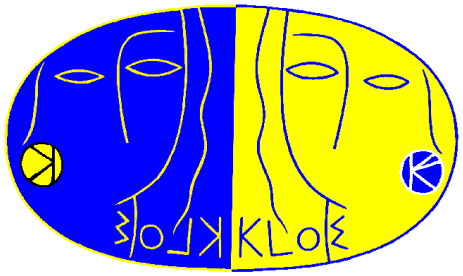
MESON 2021

Recent results on hadron physics at KLOE/KLOE-2



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on behalf of the KLOE-2 Collaboration

Presentation plan

- DAFNE collider, data collected, KLOE detector and KLOE-2 upgrade
- KLOE-2 physics program
- Brief description of finished/ongoing analysis:
  - Limit on $\eta \to \pi^+\pi^-$
  - B boson search in $\phi \to \pi^\circ\eta\gamma$
  - χPT "golden mode" $\phi \to (\eta \to \pi^\circ\gamma\gamma)\gamma$
  - $\gamma\gamma \to \pi^\circ$ process

DAFNE ϕ factory

- e^+e^- collider @$\sqrt{s} = M_\phi$(1020 MeV)

- **KLOE** data taking: 2001–2006
- Collected ~2.5 fb^{-1} at ϕ peak
- Best peak/integrated luminosity:

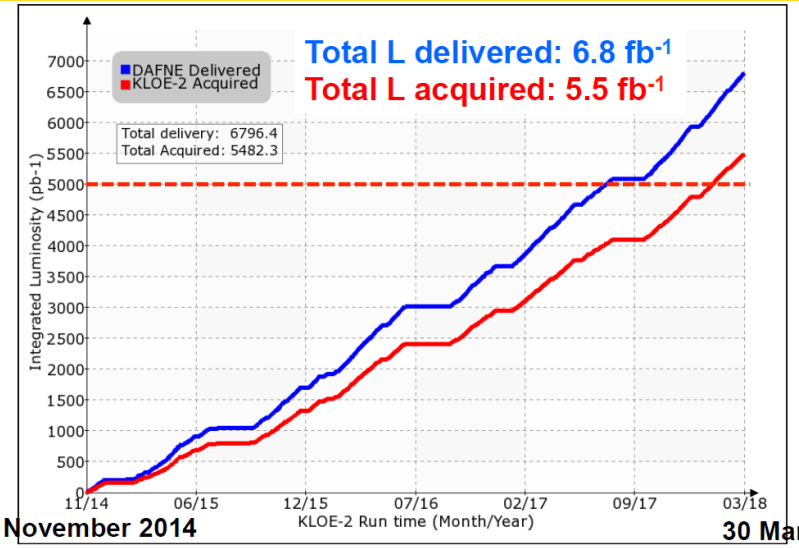
$$L_{peak} = 1.4 \cdot 10^{32}\ cm^{-2}s^{-1}$$
$$\int Ldt = 8.5\ pb^{-1}/day$$

- **KLOE-2:** 2014-2018

$$L_{peak} = 2.4 \cdot 10^{32}\ cm^{-2}s^{-1}$$
$$\int Ldt = 11\ pb^{-1}/day$$

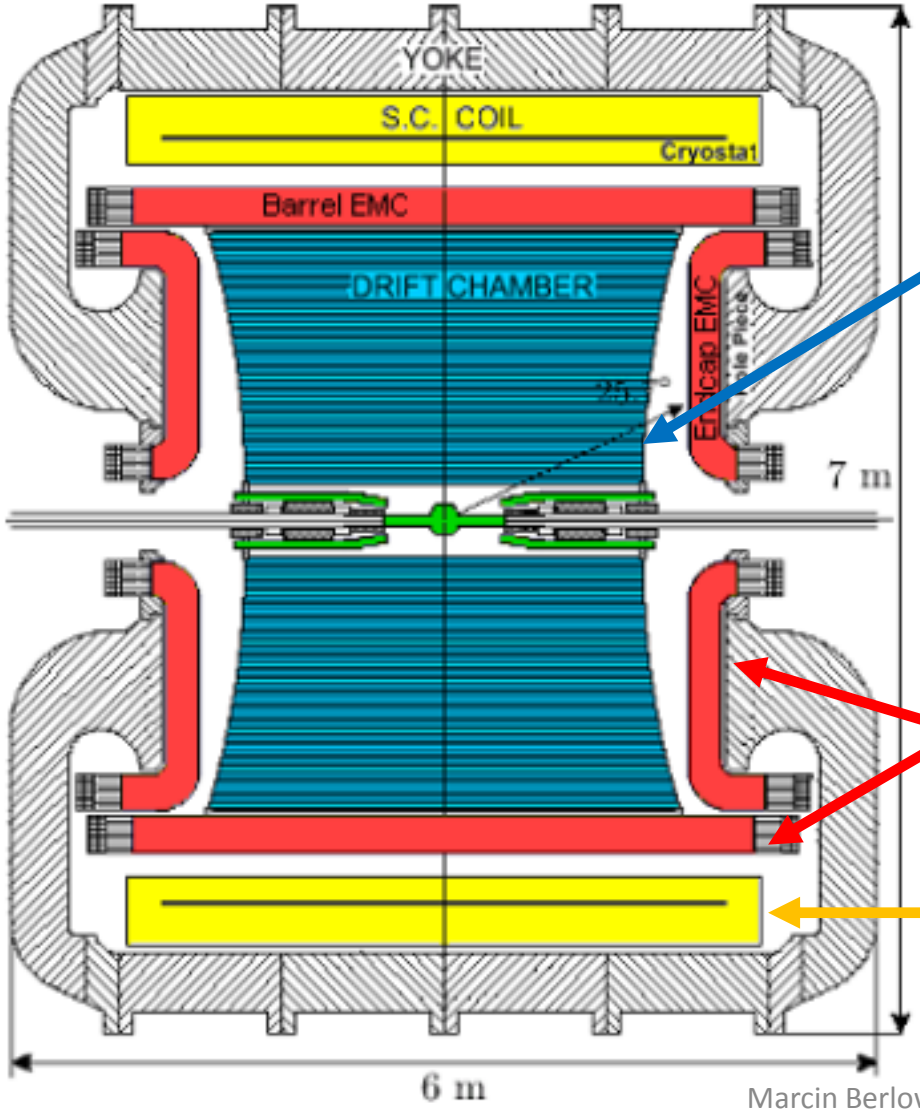
- **KLOE + KLOE-2** ~8fb^{-1} → $2.4 \cdot 10^{10}$ ϕ which is by now the largest sample collected at ϕ peak in e^+e^- collider

KLOE-2 data set:



17 November 2014 — 30 March 2018

KLOE detector



Drift chamber:

- Gas mixture: 90% He, 10% isobutane
- Resolutions: σ_{xy}~150μm, σ_z~2mm, $\frac{\sigma p_t}{p_t} < 0.4\%$ ($45° < \theta < 135°$), σ_v ~3mm

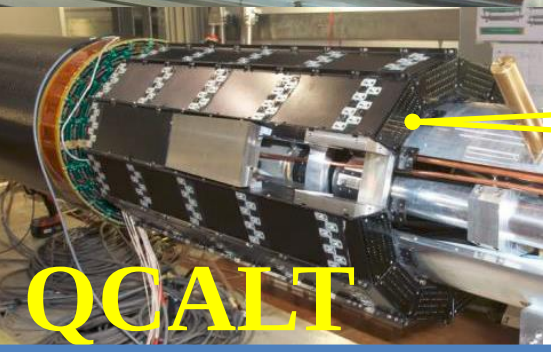
Electromagnetic calorimeter:

- Made of lead/scintillating fibers
- Covers 98% of solid angle
- Resolutions: $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(GeV)}}$,

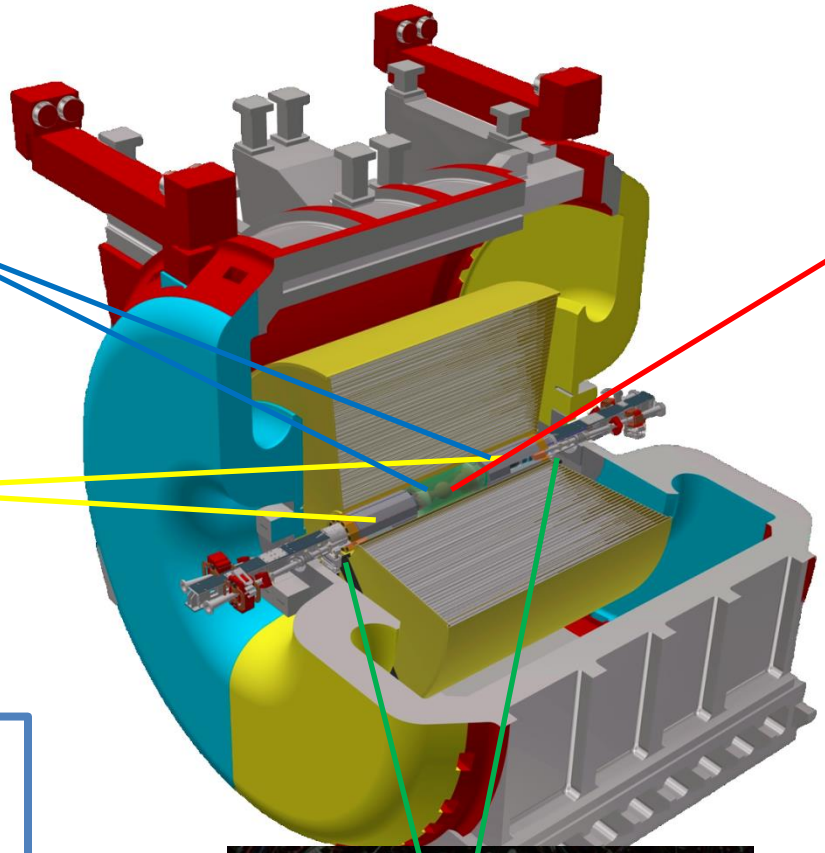
  $\sigma_T = \frac{57\ ps}{\sqrt{E(GeV)}} \oplus 140$ ps

Magnetic field ~0.52 T

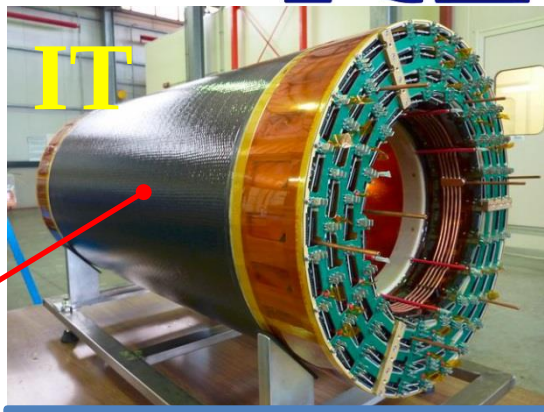
KLOE-2 upgrades



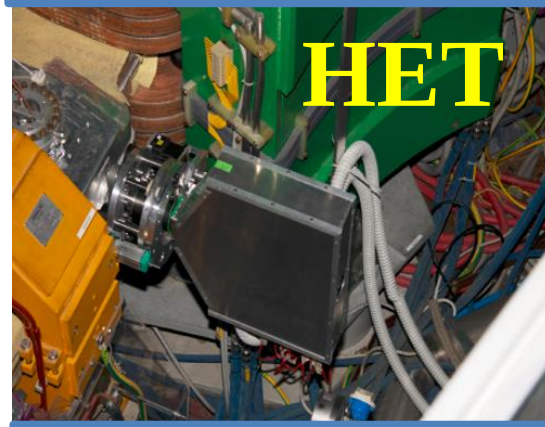
CCALT (LYSO-cristals) **& QCALT** (scintillator tiles and fibers with SiPM read-out)**:** both inside KLOE detector, to improve low polar angles acceptance for γ's & K_L decays



LET: LYSO with SiPM readout, ~1 m from the IP, γγ-physics



IT: 4 layers of cylindrical GEM detectors, larger acceptance for low p_t tracks, to improve vertex resolution at the Interaction Point



HET: Scintillator + PMT 11 m from the IP, γγ-physics

Summary of KLOE physics

- 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
- Light meson Transition Form Factors
- **Tests of χPT and other theories e.g. $\eta\to\pi^0\gamma\gamma$**
- C, P, CP violation in $\eta\to\gamma\gamma\gamma$, **$\eta\to\pi^+\pi^-$**, $\eta\to\pi^0\pi^0$, $\eta\to\pi^0\pi^0\gamma$
- CP violating $\eta \to \pi^+\pi^-e^+e^-$, other 4 charged tracks η decays
- **$\gamma\gamma$ physics: $\Gamma(\gamma\gamma\to\pi^0)$ and π^0 Transition Form Factor**
- Dark Forces searches: $e^+e^-\to U\gamma\to\pi\pi\gamma,\mu\mu\gamma$, Higgsstrahlung process in $e^+e^-\to Uh'\to\mu\mu$+missing energy, **leptophobic B boson: $\phi\to\eta B$, $B\to\pi^0\gamma$, $\eta\to\gamma\gamma$** and $\eta\to B\gamma$, $B\to\pi^0\gamma$, $\eta\to\pi^0\gamma\gamma$**,** U invisible decays, axion-like particles
- Plus Kaon Physics program e.g.: semileptonic K_S, $K_S\to\gamma\gamma$ (BR, χPT), $K_S\to3\pi^\circ$ (BR, CP violation), …

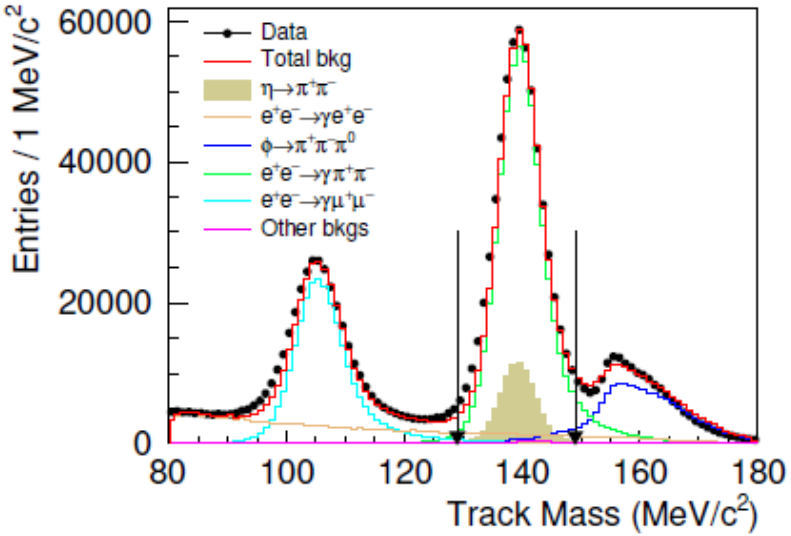
[EPJC 68 (2010) 619]
[EPJ WoC 166 (2018)]

BR limit for $\eta \to \pi^+\pi^-$

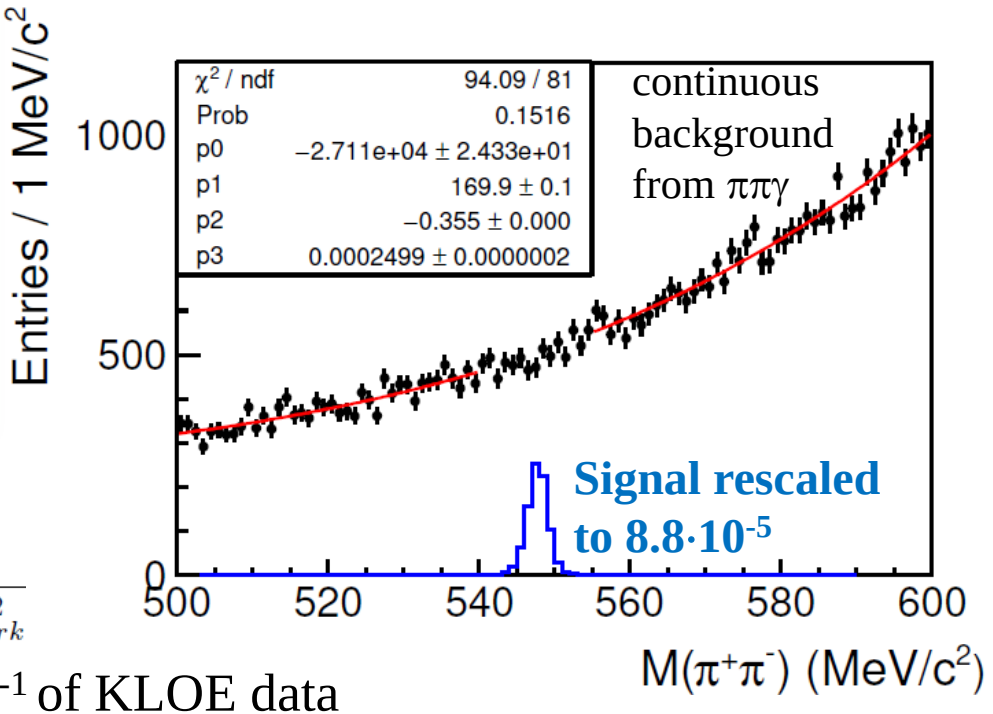
- P, CP-violating process
- In the SM the BR prediction [*Phys.ScriptaT* 99, 23 (2002)]:
  - proceed only via CPV in weak interaction $\to 10^{-27}$
  - introducing a CPV term in QCD $\to 10^{-17}$
  - allowing CPV in the extended Higgs sector $\to 10^{-15}$
- An observation of larger branching ratio would mean new source of CP violation in the strong interactions

- Previous KLOE result [*Phys.Lett.B* 606 (2005) 276] based on 0.4 fb^{-1}: $< 1.3 \cdot 10^{-5}$ @90% CL
- LHCb: $< 1.6 \cdot 10^{-5}$ @90% CL [*Phys.Lett.B* 764 (2017) 233-240]

BR limit for $\eta \to \pi^+\pi^-$



$$|\vec{p}_\phi - \vec{p}_1 - \vec{p}_2| = E_\phi - \sqrt{|\vec{p}_1|^2 + M^2_{trk}} - \sqrt{|\vec{p}_2|^2 + M^2_{trk}}$$



- New analysis using independent 1.6 fb^{-1} of KLOE data
- No event excess in the η region, limit extracted using CL_s technique

$BR(\eta\to\pi^+\pi^-) < 4.9 \cdot 10^{-6}$ @ 90% CL

- Combined with previous KLOE result: **$< 4.4 \cdot 10^{-6}$ @ 90% CL**

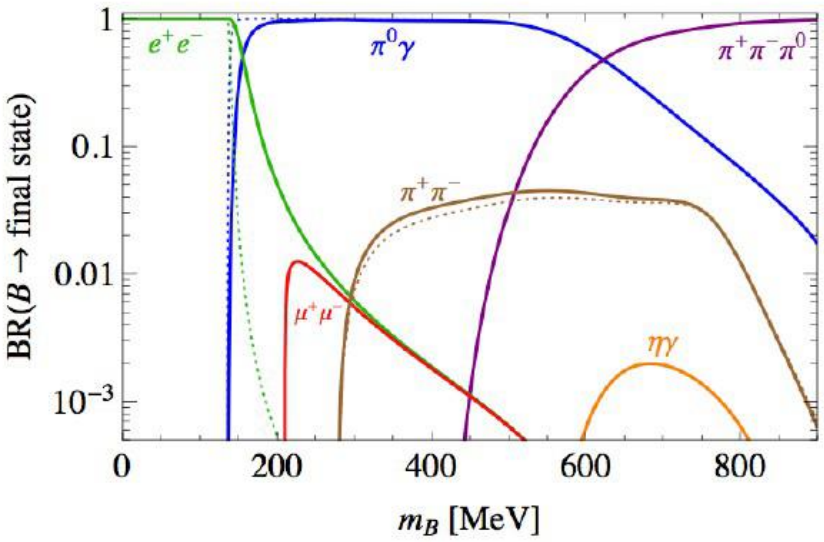
Published in JHEP10 (2020) 047

DM search – leptophobic B

- Search for a new physics - possible analog of the U boson, but B boson (leptophobic DM mediator) couples mostly to quarks, in the most basic model to baryon number via kinetic mixing term ε
- U boson searches don't exclude the existence of the B boson above m_{π° and this can still have an impact on the g-2 anomaly (a_μ^{NLO})
- We can look for a B signature in the M(π°γ) produced in either $\phi \to B\eta$ or $\eta \to B\gamma$

$$\mathcal{L} = -\frac{1}{2}\varepsilon F^{\mu\nu}F'_{\mu\nu} = -\frac{g_B}{3}\bar{q}\gamma^\mu q B_\mu$$

$$\alpha_B = \frac{{g_B}^2}{4\pi}$$

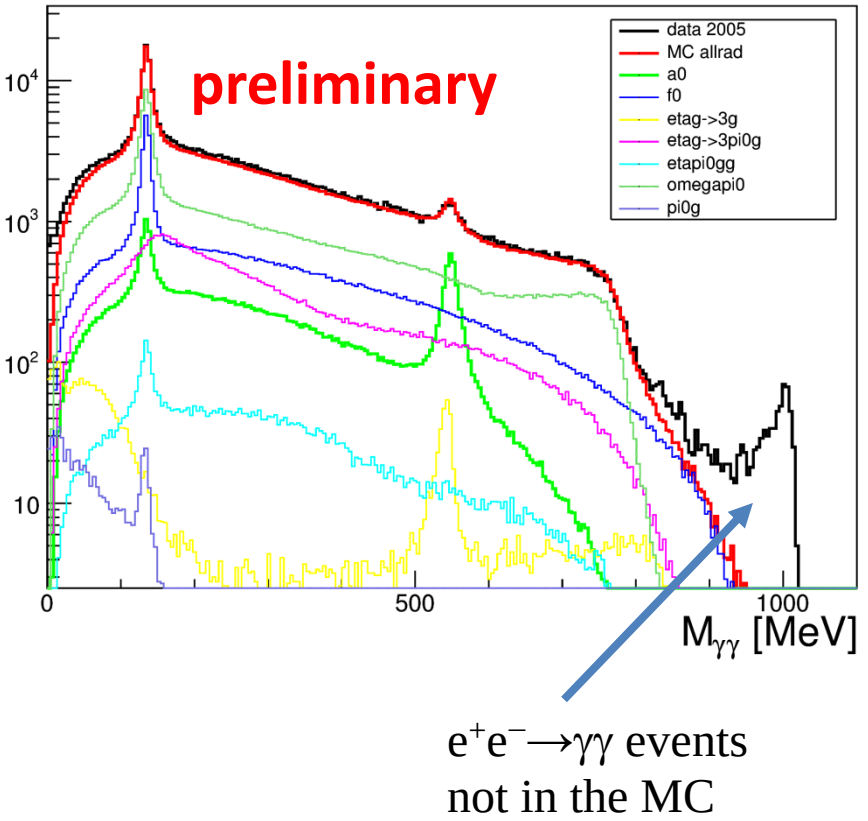


S. Tulin Phys. Rev. D 89, 114008 (2014), arXiv:1404.4370

$B \to \pi^\circ\gamma$ in $\phi \to B\eta$ channel

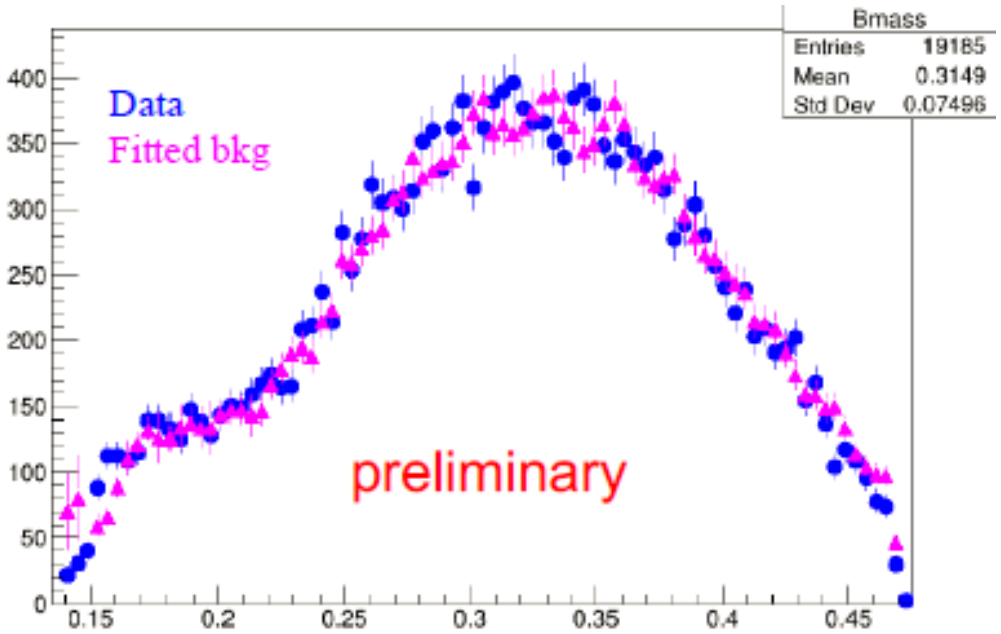
- Study on 1.7 fb^{-1} of KLOE data
- 5 prompt photons in the final state:
  - $\phi \to \eta B \to \eta(\gamma\gamma)\pi^\circ(\gamma\gamma)\gamma \to 5\gamma$
- Main background coming from: $\phi \to (a_0 \to \eta\pi^\circ)\gamma$ and $\phi \to (\eta \to 3\pi^\circ)\gamma$ with lost or merged photons
- Kinematic fit to improve resolution

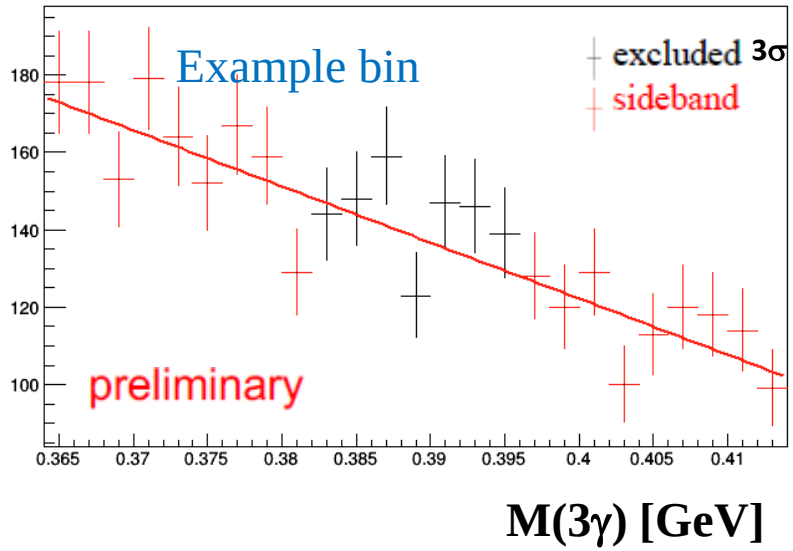
M(2γ) after kinematic fit correction



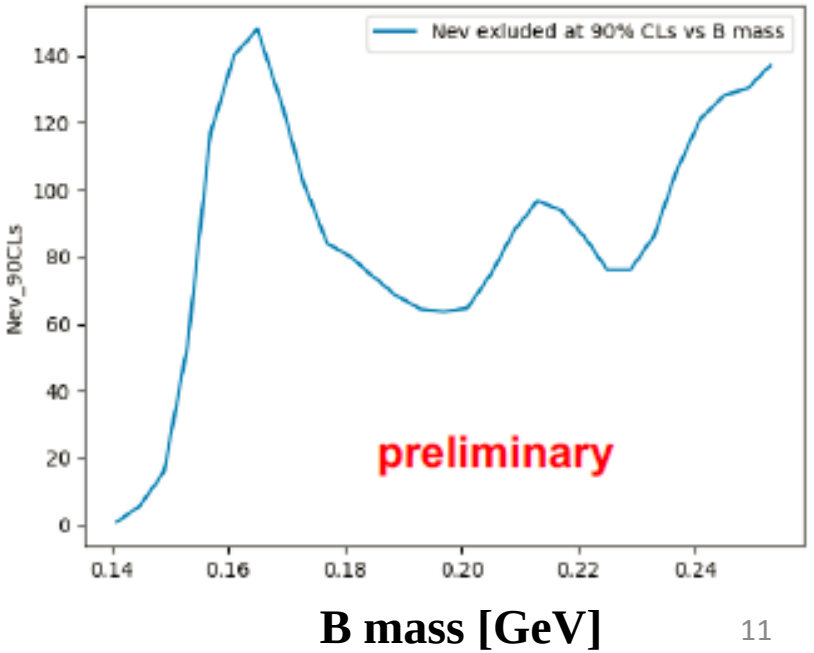
$e^+e^- \to \gamma\gamma$ events not in the MC

B→π°γ in ϕ→Bη channel





- B boson expected as sharp resonance in M(3γ)
- Sidebands background extraction for Upper Limit calculation based on CL_s technique
- Systematics studies are ongoing



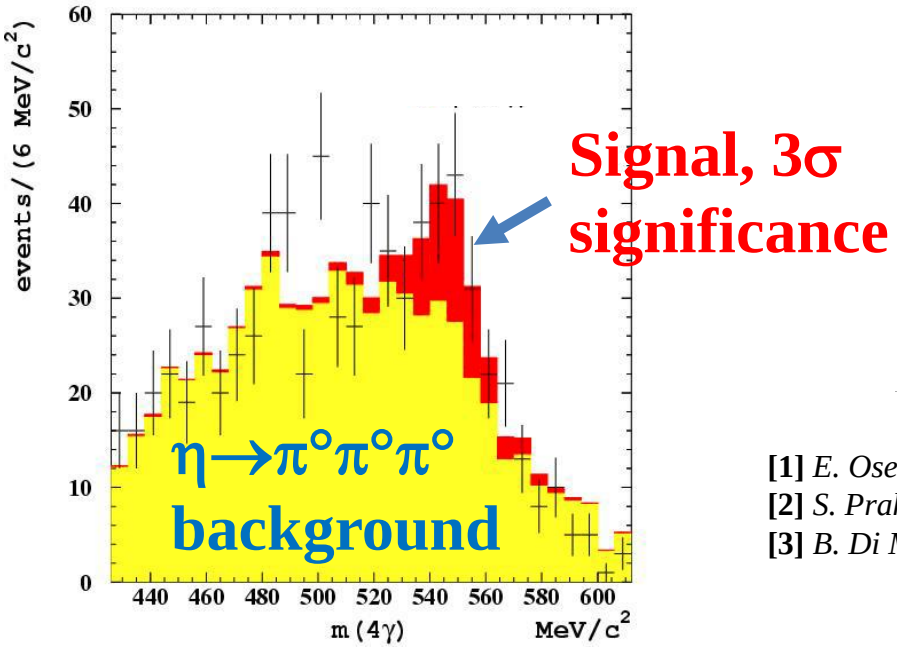
BR of $\eta \to \pi^\circ\gamma\gamma$

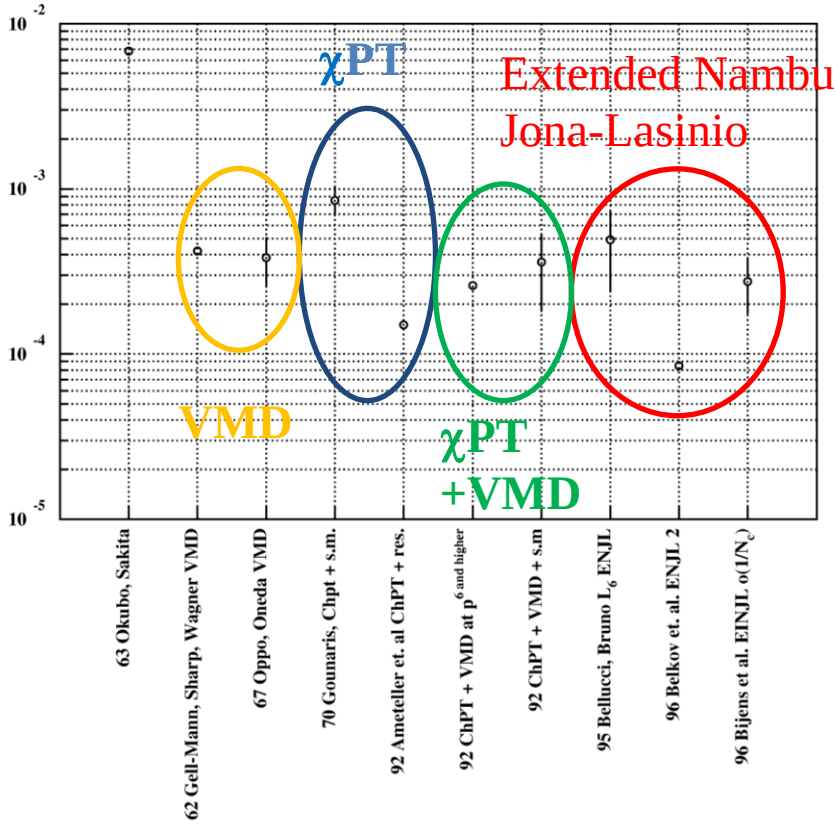
- BR discrepancy between experiments **[1]:**
  - AGS/Crystal Ball ($K^-p \to \Lambda\eta$) **[2]** (~1200 ev):

$$BR(\eta \to \pi^\circ\gamma\gamma) = (2.21 \pm 0.24_{stat} \pm 0.38_{syst}) \cdot 10^{-4}$$

  - KLOE ($\phi \to \eta\gamma$) **[3]** (63±28 ev), preliminary, based on L_{int}=450 pb^{-1}:

$$(0.84 \pm 0.27_{stat} \pm 0.14_{syst}) \cdot 10^{-4}$$





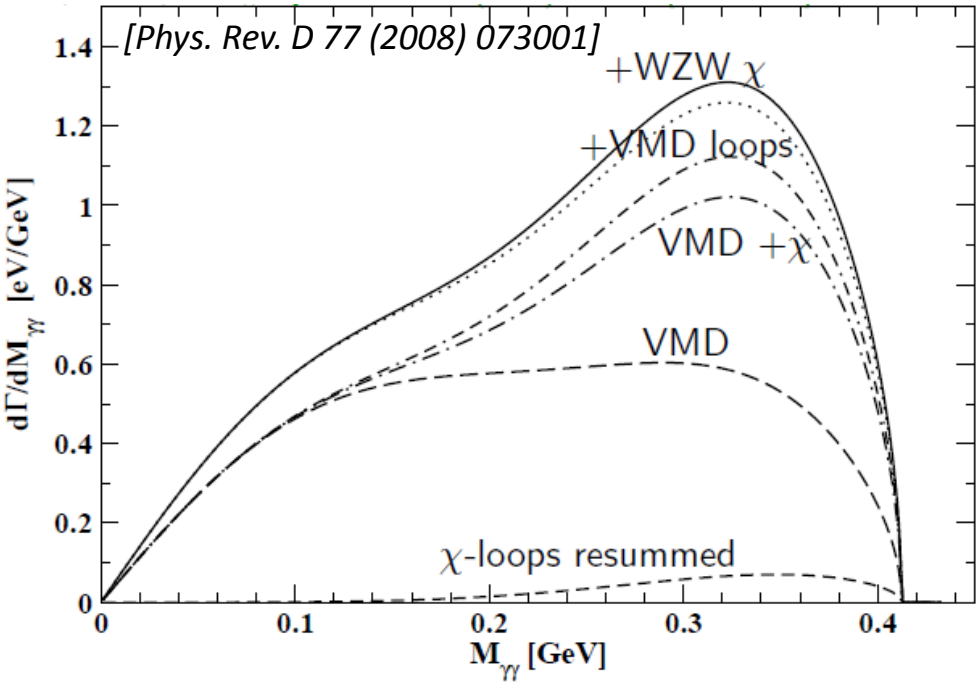
[1] *E. Oset et al, Phys. Rev. D 67, 073013 (2003),*
[2] *S. Prakhov et al., Phys. Rev. C 78 (2008) 015206*
[3] *B. Di Micco et al., Acta Phys. Slov. 56, 403 (2006),*

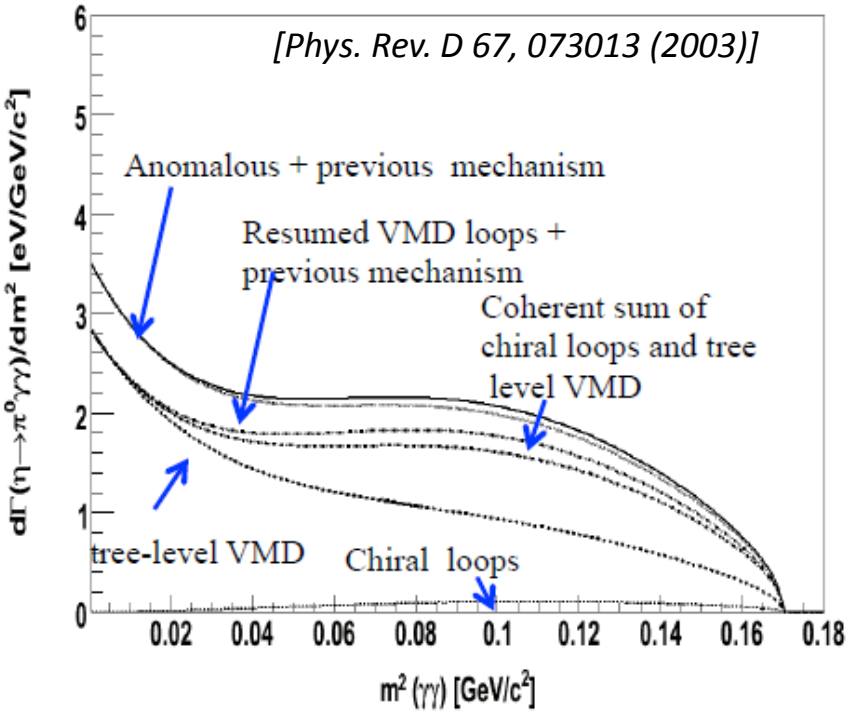
$\eta \to \pi^\circ\gamma\gamma$ χPT input

[Ll. Ametller et al. PLB 276(1) (1984)]

- χPT "golden mode": $O(p^2)$ null, $O(p^4)=0$ on the tree level and suppressed on 1-loop by G-parity and large kaon mass $\Rightarrow$ $O(p^6)$ are dominating

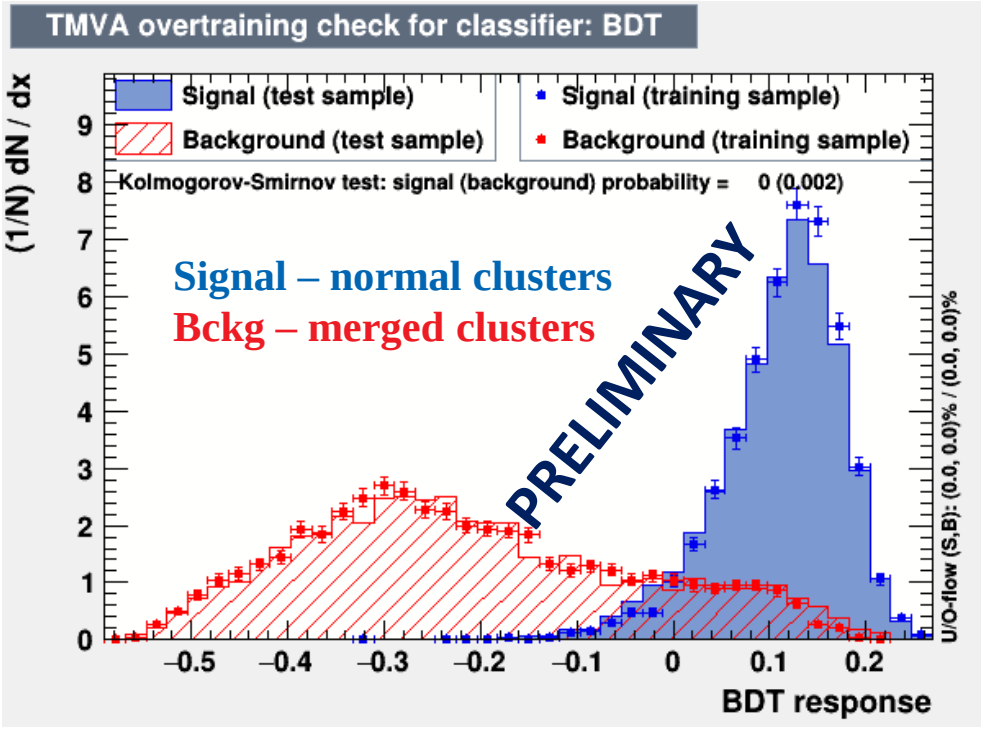
- M($\gamma\gamma$) that are not coming from π° can be used as a test of theoretical models

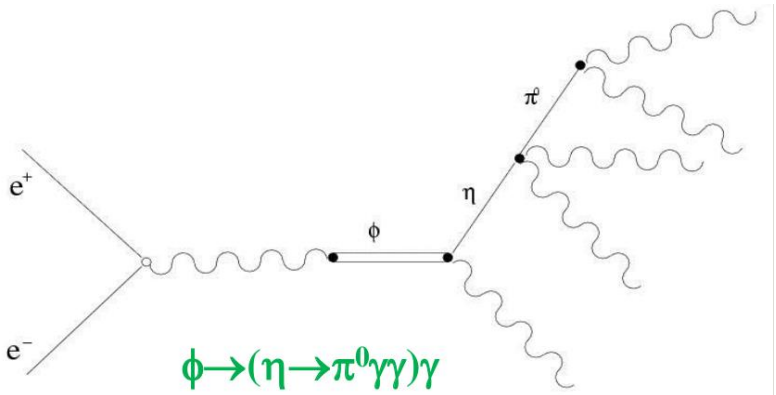




$\phi \to \eta\gamma$ with $\eta \to \pi^\circ\gamma\gamma$

- A new analysis of old KLOE data, using ~4x larger data sample (~1.7 fb^{-1})
- Similar to 5 prompt analysis of B boson
- Variables corrected by a kinematic fit to improve resolution
- Kinematic fit with $\eta(\gamma\gamma)\pi^\circ(\gamma\gamma)$ mass constrains to reject $\phi \to (a_0 \to \eta\pi^\circ)\gamma$
- Two π° events removed to suppress $\phi \to (f_0 \to \pi^\circ\pi^\circ)\gamma$ and $e^+e^- \to (\omega \to \pi^\circ\gamma)\pi^\circ$
- TMVA-BDT based rejection for $\eta \to 3\pi^\circ$ cases with merged clusters using shape of the clusters as an input

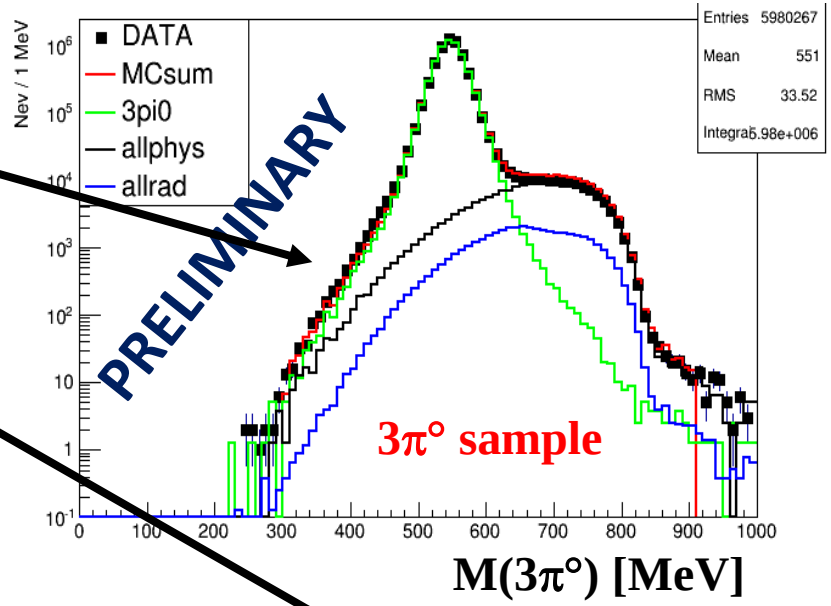


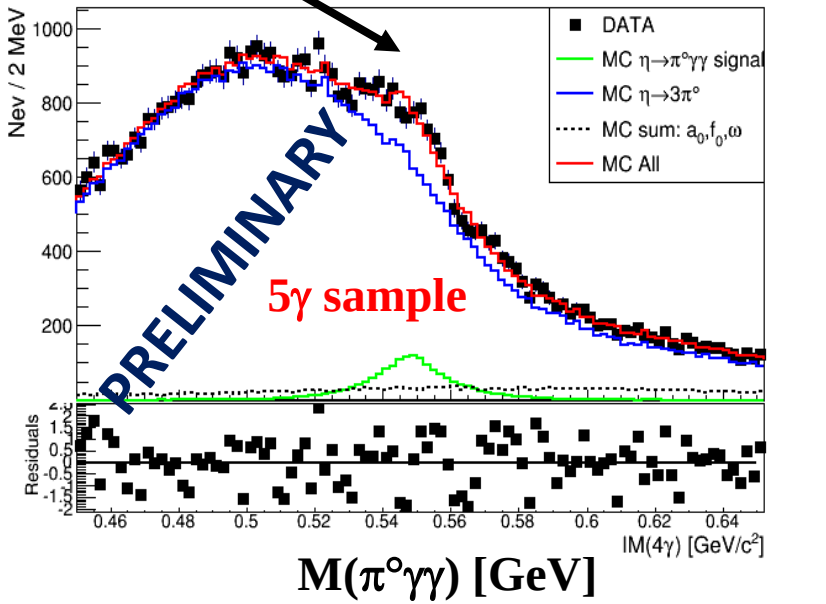


$\phi \to \eta\gamma$ with $\eta \to \pi^0\gamma\gamma$

- Normalization to $\eta \to 3\pi^0$ sample in order to reduce systematic effects
- Clear signal evidence on data distribution with S/B ratio ~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 old preliminary KLOE result

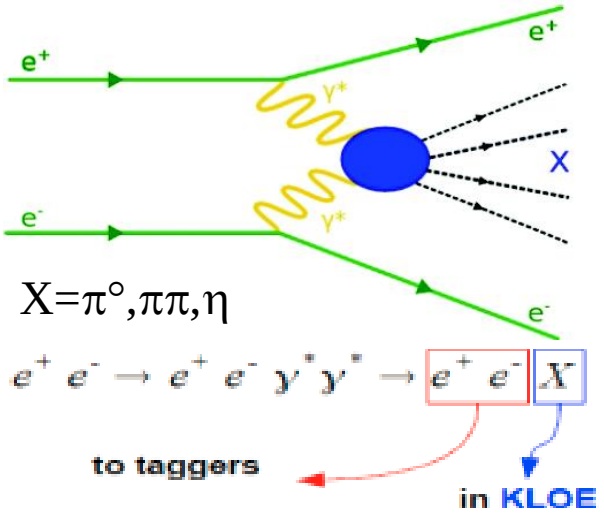
- Consistency check of different fitting strategies and systematic uncertainty evaluation ongoing
- Extraction of M($\gamma\gamma$) in progress



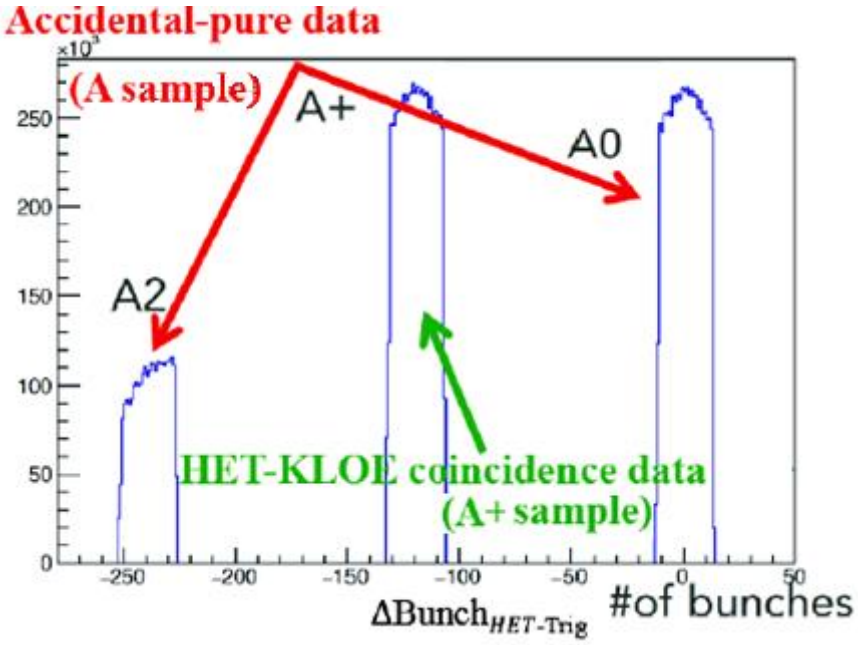


γγ physics with High Energy Tagger

- Precise measurement of $\Gamma(\pi^\circ \to \gamma\gamma)$
- Transition FF $F_{\pi\gamma^*\gamma}(q^2,0)$ in the space-like region ($|q^2|<0.1$ GeV^2)
- Impact on value and precision of $a_\mu^{LbL;\pi^\circ}$

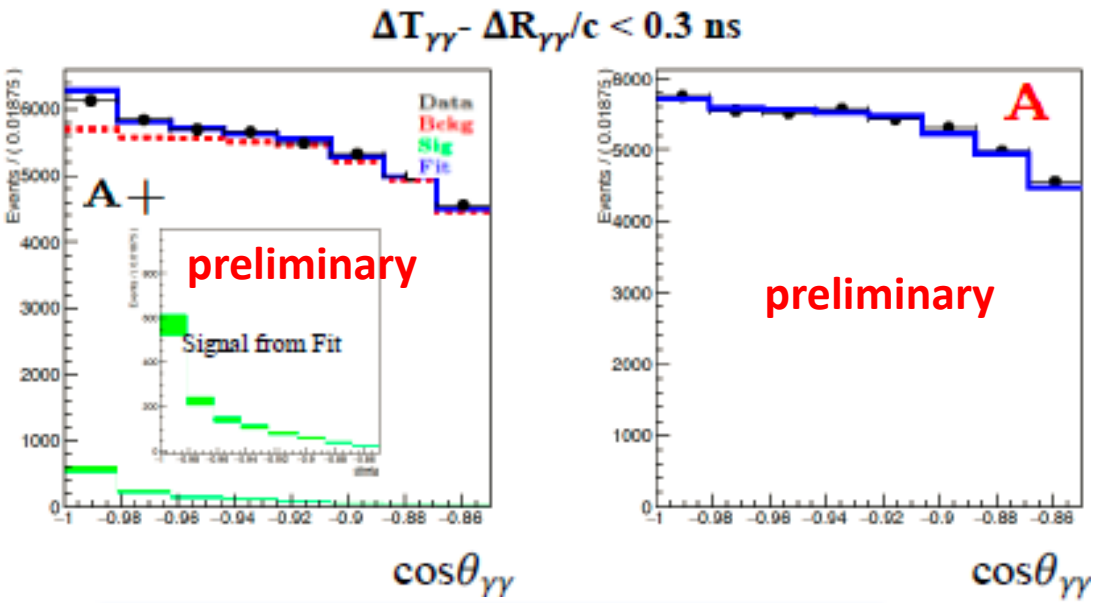


Concept – see [Eur. Phys. J. C 72 (2012) 1917]

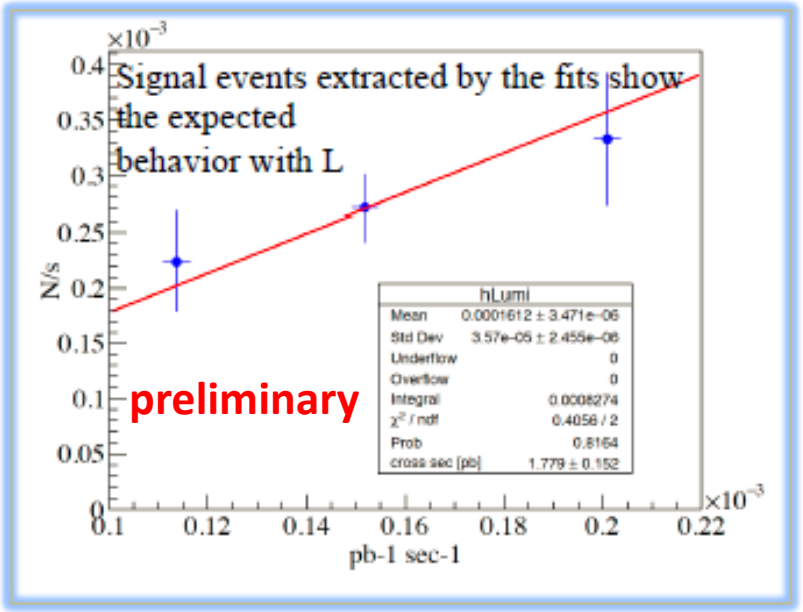


- Scintillator hodoscope + PMTs, inserted 11 m from IP
- High Energy Tagger (HET) acquisition synchronized with DAFNE and KLOE trigger
- Coincidence between HET and KLOE EMC **(A+ sample)**
- Evaluation of the uncorrelated HET-KLOE time coincidences **(A sample)**
- Number of π° tagged events from γγ fusion extracted from A+/A comparison

Status of $\gamma\gamma \rightarrow \pi^0$ search



Example of $\cos\theta_{\gamma\gamma}$ fits in coincidence (**A+**) and accidental (**A**) samples with signal enriching cut



- $3fb^{-1}$ of data with optimized calibration constants to improve time and energy resolutions
- Simultaneous fits of **A+**/**A** samples in $M_{\gamma\gamma}$, $\cos\theta_{\gamma\gamma}$, $\Delta T_{\gamma\gamma}$-$\Delta R_{\gamma\gamma}$ /c
- Fit to accidental–pure samples (**A**) used to constrain the number of accidentals in **A+**
- **8% statistical precision on signal reached from a $1.5fb^{-1}$ part of data sample**

Conclusions

- KLOE data sample is still allowing us to perform several high precision measurements such as:
  - New BR limit for $\eta \to \pi^+\pi^-$
  - Second look at input to χPT from $\eta \to \pi^\circ\gamma\gamma$ channel
  - Searches for a new physics in leptophobic sector (dark B mediator)

- In KLOE-2 the increased event sample and the new detectors providing better acceptance and resolution, are going to improve several results as well as provide a new ones like $\gamma\gamma \to \pi^\circ$

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THANK YOU for your attention!!!

SPARES

Perspectives for KLOE-2

- KLOE-2 is not only about **increased statistics:**
  - **QCALT+CCALT**: will increase acceptance for photons from the interaction point (from 21° to 10°)
  - **Inner Tracker**: will improve resolution of tracking and will help to achieve a better vertex reconstruction
  - **HET**: allows $\gamma^*\gamma^* \to \pi^\circ$ search

- With **~$2.4 \cdot 10^8$ ϕ mesons and $N_\eta \sim 3 \cdot 10^8$** in KLOE/KLOE-2 we expect:
  - ~5000 events of $\eta \to \pi^\circ\gamma\gamma$ (was ~70)
  - Better background reduction from $\eta \to 3\pi^\circ$ thanks to increased detector's acceptance for photons coming at small angles
  - Improvement of a factor of ~3.5 in $\pi^\circ\gamma$ invariant mass sensitivity for the upper limit calculation
- The expected upper limit for $\eta \to \pi^+\pi^-$ with the full KLOE/KLOE-2 statistics is $2.7 \cdot 10^{-6}$@ 90% CL

[EPJC 68 (2010) 619]
[EPJ WoC 166 (2018)]

Low angle radiative Bhabha cross section

- HET counting rates dominated by low-angle radiative Bhabha's scattering
- BHA useful to check HET detector operational stability and validate acceptance and efficiency of the detector by comparison with the MC simulations
- Only plastics from 11 to 28 are used for π° search