

10-17 July 2019 - Ghent, Belgium

# Low energy hadron physics at KLOE/KLOE-2

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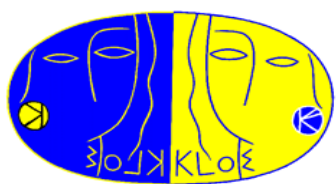
INFN – LNF Frascati, Italy

On behalf of the KLOE-2 Collaboration

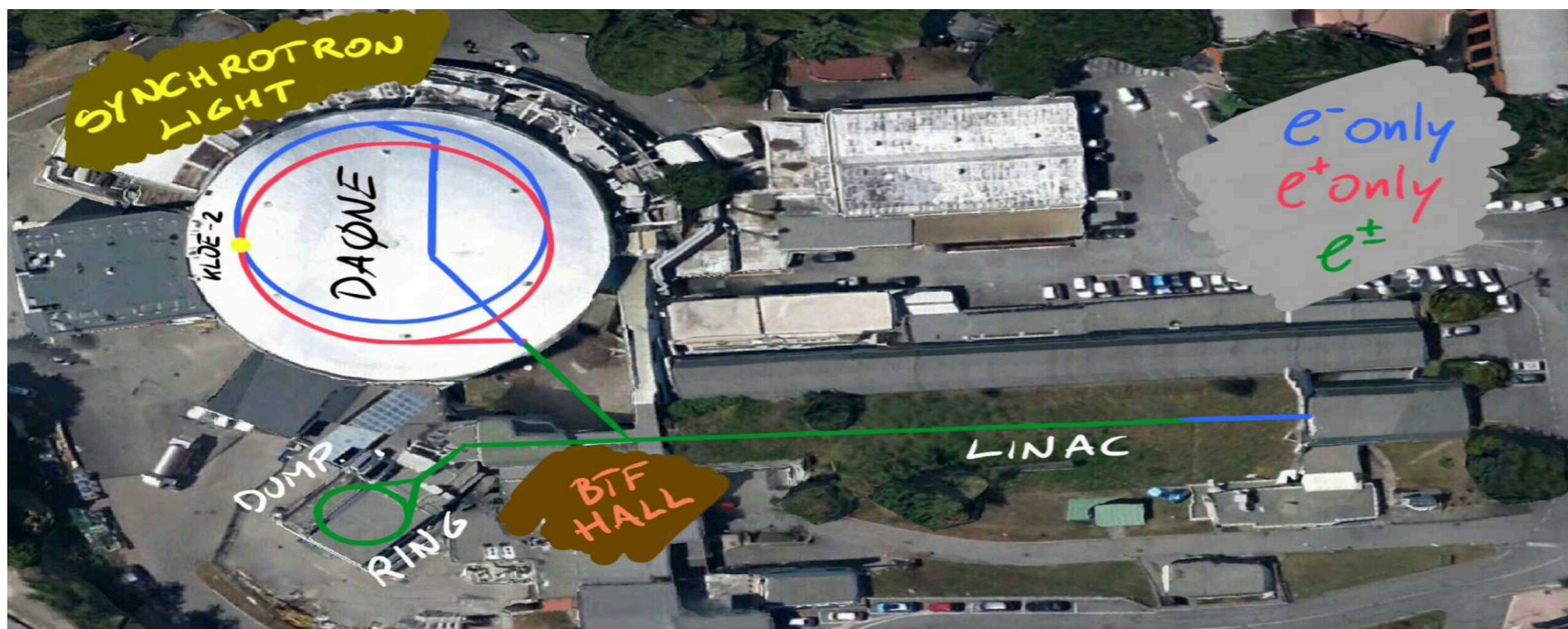


# Outline

- DAΦNE and KLOE-2 Experiment
- CP violation decay  $\eta \rightarrow \pi^+ \pi^-$
- The  $\eta \rightarrow \pi^0 \gamma \gamma$  decay
- Dark B mediator searches
- $\gamma \gamma$  studies
- Conclusion



# DAΦNE: $\phi$ -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  $\sim 2 \times 12.5$  mrad

See A. De Santis's talk





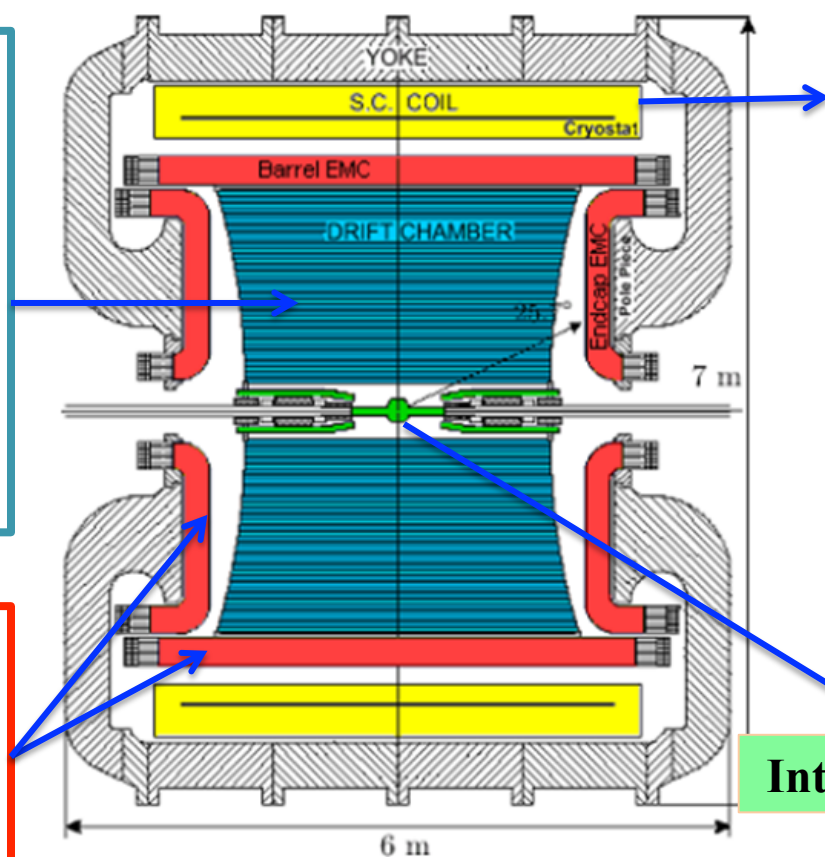
# The KLOE detector

## Drift Chamber:

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



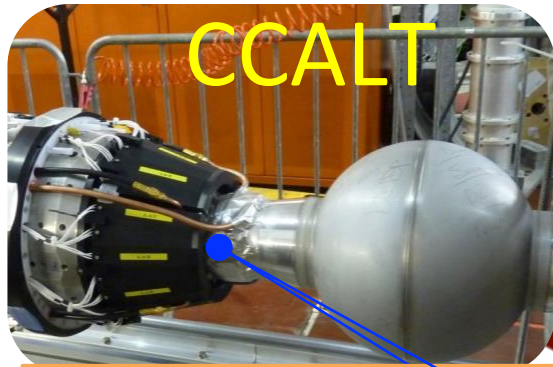
**SC Magnet:**  
 $B = 0.52$  T

**Interaction point (IP)**

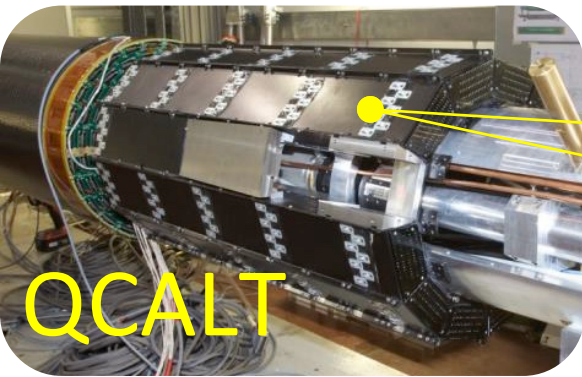


# KLOE-2

CCALT

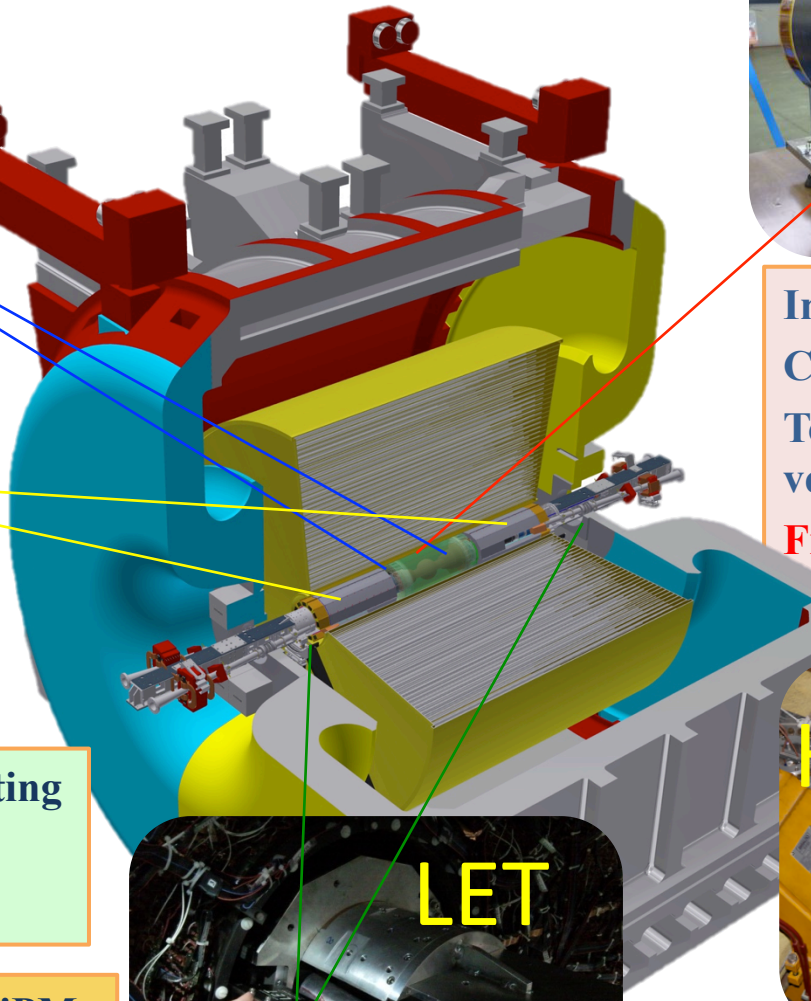


CCALT – LYSO Crystal  
w SiPM - Low polar angle  $\gamma$

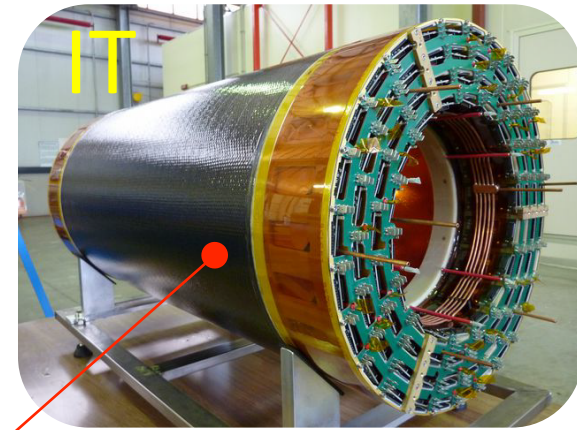


QCALT – Tungsten / Scintillating  
Tiles w SiPM -  $K_L$  decays  
Quadrupole Instrumentation

LET: 2 calorimeters LYSO + SiPMs  
@  $\sim 1$  m from IP  
 $e^+e^-$  taggers for  $\gamma\gamma$  physics (HET)



IT



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

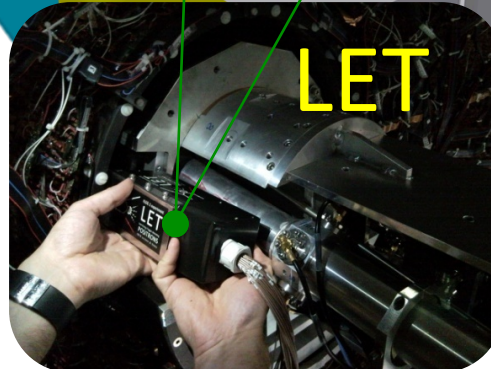
HET

11 m from IP



HET: Scintillator hodoscope +PMTs  
pitch:5 mm;

LET

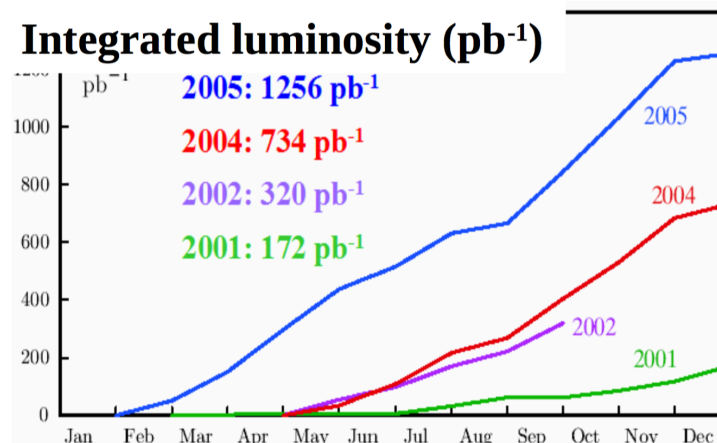




# KLOE/KLOE-2 data sample



- KLOE has collected  $\sim 2.5 \text{ fb}^{-1}$  @  $\phi$  peak and  $250 \text{ pb}^{-1}$  off-peak
- KLOE-2 data-taking campaign completed on 30<sup>th</sup> March 2018, collected  $\approx 5.5 \text{ fb}^{-1}$  @  $\phi$  peak

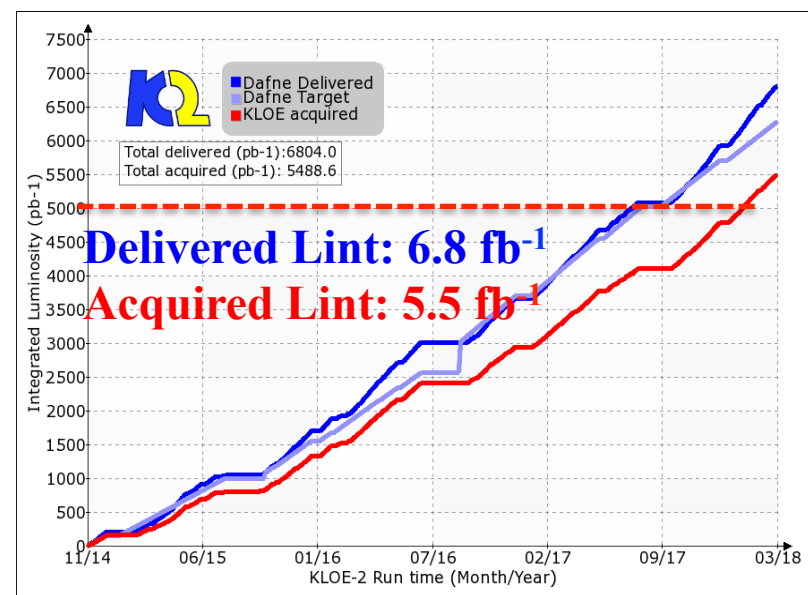


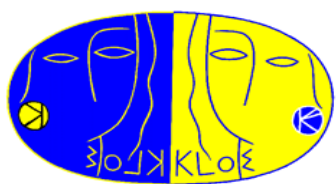
**KLOE+KLOE-2 data sample:**

**$\sim 8 \text{ fb}^{-1}$ , the largest sample collected at  $\phi$**

**$\sim 2.4 \times 10^{10}$   $\phi$  mesons**

**Unique data sample for typology and statistical relevance**

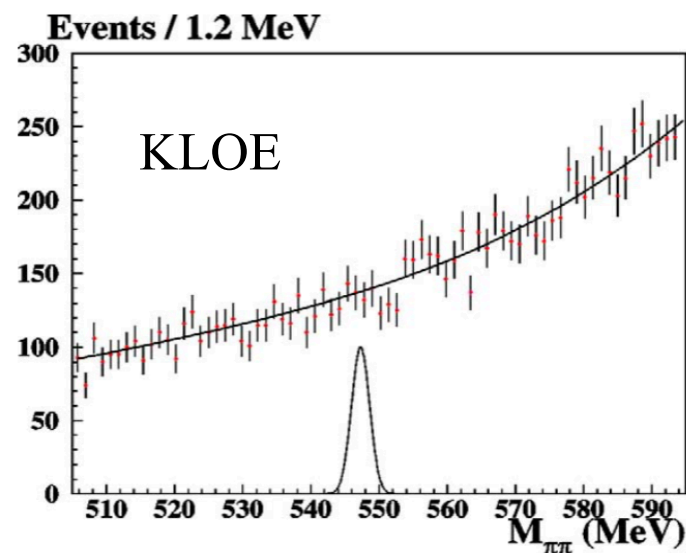




# CP violating process: $\eta \rightarrow \pi^+ \pi^-$



- The Br prediction in SM [Phys. Scripta T99, 23 (2002)]
  - ✓ proceed only via the CP-violating in weak interaction  $\rightarrow 10^{-27}$
  - ✓ introducing a CP violating term in QCD  $\rightarrow$  to  $10^{-17}$
  - ✓ allowing CP violation in the extended Higgs sector  $\rightarrow 10^{-15}$
- Using the present upper bound on the nEDM  $\rightarrow 5.3 \times 10^{-17}$  [Phys. Rev. D 99 (2019) 031703 (R)]
- Any observation of larger branching ratio  $\rightarrow$  a new source of CP violation in the strong interaction
- The best limit  $1.3 \times 10^{-5}$  @ 90% C.L. by KLOE with  $\sim 350 \text{ pb}^{-1}$  (eff=16.6%)
- A recent limit  $1.6 \times 10^{-5}$  @ 90% C.L. from LHCb with  $\text{Lint} \sim 3.3 \text{ fb}^{-1}$



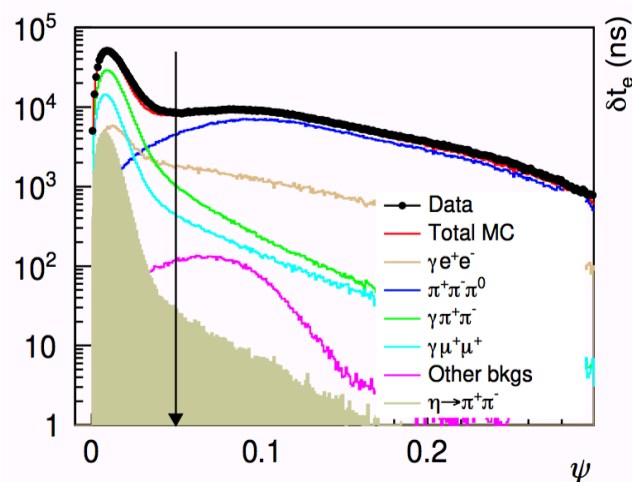




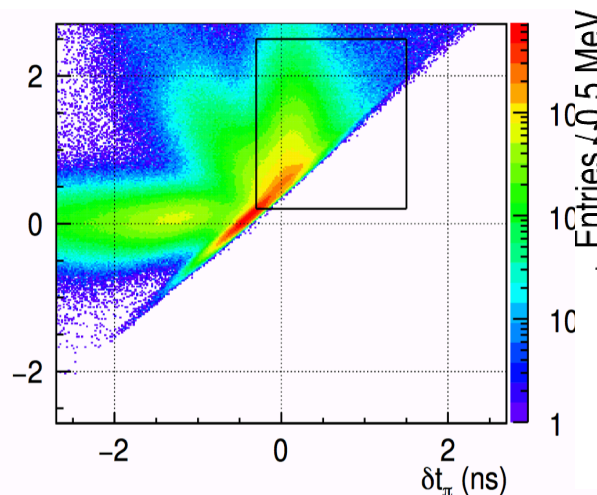
# Selection of $\phi \rightarrow \gamma \eta (\pi^+ \pi^-)$ events



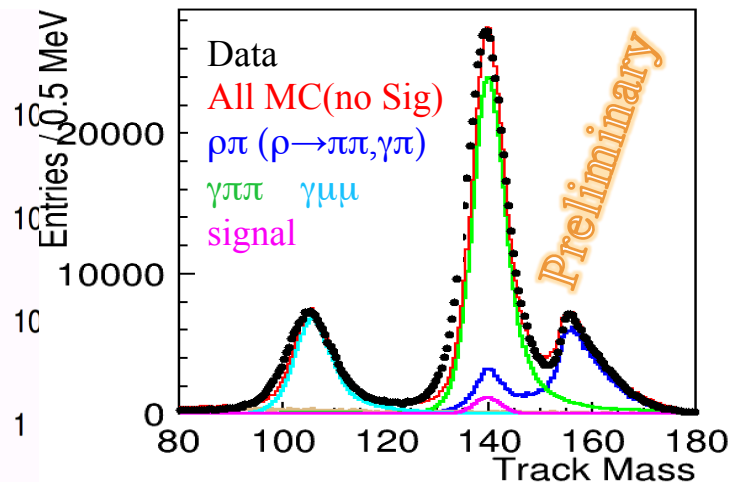
- 2004/2005 data ( $L_{\text{int}} \sim 1.7 \text{ fb}^{-1}$ )
- One vertex with two opposite charged tracks (reaching EMC):
  - $R_v < 8 \text{ cm}$  &&  $|Z_v| < 10 \text{ cm}$ ,  $45 < \theta_{\text{trk}} < 135^\circ$
- One prompt photon with energy in (250, 470) MeV
  - $45 < \theta_\gamma < 135^\circ$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



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



PID with ToF technique to reject  $e^+e^- \gamma$



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

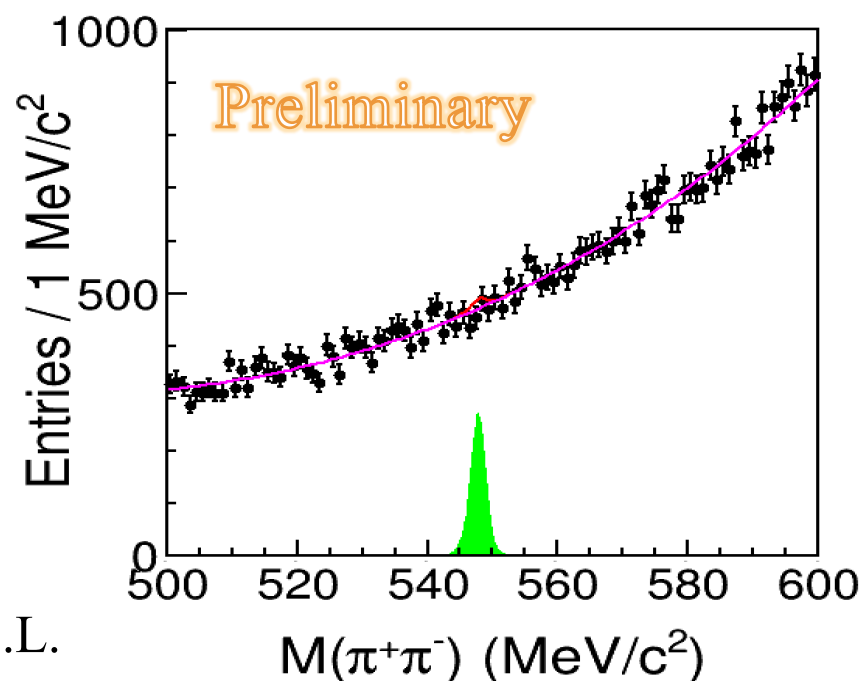
$$|\vec{p}_\phi - \vec{p}_1 - \vec{p}_2| = E_\phi - \sqrt{p_1^2 + T_M^2} - \sqrt{p_2^2 + T_M^2}$$



# Preliminary result

- Continue backgrounds from  $\gamma\pi\pi$
- No event excess in the  $\eta$  region
- After all the cuts, efficiency  $\sim 13.6\%$
- Un-binned maximum likelihood fit with 3<sup>rd</sup> polynomial function + MC signal shape

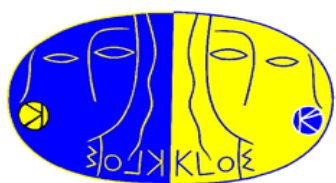
Bayesian approach  $\rightarrow N^{\text{UL}} = 50.4$  @ 90% C.L.



**Preliminary U.L.:  $\text{Br}(\eta \rightarrow \pi^+ \pi^-) < 5.8 \times 10^{-6}$  @ 90% C.L.**

**With all KLOE/KLOE-2 data ( $8 \text{ fb}^{-1}$ )  $\Rightarrow$**

**The expected upper limit is  $2.7 \times 10^{-6}$  @ 90% C.L.**



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

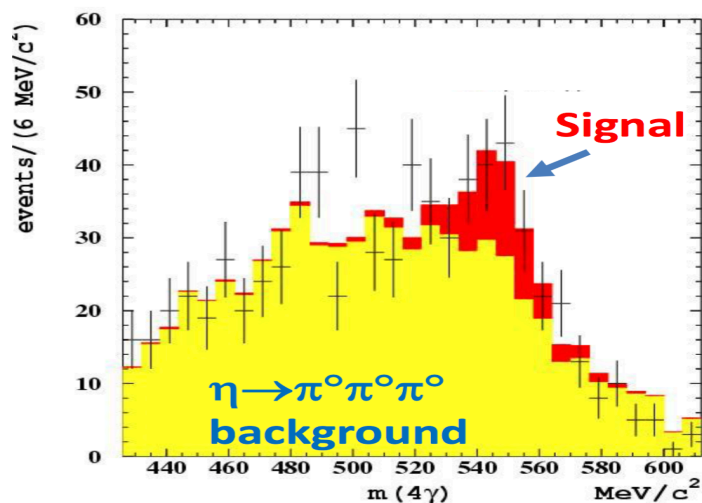
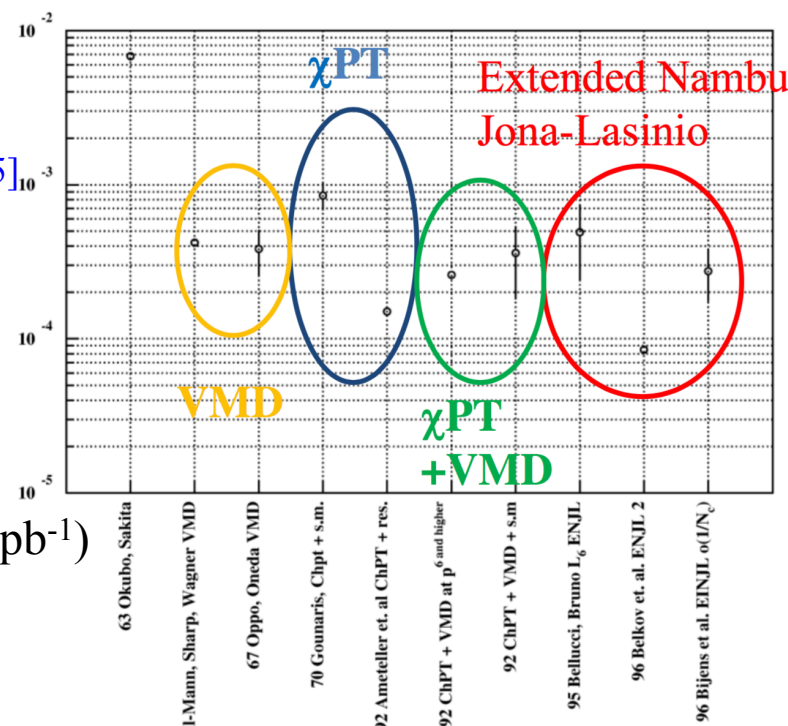


- ChPT “golden mode”:  $O(p^2)$  null,  $O(p^4)$  suppressed,  **$O(p^6)$  dominates** [PLB 276(1) (1984) 185]
- Due to high backgrounds from  $\eta \rightarrow \pi^0 \pi^0 \pi^0$ , discrepancy from different experiments:

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

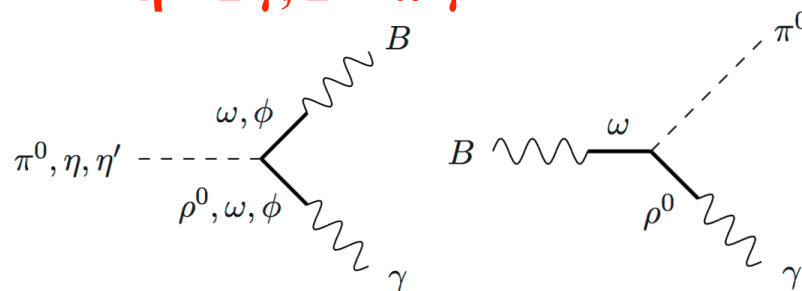
$$\text{Br} = (25.2 \pm 2.5) \times 10^{-5} \quad \text{CB@MAMI}$$

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

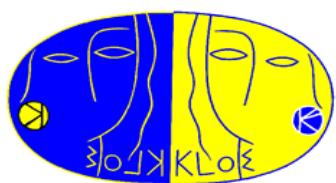


- Search for a B boson at the QCD scale [S. Tulin, PRD 89 (2014) 14008]

$$- \eta \rightarrow B \gamma, B \rightarrow \pi^0 \gamma$$



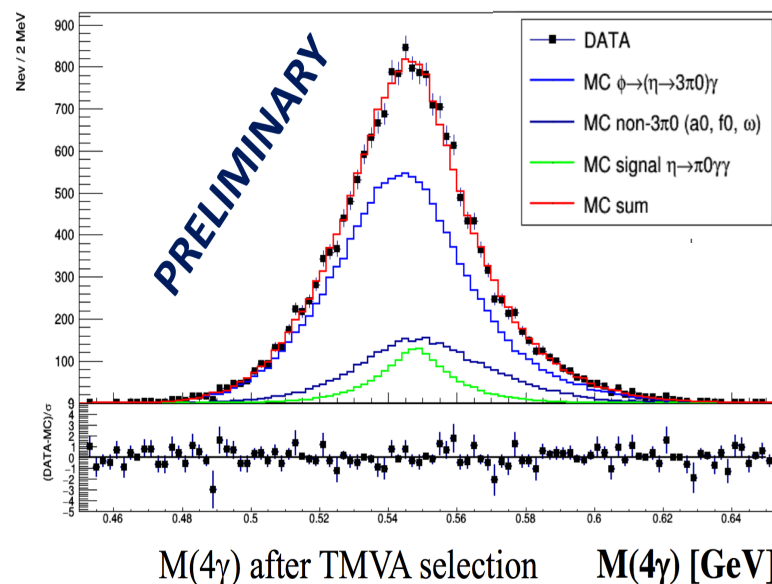




$$\eta \rightarrow \pi^0 \gamma \gamma$$



- A new analysis of KLOE data with 4x larger data sample ( $\sim 1.7 \text{ fb}^{-1}$ )
- Tagging  $\eta \rightarrow \pi^0 \gamma \gamma$  with the recoil photon of  $E=363 \text{ MeV}$  from  $\phi \rightarrow \gamma \eta$  decay
- Main backgrounds:  $\phi \rightarrow \gamma a_0(\eta \pi^0)$ ,  $\gamma f_0(\pi^0 \pi^0)$ ,  $e^+ e^- \rightarrow \pi^0 \omega(\gamma \pi^0)$ ,  $\phi \rightarrow \gamma \eta(3\pi^0)$  with lost or merged photons
- Kinematic fits to suppress backgrounds (ToF of  $5\gamma$ 's and E&P conservation)
- TMVA with cluster shape to separate single photon from merged photon clusters
- **S/B $\sim 0.4$  achieved with efficiency $\sim 21\%$**



**Further background subtraction is ongoing, the preliminary result is expected at the end of the year**

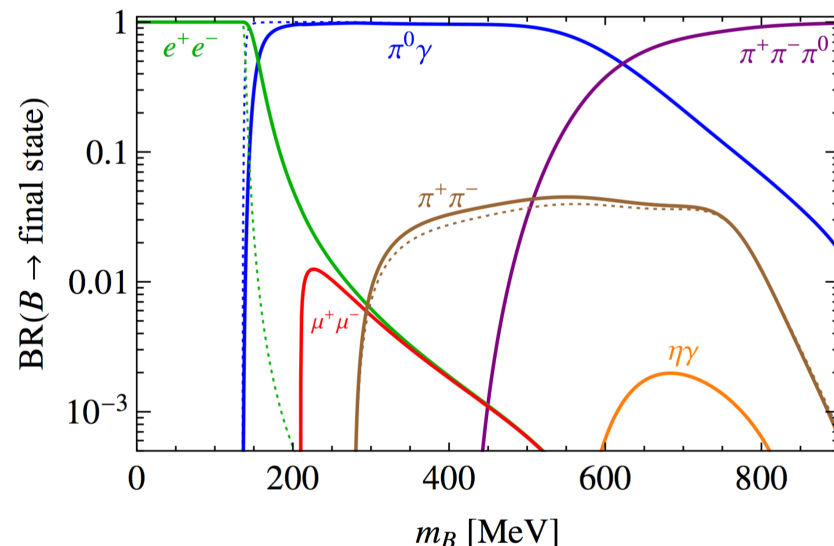


# $B \rightarrow \pi^0 \gamma$ in $\phi \rightarrow B \eta (\gamma \gamma)$



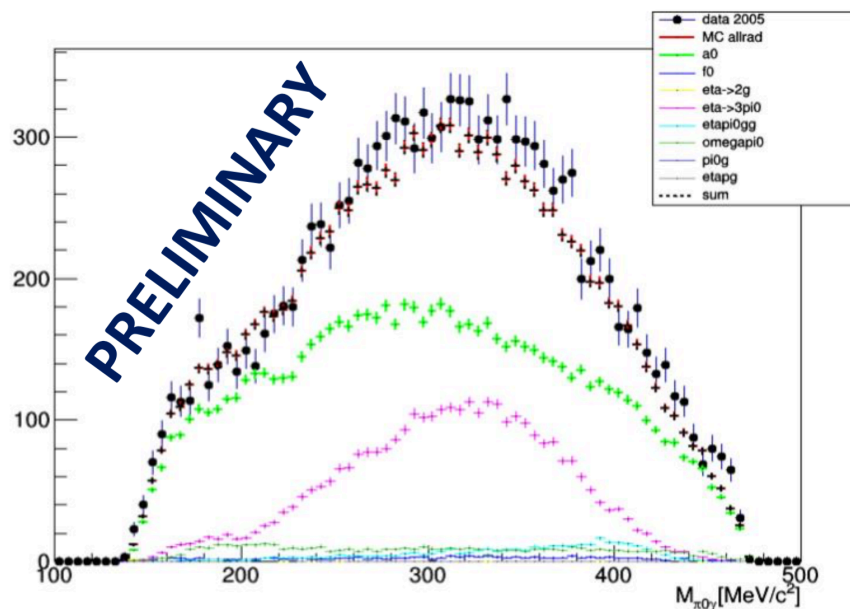
- $\pi^0 \gamma$  is the leading decay mode of B boson
- 5 prompt photons in the final state
- Main backgrounds:  $\phi \rightarrow \gamma a_0 (\eta \pi^0)$  and  $\gamma \eta (3 \pi^0)$  with lost or merged photons
- Kinematic fits to suppress backgrounds (ToF of  $5\gamma$ 's, E&P conservation,  $\eta/\pi^0$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

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

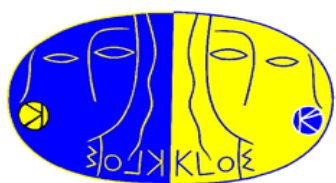


Discovery signal depends on mass  $m_B$

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



$M(3\gamma)$  [GeV]

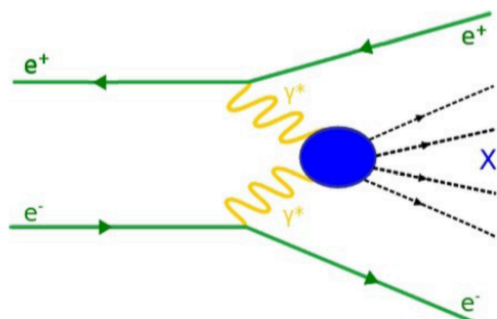


# $\gamma\gamma$ physics at KLOE-2



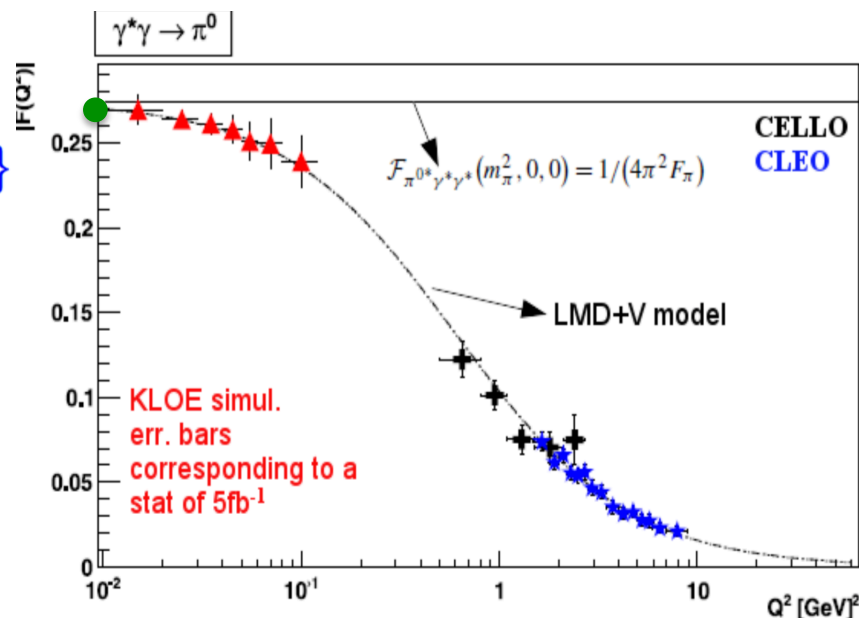
$$e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^- X$$

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



## Physic goal:

- $\Gamma_{\pi^0 \rightarrow \gamma\gamma}$  at 1 % level (green point)
  - ✓  $\Gamma_{\pi^0 \rightarrow \gamma\gamma}(\text{Th.}) = 8.09 \pm 0.11 \text{ eV} \sim 1.4\% \text{ precision}$
  - ✓  $\Gamma_{\pi^0 \rightarrow \gamma\gamma}(\text{Exp.}) = 7.82 \pm 0.22 \text{ eV} \sim 2.8\% \text{ precision}$
- Report recently at Phipsi2019 (PrimEx collaboration)
  - $\Gamma_{\pi^0 \rightarrow \gamma\gamma}(\text{Exp.}) = 7.802 \pm 0.117 \text{ eV} \sim 1.5\% \text{ precision}$
- first measure of the  $\mathcal{F}_{\pi^0 \gamma^* \gamma}(q^2)$  at  $q_{\gamma^*}^2 \leq 0.1 \text{ GeV}^2$  (red points)



have impact on the hadronic  
 light-by-light scattering  
 contribution to the muon  $g-2$   
 (Eur. Phys. J. C 72 (2012) 1917)

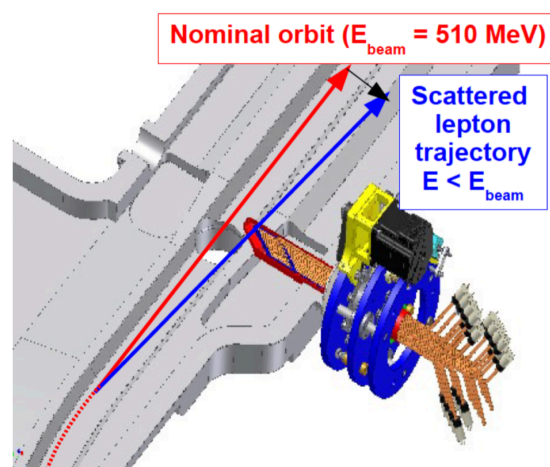
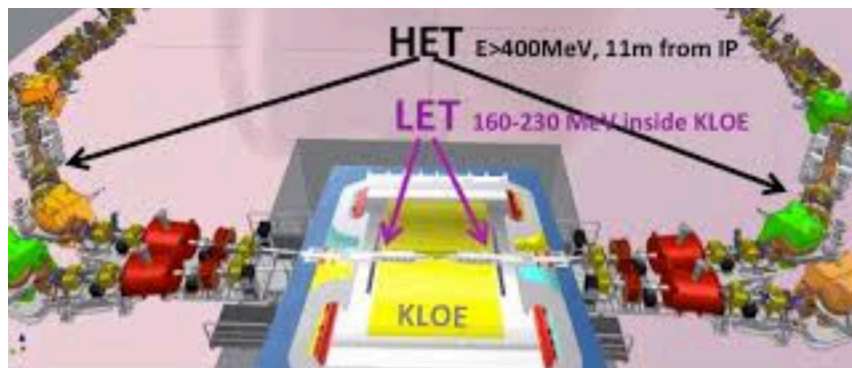




# HET & $\gamma^*\gamma^* \rightarrow \pi^0$ analysis



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



28 plastic scintillators  
( $5 \times 6 \times 3$  mm<sup>3</sup>)

1 Long Plastic for coincidence

DAQ systems for HET and KLOE are asynchronous

## Analysis strategy

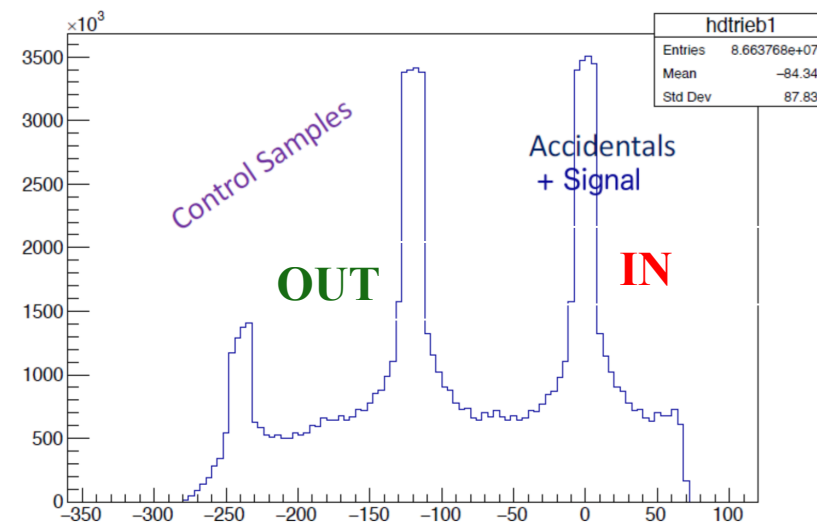
Hits in HET station and at least one bunch in KLOE  
associated with only 2 clusters in EMC

HET acquisition time 2.5 times larger than KLOE  $\rightarrow$

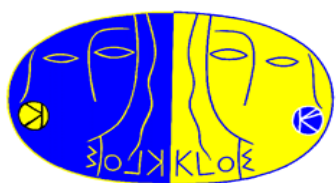
**OUT sample:** outside overlapping time window HET-only

**IN sample:** overlapping KLOE-HET time window

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



Delay between HET hits and Trigger (ns)

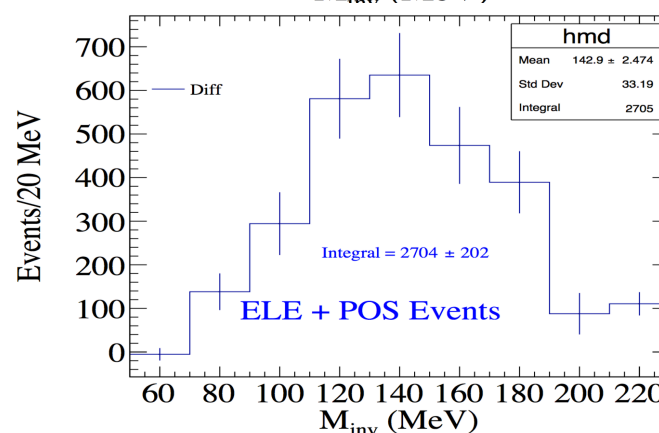
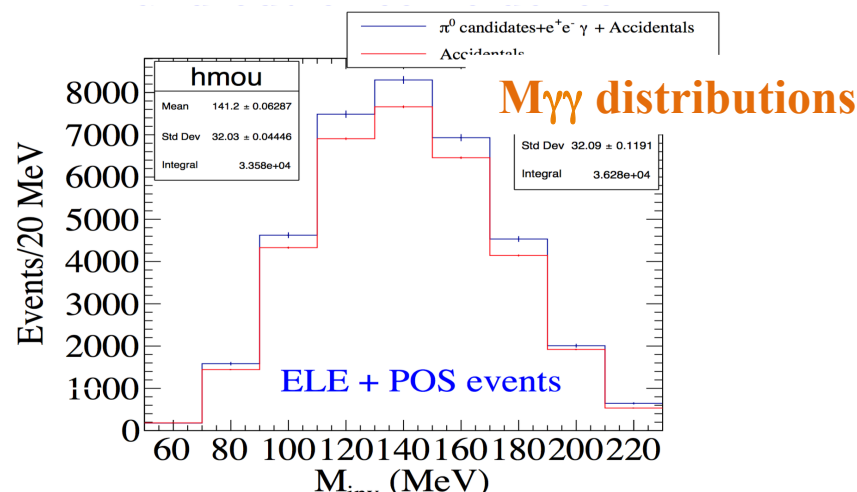
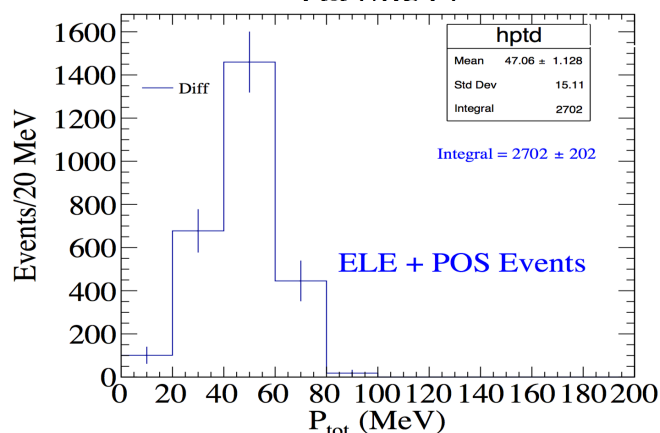
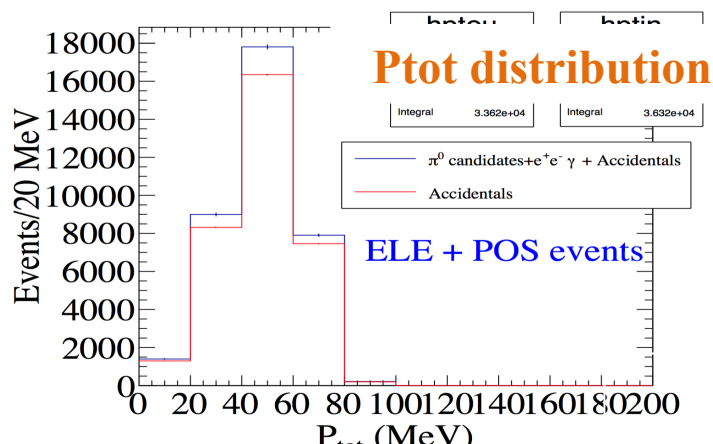


# $\gamma^*\gamma^* \rightarrow \pi^0$ : preliminary results

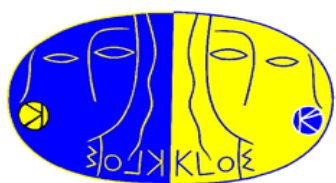


- ✓ 500 pb<sup>-1</sup> data of 2017
- ✓  $|\Delta P_{x,y}|_{\gamma\gamma} < 50$  MeV

- ✓ TMVA is helpful to separate signal from background (radiative Bhabha)



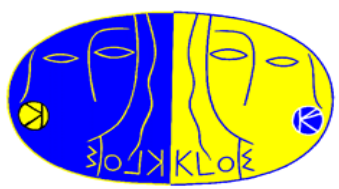
Identification of background events and analysis with more statistics in progress



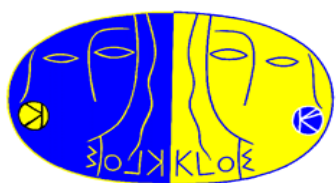
# Conclusions

- KLOE/KLOE-2 have collected  $8\text{fb}^{-1}$  data at  $\phi$  peak ( $2.4 \times 10^{10}$   $\phi$  mesons)  $\sim$  a unique sample worldwide
- Invaluable for performing precise measurements of hadron physics in low energy region and looking for very rare decays
  - achieved fruitful results on:  $\phi$  decays,  $\eta/\eta'$  decays, rare Kaon decays...
- With the ongoing analysis, more results are foreseen:
  - The most stringent U.L. for P/CP violating decay  $\eta \rightarrow \pi^+ \pi^-$
  - Precision measurement of  $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)$
  - Precision measurement of  $\Gamma_{\pi^0 \rightarrow \gamma \gamma}$  and first measure of  $\mathcal{F}_{\pi^0 \gamma^* \gamma}(q^2)$  at  $q_{\gamma^*}^2 \leq 0.1 \text{ GeV}^2$
  - Dark B mediator searches in  $\pi^0 \gamma$  final states
  - The ISR process of  $e^+ e^- \rightarrow \omega \gamma_{\text{ISR}}$  (see B. Cao's poster in detail)
  - ...





Thanks for your attention!!!



# Physics @ KLOE-2



Workshop on  $e^+e^-$  physics @ 1 GeV <https://agenda.infn.it/conferenceDisplay.py?confId=11722>

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

## A wide physics program

- Kaon Physics:  
 **$8.2 \times 10^9$   $K_S$  and  $K_L$  events**
- $\gamma\gamma$  physics  $e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^- X$
- Light meson spectroscopy  
 **$3.1 \times 10^8$   $\eta$  events**  
 **$1.48 \times 10^8$   $\eta'$  events**  
 **$4.0 \times 10^6$   $\omega$  events**
- Hadron physics below 1 GeV
- Dark sector searches

- |   |
|---|
| <ul style="list-style-type: none"><li>• Discrete symmetries test</li><li>• CKM test</li><li>• High precision tests of CPT and QM</li><li>• Rare kaon decays</li></ul>   |
| <ul style="list-style-type: none"><li>• <math>X = \pi\pi \Rightarrow</math> study of <math>f_0(500)</math></li><li>• <math>X = \pi^0/\eta \Rightarrow \Gamma(\pi^0 \rightarrow \gamma\gamma)</math>, space-like TFF</li></ul> |
| <ul style="list-style-type: none"><li>• Properties of scalar/vector mesons</li><li>• <math>\eta/\eta'</math> physics</li><li>• Rare <math>\eta</math> decays</li></ul>  |
| <ul style="list-style-type: none"><li>• ISR studies with <math>3\pi</math>, <math>4\pi</math> final states</li><li>• Measurement of <math>\alpha_\mu^{\text{HLO}}</math> in the space-like region</li></ul>                   |