Hadronic physics @ KLOE/KLOE-2

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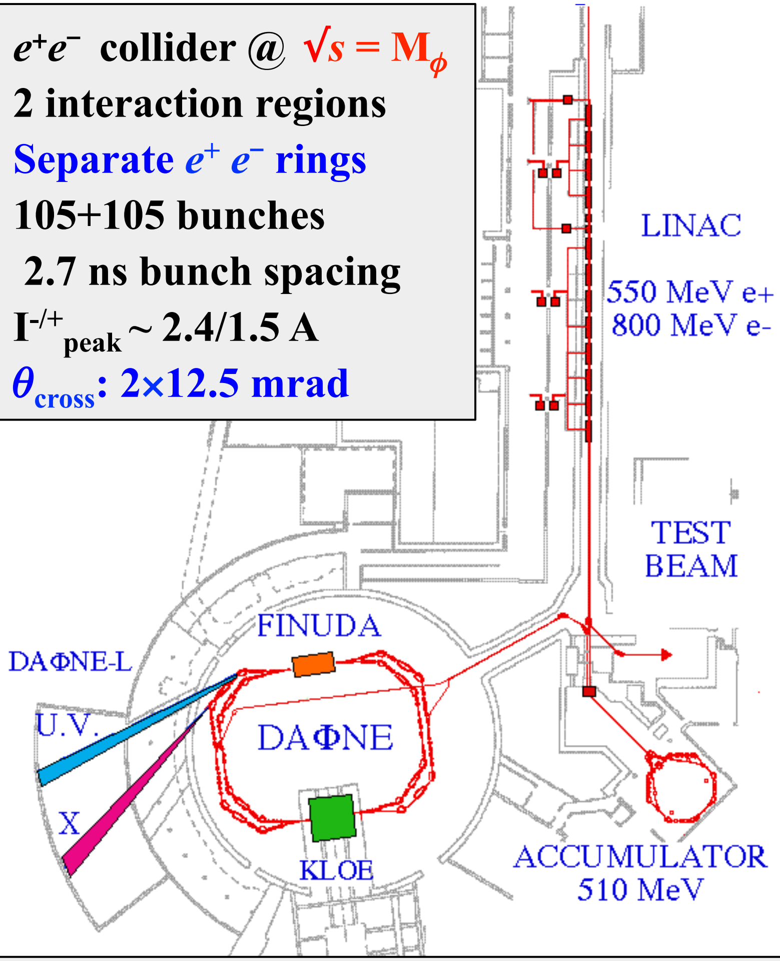
on behalf of the KLOE-2 Collaboration

- Status of DAΦNE and of KLOE-2
- Hadronic measurements with KLOE data
- Highlights of the KLOE-2 Physics Program

JLAB12 e gli altri esperimenti: punti di incontro e prospettive future
Laboratori Nazionali di Frascati
19 /12/2012

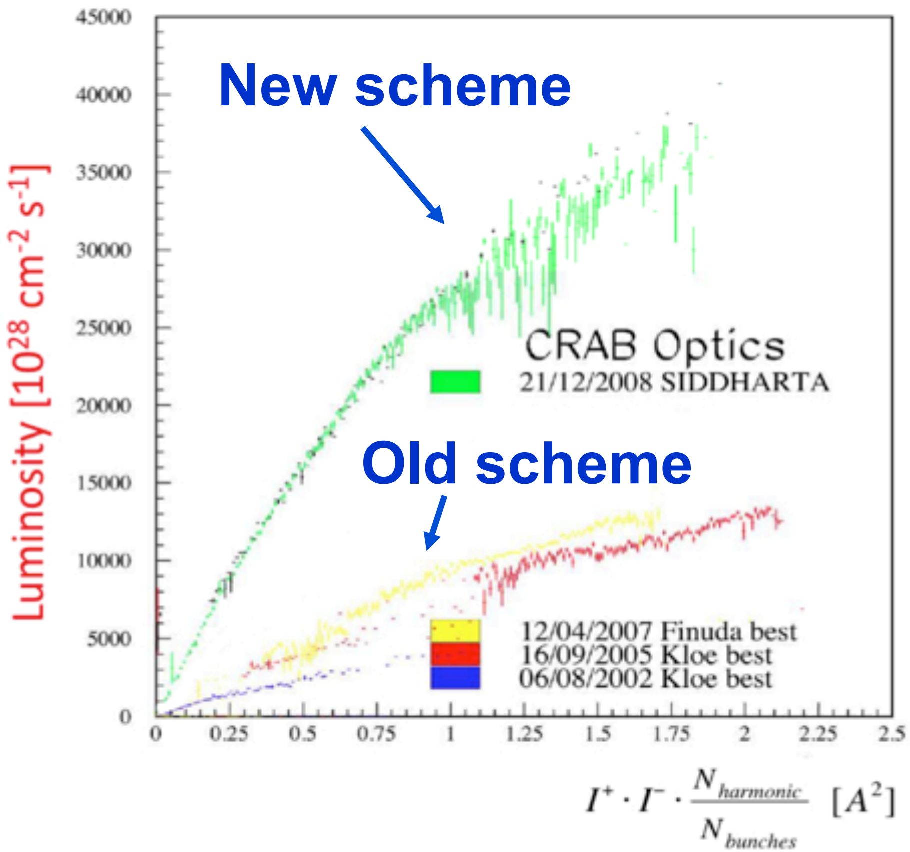
DAΦNE: the Frascati ϕ-factory

- e^+e^- collider @ $\sqrt{s} = M_\phi$
- 2 interaction regions
- Separate e^+ e^- rings
- 105+105 bunches
- 2.7 ns bunch spacing
- $I^{-/+}_{peak} \sim 2.4/1.5$ A
- θ_{cross}: 2×12.5 mrad



2008, new interaction scheme:

$L_{new} \sim 3 \times L_{old}$



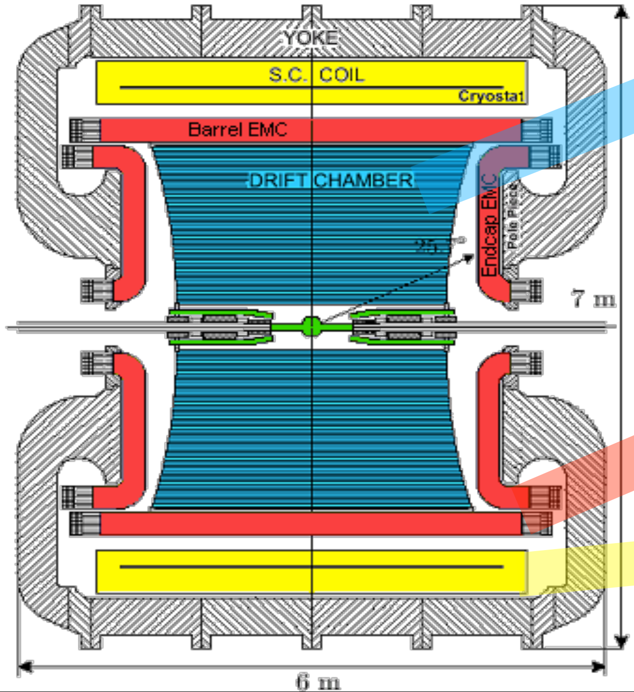
Best performances (1999-2007):

- $L_{peak} = 1.4\times10^{32}$ cm^{-2} s^{-1}
- $\int L dt = 8.5$ pb^{-1}/day

Machine commissioning for KLOE-2 completed

The KLOE experiment

KLOE experiment took data in 2001-2006, before the DAΦNE upgrade



Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **$\delta p_t / p_t < 0.4\%$ ($\theta > 45°$)**
- **$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm**

Electromagnetic calorimeter

- lead/scintillating fibers
- 98% solid angle coverage
- **$\sigma_E / E = 5.7\% / \sqrt{E(GeV)}$**
- **$\sigma_t = 57\ ps / \sqrt{E(GeV)} \oplus 100\ ps$**
- **PID capabilities**

Magnetic field: 0.52 T

Decay channel	Events (2.5 fb^{-1})
K^+K^-	3.7×10^9
$K_L K_S$	2.5×10^9
$\rho\pi + \pi^+\pi^-\pi^0$	1.1×10^9
$\eta\gamma$	9.7×10^7
$\pi^0\gamma$	9.4×10^6
$\eta'\gamma$	4.6×10^5
$\pi\pi\gamma$	2.2×10^6
$\eta\pi^0\gamma$	5.2×10^5

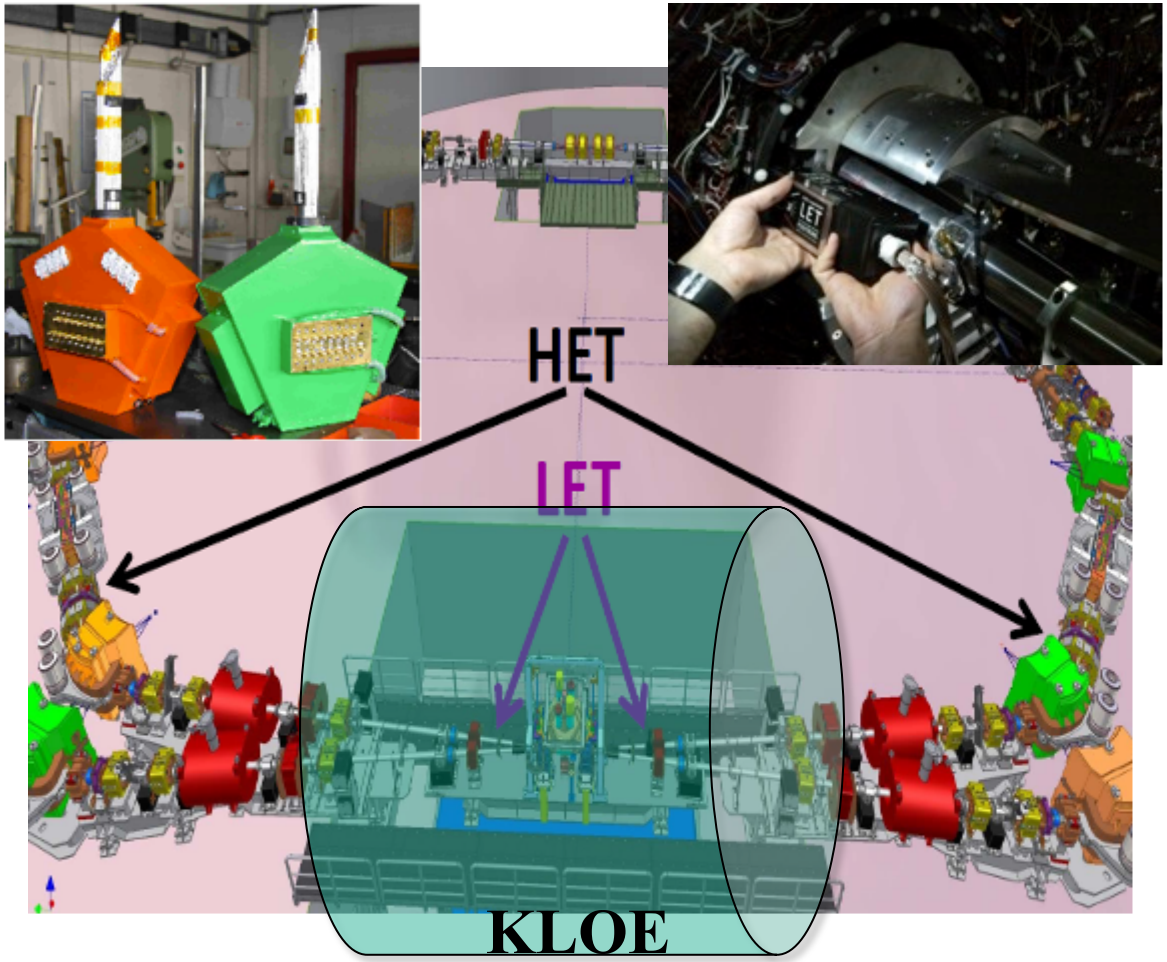
Physics at a ϕ-factory:

- Kaon physics
- Light meson spectroscopy
- Hadron production in $\gamma\gamma$ collisions
- Search for dark force mediator
- Hadronic cross-section via ISR and $\pi^+\pi^-$contribution to $(g-2)_\mu$

From KLOE to KLOE-2: $\gamma\gamma$ taggers

2+2 $\gamma\gamma$ taggers installed and ready for the KLOE-2 run

Measurement of lepton momenta in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$



LET : E=160 – 230 MeV

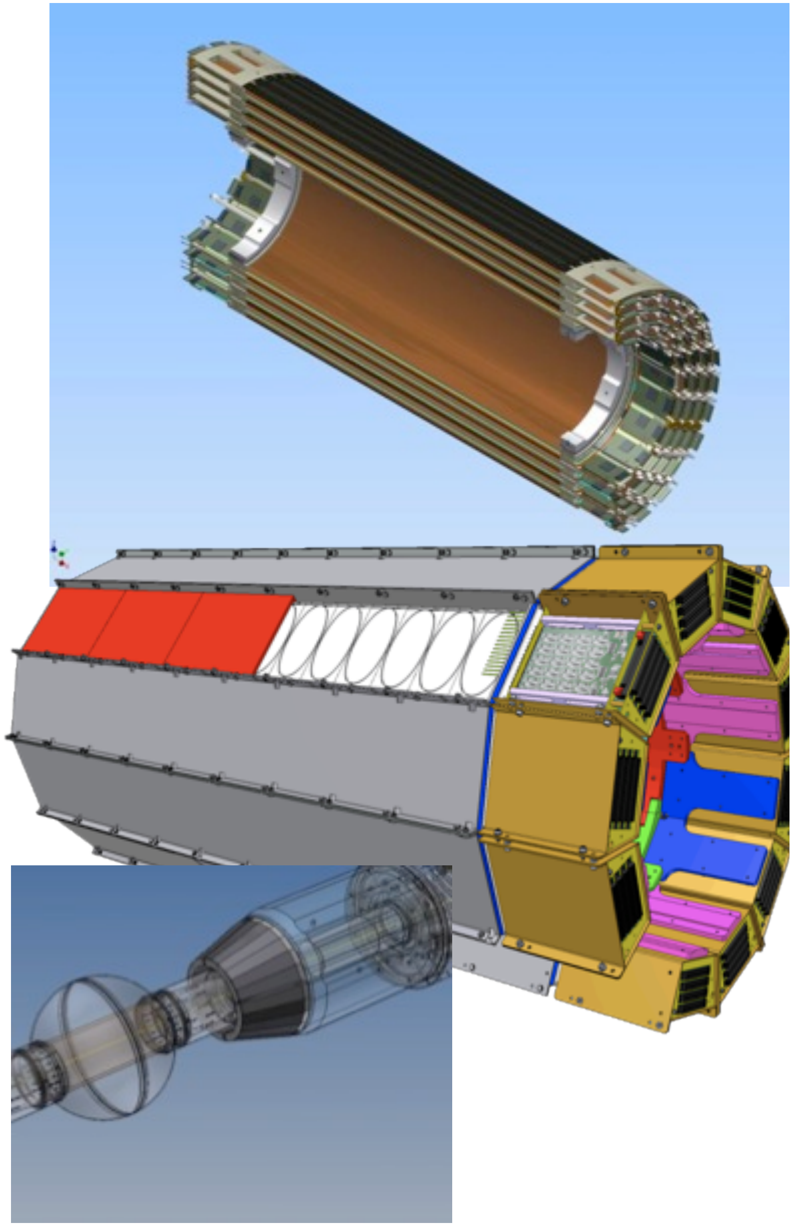
- Inside KLOE detector
- LYSO+SiPM
- σ_E<10% for E>150 MeV

HET : E > 400 MeV

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

From KLOE to KLOE-2: IP detectors

Major detector upgrades ready Feb 2013.
Installation will start March-April 2013



INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

QCALT

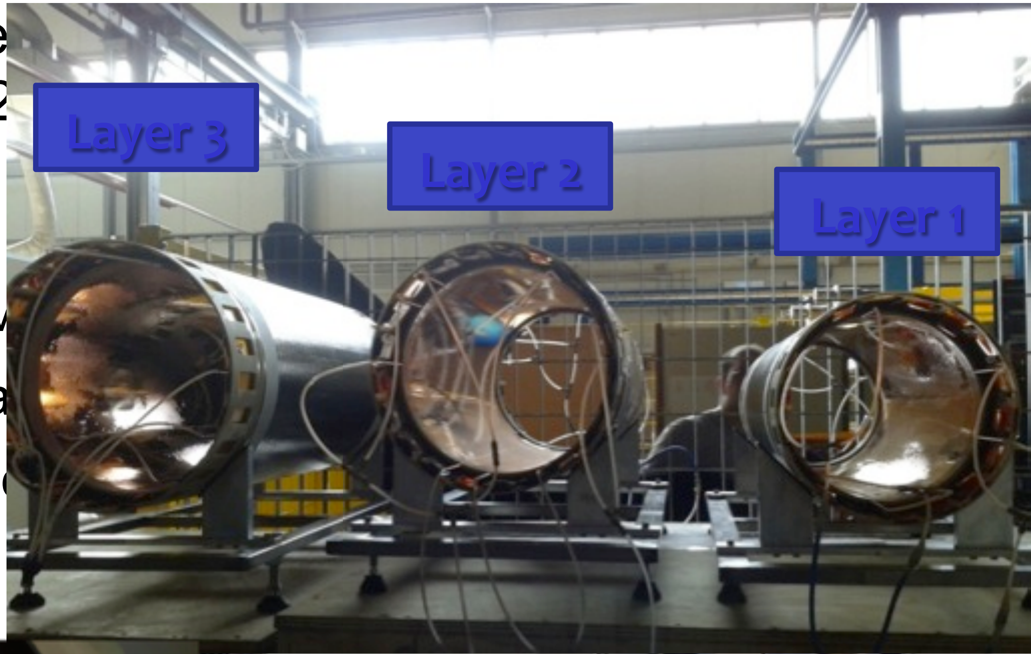
- W + scintillator tiles + WLS/SiPM
- QUADS coverage for K_L decays

CCAL

- LYSO + SiPM
- Better acceptance for low angle γ ($21^o \rightarrow 10^o$)

From KLOE to KLOE-2: IP detectors

Major detector upgrades ready Fe
Installation will start March-April 2



INNER TRACKER

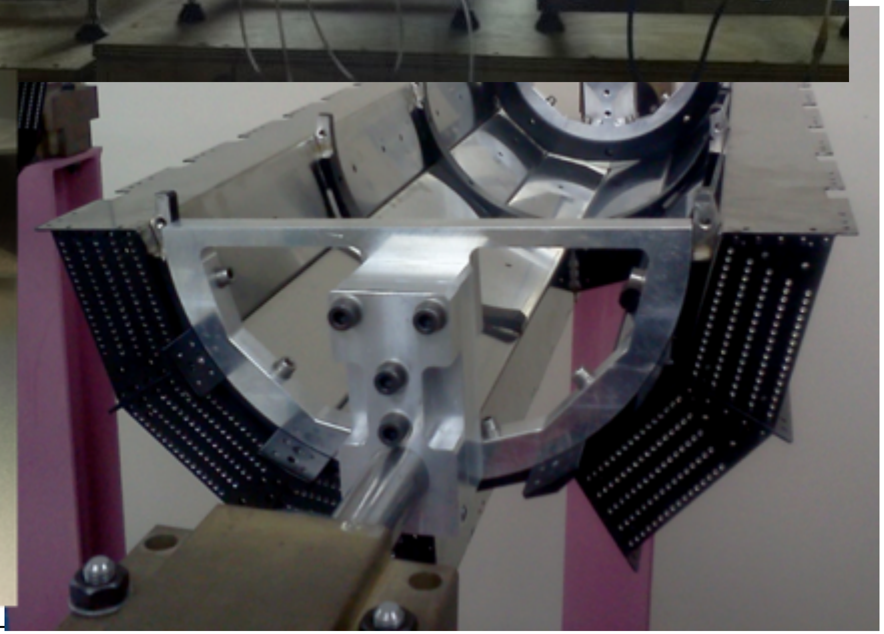
- 4 layers of cylindrical triple GEM
- Better vertex reconstruction nea
- Larger acceptance for low p_t tra

QCALT

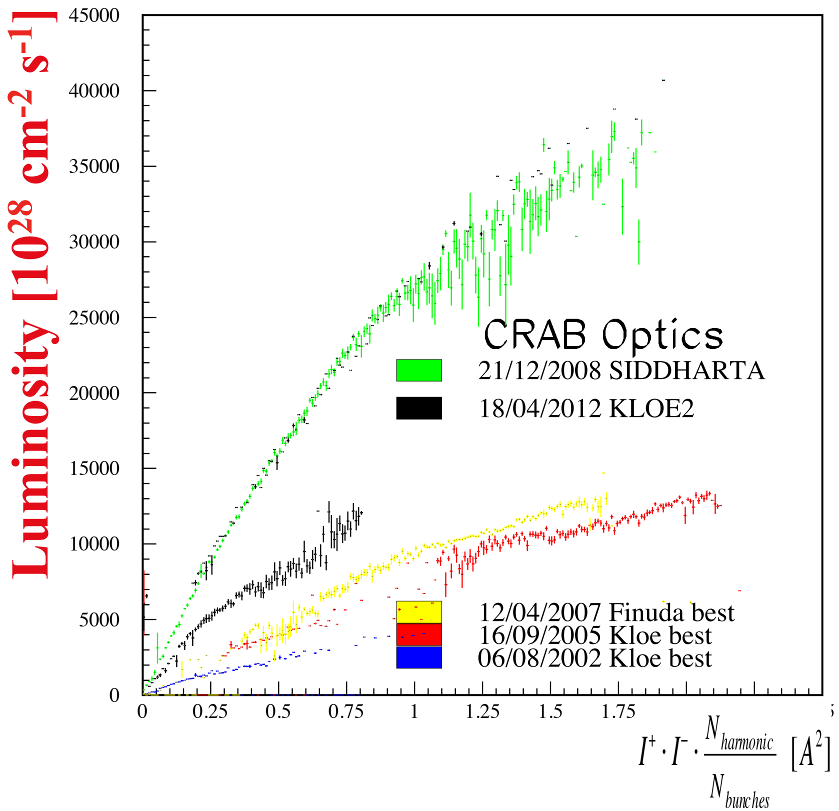
- W + scintillator tiles +
- QUADS coverage for

CCAL

- LYSO + SiPM
- Better acceptance for lo



Commissioning of the KLOE-2 run



Best performances:

➢L = 1.5×10^{32} $cm^{-2}s^{-1}$ (0.8 mA + 0.8mA)
(as best KLOE run with 1.8 A + 1.3 A)

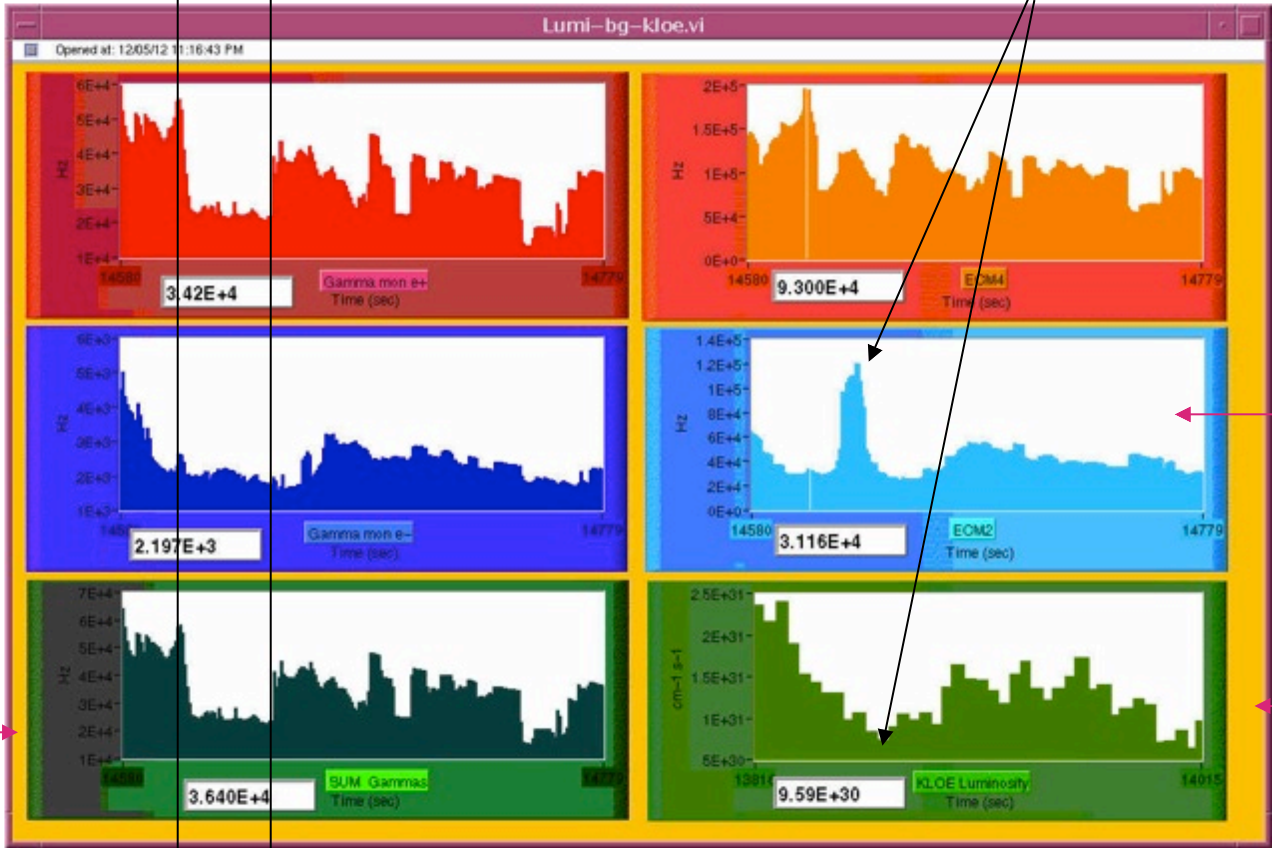
➢Background level x 2-3 w.r.t. KLOE

- First collisions for KLOE-2 @ end 2010, followed by long machine shutdowns due to severe hardware problems
- DAΦNE commissioning started on November 2011
- Performances obtained for the Siddharta 2008 run not yet reached
- Machine studies concluded → now 6 months shutdown to install upgrades → Temperature control on BeamPipe
- Crab Waist is working→ machine optimization still to be done
- New beam pipe under construction.

- Max integrated Lum~ 8.2 pb/day
- Max Lum/hour ~ 420 nb sustained for 10 hours → O(10 pb/day)
- **Max lum expected O (20 pb/Day) x 200 dd/year ~ 4 fb/Year**

OFF ON

Min luminosity, highest background when the sextupoles are OFF



KLOE background

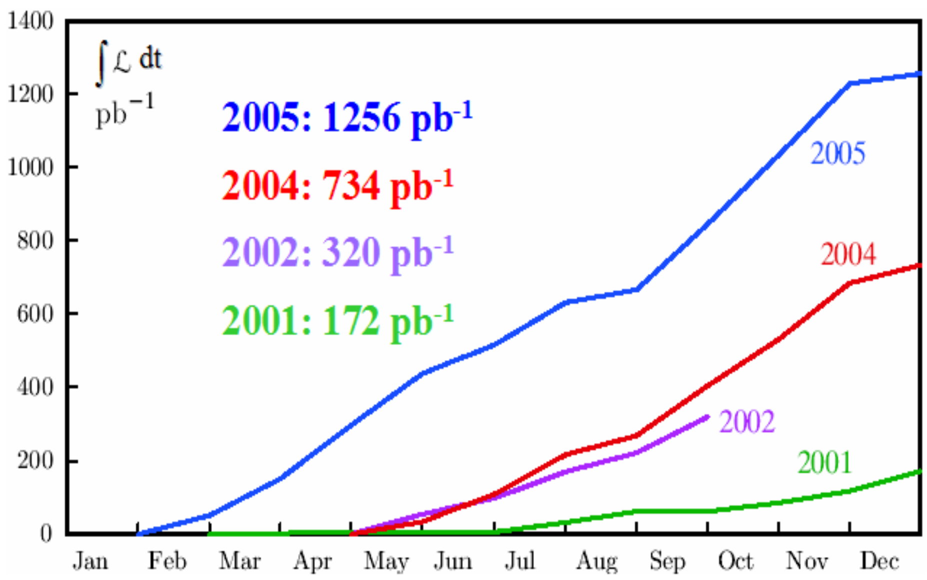
DAΦNE luminosity monitor

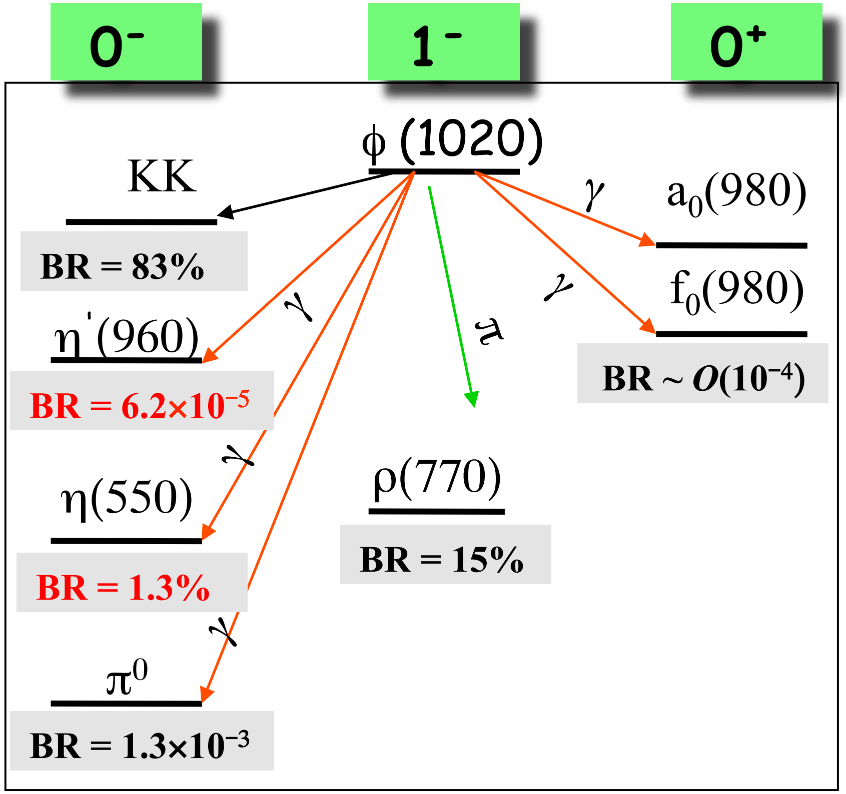
KLOE luminosity monitor

Still harvesting KLOE data…

KLOE dataset (2001-2005):

- **2.5 fb^{-1} @ $\sqrt{s}$ = M$_\phi$ (~ 8×10^9 ϕ produced)**
- **250 pb^{-1} @ 1000 MeV (off-peak data)**





- ~ 50 publications based on KLOE data set
- This 'old' KLOE data still producing new amazing results
- Most recent analyses will be discussed

η/η' physics

- **η/η' samples produced by radiative Φ decays ($\Phi \to \eta/\eta'\gamma$) and selected by looking for monochromatic photons of 353, 50 MeV energy**.

- Fit to the Dalitz-plot for η decaying to 3 pion final state used to extract Q value → related to (u/d/s) masses. This has been done with 450/pb both on neutral and $\pi^+\pi^-\pi^0$ channels. Fit by H.Leuwayler et al. Study on 2/fb in progress.

- Ratio of BR($\Phi \to \eta'\gamma$)/BR($\Phi \to \eta\gamma$) used to determine gluonium content of η.

- Limits set ($\eta \to \pi\pi$) and BR of rare decay channels ($\eta \to$ eeee, $\pi\pi$ee)

- **In the last period we focused on two channels:**

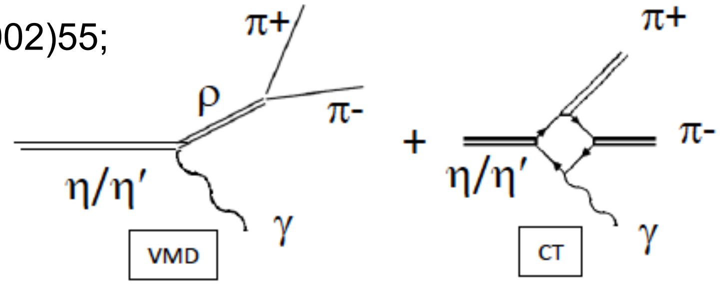
  1) $\eta \to \pi^+\pi^-\gamma$ (accepted by PLB) … plan is to move to η'

  2) $\eta' \to \eta\,\pi\pi$ (work in progress)

$\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\eta\to\pi^+\pi^-\pi^0)$

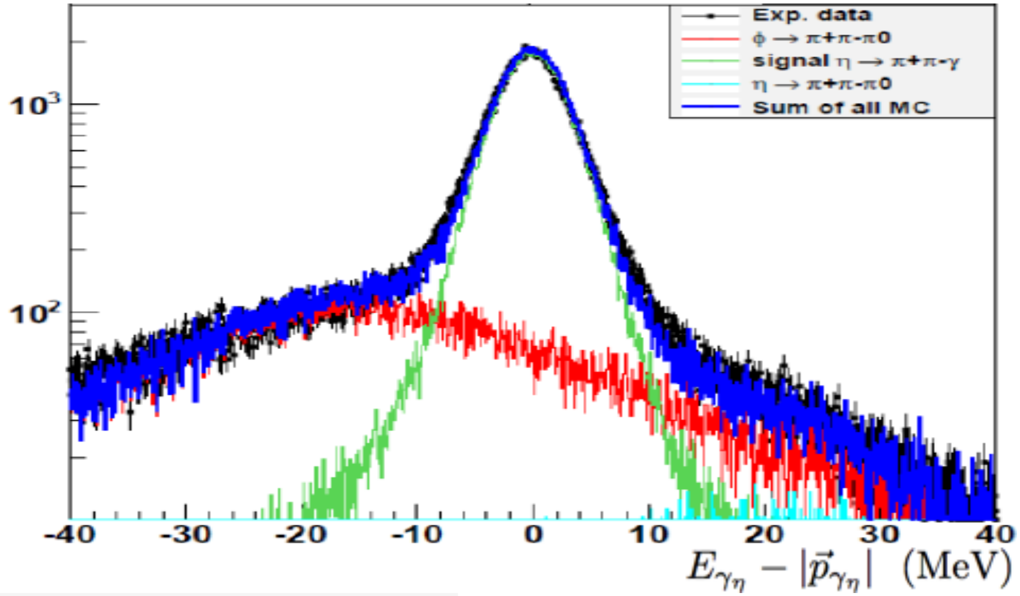
Study of the box anomaly: test of ChPT and its unitarized extensions

[Benayoun et al. EPJC31(2003)525; Holstein, Phys. Scripta, T99(2002)55; Borasoy, Nissler, NPA740(2004)362, Picciotto PRD45(1992)1569]



Sizeable effect of the Contact Term expected both in $\Gamma(\eta\to\pi^+\pi^-\gamma)$ and in $M_{\pi\pi}$ distribution

- Data sample: **558 pb^{-1}**
- **$N(\eta\to\pi^+\pi^-\gamma)$ = 204,950**
- **$N(\eta\to\pi^+\pi^-\pi^0)$ = 1.19×10^6**
- **B/S = 10%** **B/S = 0.65%**
- Main background: $\phi\to\pi^+\pi^-\pi^0$

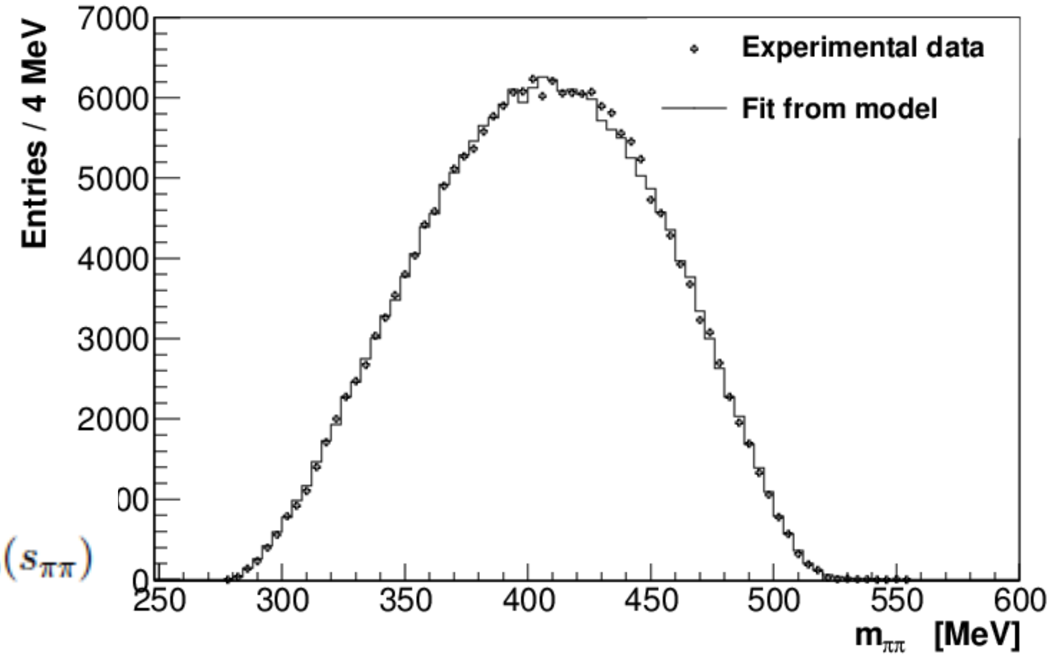


$$\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005_{stat} \pm 0.0028_{syst}$$

Consistent with CLEO measurement, with a factor of 3 improved precision

$\eta \to \pi^+\pi^-\gamma$: fit to the $M_{\pi\pi}$ spectrum

Fit to the $M_{\pi\pi}$ spectrum according to the model independent parametrization of *Stollenwerk et al.* *PLB 707 (2012), 184*



$$\frac{d\Gamma(\eta \to \pi^+\pi^-\gamma)}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2\,\Gamma_0(s_{\pi\pi})$$

$$\mathcal{A}(\delta,\alpha) = \underbrace{A(\delta)}_{\text{fitted to BR}}\left(\underbrace{1+\alpha\, s_{\pi\pi}+\mathcal{O}(s_{\pi\pi}^2)}_{\text{extracted from the spectrum}}\right)\underbrace{F_V(s_{\pi\pi})}_{\text{universal}}$$

Reaction-specific term.
Simple ChPT predicts $\alpha \sim 1\ \mathrm{GeV}^{-2}$

$$\boxed{\alpha = (\,1.32 \pm 0.08_{stat}\ {}^{+0.10}_{-0.09\ syst} \pm 0.02_{th}\,)\ \mathrm{GeV}^{-2}}$$

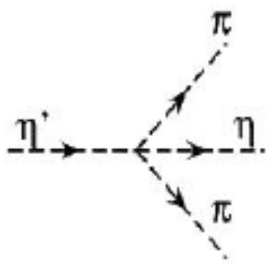
Previous measurement: α_{WASA} = (1.89±0.25±0.59±0.002) GeV^{-2}

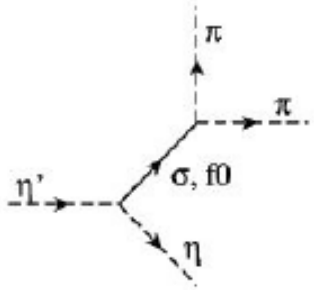
PLB 707 (2012) 243

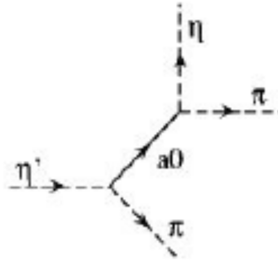
Study of $\eta-\pi$ interactions in $\eta' \to \eta\pi^+\pi^-$

- Study η-π interaction
  - Quantum numbers favor scalar resonances

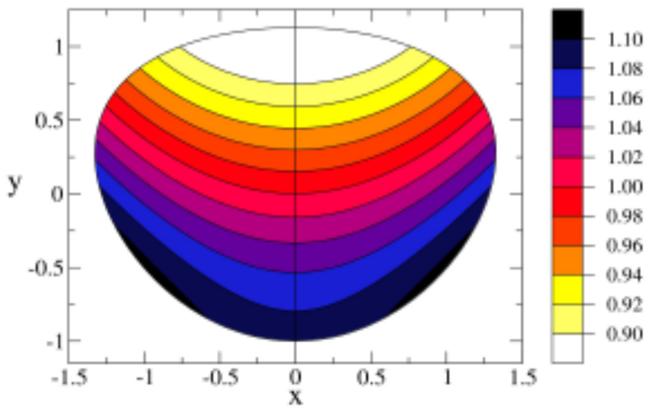
[Faribortz-Schechter,PRD60(1999)034002]





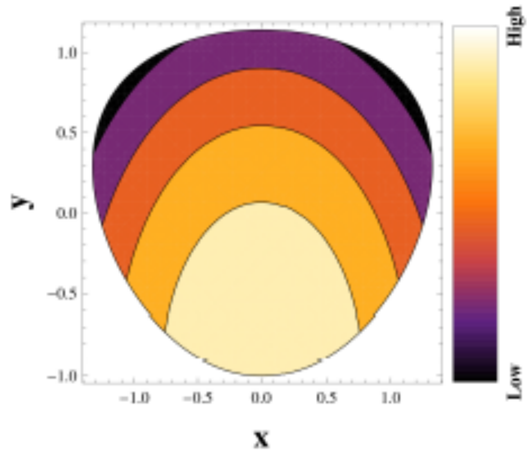


- Test predictions of ChPT and extensions



a_0(980) I=1 dominance

Borasoy et al. EPJ A26 (2007) 383



LN_C-ChPT

Escribano et al. JHEP 1105 (2011) 094

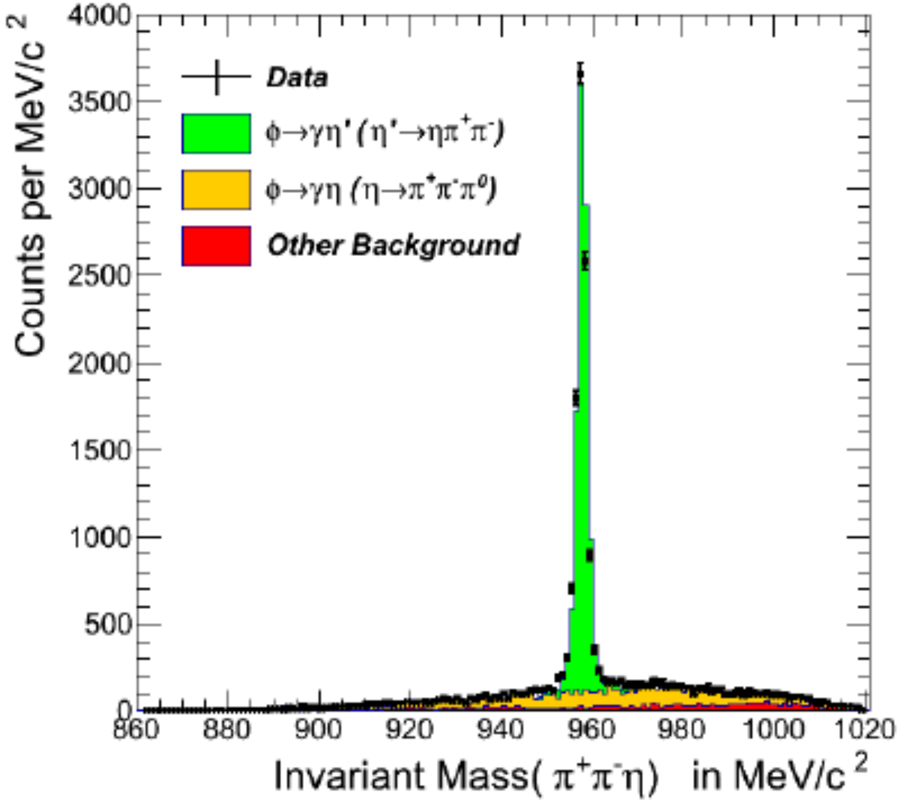
$$X = \frac{\sqrt{3}(T_{\pi^+} - T_{\pi^-})}{T_{\pi^+} + T_{\pi^-} + T_\eta}$$

$$Y = \frac{m_\eta + 2m_{\pi^\pm}}{m_{\pi^\pm}} \frac{T_\eta}{T_{\pi^+} + T_{\pi^-} + T_\eta} - 1$$

- Predictions differ on percent level → high precision needed

Study of $\eta-\pi$ interactions in $\eta' \rightarrow \eta\pi^+\pi^-$

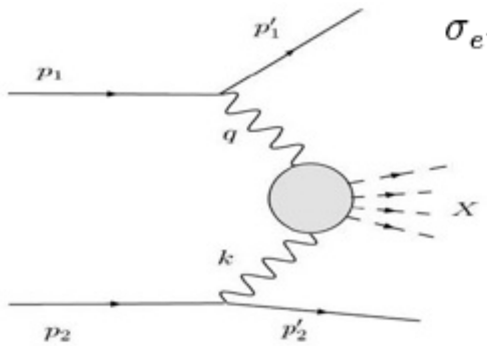
- 1.7 fb^{-1} analyzed
- Background suppression by multiple hypothesis kinematic fitting
- Main background $\eta \rightarrow \pi^+\pi^-\pi^0$
- B/S = 0.2
- ε = 23%
- 10160 ± 110 events reconstructed



Previous Measurements:

BNL (sum)	1400 events	Phys. Rev. D10 916 (1974)
CLEO	6700 events	Phys. Rev. Lett. 84 26 (2000)
VES	7000 events	Phys. Lett. B651, 22-26 (2007)
BES III	44000 events	Phys. Rev. D83, 012003 (2011)

$\gamma\gamma$ physics @ KLOE: $\Gamma_\eta(\gamma\gamma)$ measurement

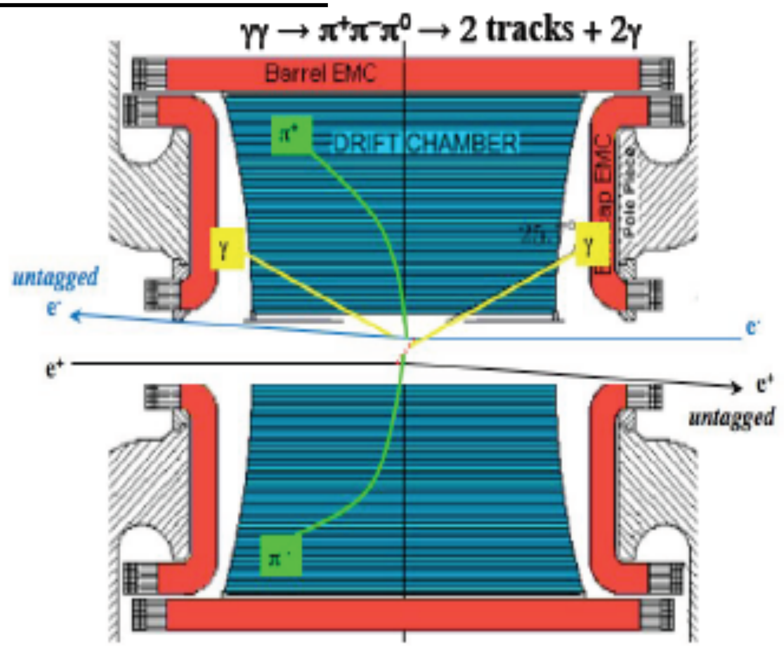


$$\sigma_{e^+e^-\to e^+e^-X} = \frac{16\alpha^2\Gamma_{X\gamma\gamma}}{m_X^3}\left(\ln\frac{E_b}{m_e}\right)^2\left((y^2+2)^2\ \ln\frac{1}{y} - (1-y^2)\ (3+y^2)\right) \qquad y = m_X/(2E_b)$$

KLOE: **no $e^\pm$ tagging** → **$\sqrt{s}$ = 1 GeV**

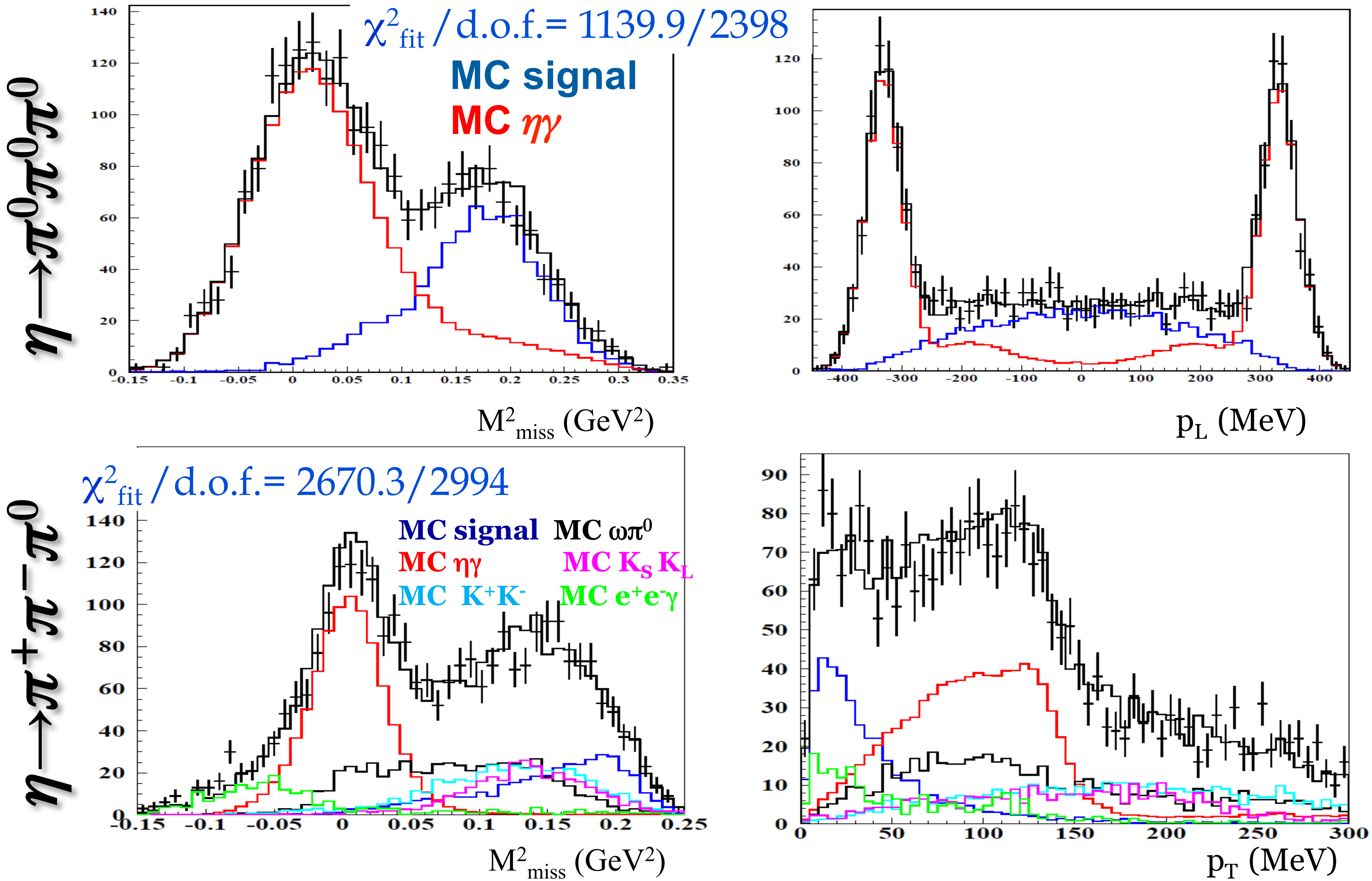
KLOE-2: **tagger to reduce background from ϕ and to close kinematics** → **$\sqrt{s} = M_\phi$**

- $\gamma\gamma\to\eta$ $(\pi^0\pi^0)$ studied (under-way) at KLOE
- Data sample: **240 pb^{-1} @ $\sqrt{s}$ = 1 GeV** (reduced bckg contamination from ϕ)
- Selected channels: $\eta\to\pi^+\pi^-\pi^0/\pi^0\pi^0\pi^0$
- Main background: $\phi\to\eta\gamma$ with undetected recoil photon



$\gamma\gamma \rightarrow \eta \rightarrow \pi\pi\pi$

2D fit to $M_{miss}^2 - p_{L/T}$ plane with signal and background shapes



$\gamma\gamma\rightarrow\eta\rightarrow\pi\pi\pi$: results

Neutral channel, ~720 signal events:

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s} = 1\text{ GeV}) = (32.0 \pm 1.5_{stat} \pm 0.9_{syst} \pm 0.2_{BR(\eta\rightarrow 3\pi)})\text{ pb}$$

Charged channel, ~390 signal events:

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s} = 1\text{ GeV}) = (34.5 \pm 2.5_{stat} \pm 1.0 \pm 0.7_{ff} \pm 0.4_{BR(\eta\rightarrow 3\pi)})\text{ pb}$$

Combined (correlated errors on neutrals, Lum, FF and rel. BRs)

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s} = 1\text{ GeV}) = (32.7 \pm 1.3_{stat} \pm 07_{syst})\text{ pb}$$

- *KLOE measurements same precision w.r.t. best previous results*
- *Extraction of $\Gamma(\eta\rightarrow\gamma\gamma)$ from X-sec measurement, FF and $\gamma\gamma$-flux*

$$\Gamma(\eta \rightarrow \gamma\gamma) = (520 \pm 20_{stat} \pm 13_{syst})\text{ eV}.$$

In agreement with PDG value of the width 510±26 ev. Most precise single determination

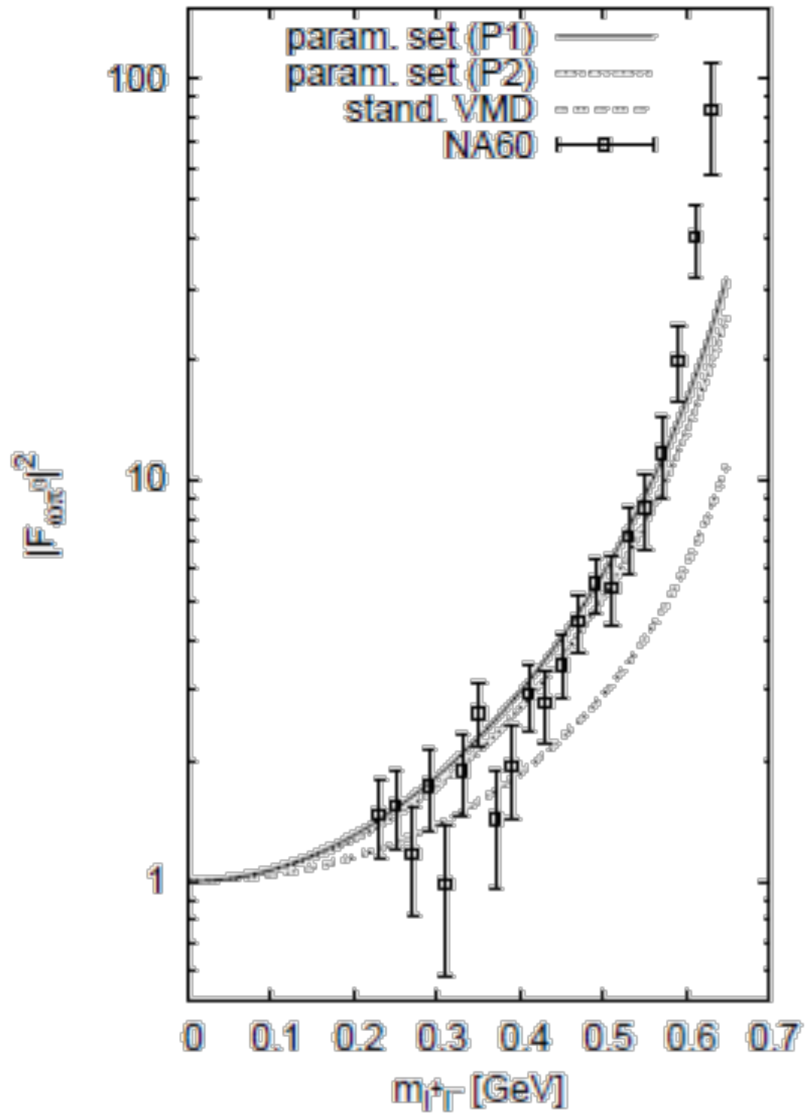
Φ Dalitz Decay

- Interest in studying low energy vector and pseudo-scalar Dalitz decay increased.

$VP\gamma^*$ transitions not fully described by VMD

$$\frac{d}{dq^2}\frac{\Gamma(\phi\to\eta e^+e^-)}{\Gamma(\phi\to\eta\gamma)}=\frac{\alpha}{3\pi}\frac{|F_{\phi\eta}(q^2)|^2}{q^2}\sqrt{1-\frac{4m^2}{q^2}}\times$$

$$\times\left(1+\frac{2m^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{m_\phi^2-m_\eta^2}\right)^2-\frac{4m_\phi^2q^2}{(m_\phi^2-m_\eta^2)^2}\right]^{3/2}$$

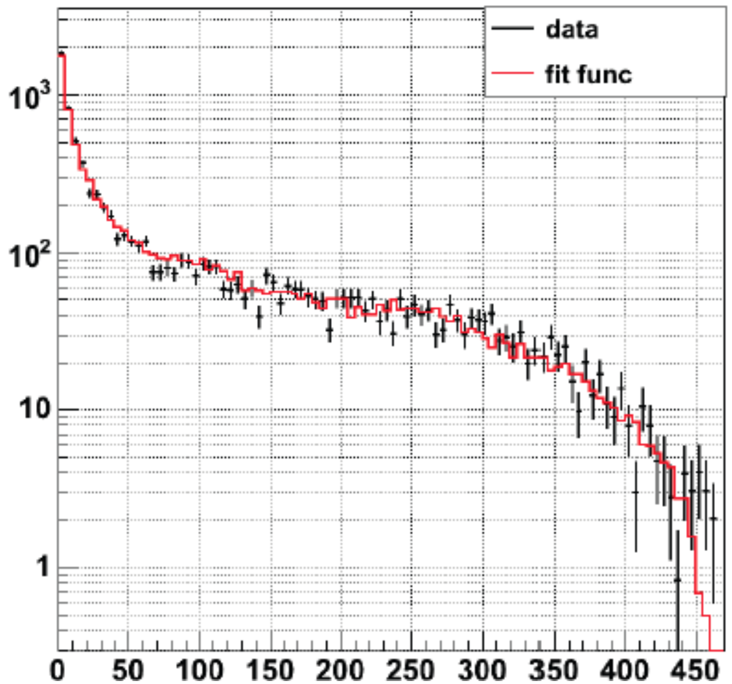


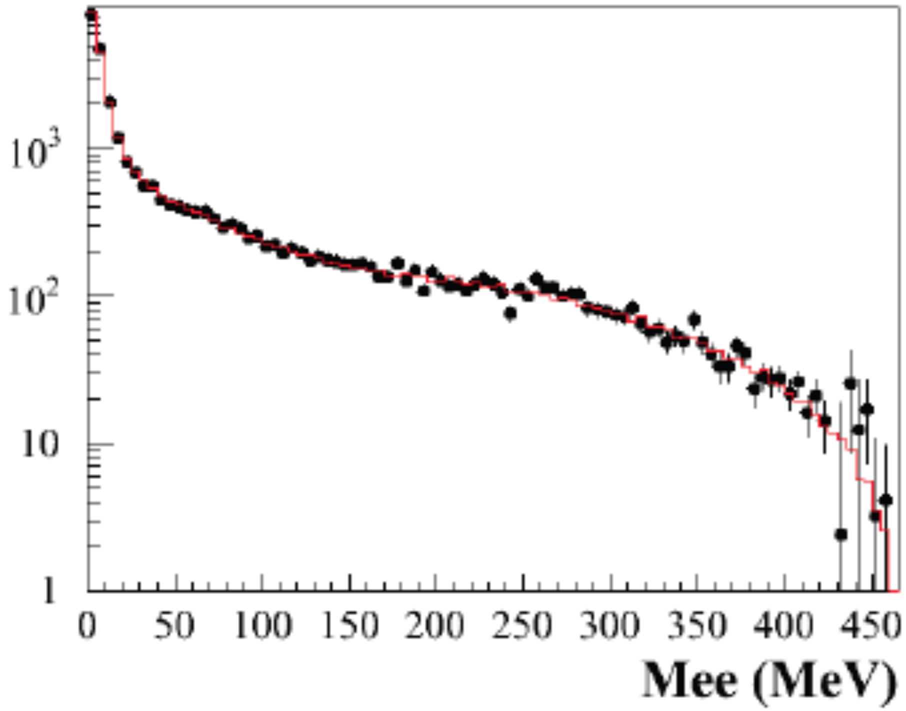
FF slope:

$$\boxed{F(q^2)=\frac{1}{1-q^2/\Lambda^2}}\quad\left\{\begin{array}{l} b=dF/dq^2|_{q^2=0}\\ b_{\phi\eta}=\Lambda_{\phi\eta}^{-2}\approx 1/m_\phi^2\approx 1\ \mathrm{GeV}^{-2}\end{array}\right.$$

Φ Dalitz Decay

- Slopes measurement for the $\Phi \rightarrow \eta\, e^+e^-$ decay in progress with ~ 1.7 fb^{-1} and for two main eta decay channels ($\pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$)
- Progresses also for the measurement of $\Phi \rightarrow \pi^0 e^+e^-$
- Plans to study also PS → Vγ* exist (e.g. $\pi^0,\eta \rightarrow \gamma\, e+e-$)



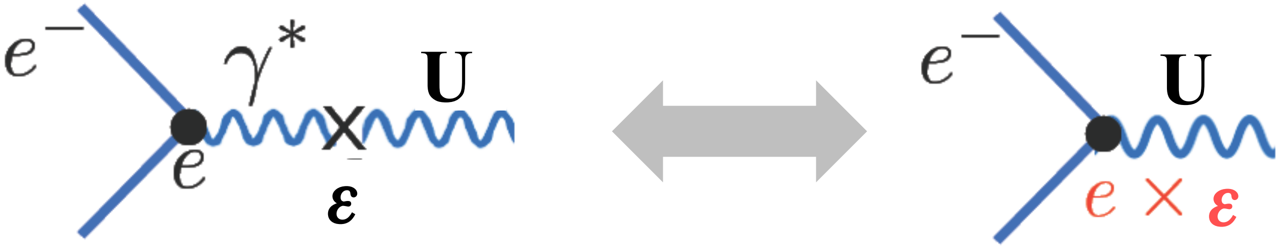


- ✓ **High precision on slope reachable (few % w.r.t. 50% of SND measurement)**
- ✓ **Very different systematics on the two channels. Combined fit planned**

Low energy dark forces

Several unexpected astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA, CoGent…) could be explained with the existence of a hidden gauge sector weakly coupled with SM through a mixing mechanism of a new **gauge boson (U, A', V…)** with the photon:

[Arkani-Hamed et al. PRD79 015014 (2009)]
[Essig et al., PRD80 015003 (2009)]



- ✓ U mass range: **1 MeV – few GeV**
- ✓ Coupling constant of electric charge to U: $\varepsilon \leq 10^{-3}$
- ✓ U production/decay through photon mixing

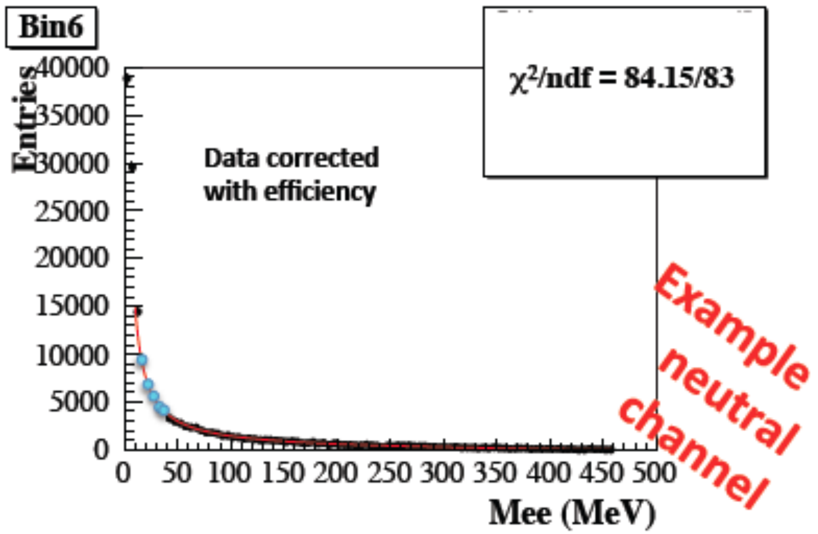
Search for dark forces @ KLOE: $\phi\to\eta U$

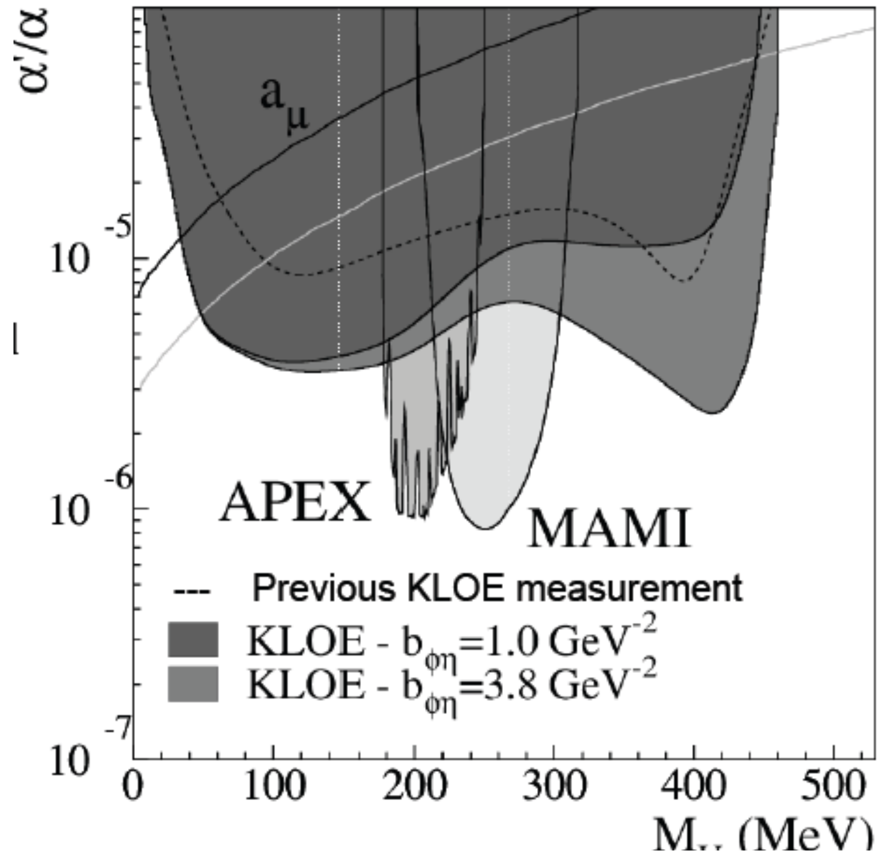
Meson having radiative decay to one photon can decay to a U boson with $\mathrm{BR}(X\to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times \mathrm{BR}(X\to Y\gamma)$

Irreducible background:
ϕ Dalitz decay $\phi\to\eta\gamma^*\to\eta l^+l^-$

Selected decay chains: $U\to e^+e^- + \eta\to\pi^+\pi^-\pi^0$
$U\to e^+e^- + \eta\to\pi^0\pi^0\pi^0$

Fit to the M_{ee} distribution to extract the shape of the irreducible bckg

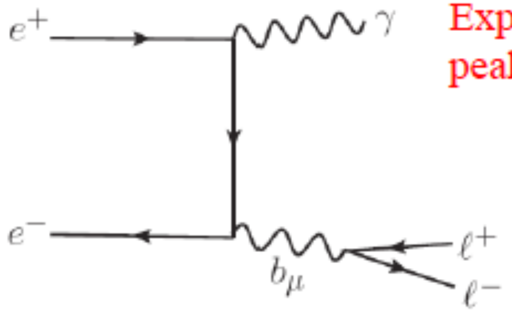




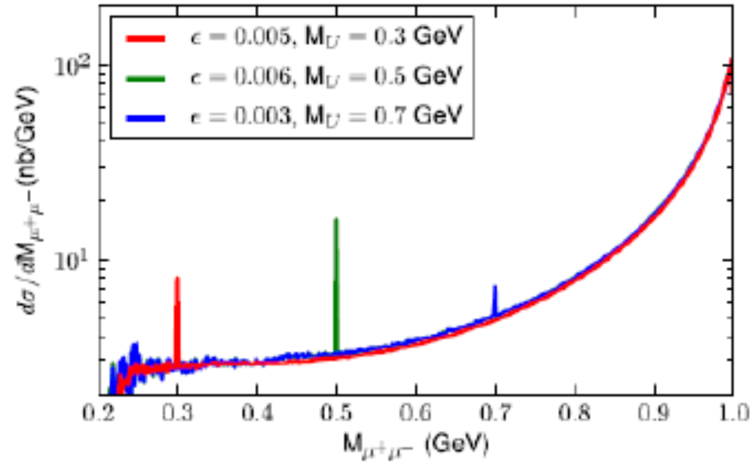
$\alpha'/\alpha \leq 1.5\times10^{-5}$ @ 90% C.L. for $30<M_U<420$ MeV
$\alpha'/\alpha \leq 5.0\times10^{-6}$ @ 90% C.L. for $60<M_U<190$ MeV

Dark forces @ KLOE: ee → U g

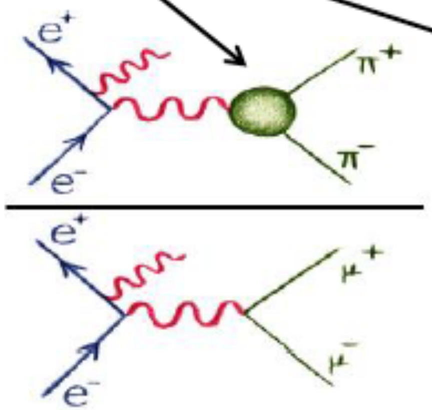
Production of a photon plus an U boson and decay in a lepton pairs: $\mathbf{e^+ e^- \rightarrow U\gamma \rightarrow \mathit{l}^+ \mathit{l}^- \gamma, \mathit{l} = e,\mu}$

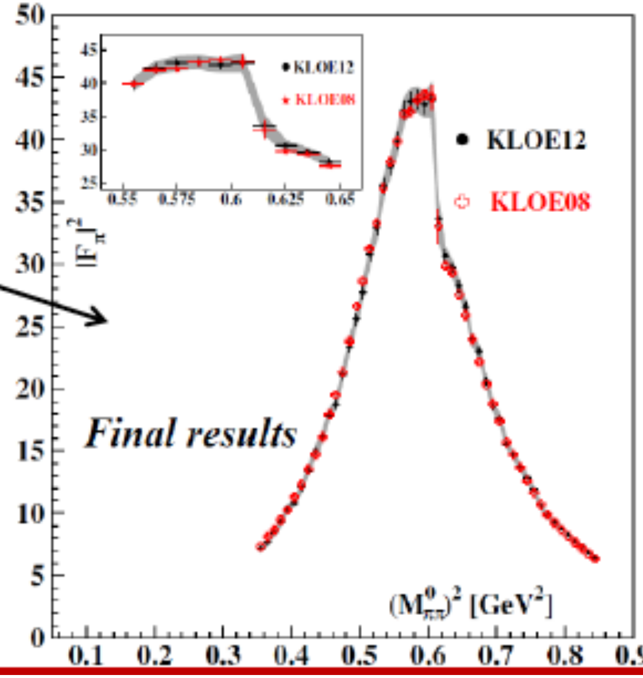


Expect a narrow Breit-Wigner peak above the continuum



We use the $\mu^+\mu^-\gamma$ final state only.
This measurement is in fact directly derived by our measurement of $|F_\pi|^2$ by the bin by bin ratio of pion over muon yields





Statistical sample:
240 pb^{-1} 2002 data

Dark forces @ KLOE: Limits on ee → U g

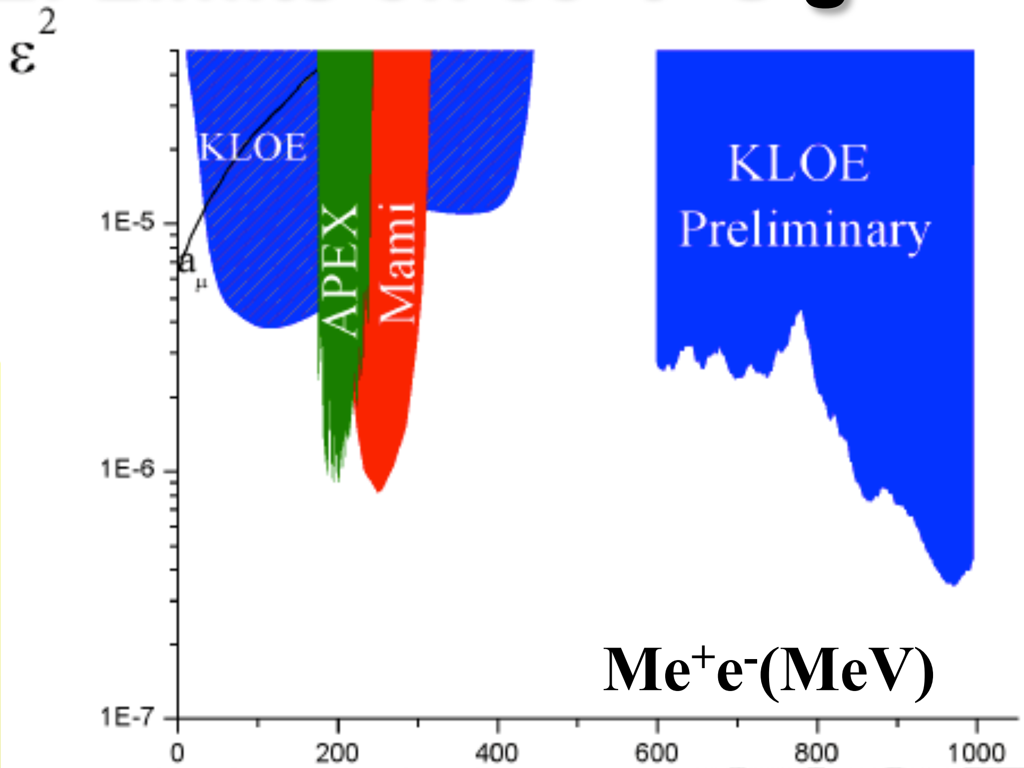
U. L. between $2.6\cdot10^{-6}$ and $3.5\cdot10^{-7}$ in the energy range 600-1000 MeV

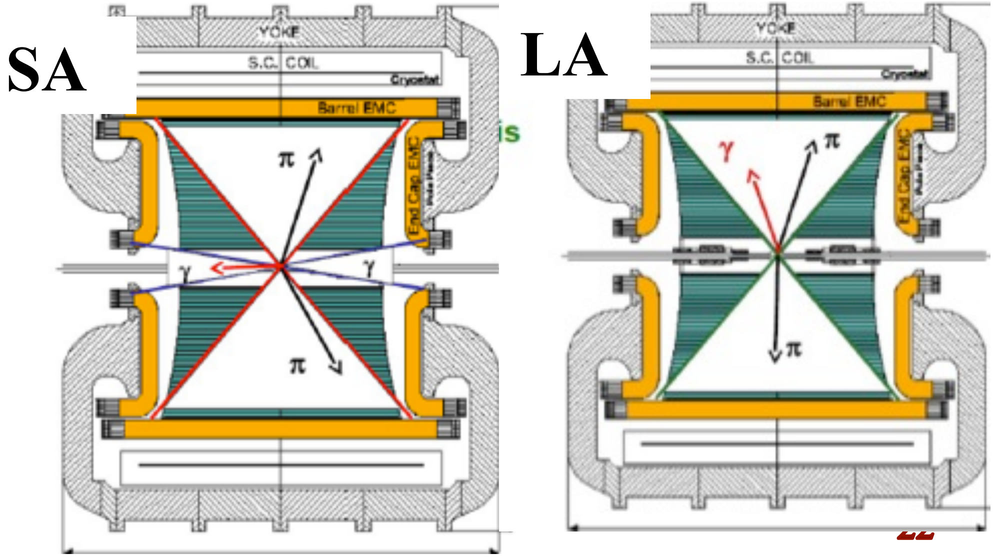
Results based on 240 pb^{-1} small angle γ analysis

Using the 2.5 fb^{-1} full KLOE data set improves the sensitivity by a factor ~ 3

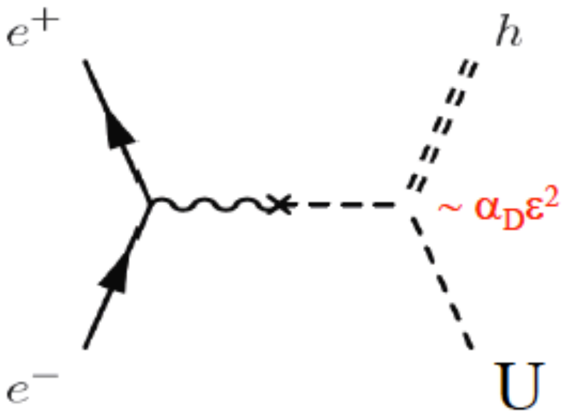
Changing the μ acceptance selections and including the offpeak sample may allow to check the low (~threshold) invariant mass region

A further factor 2 in sensitivity expected from KLOE2 experiment





Dark forces : ee → hU higgsstrahlung process



Very different scenarios depending on

$m_h < m_U \Rightarrow$ "invisible"

$m_h > m_U \Rightarrow h \to uu \to 4l, \pi + 2l, \pi$

$\varepsilon = 10^{-3}$

$\alpha_D = \alpha_{em}$ ⇨ $\tau_h > 5\ \mu s \to \beta\gamma c\tau > 100$ m

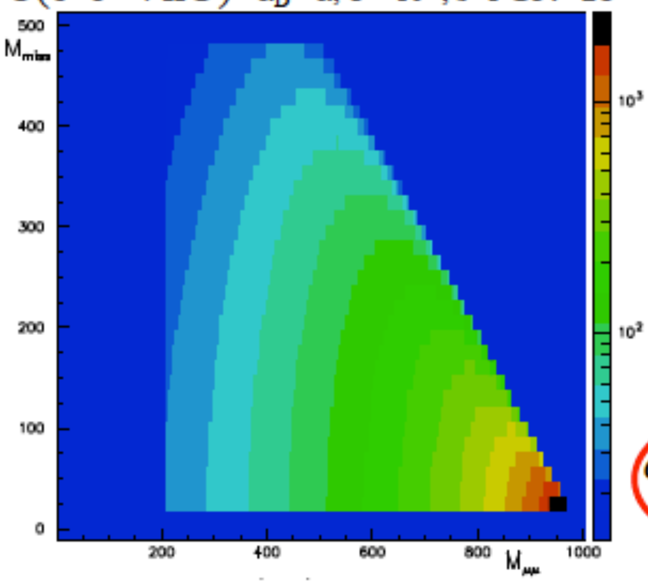
rapidly increasing with decreasing ε

invisible up to $\varepsilon \approx 10^{-2} \div 10^{-1}$ depending on m_h

$m_{U,h} \sim 100$ MeV

We study only the muon case $m_h < m_U$: $e^+e^- \to \mu^+\mu^-$ + missing energy

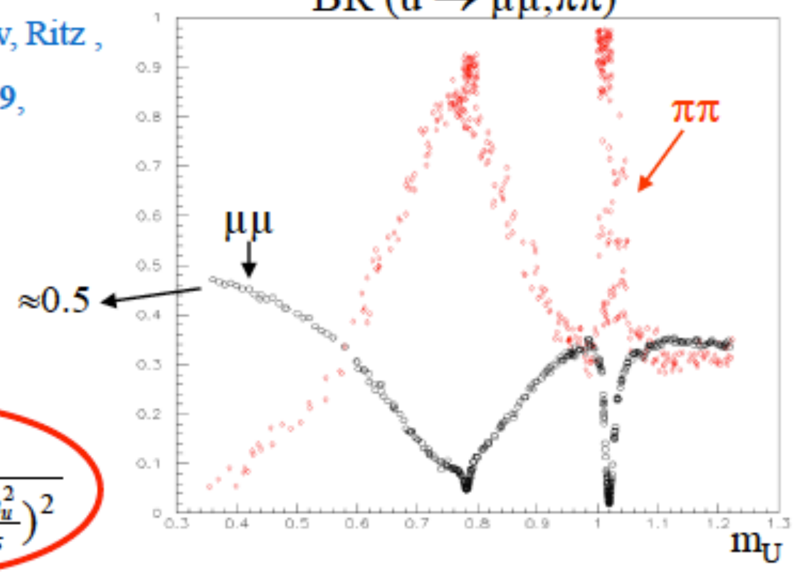
$\sigma(e^+e^- \to hU)$ $\alpha_D = \alpha$, $\varepsilon = 10^{-3}$, $s = 1$ GeV^2 fb



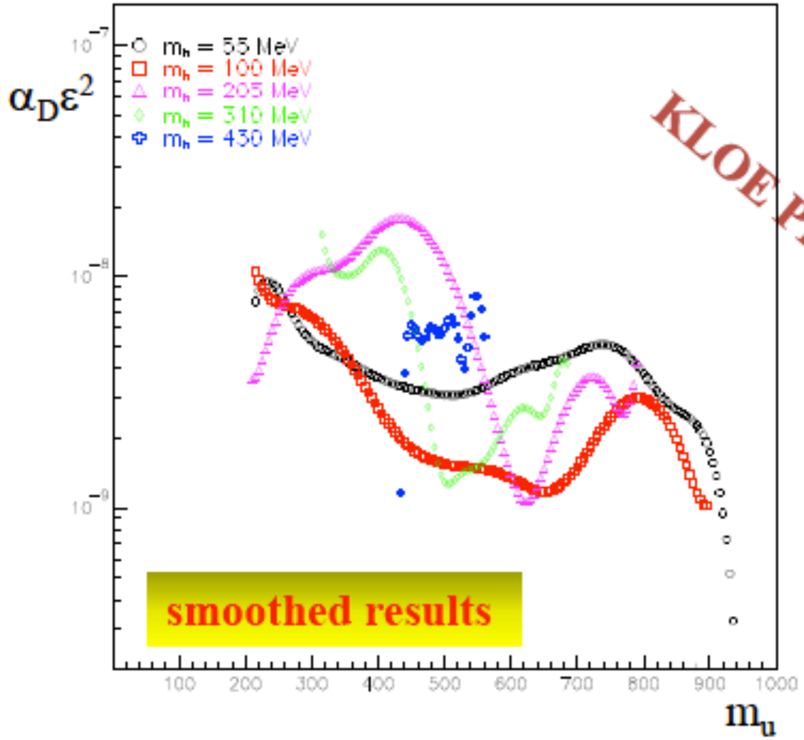
Batell, Pospelov, Ritz , Phys. Rev. D 79, 115008 (2009)

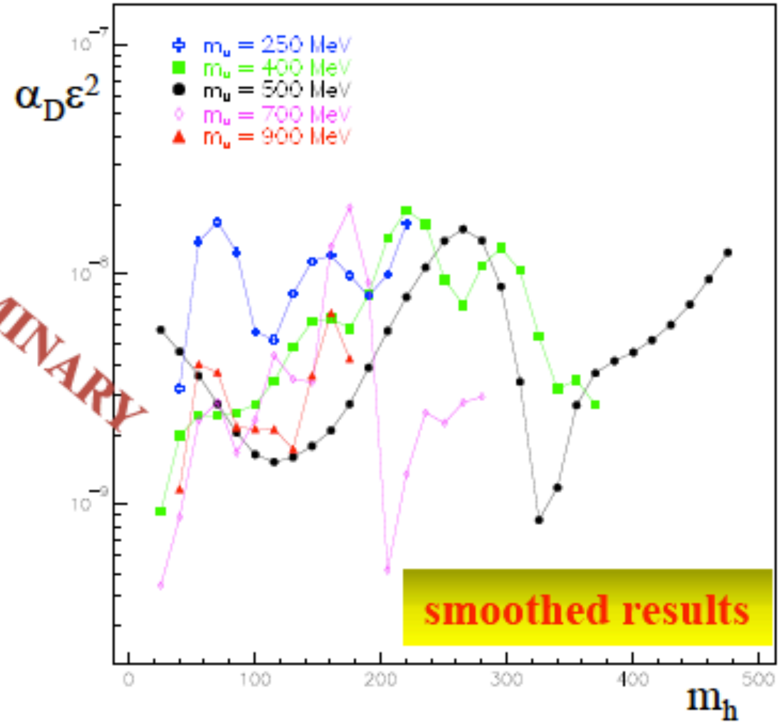
$$\sigma_{hU} \propto \frac{1}{s} \frac{1}{(1 - \frac{m_u^2}{s})^2}$$

BR ($u \to \mu\mu, \pi\pi$)



Dark forces : ee → hU higgsstrahlung process





Limits ~ $10^{-8} \div 10^{-9}$ in $\alpha_D\varepsilon^2$, which translate in $10^{-3} \div$ some 10^{-4} in ε, if $\alpha_D = \alpha_{em}$

Search complementary with BaBar one (same process , different final state and phase space)

Expect a ≈ 2.5 improvement on the limits in KLOE2 because of luminosity + suppression of the K^+K^- background due to the Inner Tracker insertion → full study of the $\varepsilon \approx 10^{-4}$ region

KLOE-2 physics program

Goal: **$O(10)$ fb^{-1} in the next 2-3 years** to extend the KLOE physics program

[G.Amelino-Camelia et al., Eur. Phys. J. C 68 (2010), 619]

❖ $\gamma\gamma$ physics	➢ Existence (and properties) of $\sigma/f_0(600)$ ➢ Study of $\Gamma(S/PS\rightarrow\gamma\gamma)$ ➢ PS transition form factor
❖ Light meson spectroscopy	➢ Properties of scalar/vector mesons ➢ Rare η decays ➢ η' physics
❖ Kaon physics	➢ Test of CPT (and QM) in correlated K decays ➢ Test of CPT in K_S semileptonic decays ➢ Test of SM (CKM unitarity,lepton universality) ➢ Test of ChPT (K_S decays)
❖ Dark forces search	➢ Vector gauge bosons @ O (1 GeV)

KLOE-2 prospects: search for U boson

- Analysis of $e^+e^-\to U\gamma\to\mu\mu\gamma$ planned on:

  i) 2 fb^{-1} sample with small-angle (un-detected SA) photon

  ii) 200 pb^{-1} @ 1 GeV sample with large-angle (detected) ISR photons

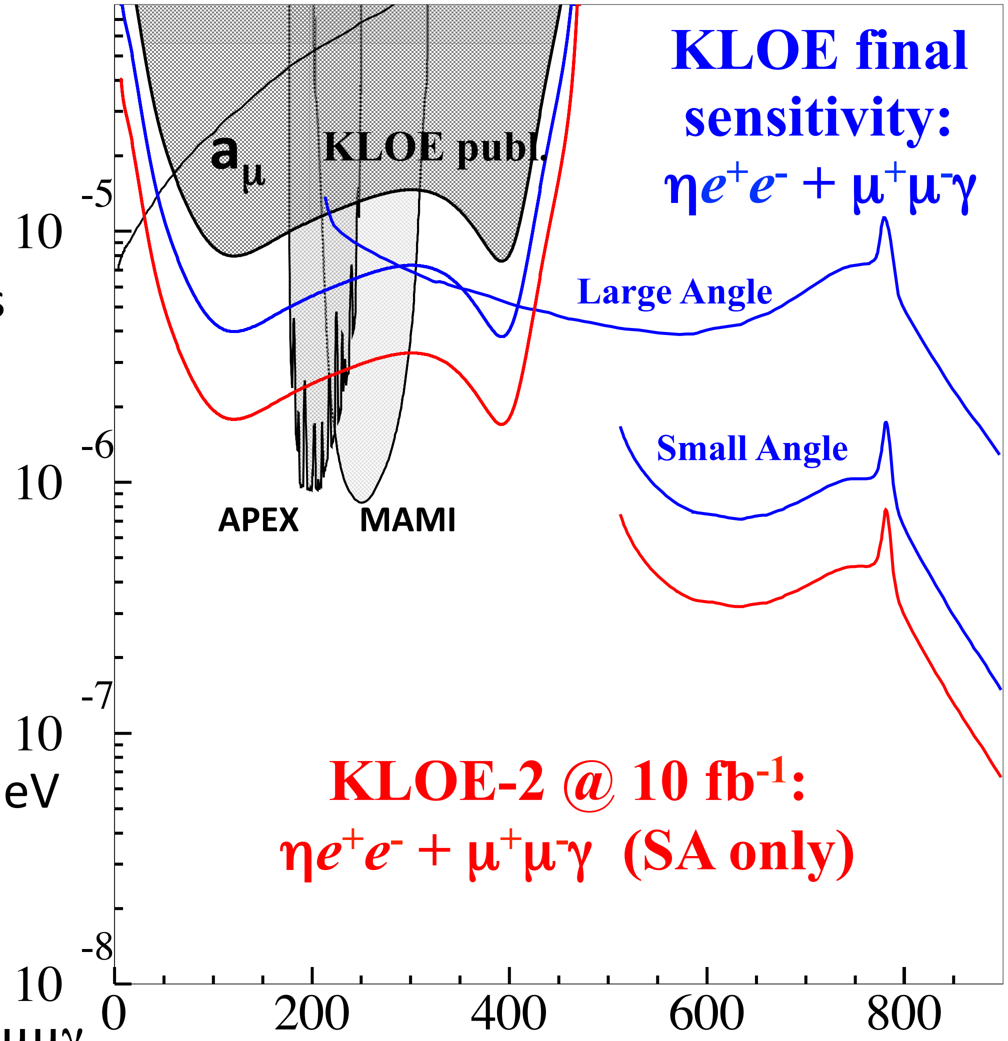
  .

  → SA will provide the best results in the range $\sim 500 < M_U < 1000$ MeV

- KLOE-2 @ 10 fb^{-1} will improve of a factor of ~ 3:

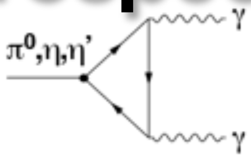
  → in the mass range $100<M_U<400$ MeV with the $\phi\to\eta U$ channel

  → in the mass range 500-1000 MeV with the SA sample of $e^+e^-\to U\gamma\to\mu\mu\gamma$



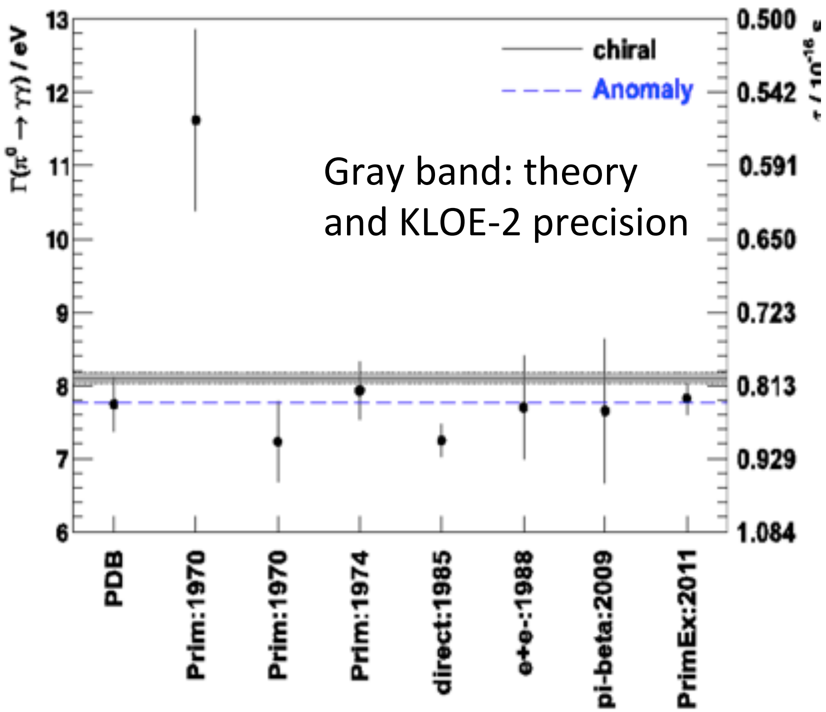
KLOE-2 prospects: $e^+e^- \to e^+e^-\pi^0$

$\Gamma(\pi^0 \to \gamma\gamma)$ width



$\Gamma(\pi^0 \to \gamma\gamma)$ **at 1%** feasible at KLOE-2 with 5-6 fb^{-1}

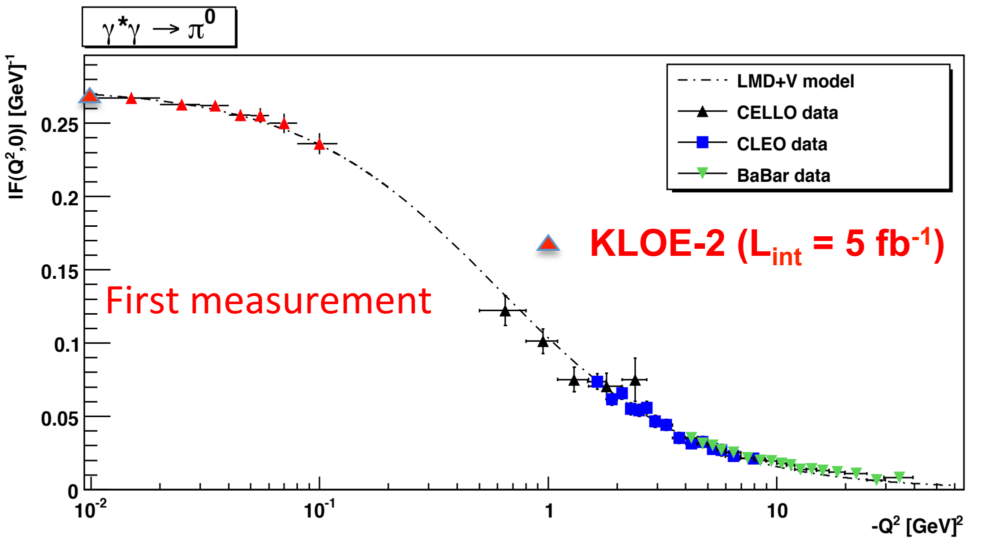
The coincidence between KLOE and HET taggers select a very clean sample of ~1900 events per fb^{-1} ($\sigma_{eff} = 3.4$ pb)



$\pi^0 \to \gamma\gamma^*$ transition form factor in the space-like region at low Q^2

$\mathcal{F}_{\pi^0\,\gamma\gamma^*}$ **at 5-6%** feasible at KLOE-2 with 5 fb^{-1}

The coincidences between KLOE and one of the HET stations are used



Light-by-light term to muon anomaly : both measurements, width and $\mathcal{F}_{\pi^0\,\gamma\gamma^*}$ contribute to a factor of ~2 reduction in the theoretical error, dominated by pseudoscalar (π^0) contribution

Conclusions

- **The high statistics data sample acquired by KLOE still produces copious results in many different fields of physics, η,η', Dalitz decay of ϕ, η, π , $\gamma\gamma$-physics, hadronic cross section, Kaon rare decays and kaon interferometry → the versality of the detector and precision of the analysis allows us to search for Dark U in 3 different decay chains.**

- **DAΦNE commissioning concluded**
  - KLOE detector ~ fully operational
  - KLOE-2 upgrades are being completed
  - Installation of new detectors foreseen for spring 2013
  - Expect to collect O(10 fb^{-1}) in the next 2-3 years

- **Rich physics program available for KLOE-2**

  [see Eur. Phys. J. C 68 (2010), 619]

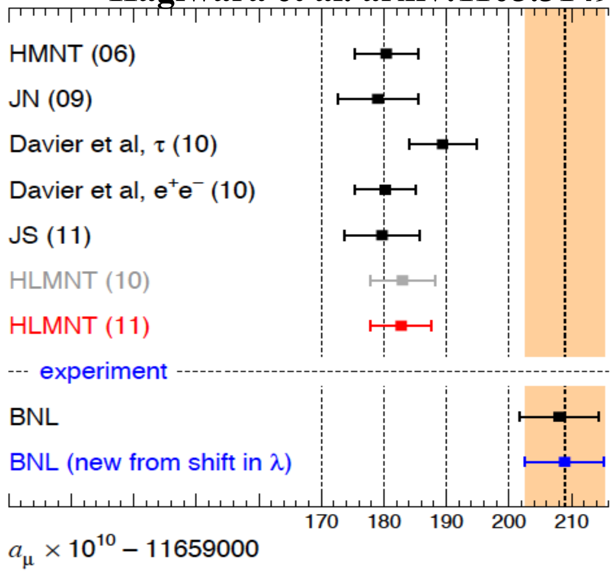
ADDITIONAL MATERIAL

- Hadronic Cross Section

Hadronic cross section

- The ~3σ discrepancy between SM predictions and BNL measurement of the muon anomaly still holds
- Dipion threshold [$2m_\pi$-0.5 GeV] contributes by a 13% fraction to a_μ^{HLO}

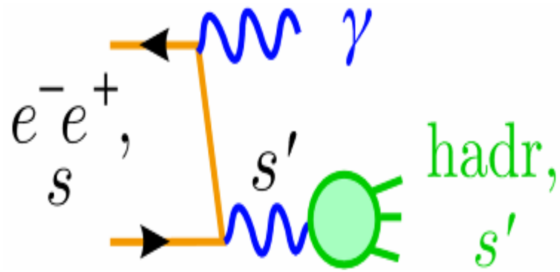
Hagiwara et al. arxiv:1105.3149



At KLOE:

$\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ measured at fixed $\sqrt{s}$ with high accuracy

ISR used to extract $\sigma(e^+e^- \to \pi^+\pi^-)$ for $\sqrt{s'}$ from $2M_\pi$ to $\sqrt{s}$



KLOE measurements, using absolute normalization:

✘240 pb^{-1} on-peak, undetected photon @ small angle (θ_γ<15°or θ_γ>165°) :

$a_\mu^{had,\pi\pi}[0.35<s'<0.95\ GeV^2] = (387.2 \pm 0.5_{stat} \pm 2.4_{syst} \pm 2.3_{th})\ 10^{-10}$

PLB 670 (2009) 285

✘233 pb^{-1} off-peak, detected photon @ large angle (50°< θ_γ<130°) :

$a_\mu^{had,\pi\pi}[0.10<s'<0.85\ GeV^2] = (478.5 \pm 2.0_{stat} \pm 5.0_{syst} \pm 4.5_{th})\ 10^{-10}$

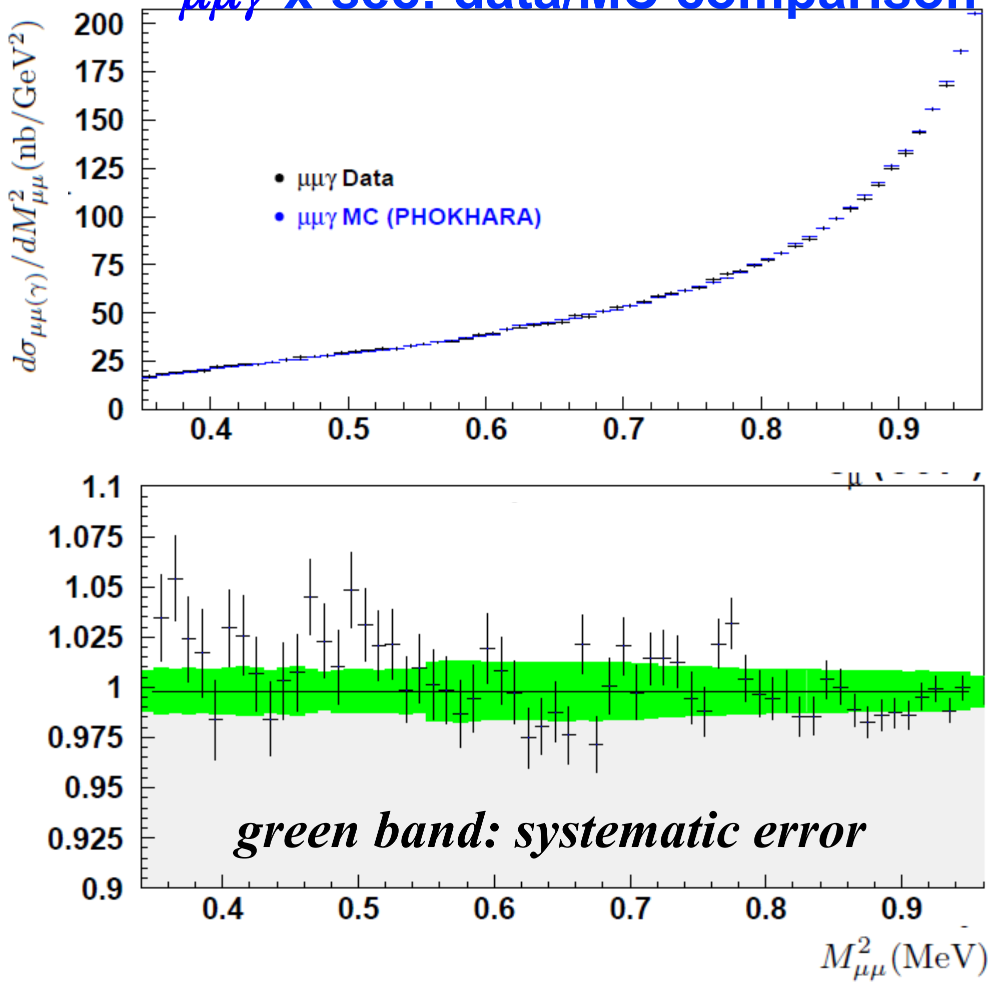
PLB 700 (2011) 102

$\sigma(e^+e^-\to\pi^+\pi^-\gamma)$ from $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio

After the two measurements normalized to luminosity, a new KLOE measurement of the hadronic cross section normalized to $\mu^+\mu^-\gamma$ performed

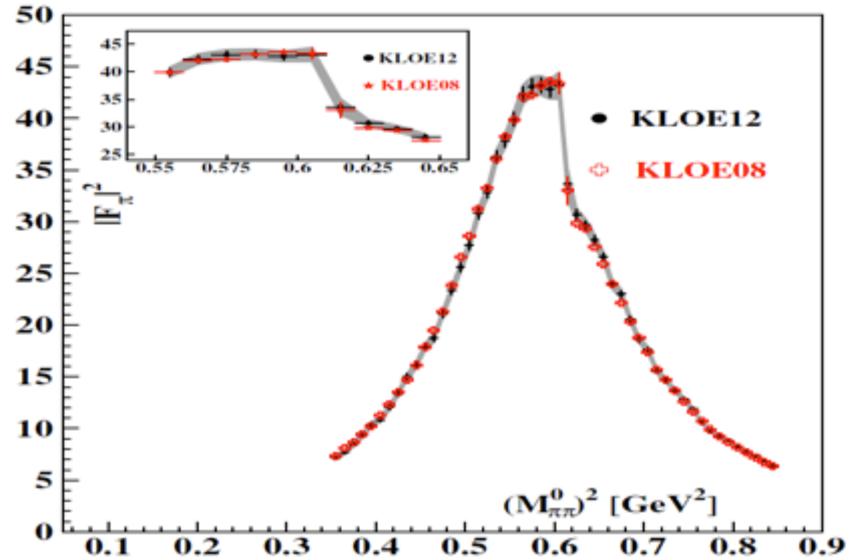
- ✓ **239.2 pb^{-1}**,with photon at small angle: **0.87/3.4 Millions of $\mu\mu\gamma/\pi\pi\gamma$ events**
- ✓ Careful work to achieve a control of $\sim$1% in the muon selection, especially in the ρ region, where $\pi\pi\gamma/\mu\mu\gamma\sim10$
  π/μ separation cross checked with three different methods
- ✓ Efficiencies done directly on data
- ✓ Excellent data/MC agreement for many kinematic variables

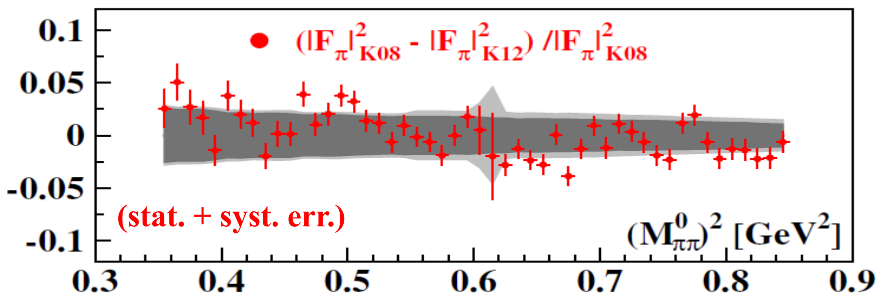
$\mu\mu\gamma$ x-sec: data/MC comparison



$|F_\pi|^2$ from $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio

	KLOE08	KLOE12
Syst. errors (%)	$\Delta^{\pi\pi}a_\mu$ abs	$\Delta^{\pi\pi}a_\mu$ ratio
Reconstruction Filter	negligible	negligible
Background subtraction	0.3	0.8 $(0.3_{\pi\pi\gamma} \oplus 0.8_{\mu\mu\gamma})$
Trackmass	0.2	0.4 $(0.2_{\pi\pi\gamma} \oplus 0.4_{\mu\mu\gamma})$
Particle ID	negligible	negligible
Tracking	0.3	0.6 $(0.3_{\pi\pi\gamma} \oplus 0.5_{\mu\mu\gamma})$
Trigger	0.1	0.1 $(0.1_{\pi\pi\gamma})$
Unfolding	negligible	negligible
Acceptance $(\theta_{\pi\pi})$	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	0.1 $(0.1_{\pi\pi\gamma} \oplus 0.1_{\mu\mu\gamma})$
Luminosity	0.3 $(0.1_{th} \oplus 0.3_{exp})$	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	1.1
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.3
Rad. function H	0.5	-
Total theory systematics	0.6	0.3
Total systematic error	0.9	1.2





Good agreement between the two measurements, especially in the ρ region

KLOE12: $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \text{GeV}^2) = (385.1 \pm 1.1_{stat} \pm 4.4_{syst} \pm 1.2_{theo}) \cdot 10^{-10}$

KLOE08: $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \text{GeV}^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{syst} \pm 2.3_{theo}) \cdot 10^{-10}$

- DARK-FORCES

Search for dark forces @ KLOE

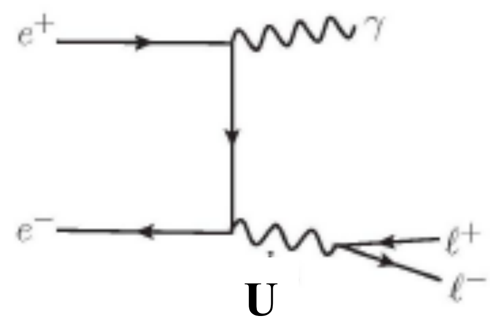
- **Meson decays**: $\phi \rightarrow \eta$U, $\eta/\pi^0 \rightarrow$Uγ ...

  Peculiar of a light meson factory

- **e⁺e⁻ collisions**: $e^+e^- \rightarrow$U$\gamma \rightarrow \ell^+\ell^-\gamma$

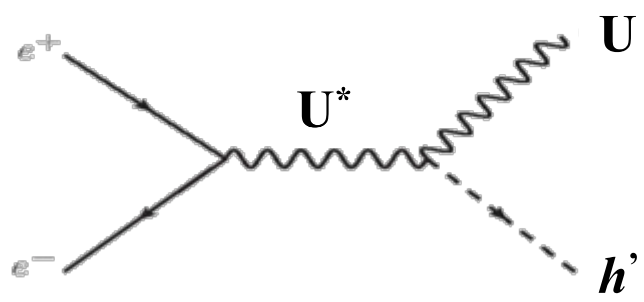
  x-sec ∝ 1/s

  100 times higher at DAΦNE w.r.t. b-factories
  Compensate lower luminosities



- ***h'* -strahlung**: $e^+e^- \rightarrow$U*$\rightarrow$Uh'

  If the hidden simmetry is spontaneously broken by a Higgs-like mechanism, the existence of at least one other scalar particle, the *h*', can be postulated



Search for dark forces @ KLOE: $\phi \to \eta U$

Meson having radiative decay to one photon can decay to a U boson with $\mathrm{BR}(X \to YU) \sim \varepsilon^2 \times |FF_{XY\gamma}|^2 \times \mathrm{BR}(X \to Y\gamma)$

$\Rightarrow$ $\sigma(\phi \to \eta U) \sim 40$ fb for $FF_{\phi\eta}=1$, $\varepsilon=10^{-3}$

Irreducible background: ϕ Dalitz decay $\phi \to \eta\gamma^* \to \eta l^+ l^-$ ($\sigma = 0.7$ nb)

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$\mathrm{BR}(X \to Y + \gamma)$	$\mathrm{BR}(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

All KLOE stat.
All decay chains

[M.Reece and L.T.Wang, JHEP 0907:051 (2009)]

Selected decay chain: $U \to e^+e^-$ + $\eta \to \pi^+\pi^-\pi^0$ (BR = 22.7%) **Published**

$\eta \to \gamma\gamma / \pi^0\pi^0\pi^0$ (BR = 39.3/32.6%) **In progress**

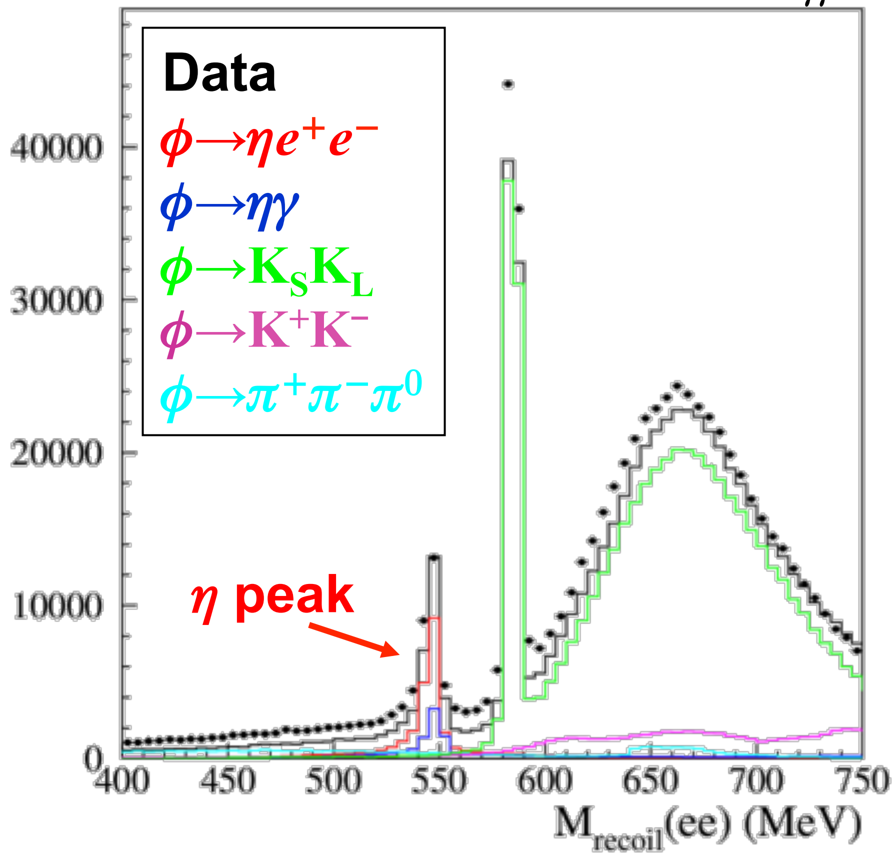
The $\phi\to\eta e^+e^-$, $\eta\to\pi^+\pi^-\pi^0$, decay

Analysis performed on **1.5 fb^{-1}**

BR($\phi\to\eta e^+e^-$) = 1.15×10^{-4} : **~123,000 events from irreducible bckg**

- 4 tracks in a cylinder around IP + 2 photon candidates
- Best $\pi^+\pi^-\gamma\gamma$ match to the η mass using the pion hypothesis for tracks. Other two tracks assigned to e^+/e^-
- $495 < M_{\pi\pi\gamma\gamma} < 600$ MeV
  $70 < M_{\gamma\gamma} < 200$ MeV
  $535 < M_{recoil}(ee) < 560$ MeV
- Photon conversion + ToF cuts

Recoil mass to the e^+e^- pair after $M_{\gamma\gamma}$ cut

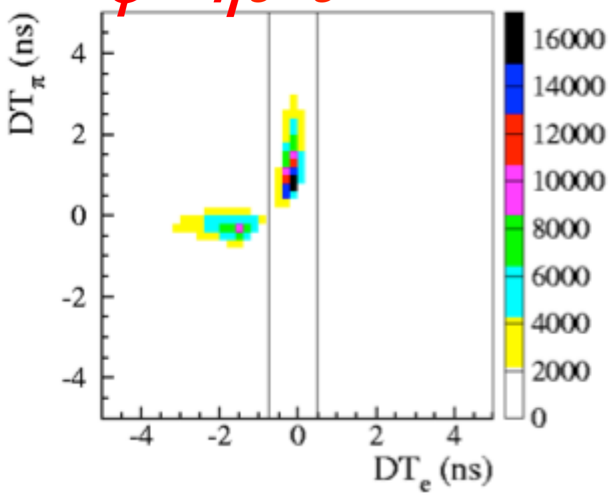


Background rejection: π-enriched events

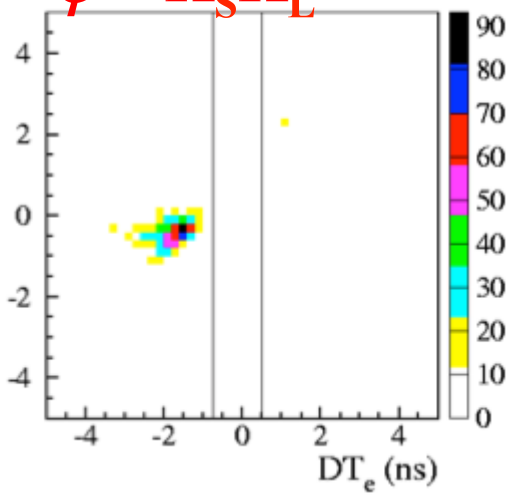
A fraction of $\phi\to\mathrm{KKbar}$ and $\phi\to\pi^+\pi^-\pi^0$ events survive analysis cuts. They can be rejected using Time-of-Flight (ToF) to the calorimeter when an EMC cluster is connected to the track

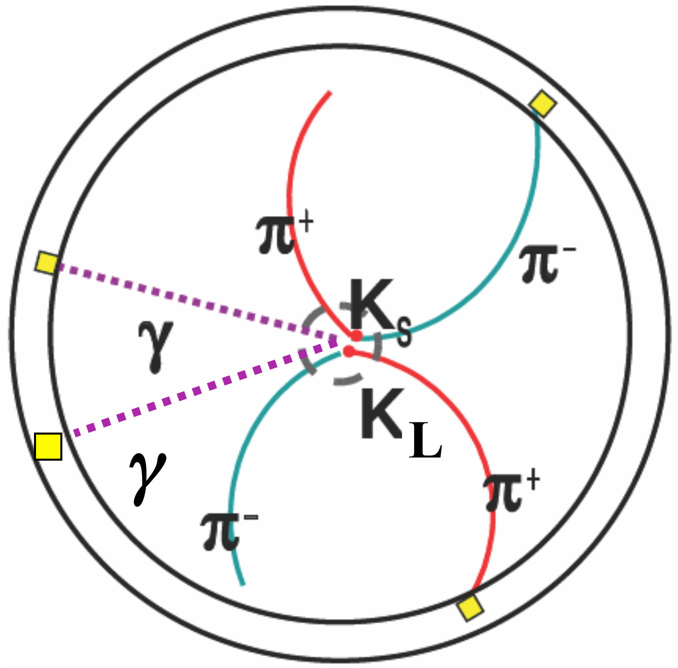
$\mathrm{DT} = \mathrm{T_{track}} - \mathrm{T_{cluster}}$ **variable evaluated in both electron ($\mathrm{DT_e}$) and pion ($\mathrm{DT_\pi}$) hypotheses**

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



$\phi\to K_S K_L$

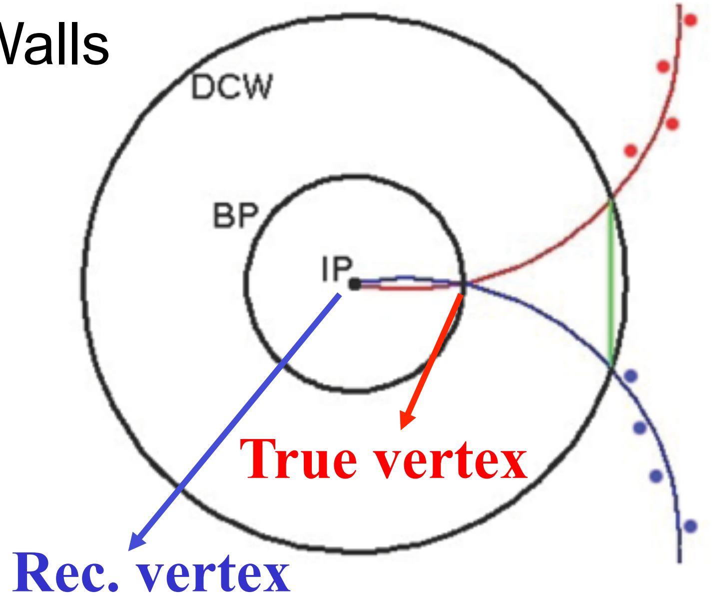


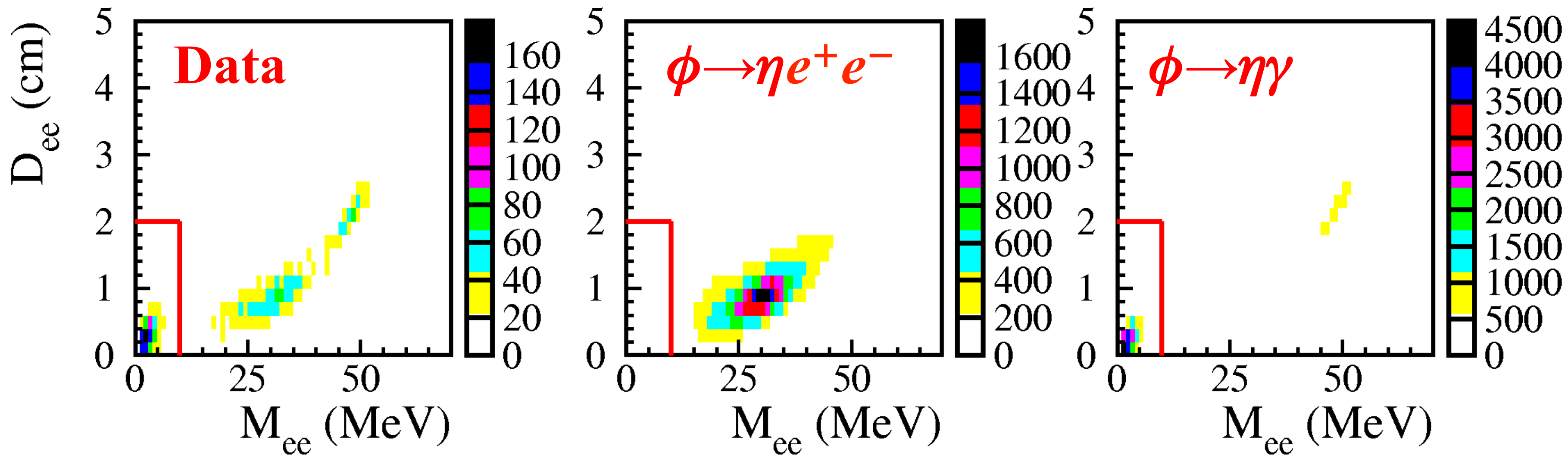


Events with e^+/e^- candidate with connected cluster outside a 3σ $\mathrm{DT_e}$ window removed

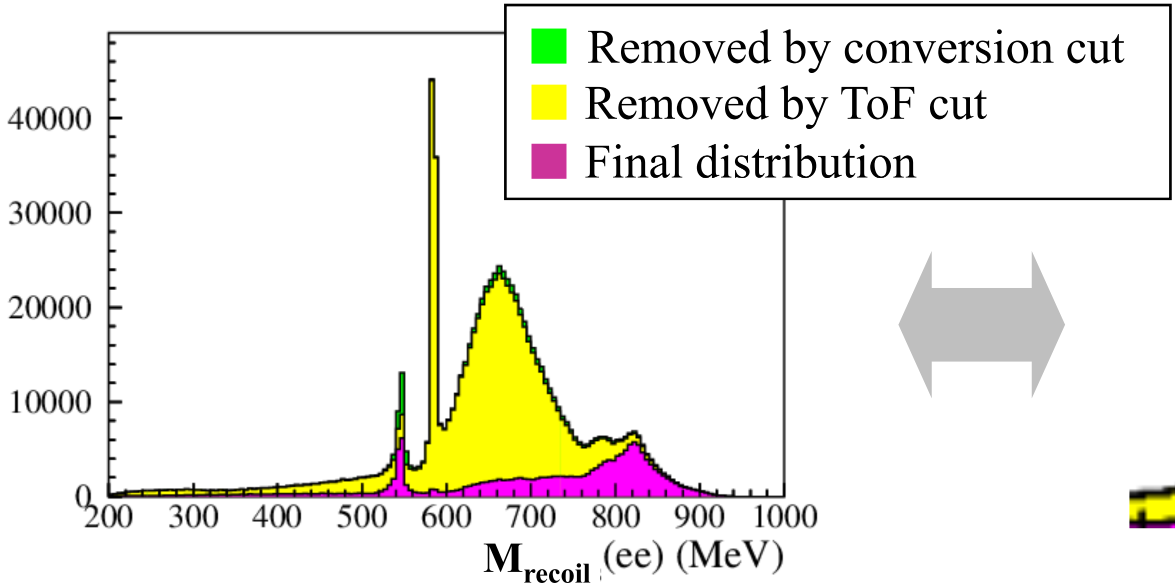
Background rejection: photon conversions

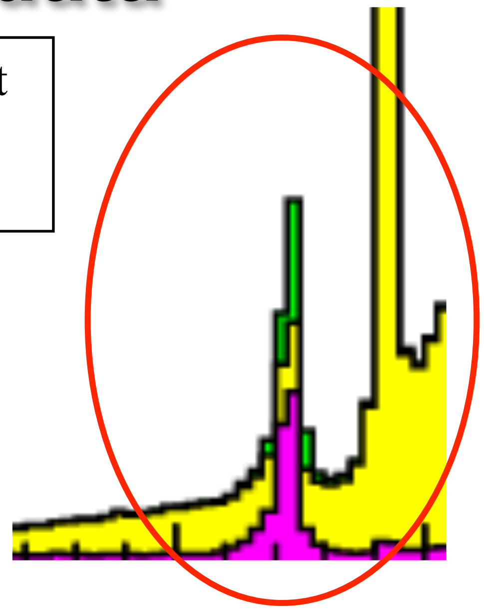
Photon conversions on Beam Pipe/DC Walls rejected by tracking back to BP/DCW surfaces the two e^+, e^- candidates and reconstructing the e^+e^- invariant mass (M_{ee}) and the distance between the two particles (D_{ee}). Both quantities are small if coming from photon conversion



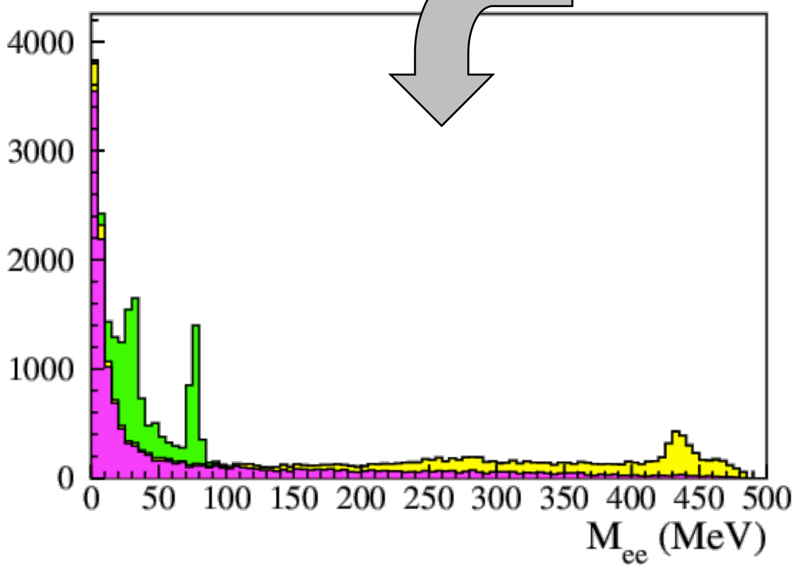


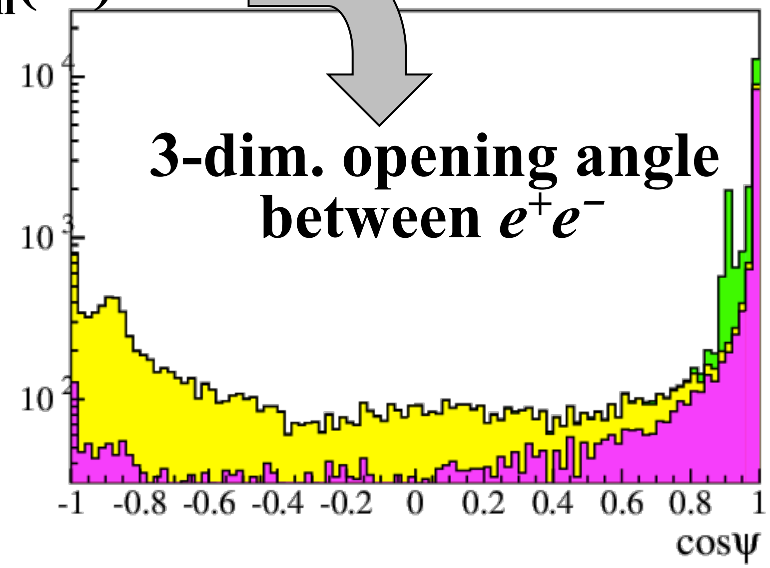
Background reduction on data



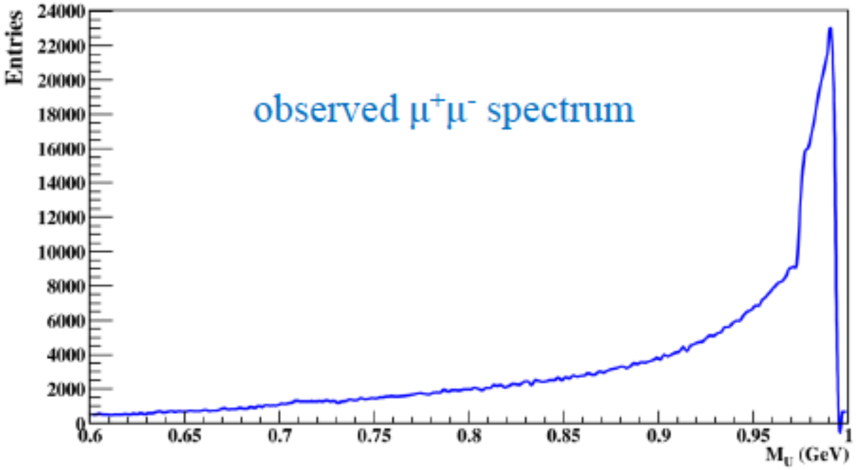


After M_{recoil}(ee) cut





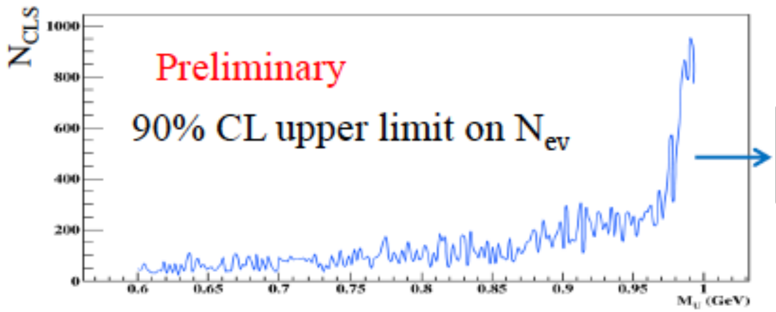
$e^+e^- \to \mu^+\mu^-\gamma$: spectrum and upper limits



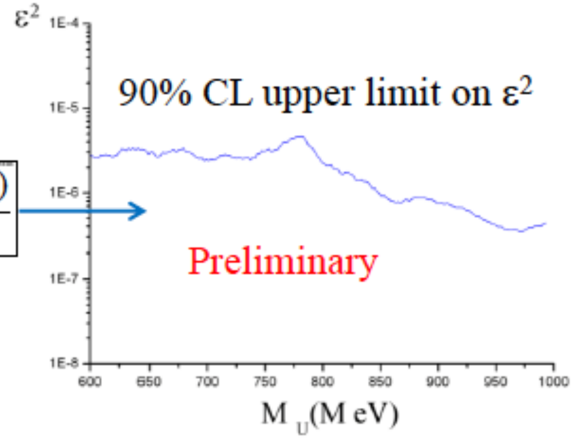
2 MeV bins

Use Phokhara prediction as background estimate (2% syst error) to evaluate upper limits

CLS technique



$$\varepsilon^2 = \frac{N_{CLS}/(\varepsilon_{eff}L)}{H \times I}$$



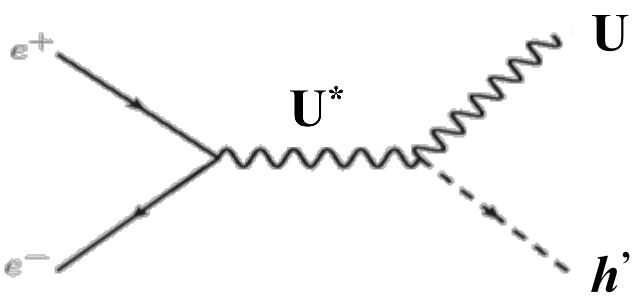
$$H = \frac{d\sigma_{\mu\mu\gamma}/d\sqrt{s_\mu}}{\sigma(e^+e^- \to \mu^+\mu^-, s)}$$

$$I = \int \sigma_U^{\mu\mu} ds_i \quad s = M_U^2 \quad s_i = \text{bin}$$

$$\sigma_U^{\mu\mu} = \sigma(e^+e^- \to U \to \mu^+\mu^-, s)$$

E.Graziani – Dark searches in KLOE - Discrete 2012 17

Search for U boson @ KLOE: *h'* -strahlung



$e^+e^- \to U\,h'$ (dominant if $m_h < m_U$)

$$\sigma \approx 20\,fb \times \left(\frac{\alpha'}{\alpha}\right)\left(\frac{\varepsilon^2}{10^{-4}}\right)\frac{10^2\,GeV^2}{s}$$

[B. Batell, M. Pospelov, A. Ritz: PRD79 (2009) 115008]

$m_h > m_U$: $h' \to UU \to 4l$

$m_h < m_U$: $h' \to$ "invisible"
$U \to ll$

Feasibility studies performed

$\left.\begin{array}{l}\varepsilon = 10^{-3}\\ \alpha' = \alpha\\ m_u >> m_h\end{array}\right\}$ $\sigma_{hU} \approx 20$ fb, $\tau_h > 10\,\mu s$ increasing with decreasing ε

Signature (in the hypothesis that the U decays only to SM particles): a pair of leptons + missing energy

Feasibility studies for *h'* -strahlung

MC signal according to: B. Batell, M. Pospelov, A. Ritz: PRD79 (2009) 115008

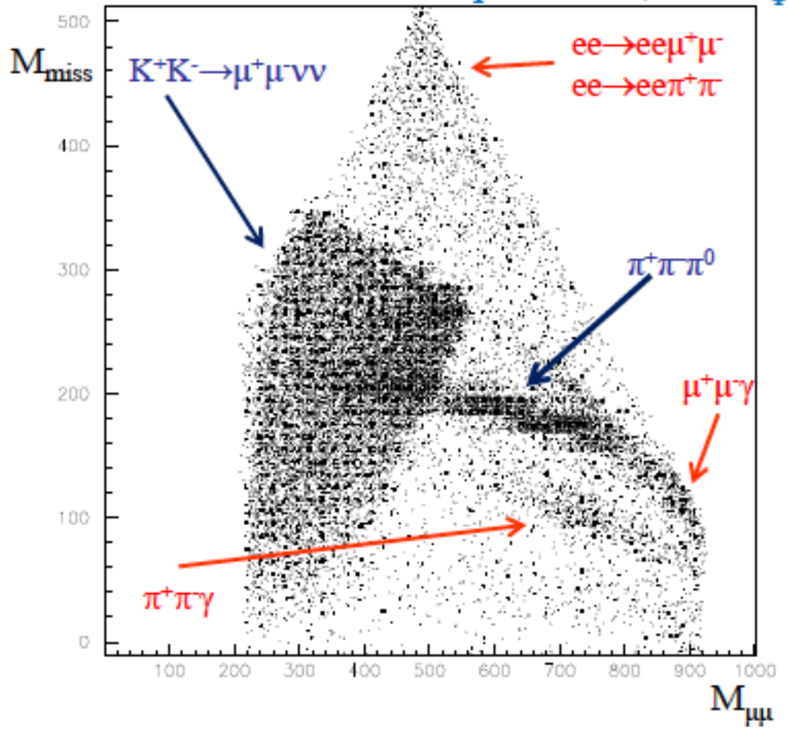
✓ $U \to e^+e^-$ not selected by our Event Classification algorithms

✓ $U \to \mu^+\mu^-$ selected with high efficiency for $m_h < 300$ MeV ➡ **Selected channel**

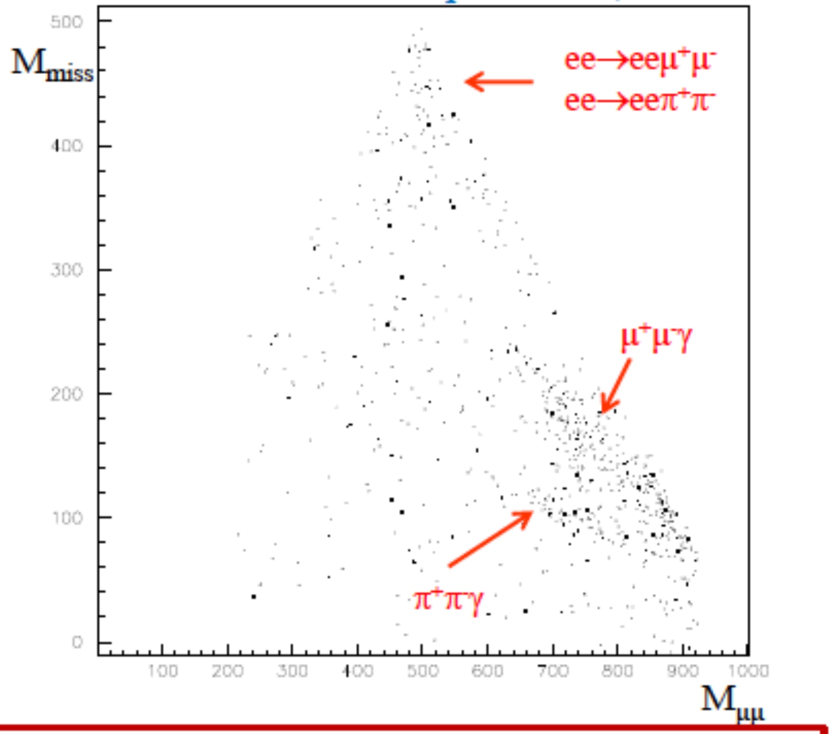
- QED background suppressed because of:
  - ✓ high detection efficiency for γ's of the KLOE calorimeter
  - ✓ missing energy = missing momentum for γ's but not for massive particles
  - ✓ angular distribution of higgs-strahlung $\sin^3\theta$
- Large contamination from $\phi \to K^+K^- \to \mu^+\mu^-\nu\nu$ background

$e^+e^- \to hU$ results: on peak + off peak data

$L=1.65\ fb^{-1}$ on peak data, $\sqrt{s}=M_\Phi$



$L=0.2\ fb^{-1}$ off peak data, $\sqrt{s}=1$ GeV



Backgrounds

- $\Phi \to K^+ K^-$, $K^\pm \to \mu^\pm \nu$
- $\Phi \to \pi^+\pi^-\pi^0$

← Φ decays

- $e^+e^- \to \mu^+\mu^-\gamma$
- $e^+e^- \to \pi^+\pi^-\gamma$
- $e^+e^- \to e^+e^-\mu^+\mu^-$
- $e^+e^- \to e^+e^-\pi^+\pi^-$

← continuum

Binning such as to keep 90-95% of the signal in one bin:
$M_{\mu\mu} \to 5$ MeV, $M_{miss} \to 15 \div 50$ MeV

The background is estimated directly on the data distributions

On the $M_{\mu\mu}$ – M_{miss} plane, counts are averaged over a sliding 5x5 bin matrix excluding the central one (regarded as a possible signal) and considered as an estimate of the background

eta

The light quark masses: study of η→3π decay

- Quark masses are fundamental parameters of the SM known only through their impact on hadronic interactions and hadron properties
- Changing perspective, the SM predictions of any process involving hadrons are affected by the knowledge of the quark masses
- Precision measurements combining isospin-symmetric results from LQCD with isospin-breaking study in ChPT

• η→πππ decay ⇒ Isospin violation
(e.m. contribution strongly suppressed)

$$\mathcal{L}_I = -\frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

In ChPT:

$$A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$$

where $\boxed{Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}}$ and, at lowest order $M(s,t,u) = \frac{3s - 4m_\pi^2}{m_\eta^2 - m_\pi^2}$

$\hat{m} = (m_d + m_u)/2$

• Large final state interactions
•In order to improve on the light quark masses precision, recent theoretical works use a dispersive relations approach and experimental inputs: η→πππ Dalitz plot

$$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$$

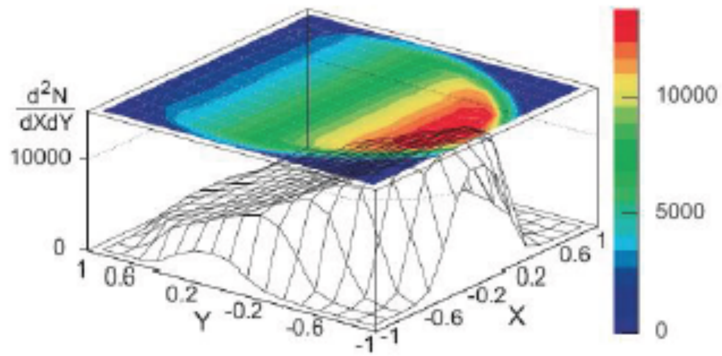
$$\Gamma_{LO}(\eta \to \pi^+\pi^-\pi^0) = 66\ \mathrm{eV}$$
$$\Gamma_{NLO}(\eta \to \pi^+\pi^-\pi^0) = 167\ \mathrm{eV}$$
$$\Gamma_{exp}(\eta \to \pi^+\pi^-\pi^0) = 296\ \mathrm{eV}$$

$\eta \to \pi^+\pi^-\pi^0$ at KLOE

$$X = \sqrt{3}\frac{E_+ - E_-}{\Delta}$$
$$Y = 3\frac{E_0 - m_0}{\Delta} - 1$$
$$(\Delta = m_\eta - 2m_{\pi^\pm} - m_0)$$

$\phi \to \eta\gamma$ ($E_{\gamma rec}$ = 363 MeV)
$\eta \to \pi^+\pi^-\pi^0 \Rightarrow \pi^+\pi^- + 3\gamma$

450 $pb^{-1} \Rightarrow 1.34 \times 10^6$ events in the Dalitz plot



$|A(X,Y)|^2 = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3$

a	$-1.090 \pm 0.005\ ^{+0.008}_{-0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006\ ^{+0.007}_{-0.016}$
e	$-0.006 \pm 0.007\ ^{+0.005}_{-0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
$P(\chi^2)$	73%

[JHEP0805(2008)006]

- *c, e* compatible with zero (C violation)
- fit without cubic term (fY^3) $\Rightarrow P(\chi^2) \sim 10^{-6}$

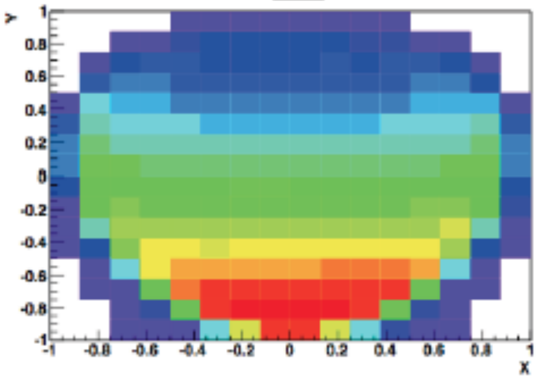
$\eta \rightarrow \pi^+\pi^-\pi^0$ at KLOE

A new analysis is in progress with:
- larger data sample: 2 fb-1
- improved analysis strategy
- reduced main systematic uncertainty due to event classification efficiency (evaluated from min. bias data)

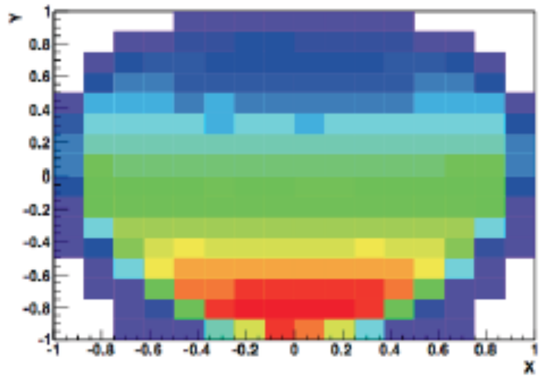
After cuts have:
- MC signal $1.7275 \cdot 10^6$
- MC background $1.63 \cdot 10^4$

Background at $\sim 1\%$

Data



MC



$\eta \to \pi^0\pi^0\pi^0$ at KLOE

- Symmetric Dalitz plot:

  $|A|^2 \propto 1 + 2\,\alpha\, Z \quad \Rightarrow$ only one parameter

$$Z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - M_\eta}{M_\eta - 3M_\pi}\right)^2 = \frac{\rho^2}{\rho^2_{max}}$$

(ρ = distance from the Dalitz plot center)

- 450 pb^{-1} ; 7 prompt photons $\Rightarrow 6.5 \times 10^5$ events

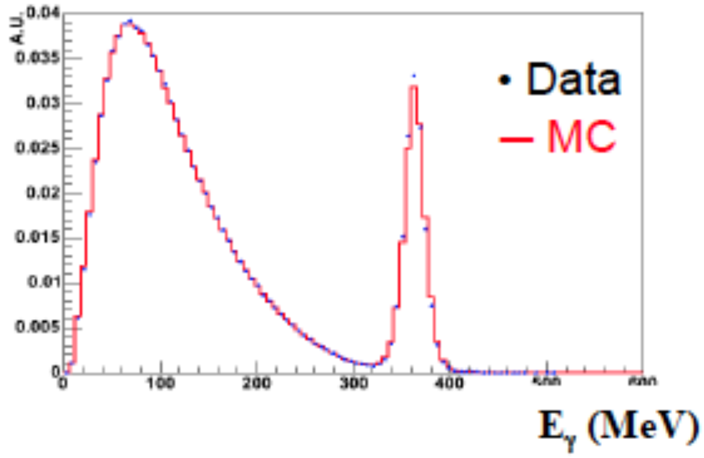
$$\boxed{\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}}$$

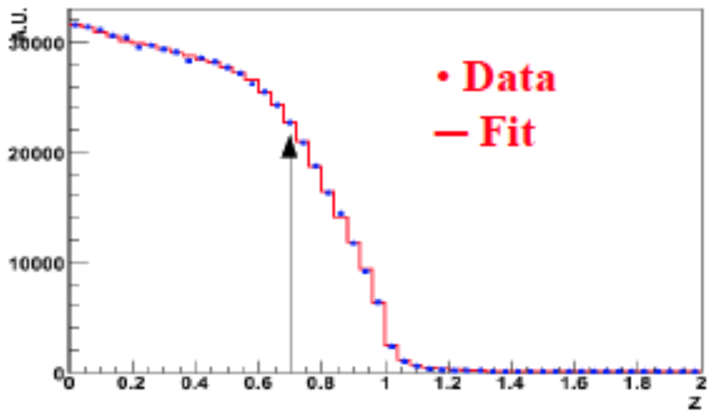
[PLB 694 (2010) 16]

Strong interactions correlate the two amplitudes $A(\eta \to \pi^+\pi^-\pi^0)$ and $A(\eta \to \pi^0\pi^0\pi^0)$: from the Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$

$$\Rightarrow \quad \alpha = -0.038 \pm 0.003^{+0.012}_{-0.008}$$

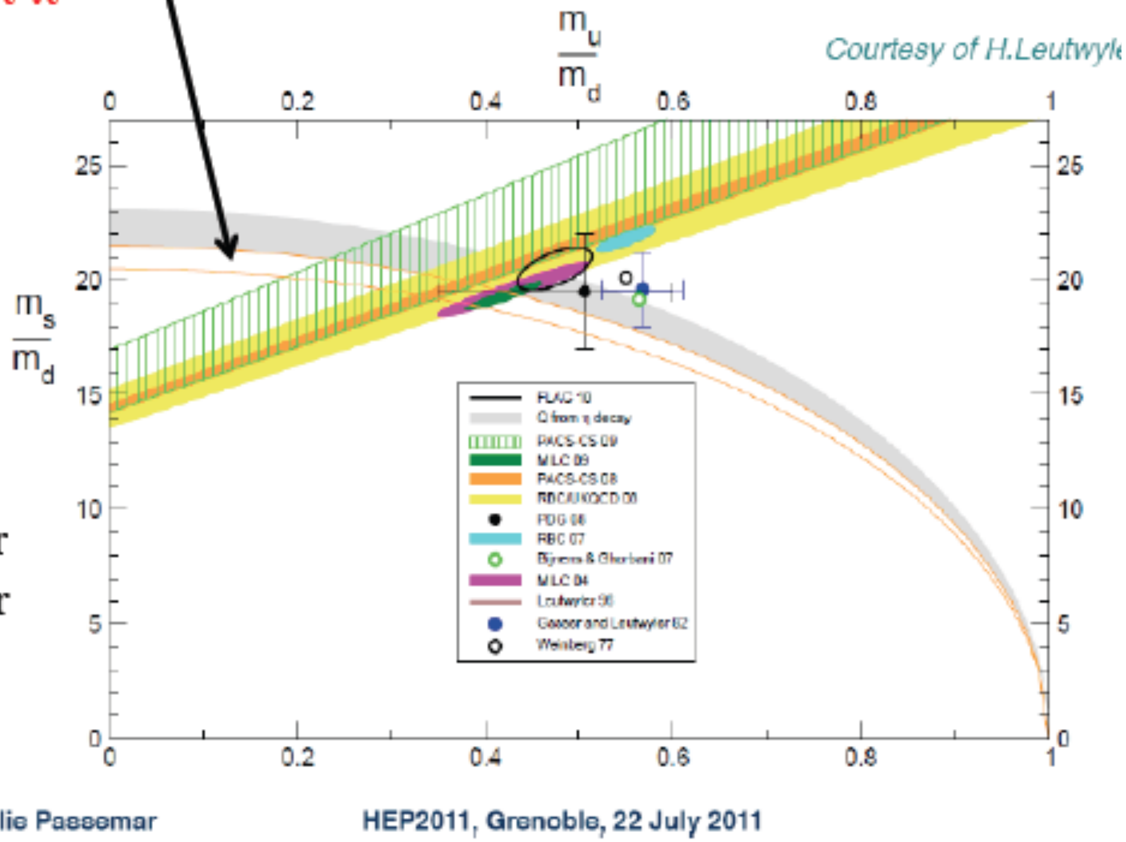
[JHEP0805(2008)006]





The light quark masses: study of $\eta \to 3\pi$ decay

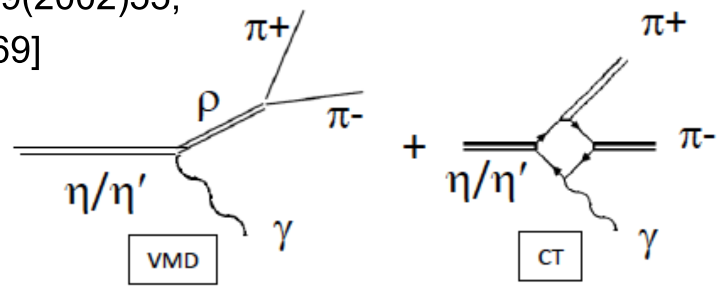
- Using dispersive relations and the fit to the $\eta \to \pi^+\pi^-\pi^0$ data a reasonable agreement with precise experimental analyses of the $\eta \to \pi^0\pi^0\pi^0$ channel, is obtained.
- The Q value obtained with this procedure provides useful information on quark masses.
- New more precise data on $\eta \to \pi^+\pi^-\pi^0$ important in order to reduce systematics on Q^2 associated to the residual mismatch with the neutral channel.
- New analysis of the whole KLOE dataset (~$2fb^{-1}$) with new analysis strategy to reduce systematics
- At KLOE-2 with the inner tracker and more data we expect a further significant improvement



$\eta/\eta' \to \pi^+\pi^-\gamma$: motivations

- **Study of the box anomaly**: test of ChPT and its unitarized extensions
  [Benayoun et al. EPJC31(2003)525; Holstein, Phys. Scripta, T99(2002)55; Borasoy, Nissler, NPA740(2004)362, Picciotto PRD45(1992)1569]

Sizeable effect of the Contact Term expected both in $\Gamma(\eta\to\pi^+\pi^-\gamma)$ and in $M_{\pi\pi}$ distribution



Decay	PDG 2010	Prediction with Contact Term (HLS)	Prediction without Contact Term
$\eta\to\pi^+\pi^-\gamma$	60±4 eV	56.3±1.7 eV	100.9±2.8 eV
$\eta'\to\pi^+\pi^-\gamma$	60±5 keV	48.9±3.9 keV	57.5±4.0 keV

HLS: Benayoun, Eur. Phys. J. C31 (2003) 525

- CLEO result (2007)
  ~ 3 σ' s lower than previous measurements

$\Gamma_{CLEO}(\eta\to\pi^+\pi^-\gamma)=(52\pm4)$ eV

$\Gamma(\eta\to\pi^+\pi^-\gamma)$ / $\Gamma(\eta\to\pi^+\pi^-\pi^0)$

value	events	author	year
0.203 ± 0.008	PDG average		
0.175 ± 0.007 ± 0.006	859	Lopez	2007
0.209 ± 0.004	18 k	Thaler	1973
0.201 ± 0.006	7250	Gormley	1970

$\eta\rightarrow\pi^+\pi^-\gamma$: fit to the $M_{\pi\pi}$ spectrum

"Model–independent approach to η/ η′ →π⁺π⁻γ

(Stollenwerk, Hanhart, Kupsc, Meiβner and Wirzba PLB707 (2012) 184-190)

$$\frac{d\Gamma\left(\eta\rightarrow\pi^+\pi^-\gamma\right)}{ds_{\pi\pi}}=\left|AP\left(s_{\pi\pi}\right)F_V\left(s_{\pi\pi}\right)\right|^2\Gamma_0\left(s_{\pi\pi}\right)$$

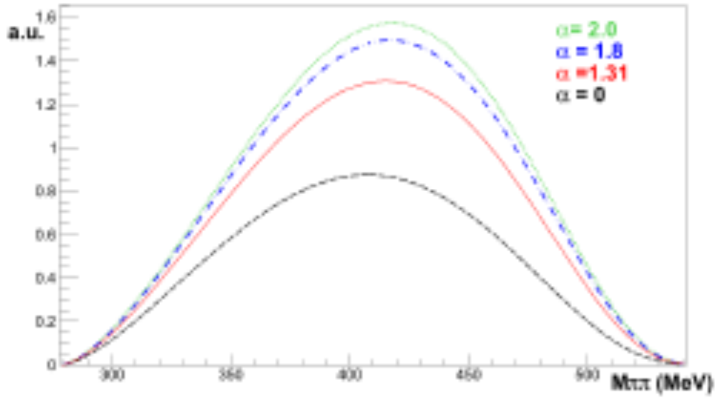
$$F_V\left(s_{\pi\pi}\right)=1+(2.12\pm0.01)s_{\pi\pi}+(2.13\pm0.01)s_{\pi\pi}^2+(13.80\pm0.14)s_{\pi\pi}^3$$

$$P\left(s_{\pi\pi}\right)=1+\alpha\cdot s_{\pi\pi}$$

$$\Gamma_0\left(s_{\pi\pi}\right)=\frac{1}{3\cdot2^{11}\cdot\pi^3 m_\eta^3}\left(m_\eta^2-s_{\pi\pi}\right)^3 s_{\pi\pi}\,\sigma\left(s_{\pi\pi}\right)^3$$

$$\sigma\left(s_{\pi\pi}\right)=\sqrt{1-4m_\pi^2/s_{\pi\pi}}$$

Free parameters: $\left\{\begin{array}{l}A\\ \alpha\end{array}\right.$

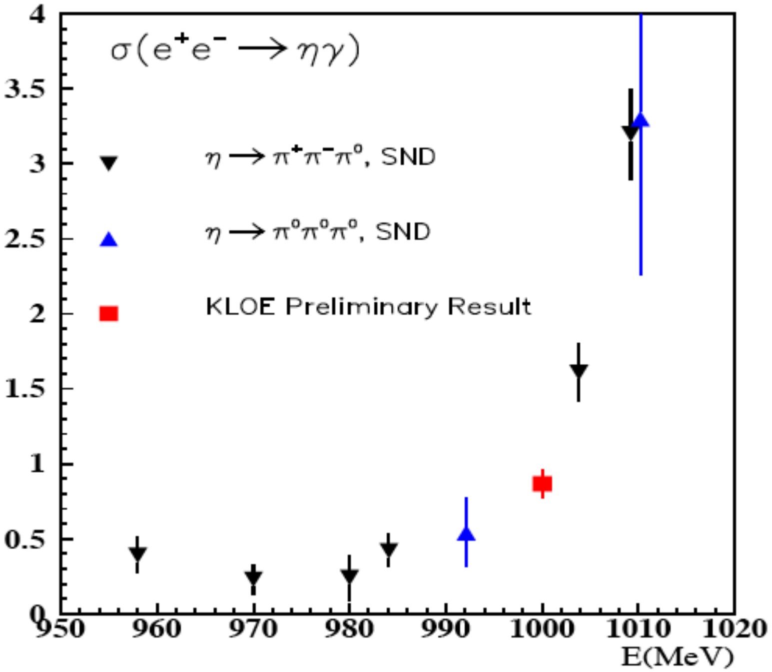


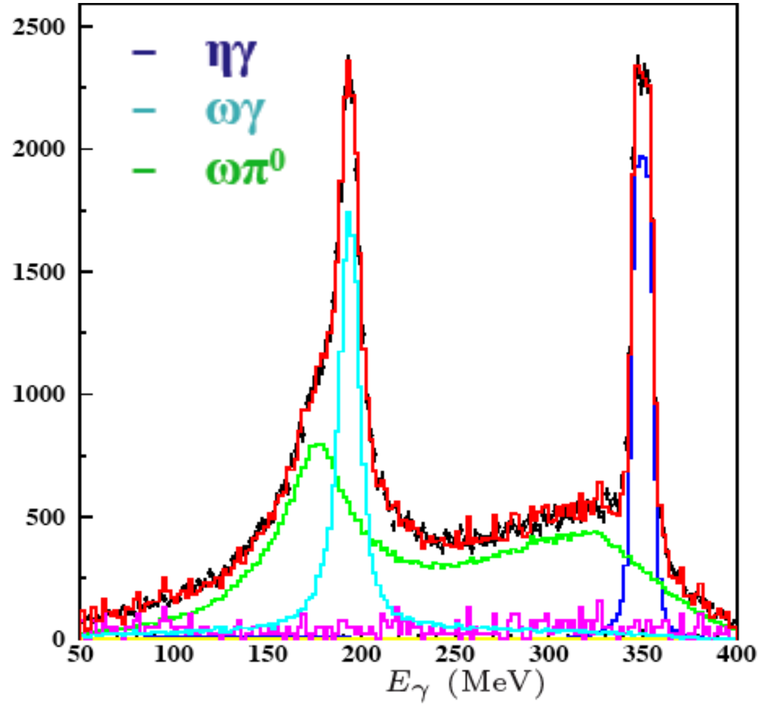
Measurement of $\sigma(e^+e^-\to\eta\gamma)$ @ 1 GeV

$e^+e^- \to \eta\gamma\to\pi^+\pi^-\pi^0\gamma$: 3 photons + 2 tracks

- pion ID
- kinematic cuts to suppress bckg from kaons from kaons
- kinematic fit

$\sigma(e^+e^-\to\eta\gamma, 1\mathrm{GeV}) = (0.866 \pm 0.009 \pm 0.093)$ nb





In agreement with the result from $\eta\to\pi^0\pi^0\pi^0$ (6γ' s with imposed π^0, η masses + miss. E)

$\sigma(e^+e^-\to\eta\gamma, 1\mathrm{GeV}) = (0.875 \pm 0.018 \pm 0.035)$ nb

Background for $\gamma\gamma\to\eta$ accurately measured from the same 240 pb^{-1} sample

For electron and positron beams colliding with energy E, the cross section for production of a state X in $\gamma\gamma$ interactions with photon 4-momenta q_1 and q_2 is

$$\sigma(e^+e^- \to e^+e^-X) = \int \sigma_{\gamma\gamma\to X}(q_1, q_2)\ \Phi(q_1, q_2)\ \frac{d\vec{q}_1}{E_1}\frac{d\vec{q}_2}{E_2}\,, \tag{2.1}$$

where the $\gamma\gamma$ differential luminosity $\Phi(q_1, q_2)$ has been calculated in [14–16] using different approximations and is proportional to $(\alpha/2\pi)^2(\ln E/m_e)^2$. For a narrow resonance of spin 0 the formation cross section is

$$\sigma_{\gamma\gamma\to X} = \frac{8\pi^2}{m_X}\Gamma_{X\to\gamma\gamma}\ \delta(w^2 - m_X^2)\ |F(q_1^2, q_2^2)|^2\,, \tag{2.2}$$

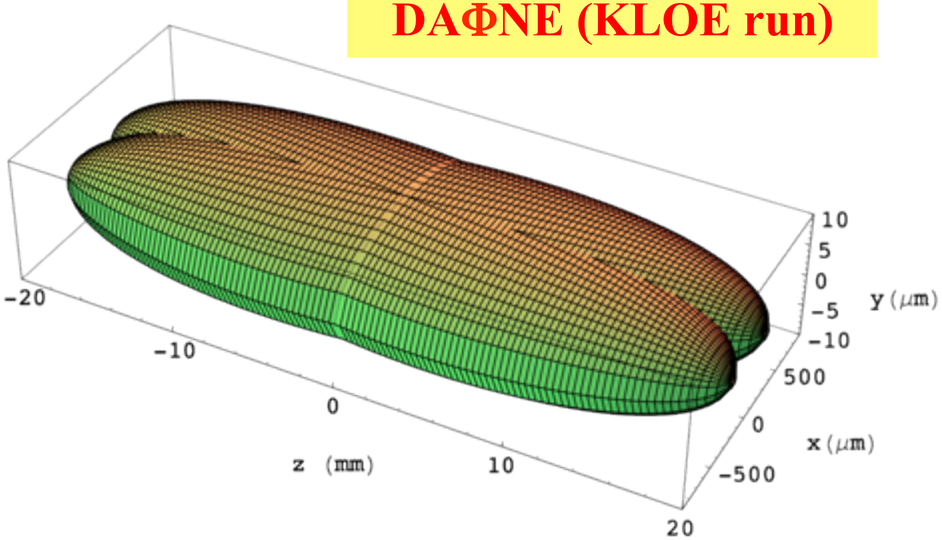
where $\Gamma_{X\to\gamma\gamma}$ is the radiative width, and $w^2 = (q_1 + q_2)^2$. The transition form factor, $F(q_1^2, q_2^2)$, is equal to one for real photons and is usually parametrized in the form

$$F(q_1^2, q_2^2) = \frac{1}{1 - bq_1^2}\,\frac{1}{1 - bq_2^2}\,, \tag{2.3}$$

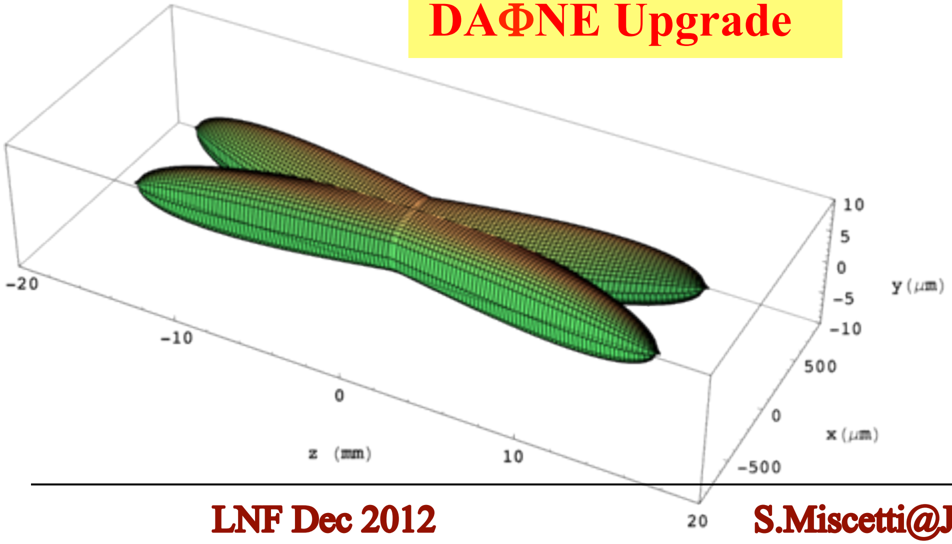
inspired by the Vector Dominance Model [17]. The parameter b for the η meson has been measured at high q^2 values in $\gamma\gamma$ experiments with single-tagging [18–20] and in the η leptonic radiative decays $\eta \to \ell^+\ell^-\gamma$ [21–23] at low q^2 values, closer to those of this measurement. The results do not show appreciable dependence on q^2 and the value assumed in this analysis, $b_\eta = (1.94 \pm 0.15)$ GeV^{-2}, was obtained as an average of the measurements at low q^2.

DAΦNE: beam profiles @ IP and parameters

DAΦNE (KLOE run)



DAΦNE Upgrade



	DAΦNE (KLOE run)	DAΦNE Upgrade
I_{bunch} (mA)	13	13
N_{bunch}	110	110
β_y^* (cm)	1.7	0.65
β_x^* (cm)	170	20
σ_y^* (μm)	7	2.6
σ_x^* (μm)	700	200
σ_z (mm)	25	20
θ_{cross} (mrad) (half)	12.5	25
$\Phi_{Piwinski}$	0.45	2.5
L ($cm^{-2}s^{-1}$)	1.5×10^{32}	$>5 \times 10^{32}$

- QM interference

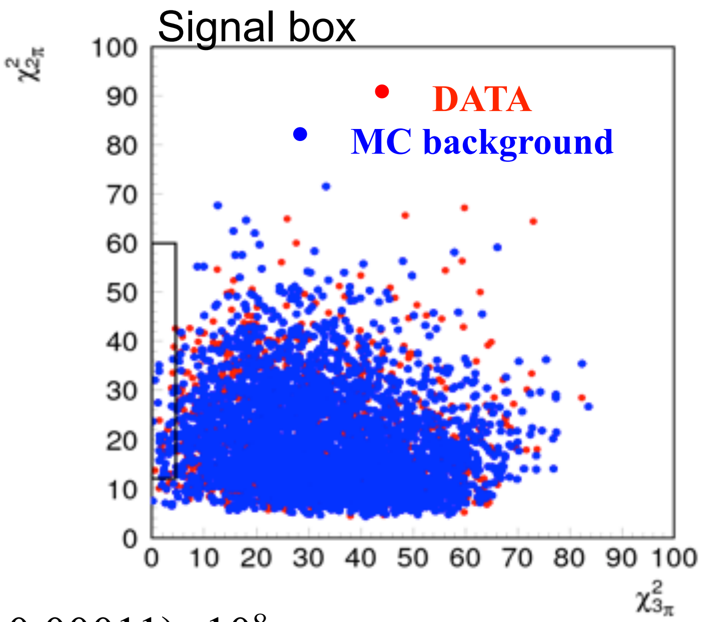
Search for $K_S \to \pi^0\pi^0\pi^0$ @ KLOE

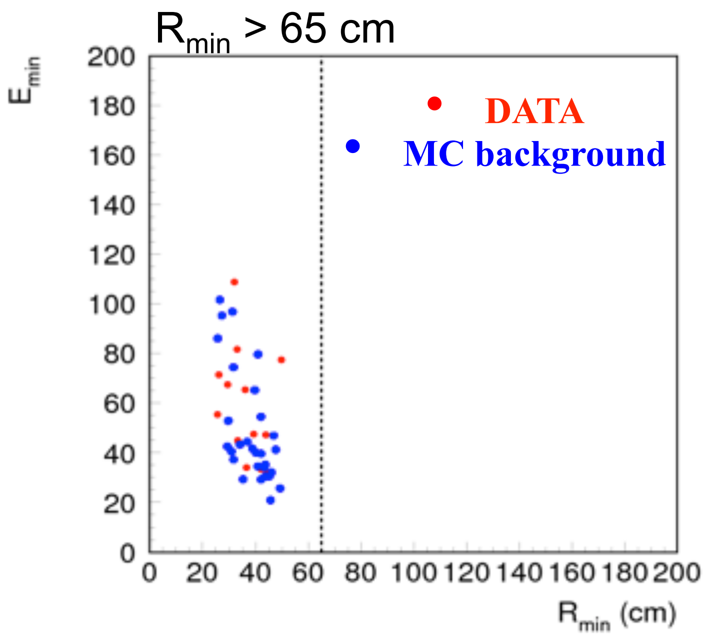
- K_L interactions in the calorimeter to tag K_S decay
- 6 prompt γ's required
- Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
- Dominant background : $K_S \to 2\pi^0$ + 2 fake clusters

The analysis has been updated
- improving clustering
- hardening Ks tagging
- processing the entire data set

- $N_{obs} = 0$
- $B_{exp} = 0$
- $S_{exp} = 0.12$

- $\varepsilon_{3\pi} = 0.23(1)$
- $N_{3\pi^0} \leq 2.33/\varepsilon_{3\pi^0}$ @ 90% C.L.
- Normalized to $N_{2\pi^0}/\varepsilon_{2\pi^0} = (1.14130 \pm 0.00011) \times 10^8$





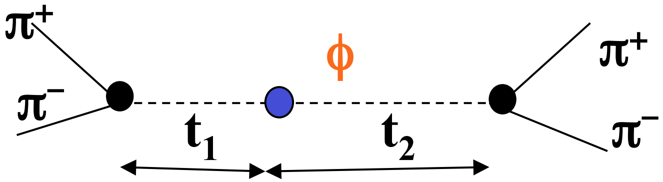
$BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ @ 90% CL

$|\eta_{000}| < 0.0088$ @ 90% CL

This result points to the feasibility of the first observation at KLOE-2

KLOE-2 prospects: $K_S K_L$ interferometry

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



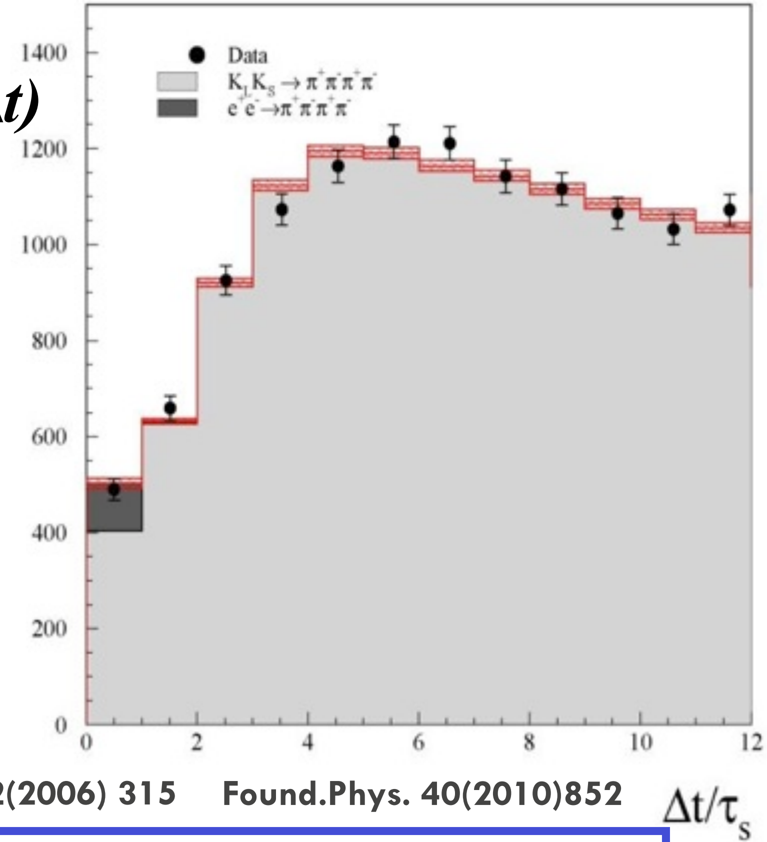
$\Delta t = |t_1 - t_2|$

Most precise test of quantum coherence in an entangled system:

$$\boxed{\zeta_{0\bar{0}} = \left(1.4 \pm 9.5_{\mathrm{STAT}} \pm 3.8_{\mathrm{SYST}}\right)\times 10^{-7}}$$

ζ decoherence parameter (QM predicts ζ=0)

$I(\Delta t)$



PLB 642(2006) 315   Found.Phys. 40(2010)852

Quantum gravity effects might induce:
1) decoherence and CPT violation
(at most $\gamma = O(m_K^2/M_{Planck}) \sim 2\times10^{-20}$ GeV)

$$\boxed{\gamma = \left(0.7 \pm 1.2_{STAT} \pm 0.3_{SYST}\right)\times 10^{-21}\ \mathrm{GeV}}$$

2) decoherence and CPT violation induce modification of the initial correlation of the kaon pair (at most $\omega = O(m_K^2/M_{Planck}/\Delta\Gamma) \sim 1\times10^{-3}$)

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

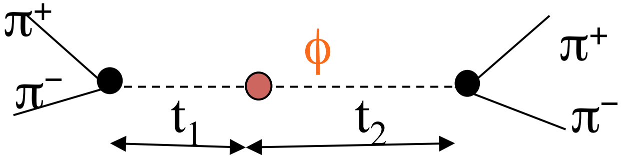
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

KLOE-2 prospects: $K_S K_L$ interferometry

Sensitivity to QM coherence and CPT-invariance

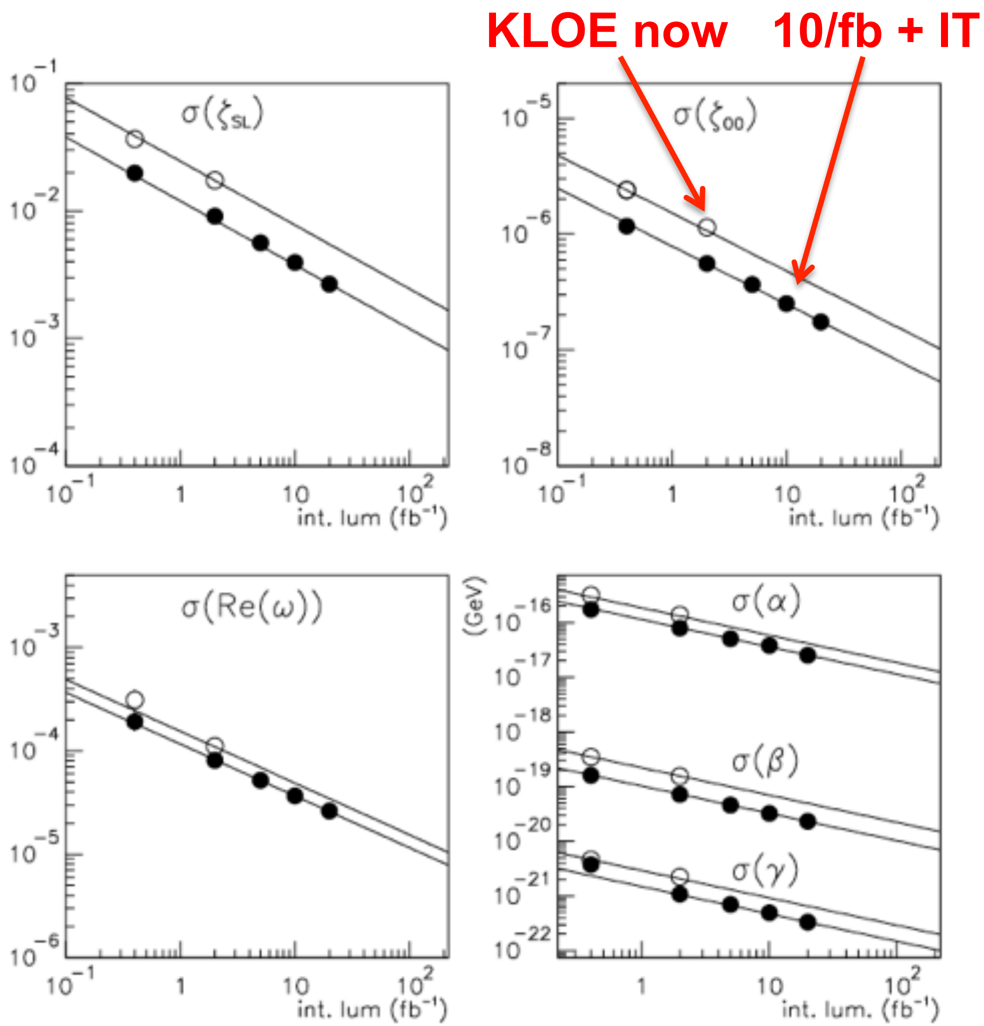
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$



$\Delta t = |t_1 - t_2|$

Most precise test of quantum coherence in an entangled system performed @ KLOE

The improvement in sensitivity with O(10 fb^{-1}) and the IT is a factor of ~ 4 with respect to the KLOE analysis, slightly dependent on the different parameters



KLOE-2 prospects: $K_S K_L$ interferometry

Sensitivity to QM coherence, CPT- and Lorentz-invariance

Param.	Present best published measurement	KLOE-2 (IT) L=5 fb^{-1}	KLOE-2 (IT) L=10 fb^{-1}	KLOE-2 (IT) L=20 fb^{-1}
ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$	$\pm 0.13 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$	$\pm 0.35 \times 10^{-2}$	$\pm 0.25 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ GeV	$\pm 2.5 \times 10^{-17}$ GeV
β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.50 \times 10^{-19}$ GeV	$\pm 0.35 \times 10^{-19}$ GeV	$\pm 0.25 \times 10^{-19}$ GeV
γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV	$\pm 0.75 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.33 \times 10^{-21}$ GeV	$\pm 0.53 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.23 \times 10^{-21}$ GeV	$\pm 0.38 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.16 \times 10^{-21}$ GeV
$\mathrm{Re}(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$	$\pm 0.49 \times 10^{-4}$	$\pm 0.35 \times 10^{-4}$
$\mathrm{Im}(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$	$\pm 0.43 \times 10^{-4}$
Δa_0	$[(0.4 \pm 1.8) \times 10^{-17}$ GeV$]$	$\pm 0.52 \times 10^{-17}$ GeV	$\pm 0.36 \times 10^{-17}$ GeV	$\pm 0.26 \times 10^{-17}$ GeV
Δa_Z	$[(2.4 \pm 9.7) \times 10^{-18}$ GeV$]$	$\pm 2.2 \times 10^{-18}$ GeV	$\pm 1.5 \times 10^{-18}$ GeV	$\pm 1.1 \times 10^{-18}$ GeV
$\Delta a_{X,Y}$	$[\pm 6.0 \times 10^{-18}$ GeV$]$	$\pm 1.3 \times 10^{-18}$ GeV	$\pm 0.95 \times 10^{-18}$ GeV	$\pm 0.67 \times 10^{-18}$ GeV

[...] KLOE preliminary

CPT & Lorentz invariance violation: SME framework

Using the same final state for both kaons ($\pi^+\pi^-$) the two decay are distinguished only by the kaon momentum direction. The decay amplitudeis written as follows:

$$I(f_1, f_2; \Delta t) = \frac{\Gamma_S^1 \Gamma_S^2}{2\Gamma} e^{-\Gamma|\Delta t|} \left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta t} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta t} - 2\Re e \left(\eta_1 \eta_2 e^{-i\Delta m \Delta t} \right) \right]$$

$$\eta_1 = \eta_\pm = \varepsilon_K - \delta(\vec{p}_{K^1}) \qquad \eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2})$$

δ_K is the CPT violation parameter in the Kaon system.

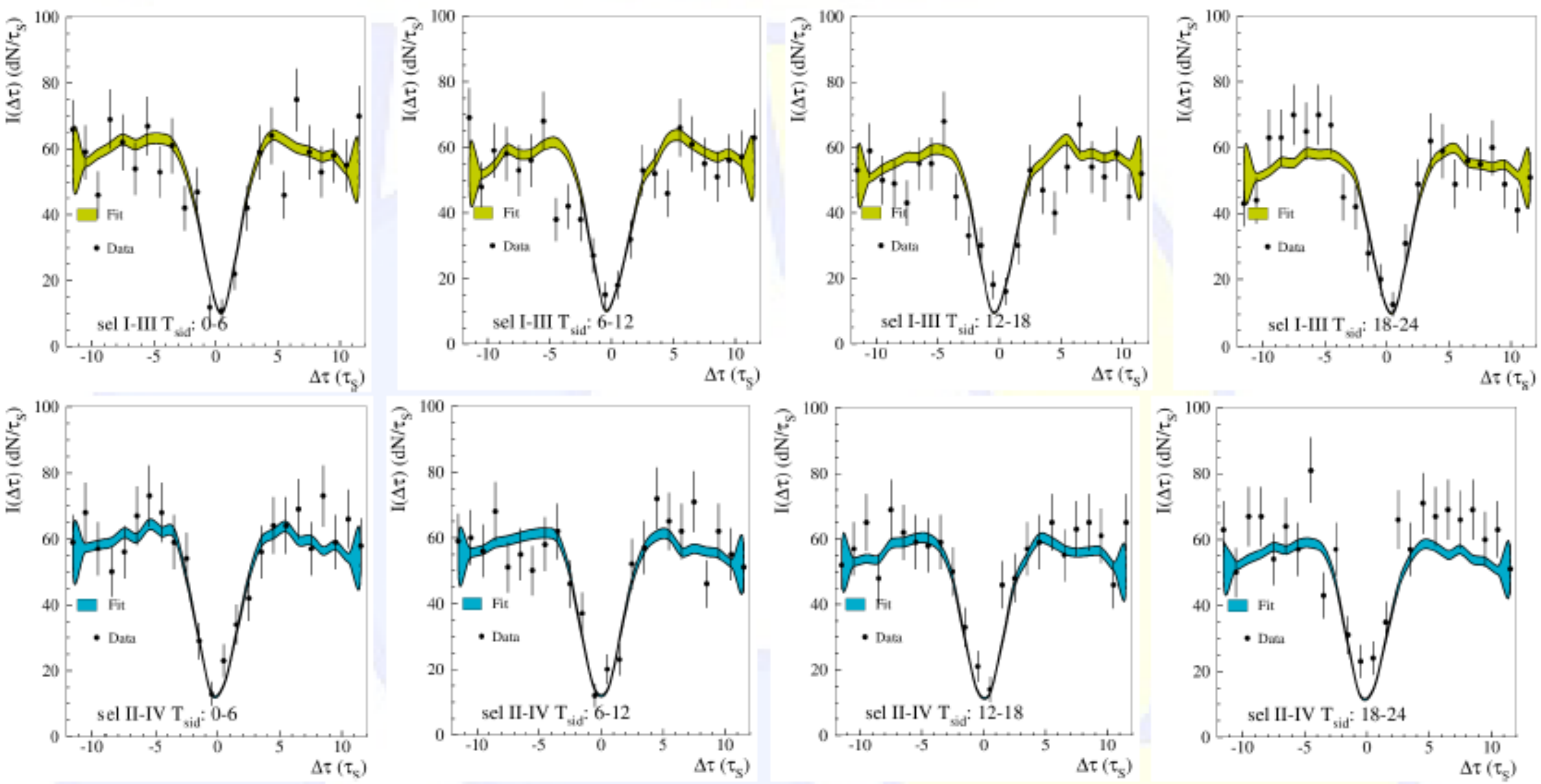
According to the SME (Kostelecky) and anti-CPT theorem, CPT violation should appears together with Lorentz Invariance breaking (Greenberg), and thus implying a direction dependent modulation.

R. Potting Talk

$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta\vec{a}) / \Delta m$$

Ordering Kaon according to their momenta it is possible to have the two η–coefficients containing two different δ_K CPT violating parameter.

Fit results



Fit error includes Data/MC correction (~2%) and single bin efficiency (~5%)

Preliminary results:

$$\Delta a_0 = (-6.2 \pm 8.2_{stat} \pm 3.3_{sys})\ 10^{-18}\ \mathrm{GeV}$$

$$\Delta a_X = (\ 3.3 \pm 1.6_{stat} \pm 1.5_{sys})\ 10^{-18}\ \mathrm{GeV}$$

$$\Delta a_Y = (-0.7 \pm 1.3_{stat} \pm 1.5_{sys})\ 10^{-18}\ \mathrm{GeV}$$

$$\Delta a_Z = (-0.7 \pm 1.0_{stat} \pm 0.3_{sys})\ 10^{-18}\ \mathrm{GeV}$$

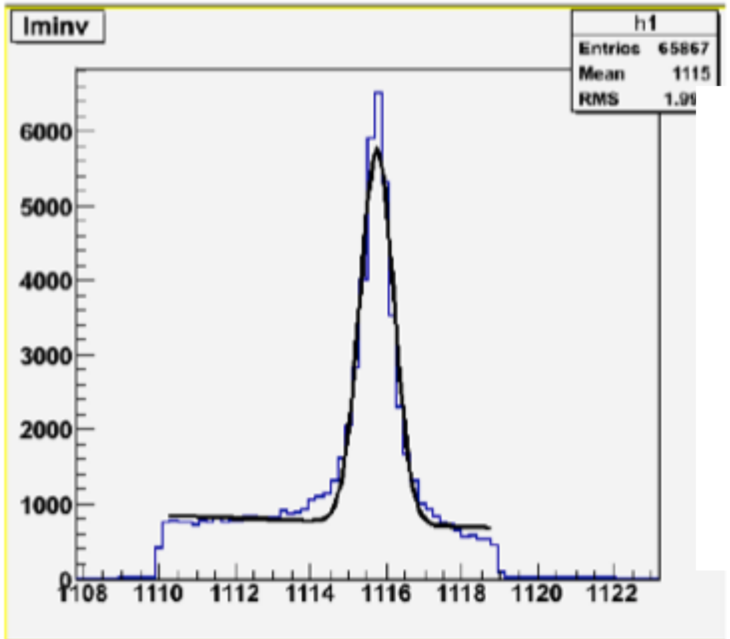
Systematics taken as the maximal fluctuation for the observed effects:
- Direct four pion contribution
- Decay time difference fitting range
- Decay time difference bin width
- Regeneration on BP

- KLOE vs AMADEUS data taking

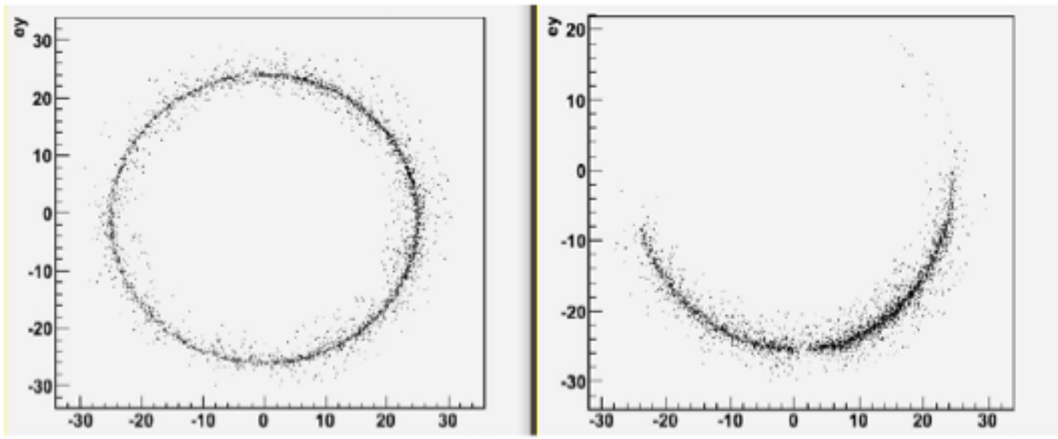
AMADEUS in KLOE (2012)

- 100 pb^{-1} acquired with DC ON since 5/11/2012
- Carbon target inserted close to DC walls
- Minor problems on EMC calibrations, DC OK
- Max Lum 1.5 x 10**32, 420 nb/hours
- 1600 Lambda/pb → equivalent to 1.3 fb-1 of old KLOE data

2012 8pb-1



Proton-pion Invariant Mass (MeV)



X vs Y (cm)