KLOE-2: status of computing and analysis

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on behalf of the KLOE-2 collaboration

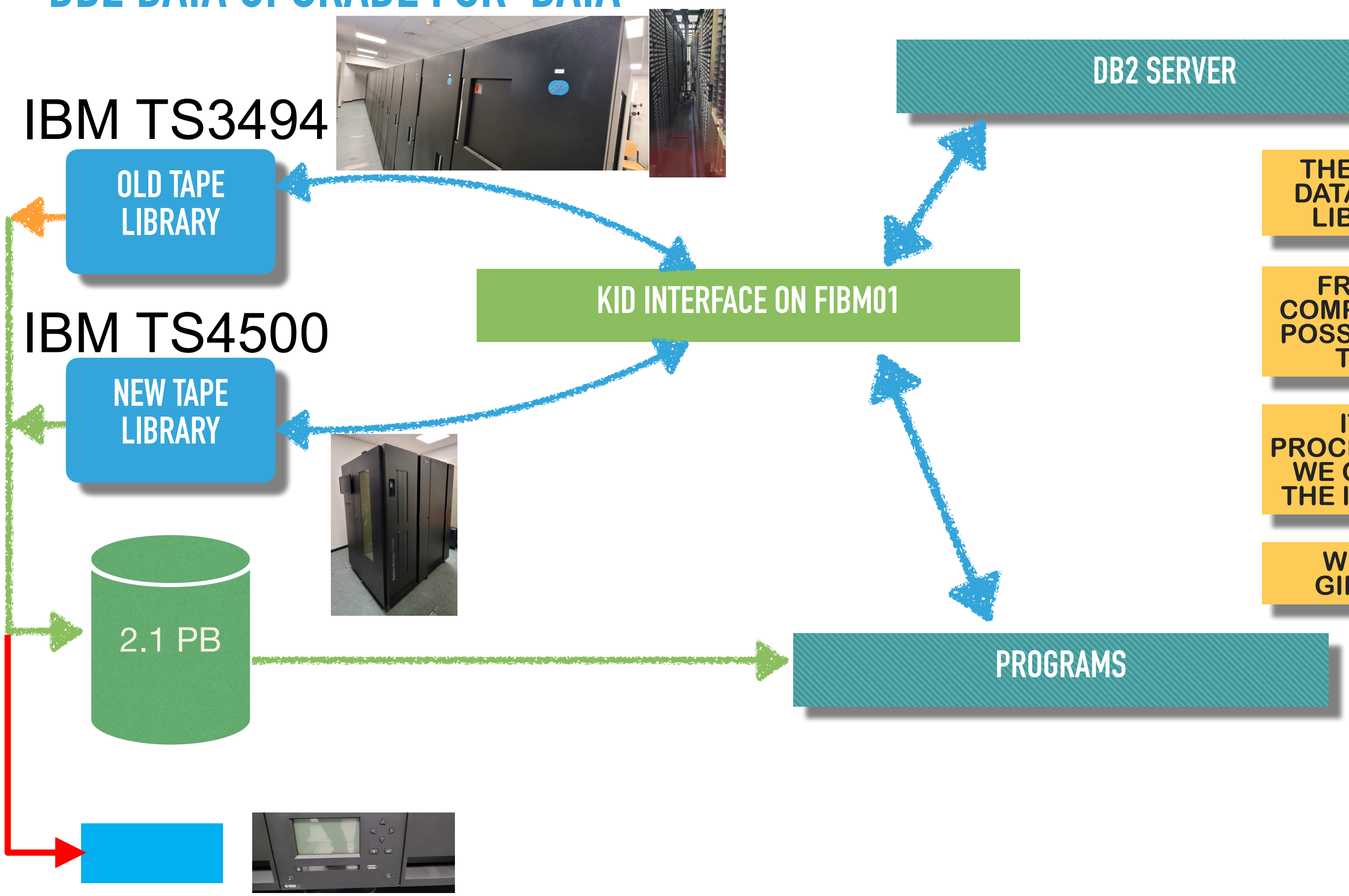
LNF Scientific Committee meeting
Frascati, 14 May 2025

KLOE computing

KLOE GENERAL MEETING

KLOE Computing center:
general architecture after the last update in 2023

DB2 DATA UPGRADE FOR DATA



IBM TS4300
small DLT tape library for disaster recovery backup

THE CERTIFICATION OF DATASET INTO THE NEW LIBRARY IS ONGOING

FRANCESCO HAS TO COMPLETE IT AS SOON AS POSSIBLE TO SWITCH OFF THE OLD LIBRARY

IT IS A SENSITIVE PROCEDURE DUE THE FACT WE CANNOT ROLL BACK THE INFORMATION EASILY

WE HAVE TO TREAD GINGERLY WITH THIS

F. Fortugno K2GM 16-1-2023

Status of offline activities

KLOE-2 Data Reconstruction
- Second round of Data reconstruction DBV-40 => **completed**
- Total integrated luminosity L = 5.1 fb^{-1}

KLOE-2 MC production
- Simulation of the main ϕ(1020) decays with Luminosity Scale Factor =1 => **completed**
- Total integrated luminosity L = 4.7 fb^{-1}

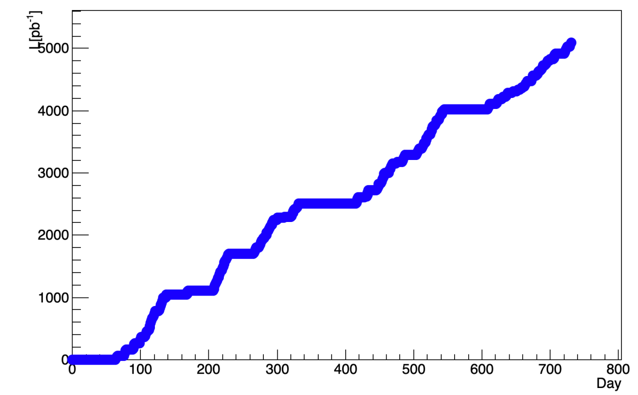
KLOE-2 ROOT output production
- Compression factor (ratio Datarec/ROOT) ~ 8 depending on run conditions
- KLOE-2 Data and MC => **completed**

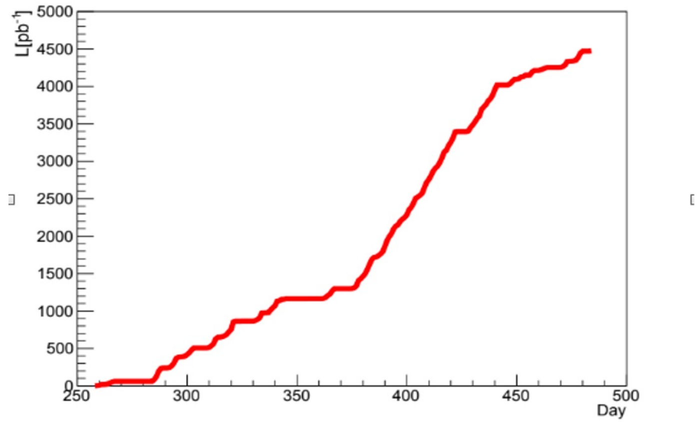
KLOE-2 data backup copy
- ROOT output Data and MC (270 TB) => **completed**
- raw data (2016-2018) on DLT unit (~1.6 PB) => **~70%**
- raw data (2014-2015) on newTL TS4500 (~1 PB) => **~89%**

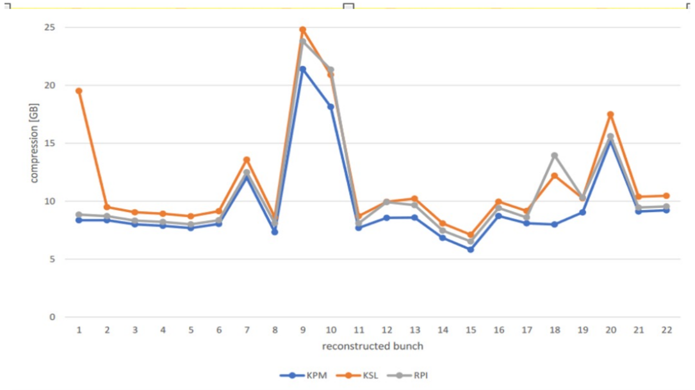
KLOE ROOT output production
- KLOE Data and MC (L = 2.5 fb^{-1}) => **~30%**

KLOE data backup copy
- raw data (120 TB) => **completed at CNAF**

  ~89% on newTL TS4500 (second backup)
- dst reconstructed data+MC (650 TB) => **~32% on newTL TS4500**
- ROOT output Data and MC (O(100 TB))=> **~30%**







Status of computing (I) - 2024

- ...to make a long story short:
- **In 2023 and 2024 some failures in the computing center had a strong impact on our activities.**
  - Subsequent temperature alarms caused failure of controlled shutdown => breaking of some disks of the working area used by several analysis groups, some user data lost!
  - Repeated malfunctions of the OLD tape library TS3493 (faulty interlocks, problems with robotic arms, oil leakage) prevented the completion of data migration from OLD to NEW tape library (TS4500), data backup operations, **and the continuation of analyses on KLOE data**

- **Since May 2024 due to the impairing illness of G. Fortugno:**
  - the KLOE computing center is running mostly unattended (a dedicated post-doc position from LNF director, not filled yet) => setup of an emergency plan.
  - Setup of an external disk buffer (650 TB) at LNF computing center for fast back-up purposes – non trivial communication protocol
  - Back-up of all files of KLOE computing disk buffers to the external LNF disk buffer

- Many thanks to: F. Sborzacchi, LNF computing service, S. Angius, R. Orrù, D. Spigone, M. Tota. We are grateful to M. Pistoni, LNF directors F. Bossi and P. Gianotti, head of research division A. Antonelli and M. Palutan, the CNAF director and staff L. dell'Agnello, D. Cesini, and C. Pellegrino, to the LNF technical division.

  Lorenzo Cotrozzi (Liverpool) in charge as KLOE-2 computing trainee and contact person among IBM, LNF computing experts, and F. Sborzacchi. Continuative mission at LNF from December 2024 to February 2025.

Status of computing (II) - 2025

several interventions required

System	Status at the end of 2024	What was done	Status today
Old tape library TS3494	Broken	IBM repaired mechanical parts; configured to work with only one robot arm for both logical partitions (A and B)	We can retrieve files on partition A through TSM, Blocked again and repaired on 22/4/2025
DB2 Database	Not accessible	Replaced KDB0A network card	Dumped in /kbackup/DB2 Running
FIBM0A	mirror boot disk broken	Intervention of a specialized company – disk replaced	Repaired on 29/4/2025 Running
FIBM0B	Not powering on	power supplies and voltage regulators replaced; intervention of a specialized company	Boot from disk and CD problems; intervention in progress
FIBM01	Not powering on	Intervention of a specialized company – PS and fans replaced	Repaired on 29/4/2025 Running
New tape library TS4500	Maintenance required	Replaced exhausted cleaning cartridges; replaced dead drive	General status: working Faulty power supply, repaired on 06/5/2025
DLT TL TS4300	Not powering on	power supplies replaced	repaired on 06/5/2025

Computing: short and medium/long term plans

SHORT

Strategy: allow people to continue doing analysis in the immediate future
=> crucial for the KLOE-2 collaboration

- restore OLD TL TS3494 minimum functionality => **done** (partition A)
- retrieve file from OLD TL (dst reconstructed data+MC) => **in progress** (114 downloaded out of 1112 cartridges - download rate 6-8 GB/min => ~2 months for all DSTs)
- complete KLOE ROOT output production => **in progress**
- expand KLOE-LNF buffer disk => **disk array order in progress**
- start transfer root files from LNF buffer to CNAF for analysis at CNAF => **in progress** (transfer rate 50-180 MB/s => 1-2 months for all ROOT files)
- run a refined KLOE data reconstruction from raw data for $\pi\pi\gamma$ analysis (see Zaid's presentation)

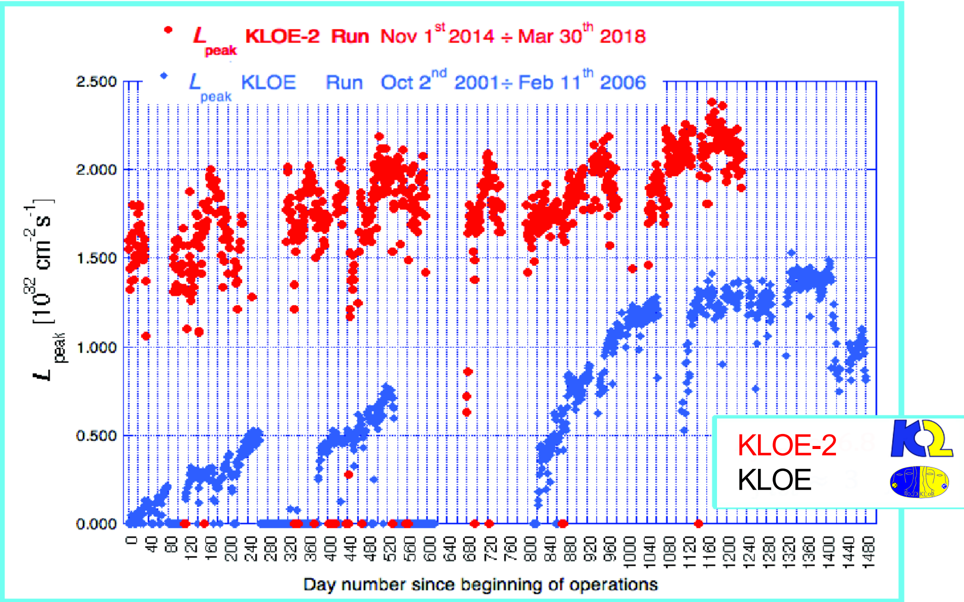
MEDIUM/LONG

Strategy: full migration to CNAF and continue there the analysis activity
(agreed and supported by CSN1)

- continue transferring KLOE and KLOE-2 root files to CNAF for analysis
- complete transfer of all files (including raw) to CNAF
- migration of KLOE soft on linux => **under study/test**
- complete back-up copies
- move NEW TL TS4500 and all cartridges at CNAF or in another facility => **feas. under study**

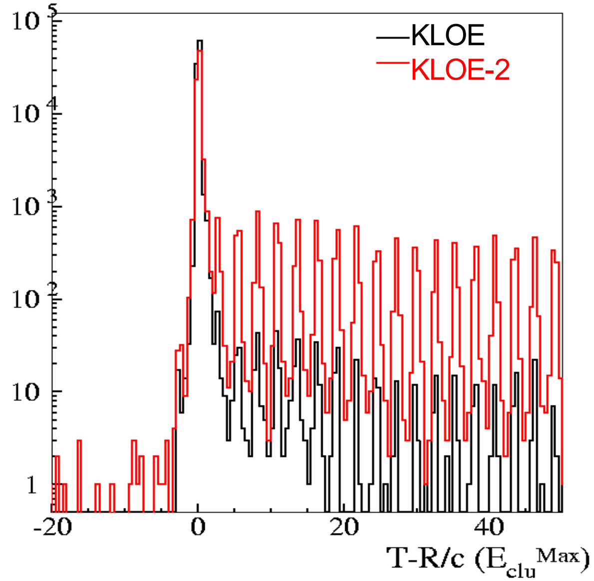
KLOE and KLOE-2 at DAΦNE

KLOE-2: L_{int} ~ 5.5 fb^{-1}
KLOE: L_{int} ~ 2.5 fb^{-1}



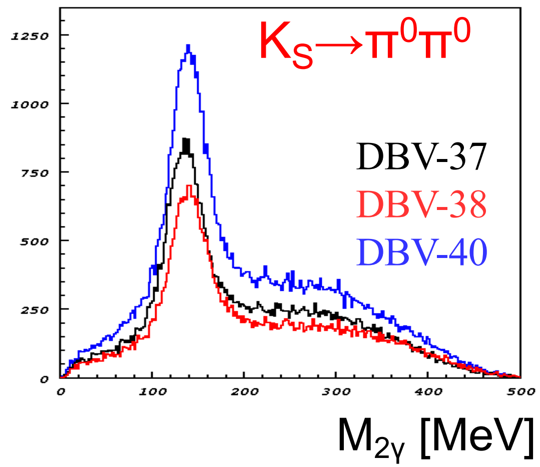
KLOE + KLOE-2 data sample:
- ~ 8 fb^{-1} ⇒ 2.4 × 10^{10} ϕ's produced
- ~ 8 x10^9 K_SK_L pairs
- ~ 3 x10^8 η's
- ⇒ the largest sample ever collected at the ϕ(1020) peak in e^+e^- collisions

background conditions



improved event T0 algorithm, improved rejection of machine bck and Bhabha scat. events

event size:
KLOE ~2 kB
KLOE-2 ~5 kB
+ 3 kB (new detectors)



Publications/Ongoing Analysis

Last Publications	
Direct tests of T, CP, CPT symmetries in transitions of neutral K mesons with the KLOE experimen	Physics Letters B 845 (2023) 138164
Measurement of the $K_S \rightarrow \pi e \nu$ branching fraction with the KLOE experiment	JHEP 02 (2023) 098
Ongoing analyses	
$K_S \rightarrow 3\pi^0$ (CP viol.)	**KLOE-2 data**
"Back from the future" effect in $K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$	**KLOE data**
Direct CP violation ε'/ε	**KLOE+KLOE-2 data – 1 PhD + 1 Master thesis**
$\eta \rightarrow \pi^0\gamma\gamma$ - χPT golden mode	**KLOE data**
$e^+e^- \rightarrow \omega\,\gamma_{ISR}$	**KLOE data – PhD Thesis**
$e^+e^- \rightarrow \pi^+\pi^-\,\gamma_{ISR}$	**KLOE data**
$\gamma\gamma \rightarrow \pi^0$	**KLOE-2 data**
B-boson search in $\phi \rightarrow \eta\pi^0\gamma$, $\eta \rightarrow \gamma\gamma$	**KLOE data**
$e^+e^- \rightarrow \eta\mu^+\mu^-$	**KLOE data**

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

$3\pi^0$ 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.

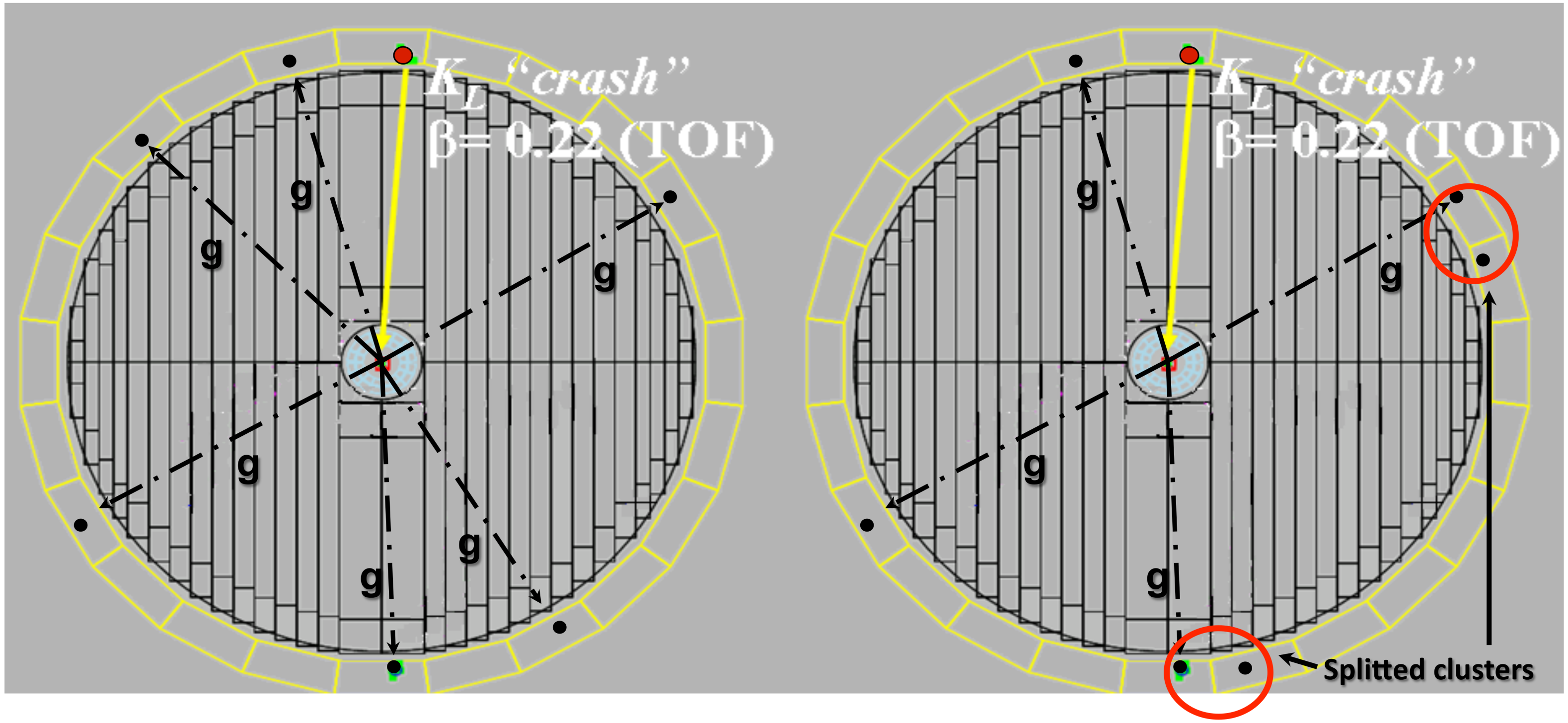
Standard Model prediction: $BR(K_S \rightarrow 3\pi^0) = 1.9 \cdot 10^{-9}$

PLB 723 (2013) 54

Best upper limit by KLOE with 1.7 fb^{-1}

$BR(K_S \rightarrow 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% CL

SIGNAL **BACKGROUND**



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

$K_S \rightarrow 2\pi^0$ + accidental/splitted clusters

$K_L \rightarrow 3\pi^0$, $K_S \rightarrow \pi^+\pi^-$ („fake K_L crash")

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

- <u>Analyzed data:</u>
  full KLOE-2 data set

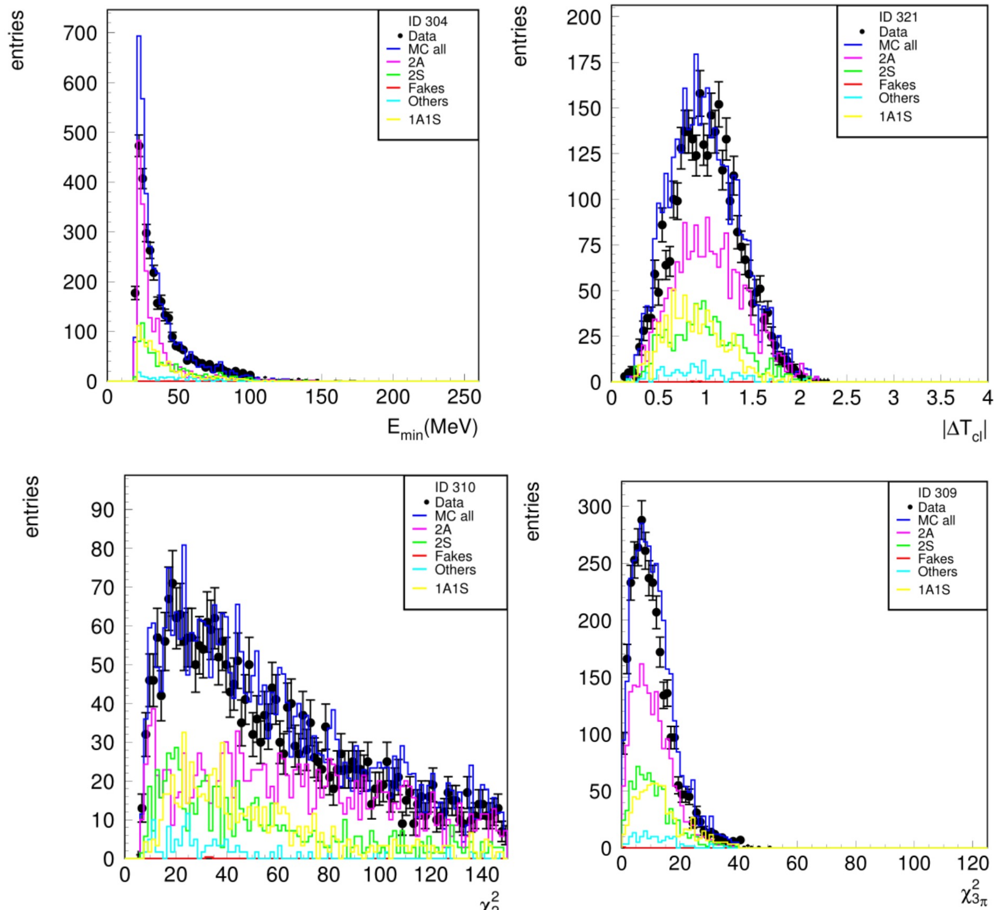
- <u>MC simulations:</u>
  All_phys - full KLOE-2 data set, LSF=1

- Preselection with the following requirements:
  - K_L-crash: E>150 MeV, 0.20< β < 0.225
  - prompt photons: E_{cl} > 20 MeV; $|\cos\theta_{cl}| \leq 0.915$ and $|\Delta T_{cl}| \leq \mathrm{Min}(3.0 \cdot \sigma_T(E_{cl}), 2\ \mathrm{ns})$
- $K_S \to 2\pi^0$ (4 prompt photons) used for normalization
- Main background source: $K_S \to 2\pi^0$ with two additional clusters (shower splitting/accidentals)
- Selection criteria hardened to face the larger machine background

6γ sample selection

- Track Veto
- Kinematic fit
- $\Delta E/\sigma_E = (E_{K_S} - \Sigma E_\gamma)/\sigma_E$ cut
- Signal region definition $\chi^2_{2\pi}$ vs $\chi^2_{3\pi}$
- R_{min} & E_{min}:
- Photon coincidence time: Δt

plots before R_{min}&E_{min} cut



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

- Optimization of the selection cuts => minimization procedure

signal:

- $\chi^2_{fit} < 85$
- $1.9 \leq \Delta E/\sigma_E \leq 3.9$
- $13.86 \leq \chi^2_{2\pi} \leq 100$
- $\chi^2_{3\pi} \leq 3.70$
- $R_{min} > 55.5$ cm
- $E_{min} > 45.0$ MeV
- $P_t < 100$ MeV/c
- $R_t > 170$ cm
- $\Delta t < 0.80$

tag:

- $E_{cr} > 150$ MeV
- $0.20 \leq \beta_{cr} \leq 0.225$

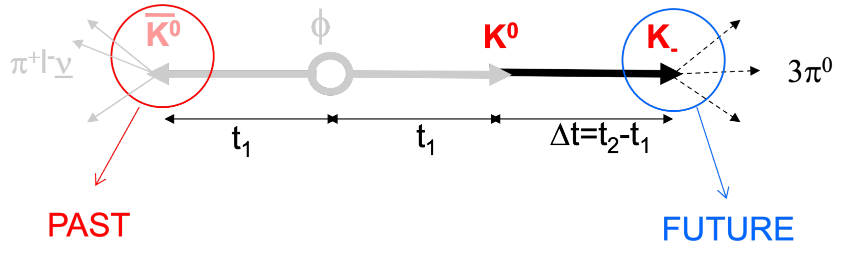
- The analysis chain efficiencies:

Acceptance $\varepsilon = 38.8$ [%] → Track Veto $\varepsilon = 99.5$ [%] → χ^2_{fit} $\varepsilon = 86.3$ [%] → Sbox $\varepsilon = 68.8$ [%] → $\Delta E/\sigma_E$ $\varepsilon = 61.6$ [%] → R_{min} & E_{min} $\varepsilon = 71.8$ [%] → Δt $\varepsilon = 80.7$ [%] → Rt vs Pt $\varepsilon = 80.2$ [%] → **Counting $\varepsilon = 6.6$ [%]**

- At the end of the analysis we count **0 candidates** in the background simulations.
- Taking into account the signal efficiency reduction and increase of statistics we are at the level of the last result obtained with 1.7 fb^{-1} of the KLOE data.
- Final optimization in progress before unblinding the result.

“Back from the future” effect

Exploiting the Lee-Yang formalism:



From past to future:

The state of the last decaying particle (particle-2) - due to the decay of its entangled partner **in the past** - is prepared at $t = t_1$ as:

$$|K^{(2)}(t=t_1)\rangle = N_2[|K_L\rangle - \eta_1 |K_S\rangle]$$

a state which depends on η_1 of particle-1.

Details in:

PHYSICAL REVIEW D **105,** 116004 (2022)

Can future observation of the living partner post-tag the past decayed state in entangled neutral K mesons?

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From future to past:

The state of the first decaying particle (particle-1) - due to the decay of its entangled partner **in the future** - is prepared at $t = 0$ as:

$$|K^{(1)}(t=0)\rangle = N_1\{\eta_2 e^{-i\lambda_L t_2} |K_S\rangle - e^{-i\lambda_S t_2} |K_L\rangle\}$$

a state which depends on η_2 **and t_2** i.e. **the future** of particle-2.

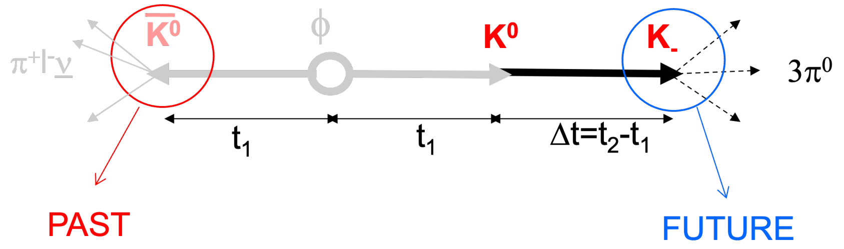
From this the K_S tagging condition is derived:

$$\frac{e^{-\frac{\Delta\Gamma\Delta t}{2}}}{|\eta_2|} \ll 1 \qquad [K_S\text{-tag}]$$

This effect naturally leads to the definition of new observables, that e.g. could be exploited in discrete symmetries tests.

"Back from the future" effect

Exploiting the Lee-Yang formalism:



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PHYSICAL REVIEW D **105,** 116004 (2022)

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From future to past:

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This effect naturally leads to the ... observables, that e.g. could be e... symmetries tests.

...the K_S tagging condition is

$$\ldots \ll 1 \qquad [K_S\text{-tag}]$$

Back *from* the future

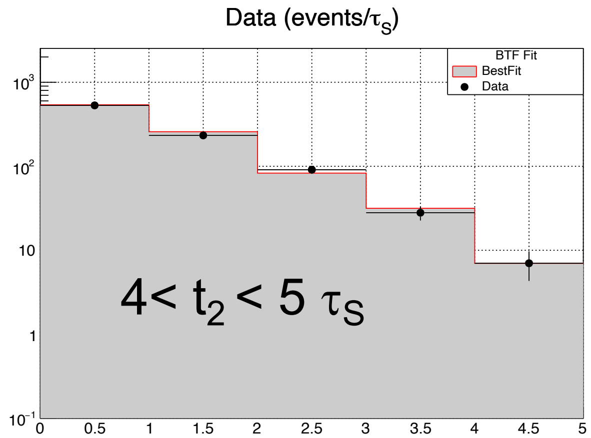
“Back from the future” effect

post-tagged state parametrization in terms of $\rho(t_2)$: dependence on t_2
=> evidence of the effect

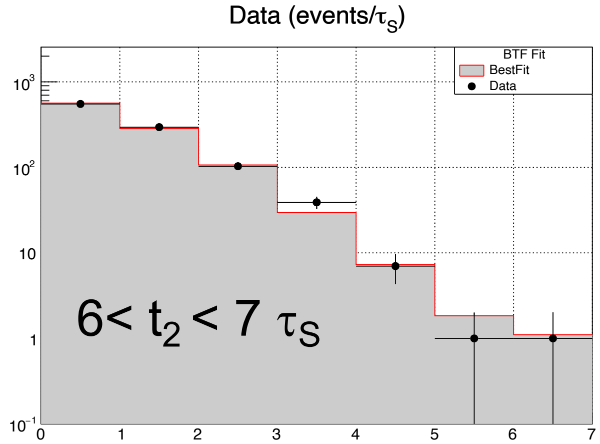
$$|K^{(1)}(t_1 = 0)\rangle = \mathcal{N}\{|K_S\rangle - \rho(t_2)/\eta_2|K_L\rangle\}$$

$f_1 = f_2 = \pi^+\pi^-$

examples of t_1 distributions with t_2 fixed



t_1 (τ_S)



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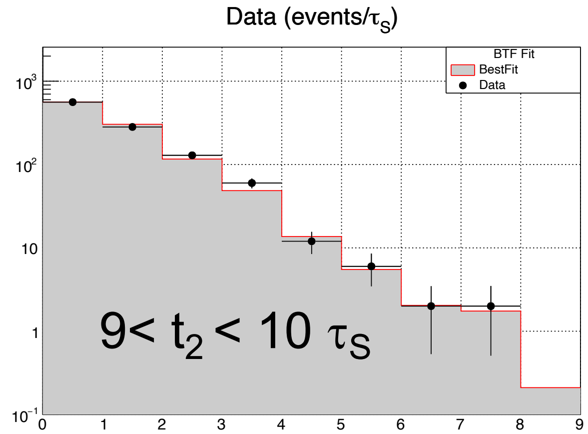

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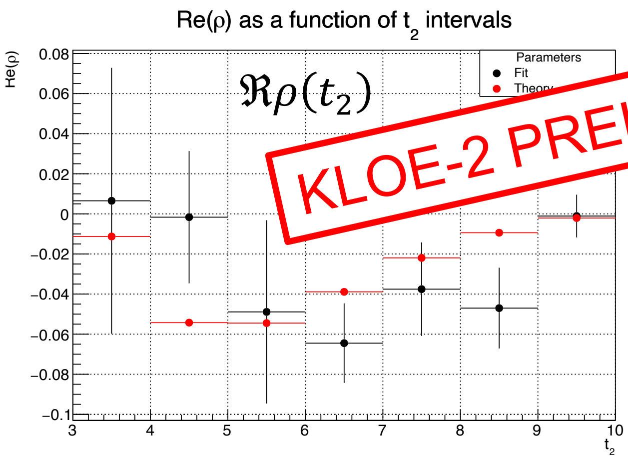
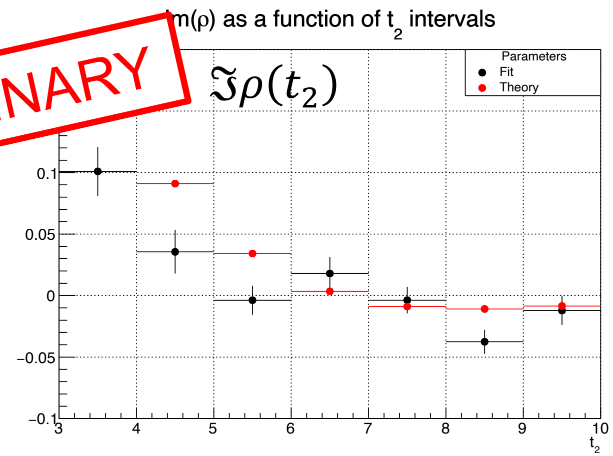


t_2 (τ_S)

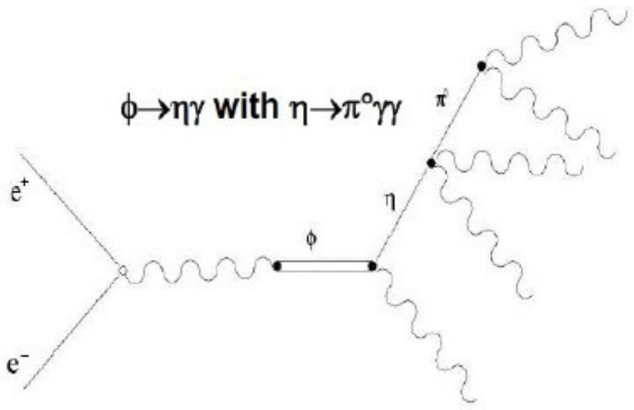


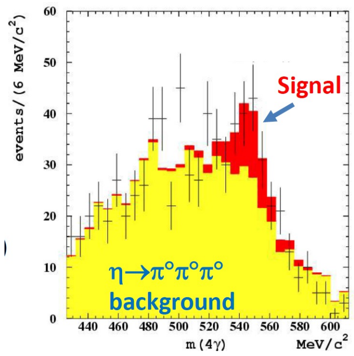
t_2 (τ_S)

KLOE-2 PRELIMINARY

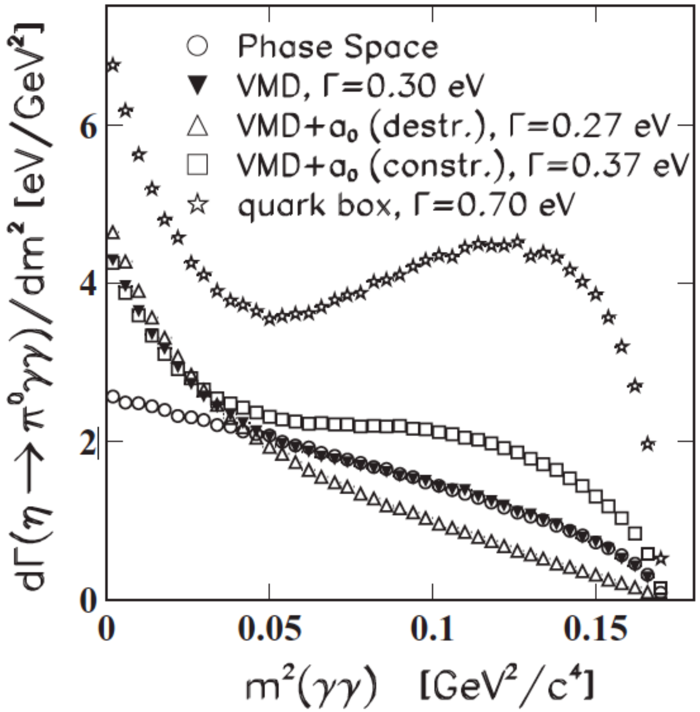
$\eta \to \pi^0\gamma\gamma$ decay

- $\eta \to \pi^0\gamma\gamma$ (from $\phi \to \eta\gamma$): χPT golden mode,
  $O(p^2)$ null, $O(p^4)$ suppressed
  $\Rightarrow$ sensitive to $O(p^6)$
  Br = $(2.21 \pm 0.24 \pm 0.47) \times 10^{-4}$ CB@AGS(2008)
  [PRC 78 (2008) 015206]
  Br = $(2.52 \pm 0.25) \times 10^{-4}$ CB@MAMI (2014)
  [PRC 90 (2014) 025206]
  Old KLOE preliminary: $(8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$
  (L = 450 pb^{-1} ~ 70 signal events)
  [Acta Phys.Slov.56(2006)403]

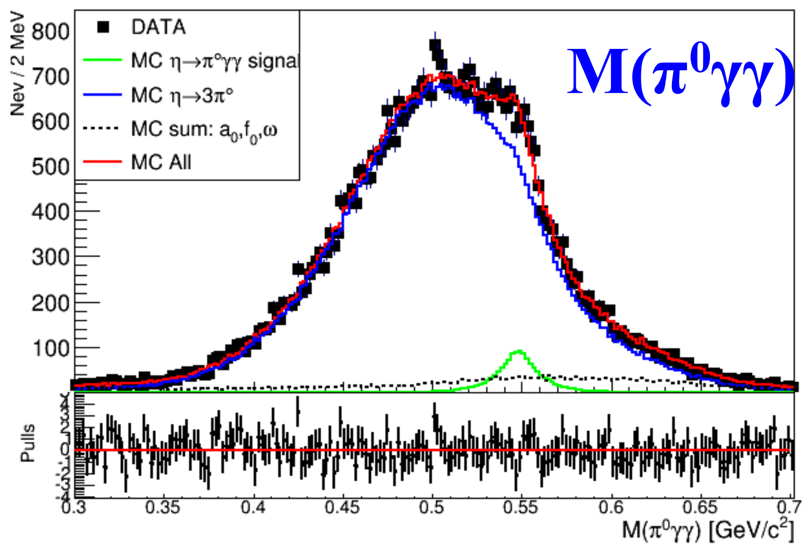




- Invariant mass of non-π^0 photons can be used to test theoretical models
- Recent theoretical prediction based on LσM + VMD
  Br($\eta \to \pi^0\gamma\gamma$) = $(1.30 \pm 0.08) \times 10^{-4}$
  [R.Escribano et al., PRD 102 (2020) 034026]

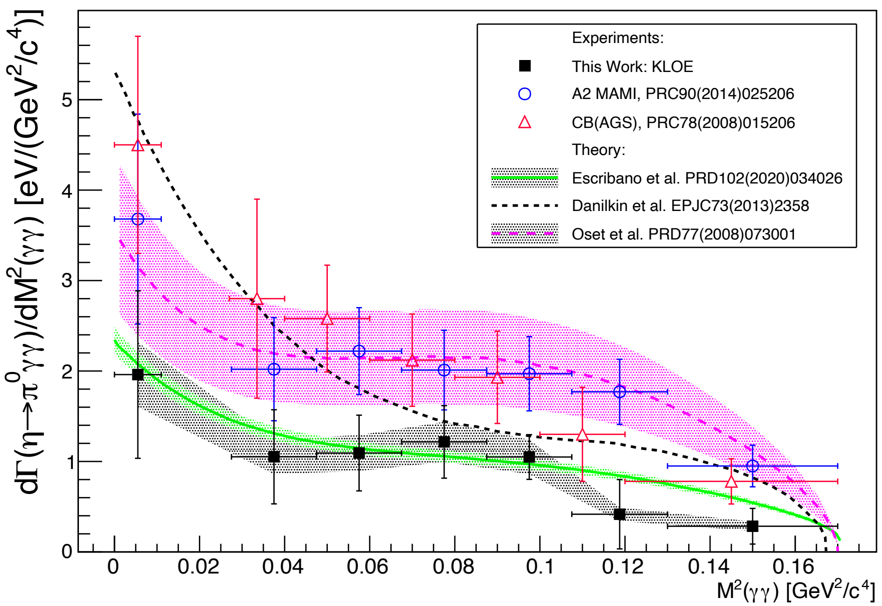


$\eta \rightarrow \pi^0\gamma\gamma$ decay



- Integrated luminosity of 1.7 fb^{-1} (~$7\cdot10^{7}$ η's)
- 5 prompt photons selection, no charged tracks
  ~ 1200 signal events
- Data distribution fit with MC components:

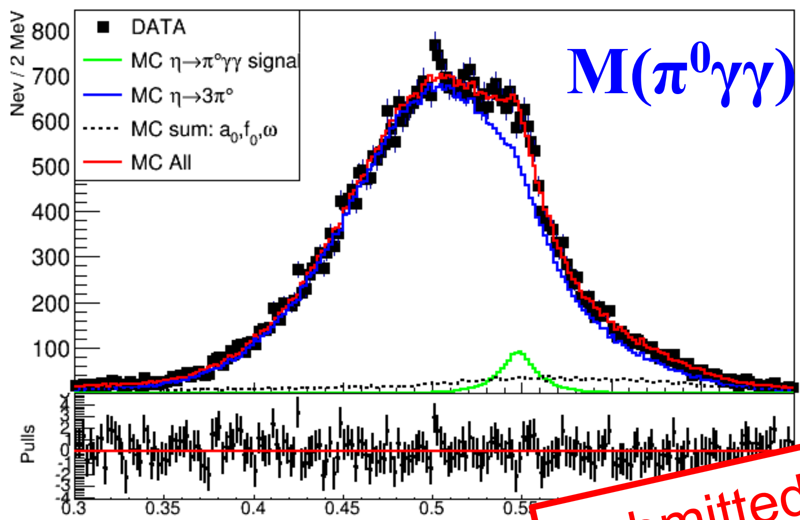
  $\eta\rightarrow3\pi^0$, $\eta\rightarrow\pi^0\gamma\gamma$ signal, sum of non- $3\pi^0$
- Fit χ^2/ndf=215/200 (fit prob=22%)
- Normalized with $\eta\rightarrow 3\pi^0$ sample with 7 photons
- The main sources for systematic uncertainty come from 5 prompt photon selection, analysis cuts and normalization



$$BR(\eta\rightarrow\pi^0\gamma\gamma) = (0.98 \pm 0.11_{stat} \pm 0.14_{syst})\cdot10^{-4}$$

- Separate fits in bins of M2(γγ)
- Second bin missing due to the veto for π0π0 events (from ϕ→f0(980)γ, with f0(980) →π0π0 and e+e−→ωπ0 with ω→π0γ)

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



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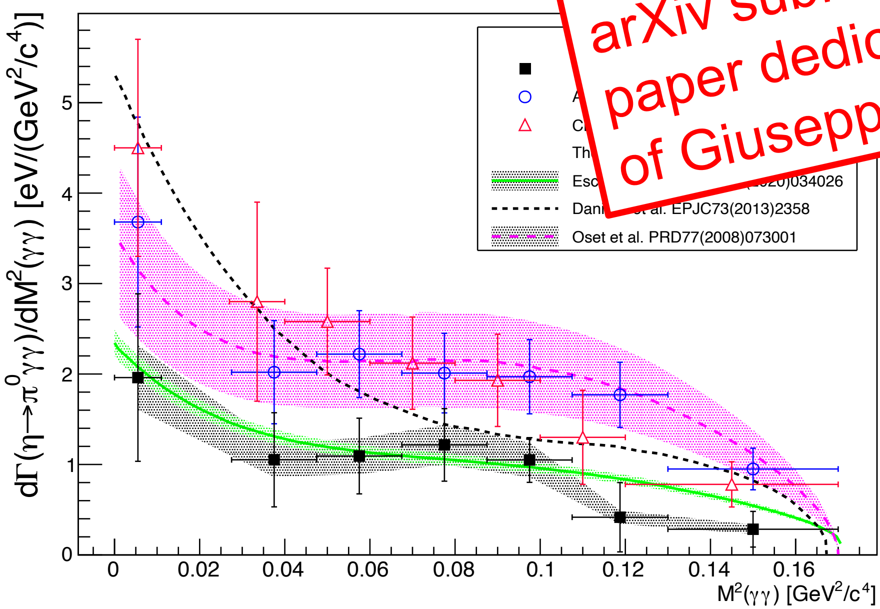
- ...ystematic uncertainty come from 5 ...n, analysis cuts and normalization

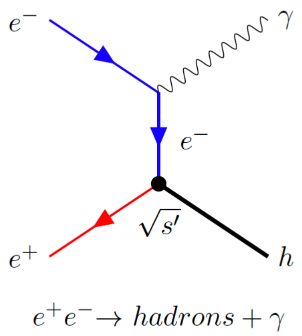
Submitted to JHEP
arXiv submit/6433313
paper dedicated to the memory
of Giuseppe Fabio Fortugno



$BR(\eta \rightarrow \pi^0\gamma\gamma) =$
$(0.98 \pm 0.11_{stat} \pm 0.14_{syst}) \cdot 10^{-4}$

- Separate fits in bins of M2($\gamma\gamma$)
- Second bin missing due to the veto for $\pi0\pi0$ events (from $\phi \rightarrow f0(980)\gamma$, with $f0(980) \rightarrow \pi0\pi0$ and $e+e- \rightarrow \omega\pi0$ with $\omega \rightarrow \pi0\gamma$)

$e^+ e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$



- 3π channel relevant for a_μ^{HVP} evaluation
- $e^+e^- \rightarrow 3\pi$ measurement feasible using ISR technique

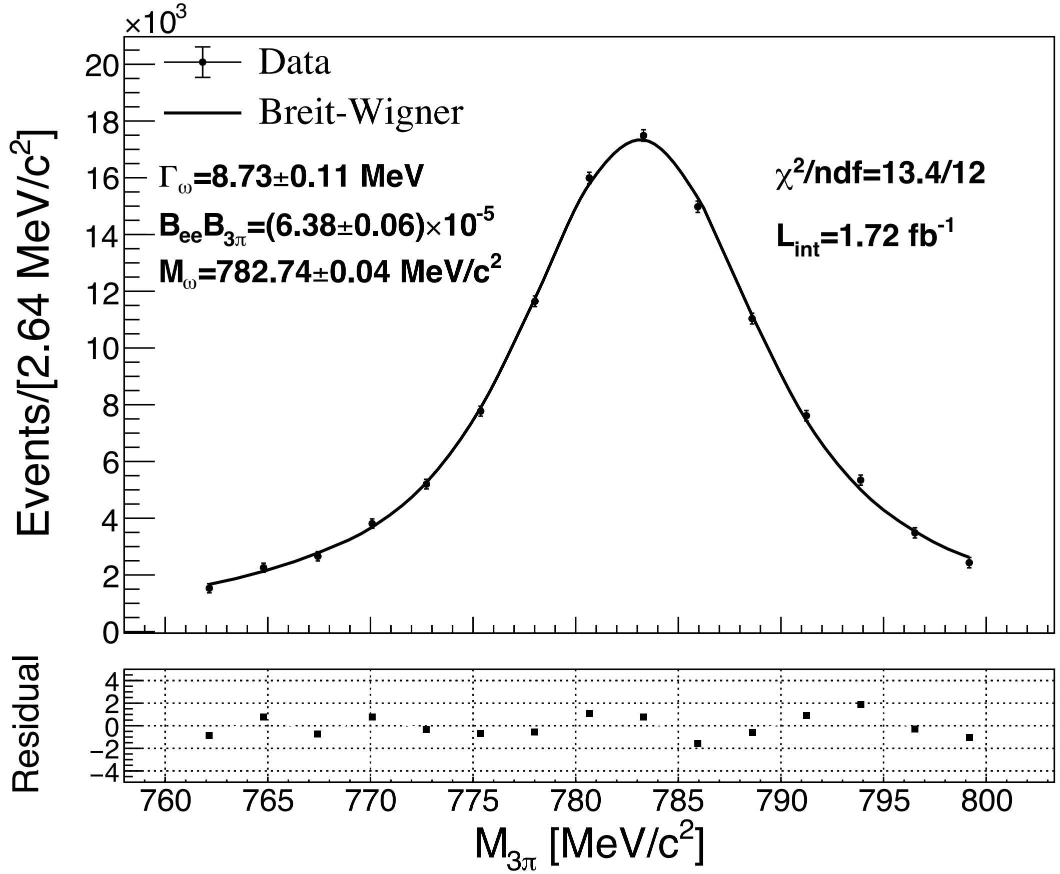
Sample statistics: about 1.7 fb-1

Event selection:

- $K_S K_L$ stream
- at least two tracks with opposite curvature
- three neutral clusters with $|\cos\theta|<0.92$,
- Eclu >15 MeV, Tclu-Rclu/c < min $(2,5\sigma_t)$ ns

In the plot:

- Breit-Wigner cross section assumed
- convolution bin-by-bin with the acceptance-corrected smearing matrix.
- A fit to the data (the background-subtracted signal) is performed to extract the ω parameters
- evaluation of systematic uncertainties in progress => dominant contribution from the efficiency correction.



Conclusions

- We faced a hard period due to the mentioned difficulties with computing.
- Thanks to the help of many people, we were able to setup an emergency plan and to define a clear strategy for the future.
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- Most of the hardware faults were recovered, the KLOE reconstructed data are being retrieved from the old tape library, and the KLOE/KLOE-2 data transfer to CNAF started and is ongoing. Shifts from KLOE-2 members are planned to complete all the operations including backups as soon as possible.

- Even though analysis activities slowed down in the last year due to the mentioned difficulties on computing, there are still several interesting analyses ongoing.
- The Liverpool group, that recently joined KLOE-2, is leading an intense theory and analysis activity, the $\pi\pi\gamma$ initiative, with ambitious goals (=> Zaid's talk).
- The KLOE and KLOE-2 data constitute a unique sample, the largest ever collected of its kind, collected with a general-purpose detector, and very rich in Physics.
- It's a precious cultural heritage for the entire INFN community, it was a sizeable investment of human and financial resources, and it must be preserved for the future, for future ideas and analyses that certainly will come up.