The KLOE-2 Experiment at DAPHNE

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on behalf of the KLOE-2 collaboration

Conference on Flavour Physics and CP violation
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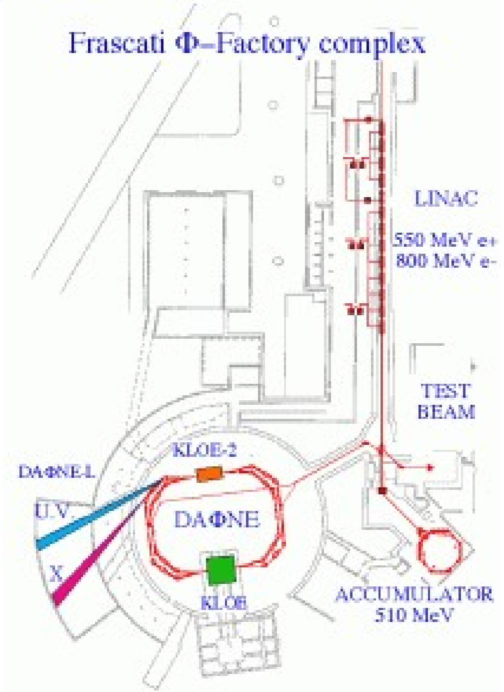
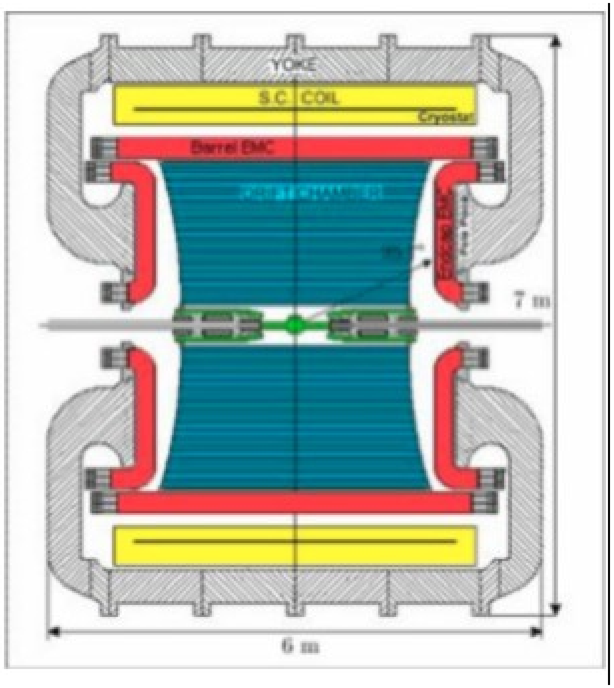
KLOE @ DAΦNE



- e^+e^- collider $\sqrt{s} = M_\Phi$
  - 2 interaction regions
  - e^+e^- separated rings
  - 105+105 bunches spaced by 2.7 ns
- KLOE data taking campaign ended in 2006
  - ~2.5 fb-1
  - +250 pb-1 off-peak
- DAΦNE upgrade (2008):new interaction scheme
  - Large beam crossing angle
  - Crab waist sextupoles

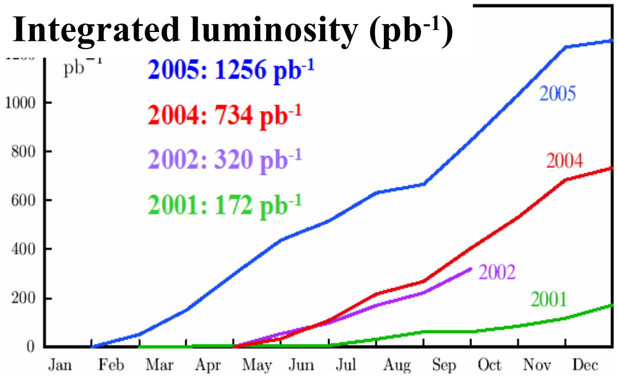
- **Calorimeter**
- 98% coverage full solid angle
- $\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_T = 57$ ps $/ \sqrt{E(GeV)} \oplus 140$ ps
- Barrel + 2 end-caps:
  - Pb/scintillating fiber read out by 4880 PMTs

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



Magnetic field B = 0.52 T

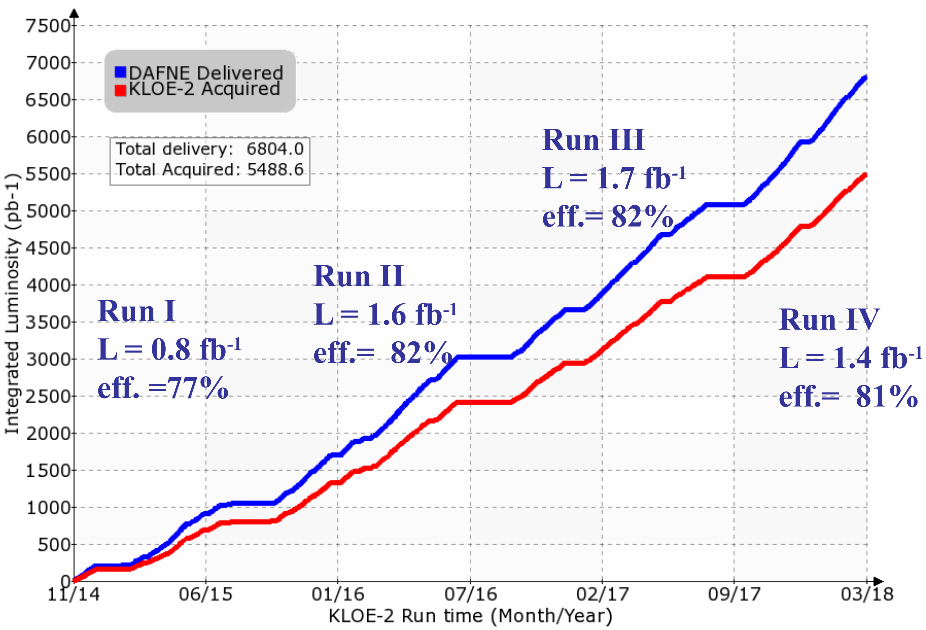
KLOE/KLOE-2 Experiment



- 1999: KLOE experiment starts
- 2000 – 2006: KLOE data-taking campaign
  - 2.5 fb^{-1}@$\sqrt{s}$=M_ϕ
  - +250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV

- 2008: DAΦNE upgrade: new interaction scheme
- Dec.2012-July 2013: installation of the new detectors
- 2014-2018: KLOE-2 data-taking campaign

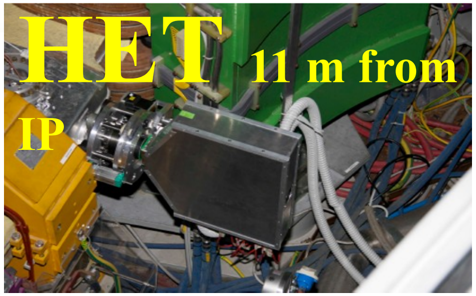
5.5 fb^{-1} collected @$\sqrt{s}$=M_ϕ



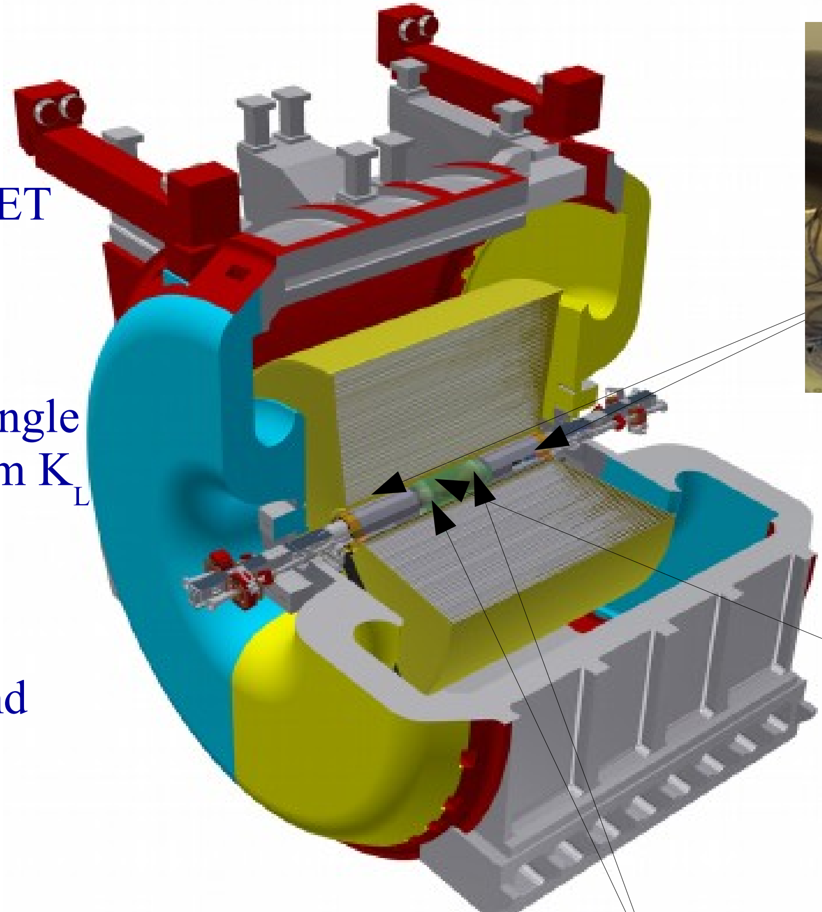
KLOE + KLOE-2 data sample
~ 8 fb^{-1} represents the largest sample collected at a Φ-factory

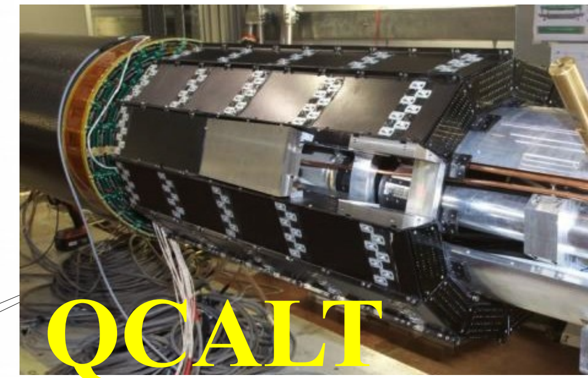
About 2.4 x 10^{10} Φ-mesons

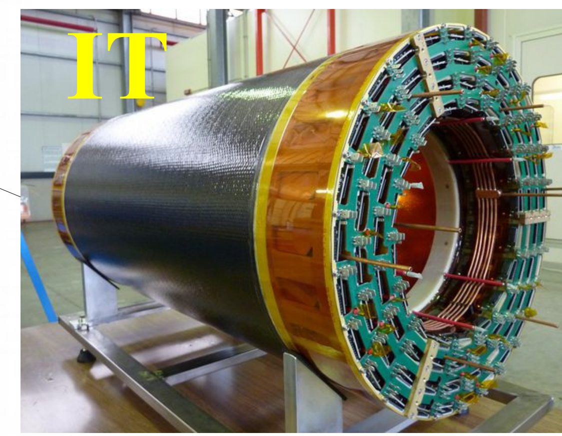
KLOE-2

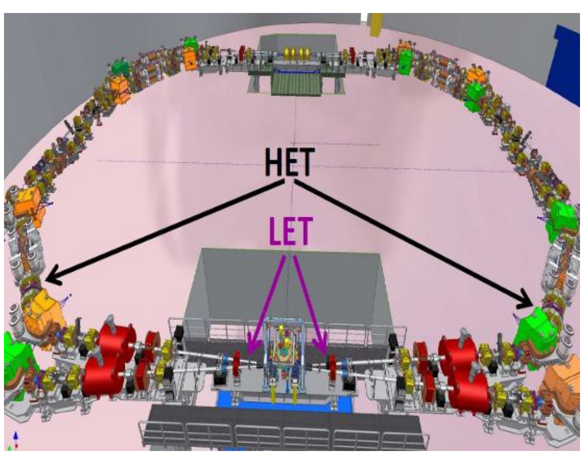


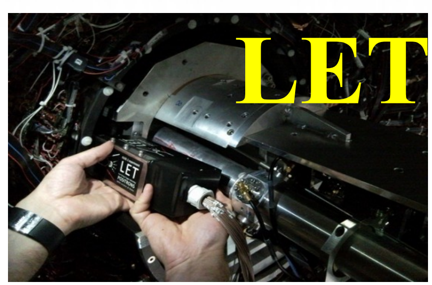
- LET (Low Energy Tagger) & HET (High Energy Tagger)
  - e+e--taggers for γγ-physics
- CCALT & QCALT
  - 2 new calorimeters (for low angle γs & quadrupole coverage from K_L decays)
- IT (Inner Tracker)
  - 4 layers of C-GEM
  - better vertex reconstruction and Track parameters

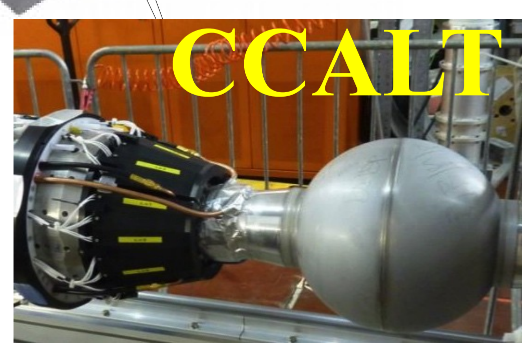












$\gamma^*\gamma^* \to \pi^0$ HET analysis

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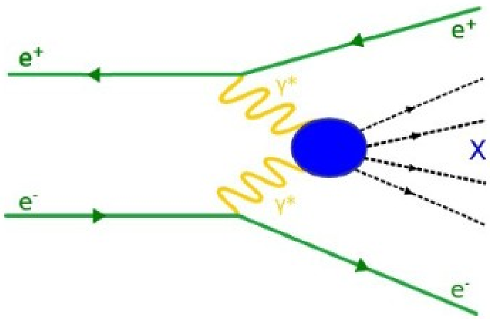
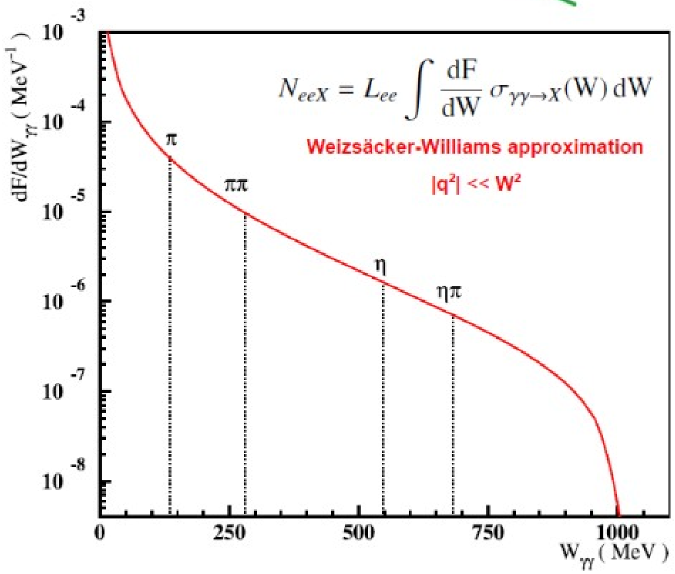
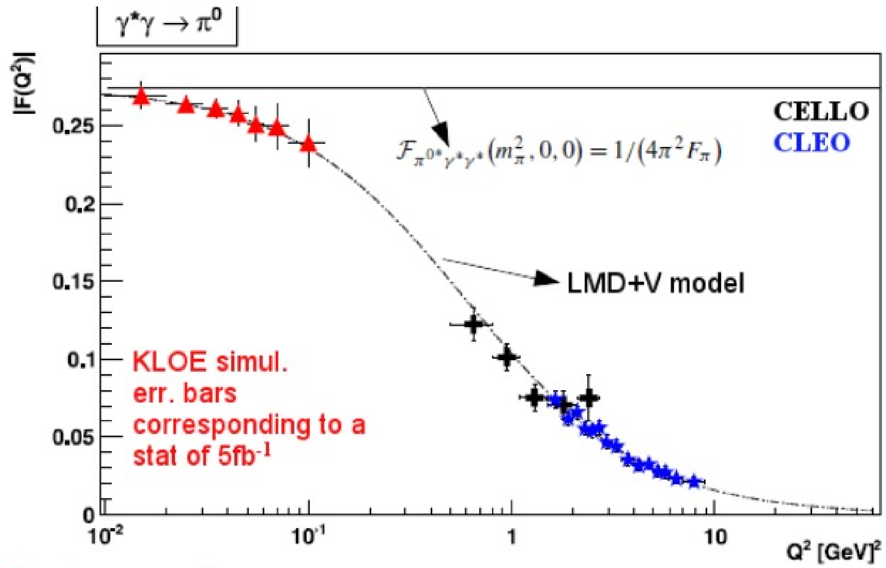
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-X$$

for quasi-real photons $J^{PC}(X) = \{0^{\pm,+}, 2^{\pm,+}\}$
$\to X = \{\pi^0,\ \pi\pi,\ \eta\}$

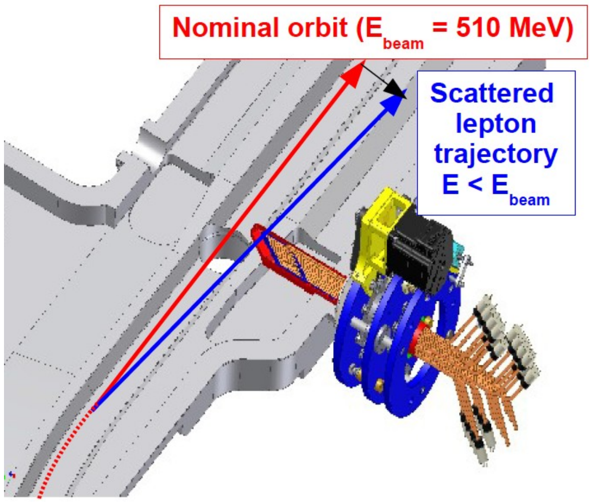


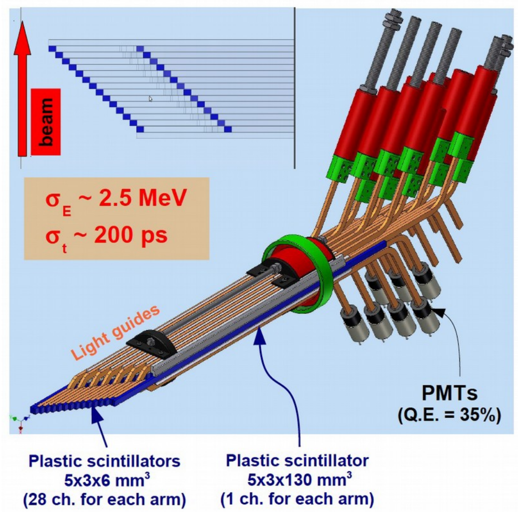




Precision measurement of $\Gamma(\pi^0 \to \gamma\gamma)$
First measurement transition form factor $F_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2
($|q^2| < 0.1$ GeV^2), impact on value and precision of $a_\mu^{LbL;\pi 0}$

$\gamma^*\gamma^* \rightarrow \pi^0$ HET analysis

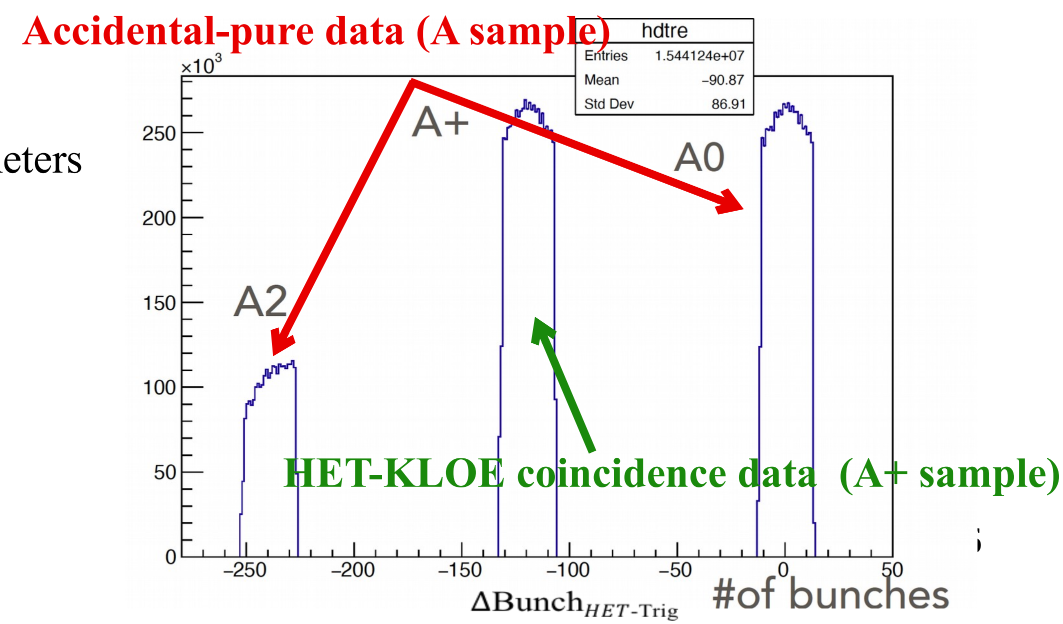




Analysis strategy
Hits in one HET station and 2 clusters in KLOE originating from the same bunch crossing

HET and KLOE data are acquired asynchronously. HET acquisition time 2.5 times larger than KLOE → out-coincidence (HET only) sample + in-coincidence sample → background subtraction

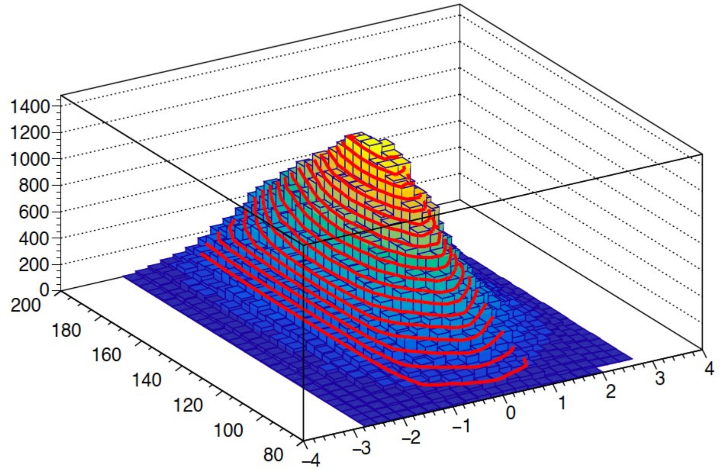
Bending dipoles of DAΦNE closer to IP act as spectrometers for the scattered e^+/e^- (420 < E < 495 MeV)
Strong correlation between E and trajectory
Scintillator hodoscope + PMTs, inserted in roman pots
Pitch: 5 mm, ~ 11 m from IP



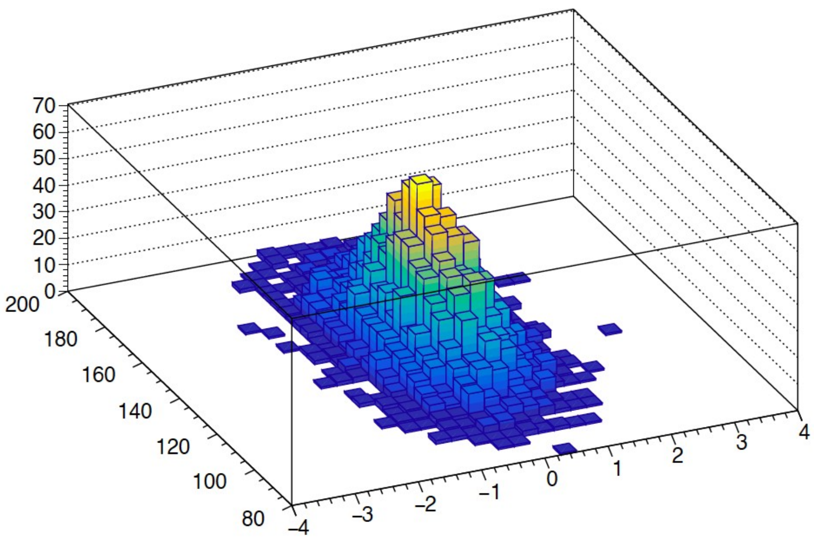
γ*γ* → π^0 HET analysis

A+ sample , HET ele, $1fb^{-1}$

Fit performed with TFractionFitter



Amount of EKHARA signal events estimated with the fit for $\sigma_T = 500$ ps



$1.5fb^{-1}$ of data have been re-reprocessed with optimized calibration
constants to improve time and energy resolutions

Single-arm selection:

-Sample of 2 clusters associated with the same bunch crossing in the KLOE barrel calorimeter

-Selected bunch crossing, and, independently selected HET signal, are in a time window of 40 ns around the KLOE trigger

-Comparison of A/A+ samples for $1fb^{-1}$ sample shows 3.5(0.7)k tagged events in the mass region where π^0's from fusion are expected

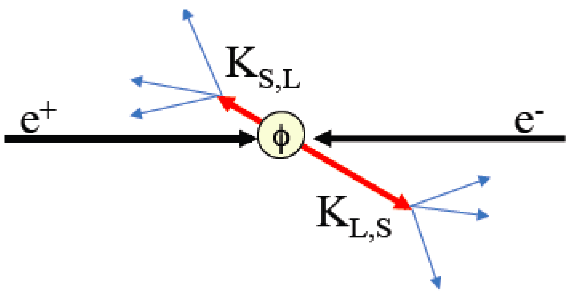
-Fit using A sample as background model provides coherent, stable results

-Work in progress to further reduce the background

-Plans to improve measurement accuracy

-Low angle radiative bhabha cross section normalization channel, in progress

Kaon Physics



$\lambda(\mathbf{K_S}) = \mathbf{6\ mm}$

$\lambda(\mathbf{K_L}) = \mathbf{3.5\ m}$

Neutral kaons are produced in an antisymmetric quantum state ($J^{PC} = 1^{--}$)

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$

$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

- At KLOE-2, kaons are produced almost collinear in monochromatic pairs with longitudinal momenta of 110 MeV/c
- Tagging one kaon ensures the presence of the other one on the opposite side
- Unique capability of selecting a pure beam of K_S (tagging the K_L partner)
  - Not available at fixed target experiments
- Studies of quantum mechanics and fundamental symmetries from interference pattern and entanglement, K_S rare decays

K_S charge asymmetry

[JHEP 1809 (2018) 021]

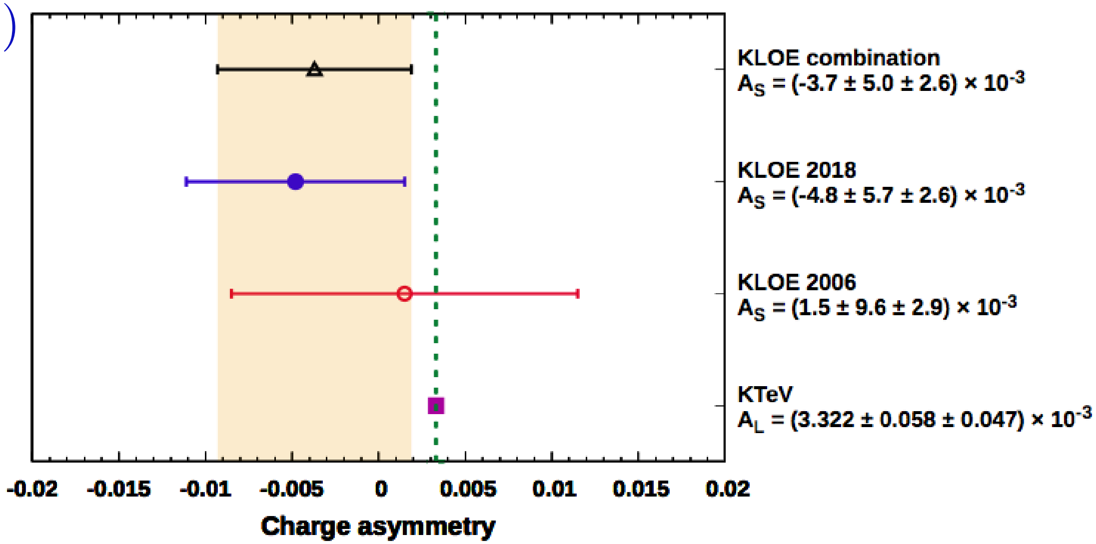
$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

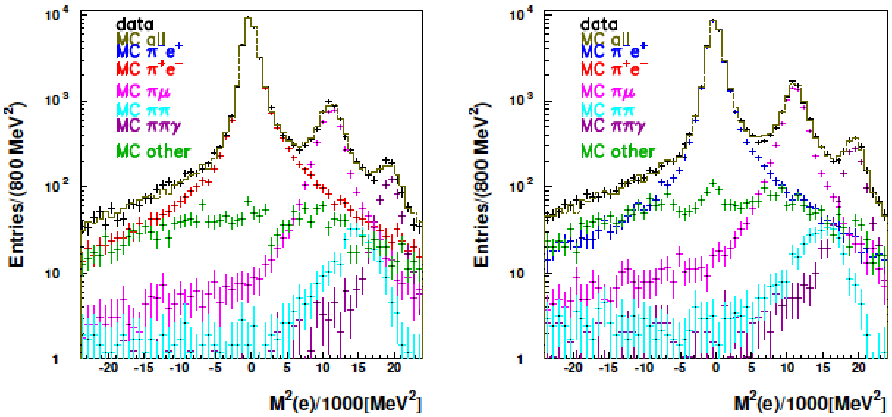
$A_{S,L} \neq 0$ => CP violation

$A_S \neq A_L$ => CPT violation

One of the cleanest and most precise test of CPT symmetry

Analyzed 1.7 fb^{-1}





$A_S = (\ -4.8 \pm 5.7 \pm 2.6) \times 10^{-3}$

with KLOE-2 data: δA_S(stat) → ~ 3×10^{-3}

$K_S \to 3\pi^0$

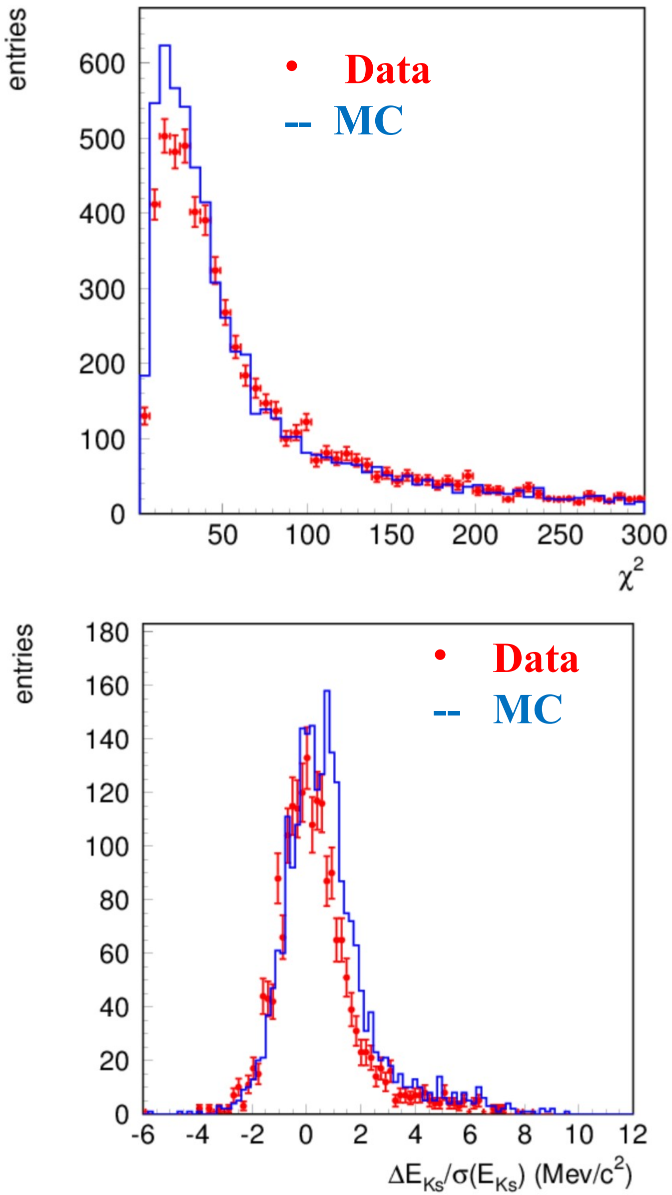
- **Data sample: KLOE-2 data (~1.5 fb^{-1})**
- CP violating, never observed
- Expected Br ~ 2×10^{-9} (SM)
- Best upper limit by KLOE:
  $Br(K_S \to 3\pi^0) < 2.6\times10^{-8}$ @ 90% C.L.
  with 1.7 fb^{-1} [PLB723(2013)54]

Pre-selection with the following requirements:

- K_L-crash: E>150 MeV, $0.2 < \beta < 0.225$
- prompt photons: $E_{cl} > 20$ MeV; $|\cos\theta_{cl}| \leq 0.915$
  and $|\Delta T_{cl}| \leq Min(3\cdot\sigma_T(E_{cl}), 2\ ns)$
- $K_S \to 2\pi^0$ (4 prompt photons) used for normalization
- Main background source: $K_S \to 2\pi^0$ with two additional clusters (shower splitting/accidentals)

Hardened selection to face machine background

Full KLOE-2 statistics + optimized analysis can reach Br ~ 10^{-8}



T/CPT test with $\varphi \to K_S K_L \to 3\pi^0\, \pi\nu e,\ \pi\pi\ \pi\nu e$

Direct tests of the T and CPT symmetry
by comparison of rates
of the following processes:

- $\Phi \to K_S K_L \to \pi e \nu, 3\pi^0$
- $\Phi \to K_S K_L \to \pi^+\pi^-, \pi e \nu$

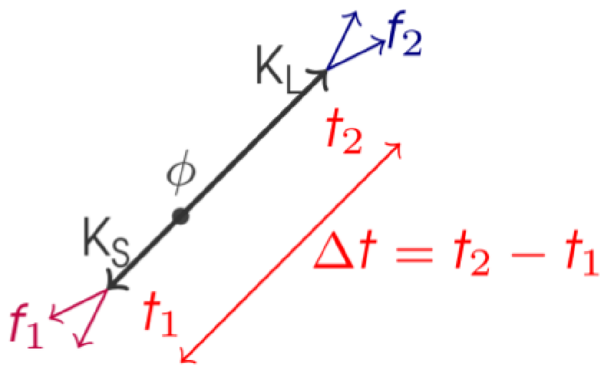
- J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, *Direct test of time-reversal symmetry in the entangled neutral kaon system at a Φ factory*, Nucl. Phys. B 868 (2013) 102
- J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, *Probing CPT in transitions with entangled neutral kaons*, JHEP 1510 (2015) 139

Observables (Focusing on the asymptotic region $\Delta\tau >> \tau_S$):

T-violation sensitive:

$$R_2^T = \frac{I(\pi^+ e^- \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^- e^+ \nu)}$$

$$R_4^T = \frac{I(\pi^- e^+ \nu, 3\pi^0)}{I(\pi^+\pi^-, \pi^+ e^- \nu)}$$



CPT-violation sensitive:

$$R_{2,\mathcal{CPT}}^{exp}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$$R_{4,\mathcal{CPT}}^{exp}(\Delta t) = \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

Double ratios:

$$\frac{R_2^T}{R_4^T} = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$$

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

CP-violation sensitive (auxilliary):

$$R_2^{CP}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}$$

$$R_4^{CP}(\Delta t) = \frac{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

T/CPT test with $\phi \rightarrow K_S K_L \rightarrow 3\pi^0 \pi \nu e$, $\pi\pi$ $\pi \nu e$

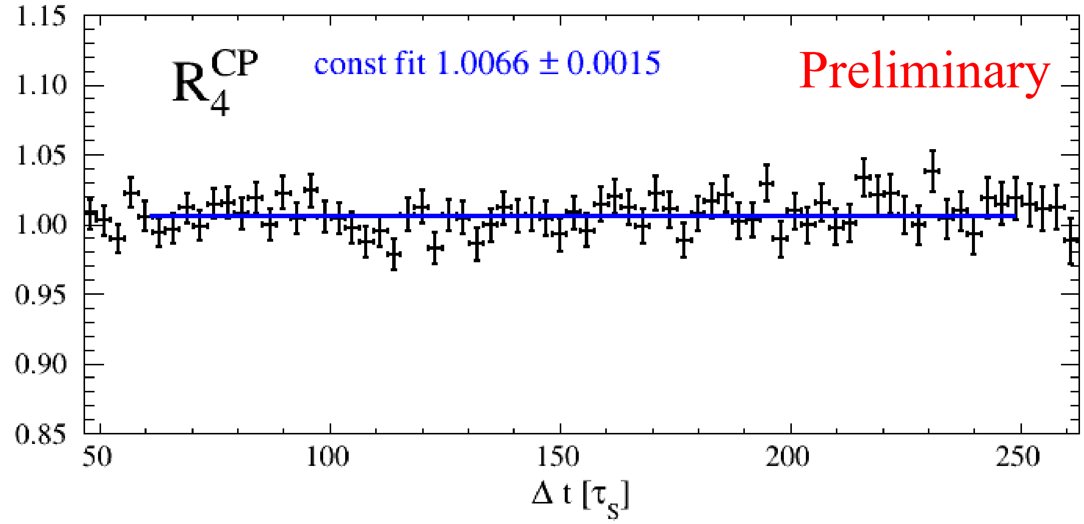
Auxiliary CP-violation sensitive observable shows control over K_L selection efficiencies

$$R_4^{CP}(\Delta t) = \frac{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

Expected:

$$R_4^{CP}(\Delta t \gg \tau_S) = 1 + 4\Re\epsilon \approx 1.0064$$

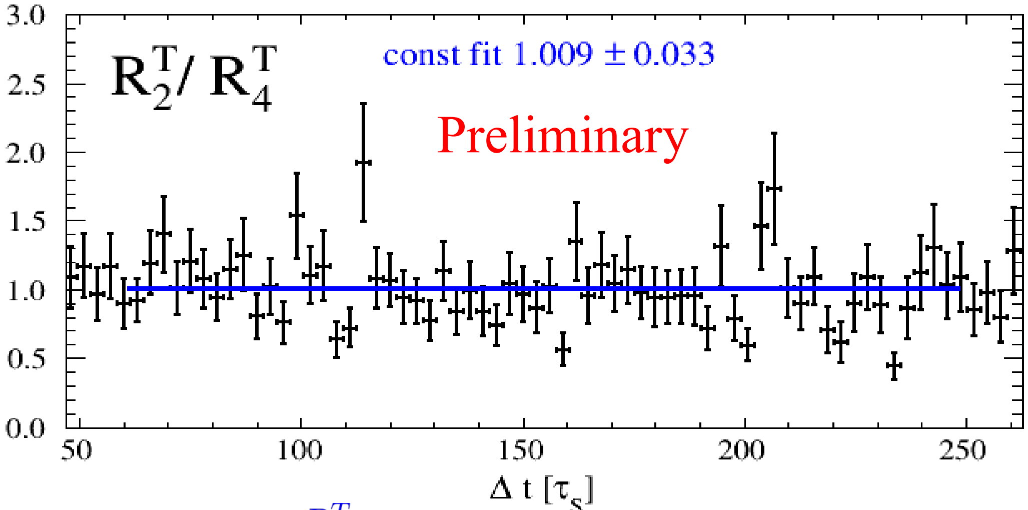
L=1.7fb[-1]



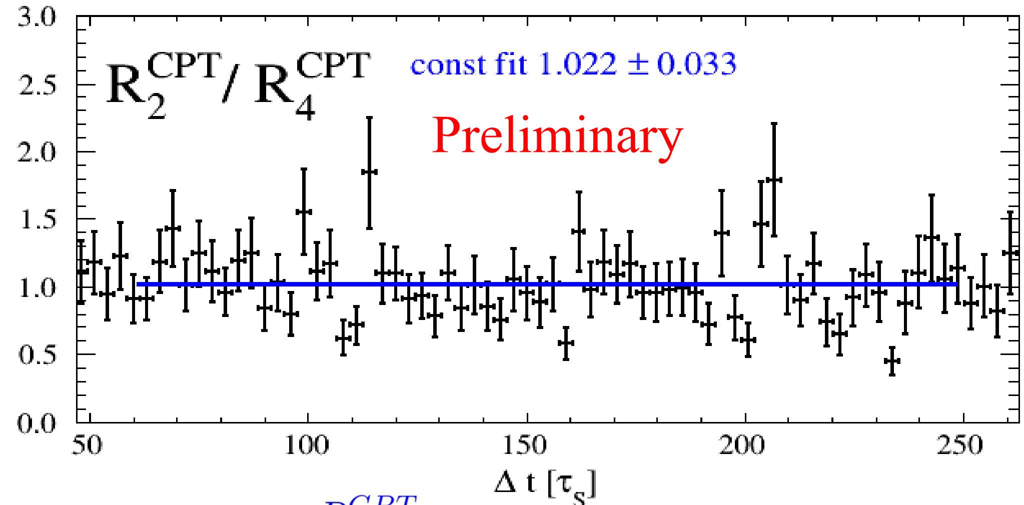
Double ratios:

T asymmetric $\frac{R_2^T}{R_4^T} = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$

CPT asymmetric $\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$



Expected: $\frac{R_2^T}{R_4^T} \overset{\Delta t \gg \tau_S}{=} 1 - 8\mathrm{Re}(\epsilon)$

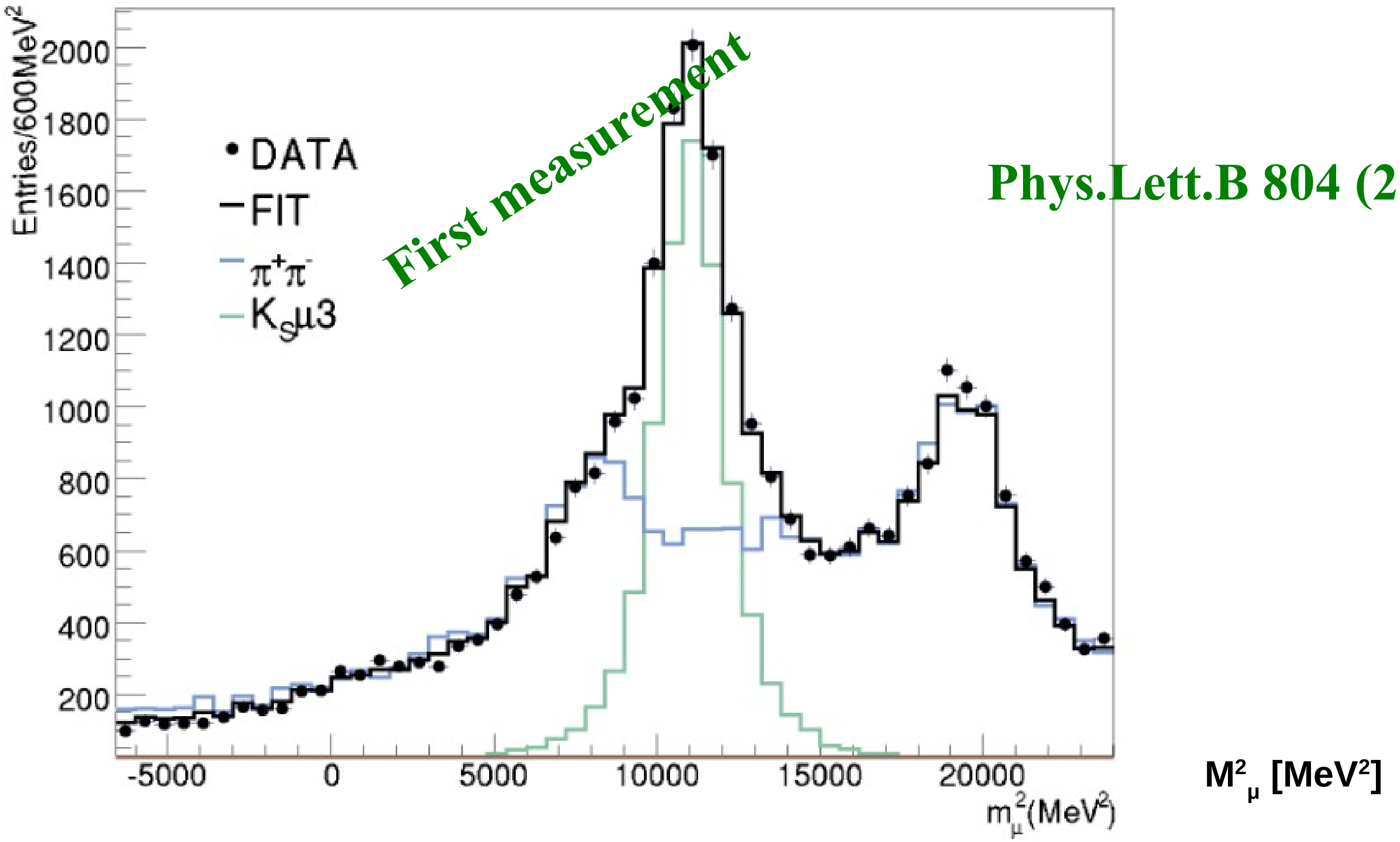


Expected: $\frac{R_2^{CPT}}{R_4^{CPT}} \overset{\Delta t \gg \tau_S}{=} 1 - 8\mathrm{Re}(\delta)$

$K_S \to \pi\mu\nu$

- **First measurement** of Ks $\to \pi\mu\nu$ Branching Ratio
  - 1.6 fb^{-1}
- Lepton universality test and measurement of Vus CKM matrix element,

$BR(K_S \to \pi\mu\nu) = (4.56 \pm 0.11_{stat} \pm 0.17_{syst}) \times 10^{-4}$

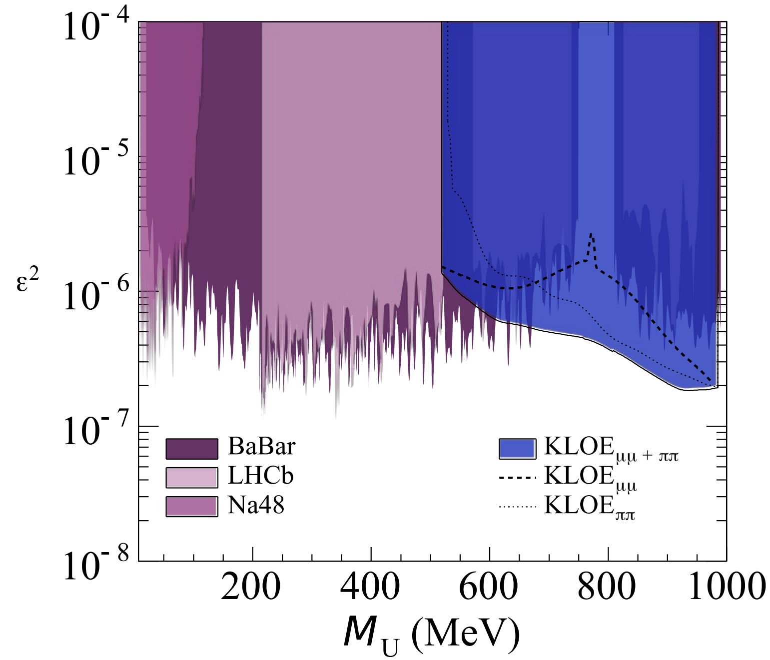


Phys.Lett.B 804 (2020) 135378

Dark Matter: U boson combined limit

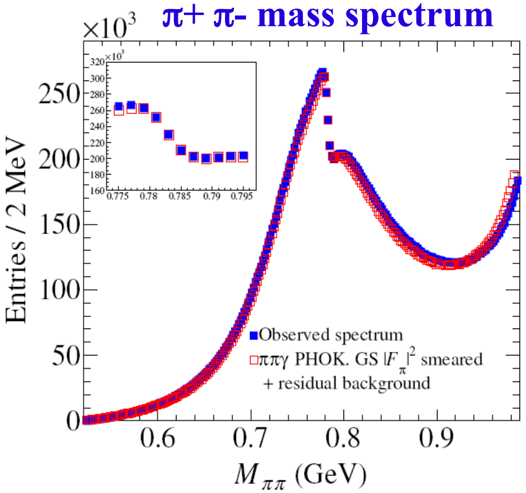
- $\mu\mu\gamma$ limit at full KLOE statistics
- $\pi\pi\gamma$ limit at the same luminosity (1.93 fb^{-1})
- Combining procedure requires:
  - Double inputs of data, expected background, U signal and systematical errors
  - Info on different efficiency and U decay branching fractions: BR(U → μμ, ππ)
- Combined limit extracted by means of CLs Technique
- The limit on ε^2 is extracted when $N^{tot}_U = N^{\mu\mu}_U + N^{\pi\pi}_U$ reaches CLs < 0.1

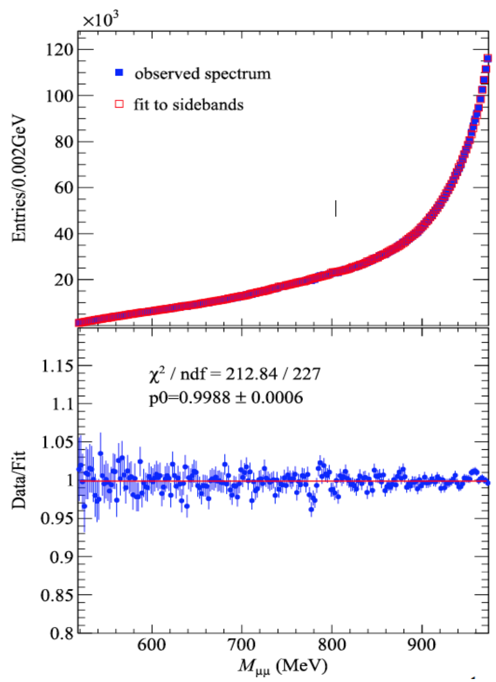
Best limit in the 600 MeV – 1000 MeV mass region



Phys.lett.B 784 (2018) 336-341

π+ π- mass spectrum





B-boson searches

- B boson couples mainly to quarks

[Tulin, PRD89(2014)114008]

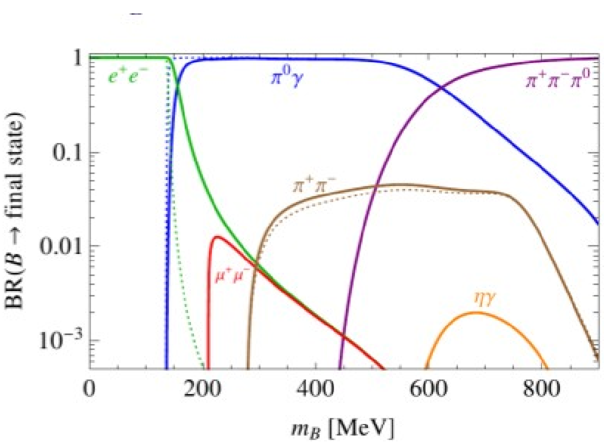
- Most basic model → coupling to baryon number

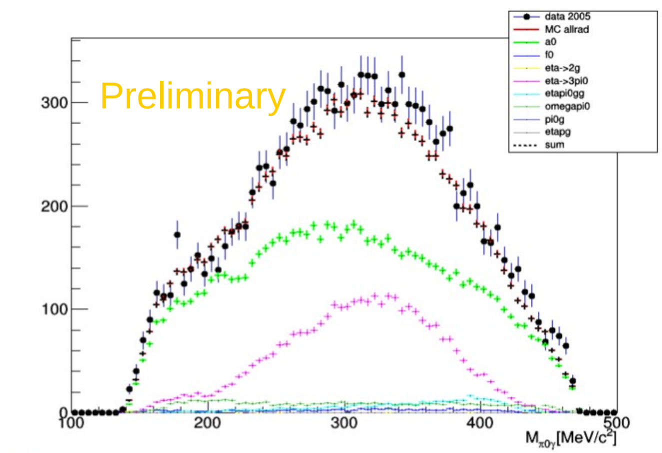
$$\mathscr{L} = \frac{g_B}{3}\,\bar{q}\gamma^{\mu} q B_{\mu}$$

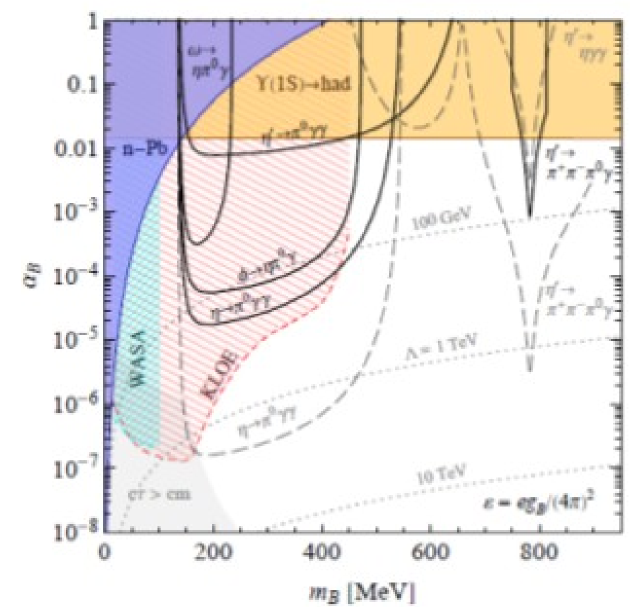
$$g_B \lesssim 10^{-2} \times (m_B/100\ \text{MeV})$$

$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\ \text{MeV})^2$$

- Discovery signal depends on mass m_B







Decay → Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	···	···	···
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	···	···
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	···	···
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	···	

KLOE/KLOE-2 searches

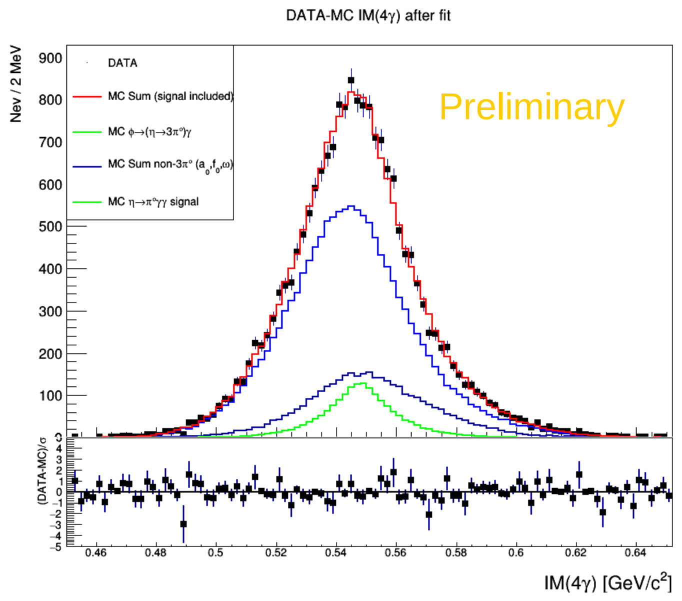
$\eta \to \pi^0\gamma\gamma$ χ-PT golden mode

$\eta \to \pi^0\gamma\gamma$ (from $\phi \to \eta\gamma$): χPT golden mode

Imput for χPT parameters: $O(p^2)$ null at tree level, $O(p^4)$ suppressed by G-parity at first loop ⇒ sensitive to **$O(p^6)$**

Br = $(22.1 \pm 2.4 \pm 4.7)\times10^{-5}$ CB@AGS(2008)
Br = $(25.2\pm2.5)\times10^{-5}$ CB@MAMI (2014)

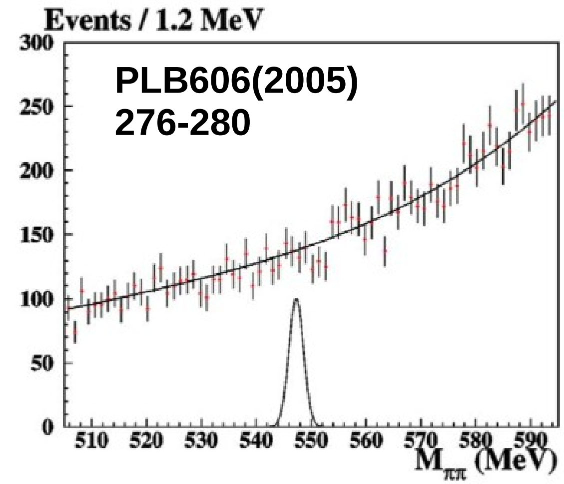
Old KLOE preliminary: $(8.4\pm2.7\pm1.4)\times10^{-5}$
(L = 450 pb^{-1} ~ 70 signal events)



- 1.7 fb^{-1} KLOE data used
- Main bckg is $\phi\to\eta\gamma$, with $\eta\to3\pi^0$ with lost or merged photons
- New TMVA-BDT based rejection which allows to remove 50% of the background generating from $\eta \to 3\pi^0$

$\eta \rightarrow \pi^+\pi^-$ (P and CP viol.)

- $\eta \rightarrow \pi^+\pi^-$ is P and CP violating process
  The BR prediction in SM [Phys. Scripta T99, 23 (2002)]
  - proceeds only via the CP-violating in weak interaction $\rightarrow 10^{-27}$
  - introducing a CP violating term in QCD $\rightarrow$ to 10^{-17}
  - allowing CP violation in the extended Higgs sector $\rightarrow 10^{-15}$
- **Any observation of larger branching ratio would indicate a new source of CP violation in the strong interaction**

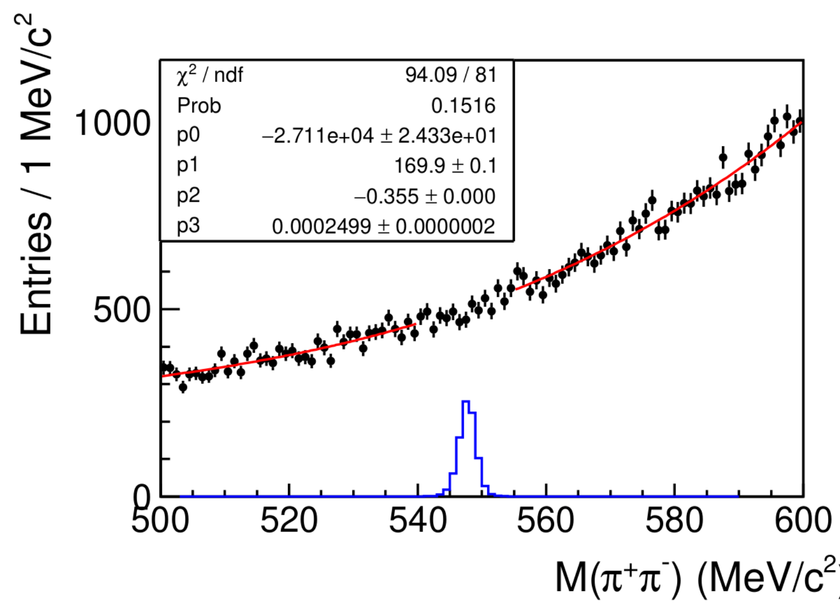


- The best limit **$Br(\eta \rightarrow \pi^+\pi^-) < 1.3\times10^{-5}$** @ 90% C.L. by **KLOE** with L_{int} ~ 350 pb^{-1}
- A recent limit $BR(\eta \rightarrow \pi^+\pi^-) < 1.6\times10^{-5}$ @ 90% C.L. from the LHCb with Lint~3.3 fb^{-1}

Final result for 1.6 fb^{-1} of KLOE sample:
Continuum background from $\pi\pi\gamma$
After all the cuts, efficiency for KLOE is 14%
No event excess in the η region

$Br(\eta \rightarrow \pi^+\pi^-) < 4.9\times10^{-6}$ @ 90% C.L.

The combined upper limit with previous KLOE result is $Br(\eta \rightarrow \pi^+\pi^-) < 4.4\times10^{-6}$ @ 90% C.L.



With all KLOE/KLOE-2 data $\rightarrow$ the upper limit is expected to reach 2.7×10^{-6} @ 90% CL

KLOE-2 Physics Program

Light meson Physics:

- η decays, ω decays

Transition Form Factors

- C,P,CP violation: improve limits on
  $\eta \rightarrow \gamma\gamma\gamma$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\pi^0\gamma$
- improve $\eta \rightarrow \pi^+\pi^- e^+ e^-$
- χpT : $\eta \rightarrow \pi^0\gamma\gamma$
- Light scalar mesons: $f_0(500)$ in $\phi \rightarrow K_S K_S \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \rightarrow \pi^0$ and π^0 TFF

$e^+e^- \rightarrow \pi^0\gamma\gamma_{ISR}$ (π^0 TFF)

- search for axion-like particles

Dark force searches:

- Improve limits on

Uγ associate production

$e^+e^- \rightarrow U\gamma \rightarrow \pi\pi\gamma, \mu\mu\gamma$

Higgsstrahlung:

$e^+e^- \rightarrow Uh' \rightarrow \mu^+\mu^-$ + miss. energy

- Leptophobic B boson search:
  $\phi \rightarrow \eta B$, $B \rightarrow \pi^0\gamma$, $\eta \rightarrow \gamma\gamma$
  $\eta \rightarrow B\gamma$, $B \rightarrow \pi^0\gamma$, $\eta \rightarrow \pi^0\gamma\gamma$
- Search for U invisible decays

Kaon Physics:

- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \rightarrow 3\pi^0$
  direct measurement of Im(ε'/ε)
- CKM V_{us}:
  K_S semileptonic decays and A_S
  (CP and CPT test)
  $K_{\mu 3}$ form factors, K_{l3} radiative corrections
- χpT : $K_S \rightarrow \gamma\gamma$
- Search for rare K_S decays

Hadronic cross section:

- ISR studies with 3π, 4π final states
- F_π with increased statistics

Measurement of a_μ^{HLO} in the space-like region using Bhabha process

KLOE-2 Coll., EPJC68(2010)619
http://agenda.infn.it/event/kloe2ws
Proceedings: EPJ Web Conf., 166 (2018)

Conclusions

KLOE-2 data-taking succesfully completed on March 30, 2018

~ 20 years after the first events collected in KLOE

Luminosity acquired L = 5.5 fb^{-1}

KLOE + KLOE-2 sample ⇒ ~ 8 fb^{-1} -- unique sample worldwide

⇒ ~ 2.4 × 10^{10} ϕ's produced largest sample collected in a ϕ-factory

The data sample collected by KLOE provided important results on decay dynamics of light mesons, Transition Form Factors, discrete symmetries of the nature, and also on searches for New Physics in the Dark Sector

KLOE-2 increased statistics together with new detectors broadens the KLOE physics program and extends the sensitivity reach

Backup slides

T/CPT test with $\varphi \to K_S K_L \to 3\pi^0\, \pi\nu e,\ \pi\pi\ \pi\nu e$

$$R_2^T = \frac{N(\pi^+e^-,\ 3\pi^0;\Delta t)}{N(\pi\pi,\ \pi^-e^+;\Delta t)} \times \frac{\varepsilon^S(\pi\pi)\ \varepsilon^L(\pi^-e^+;\Delta t) \times C_{DATA/MC}}{\varepsilon^S(\pi^+e^-)\ \varepsilon^L(3\pi^0;\Delta t) \times C_{DATA/MC}}$$

Corrections to MC-based $K_L \to \pi e \nu$ event selection efficiencies based on a control sample tagged by $K_S \to 2\pi^0$

$K_S K_L \to 2\pi^0 \pi e \nu$ DATA / $K_S K_L \to 2\pi^0 \pi e \nu$ MC