Status of KLOE-2

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on behalf of the KLOE-2 collaboration

LNF Scientific Committee meeting
Frascati (COVID), November 16th 2020

Outline

- Status of the reconstruction
- Monte Carlo Production
- Publications/Ongoing Analysis
  - Discussion of ongoing analysis
- Conclusions

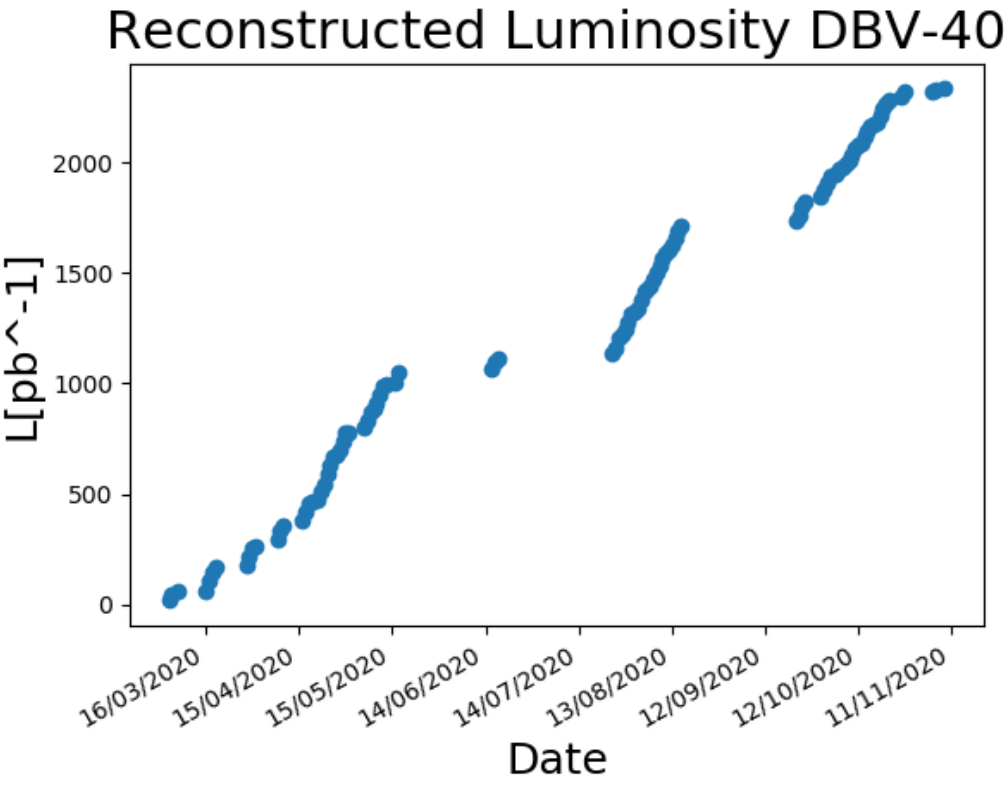
Data Reconstruction Status

- Final round of data reconstruction started on March 2020 with DBV-40 tag

- After 1 fb-1 reconstructed stop for data quality

- Reconstructed $\mathbf{L_{int} = 2.4\ fb^{-1}}$ to date
- Reconstruction rate ~30 pb^{-1}/day (only the reconstruction/no dead time)

- Prod2root production for data preservation
  - Sample produced for test
  - Used in data quality studies
  - Integration in DB2 to be finalized



Monte Carlo status

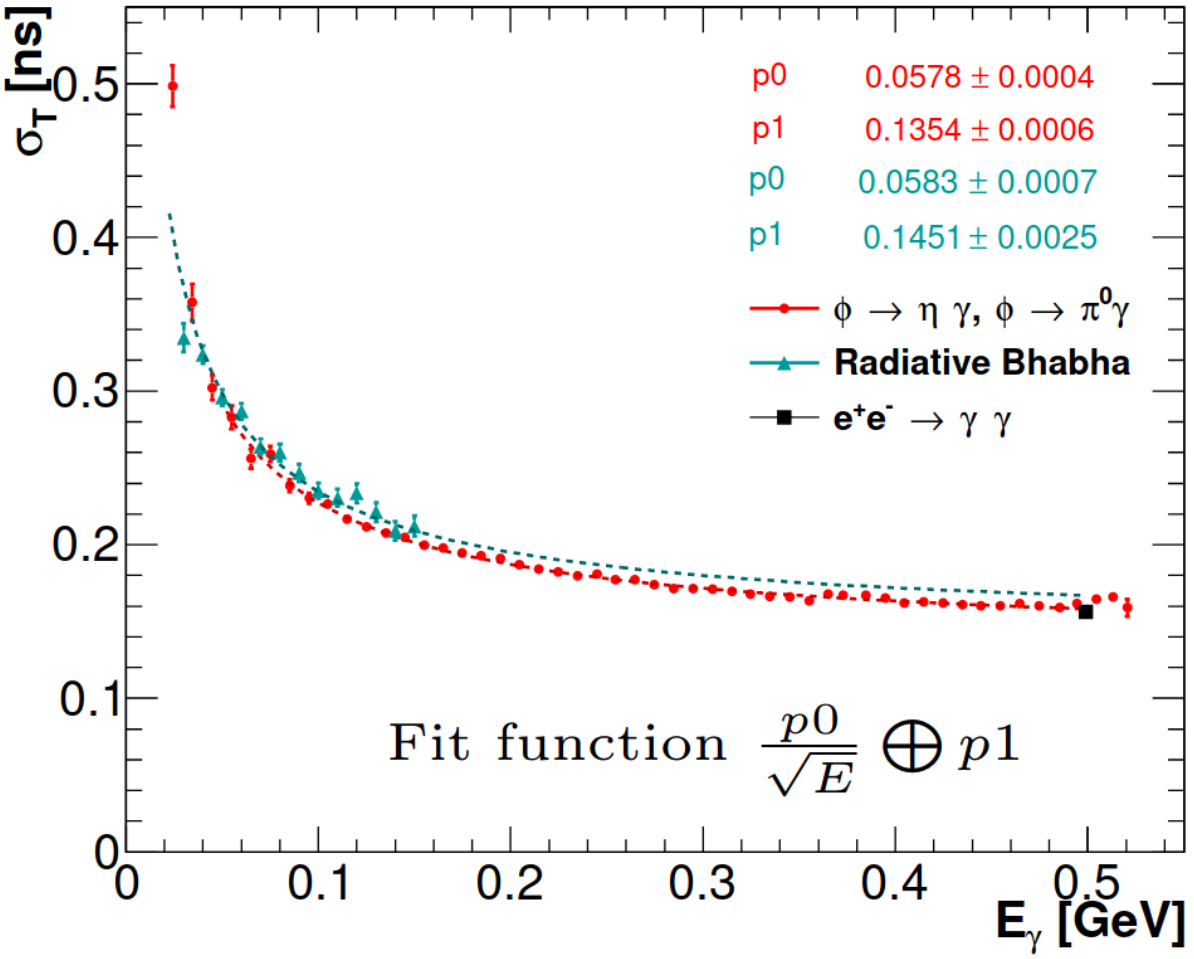
- **Full MC data sample with Luminosity Scale Factor (LSF) = 1 produced and reconstructed with version DBV-38**

Simulation	DBV Version	MC Version	LSF	Luminosity (pb-1)
$\varphi \rightarrow$ all	38	201	1.00	3703
$K_S \rightarrow 3\pi 0$	38	201	1×10^6	2032
e+e- $\rightarrow$ e+e-	38	201	0.01	353
e+e- $\rightarrow \gamma\gamma$	38	201	1.00	23
$\varphi \rightarrow$ all	39	210	1.00	93
e+e-$\rightarrow$ e+e-	39	210	0.01	93

- Production rate $\sim$ 15 pb $^{-1}$ /day (performed in parallel, but by allocating most of the computing power to the data reconstruction).

Monte Carlo status

- **Detector performances studies to parameterize the MC simulation**
  - **e.g. calorimeter time resolution**



- **New production with DBV-40 incorporating the updated detector response descriptions to be started soon**

Publications/Ongoing Analysis

Last Publications	
Measurement of the branching fraction for the decay $K_S \to \pi\mu\nu$ with the KLOE detector	Physics Letters B 804 (2020)
$\eta \to \pi^+\pi^-$ (P and CP viol.)	JHEP 10 (2020) 047

Ongoing analyses	
T/CPT tests with $\phi \to K_S K_L \to 3\pi^0$ $\pi e\nu$, $\pi\pi$ $\pi e\nu$	KLOE data
$K_S \to \pi^+\pi^-\pi^0$	KLOE data
$K_S \to 3\pi^0$ (CP viol.)	KLOE-2 data
Search for decoherence and CPTV in KSKL$\to \pi^+\pi^-$ $\pi^+\pi^-$	KLOE data
$\gamma\gamma \to \pi^0$	KLOE-2 data
$\eta \to \pi^0\gamma\gamma$ - χPT golden mode	KLOE / KLOE-2 data
B-boson search in $\phi \to \eta\pi^0\gamma$, $\eta\to\gamma\gamma$	KLOE/KLOE-2 data
$e^+e^-\to(\gamma)\eta\pi^+\pi^-/\mu^+\mu^-$	KLOE data

Publication $\eta \to \pi^+\pi^-$ (P and CP viol.) Analysis

$B(\eta \to \pi^+\pi^-) < 4.9\times10^{-6}$

KLOE data 2004-05 ($L=1.6$ fb^{-1})

three times better than previous KLOE result (Phys. Lett. B606(2005) 276)

Combined KLOE(2005)/KLOE(2020) ($L=1.6+0.4$ fb^{-1})

$B(\eta \to \pi^+\pi^-) < 4.4\times10^{-6}$

JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *June 29, 2020*
ACCEPTED: *September 7, 2020*
PUBLISHED: *October 7, 2020*

Upper limit on the $\eta \to \pi^+\pi^-$ branching fraction with the KLOE experiment

The KLOE-2 collaboration

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JHEP10(2020)047

T/CPT Tests with $\phi \to K_S K_L \to 3\pi^0 \nu e, \pi\pi \nu e$

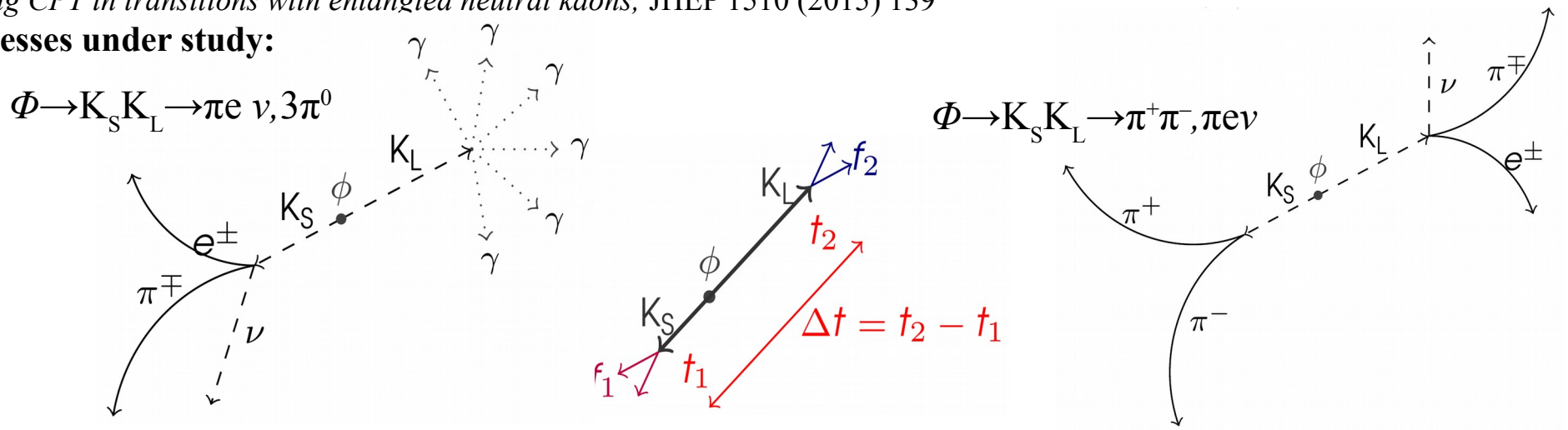
Concept:

First such measurement with kaons
Model independent test

J. Bernabeu, A. Di Domenico and P. Villanueva-Perez,
Direct test of time-reversal symmetry in the entangled neutral kaon system at a Φ factory, Nucl. Phys. B 868 (2013) 102

J. Bernabeu, A. Di Domenico and P. Villanueva-Perez,
Probing CPT in transitions with entangled neutral kaons, JHEP 1510 (2015) 139

Processes under study:



Observables of the tests (we focus on the asymptotic region):

T-violation sensitive

$$R_2^T(\Delta t) \sim \frac{I(\pi^+ e^- \nu, 3\pi^0;\ \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu;\ \Delta t)}$$

$$R_4^T(\Delta t) \sim \frac{I(\pi^- e^+ \nu, 3\pi^0;\ \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \nu;\ \Delta t)}$$

CPT-violation sensitive

$$R_2^{CPT}(\Delta t) \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}$$

$$R_4^{CPT}(\Delta t) \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}$$

Double ratios:

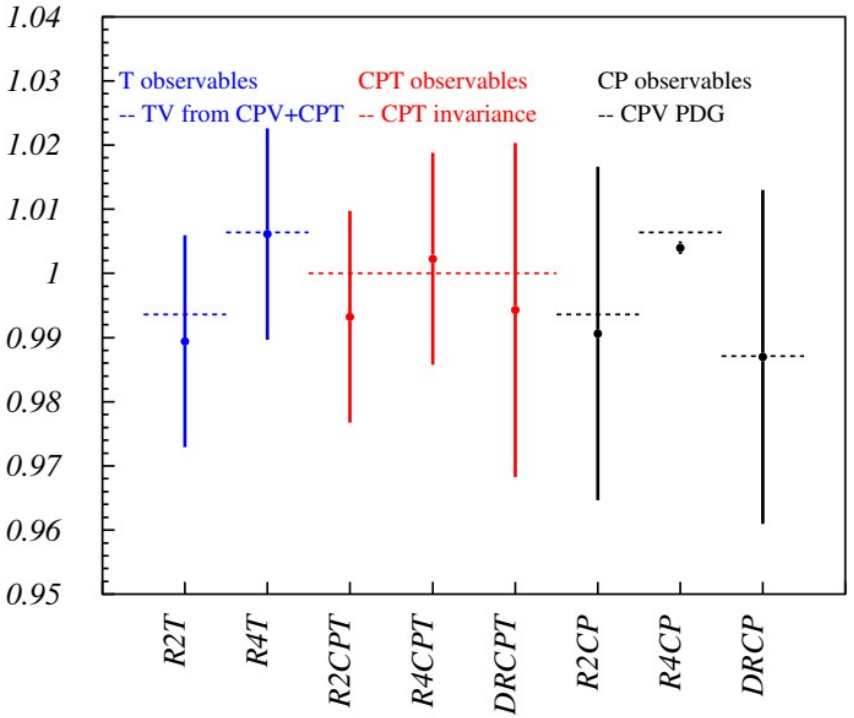
$$\text{DRCP} = \frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$$

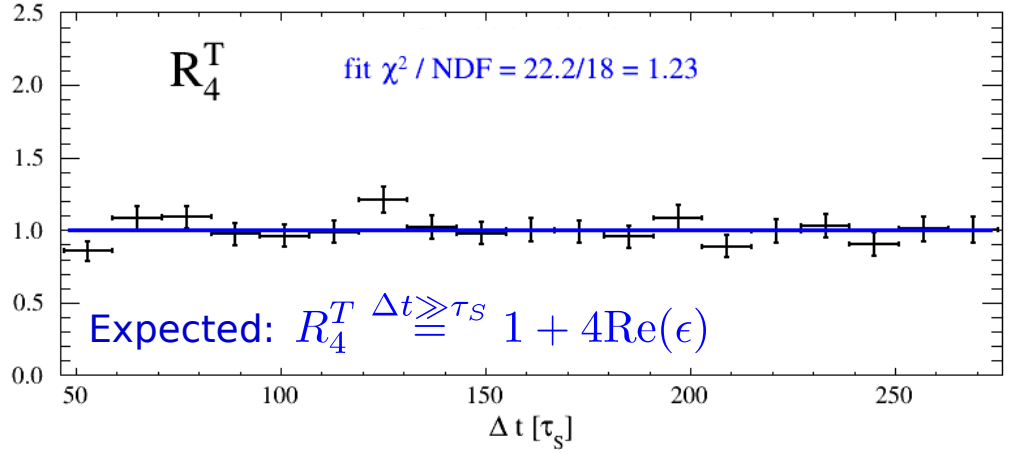
$$\frac{R_2^{CPT}}{R_4^{CPT}}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

T/CPT Tests with $\phi \to K_S K_L \to 3\pi^0 \pi\nu e, \pi\pi \pi\nu e$

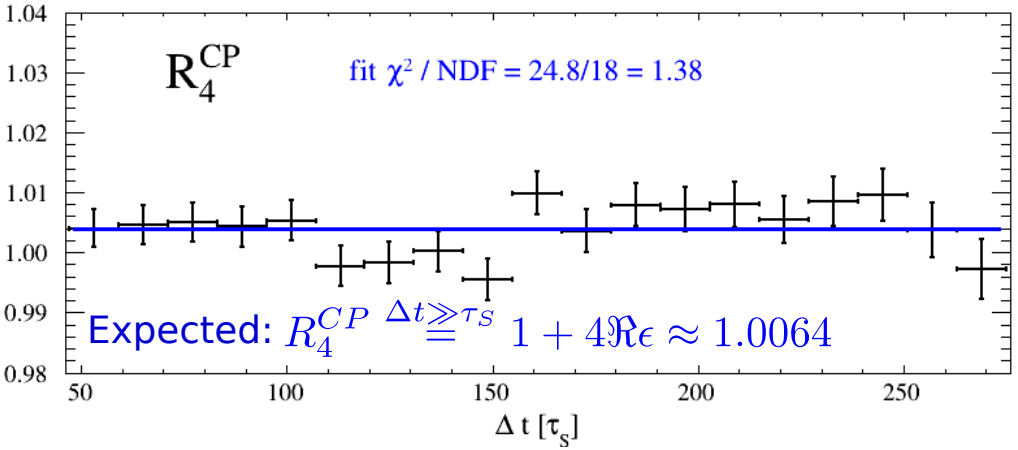
- Analysis at the final stage
  - last systematic effects under study
- Refined statistical treatment of single and double ratios

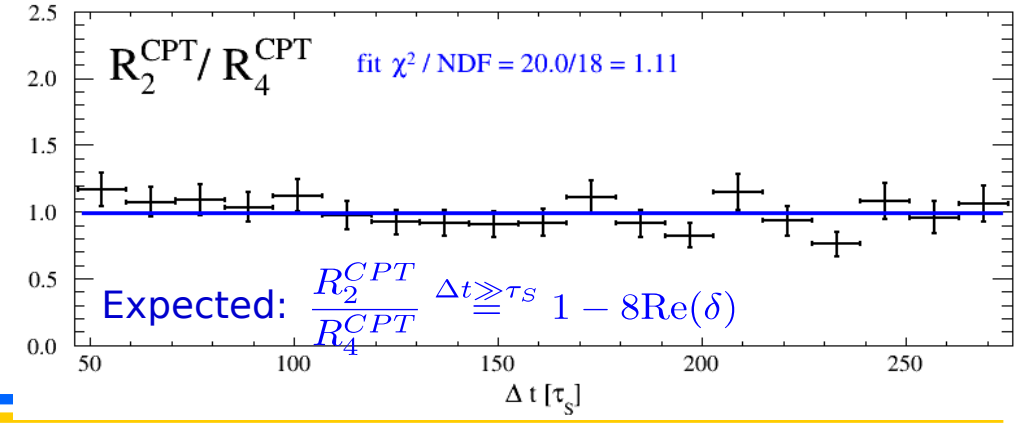
Preliminary results
(statistical uncertainty only)





Note different scale!





Contributions to systematic studies:

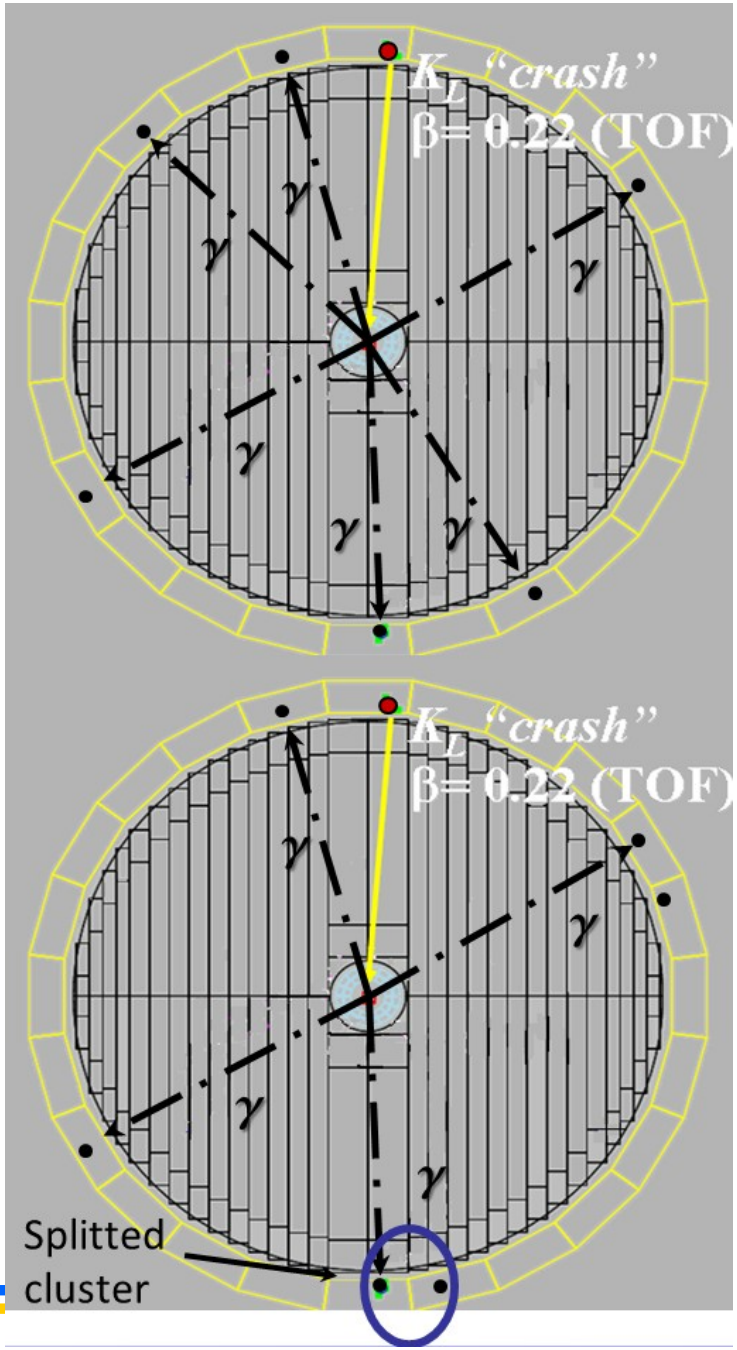
Effect	R_2^T	R_4^T	R_2^{CPT}	R_4^{CPT}	double ratio R_2^{CPT} / R_4^{CPT}	R_4^{CP}
Δ bin width	√	√	√	√	√	√
Smoothing of efficiencies	√	√	√	√	√	√
Uncertainty on the D factor	√	√	√	√	√	√
Center of the fitting range	√	√	√	√	√	√
Width of the fitting range	√	√	√	√	√	√
Trigger and background filter efficiencies	√	√	√	√	√	√
Bias on the double ratio estimation method	√	√	√	√	√	√
Event classification efficiencies	X	X	X	X	X	X
Event selection cuts	X	X	X	X	X	X

$K_S \rightarrow 3\pi^0$

- $3\pi^0$ 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.

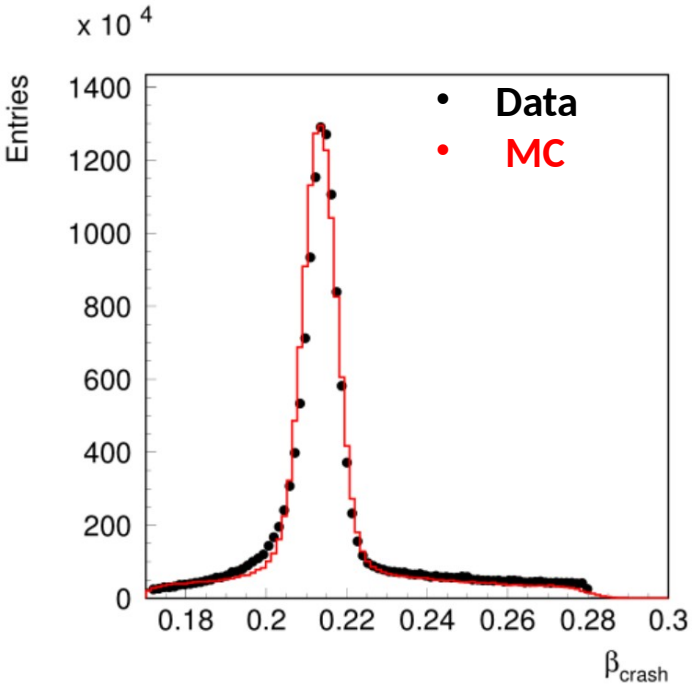
- Standard Model prediction:
  - $BR(K_S \rightarrow 3\pi^0) = 1.9 \times 10^{-9}$

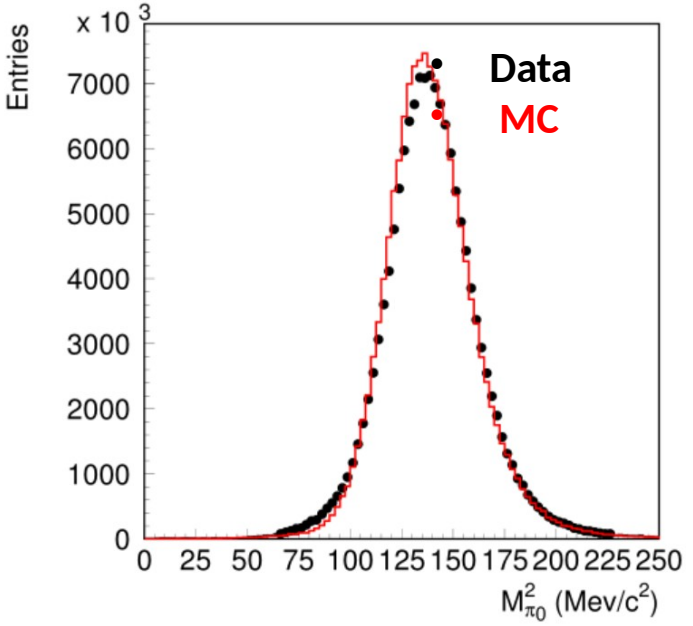
- Best upper-limit by KLOE with 1.7 fb^{-1}
  PLB 723 (2013) 54
  - $BR(K_S \rightarrow 3\pi 0) < 2.6 \times 10^{-8}$ @ 90% CL



$K_S \rightarrow 3\pi^0$ with KLOE-2

- **Analysed data:**
  - **Runs 80231-95093 (in total ~4 fb^{-1}, DBV-38)**
- **MC simulations:**
  - $K_S \rightarrow 3\pi^0$ signal: runs 80231-89035 (~1.7 fb^{-1}, Datarec v38, LSF = 10^6)
  - **All_phys: 80231-95093 (in total ~4 fb^{-1}, DBV-38, LSF=1)**
- Preselection with the following requirements:
  - K_L-crash: E>150 MeV, 0.2< β < 0.225
  - prompt photons: $E_{cl} > 20$ MeV; $|\cos\theta_{cl}| \leq 0.915$ and $|\Delta T_{cl}| \leq \mathrm{Min}(3.0 \cdot \sigma_T(E_{cl}), 2\ \mathrm{ns})$
  - $K_S \rightarrow 2\pi^0$ (4 prompt photons) used for normalization

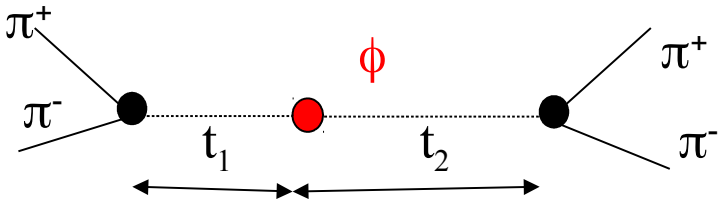




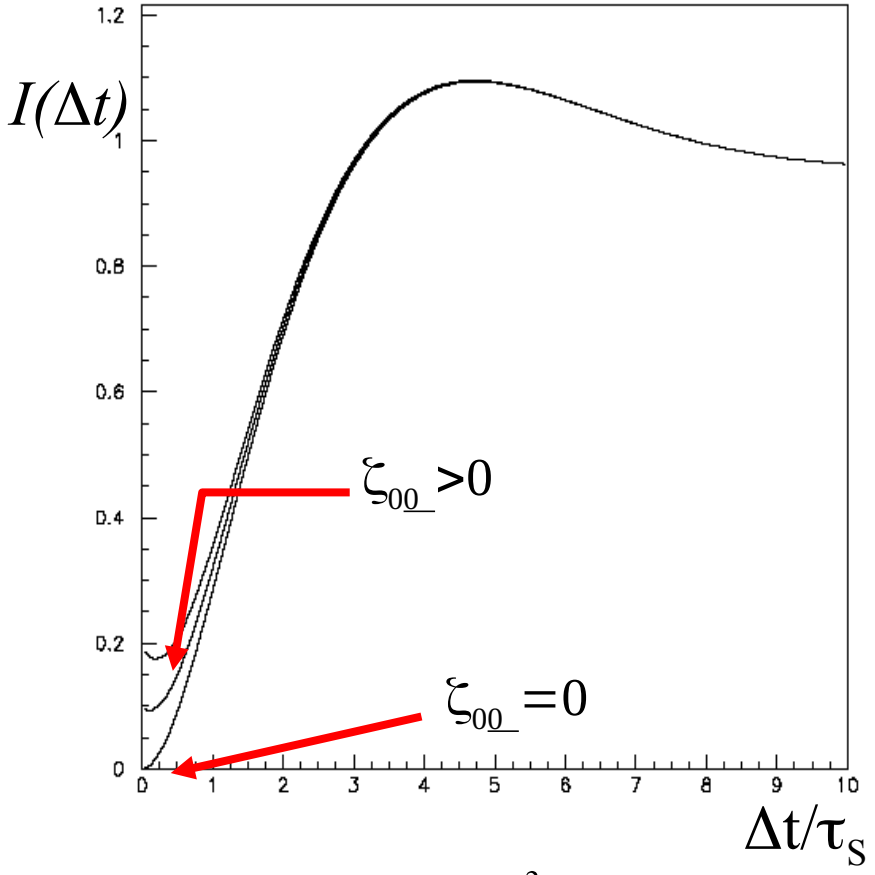
- Cuts optimization procedure is in progress
- Improvement based on MVA approach under study
- Started preselection with DBV-40

Search for decoherence and CPTV in $\phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$

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



$\Delta t = |t_1 - t_2|$



Most precise test of quantum coherence in an entangled system:

$$I\left(\pi^+\pi^-,\pi^+\pi^-;\Delta t\right) = \frac{N}{2}\left[\left|\left\langle\pi^+\pi^-,\pi^+\pi^-\left|K^0\overline{K}^0(\Delta t)\right\rangle\right|^2 + \left|\left\langle\pi^+\pi^-,\pi^+\pi^-\left|\overline{K}^0K^0(\Delta t)\right\rangle\right|^2\right.\right.$$
$$\left.\left. -\left(1-\zeta_{0\overline{0}}\right)\cdot 2\Re\left(\left\langle\pi^+\pi^-,\pi^+\pi^-\left|K^0\overline{K}^0(\Delta t)\right\rangle\left\langle\pi^+\pi^-,\pi^+\pi^-\left|\overline{K}^0K^0(\Delta t)\right\rangle^*\right.\right)\right]$$

$\zeta_{0\overline{0}}$ decoherence parameter in the $K^0\overline{K}^0$ basis
(QM predicts $\zeta_{0\overline{0}}=0$)
[or ζ_{SL} in the K_S-K_L basis]

Search for decoherence and CPTV in $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

Decoherence effects might arise in a quantum gravity picture necessarily entailing CPT violation [Ellis et. al, NP B241 (1984) 381; Ellis, Mavromatos et al. PRD53 (1996)3846]:

1)In this case the relevant parameter in the modified time evolution of neutral kaons is the γ parameter (at most $\gamma = O(m_K^2/M_{planck}) \sim 2\times10^{-20}$ GeV)

2) the initial entangled state is modified adding a tiny symmetric part -> ω effect (at most $\omega = O(m_K^2/M_{planck}/\Delta\Gamma) \sim 1\times10^{-3}$)

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

Previous KLOE measurement **L=380 pb^{-1}**

KLOE PLB 642 (2006) 315

$\zeta_{SL} = (1.8 \pm 4.0 \pm 0.7) \cdot 10^{-2}$

$\zeta_{00} = (1.0 \pm 2.1 \pm 0.4) \cdot 10^{-6}$

$\gamma = (1.3^{+2.8}_{-1.4} \pm 0.4) \cdot 10^{-21}\ GeV$

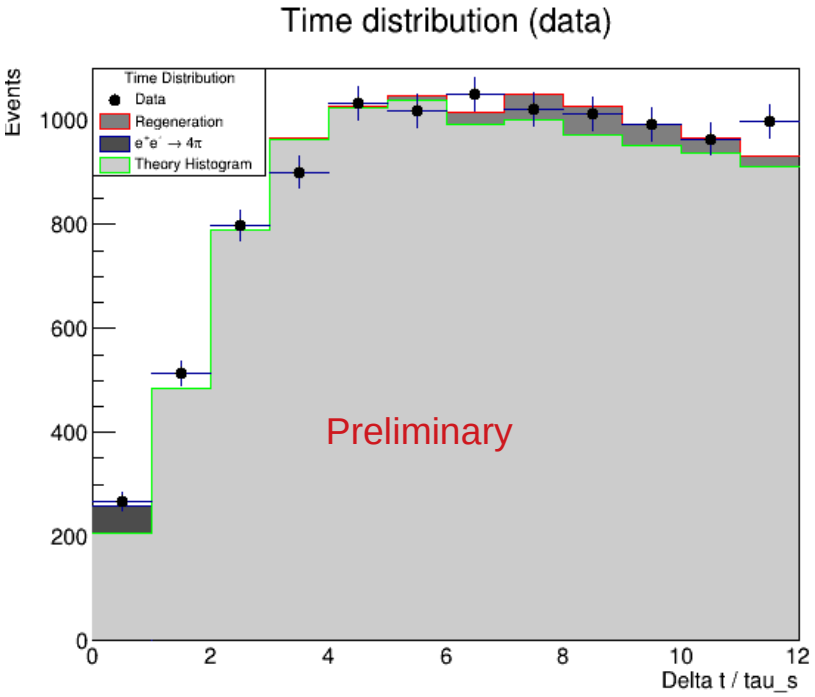
$\Re(\omega) = (1.1^{+8.7}_{-5.3} \pm 0.9) \cdot 10^{-4}$

$\Im(\omega) = (3.4^{+4.8}_{-5.0} \pm 0.6) \cdot 10^{-4}$

Search for decoherence and CPTV in $\phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$

- KLOE data: L=1.7 fb^{-1}
- Fit including Δt resolution and efficiency effects + regeneration
- Improvements wrt past analysis:

- $\cos(\theta_{\pi+\pi-})$ > -0.975 cut to improve Δt resolution
- improved $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ background evaluation from 2D fit to sidebands



KLOE preliminary
L= 1.7 fb^{-1}

$\zeta_{SL} = (xx \pm 1.7 \pm 0.8) \cdot 10^{-2}$

$\zeta_{00} = (xx \pm 8.8 \pm 4.3) \cdot 10^{-7}$

$\gamma = (xx \pm 1.0 \pm 0.5) \cdot 10^{-21}\ \text{GeV}$

$\text{Re}(\omega) = (xx \pm 2.0 \pm 0.8) \cdot 10^{-4}$

$\text{Im}(\omega) = (xx \pm 2.8 \pm 1.2) \cdot 10^{-4}$

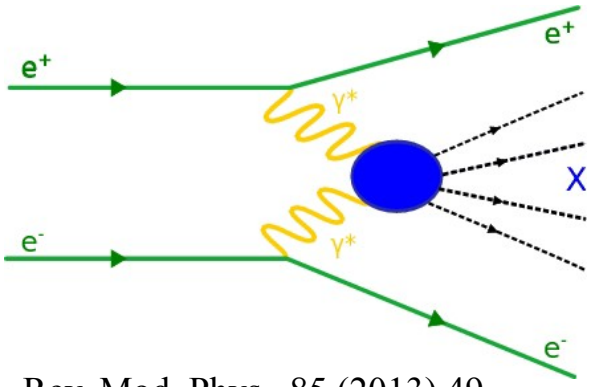
Statistical uncertainty reduced by half
Central values consistent with zero

$\gamma\gamma$ physics with High Energy Tagger (HET)

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

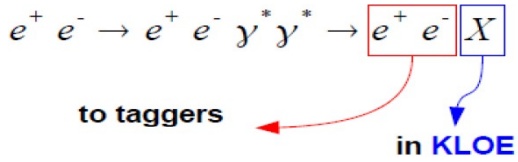
$$[C(X) = +1]$$

$$X = \pi^0, \pi\pi, \eta$$

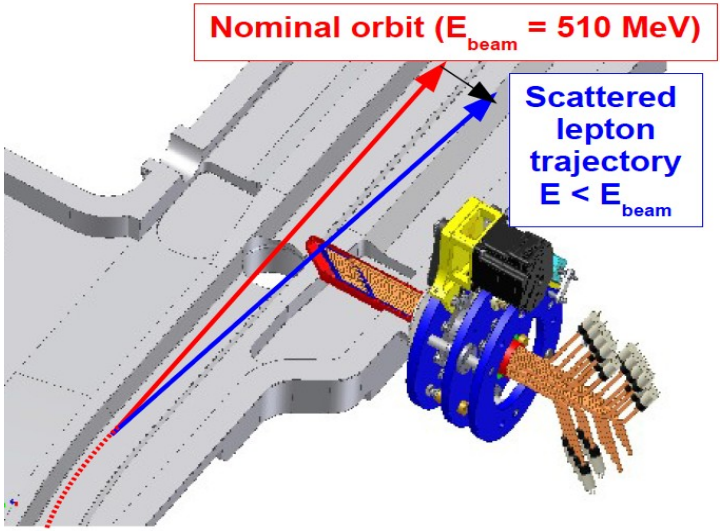


Rev. Mod. Phys., 85 (2013) 49

- Precision measurement of $\Gamma(\pi^0 \to \gamma\gamma)$
- Transition form factor $F_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2| < 0.1\,\mathrm{GeV}^2$), impact on value and precision of a_μ



Measurement concept:
Eur. Phys. J. C 72 (2012) 1917



First bending dipoles of DAΦNE act as spectrometers for scattered leptons (420 < E < 495 MeV)

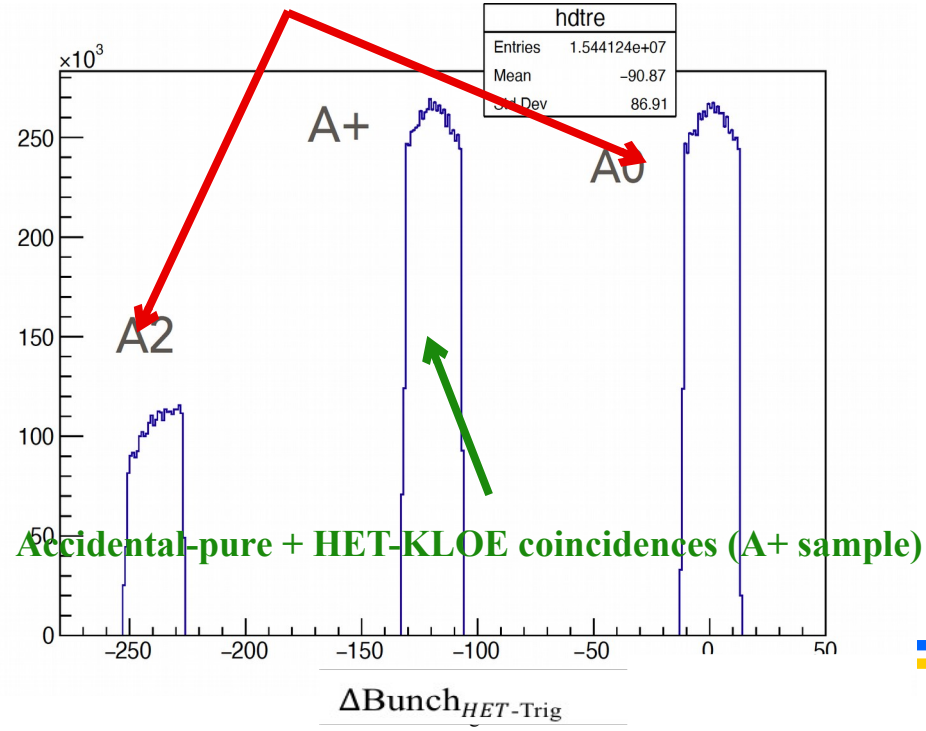
Scintillator hodoscope + PMTs, inserted in Roman pots pitch: 5 mm, ~ 11 m from IP (σ_E~2.5 MeV σ_t~500 ps)

HET is acquired asynchronously w.r.t. the KLOE-2 DAQ (Xilinx Virtex 5 - FPGA),synchronization with the "Fiducial» signal from DAΦNE (each 325 ns)and the KLOE trigger

HET acquisition window corresponds to about 2.5 DAΦNE revolutions, data are recorded only when a KLOE trigger is asserted

The analysis is based on the HET-KLOE coincidences and the accidental-pure samples used for background modelling (shape and number)

Accidental-pure data (A sample)



Accidental-pure + HET-KLOE coincidences (A+ sample)

Status of $\gamma\gamma$ Search

The reconstruction of 3 fb^{-1} of good-quality data has been completed (2015-16-17-18 data-taking periods)

Single-arm selection:

-Sample of 2 clusters associated with the same bunch crossing the KLOE barrel calorimeter

-Selected bunch crossing, and, independently selected HET signal, are in a time window of 40 ns around the KLOE trigger

Analysis Strategy:

-Simultaneous fits of A+/A samples in $M_{\gamma\gamma}$, $\Delta T_{\gamma\gamma}$- $\Delta R_{\gamma\gamma}/c$, $\cos\theta_{\gamma\gamma}$.

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

-Time coincidence window : 8 ns (3 bunch crossings)

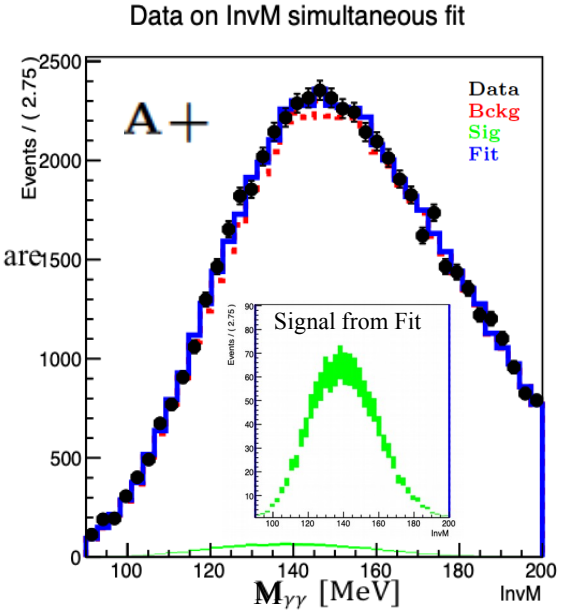
-Accidental pure sample (A) used to model background pdf

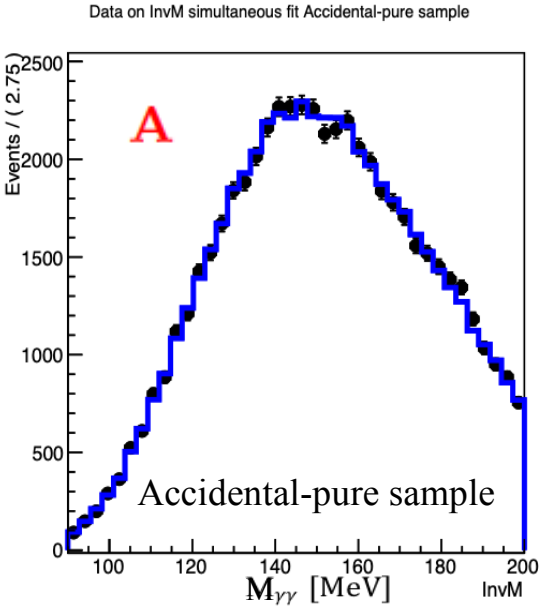
-Signal pdfs by Ekhara simulation, control samples and BDSIM transport of the leptons through the beam line

-$M_{\gamma\gamma}$, $\cos\theta_{\gamma\gamma}$ with a signal-enriching cut ($\Delta T_{\gamma\gamma}$-$\Delta R_{\gamma\gamma}/c < 0.3$ ns) separately fitted. Signal fraction (0.55) fixed from the analysis of control samples

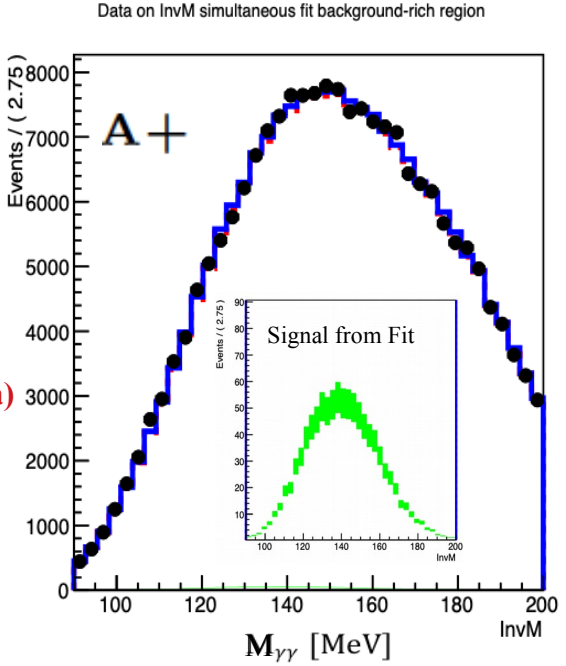
10% precision on signal reached with ~ 1.5 fb^{-1} (2017-18 data)

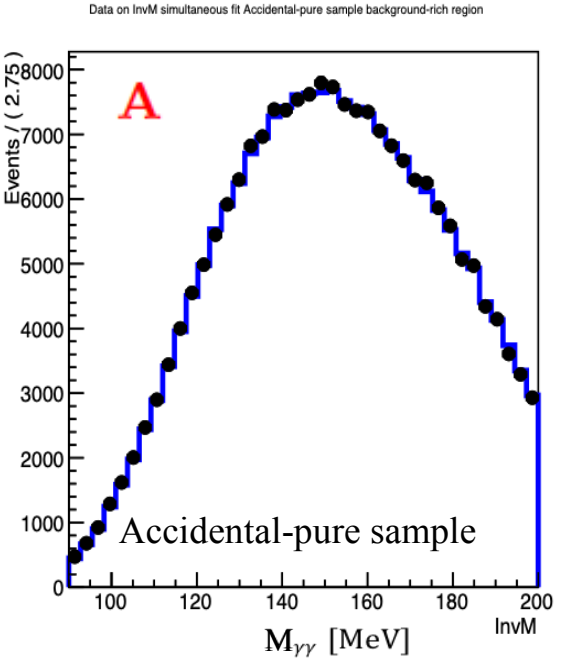
$\Delta T_{\gamma\gamma}$- $\Delta R_{\gamma\gamma}/c < 0.3$ ns





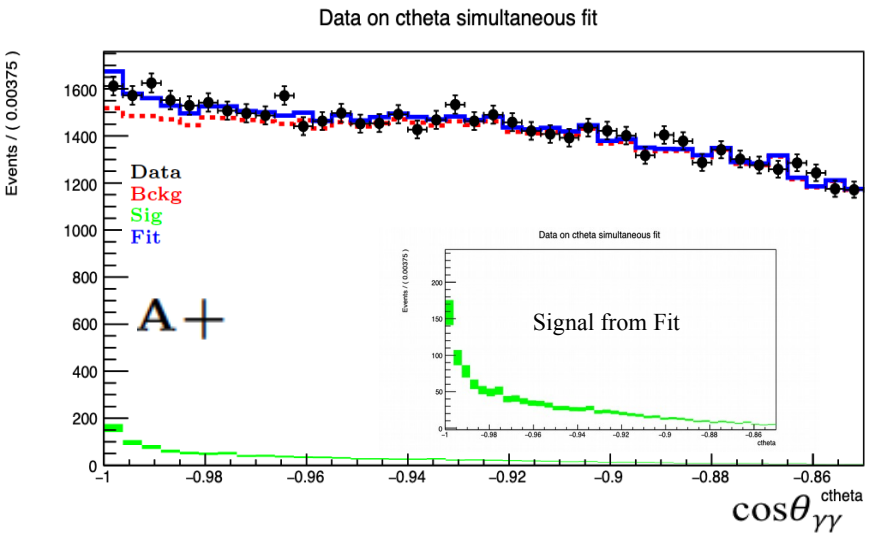
$\Delta T_{\gamma\gamma}$- $\Delta R_{\gamma\gamma}/c > 0.3$ ns

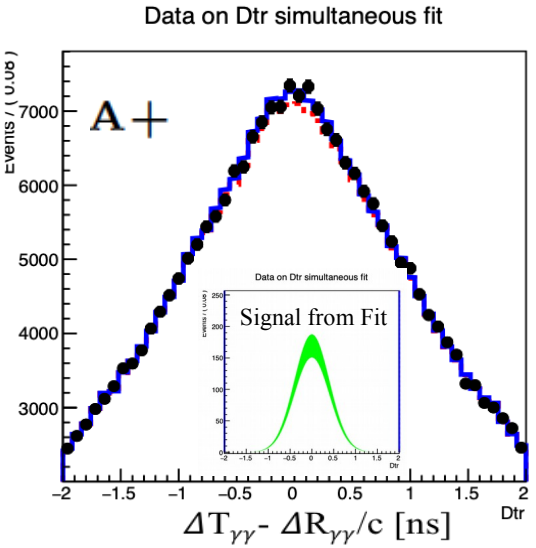


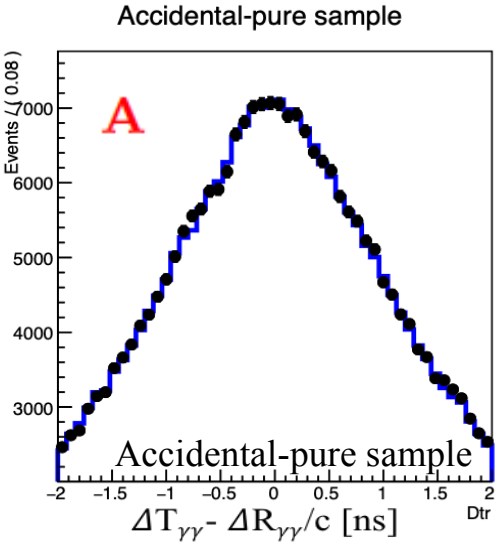


Status of $\gamma\gamma \to \pi^0$ Search

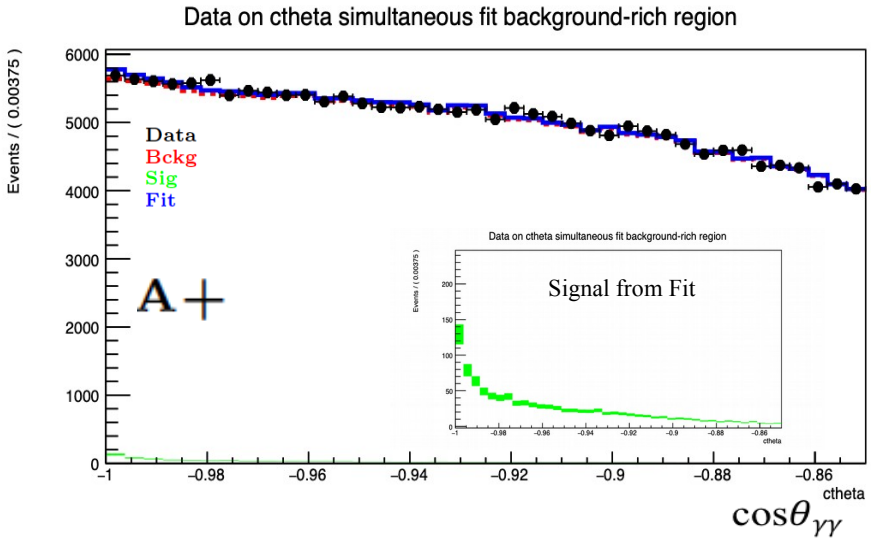
$\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c < 0.3$ ns







$\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c > 0.3$ ns



-Signal modelling: improvements are being studied on control samples:

-Length of the interaction region modifies cos distribution. Bhabha's vertex reconstruction in KLOE are being used to obtain position/length and verify stability

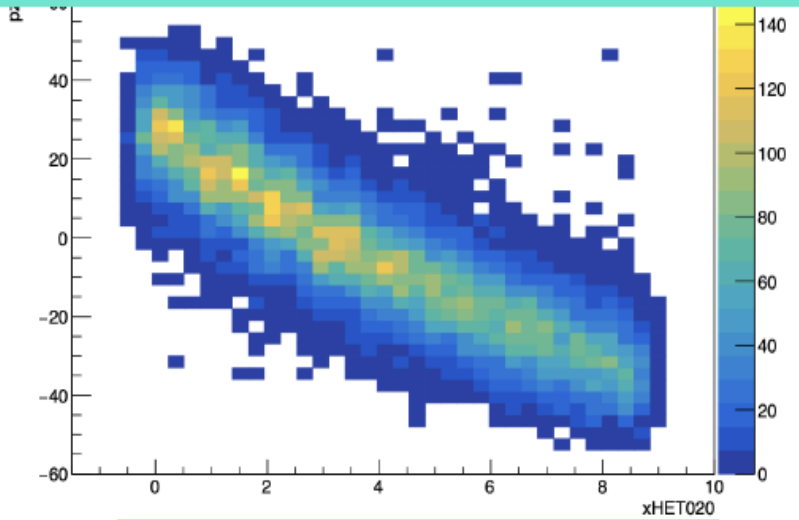
-Photon energy distribution depends on calorimeter trigger thresholds. Radiative Bhabha in KLOE used to measure thresholds per sector / per data-taking periods. Control of the results in progress

-Thorough control of the results on the constant term in the time resolution of the calorimeter to validate T- R/c distribution

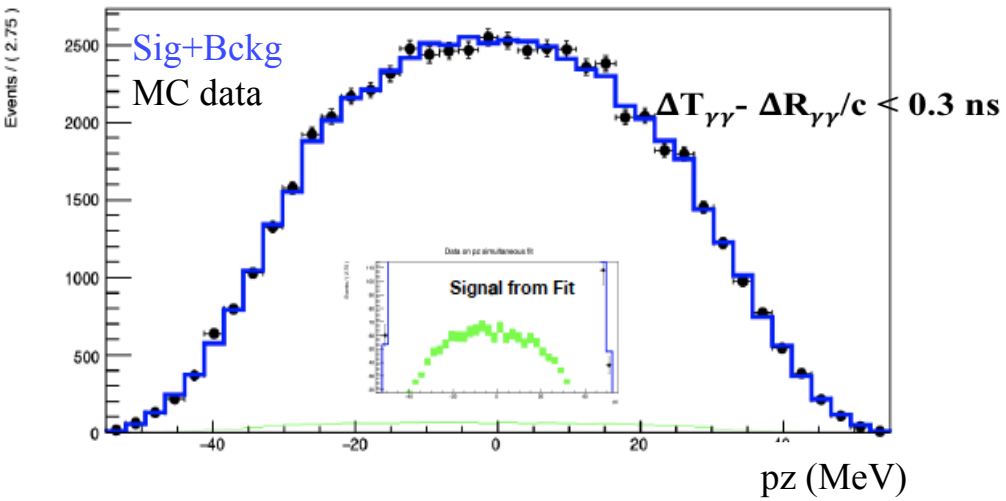
Toy MC - Fit results - pz, xHET correlation included

- The correlation between pion momentum and HET channel must be considered to improve the precision at few percent level with all data available
- Acceptance per channel measured with radiative Bhabha in the HET needed. Work in progress.
- Toy MC used to evaluate precision when correlation between pion momentum and HET channel is added - 6% reached

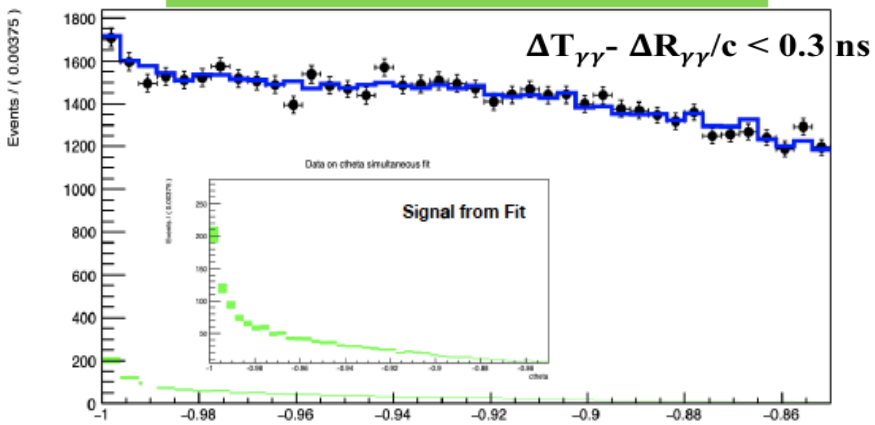
xHET(cm), pz(MeV) correlation: MC signal



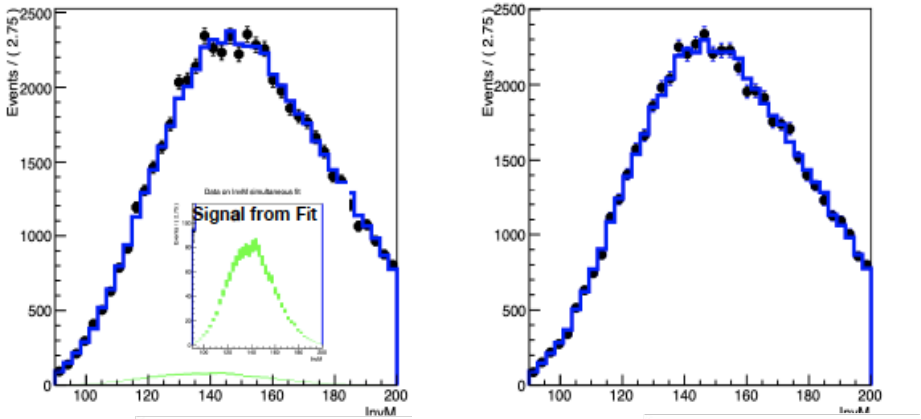
Fit Result : Toy MC - pz (MeV)



Fit results: Toy MC - cos(aph)

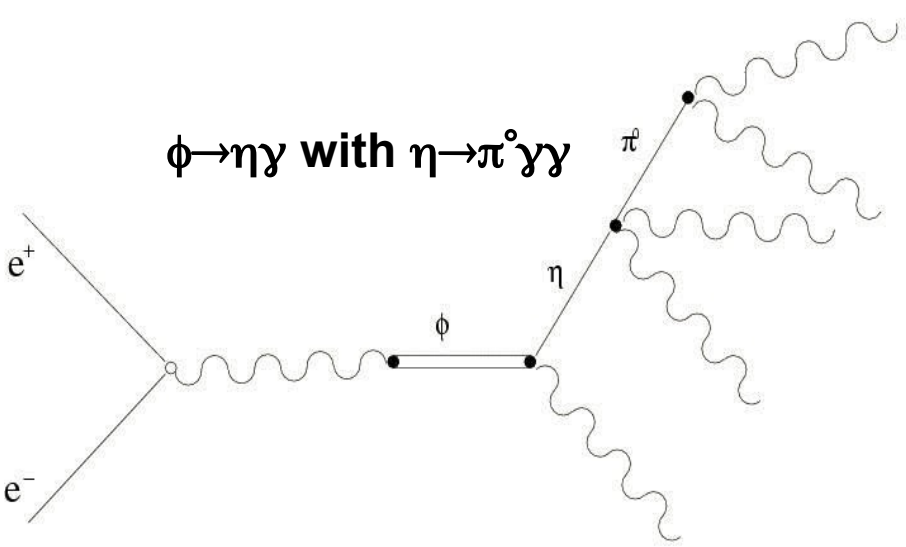


Fit results: Toy MC - InvM (MeV)



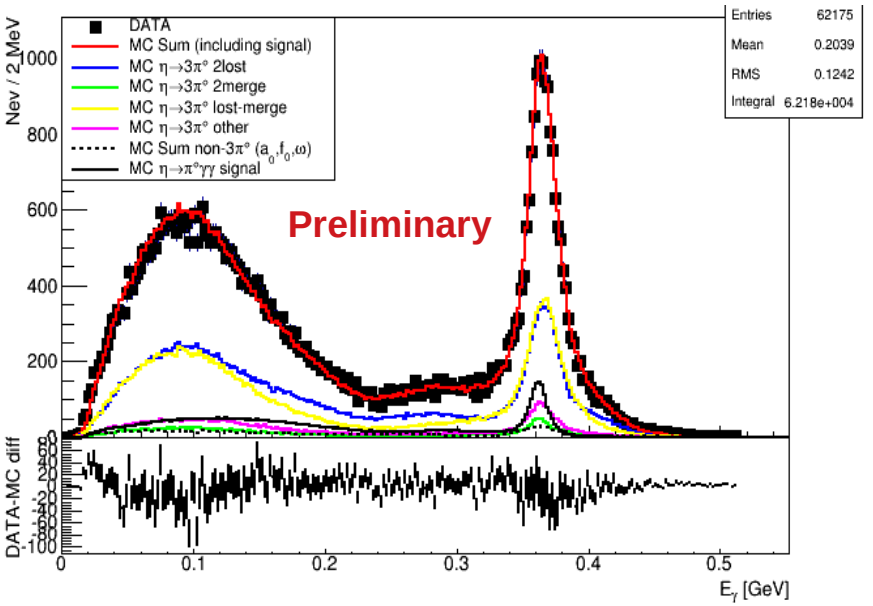
$\eta \to \pi^0\gamma\gamma$ decay

- $\eta \to \pi^0\gamma\gamma$ (from $\phi \to \eta\gamma$): χPT golden mode,
  $O(p^2)$ null, $O(p^4)$ suppressed $\Rightarrow$ sensitive to $O(p^6)$
  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 = 1.7 fb^{-1} of KLOE data
- Main background is $\phi \to \eta\gamma$, with $\eta \to 3\pi^0$ with lost or merged photons
- Kinematic fit constraining only TOF of photons plus E&p conservation to improve the resolution
- Multivariate Analysis with cluster shape variables to separate single photon from merged photon clusters
- Good data-MC description in various variables



- Cluster energy distribution fit to data with signal+background MC shapes

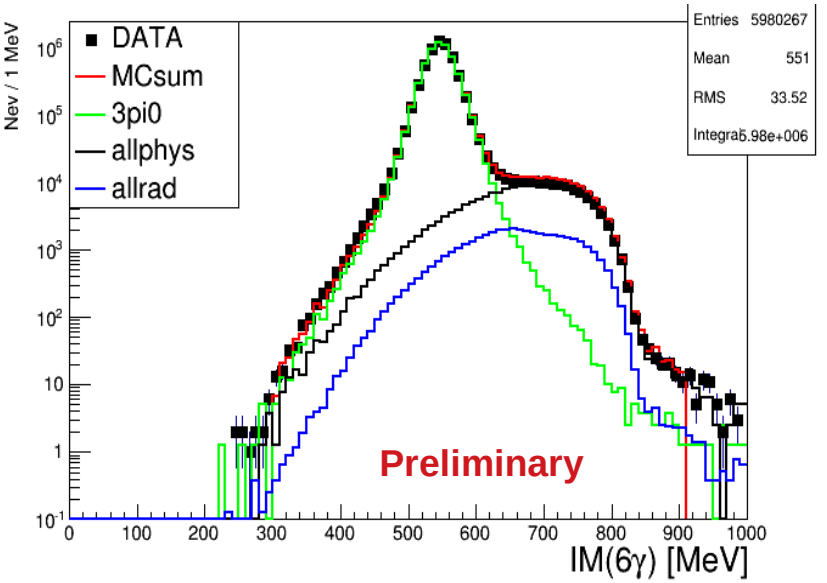
$\eta \to \pi^0\gamma\gamma$ decay

- Normalization to $\eta \to 3\pi^0$ sample in order to reduce systematic effects

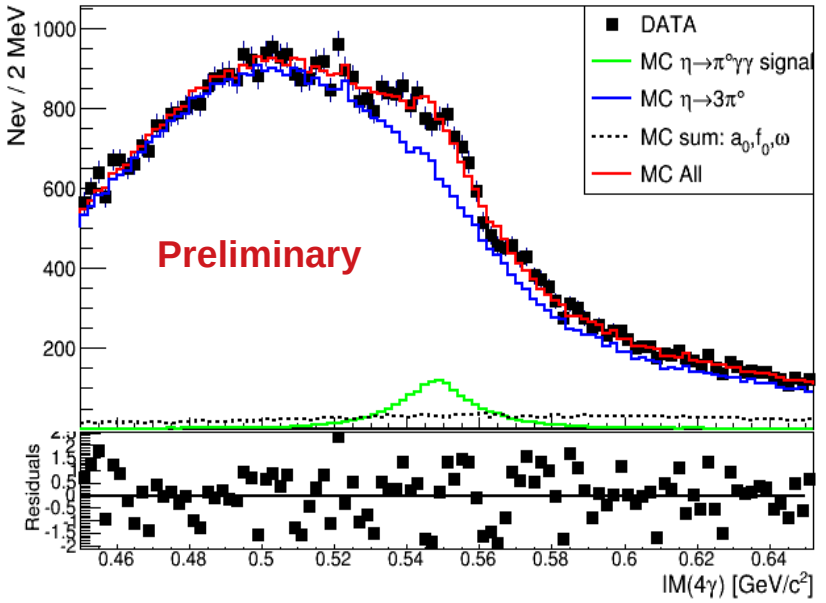
- Clear signal evidence on data distribution S/B~0.1 in the signal region, achieved with ε_s~20%
- Number of signal events ~1700
- Statistical uncertainty reduced by a factor three with respect to the preliminary KLOE result

- Consistency check of different fitting strategies and systematic uncertainty evaluation ongoing

Clear $\eta \to \pi^0\gamma\gamma$ signal evidence

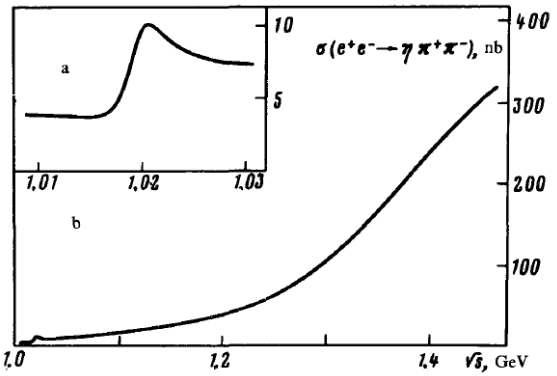


- Normalization to $\eta \to 3\pi^0$ sample



$e^+e^- \to (\gamma)\eta\pi^+\pi^-/\mu^+\mu^-$

- In VMD model, $e^+e^- \to \eta\pi^+\pi^-$ is proceed via ρ resonances, mainly via ρη intermediate state. KLOE/KLOE-2 data allow to measure the line shape around φ
- $\phi \to \eta\pi^+\pi^-$ violates the OZI rule and G-parity, VMD predicts the Br~ 0.35×10^{-6}. Br<1.8×10^{-5} @ 90% CL @ CMD-2 PLB491(2000)81
- The same sample can be also used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$, Br<0.94×10^{-5} @ 90% CL @ CMD-2 PLB501(2001)191

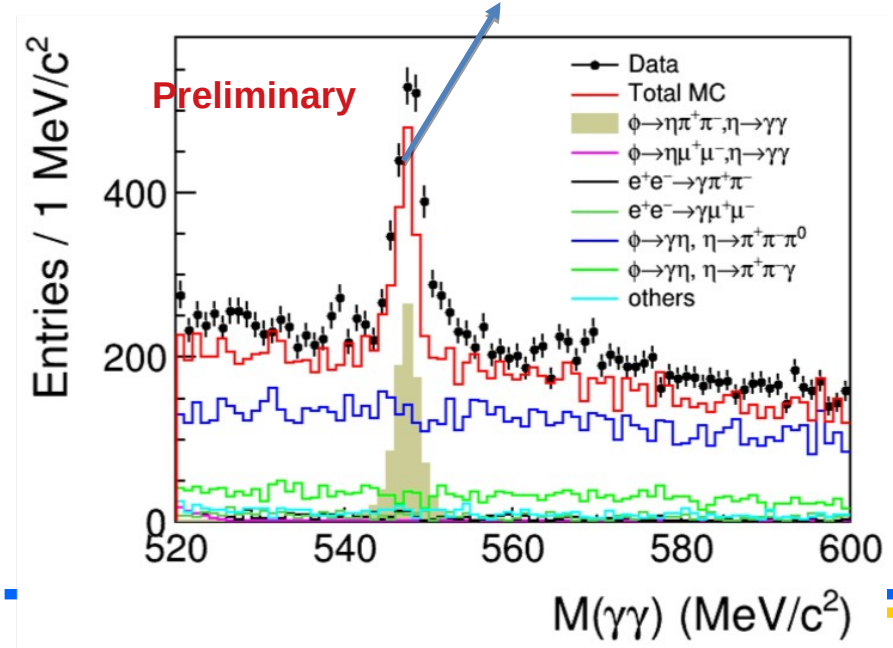


With ~700 pb^{-1} KLOE data, analysis procedure for $\phi\to\eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ is established:

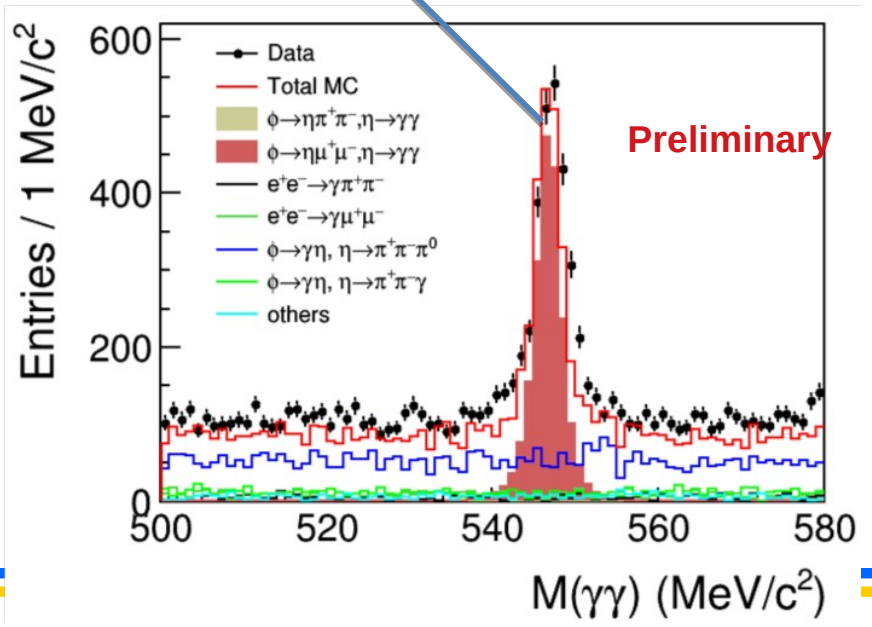
- *$\eta\to\gamma\gamma/\pi^0\pi^0\pi^0$*
- *2 charged tracks*
- *2 or 6 prompt photons*

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

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



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



Conclusions

- Final round of Data Reconstruction started on March, about 2.4 fb^{-1} produced
- Root output implemented and test production used in data quality, integration on DB2 ongoing
- Full MC data sample produced and reconstructed with version DBV-38; data-MC optimization studies been performed and to be included for the DBV-40 version; Production to be started soon
- New publication $\eta \rightarrow \pi^+\pi^-$ (P and CP violation) JHEP 10 (2020) 047
- Several analyses ongoing both with KLOE and KLOE-2 samples in good advance states

Recommendations KLOE:
In all cases of ongoing data analyses, there is good progress and the SC recommends to keep going and to advance these important results further.