Status of KLOE-2

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on behalf of the KLOE-2 collaboration

3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics
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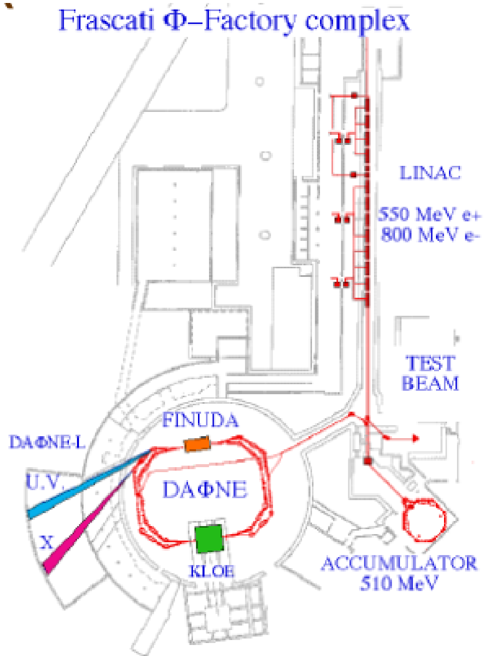
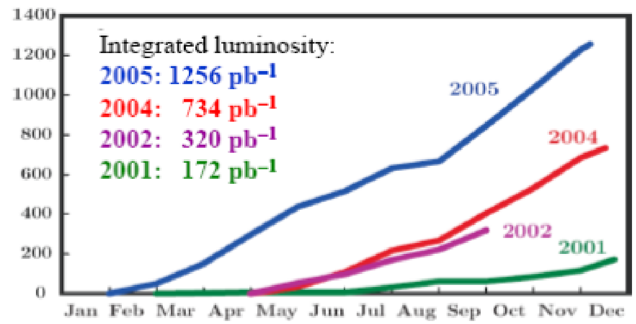
KLOE @ DAΦNE



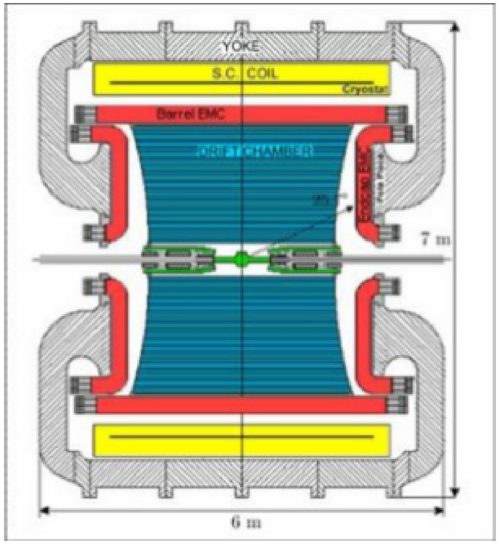


- **Drift Chamber**
- Low-mass gas mixture 90% Helium + 10% isobutane
- $\delta p_\perp / p_\perp < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2$ mm
- 12582 cells
- Stereo geometry
- 4m diameter, 3.3m long

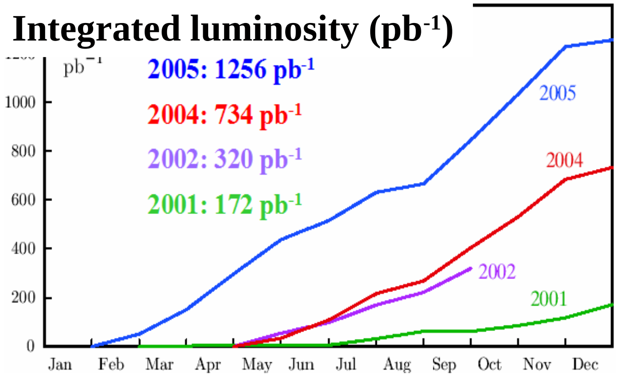
- $e^+ e^-$ collider $\sqrt{s} = M_\Phi = 1019.4$ MeV
  - 2 interaction regions
  - $e^+ e^-$ separated rings
  - 105 + 105 bunches spaced by 2.7 ns
- KLOE data taking campaign ended in 2006
  - ~ 2.5 fb^{-1}
  - ~ 260 pb^{-1} off-peak
- DAΦNE upgrade (2008): new interaction scheme
  - Large beam crossing 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

Magnetic field B = 0.52 T

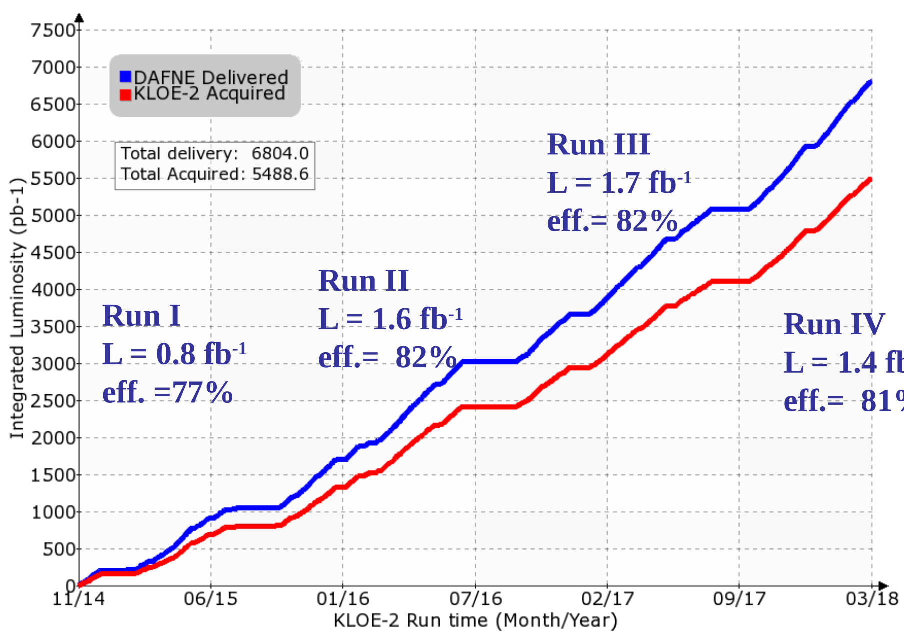


KLOE/KLOE-2 Experiment



- 1999: KLOE experiment starts
- 2000 – 2006: KLOE data-taking campaign
  - 2.5 fb^{-1}@$\sqrt{s}=M_\phi$
  - + 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 @$\sqrt{s}=M_\phi$

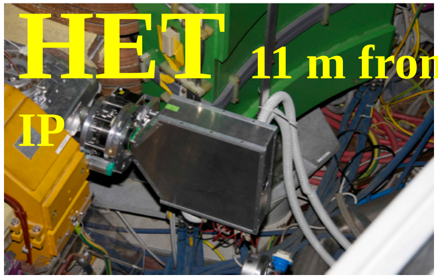


5 fb^{-1}

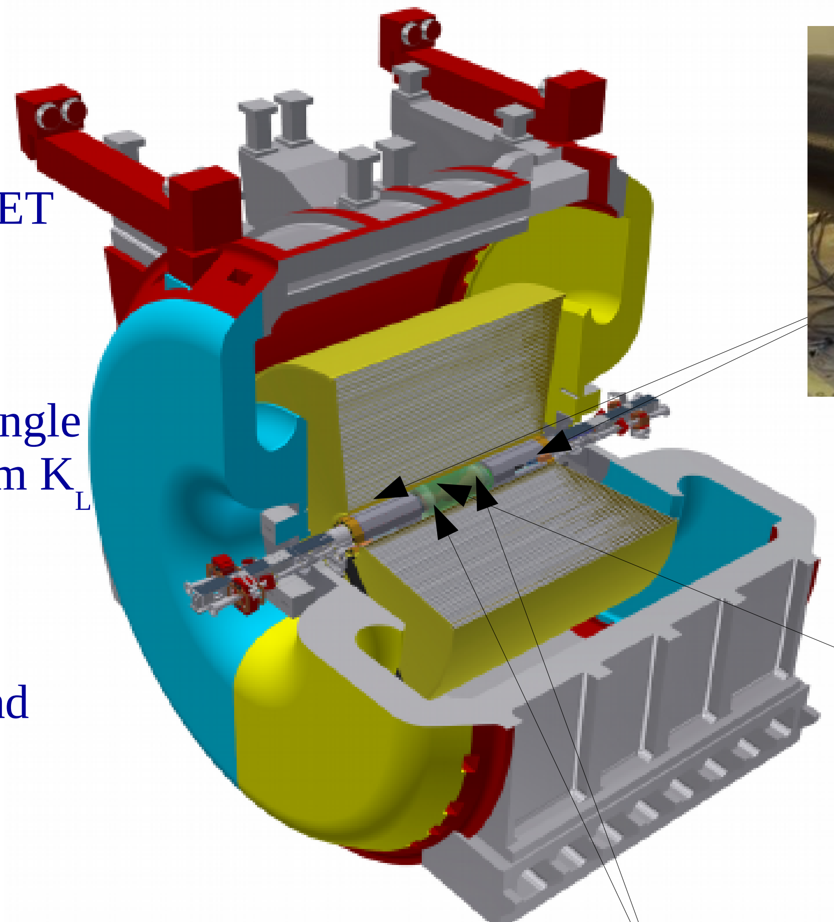
KLOE + KLOE-2 data sample ~ 8 fb^{-1} represents the largest sample collected at a Φ-factory

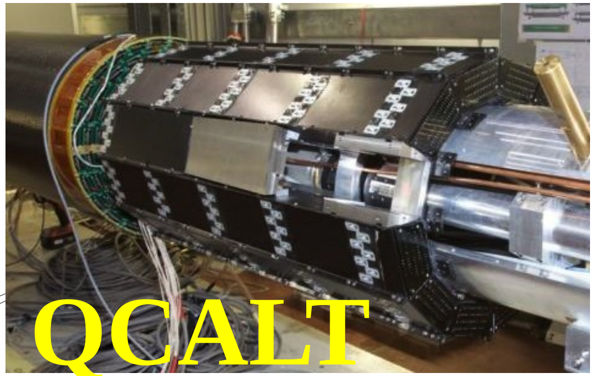
About 2.4 x 10^{10} Φ-mesons

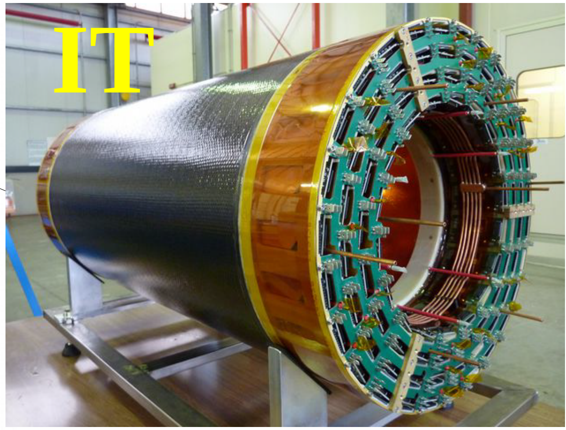
KLOE-2

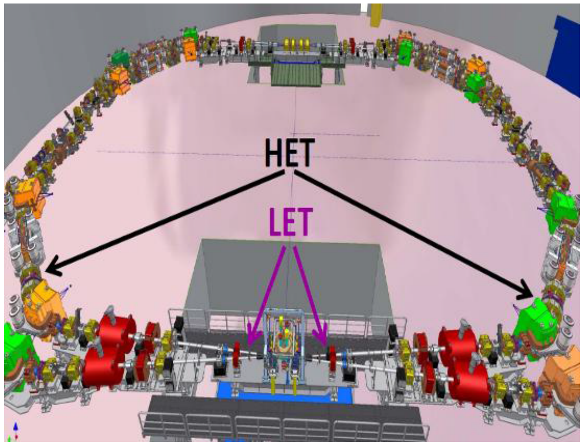


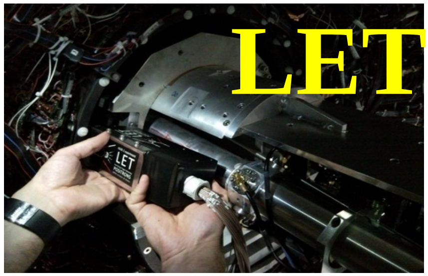
- LET (Low Energy Tagger) & HET (High Energy Tagger)
  - e+e--taggers for γγ-physics
- CCALT & QCALT
  - 2 new calorimeters (for low angle γs & quadrupole coverage from K_L decays)
- IT (Inner Tracker)
  - 4 layers of C-GEM
  - better vertex reconstruction and Track parameters











KLOE-2 Physics Program

Light meson Physics:

- η decays, ω decays

Transition Form Factors

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

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

- search for axion-like particles

Dark force searches:

- Improve limits on

Uγ associate production

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

Higgsstrahlung:

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

- Leptophobic B boson search:
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- 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:
  $K_S \to 3\pi^0$
  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 : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Hadronic cross section:

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

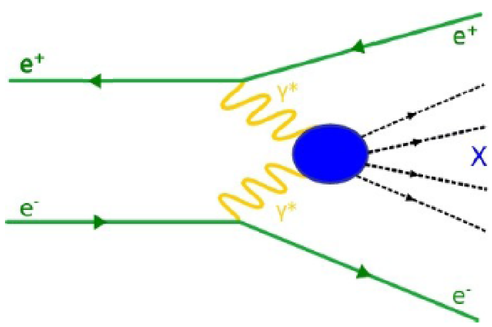
Measurement of a_μ^{HLO} in the space-like region using Bhabha process

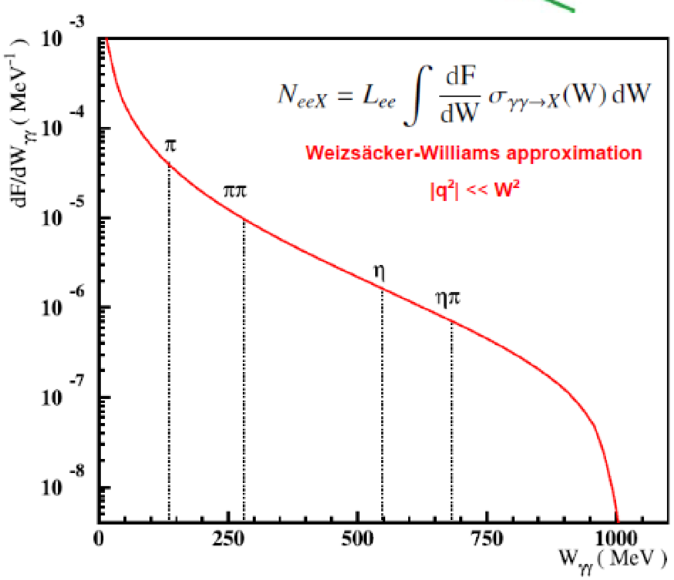
KLOE-2 Coll., EPJC68(2010)619
http:// agenda.infn.it/event/kloe2ws **Proceedings: EPJ WoC 166 (2018)**

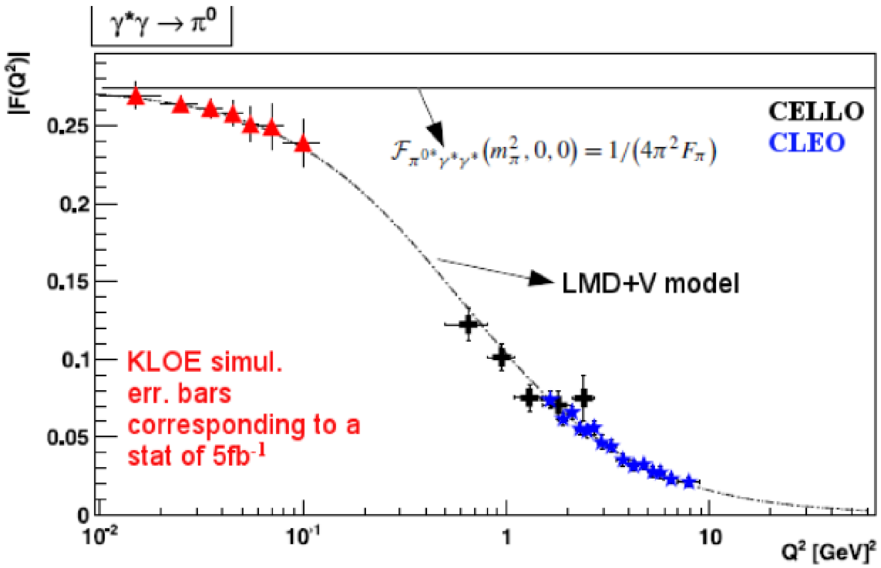
$\gamma^*\gamma^* \rightarrow \pi^0$ HET analysis

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

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

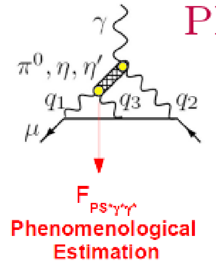






Physics goal:

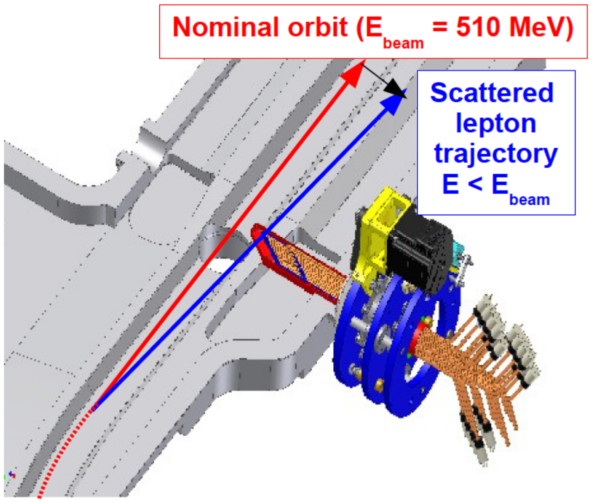
- ⋆ Precision measurement (1%) of the $\Gamma_{\pi^0\rightarrow\gamma\gamma}$
  $\Gamma^{Th.}_{\pi^0\rightarrow\gamma\gamma} = 8.09 \pm 0.11\text{eV}$ (1.4% precision)
  $\Gamma^{Exp}_{\pi^0\rightarrow\gamma\gamma} = 7.82 \pm 0.22$ (2.8% precision, via Primakoff Effect, most precise measurement);
- ⋆ First measurements of the $F_{\pi^0\gamma^\star\gamma}(q^2, 0)$ in the space-like region for $q^2 < 0.1\ \text{GeV}^2$

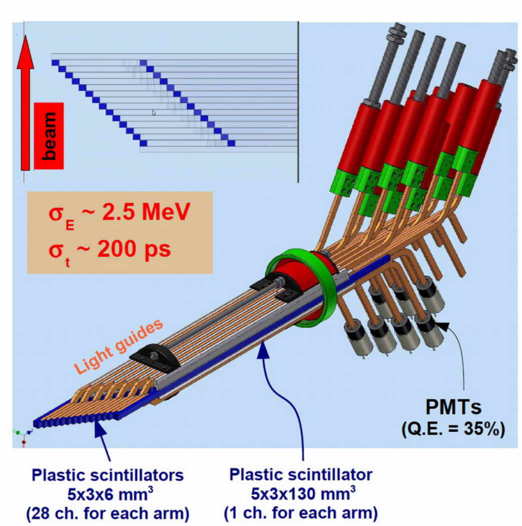


Physics motivation:

impact on the value and precision of the $a_\mu^{\text{LbyL};\pi^0}$

γ*γ* → π^0 HET analysis

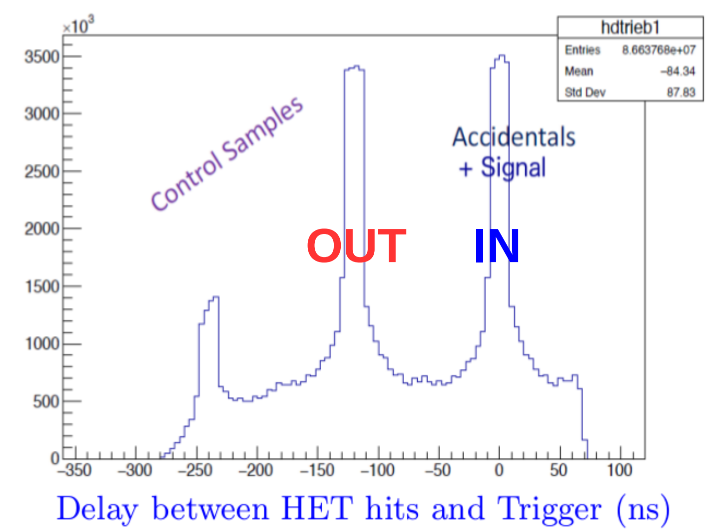




Analysis strategy
Hits in one HET station and at least one bunch in KLOE associated with only 2 clusters in the EMC

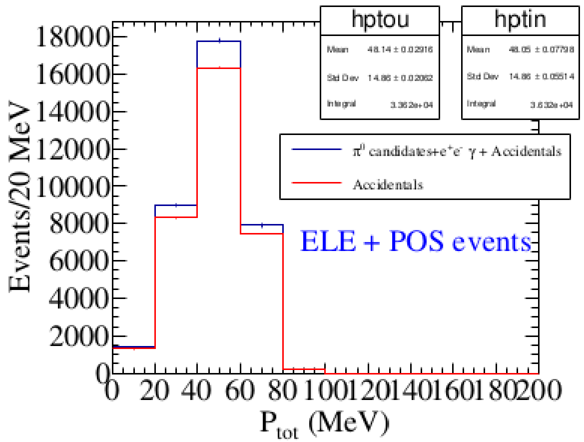
HET and KLOE data are acquired asynchronously. HET acquisition time 2.5 times larger than KLOE → out-coincidence (HET only) sample + in-coincidence sample → background subtraction

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

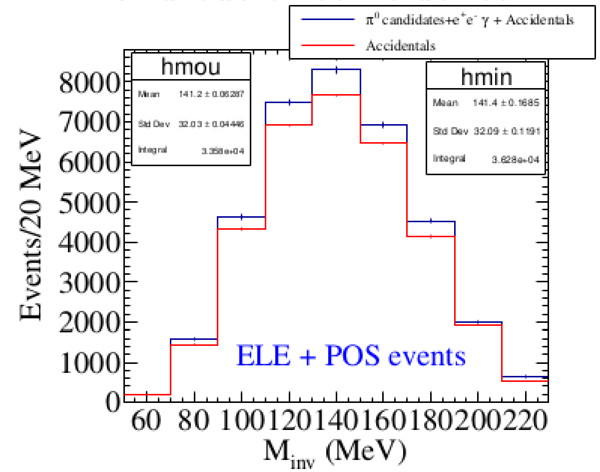


γ*γ* → π^0 HET analysis

Ptot distributions of coincidence and out-of-coincidence events

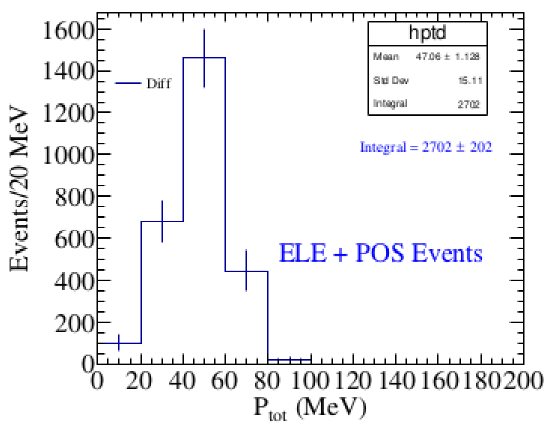


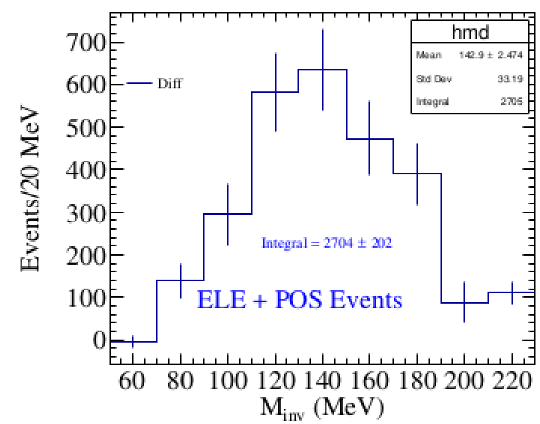
$M_{\gamma\gamma}$ distributions of coincidence and out-of-coincidence



OUT

IN





γ*γ*→π^0 signal is expected at low P_{tot} of the 2γ

From the TMVA studies we understand that radiative Bhabha's events are on top of the signal events

Identification of the background events work in progress

Measurement of the running of the $\alpha_{em}(s)$

$$\left|\frac{\alpha(\mathbf{s})}{\alpha(\mathbf{0})}\right|^{2} = \frac{\mathbf{d}\sigma_{\mathbf{data}}(\mathbf{e}^{+}\mathbf{e}^{-} \to \mu^{+}\mu^{-}\gamma(\gamma))/\mathbf{d}\sqrt{\mathbf{s}}}{\mathbf{d}\sigma^{\mathbf{0}}_{\mathbf{MC}}(\mathbf{e}^{+}\mathbf{e}^{-} \to \mu^{+}\mu^{-}\gamma(\gamma))/\mathbf{d}\sqrt{\mathbf{s}}}$$

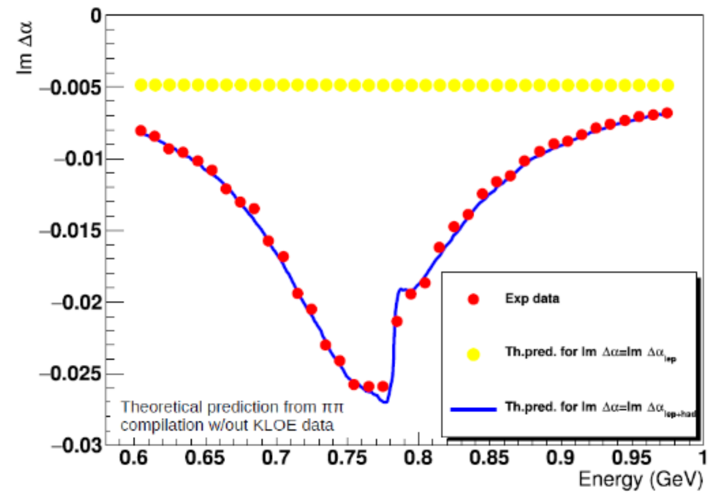
First time Im $\Delta\alpha$ and Re $\Delta\alpha$ extracted

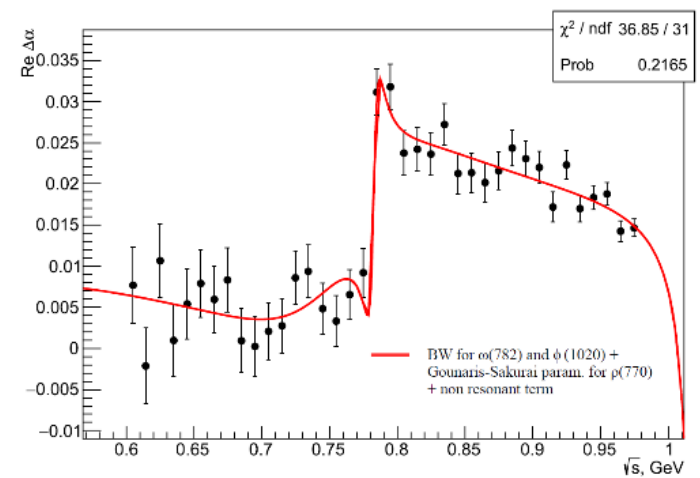
Method:
$\mu^+\mu^-\gamma$ data corrected for FSR (PHOKARA MC generator)
Normalization to MC with $\alpha = \alpha(0)$

$$\alpha(\mathbf{s}) = \frac{\alpha(\mathbf{0})}{\mathbf{1} - \boldsymbol{\Delta}\alpha}$$

$$\mathbf{Re}\ \boldsymbol{\Delta}\alpha = \sqrt{|\alpha(\mathbf{0})/\alpha(\mathbf{s})|^{2} - (\mathbf{Im}\ \boldsymbol{\Delta}\alpha)^{2}}$$

$$\mathbf{Im}\ \boldsymbol{\Delta}\alpha = -\frac{\alpha}{\mathbf{3}}\mathbf{R}(\mathbf{s})$$





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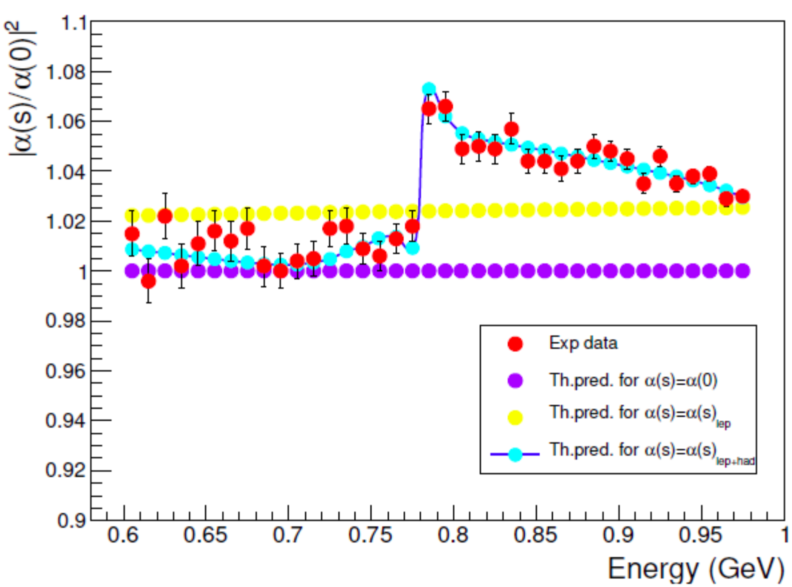
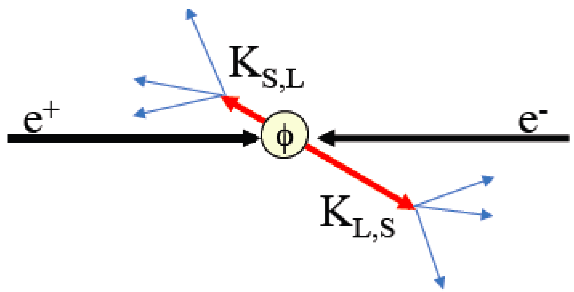


$$\mathbf{Br}(\omega \to \mu^{+}\mu^{-}) = (\mathbf{6.6} \pm \mathbf{1.4} \pm \mathbf{1.7}) \times \mathbf{10}^{-5}$$

(PDG: (9.0 ± 3.1) × 10^{-5})

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

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

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

- At KLOE-2, kaons are produced almost collinear in monochromatic pairs with longitudinal momenta of 100 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 in the KLOE-2 calorimeter)
  - Not available at fixed target experiments
- Studies of quantum mechanics and fundamental symmetries from interference pattern and entanglement

K_S charge asymmetry

[JHEP 1809 (2018) 021]

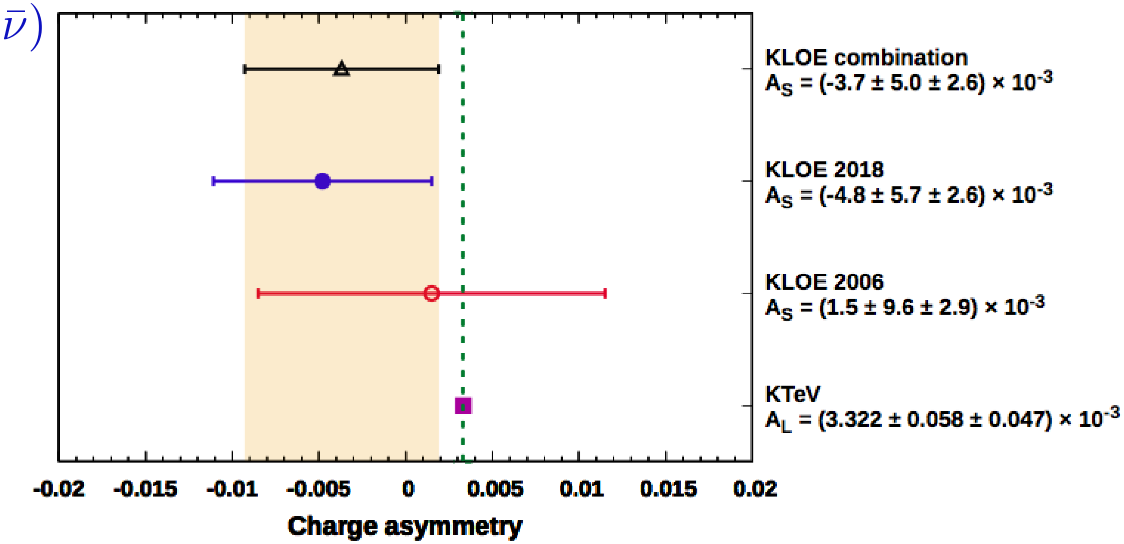
$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

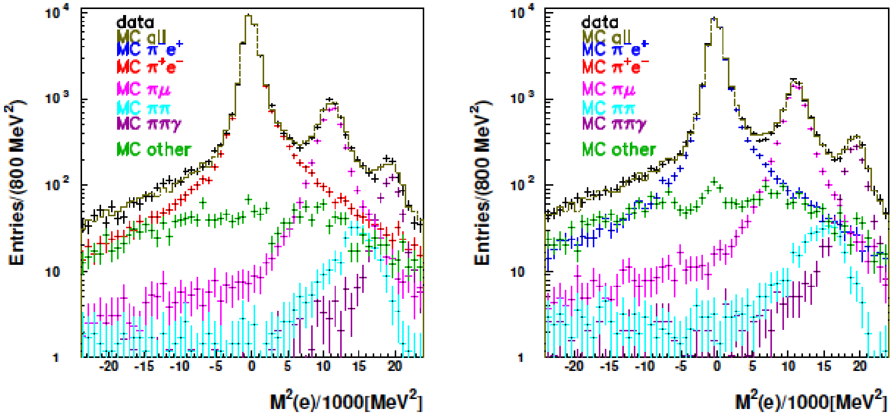
$A_{S,L} \neq 0$ => CP violation

$A_S \neq A_L$ => CPT violation

One of the cleanest and most precise test of CPT symmetry

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





See D. Kisielewska poster*

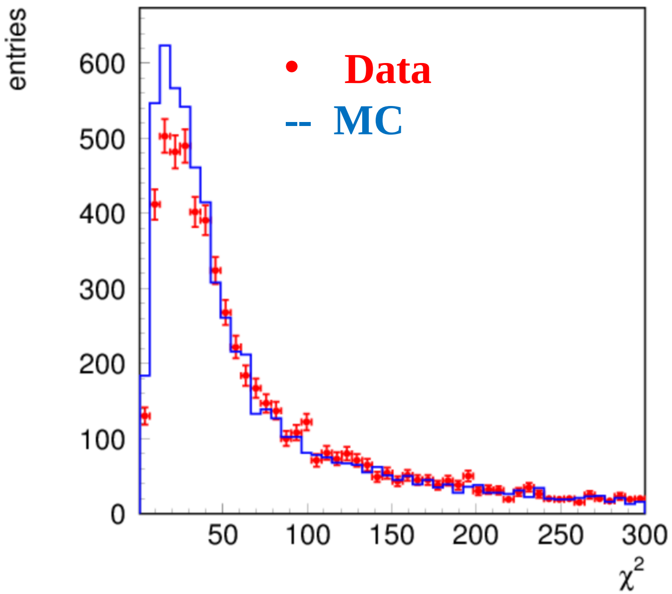
$$A_S = (-4.8 \pm 5.7 \pm 2.6) \times 10^{-3}$$

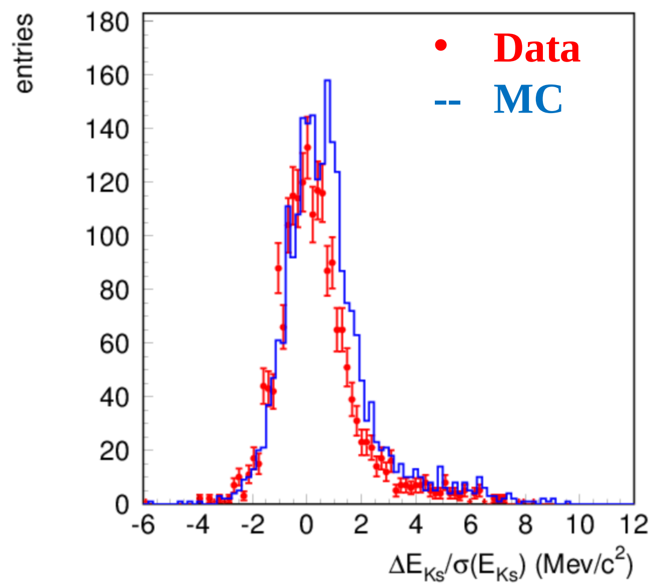
$K_S \to 3\pi^0$

- **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 $\phi \to K_S K_L \to 3\pi^0\, \pi\nu e,\ \pi\pi\ \pi\nu e$

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

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

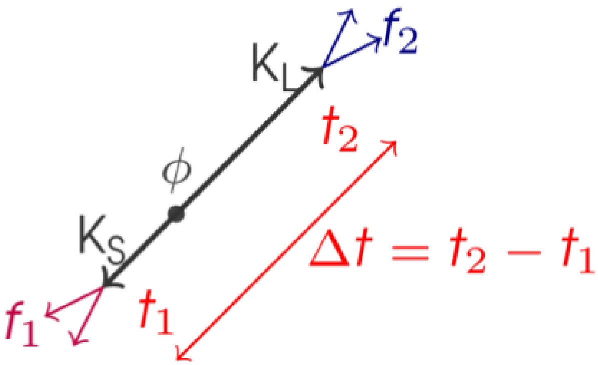
- J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, *Direct test of time-reversal symmetry in the entangled neutral kaon system at a Φ factory*, Nucl. Phys. B 868 (2013) 102
- J. Bernabeu, A. Di Domenico and P. Villanueva-Perez, *Probing CPT in transitions with entangled neutral kaons*, JHEP 1510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

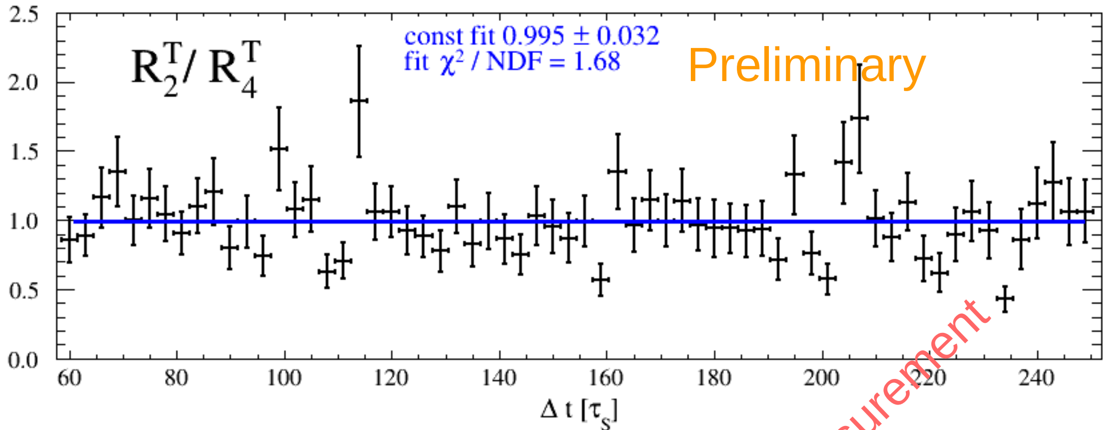
$$R_2^{CP}(\Delta t) = \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}$$

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

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

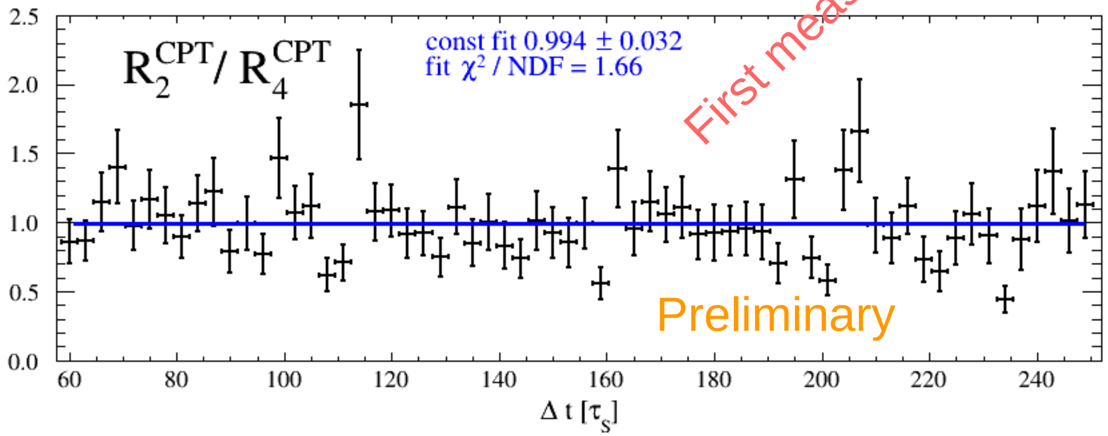
T asymmetric R_2^T / R_4^T

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



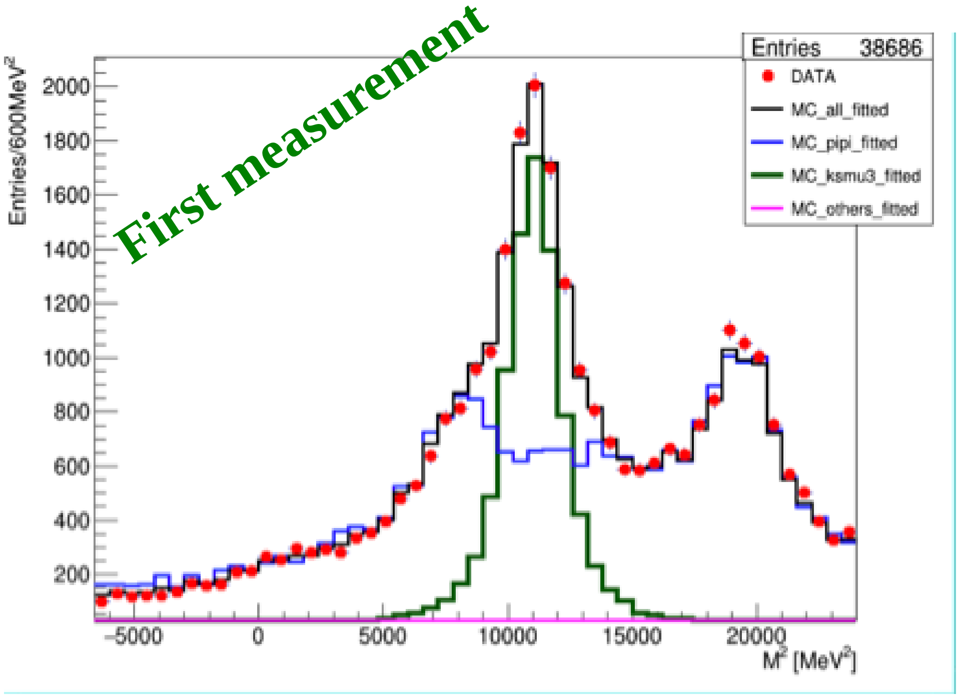
CPT asymmetric
R_2^{CPT} / R_4^{CPT}

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



$K_S \rightarrow \pi\mu\nu$

- **First measurement** of Ks →πμν Branching Ratio
  - 7223 events from 1.6 fb^{-1}
  - Expected value Br(KSμ3) = $(4.69 \pm 0.05)\times10^{-4}$ [from KLOE + KTeV + e/mu universality]
- Lepton universality test
- Uncertainties preliminary measurement
  - 2.5 % stat ± 3.1 % sys
- Analysis is almost finished
  - final checks on some systematic uncertainties ongoing



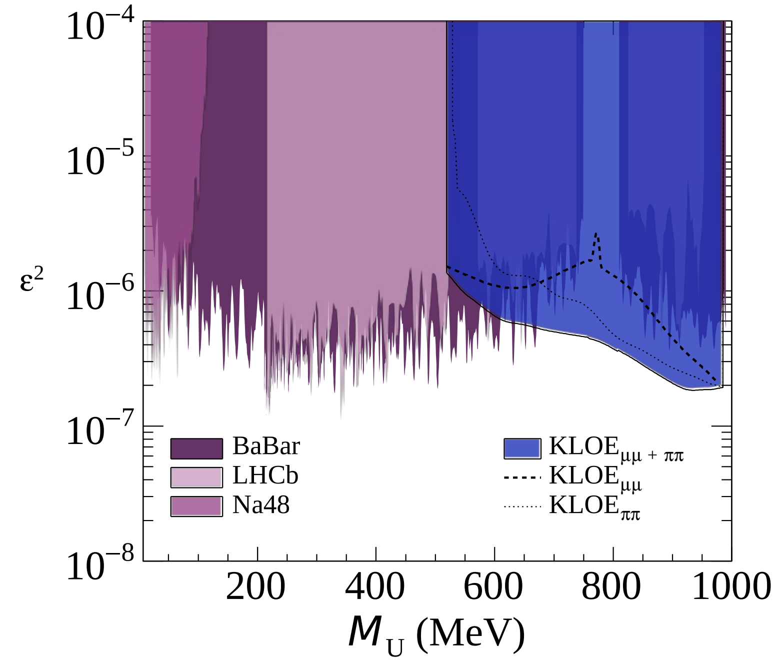
M^2_μ [MeV²]

[1] KTeV Collaboration, T. Alexopoulos, et al., Phys. Rev. D 70 (2004) 092007.

Dark Matter: U boson combined limit

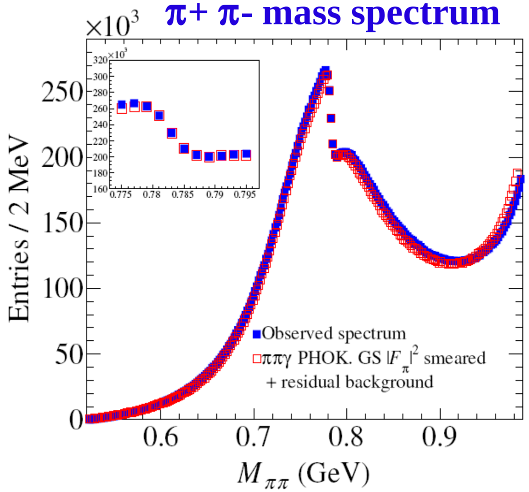
- New $\mu\mu\gamma$ limit at full KLOE statistics
- $\pi\pi\gamma$ limit at the same luminosity (1.93 fb^{-1})
- Combining procedure requires:
  - Double inputs of data, expected background, U signal and systematical errors
  - Info on different efficiency and U decay branching fractions: BR(U → $\mu\mu$, $\pi\pi$)
- 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

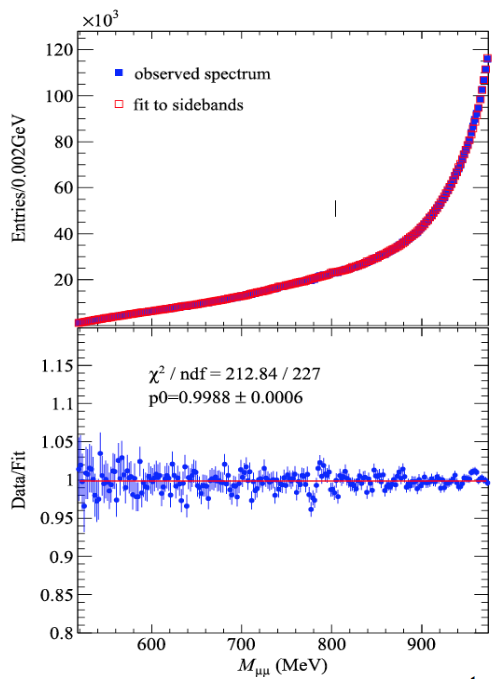
Best limit in the 600 MeV – 1000 MeV mass region



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

π+ π- mass spectrum





B-boson searches

- B boson couples mainly to quarks

[Tulin, PRD89(2014)114008]

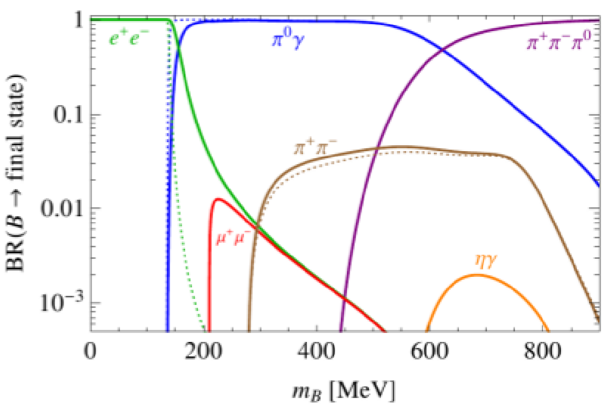
- Most basic model → coupling to baryon number

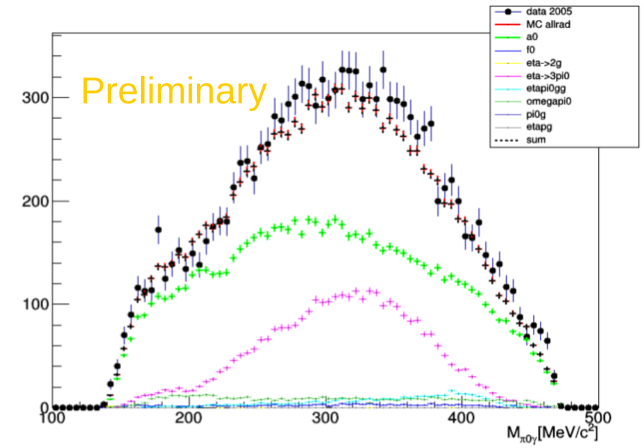
$$\mathscr{L} = \frac{g_B}{3}\,\bar{q}\gamma^{\mu} q B_{\mu}$$

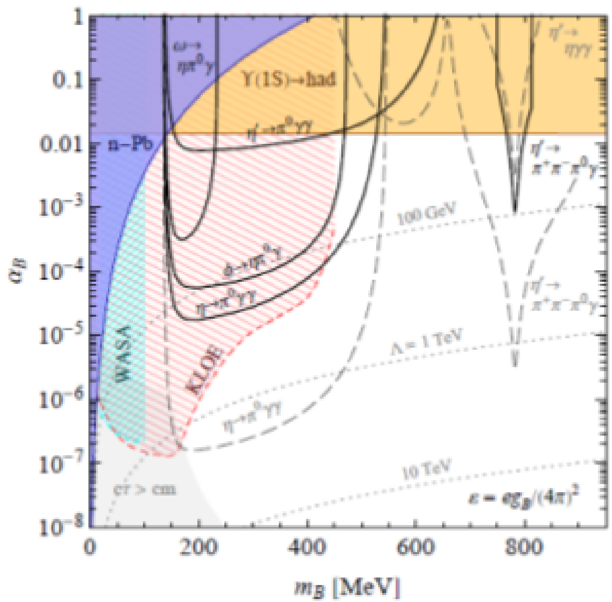
$$g_B \lesssim 10^{-2} \times (m_B/100\ \text{MeV})$$

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

- 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

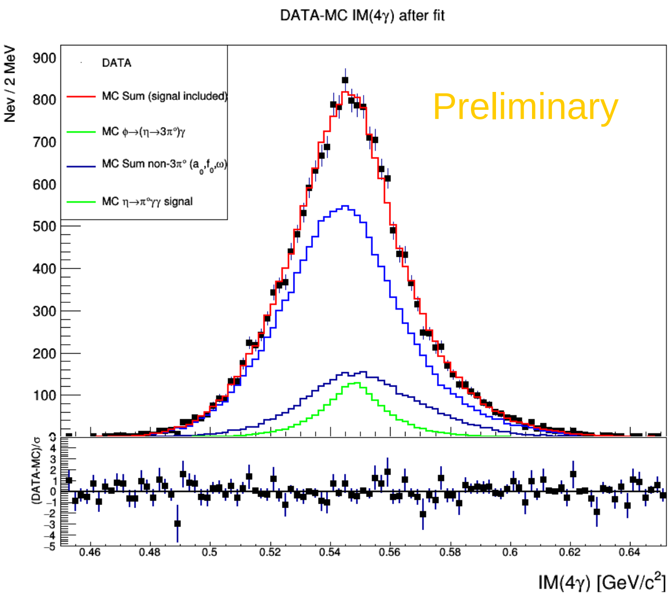
$\eta \rightarrow \pi^0 \gamma\gamma$ χ-PT golden mode

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

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

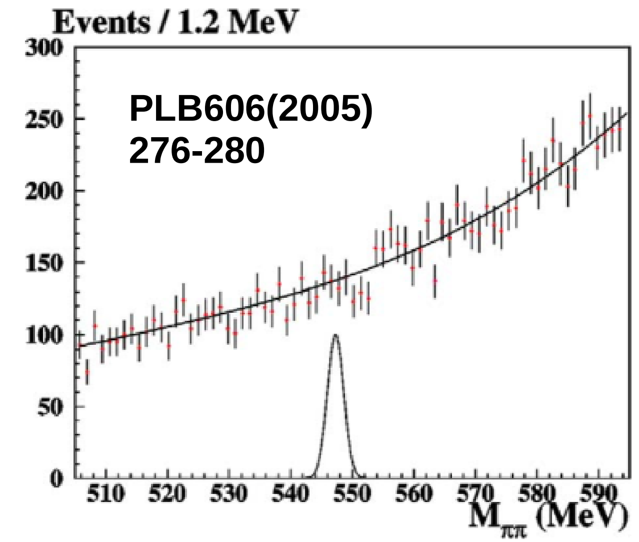
Br = $(22.1 \pm 2.4 \pm 4.7)\times10^{-5}$ CB@AGS(2008)
Br = $(25.2\pm2.5)\times10^{-5}$ CB@MAMI (2014)

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



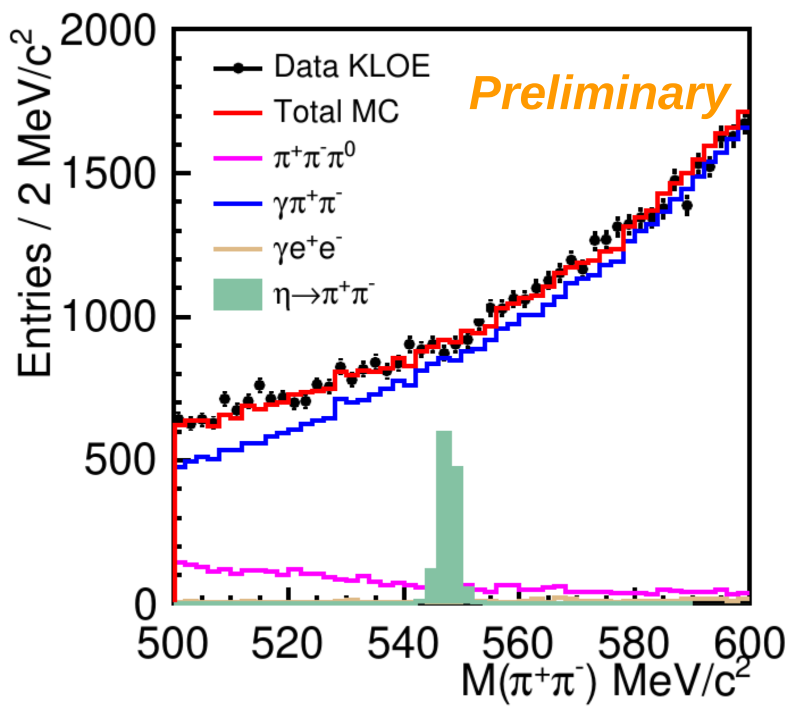
- 1.7 fb^{-1} KLOE data used
- Main bckg is $\phi \rightarrow \eta\gamma$, with $\eta \rightarrow 3\pi^0$ with lost or merged photons
- New TMVA-BDT based rejection which allows to remove 50% of the background generating from $\eta \rightarrow 3\pi^0$

$\eta \rightarrow \pi^+\pi^-$ (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 → 10^{-27}
  - introducing a CP violating term in QCD → to 10^{-17}
  - allowing CP violation in the extended Higgs sector → 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 $L_{int} \sim 350\ pb^{-1}$
- A recent limit $BR(\eta \rightarrow \pi + \pi -) < 1.6\times10^{-5}$ @ 90% C.L. from the LHCb with Lint~3.3 fb^{-1}



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

$Br(\eta \rightarrow \pi + \pi -) < 5.8\times10^{-6}$ @ 90% C.L.

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

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