Recent results on quantum interferometry and hadron physics at KLOE-2

Workshop on status and perspectives of physics at high intensity
09-11 November 2022, Laboratori Nazionali di Frascati

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Outline

- KLOE-2 Introduction & Dataset
- Quantum interferometry with Kaons
  - QM tests
  - CPT in transitions
- Hadron physics
  - $\eta \to \pi^0\gamma\gamma$
  - $\varphi \to \eta\ \pi^+\pi^-$, $\eta\mu^+\mu^-$
  - $\pi^+\pi^-\pi^0$ cross section
  - Leptophobic Dark-Matter searches
  - $\gamma\gamma \to \pi^0$
- Conclusions

KLOE-2: main detectors

Drift Chamber

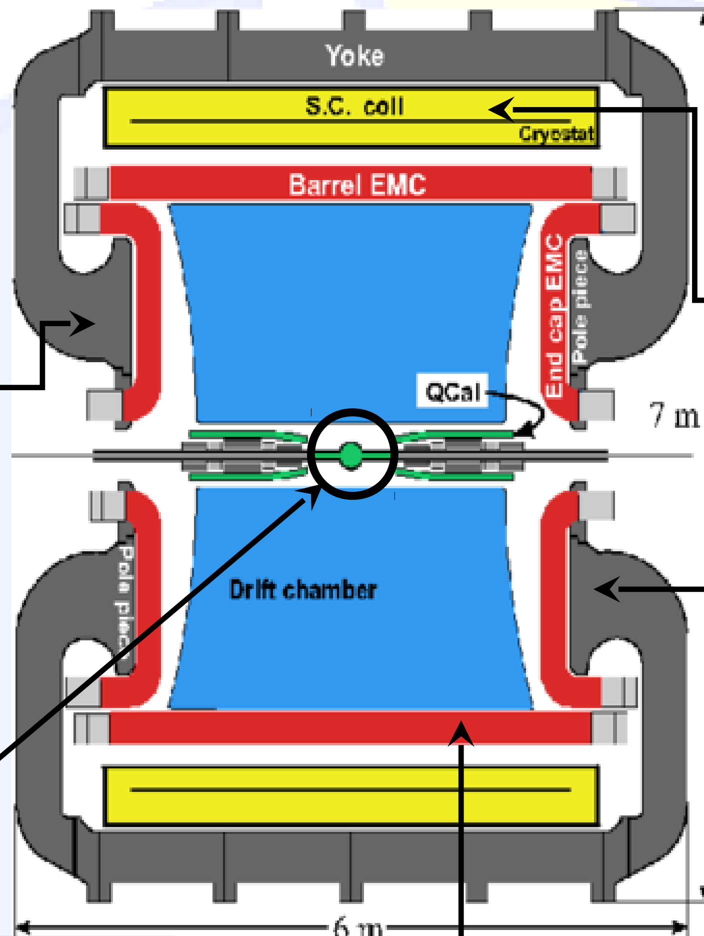
$\sigma_p/p \cong 0.4$ %

(tracks with $\theta > 45°$)

$\sigma^{hit} \cong 150\ \mu m$ (xy), 2 mm (z)

$\sigma^{vertex} \sim 1$ mm

General purpose detector



SC Magnet

B = 0.52 T

End Cap

Barrel

Calorimeter e.m.

Both side read-out (PM)

$\sim 4\pi$ solid angle coverage

$\sigma_E/E \cong 5.7\% /\sqrt{E(GeV)}$

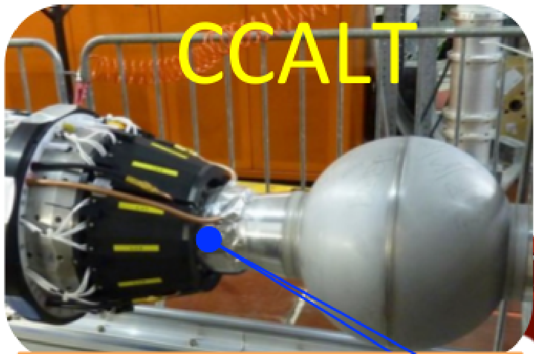
$\sigma_t \cong 54$ ps $/\sqrt{E(GeV)} \oplus 100$ ps

Interaction point (IP)

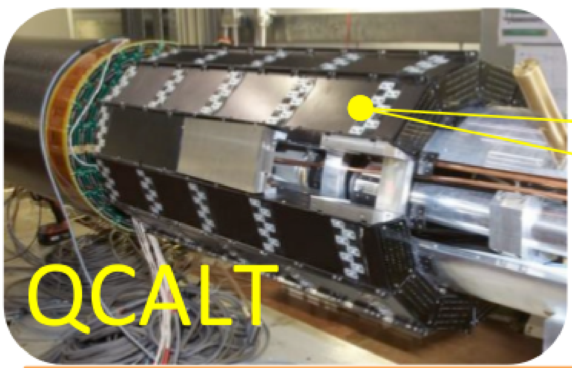
Sphere Al-Be (Ø 20 cm)

KLOE-2: interaction region detectors

KLOE-2

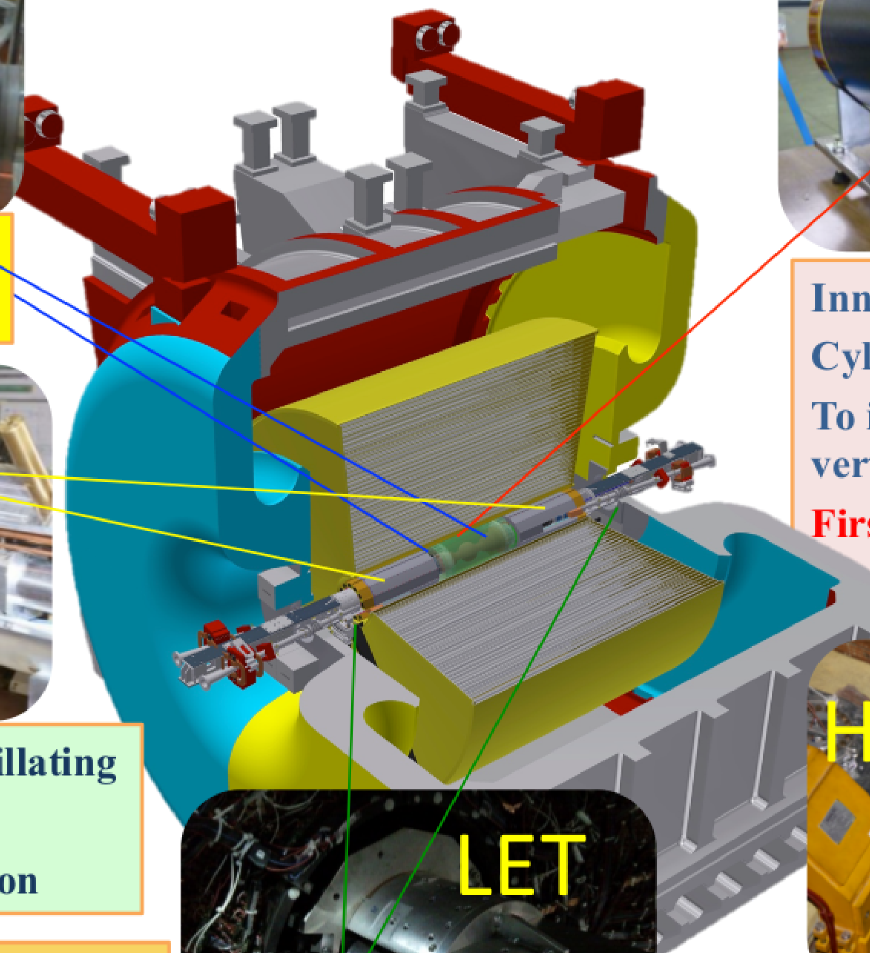


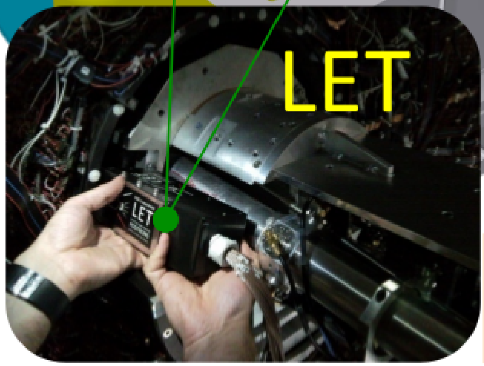
CCALT – LYSO Crystal w SiPM - Low polar angle

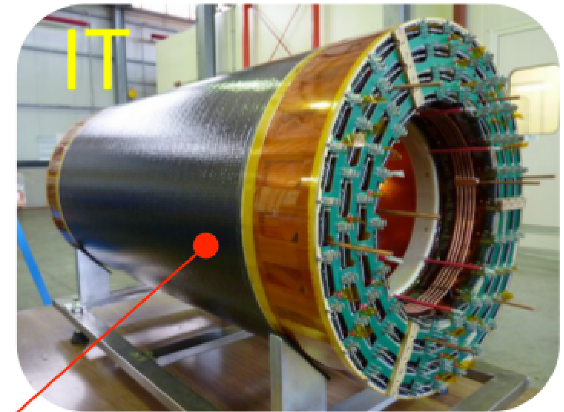


QCALT – Tungsten / Scintillating Tiles w SiPM - K_L decays Quadrupole Instrumentation

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



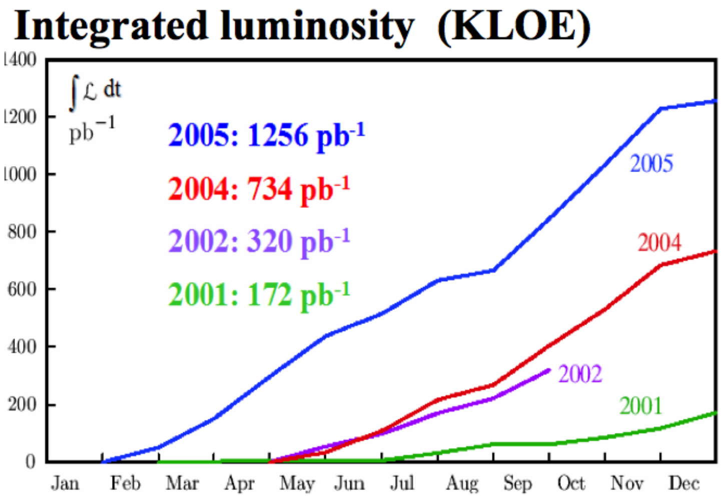




Inner Tracker – 4 layers of Cylindrical GEM detectors
To improve the track and vertex reconstruction
First time CGEM in high energy experiment

HET: Scintillator hodoscope +PMTs pitch:5 mm; placed at 11 m from IP

KLOE-2 dataset

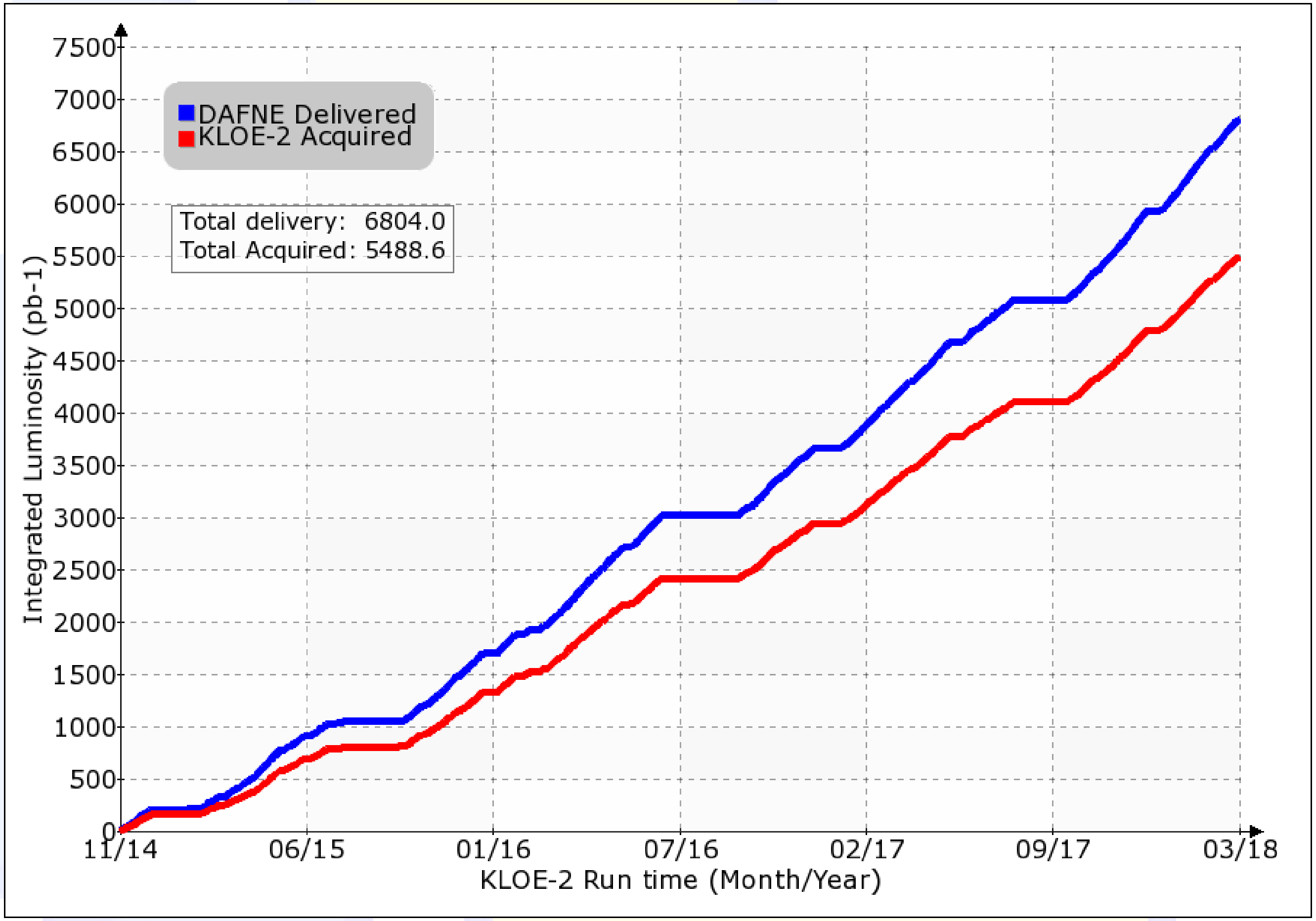


KLOE dataset:
2.5 fb^{-1}
$L_{peak} = 1.52 \times 10^{32}\ cm^{-2}s^{-1}$

KLOE-2 dataset:

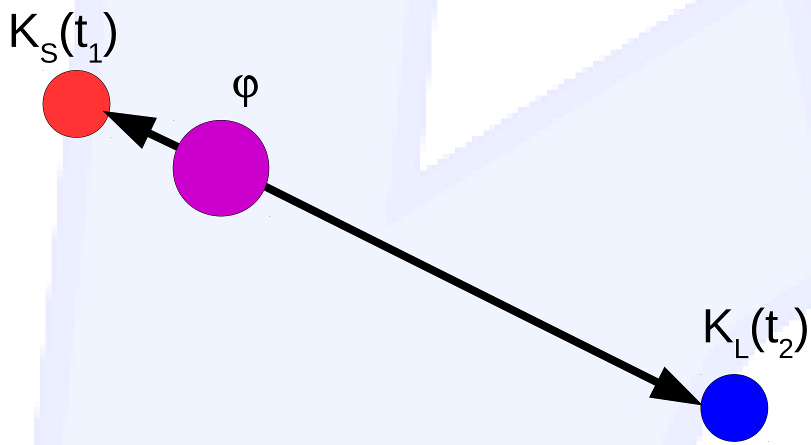
5.5 fb^{-1}(2014/18)

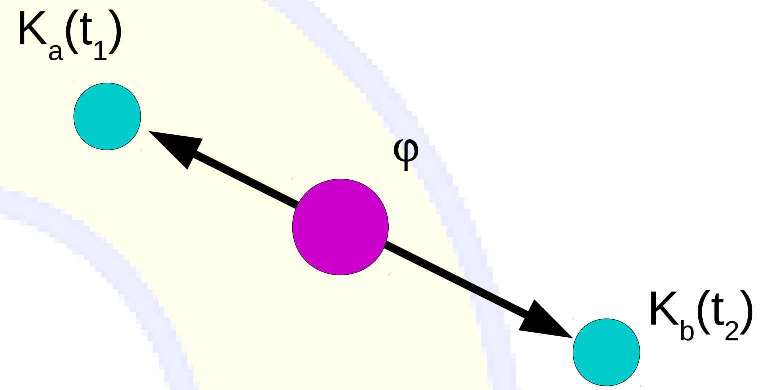
$L_{peak} = 2.38 \times 10^{32}\ cm^{-2}\ s^{-1}$
(Crab-Waist)



KLOE+KLOE-2 data sample:
8 fb^{-1} → 2.4 x 10^{10} φ(1020) mesons decay recorded

Neutral kaons at KLOE-2





KAON MASS EIGENSTATES TAGGING ($t_1 \ll t_2$)

SINGLE KAON PROPERTY:
- Branching fractions
- Form factors
- Lifetimes

INTERFERENCE ($t_1 \sim t_2$)

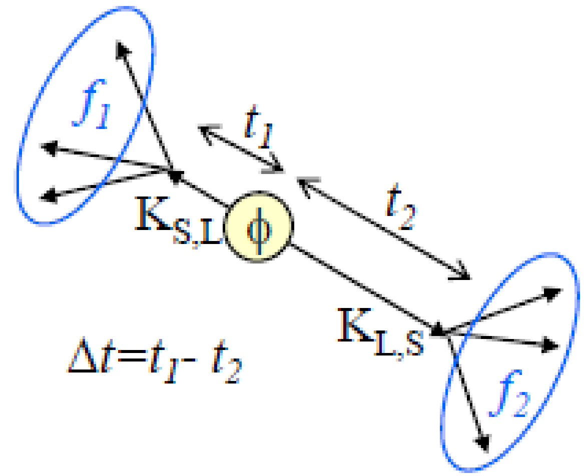
KAON SYSTEM TIME EVOLUTION:
Tests of:
- T/CPT in transitions
- CPT & Lorentz Invariance
- QM coherence

Correlation in two kaon state

The ϕ meson decay in entangled pair of neutral kaons with $J^{PC} = 1^{--}$ quantum numbers:

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

The antisymmetry of the state is preserved in its time evolution; the decay amplitude for the state into final states f_1, f_2 at time t_1, t_2 is:

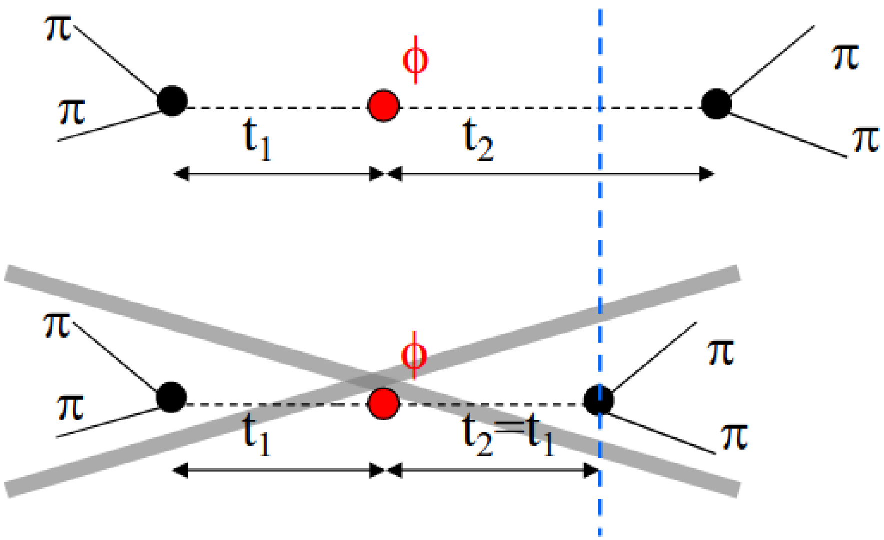


$$|\langle f_1(t_1), f_2(t_2)|i\rangle|^2 = \frac{N}{\sqrt{2}}\Big\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2} \cos\left[\Delta m(t_2 - t_1) + \phi_1 - \phi_2\right]\Big\}$$

Interference term

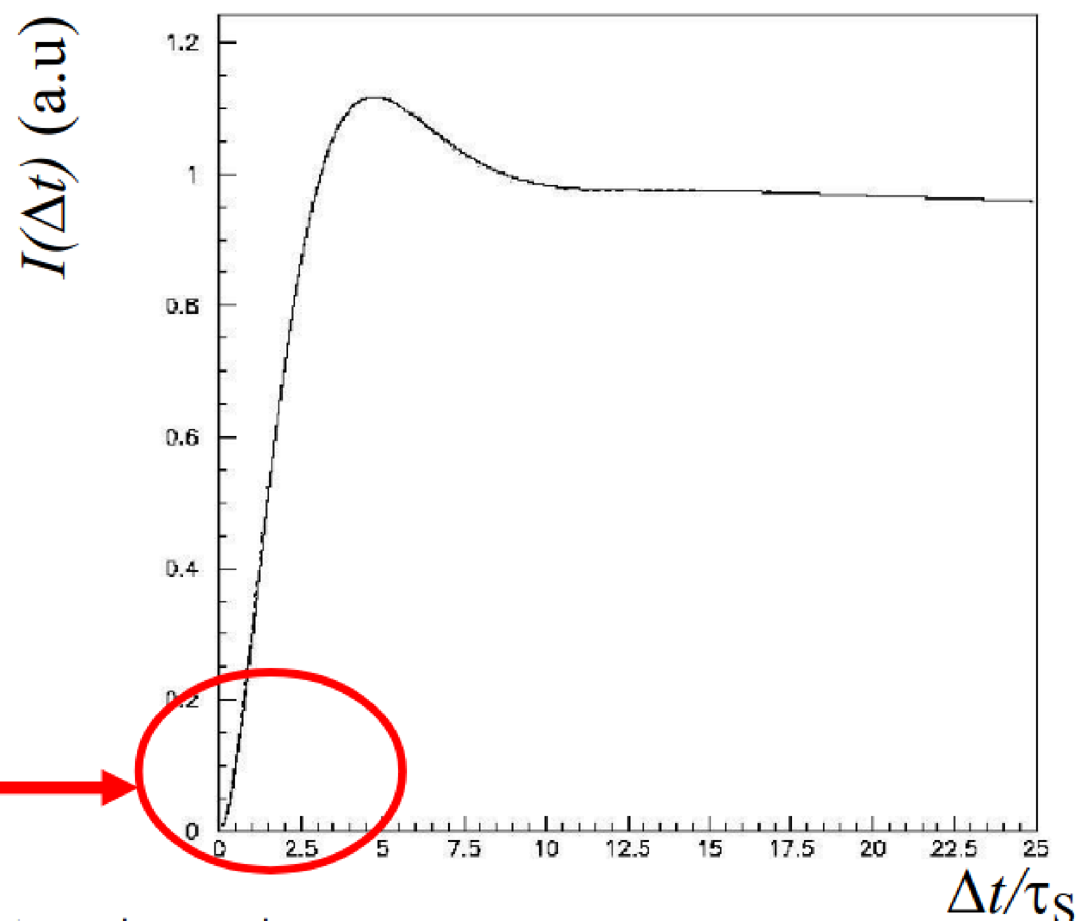
EPR correlations in entangled neutral kaons

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



Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

(this specific channel is suppressed by CP viol. $|\eta_{+-}|^2 = |A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-)|^2 \sim |\varepsilon|^2 \sim 10^{-6}$)



EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the fully destructive quantum interference

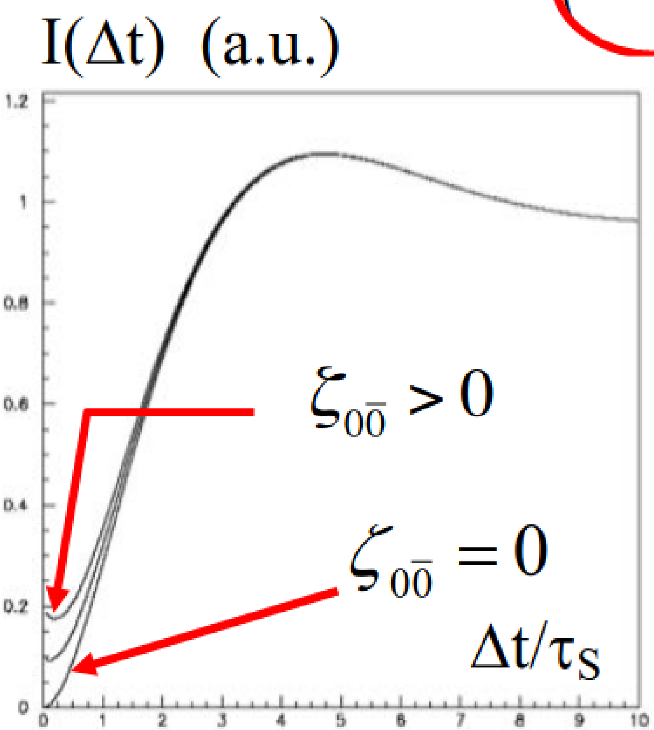
$\Delta t = |t_1 - t_2|$

Test of quantum coherence

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

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\Big[\left|\langle \pi^+\pi^-,\pi^+\pi^- | K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle \pi^+\pi^-,\pi^+\pi^- | \overline{K}^0 K^0(\Delta t)\rangle\right|^2$$

$$-(1-\zeta_{0\bar{0}})\cdot 2\Re\left(\langle \pi^+\pi^-,\pi^+\pi^- | K^0\overline{K}^0(\Delta t)\rangle\langle \pi^+\pi^-,\pi^+\pi^- | \overline{K}^0 K^0(\Delta t)\rangle^*\right)\Big]$$



Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \rightarrow \quad$ QM

$\zeta_{0\bar{0}} = 1 \quad \rightarrow \quad$ total decoherence

(also known as Furry's hypothesis or spontaneous factorization)
W.Furry, PR 49 (1936) 393

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

Test of quantum coherence: KLOE-2 results

KLOE-2 JHEP 04 (2022) 059

$$\zeta_{0\bar{0}} = (-0.5 \pm 8.0_{stat} \pm 3.7_{syst})\times 10^{-7}$$

CP violating process:

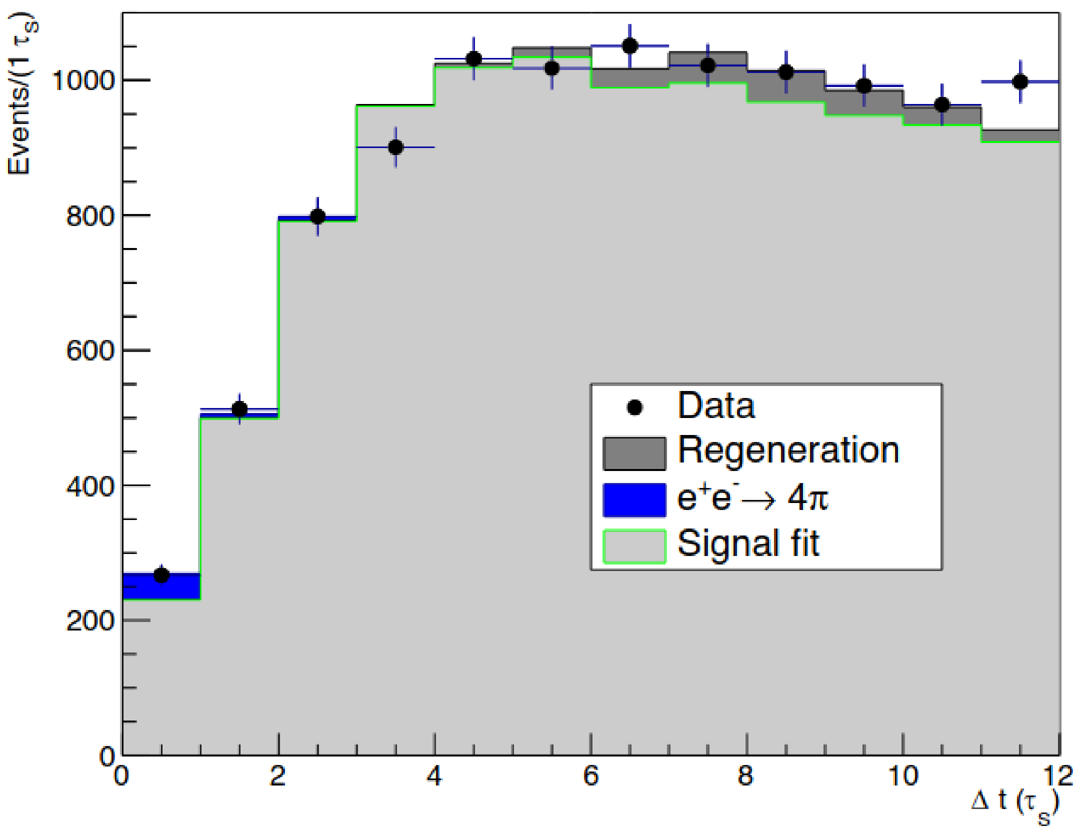
terms $\zeta_{00}/|\eta_{+-}|^2$ with $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$

=> high sensitivity to ζ_{00} ;

CP violation in kaon mixing acts as amplification mechanism

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$



Possible decoherence due to quantum gravity effects (apparent loss of unitarity) implying also CPT violation => modified Liouville – von Neumann equation for the density matrix of the kaon system depends on a CPTV parameter g [J. Ellis et al. PRD53 (1996) 3846]

In this scenario γ can be at most:

$$O(m_K^2/M_{PLANCK}) = 2\times 10^{-20}\ GeV$$

KLOE-2 result

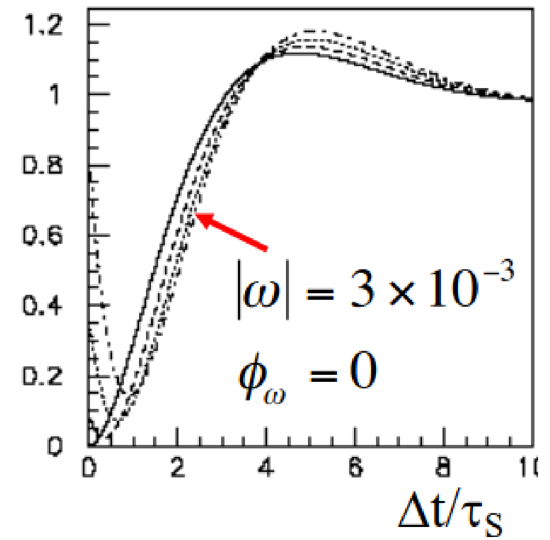
$$\gamma = (1.3 \pm 9.4_{stat} \pm 4.2_{syst})\times 10^{-22}\ \text{GeV}$$

CPT Violation in entangled Kaon states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator "ill-defined") the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



$$|i\rangle \propto \left(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right) + \omega\left(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle\right)$$

at most one expects:

$$|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}$$

In some microscopic models of space-time foam arising from non-critical string theory [Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014] : $|\omega| \sim 10^{-4} \div 10^{-5}$

The maximum sensitivity to ω is expected for $f_1=f_2=\pi^+\pi^-$ (terms: $|\omega|/|\eta_{+-}|$)
All CPTV effects induced by QG $(\alpha,\beta,\gamma,\omega)$ could be simultaneously disentangled.

The fit with $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$ yields (1.7 fb-1):

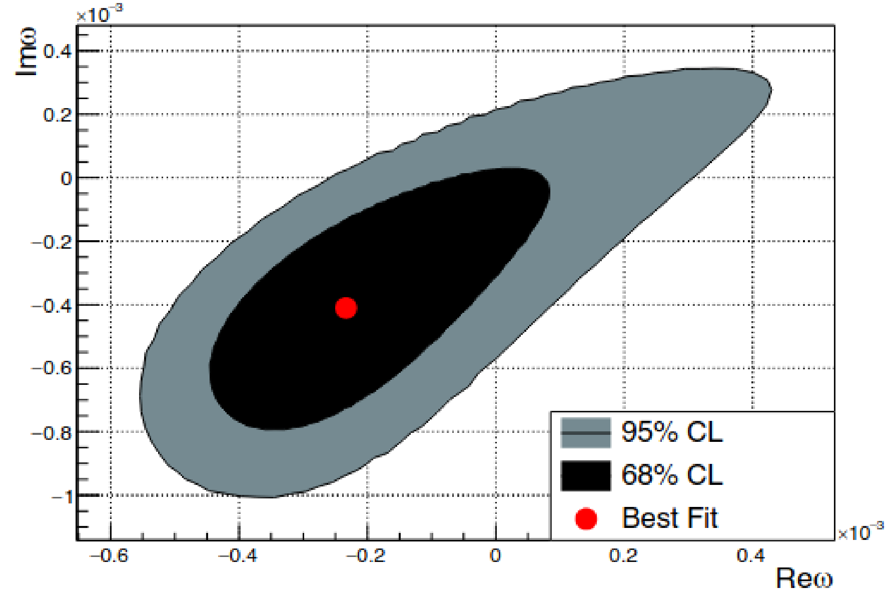
$$\Re\omega = \left(-2.3^{+1.9}_{-1.5}{}_{stat} \pm 0.6_{syst}\right)\times 10^{-4}$$
$$\Im\omega = \left(-4.1^{+2.8}_{-2.6}{}_{stat} \pm 0.9_{syst}\right)\times 10^{-4}$$
$$|\omega| = (4.7 \pm 2.9_{stat} \pm 1.0_{syst})\times 10^{-4}$$
$$\phi_\omega = -2.1 \pm 0.2_{stat} \pm 0.1_{syst} \text{ rad}$$

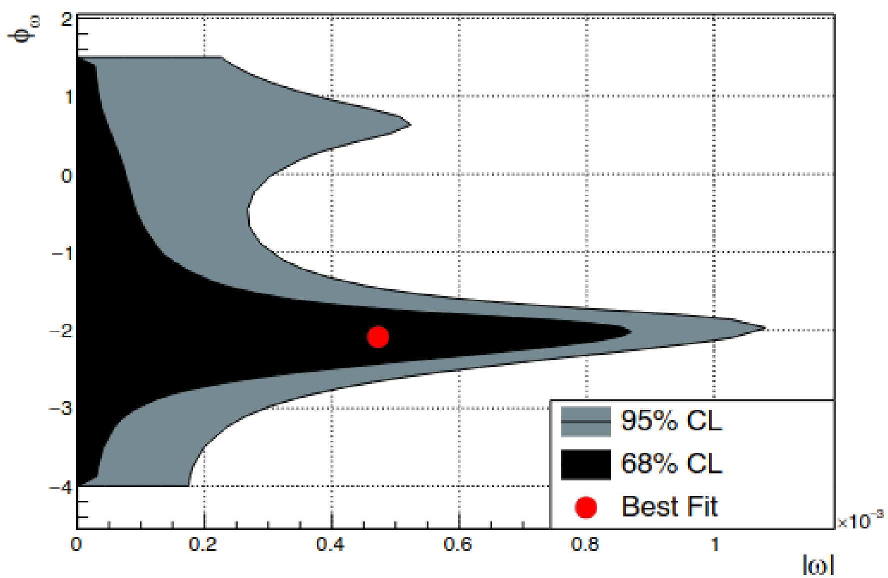
from $$|\omega|^2 = \frac{BR(\phi \to K_S K_S, K_L K_L)}{BR(\phi \to K_S K_L\ )}$$

$BR(\phi \to K_S K_S, K_L K_L) < 2.4\times 10^{-7}$
at 90% C.L.

KLOE-2 JHEP 04 (2022) 059

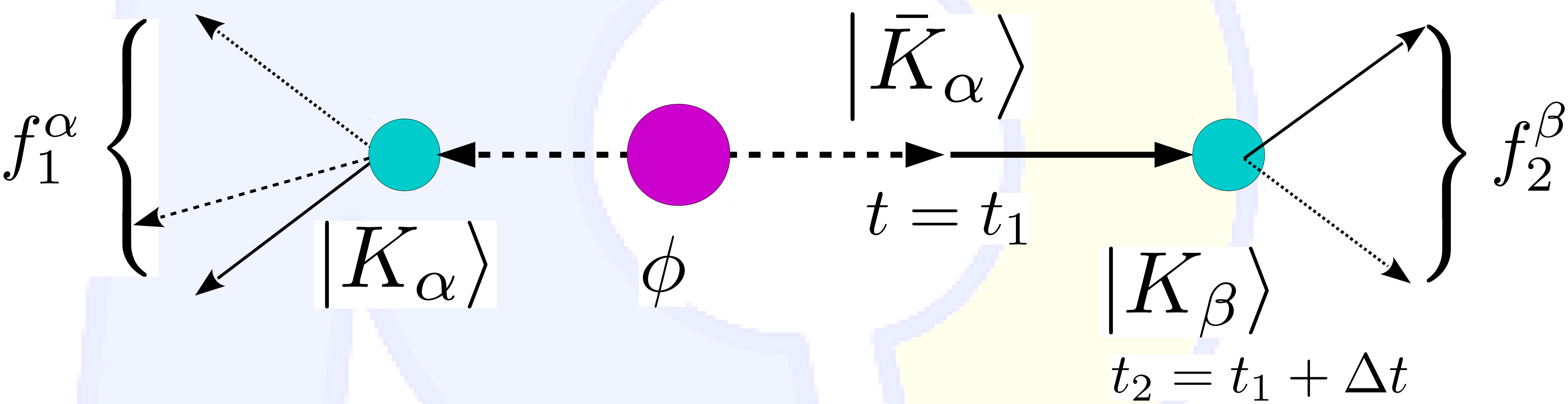
In the B system:
$-0.0084 \le \Re\omega \le 0.0100$ at 95% C.L.
Alvarez, Bernabeu, Nebot JHEP 0611, 087
(see also Bernabeu et al, EPJC (2017) 77:865)





CPT test in transitions: time dependent tagging

Entanglement allows to "prepare" the initial state desired by "tagging" the other kaon decay:
The "first kaon" (K_α) decays (f_1^α) is observed at t_1. This decay reveals the state of the kaon system at the time t_1.



The f_2^β decay is observed at t_2. In this way we have to possibility to observe the $|\bar{K}_\alpha\rangle \to |K_\beta\rangle$ transition probability as a function of the time difference Δt.

Transition amplitudes transformations

Transformations under discrete symmetry connect different transitions between CP and Flavor eigenstates.

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

$K^0/\bar{K}^0$ Flavor eigenstate

K_+/K_- CP eigenstate

Direct and model independent tests of time-reversal (T) and CPT symmetry $\to$ comparison of **transition rates between flavor and CP eigenstates**

Bernabeu et al Nucl.Phys. B 868 (2013) 102
Bernabeu et al. JHEP 10 (2015) 139

T, CP, CPT tests in neutral kaon transitions at KLOE

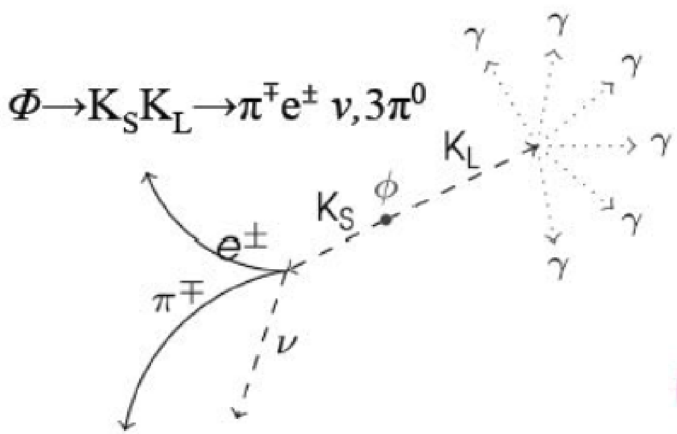
CPT | **T** | **CP** | **observables**

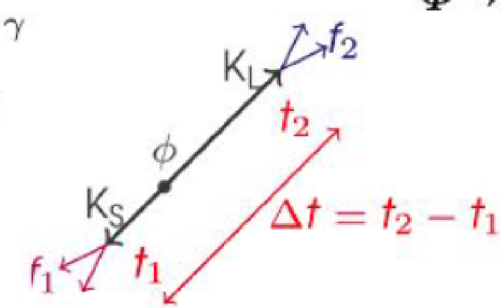
$$R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)} \qquad R^{\rm exp}_{2,\mathcal{T}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\pi\pi,\ell^+;\Delta t)} \qquad R^{\rm exp}_{2,\mathcal{CP}}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\ell^+,3\pi^0;\Delta t)}$$

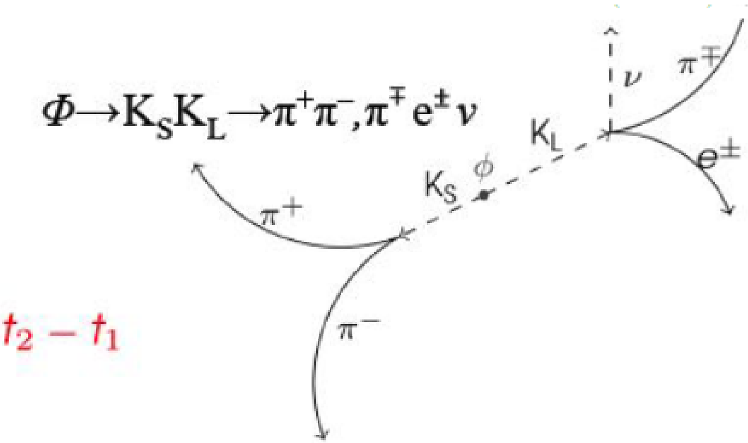
$$R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^+,3\pi^0;\Delta t)}{I(\pi\pi,\ell^+;\Delta t)} \qquad R^{\rm exp}_{4,\mathcal{T}}(\Delta t) \equiv \frac{I(\ell^+,3\pi^0;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)} \qquad R^{\rm exp}_{4,\mathcal{CP}}(\Delta t) \equiv \frac{I(\pi\pi,\ell^+;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)}$$

$$\mathcal{DR}_{\mathcal{CPT}}(\Delta t \gg \tau_S) \equiv \frac{R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t \gg \tau_S)} \qquad \mathcal{DR}_{\mathcal{T},\mathcal{CP}}(\Delta t \gg \tau_S) \equiv \frac{R^{\rm exp}_{2,\mathcal{T}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\mathcal{T}}(\Delta t \gg \tau_S)} \equiv \frac{R^{\rm exp}_{2,\mathcal{CP}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\mathcal{CP}}(\Delta t \gg \tau_S)}$$

Corresponding to study the following processes at KLOE:

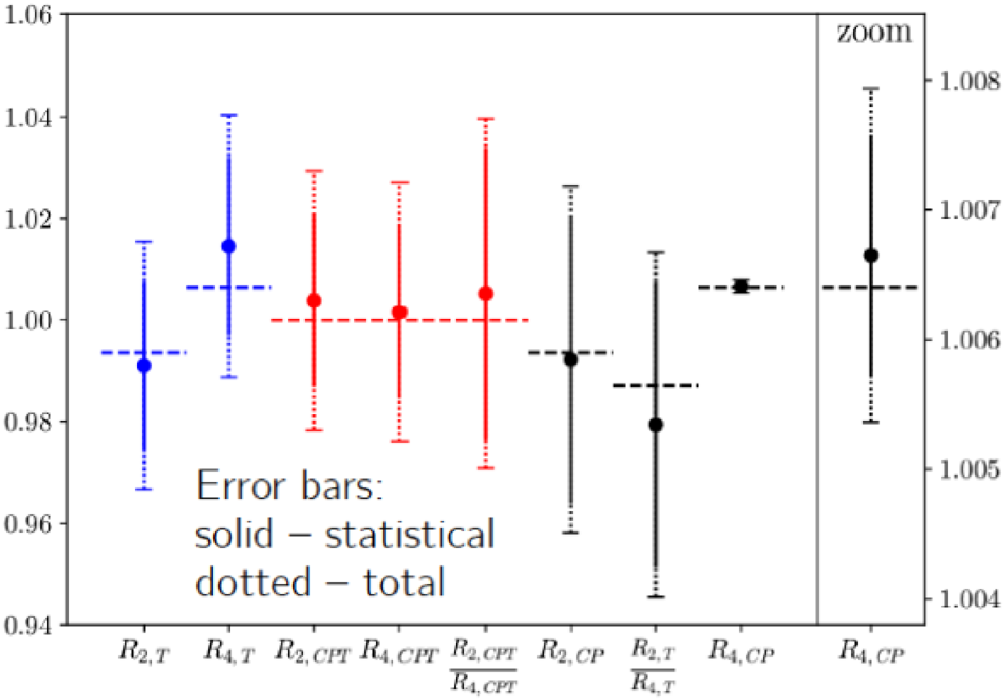


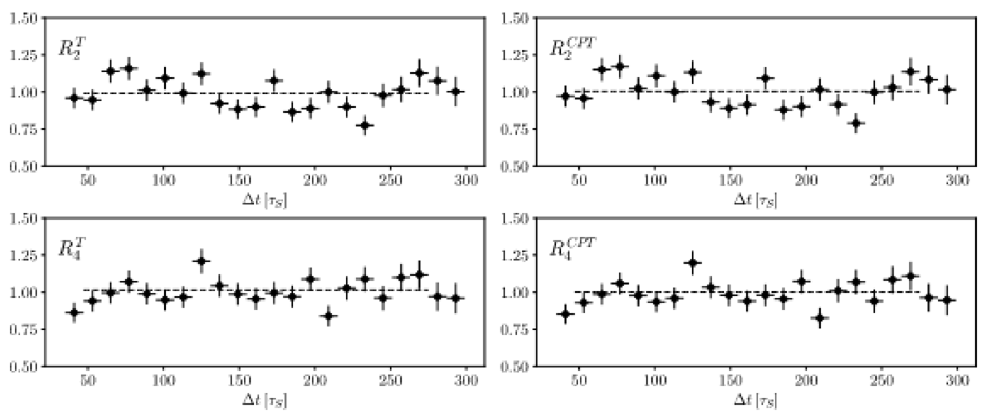




T, CP, CPT tests in neutral kaon transitions at KLOE

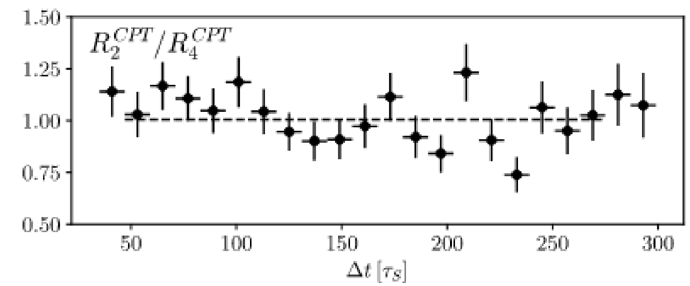
horizontal dashed lines denote expected values:
CPT invariance and TV extrapolated from observed CPV (PDG)





KLOE-2 result (2022)
(paper in preparation)

$$R_2^T = 0.991 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D,$$
$$R_4^T = 1.015 \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_D,$$
$$R_2^{CPT} = 1.004 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_D,$$
$$R_4^{CPT} = 1.002 \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_D,$$
$$R_2^{CP} = 0.992 \pm 0.028_{stat} \pm 0.019_{syst},$$
$$R_4^{CP} = 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst},$$
$$R_2^T/R_4^T = 0.979 \pm 0.028_{stat} \pm 0.019_{syst},$$
$$R_2^{CPT}/R_4^{CPT} = 1.005 \pm 0.029_{stat} \pm 0.019_{syst}.$$

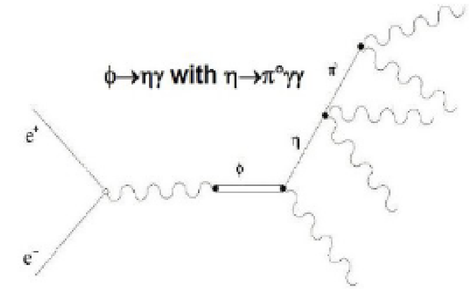


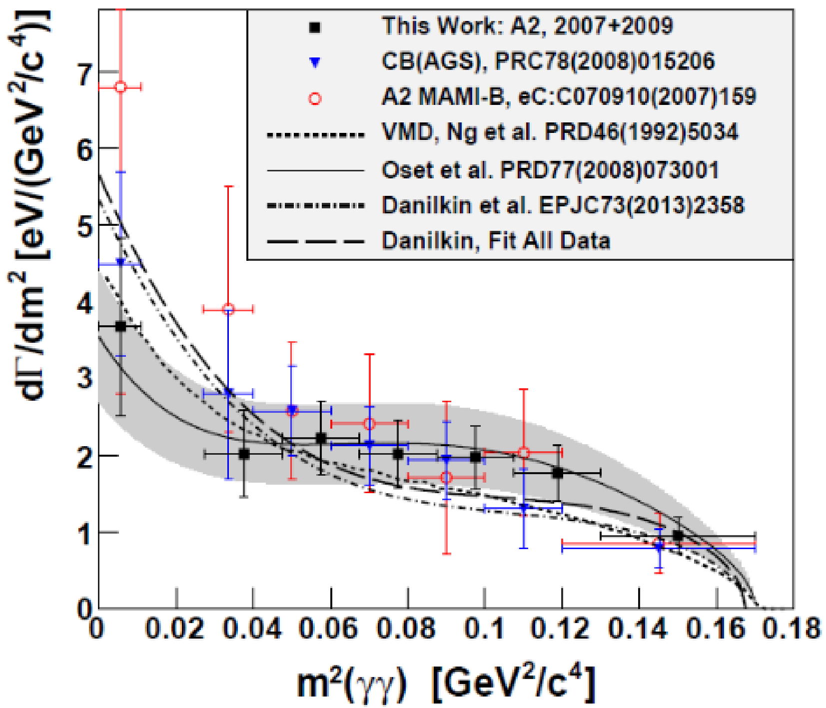
First T and CPT test in kaon transitions

Hadron physics

$\eta \to \pi^0\gamma\gamma$

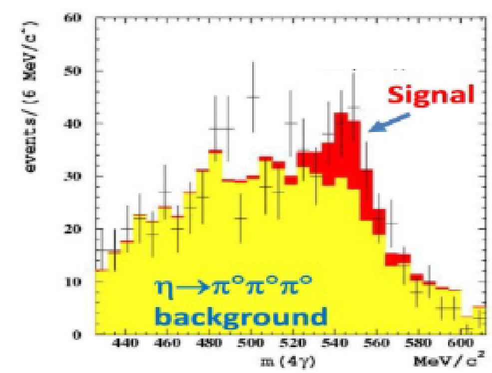
- $\eta\to\pi^0\gamma\gamma$ (from $\phi\to\eta\gamma$): χPT golden mode,
  - $O(p^2)$ null, $O(p^4)$ suppressed $\Rightarrow$ sensitive to $O(p^6)$
- Mass of non-π^0 photons can be used as a test of theoretical models





Previous measurements:

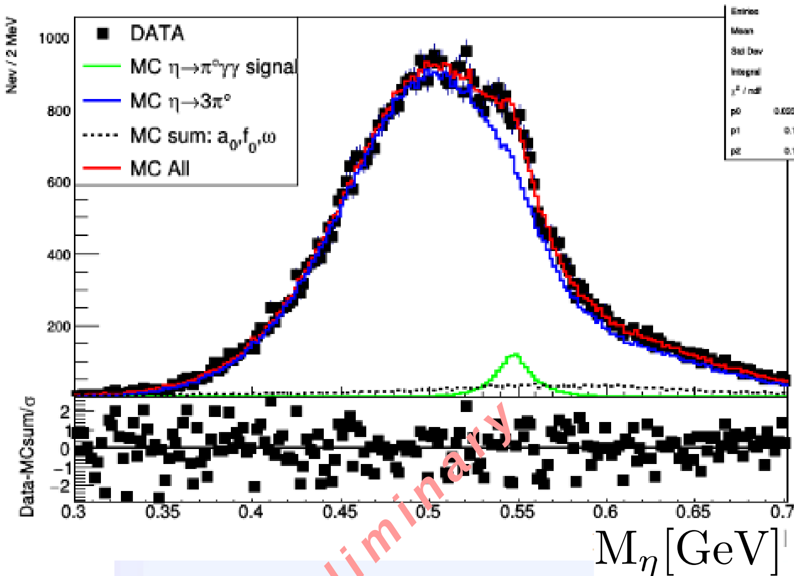
- **BR = $(22.1 \pm 2.4 \pm 4.7) \times 10^{-5}$ CB@AGS (2008) *[PRC 78 (2008) 015206]***
- **BR = $(25.6 \pm 2.4) \times 10^{-5}$ CB@MAMI (2014) A2 MAMI *[PRC 90 (2014) 025206]***
  - **Sample of ~$6\cdot10^7$ η's**
  - **~1200 $\eta\to\pi^0\gamma\gamma$ events found**
- **Old KLOE preliminary: $(8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$**
  - **(L = 450 pb^{-1} ~ 70 signal events) [*B. Di Micco et al, Acta Phys. Slov. 56, 403 (2006)]***



[B. Di Micco et al, Acta Phys. Slov. 56, 403 (2006)]

- Latest theoretical studies by Escribano et al [PRD 102 (2020) 034026]
  - Calculated BR = $1.30(8) \cdot 10^{-4}$
- Many previous predictions differ by a factor ~2

$\eta \rightarrow \pi^0\gamma\gamma$



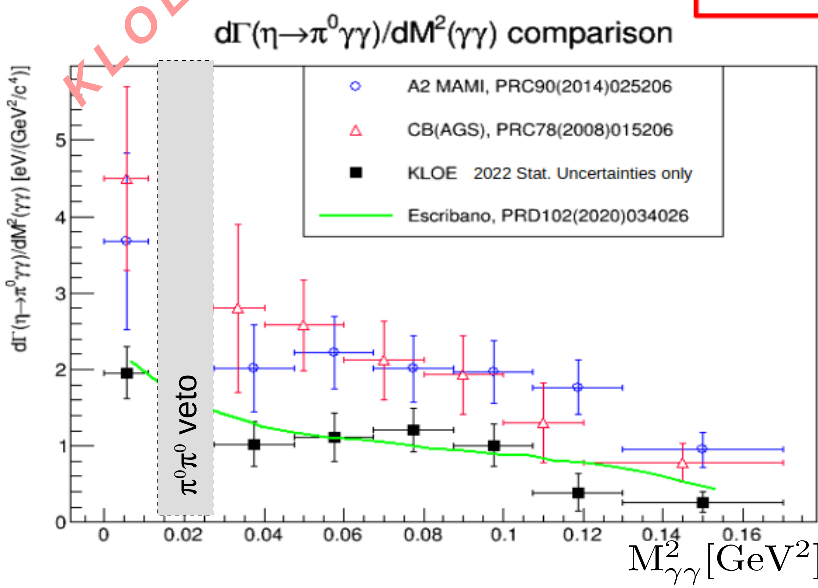
- Integrated luminosity of 1.7 fb^{-1} (~$7\cdot10^{7}$ η's)
- 5γ sample selected
- Data distribution fit with three MC components:
  - $\eta\rightarrow3\pi^0$,
  - $\eta\rightarrow\pi^0\gamma\gamma$ signal
  - Sum of non-3pi^0
- Fit χ^2/(ndf=98)=1.033 (fit_prob=39%)

Normalized with $\eta\rightarrow 3\pi^0$ (7γ sample) to reduce systematic

KLOE-2 Preliminary

$$\frac{BR(\eta\rightarrow\pi^0\gamma\gamma)}{BR(\eta\rightarrow3\pi^0)} = \frac{N_S/\varepsilon_S}{N_{3\pi^0}/\varepsilon_{3\pi^0}}$$

$$\mathbf{BR = (1.21 \pm 0.13_{stat} \pm 0.25_{syst}) \cdot 10^{-4}}$$

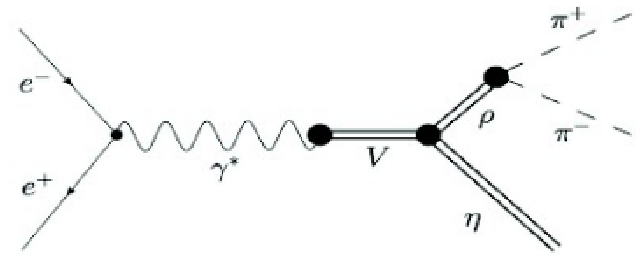


Separate fits to M^2(γγ) slices
Significantly lower (~1/2) compared with other experiments
confirms old KLOE preliminary result

Escribano et al. ***[PRD 102 (2020) 034026]***
(BR=1.30(8)$\cdot10^{-4}$) reproduce our data

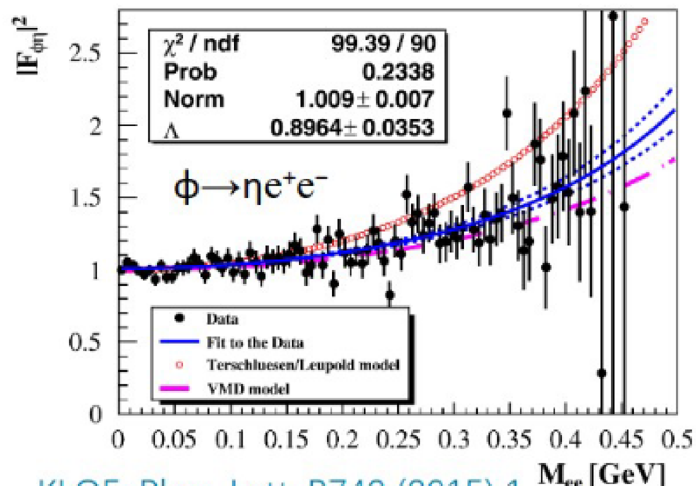
$\varphi \to \eta\ \pi^+\pi^-$, $\eta\mu^+\mu^-$

- **In VMD model, $e^+e^- \to \eta\pi^+\pi^-$ proceeds via ρ resonances, mainly via ρη intermediate state. KLOE/KLOE-2 data allow to measure the line shape around ϕ**



- **$\varphi \to \eta\pi^+\pi^-$ violates the OZI rule and G-parity**
  - **VMD predicts the Br~ 0.35×10^{-6}.**
  - **Br<1.8×10^{-5} @ 90% CL @ CMD-2 *PLB491(2000)81***

- **The same sample can be also used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$**
  - **Br<0.94×10^{-5} @ 90% CL @ CMD-2 *PLB501(2001)191***
  - **Investigate the transition form factor**

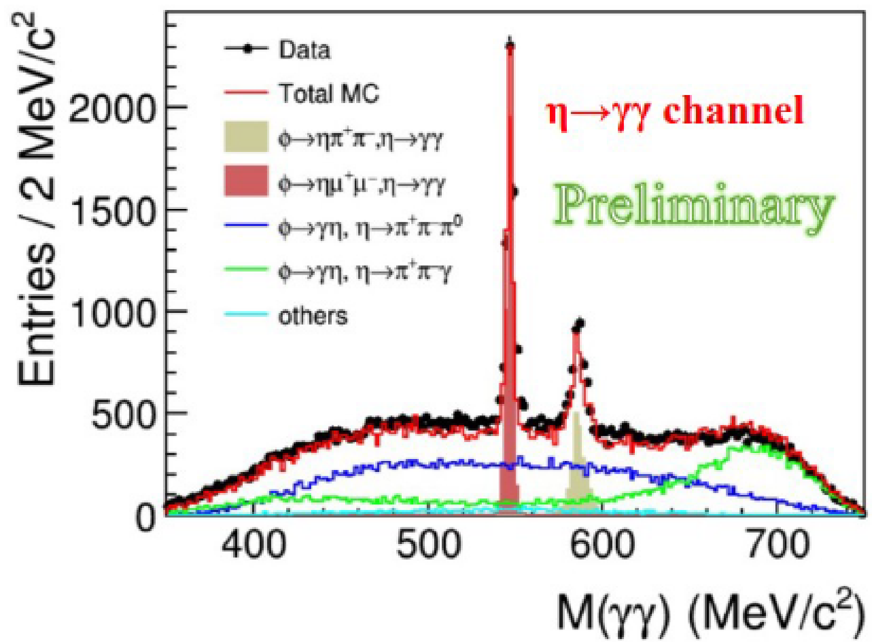


KLOE: Phys. Lett. B742 (2015) 1

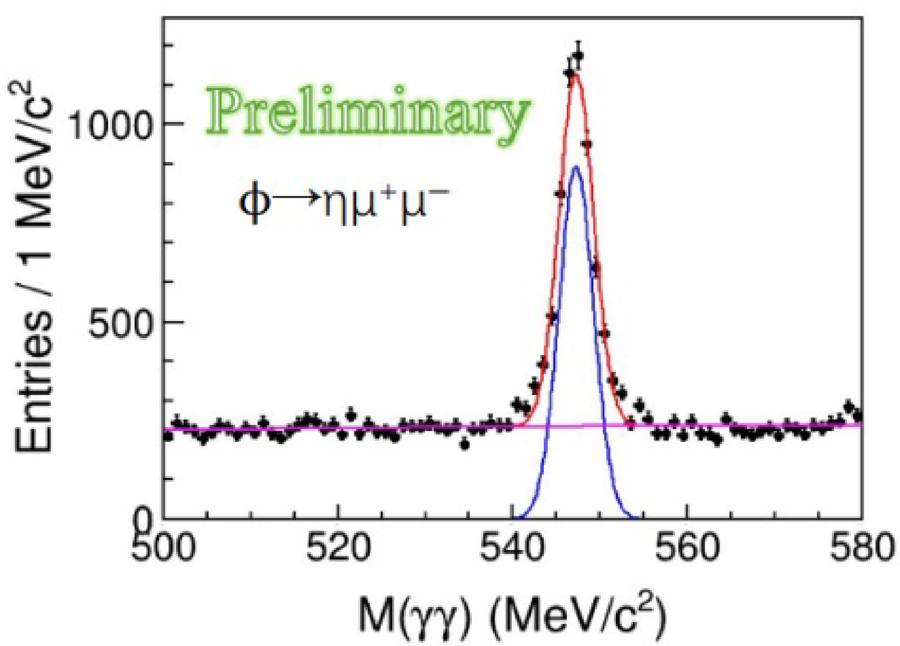
$$\frac{1}{\Gamma(\phi\to\gamma\eta)}\frac{d\Gamma(\phi\to\eta\mu^+\mu^-)}{dq^2} = |F_{\phi\eta}(q^2)|^2 \times \frac{\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4M_\mu^2}{q^2}}\left(1+\frac{2M_\mu^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{M_\phi^2-M_\eta^2}\right)^2-\frac{4M_\phi^2 q^2}{(M_\phi^2-M_\eta^2)^2}\right]^{3/2}$$

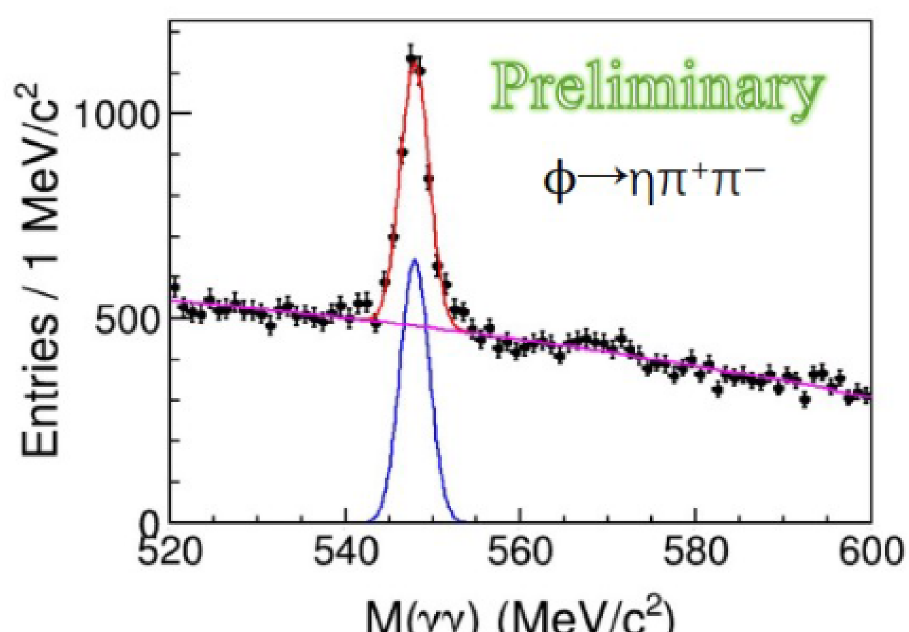
$\varphi \to \eta\ \pi^+\pi^-$, $\eta\mu^+\mu^-$

- **1.7 fb^{-1} data analyzed**
- **Clear signals for both $e^+e^- \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$**
- **Ongoing analysis**



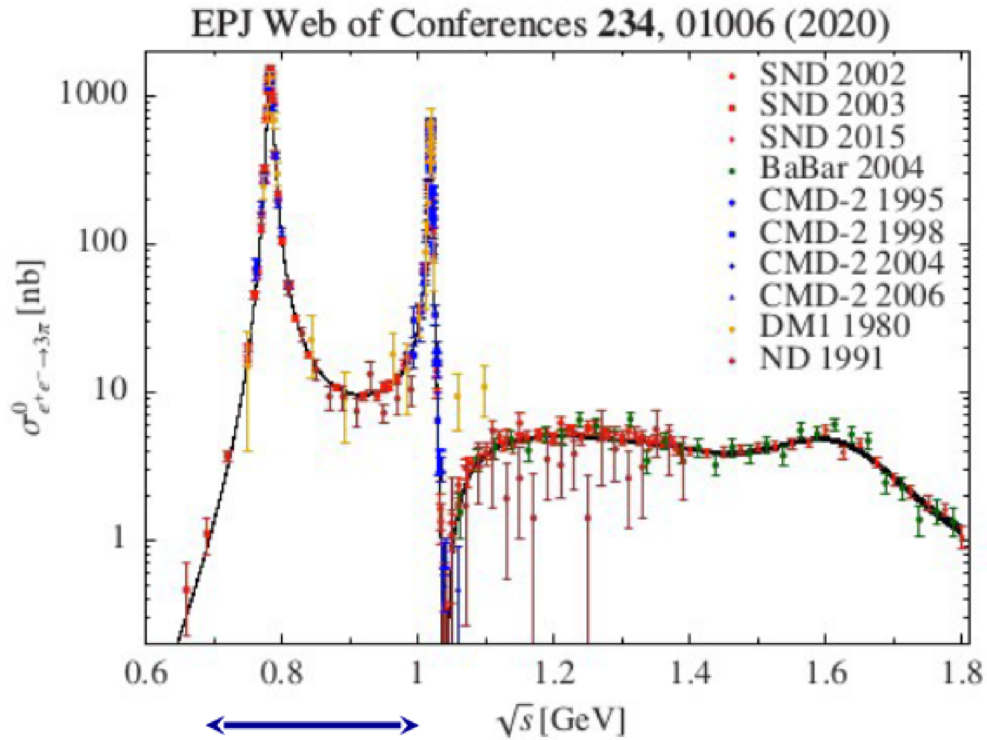
clear $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ signals





$e^+e^- \to \pi^+\pi^-\pi^0\,\gamma_{ISR}$ cross section measurement

- $e^+e^-\to\pi^+\pi^-\pi^0$ is the **second largest contribution** to the calculation of the **Hadronic Vacuum Polarization for $(g-2)_\mu$** and to its uncertainty
- Initial State Radiation (**ISR**) measurement at KLOE is **complementary to energy scan** in the range $\sqrt{s} < M_\phi$ (SND and CMD-2)



Current measurement by
CMD-2/SND via energy scan
BES3/BaBar via ISR

Goals:

- Measure the cross section in the $\omega(782)$ region
- Evaluate the product $Br(\omega\to e^+e^-) \times Br(\omega\to\pi^+\pi^-\pi^0)$

$e^+e^- \to \pi^+\pi^-\pi^0 \gamma_{ISR}$ cross section measurement

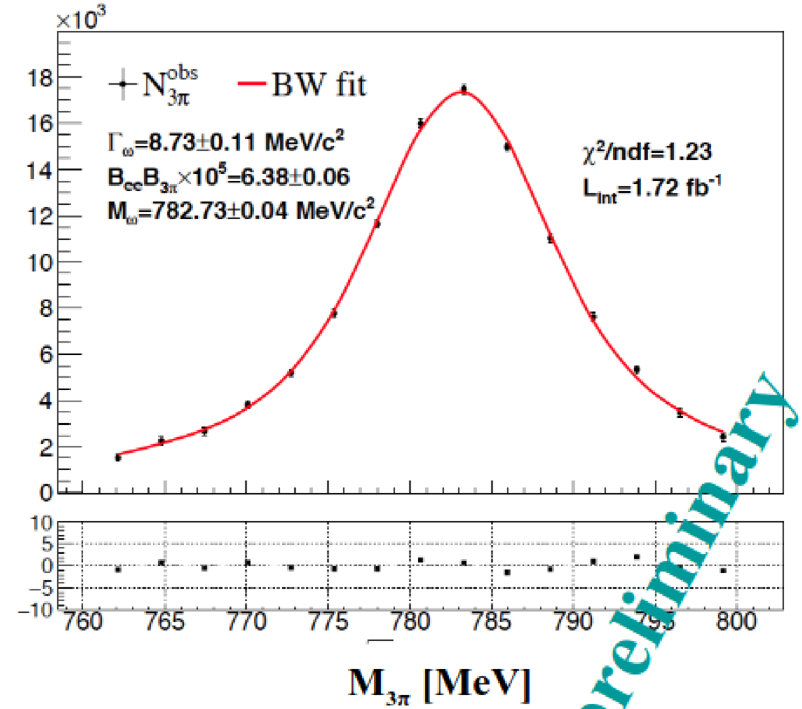
L = 1.7 fb^{-1} at φ peak

Selection:

- **At least 2 tracks with opposite curvature**
- **3 neutral clusters**
- **Kinematic fit**

Signal extraction:

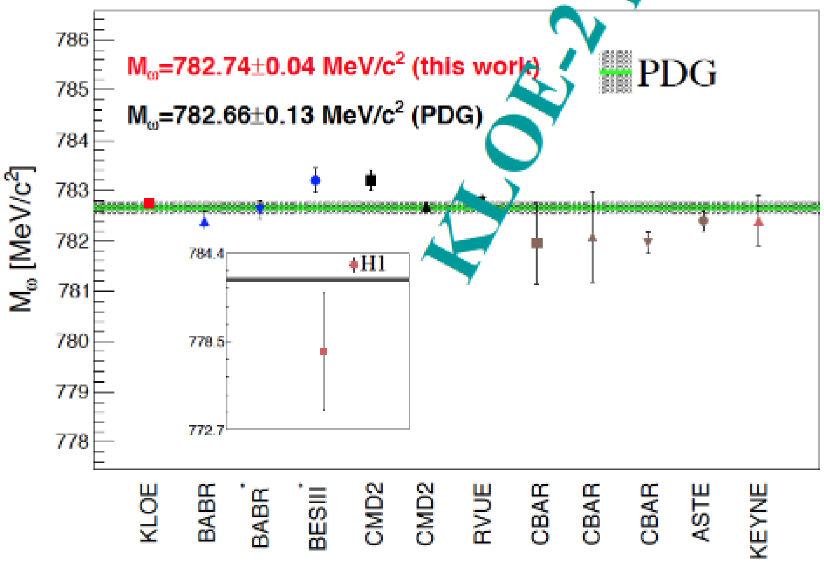
- **Fit with Breit-Wigner convoluted with simulated resolution**
- **ISR correction factor taken into account**



KLOE results* compared with PDG

	M_ω [MeV/c²]	Γ_ω [MeV]	$\mathcal{B}_{ee}\times\mathcal{B}_{3\pi}$ [10^{-5}]
KLOE	782.73 ± 0.04	8.73 ± 0.11	6.38 ± 0.06
PDG	782.66 ± 0.13	8.68 ± 0.13	6.60 ± 0.16

*** Only stat. uncertainty**



Leptophobic B-boson

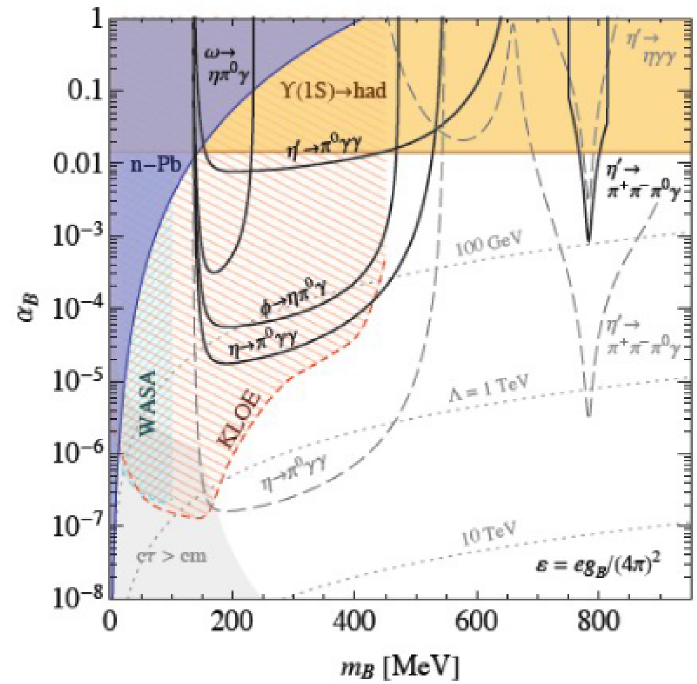
- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the ω(782) ⇒ $I^G=0^-$

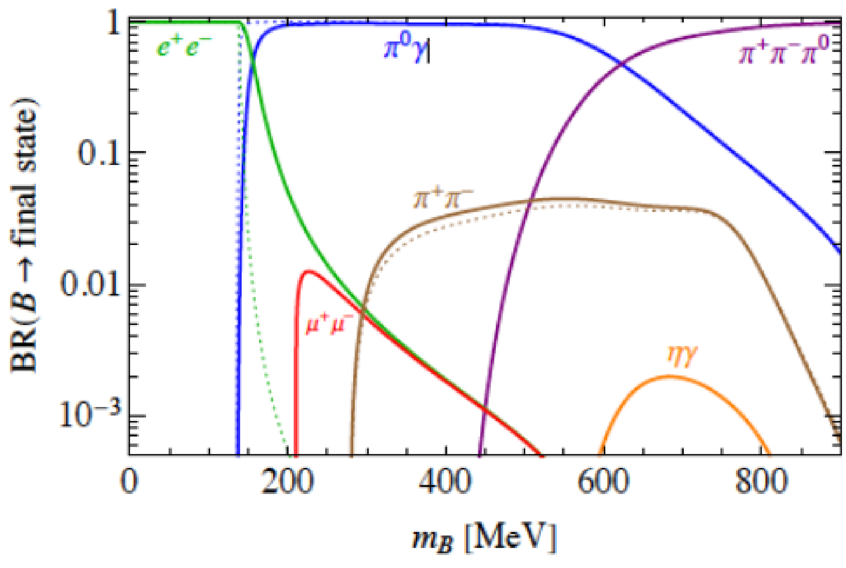
$$\mathcal{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu \qquad \alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\,\mathrm{MeV})$$

- Dominant decay channel (m_B < 600 MeV): $B \to \pi^0\gamma$
- Can be studied in:

$\phi \to \eta B$ ⇒ $\eta\pi^0\gamma$ ⇒ 5 prompt γ final state
$\eta \to B\gamma$ ⇒ $\pi^0\gamma\gamma$ “ “
$e^+e^- \to \pi^0\gamma\ \gamma_{ISR}$

[Tulin, PRD89(2014)114008]

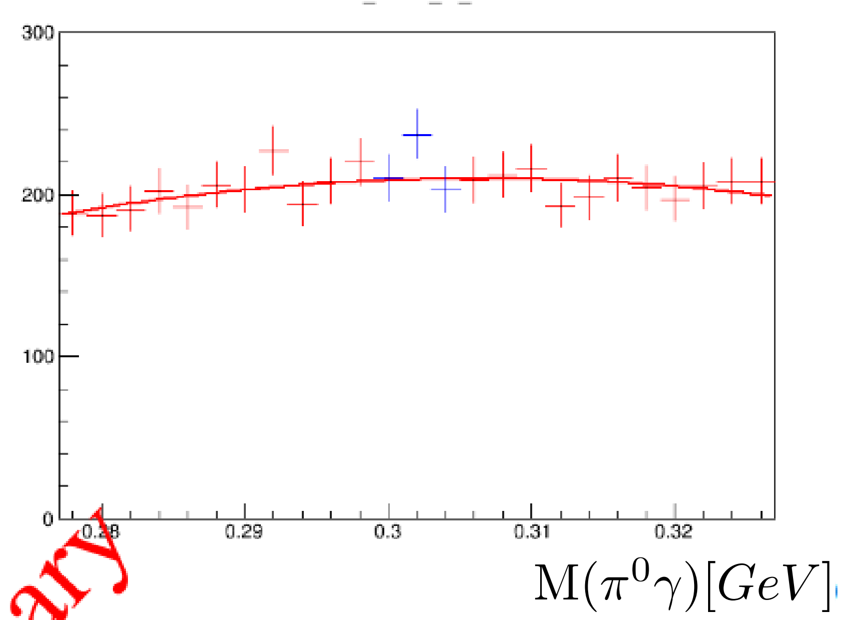




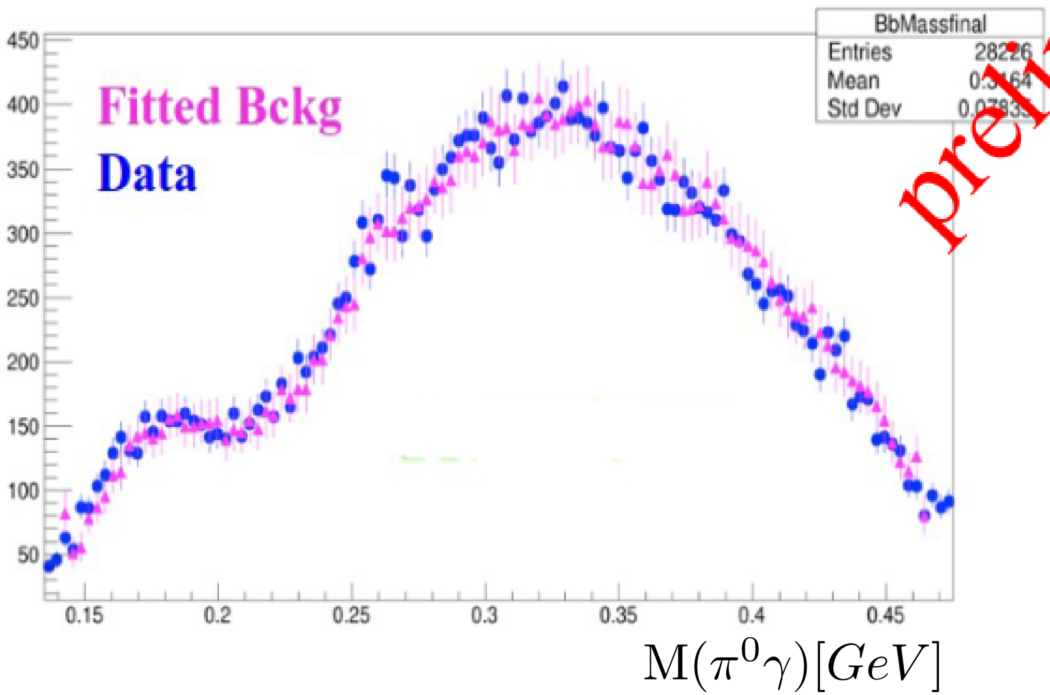
Decay → Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	···	···	···
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	···	···
$\eta' \to B\gamma$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

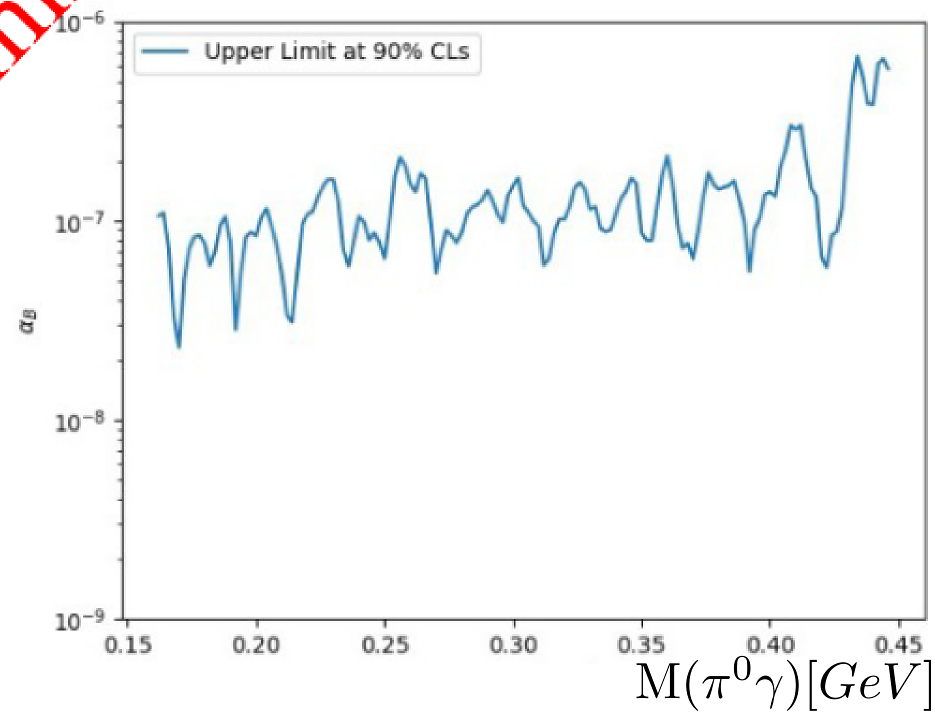
Leptophobic B-boson

- **Study on ~1.7 fb^{-1} KLOE data sample**
- **Background evaluation from sidebands**
- **Selection of 5 prompt γ's**
- **Kinematic fit to improve energy resolution**
- **Main residual background**
  from $\phi \rightarrow a0\gamma \rightarrow \eta\pi^0\gamma$ and $\phi \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma$ with lost or merged photons.
- **No signal is observed**
  - **Upper limit calculation**
  - **Upper limit in number of events at 90% CLs sets limits on the coupling constant α_B at O(10^{-7})**



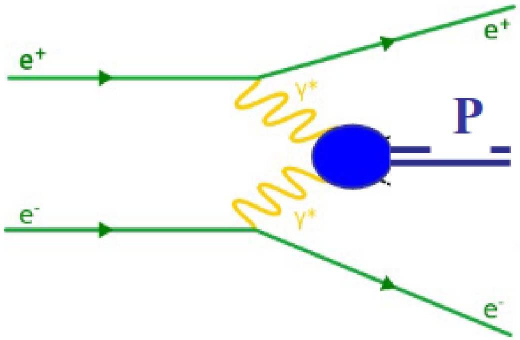
preliminary



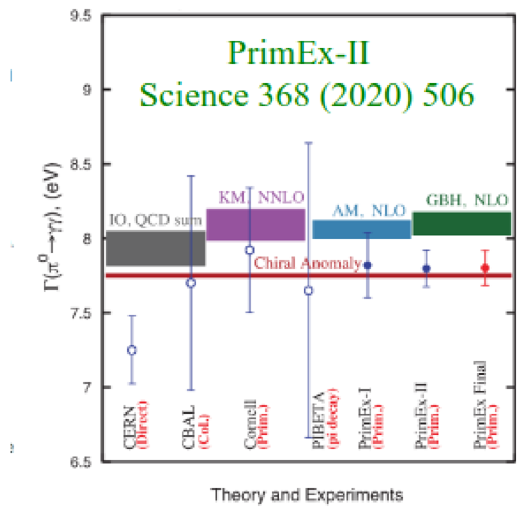


$\gamma^*\gamma^* \to \pi^0$ analysis strategy

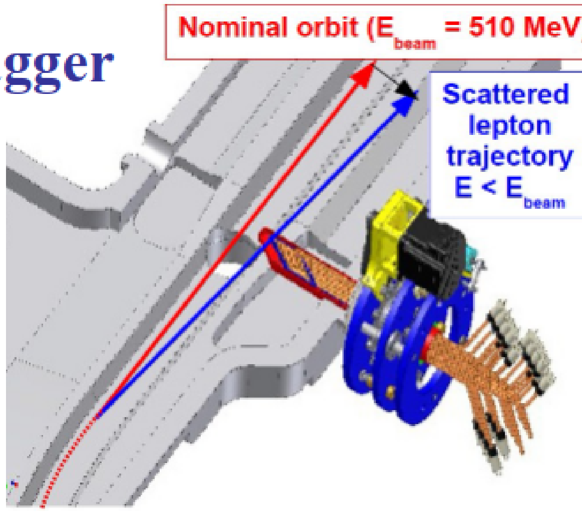
$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\mathbf{P} \quad [\mathbf{C}(\mathbf{P}) = +1]$$



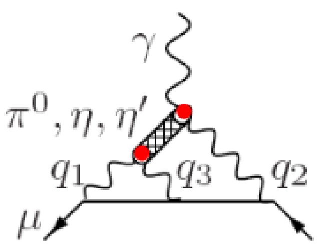
Goal: measurement of $\Gamma(\pi^0 \to \gamma\gamma)$ @ few % level



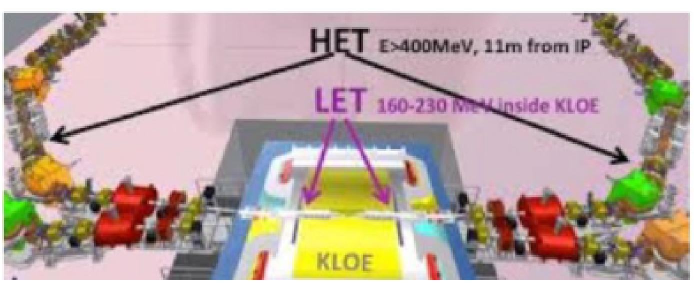
HET: e^+/e^- tagger

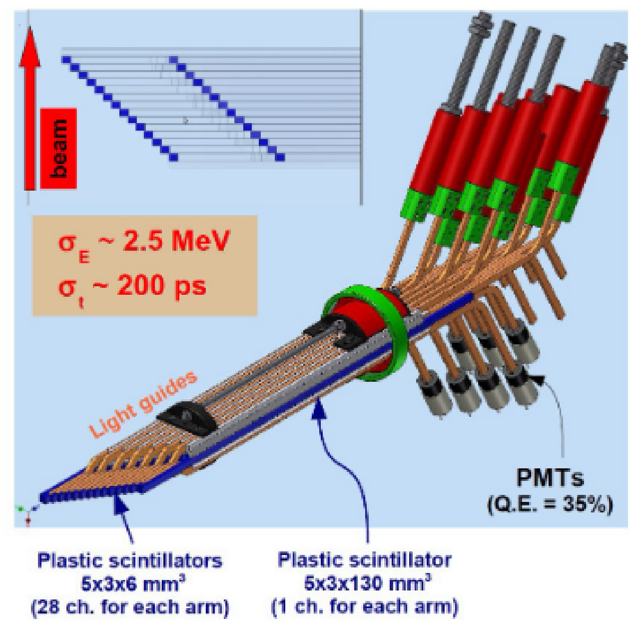


- **Transition Form Factor $F_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2| < 0.1$ GeV^2), relevant for the Light-by-Light scattering contribution to $(g-2)_\mu$**



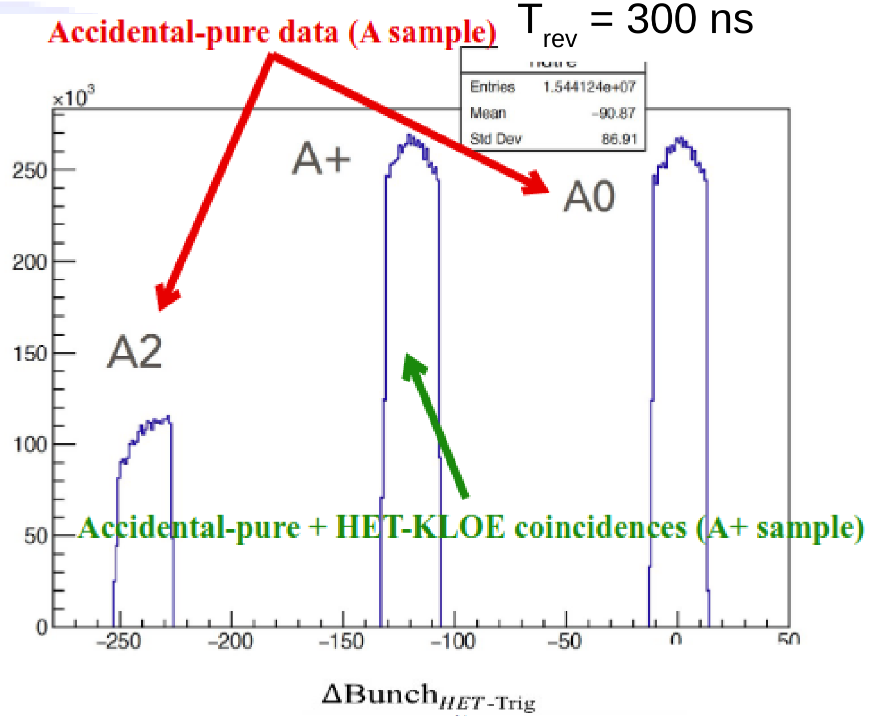
High energy tagger (HET) located 11 m away the IP after the bending dipoles acting like spectrometer for scattered e+/e- (420<E<495 MeV)





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

$\Delta T(\text{crossing}) = 2.5$ ns
$T_{rev} = 300$ ns



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

Analysis Strategy:

-ML fits of A+/A samples.

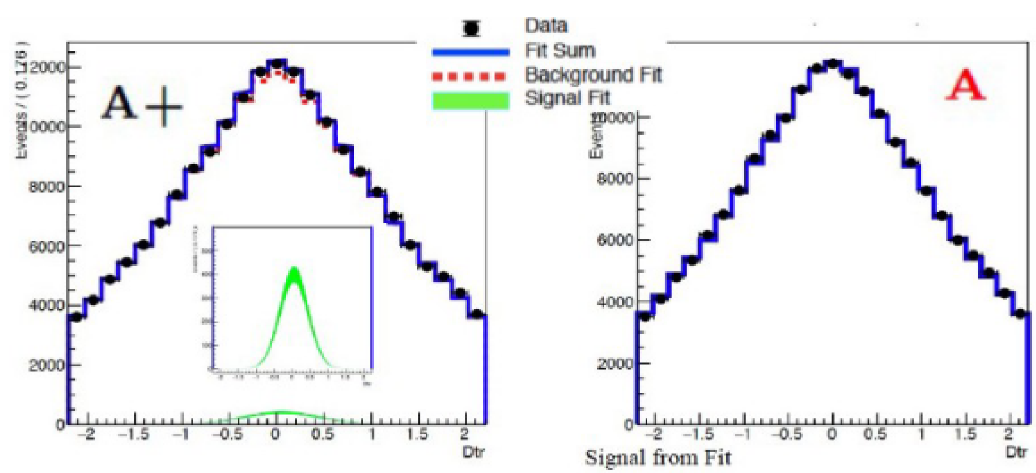
-Fit to accidental−pure samples used to constrain the number of accidentals in A+

-Time coincidence window : 4 ÷ 5 bunch crossings depending on the period

-Accidental pure sample (A) used to model background pdf

-Signal pdfs by Ekhara simulation, control samples and BDSIM transport of the leptons through the beam line

Simultaneous fit of A+ signal rich and A samples

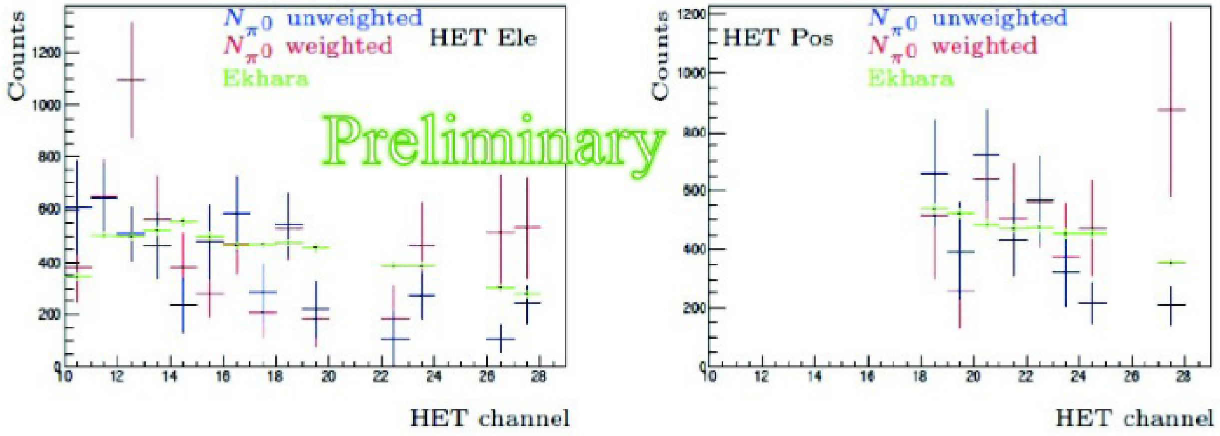


$\gamma^*\gamma^* \to \pi^0$ analysis preliminary results

$$\frac{\sigma_{\pi^0}}{\sigma_{\text{Bha}}} = \frac{N_{\pi^0}^{\text{meas}}}{\epsilon_{\text{ana}}\, N_{\text{Bha}}^{\text{meas}}} \frac{A_{\text{Bha}}}{A_{\pi^0}}$$

$$N_{\text{Bha}}^{\text{meas}} = \sigma_{\text{Bha}}^{\text{meas}} \int \mathbf{Ldt}$$

The number of tagged π^0 with 3 fb^{-1} data



- ✓ $N_{\pi 0}$ counting: final checks on weights ongoing
- ✓ Normalize to Radiative Bhabha at very small angle
- ✓ $\sigma_{\text{Bha}}^{\text{meas}}$ is measured at few % level
- ✓ Luminosity measurement from KLOE online and cross-checks with $e^+e^- \to \gamma\gamma$
- ✓ ε_{ana}: Analysis efficiency evaluation completed
- ✓ $A_{bha}/A_{\pi 0}$: Full simulation of signal and control sample, evaluated from Ekhara/BBBREM generator + BDSIM for lepton transport, **evaluation of systematics in progress**

Conclusions

- The KLOE-2 experiment at the upgraded DAFNE successfully completed its data taking campaign collecting L=5.5 fb^{-1} by the end of March 2018
- **KLOE+KLOE-2 data sample (~8 fb^{-1}) represents the largest sample ever collected at φ-meson peak**
- The **entangled neutral kaon system at a φ-factory is a unique laboratory** for the search for decoherence effects, the study of discrete symmetries, and KS physics:
  - **Improved search for decoherence and CPT violation effects** in $\varphi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ in same cases with a precision reaching the interesting Planck's scale region.
  - **First direct test of T and CPT symmetries in neutral kaon transitions**.
  - A **new measurement of the** $K_S \rightarrow \pi e \nu$ **branching fraction** and a new derivation of $f(0)\,|V_{us}|$
  - These results add up to previous studies on kaons, e.g. on $K_S \rightarrow \pi \mu \nu$, A_S and CPT and Lorentz symmetry tests.
- The data sample collected by KLOE provided important results on decay dynamics of light mesons, transition form factors, hadronic cross sections and also on searches for new physics in the Dark-Sector
- High precision investigation on light hadron physics with KLOE/KLOE-2 data are in progress
- Furter details on KLOE-2 physics program

KLOE-2 Physics programme
KLOE-2 Collaboration: EPJ **C68** (2010) 619
Proceedings: EPJ WoC 166 (2018)
https://agenda.infn.it/event/kloe2ws

Thank You!