New Physics @ KLOE/KLOE-2

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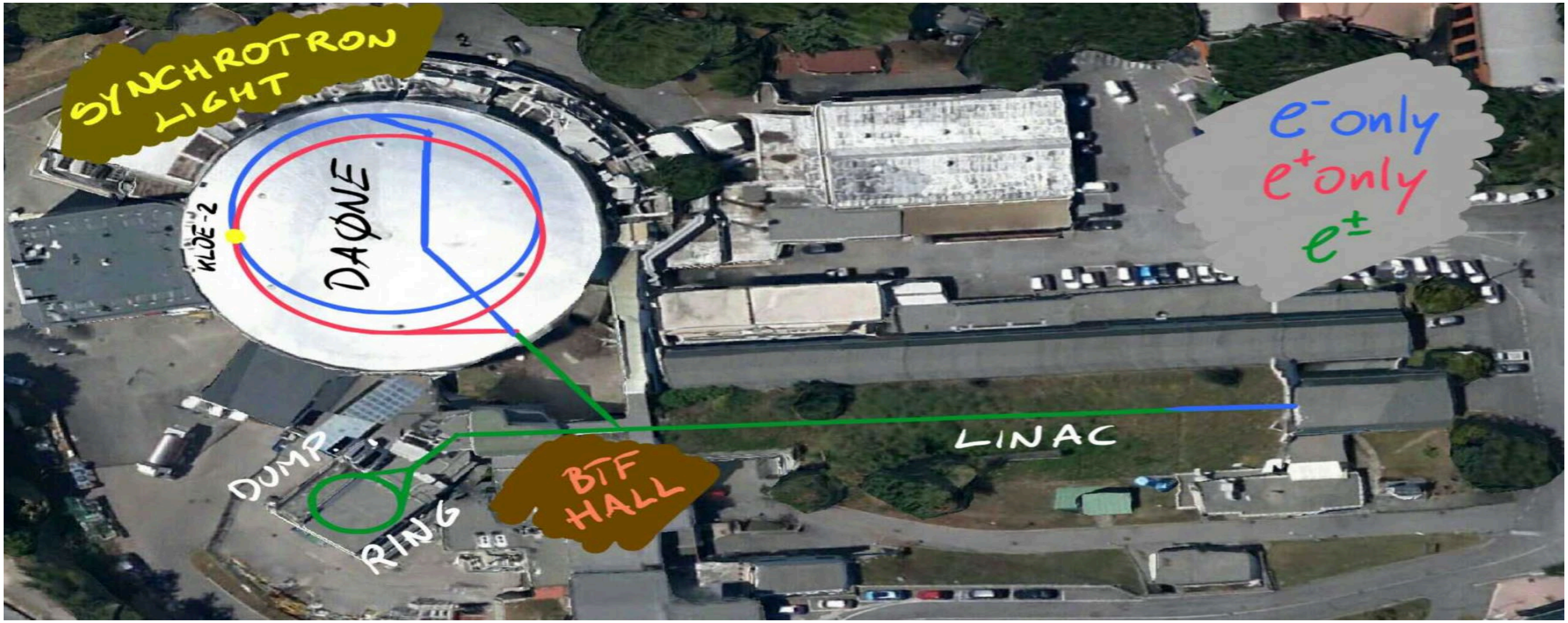
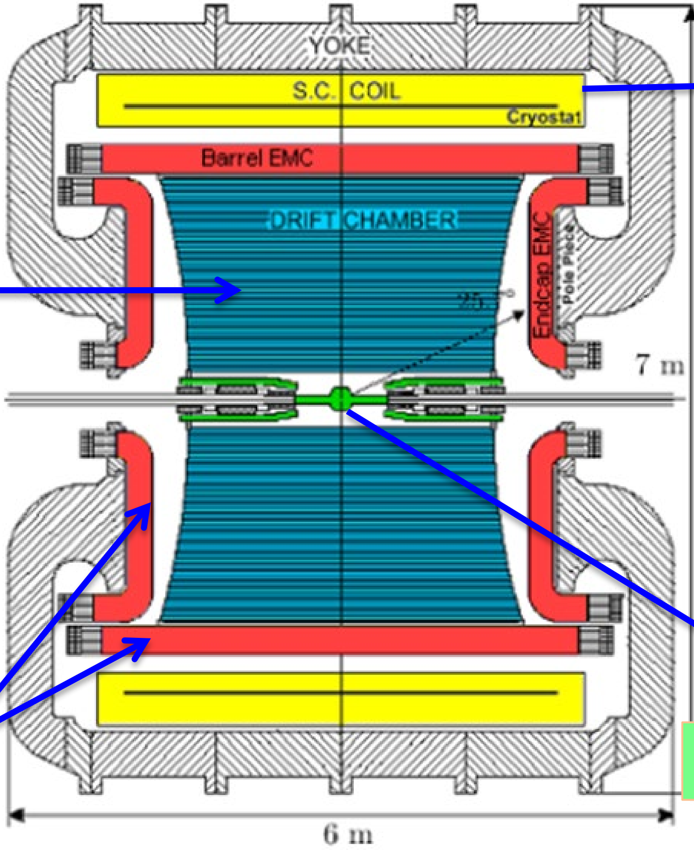
DAΦNE: ϕ-factory



- Double rings e^+e^- collider @ $\sqrt{s}=M_\phi=1019.4$ MeV
- 105 bunches in each ring with a time interval of 2.7 ns
- 2 interaction regions
- Updated DAΦNE (2008) → increased the peak luminosity
  - Crab-Waist interaction scheme
  - Large beam crossing angle ~ 2 × 12.5 mrad

The KLOng Experiment



Drift Chamber:

- 12582 sense cells
- Stereo geometry
- 4 m diameter, 3.3 m long
- Low-mass gas mixture: 90% Helium-10% isobutane
- $\delta p_T/p_T < 0.4\% \ (\theta>45^0)$
- $\sigma_{xy} \approx 150$ mm, $\sigma_z \approx 2$ mm

Calorimeter:

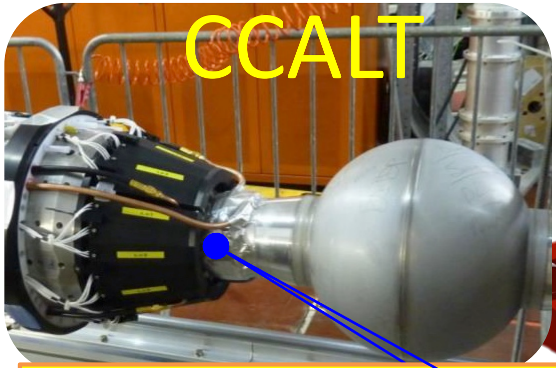
- 98% coverage of full solid angle
- $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$
- $\sigma_t = 55\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 140\ \mathrm{ps}$
- Barrel + 2 end-caps

SC Magnet:

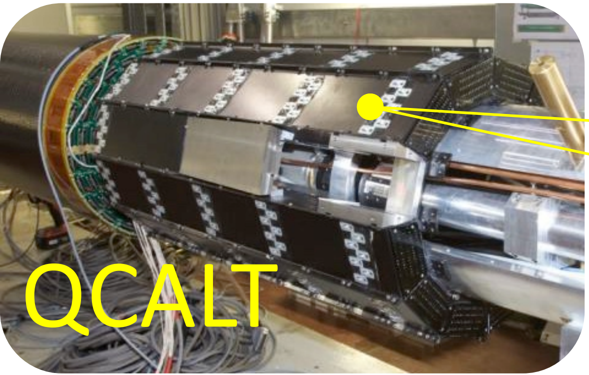
B = 0.52 T

Interaction point (IP)

KLOE-2

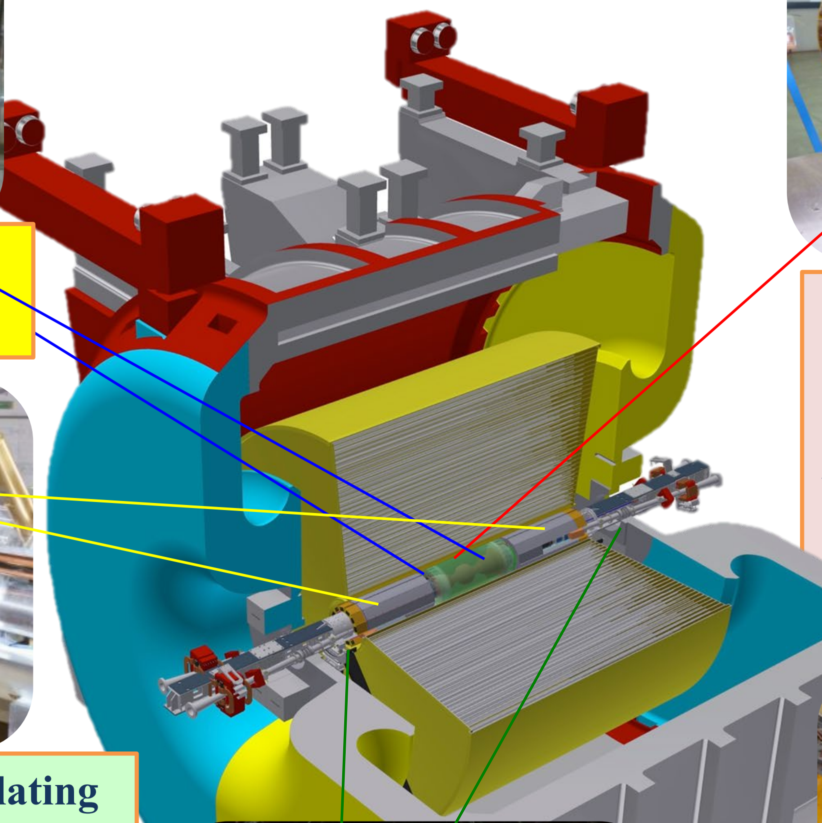


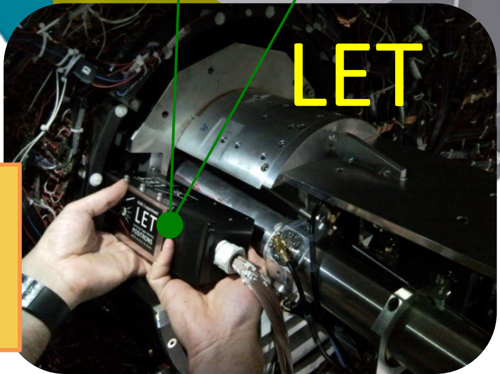
CCALT – LYSO Crystal w SiPM - Low polar angle γ

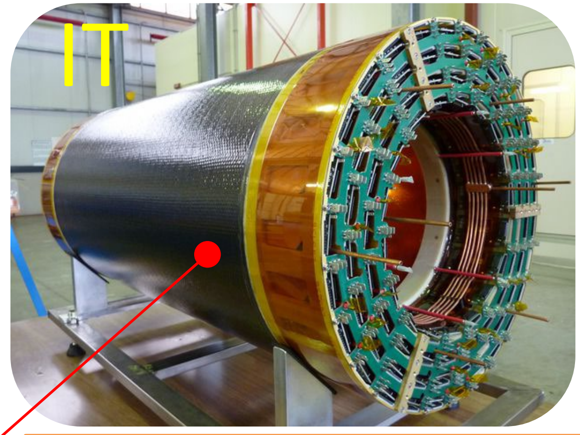


QCALT – Tungsten / Scintillating Tiles w SiPM - K_L decays
Quadrupole Instrumentation

LET: 2 calorimeters LYSO + SiPMs @ ~ 1 m from IP
e^+e^- taggers for γγ physics (HET)







Inner Tracker – 4 layers of Cylindrical GEM detectors
To improve the track and vertex reconstruction
First time CGEM in high energy experiment

HET: Scintillator hodoscope +PMTs pitch:5 mm;

KLOE/KLOE-2 data sample

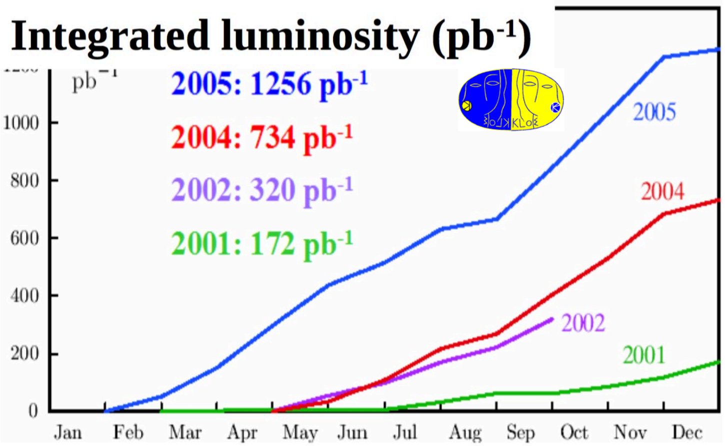
- KLOE has collected ~ 2.5 fb^{-1} @ ϕ peak and 250 pb^{-1} off-peak
  - Best performance: $L_{peak}=1.4\times10^{32}cm^{-1}s^{-1}$
- KLOE-2 data-taking campaign completed on 30th March 2018, collected ≈ 5.5 fb^{-1} @ ϕ peak
  - Best performance: $L_{peak}=2\times10^{32}cm^{-1}s^{-1}$

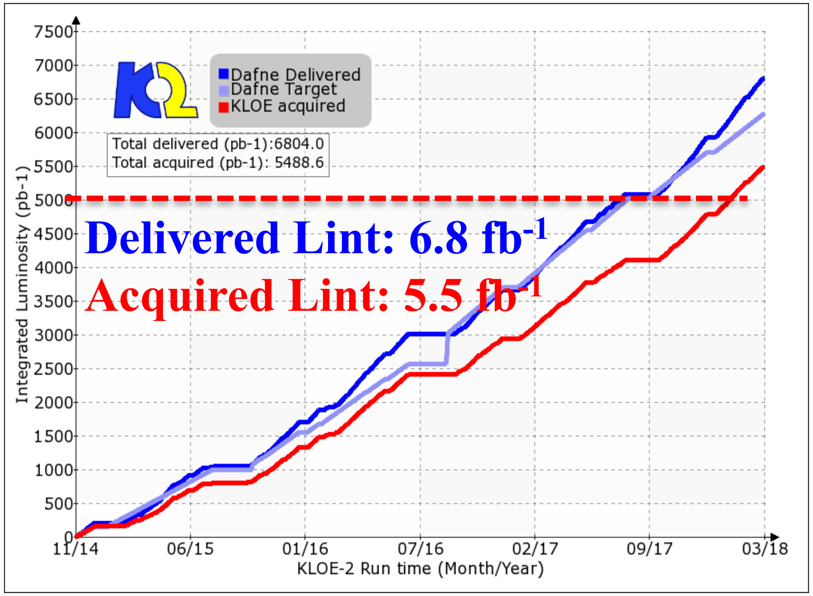
KLOE+KLOE-2 data sample:

~8 fb^{-1}, the largest sample collected at ϕ

~2.4×10^{10} ϕ mesons

Unique data sample for typology and statistical relevance



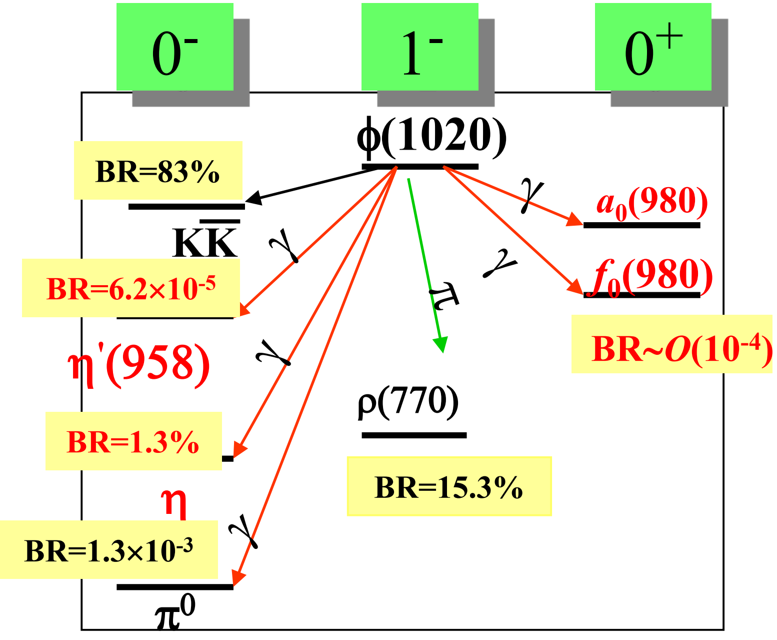


Delivered Lint: 6.8 fb^{-1}

Acquired Lint: 5.5 fb^{-1}

Physics @ KLOE-2

- **Kaon physics: 8.2×10^9 Ks and K_L events**
  - CKM unitarity test, CPT and QM tests with kaon interferometry, Direct tests of T and CPT using entanglement, Ks rare decays…
- **Scalar and pseudoscalar mesons**
  - 3.1×10^8 η events
  - 1.48×10^8 η' events
  - 4.0×10^6 ω events
  - **Light meson transition form factors**
- **γγ physics $e^+e^-\to e^+e^-\gamma^*\gamma^*\to e^+e^-X$**
  - $X=\pi\pi \Rightarrow$ study of $f_0(500)$
  - $X=\pi^0/\eta \Rightarrow \Gamma(\pi^0\to\gamma\gamma)$, space-like TFF



8 fb^{-1} → 2.4×10^{10} φ mesons

- **Hadronic X-section via ISR $[e^+e^-\to\gamma(2\pi, 3\pi, 4\pi)]$: hadronic corrections to $(g-2)_\mu$**
- **Dark force searches:**
  - $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$ – Higgsstrahlung: $e^+e^-\to Uh'\to\mu^+\mu^-$ + miss. Energy
  - Leptophobic B boson search: $\phi\to\eta B$ $(B\to\pi^0\gamma)$, $\eta\to B\gamma$ $(B\to\pi^0\gamma)$

Eur. Phys. J. C 68 (2010) 619

Workshop on e^+e^- physics @ 1GeV https://agenda.infn.it/conferenceDisplay.py?confId=11722

CKM unitarity

The most precise test of CKM unitarity by $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=1+\Delta_{CKM}$ $(\sim 10^{-4})$

$|V_{ud}|$ from super allowed nuclear β decay, $|V_{ub}|$ from semileptonic B decays $(\sim 10^{-5})$,

$|V_{us}|$ from $K\rightarrow\pi l\nu$ contributes ~50% of the uncertainties

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{Kl}(\{\lambda\}_{Kl}) (1 + 2\Delta_K^{SU(2)} + 2\Delta_{Kl}^{EM})$$

with $K\in\{K^+, K^0\}$; $l\in\{e,\mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

Inputs from theory:

S_{EW}	Universal short distance EW correction (1.0232)
$f_+^{K^0\pi^-}(0)$	Hadronic matrix element at zero momentum transfer (t=0)
$\Delta_K^{SU(2)}$	Form factor correction for strong SU(2) breaking
Δ_{Kl}^{EM}	Long distance EM effects

Inputs from experiment:

$\Gamma(K_{l3(\gamma)})$	**Branching ratios** with well determined treatment of radiative decays; **lifetimes**
$I_{Kl}(\lambda)$	Phase space integral: λs parameterize form factor dependence on t : ***K_{e3} : only λ_+ (or λ_+' λ_+'')*** ***$K_{\mu 3}$: need λ_+ and λ_0***

Vus from neutral kaons

BR(K_{e3}) = 0.4008(15) BR($K_{\mu3}$) = 0.2699(14)	Based on 13x10^6 K_L decays tagged by $K_S\rightarrow\pi^+\pi^-$	PLB 632 (2006)
τ_L= 50.92(30) ns	Fit the time dependence over 0.4τ_L of 8.5$\times$10^6 $K_L\rightarrow\pi^0\pi^0\pi^0$ decays tagged by $K_S \rightarrow \pi^+\pi^-$	PLB 626 (2005)
λ_+' = (25.5 ± 1.8)$\times$10^{-3} λ_+'' = (1.4 ± 0.8)$\times$10^{-3}	Based on 2x10^6 K_Le3 decays tagged by $K_s\rightarrow\pi^+\pi^-$	PLB 636 (2006)
BR($K_S \rightarrow \pi e \nu$)= 7.046(91) $\times$10^{-4}	From tagged K_S beam 1.2$\times$10^8 events (20% of full data sample)	PLB 636 (2006)
λ_+' = (25.6 ± 1.5$_{stat}$ ± 0.9$_{syst}$)$\times$10^{-3} λ_+''= (1.5 ± 0.7$_{stat}$ ± 0.4$_{syst}$)$\times$10^{-3} λ_0 = (15.4 ± 1.8$_{stat}$ ± 1.3$_{syst}$)$\times$10^{-3}	Based on 1.8x10^6 $K_L\mu$3 decays tagged by $K_s\rightarrow\pi^+\pi^-$ and from combined fit with K_Le3 data	JHEP 12 (2007)

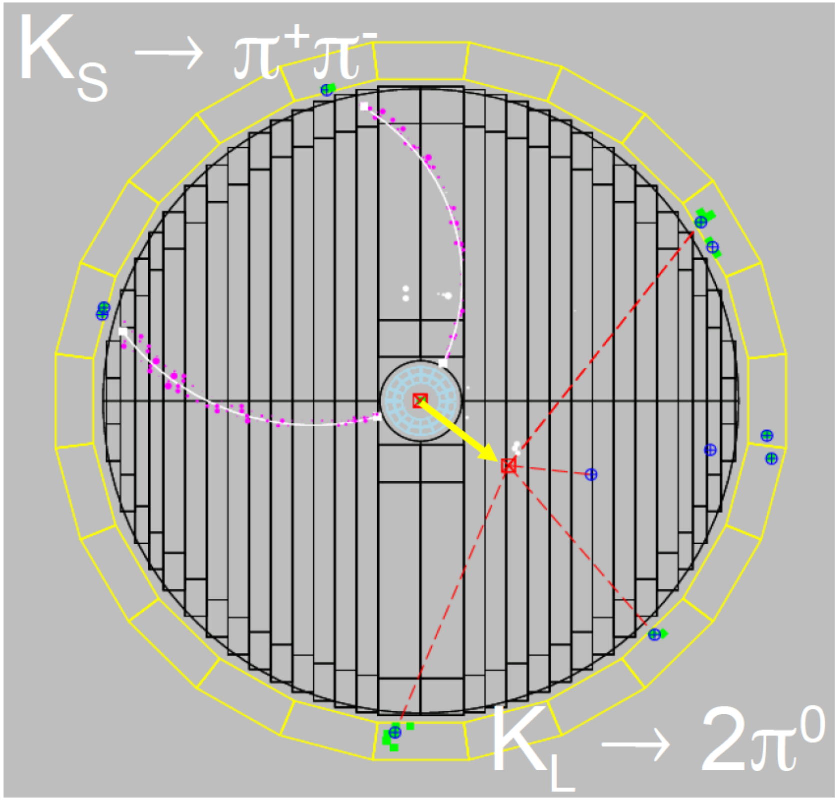
KLOE has measured all relevant inputs for charged and neutral kaons: BR's, lifetimes (K_L,K±) , form factors (FFs) → will be updated with all KLOE/KLOE-2 data

$f_+(0)|V_{us}|$

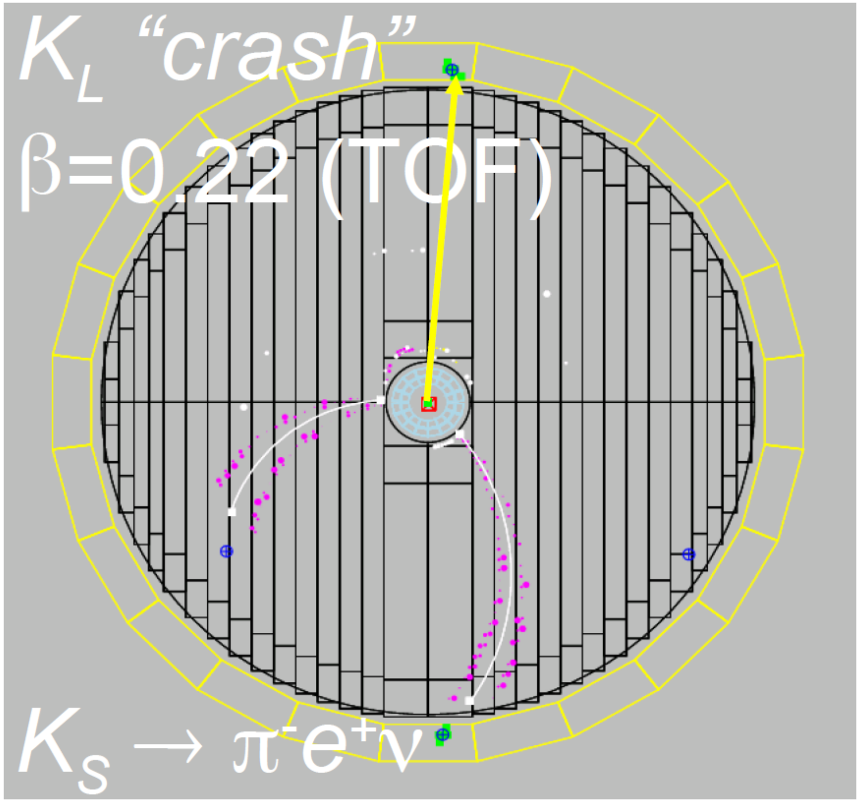
- $V_{us}f_+(0)$ from KLOE ~ 0.28% (JHEP 0804 (2008) 059)
- world average ~ 0.19%
- Expected at KLOE-2 with 5fb-1 ~ 0.14% with world average

		World average					KLOE-2 prospects with 5 fb^{-1}				
	$f_+(0)\|V_{us}\|$	**%err**	**BR**	**τ**	**δ**	**I_{Kl}**	**%err**	**BR**	**τ**	**δ**	**I_{Kl}**
K_Le3	0.2163(6)	0.26	0.09	0.20	0.11	0.05	**0.20**	0.09	0.13	0.11	0.06
$K_L\mu3$	0.2166(6)	0.28	0.15	0.18	0.11	0.06	**0.24**	0.15	0.13	0.11	0.08
K_Se3	0.2155(13)	0.61	0.60	0.02	0.11	0.05	**0.32**	0.30	0.03	0.11	0.06
$K^\pm e3$	0.2172(8)	0.36	0.27	0.06	0.23	0.05	**0.48**	0.25	0.05	0.40	0.06
$K^\pm\mu3$	0.2170(11)	0.51	0.45	0.06	0.23	0.06	**0.48**	0.27	0.05	0.39	0.08
Aver	0.2165(4)	0.19					**0.14**				

Neutral kaons beams



K_L tagged by Ks→π+π- vertex at IP



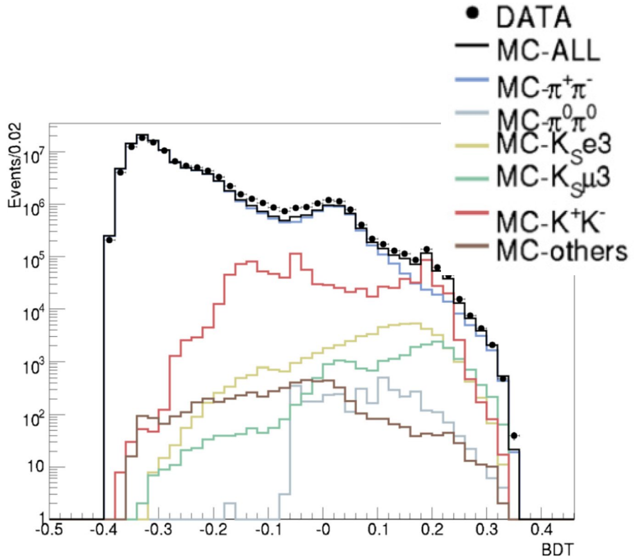
Ks tagged by K_L interaction in EmC

Measurement of the BR Ks→πμν

PLB 804 (2020) 135378

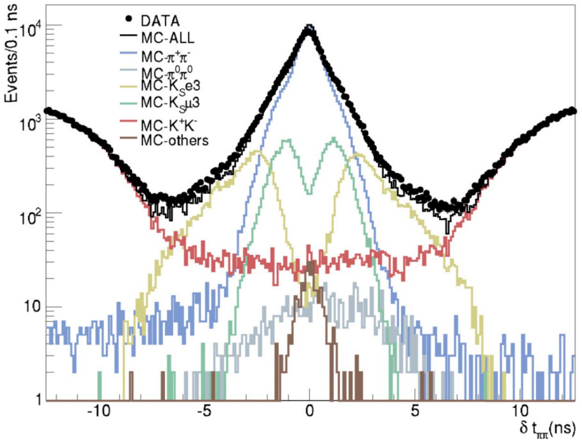
Motivation:

- BR($K_S \rightarrow \pi\mu\nu$) was never measured before
- Independent determination of |*Vus*|
- Test of the lepton-flavour universality



Analysis:

- Performed with the complete KLOE dataset (1.7fb-1)
- Presence of Ks tagged by interaction of K_L in EMC
- Event selection based on:
  - time-of-flight analysis
  - BDT using kinematic variables
- $K_S \rightarrow \pi^+\pi^-$ used as a normalization sample

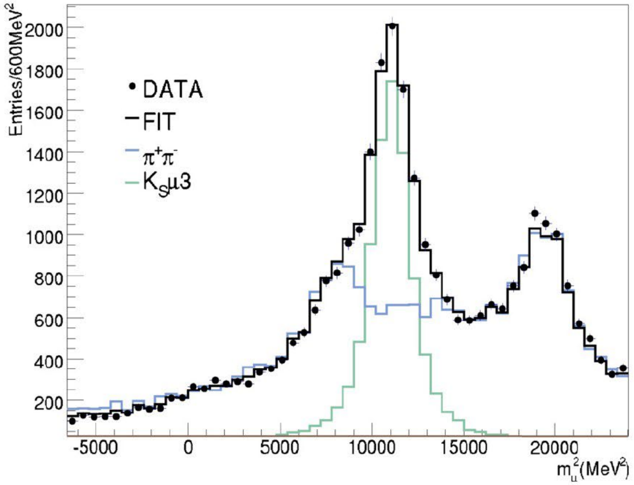


Measurement of the BR Ks→πμν

PLB 804 (2020) 135378

- Ks→πμν events counted using a fit to the spectrum of reconstructed muon mass squared
- 7223±180 signal events found

$$m_\mu^2 = \left(E_{K_S} - E_\pi - p_{\text{miss}}\right)^2 - p_\mu^2$$



First ever measurement:

$$Br(Ks \to \pi\mu\nu) = \left(4.56 \pm 0.11_{stat} \pm 0.17_{syst}\right) \times 10^{-4}$$

$$|f_+(0)V_{us}|_{Ks\to\pi\mu\nu} = 0.2126 \pm 0.0046$$

- Assuming universality of the kaon–lepton coupling

$$\mathcal{B}(K_S \to \pi\mu\nu)_{\text{PDG}} = \mathcal{B}(K_S \to \pi e\nu) \times R(I_K^\ell) \times \frac{(1+\delta_{\text{EM}}^{K\mu})^2}{(1+\delta_{\text{EM}}^{Ke})^2} = (4.69 \pm 0.06) \times 10^{-4}$$

kaon–lepton coupling universality test $r_{\mu e} = \dfrac{|f_+(0)V_{us}|^2_{K_S\to\pi\mu\nu}}{|f_+(0)V_{us}|^2_{K_S\to\pi e\nu}} = 0.975 \pm 0.044$

Consistent with other Kaon results

Ks semileptonic charge asymmetries

JHEP09(2018)021

The charge asymmetries of K_S and K_L:

T CPT violation in K^0-K^0bar mixing

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} = 2[\mathrm{Re}(\varepsilon_K) \pm \mathrm{Re}(\delta_K) - \mathrm{Re}(y) \pm \mathrm{Re}(x_-)]$$

CPT violation in ΔS=ΔQ ΔS≠ΔQ amplitudes

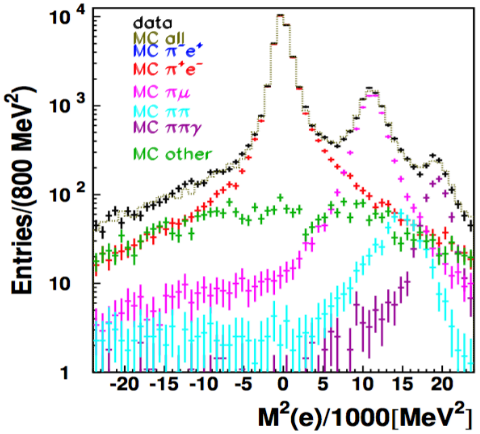
- $A_{S,L} \neq 0$ implies CP violation
- Assuming CPT invariance: $A_S = A_L = 2\mathrm{Re}(\varepsilon)$ expected to be around 3×10^{-3}, accounting for the CP impurity in the mixing in the physical state
- Any difference between A_S and A_L is of particular importance as a test of the CPT symmetry
- **$A_L = (3.322 \pm 0.058 \pm 0.047) \times 10^{-3}$ KTeV PRL 88 (2002) 181601**
- **$A_S = (1.5 \pm 9.6 \pm 2.9) \times 10^{-3}$ KLOE PLB 636 (2006) 173 (Lint = 410 pb^{-1})**

Ks semileptonic charge asymmetries

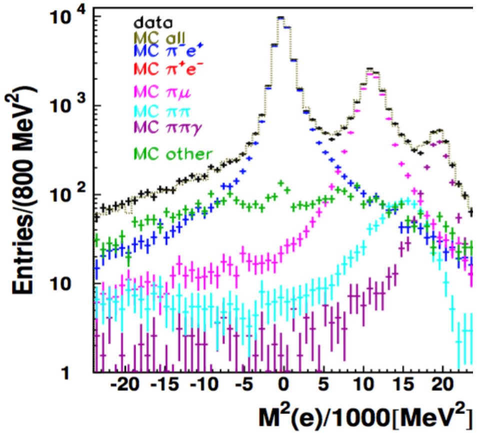
JHEP09(2018)021

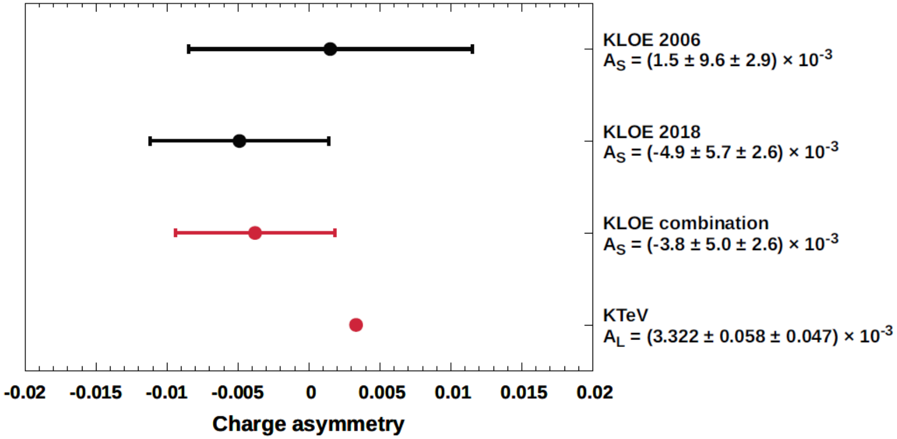
- The new KLOE A_S analysis has been finalized with 1.7 fb^{-1} data sample

$K_S \rightarrow \pi^+ e^- \bar{\nu}$



$K_S \rightarrow \pi^- e^+ \nu$





- Combined with the previous KLOE analysis: $A_S = (-3.7 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}.$

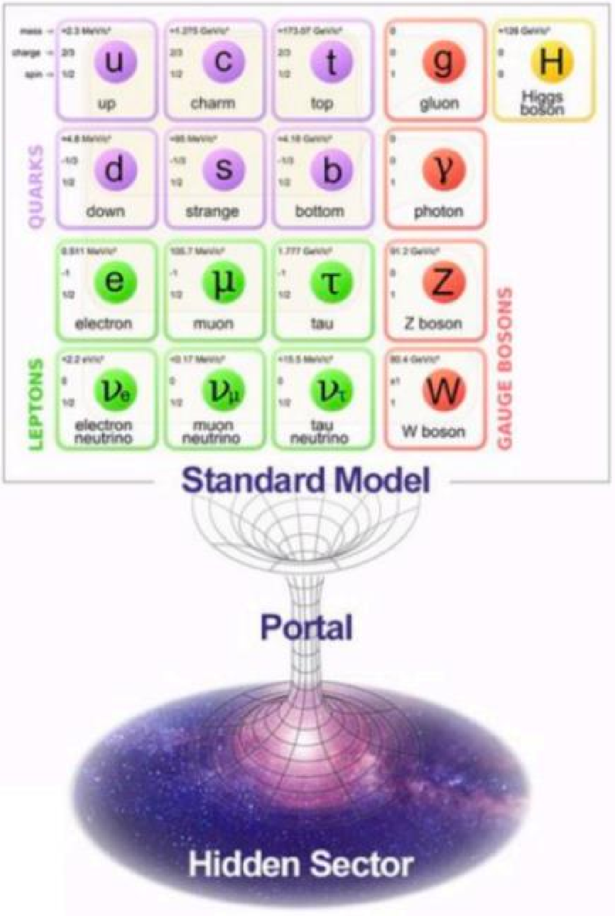
Using the A_L, $Re(\delta_K)$ and $Re(\varepsilon_K)$ from other experiments as input, the CPT-violating parameter are extracted as:

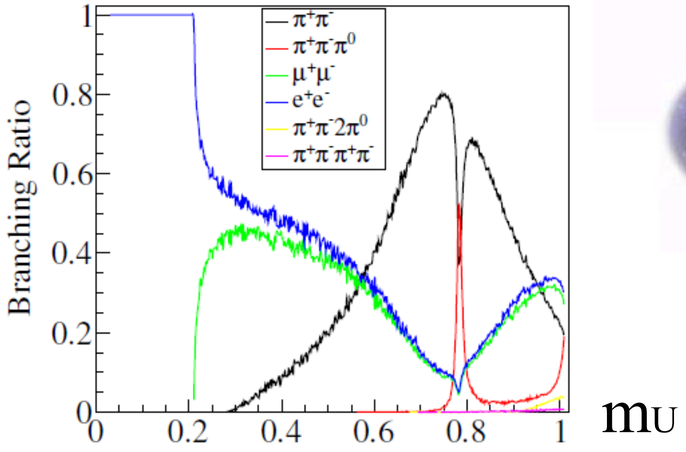
$$Re(x_-) = (-2.0 \pm 1.4) \times 10^{-3},$$
$$Re(y) = (1.7 \pm 1.4) \times 10^{-3}.$$

With 5 fb^{-1} data at KLOE-2 accuracy is expected to be improve significantly

Dark force searches

- A new light vector gauge boson U is introduced as a intermediary between the DM and the SM particles, which could interact with the photon via a kinetic mixing term $\varepsilon^2 = \alpha'/\alpha$
- ε values in the $10^{-12} - 10^{-3}$ range have been predicted in the literature
- Experimental searches for Dark Forces can be achieved at:
  - e+e- colliders
    - Rare meson decays, ISR
  - Beam dump and fixed target experiments





Dark forces at KLOE

- Decay of the ϕ meson into a U boson + pseudoscalar η
  - $\phi \rightarrow U\eta, U \rightarrow e^+e^-, \eta \rightarrow \pi\pi\pi$ Phys. Lett. B706 (2012) 251
    Phys. Lett. B720 (2013) 111
- Associated Uγ production:
  - $e^+e^- \rightarrow U\gamma\ with\ U \rightarrow \mu^+\mu^-$ Phys. Lett. B736 (2014) 459
  - $e^+e^- \rightarrow U\gamma\ with\ U \rightarrow e^+e^-$ Phys. Lett. B750 (2015) 633
  - $e^+e^- \rightarrow U\gamma\ with\ U \rightarrow \pi^+\pi^-$ Phys. Lett. B757 (2016) 356
  - Combined analysis $\mu^+\mu^-$ and $\pi^+\pi^-$ Phys. Lett. B 784 (2018) 336
- Higgsstrahlung process, in the m(*h'*)<m(U) scenario, with an invisible Higgs:
  - $e^+e^- \rightarrow Uh', with\ h' \rightarrow invisible\ and\ U \rightarrow \mu^+\mu^-$ Phys. Lett. B 747 (2015) 365
- Leptophobic B boson search (ongoing)

U boson in $\phi \to \eta e^+ e^-$

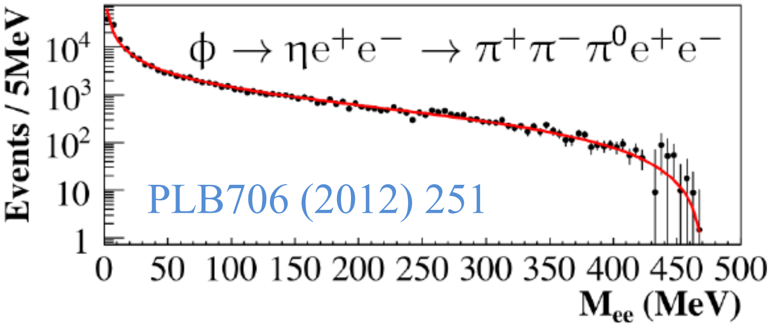
PLB720 (2013) 111
PLB706 (2012) 251

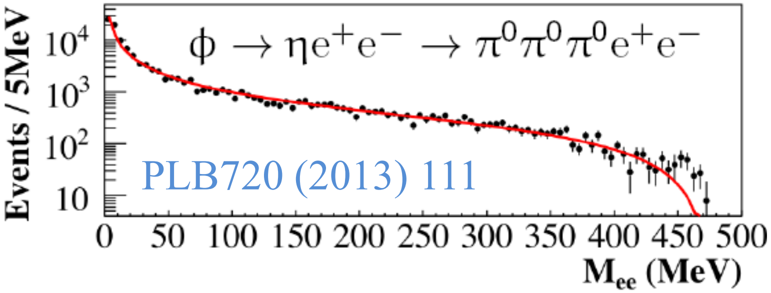
- Mesons undergoing radiative decays to photons could also decay to a U boson with branching fraction $Br(X \to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times Br(X \to Y\gamma)$

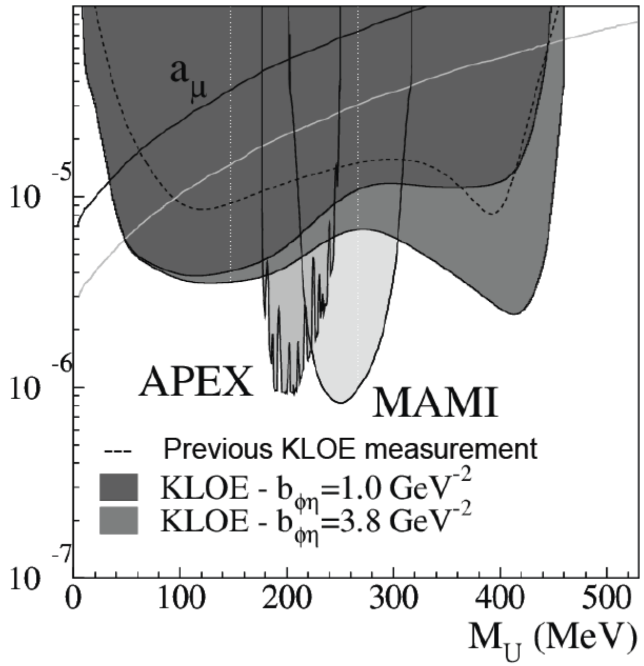
$$\sigma(\phi \to \eta e^+ e^-) = 0.7\ nb$$

$$\sigma(\phi \to \eta U) \approx 40\ fb \text{ for } FF_{\phi\eta} \approx 1 \text{ and } \varepsilon \approx 10^{-3}$$

FF is the form factor





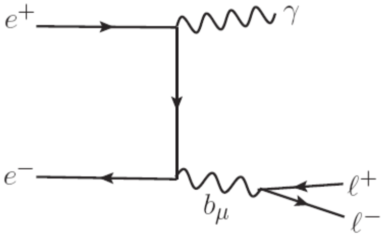


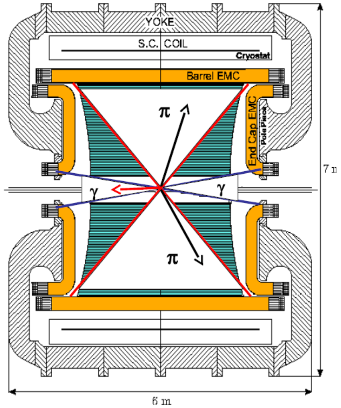
$\varepsilon^2 \leq 1.7 \times 10^{-5}$ @ 90% C.L. for 30<M_U<400 MeV

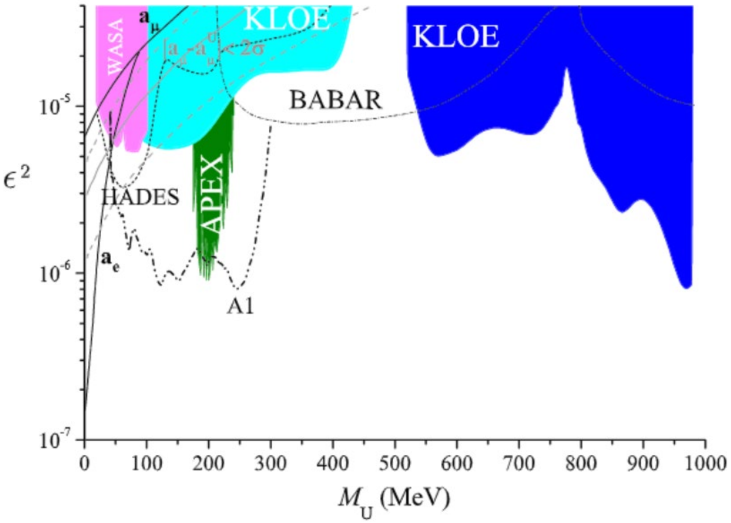
$\varepsilon^2 \leq 8.0 \times 10^{-6}$ @ 90% C.L. for 50<M_U<210 MeV

U boson in $e^+e^-\to\mu^+\mu^-\gamma$

Phys. Lett. B736 (2014) 459





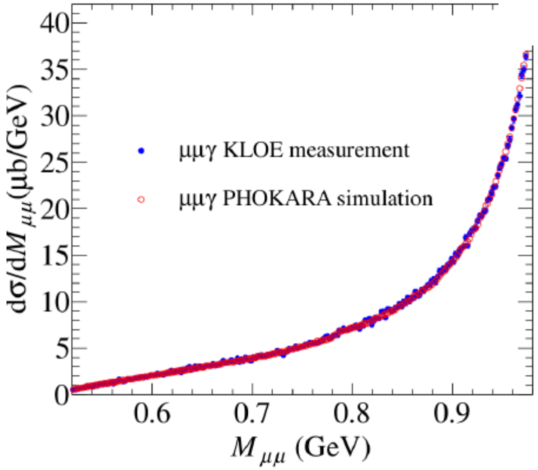


- undetected small angle photon $\theta_\gamma<15^o$ $\theta_\gamma>165^o$
- two opposite sign charged tracks $50^o<\theta_\mu<130^o$

Results based on ~ 240 pb-1

UL evaluated from raw spectra with CLs technique. Total sys. uncertainty approx. 2%.

Result updated with full KLOE statistics 1.93 fb−1 (see next slides)

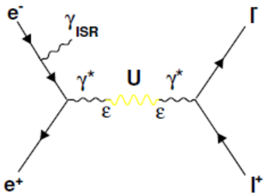


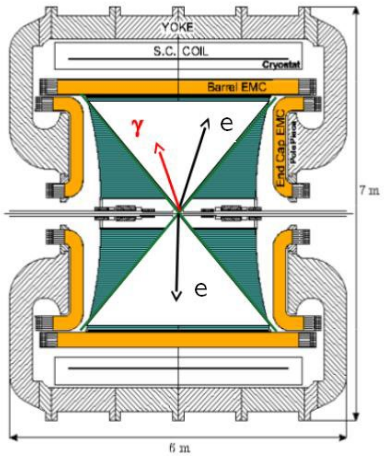
UL on ε^2 compared to

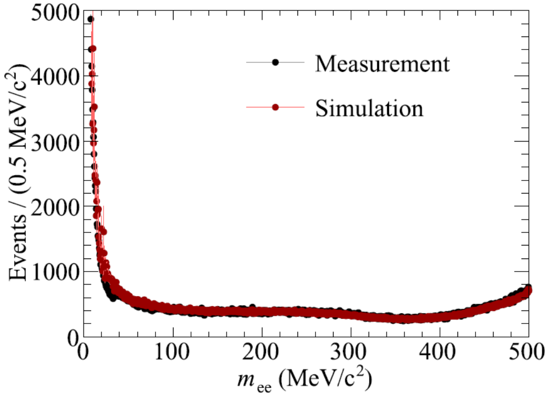
- ✓ BABAR PRL113(2014)201801
- ✓ WASA PLB726(2013)
- ✓ HADES PLB731(2014)
- ✓ APEX PRL107(2011)
- ✓ A1/MAMI PRL112(2014)

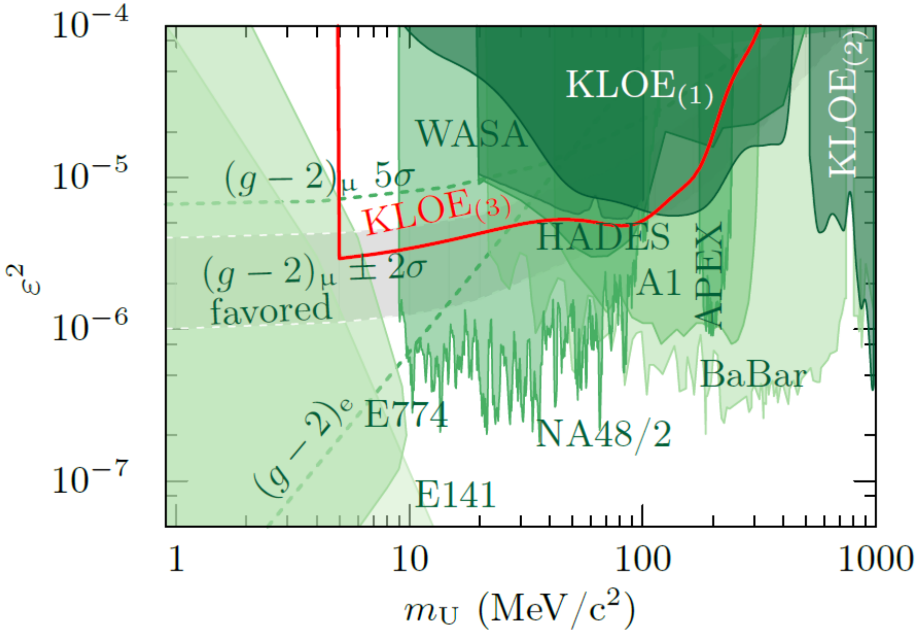
U boson in $e^+e^- \rightarrow e^+e^-\gamma$

Phys.Lett. B750 (2015) 633









- detected large angle photon $\theta_\gamma<50^o$ and $\theta_\gamma>130^o$
- two opposite sign charged tracks $50^o<\theta_e<130^o$

✓ **L=1.93 fb-1**

✓ Babayaga-NLO simulation (with weighted events)

✓ No event excess

✓ background contamination ≈1.5%

✓ allows to explore the $2m_e$ threshold region

UL on ε^2 compared to

✓ BABAR PRL113(2014)201801

✓ WASA PLB726(2013)

✓ HADES PLB731(2014)

✓ APEX PRL107(2011)

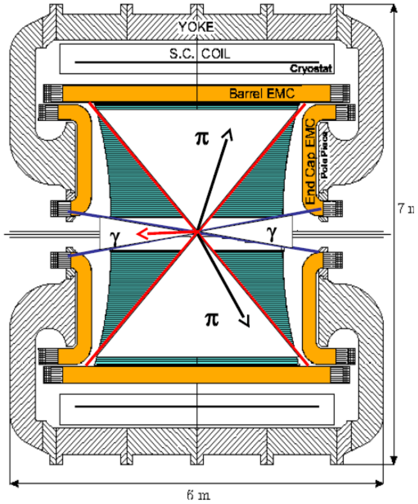
✓ A1/MAMI PRL112(2014)

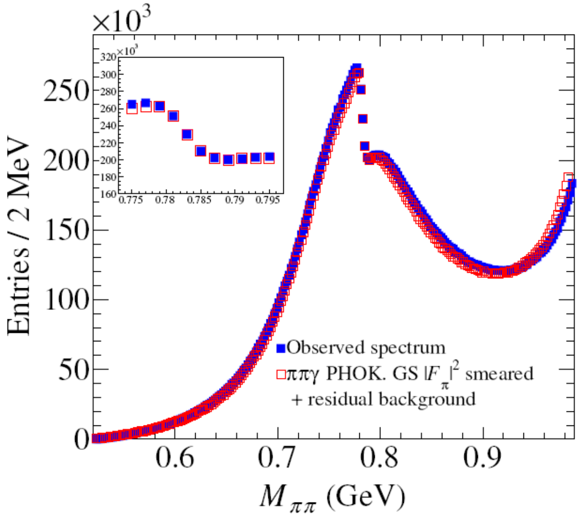
✓ NA48/2 PLB 746 (2015)

U boson in $e^+e^-\to\pi^+\pi^-\gamma$

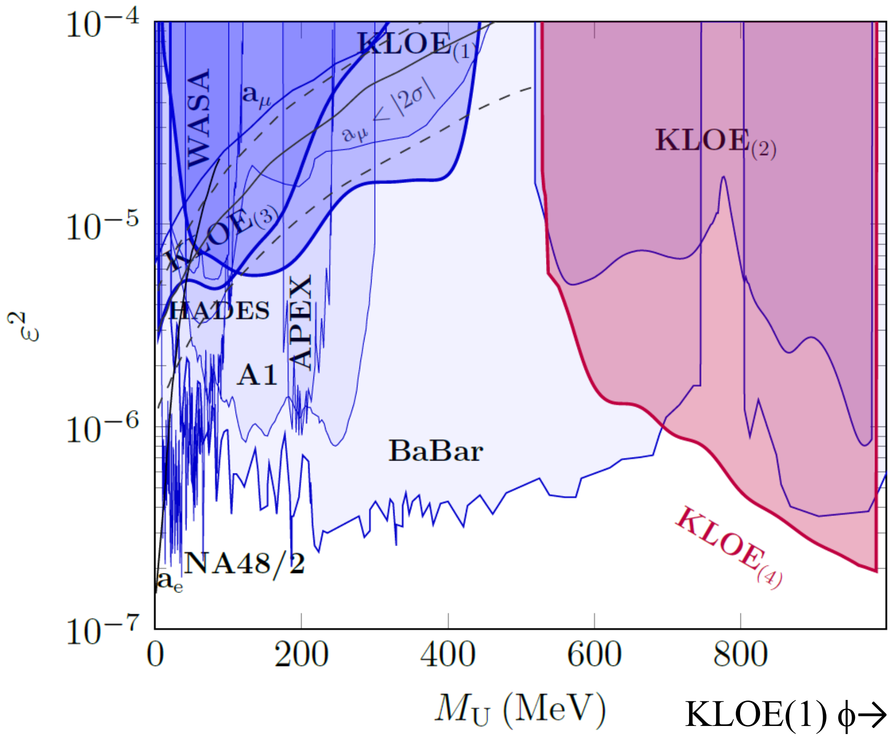
PLB757(2016)356

- **L=1.93 fb-1**
- undetected small angle photon $\theta_\gamma<15^o$, $\theta_\gamma>165^o$
- two opposite sign charged tracks $50^o<\theta<130^o$





$\pi^+\pi^-$ **mass spectrum**

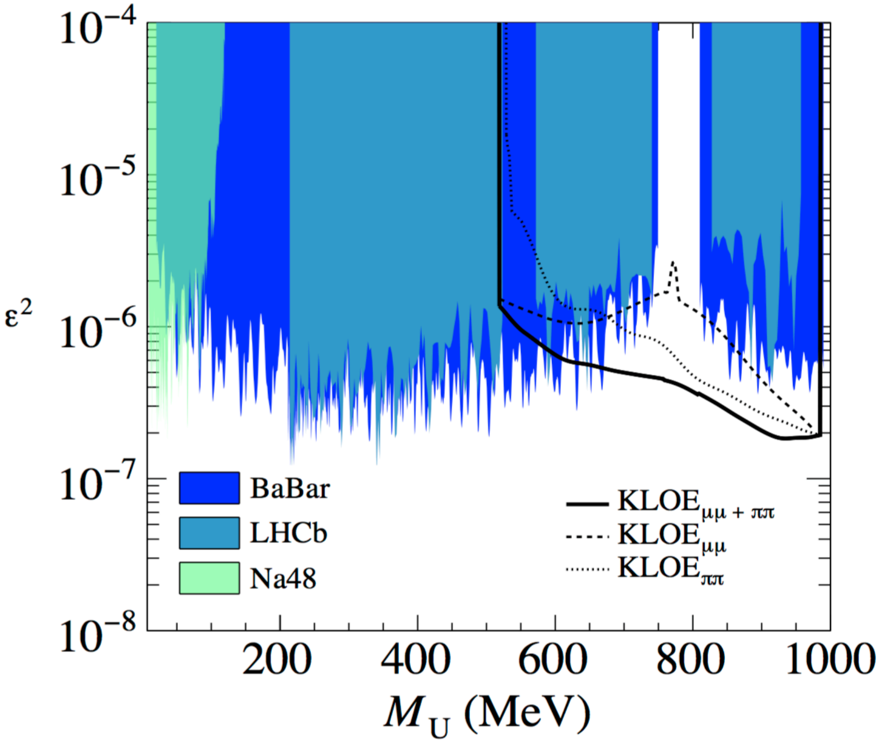


KLOE(1) $\phi\to\eta e^+e^-$
KLOE(2) $\mu^+\mu^-\gamma$
KLOE(3) $e^+e^-\gamma$
KLOE(4) $\pi^+\pi^-\gamma$

Combined limit with $U \to \mu^+\mu^-$ and $\pi^+\pi^-$

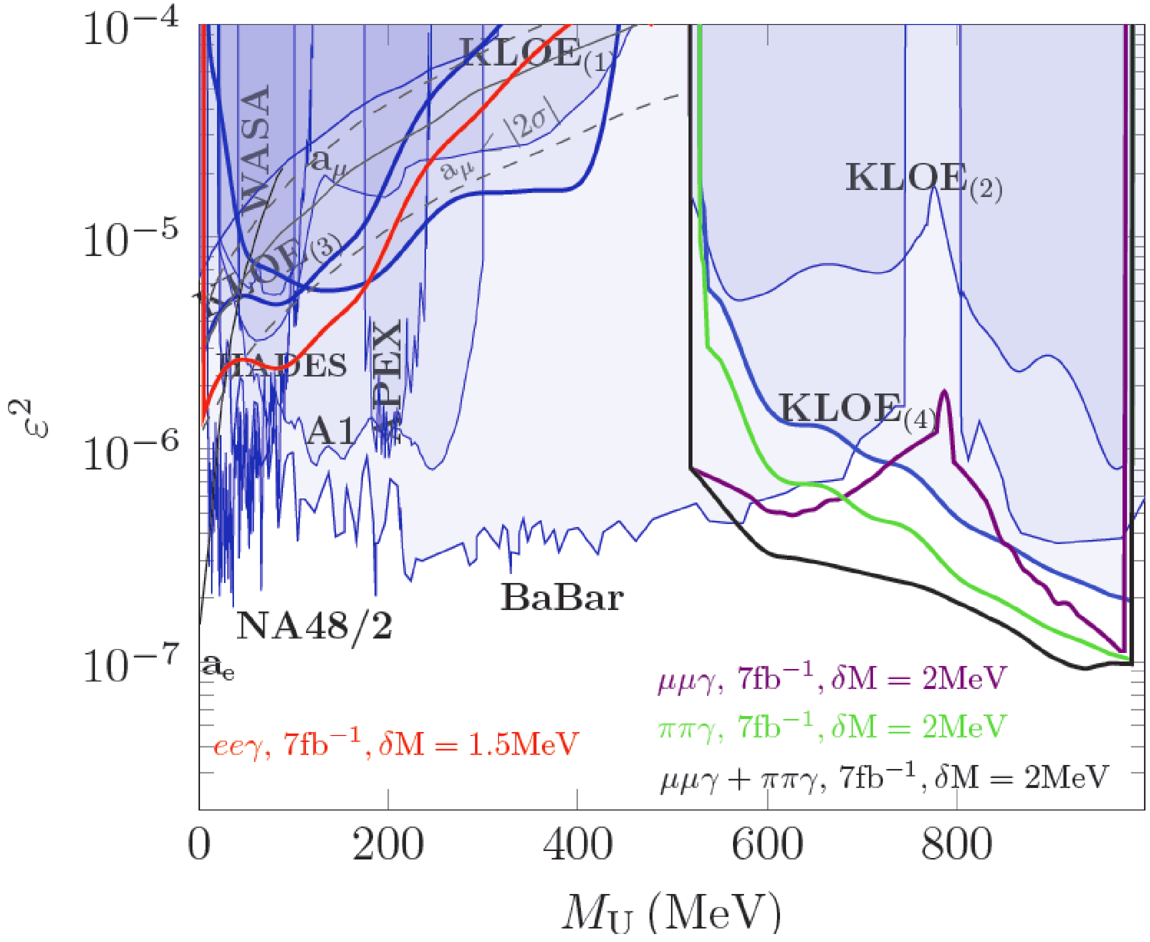
PLB 784 (2018) 336

- New $\mu\mu\gamma$ limit with full KLOE statistics (1.93 fb^{-1}) in $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ process
- Combining procedure with the limit from $\pi\pi\gamma$ requires:
  - Double inputs of data, expected background, U signal and systematical errors
  - Information on different efficiency and U decay branching fractions: BR($U \to \mu\mu$, $\pi\pi$)
- Combined limit extracted by means of CLs Technique
- The limit on ε^2 is extracted when $N_U^{tot} = N_U^{\mu\mu} + N_U^{\pi\pi}$ reaches CLs < 0.1



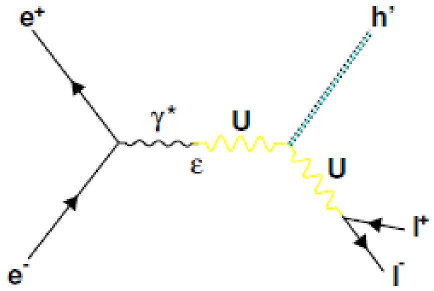
Best limit in the 600 MeV-1000 MeV mass range

U Boson in $e^+e^- \to e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$
KLOE-2 projections



Higgsstrahlung process

PLB 747(2015)365

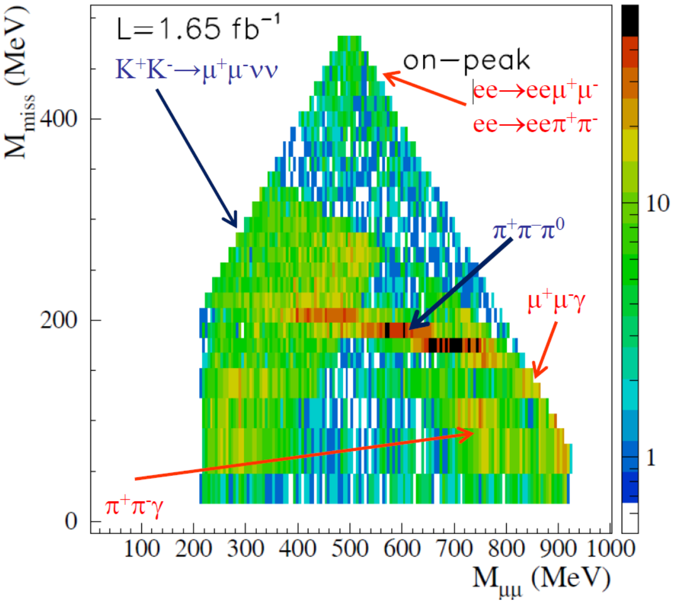


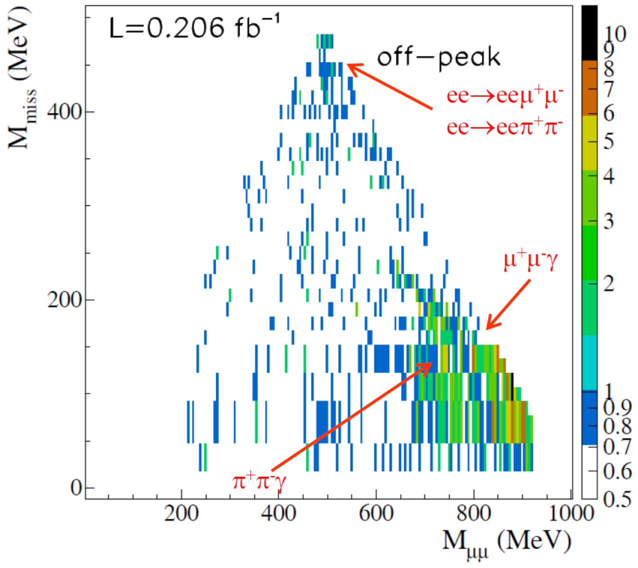
Two different scenarios:

✓$m(h') > 2m(U)$, with decays $e^+e^- \rightarrow h'U \; with \; h' \rightarrow UU$,
thus $6l, 2\pi + 4l, 6\pi$ in the final State

✓$m(h') < 2m(U)$, where h' is “invisible“ and $U \rightarrow \mu^+\mu^-$

→ enhancement in the Mmiss vs Mμμ distribution

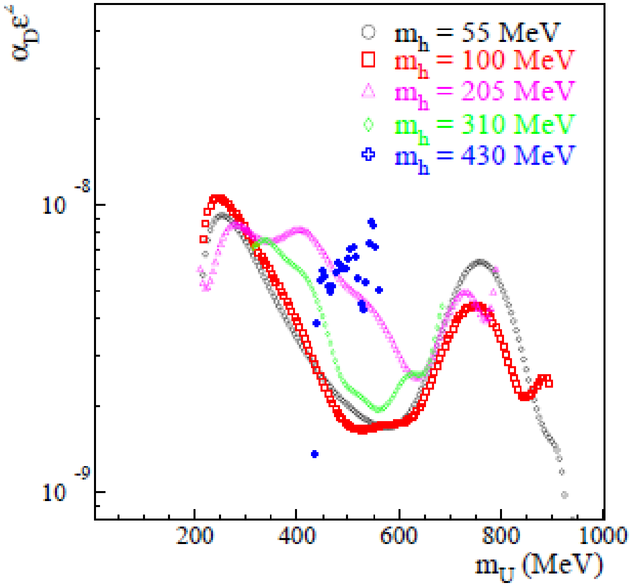




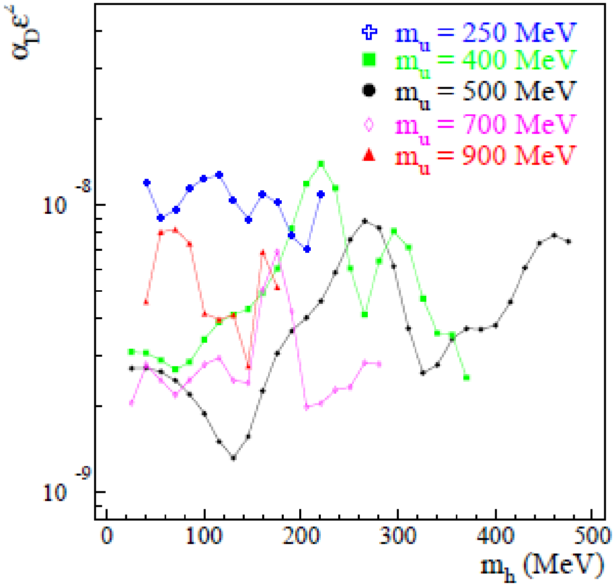
Higgsstrahlung process

PLB 747(2015)365

Combined results on- and off- peak data



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

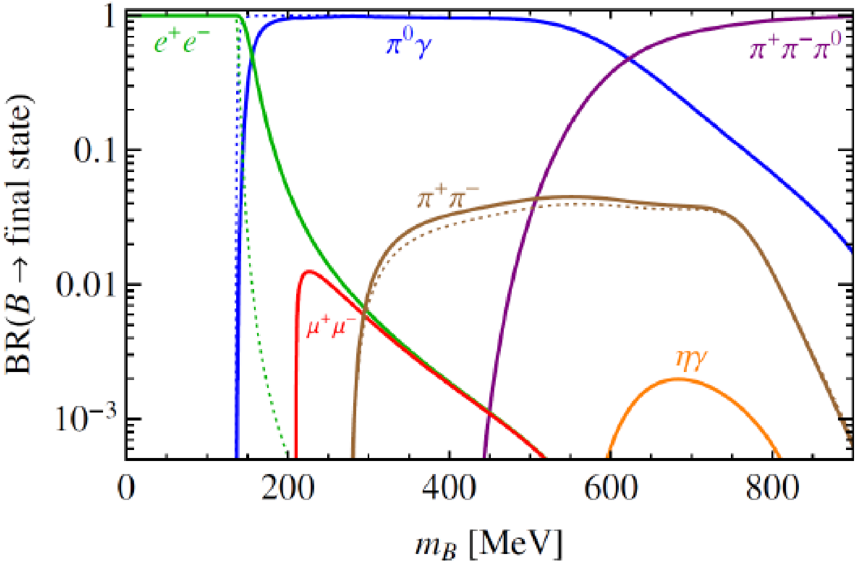


Limit on $\alpha_D\varepsilon^2$ vs $m(h')$ at 90% CL

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

Limits ~ 10^{-8} - 10^{-9} in $\alpha_D\varepsilon^2$ → translate in 10^{-3} to some 10^{-4} in ε if $\alpha_D = \alpha_{EM}$

Leptophobic B boson search at KLOE-2



S. Tulin, PRD 89 (2014) 114008

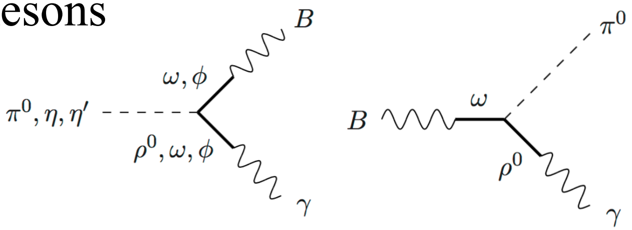
- ✓ a new weakly coupled force at the QCD scale
- ✓ coupling to the baryon number, 100 MeV–GeV mass range

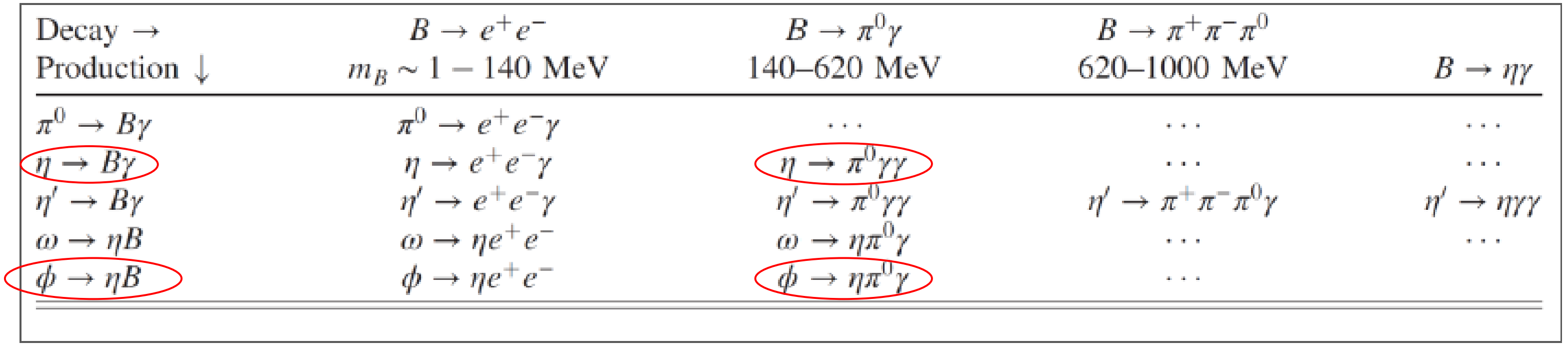
$$\mathscr{L} = \frac{g_B}{3}\bar{q}\gamma^\mu q B_\mu$$

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

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

- ✓ can be searched for in rare radiative decays of light mesons





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	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	

Both processes currently under investigation at KLOE-2

CP violating process: $\eta \to \pi^+\pi^-$

JHEP10 (2020) 047

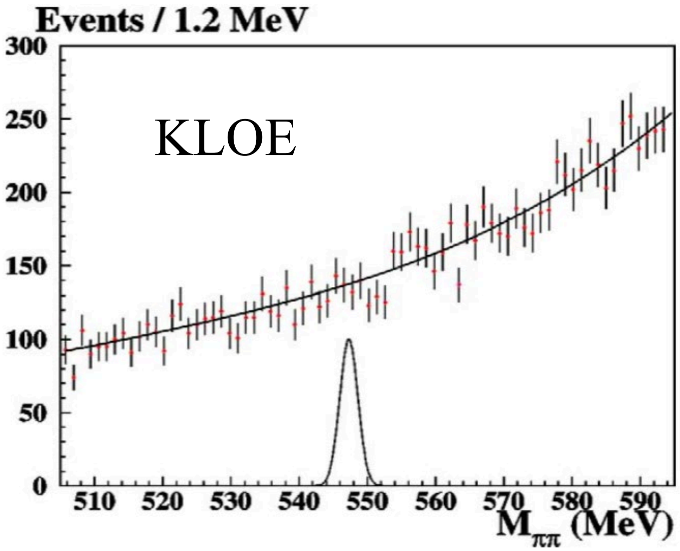
- The Br prediction in SM [Phys. Scripta T99, 23 (2002)]
  - ✓ proceed only via the CP-violating in weak interaction → 10^{-27}
  - ✓ introducing a CP violating term in QCD → to 10^{-17}
  - ✓ allowing CP violation in the extended Higgs sector → 10^{-15}

- Using the present upper bound on the nEDM → 5.3×10^{-17} [Phys. Rev. D 99 (2019) 031703 (R)]

- Any observation of larger branching ratio → a new source of CP violation in the strong interaction

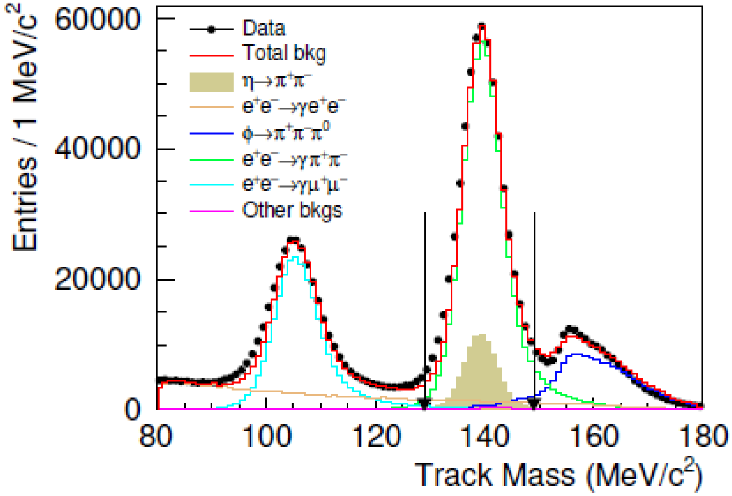
- The best limit 1.3×10^{-5} @ 90% C.L. by KLOE with ~ 350 pb^{-1}

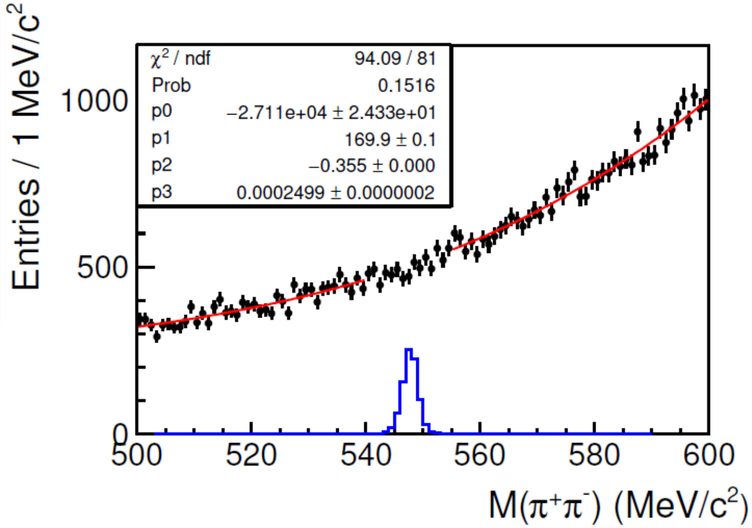
- A recent limit 1.6×10^{-5} @ 90% C.L. from LHCb with Lint~3.3 fb^{-1}



Search for eta->pi+pi-

JHEP10 (2020) 047





$$|\vec{p}_\phi - \vec{p}_1 - \vec{p}_2| = E_\phi - \sqrt{|\vec{p}_1|^2 + M_{trk}^2} - \sqrt{|\vec{p}_2|^2 + M_{trk}^2}$$

- New analysis using independent 1.7 fb-1 of KLOE data
- No event excess in the eta region, limit extracted using CLs technique

$Br(\eta\to\pi^+\pi^-) < 4.9 \times 10^{-6}$ @ 90% C.L.

- Combined with previous KLOE result:

$Br(\eta\to\pi^+\pi^-) < 4.4 \times 10^{-6}$ @ 90% C.L.

Summary

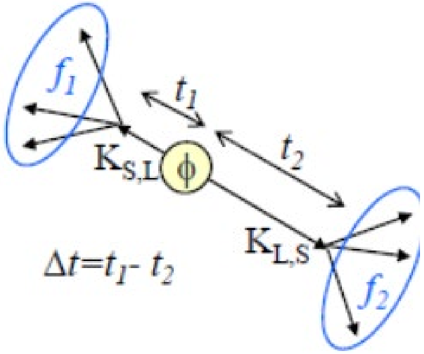
- KLOE is continuing exploit light dark matter or mediators at low energy region
- KLOE/KLOE-2 have collected 8fb^{-1} data at ϕ peak (2.4×10^{10} ϕ mesons) ~ Dawn of more precise results and new measurements from KLOE-2 with data sample ~8 fb^{-1}.

Thanks for your attention!!!

CPT Symmetry and Quantum Mechanics

A pure two-kaon state produced from ϕ decays

$$|i\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle|\overline{K}_0\rangle - |\overline{K}_0\rangle|K_0\rangle) = \mathcal{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle),$$



The decay rate of the system

$$I(f_1,t_1;f_2,t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}\right\}$$

$$\left\{-2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2} \cos(\Delta m(t_2-t_1)+\varphi_1-\varphi_2)\right\}$$

interference term

$$\eta_j = \frac{\langle f_j|K_L\rangle}{\langle f_j|K_S\rangle}$$

The two decays are correlated even if kaons are distant in space

I(f1,f1; Δt=0)=0 Complete destructive quantum Interference prevents the two kaons from decaying into the same final state at the same time

$$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^0\pi^0 \Longrightarrow \frac{\varepsilon'}{\varepsilon}\ \text{(CPV)}$$

$$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\pm \nu\, \pi^0\pi^0\pi^0, \pi\pi \Longrightarrow \text{T violation}$$

$$\phi \longrightarrow K_S K_L \longrightarrow \pi^- l^+ \nu\, \pi^+ l^- \bar{\nu} \Longrightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$

$$\phi \longrightarrow K_S K_L \longrightarrow \pi^\pm l^\mp \nu \pi\pi \Longrightarrow \text{CPT and } \Delta S = \Delta Q \text{ rule}$$

$$\phi \longrightarrow K_S K_L \longrightarrow \pi^+\pi^-\pi^+\pi^-\ \text{CPT, Quantum Mechanics}$$

CPT and Lorentz invariance violation

Using the same final state for both kaons ($\pi^+\pi^-$) the two decay are distinguished only by the kaon momentum direction. The decay amplitude is written as follows:

$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_1\eta_2^* e^{-i\Delta m\Delta\tau}\right)\right]$$

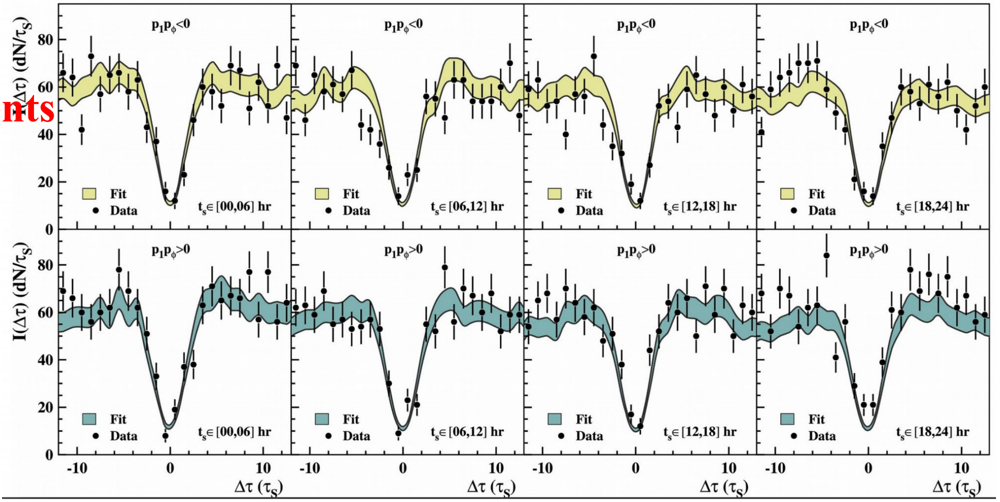
$$\eta_1 = \eta_\pm = \varepsilon_K - \delta(\vec{p}_{K^1}) \qquad \eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2})$$

δ_K is the CPT violation parameter in the Kaon system

In the framework of SME, δ_K depends on the kaon four-momentum:

$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta\vec{a})/\Delta m$$

Δa_μ are four CPT & Lorentz violating coefficients



KLOE (1.7 fb^{-1}), PLB 730(2014)89

$$\Delta a_0 = (-6.0 \pm 7.7 \pm 3.1) \cdot 10^{-18}\ \text{GeV}$$

$$\Delta a_x = (0.9 \pm 1.5 \pm 0.6) \cdot 10^{-18}\ \text{GeV}$$

$$\Delta a_y = (-2.0 \pm 1.5 \pm 0.5) \cdot 10^{-18}\ \text{GeV}$$

$$\Delta a_z = (3.1 \pm 1.7 \pm 0.5) \cdot 10^{-18}\ \text{GeV}$$

LHCb, PRL 116(2016)241601, mixing B

$B^0 \to J/\psi K_S$ $\quad \Delta a_{x,y,\parallel} \approx 10^{-15}\text{GeV}$

$\Delta a_\perp \approx 10^{-13}\text{GeV}$

$B_S^0 \to J/\psi K^+K^-$ $\quad \Delta a_{x,y,\parallel} \approx 10^{-14}\text{GeV}$

$\Delta a_\perp \approx 10^{-12}\text{GeV}$

BaBar, PRL 100(2000)131802,
entangled $\Psi(4S) \to B\bar{B} \to (Xl\nu)(Xl\nu)$

$\Delta a_{\perp,\parallel} \approx 10^{-13}\text{GeV}$

FOCUS, PLB 556(2003)7, mixing D

$\Delta a_{x,y,\parallel} \approx 10^{-13}\text{GeV}$

Combined $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and $a_\mu^{\pi\pi}$

JHEP 03 (2018) 173

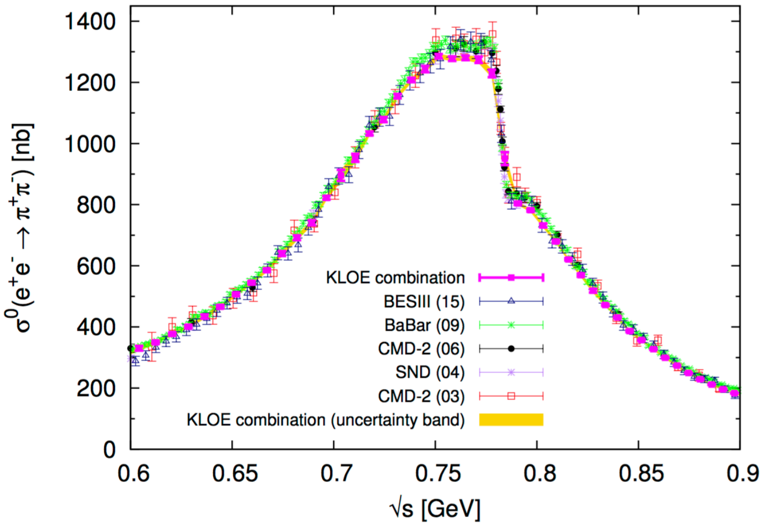
- Three KLOE $\sigma(e+e- \to \pi+\pi-\gamma(\gamma))$ with ISR:
  - **KLOE08: small angle photon**
    - $\theta\gamma < 15°$ || $\theta\gamma > 165°$, $\sqrt{s} = 1.02$GeV, PLB 670 (2009) 285
  - **KLOE10: large angle photon**
    - $45° < \theta\gamma < 135°$, $\sqrt{s} = 1.0$ GeV, PLB 700 (2011) 102
  - **KLOE12: small angle photon**
    - $\sqrt{s} = 1.02$GeV, PLB720 (2013) 336

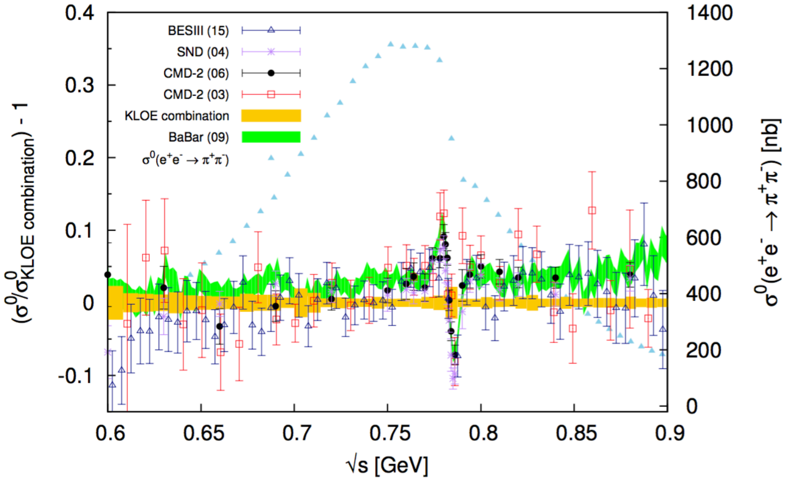
KLOE08 & KLOE10 $\sigma^0_{\pi\pi(\gamma)}(s') = \sigma_{\pi\pi(\gamma)}(s')|1 - \Pi(s')|^2,$

KLOE12 $\sigma^0_{\pi\pi(\gamma)}(s') = \dfrac{\mathrm{d}\sigma(\pi^+\pi^-\gamma)/\mathrm{d}s'}{\mathrm{d}\sigma(\mu^+\mu^-\gamma)/\mathrm{d}s'} \times \sigma^0_{(\gamma)}(e^+e^- \to \mu^+\mu^-, s')$

All three meas are undressed of all VP effects and including FSR (overlapping range in the 0.6-0.95 GeV)

Iterative linear $\chi2$ function minimization method is used for the combination→ construction of full statistical and syst. covariance matrices needed





Combined of $\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma))$ and $a_\mu^{\pi\pi}$

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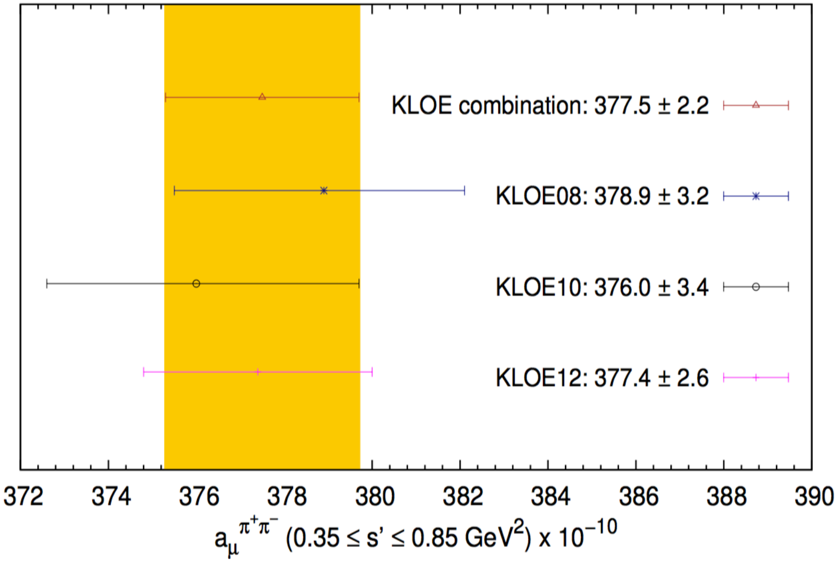

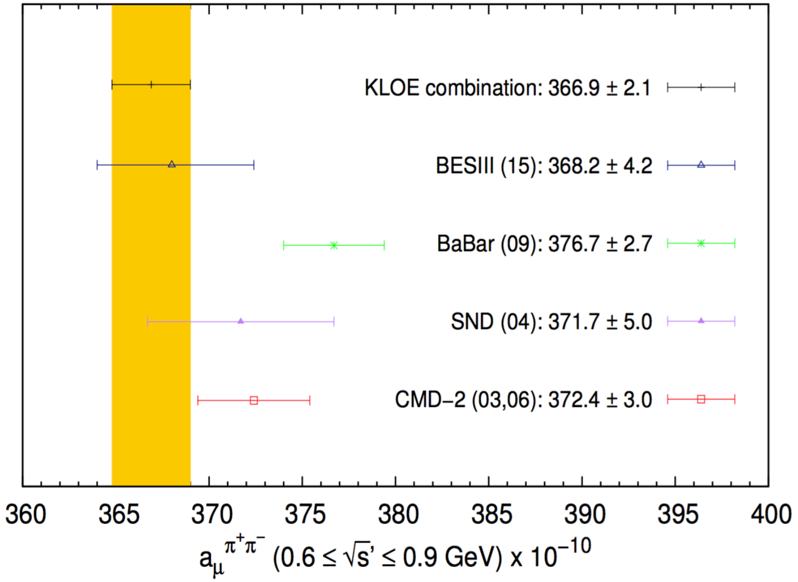

$$a_\mu^{\pi\pi} = \int_{x_1}^{x_2} \sigma_{ee\rightarrow\pi\pi}(\mathrm{s})\mathrm{K}(\mathrm{s})\mathrm{ds},$$

$$a_\mu^{\pi^+\pi^-}(\text{KLOE combination}, 0.10 < s' < 0.95\ \text{GeV}^2) = (489.8 \pm 5.1) \times 10^{-10},$$

KLOE comb $a_\mu^{\pi+\pi-}$ consistent with KLOE08, KLOE10 and KLOE12 individual estimations

In agreement with CMD-2, SND and BESIII results within 1.5σ

Difference with BaBar < 3σ