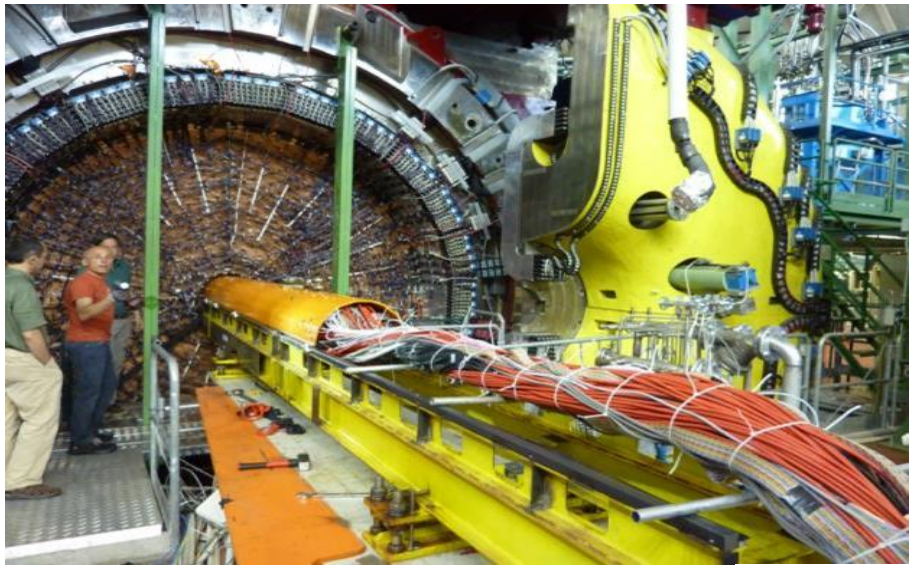
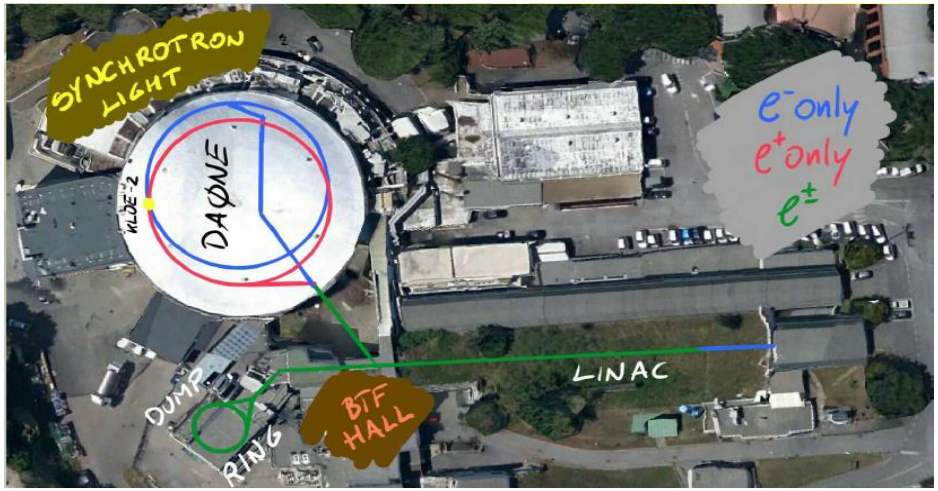
The KLOE-2 Experiment at DAΦNE



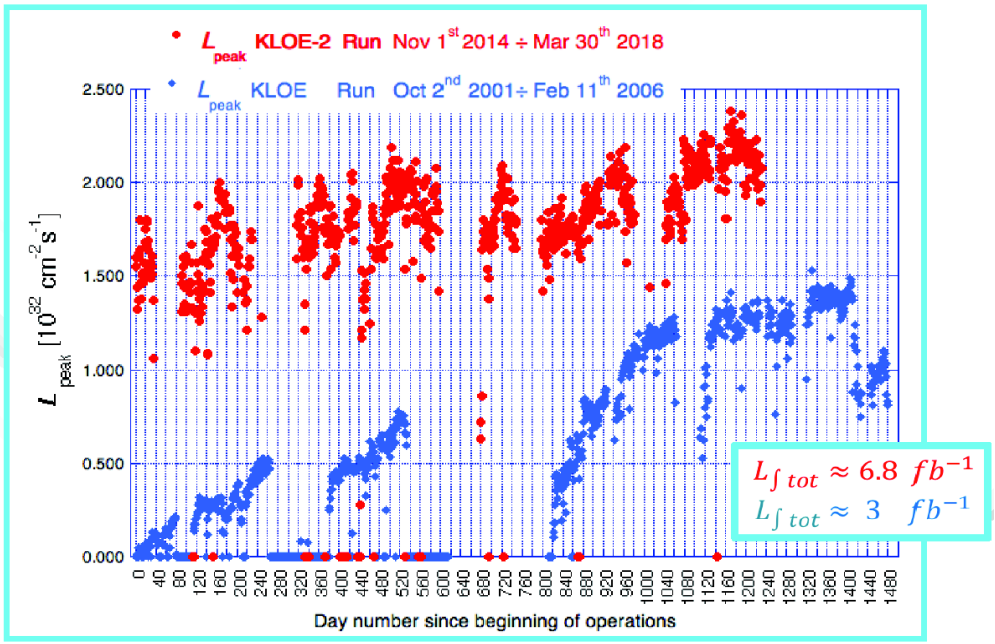
The DAΦNE phi-factory

$\sqrt{s}$ = 1020 MeV
TRF = 2.7 ns, up to 120 bunches
Topping-up injection
Worked for KLOE (2000-2006):
15 mrad crossing angle
Max peak lumi: 1.5 10^{32} $cm^{-1}s^{-1}$
Best daily int. lumi: 8.5 pb^{-1}

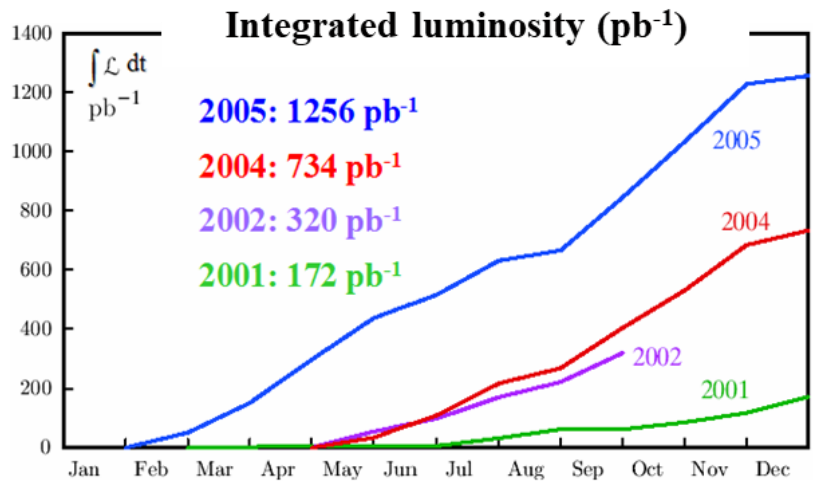


Upgraded in 2008 with crab-waist scheme (P.Raimondi) :
50 mrad crossing angle + sextupole focus

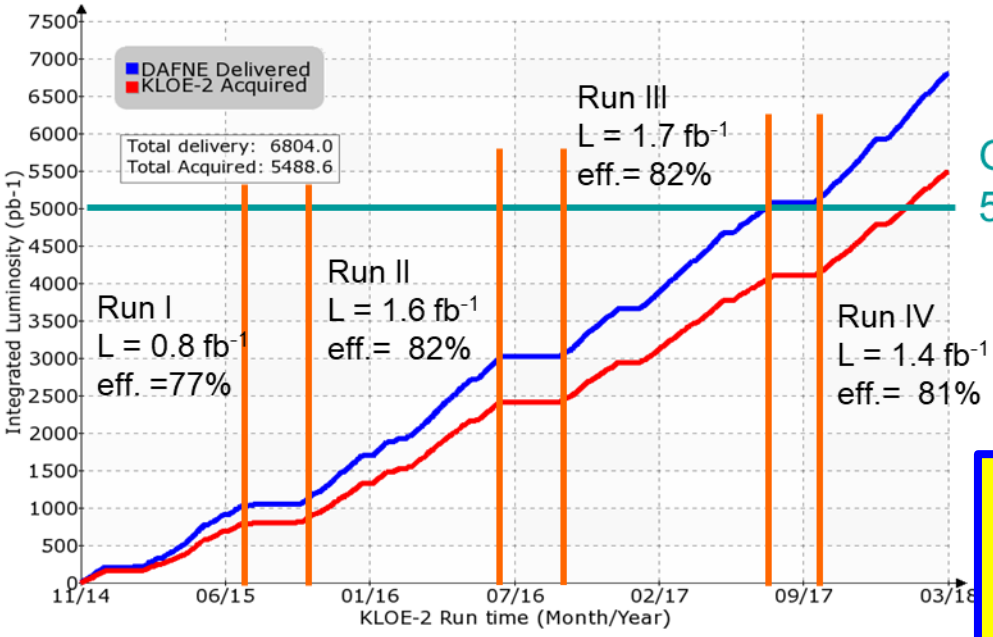
Worked for KLOE-2 (2014-2018):
Max peak lumi: 2.4 10^{32} $cm^{-1}s^{-1}$
Best daily int. lumi: 11 pb^{-1}



KLOE and KLOE-2



KLOE pilot run in 1999.
In the years 2000-2006 collected:
2.5 fb^{-1} at √s=M$_\phi$
250 pb-1 at √s = 1000 MeV



Goal: 5 fb^{-1}

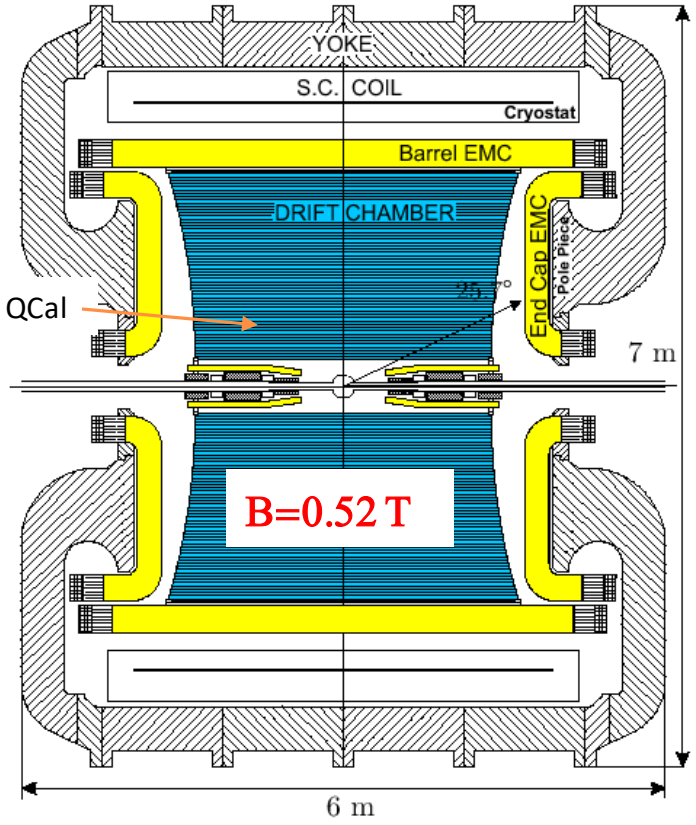
KLOE detector upgraded in 2012-2013:
Tracking and forward region.

KLOE-2 data taking campaign:
november 2014-march 2018

Collected: 5.5 fb^{-1} at √s=M$_\phi$

KLOE + KLOE-2 data sample:
~ 8 fb^{-1} ® 2.4 × 10^{10} ϕ's produced
~ 8 x10^9 K_SK_L pairs ~ 3 x10^8 η's
⇒ the largest sample ever collected at the ϕ(1020) peak in e^+e^- collisions

The KLOE-1 detector



Large volume Drift Chamber (13K cells, He gas mixt.) :

4m-∅, 3.75m-length, all-stereo

σ_p/p = 0.4 % (tracks with $\theta > 45°$)

σ_x^{hit} = 150 μm (xy), 2 mm (z)

σ_x^{vertex} ~1 mm $\sigma_{M\pi\pi}$ ~ 1 MeV

Pb-SciFi Calorimeter (barrel + endcap, 15 X_0 depth, 98% solid angle coverage) :

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

$\sigma_T = 54$ ps $/ \sqrt{E(GeV)} \oplus 50$ ps

- **PID capabilities mostly from TOF**

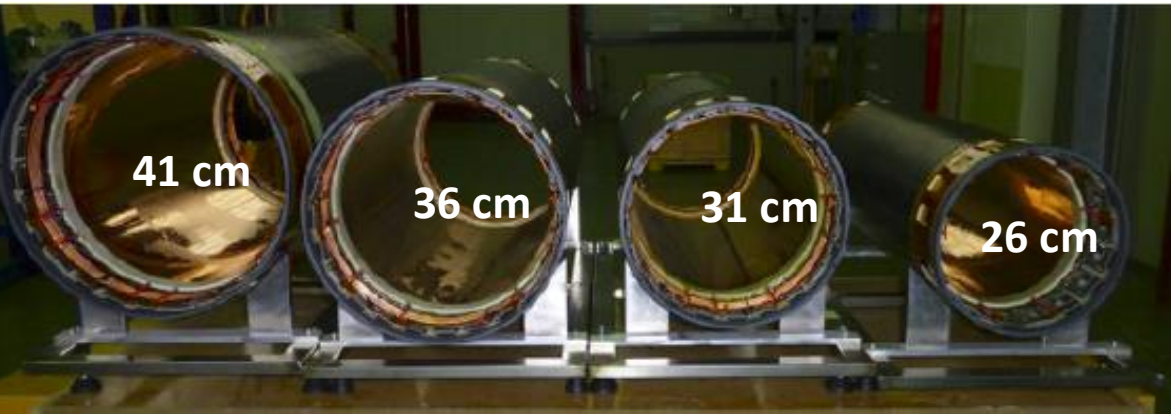
Interaction region:
Instrument quadrupoles,
Al-Be spherical beam pipe

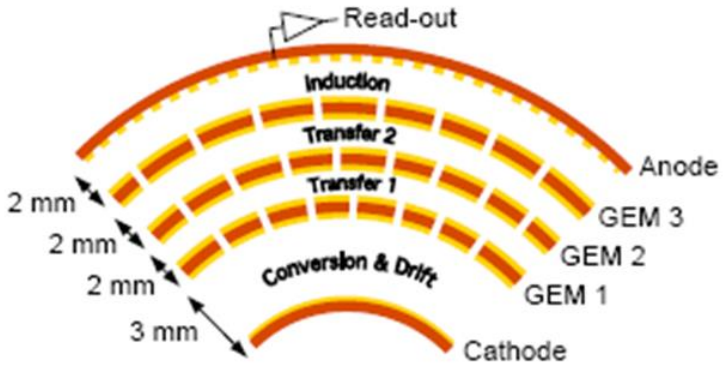
The KLOE-2 Inner Tracker

The first cylindrical GEM detector ever built and operated:

4 coaxial layers of cylindrical triple GEMs
70 cm active length, 130-205 mm radia
X-V stereo readout
2% X_0 total material budget

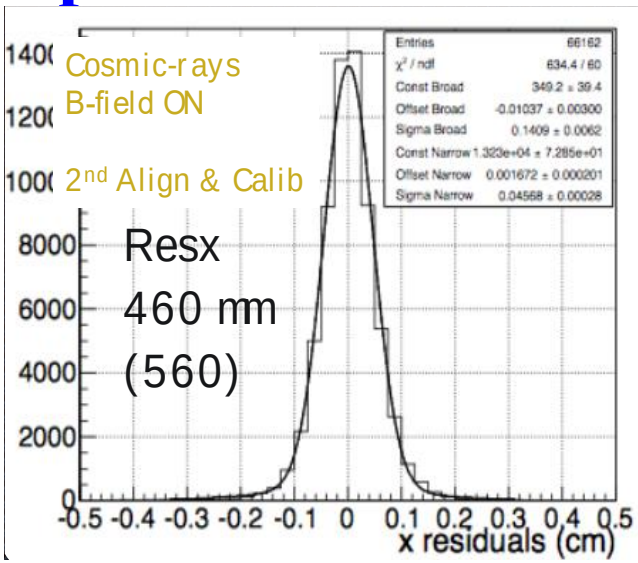
- **Large GEM foils produced at CERN with single-mask technique.**
- **Wrapping and insertion technique developed at Frascati.**
- **1600 HV channels, to reduce energy of discharges.**
- **Operated with Ar-Iso 90-10% gas mixture at a nominal gain of 12000**
- **1k X-strips + 1M V-pads with <0.5% dead area**

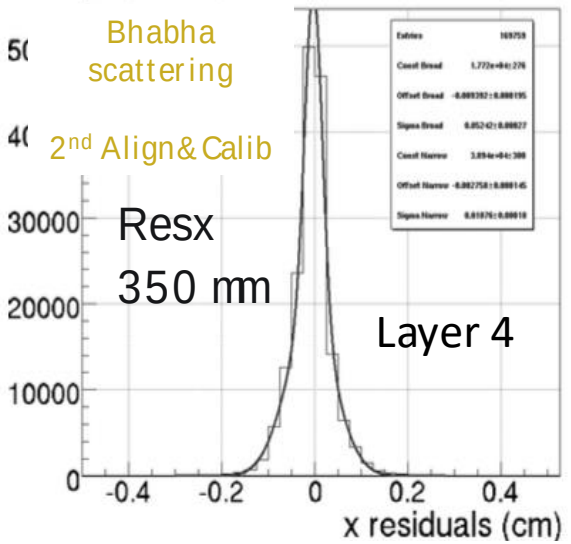




IT performance

Alignment and calibration with cosmic rays :
Correct for non radial tracks and magnetic field effects.
Use DC as reference.
Cross Check with Bhabhas.



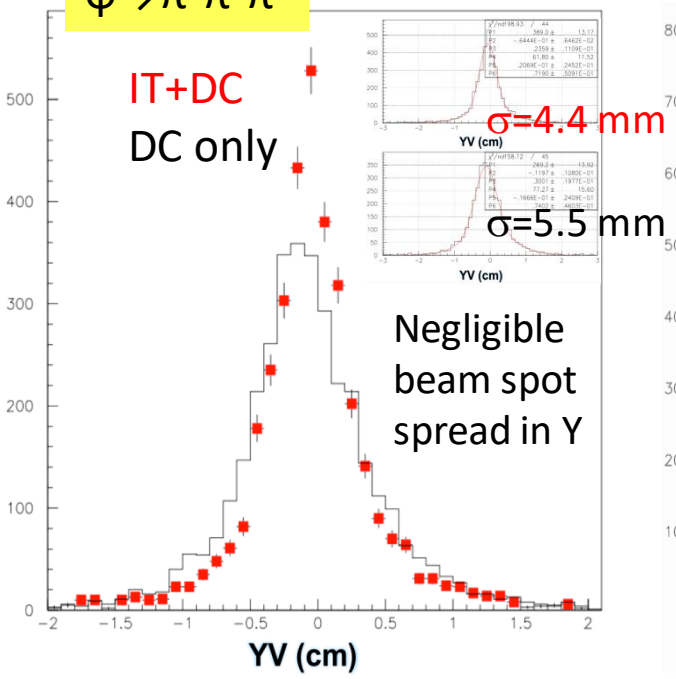


Integrated DC+IT tracking
Start with DC reconstructed tracks, add IT clusters and reconstruct IT+DC tracks

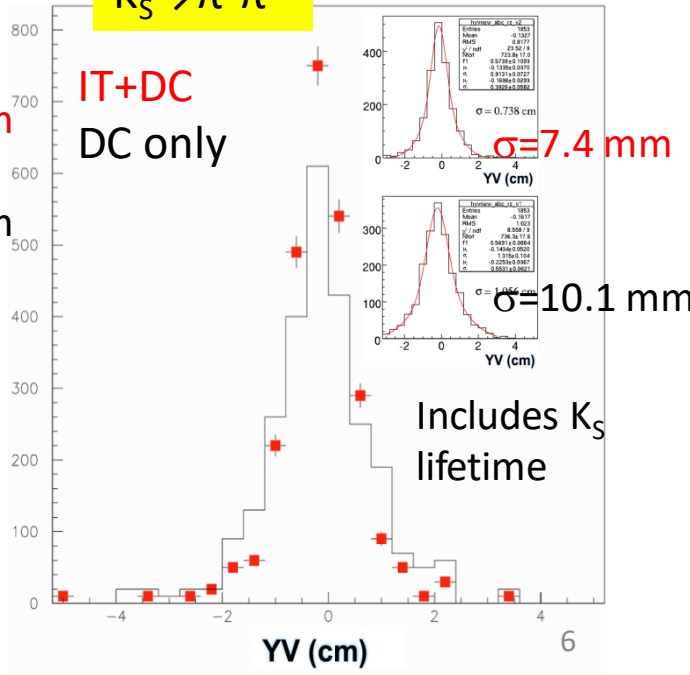
Improvement in vertex reconstruction for
$\varphi \rightarrow \pi^+\pi^-\pi^0$ and $K_S \rightarrow \pi^+\pi^-$

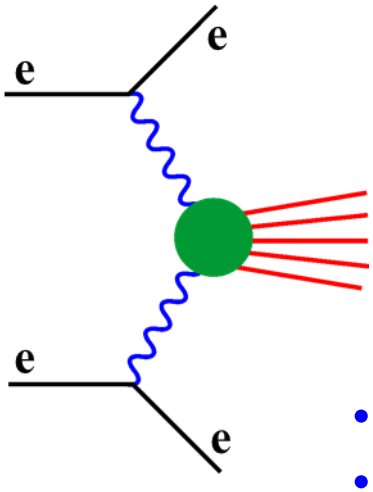
Further improvement with refined align & calib

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



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



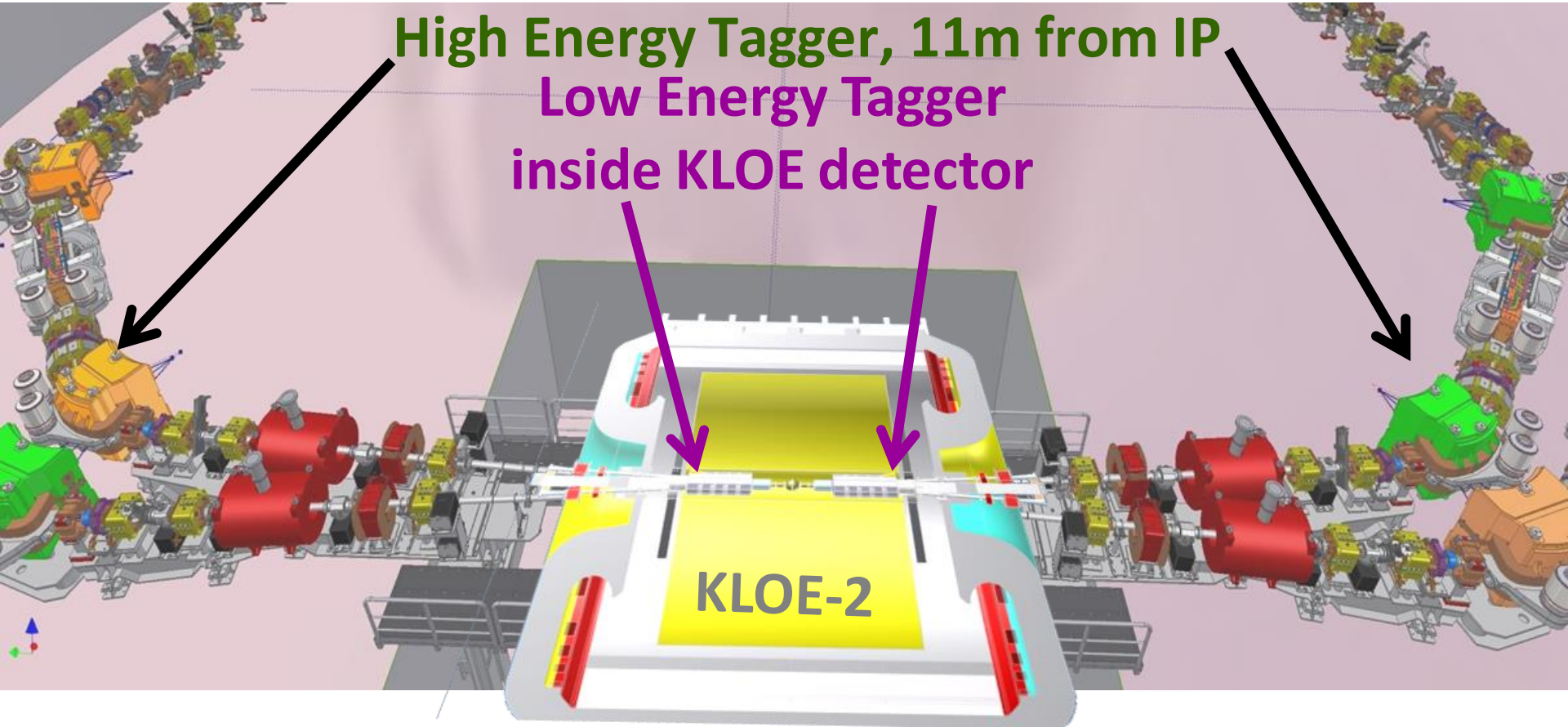


γγ taggers

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

inside KLOE-2 to Tagger

- Use DAFNE magnets as a spectrometer to select FS $e^{\pm}$ momentum
- Kill background coming from ϕ decays and close kinematics



High Energy Tagger (HET)

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

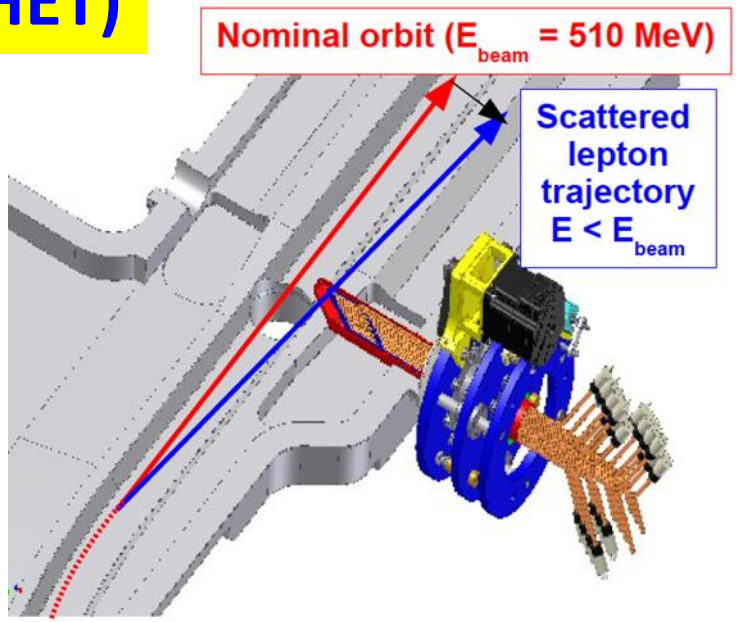
HET is acquired asynchronously w.r.t. the KLOE-2 DAQ (Xilinx Virtex 5 - FPGA)

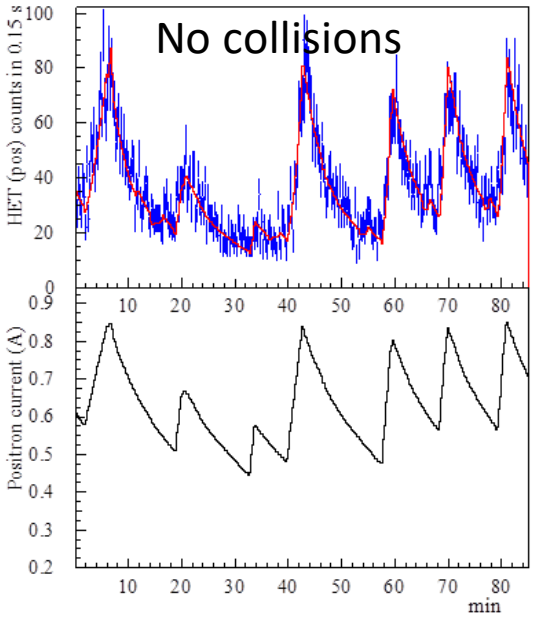
Synchronization with the "Fiducial" signal from DAΦNE

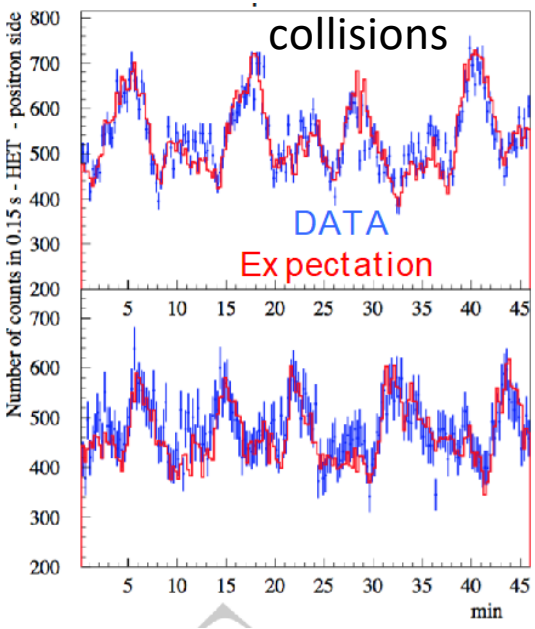
HET signals corresponding to 3 DAΦNE revolutions are recorded for each KLOE trigger.

Off-time hits used to evaluate background.

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







Search for γγ–> π^0 production

Single Arm and Double Arm (coincidence)

event analysis in progress

MultiVariate Analysis approach

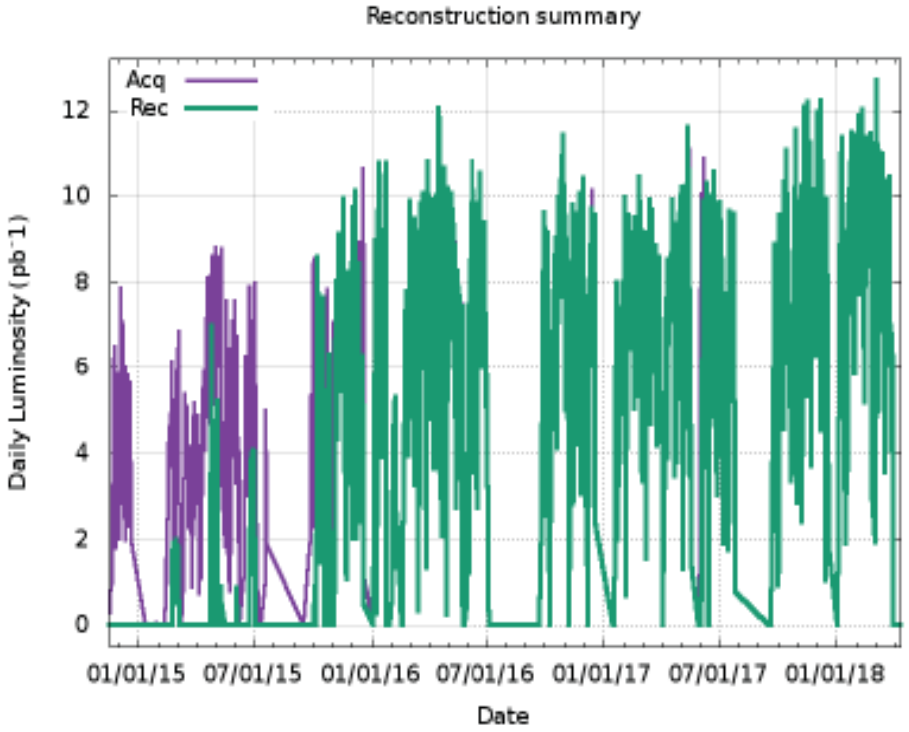
Ricostruzione dei dati

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

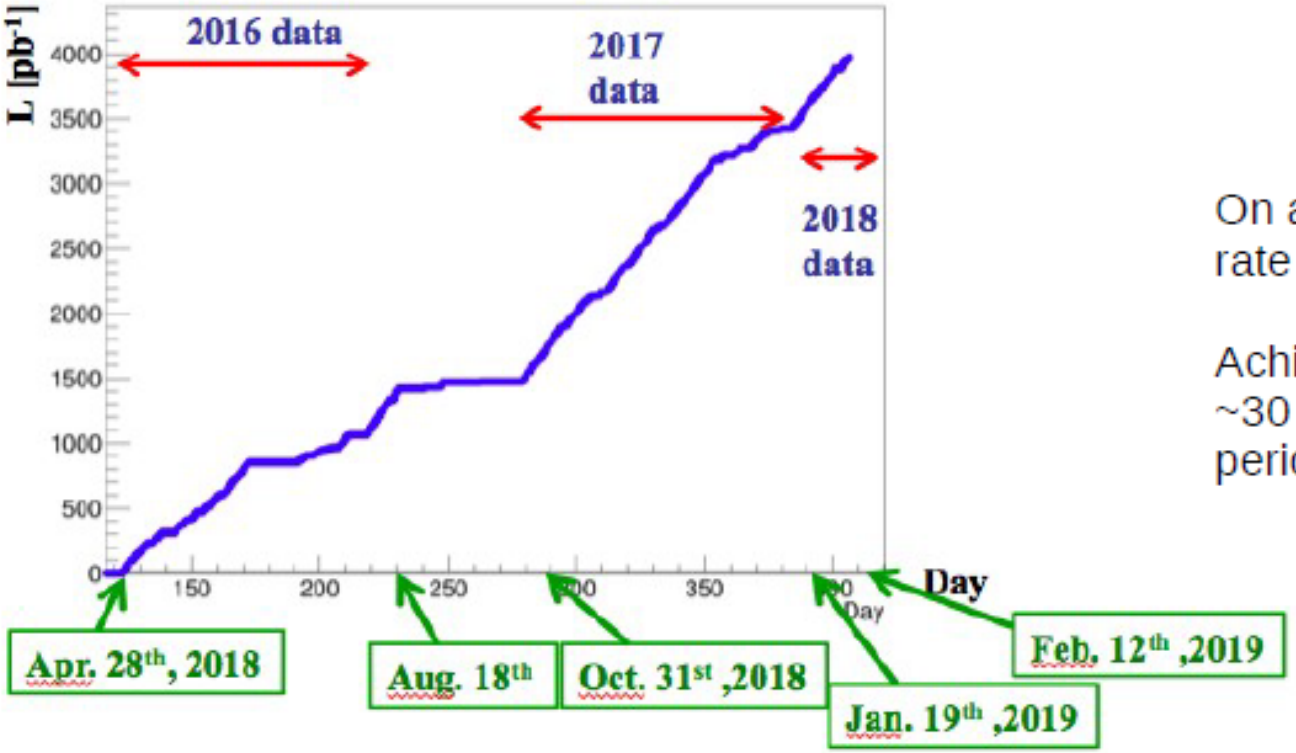
MC update in progress:
- Data/MC cross-check
- Fine tuning of the detector performance

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



	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

Reconstruction rate



On average reconstruction rate ~20pb^{-1}/day

Achieved peak rate of ~30 pb^{-1}/day in the last period

First (almost) full data processing completed in 10 months.

Second, final processing will start in autumn.

Output will be provided in root format and made available to the community for future analyses

KLOE-2 Physics

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

Kaon Physics:

- CPT and QM tests with kaon interferometry.
- Direct T and CPT tests with entanglement
- CP violation and CPT test: $K_S \to 3\pi^0$, $\mathrm{Im}(\varepsilon'/\varepsilon)$
- CKM V_{us}: $K_S l3$ and A_S (CP and CPT test) , $K_{\mu 3}$ f.f., K_{l3} radiative corrections
- χpT : $K_S \to \gamma\gamma$.

Dark force searches:

- Uγ associate production $e^+e^- \to U\gamma \to \pi\pi\gamma$, $\mu\mu\gamma$
- Higgsstrahlung: $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy

- Leptophobic B boson search: $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$; $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Light meson Physics:

- η decays, ω decays; Transition Form Factors.
- C,P,CP violation: improve limits on $\eta \to \gamma\gamma\gamma$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$; χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $f_0(500)$ in $\phi \to K_S K_S \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF, $e^+e^- \to \pi^0\gamma\gamma_{ISR}$ (π^0 TFF)
- search for axion-like particles

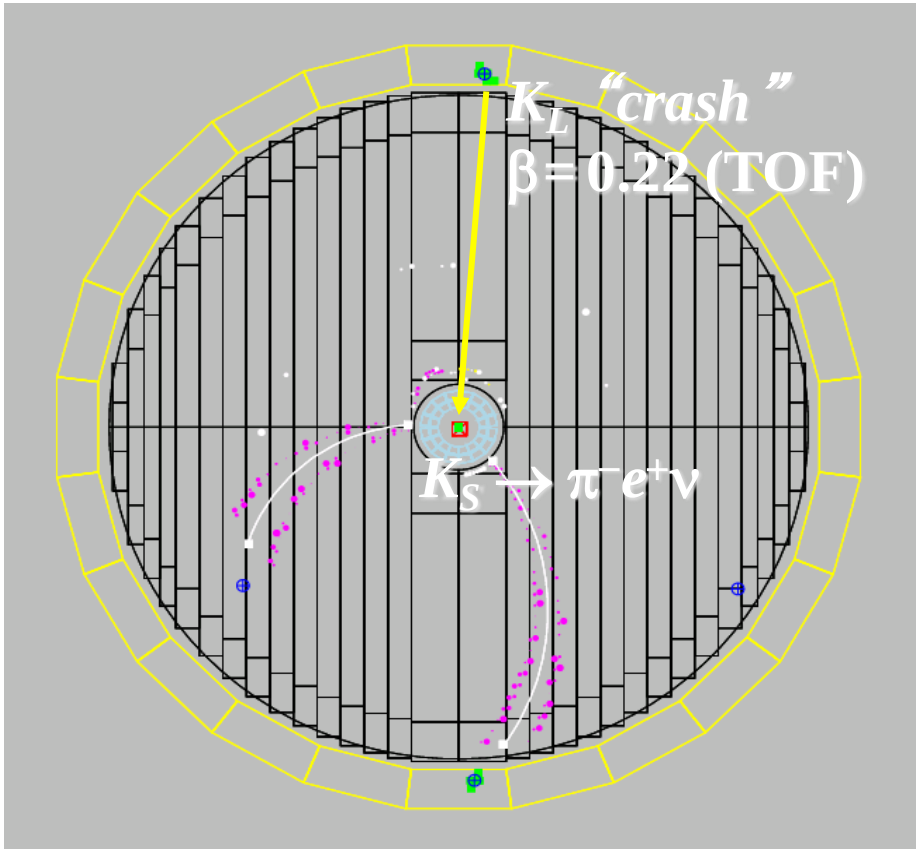
Hadronic cross section:

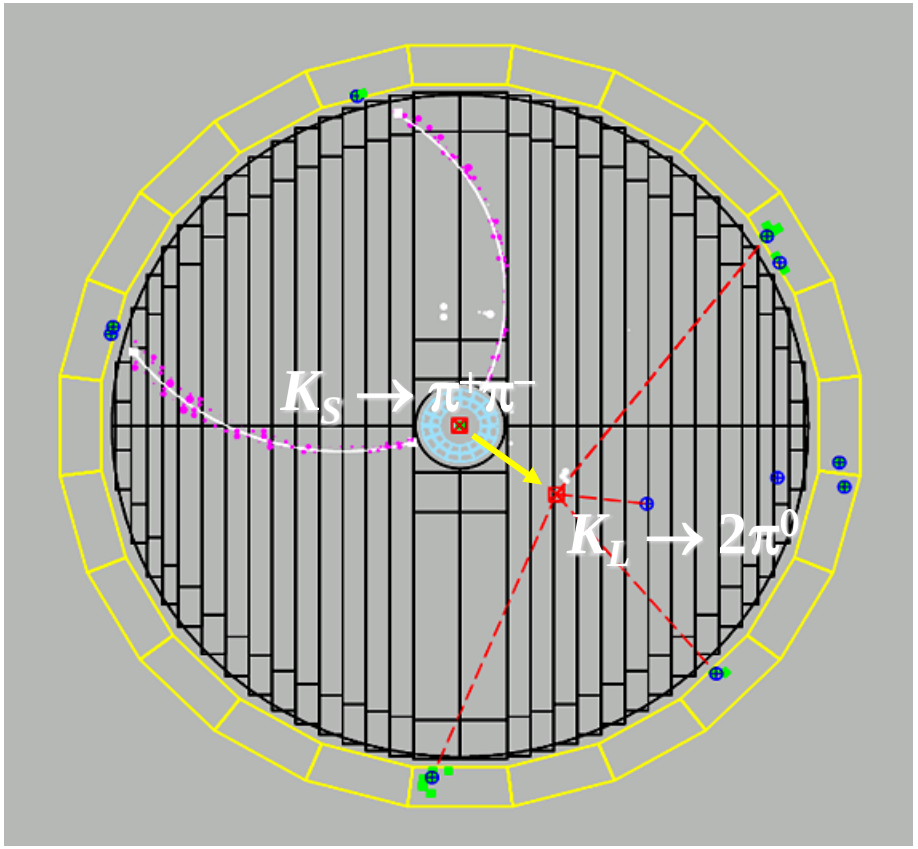
- ISR studies with 3π, 4π final states
- F_π with increased statistics
- Measurement of a_μ^{HLO} in the space-like region using Bhabha process

Analisi in corso

$\gamma^*\gamma^* \rightarrow \pi^0$	KLOE-2 data
$K_S \rightarrow \pi\nu e$ K_L crash	KLOE-2 data
$K_S \rightarrow \pi^+\pi^-$ $K_L \rightarrow \pi^+\pi^-$	KLOE-2 data
$K_S \rightarrow 3\pi^0$ (CP viol.)	KLOE-2 data / KLOE data NN studies
T/CPT test with $\varphi \rightarrow K_S K_L \rightarrow 3\pi^0 \pi\nu e$, $\pi\pi$ $\pi\nu e$	KLOE data: PhD thesis
$K_S \rightarrow \pi\nu e$; $K_S \rightarrow \pi\mu\nu$	KLOE data: PhD thesis
$K_S \rightarrow \pi^+\pi^-\pi^0$	KLOE data
B-boson search in $\varphi \rightarrow \eta\pi^0\gamma$	KLOE/KLOE-2 data
$\eta \rightarrow \pi^0\gamma\gamma$ χ-PT golden mode + B boson search	KLOE/KLOE-2 data
$\eta \rightarrow \pi^+\pi^-$ (P and CP viol.)	KLOE/KLOE-2 data
$e^+e^- \rightarrow \omega\gamma_{ISR}$	KLOE data

Neutral kaon tagging at KLOE





K_S tagged by K_L interaction in EmC

K_L velocity in ϕ rest frame $\beta^* = 0.218$

Efficiency ~ 30% (largely geometrical)

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

K_S momentum resolution: ~ 2 MeV

K_L tagged by $K_S \to \pi^+\pi^-$ vertex at IP

Efficiency ~ 70% (mainly geometrical)

K_L angular resolution: ~ 1°

K_L momentum resolution: ~ 2 MeV

Direct tests of CPT and T in neutral kaons transitions

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

EPR correlations in neutral kaon system are used to study transitions of orthogonal CP eigenstates $K_{\pm}$:

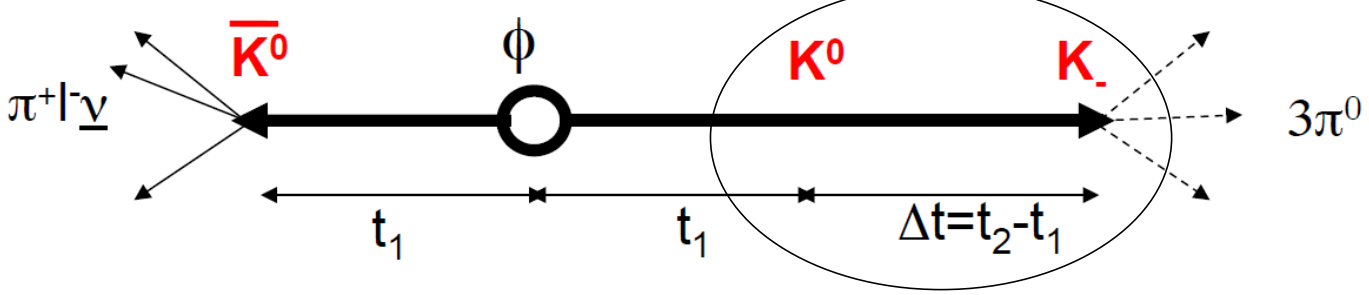
Entanglement: prepare the state

Decay: filters the measurement

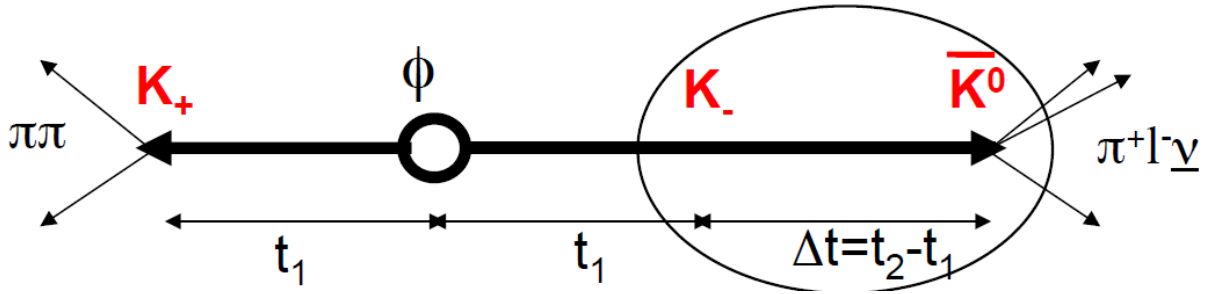
CP and T conjugate processes:

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

Reference process: $K^0 \rightarrow K_-$



CPT-conjugate process: $K \rightarrow \overline{K}^0$



List of CP/CPT tests with neutral kaons at KLOE

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(ε) Im(δ)	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	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(ω)	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	Im(ω)	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	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 asimmetry

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

T, CPT viol. in mixing

CPTV in $\Delta S=\Delta Q$ $\Delta S\neq\Delta Q$ decays

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

$A_S\neq A_L$ signals CPT violation

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

KTEV PRL88,181601(2002)

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

KLOE PLB 636(2006) 173 with 410 pb^{-1}

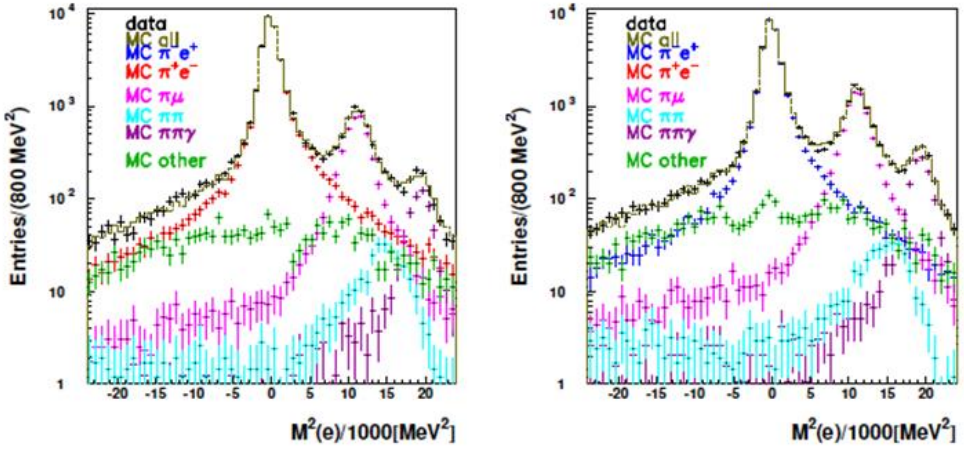
New measurement using 1.7 pb^{-1} sample of KLOE data. Combination with previous yelds:

$A_S = (-3.8 \pm 5.0 \pm 2.6) \times 10^{-3}$ **JHEP 09 (2018)21**

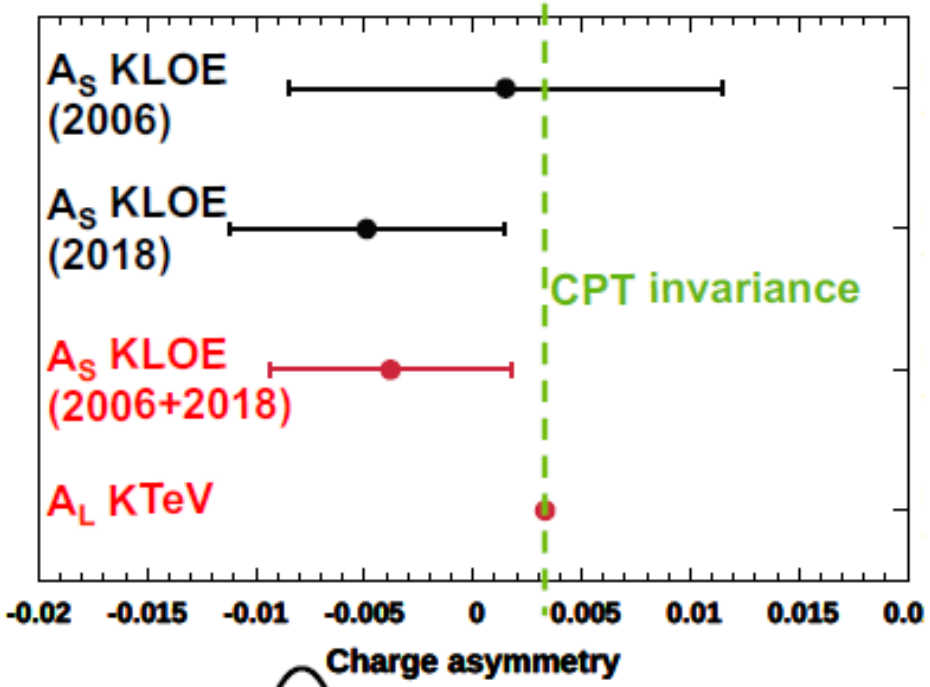
PID thanks to excellent TOF resolution!

Signal extracted by fit to $M^2(e)$ distribution

Error still statistics dominated: analysis will be extended to KLOE-2 data sample



K_S semileptonic charge asimmetry /2



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

KLOE (2018)

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

Combination KLOE(2006)+KLOE (2018)

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

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

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

CPT & $\Delta S=\Delta Q$ viol.
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$$A_S + A_L = 4(\Re\varepsilon - \Re y) \rightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$

CPT viol.

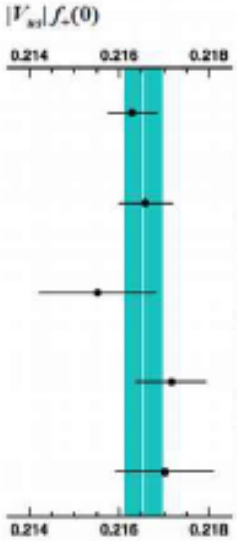
input from other experiments

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

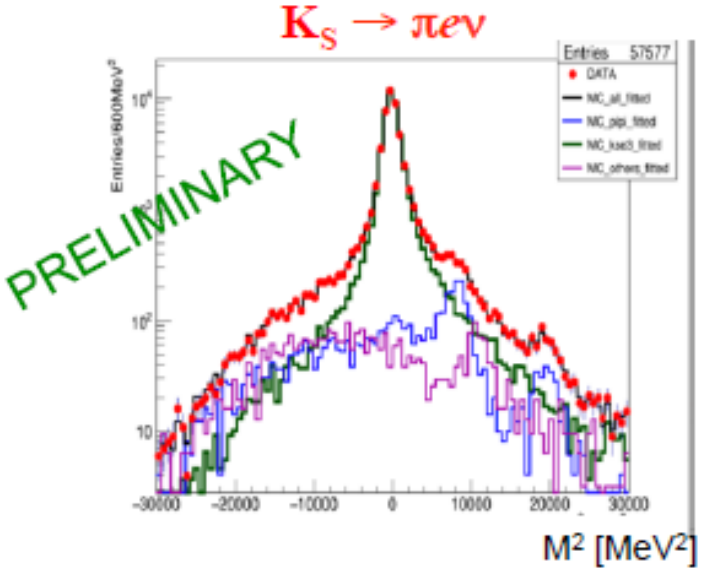
$K_S \rightarrow \pi e \nu$ Branching ratio

Precision measurement of V_{us}
From K_{Se3} the largest contribution to the uncertainty
[old KLOE meas. Br(KSe3) = (7.046 ± 0.091)x10^{-4}]

New analysis scheme based on BDT selection and TOF identification.
49647 events in 1.6 fb-1
Systematics are being studied



		% err	Approx. contrib. to % err from: 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



Tesi A.Selce

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

First measurement of Br(Ksμ3)

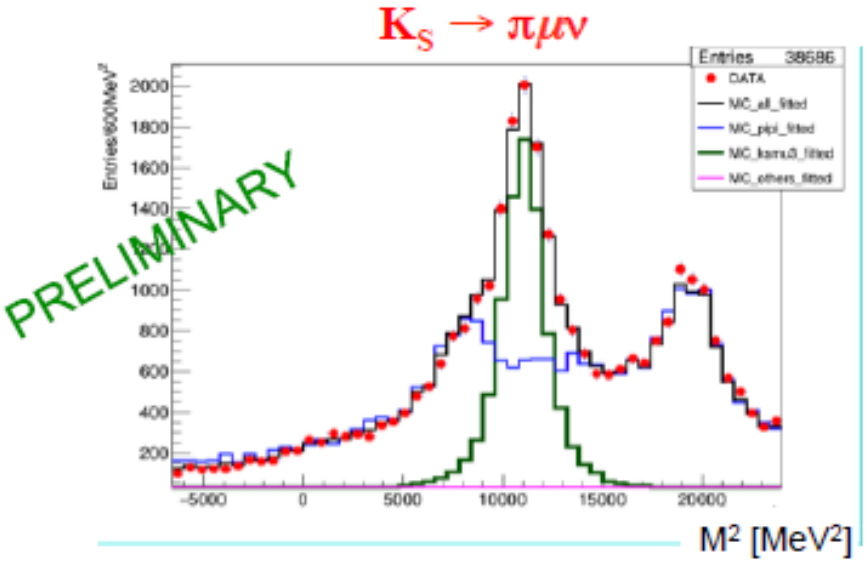
7223 events in 1.6 fb^{-1}

Expected $Br(K_{S\mu 3}) = (4.69 \pm 0.05) \times 10^{-4}$

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



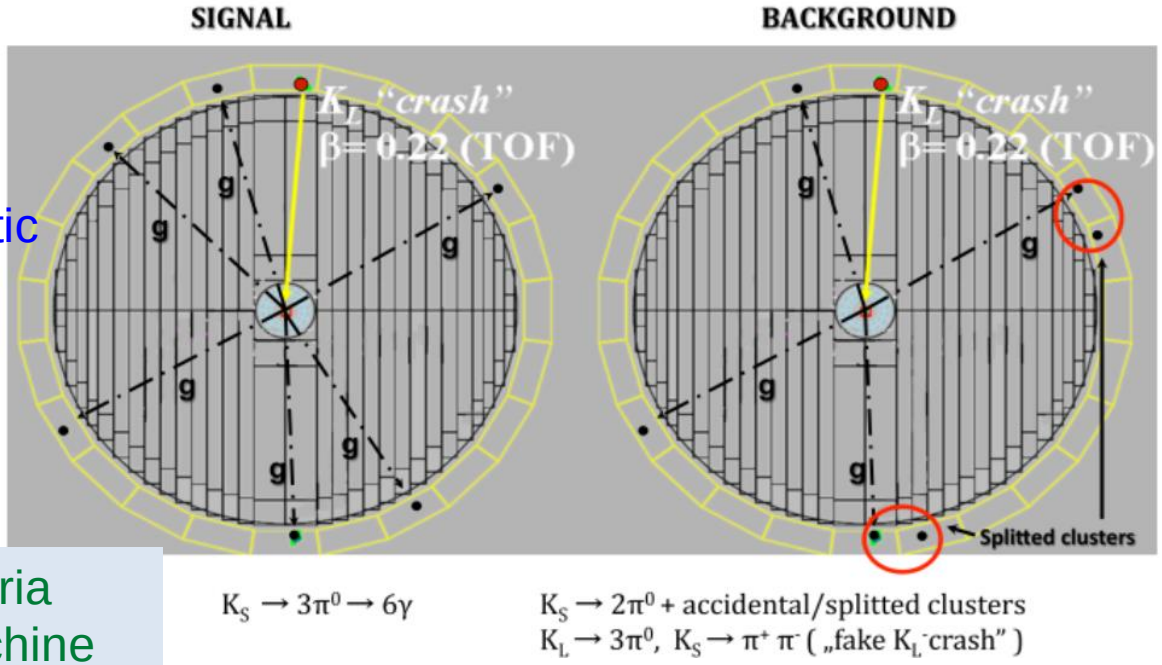
Tesi A.Selce

Search for $K_S \rightarrow \pi^0\pi^0\pi^0$

$3\pi^0$ is a pure CP=-1 state: observation of $K_S \rightarrow 3\pi^0$ is an unambiguous sign of CP violation in mixing and/or in decay. SM prediction: $BR(K_S \rightarrow 3\pi^0) = 1.9 \cdot 10^{-9}$

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

Signature: "K_L crash" (K_L in the calorimeter) + 6 prompt photons
Analysis: γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypotheses
Main bckg: $K_S \rightarrow 2\pi^0$ (4 prompt photons), also used as normalization

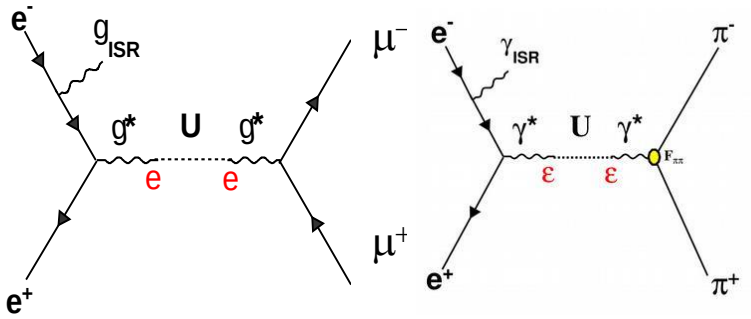


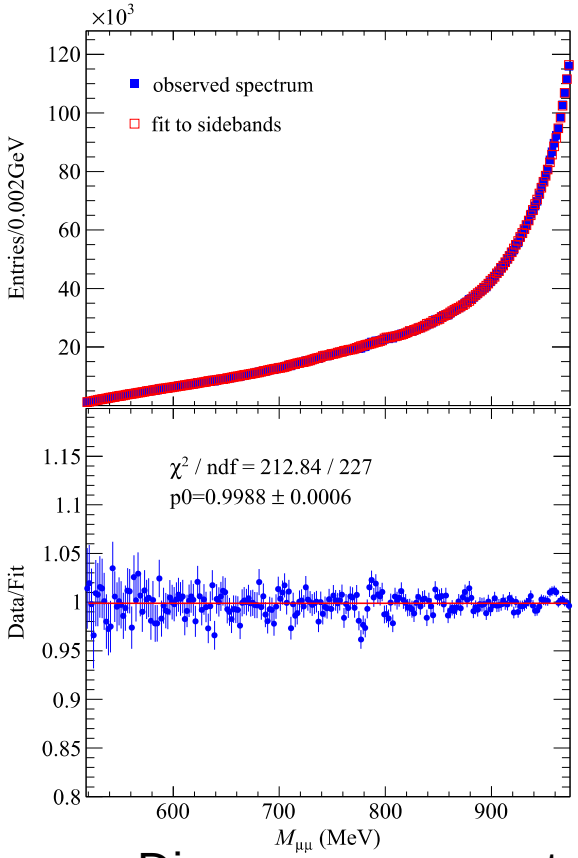
KLOE-2 analysis: selection criteria hardened to face the larger machine bckg: **~ 10x better bckg rejection**

@KLOE-2, using old analysis scheme on 300 pb^{-1} data sample, 1 signal event selected ($\varepsilon_{3\pi}$ ~ 19 %) $\Rightarrow Br(K_S \rightarrow 3\pi^0) \lesssim 2.5 \times 10^{-7}$ @90% CL (preliminary)
Full KLOE-2 statistics + optimized analysis can reach $\lesssim 10^{-8}$

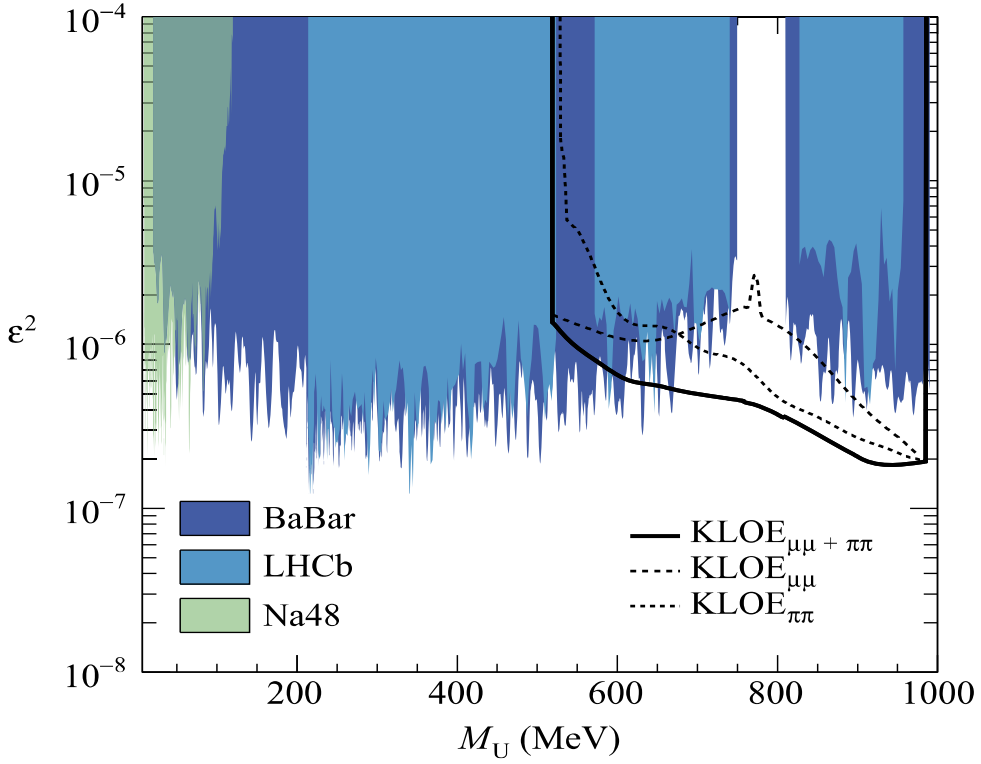
Search for U-boson in $\mu^+\mu^-\gamma$ / $\pi^+\pi^-\gamma$

Dark mediators (U-boson) at GeV scale searched in KLOE data at $\sqrt{s} \sim 1$ GeV.
1/s cross section scaling makes a factor ~100 advantage in integrated L wrt to B factories





Dimuon mass spectrum



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η decays

The light quark masses: study of $\eta \to \pi^+\pi^-\pi^0$ decay ⇒ **Isospin violation**

e.m. strongly suppressed, induced dominantly by the strong interaction associated with the u-d quark mass difference

Dalitz plot fitted with: $|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + \ldots$

c and *e* parameters are C violating: measurement consistent with zero.

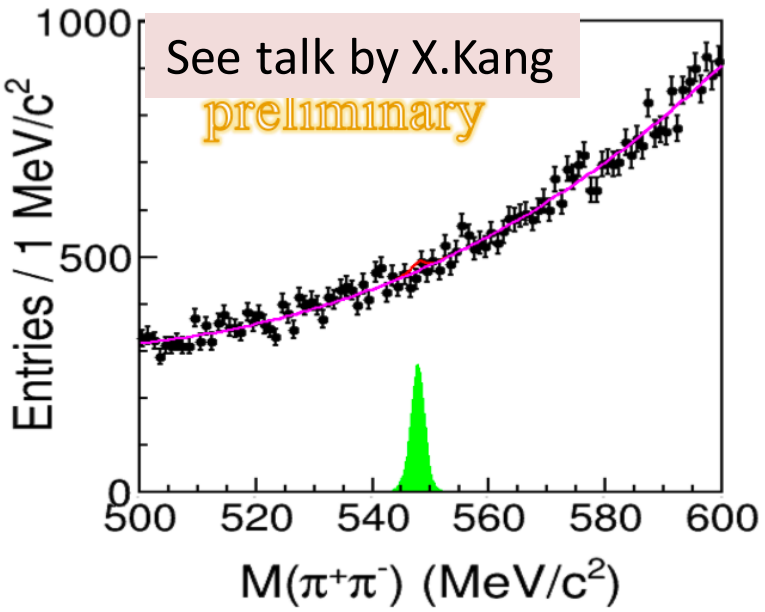
JHEP 05(2016)019

Search for the P,CP violating $\eta \to \pi^+\pi^-$ decay

Old KLOE result using a 350 pb^{-1} sample.
BR($\eta \to \pi^+\pi^-$)<1.3 x 10^{-5} @ 90% c.l.
PLB 606 (2005) 276

L~1.7 fb-1 analysis in progress:
Preliminary UL at 6.3 x 10^{-6} @90% c.l.

Plan to include all KLOE-2 sample.

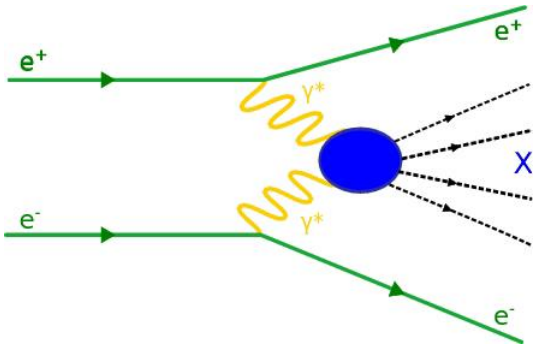


γγ physics @ KLOE-2

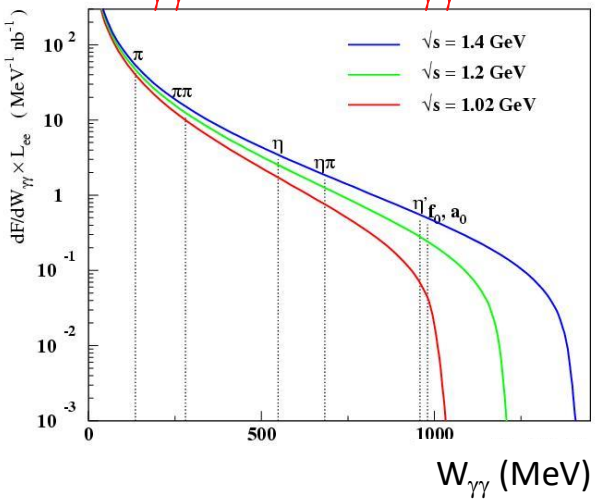
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^- X$$

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

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



$$\frac{dN}{dW_{\gamma\gamma}} = L_{int}\frac{dF}{dW_{\gamma\gamma}}\sigma(\gamma\gamma \to X)$$

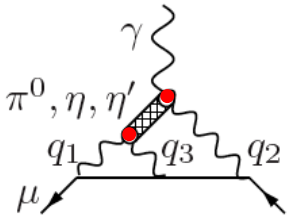


Precision measurement of Γ(π⁰→γγ)

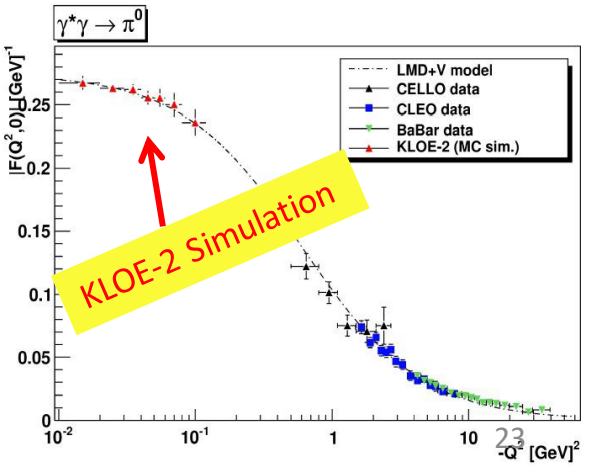
- Theory: Γ(π⁰→γγ)=(8.09±0.11) eV ⇒ 1.4% uncert. [Kampf-Moussallam PRD79(2009)076005]
  Expt.: Γ(π⁰→γγ)=(7.82±0.14±0.17) eV ⇒ 2.8% uncert. PrimEx [PRL106(2011)162303]:
  PrimExII preliminary: (7.74±0.06±0.12) eV [Hadron 2017] (1.7 %)

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

Constraints to the HLbL contribution to $(g-2)_\mu$



unexplored q^2 region
measure the slope at $q^2 \to 0$



Summary

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 data analysis is still providing 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.

The KLOE+KLOE-2 data sample (~ 8 fb^{-1}) is worldwide unique for typology and statistical relevance. A lot of physics information has still to be mined in it.

Analysis is ongoing and will both improve KLOE results and produce new ones. A data preservation strategy is also being pursued.