The KLOE-2 experiment at DAΦNE

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on behalf of the KLOE-2 collaboration

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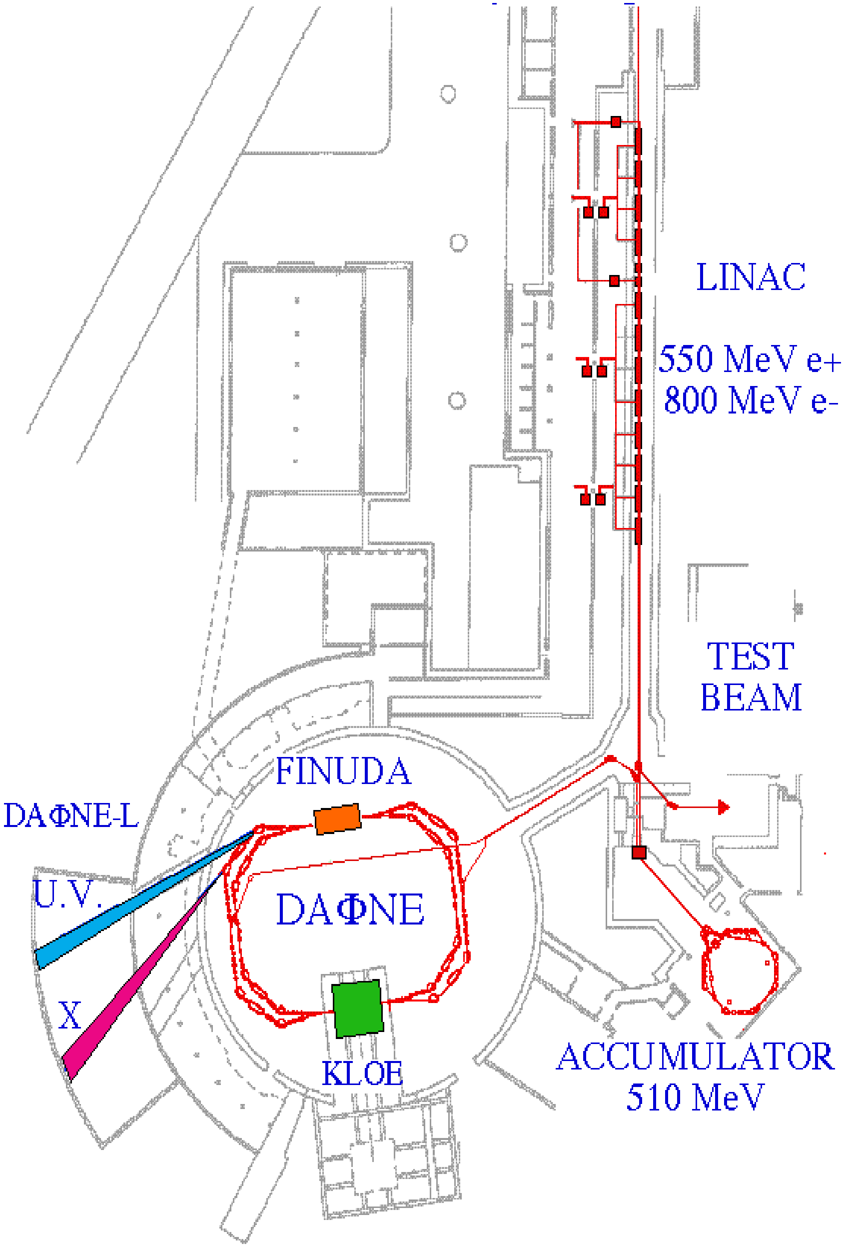
The DAFNE Φ-factory

- e^+e^- collider @ $\sqrt{s} = M_\varphi = 1019.4$ MeV
- LAB momentum $p_\varphi \sim 15$ MeV/c
- $\sigma_{peak} \sim 3\ \mu b$
- Separate e^+e^- rings to reduce beam-beam interaction



KLOE (K LOng Experiment)

Large cylindrical drift chamber

- Uniform tracking and vertexing in all volume
- Helium based gas mixture (90% He – 10% $IsoC_4H_{10}$)
- Stereo wire geometry

$\sigma_p/p = 0.4\ \%$

$\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2\ mm$

$\sigma_{vtx} \sim 3\ mm$

$\sigma(M_{\pi\pi}) \sim 1\ MeV$

Lead/scintillating-fiber calorimeter

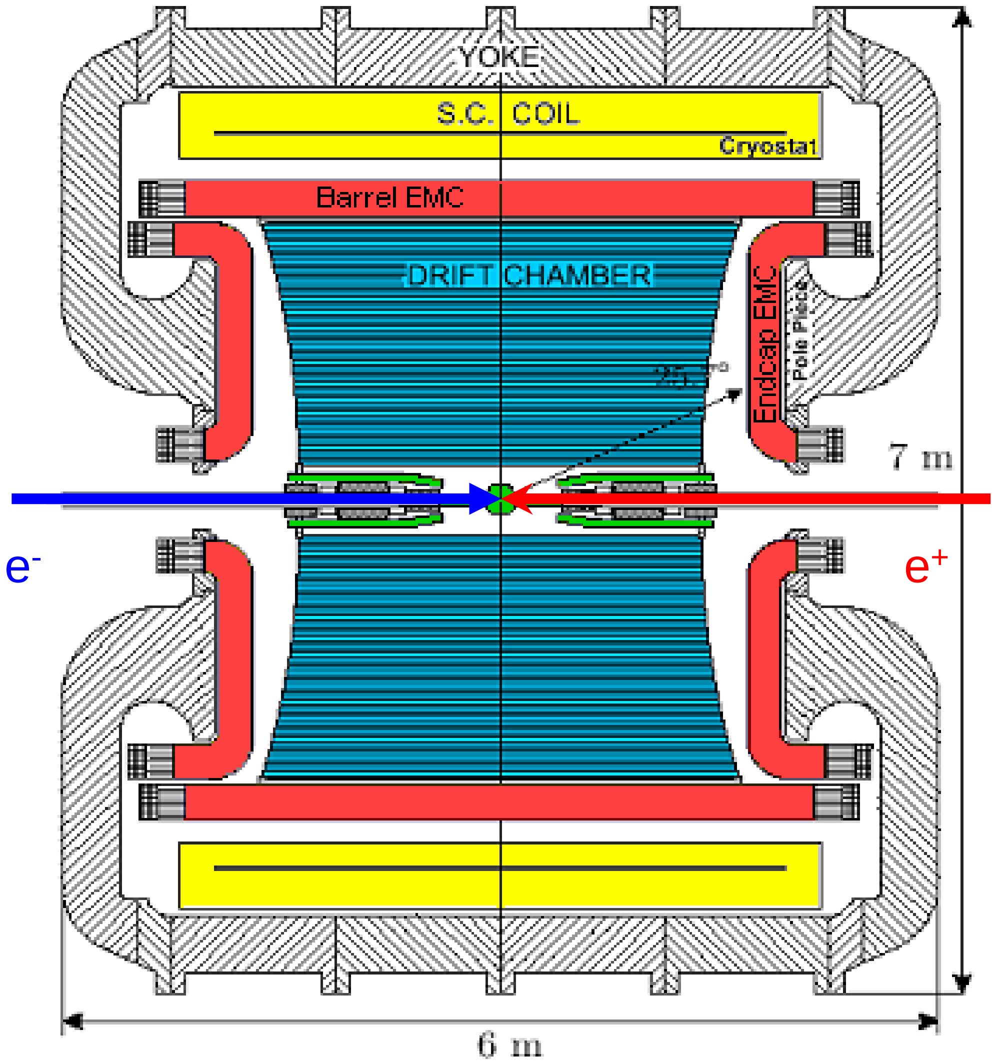
- Hermetical coverage
- High efficiency for low energy photons

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

$\sigma_t = 57\ ps / \sqrt{E(GeV)} \oplus 100\ ps$

Superconducting coil

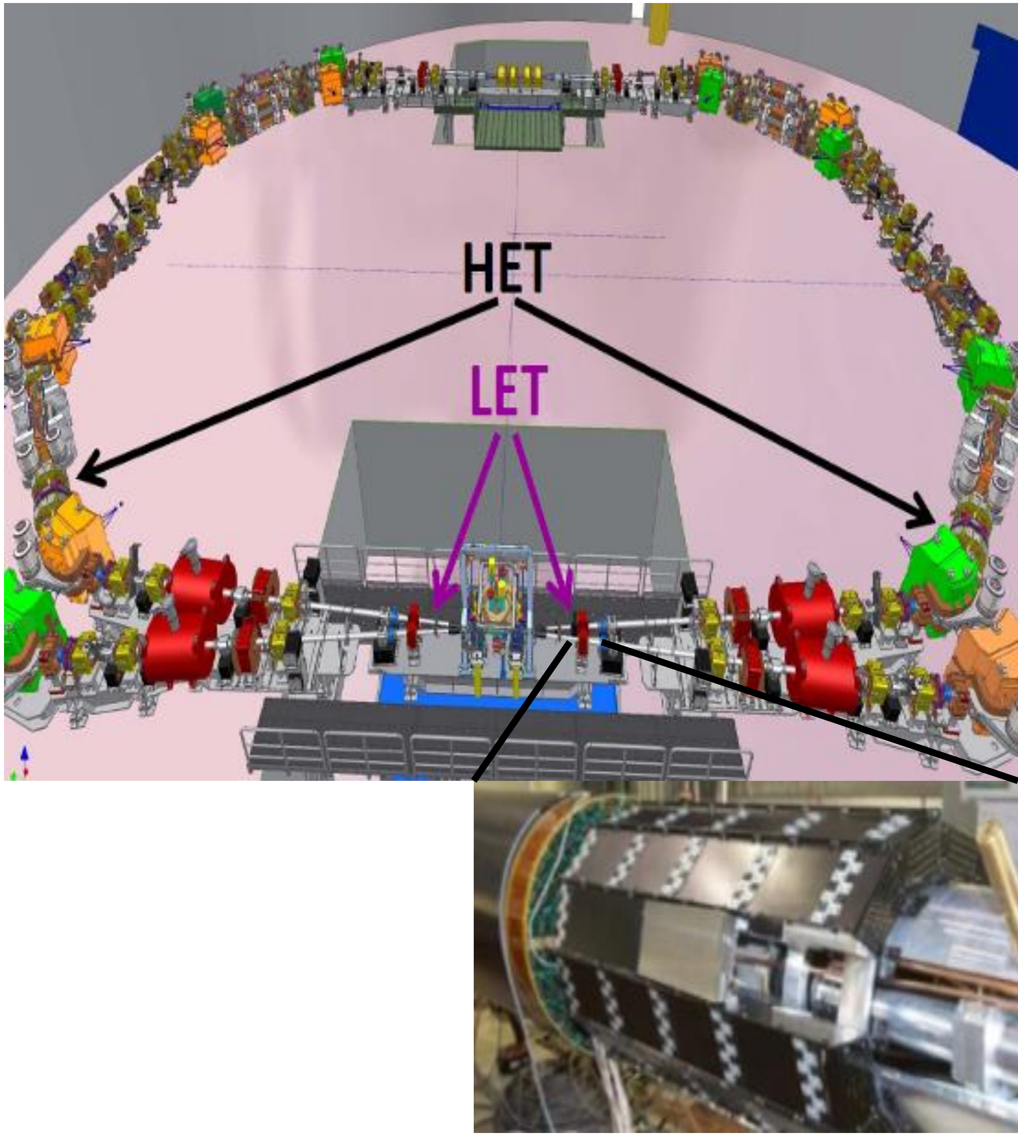
B = 0.52 T



- **Taggers for leptons momenta measurement in the $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$ reaction**

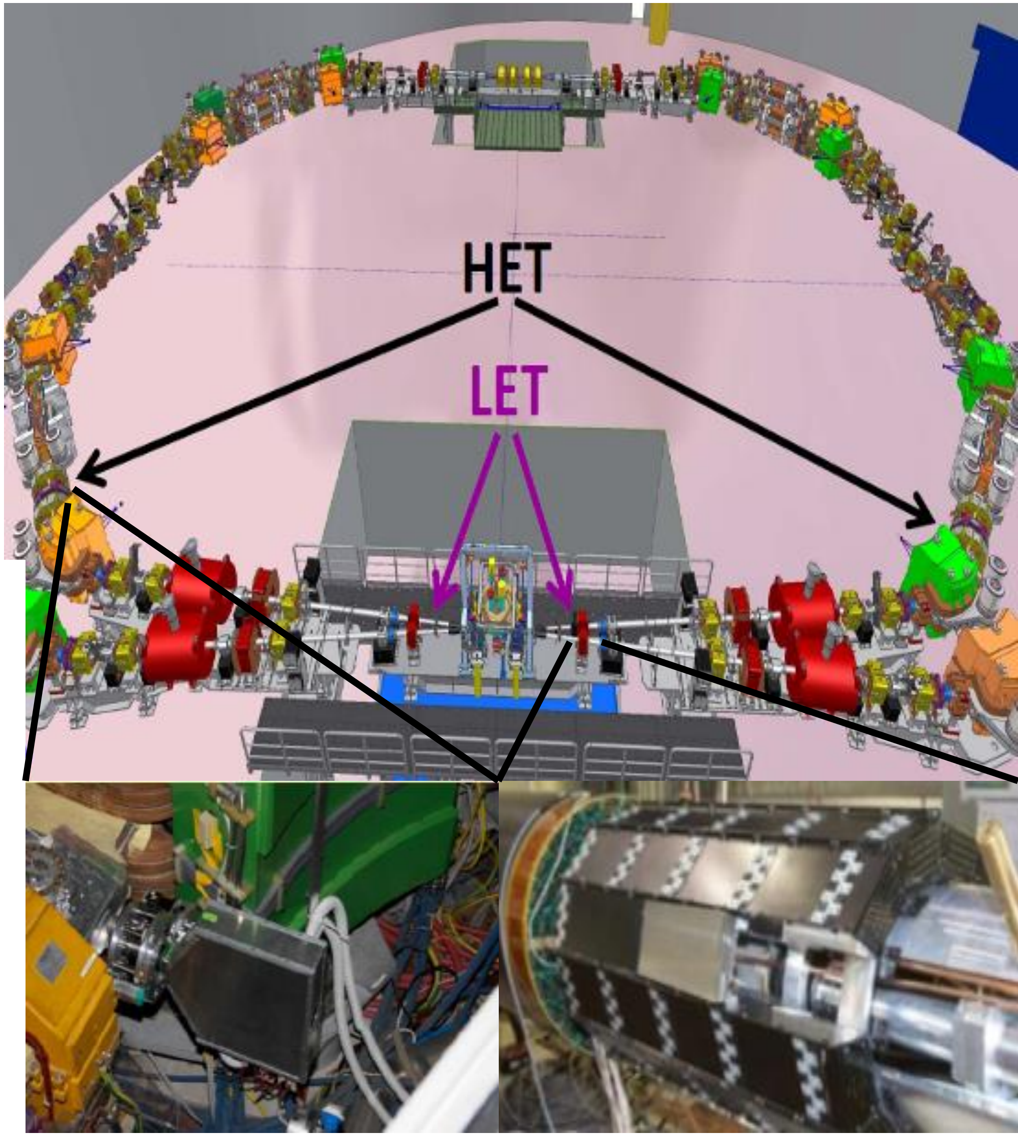
LET: $E_e \sim$ 150-400 MeV

- Inside KLOE detector
- 20 LYSO crystals in a matrix of 6 x 7.5 x 12 cm^3 readout by SiPM
- $\sigma_E/E<10\%$ for E>150 MeV



KLOE upgrades: γγ taggers

- Taggers for leptons momenta measurement in the $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$ reaction



LET: E_e ~ 150-400 MeV

- Inside KLOE detector
- 20 LYSO crystals in a matrix of 6 x 7.5 x 12 cm^3 readout by SiPM
- $\sigma_E/E<10\%$ for E>150 MeV

HET: E_e > 400 MeV

- Plastic scintillator hodoscopes
- Placed after first dipoles (11 m from IP)
- Capable to resolve the RF frequency on-line and cross-correlate the signal with KLOE trigger
- σ_E ~ 2.5 MeV; σ_T ~ 200 ps

Acta Phys. Pol. B 46, 81 (2015)
NIM A 617, 266 (2010)
NIM A 617, 81 (2010)

KLOE upgrades: IR detectors

QCALT

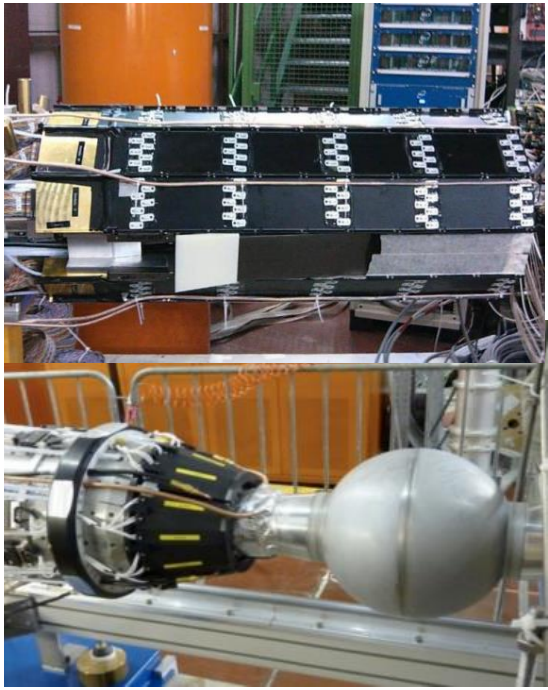
- Scintillator tiles +tungsten slabs red out by SiPM's
- Low-beta quadrupoles: coverage for K_L decays

CCALT

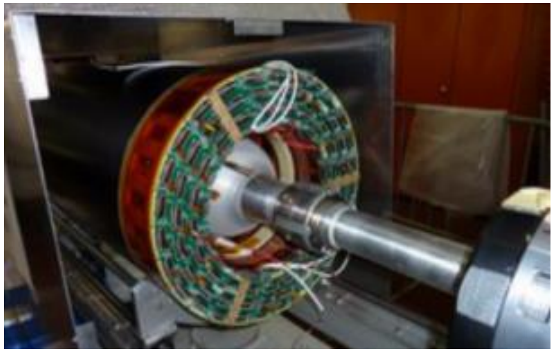
- LYSO crystals+ SiPM read-out
- Increase acceptance for γ's from IP (24°→11°)
- Can be used as fast luminometer for DAΦNE

INNER TRACKER

- First cilindrical GEM detector
- 4 layers with 700 mm active length
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks
- Increased sensitivity for the kaon interferometry measurements



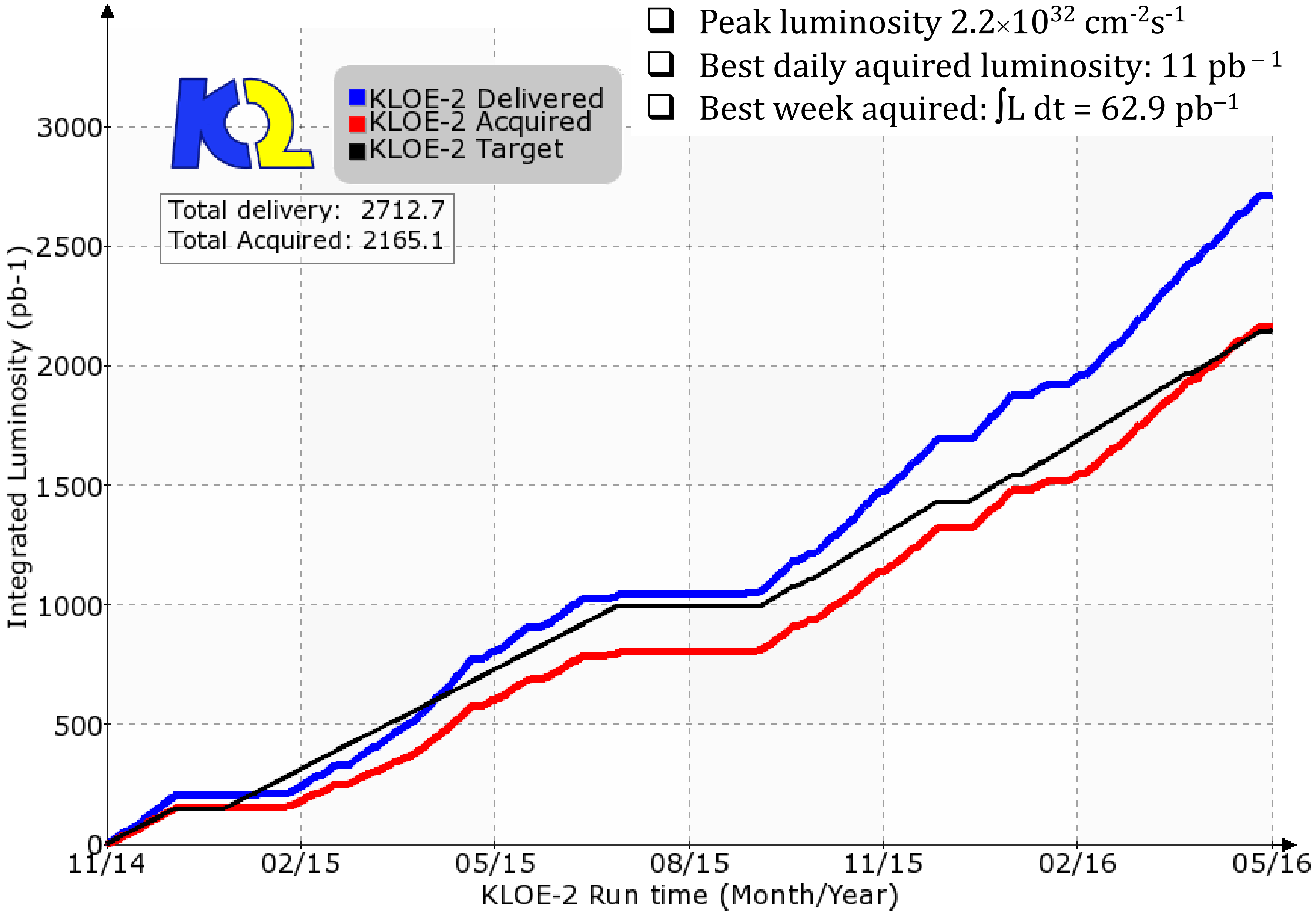
Acta Phys. Pol. B 46 , 87 (2015)
QCALT: NIMA 617, 105 (2010)
CCALT: NIM A 718 , 81 (2013)



Acta Phys. Pol. B 46, 73 (2015)
NIMA 628 (2011),194

KLOE-2 data-taking

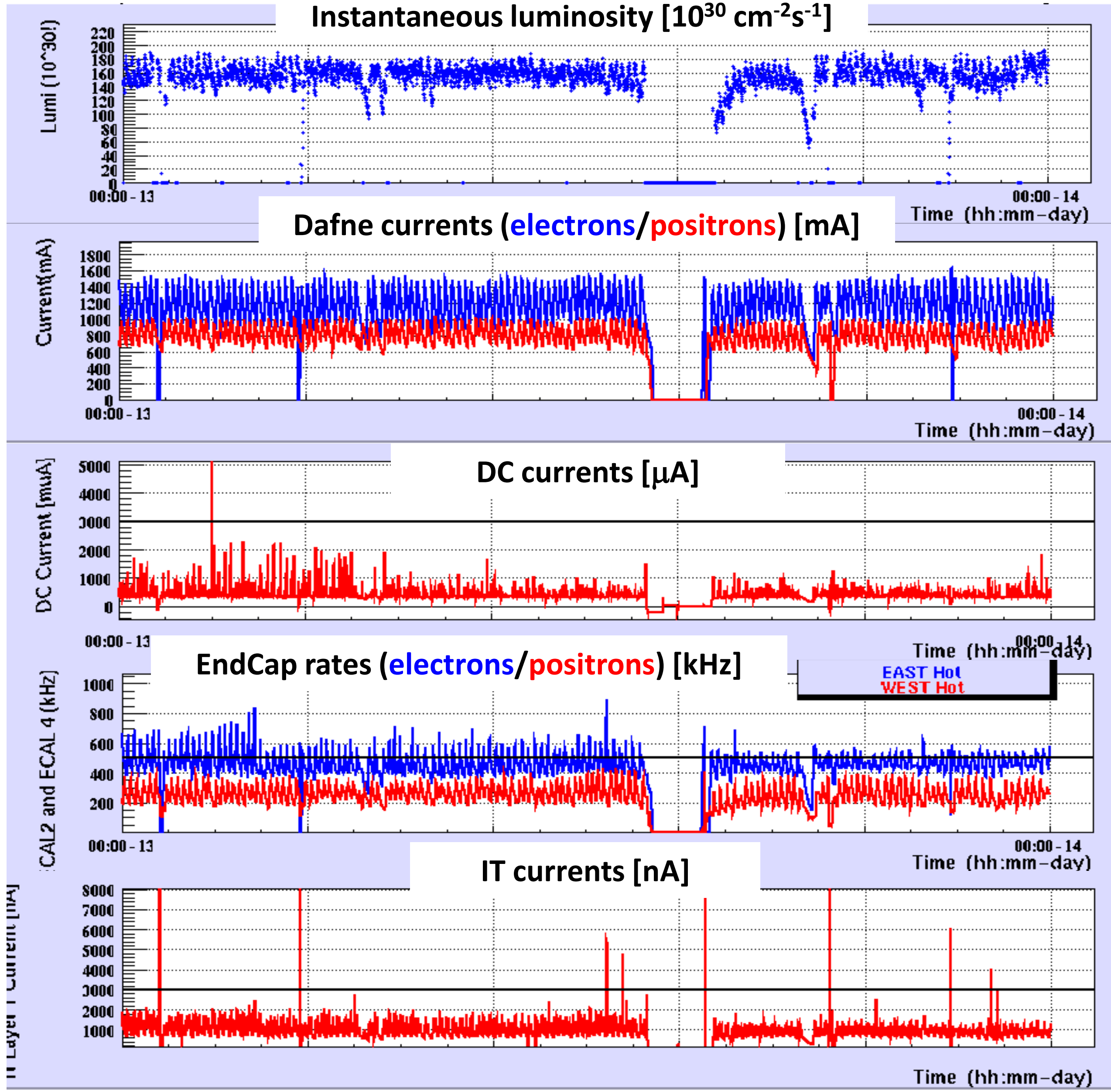
- Peak luminosity 2.2×10^{32} cm^{-2}s^{-1}
- Best daily aquired luminosity: 11 pb^{-1}
- Best week aquired: $\int L\,dt = 62.9$ pb^{-1}



KLOE-2 data-taking

- <u>One of the best days:</u> 13.01.2016

- <u>On average:</u>
- $L_{inst} > 1.8 \cdot 10^{32} cm^{-2}s^{-1}$
- ECAL rates ~ 500 kHz
- DC currents < 3 mA
- IT L1 currents < 3 μA



KLOE-2 Physics Program

❖ Goal: collect at least 5 fb^{-1} in the next 2 years to complete a rich physics program:

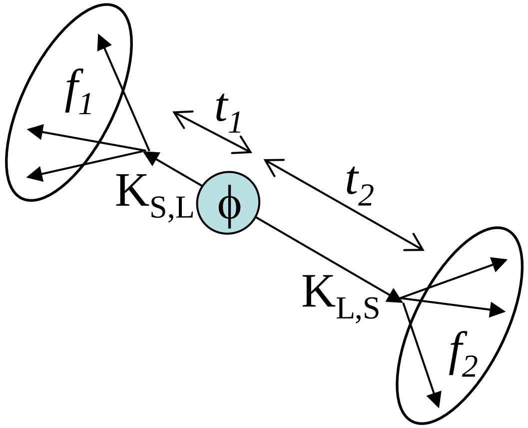
- **$\gamma\gamma$ physics**
  - π^0 width and $\pi^0 \rightarrow \gamma\gamma^*$ transition form factor in the space-like region
- **Light meson spectroscopy**
  - Properties of scalar/vector mesons
  - Rare η decays
  - η' physics
- **Kaon physics**
  - Test of CPT (and QM) in correlated kaon decays
  - Tests of CP & CPT in K_S decays
  - Test of SM (CKM unitarity, lepton universality)
  - Test of ChPT (K_S decays)
- **Dark forces searches** (Light bosons @ O(1 GeV))
- **Hadronic cross section** ($\alpha_{em}(M_Z)$ and (g-2))

[G.Amelino-Camelia et al., Eur. Phys. J. C 68 (2010), 619-681]

Kaon interferometry at the Φ-factory

➢ ϕ decays provide entangled kaons pairs:

$$|\phi> = \frac{1}{\sqrt{2}}\left(|K^0>|\overline{K^0}> - |\overline{K^0}>|K^0>\right) = N(|K_S(\vec{p})>|K_L(-\vec{p})> - |K_S(-\vec{p})>|K_L(\vec{p})>)$$



$$N = \frac{\sqrt{(1+|\varepsilon_S|^2)(1+|\varepsilon_L|^2)}}{(1-\varepsilon_S\varepsilon_L)}$$

➢ The intensity of kaon decays into final states f_1 and f_2 at proper times t_1 and t_2:

➢ **Complete destructive quantum interference prevents the two kaons from decaying into the same final state at the same time**

❖ Interference patterns for different kaon decays provide studies of different symmetries:

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

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

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

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

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

PLB 642(2006) 315
J.Phys.Conf.Ser.171(2009) 012008

CPT and Lorentz symmetry tests

$$I(\pi^+\pi^-,\pi^+\pi^-,\Delta\tau) \propto |\eta_1|^2 e^{\Gamma_L|\Delta\tau|} + |\eta_2|^2 e^{-\Gamma_S|\Delta\tau|} - 2|\eta_1||\eta_2| e^{\frac{-(\Gamma_S+\Gamma_L)}{2}|\Delta\tau|}\cos(\Delta m|\Delta\tau|)$$

$$\eta_{1(2)} = \varepsilon - \delta(\vec{p}_{K_{1(2)}})$$

- According to the SME and anti-CPT theorem, CPT violation should appear together with Lorentz Invariance breaking ⇒ direction dependent modulation of δ:

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

V. A. Kostelecký Phys. Rev. D 64, 076001, O. W. Greenberg Phys. Rev. Lett. 89, 231602

- KLOE obtained the best results for the CPT and Lorentz violation parameters and with new data we plan to increase further the sensitivity

$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{sys})\ 10^{-18}$ GeV
$\Delta a_x = (0.9 \pm 1.5_{stat} \pm 0.6_{sys})\ 10^{-18}$ GeV
$\Delta a_y = (-2.0 \pm 1.5_{stat} \pm 0.5_{sys})\ 10^{-18}$ GeV
$\Delta a_z = (3.1 \pm 1.7_{stat} \pm 0.6_{sys})\ 10^{-18}$ GeV

PLB 730 (2014) 89

Rare K_S decays & CPV

- $K_S \to \pi^0\pi^0\pi^0$: unambiguous sign of CP violation
- $K_S \to \pi^+\pi^-\pi^0$: CPV for for L=0,2, but contains also conserving amplitude

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0|H|K_S\rangle}{\langle \pi^0\pi^0\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{000} \qquad \eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0|H|K_S\rangle}{\langle \pi^+\pi^-\pi^0|H|K_L\rangle} = \varepsilon + \varepsilon'_{+-0}$$

- In the lowest order of the χPT: $\varepsilon'_{000} = \varepsilon'_{+-0} = -2\varepsilon'$

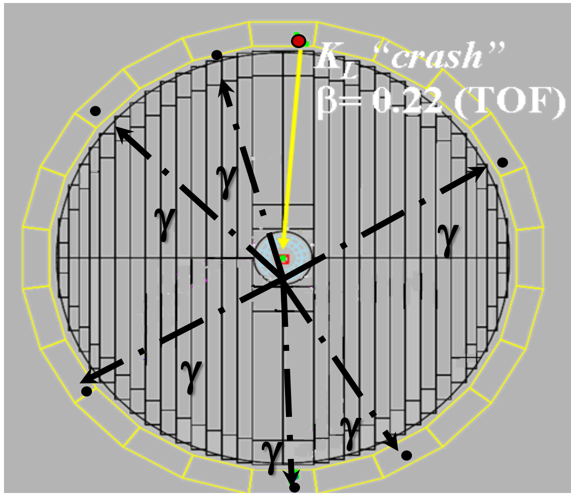
$$Im(\eta_{+-0}) = -0.002 \pm 0.009; \qquad Im(\eta_{000}) = (-0.1 \pm 1.6)\cdot 10^{-2}$$

- KLOE set the best upper limit on $|\eta_{000}|$:

$$BR(K_S \to 3\pi^0) < 2.6\cdot 10^{-8} \Rightarrow |\eta_{000}| = \sqrt{\frac{\tau_L\, BR(K_S \to 3\pi^0)}{\tau_S\, BR(K_L \to 3\pi^0)}} \le 0.0088 \text{ @ } 90\%\ C.L.$$

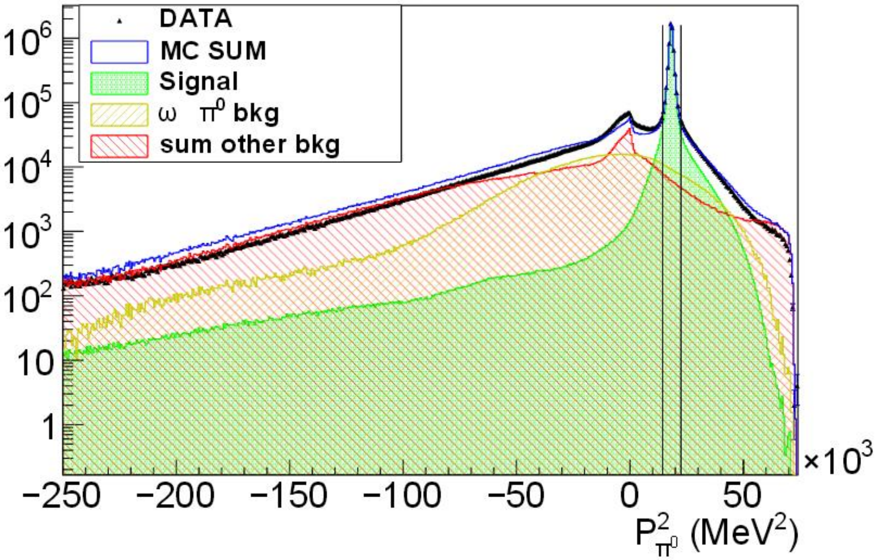
D. Babusci et al., Phys. Lett. B 723 (2013) 54

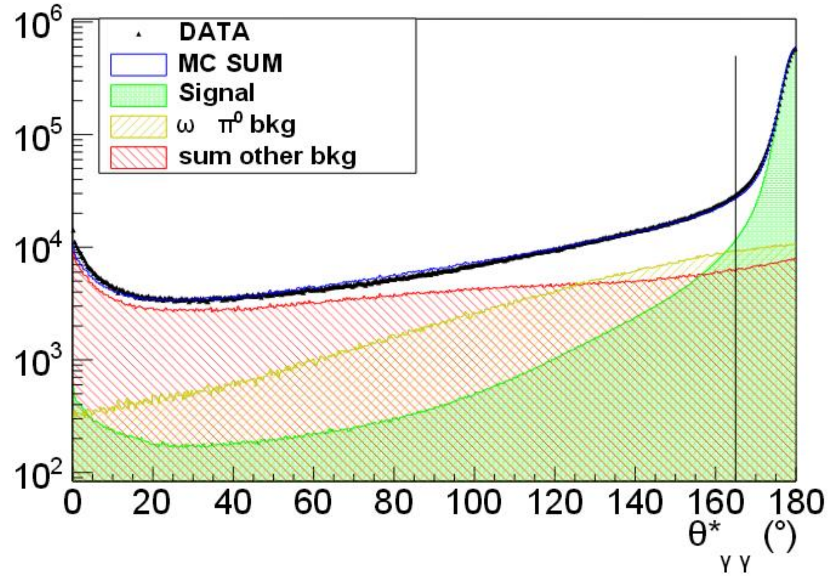
- Uncertainties of both η_{000} and η_{+-0} contribute to phase of ε
- Current experimental accuracy on BR($K_S \to \pi^+\pi^-\pi^0$) is 30% (CPLEAR, NA48 and E621)
- First direct search for $K_S \to \pi^+\pi^-\pi^0$ is ongoing with the old KLOE data set (with expected accuracy lower than 20 %)
- **With KLOE-2 data we expect to improve sensitivity for both branching ratios**



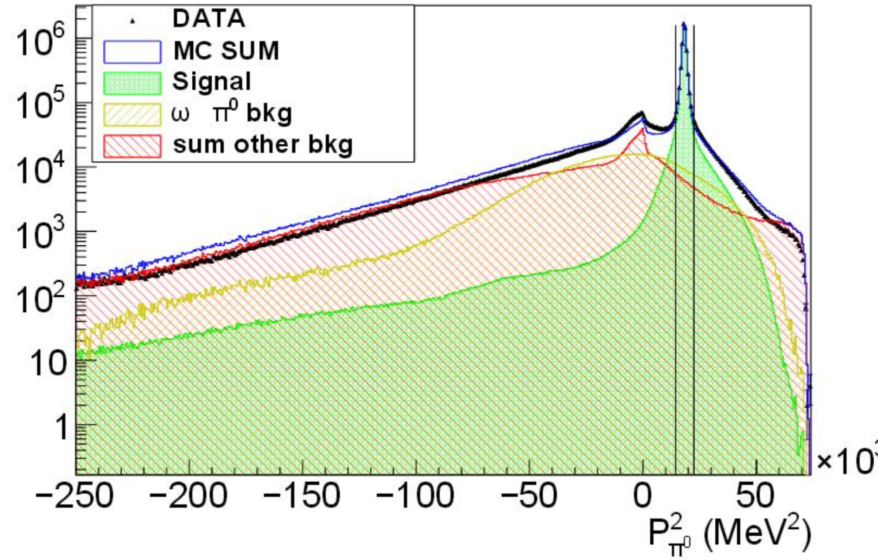
❖ The $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution

- ❖ χPT and C symmetry test
- ❖ New independent measurement, $4.48 \cdot 10^6$ events
- ❖ Overall efficiency 37.6% with 0.96% residual background contamination





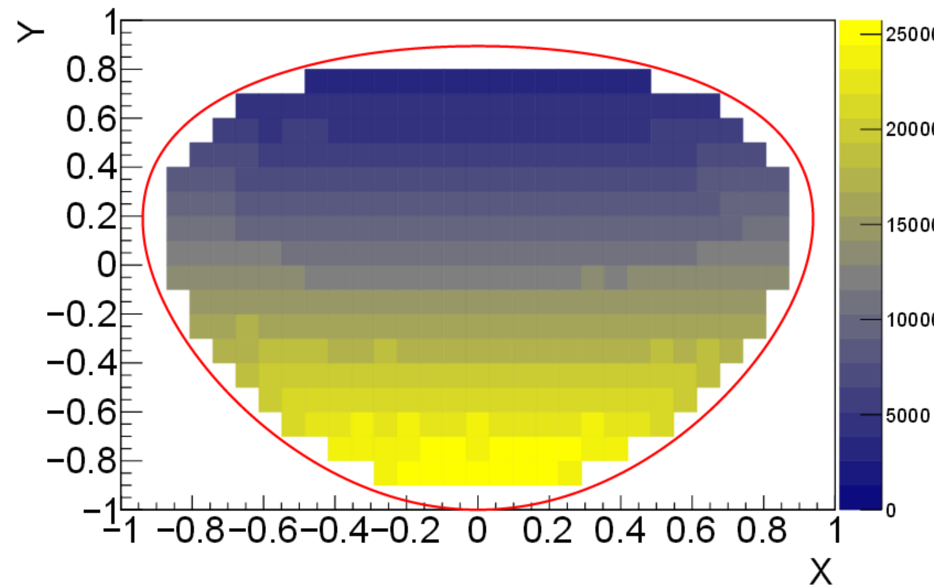
❖ The $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution



- ❖ χPT and C symmetry test
- ❖ New independent measurement, $4.48 \cdot 10^6$ events
- ❖ Overall efficiency 37.6% with 0.96% residual background contamination

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

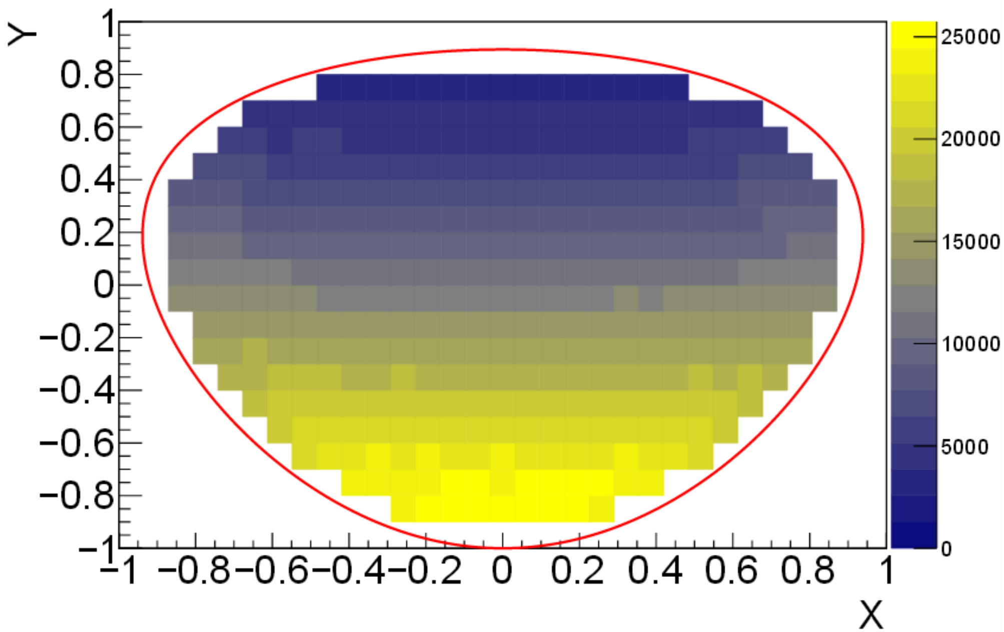
$$X = \sqrt{3}\frac{T_{\pi^+}+T_{\pi^-}}{Q_\eta};\ Y = \frac{3T_{\pi^0}}{Q_\eta} - 1;\ Q_\eta = T_{\pi^+}+T_{\pi^-}-T_{\pi^0}$$



❖ Dalitz plot fit including the g parameter:

$$a = -1.095 \pm 0.003^{+0.003}_{-0.002}$$
$$b = +0.145 \pm 0.003 \pm 0.005$$
$$d = +0.081 \pm 0.003^{+0.006}_{-0.005}$$
$$f = +0.141 \pm 0.007^{+0.007}_{-0.008}$$
$$g = -0.044 \pm 0.009^{+0.012}_{-0.013}$$

JHEP 1605 (2016) 019



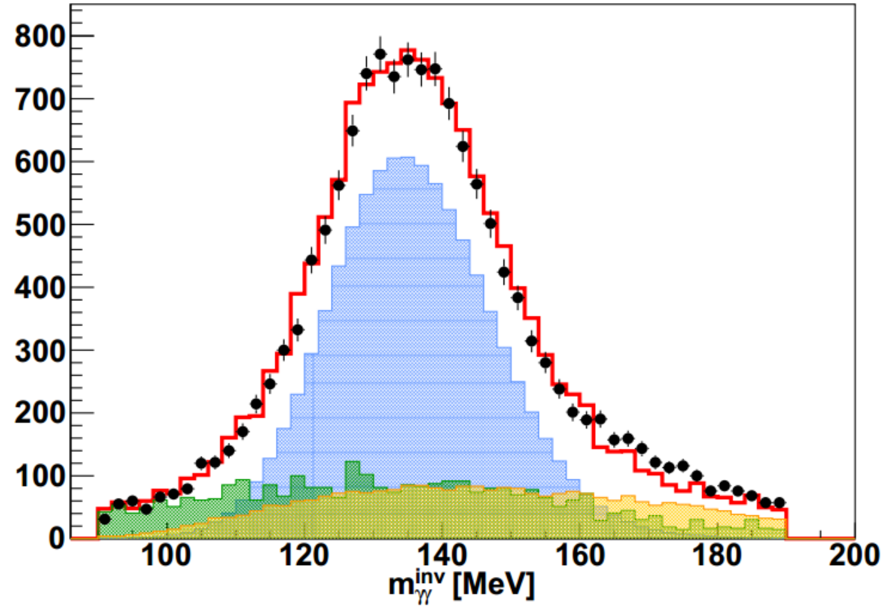
❖ Results assuming $g = 0$:

$$a = -1.104 \pm 0.003 \pm 0.002$$
$$b = +0.142 \pm 0.003^{+0.005}_{-0.004}$$
$$d = +0.073 \pm 0.003^{+0.004}_{-0.003}$$
$$f = +0.154 \pm 0.006^{+0.004}_{-0.005}$$

❖ Charge asymmetries:

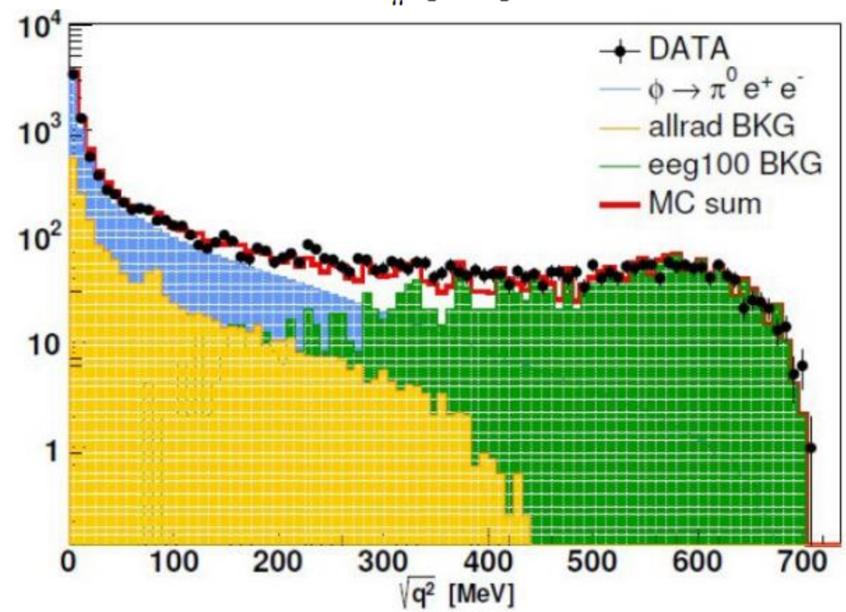
$$A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}$$
$$A_Q = (+1.8 \pm 4.5^{+4.8}_{-2.3}) \cdot 10^{-4}$$
$$A_S = (-0.4 \pm 4.5^{+3.1}_{-3.5}) \cdot 10^{-4}$$

- Meson Transition Form Factors
- Test on the theoretical description of meson structure
- Light-by-Light contribution to a_{μ}
- Used to determine upper limit in dark forces searches



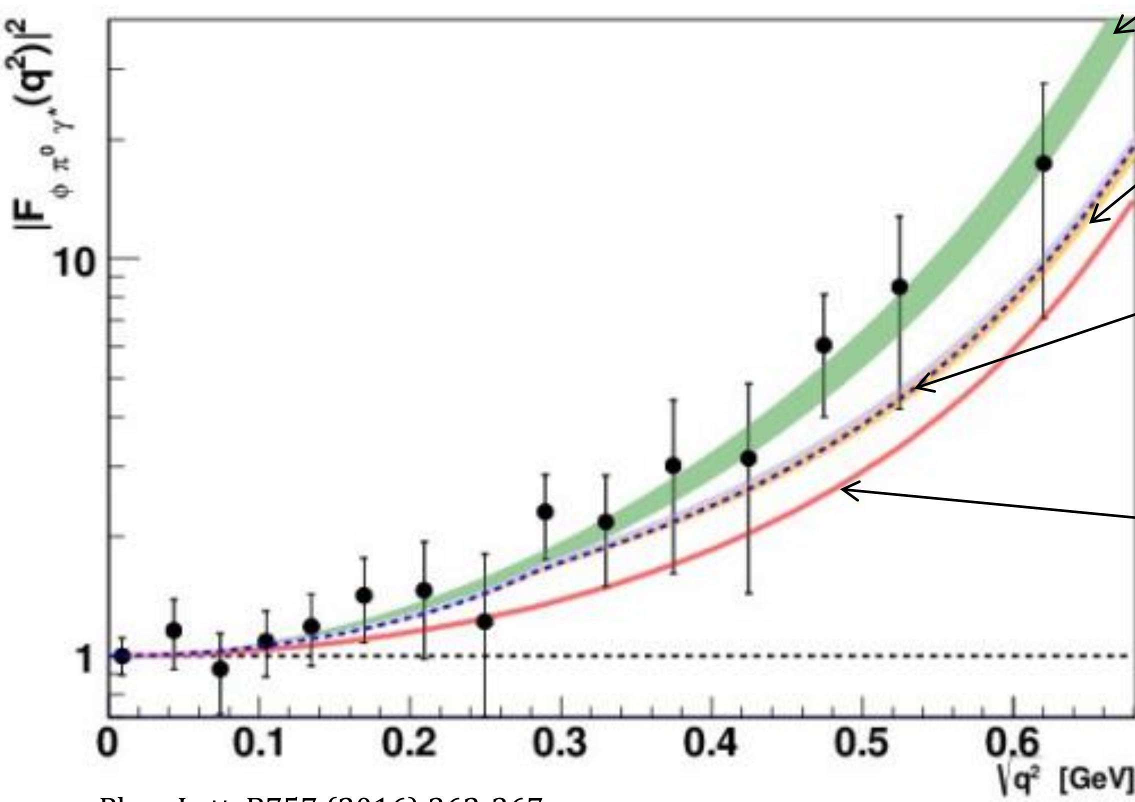
$\varphi \rightarrow e^+e^-\pi^0$

- **The first measurement of the transition form factor $|F\varphi_{\pi}(q)|$**
- ~ 9500 signal events selected
- Main background: radiative bhabha scattering and $\Phi \rightarrow \pi^0 \gamma$



Hadron physics

$\varphi \rightarrow e^+e^-\pi^0$



S. Ivashyn, Prob. Atomic. Sci. Technol. 2012, N1 (2012) 179

S. P. Schneider, B. Kubis, F. Niecknig, Phys. Rev. D 86 (2012) 054013. 219

I. Danilkin, et al., Phys. Rev. D 91 (2015) 094029

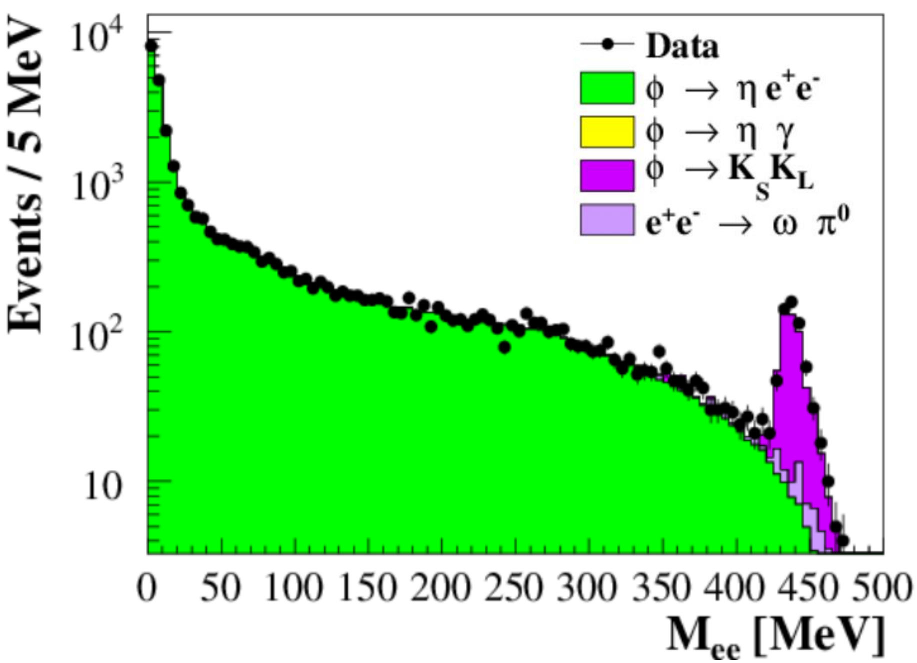
L. G. Landsberg, Phys. Rept. 128 (1985) 301

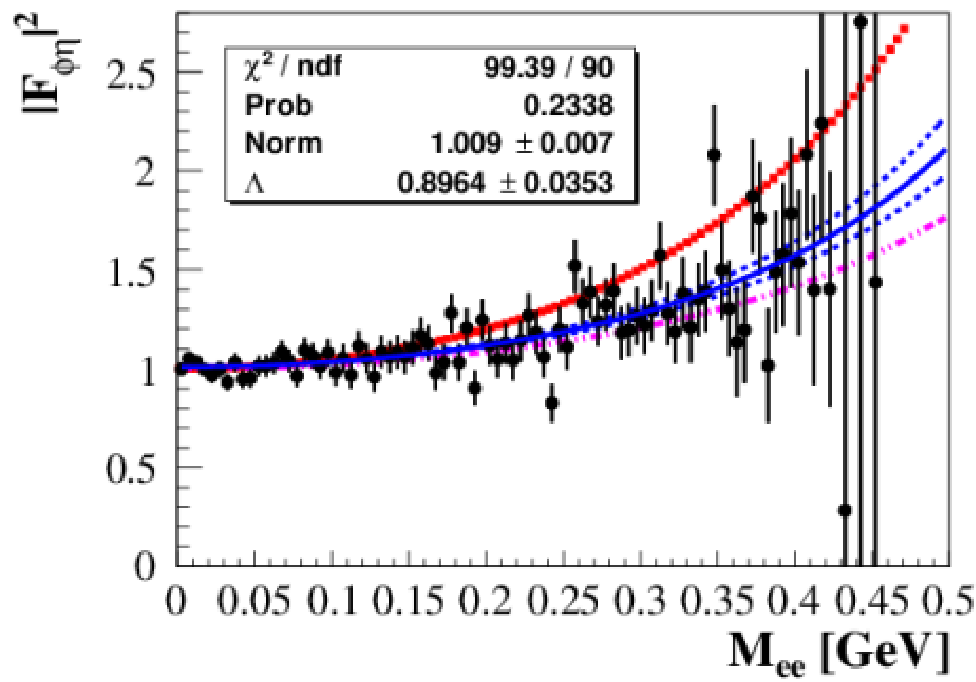
Phys. Lett. B757 (2016) 362-367

$$\mathrm{BR}\,(\phi \rightarrow \pi^0 e^+ e^-) = (\,1.35 \pm 0.05\,^{+0.05}_{-0.10}\,) \times 10^{-5}$$

$\varphi \to e^+e^-\eta$

- Needed to validate non-VMD models of form factors
- 31000 signal events selected with $\eta \to 3\pi^0$ (~3% of K_SK_L events contamination)





$$b_{\eta,\Phi} = (1.17 \pm 0.10^{+0.07}_{-0.11})\,GeV^{-2}$$

$$BR(\Phi \to \eta e e) = (1.075 \pm 0.007 \pm 0.038)\,x\,10^{-4}$$

C. Terschlusen and S. Leupold,, Phys. Lett. B 691, 191-201 (2010)

KLOE fit ($\Lambda \pm 1\sigma$)

VMD expectation

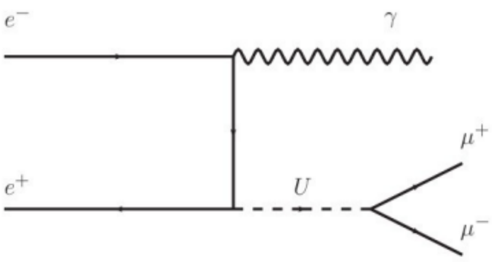
Hadron physics

❖ Search for dark forces

❖ Associated production of U and γ,

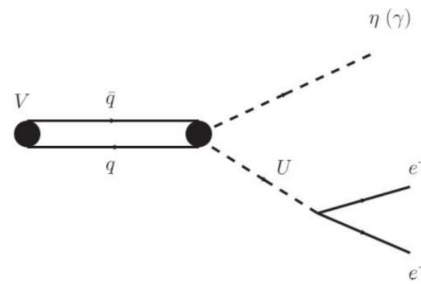
$e^+e^- \rightarrow U\gamma$ with:

- ○ $U \rightarrow e^+e^-$ **Phys. Lett. B 736 (2014) 459**
- ○ $U \rightarrow \mu^+\mu^-$ **Phys. Lett. B750 (2015) 633**
- ○ $U \rightarrow \pi^+\pi^-$ **Phys. Lett. B757 (2016) 356**



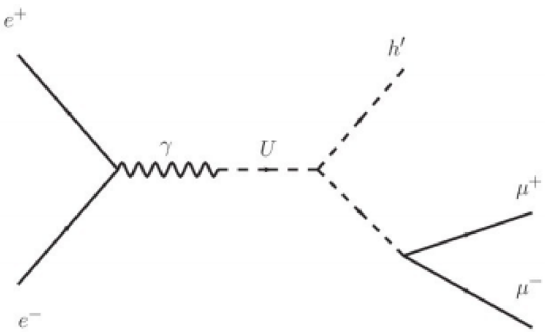
❖ $\Phi \rightarrow \eta U$ with $U \rightarrow e^+e^-$

and $\eta \rightarrow \pi^+\pi^-\pi^0$ / $\pi^0\pi^0\pi^0$ **Phys. Lett. B720 (2013) 111**

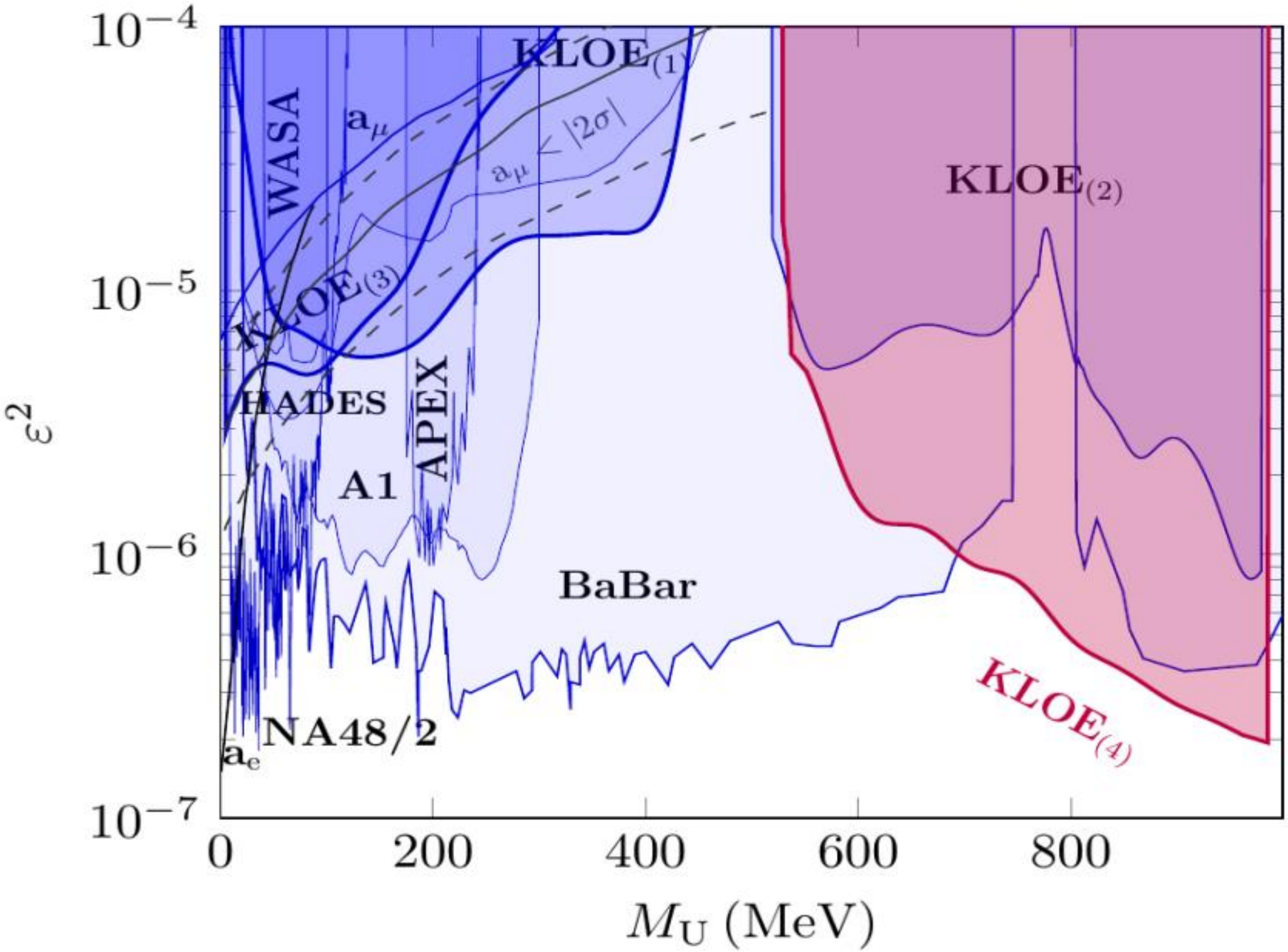


❖ Search for Higgsstrahlung:

$e+e- \rightarrow Uh'$ with h' invisible **Phys. Lett. B 747 (2015) 365**



❖ Search for dark forces



KLOE(1): $\Phi \rightarrow \eta e^+ e$
KLOE(2): $e^+e^- \rightarrow \mu^+\mu^-\gamma$
KLOE(3): $e^+e^- \rightarrow e^+e^-\gamma$
KLOE(4): $e^+e^- \rightarrow \pi^+\pi^-\gamma$

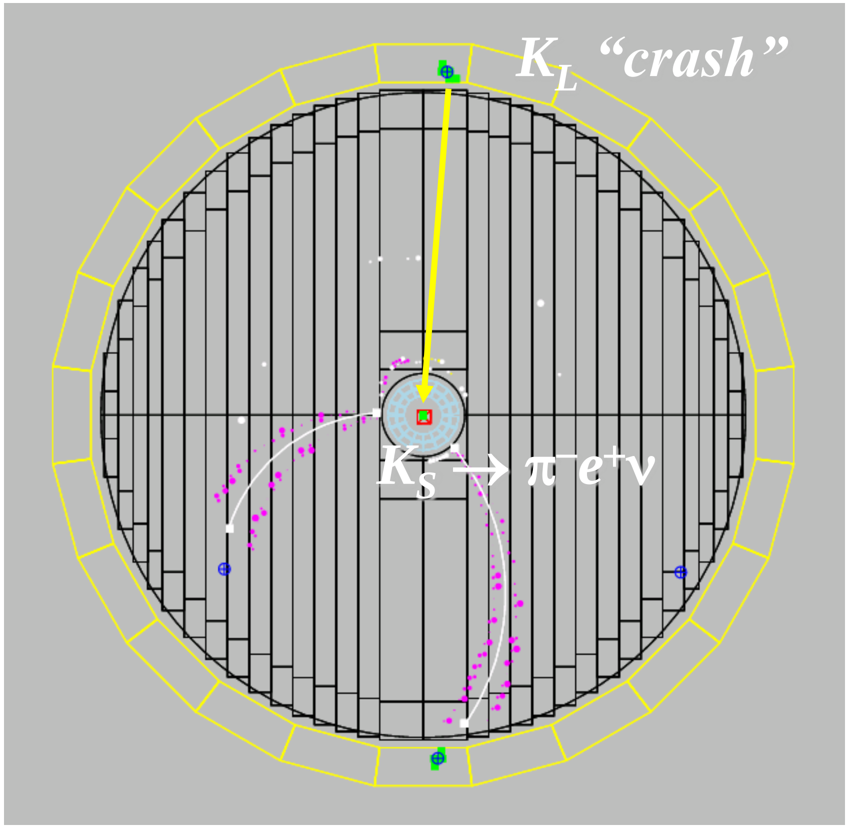
Summary and outlook

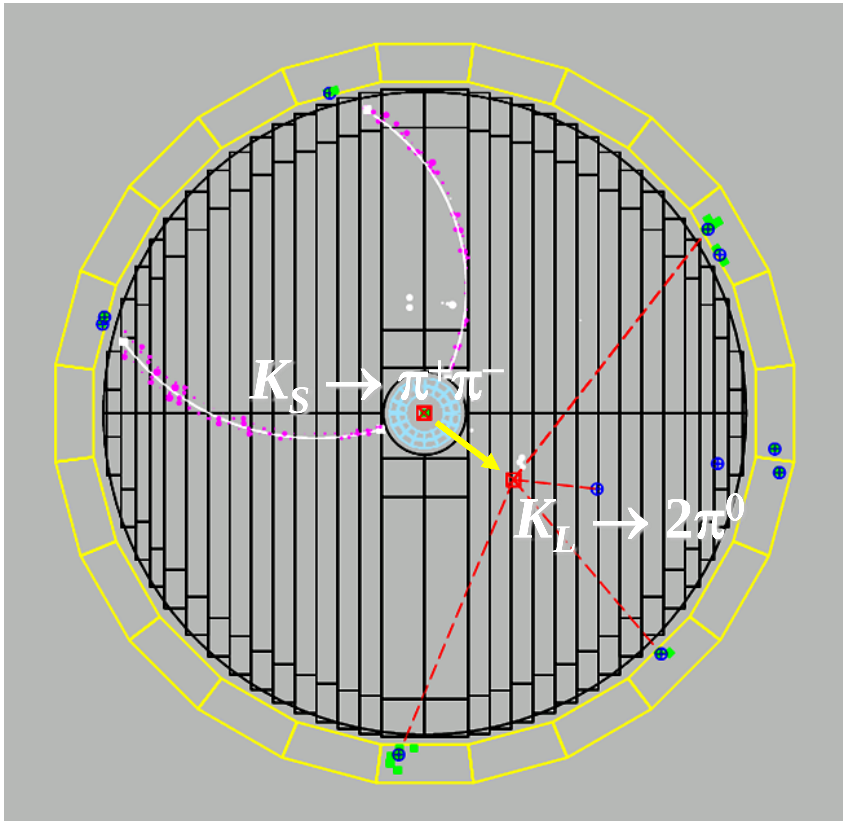
- KLOE-2 has inherited a very good quality data set which is still analysed in view of many different physics topics
- The new data-taking with upgraded detector started in November 2014 giving unique opportunity to improve the exsisting results and extend the physics program of KLOE
- Our goal is to reach at least 5 fb^{-1} of integrated luminosity in the next two years
- The data-taking is progessing according to the expectations with continous increase of the DAΦNE performance

SPARES

K_S and K_L tagging

A Φ-factory offers the possibility to select pure kaon beams:





***K_S* tagged by *K_L* interaction in EmC**

Efficiency ~ 30%

K_S angular resolution: ~ 1° (0.3° in φ)

K_S momentum resolution: ~ 2 MeV

***K_L* tagged by *K_S* → π⁺π⁻ vertex at IP**

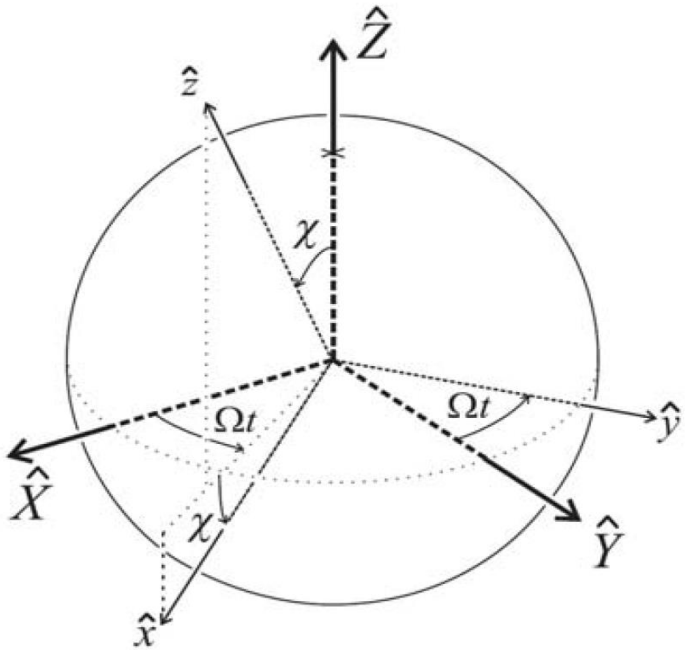
Efficiency ~ 70%

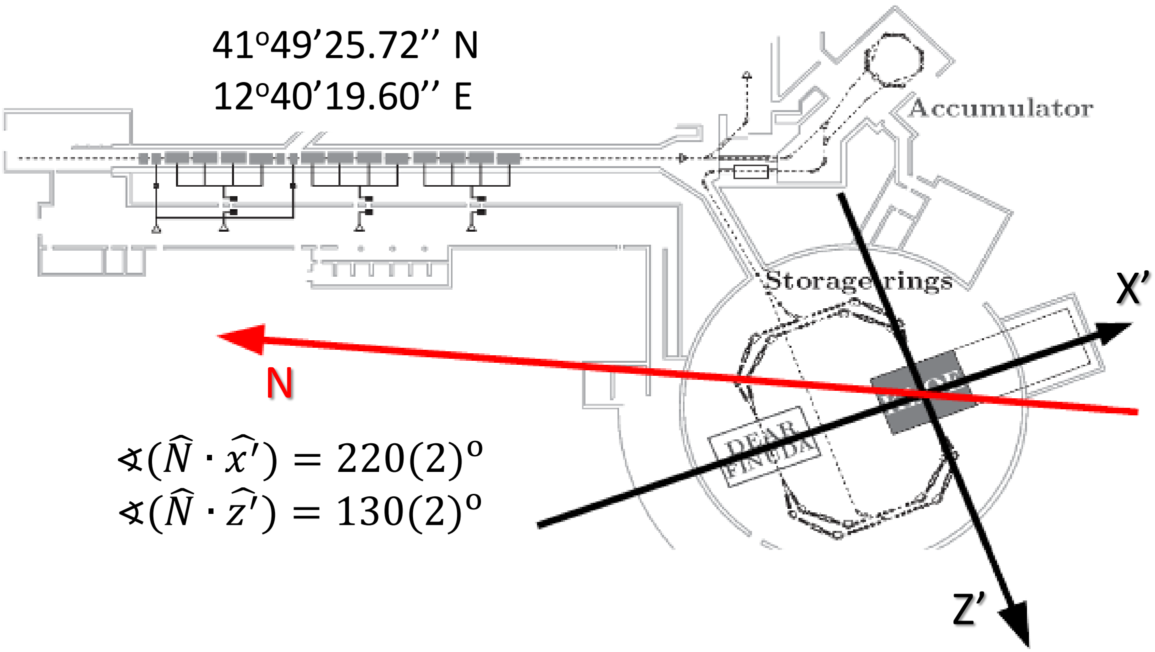
K_L angular resolution: ~ 1°

K_L momentum resolution: ~ 2 MeV

CPT and Lorentz symmetry tests

- Choice of the reference frame: the $\hat{Z}$ axis along the Earth's rotation axis (accounting for the sidereal time dependence due to the Earth rotation)





$\measuredangle(\hat{N} \cdot \hat{x}') = 220(2)^{o}$

$\measuredangle(\hat{N} \cdot \hat{z}') = 130(2)^{o}$

$$
\begin{aligned}
\delta(\vec{p},t) = & \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \{\Delta a_0 + \beta_K \Delta a_Z (\cos\theta\cos\chi - \sin\theta\cos\phi\sin\chi) \\
& -\beta_K \Delta a_X \sin\theta \sin\phi \sin\Omega t \\
& +\beta_K \Delta a_X (\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi)\cos\Omega t \\
& +\beta_K \Delta a_Y (\cos\theta\sin\chi + \sin\theta\cos\phi\cos\chi)\sin\Omega t \\
& +\beta_K \Delta a_Y \sin\theta\sin\phi\cos\Omega t\}
\end{aligned}
$$

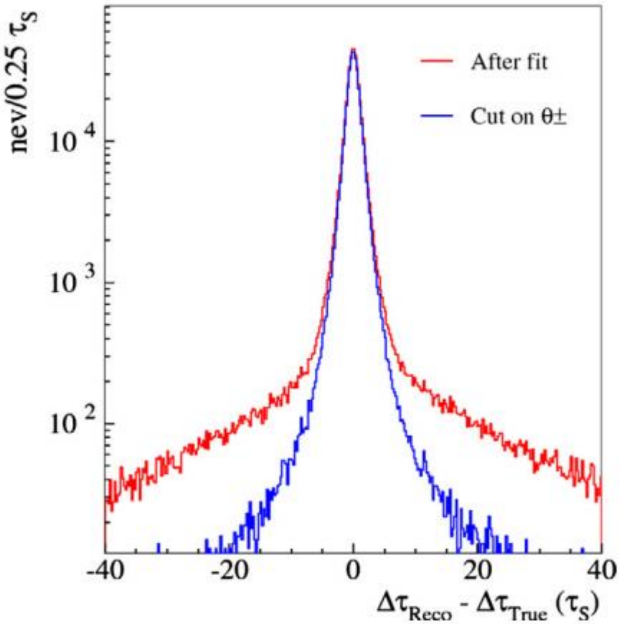
Sidereal time

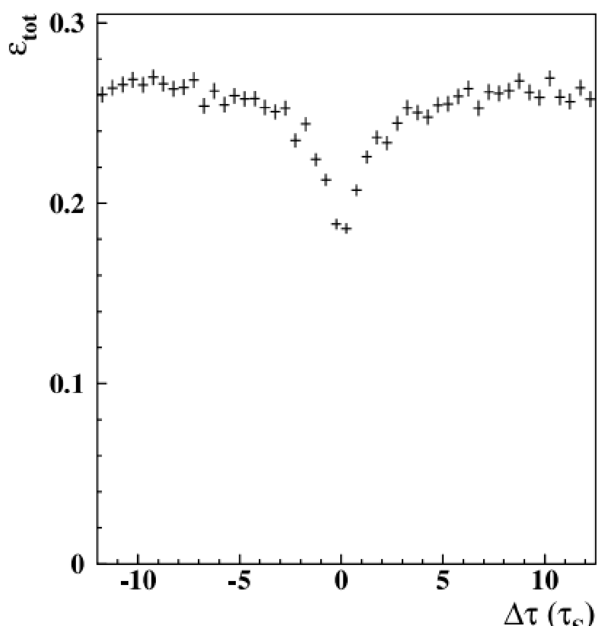
- **Measurement of the $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+ \pi^-$**

- Events preselection requiring 2 reconstructed vertices with two tracks and:
  - $|M_{rec} - m_K| < 5$ MeV/c^2 (assuming pion hypothesis for both tracks)
  - $\sqrt{E^2{}_{miss} + \vec{p}^2{}_{miss}} < 10$ MeV
  - -50 MeV^2/c^4 $< M^2{}_{miss} <$ 10 MeV^2/c^4
  - $\left| p^*{}_{1,2} - p^*{}_0 \right| < 10$ MeV/c $\left(p^*{}_0 = \sqrt{\frac{s}{4} - m^2{}_K} \right)$

- A global kinematic fit applied to improve the kaon decay length reconstruction
- Cut on the pion opening angle $\cos\vartheta < -0.975$ (events with deteriorated time resolution)
- Vertices inside the beam pipe (reduction of the K_S regeneration background) $\Rightarrow \Delta\tau \in [-12\tau_S; -12\tau_S]$

- The residual background contamination: regeneration (2%) and $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$(0.5%)



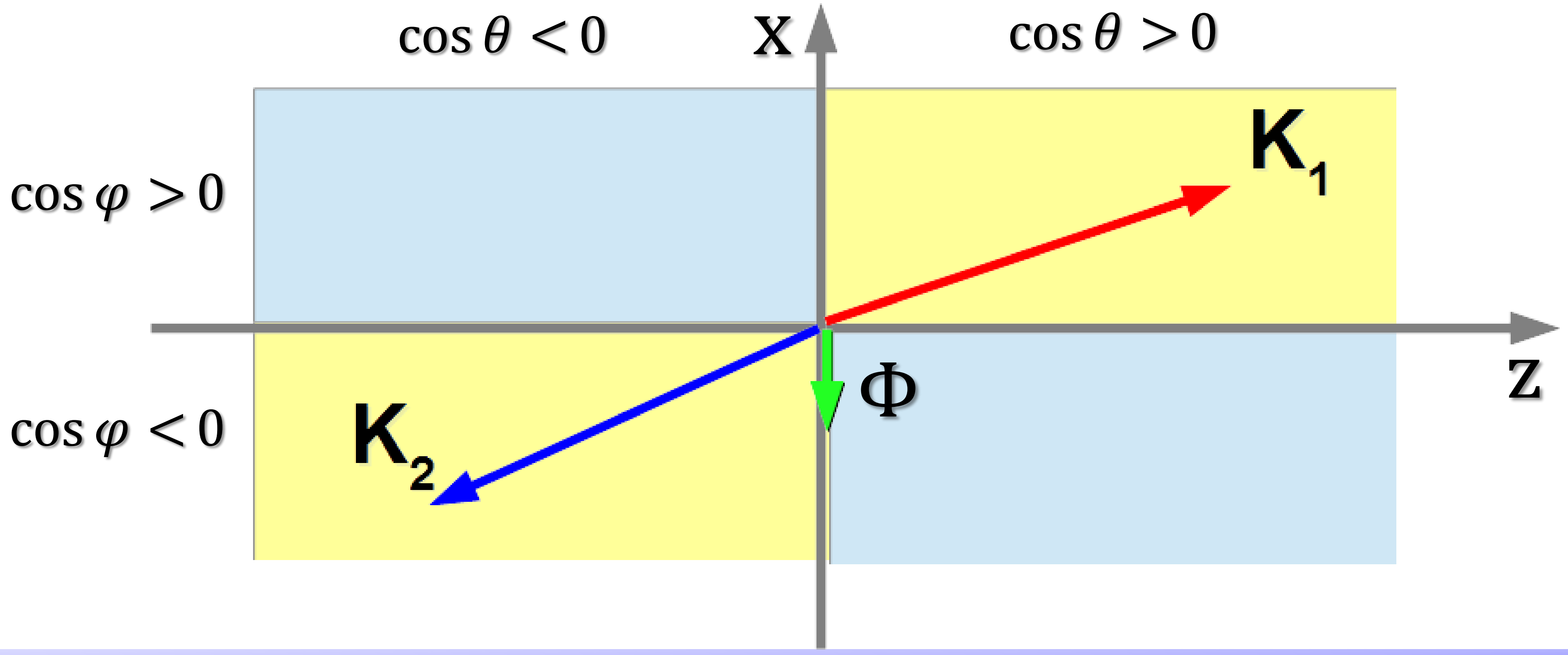


CPT and Lorentz symmetry tests

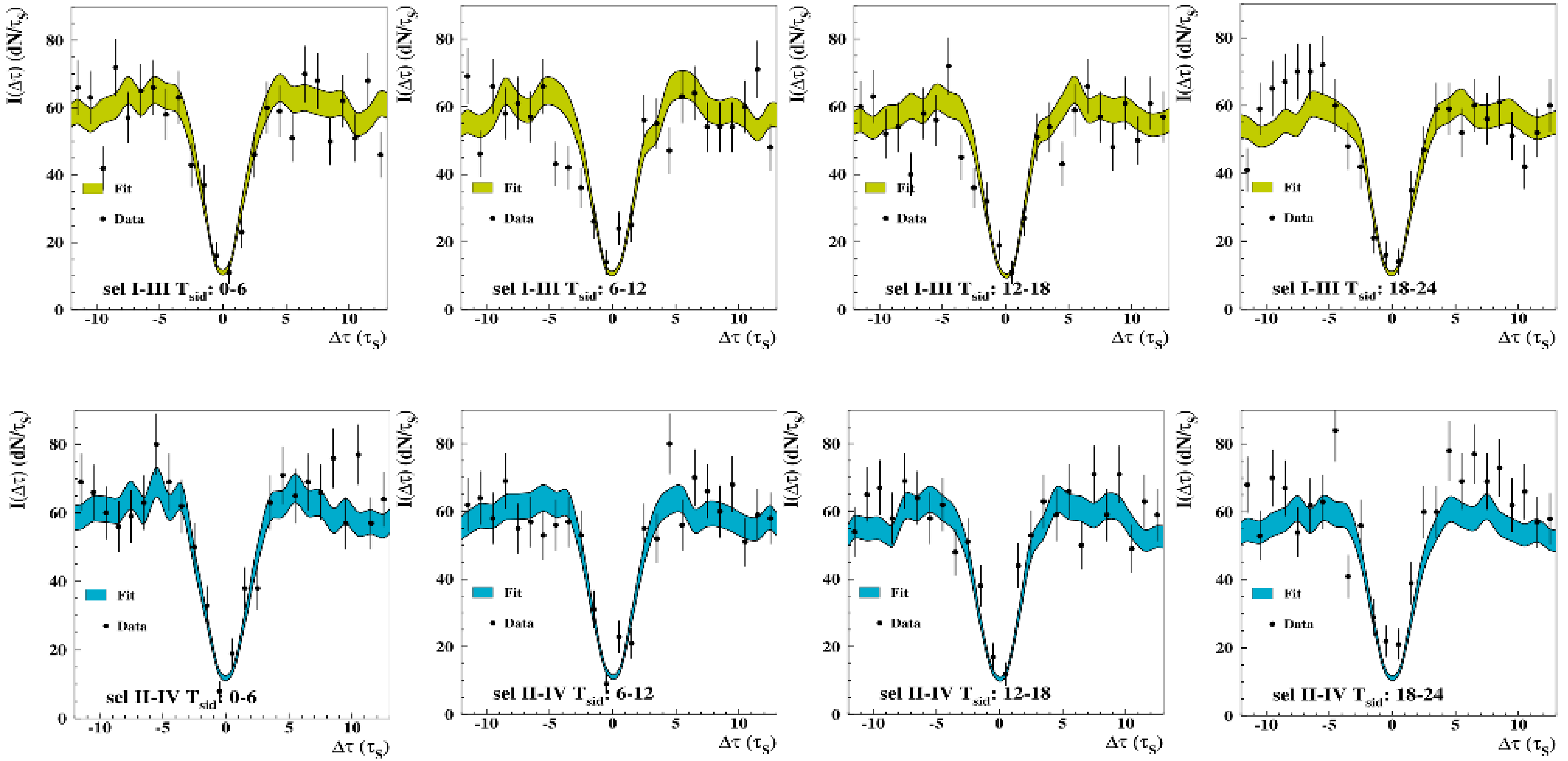
- Kaons were ordered according to their *z* momenta component
- Data sample analyzed for different intervals of sidereal time and kaon emission angle:

$$4_{\text{sidereal}} \times 2_{\text{angular}} = 8\ I(\Delta\tau) \text{ distributions}$$

- Simultaneous fit to all distributions taking into account the 4π background subtraction and data/MC efficiency correction for regeneration



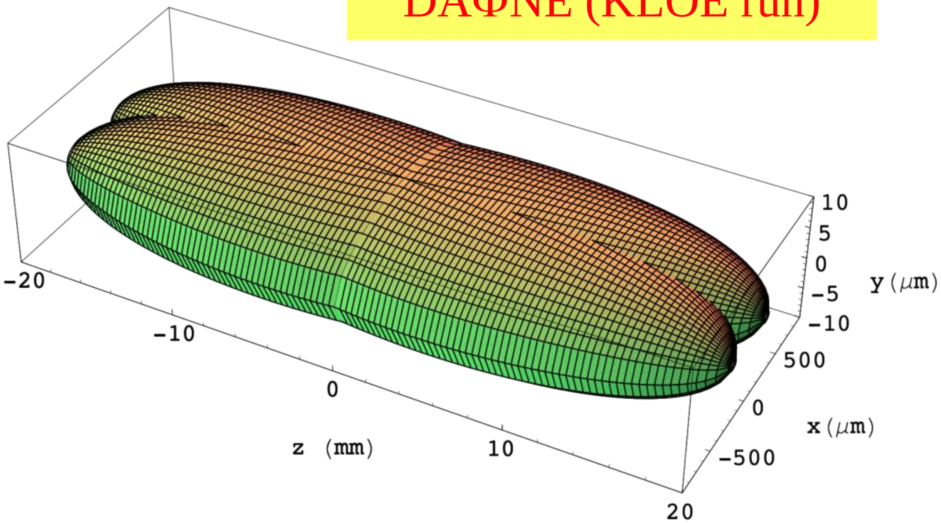
CPT and Lorentz symmetry tests



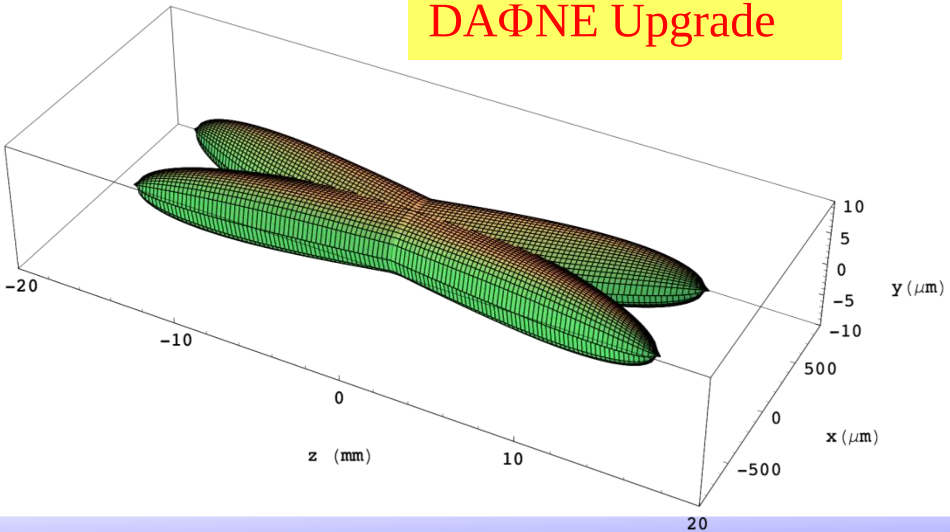
192 Data points fit simultaneously with 5 free parameters; $\chi^2_{Fit}/ndof = 211/187$ (P=10%)

DAΦNE upgrade

DAΦNE (KLOE run)



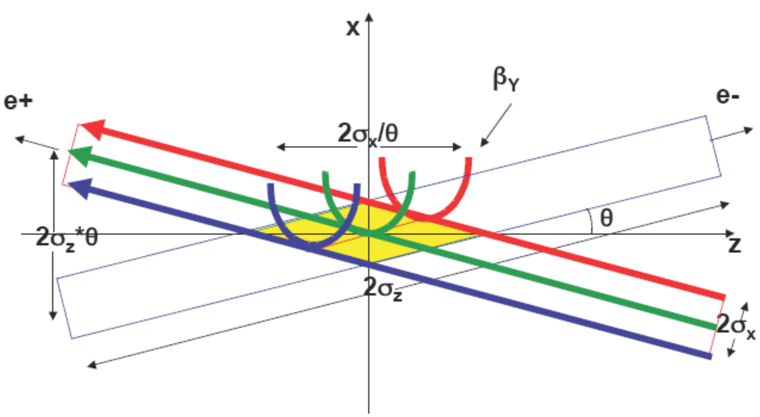
DAΦNE Upgrade

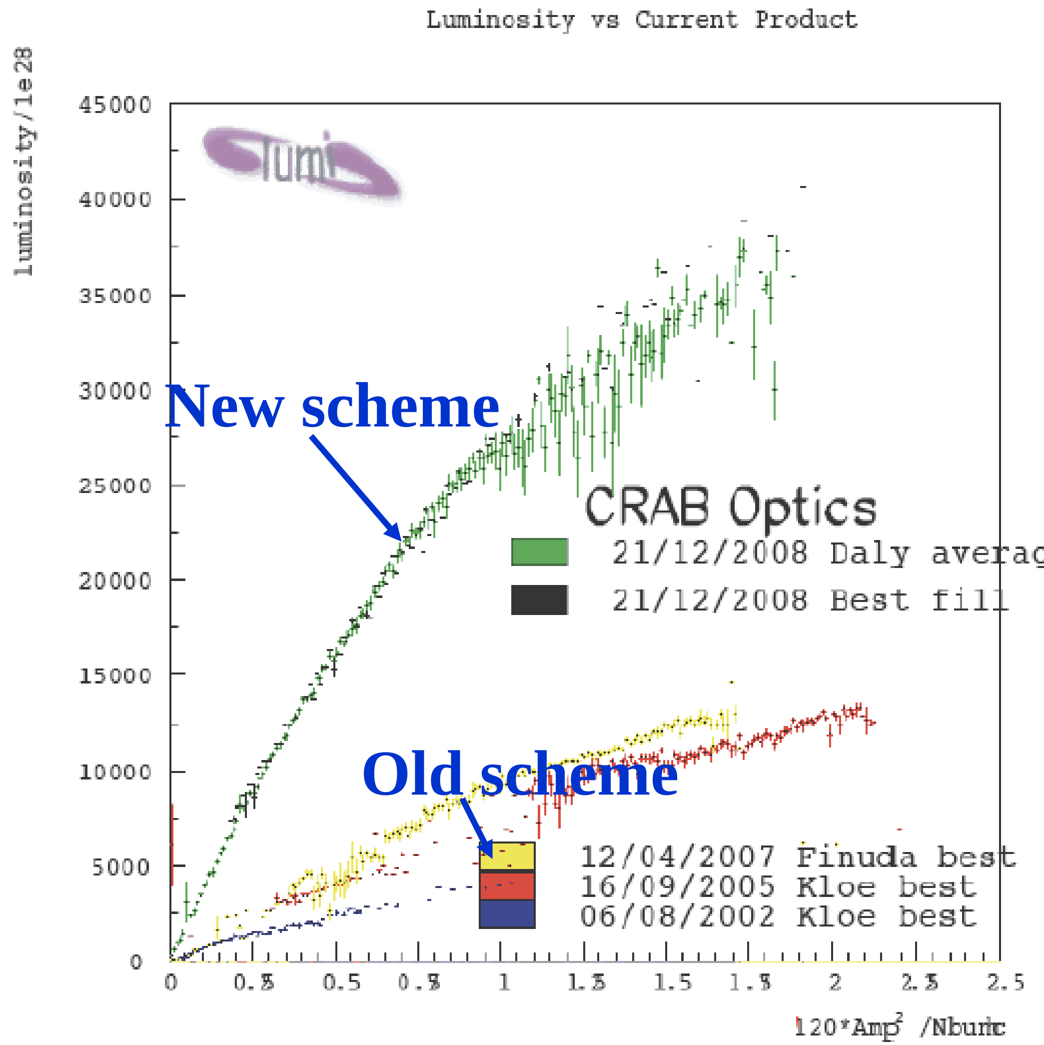


	DAΦNE (KLOE run)	DAΦNE Upgrade
I_{bunch} (mA)	13	13
N_{bunch}	110	110
β_y^* (cm)	1.7	0.65
β_x^* (cm)	170	20
σ_y^* (μm)	7	2.6
σ_x^* (μm)	700	200
σ_z (mm)	25	20
θ_{cross} (mrad) (half)	12.5	25
$\Phi_{Piwinski}$	0.45	2.5
L ($cm^{-2}s^{-1}$)	1.5×10^{32}	$>5 \times 10^{32}$

DAΦNE upgrade

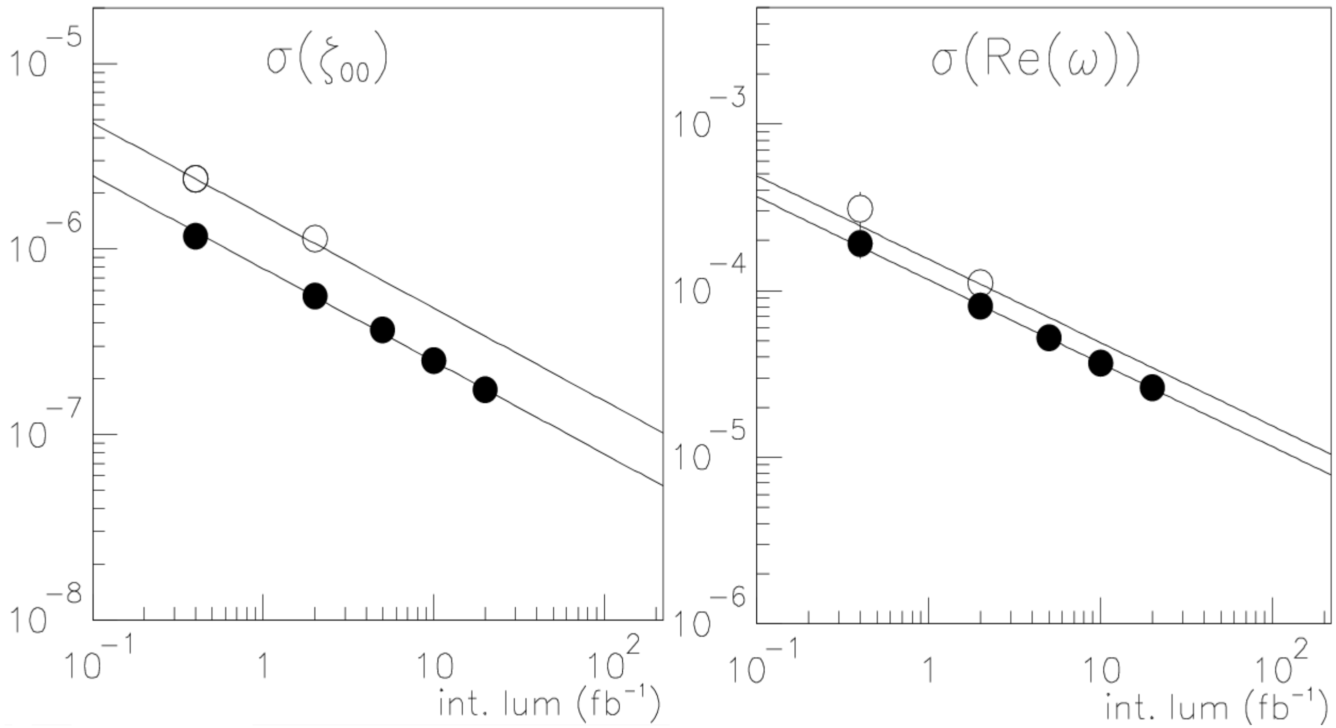
- $L_{new} \sim 3 \times L_{old}$
- $\int L\,dt$ = 1 pb^{-1}/hour





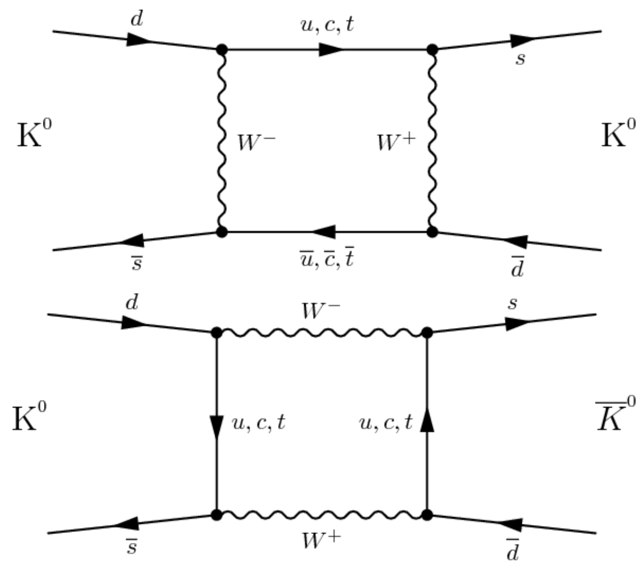
$$I(\pi^+\pi^-,\pi^+\pi^-,\Delta\tau) \propto e^{-(\Gamma_S+\Gamma_L)|\Delta\tau|}\left[|\eta_1|^2 e^{\frac{-\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{\frac{-\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_1\eta_2{}^* e^{-i\Delta m\Delta\tau}\right)\right]$$

- ○ sensitivity with the present KLOE resolution ($\sigma(\Delta t) \approx \tau_S$)
- ● sensitivity with improved resolution ($\sigma(\Delta t) \approx 0.3\ \tau_S$ expected)



Introduction

- Time evolution of the $K^0 \leftrightarrow \overline{K^0}$ system in the rest frame:



$$i\frac{\partial}{\partial t}\begin{pmatrix}|K^0>\\ |\overline{K^0}>\end{pmatrix} = \mathbf{H}\begin{pmatrix}|K^0>\\ |\overline{K^0}>\end{pmatrix} = \left[\boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}\right]\begin{pmatrix}|K^0>\\ |\overline{K^0}>\end{pmatrix}$$

$$\boldsymbol{\Gamma} = \begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma^*_{12} & \Gamma_{22}\end{pmatrix} \qquad \boldsymbol{M} = \begin{pmatrix}M_{11} & M_{12}\\ M^*_{12} & M_{22}\end{pmatrix}$$

- The eigenstates of **H**:

$$|K_S> = \frac{1}{\sqrt{1+|\varepsilon_S|^2}}(\,|K_1> + \varepsilon_S|K_2>\,)\ (\tau = 0.9\cdot 10^{-10}\ \text{s};\ c\tau = 2.68\ \text{cm})$$

$$|K_L> = \frac{1}{\sqrt{1+|\varepsilon_L|^2}}(|K_2> + \varepsilon_L|K_1>)\ (\tau = 5.1\cdot 10^{-8}\ \text{s};\ c\tau = 155\ \text{cm})$$

$\boldsymbol{\varepsilon_S \neq \varepsilon_L \Rightarrow}$ **CPTV**