Latest results from KLOE-2

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MENU 2023
October 18th, 2023 – Mainz

INFN
Istituto Nazionale di Fisica Nucleare

Outline

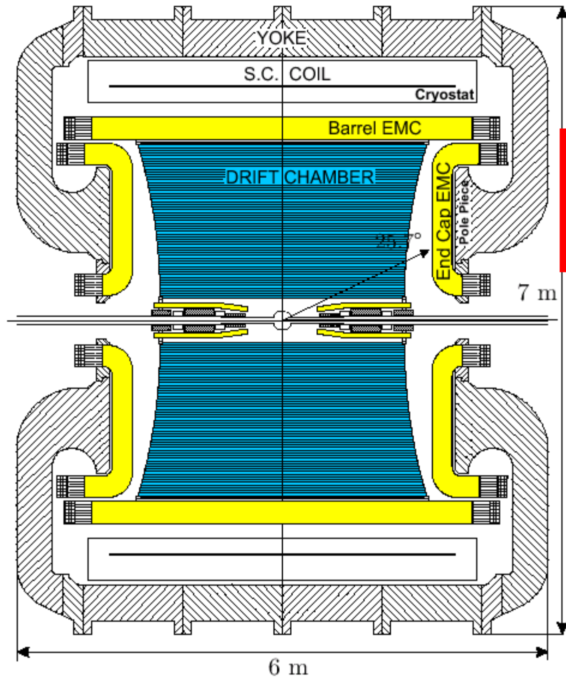
- **KLOE / KLOE-2**
- **T and CPT tests in neutral kaon transitions** [PLB845(2023)138164]
- $\eta \to \pi^0 \gamma\gamma$
- $\phi \to \eta \mu^+ \mu^-$
- $\gamma^* \gamma^* \to \pi^0$
- **Conclusions**

KLOE @ DAΦNE

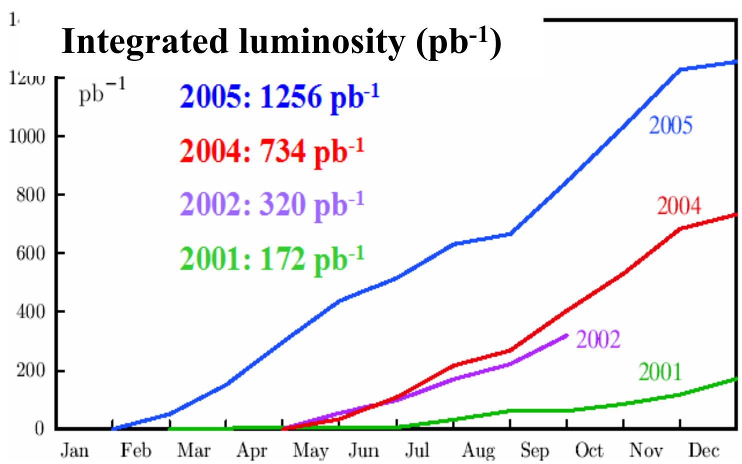
- **DAΦNE: Frascati ϕ-factory, e^+e^- collider @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$; $\sigma_{peak} \approx 3.1\ \mu b$**

- **Best performance in KLOE run (2005):**
  $L_{peak} = 1.5 \times 10^{32}\ cm^{-2}s^{-1}$
  $\int Ldt = 8.5\ pb^{-1}/day$

- **2001 – 2006: KLOE data-taking**
  $\Rightarrow$ 2.5 fb^{-1}@$\sqrt{s}=M_\phi$
  + 250 pb^{-1} off-peak @ $\sqrt{s}=1000$ MeV



Magnetic field:
0.52 T

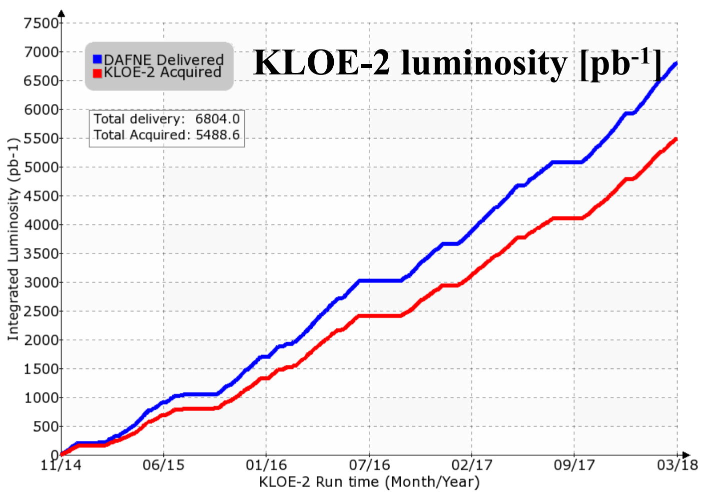


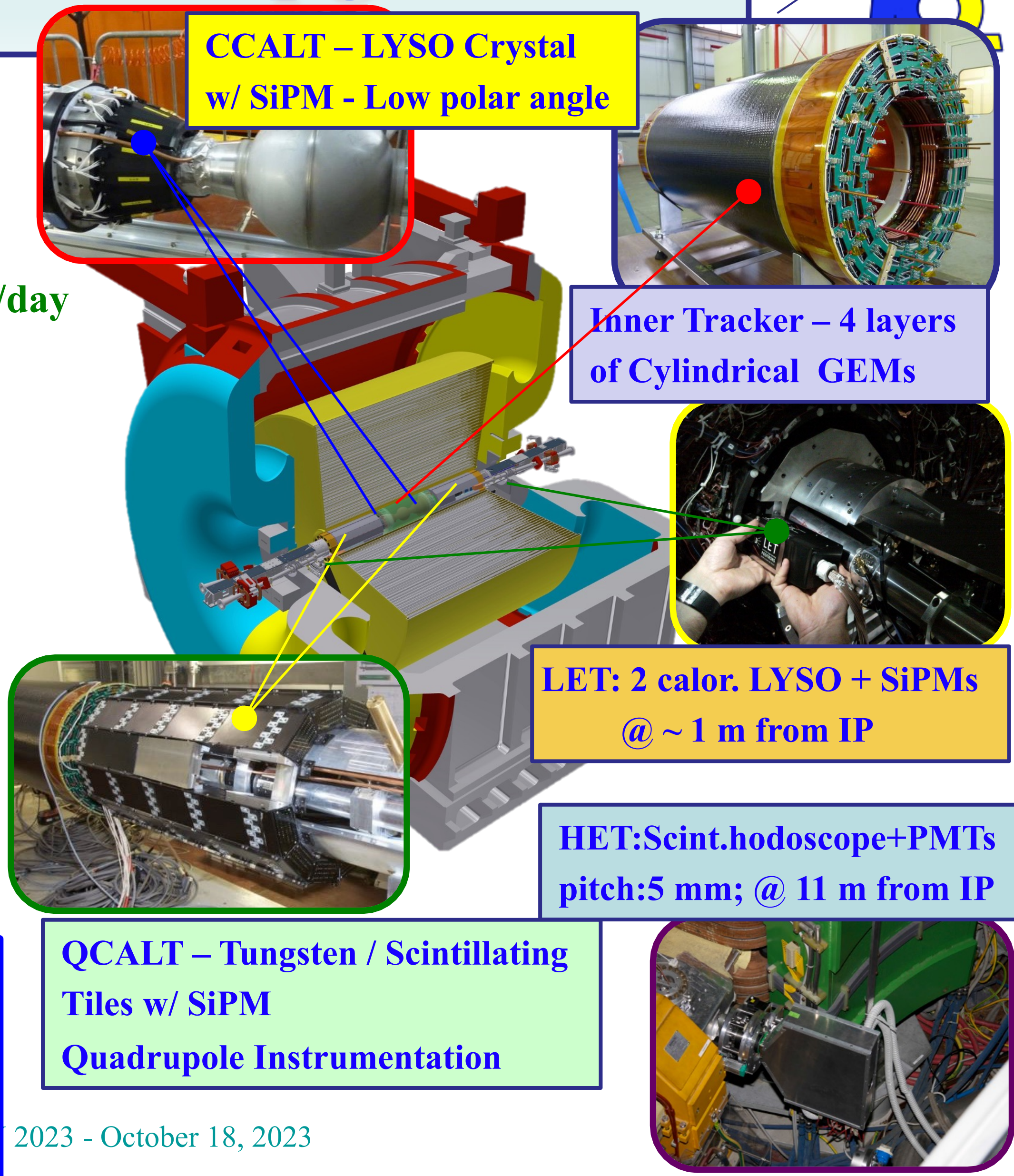
Drift chamber: 90% He-10% iC_4H_{10}
- **$\delta p_T/p_T = 0.4\%$**
- **$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm; $\sigma_{vertex} \approx 3$ mm**

Calorimeter (Pb-Sci.Fi.): 98% of 4π
- **$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$**
- **$\sigma_t = 54\ ps/\sqrt{E(GeV)} \oplus 100$ ps**

KLOE-2 @ DAΦNE upgraded

- DAΦNE upgrade (2008), new interaction scheme: large beam crossing angle + crabbed waist sextupoles
- Best performance in KLOE-2 run: $L_{peak} = 2.4 \times 10^{32}\,cm^{-2}s^{-1}$ -- $\int Ldt = 14\,pb^{-1}/day$
- 2014 – 2018: KLOE-2 data-taking ⇒ $5.5\,fb^{-1}$ collected @$\sqrt{s}=M_{\phi}$





KLOE + KLOE-2 data sample:
$\sim 8\,fb^{-1} \Rightarrow 2.4 \times 10^{10}$ ϕ's produced
⇒ the largest sample ever collected at a ϕ-factory

CPT and T tests in neutral kaon transitions

- T and CPT are described in QM by antiunitary operators ⇒ tests require the exchange of *in* and *out* states, and the reversal of all momenta and spins
- The entanglement of neutral kaons produced at a ϕ-factory $(e^+e^- \to \phi \to \mathbf{K^0\bar{K}^0})$ can be exploited for direct tests of T and CPT symmetries in neutral kaon transitions
- Due to Bose statistics and angular momentum conservation, the initial state is fully antisymmetric and can be written in terms of any pair of orthogonal states

$$|i> = \frac{1}{\sqrt{2}}(|K^0>|\bar{K}^0> - |\bar{K}^0>|K^0>) = \frac{1}{\sqrt{2}}(|K_+>|K_-> - |K_->|K_+>)$$

$|\mathbf{K^0}>, |\bar{\mathbf{K}}^\mathbf{0}>$ are identified by the decay into $\pi^-\ell^+\nu$, $\pi^+\ell^-\bar{\nu}$ respectively,

assuming the $\Delta S = \Delta Q$ rule

$|K_->$, $|K_+>$ are the neutral states tagged by the observation of the partner decay into the CP = +1 eigenstate $\pi\pi$ and CP = −1 eigenstate $3\pi^0$, respectively

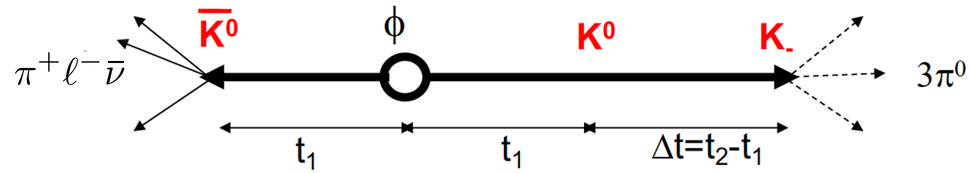
- $|K_->$, $|K_+>$ are orthogonal if one neglects direct CP violation effects (ε′)

[J.Bernabeu, A.Di Domenico, P.Villanueva-Perez: NPB868(2013)102, JHEP1510(2015)139]

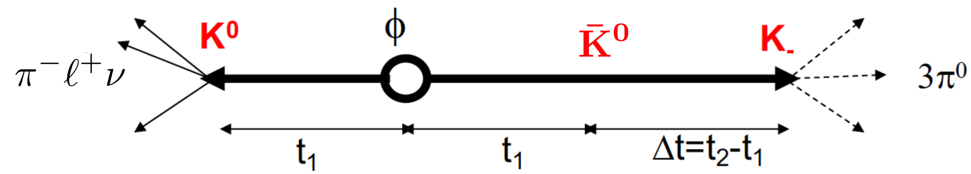
CPT and T tests in neutral kaon transitions

[J.Bernabeu, A.Di Domenico, P.Villanueva-Perez: NPB868(2013)102, JHEP1510(2015)139]

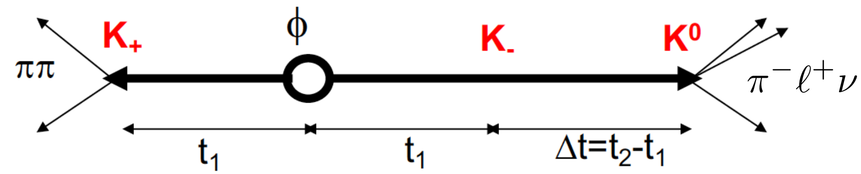
- Assume as reference the process: $\mathrm{K}^0 \rightarrow \mathrm{K}_-$



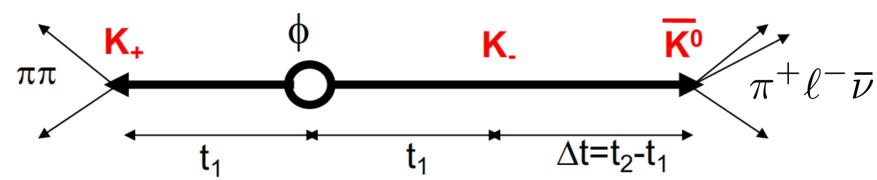
- CP conjugate: $\bar{\mathrm{K}}^0 \rightarrow \mathrm{K}_-$



- T conjugate: $\mathrm{K}_- \rightarrow \mathrm{K}^0$



- CPT conjugate: $\mathrm{K}_- \rightarrow \bar{\mathrm{K}}^0$



- The first kaon decay (at t_1) is used to tag the second one, and the decay at time t_2 is used to filter the final state

CPT and T tests in neutral kaon transitions

- **Ratios of decay rates can be constructed, sensitive to the different symmetries**

$$R_2^T(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^+ e^- \overline{\nu}, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)} \times \frac{1}{D}.$$

$$R_4^T(\Delta t) = \frac{P[\overline{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \overline{\mathrm{K}}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^+ e^- \overline{\nu}; \Delta t)} \times \frac{1}{D}$$

$$R_2^{CPT}(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \overline{\mathrm{K}}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^+ e^- \overline{\nu}, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^+ e^- \overline{\nu}; \Delta t)} \times \frac{1}{D},$$

$$R_4^{CPT}(\Delta t) = \frac{P[\overline{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} = \frac{\mathrm{I}(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{\mathrm{I}(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)} \times \frac{1}{D}$$

$$R'_{2,\mathrm{CP}}(\Delta t) \equiv \frac{I(\pi^+ e^- \overline{\nu}, 3\pi^0; \Delta t)}{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}$$

$$R'_{4,\mathrm{CP}}(\Delta t) \equiv \frac{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \overline{\nu}; \Delta t)}$$

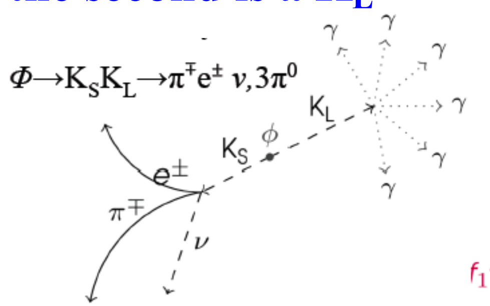
- **Double ratios:**

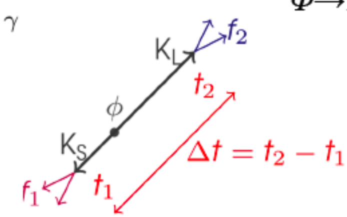
$$\frac{R_2^T}{R_4^T}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^-)}{I(\pi^+\pi^-, e^+)}$$

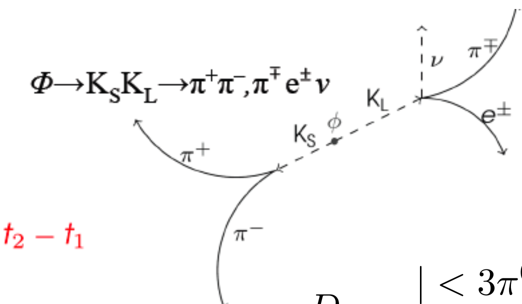
$$\frac{R_2^{CPT}}{R_4^{CPT}}(\Delta t) = \frac{I(3\pi^0, e^-)}{I(3\pi^0, e^+)} \frac{I(\pi^+\pi^-, e^+)}{I(\pi^+\pi^-, e^-)}$$

(CPT double ratio is model independent)

- **In the asymptotic region, $\Delta t >> \tau_S$, the first decaying kaon is essentially a K_S and the second is a K_L**





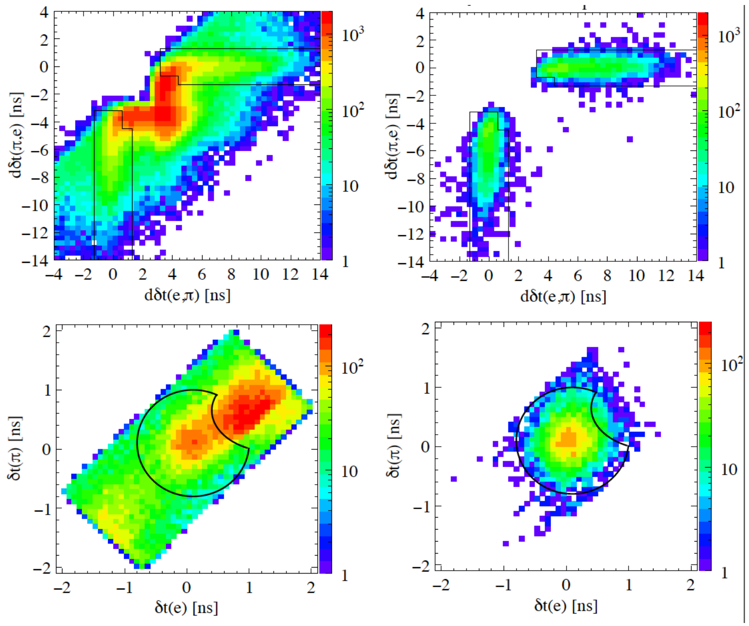


$$D = \frac{|<3\pi^0|\mathcal{T}|K_->|^2}{|<\pi^+\pi^-|\mathcal{T}|K_+>|^2} \simeq \frac{Br(K_L \to 3\pi^0)\Gamma_L}{Br(K_S \to \pi\pi)\Gamma_S}$$

CPT and T tests in neutral kaon transitions

- Analyzed sample: $L = 1.7\ \mathrm{fb}^{-1}$
- Selection of $\phi \to K_S K_L \to \pi^{\pm} e^{\mp} \nu\ \pi^0\pi^0\pi^0$
- Semileptonic decay identification with ToF technique

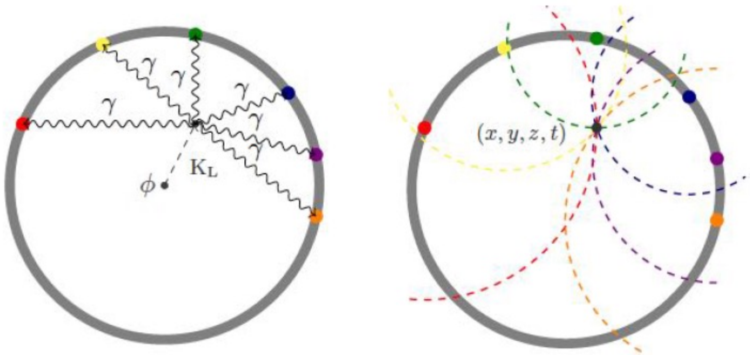
Data | MC – signal



$$\delta t(m_{e,\pi}) = T - \frac{L}{\beta(m_{e,\pi})} \qquad \beta(m_{e,\pi}) = \frac{p}{\sqrt{p^2 + m_{e,\pi}^2}}$$

$$d\delta t(e,\pi) = \delta t_1(m_e) - \delta t_2(m_\pi)$$

$$d\delta t(\pi,e) = \delta t_1(m_\pi) - \delta t_2(m_e)$$



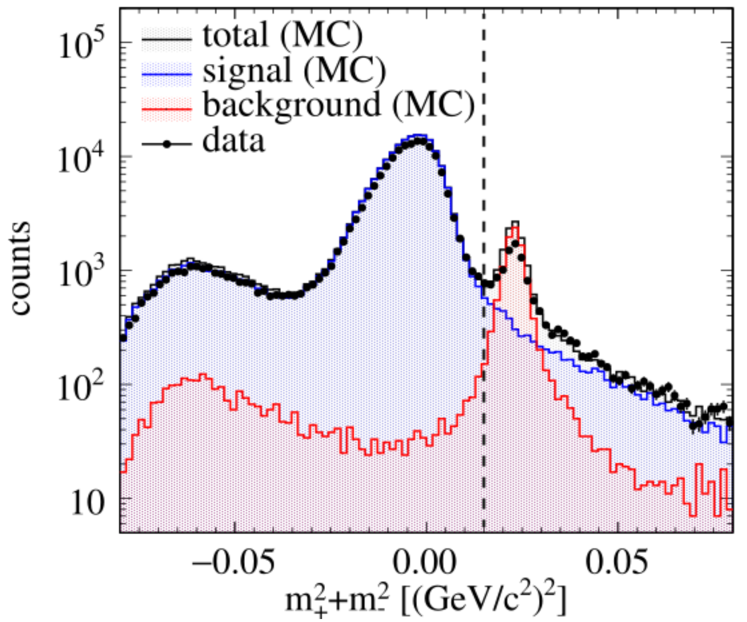
- $K_L \to \pi^0\pi^0\pi^0$: 6 photons in the EMC
- Neutral vertex reconstruction with trilateration method

CPT and T tests in neutral kaon transitions

- **Selection of $\phi \to K_S K_L \to \pi^+\pi^- \pi^\pm e^\mp \nu$:**
  - **Vertex with two tracks with opposite charge close to the I.P.**
  - **Late semileptonic decay, vertex with two tracks with opposite charge**

$$m^2_\pm = [E_K - E_\mp(\pi) - p^2_{miss}]^2 - p^2_\pm$$

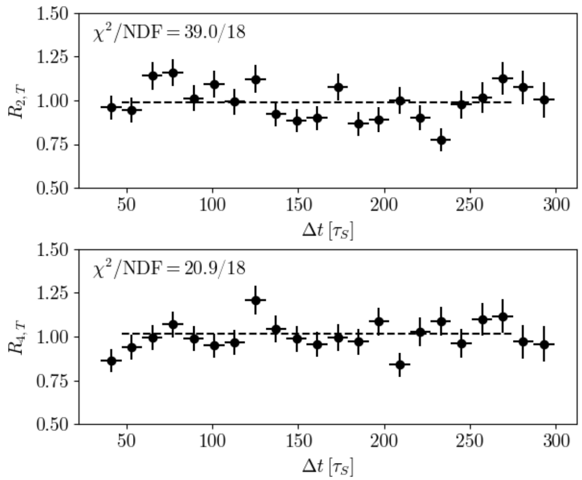
$$\vec{p}_{miss} = \vec{p}_K - \vec{p}_+ - \vec{p}_-$$



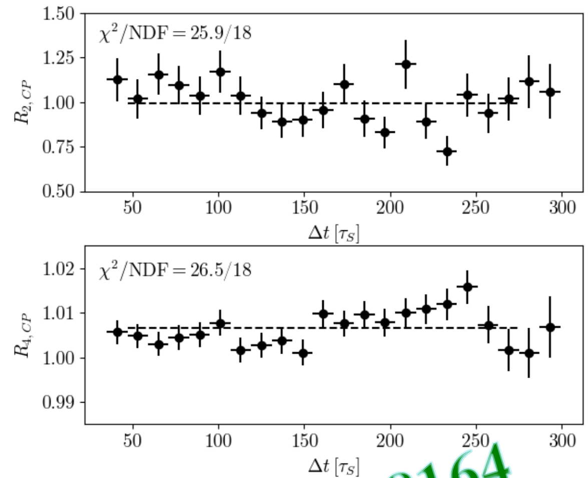
- **$E_\mp(\pi)$ is the energy of the charged track in the pion mass hypothesis**

CPT and T tests in neutral kaon transitions

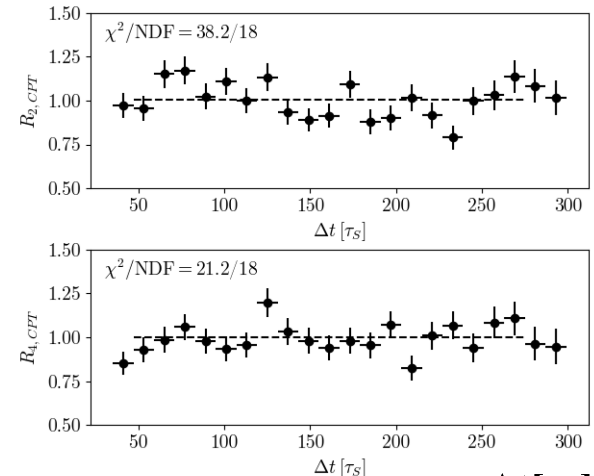
T-sensitive



CP-sensitive



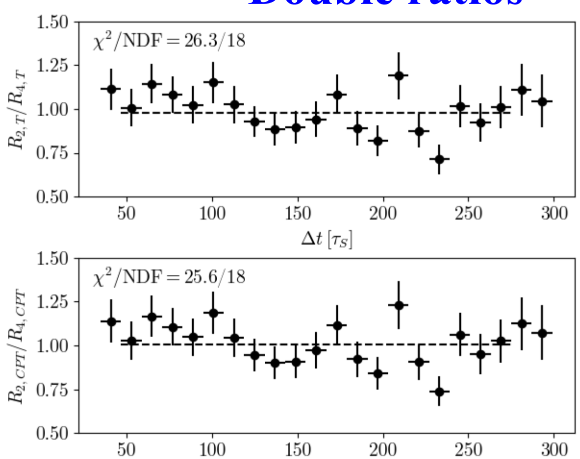
CPT-sensitive



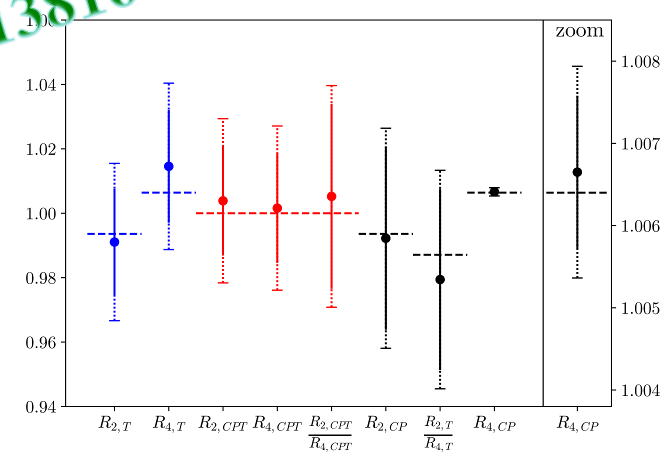
$\Delta t[\tau_S]$

PLB845(2023)138164

Double ratios



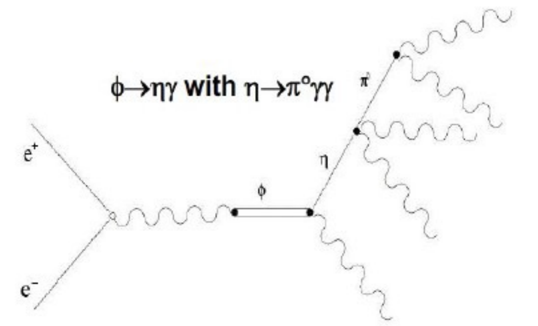
$\Delta t[\tau_S]$



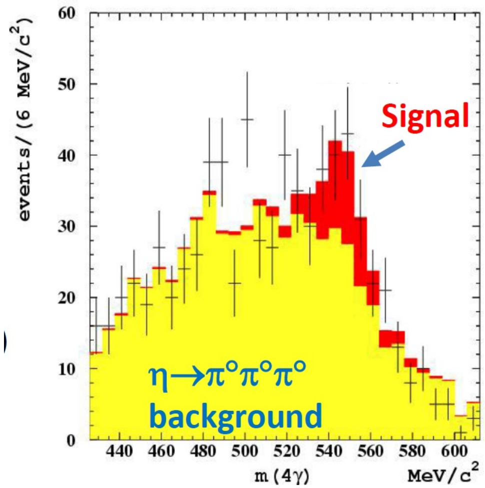
Expected: ---- T viol. from CP viol. assuming CPT
---- CPT invariance (exp. ratios =1)
---- CP viol. from PDG

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

- **ChPT golden mode ⇒ sensitive to $O(p^6)$, $O(p^2)$ null, $O(p^4)$ suppressed**

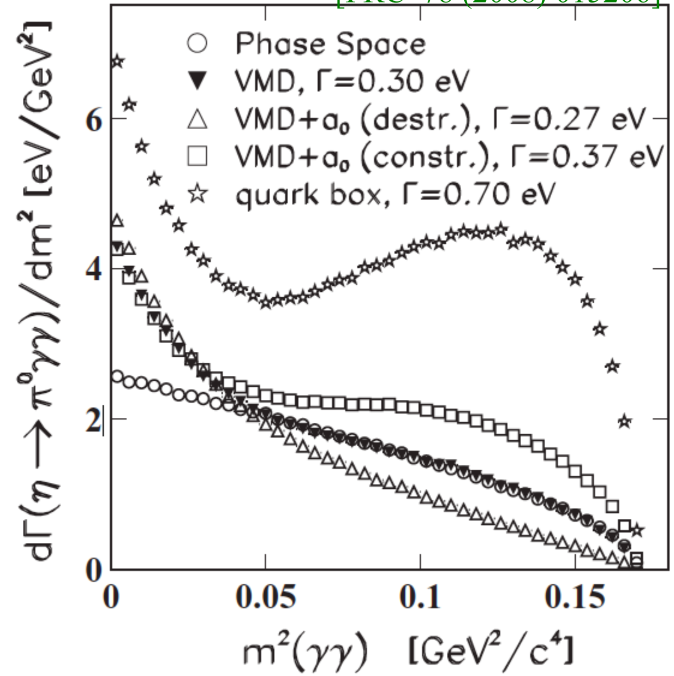


- **Br = $(2.21 \pm 0.24 \pm 0.47)\times 10^{-4}$ CB@AGS (2008)**
  [PRC 78 (2008) 015206]
  Br = $(2.52 \pm 0.25)\times 10^{-4}$ A2@MAMI (CB + TAPS) (2014)
  [PRC 90 (2014) 025206]
- **Old KLOE preliminary result:**
  $(0.84 \pm 0.30)\times 10^{-4}$
  (L = 450 pb^{-1} ~ 70 signal events)
  [Acta Phys.Slov.56(2006)403]



- **Invariant mass of non-π^0 photons can be used to test theoretical models**

[PRC 78 (2008) 015206]

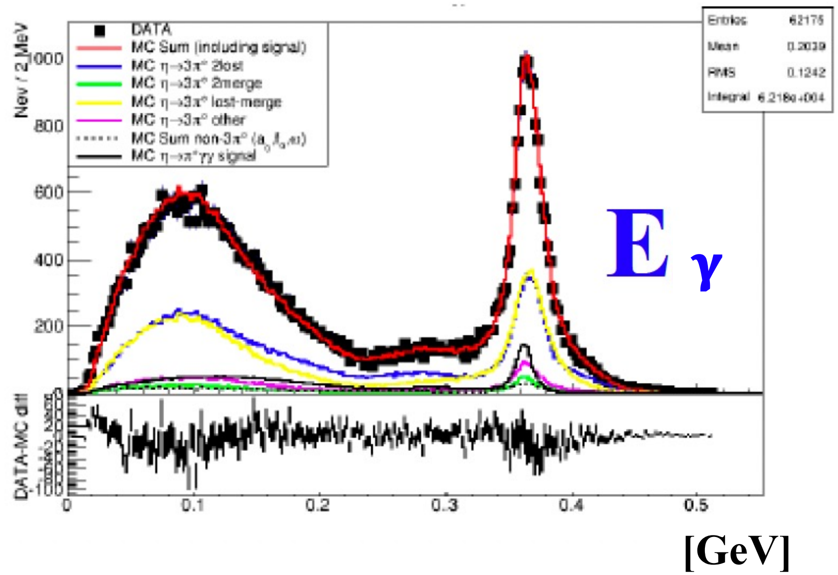


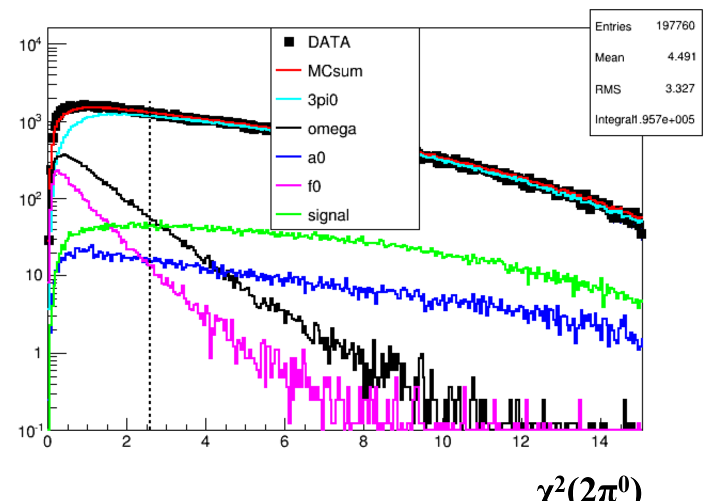
$\eta\to\pi^0\gamma\gamma$

- $\phi\to\eta\gamma$, $\eta\to\pi^0\gamma\gamma$ – L = 1.7 fb^{-1}
- Selected sample:
  fully neutral events with 5 prompt photons in the EMC
- Main bckg: $\phi\to\eta\gamma$, $\eta\to3\pi^0$
  with lost or merged photons
- Other bckg:
  - $\pi^0\pi^0\gamma$ final state from $\phi\to f_0(980)\gamma$ and $e^+e^-\to\omega\pi^0$ with $\omega\to\pi^0\gamma$
  - $\eta\pi^0\gamma$ from $\phi\to a_0(980)\gamma$

  ⇒ strongly reduced through kinematic fits with mass constraints
- Further cut to reduce the $\pi^0\pi^0\gamma$ events

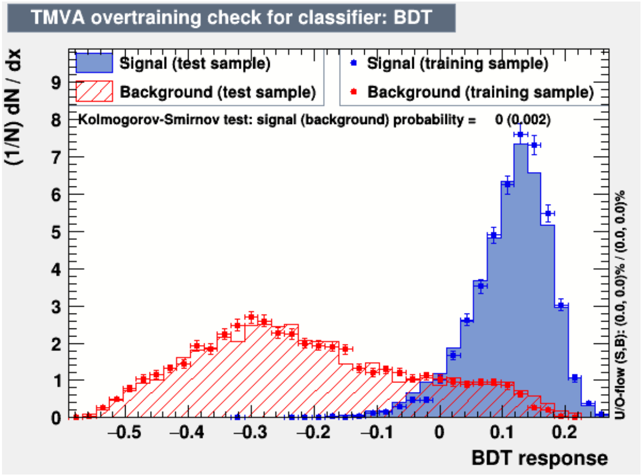
$$\chi^2(2\pi^0) = \frac{[\mathrm{m}(\gamma_1\gamma_2) - \mathrm{m}_{\pi^0}]^2}{\sigma^2(\gamma_1\gamma_2)} + \frac{[\mathrm{m}(\gamma_3\gamma_4) - \mathrm{m}_{\pi^0}]^2}{\sigma^2(\gamma_3\gamma_4)}$$

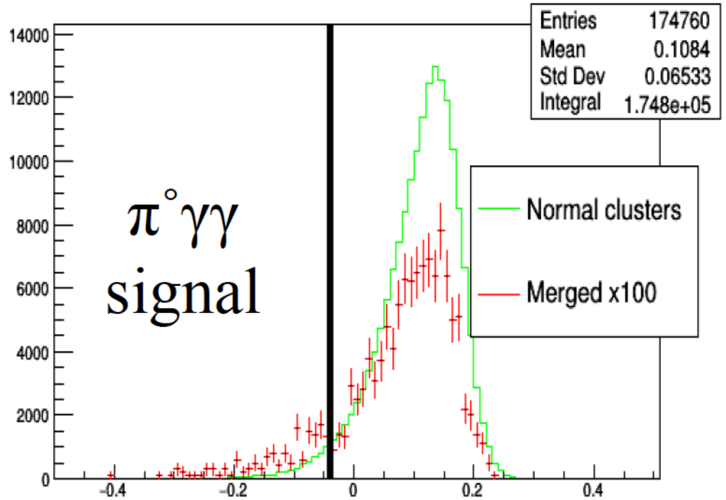


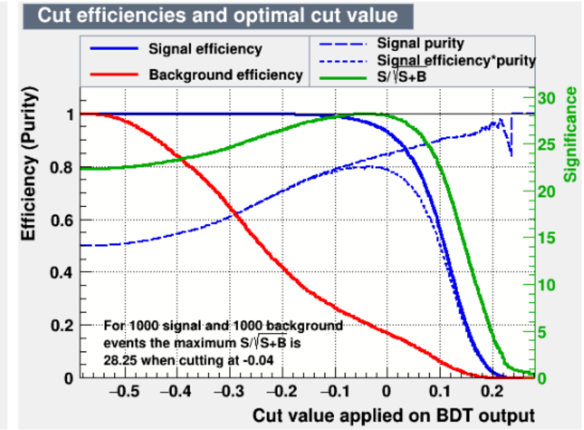


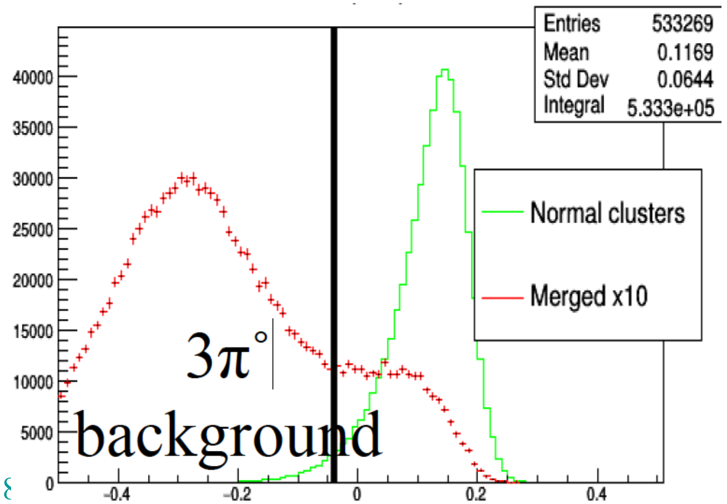
$\eta\to\pi^0\gamma\gamma$

- **Background $\eta\to3\pi^0$ with merged photons, reduced with Multivariate Analysis: BDT with 12 cluster shape variables**





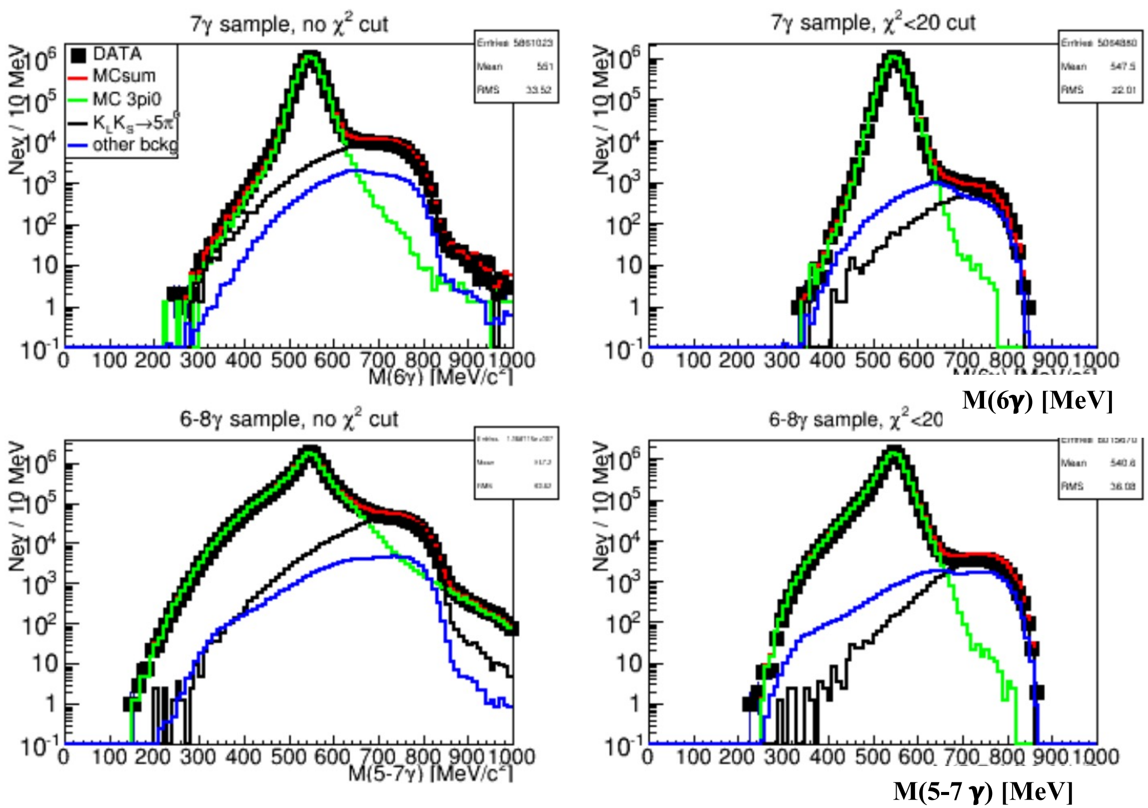




$\eta \to \pi^0 \gamma\gamma$

- **Normalization sample: $\phi \to \eta\gamma$, $\eta \to 3\pi^0$**
  ⇒ 7 prompt clusters, very clean, low background final state

- **N_η (8.13×10^7) evaluated from events with exactly 7 prompt photons, and checked with the sample with $6 \leq N_{prompt} \leq 8$**

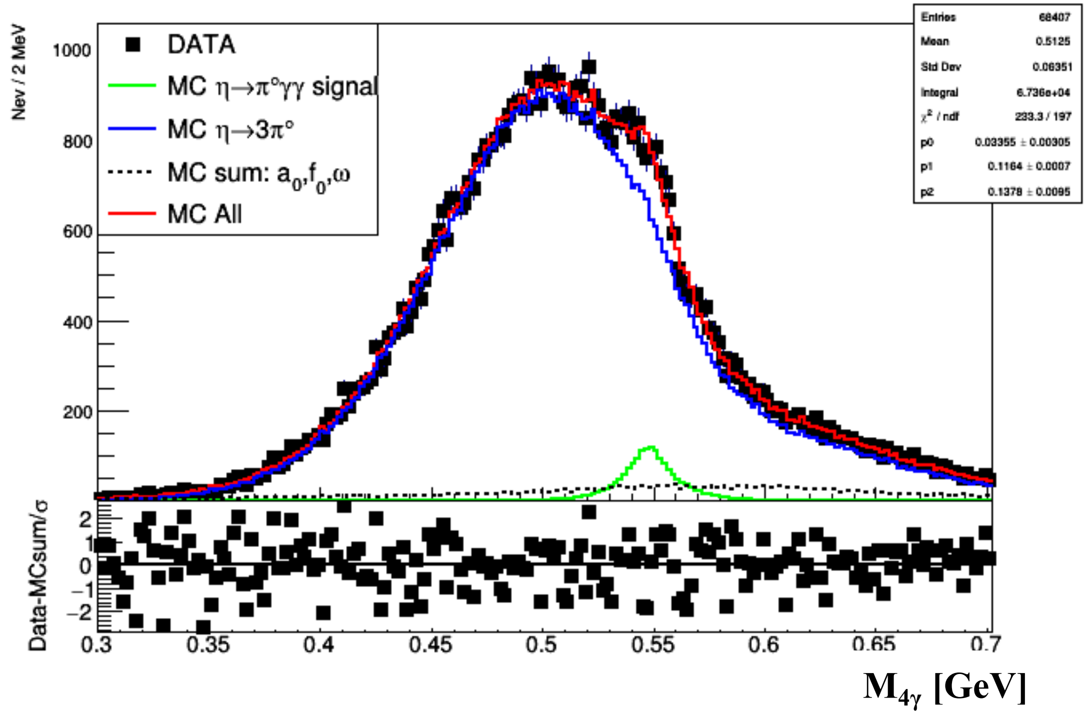


$\eta \rightarrow \pi^0 \gamma\gamma$

- **Signal extraction: fit with three components, using MC shapes for signal and bckg.**

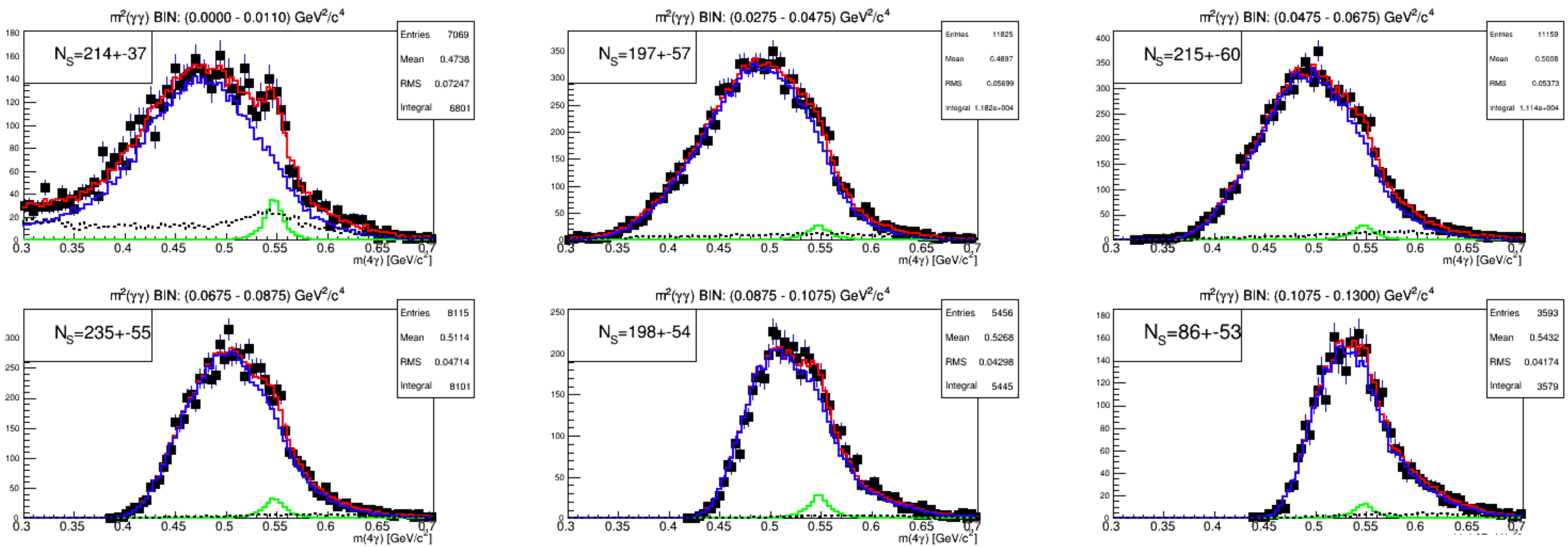
⇒ ~1200 signal events (same statistics as A2 measurement)

- **Agreement with our old preliminary result**
- **About 4 σ discrepancy with the other measurements**

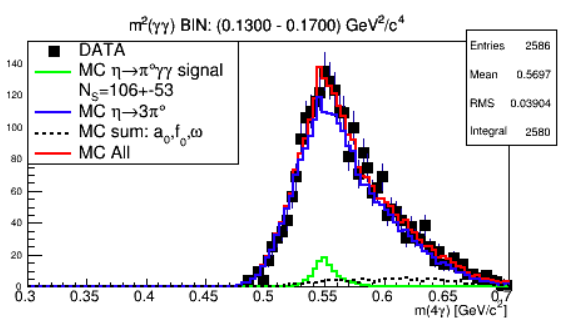


$Br(\eta \rightarrow \pi^0 \gamma\gamma) = (0.99 \pm 0.11_{stat} \pm 0.24_{syst}) \times 10^{-4}$

$d\Gamma(\eta\to\pi^0\gamma\gamma)/dM^2_{\gamma\gamma}$



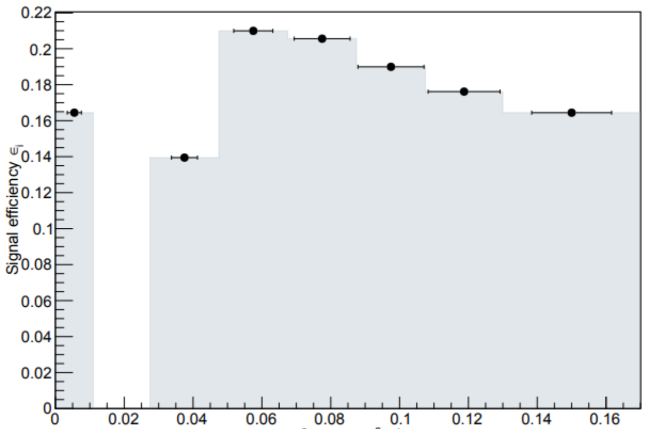
$M_{4\gamma}$ [GeV]



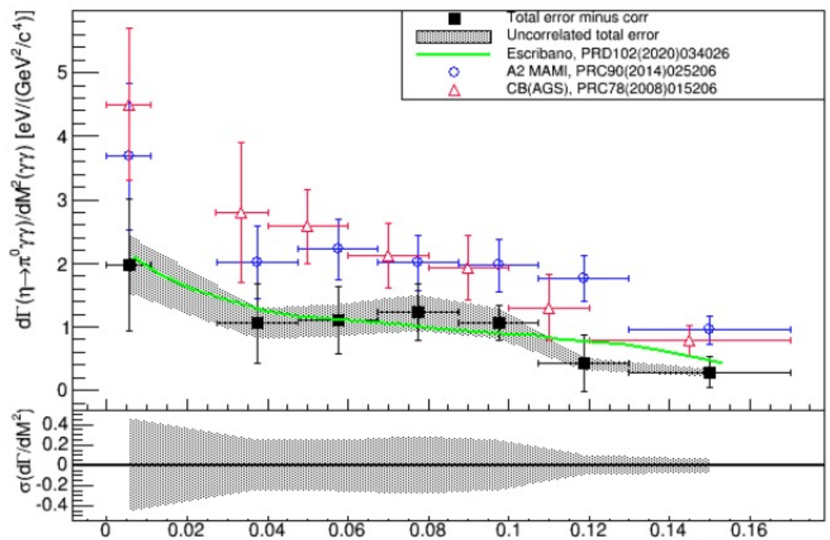
- Separate fits in bins of $M^2(\gamma\gamma)$
- Same binnning as in A2 analysis
- Bin 0.011-0.0275 GeV² missing due to $\pi^0\pi^0$ veto
- Good fit quality for all bins

$d\Gamma(\eta\to\pi^0\gamma\gamma)/dM^2_{\gamma\gamma}$

Efficiency vs $M^2_{\gamma\gamma}$



$M^2_{\gamma\gamma}$ [GeV^2]



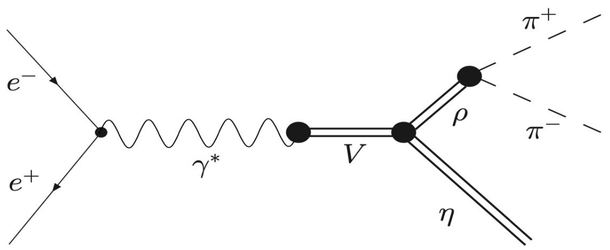
$M^2_{\gamma\gamma}$ [GeV^2]

- **From separate fits**
  $\Rightarrow Br(\eta\to\pi^0\gamma\gamma) = (1.01 \pm 0.11_{stat}) \times 10^{-4}$

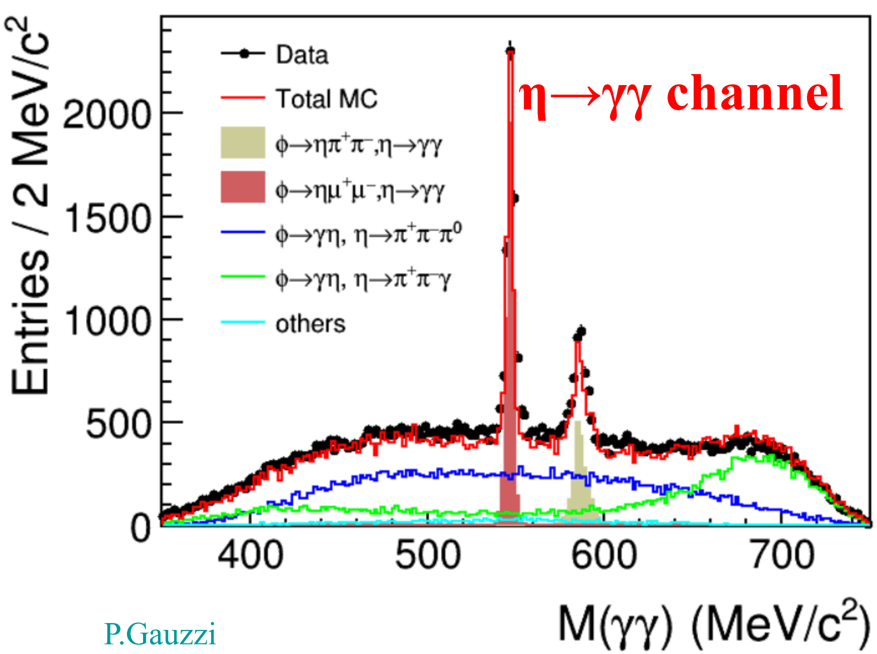
—— **Prediction based on LσM + VMD**
$\Rightarrow Br(\eta\to\pi^0\gamma\gamma) = (1.30 \pm 0.08) \times 10^{-4}$
[R.Escribano et al., PRD 102 (2020) 034026]

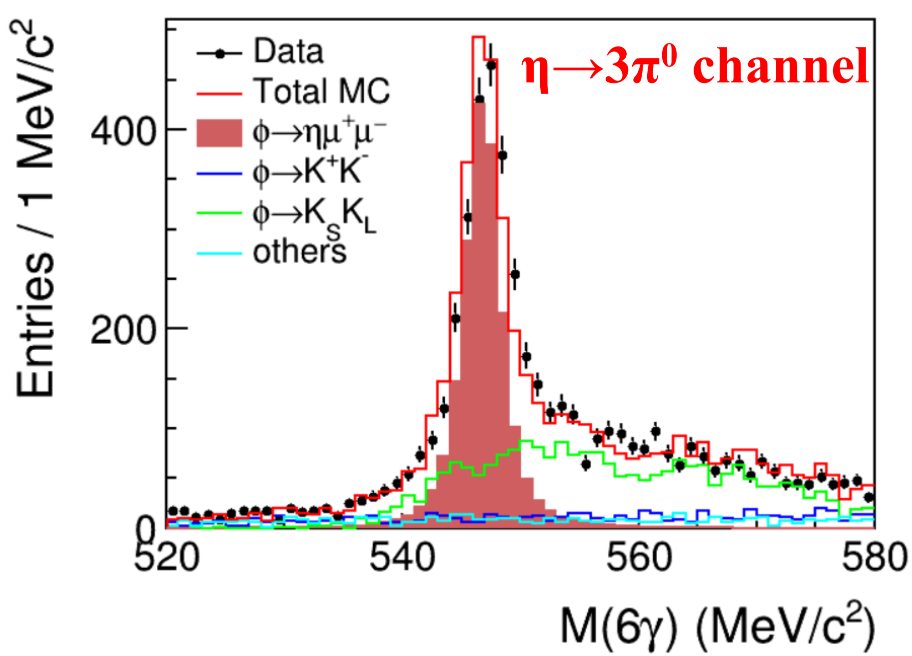
$\phi\to\eta\pi^+\pi^-, \eta\mu^+\mu^-$

- **In VMD models $e^+e^-\to\eta\pi^+\pi^-$ occurs through the $\rho\eta$ intermediate state**
- **$\phi\to\eta\pi^+\pi^-$ violates the OZI rule and G-parity**
  ⇒ Br($\phi\to\eta\pi^+\pi^-$) < 1.8 × 10^{-5} @ 90% C.L.
  [CMD-2, PLB491(2000)81]



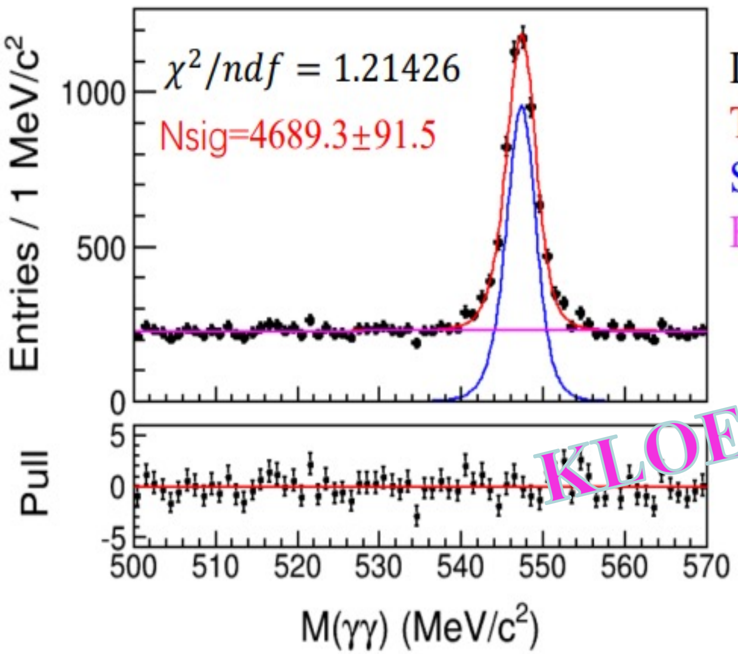
- **The same data sample can be used to search for the Dalitz decay $\phi\to\eta\mu^+\mu^-$**
  ⇒ Br($\phi\to\eta\mu^+\mu^-$) < 9.4 × 10^{-6} @90% C.L. [CMD-2, PLB501(2001)191]
- **Focus on $\phi\to\eta\mu^+\mu^-$ process, exploiting both $\eta\to\gamma\gamma$ and $\eta\to3\pi^0$ decays – L = 1.7 fb^{-1}**



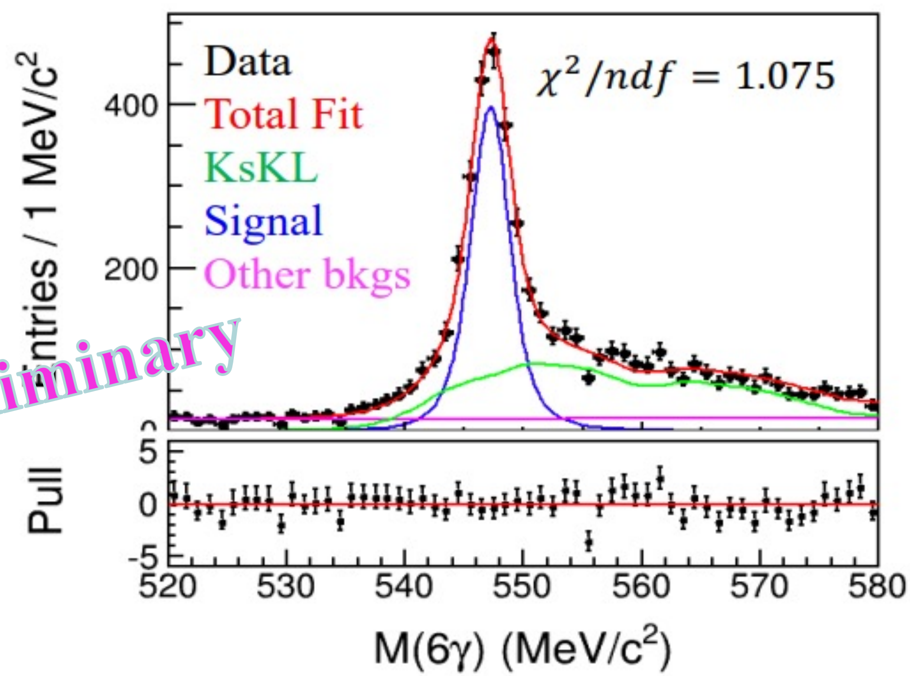


$\phi \rightarrow \eta \mu^+ \mu^-$

$\eta \rightarrow \gamma\gamma$



$\eta \rightarrow \pi^0\pi^0\pi^0$



$$Br(\phi \rightarrow \eta\mu^+\mu^-) = (5.65 \pm 0.11) \times 10^{-6}$$

$$Br(\phi \rightarrow \eta\mu^+\mu^-) = (5.76 \pm 0.19) \times 10^{-6}$$

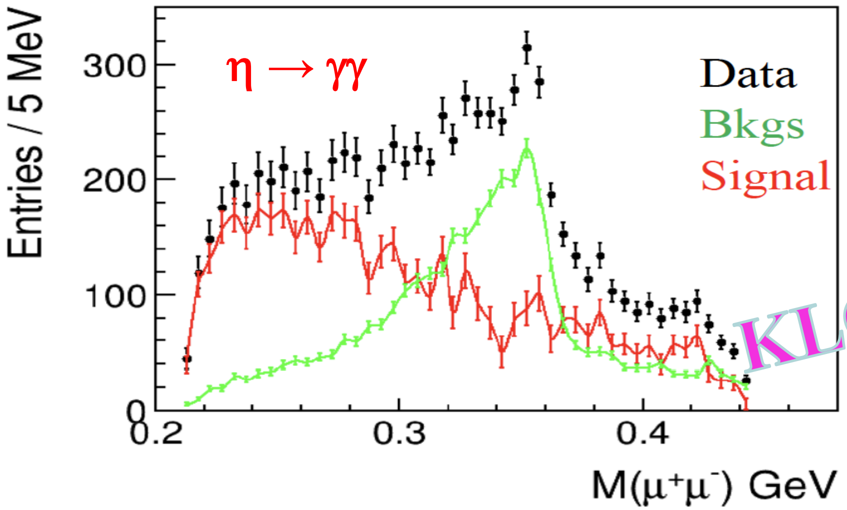
- **Systematic uncertainties under evaluation**

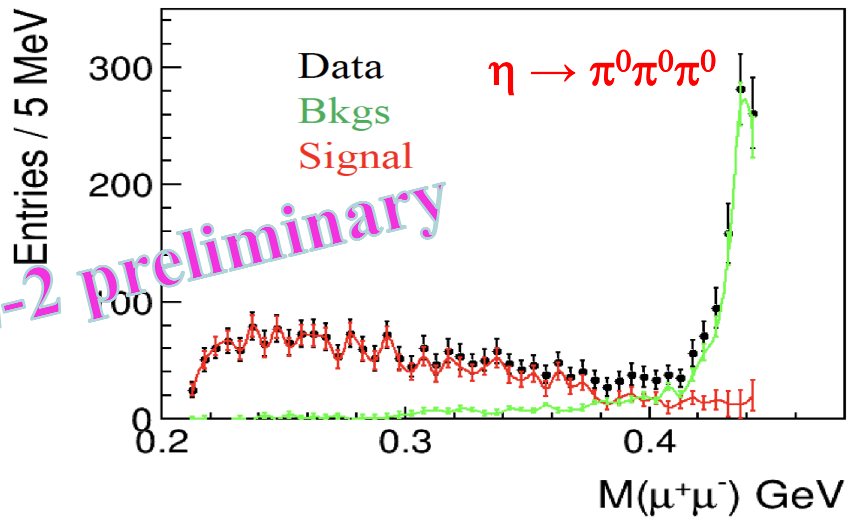
$\phi \rightarrow \eta\mu^+\mu^-$

- **The Transition Form Factor can be extracted from the distribution of $M_{\mu\mu}$**

$$\frac{1}{\Gamma(\phi \to \gamma\eta)}\frac{d\Gamma(\phi \to \eta\mu^+\mu^-)}{dq^2} = \left|F_{\phi\eta}(q^2)\right|^2 \times \frac{\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4M_\mu^2}{q^2}}\left(1+\frac{2M_\mu^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{M_\phi^2-M_\eta^2}\right)^2-\frac{4M_\phi^2 q^2}{(M_\phi^2-M_\eta^2)^2}\right]^{3/2}$$

- **According to VMD:** $F(q^2) = \dfrac{1}{1-\frac{q^2}{\Lambda^2}}$ $\quad \Lambda^{-2} = \left.\dfrac{dF}{dq^2}\right|_{q^2=0}$

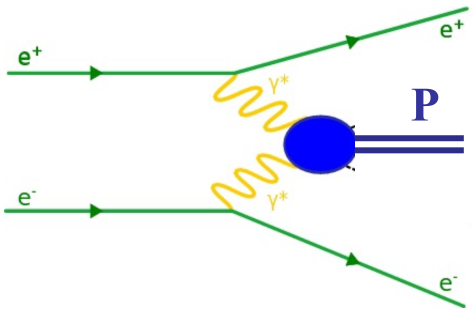




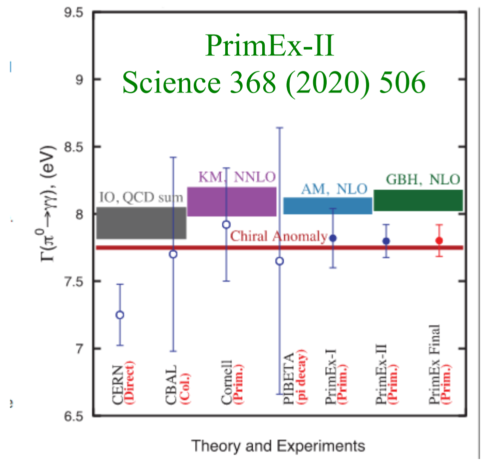
$\Lambda^{-2} = (3.01 \pm 0.10)\ \mathrm{GeV}^{-2}$ $\qquad$ $\Lambda^{-2} = (2.90 \pm 0.20)\ \mathrm{GeV}^{-2}$

$\gamma^*\gamma^* \to \pi^0$

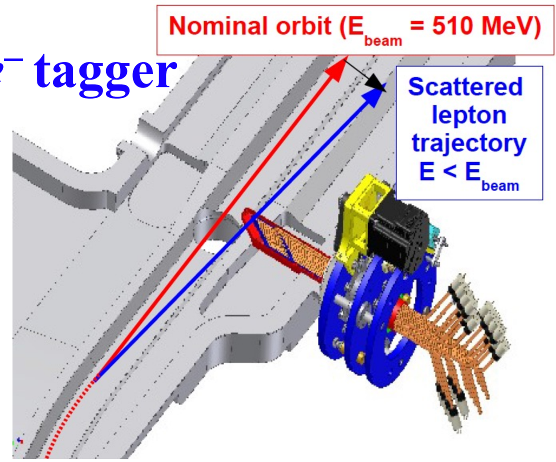
$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-\mathbf{P} \quad [\mathbf{C(P) = +1}]$



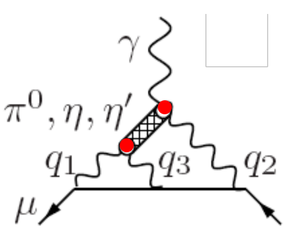
Goal: measurement of $\Gamma(\pi^0 \to \gamma\gamma)$ @ few % level



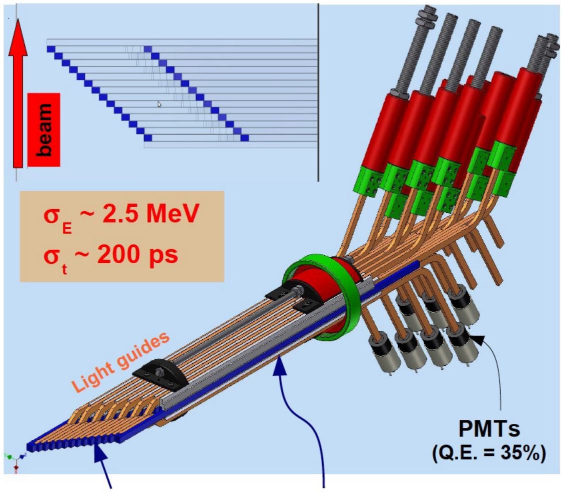
HET: e^+/e^- tagger



- **Transition Form Factor $\mathcal{F}_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2| < 0.1$ GeV^2), relevant for the Light-by-Light scattering contribution to $(g-2)_\mu$**



- **Bending dipoles of DAΦNE closer to IP act as spectrometers for the scattered e^+/e^-**
  Strong correlation between E and trajectory
- **Scintillator hodoscope + PMTs, inserted in Roman pots, pitch: 5 mm, ~ 11 m far from IP**



Plastic scintillators 5x3x6 mm^3 (28 ch. for each arm)

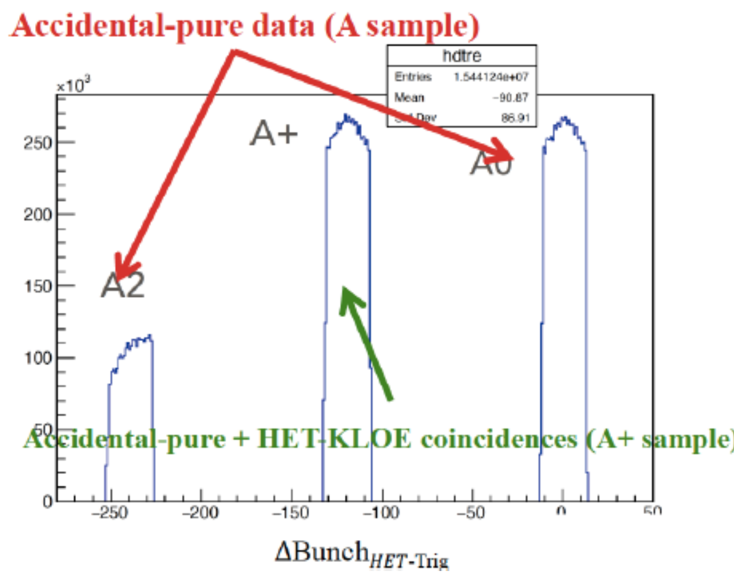
Plastic scintillator 5x3x130 mm^3 (1 ch. for each arm)

$\gamma^*\gamma^*\rightarrow\pi^0$

Single arm selection (L = 3 fb^{-1})

- **Two-clusters in the Barrel Calorimeter**
- **Selected bunch crossing and HET signal in a time window of 40 ns around the KLOE Trigger**

- **HET acquisition time corresponds to 2.5 DAΦNE revolutions**

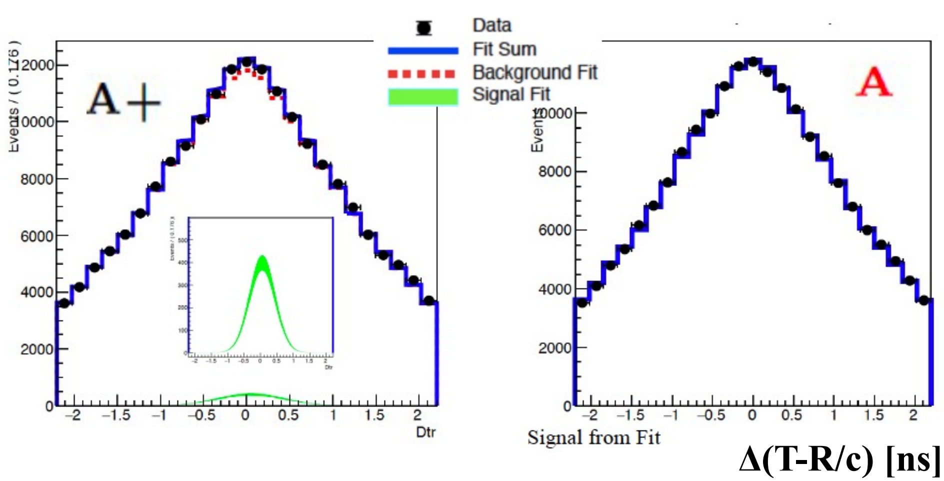


Analysis based on "A+"/"A" comparison:

- **"A+" sample: overlapping time window KLOE-HET (signal + bckg.)**
- **"A" sample: outside overlap window HET only**

- **Simultaneous fits on several variables**

- **Example of fit on one HET readout channel**



$\gamma^*\gamma^*\rightarrow\pi^0$

$$\frac{\sigma_{\pi^0}}{\sigma_{\rm Bha}} = \frac{N^{\rm meas}_{\pi^0}}{\epsilon_{\rm ana}\, N^{\rm meas}_{\rm Bha}} \frac{A_{\rm Bha}}{A_{\pi^0}}$$

$$N^{\rm meas}_{\rm Bha} = \sigma^{\rm meas}_{\rm Bha} \int {\rm Ldt}$$

$\int$ Ldt → from KLOE online

$\sigma^{\rm meas}_{\rm Bha}$ → measured at few % level

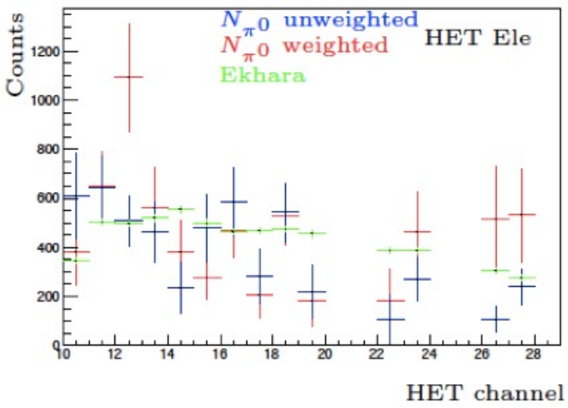
N_{π^0} counting: final checks on weights ongoing

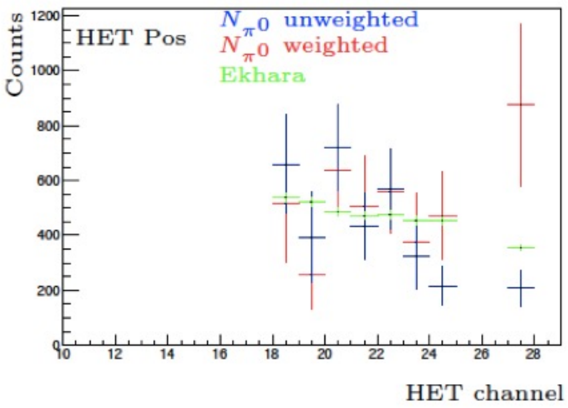
ε_{ana}: Analysis efficiency evaluation completed

Normalization to Radiative Bhabha at very small angle

Luminosity measurement from KLOE online and cross-checks with $e^+e^-\rightarrow\gamma\gamma$

$\frac{A_{\rm Bha}}{A_{\pi^0}}$: evaluation of systematics in progress

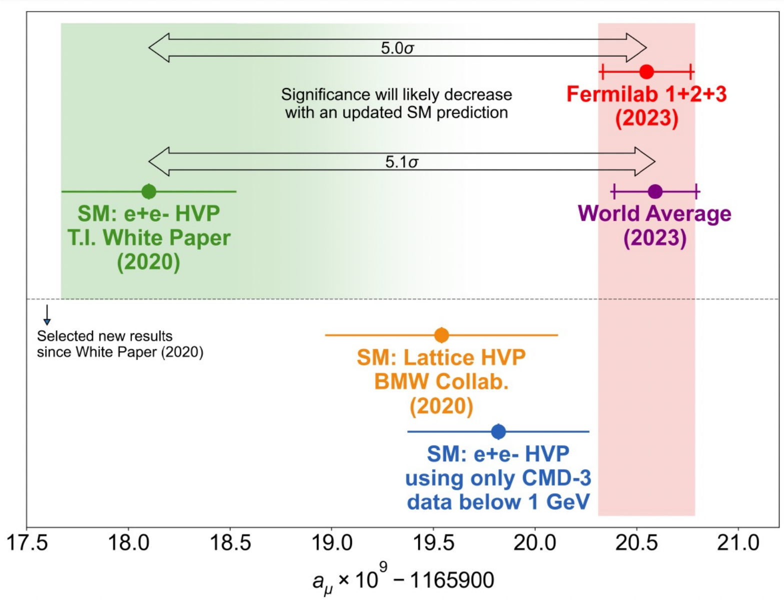




Combining electron + positron sides
⇒ 6.5 % precision

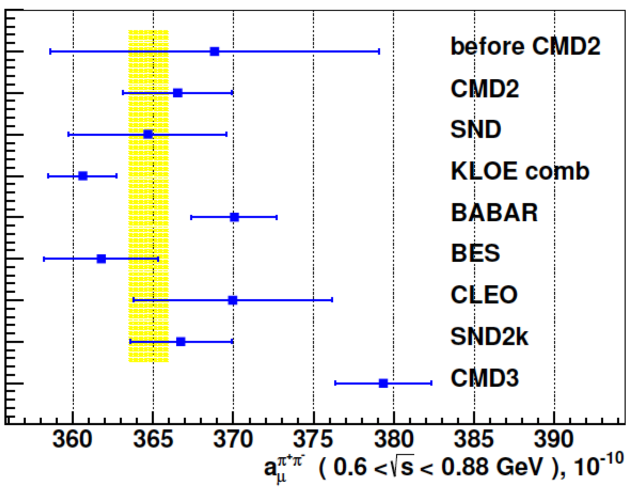
$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

- **Renewed interest in the KLOE data after the recent results of g-2 @ FNAL, and the measurement of the hadronic cross section with the energy scan method by CMD-3**



[G.Venanzoni, Muon g-2 @ EPS-HEP 2023]

[CMD-3, arXiv.2302.08834]



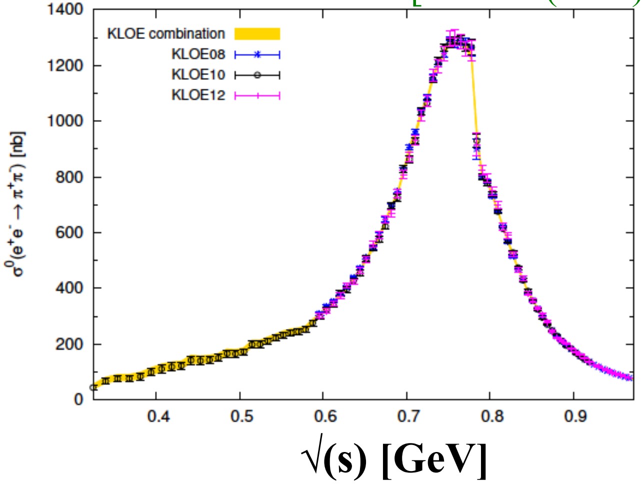
$e^+e^- \to \pi^+\pi^-\gamma_{ISR}$

KLOE measurements:

- **KLOE08: small angle analysis, 240 pb^{-1} @ M_ϕ**
  Phys.Lett.B670(2009)285
- **KLOE10: large angle analysis, 250 pb^{-1}@ 1 GeV**
  Phys.Lett.B700(2011)102
- **KLOE12: ratio $\pi^+\pi^-\gamma$ / $\mu^+\mu^-\gamma$, 240 pb^{-1} @ M_ϕ**
  Phys.Lett.B720(2013)336

$$a_\mu^{\pi\pi}[0.1 - 0.95\ \mathrm{GeV}^2] = (489 \pm 1.7 \pm 4.8) \times 10^{-10}$$

KLOE Combination [JHEP03(2018)173]



- **New measurement starting with the 2004-05 KLOE data sample L = 1.7 fb^{-1}**
  ~ 7 times the statistics of the old measurement

  (New group from Liverpool joined the Collaboration)
- **Blind analysis, to avoid any bias from previous results**
- **Aim: factor of about 2 improvement in the total uncertainty, measuring the hadronic cross-section at few permil level**

Conclusions

- **KLOE-2 data-taking completed on 2018**
  ~ 20 years after KLOE was turned on

- **KLOE + KLOE-2 sample ⇒ ~ 8 fb^{-1} – unique sample worldwide**
  ⇒ ~ 2.4 × 10^{10} ϕ's produced

- **The data sample collected by KLOE provided important results on decay dynamics of light mesons, Transition Form Factors, discrete symmetries of the nature, and also on searches for New Physics in the Dark Sector**

- **The high precision investigation on light hadron physics and on fundamental symmetries will continue with the analysis of the KLOE/KLOE-2 data**

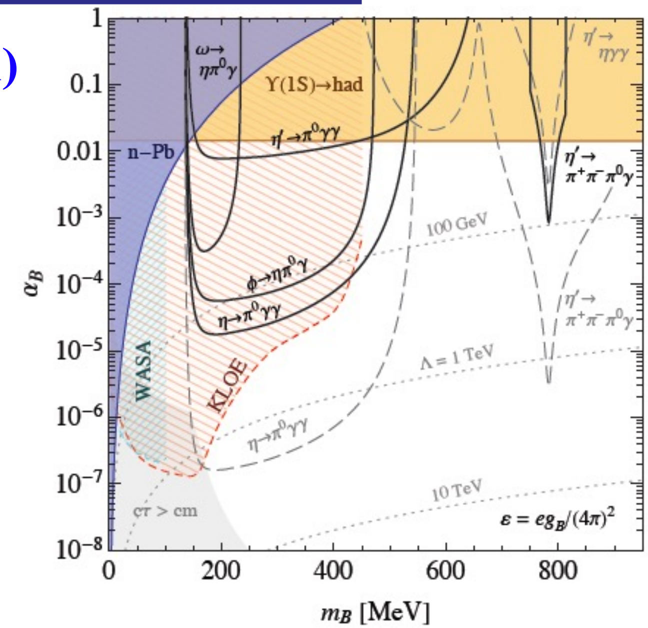
Spare

Leptophobic B-boson

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

- **Can have an impact in (g-2) muon anomaly**

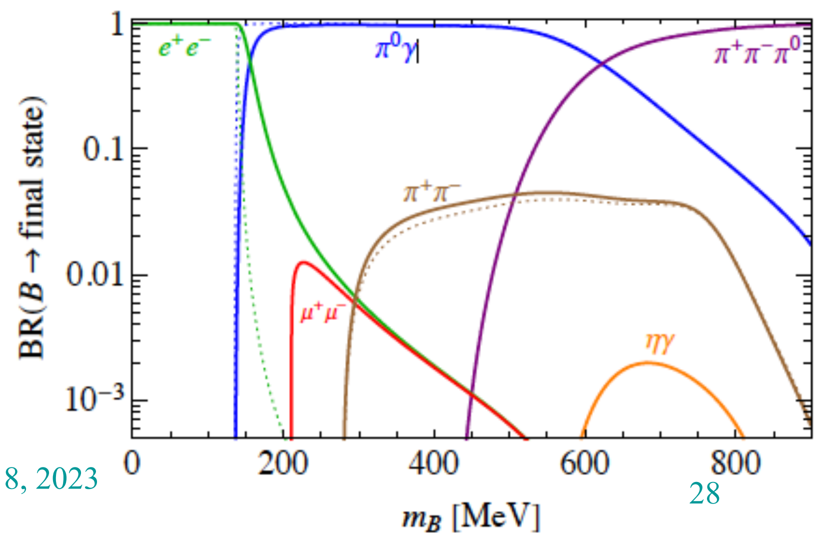
[S.Tulin, PRD89(2014)114008]



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

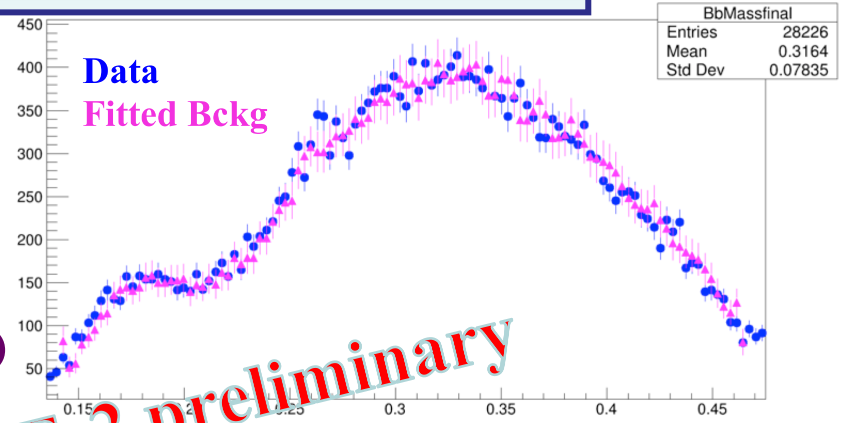
- **Dominant decay channel (m_B < 600 MeV):**
  $B \to \pi^0\gamma$

- **Can be searched for in:**
  $\phi \to \eta B \Rightarrow \eta\pi^0\gamma \Rightarrow$ 5 prompt γ final state
  $\phi \to \eta\gamma$, with $\eta \to B\gamma \Rightarrow \eta \to \pi^0\gamma\gamma$
  $e^+e^- \to B\gamma_{ISR} \to \pi^0\gamma\, \gamma_{ISR}$



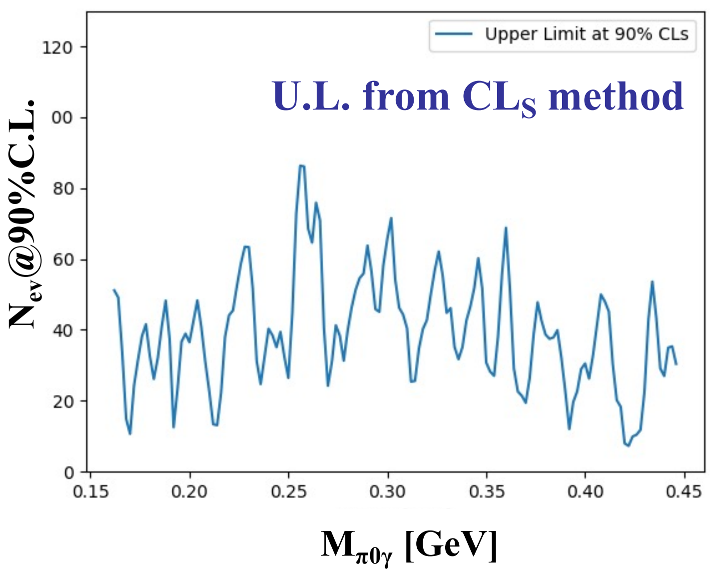
Leptophobic B-boson

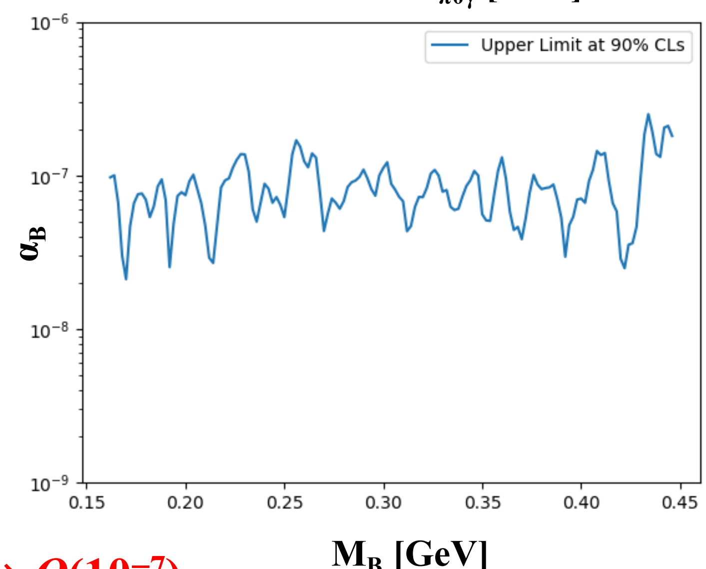
- L = 1.7 fb^{-1} analyzed, 5 prompt photon events
- Main background from $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$ and $\phi \to \eta\gamma \to 3\pi^0\gamma$ with lost/merged photons
- Background evaluation from sidebands (fit region 5 σ with 1σ exclusion region, σ ~ 2 MeV)



KLOE-2 preliminary

$M_{\pi^0\gamma}$ [GeV]





- Upper limit at 90% C.L. on the coupling $\alpha_B \Rightarrow O(10^{-7})$

CPT and T tests in neutral kaon transitions

$$R_{2,\mathrm{T}} \equiv \frac{R^{\mathrm{exp}}_{2,\mathrm{T}}(\Delta t \gg \tau_S)}{D} = 1 - 4\Re\epsilon + (4\Re x_+ + 4\Re y)\,,$$

$$R_{4,\mathrm{T}} \equiv \frac{R^{\mathrm{exp}}_{4,\mathrm{T}}(\Delta t \gg \tau_S)}{D} = 1 + 4\Re\epsilon + (4\Re x_+ - 4\Re y)\,,$$

$$R_{2,\mathrm{CP}} \equiv R^{\mathrm{exp}}_{2,\mathrm{CP}}(\Delta t \gg \tau_S) = 1 - 4\Re\epsilon_S + (4\Re y - 4\Re x_-)\,,$$

$$R_{4,\mathrm{CP}} \equiv R^{\mathrm{exp}}_{4,\mathrm{CP}}(\Delta t \gg \tau_S) = 1 + 4\Re\epsilon_L - (4\Re y + 4\Re x_-)\,,$$

$$R_{2,\mathrm{CPT}} \equiv \frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{D} = 1 - 4\Re\delta + (4\Re x_+ - 4\Re x_-)\,,$$

$$R_{4,\mathrm{CPT}} \equiv \frac{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)}{D} = 1 + 4\Re\delta + (4\Re x_+ + 4\Re x_-)\,,$$

$$DR_{\mathrm{T,CP}} \equiv \frac{R_{2,\mathrm{T}}}{R_{4,\mathrm{T}}} \equiv \frac{R_{2,\mathrm{CP}}}{R_{4,\mathrm{CP}}} = 1 - 8\Re\epsilon + (8\Re y)\,,$$

$$DR_{\mathrm{CPT}} \equiv \frac{R_{2,\mathrm{CPT}}}{R_{4,\mathrm{CPT}}} = 1 - 8\Re\delta - (8\Re x_-)\,,$$

$\epsilon_{S,L} = \epsilon \pm \delta$ ⇒ CP, T, and CPT viol. parameters

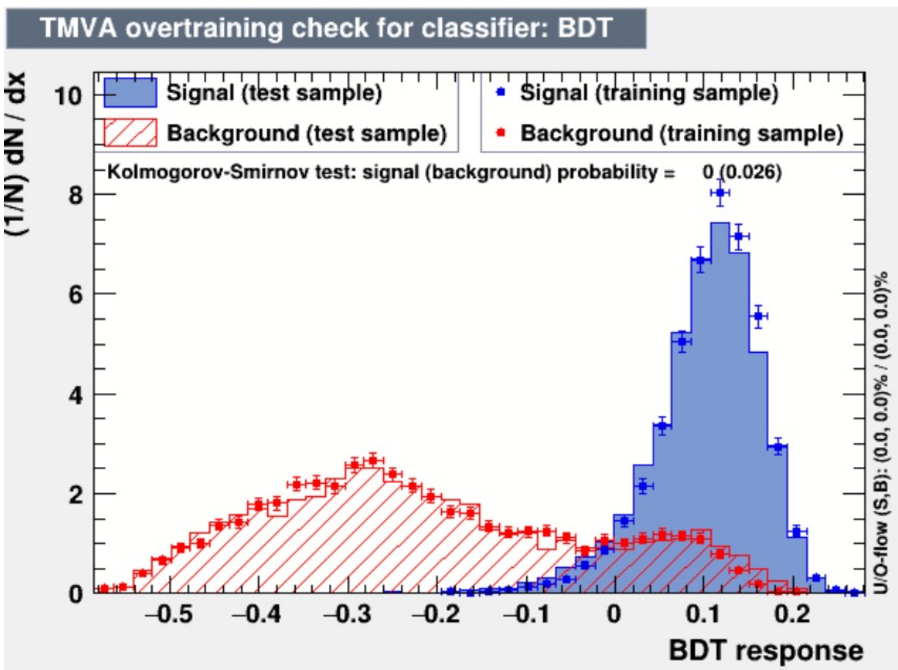
y ⇒ CPT viol. assuming $\Delta S = \Delta Q$

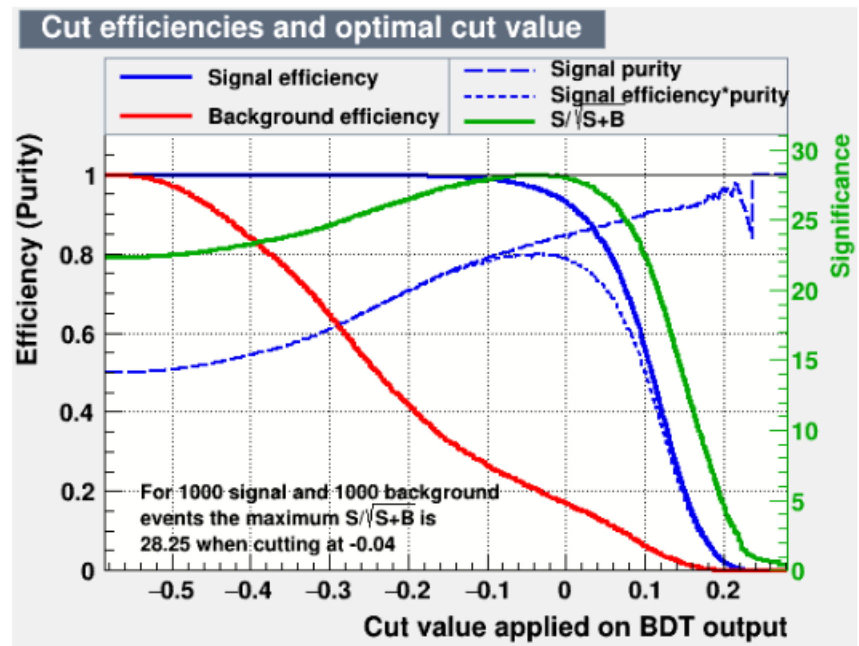
x_+ ⇒ CPT invariance with $\Delta S \neq \Delta Q$

x_- ⇒ CPT violation with $\Delta S \neq \Delta Q$

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

- **Rejection of $\eta\to3\pi^0$ with merged photons with Multivariate Analysis based on cluster shape variables on the EMC**

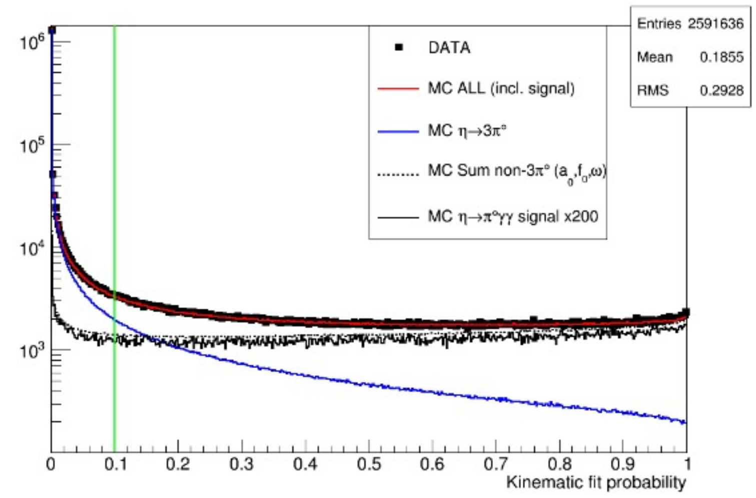




$\eta \to \pi^0 \gamma\gamma$

Analysis scheme:

1. **5 prompt γ's, with $E_{tot} > 800$ MeV, with $E_\gamma > 20$ MeV and $\vartheta_\gamma > 25^\circ$**
2. **No charged tracks in the drift chamber**
3. **Kinematic fit with energy-momentum conservation and prompt photon conditions (9 constraints) $P(\chi^2) > 10\%$**



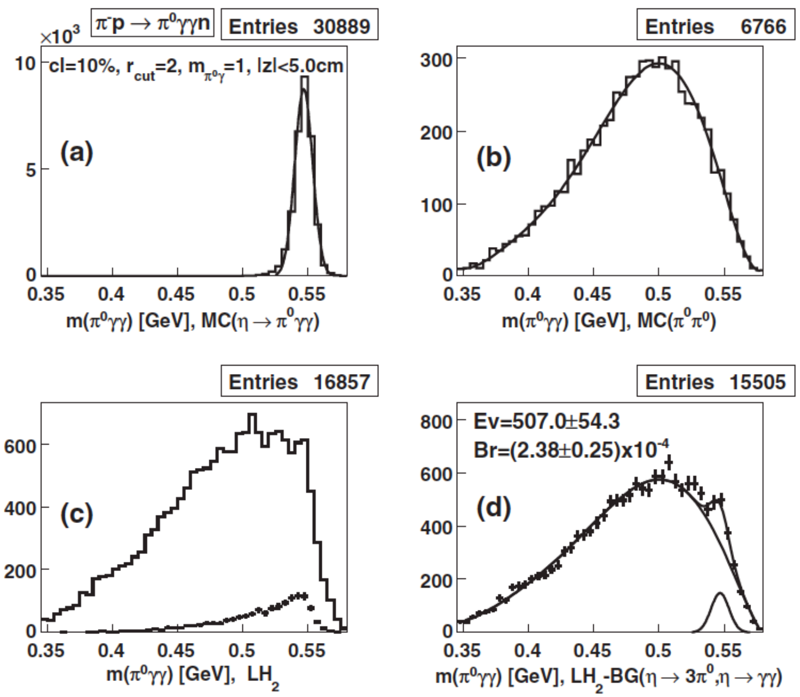
4. **Kinematic fit with 11 constraints (9 + mass of η and π^0) to reject $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$ events $P(\chi^2) < 10\%$**
5. **Kinematic fit with 11 constraints (9 + 2 π^0 masses) to reject $\pi^0\pi^0\gamma$ events ($\phi \to f_0(980)\gamma$ and $e^+e^- \to \omega\pi^0$ with $\omega \to \pi^0\gamma$) $P(\chi^2) < 10\%$**

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

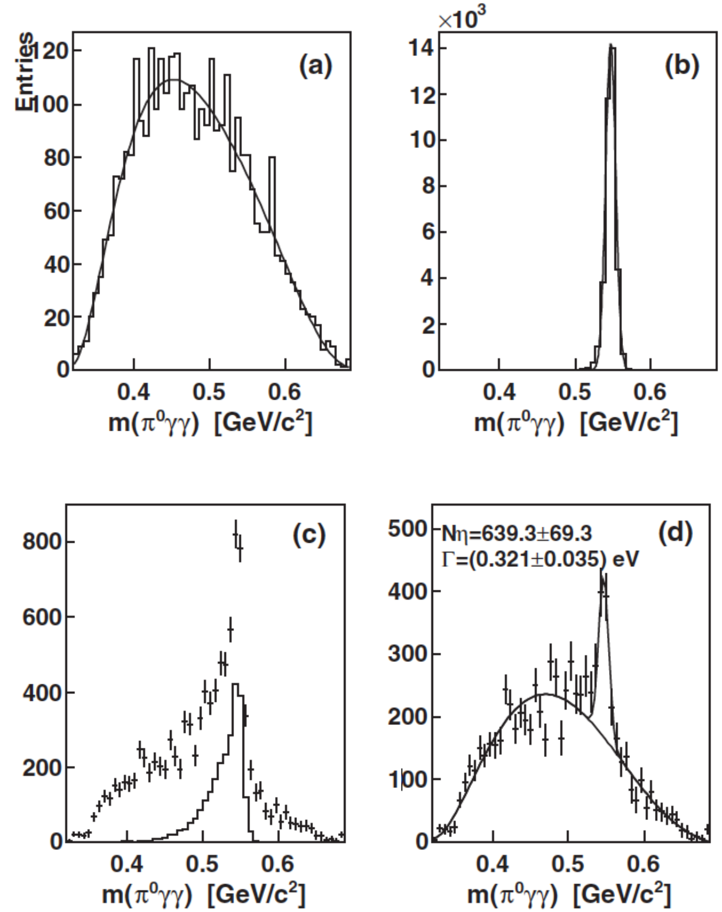
6. **Photon pairing** $\chi^2(2\pi^0) = \frac{[\mathbf{m}(\gamma_1\gamma_2) - \mathbf{m}_{\pi^0}]^2}{\sigma^2(\gamma_1\gamma_2)} + \frac{[\mathbf{m}(\gamma_3\gamma_4) - \mathbf{m}_{\pi^0}]^2}{\sigma^2(\gamma_3\gamma_4)}$ **$\chi^2 < 2.6$**

7. **Kinematic fit to reject $\eta \to 3\pi^0$ background with lost γ's, 9 constraints ⇒ momenta of the 2 missing γ's from fit, if there is no solution ⇒ event retained (good event)**
8. **MVA analysis to reject $\eta \to 3\pi^0$ with merged γ's**

Crystal Ball / A2



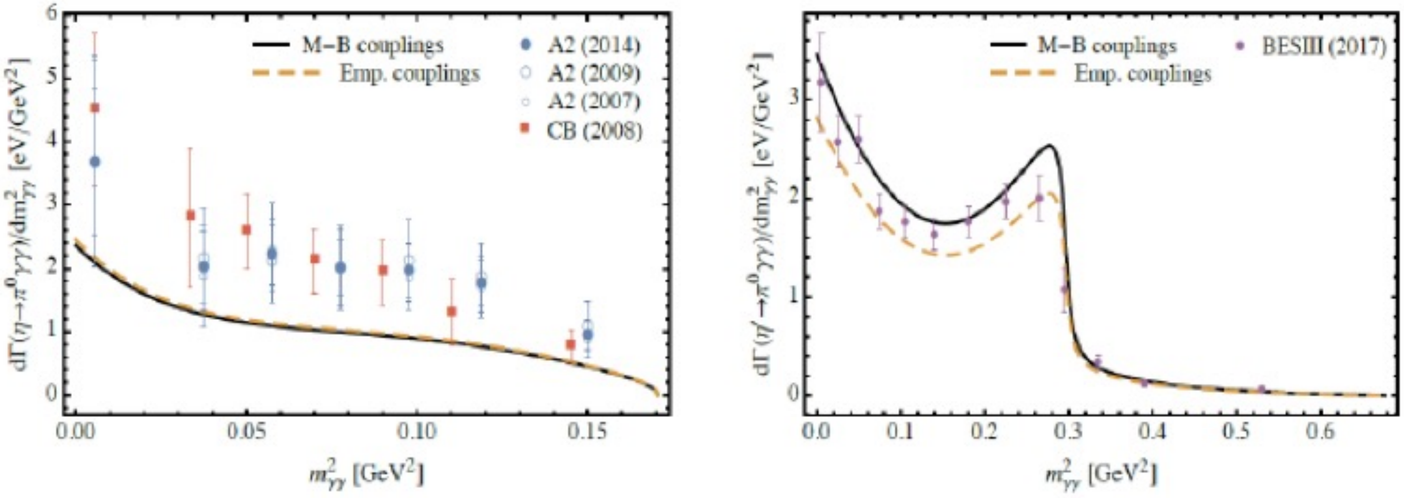
[PRC 78 (2008) 015206]



[PRC 90 (2014) 025206]

New $\eta \to \pi^0 \gamma\gamma$ prediction

- **Escribano et al., PRD102(2020)034026**
- **Prediction based on VMD + LσM**
- **Within the same framework they are able to predict the $M^2_{\gamma\gamma}$ spectrum of $\eta' \to \pi^0 \gamma\gamma$ from BESIII** [PRD96(2017)012005]



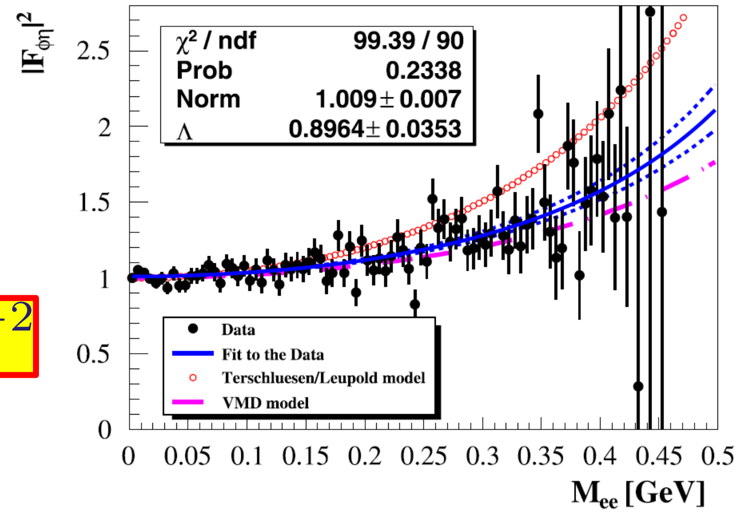
(a) $\eta \to \pi^0\gamma\gamma$ decay. (b) $\eta' \to \pi^0\gamma\gamma$ decay.

TFFs from Dalitz decays

- $\phi \to \eta e^+e^-$, $\eta \to \pi^0\pi^0\pi^0$

$$\Lambda^{-2} = (1.28 \pm 0.10 \pm 0.09)\mathrm{GeV}^{-2}$$

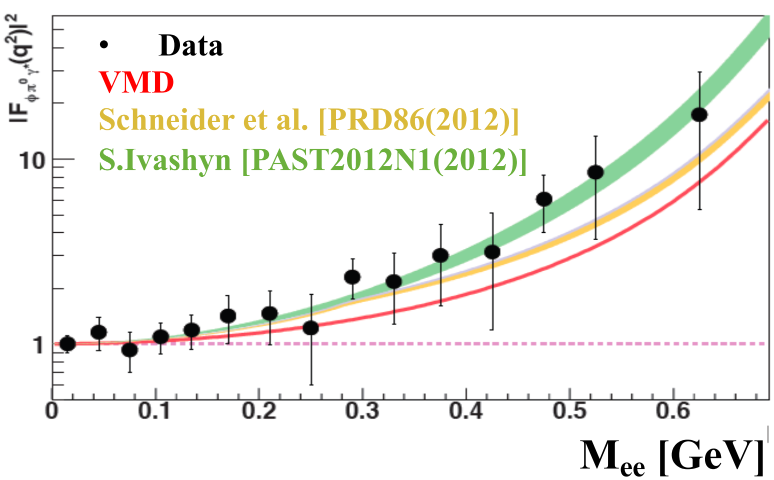
[KLOE - PLB742(2015)1]



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

$$\Lambda^{-2} = (2.02 \pm 0.11)\ \mathrm{GeV}^{-2}$$

[KLOE - PLB757(2016)362]



KLOE-2 Physics

Kaon Physics:
- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \rightarrow 3\pi^0$
  direct measurement of $Im(\varepsilon'/\varepsilon)$
- CKM V_{us}:
  K_S semileptonic decays and A_S
  (CP and CPT test)
  $K_{\mu 3}$ form factors, K_{l3} radiative corrections
- χpT : $K_S \rightarrow \gamma\gamma$
- Search for rare K_S decays

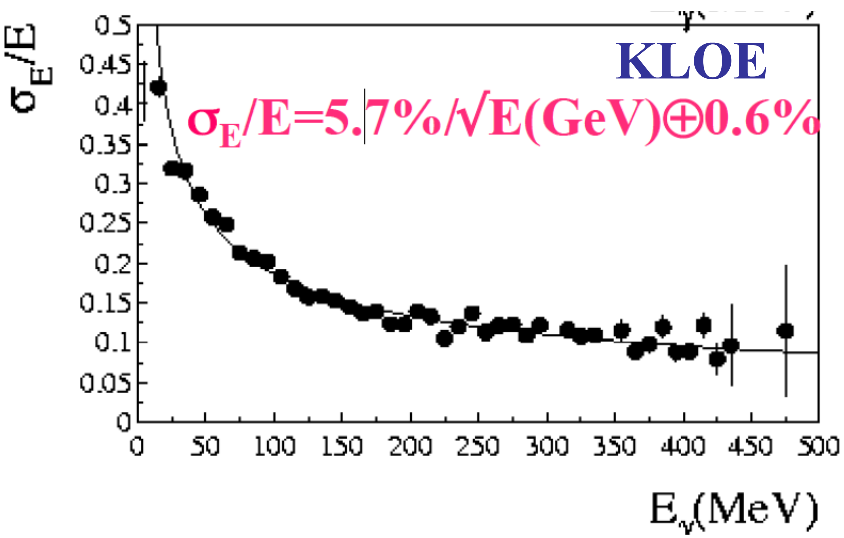
Light meson Physics:
- η decays, ω decays
- Transition Form Factors
- C,P,CP violation: improve limits on
  $\eta \rightarrow \gamma\gamma\gamma,\ \pi^+\pi^-,\ \pi^0\pi^0,\ \pi^0\pi^0\gamma$
- $\eta \rightarrow \pi^+\pi^- e^+ e^-$
- ChPT : $\eta \rightarrow \pi^0\gamma\gamma$
- Light scalar mesons: $f_0(500)$ in $\phi \rightarrow K_S K_S \gamma$
- γγ Physics: $\gamma\gamma \rightarrow \pi^0$ and π^0 TFF
- $e^+e^- \rightarrow \pi^0\gamma\gamma_{ISR}$ (π^0 TFF)

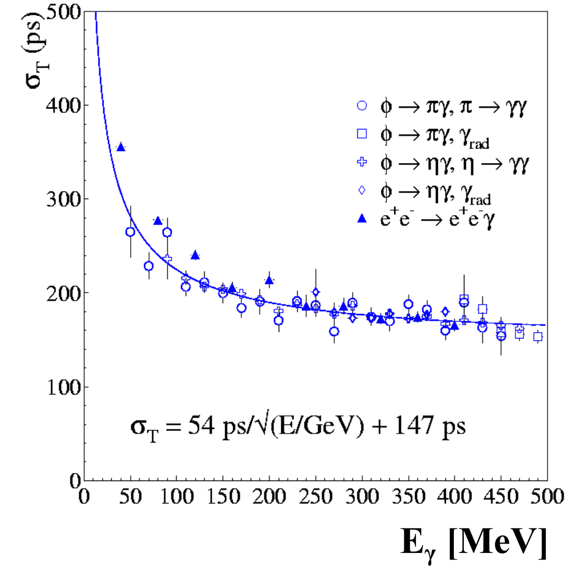
Hadronic cross section:
- ISR studies: 2π, 3π, 4π final states
- F_π with increased statistics

Dark force searches:
- Improve limits on
  - Uγ associate production
    $e^+e^- \rightarrow U\gamma \rightarrow \pi\pi\gamma,\ \mu\mu\gamma$
  - Higgsstrahlung:
    $e^+e^- \rightarrow Uh' \rightarrow \mu^+\mu^- +$ miss. energy
- Leptophobic B boson search:
  $\phi \rightarrow \eta B,\ B \rightarrow \pi^0\gamma,\ \eta \rightarrow \gamma\gamma$
  $\eta \rightarrow B\gamma,\ B \rightarrow \pi^0\gamma$
- Search for axion-like particles

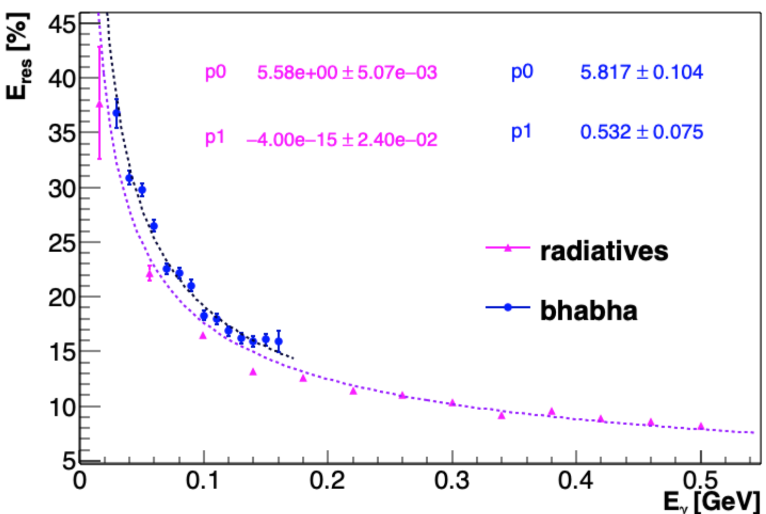
- KLOE-2 Coll., EPJC68(2010)619
- EPJ WoC 166 (2018)

KLOE EMC resolutions

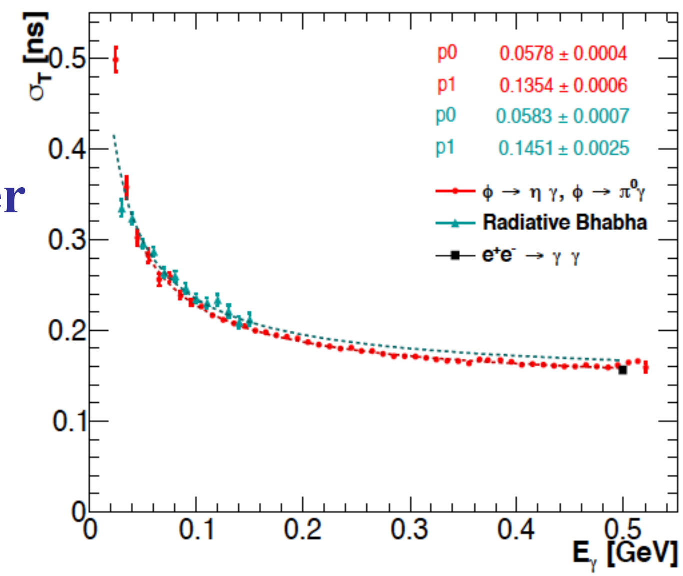




KLOE -2



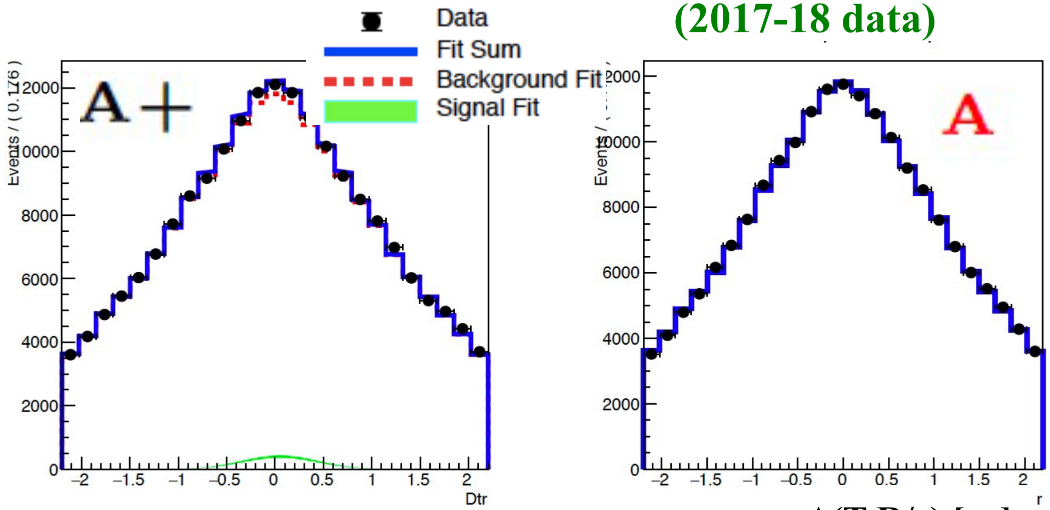
> 15 years after



$\gamma\gamma \rightarrow \pi^0$

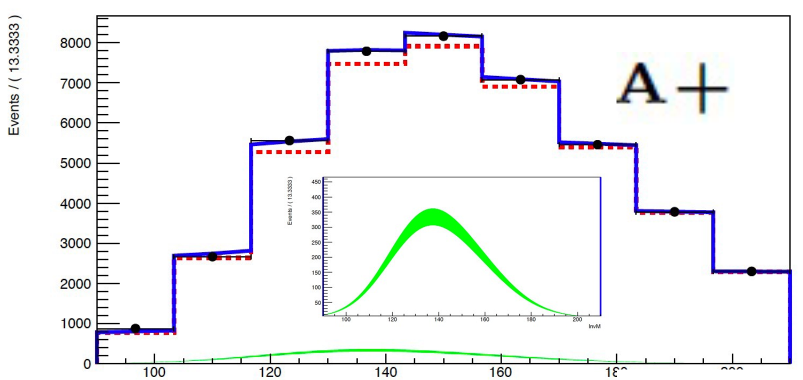
- **Example of fit on one HET readout channel**

(2017-18 data)



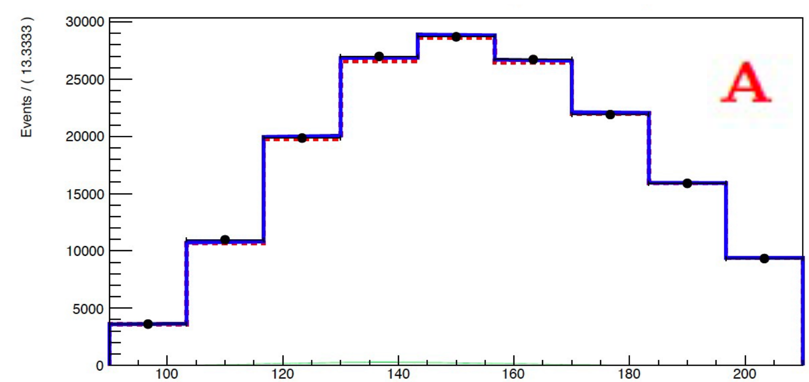
Δ(T-R/c) [ns]

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



$M_{\gamma\gamma}$ [MeV]

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



$M_{\gamma\gamma}$ [MeV]

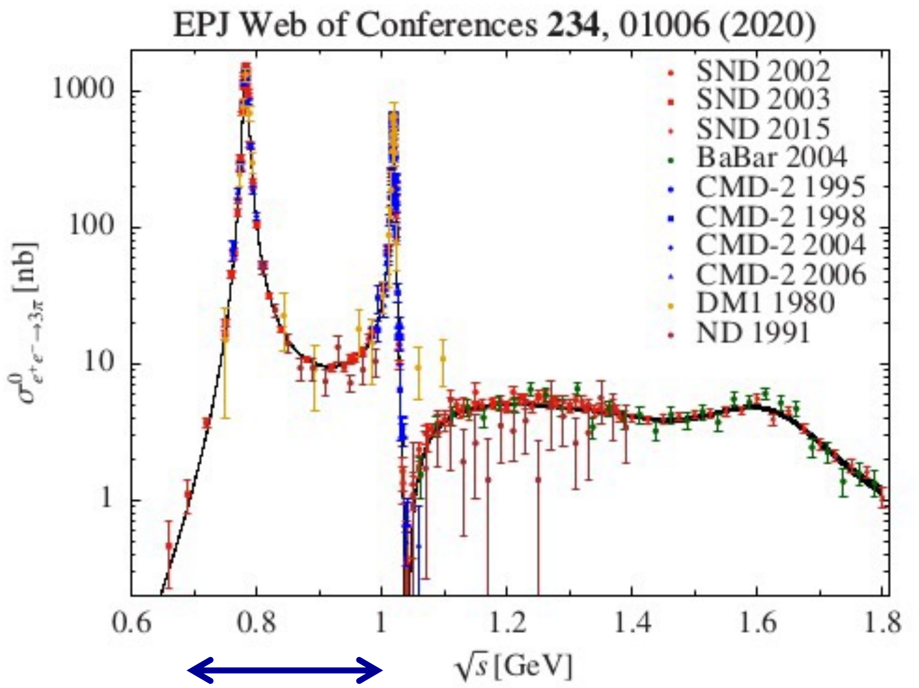
$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

Syst. errors (%)	$\Delta^{\pi\pi}a_\mu$ abs [4]	$\Delta^{\pi\pi}a_\mu$ ratio
Background Filter (FILFO)	negligible	negligible
Background subtraction	0.3	0.6
Trackmass	0.2	0.2
Particle ID	negligible	negligible
Tracking	0.3	0.1
Trigger	0.1	0.1
Unfolding	negligible	negligible
Acceptance ($\theta_{\pi\pi}$)	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	0.1
Luminosity	0.3 ($0.1_{th} \oplus 0.3_{exp}$)	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	0.7
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.2
Rad. function H	0.5	-
Total theory systematics	0.6	0.2
Total systematic error	0.9	0.7

[from P.Beltrame]

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

- $e^+e^-\rightarrow\pi^+\pi^-\pi^0$ is the second largest contribution to the calculation of the Hadronic Vacuum Polarization for $(g-2)_\mu$ and to its uncertainty
- Initial State Radiation (ISR) measurement at KLOE is complementary to energy scan in the range $\sqrt{s} < M_\phi$ (SND and CMD-2)



Goals:

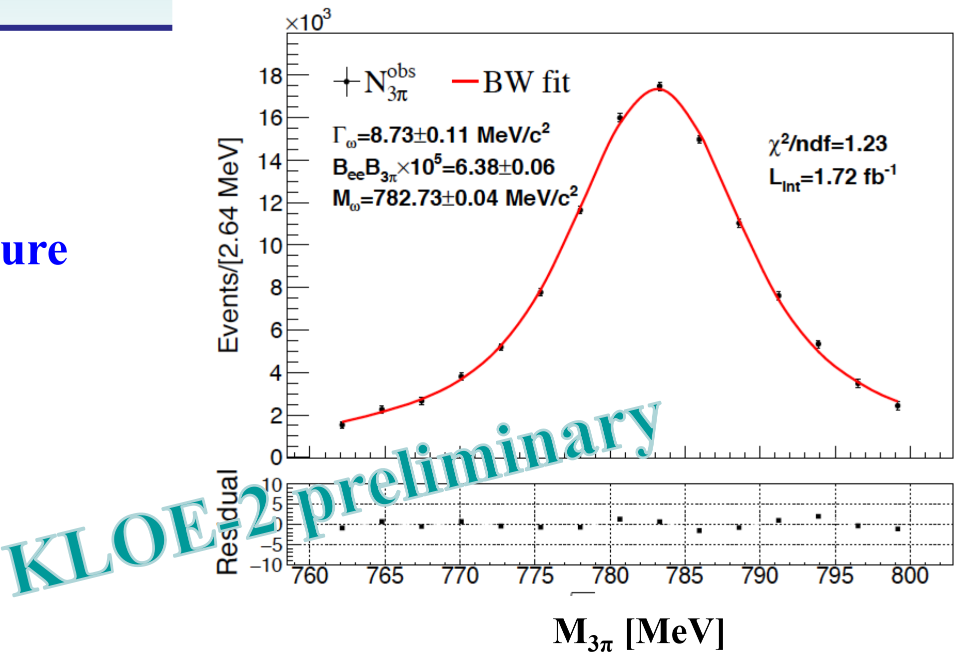
- Measure the cross section in the ω(782) region
- Evaluate the product $Br(\omega\rightarrow e^+e^-) \times Br(\omega\rightarrow\pi^+\pi^-\pi^0)$

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

- $L = 1.7\ fb^{-1}$ at ϕ peak

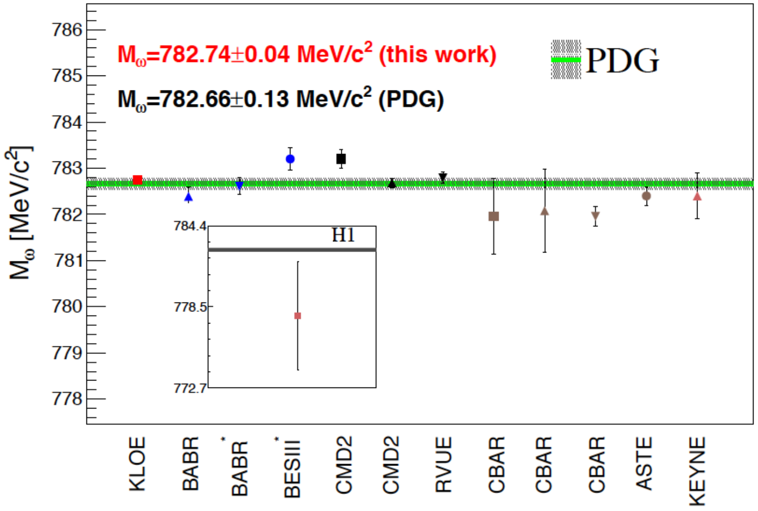
Selection:

- At least 2 tracks with opposite curvature
- 3 neutral clusters
- Kinematic fit
- Fit with Breit-Wigner convoluted with smearing matrix
- ISR correction factor taken into account



KLOE results* compared with PDG

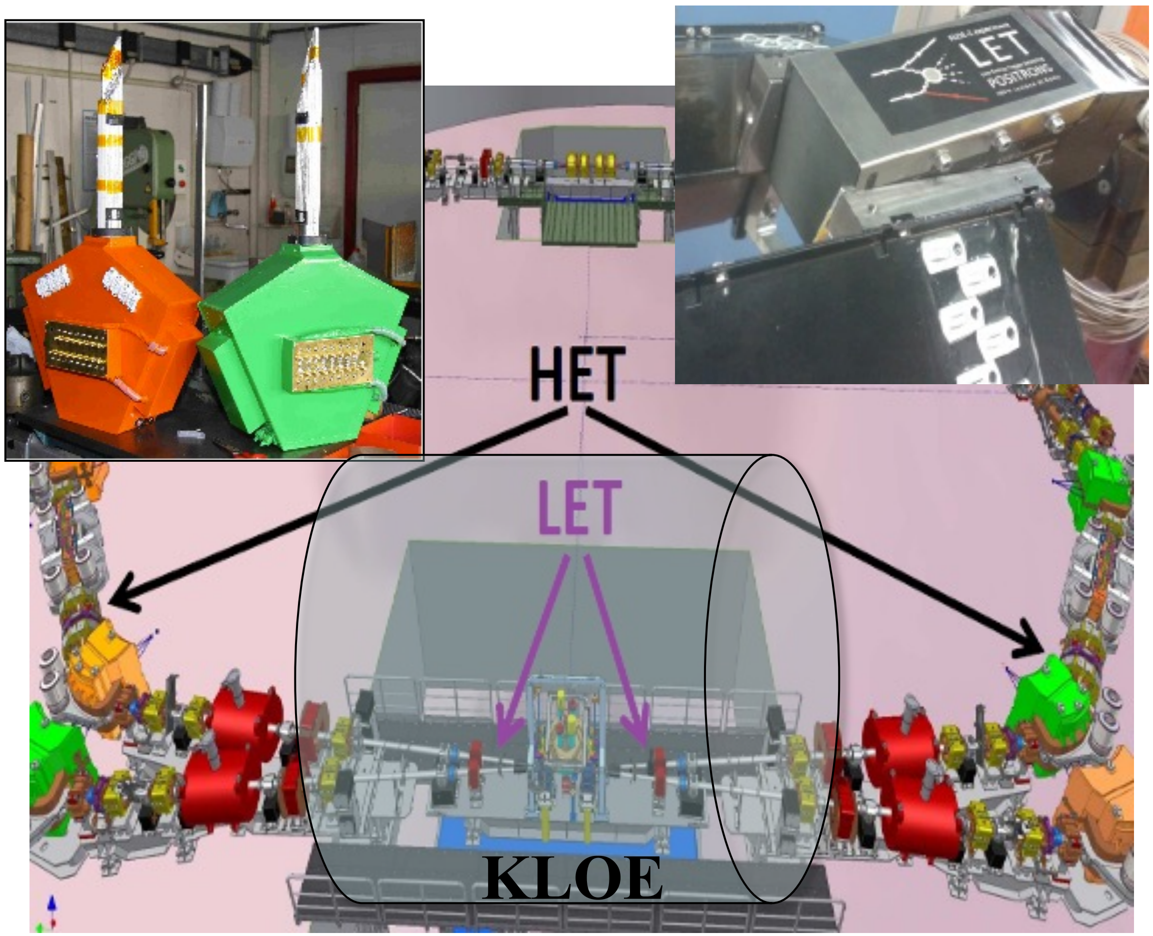
	M_ω [MeV/c²]	Γ_ω [MeV]	$\mathcal{B}_{ee}\times\mathcal{B}_{3\pi}$ [10^{-5}]
KLOE	782.73 ± 0.04	8.73 ± 0.11	6.38 ± 0.06
PDG	782.66 ± 0.13	8.68 ± 0.13	6.60 ± 0.16



* Only stat. uncertainty

KLOE-2: γγ taggers

γγ taggers installed for the measurement of scattered lepton momenta in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$



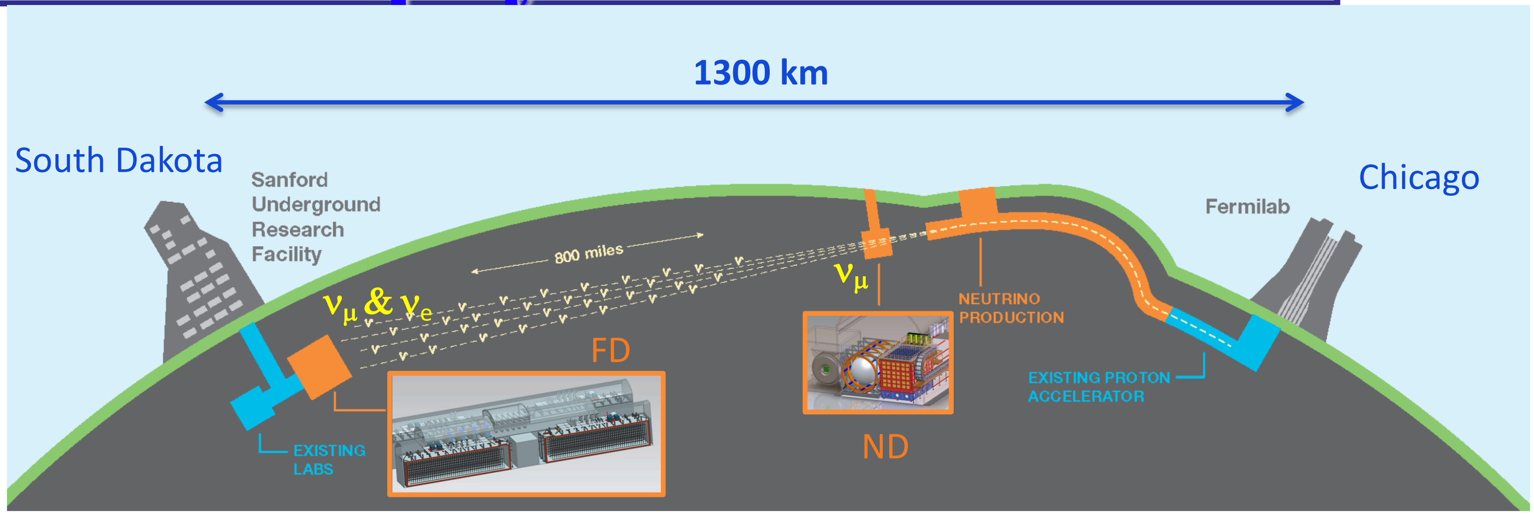
LET : E=160-230 MeV

- Inside KLOE detector
- LYSO+SiPM
- s_E<10% for E>150 MeV

HET : E > 400 MeV

- 11 m from IP
- Scintillator hodoscopes
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps

The future of KLOE: neutrino physics in DUNE

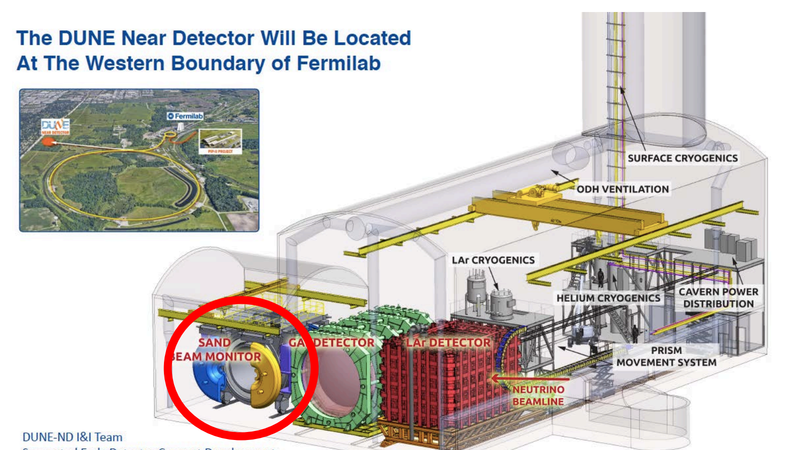


DUNE primary goals:
CP phase/CP violation; Mass ordering, mixing parameters
Nucleon Decay; Neutron/Anti-Neutron Oscillation
Supernova Burst Neutrinos

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

In order to get the physical quantities, we have to control flux, energy distribution/geometry of the beam, efficiencies, acceptances, etc..

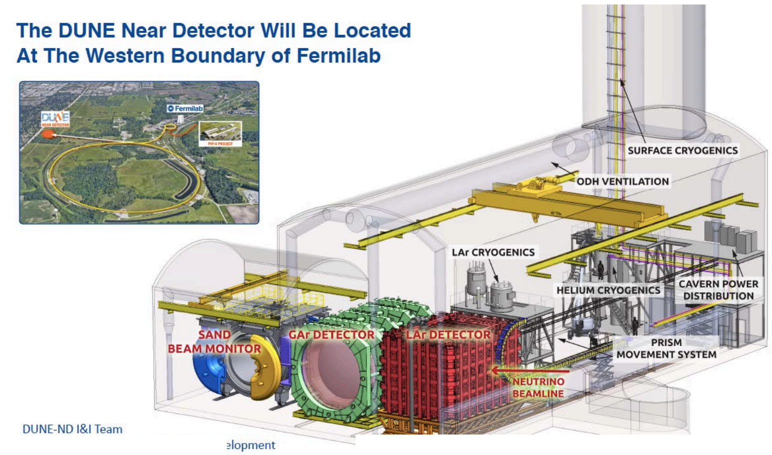
Need one (or more) sophisticated Near Detector to control beam and systematics



KLOE EMC + Magnet → **SAND: System for on-Axis Neutrino Detection**

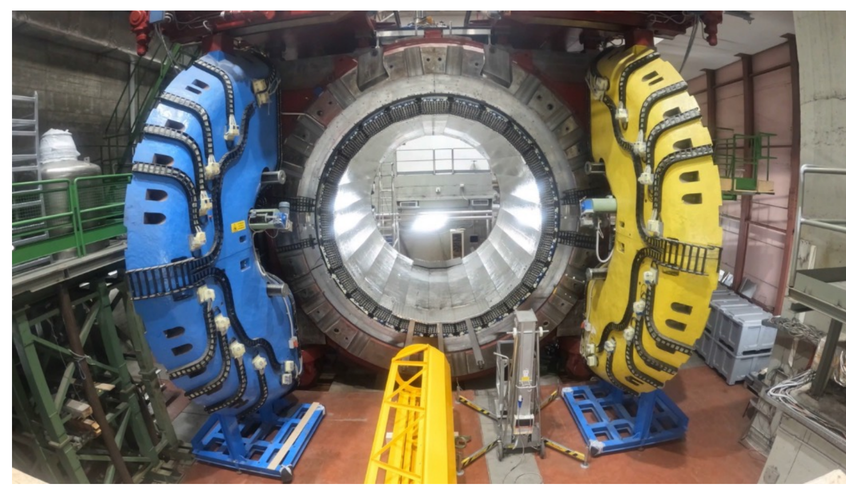
KLOE-to-SAND

- KLOE dismounting in progress at LNF
- Drift chamber extracted



KLOE EMC
+ Magnet

SAND: System for on-Axis Neutrino Detection



- Preparing for the extraction of the barrel modules
- Then dismounting the Endcaps, extraction of the s.c. coil, and dismounting of the iron yoke