L'esperimento KLOE-2
a DAΦNE

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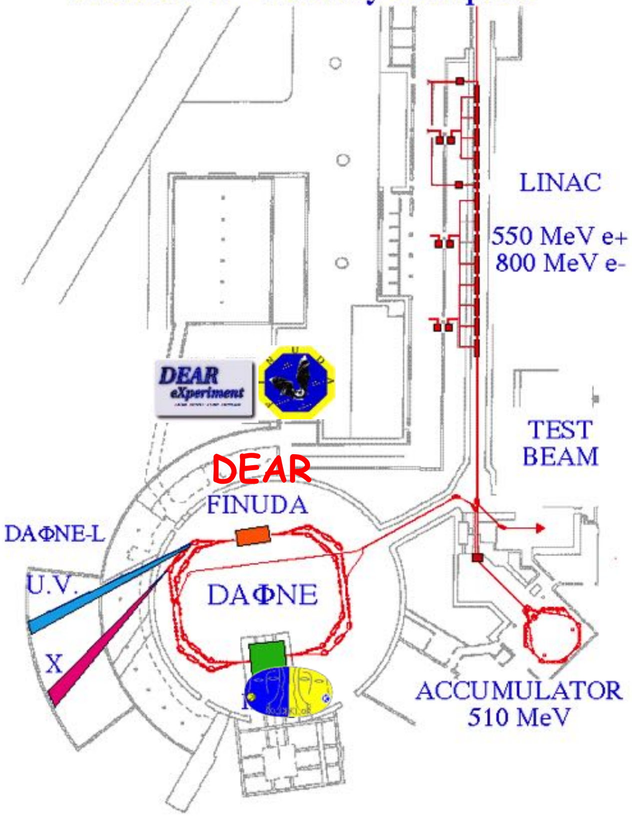
a nome della Collaborazione KLOE-2

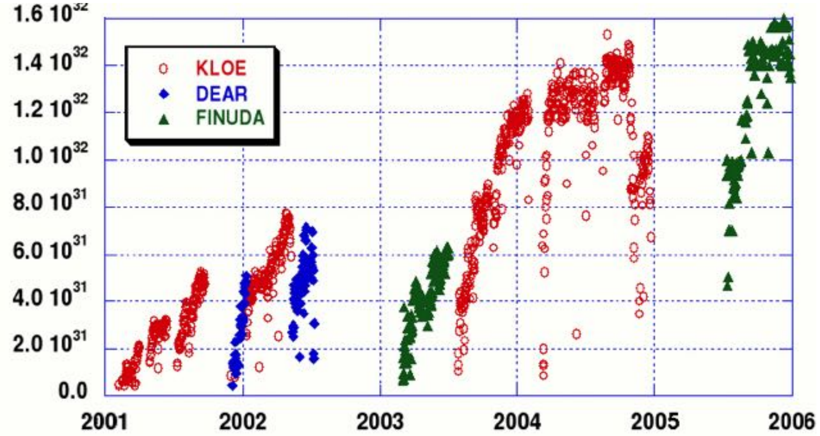
Colloquium INFN – Firenze – 25 giugno 2019

DAΦNE : the Frascati Φ-factory

Frascati Φ–Factory complex

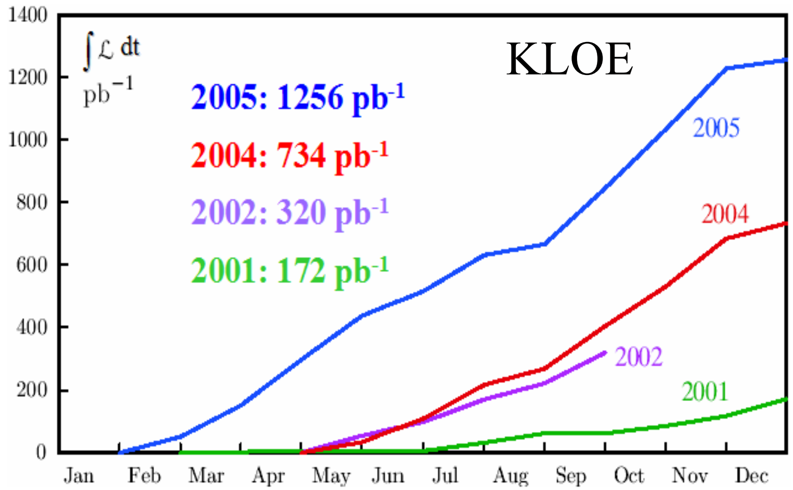


- Frascati ϕ-factory: e^+e^- collider @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$; $\sigma_{peak} \approx 3.1\ \mu b$
- Beam energy : 510 MeV
- Max number of bunches : 120
- Bunch spacing : 2.7 ns
- $\sigma(x) \sim 1$ mm , $\sigma(y) \sim 20\ \mu m$ $\sigma(z) \sim 2$ cm
- Beam current : 1.2 – 1.4 A

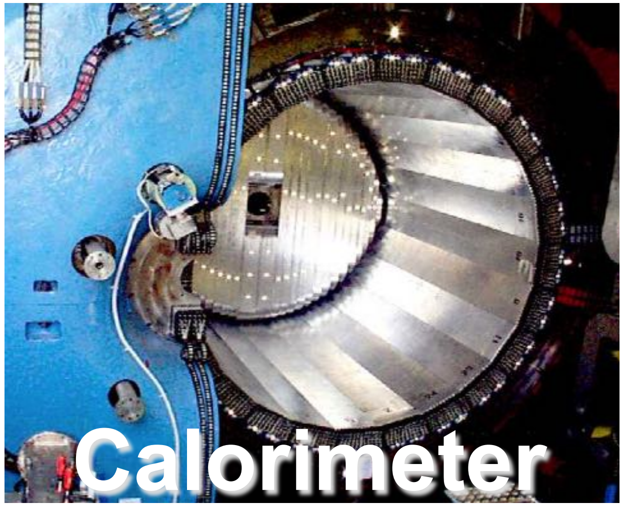


- Best performance in KLOE run (1999-2006): $L_{peak} = 1.5 \times 10^{32}\ cm^{-2}s^{-1}$ max daily $\int Ldt = 8.5\ pb^{-1}$/day

Total $\int Ldt = 2.5\ fb^{-1}$ + 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV



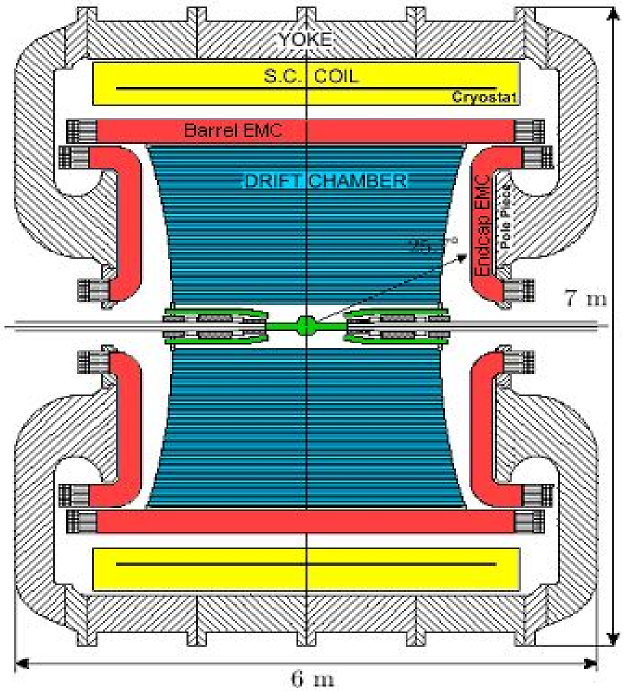
The KLOE detector at DAΦNE



Lead/scintillating fiber
4880 PMTs
98% coverage of solid angle

Superconducting coil

B = 0.52 T



4 m diameter × 3.3 m length
90% helium, 10% isobutane
12582/52140 sense/total wires
All-stereo geometry

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

$\sigma_t \cong 54$ ps $/\sqrt{E(\mathrm{GeV})} \oplus 50$ ps
(relative time between clusters)

$\sigma_{\gamma\gamma} \sim 2$ cm (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

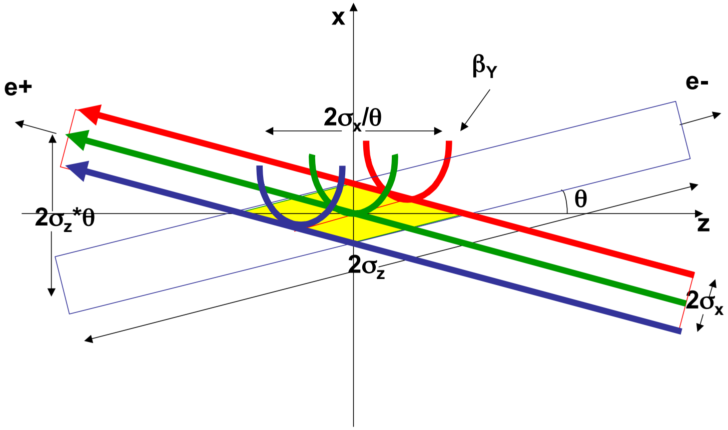
$\sigma_p/p \cong 0.4$ % (tracks with $\theta > 45°$)

$\sigma_x^{hit} \cong 150$ mm (xy), 2 mm (z)

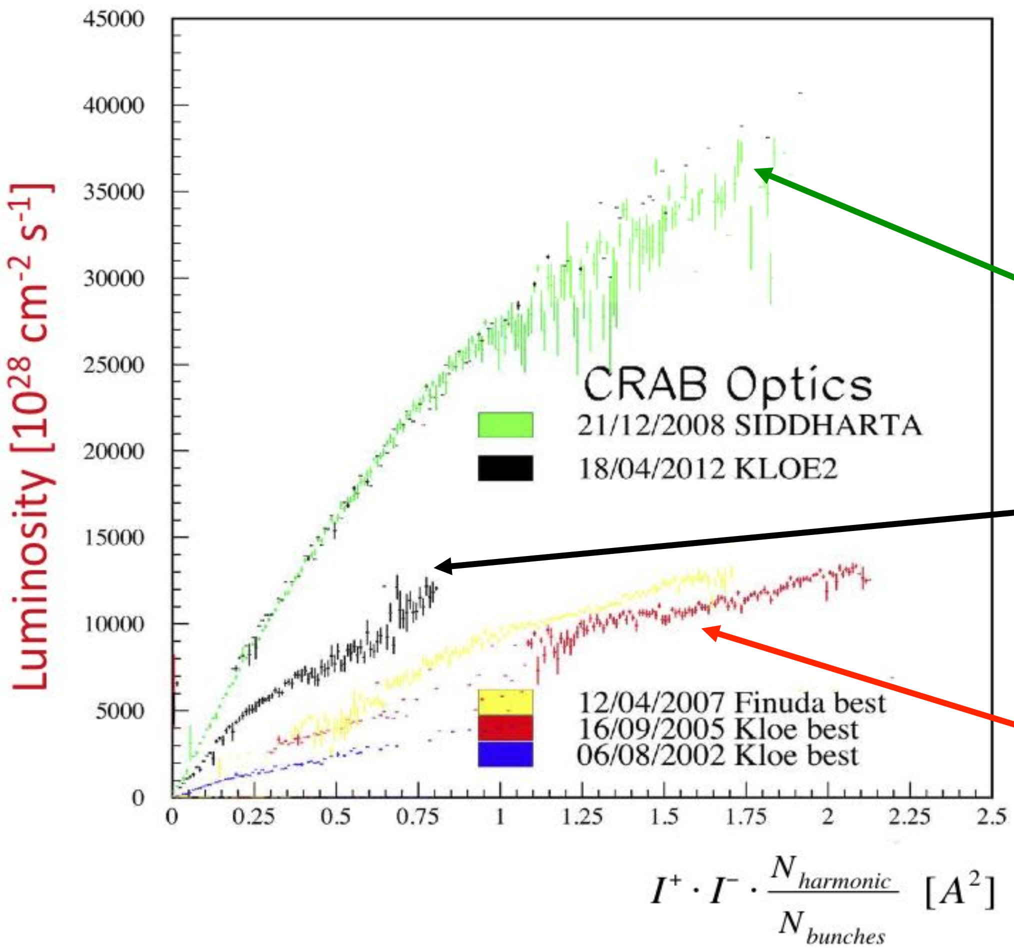
$\sigma_x^{vertex} \sim 1$ mm

DAΦNE luminosity upgrade

DAΦNE upgrade (2008) with a new interaction scheme with large Piwinski angle~(σz/σx)(θ/2) + crab waist sextupoles



Crabbed waist is realized with a sextupole in phase with the IP in X and at π/2 in Y



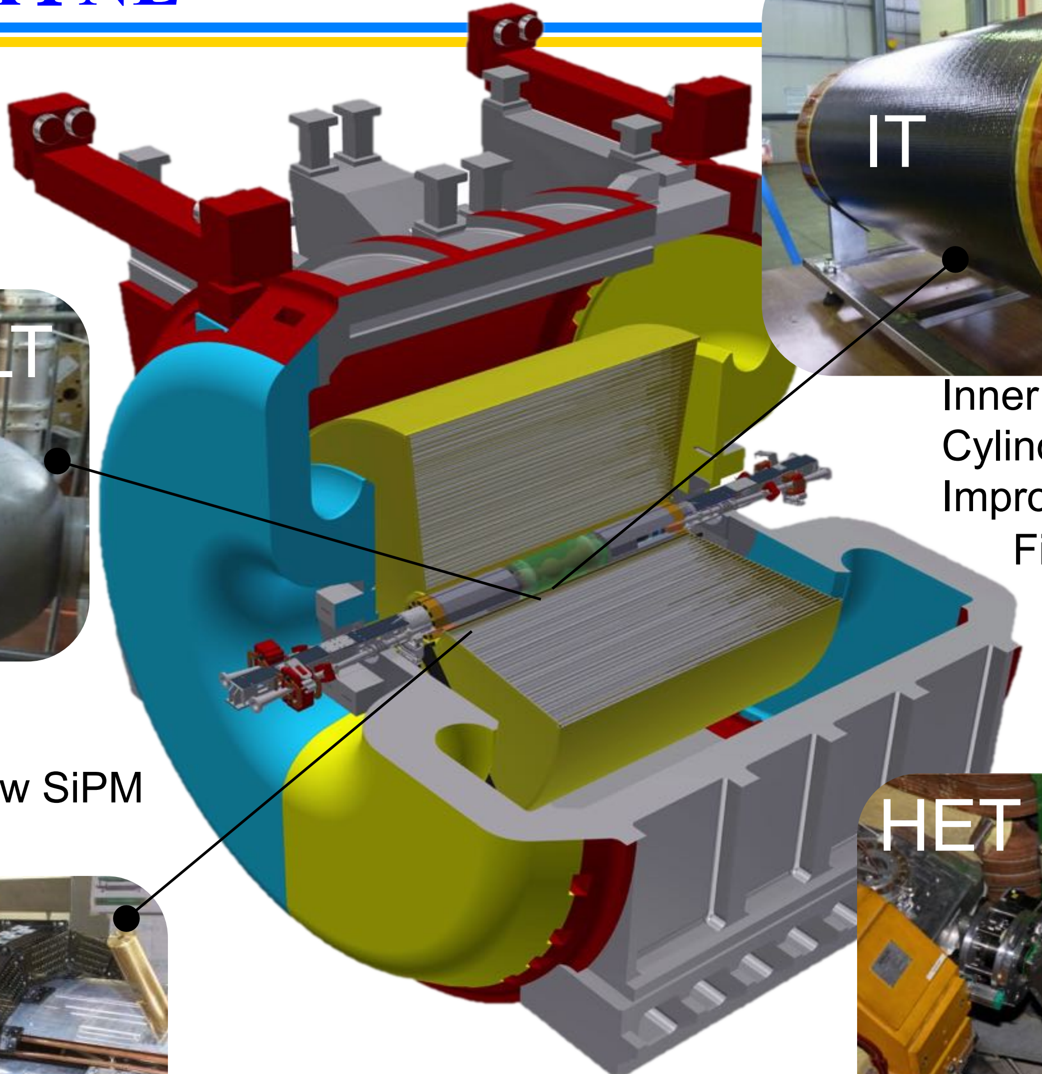
NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

Commissioning phase
New coll. scheme + KLOE det.

Old collision scheme

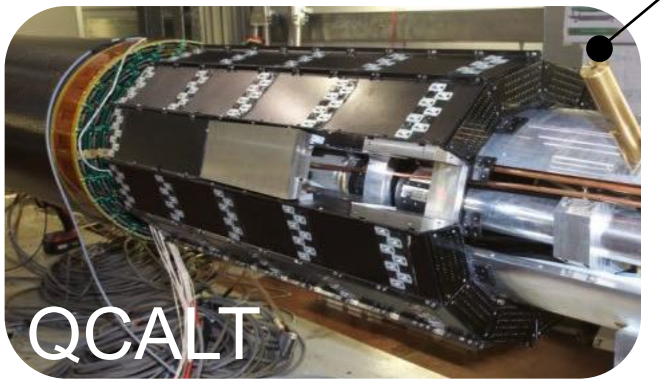
KLOE-2 at DAΦNE

LYSO Crystal w SiPM
Low polar angle



Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.

Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation



Scintillator hodoscope +PMTs,
pitch 5 mm

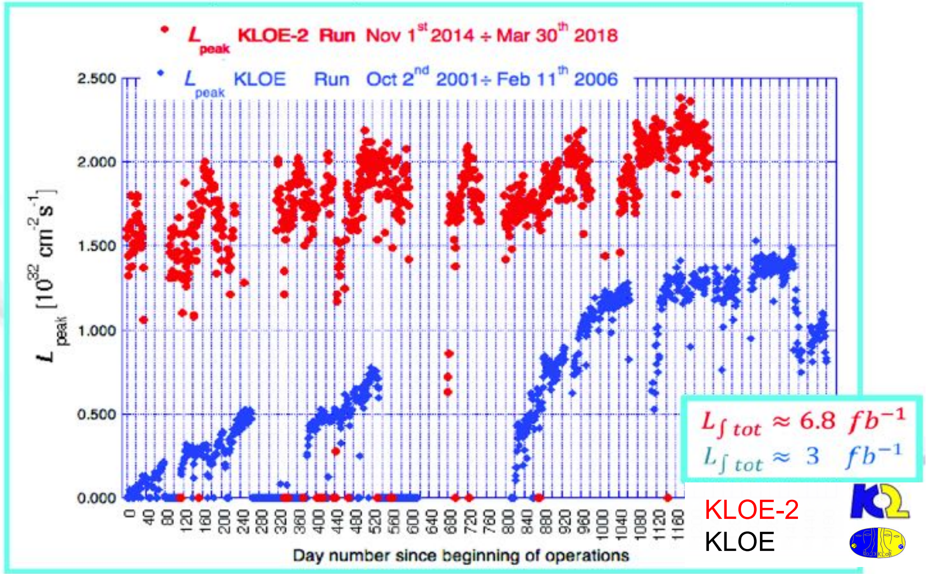
The KLOE-2 data-taking

- Dec.2012-July 2013: installation of KLOE-2 new detectors
- July 2013: DAΦNE operations started for KLOE-2
- **November 17, 2014: start of KLOE-2 run**
- **March 30, 2018: End of KLOE-2 data-taking**

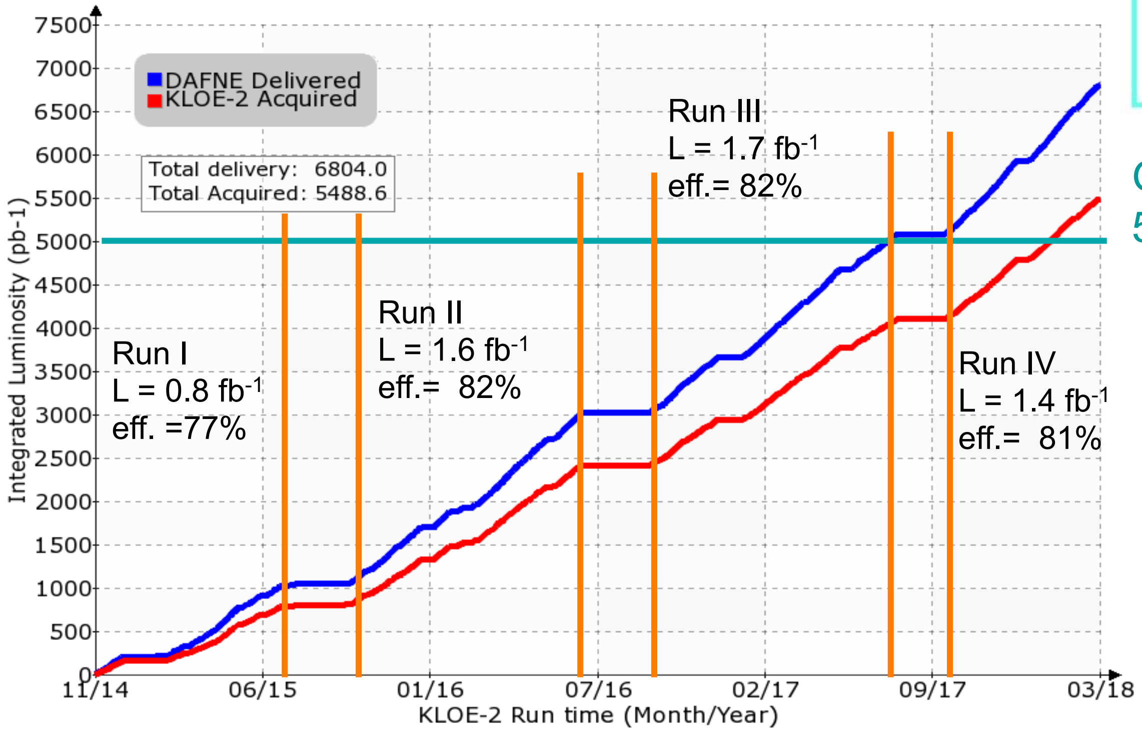
⇒ 5.5 fb^{-1} collected @$\sqrt{s}$=M$_\phi$

- **Best performance in KLOE-2 run:**

L_{peak} = 2.4 × 10^{32} cm^{-2}s^{-1} ∫Ldt = 14 pb^{-1}/day



Goal:
5 fb^{-1}



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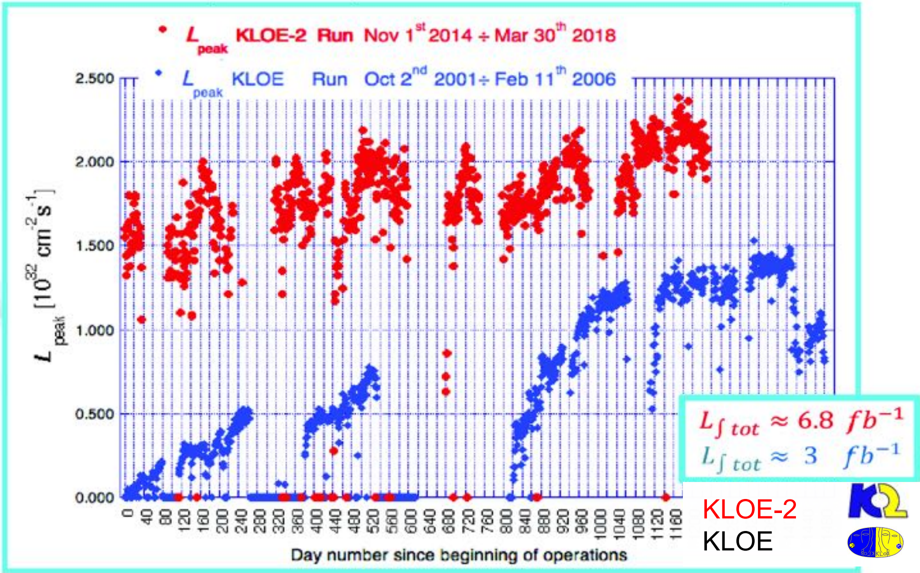
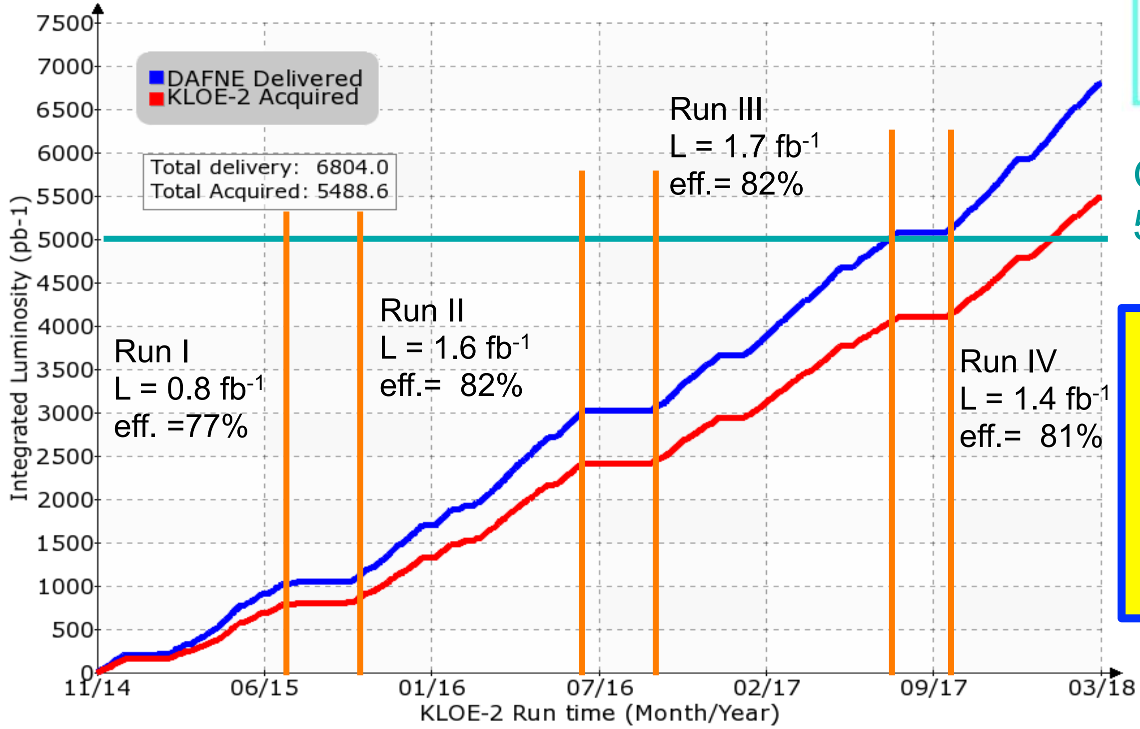




Goal:
5 fb^{-1}

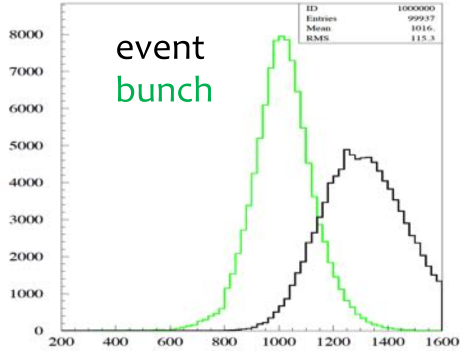
KLOE + KLOE-2 data sample:
~ 8 fb^{-1} ⇒ 2.4×10^{10} φ's produced
~ 8 $\times 10^9$ $K_S K_L$ pairs ~ 3 $\times 10^8$ η's
⇒ the largest sample ever collected at the φ(1020) peak in e^+e^- collisions

March 30, 2018: closing of the last KLOE-2 physics run

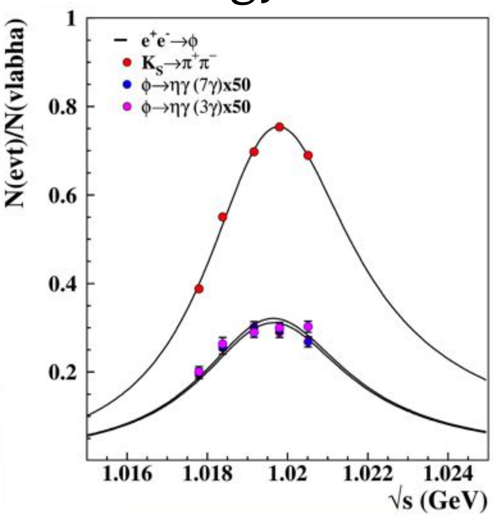
Optimization of the run conditions

Data selection with "bunching":
reduction of machine background by selecting the bunch crossing in the event with TOF

Total EMC Bhabha energy



Energy scan

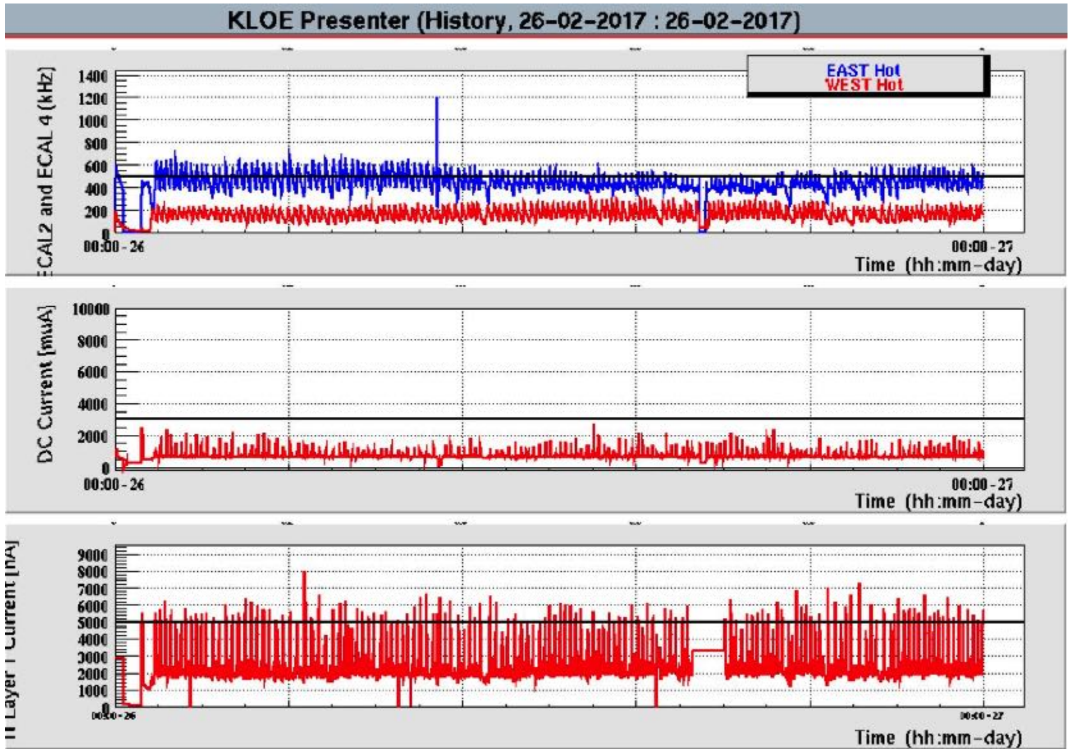


Conclusions:
KLOE absolute √s fine calibration: -240 keV (after 10 years!)

DAFNE: √s has been shifted by +550 keV to run exactly on φ peak

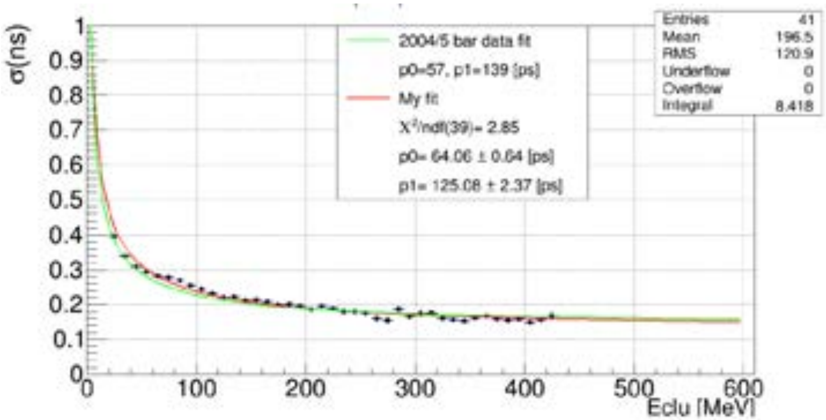
Provide online feedback information (EMC counts, DC and IT currents) to DAFNE to optimize beam injections (sinergy DAFNE-KLOE-2)

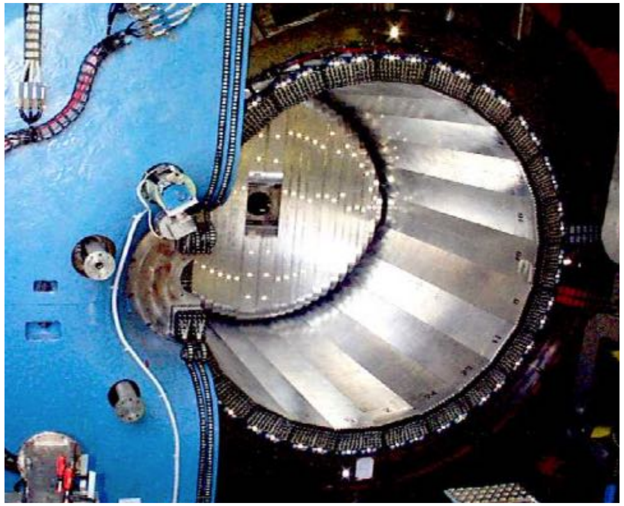
Hot End-caps counters ele < 500 kHz pos< 300 kHz
DC integrated current mostly < 2 mA
IT layer 1 integrated current mostly < 5 μA



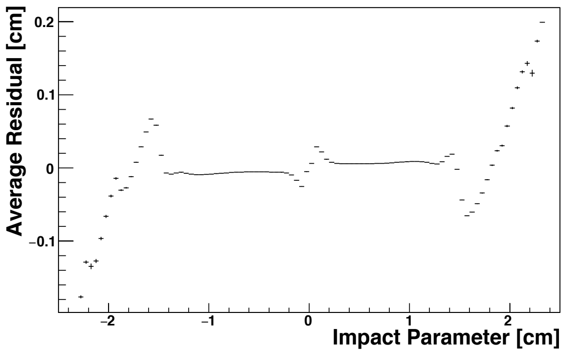
Data quality

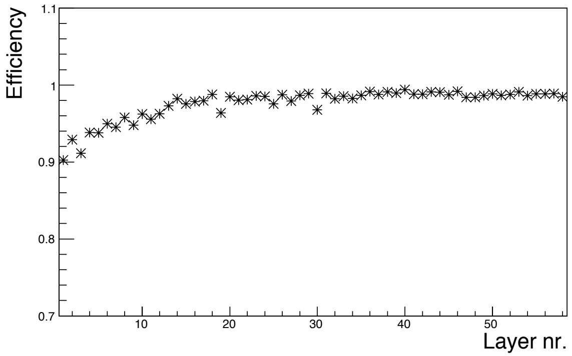
Stable EMC time/energy resolution

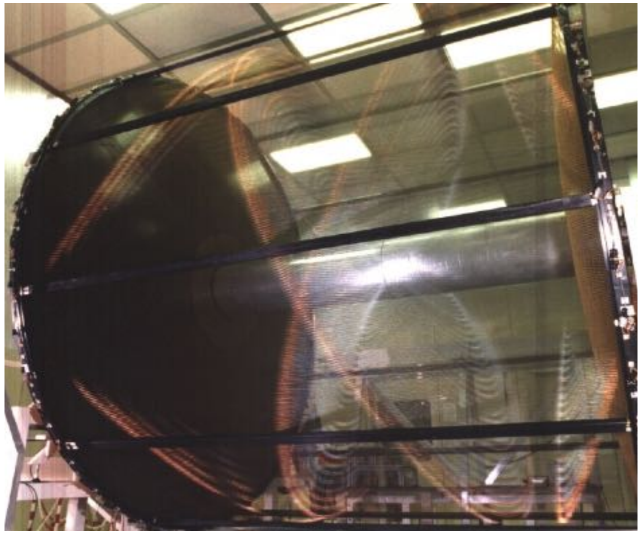




Stable DC resolution and efficiency

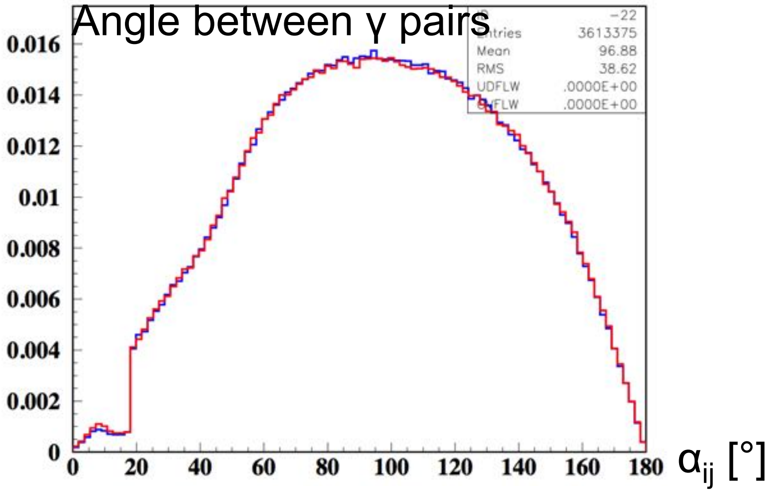




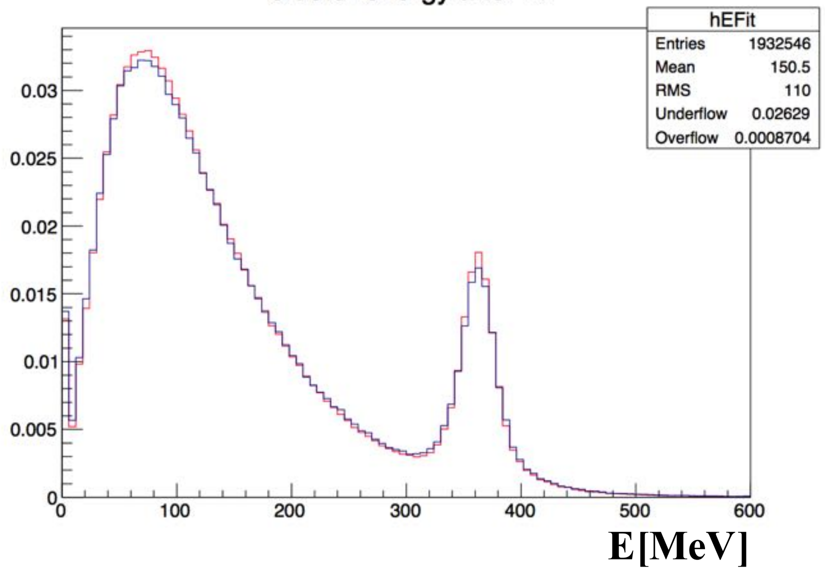


Data quality benchmark analyses

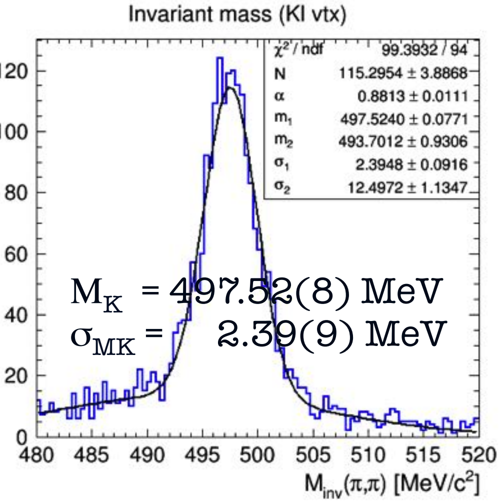
$\phi \to \eta\gamma$ with $\eta \to 3\pi^0$



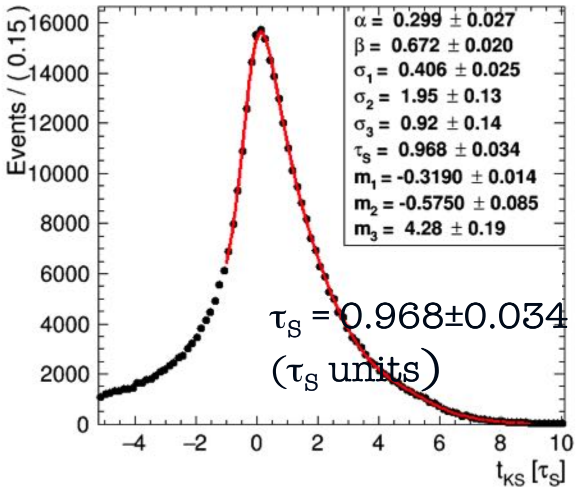
$\phi \to \eta\gamma$ with $\eta \to 3\pi^0$



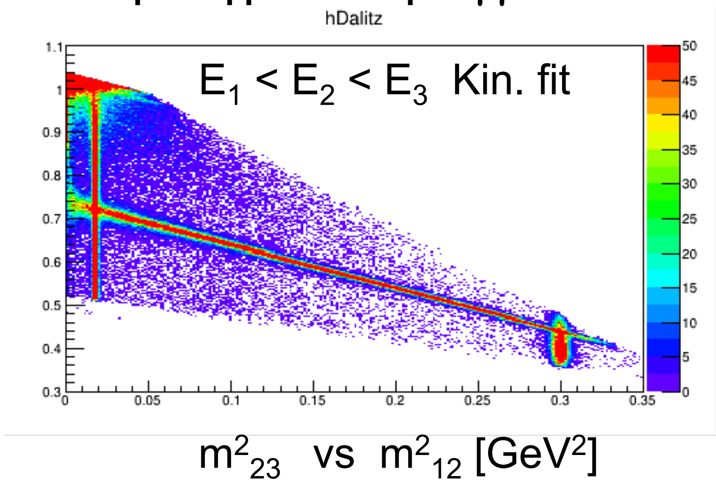
K_L inv mass with $K_L \to \pi^+\pi^-$



K_S lifetime with $K_S \to \pi^+\pi^-$

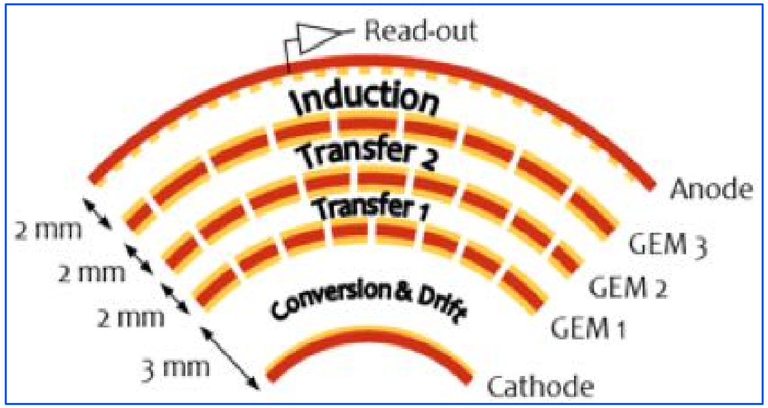


$\phi \to \eta\gamma$ with $\eta \to \gamma\gamma$

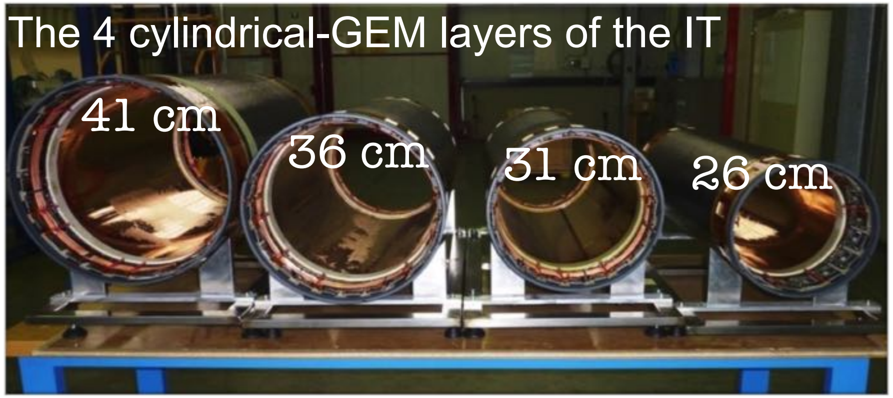


Inner Tracker (IT)

- First cylindrical triple-GEM detector used in a high-energy experiment



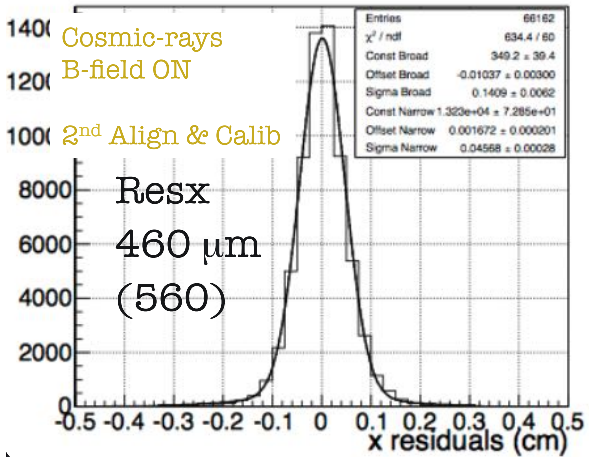
- 4 layers of cylindrical triple GEMs
- 70 cm active length
- XV strips/pads readout ($20^o \div 30^o$ stereo angle)
- $\sigma_{r\phi} \sim 250\ \mu m$ and $\sigma_z \sim 400\ \mu m$
- 25k chan FEE / 1600 HV chan
- Ar/Isobutane 90/10 gas mixture
- 12k gas gain
- 2% of radiation length in the active region

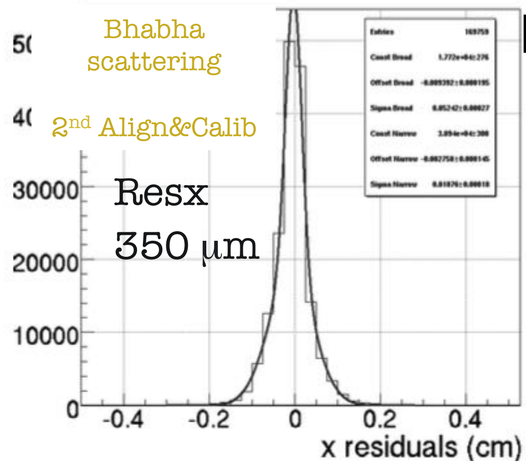


CAEN HV board (A1515) designed specifically for GEM detectors read-out currents with 0.1 nA resolution

IT performance

- IT alignment and calibration with cosmic ray events
- Non radial tracks and magnetic field effects
- Check with Bhabha scattering events



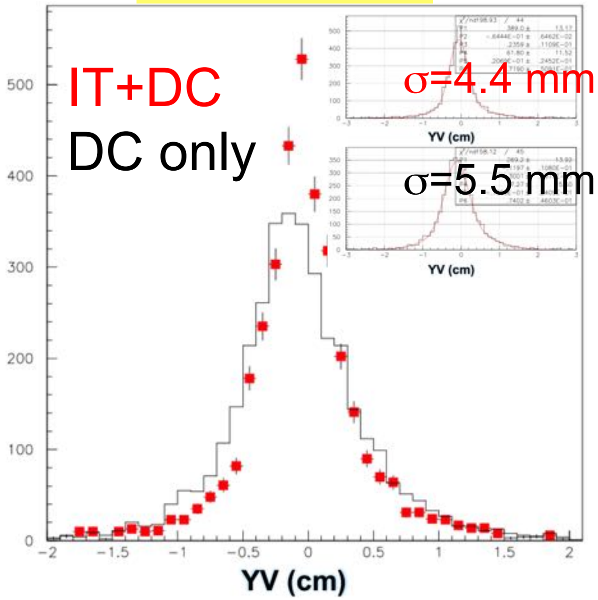


Layer 4

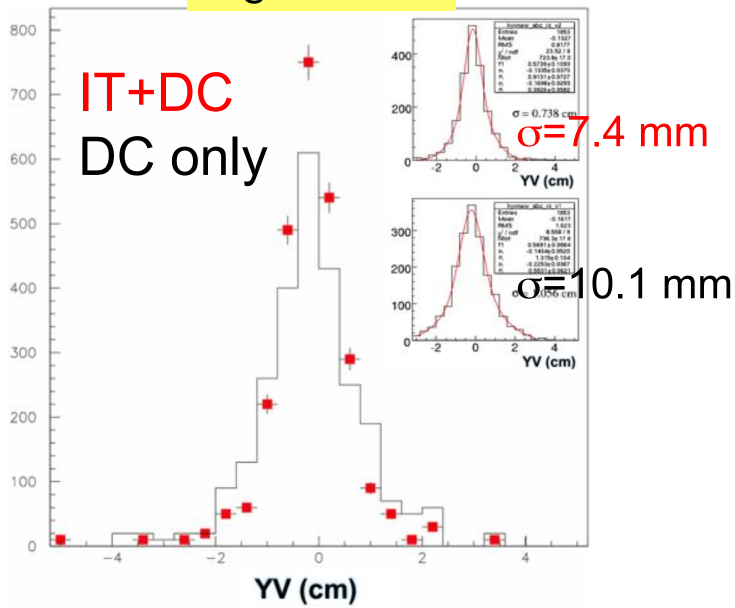
- Integrated DC+IT tracking Start with DC reconstructed tracks, add IT clusters and reconstruct IT+DC tracks

- Improvement in vertex reconstruction for $\phi \to \pi^+\pi^-\pi^0$ and $K_S \to \pi^+\pi^-$

$\phi \to \pi^+\pi^-\pi^0$



$K_S \to \pi^+\pi^-$

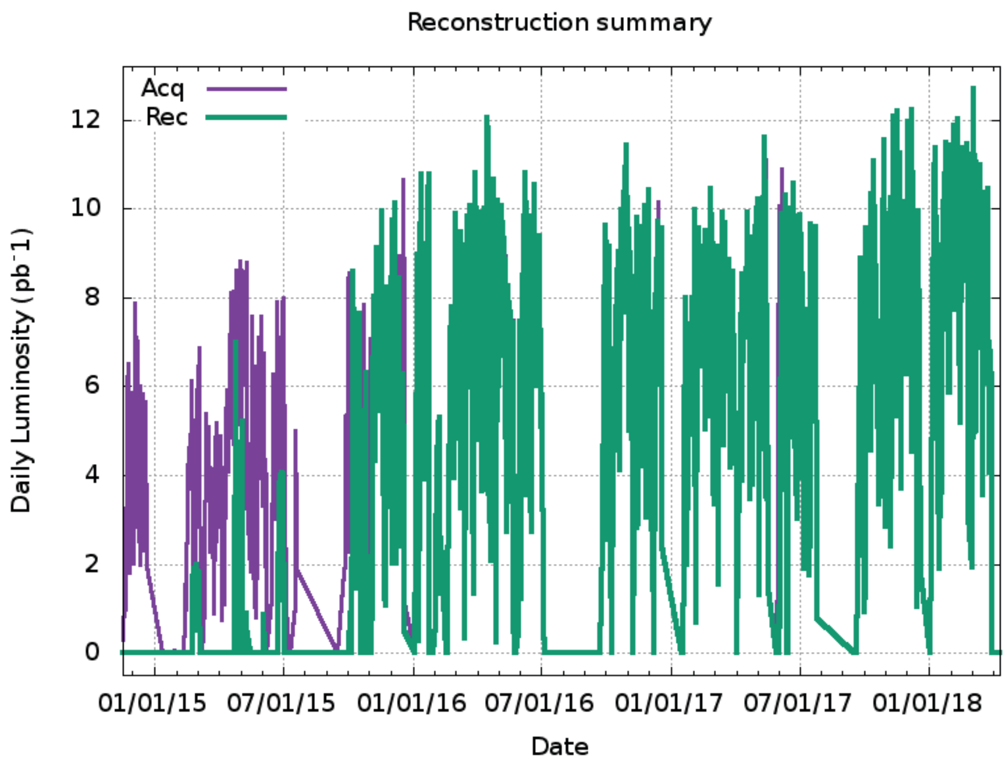


Data reconstruction

Data reconstruction completed in February 2019
Average reconstruction rate ~20 pb^{-1}/day
(4 fb^{-1} in 10 months)
Data Quality performed
Feedback to a new release
Final reconstruction campaign is starting: July 2019
Data preservation
Test & official code implementation ongoing

Monte Carlo production rate ~15 pb^{-1}/day
All ϕ decays produced along with Bhabha's sample
MC data for 2.3 fb^{-1} available

MC update in progress:
- Data/MC cross-check
- Fine tuning of the detector performance



	Run I	Run II	Run III	Run IV
Total Lum	0.7 fb-1	1.4 fb-1	1.6 fb-1	1.3 fb-1
Recon Lum	0.03 fb-1	1.2 fb-1	1.6 fb-1	1.3 fb-1

New TAPE LIBRARY IBM TS4500 R2
Improved data-servers, new architecture with large disk array buffer, new GPFS protocol

KLOE-2 Physics

KLOE-2 coll. EPJC (2010) 68, 619
http:// agenda.infn.it/event/kloe2ws procs. EPJ WoC 166 (2018)

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) (lattice calc. improved)
- CKM Vus:
  K_S semileptonic decays and A_S
  (also CP and CPT test)
  $K\mu3$ form factors, Kl3 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

Dark forces:

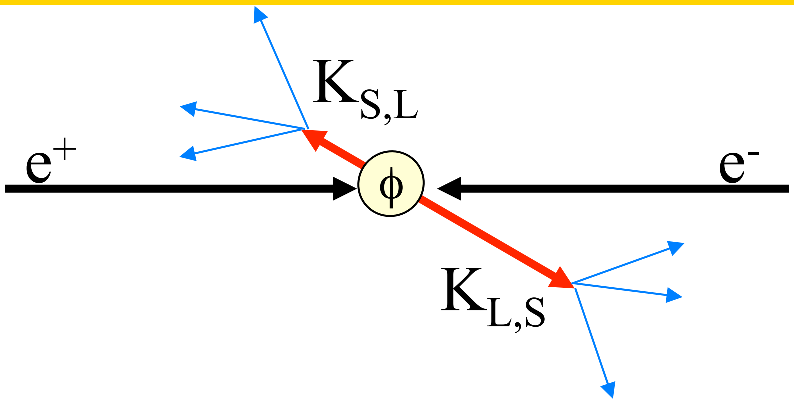
- Improve limits on:
  $U\gamma$ associate production
  $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$
- Higgstrahlung
  $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy
- Leptophobic B boson search
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

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
- Search for axion-like particles

Neutral kaons at a ϕ-factory

Production of the vector meson ϕ in e^+e^- annihilations:



- $e^+e^- \to \phi$ $\sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- $BR(\phi \to K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:

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

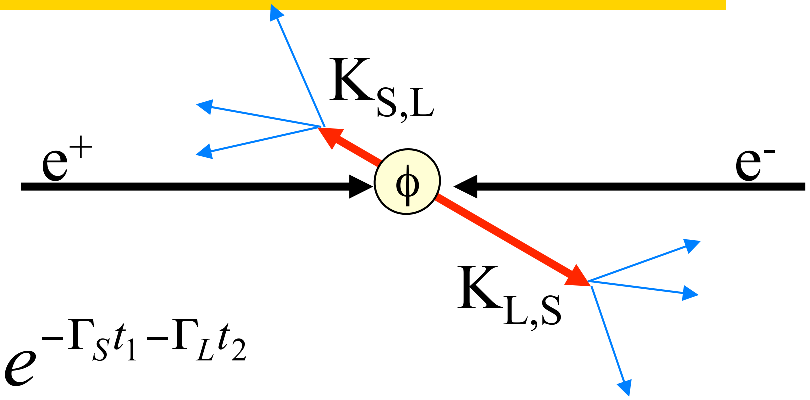
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\lambda_L = 3.5$ m

$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)}\Big/\left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

Neutral kaon interferometry

$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$



$$I(f_1, t_1; f_2, t_2) = C_{12} \{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)(t_1 + t_2)/2} \cos[\Delta m (t_2 - t_1) + \phi_1 - \phi_2] \}$$

characteristic interference term
at a φ-factory => interferometry

Neutral kaon interferometry

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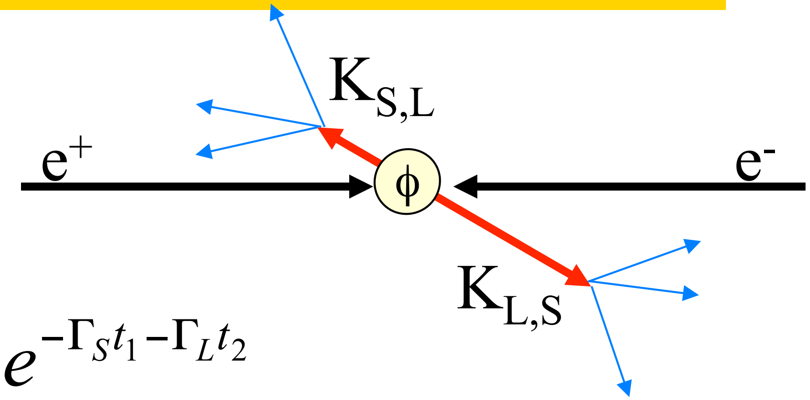

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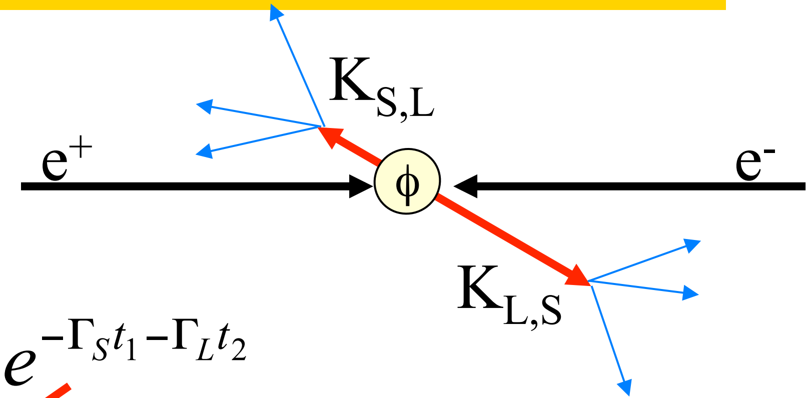
characteristic interference term
at a φ-factory => interferometry

For times $t_1 \gg \tau_S$ (or $t_2 \gg \tau_S$):

K_S physics

$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$



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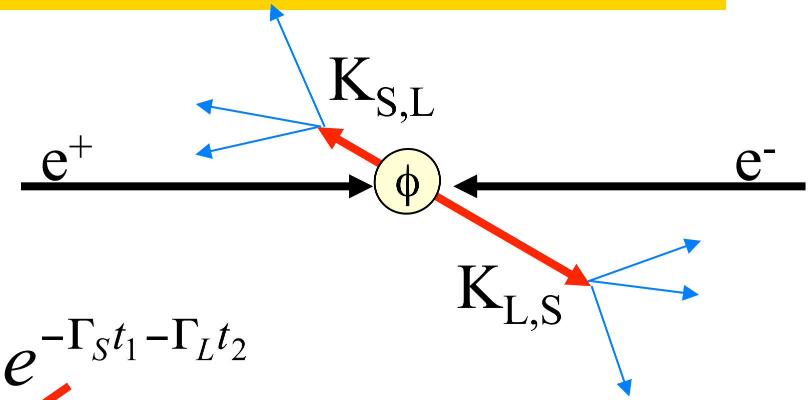
$$- 2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2} \cos[\Delta m(t_2 - t_1) + \phi_1 - \phi_2]\Big\}$$

For times $t_1 >> \tau_S$ (or $t_2 >> \tau_S$): => K_S physics

K_S physics

$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$



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For times $t_1 \gg \tau_S$ (or $t_2 \gg \tau_S$): => K_S physics

i.e. the state behaves like an incoherent mixture of states:

$$|K_S(t_1)\rangle |K_L(t_2)\rangle \quad \text{or} \quad |K_L(t_1)\rangle |K_S(t_2)\rangle$$

The detection of a kaon at large times **tags** a K_S

⇒ possibility to select a pure K_S beam

(unique at a ϕ-factory, not possible at fixed target experiments)

List of KLOE CP/CPT tests with neutral kaons

Mode	Test	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 10) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(x_-)$	$(-0.8 \pm 2.5) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(y)$	$(0.4 \pm 2.5) \times 10^{-3}$
All $K_{S,L}$ BRs, η's etc... (unitarity)	CP CPT	$Re(\varepsilon)$ $Im(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(-6.2 \pm 8.8) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(-0.7 \pm 1.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV

K_S semileptonic charge asymmetry

K_S and K_L semileptonic charge asymmetry

T CPT viol. in mixing

$$A_{S,L} = \frac{\Gamma\left(K_{S,L} \to \pi^- e^+ \nu\right) - \Gamma\left(K_{S,L} \to \pi^+ e^- \bar{\nu}\right)}{\Gamma\left(K_{S,L} \to \pi^- e^+ \nu\right) + \Gamma\left(K_{S,L} \to \pi^+ e^- \bar{\nu}\right)} = 2\Re\varepsilon \pm 2\Re\delta - 2\Re y \pm 2\Re x_-$$

CPTV in ΔS=ΔQ ΔS≠ΔQ decays

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

$A_S \neq A_L$ signals CPT violation

$$\mathbf{A_L = (\, 3.322 \pm 0.058 \pm 0.047 \,) \times 10^{-3}}$$

KTEV PRL88,181601(2002)

$$\mathbf{A_S = (\, 1.5 \pm 9.6 \pm 2.9 \,) \times 10^{-3}}$$

KLOE PLB 636(2006) 173

Data sample: L=410 pb^{-1}

$$A_S - A_L = 4\left(\Re\delta + \Re x_-\right) \longrightarrow \Re x_- = (\, -0.8 \pm 2.5) \times 10^{-3}$$

CPT & Δ*S*=Δ*Q* viol.

$$A_S + A_L = 4\left(\Re\varepsilon - \Re y\right) \longrightarrow \Re y = (\, 0.4 \pm 2.5) \times 10^{-3}$$

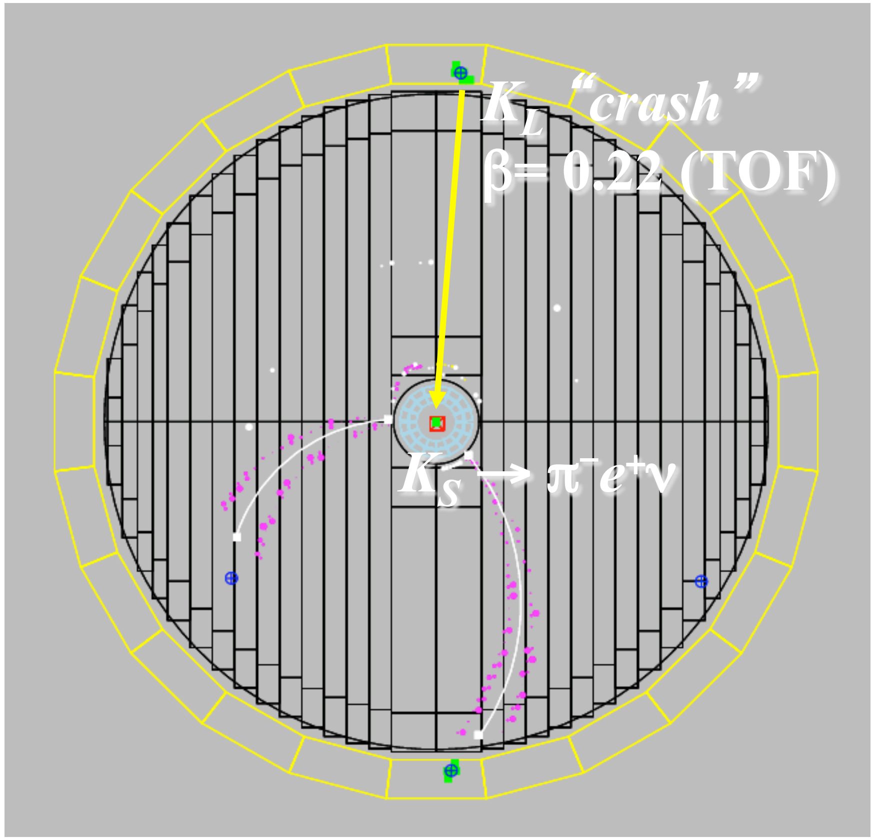
CPT viol.

input from other experiments

KLOE PLB 636(2006) 173

K_S semileptonic charge asymmetry

$$|i\rangle \propto \left[|K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle \right]$$

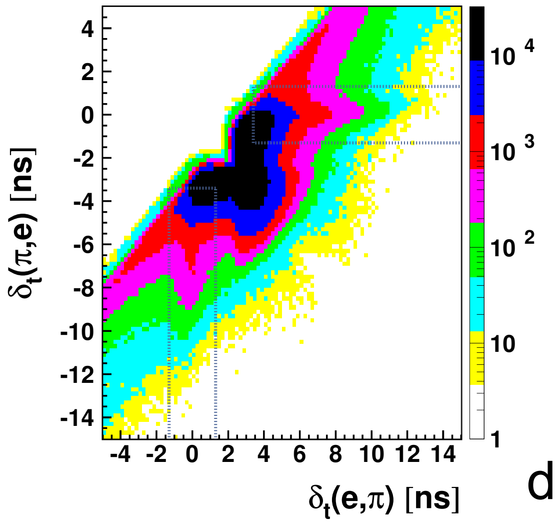


***K_S* tagged by *K_L* interaction in EmC**
Efficiency ~ 30% (largely geometrical)

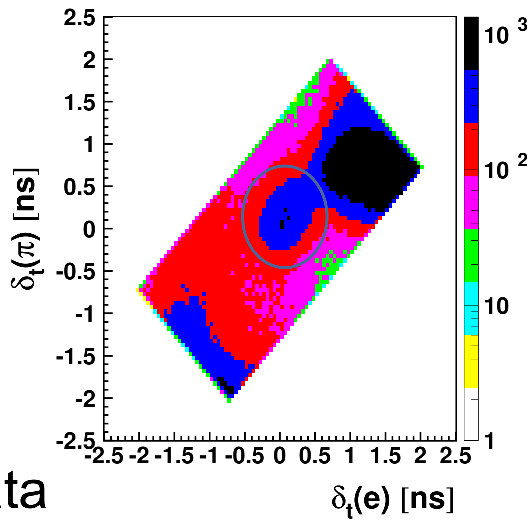
- Pure K_S sample selected exploiting entanglement
- L=1.6 fb^{-1}; ~ 4 × statistics w.r.t. previous measurement
- Pre-selection: 1 vtx close to IP with $M_{inv}(\pi,\pi)<M_K$ + K_L crash
- PID with time of flight technique

$$\delta_t(X) = (t_{cl} - T_0) - \frac{L}{c\beta(X)} \quad ; \quad X = e,\pi$$

$$\delta_t(X,Y) = \delta_t(X)_1 - \delta_t(Y)_2$$



data

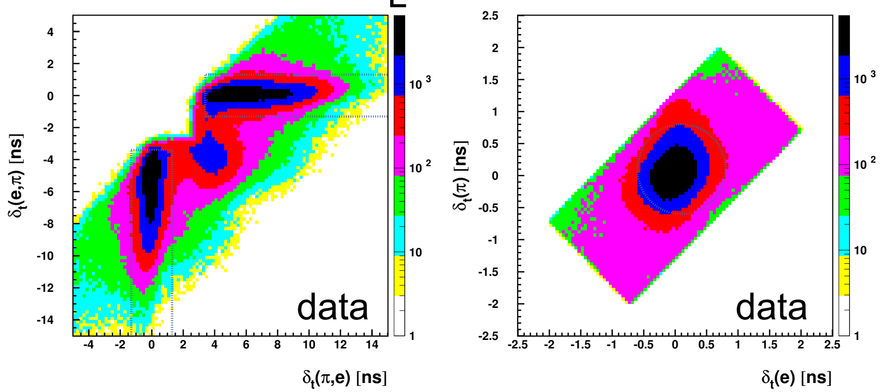


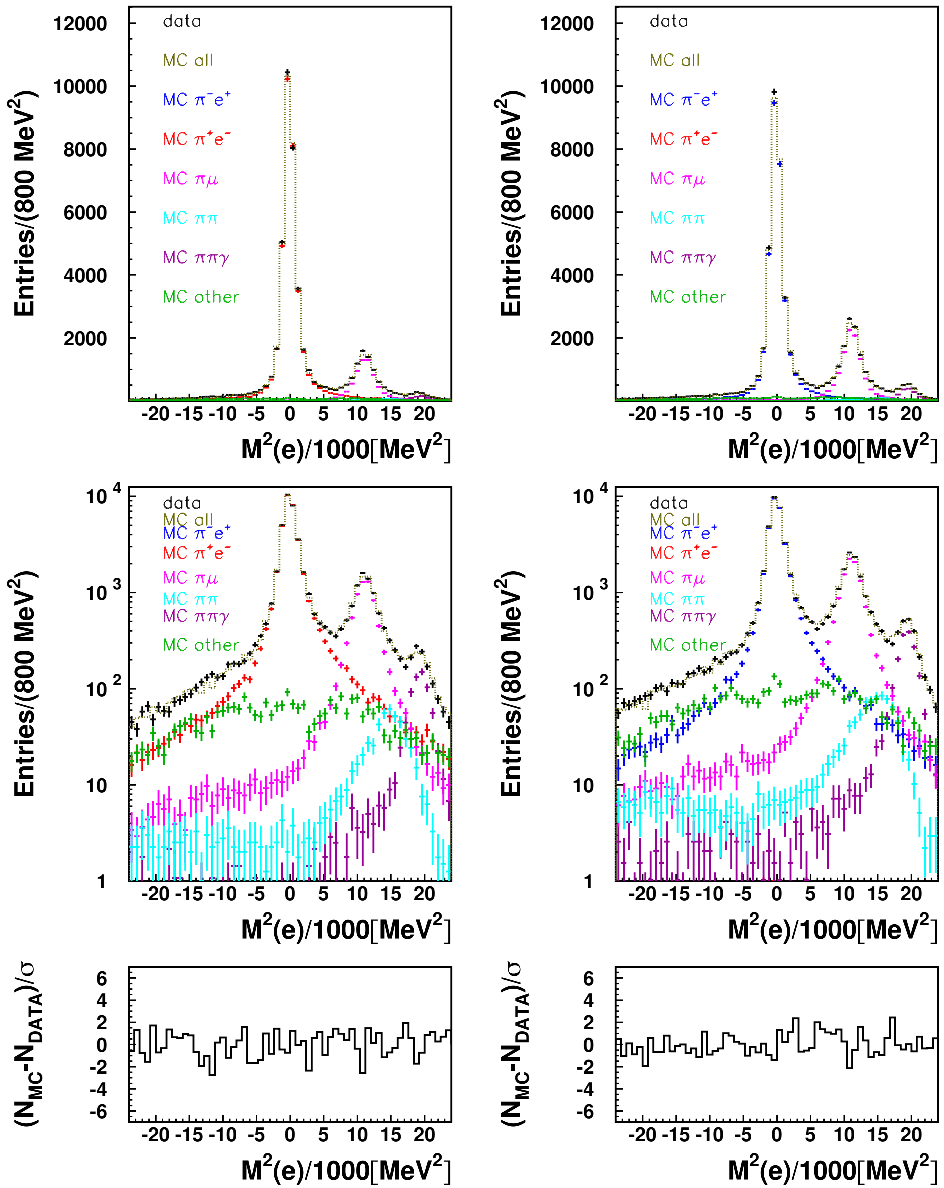
K_S semileptonic charge asymmetry

- Fit of $M^2(e)$ distribution varying MC normalizations of signal and bkg contributions.
- Total $\chi^2/ndf = 118/109$
- Total efficiencies: $\varepsilon^+=(7.39\pm0.03)\%$ and $\varepsilon^-=(7.81\pm0.03)\%$

- Control sample: $K_L \to \pi e \nu$ close to IP tagged by $K_S \to \pi^0\pi^0$
- track to EMC cluster and TOF efficiency correction from control sample

$K_L \to \pi e \nu$





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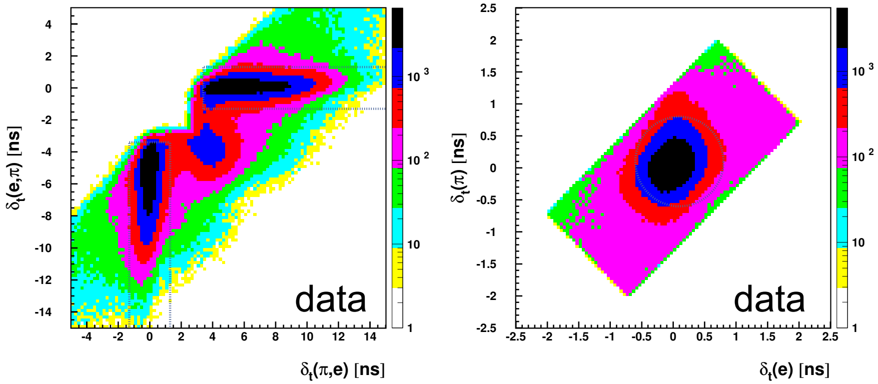
$K_L \rightarrow \pi e \nu$



$$A_S = \frac{N(\pi^- e^+)/\varepsilon^+ - N(\pi^+ e^-)/\varepsilon^-}{N(\pi^- e^+)/\varepsilon^+ + N(\pi^+ e^-)/\varepsilon^-}$$

Systematic uncertainties on A_S

Contribution		Systematic uncertainty (10^{-3})
Trigger and event classification	σ_{TEC}	0.28
Tagging and preselection	$E_{clu}(crash)$	0.55
"	β^*	0.67
"	z_{vtx}	0.01
"	ρ_{vtx}	0.05
"	α	0.46
"	$M_{inv}(\pi,\pi)$	0.20
Time of flight selection	$\delta_t(\pi,\pi)$	0.71
"	$\delta_t(e,\pi)$ vs $\delta_t(\pi,e)$	0.87
"	$\delta_t(e)$ vs $\delta_t(\pi)$	1.82
Momenta smearing	σ_{MS}	0.58
Fit procedure	σ_{HBW}	0.61
"	Fit range	0.49
Total		2.6

K_S semileptonic charge asymmetry

Data sample: L=1.6 fb^{-1}

KLOE (2018)

$$A_S = (-4.8 \pm 5.6 \pm 2.6) \times 10^{-3}$$

K_S semileptonic charge asymmetry

Data sample: L=1.6 fb^{-1}

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$$A_S = (-4.8 \pm 5.6 \pm 2.6) \times 10^{-3}$$

Combination KLOE(2006)+KLOE (2018)

$$A_S = (-3.8 \pm 5.0 \pm 2.6) \times 10^{-3}$$

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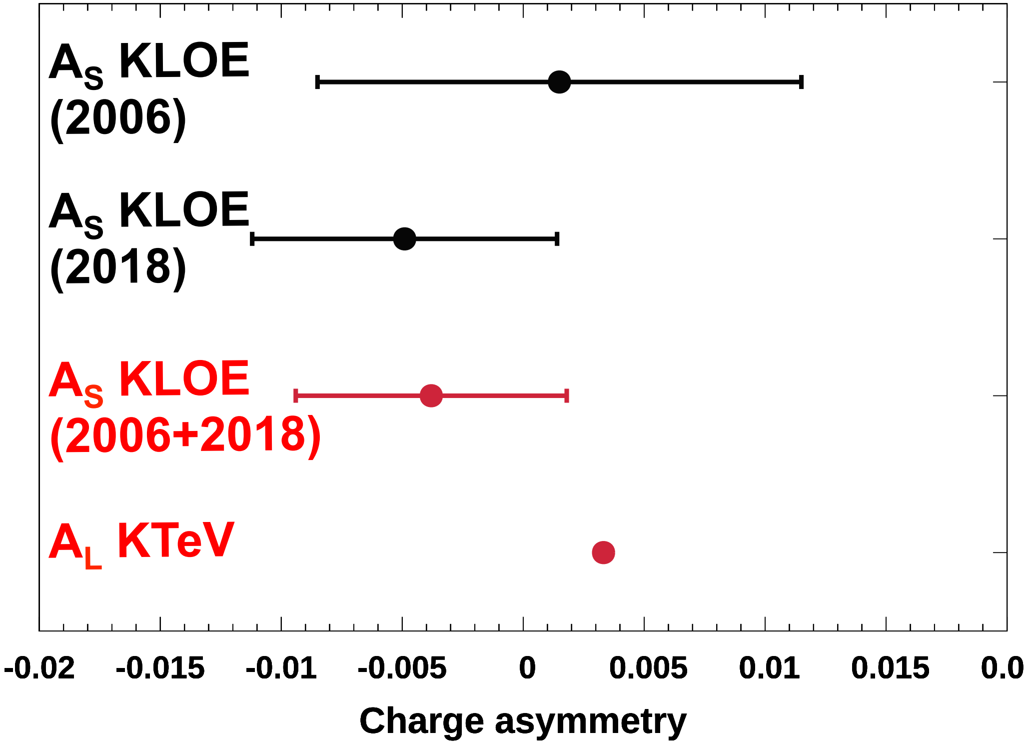
input from other experiments

K_S semileptonic charge asymmetry



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JHEP 09 (2018) 21

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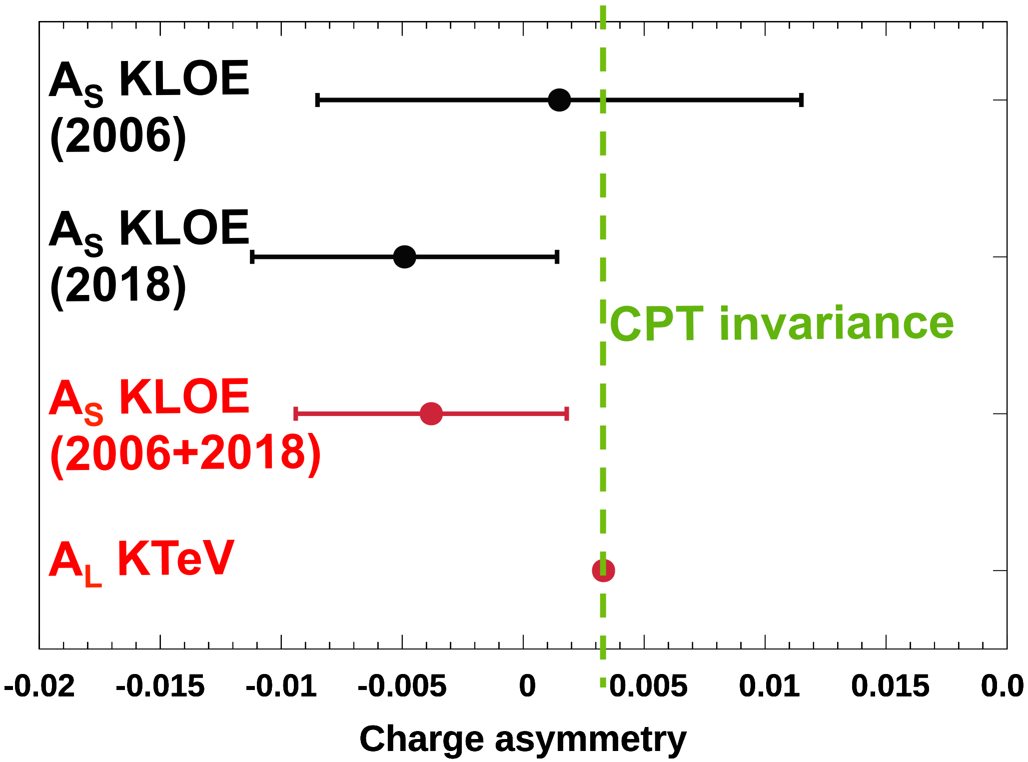

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JHEP 09 (2018) 21

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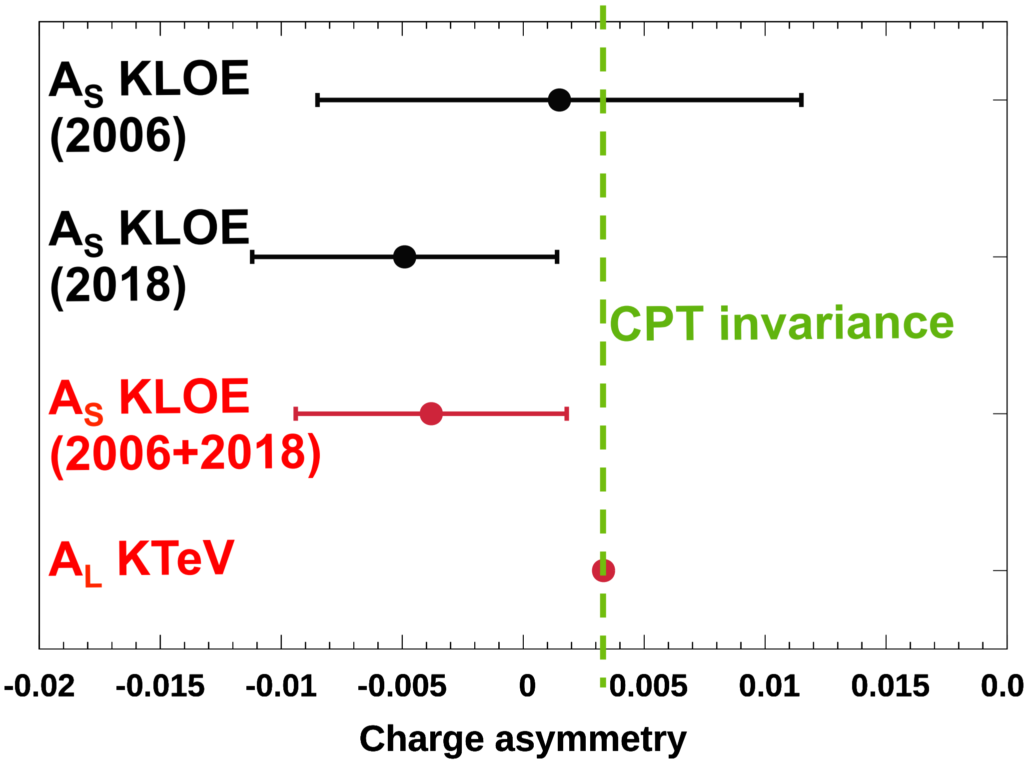

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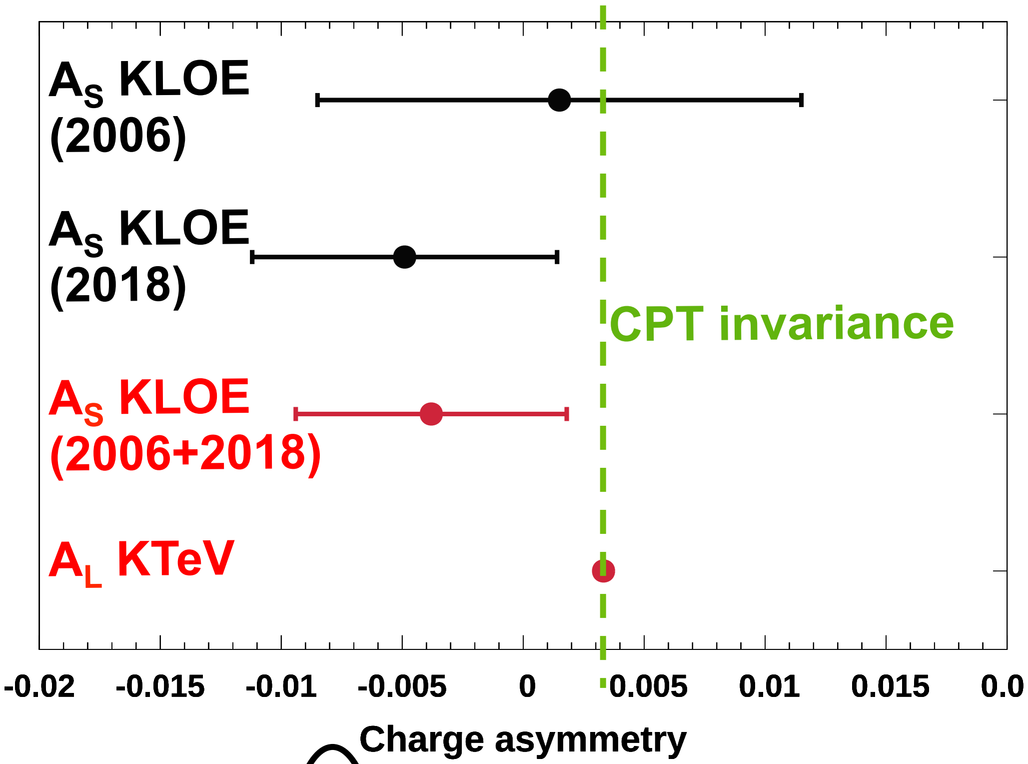
JHEP 09 (2018) 21

with KLOE-2 data: δA_S(stat) $\rightarrow \sim 3\times10^{-3}$

K_S semileptonic charge asymmetry



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

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (-2.0 \pm 1.4) \times 10^{-3}$$

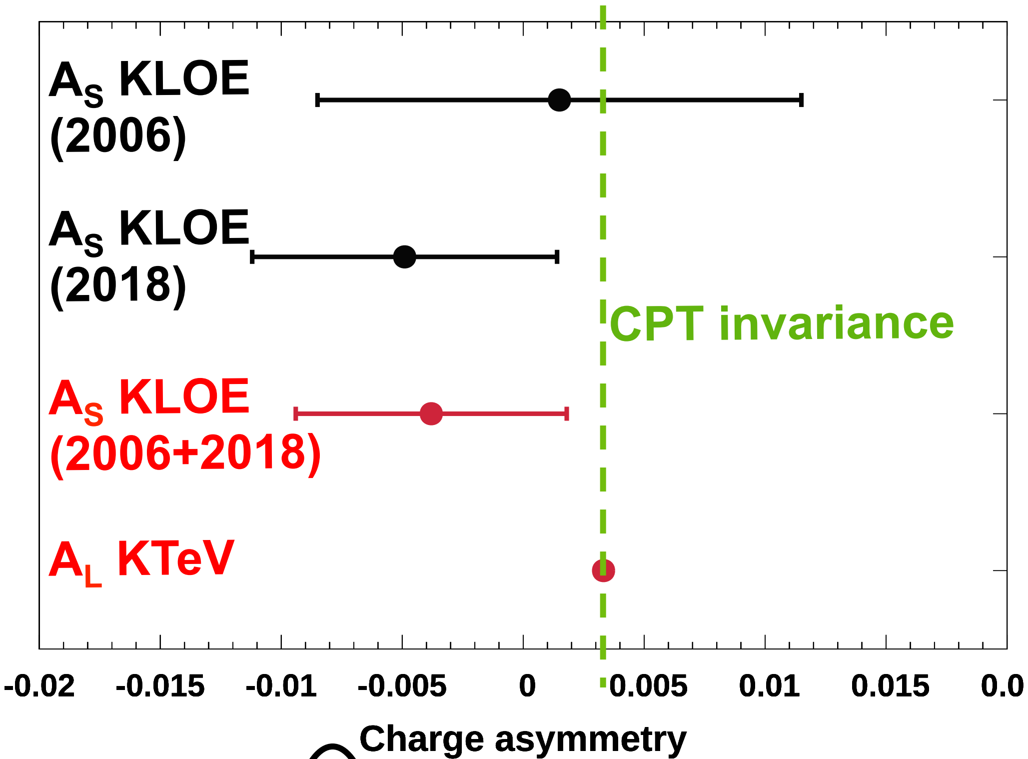
CPT & $\Delta S=\Delta Q$ viol. **JHEP 09 (2018) 21**

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$

CPT viol.

input from other experiments

K_S semileptonic charge asymmetry



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JHEP 09 (2018) 21

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$

CPT viol.

input from other experiments

(A_S+A_L) => improvement of CPT test (Imδ) using Bell-Steinberger relationship

Branching ratio of $K_S \rightarrow \pi e \nu$ decay

Precision measurement of V_{us}

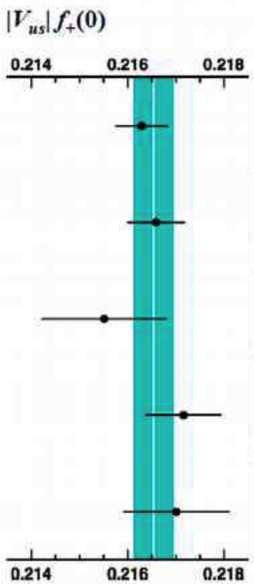
From K_{Se3} the largest contribution to the uncertainty

[old KLOE meas. Br(KSe3) = $(7.046 \pm 0.091) \times 10^{-4}$]

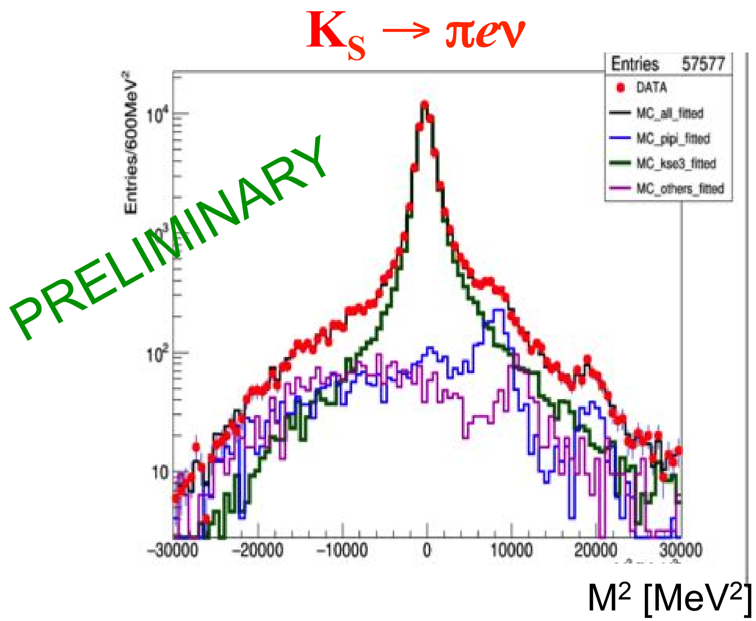
New analysis scheme based on BDT selection and TOF identification.

49647 events in 1.6 fb-1

Systematics are being studied



			Approx. contrib. to % err from:			
		% err	BR	τ	Δ	Int
$K_L e3$	0.2163(6)	0.26	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2166(6)	0.28	0.15	0.18	0.11	0.06
$K_S e3$	0.2155(13)	0.61	0.60	0.02	0.11	0.05
$K^{\pm} e3$	0.2172(8)	0.36	0.27	0.06	0.23	0.05
$K^{\pm} \mu 3$	0.2170(11)	0.51	0.45	0.06	0.23	0.06



Branching ratio of $K_S \rightarrow \pi\mu\nu$ decay

First measurement of Br(Ksμ3)

7223 events in 1.6 fb^{-1}

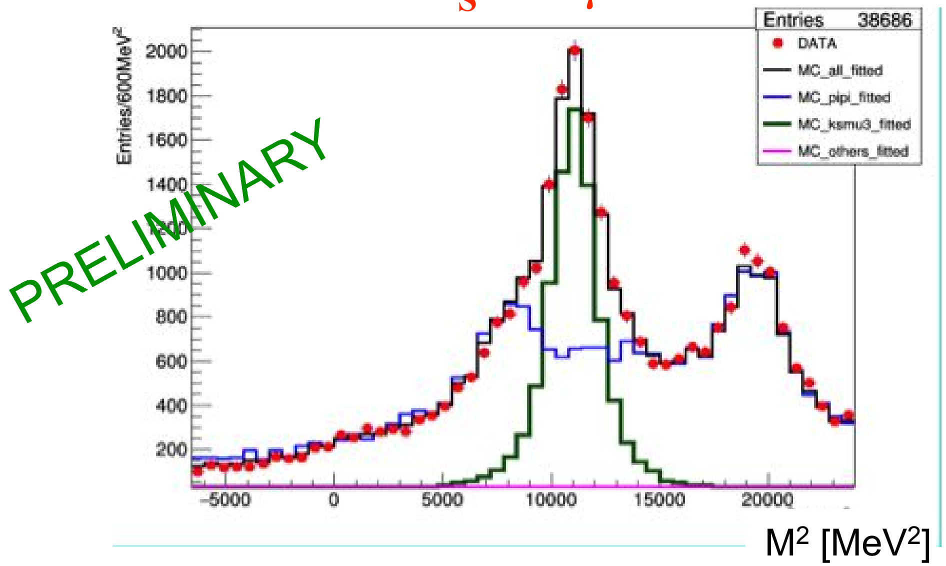
Expected Br($K_{S\mu3}$) = (4.69 ± 0.05) x 10^{-4}

Uncertainty of the preliminary measurement
2.5 % stat ± 3.1 % syst

Control of the systematics being finalized

Lepton universality test and improvement of V_{us} precision

$K_S \rightarrow \pi\mu\nu$

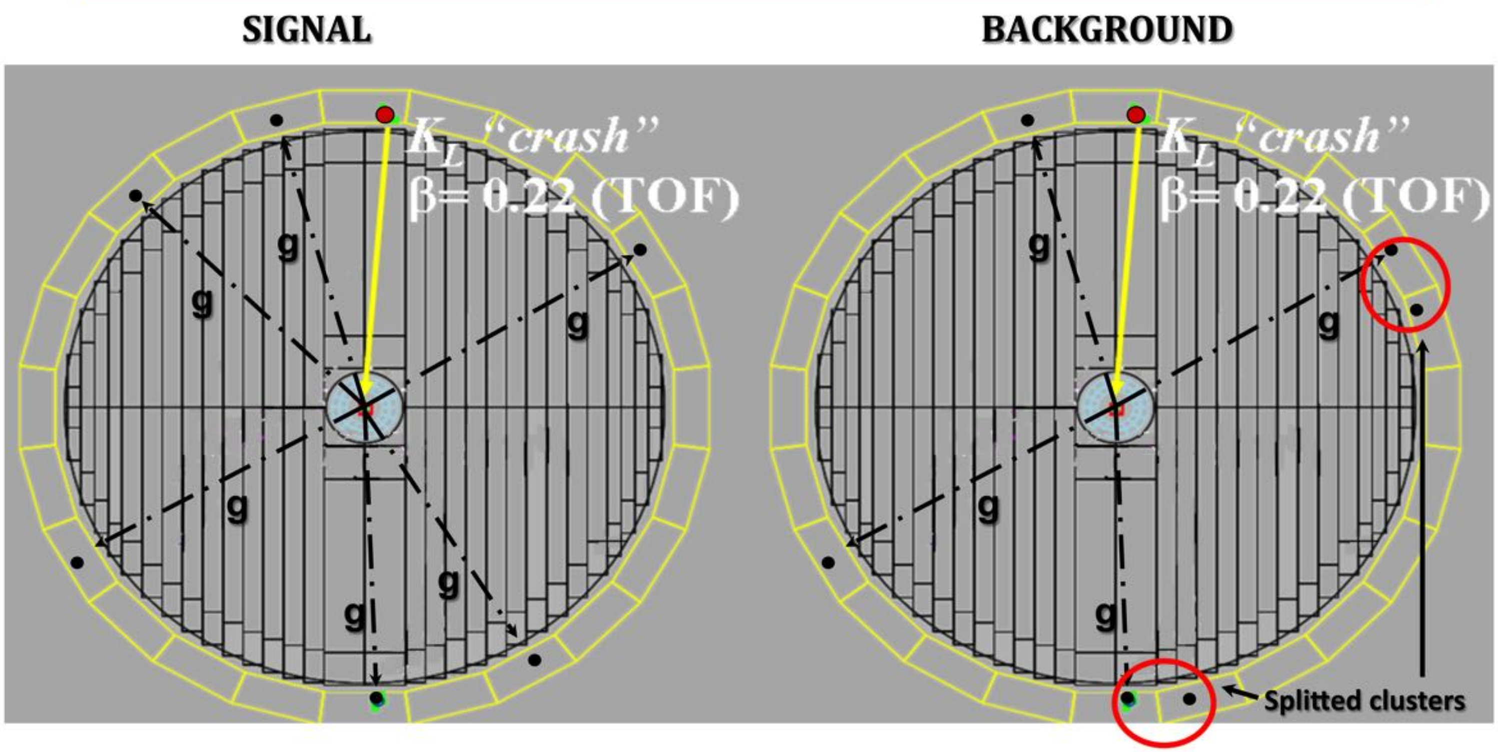


Search for the CP violating $K_S \to \pi^0\pi^0\pi^0$ decay

$3\pi^0$ is a pure CP=-1 state; observation of $K_S \to 3\pi^0$ is an unambiguous sign of CP violation in mixing and/or in decay.

Standard Model prediction: $BR(K_S \to 3\pi^0) = 1.9 \cdot 10^{-9}$ PLB 723 (2013) 54

Best upper limit by KLOE with 1.7 fb^{-1} **$BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% CL**



$K_S \to 3\pi^0 \to 6\gamma$

$K_S \to 2\pi^0$ + accidental/splitted clusters
$K_L \to 3\pi^0$, $K_S \to \pi^+\pi^-$ („fake K_L crash")

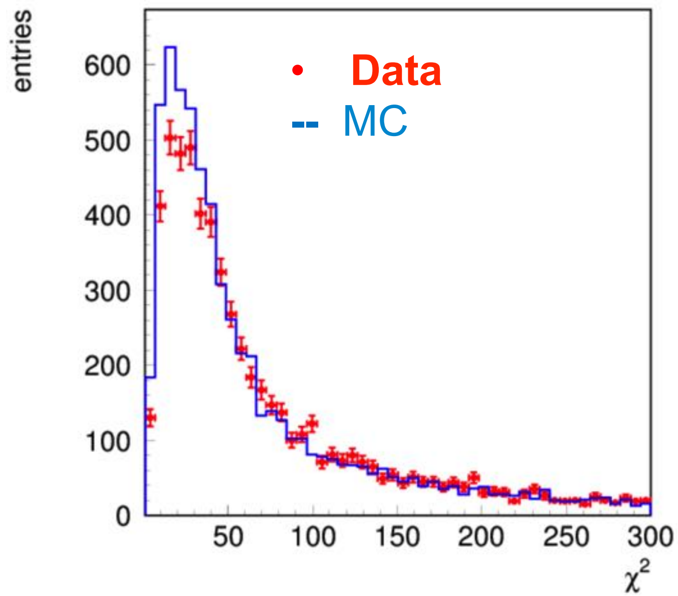
Search for the CP violating $K_S \rightarrow \pi^0\pi^0\pi^0$ decay

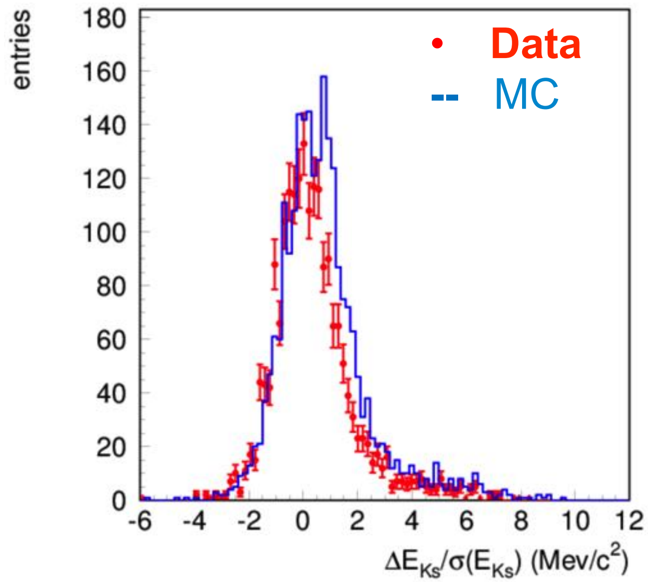
KLOE-2 analysed data $L \approx 1.5\ fb^{-1}$

- "K_L crash" (K_L in the EMC) + 6 prompt photons
- Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
- Main bckg: $K_S \rightarrow 2\pi^0$ (4 prompt photons), also used for normalization
- Selection criteria hardened to face the larger machine background: ~ 10x better background rejection

- Cut-based analysis : Track Veto, Kinematic fit on KS, consistency between KL/KS kinematics, Photon-pairing in both $3\pi^0$ and $2\pi^0$ hypotheses, distance btw clusters.
- zero candidates obtained from MC; ε=29% (was 36%)
- mva approach in progress might improve the efficiency while keeping the same bck rejection

- New limit with KLOE-2 statistics and optimised analysis is expected a factor of 2 better than previous UL($\lesssim 10^{-8}$)





CPT test: motivation

CPT theorem holds for any QFT formulated on flat space-time which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).
Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
huge effort in the last decades to study and shed light on QG phenomenology
⇒ Phenomenological CPTV parameters to be constrained by experiments

Consequences of CPT symmetry: equality of masses, lifetimes, |q| and |μ| of a particle and its anti-particle.

Neutral meson systems offer unique possibilities to test CPT invariance; e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system $\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}$

neutral B system $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

Many other interesting CPT tests: see other presentations to this workshop

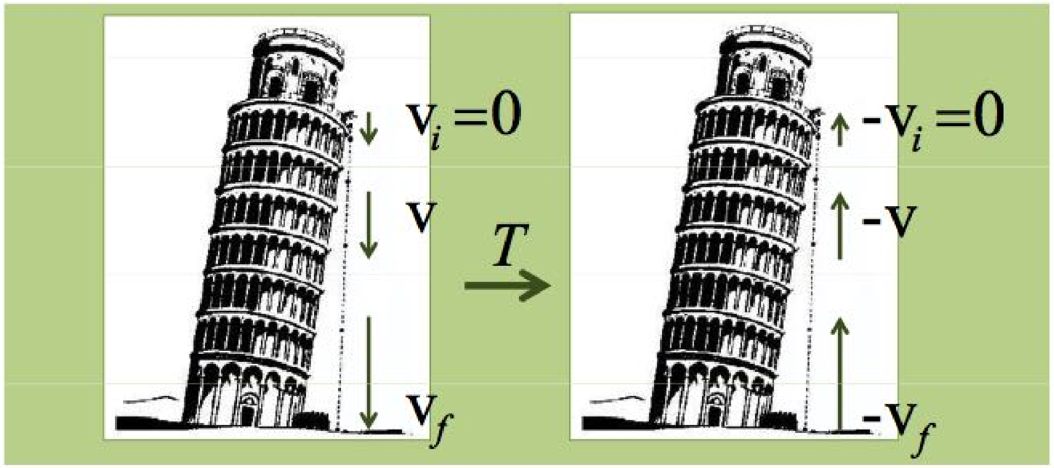
Direct T and CPT test in transitions

- Is it possible to test the CPT symmetry directly <u>in transition processes</u> between kaon states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states?
- CPT violating effects may not appear at first order in diagonal mass terms (survival probabilities) while they can manifest at first order in transitions (non-diagonal terms).
- Clean formulation required. Possible spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have to be well under control.
- In standard WWA the test is related to Reδ, a genuine CPT violating effect independent of $\Delta\Gamma$, i.e. not requiring the decay as an essential ingredient.

Probing CPT: J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139
Time-reversal violation: J. Bernabeu, A.D.D., P. Villanueva, NPB 868 (2013) 102

Time Reversal

•The transformation of a system corresponding to the inversion of the time coordinate, the formal substitution t → −t, is usually called '**time reversal**', but a more appropriate name would actually be **motion reversal**.



•Exchange of in <-> out states and reversal of all momenta and spins tests time reversal, i.e. the symmetry of the responsible dynamics for the observed process under time reversal t → −t (transformation implemented in QM by an antiunitary operator)

•Similarly for CPT tests: the exchange of in <-> out states etc.. is required.

Definition of states

We need two orthogonal bases:

1) $|K^0\rangle$ and $|\bar{K}^0\rangle$ assuming $\Delta S=\Delta Q$ rule identified by their $\pi l\nu$ decay (l^+ or l^-)

2) $|K_+\rangle$ and $|K_-\rangle$ (* not to be confused with charged kaons K^+ and K^-)

Let us also consider the states $|K_+\rangle$, $|K_-\rangle$ defined as follows: $|K_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP $= +1$ state; analogously $|K_-\rangle$ is the state filtered by the decay into $3\pi^0$, a pure CP $= -1$ state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^0$, defined, respectively, as

$$|\widetilde{K}_-\rangle \equiv \widetilde{N}_- \left[|K_L\rangle - \eta_{\pi\pi}|K_S\rangle\right]$$
$$|\widetilde{K}_+\rangle \equiv \widetilde{N}_+ \left[|K_S\rangle - \eta_{3\pi^0}|K_L\rangle\right]$$

$$\eta_{\pi\pi} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle}$$
$$\eta_{3\pi^0} = \frac{\langle 3\pi^0|T|K_S\rangle}{\langle 3\pi^0|T|K_L\rangle}$$

Orthogonal bases: $\{K_+, \widetilde{K}_-\}$ $\{\widetilde{K}_+, K_-\}$

Even though the decay products are orthogonal, the filtered $|K_+\rangle$ and $|K_-\rangle$ states can still be non-orthoghonal.

Condition of orthoghonality:

$$\eta_{\pi\pi} + \eta^\star_{3\pi^0} = \epsilon_L + \epsilon^\star_S$$

Neglecting direct CP violation ε' →

$$|K_+\rangle \equiv |\widetilde{K}_+\rangle$$
$$|K_-\rangle \equiv |\widetilde{K}_-\rangle$$

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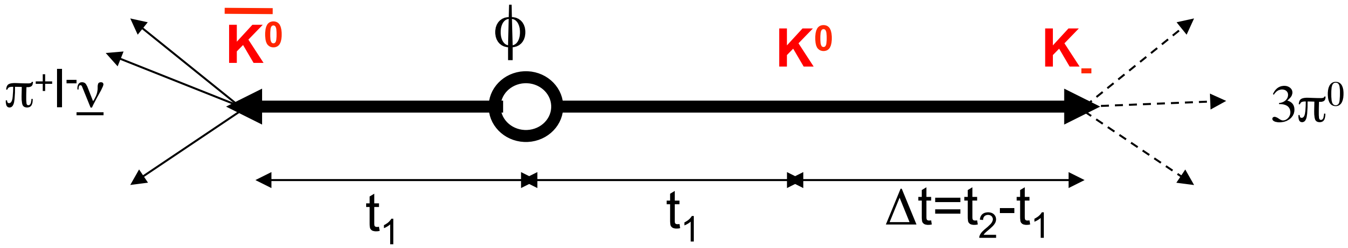
Direct test of T and CPT in neutral kaon transitions

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

- decay as filtering measurement
- entanglement → preparation of state



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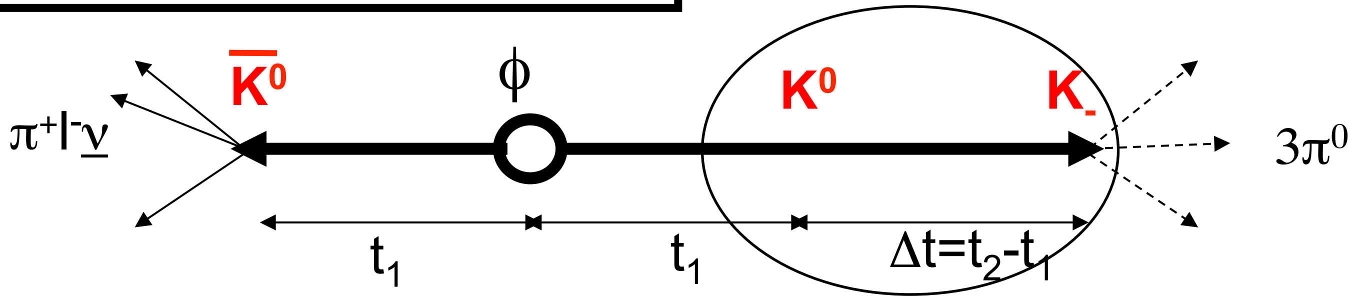


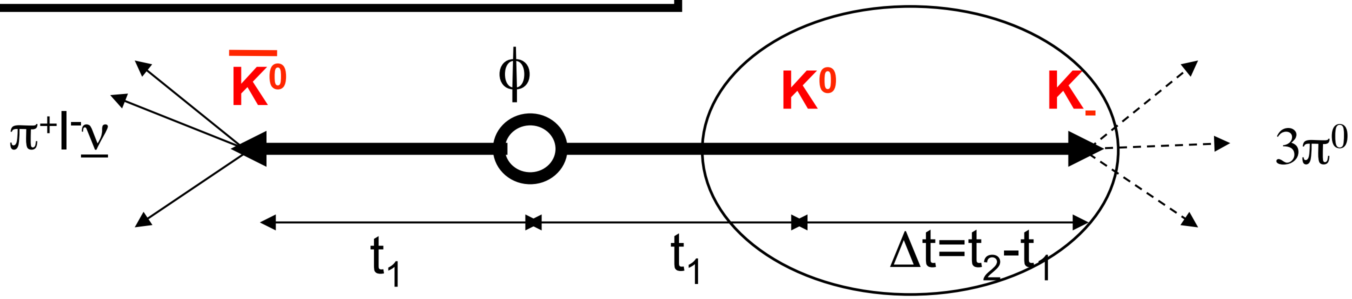
$K^0 \rightarrow K_-$ reference process

Direct test of T and CPT in neutral kaon transitions

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

•decay as filtering measurement
•entanglement → preparation of state



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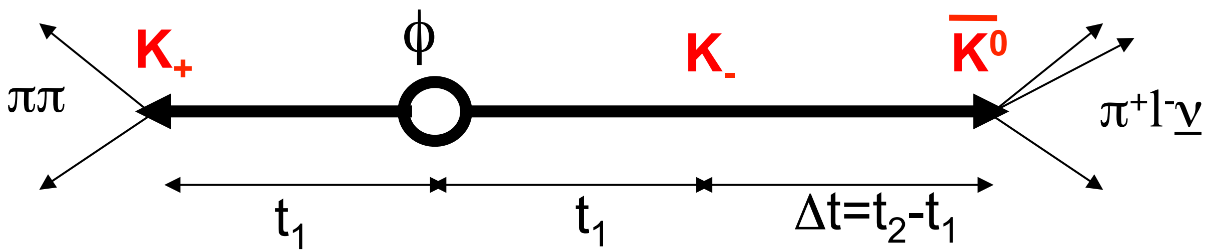

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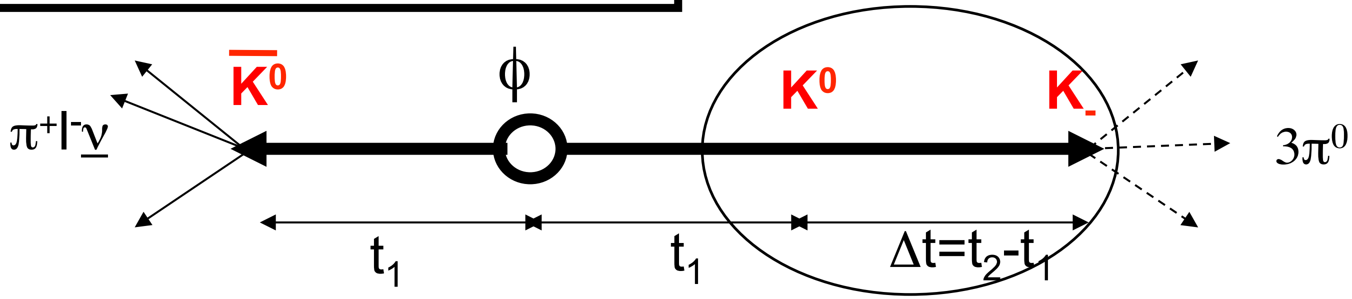
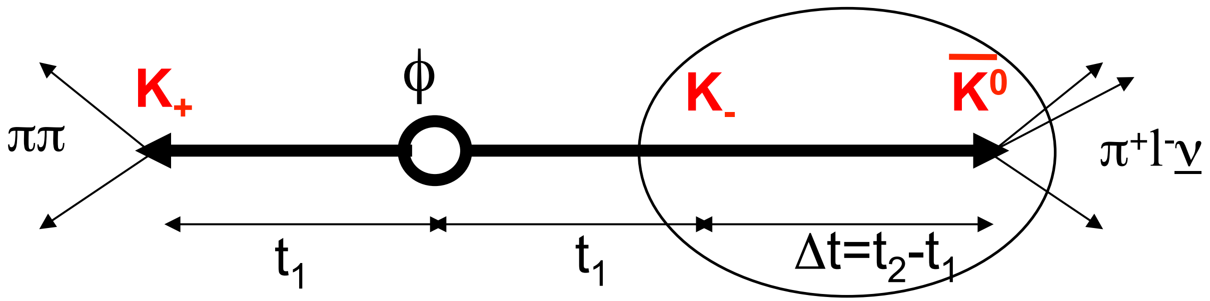


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \bar{K}^0$ CPT-conjugated process



Direct test of T and CPT in neutral kaon transitions

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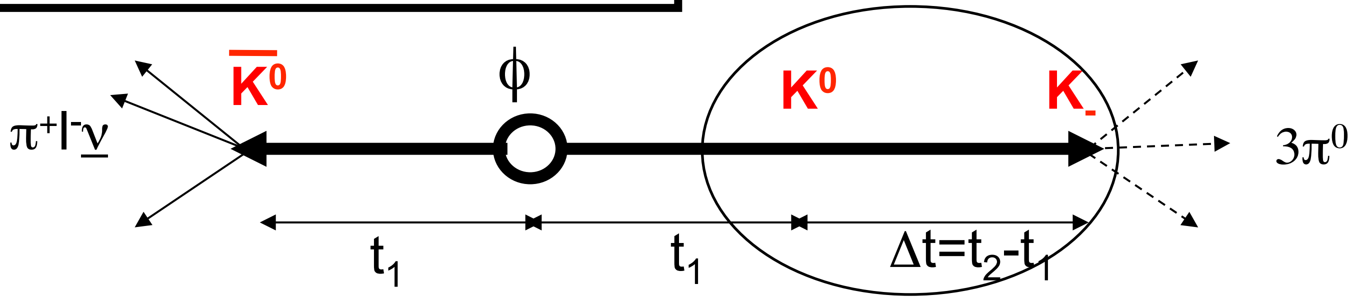
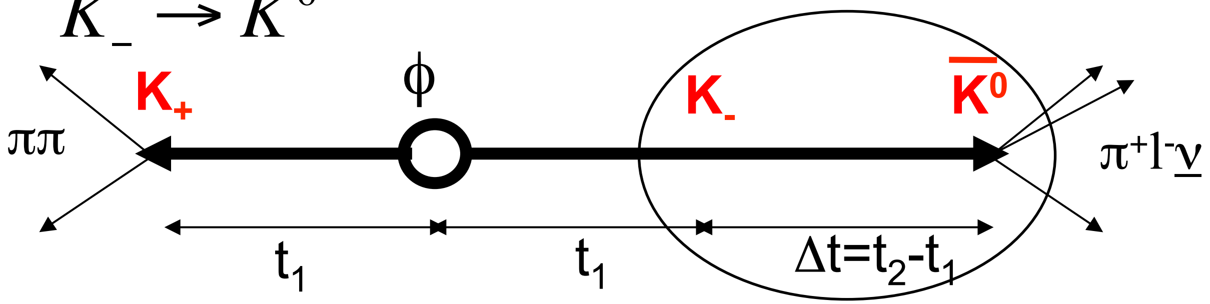


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \overline{K}^0$ CPT-conjugated process

Note: CP and T conjugated process

$\overline{K}^0 \rightarrow K_-$ $\quad K_- \rightarrow K^0$



Direct test of T and CPT in neutral kaon transitions

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

Unique direct CPT and T test in kaon transitions, theoretically very clean and model independent. Negligible spurious effects from $\Delta S \neq \Delta Q$ or direct CP violation.

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$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$

Unique direct CPT and T test in kaon transitions, theoretically very clean and model independent. Negligible spurious effects from $\Delta S \neq \Delta Q$ or direct CP violation.

One can define the following ratios of probabilities:

T

$$
\begin{aligned}
R_{1,\mathrm{T}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] \\
R_{2,\mathrm{T}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_{3,\mathrm{T}}(\Delta t) &= P\left[K_+(0) \to K^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right] \\
R_{4,\mathrm{T}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]
\end{aligned}
$$

CPT

$$
\begin{aligned}
R_{1,\mathrm{CPT}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right] \\
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R_{4,\mathrm{CPT}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]
\end{aligned}
$$

Any deviation from $R_{i,/T/CPT}$=1 constitutes a violation of T/CPT symmetry

J. Bernabeu, A.D.D., P. Villanueva JHEP 10 (2015) 139, NPB 868 (2013) 102, A.D.D., APPB 48 (2017) 1919

Direct test of T and CPT in neutral kaon transitions

- First test of T and CPT in transitions with neutral kaons (L=1.7 fb^{-1})
- $\phi \to K_S K_L \to \pi e^{\pm}\nu\ 3\pi^0$ and $\pi^+\pi^-\ \pi e^{\pm}\nu$
- Selection efficiencies corrected from data with 4 independent control samples

$K_S K_L \to \pi e^{\pm}\nu\ 3\pi^0$ → $K_S \to \pi e \nu$ Klcrash ; $K_S K_L \to \pi^+\pi^-\ 3\pi^0$

$K_S K_L \to \pi^+\pi^-\ \pi e^{\pm}\nu$ → $K_S \to \pi^+\pi^-$-Klcrash ; $K_S K_L \to \pi^0\pi^0\ \pi e \nu$

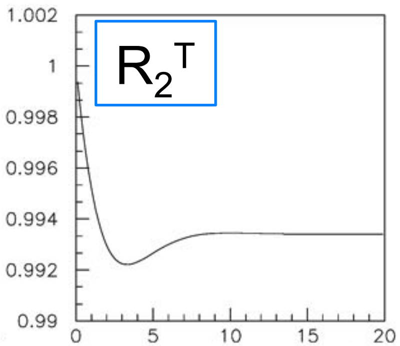
T test

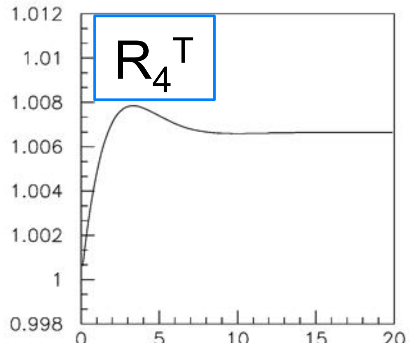
$$R_{2,T}(\Delta t) = \frac{P\left[K^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to K^0(\Delta t)\right]}$$

$$R_{2,T}(\Delta t >> \tau_S) = 1 - 4\Re\varepsilon$$

$$R_{4,T}(\Delta t) = \frac{P\left[\bar{K}^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]}$$

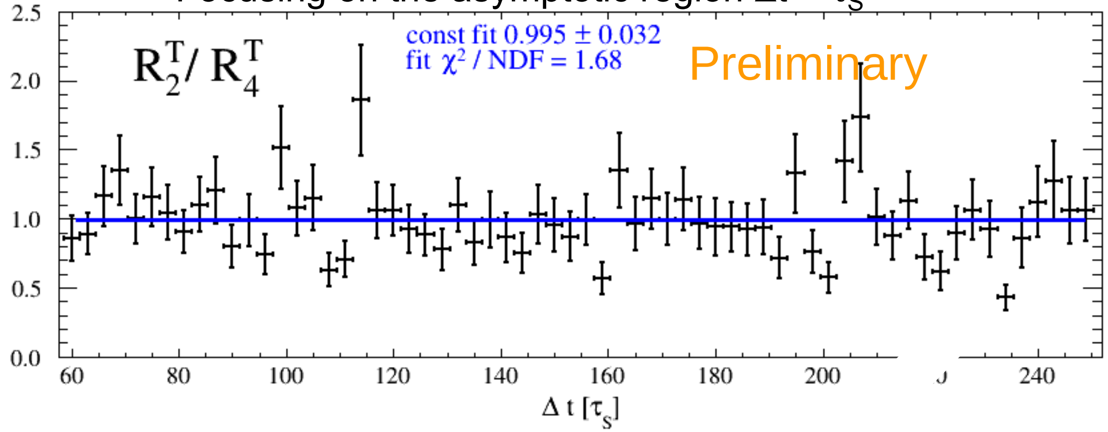
$$R_{4,T}(\Delta t >> \tau_S) = 1 + 4\Re\varepsilon$$





(L=1.7 fb^{-1})

Focusing on the asymptotic region $\Delta t >> \tau_S$



Direct test of T and CPT in neutral kaon transitions

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$$R_{2,T}(\Delta t) = \frac{I(e^-, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, e^+; \Delta t)}$$

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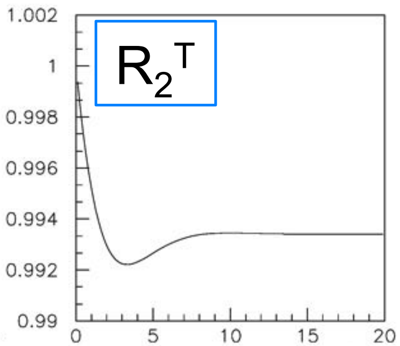

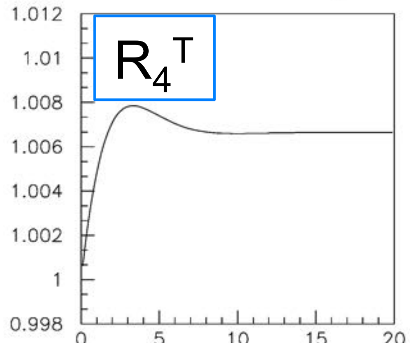

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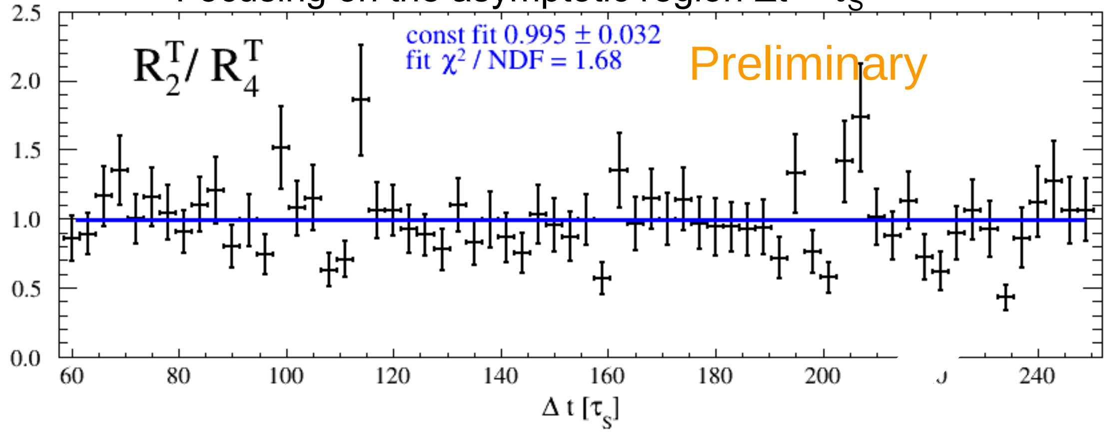

Direct test of T and CPT in neutral kaon transitions

CPT test

DR_{CPT}= 0.994 ± 0.032 (L=1.7 fb^{-1})

$$R_{2,CPT}(\Delta t) = \frac{P\left[K^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to \overline{K}^0(\Delta t)\right]}$$

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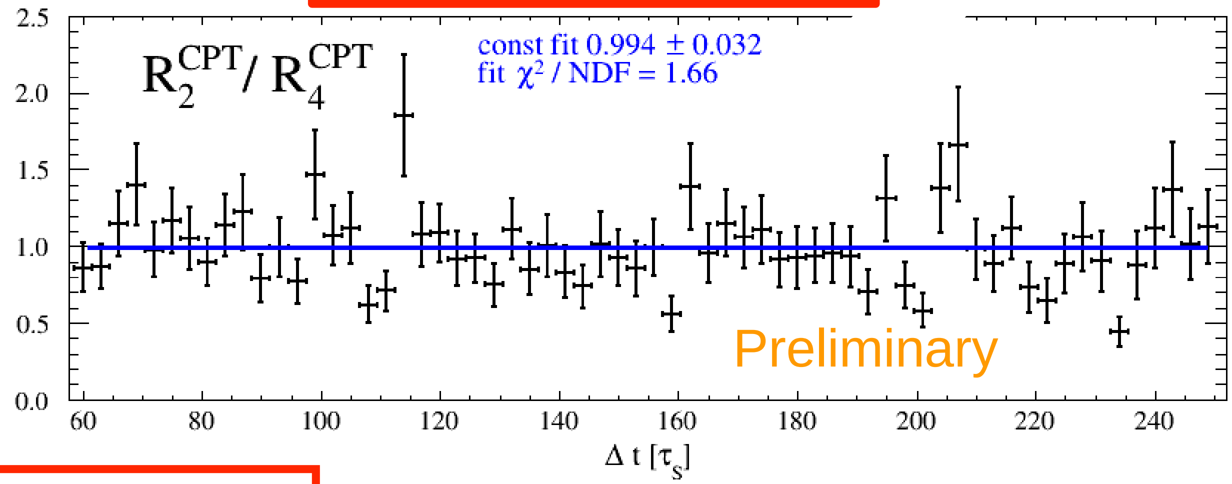

Focusing on the asymptotic region $\Delta t >> \tau_S$

$$DR_{CPT} = \frac{R_{2,CPT}(\Delta t >> \tau_S)}{R_{4,CPT}(\Delta t >> \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

DR_{CPT} is the cleanest CPT observable; $DR_{CPT} \neq 1$ implies CPT violation.
KLOE-2 can reach a precision <1%.

There exists a connection between DR_{CPT} and the $A_{S,L}$ charge asymmetries :

$$DR_{CPT} = 1 + 2(A_L - A_S)$$

Using KTeV result on A_L and KLOE on A_S: **DR_{CPT}= 1.016 ± 0.011** (preliminary)

Direct test of T and CPT in neutral kaon transitions

CPT test

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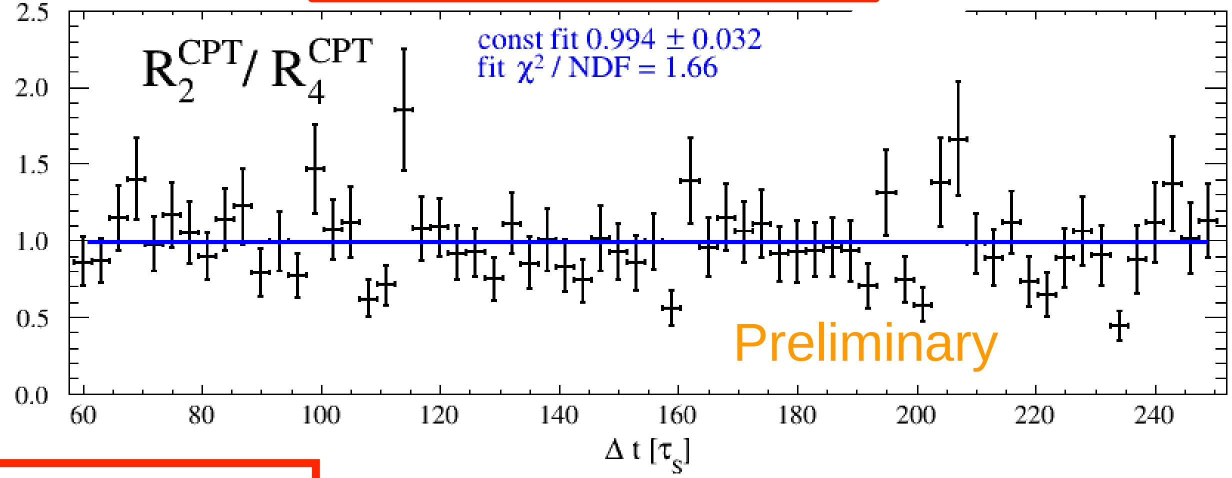

Focusing on the asymptotic region $\Delta t \gg \tau_S$

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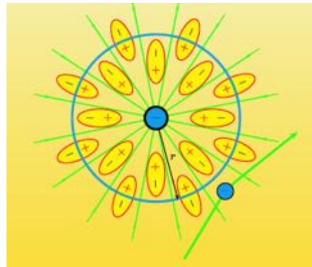
Measurements of the running of $\alpha_{e.m.}(s)$ via $e^+e^- \to \mu^+\mu^-\gamma$

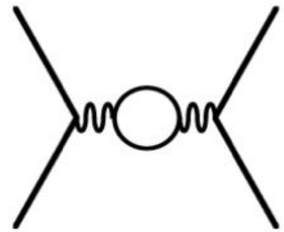
- The fine-structure constant α is a running parameter due to vacuum polarization effects



$$\alpha(q^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

$$\Delta\alpha(q^2) = -[\Pi(q^2) - \Pi(0)]$$

$\Pi(q^2)$: vacuum polarization function

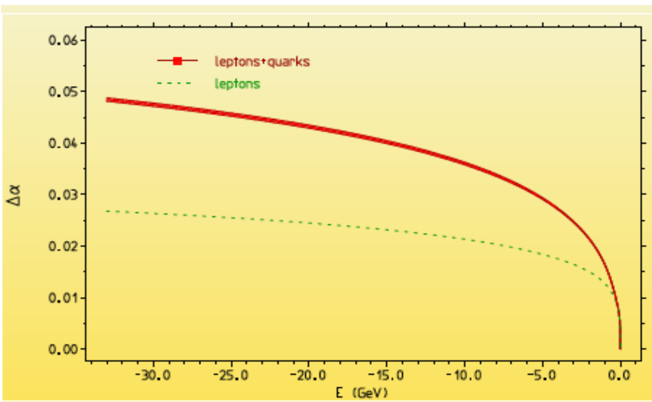


$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$

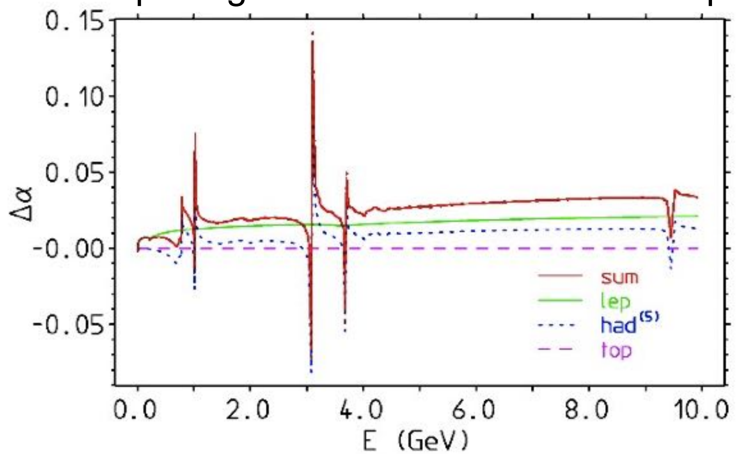
- Hadronic contribution not perturbative can be evaluated with dispersion relation ⇒

$$\Delta\alpha^{(5)}_{had}(q^2) = -\frac{\alpha(0)q^2}{3\pi}\int_{s_0}^{\infty}\frac{R_{had}(s)}{s(s-q^2-i\varepsilon)}ds$$

Smooth behaviour at space-like q^2



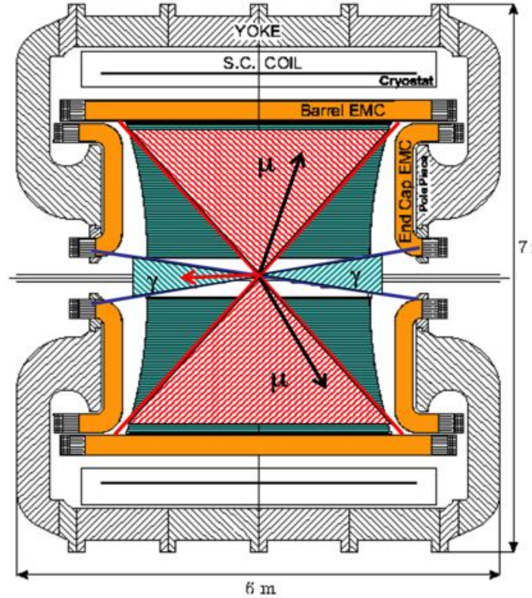
Opening of resonances at time-like q^2



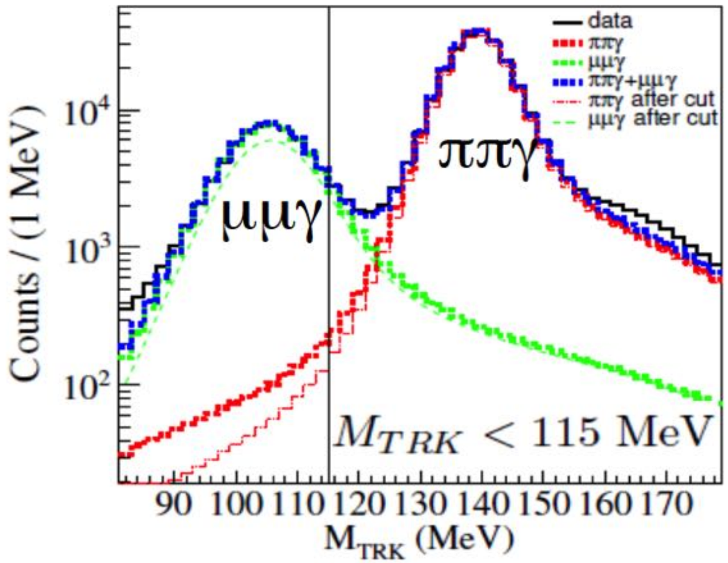
Measurements of the running of $\alpha_{e.m.}(s)$ via $e^+e^- \to \mu^+\mu^-\gamma$

- $e^+e^-\to\mu^+\mu^-\gamma(\gamma)$ data from ISR; $s=q^2=M(\mu^+\mu^-)$
- Corrected for FSR (PHOKARA MC generator)
- Normalization to MC with $\alpha = \alpha(0)$

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



- 2 tracks at large angle (50°<ϑ<130°)
- Photon at small angle (ϑ<15° or ϑ>165°) to reduce FSR
- Photon not detected; momentum reconstructed from kinematics $\vec{p}_\gamma = -(\vec{p}_+ + \vec{p}_-)$



- L = 1.7 pb^{-1}
- Main bckg: $e^+e^-\to\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $e^+e^-\gamma$
- About 4.5 × 10^6 $\mu^+\mu^-\gamma$ events selected
- Residual bckg < 1%

Measurements of the running of $\alpha_{e.m.}(s)$ via $e^+e^- \to \mu^+\mu^-\gamma$

$$\frac{d\sigma(e^+e^- \to \mu^+\mu^-\gamma(\gamma))}{d\sqrt{s}} = \frac{N_{obs} - N_{bckg}}{\Delta\sqrt{s}} \times \frac{1-\delta_{FSR}}{\varepsilon(s)L}$$

- Systematic uncert. ~ 1%

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

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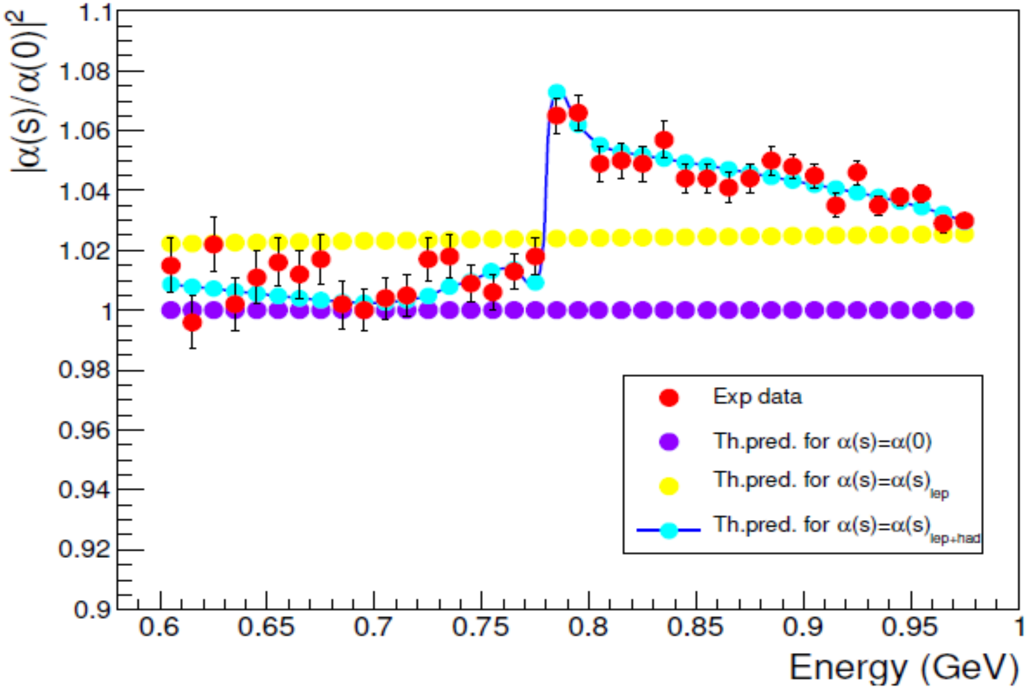
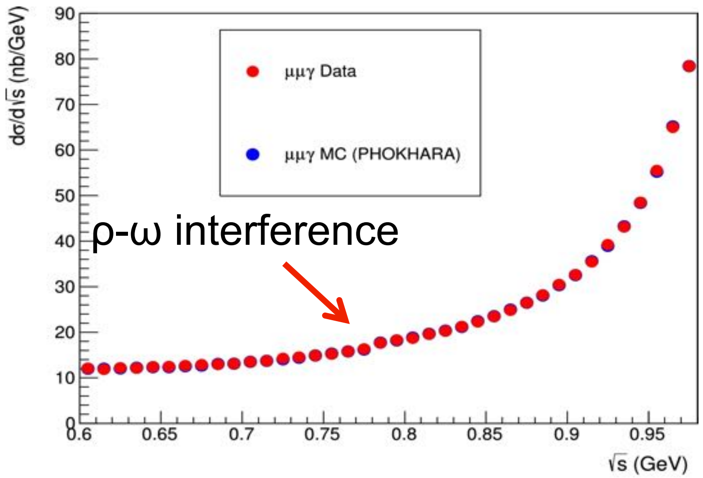
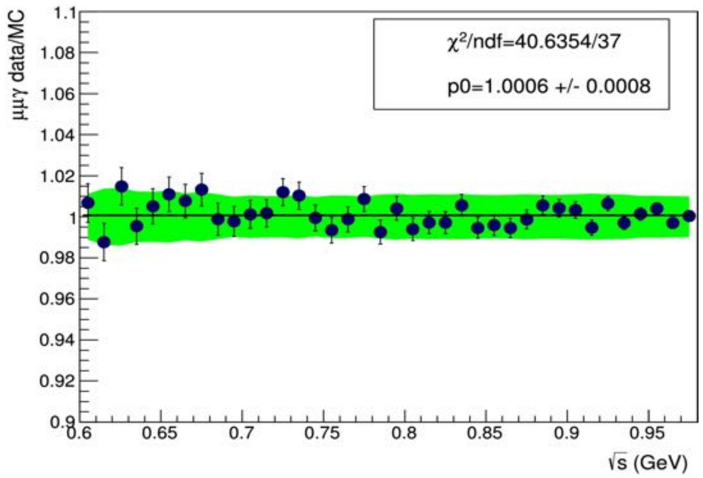




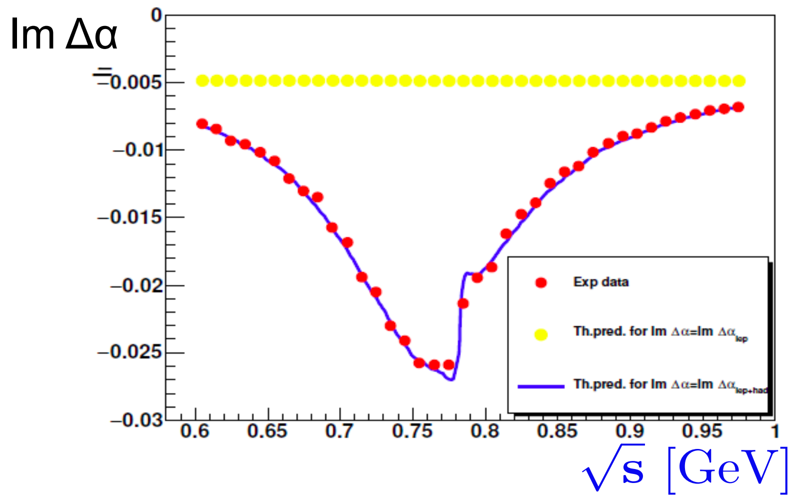


Theoretical prediction obtained from dispersion relations and available data on $R_{had}(s)$ (F.Jegerlehner)

Measurements of the running of $\alpha_{e.m.}(s)$ via $e^+e^- \to \mu^+\mu^-\gamma$

- $\Delta\alpha$ is complex in the time-like region
- Optical theorem: $$\mathbf{Im}\ \Delta\alpha = -\frac{\alpha}{3}\mathbf{R(s)}$$
- Im $\Delta\alpha$ from $\sigma(e^+e^-\to\pi^+\pi^-)$ from KLOE data on σ_{hadr}

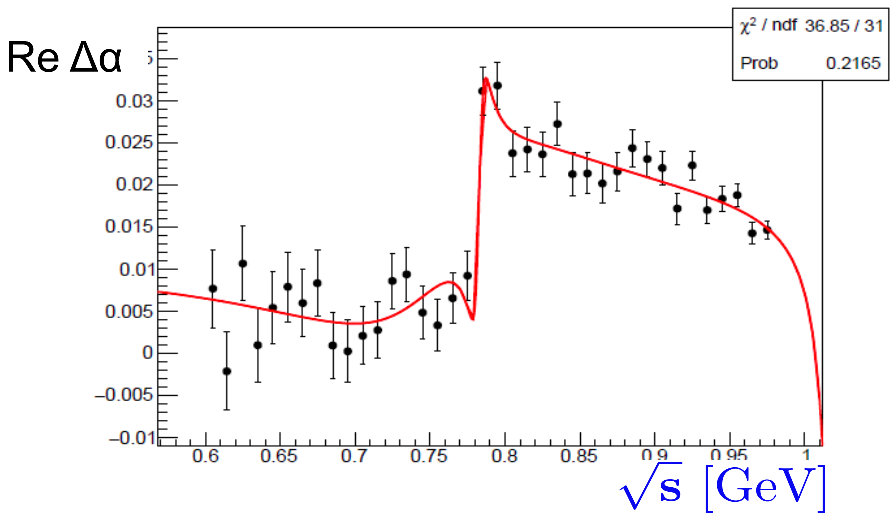
(theoretical curve from ππ compilation w\out KLOE)



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

- Fit: BW for ω(782) and ϕ(1020) + Gounaris-Sakurai param. for ρ(770) + non resonant term

	Fit	PDG
M_ρ [MeV]	775 ± 6	775.26 ± 0.25
Γ_ρ [MeV]	146 ± 9	147.0 ± 0.9
M_ω [MeV]	782.7 ± 1.1	782.65 ± 0.12
$Br(\omega\to\mu^+\mu^-)Br(\omega\to e^+e^-)$	$(4.3 \pm 1.8)\times 10^{-9}$	$(6.5 \pm 2.3)\times 10^{-9}$
χ^2/ndf	1.19	

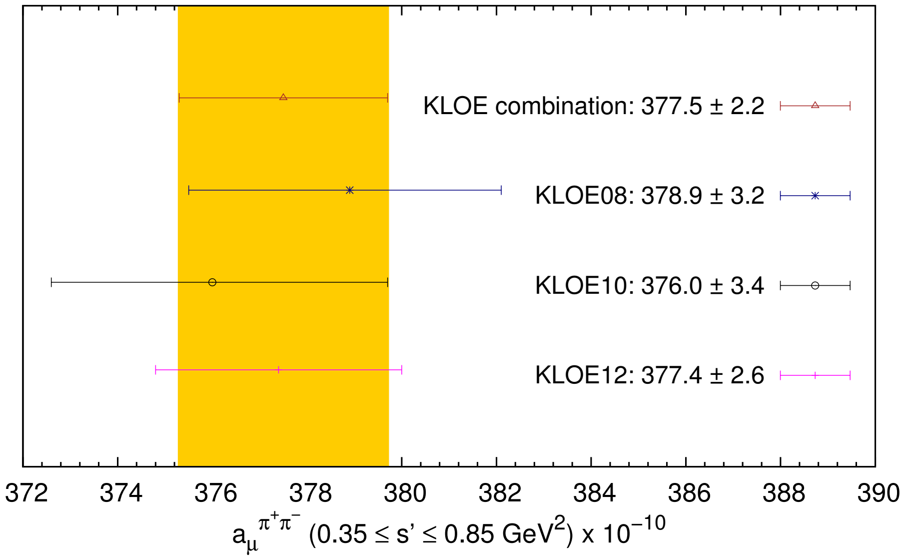


$$\mathbf{Br}(\omega\to\mu^+\mu^-) = (\mathbf{6.6}\pm\mathbf{1.4}\pm\mathbf{1.7})\times\mathbf{10^{-5}}$$

(PDG: $(9.0 \pm 3.1) \times 10^{-5}$)

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

Consistency of KLOE measurements



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

in agreement with CMD-2, SND and BESIII meas within 1.5σ

Difference with BaBar $< 3\sigma$

$$a_\mu^{\pi^+\pi^-} \text{ KLOE Comb} = (489.8 \pm 5.1) \times 10^{-10}$$

$$(0.10 < s' < 0.95\,\text{GeV}^2)$$

uncertainties in all $a_\mu^{\pi^+\pi^-}$ estimations are the sum in quadrature of both stat and syst errors

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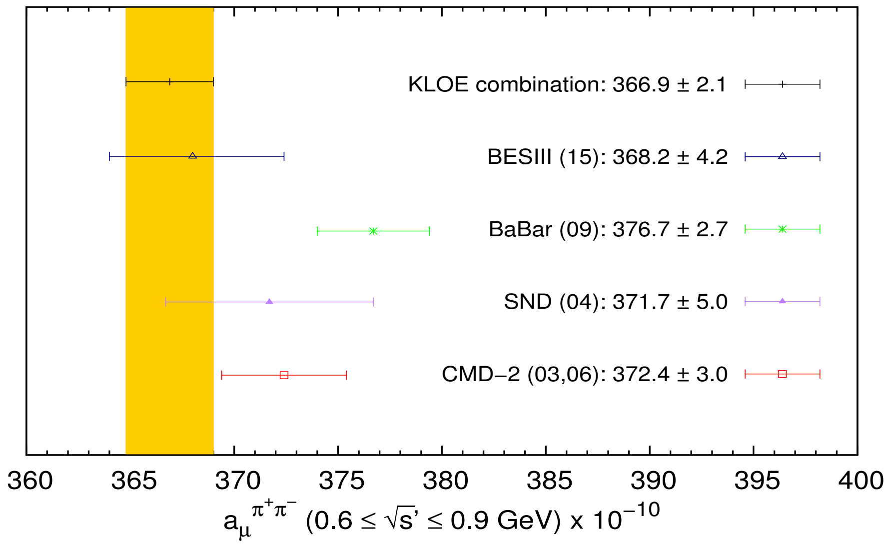
Comparison with other experiments

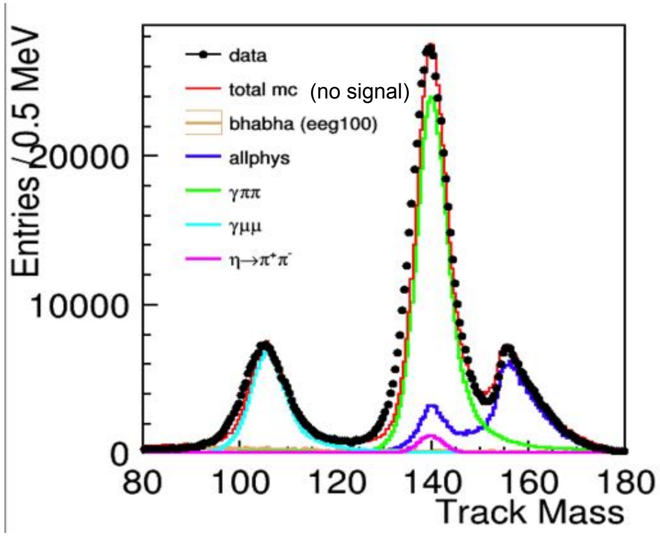


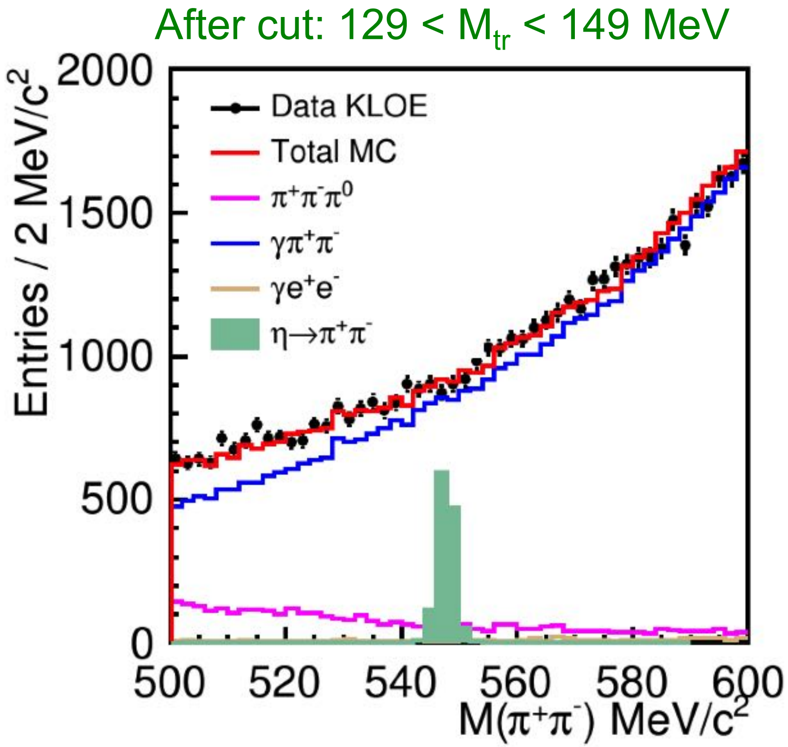
Search for $\eta \to \pi^+\pi^-$ decay

- P and CP violating, Br expected of order 10^{-27} in the SM
- Detection at any accessible level would be signal of CP viol. beyond the SM

Best limit Br<1.3×10^{-5} @ 90% C.L. (L = 350 pb^{-1}) [KLOE, PLB606(2005)276]

LHCb recent measurement: Br<1.6×10^{-5} @ 90% C.L. [PLB764(2017)233]



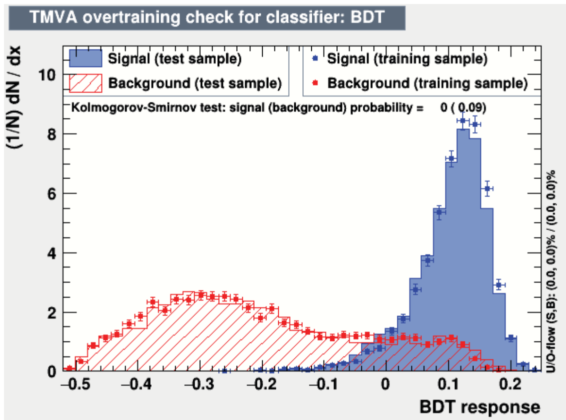


- Continuum background from ππγ
- After all the cuts, efficiency for KLOE is 14%
- No event excess in the η region

- L = 1.7 fb^{-1} (KLOE data) ⇒ preliminary U.L.: Br < 5.8×10^{-6} @ 90% C.L.
- Combining KLOE + KLOE-2 statistics (8 fb^{-1}) ⇒ U.L. expected ~ 3×10^{-6}

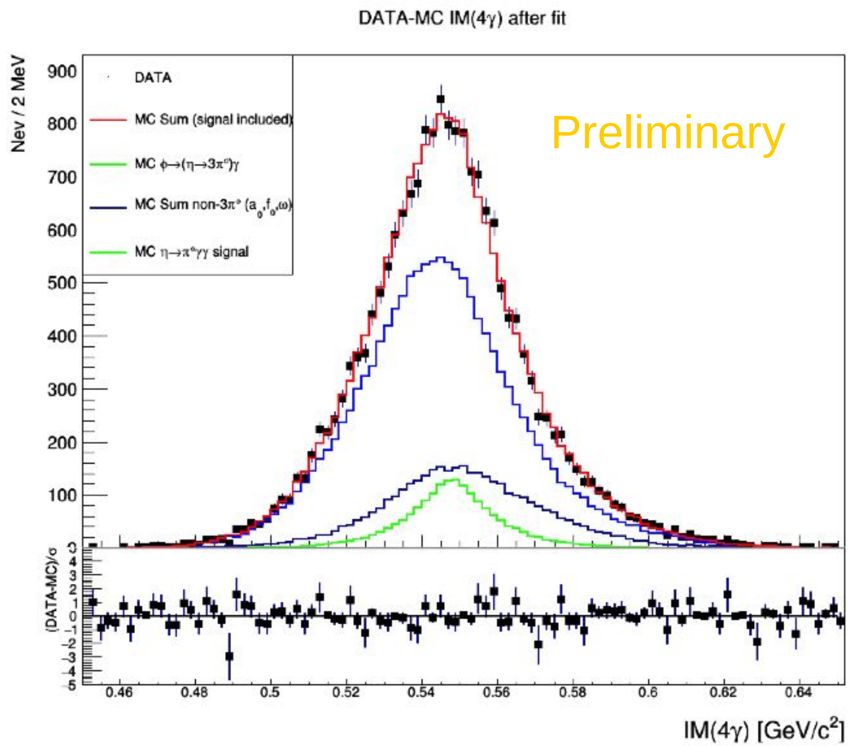
$\eta \rightarrow \pi^0\gamma\gamma$ decay

- $\eta\rightarrow\pi^0\gamma\gamma$ (from $\phi\rightarrow\eta\gamma$): χPT golden mode,
  $O(p^2)$ null, $O(p^4)$ suppressed
  $\Rightarrow$ 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)



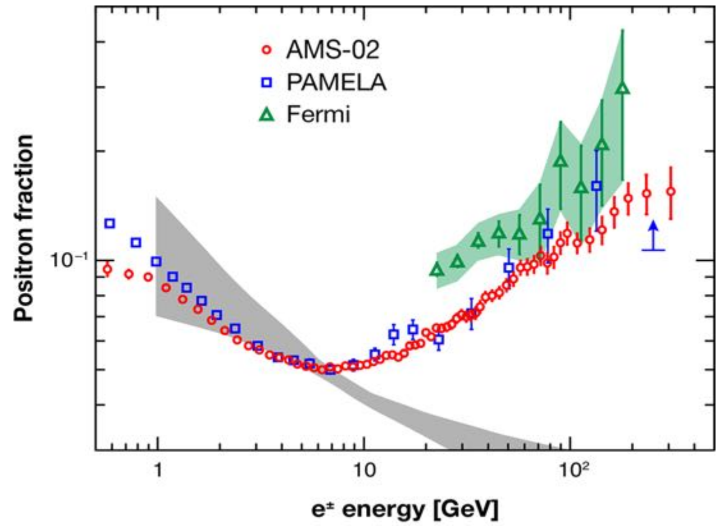
5 prompt photon sample:

- L = 580 pb^{-1} of KLOE data
- Main bckg is $\phi\rightarrow\eta\gamma$, with $\eta\rightarrow3\pi^0$ with lost or merged photons
- Multivariate Analysis with cluster shape variables to separate single photon from merged photon clusters
- Signal evidence on data distribution S/B~0.4 achieved with ε_s~21%

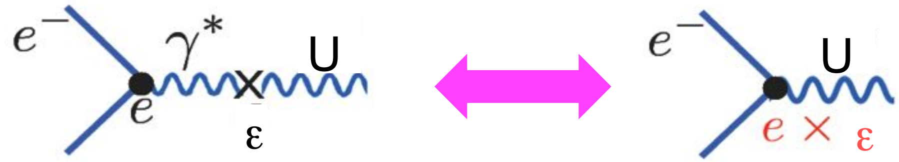


Search for dark forces at KLOE/KLOE-2

- Several astrophysical anomalies (AMS02, PAMELA, FERMI, INTEGRAL, DAMA, …) can be explained by the presence of a new $U(1)_D$ gauge particle, the so-called Dark Photon (U, A′, γ′ , …)
  [Arkani-Hamed at al.,PRD79(2009)015014]



- This massive dark photon mixes with the ordinary photon

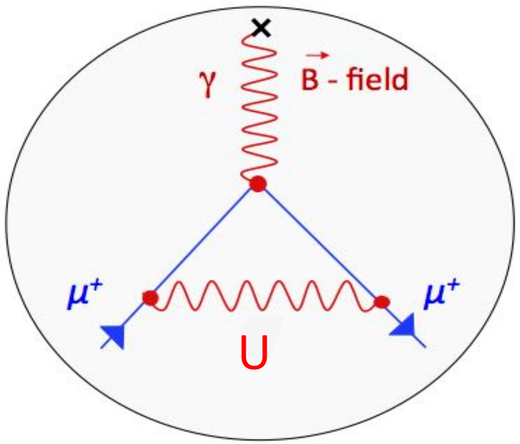


$$\mathcal{L}_{\mathbf{mix}} = -\frac{\varepsilon}{\mathbf{2}}\mathbf{F}^{\mathbf{QED}}_{\mu\nu}\mathbf{F}^{\mu\nu}_{\mathbf{Dark}} \qquad \Rightarrow \alpha_{\mathbf{D}} = \varepsilon^{\mathbf{2}}\alpha_{\mathbf{em}}$$

$$(\varepsilon \sim \mathbf{10^{-2}} - \mathbf{10^{-4}})$$

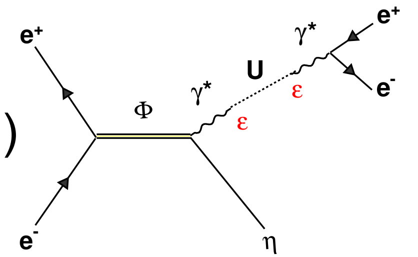
- This new force carrier could also explain the $(g\text{-}2)_\mu$ discrepancy

[Pospelov,PRD80(2009)095002]

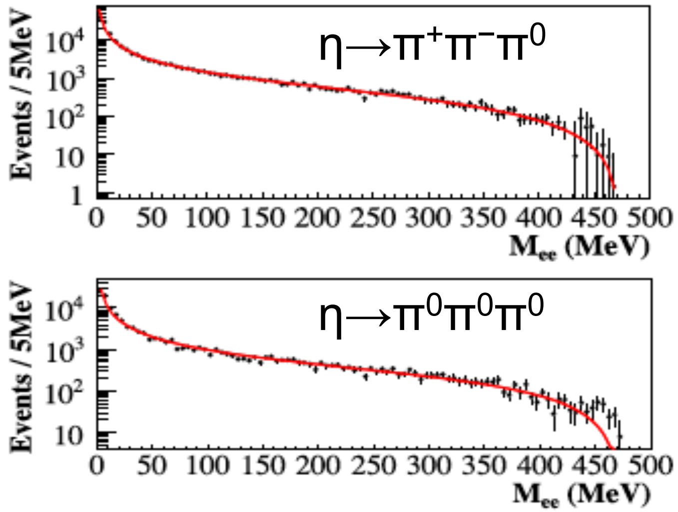


Search for dark forces at KLOE/KLOE-2

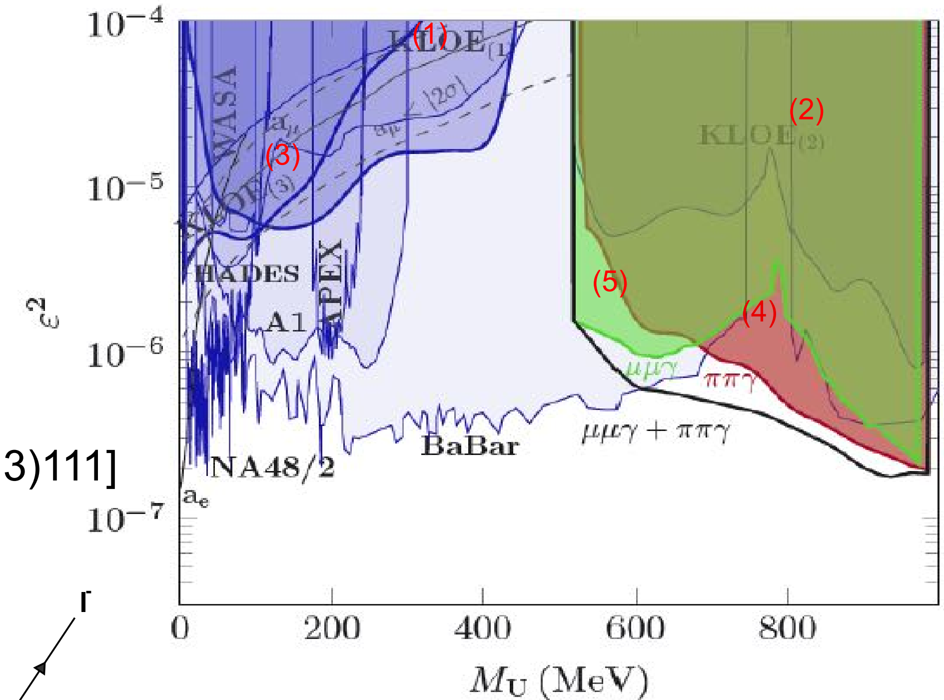
Dalitz decays involving light pseudoscalar mesons can be used to search for Dark Photons, in the hypothesis that the U is the lightest particle of the dark sector, by looking for spikes in the dilepton invariant mass distribution($U \to \ell^+\ell^-$)



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



(1)$\phi \to \eta U$; $U \to e^+e^-$, $\eta \to 3\pi$ [PLB 705(2012)501, 720(2013)111]



Search in $e^+e^- \to e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$

(2) $e^+e^- \to U\gamma$; $U \to \mu^+\mu^-$ [PLB736(2014)459

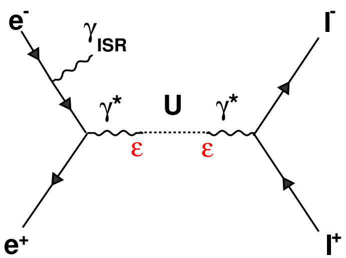
(3) $e^+e^- \to U\gamma$; $U \to e^+e^-$ [PLB750(2015)633]

(4) $e^+e^- \to U\gamma$; $U \to \pi^+\pi^-$ [PLB757(2016)35

(5) $U \to \mu^+\mu^-$ updated with full statistics

Black line: (5) + (4) combined

[PLB784(2018)336] (see next slide)



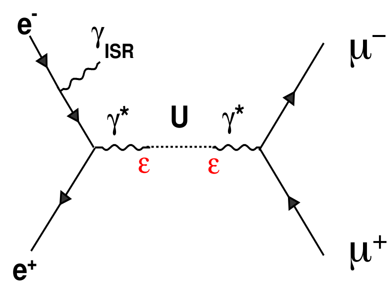
KLOE-2 prospects:

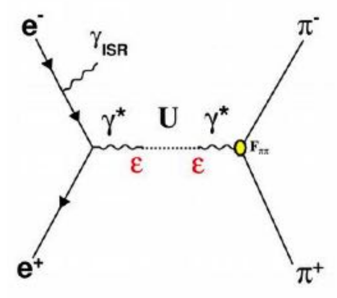
5 + 2 fb^{-1}, improvements in mass and vertex resolutions

⇒ Improve limits on U boson

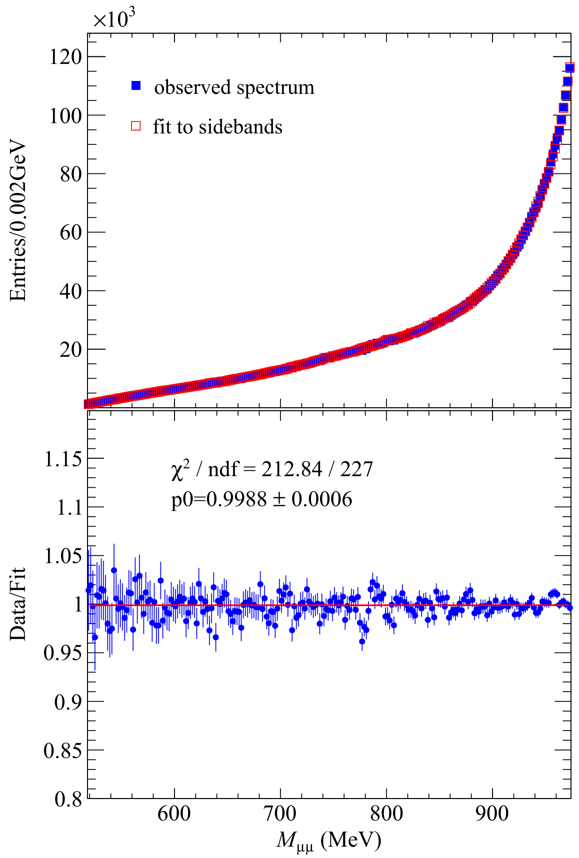
Search for U-boson in $\mu^+\mu^-\gamma$ / $\pi^+\pi^-\gamma$

Probing the dark sector at GeV scale
Search for possible U-boson at $\sqrt{s}$ ~ 1 GeV
Advantage of 1/s cross section scaling wrt
B-factories: a factor ~100 compensates for integrated L
Full KLOE statistics: L = 1.93 fb^{-1}

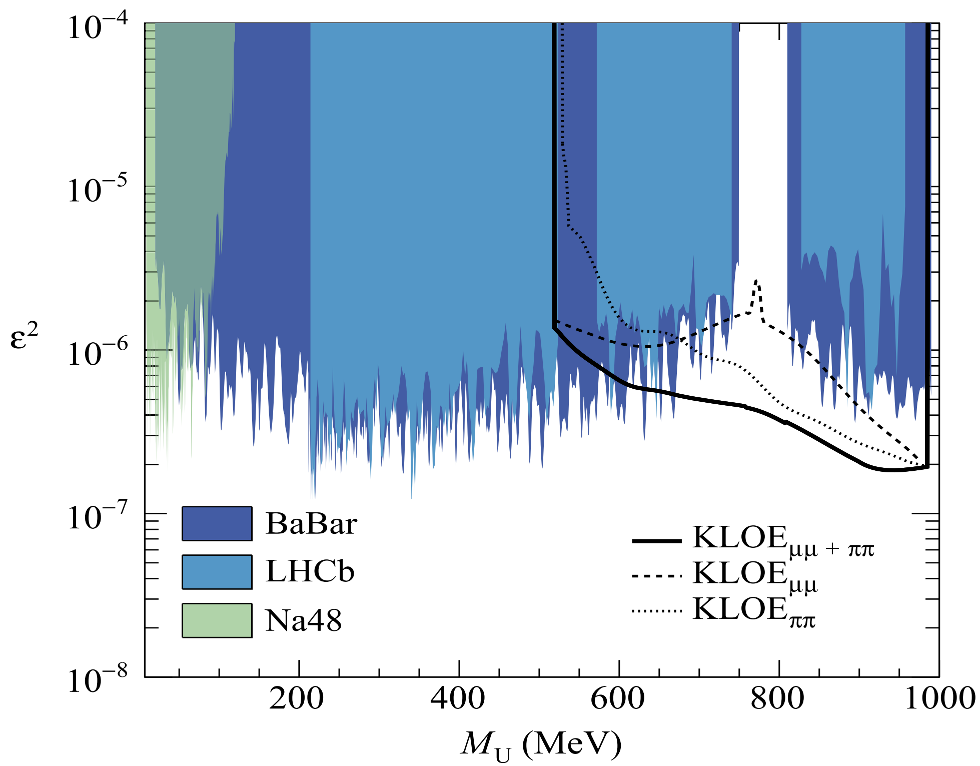




PLB 784 (2018) 336



Dimuon mass spectrum



ε < (6 – 1.94) × 10^{-7} above 650 MeV

Leptophobic B boson

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

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

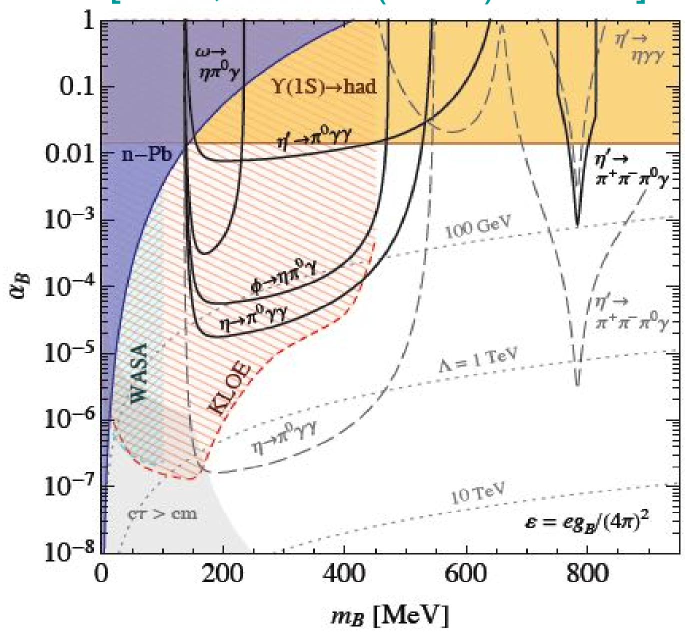
- Dominant decay channel (m_B < 600 MeV): $B \to \pi^0\gamma$
- Can be studied in:

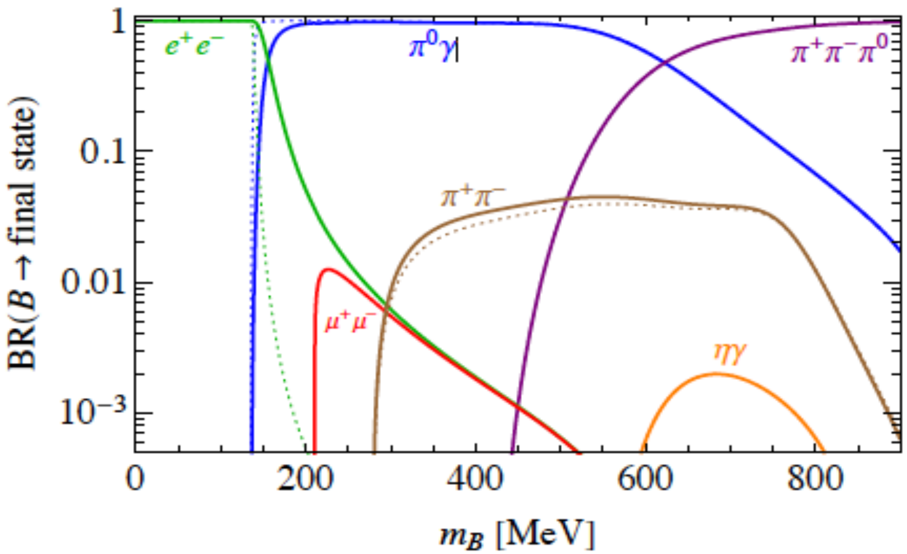
$\phi \to \eta B \;\Rightarrow\; \eta\pi^0\gamma \;\Rightarrow$ 5 prompt γ final state

$\eta \to B\gamma \;\Rightarrow\; \pi^0\gamma\gamma$ " "

$e^+e^- \to \pi^0\gamma\, \gamma_{ISR}$

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

Search for the B boson

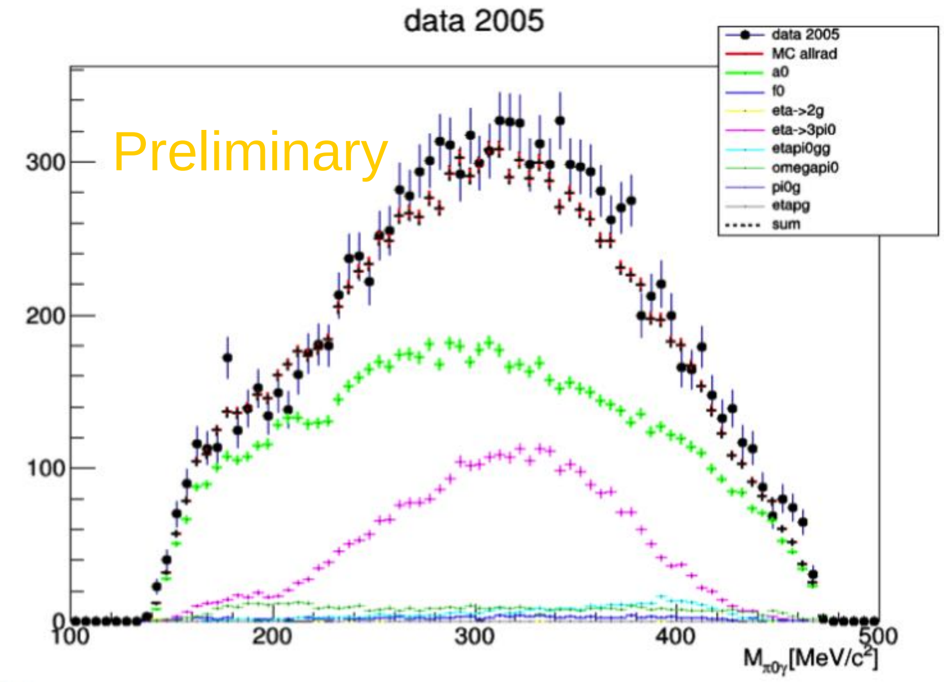
Current study based on ~0.8 fb^{-1}

Analysis of the whole sample in progress ($1.7\ fb^{-1}$)

$\phi \to \eta B$, signal efficiency ~12.5%

Main background from $\phi \to a0\gamma \to \eta\pi^0\gamma$ and $\phi \to \eta\gamma \to 3\pi^0\gamma$ with lost or merged photons.

$\phi\to\eta B$

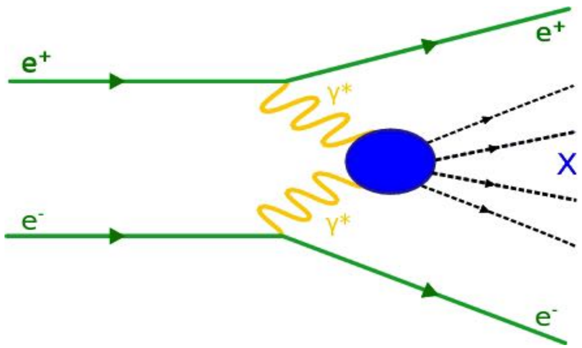


γγ physics with High Energy Tagger (HET)

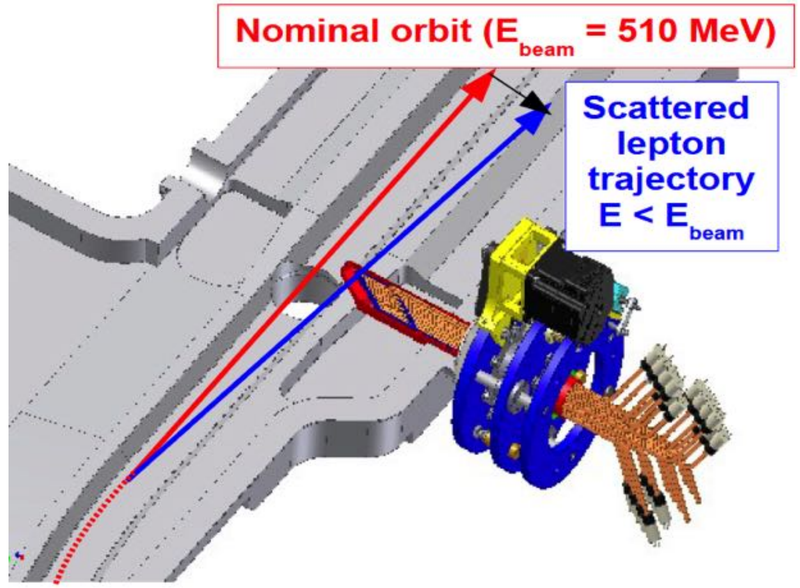
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-X$$

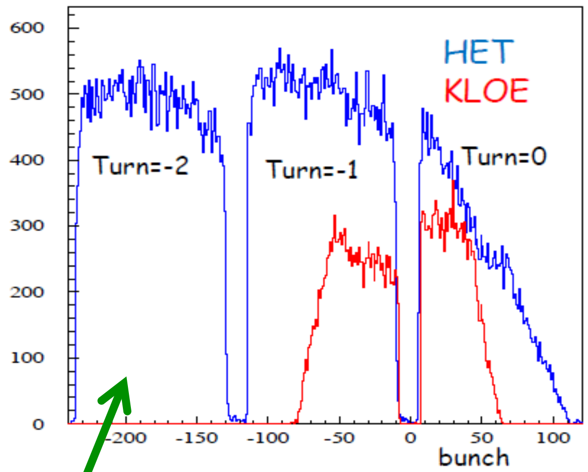
$$[\mathbf{C(X) = +1}]$$

$$\mathbf{X} = \pi^{\mathbf{0}}, \pi\pi, \eta$$



- Precision measurement of $\Gamma(\pi^0\to\gamma\gamma)$
- Transition form factor $\mathcal{F}_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2|< 0.1$ GeV^2)





Data out of coincidence window used to evaluate background

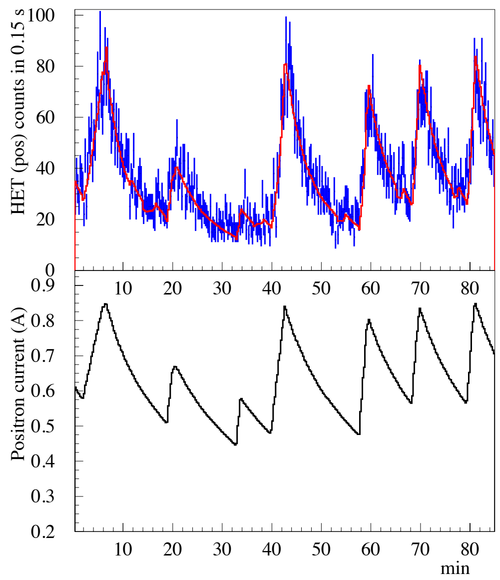
- First bending dipoles of DAΦNE act as spectrometers for the scattered e^+/e^- (420 < E < 495 MeV)
- Strong correlation between E and trajectory
- Scintillator hodoscope + PMTs, inserted in roman pots Pitch: 5 mm, ~ 11 m from IP (σ_E~2.5 MeV σ_t~200 ps)
- HET is acquired asynchronously w.r.t. the KLOE-2 DAQ (Xilinx Virtex 5 - FPGA)
- Synchronization with the “Fiducial” signal from DAΦNE
- HET signals corresponding to 3 DAΦNE revolutions are recorded for each KLOE trigger

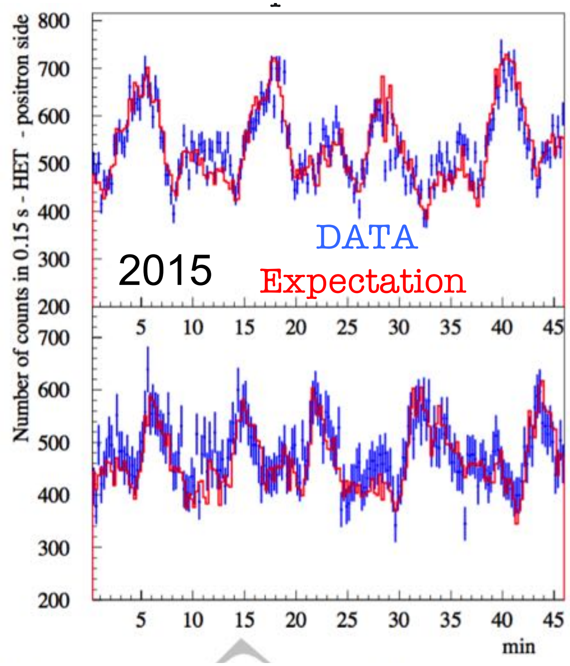
γγ physics with High Energy Tagger (HET)

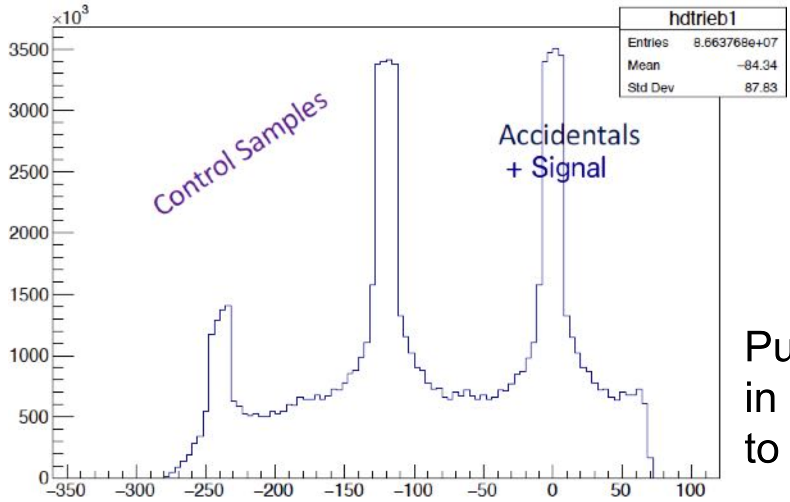
- Collisions clearly seen by rate increase and dependence on DAFNE Luminosity
- HET counting rate dominated by Bhabha scattering

No Collisions HET pos with Collisions

$$\mathbf{R_{HET} = R_{trig}(\alpha_L L + \beta_\pm I^2_\pm)}$$







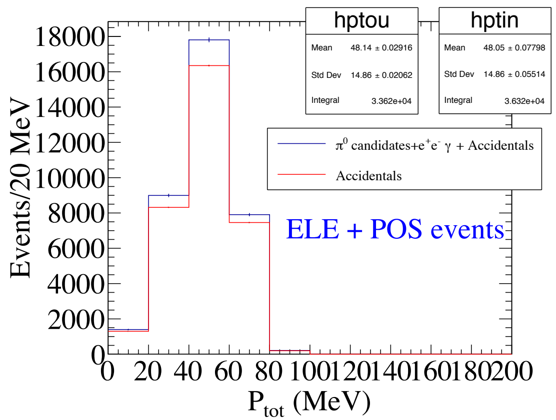
Delay between HET hits and Trigger (ns)

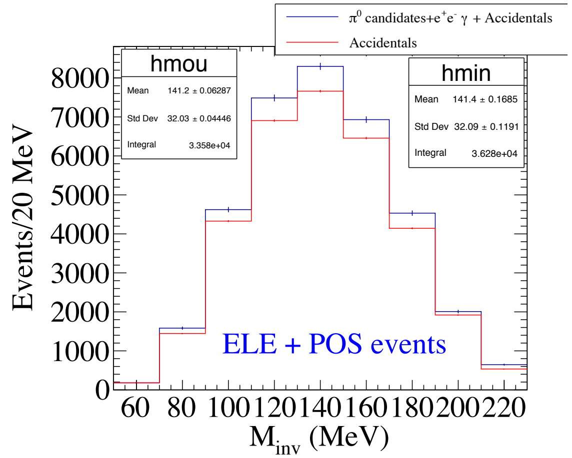
Pure accidentals are continuously monitored in the out of coincidence window and subtracted to time coincidences.

Search for $\gamma\gamma \to \pi^0$ production

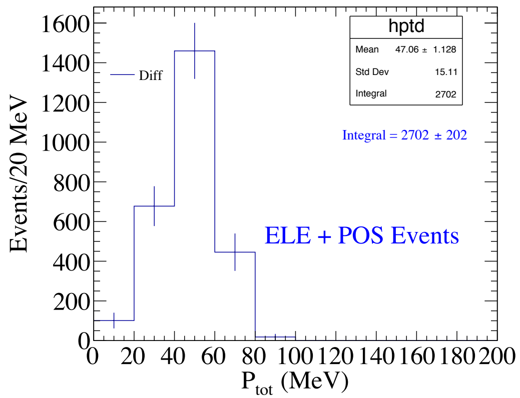
- Evidence of tagged sample with the analysis of stable(18/28)channels in the e^--side station, on 500 pb^{-1}
- The sample includes radiative Bhabha's with photons in KLOE and signal events $\gamma\gamma \to \pi^0$'s (Ekhara-like events)
- Multivariate analysis helpful to separate Ekhara-like from radiative Bhabha's
- Dependence of the results on HET- multiplicity is being investigated
- Simulation of Bhabha's sample in different conditions in progress to obtain (acceptance x efficiency) and associated systematics

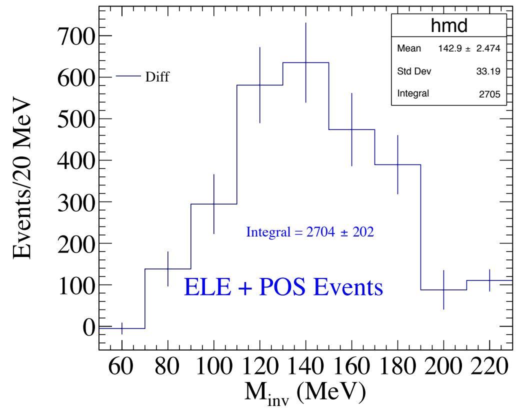
P_{tot}





$M_{\gamma\gamma}$

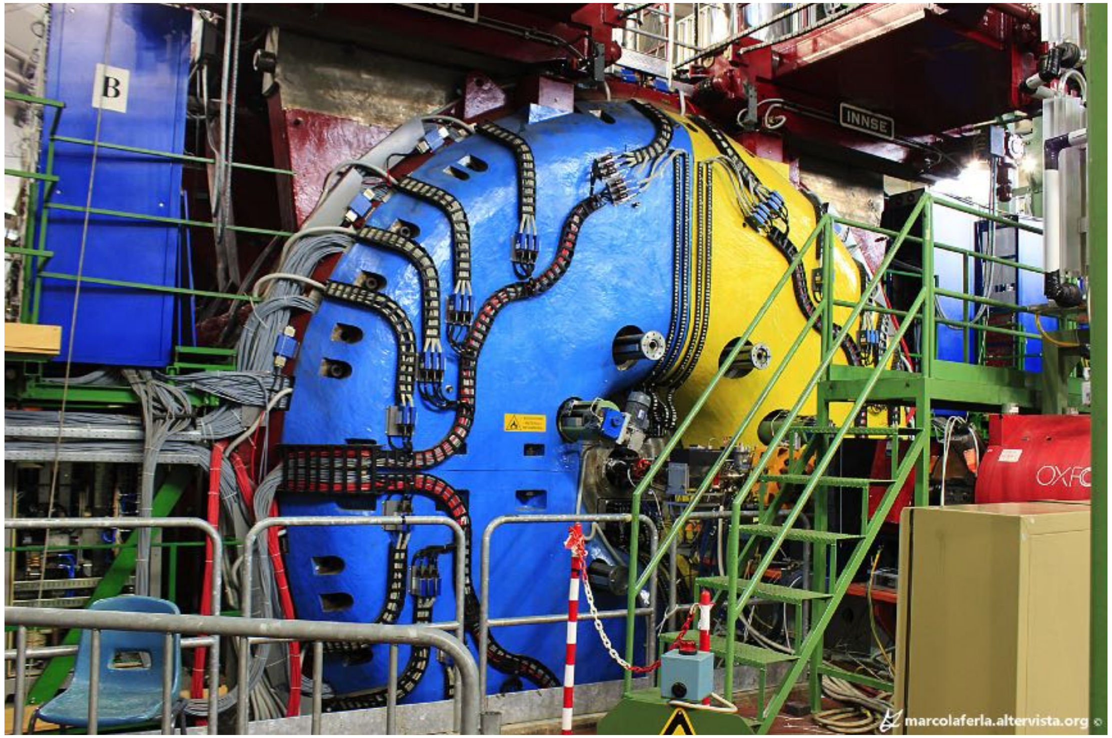




Conclusions

- The KLOE-2 experiment at the upgraded DAΦNE successfully completed its data taking campaign collecting L=5.5 fb^{-1} by the end of March 2018.

- The data sample collected by KLOE provided important results on tests of fundamental discrete symmetries, kaon physics, decay dynamics of light mesons, Transition Form Factors, and searches for New Physics in the Dark Sector, among the several items pursued.



- The KLOE+KLOE-2 data sample
- (~ 8 fb^{-1}) is worldwide unique for typology and statistical relevance.

- This data sample is rich in physics. Its analysis is ongoing and will improve the high precision investigation on light hadron Physics and fundamental symmetries.

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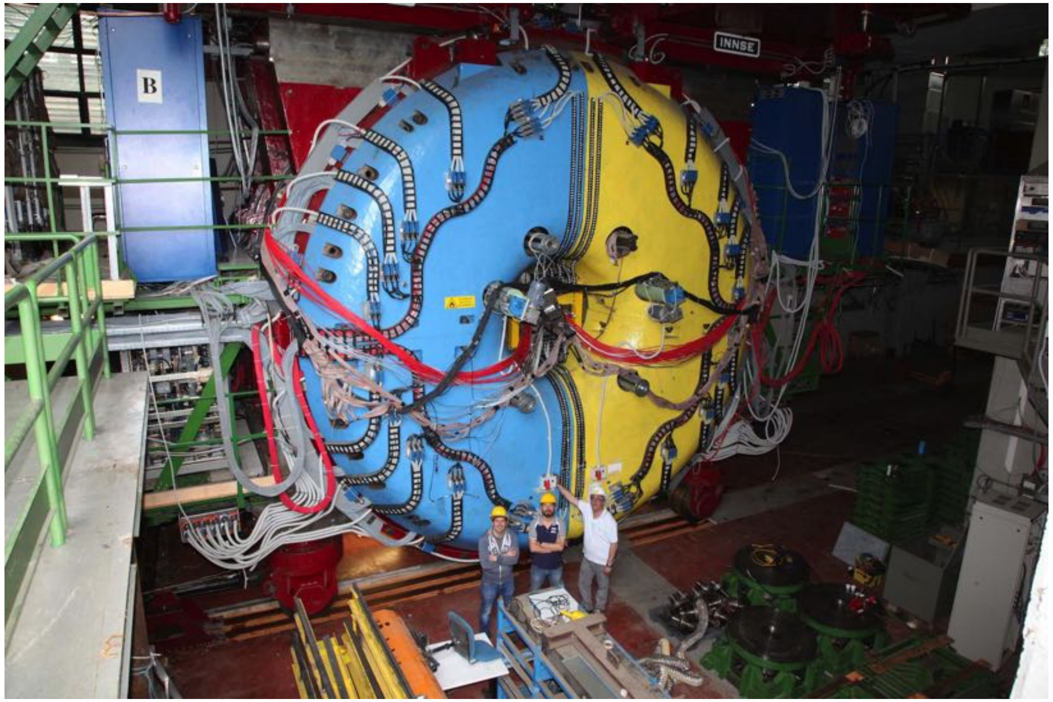

KLOE-2 roll-out

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