Overview of light hadron physics at KLOE/KLOE-2

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On behalf of the KLOE-2 Collaboration

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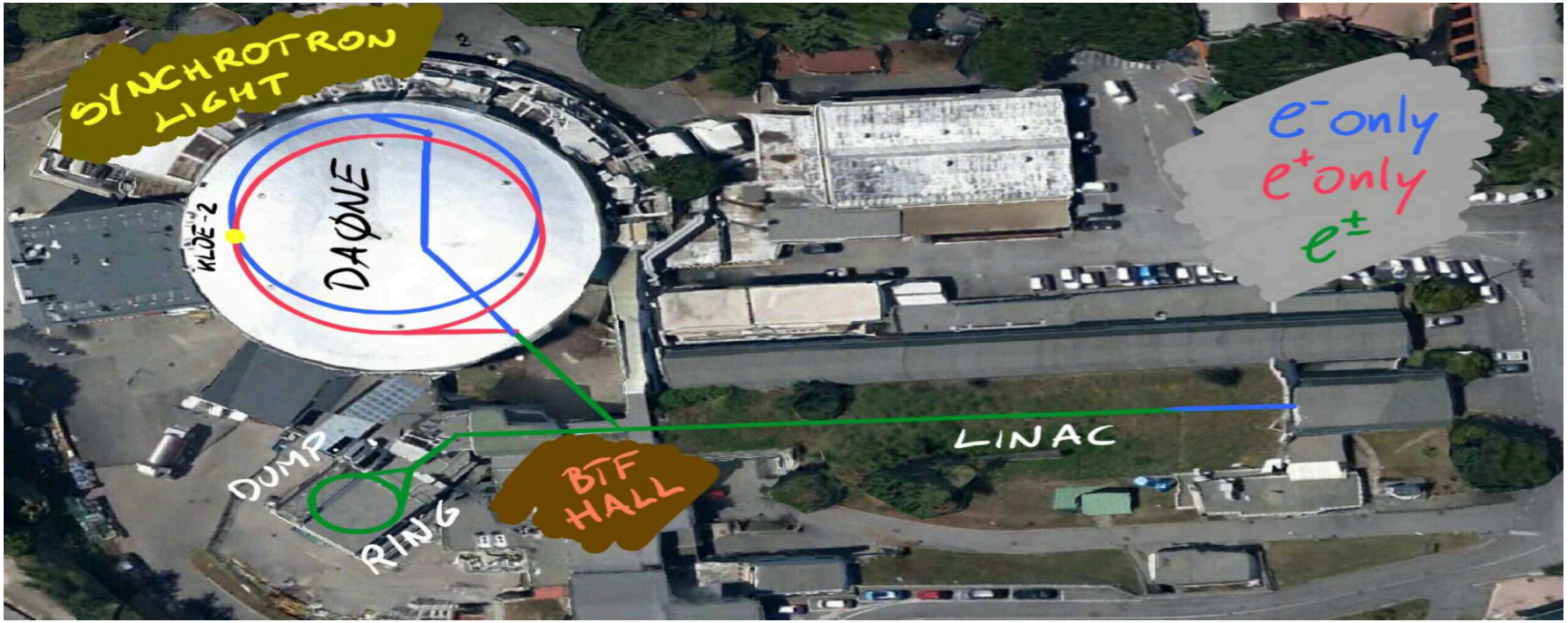
DAΦNE: ϕ-factory



- Double rings e^+e^- collider @ $\sqrt{s}=M_\phi=1019.4$ MeV
- 105 bunches in each ring with a time interval of 2.7 ns
- 2 interaction regions
- Updated DAΦNE (2008) → increased the peak luminosity
  - Crab-Waist interaction scheme
  - Large beam crossing angle ~ 2×12.5 mrad

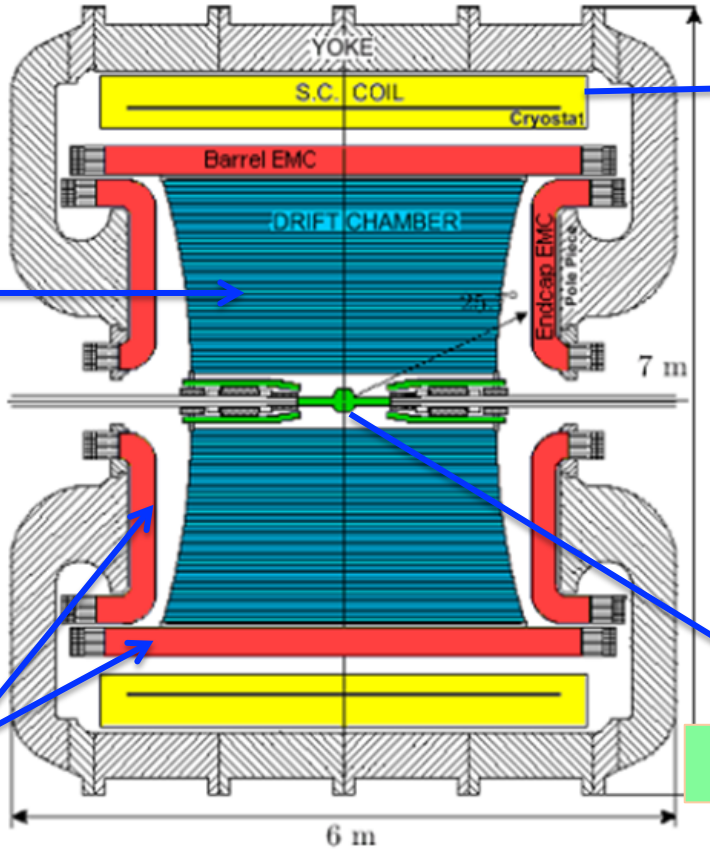
The KLOE detector

Drift Chamber:

- 12582 sense cells
- Stereo geometry
- 4 m diameter, 3.3 m long
- Low-mass gas mixture: 90% Helium-10% isobutane
- $\delta p_T/p_T < 0.4\%$ ($\theta > 45^0$)
- $\sigma_{xy} \approx 150$ mm, $\sigma_z \approx 2$ mm

Calorimeter:

- 98% coverage of full solid angle
- $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$
- $\sigma_t = 55 \text{ ps}/\sqrt{E(\text{GeV})} \oplus 140 \text{ ps}$
- Barrel + 2 end-caps

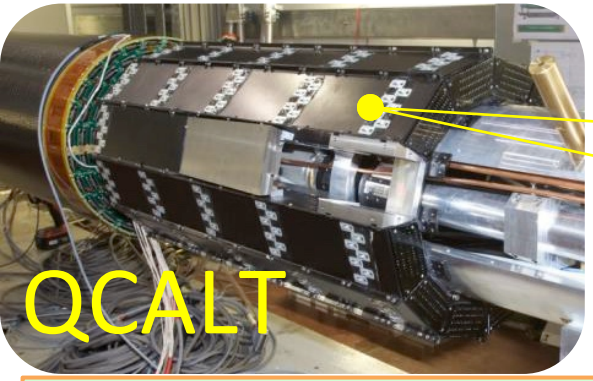


SC Magnet:
B = 0.52 T

Interaction point (IP)

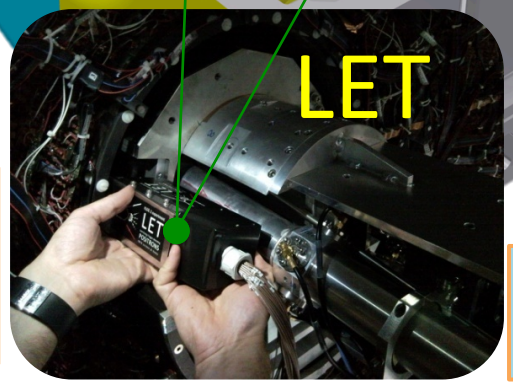
KLOE-2

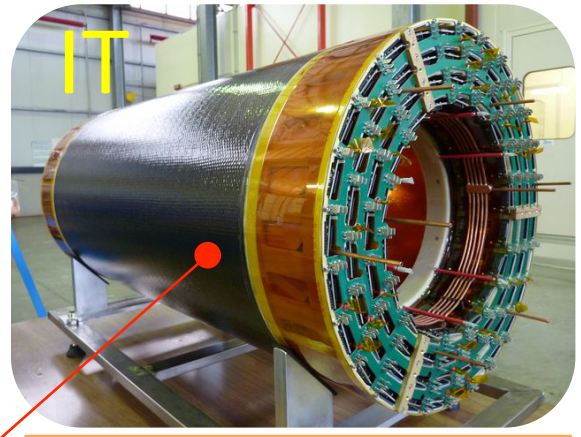
CCALT – LYSO Crystal
w SiPM - Low polar angle γ



QCALT – Tungsten / Scintillating
Tiles w SiPM - K_L decays
Quadrupole Instrumentation

LET: 2 calorimeters LYSO + SiPMs
@ ~ 1 m from IP
e^+e^- taggers for γγ physics (HET)



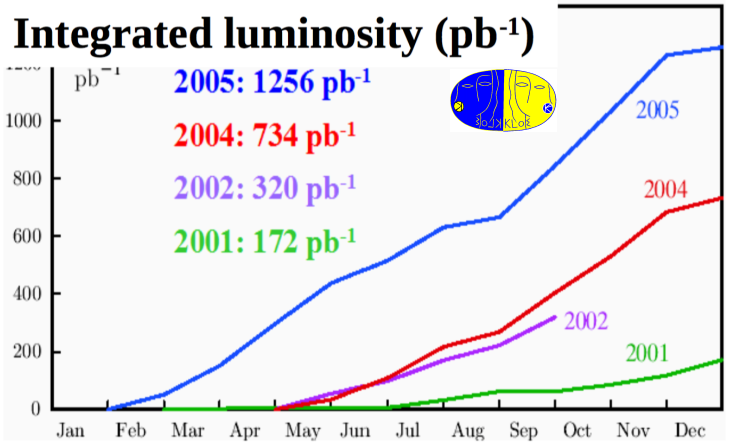


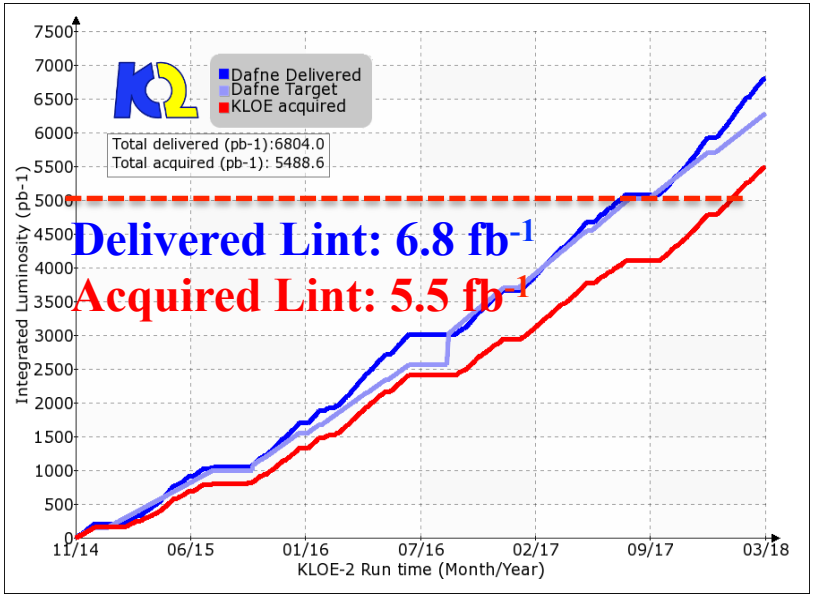
Inner Tracker – 4 layers of
Cylindrical GEM detectors
To improve the track and
vertex reconstruction
First time CGEM in high
energy experiment

HET: Scintillator hodoscope +PMTs
pitch:5 mm;

KLOE/KLOE-2 data sample

- KLOE has collected ~ 2.5 fb^{-1} @ ϕ peak and 250 pb^{-1} off-peak
  - Best performance: $L_{peak}=1.4\times10^{32}cm^{-1}s^{-1}$
- KLOE-2 data-taking campaign completed on 30th March 2018, collected ≈ 5.5 fb^{-1} @ ϕ peak
  - Best performance: $L_{peak}=2\times10^{32}cm^{-1}s^{-1}$





KLOE+KLOE-2 data sample:

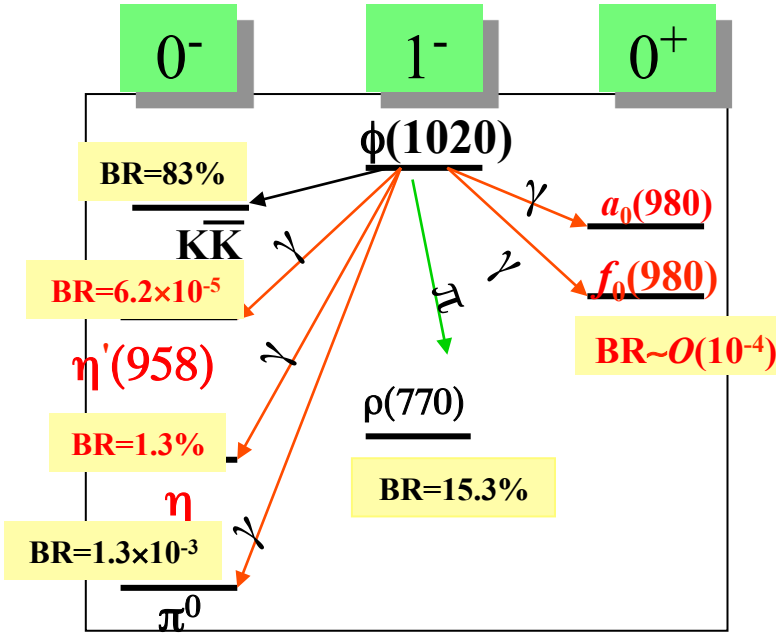
~8 fb^{-1}, the largest sample collected at ϕ

~2.4×10^{10} ϕ mesons

Unique data sample for typology and statistical relevance

Physics @ KLOE-2

- **Kaon physics: 8.2×10^9 Ks and K_L events**
  - CKM unitarity test, CPT and QM tests with kaon interferometry, Direct tests of T and CPT using entanglement, Ks rare decays…
- **Scalar and pseudoscalar mesons**
  - 3.1×10^8 η events
  - 1.48×10^8 η' events
  - 4.0×10^6 ω events
- **Light meson transition form factors**
- **γγ physics $e^+e^-\to e^+e^-\gamma^*\gamma^*\to e^+e^-X$**
  - X=ππ ⇒ study of $f_0(500)$
  - X=π^0/η⇒ Γ($\pi^0\to\gamma\gamma$), space-like TFF
- **Hadronic X-section via ISR [$e^+e^-\to\gamma(2\pi, 3\pi, 4\pi)$]: hadronic corrections to $(g-2)_\mu$**
- **Dark force searches:**
  - $e^+e^-\to U\gamma\to\pi\pi\gamma, \mu\mu\gamma$ – Higgsstrahlung: $e^+e^-\to Uh'\to\mu^+\mu^-$ + miss. Energy
  - Leptophobic B boson search: $\phi\to\eta B$ ($B\to\pi^0\gamma$), $\eta\to B\gamma$ ($B\to\pi^0\gamma$)

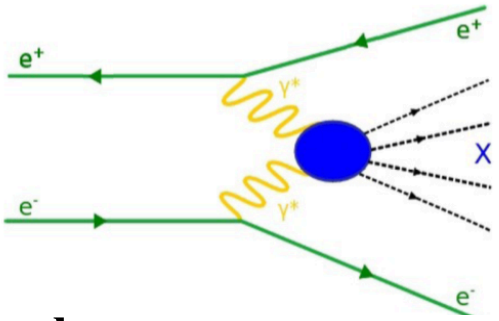


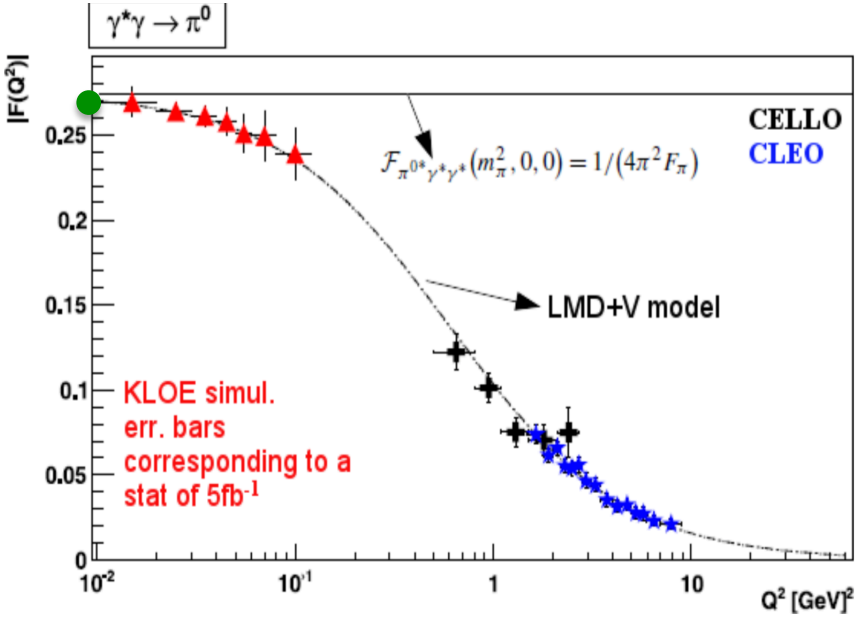
Eur. Phys. J. C 68 (2010) 619

HET & $\gamma^*\gamma^* \to \pi^0$ analysis

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

for quasi-real photons $J^{PC}(X) = \{0^{\pm,+}, 2^{\pm,+}\}$
$\to X = \{\pi^0, \pi\pi, \eta\}$





Physic goal:

- $\Gamma_{\pi 0\to\gamma\gamma}$ at 1 % level (green point)
  - ✓ $\Gamma_{\pi 0\to\gamma\gamma}$ (Th.) = 8.09±0.11 eV ~1.4% precision
  - ✓ $\Gamma_{\pi 0\to\gamma\gamma}$ (Exp.) = 7.82±0.22 eV ~2.8% precision

  Report at Hadron2019 (PrimEx collaboration)

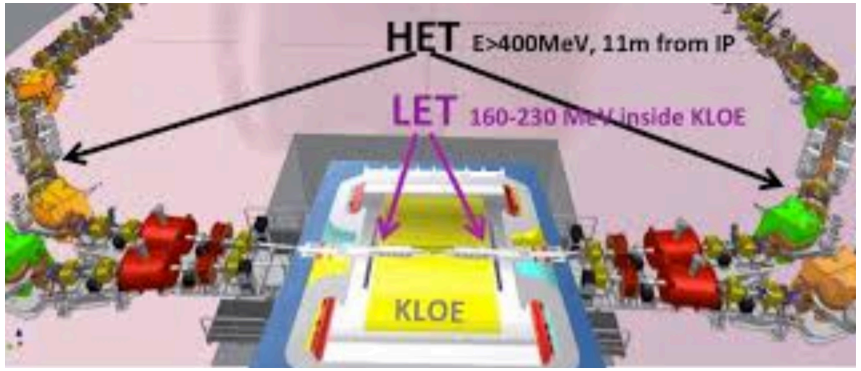
  $\Gamma_{\pi 0\to\gamma\gamma}$ (Exp.) = 7.80 ± 0.05± 0.11 eV~1.5% precision
- first measurement of the $\mathcal{F}_{\pi 0\gamma^*\gamma}(q^2)$ at $q_{\gamma^*}{}^2 \leq 0.1$ GeV^2 (red points)

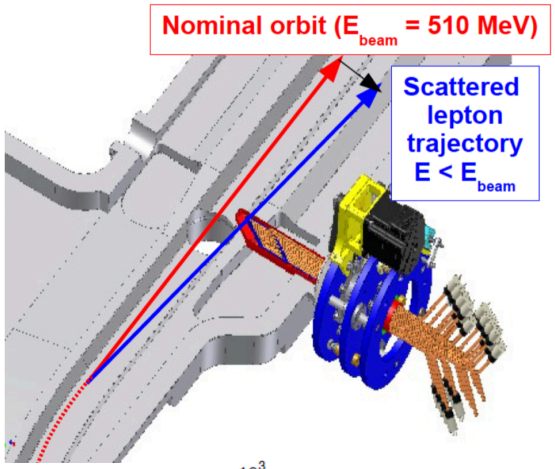
The slope of TFF near $q^2=0$ is crucial for hadronic light-by-light contributions to g_μ-2

(Eur. Phys. J. C 72 (2012) 1917)

HET & $\gamma^*\gamma^* \rightarrow \pi^0$ analysis

located 11m away the IP after the bending dipoles acting like spectrometer for the scattered e^+/e^- (420<E<495 MeV)





28 plastic scintillators (5x6x3 mm^3)

1 Long Plastic for coincidence

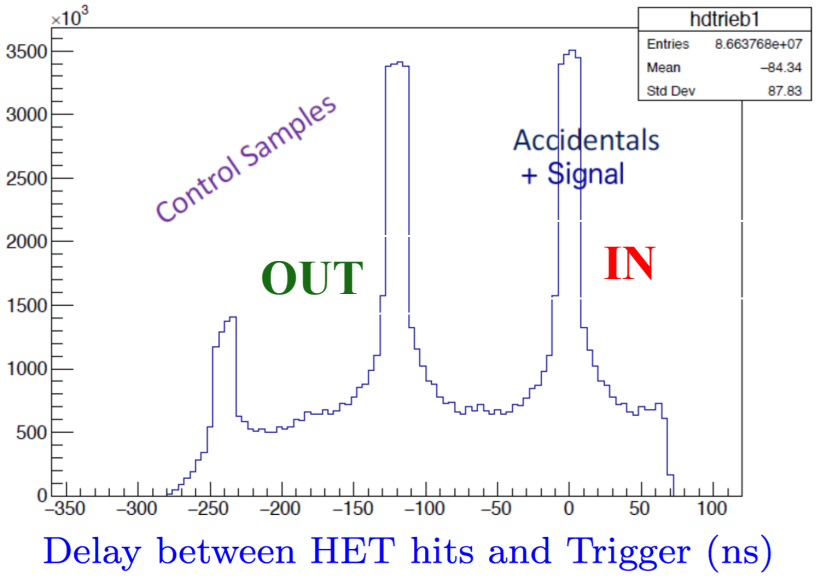
DAQ systems for HET and KLOE are asynchronous

Analysis strategy

Hits in HET station and at least one bunch in KLOE associated with only 2 clusters in EMC

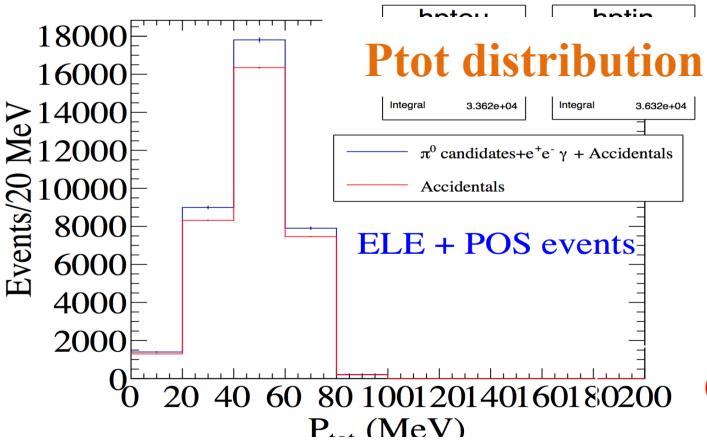
HET acquisition time 2.5 times larger than KLOE →
OUT sample: outside overlapping time window HET-only
IN sample: overlapping KLOE-HET time window

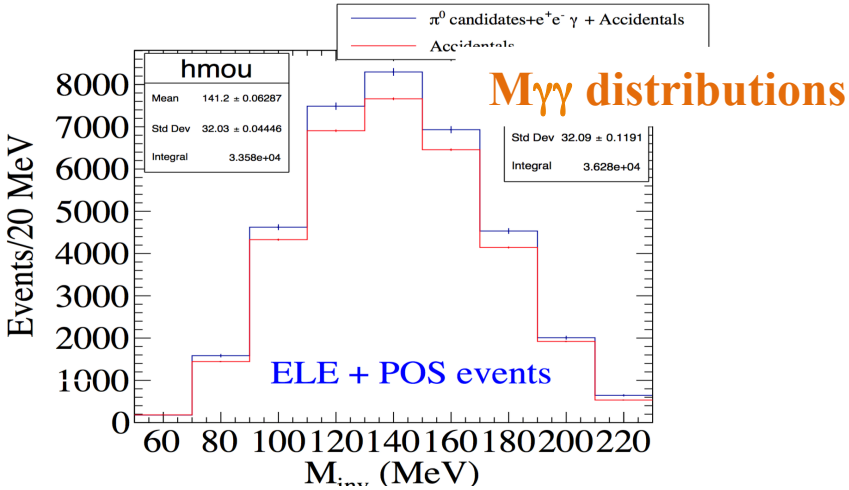
Subtract **IN** and **OUT** events in the same time window



$\gamma^*\gamma^* \rightarrow \pi^0$: preliminary results

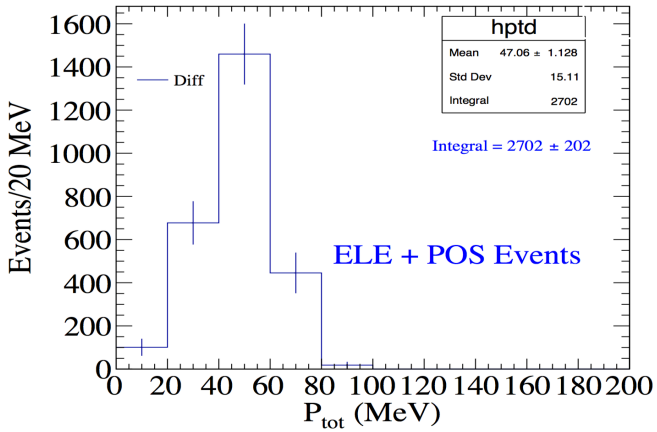
- ✓ 500 pb^{-1} data of 2017
- ✓ $|\Delta Px,y|_{\gamma\gamma} < 50$ MeV
- ✓ TMVA is helpful to separate signal from background (radiative Bhabha)

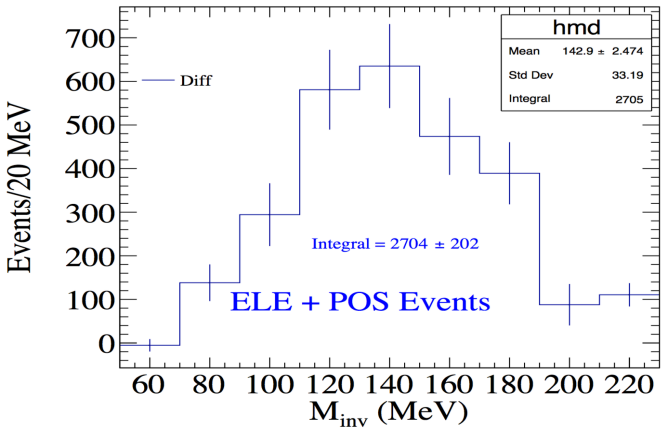




OUT

IN



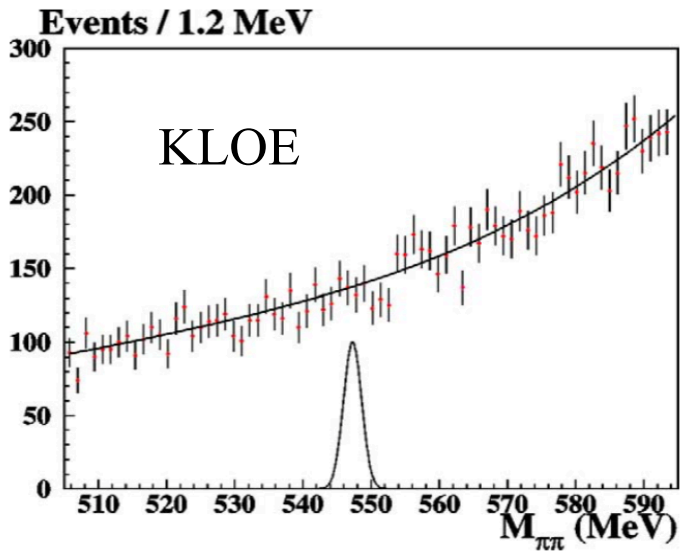


Identification of background events and analysis with more statistics in progress

CP violating process: $\eta \to \pi^+\pi^-$

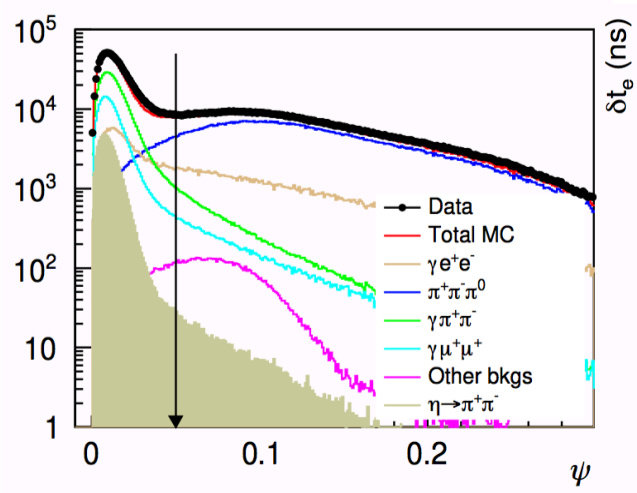
- The Br prediction in SM [Phys. Scripta T99, 23 (2002)]
  - ✓ proceed only via the CP-violating in weak interaction → 10^{-27}
  - ✓ introducing a CP violating term in QCD → to 10^{-17}
  - ✓ allowing CP violation in the extended Higgs sector → 10^{-15}
- Using the present upper bound on the nEDM → 5.3×10^{-17} [Phys. Rev. D 99 (2019) 031703 (R)]
- Any observation of larger branching ratio → a new source of CP violation in the strong interaction

- The best limit 1.3×10^{-5} @ 90% C.L. by KLOE with ~ 350 pb^{-1}
- A recent limit 1.6×10^{-5} @ 90% C.L. from LHCb with Lint~3.3 fb^{-1}

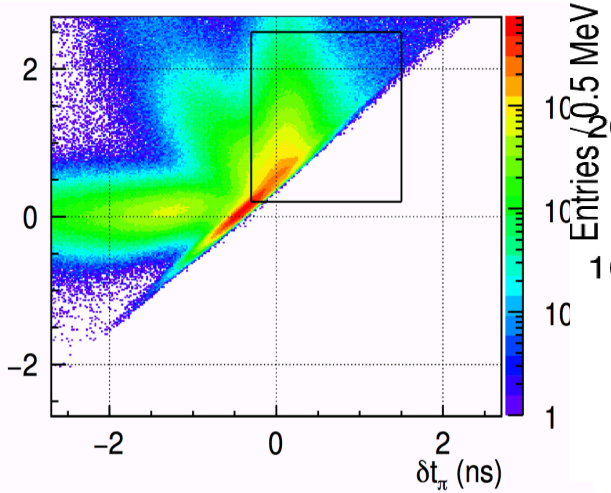


Selection of $\phi \to \gamma\eta(\pi^+\pi^-)$ events

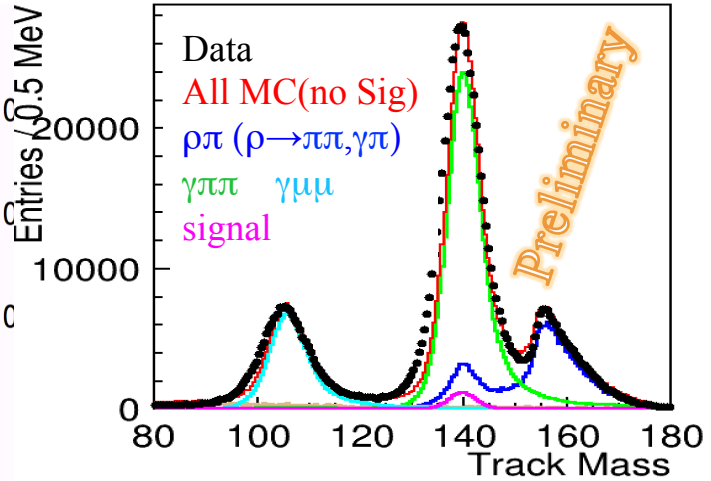
- 2004/2005 data ($L_{int} \sim 1.7\ fb^{-1}$)
- One vertex with two opposite charged tracks (reaching EMC):
  - $Rv<8$ cm && $|Zv|<10$ cm, $45<\theta_{trk}<135°$
- One prompt photon with energy in (250, 470) MeV
  - $45<\theta_\gamma<135°$ to suppress $\gamma\pi^+\pi^-$ (ISR) backgrounds



Angle between $\pi^+\pi^-$ missing direction and prompt photon



PID with ToF technique to reject e+e−γ



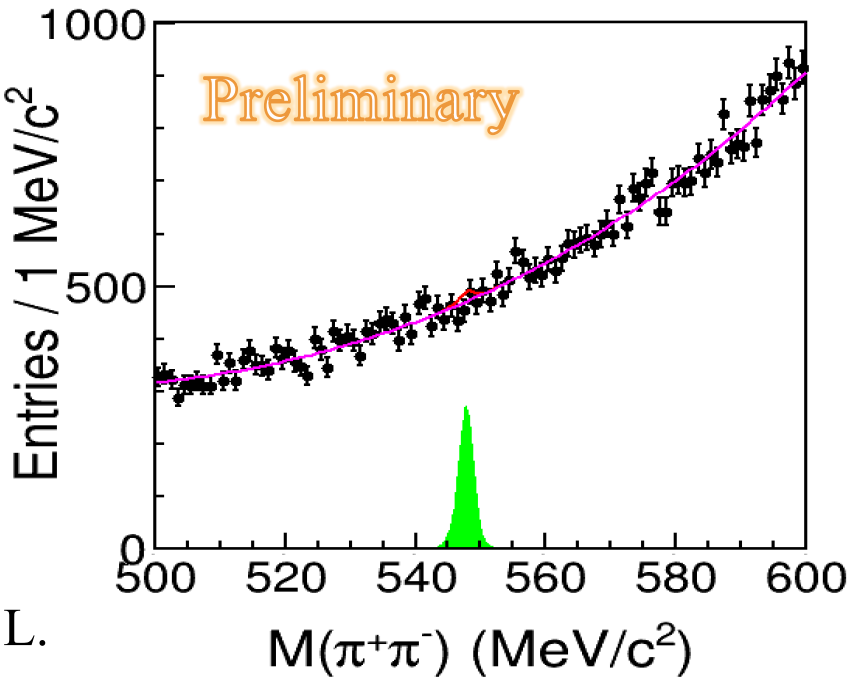
$129 < T_M < 149$ MeV to reject $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\pi^0$

$$|\vec{p}_\phi - \vec{p}_1 - \vec{p}_2| = E_\phi - \sqrt{p_1^2 + T_M^2} - \sqrt{p_2^2 + T_M^2}$$

Preliminary result

- Continue backgrounds from γππ
- No event excess in the η region
- After all the cuts, efficiency ~ 13.6%

- Un-binned maximum likelihood fit with 3rd polynomial function + MC signal shape



Bayesian approach → $N^{UL} = 50.4$ @ 90% C.L.

Preliminary U.L.: Br(η→π⁺π⁻) < 5.8 ×10⁻⁶ @ 90% C.L.

With all KLOE/KLOE-2 data (8 fb⁻¹) ⇒

The expected upper limit is 2.7×10⁻⁶ @ 90% C.L.

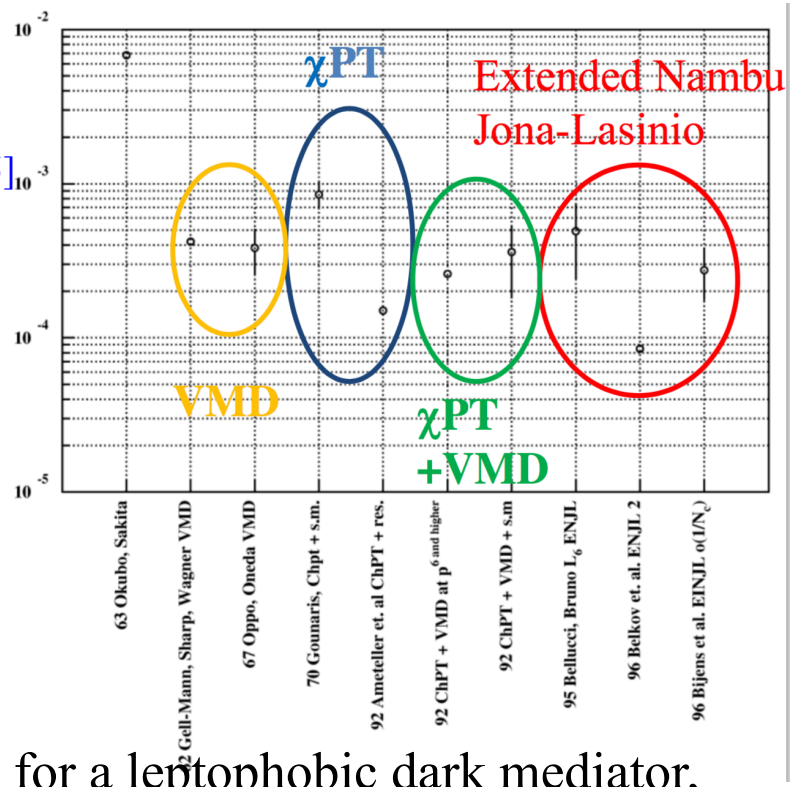
$\eta \to \pi^0\gamma\gamma$ analysis

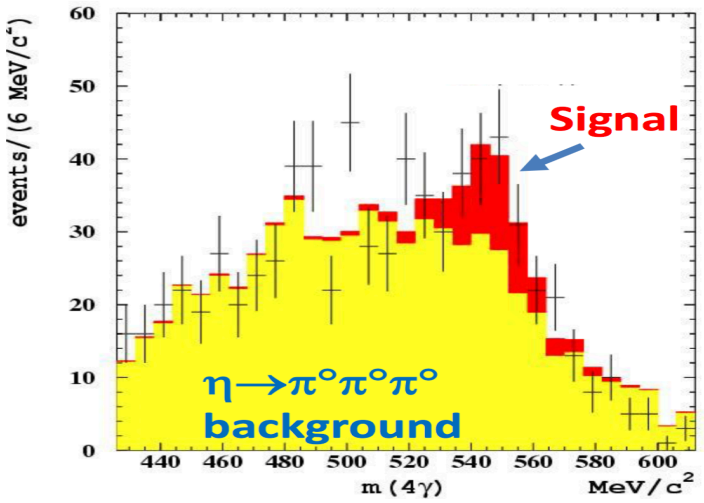
- ChPT "golden mode": $O(p^2)$ null, $O(p^4)$ suppressed, **$O(p^6)$ dominates** [PLB 276(1) (1984) 185]
- Due to high backgrounds from $\eta \to \pi^0\pi^0\pi^0$, discrepancy from different experiments:

$Br = (22.1 \pm 2.4 \pm 4.7) \times 10^{-5}$ CB@AGS (2008)

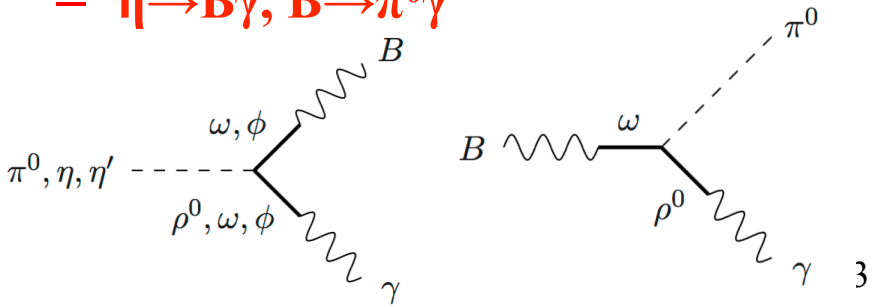
$Br = (25.2 \pm 2.5) \times 10^{-5}$ CB@MAMI

$Br = (8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$ KLOE preliminary (~450pb^{-1})





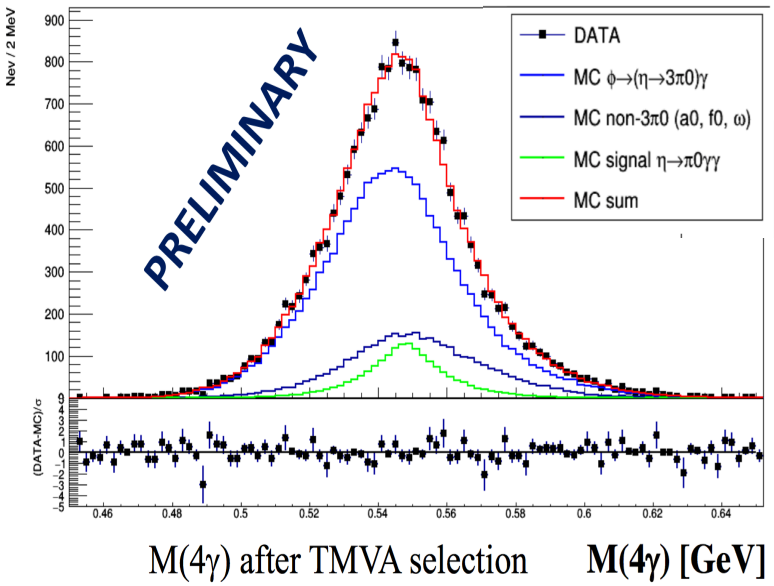
- Search for a leptophobic dark mediator, B meson [S. Tulin, PRD 89 (2014) 14008]
  - **$\eta \to B\gamma$, $B \to \pi^0\gamma$**



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

- A new analysis of KLOE data with 4x larger data sample (~1.7 fb^{-1})
- Tagging $\eta \to \pi^0\gamma\gamma$ with the recoil photon of E=363 MeV from $\phi \to \gamma\eta$ decay

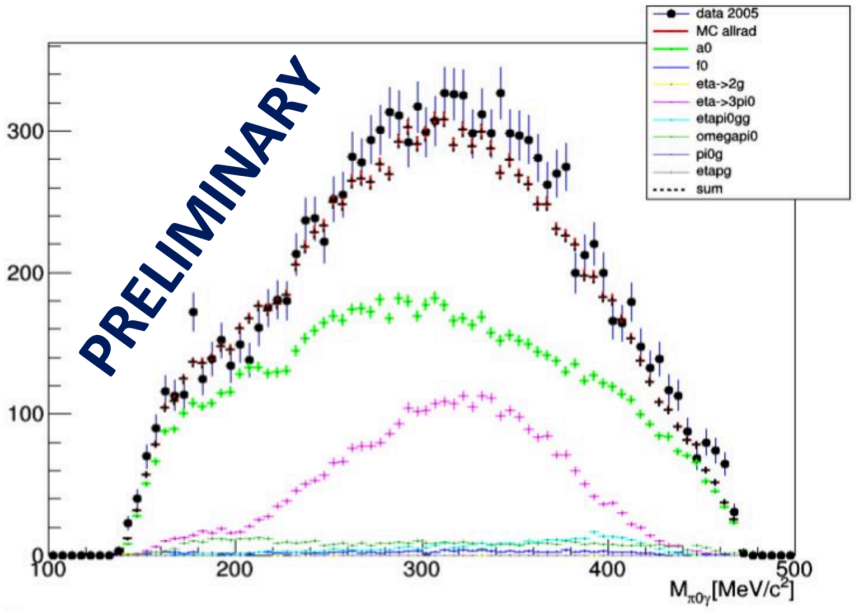
- Main backgrounds: $\phi \to \gamma a_0(\eta\pi^0)$, $\gamma f_0(\pi^0\pi^0)$, $e^+e^- \to \pi^0\omega(\gamma\pi^0)$, $\phi \to \gamma\eta(3\pi^0)$ with lost or merged photons
- Kinematic fits to suppress backgrounds (ToF of 5γ's and E&P conservation)
- TMVA with cluster shape to separate single photon from merged photon clusters
- S/B~0.4 achieved with efficiency~21%



Further background subtraction and preliminary U.L. calculation is ongoing

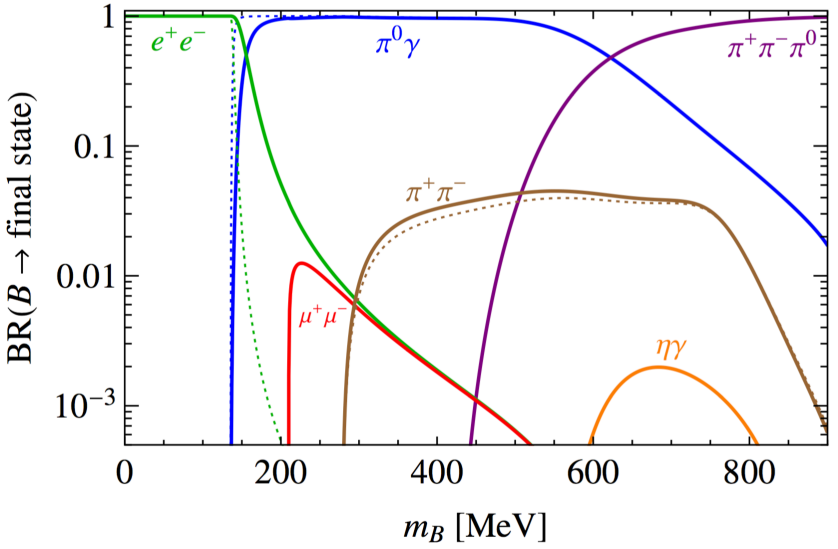
$B \to \pi^0\gamma$ in $\phi \to B\eta(\gamma\gamma)$

- $\pi^0\gamma$ is the leading decay mode of B boson
- 5 prompt photons in the final state
- Main backgrounds: $\phi \to \gamma a_0(\eta\pi^0)$ and $\gamma\eta(3\pi^0)$ with lost or merged photons
- Kinematic fits to suppress backgrounds (ToF of 5γ's, E&P conservation, η/π^0)



M(3γ) [GeV]

B boson couples mainly to quarks
[S. Tulin, PRD 89 (2014) 14008]



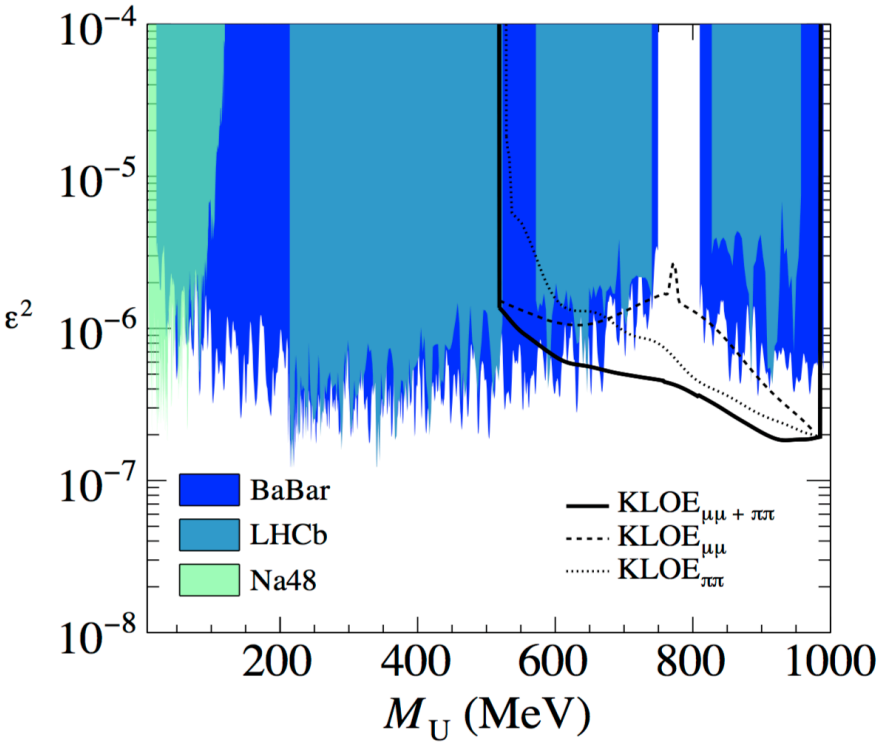
Discovery signal depends on mass m_B

U.L. extraction for dark B mediator with more statistics is ongoing

Dark Matter: combined limit on γU with $U \to \mu^+\mu^-$ and $\pi^+\pi^-$

PLB 784 (2018) 336

- New μμγ limit with full KLOE statistics (1.93 fb^{-1}) in $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ process
- ππγ limit at the same luminosity (1.93 fb^{-1}) PLB757(2016)356
- Combining procedure requires:
  - Double inputs of data, expected background, U signal and systematical errors
  - Information on different efficiency and U decay branching fractions: BR(U → μμ, ππ)
- Combined limit extracted by means of CLs Technique
- The limit on ε^2 is extracted when $N_U^{tot} = N_U^{\mu\mu} + N_U^{\pi\pi}$ reaches CLs < 0.1



Best limit in the 600 MeV-1000 MeV mass range

Combined $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and $a_\mu^{\pi\pi}$

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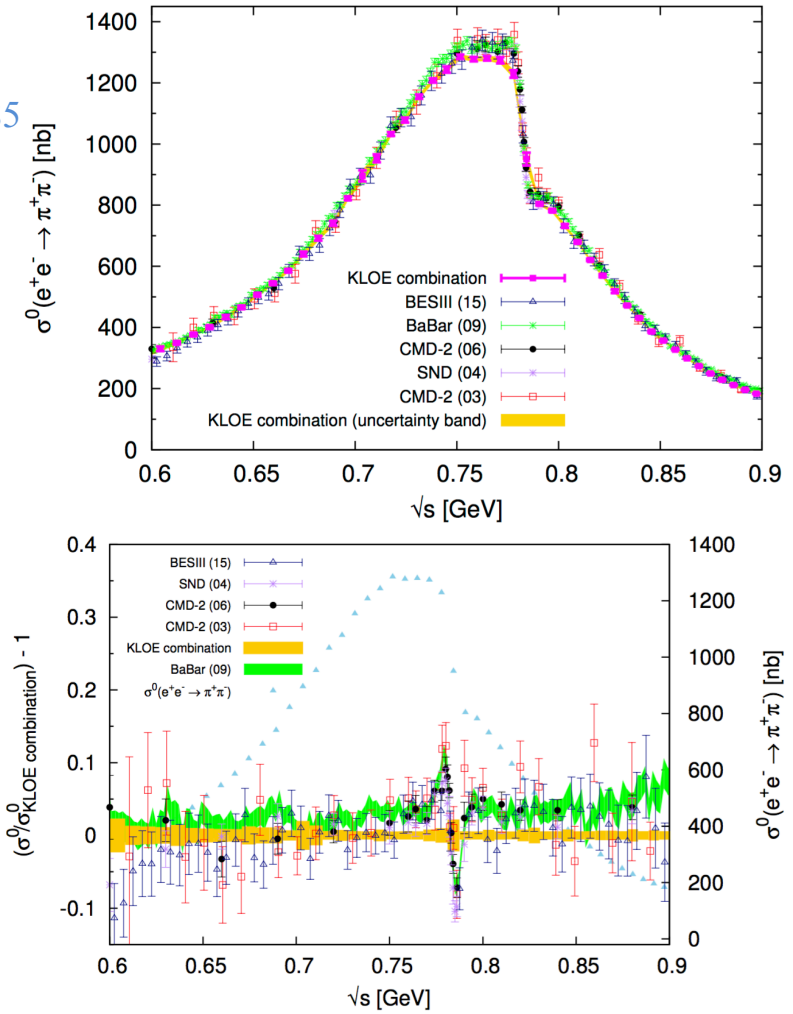
- Three KLOE $\sigma(e+e- \to \pi+\pi-\gamma(\gamma))$ with ISR:
  - **KLOE08: small angle photon**
    - $\theta\gamma < 15^\circ \,||\, \theta\gamma > 165^\circ$, $\sqrt{s} = 1.02$GeV, PLB 670 (2009) 285
  - **KLOE10: large angle photon**
    - $45^\circ < \theta\gamma < 135^\circ$, $\sqrt{s} = 1.0$ GeV, PLB 700 (2011) 102
  - **KLOE12: small angle photon**
    - $\sqrt{s} = 1.02$GeV, PLB720 (2013) 336

KLOE08 & KLOE10 $\sigma^0_{\pi\pi(\gamma)}(s') = \sigma_{\pi\pi(\gamma)}(s')|1 - \Pi(s')|^2,$

KLOE12 $\sigma^0_{\pi\pi(\gamma)}(s') = \dfrac{\mathrm{d}\sigma(\pi^+\pi^-\gamma)/\mathrm{d}s'}{\mathrm{d}\sigma(\mu^+\mu^-\gamma)/\mathrm{d}s'} \times \sigma^0_{(\gamma)}(e^+e^- \to \mu^+\mu^-, s')$

All three meas are undressed of all VP effects and including FSR (overlapping range in the 0.6-0.95 GeV)

Iterative linear $\chi 2$ function minimization method is used for the combination→ construction of full statistical and syst. covariance matrices needed



Combined of $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and $a_\mu^{\pi\pi}$

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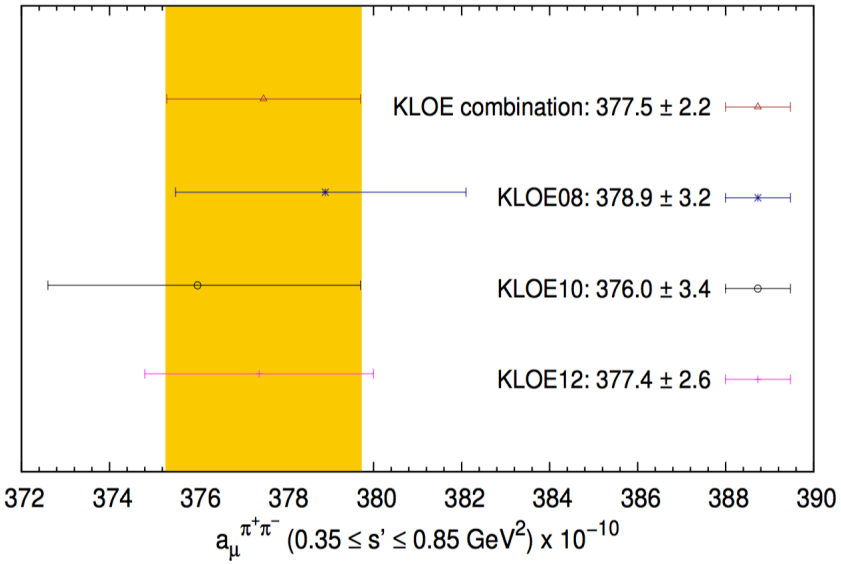

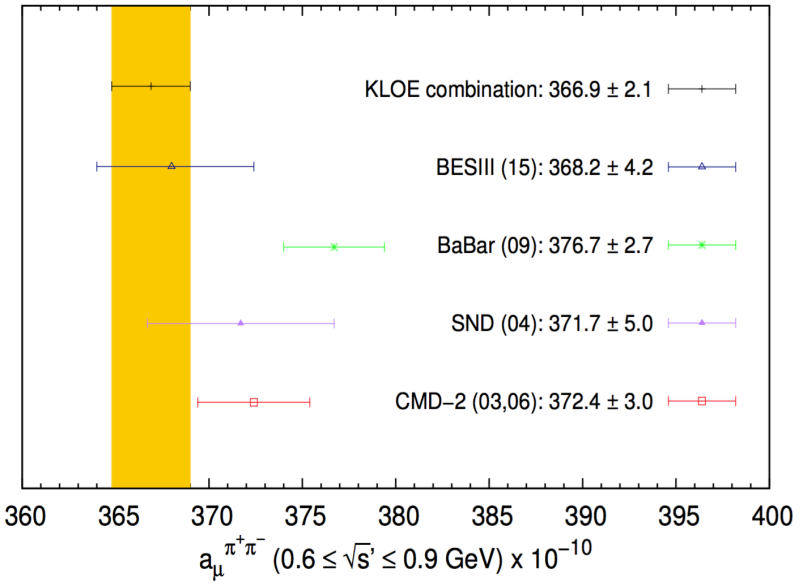

$$a_\mu^{\pi\pi} = \int_{x_1}^{x_2} \sigma_{ee\to\pi\pi}(s)K(s)ds,$$

$$a_\mu^{\pi^+\pi^-}(\text{KLOE combination}, 0.10 < s' < 0.95\ \text{GeV}^2) = (489.8 \pm 5.1) \times 10^{-10},$$

KLOE comb $a_\mu^{\pi+\pi-}$ consistent with KLOE08, KLOE10 and KLOE12 individual estimations

In agreement with CMD-2, SND and BESIII results within 1.5σ

Difference with BaBar < 3σ

Conclusions

- KLOE/KLOE-2 have collected 8fb^{-1} data at ϕ peak (2.4×10^{10} ϕ mesons) ~ a unique worldwide sample
- KLOE is continuing to exploit the high statistics data samples collected at DAΦNE to perform precision measurements in hadron physics
- With the ongoing analysis and more statistics, more results are foreseen

Thanks for your attention!!!