution

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)	–	–
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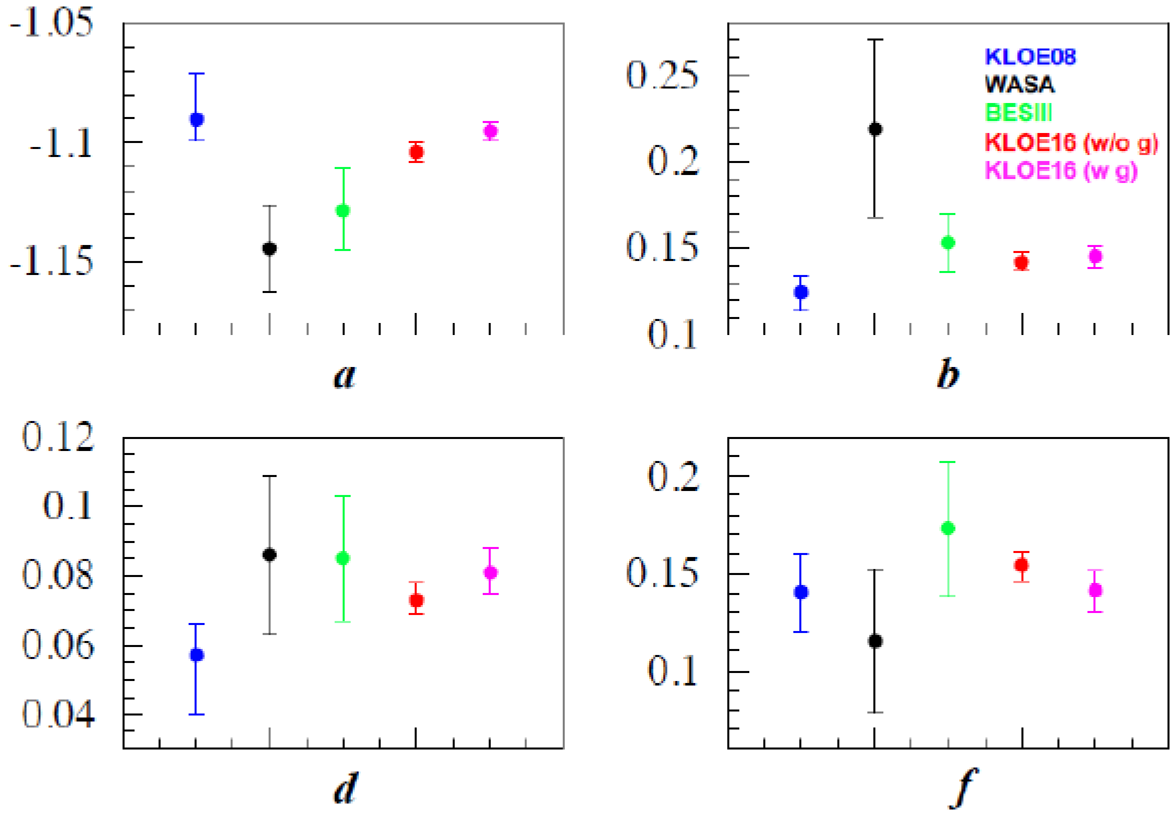
Calculations						
ChPT LO	[10]	1.039	0.27	0	0	–
ChPT NLO	[10]	1.371	0.452	0.053	0.027	–
ChPT NNLO	[10]	1.271 ± 0.075	0.394 ± 0.102	0.055 ± 0.057	0.025 ± 0.160	–
dispersive	[22]	1.16	0.26	0.10	–	–
simplified disp	[5]	1.21	0.33	0.04	–	–
NREFT	[12]	1.213 ± 0.014	0.308 ± 0.023	0.050 ± 0.003	0.083 ± 0.019	0.039 ± 0.002
UChPT	[11]	1.054 ± 0.025	0.185 ± 0.015	0.079 ± 0.026	0.064 ± 0.012	–

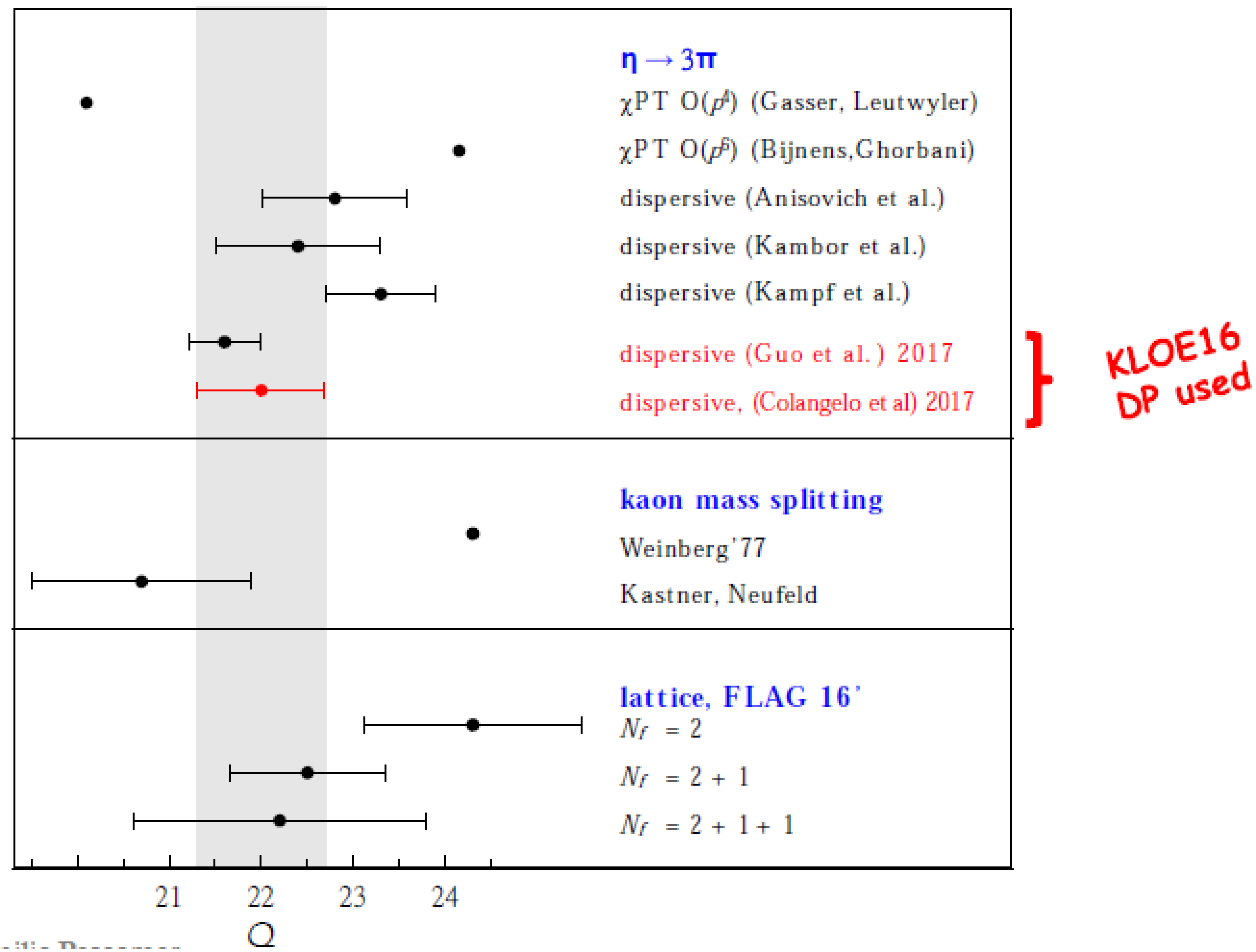
$\eta \rightarrow \pi^+\pi^-\pi^0$ DP parameters



KLOE08 - [JHEP 0805 (2008) 006]
WASA - [PRC90 (2014) 045207]
BESIII - [PRD92 (2015) 012014]
KLOE16 - [JHEP 1605 (2016) 019]

Comparison of results for Q

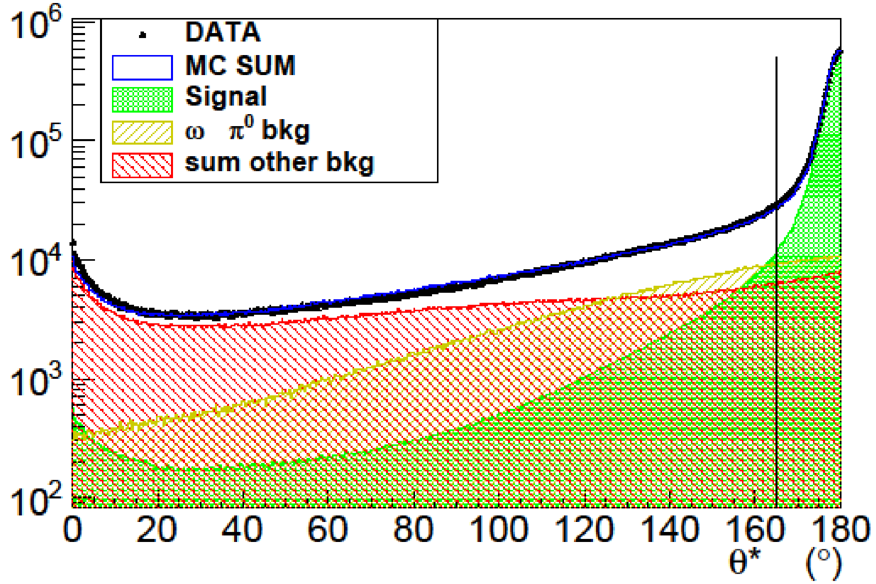
$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

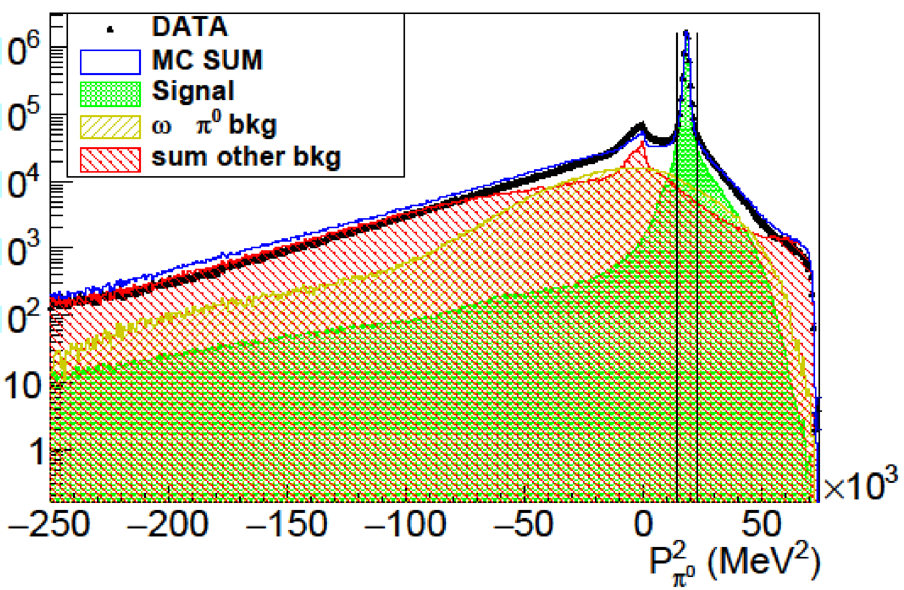


The $\eta \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot distribution

- New independent measurement (*JHEP 1605 (2016) 019*)
  - 1.7 fb^{-1} ==> 4.48 x 10^6 events
  - New analysis scheme
  - Overall efficiency 38%
  - Fit including also the g parameter

JHEP 1605 (2016) 019





$e^+e^- \rightarrow U\gamma$ with $U \rightarrow \pi^+\pi^-$

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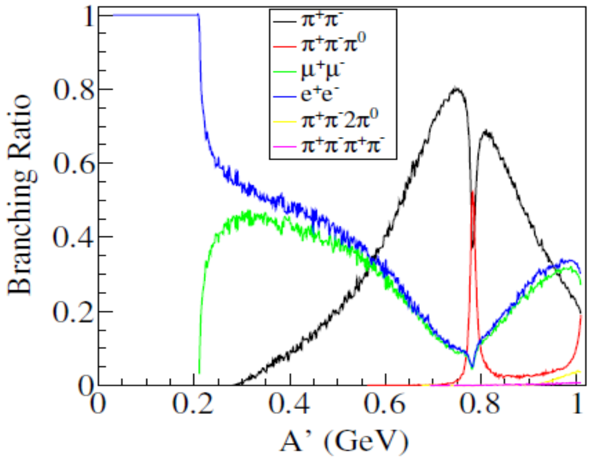
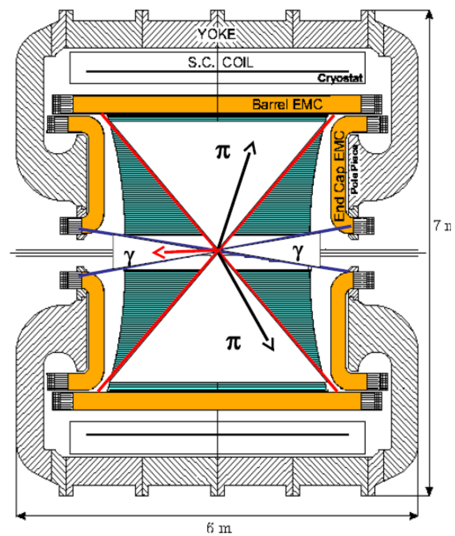
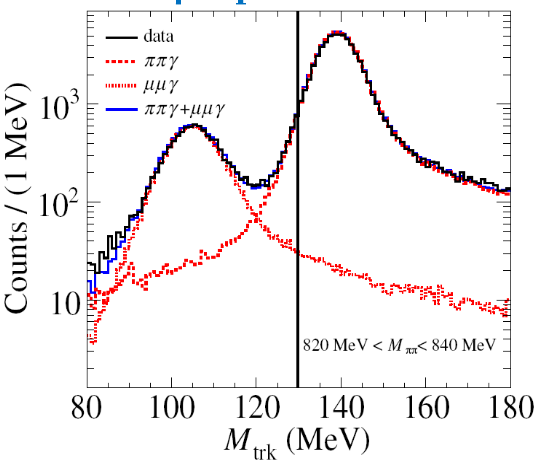




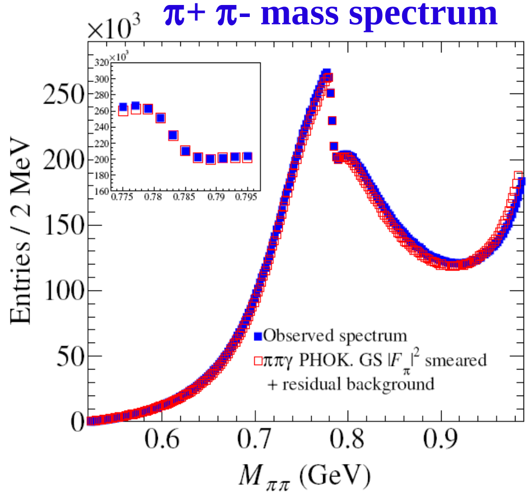
two opposite sign charged tracks $50° < \theta_\pi < 130°$

undetected small angle photon $\theta\gamma < 15°$, $\theta\gamma > 165°$

π/μ separation



π+ π- mass spectrum



L=1.93 fb^{-1}

Search for CP-violating $K_s \rightarrow \pi^0\pi^0\pi^0$

3 π^0 is a pure CP=-1 state . Any observation of $K_s \rightarrow \pi^0\pi^0\pi^0$ is a sign of CP violation

SM prediction BR($K_s \rightarrow \pi^0\pi^0\pi^0$) = 1.9 * 10^{-9}

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0 | T | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | T | K_L \rangle} = \varepsilon + \varepsilon'_{000}$$

Direct CP-violating term
expected << ε

Best upper limit by KLOE with 1.7 fb^{-1}

$\boxed{\mathbf{BR(K_S \rightarrow 3\pi^0) < 2.6 \times 10^{-8}\ @\ 90\%\ CL}}$

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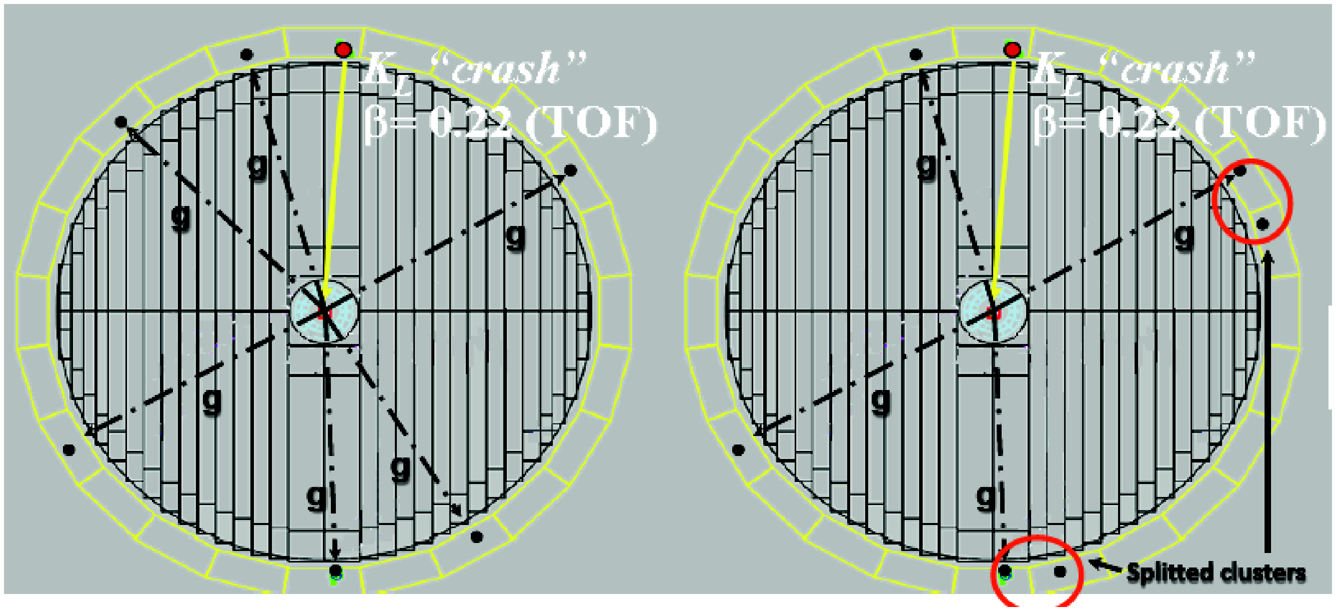
$\boxed{\mathbf{|\eta_{000}| < 0.0088\ @\ 90\%\ CL}}$

KLOE-2 data: L ≈ 300 pb^{-1} analyzed
"K_L crash" (K_L in the EMC) + 6 prompt photons
Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
Main bckg: $K_S \rightarrow 2\pi^0$ (4 prompt photons), also used for normalization

Search for CP-violating $K_s \to \pi^0\pi^0\pi^0$

SIGNAL **BACKGROUND**



SIGNAL:

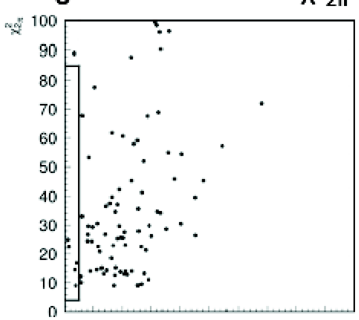
$K_S \to 3\pi^0 \to 6\gamma$

BACKGROUND:

$K_S \to 2\pi^0$ + accidental/splitted clusters

$K_L \to 3\pi^0$, $K_S \to \pi^+\pi^-$ („fake K_L crash")

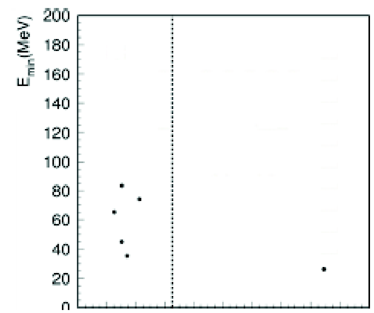
Signal box definition: $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$



- After all analysis cuts

  $\varepsilon_{3\pi}$ = 19.2 %

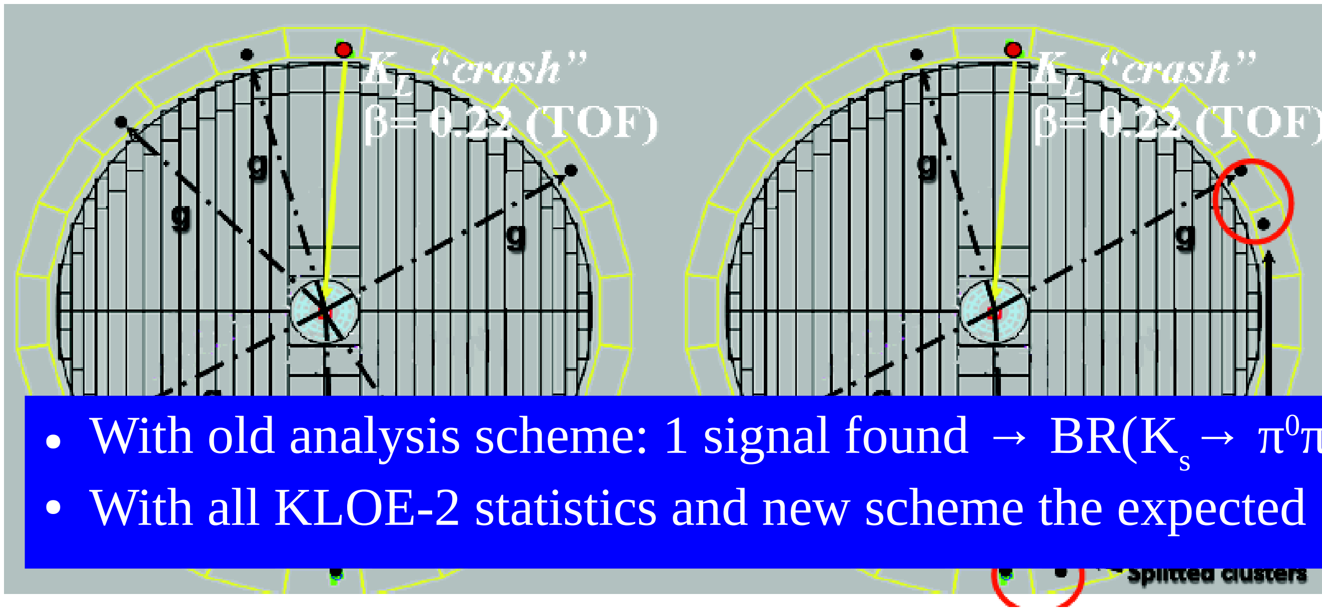
R_{min} : minimum distance between clusters



Track Veto → **χ^2_{fit}** → **$\Delta E/\sigma_E$** → **Sbox** → **R_{min}** → **counting**

Search for CP-violating $K_s \rightarrow \pi^0\pi^0\pi^0$

SIGNAL | BACKGROUND



SIGNAL:

$K_S \rightarrow 3\pi^0 \rightarrow 6\gamma$

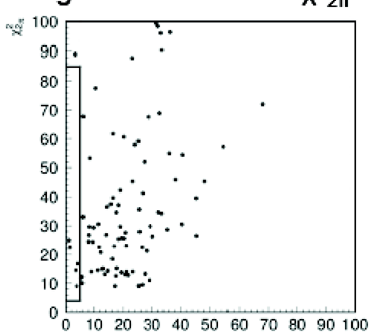
BACKGROUND:

$K_S \rightarrow 2\pi^0$ + accidental/splitted clusters

$K_L \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+\pi^-$ („fake K_L crash")

- With old analysis scheme: 1 signal found → BR($K_s \rightarrow \pi^0\pi^0\pi^0$) ~$10^{-7}$ (preliminary)
- With all KLOE-2 statistics and new scheme the expected sensitivity of <= 10^{-8}

Signal box definition: $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$



- After all analysis cuts $\varepsilon_{3\pi}$ = 19.2 %

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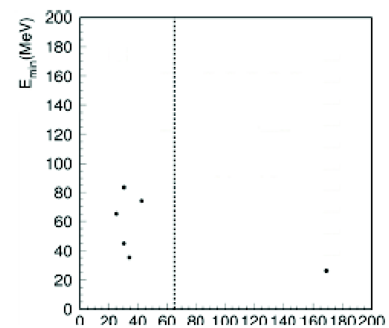

Track Veto → χ^2_{fit} → $\Delta E/\sigma_E$ → Sbox → R_{min} → counting