Recent Results on Hadron Physics at KLOE-2

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on behalf of the KLOE-2 Collaboration

International Workshop on e^+e^- collisions from Phi to Psi

Budker Institute of Nuclear Physics, Novosibirsk
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DAΦNE and KLOE-2 Experiment

Running of $\alpha(s)$

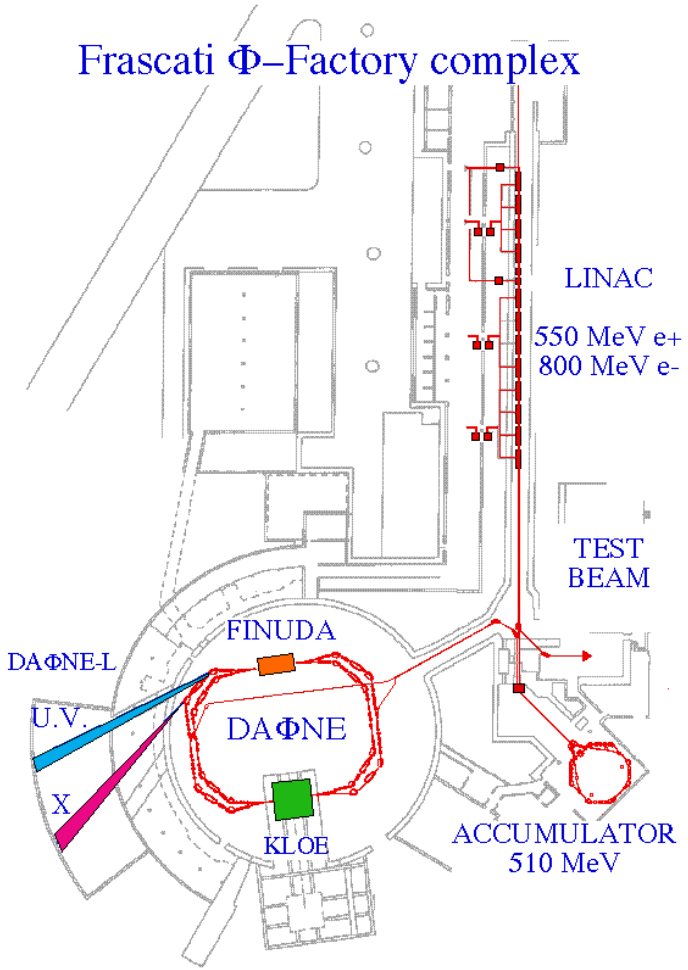
Combination of $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and $a_\mu^{\pi\pi}$

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

$\gamma\gamma$ studies

Conclusions

DAΦNE: THE Φ-FACTORY



e^+e^- collider @ $\sqrt{s} = M_\Phi = 1.0194$ GeV

2 interaction regions

2 separate rings

105 +105 bunches, $T_{RF} = 2.7$ ns

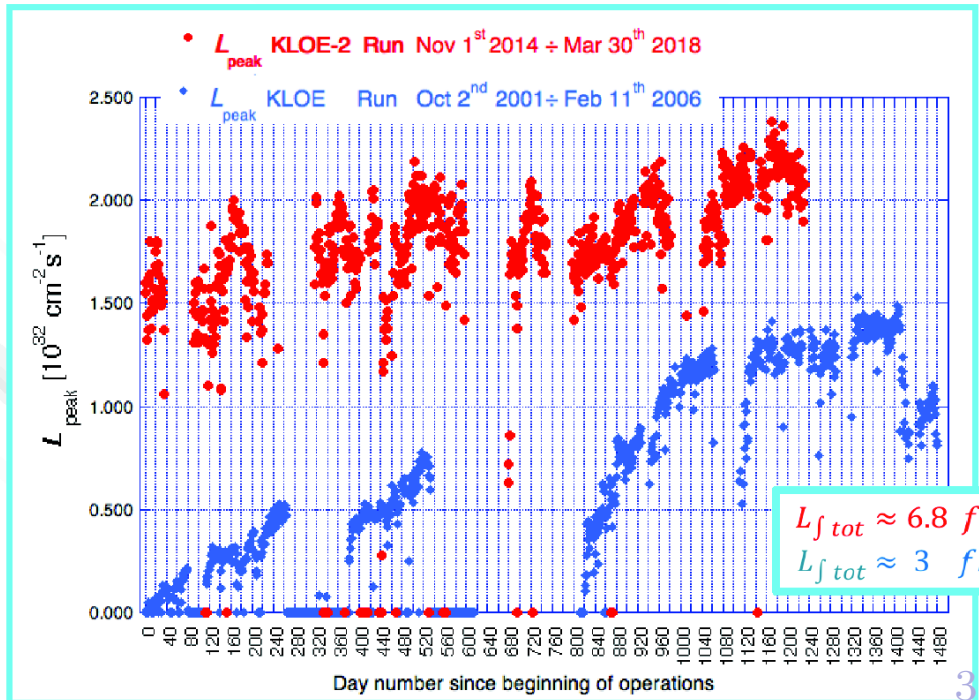
Injection during data taking

Crossing angle: 2×12.5 mrad

Best Performance (1999–2006):
$L_{\rm peak} = 1.5 \times 10^{32}$ cm^{-2} s^{-1}

Best Performance (2014–2018):

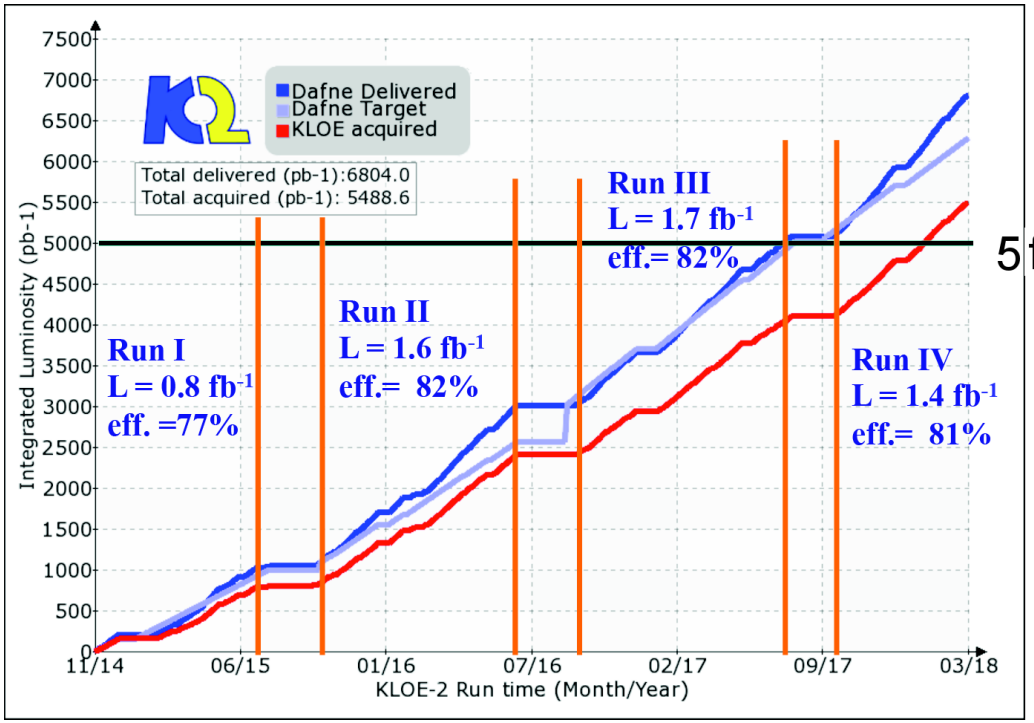
$L_{\rm peak} = 2.4 \times 10^{32}$ cm^{-2} s^{-1}



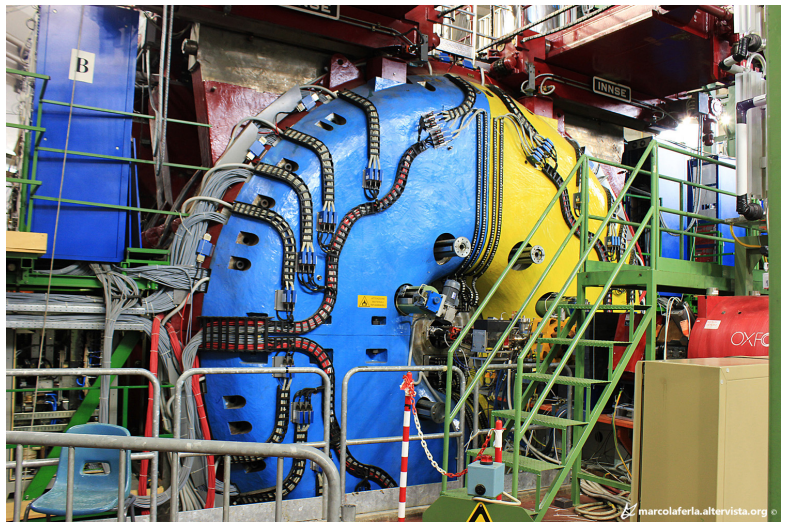
DAΦNE UPGRADES

New interaction region: large beam crossing angle + sextupoles for crabbed waist optics → 59% increase in terms of peak luminosity

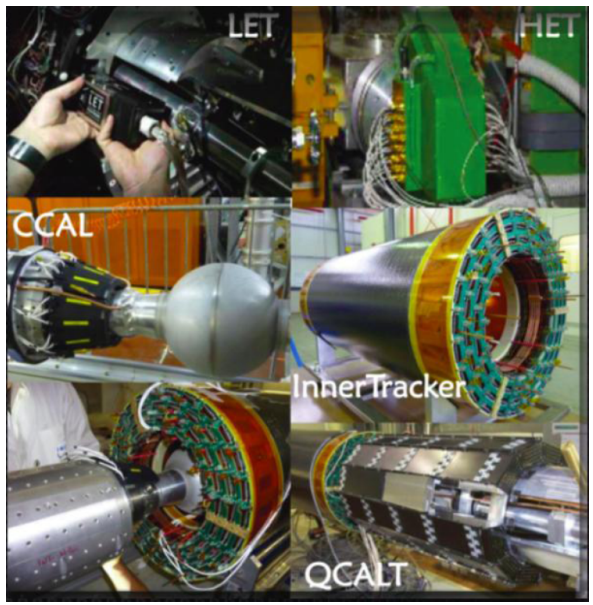
The KLOE-2 Experiment



The KLOE detector has been rolled out from the IR after almost 20 years of operation



The KLOE-2 sub-detectors



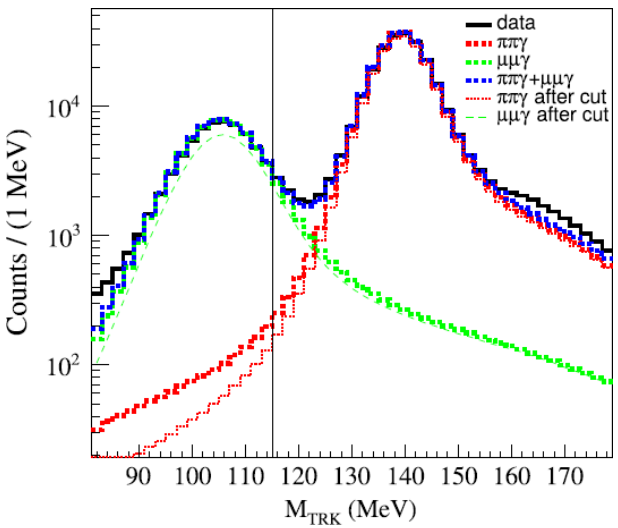
KLOE-2 experiment ended on March 30$^{\text{th}}$ 2018:

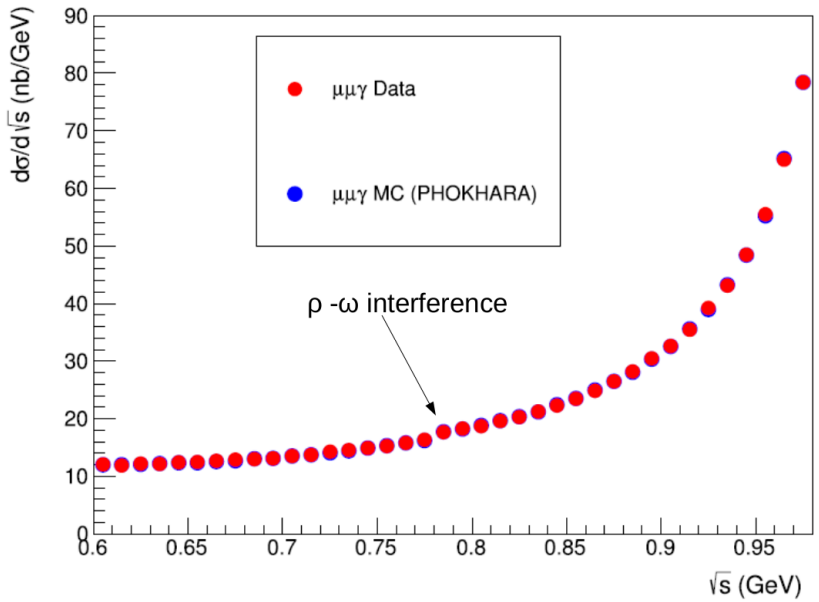
$$\int L_{\text{delivered}} = 6.8 \text{ fb}^{-1}$$

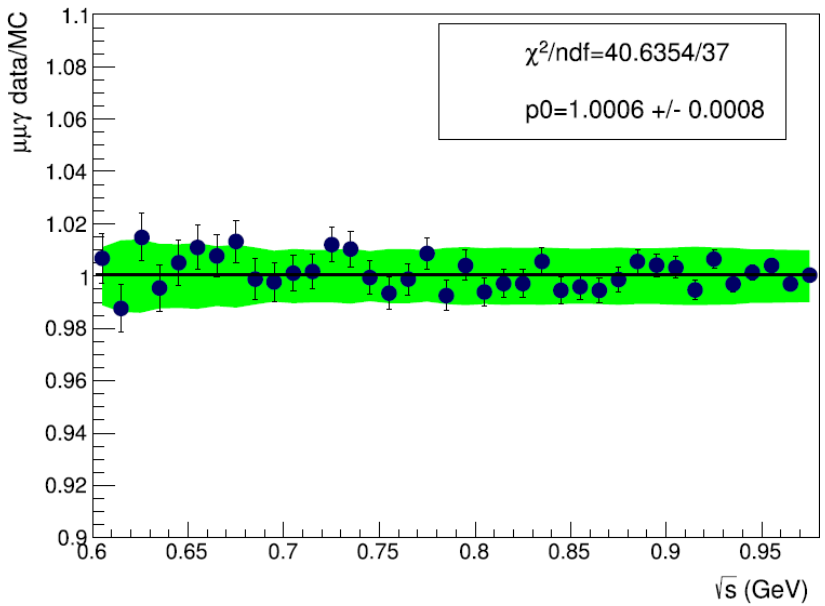
$$\int L_{\text{acquired}} = 5.5 \text{ fb}^{-1}$$

KLOE + KLOE-2 data sample:
$8 \text{ fb}^{-1} \rightarrow 2.4 \times 10^{10}$ ϕ mesons produced, the largest sample ever collected at the $\phi(1020)$ peak in collider experiments

Running of $\alpha(s)$







Statistics: KLOE data collected on 2004-05 corresponding to L= 1.7 fb^{-1}.

Small angle event selection:
($50^\circ < \theta_\mu < 130^\circ$, $\theta_\gamma < 15^\circ$, $> 165^\circ$), photon not detected, $\vec{p}_\gamma$ reconstructed from kinematics

High statistics ISR signal

Significant reduction of ϕ resonant and FSR bckgs

Good π/μ separation thanks to $M_{\rm trk}$ and $\sigma_{M_{\rm trk}}$ cuts

About $4.5 \times 10^6 \mu^+\mu^-\gamma$ events selected

Residual bckg: $\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^0$, $e^+e^-\gamma$ $< 1\%$

$e^+e^- \to \mu^+\mu^-\gamma$ cross section measured with syst err $< 1\%$

Running of $\alpha(s)$

First time Im $\Delta\alpha$ and Re $\Delta\alpha$ extracted

Method:

$\mu^+\mu^-\gamma$ data corrected for FSR (PHOKARA MC generator)

Normalization to MC with $\alpha = \alpha(0)$

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{|\mathrm{d}\sigma_{\mathrm{data}}(\mu^+\mu^-\gamma(\gamma))|_{\mathrm{ISR}}/\mathrm{d}\sqrt{s}}{|\mathrm{d}^0\sigma_{\mathrm{MC}}(\mu^+\mu^-\gamma(\gamma))|_{\mathrm{ISR}}/\mathrm{d}\sqrt{s}},$$

$\sqrt{s} = M_{\mu\mu}$

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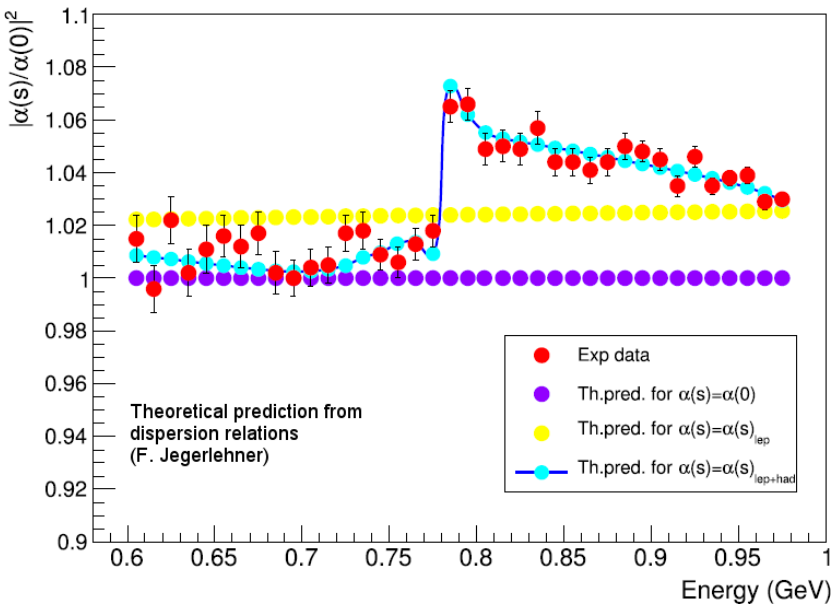
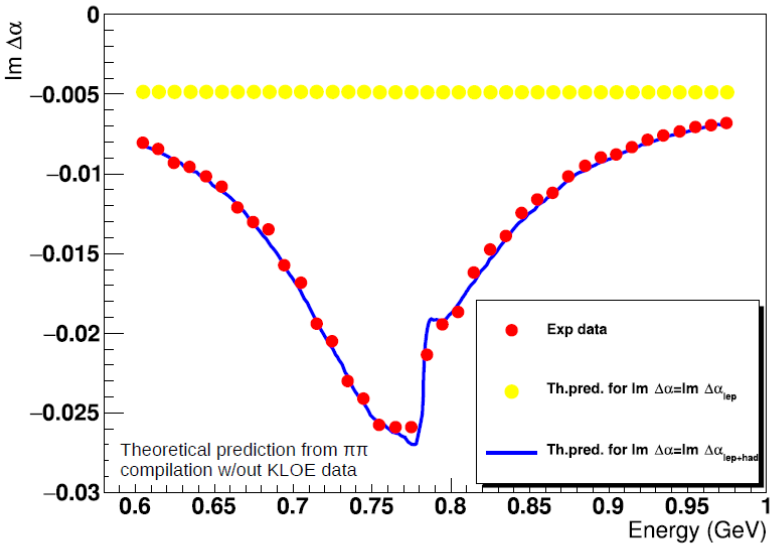
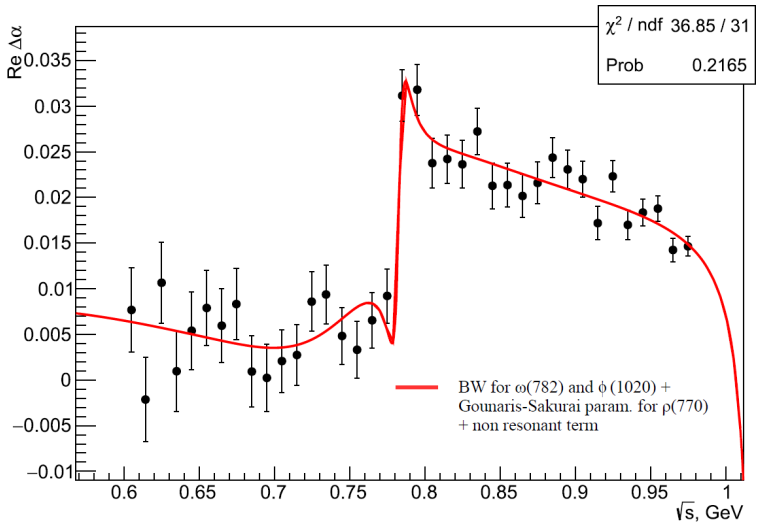
$> 5\sigma$ significance of $\Delta\alpha_{had}$ contribution to $\alpha(s)$







Im $\Delta\alpha = -\frac{\alpha}{3}$R(s) from KLOE $\sigma(e^+e^- \to \pi^+\pi^-)$

Re $\Delta\alpha = \sqrt{|\alpha(s)/\alpha(0)|^2 - (\mathrm{Im}\Delta\alpha)^2}$

$\mathrm{Br}(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4 \pm 1.7) \times 10^{-5}$

(PDG: $(9.0 \pm 3.1) \times 10^{-5}$)

KLOE $\sigma_{\rm comb}(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ AND $a_\mu^{\pi\pi}$

Three KLOE $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ with ISR:

KLOE08: small angle photon selection ($\theta_\gamma < 15^\circ$, $> 165^\circ$), $\sqrt{s} = 1.02$ GeV, Phys. Lett. B 670 (2009) 285

KLOE10: large angle photon selection($45^\circ < \theta_\gamma < 135^\circ$), $\sqrt{s} = 1.0$ GeV, Phys. Lett. B 700 (2011) 102

KLOE12: small angle photon selection, $\sqrt{s} = 1.02$ GeV, $\sigma_{ee\to\pi\pi}$ from π/μ, Phys. Lett. B 720 (2013) 336

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

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

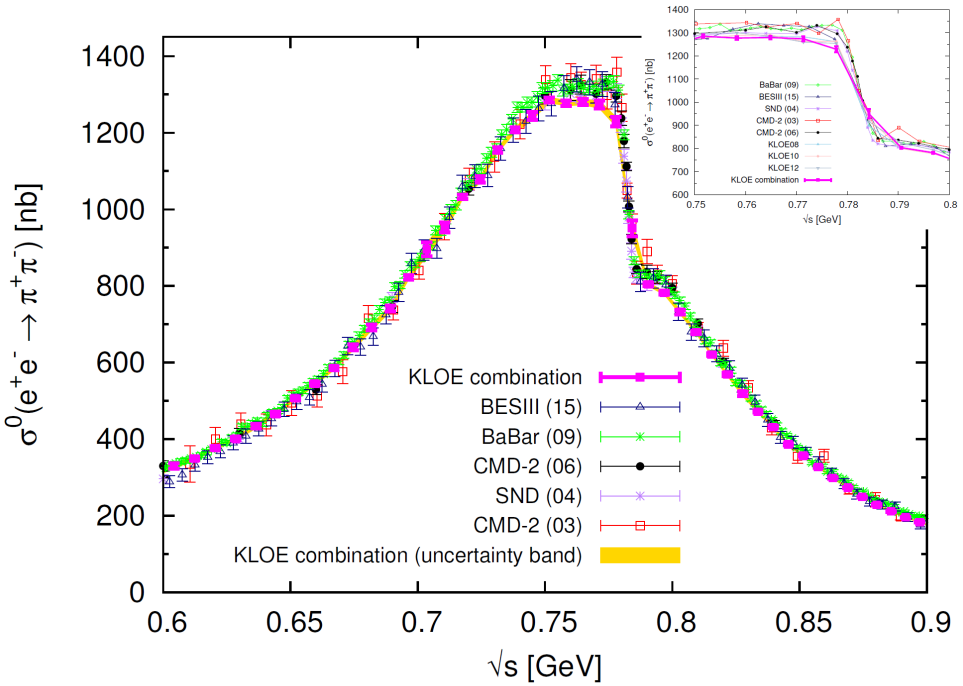
KLOE12 $\to$
$\sigma^0_{\pi\pi(\gamma)} = \frac{d\sigma(\pi\pi\gamma)/ds'}{d\sigma(\mu\mu\gamma)/ds'} \times \sigma^0_{(\gamma)}(ee \to \mu\mu, s')$
$s' = M^2_{\pi\pi} = M^2_{\mu\mu}$

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

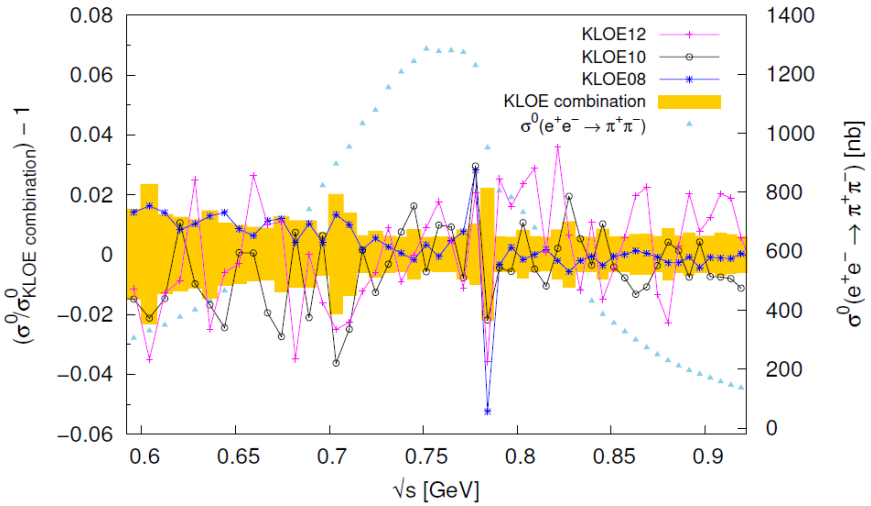
$$|F_\pi(s')|^2 = \frac{3}{\pi}\frac{s'}{\alpha^2\beta_\pi^3(s')}\frac{\sigma^0_{\pi\pi(\gamma)(s')}}{|1-\prod(s')|^2}(1-\frac{\alpha}{\pi}\eta_\pi(s'))$$

KLOE08, KLOE10 and KLOE12 updated and then combined $\to$ iterative linear χ^2 function minimization method $\to$ construction of full statistical and systematic covariance matrices needed

KLOE $\sigma^0_{\pi\pi\gamma(\gamma)}$ meas invaluable to precisely determine $a_\mu^{\pi\pi}$

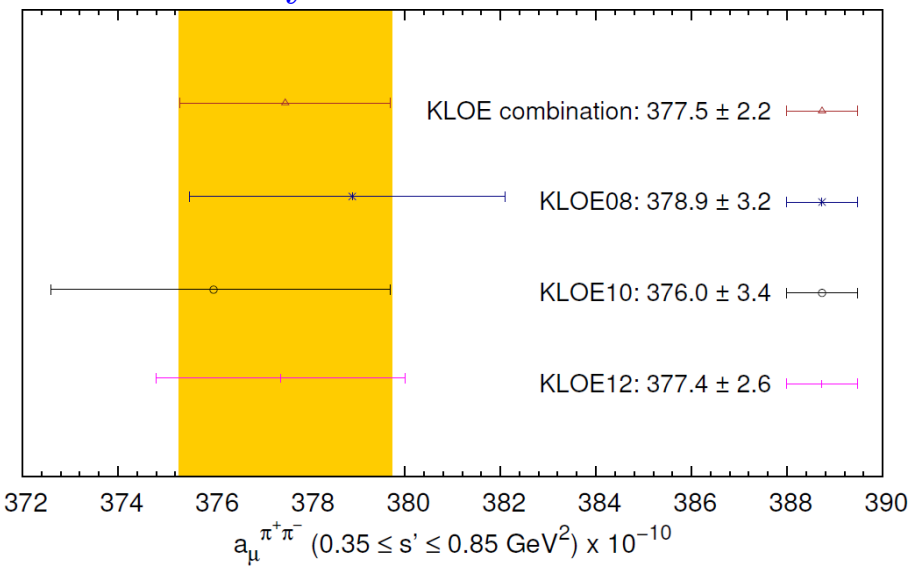


Normalised difference in the overlapping data range



KLOE $\sigma_{\rm comb}(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ AND $a_\mu^{\pi\pi}$

Consistency of KLOE measurements



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

in agreement with CMD-2, SND and BESIII meas within 1.5σ

Difference with BaBar $< 3\sigma$

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

uncertainties in all $a_\mu^{\pi^+\pi^-}$ estimations are the sum in quadrature of both stat and syst errors

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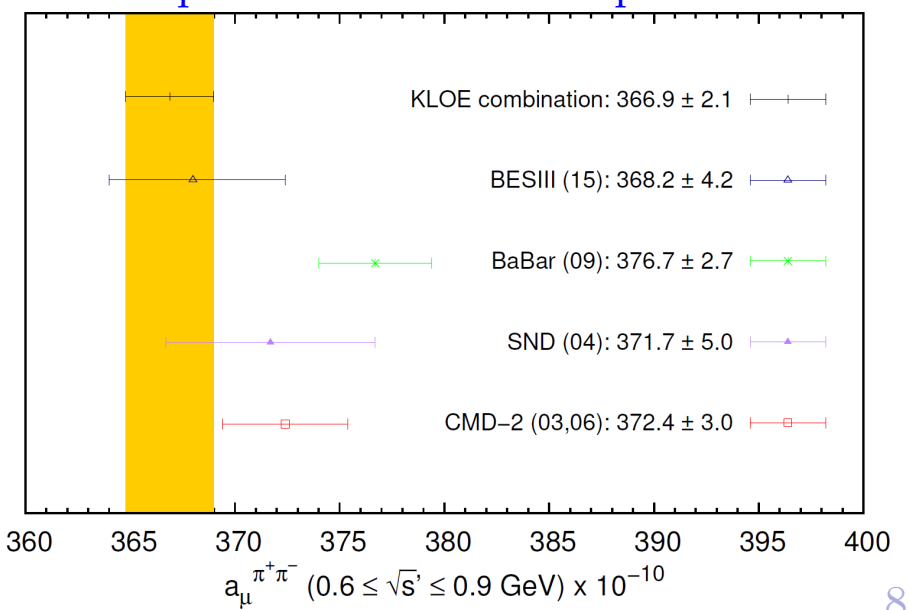
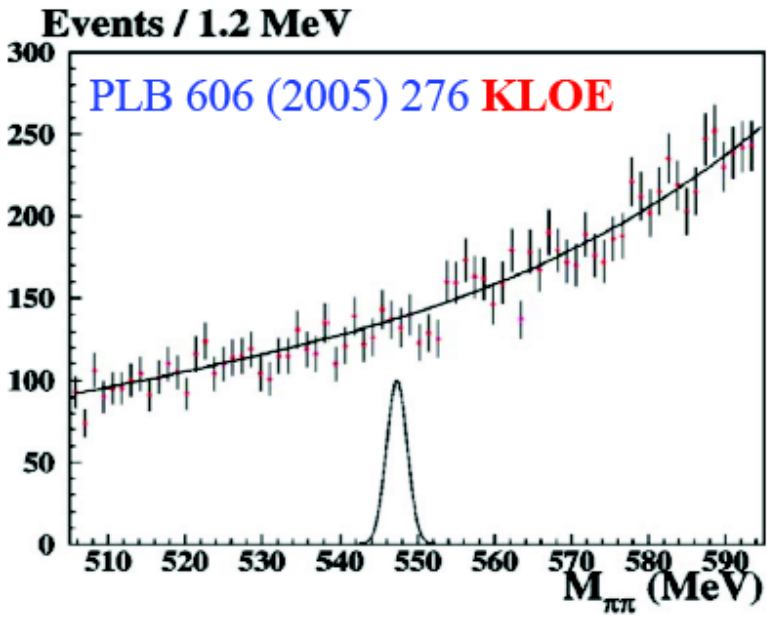
Comparison with other experiments



$\eta \to \pi^+\pi^-$ LIMIT



- ⋆ P and CP violating process
- ⋆ Br($\eta \to \pi\pi$) prediction in SM [Phys. Scripta T99, 23 (2002)]:
  10^{-27} → only via the CP-violating in weak interaction
  to 10^{-17} → introducing a CP violating term in QCD
  10^{-15} allowing CP violation in the extended Higgs sector
- ⋆ Any observation of larger branching fraction would indicate a new source of CP violation in the strong interaction

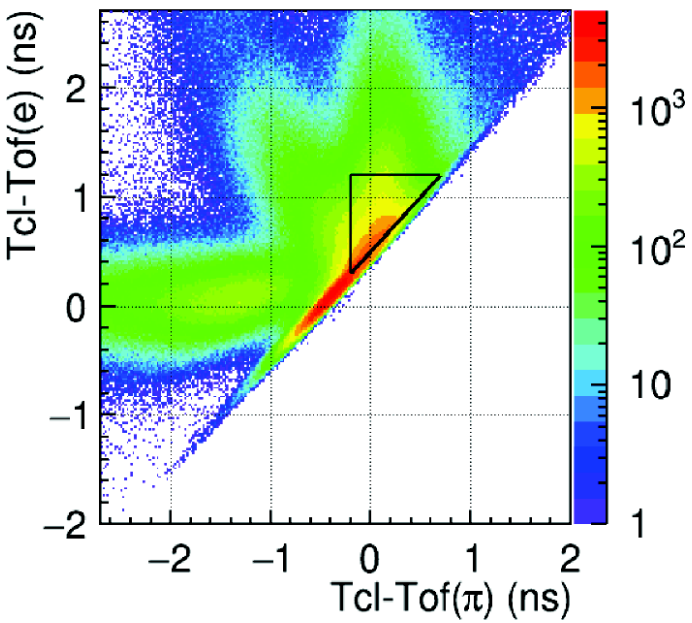
Best UL set by KLOE with $\mathcal{L} \sim 350\,\mathrm{pb}^{-1}$
$Br(\eta \to \pi\pi) < 1.3 \times 10^{-5}$, 90% CL
recent UL from the LHCb, 1.6×10^{-5}, 90% CL [PLB 764 (2017) 233]

$\eta \to \pi^+\pi^-$ LIMIT

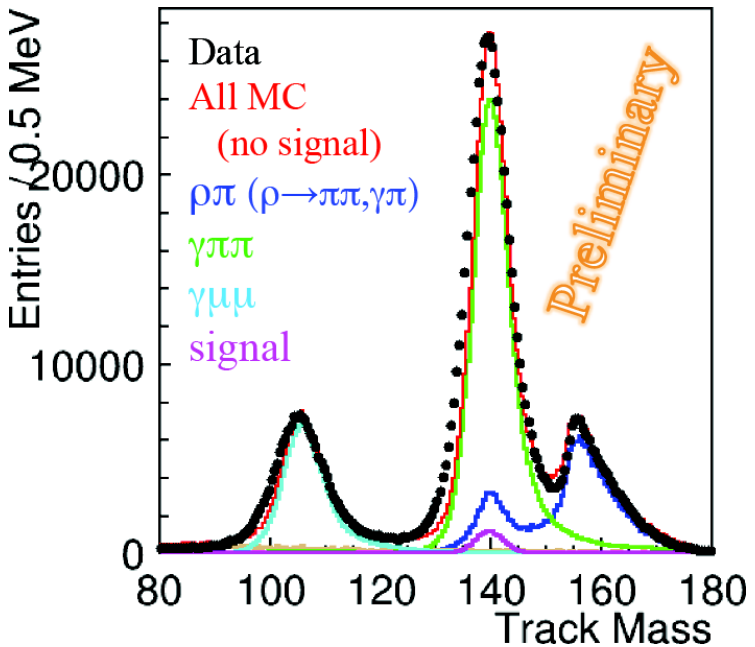
$\mathcal{L} \sim 1.7\text{fb}^{-1}$ are used to update the upper limit

Selection of $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-$ events:
one vertex with two opposite charged tracks (reaching EMC)
tracks required to be at large angle $45^\circ < \theta_{\text{trk}} < 135^\circ$
one prompt photon in time with $45^\circ < \theta_\gamma < 135^\circ$ to suppress ISR
Angle between p_{miss} and prompt photon direction < 0.03 rad

PID with ToF technique to reject $e^+e^-\gamma$ bckgs
$\to 0.3 < \delta t(e) < 1.2\,\text{ns}$ $-0.2 < \delta t(\pi) < 0.7\,\text{ns}$

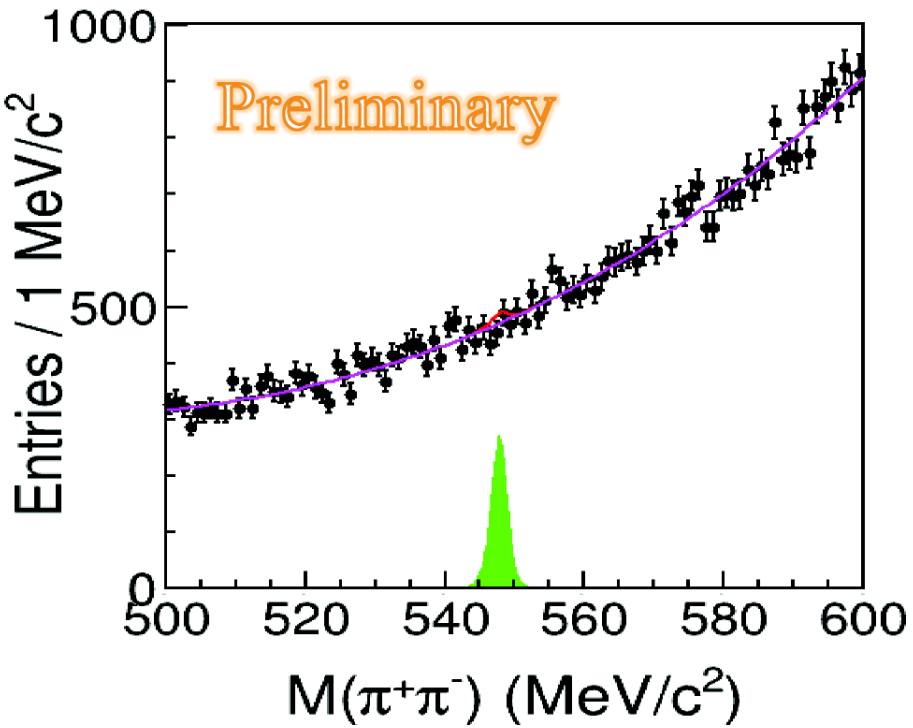


Track mass $129 < M_{\text{trk}} < 149\,\text{MeV}$ to reject
$\mu^+\mu^-\gamma$ and $\pi^+\pi^-\pi^0$ bckgs



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

$\eta \to \pi^+\pi^-$ LIMIT



Preliminary results:

- Continue backgrounds from $\pi\pi\gamma$
- After all the cuts, efficiency = (13.6 ± 0.02) %
- No event excess in the η region
- Fit with 3^{rd} polynomial function + MC signal shape
- $N_{UL} = 50.4$, 90% CL
- UL systematics: alternative fits performed, negligible diff found, maximum N_{UL} chosen

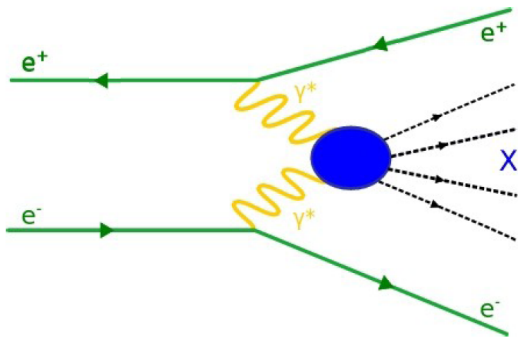
$Br(\eta \to \pi\pi) < 5.8 \times 10^{-6}$ 90% CL

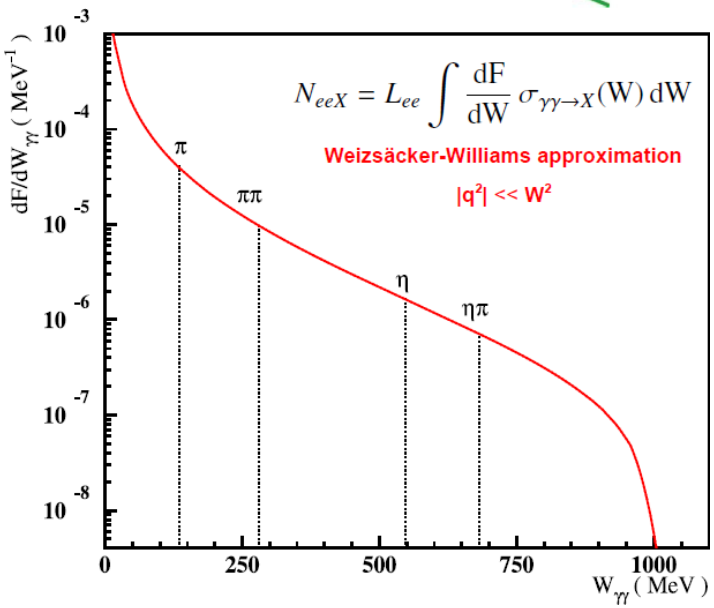
With all KLOE/KLOE-2 data ($8 fb^{-1}$) $\to$ the upper limit is expected to reach 2.7×10^{-6} 90% CL

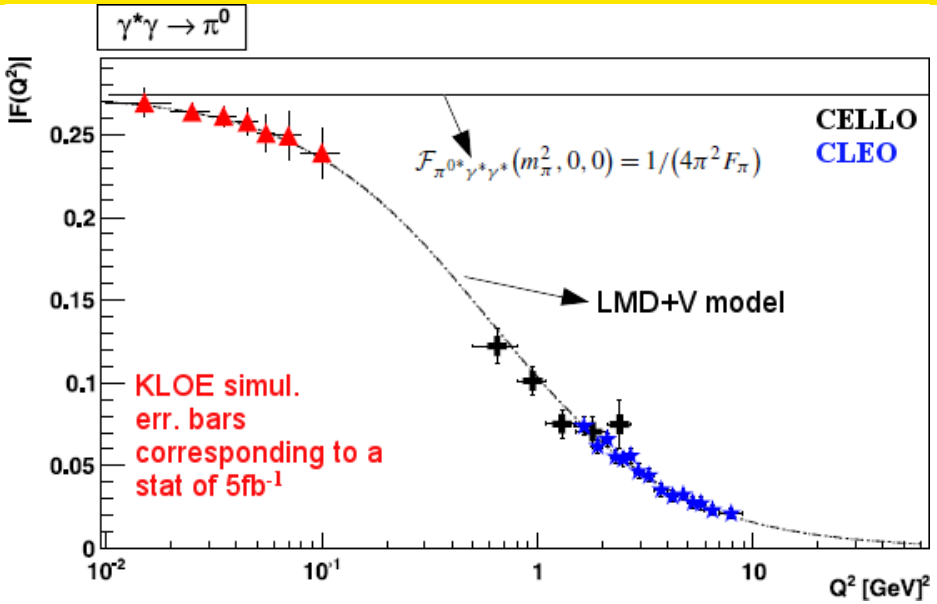
$\gamma\gamma$ Physics at KLOE-2 : Motivations

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

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

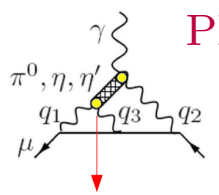






Physics goal:

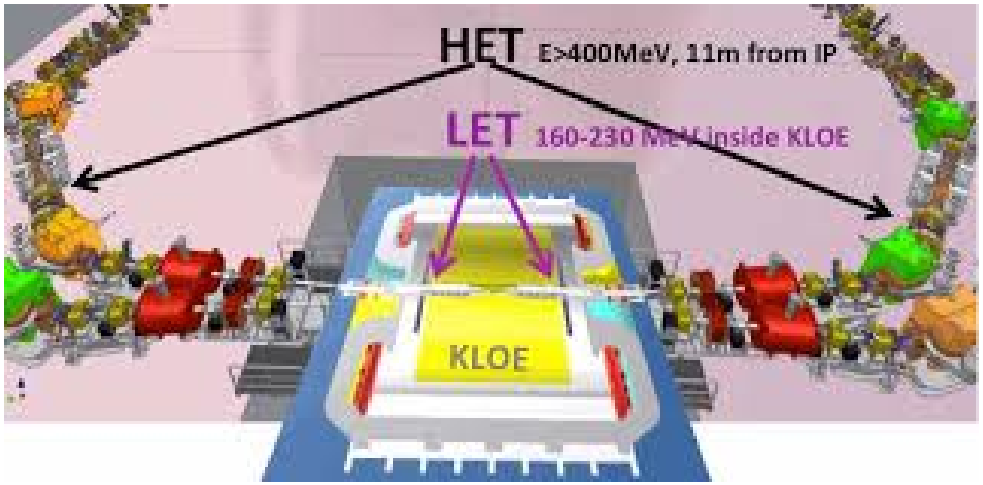
- Precision measurement (1%) of the $\Gamma_{\pi^0\to\gamma\gamma}$
  $\Gamma^{\text{Th.}}_{\pi^0\to\gamma\gamma} = 8.09 \pm 0.11$eV (1.4% precision)
  $\Gamma^{\text{Exp}}_{\pi^0\to\gamma\gamma} = 7.82 \pm 0.22$ (2.8% precision, via Primakoff Effect, most precise measurement);
- First measurements of the $F_{\pi^0\gamma^\star\gamma}(q^2, 0)$ in the space-like region for $q^2 < 0.1\,\text{GeV}^2$



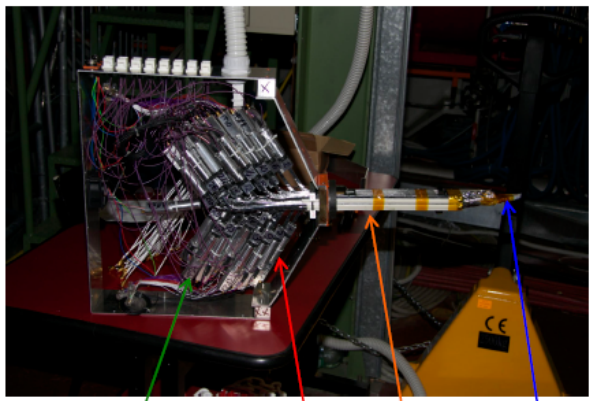
Physics motivation:
impact on the value and precision of the $a_\mu^{\text{LbyL};\pi^0}$

The HET Detector

The HET stations are located 11m away the IP after the bending dipoles acting like spectrometer position detector



28 plastic scintillators (5x3x6 mm^3) inserted in roman pots with 1^{st} plastic at about 5 cm from the beam
1 Long Plastic for coincidence



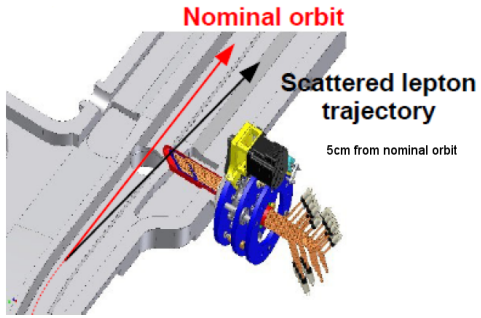
Position detector:

$\sigma_\theta \sim 2,5\text{mrad}$, $\sigma_r \sim 5\text{mm}$, $\sigma_t \sim 500(1)\text{ps}$

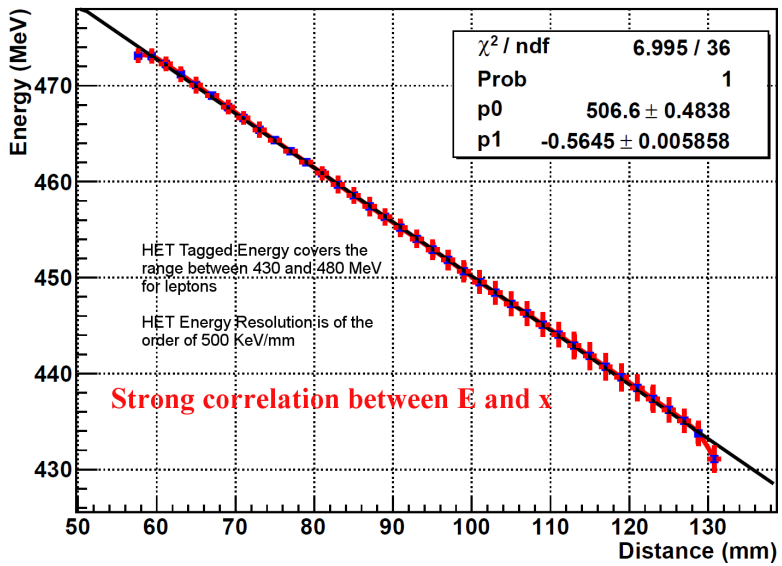
$$e^+ e^- \to e^+ e^- y^* y^* \to e^+ e^- X$$

to taggers

in KLOE



Energy of leptons vs Distance from the nominal orbit



Energy acceptance $\sim$ 430–480 MeV
Angular acceptance $0^\circ \div 1.5^\circ$

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

2015-2016 reconstructed data sample of 500 pb^{-1} → no firm evidence of $\gamma^*\gamma^* \to \pi^0$ events obtained. MVA also performed → no clear evidence of the tagged signal found comparing analyzed and control samples.

Some issues with the HET FEE, affecting HET efficiency, discovered and fixed with the installation of new discriminators in January 2017

A new reconstruction of a 2017 data sample of 500 pb^{-1} has been completed:

Reconstruction output (ntuples) 6.55 TB
Data stored in root format 3.37 TB
3 levels of data reduction applied 0.45 TB → 91 GB → 5.28 GB

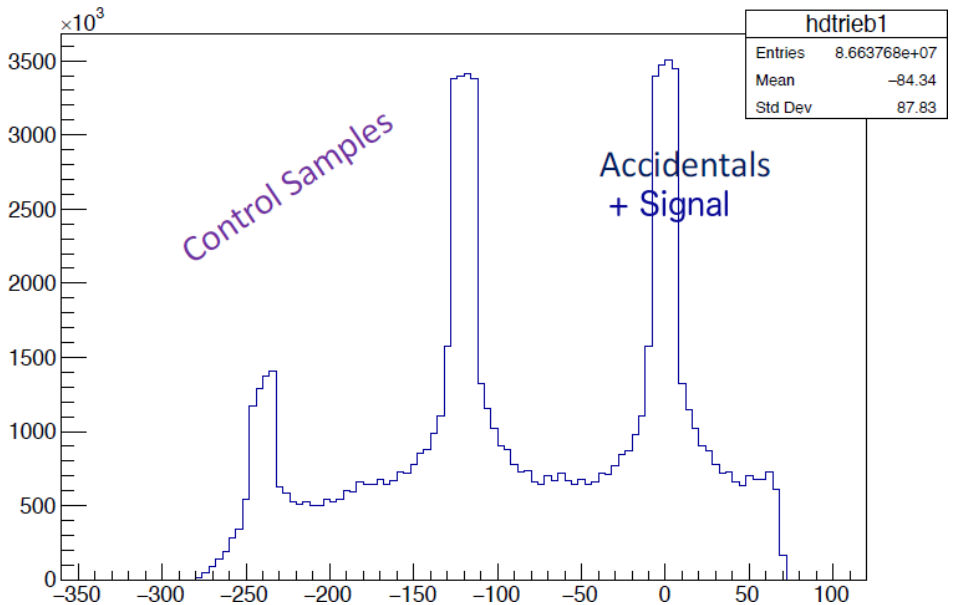
DA selection: hits in both HET stations with $|\Delta T|$ within 4 KLOE bunches

SA selection: hits in one HET station and at least one bunch in KLOE associated with only 2 clusters in the EMC.

KLOE and HET Bunch times compatible with Trigger signal.

DAFNE turn not considered → the control sample stored as well → event by event subtraction of accidentals.

Very loose kinematics cuts on the selected clusters applied



Delay between HET hits and Trigger (ns)

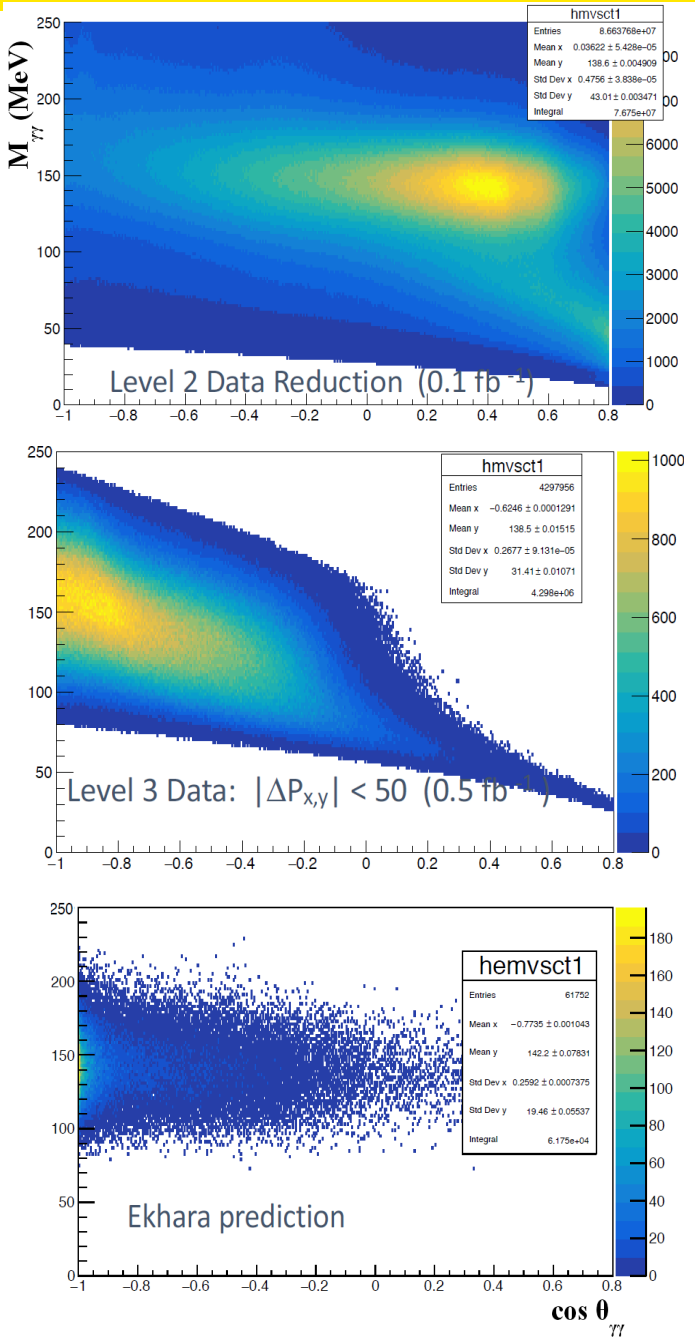
$\gamma^*\gamma^* \to \pi^0$ Analysis

$|\Delta P_{x,y}| < 50$ MeV cut very effective to reject backgorund, applied at level 3 of data reduction

A deep data quality has been performed by measuring low angle Bhabha cross section per HET channel, over a time scale of two years

A subset of HET scintillators with stable rates has been identified

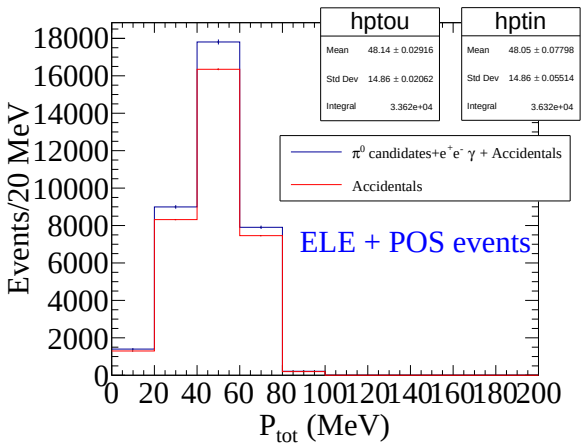
The π^0 search is focused on events registered in 10/28 stable HET plastics



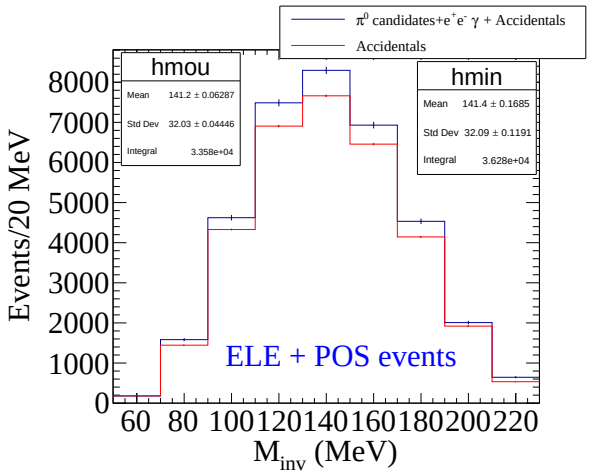
$\gamma^*\gamma^* \to \pi^0$: PRELIMINARY RESULTS

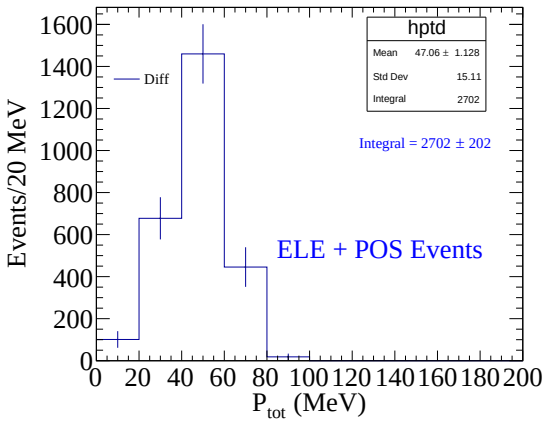
$\gamma^*\gamma^* \to \pi^0$ signal is expected at low $P_{\rm tot}$ of the 2γ

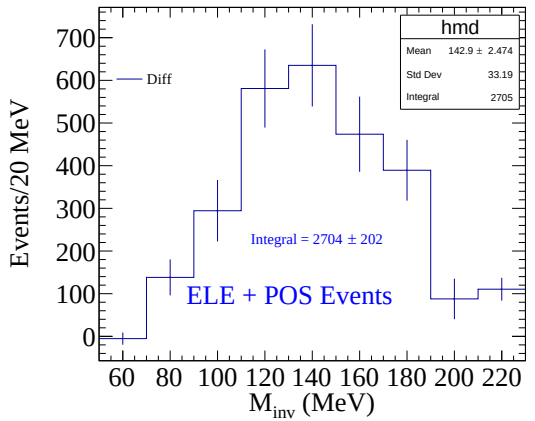
Ptot distributions of coincidence and out-of-coincidence events



$M_{\gamma\gamma}$ distributions of coincidence and out-of-coincidence







Statistical evidence of the tagged sample established

Multivariate analysis to separate π^0 from radiative Bhabha's ongoing

Conclusions

- ⋆ KLOE/KLOE-2 data samples invaluable to perform precise measurements in hadronic physics and test symmetries.
- ⋆ $\Delta\alpha_{\rm had}$ contribution to $\alpha(s)$ established at more than 5σ, real and imaginary part of $\Delta\alpha$ extracted for the first time, PLB 767 (2017) 485.

  KLOE $\sigma^0_{\pi\pi\gamma(\gamma)}$ measurements combined and used to estimate $a_\mu^{\pi\pi}$, combined estimation in agreement with CMD-2, SND and BESIII measurements within 1.5σ, difference with Babar estimation $< 3\sigma$, JHEP 03 (2018) 173.
- ⋆ Preliminary $\eta \to \pi^+\pi^-$ limit extracted using about 1.7 fb^{-1} of KLOE data, $Br(\eta \to \pi\pi) < 5.8 \times 10^{-6}$ 90% CL; the UL is expected to improve of a factor 2 using full KLOE/KLOE-2 statistics (8 fb^{-1}).
- ⋆ $\gamma^*\gamma^*$ studies :

  Subset of HET scintillators giving stable rates over months/years found.

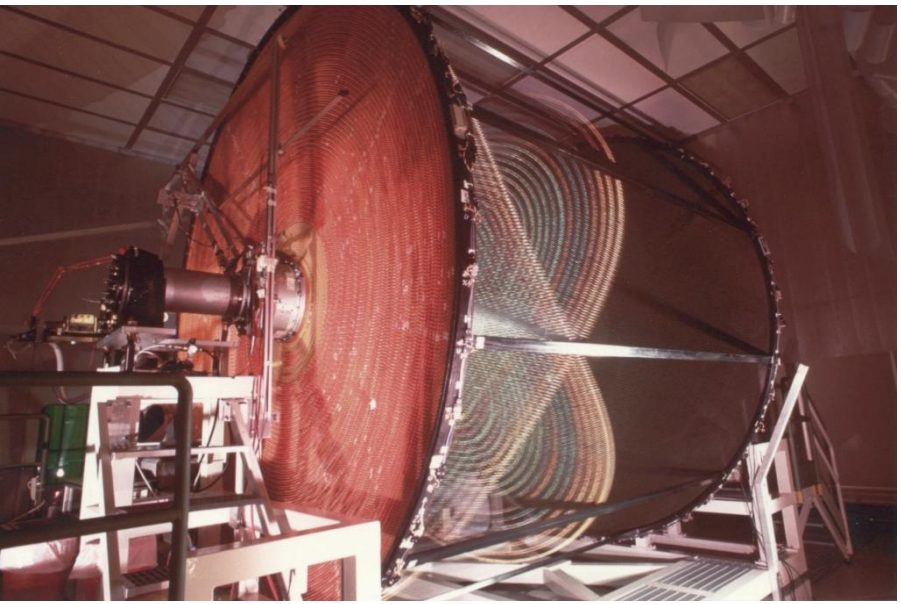
  Firm evidence of tagged events at low momenta of the reconstructed π^0 candidates established.

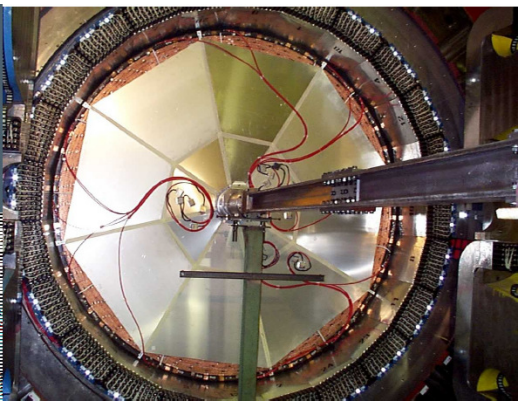
  MVA ongoing to separate $\gamma^*\gamma^* \to \pi^0$ events from the background of radative Bhabha's.

Thank You!

SPARES

The KLOE DC





$\sigma_{xy} \sim 150\mu m$

$\sigma_z = 2mm$

$\sigma_{p_\perp}/p_\perp \sim 0.4\%$ (LA tracks)

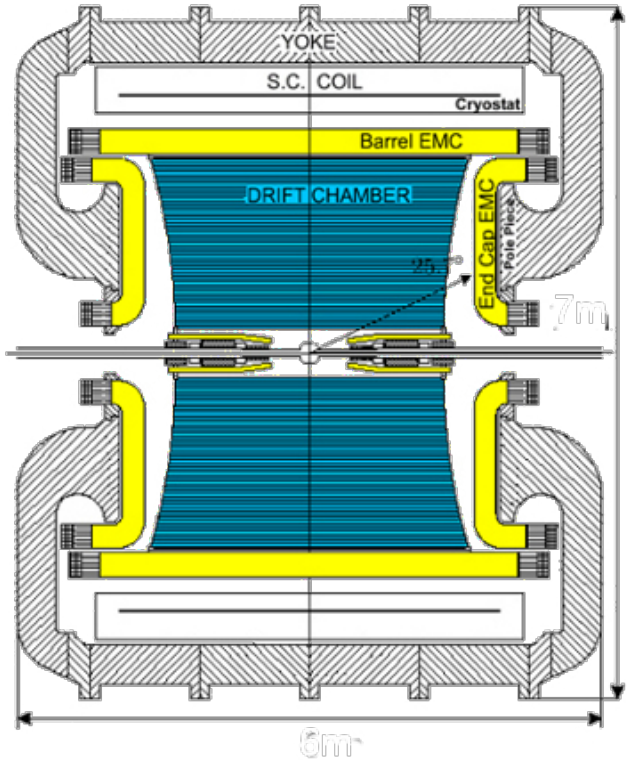
vertex resolution $\sim$3mm

12,000 sense wires

Stereo geometry

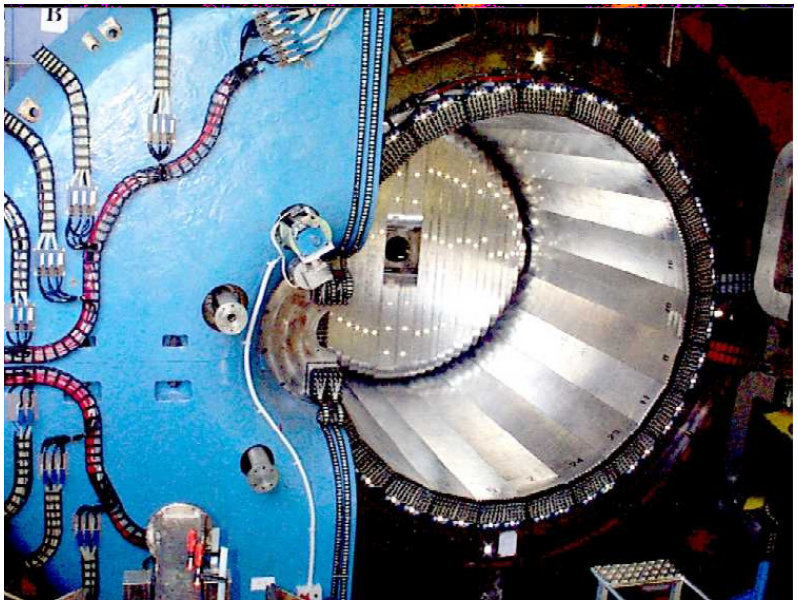
4m diameter, 3m long

gas mixture: 90% He 10% iC_4H_{10}



Excellent momentum resolution

The KLOE EMC



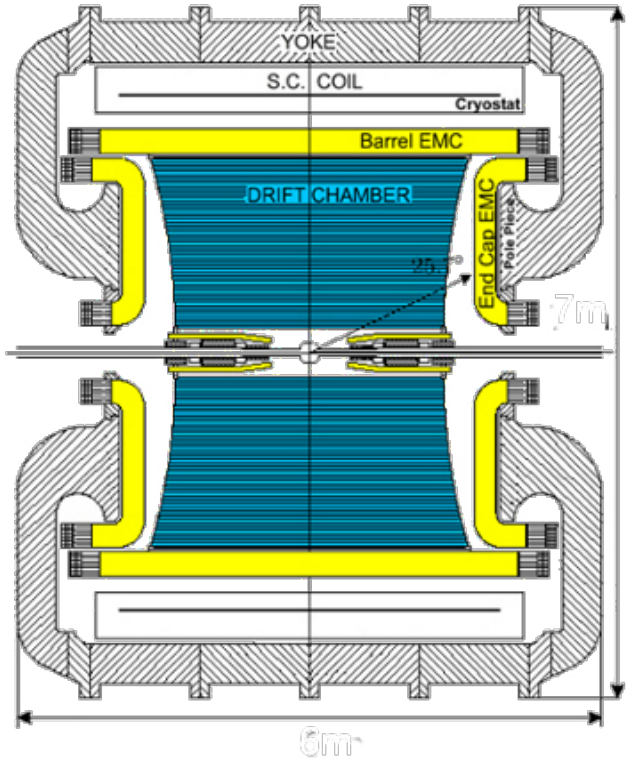
End-caps C-shaped to minimize dead zones: 98% coverage of full solid angle

$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$

$\sigma_T = 54ps/\sqrt{E(GeV)} \oplus 140ps$

Barrel + 2 end-caps:

Pb/scintillating fiber, 4880 PM



Excellent time resolution

The KLOE sub-detectors

INNER TRACKER:

- four layers of cylindrical triple GEM
- better vertex reconstruction near IP
- higher acceptance to low p_t tracks

CCALT:

- LYSO crystal + SiPM
- increase of angular acceptance to γ's from IP from 21° to 10°

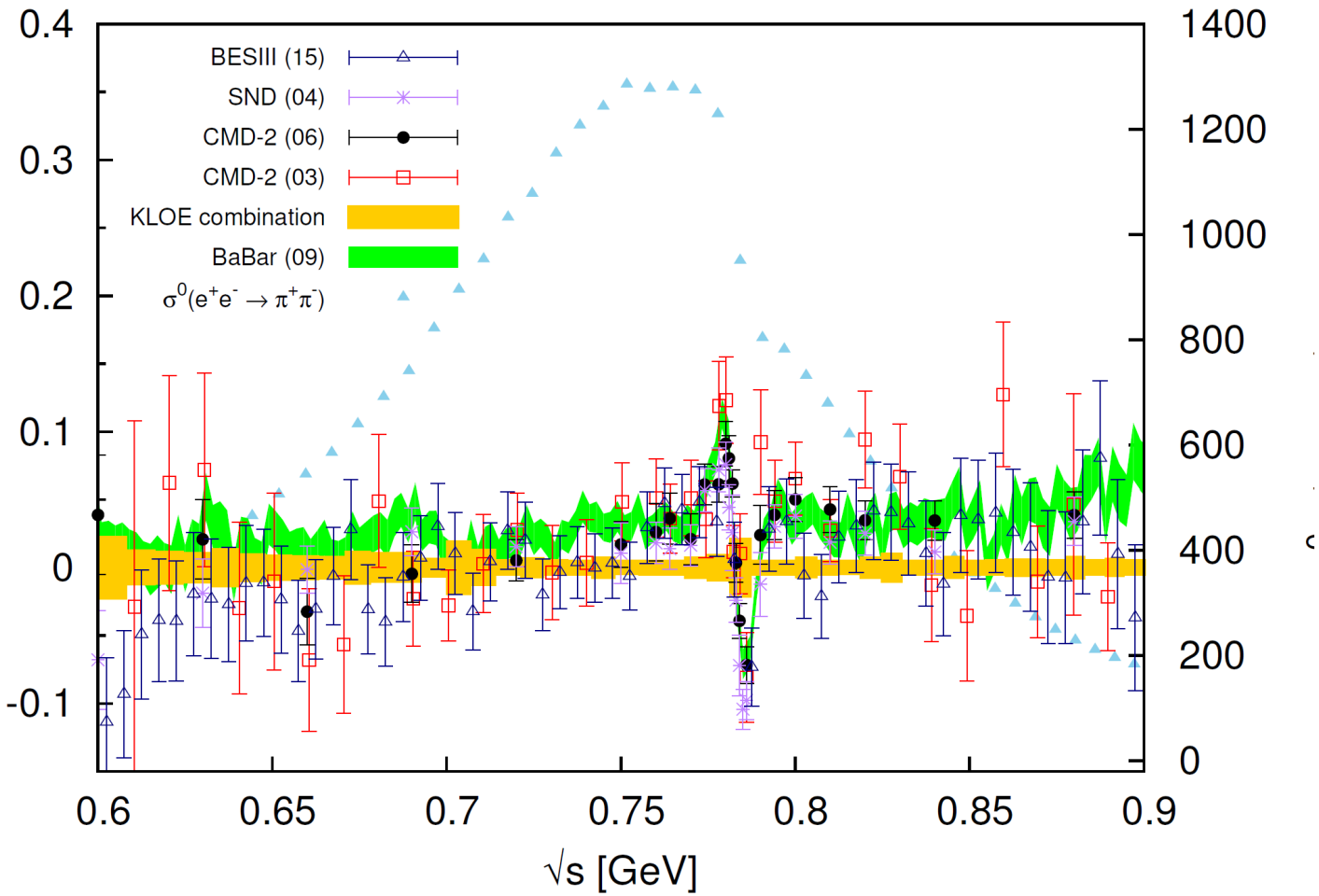
QCALT:

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

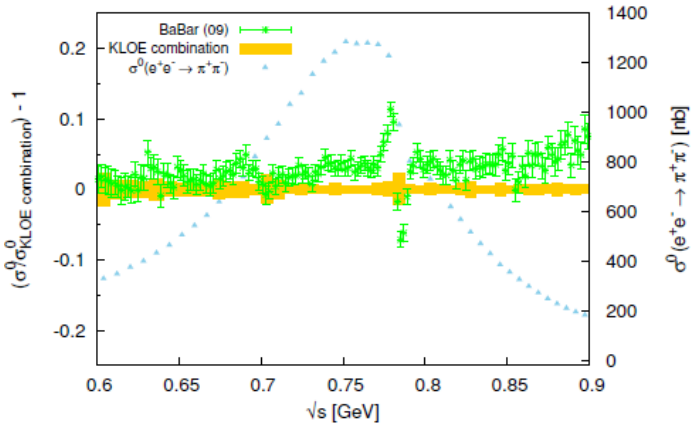
LET and HET :

- Low and High energy tagger stations for e^+e^- coming from two-photon interaction
- LET: LYSO + SiPM
- HET: EJ228 plastic scinitllator hodoscope + Xilinx Virtex-5 FPGA

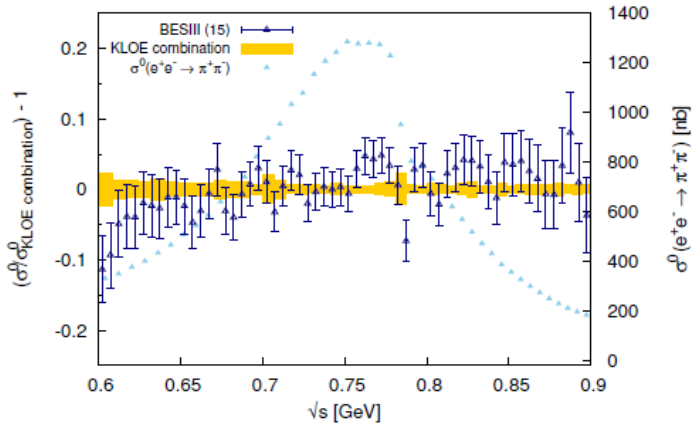
$\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ AND $a_\mu^{\pi\pi}$



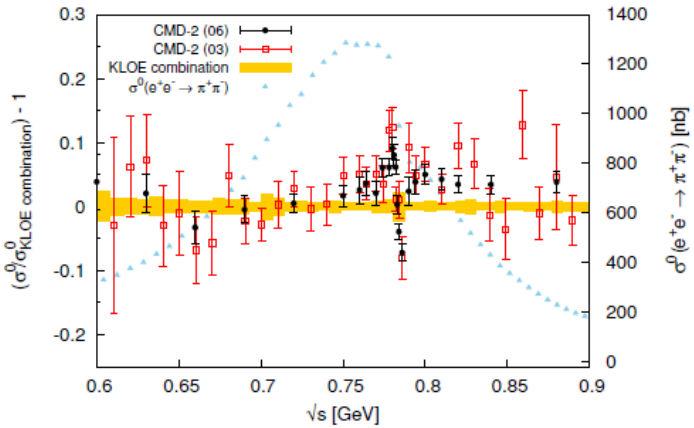
$\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ AND $a_\mu^{\pi\pi}$



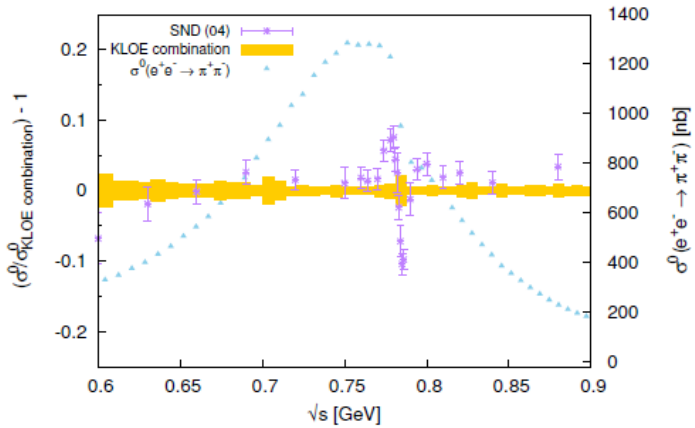
KLOE combination vs. BaBar



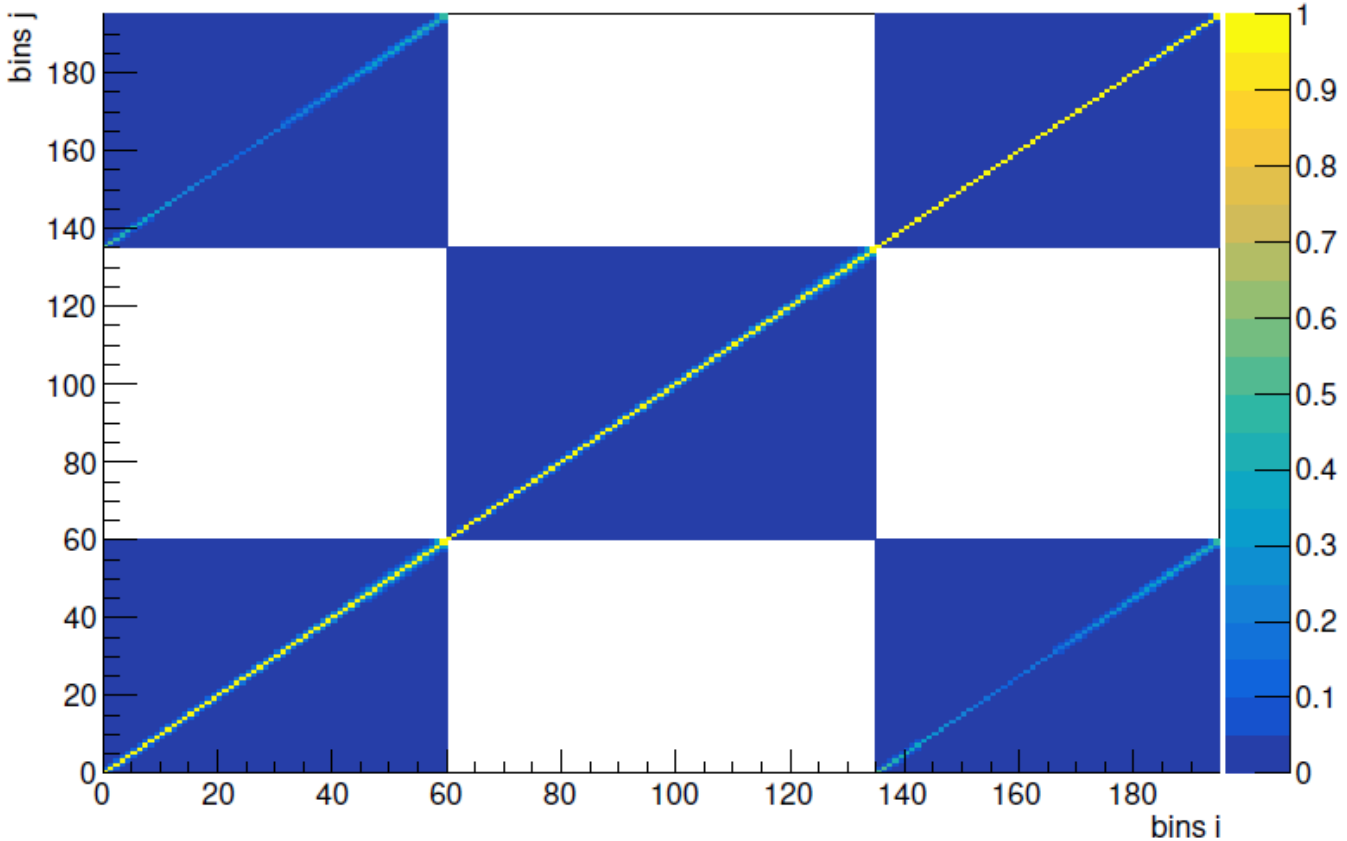
KLOE combination vs. BESIII



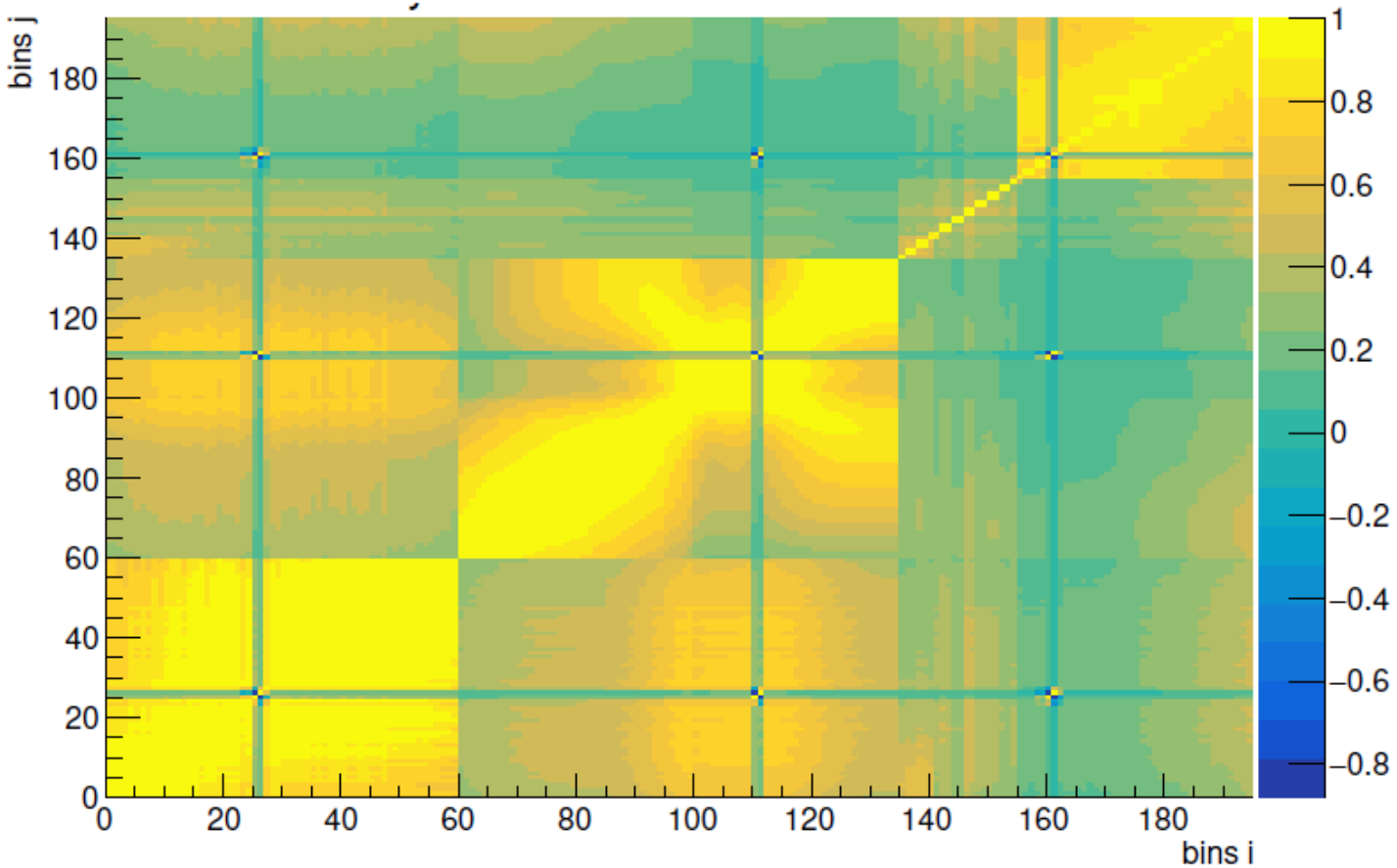
KLOE combination vs. CMD-2



KLOE combination vs. SND



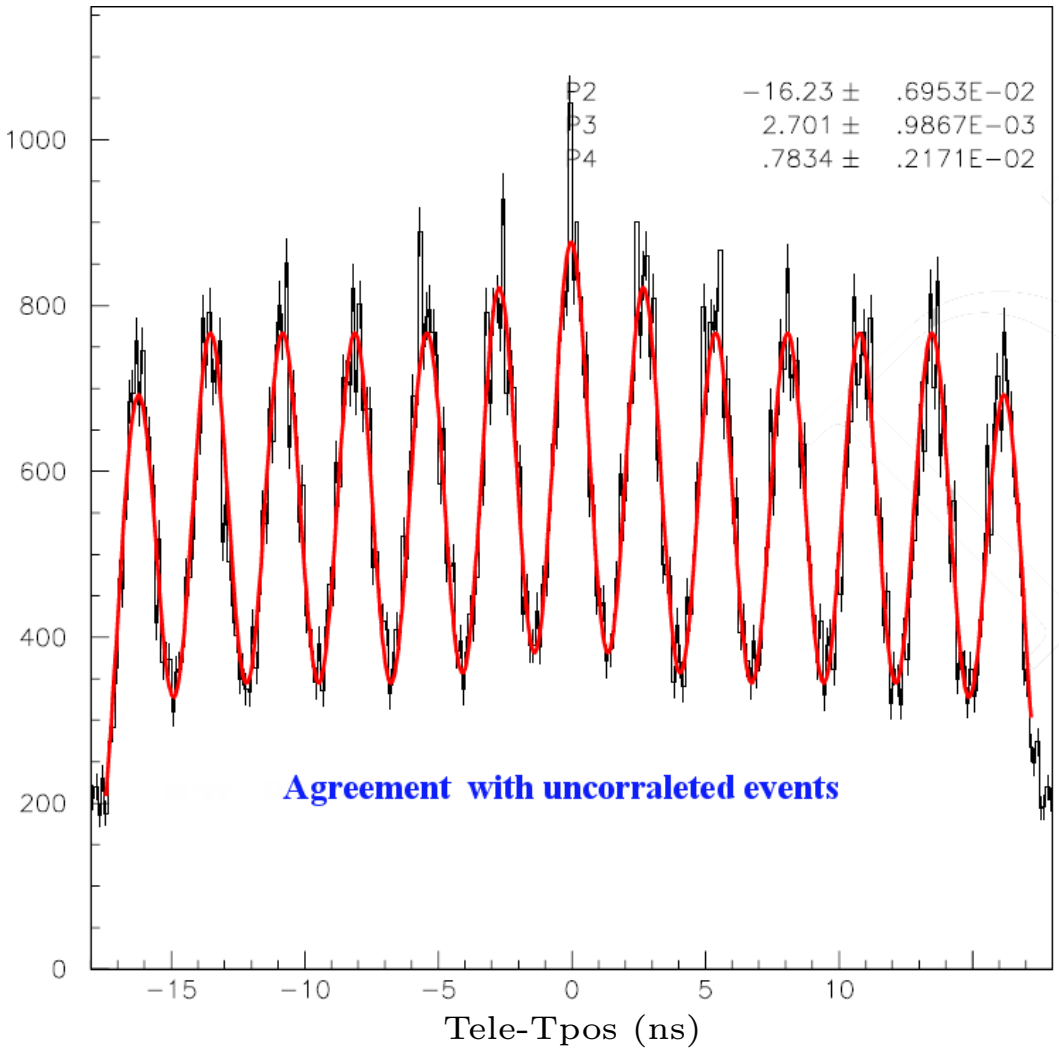
Statistical correlation matrix



Systematic correlation matrix

Time resolution of the HET detector

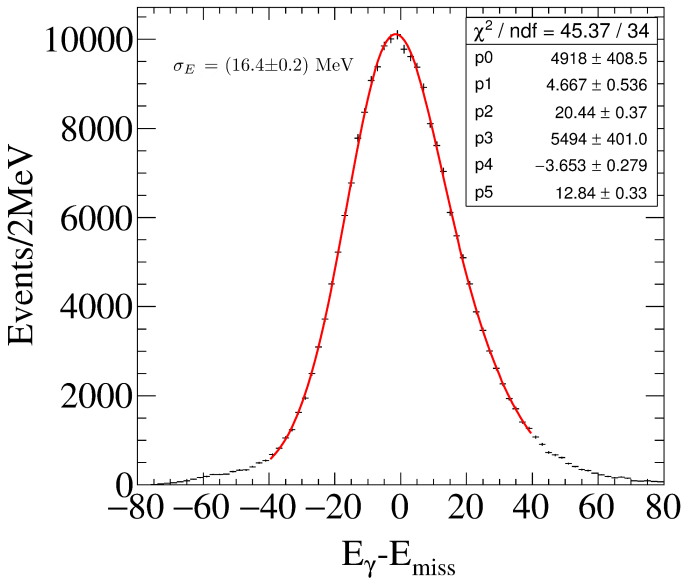
Hit delay distribution between HET ele-pos
Fit performed with 13 Gaussian of same σ

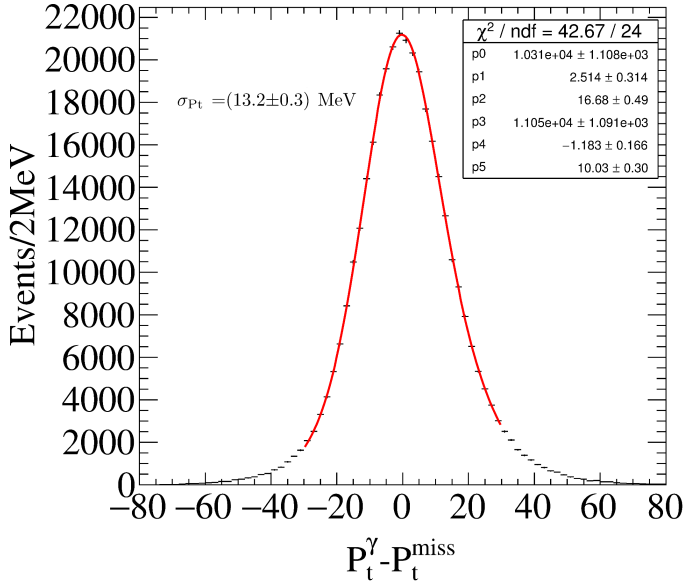


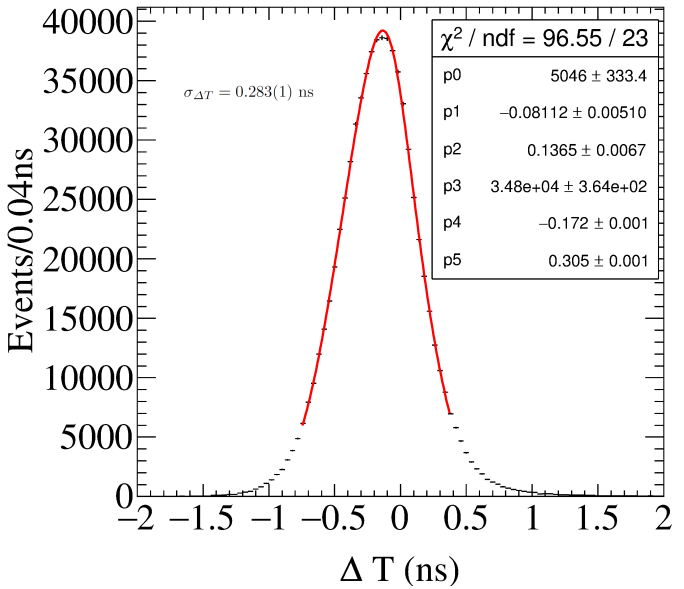
Time resolution is σ_t=550(1)ps
Time offset between stations of 24±10 ps

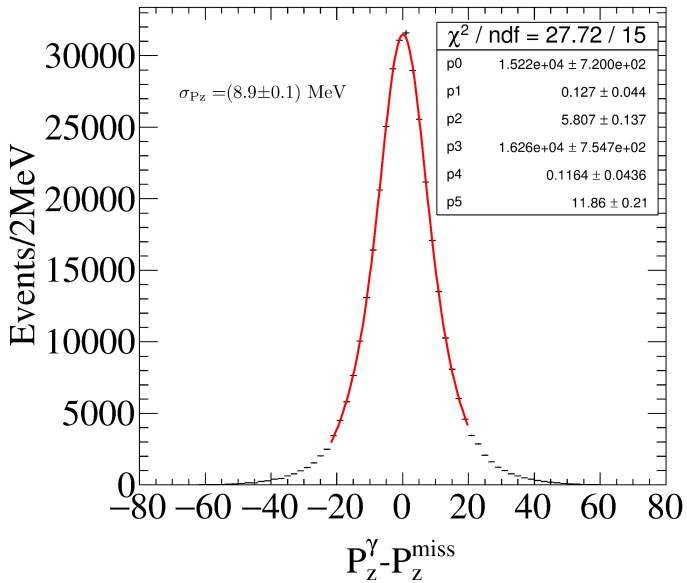
Resolution studies

Energy, momenta and time resolutions on 70 MeV energy photons. The study was performed by means of a control sample of radiative Bhabhas



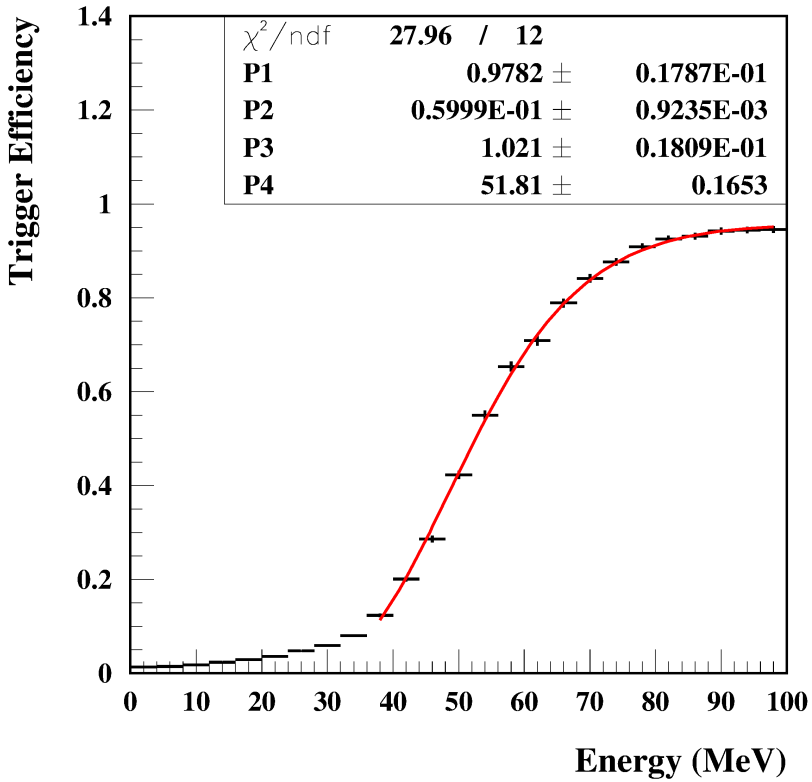


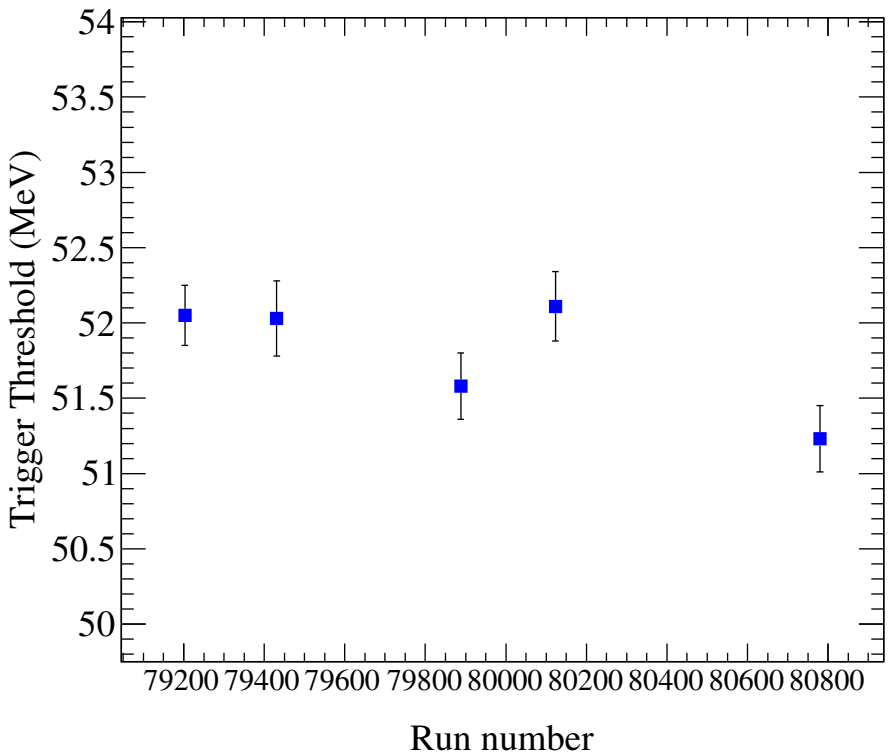




Trigger efficiency

Study based on a control sample of radiative Bhabhas

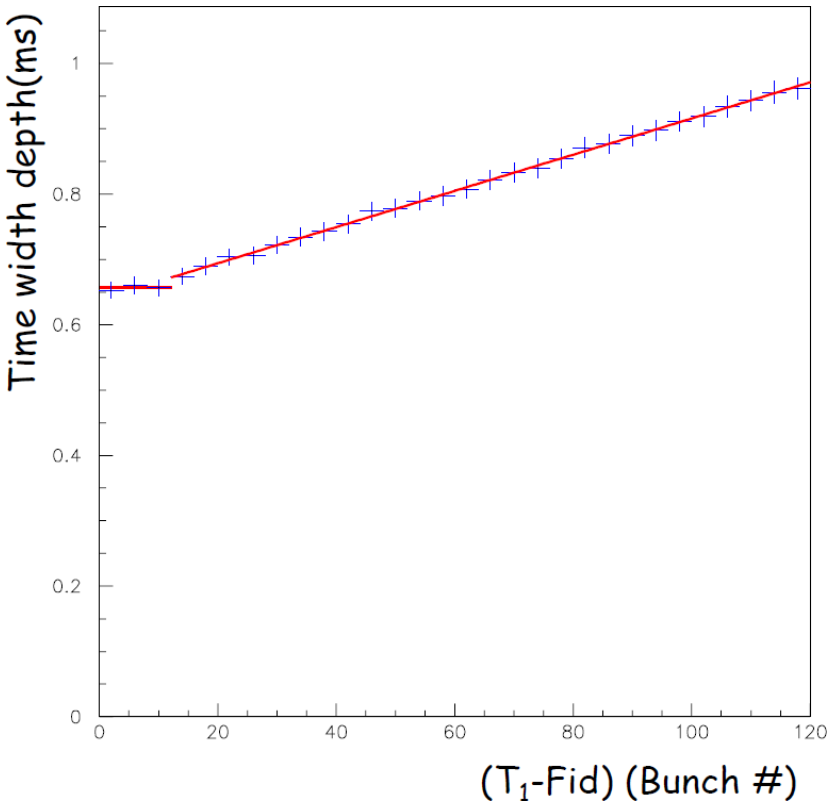


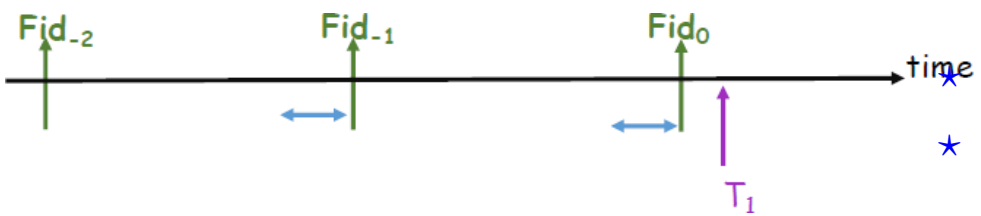


Trigger eff on 70 MeV energy photons is of about 80%

Stability of the trigger threshold over the running period November 2015–January 2016

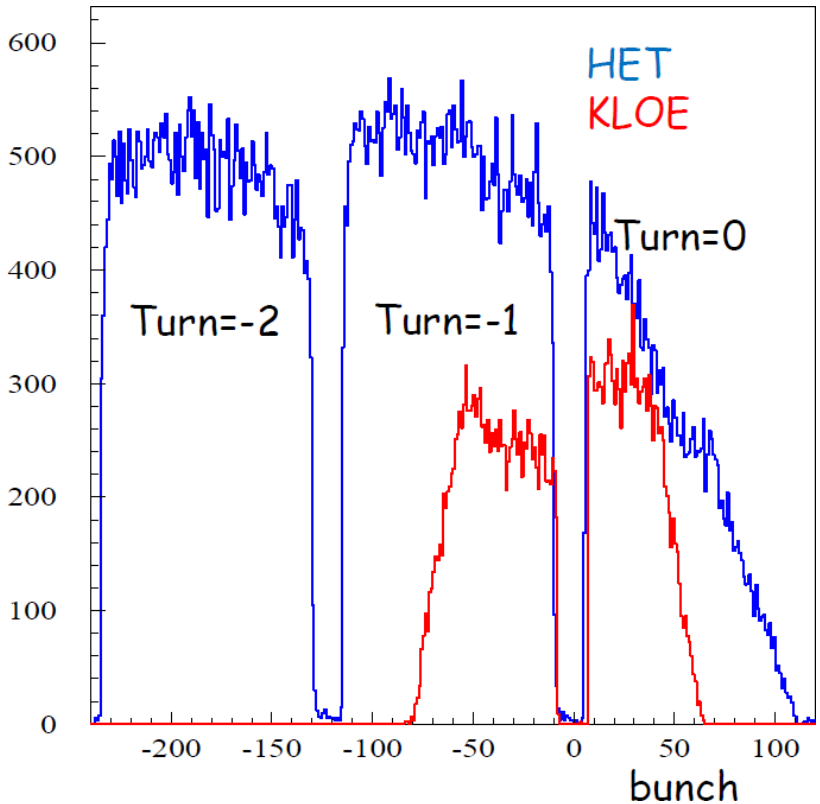
The HET DAQ





- ⋆ HET discriminators provide an output signal with a width of ∼2 ns → possibility to discriminate 2 consecutive bunches in DAΦNE ($\Delta T_{\text{bunch}} = 2.7$ ns)
- ⋆ TDCV5 uses custom logic in order to manage signals from HET, DAΦNE and KLOE
- ⋆ HET data acquisition system has been designed to register hits from two complete machine turns plus the part of a third turn preceding the trigger signal (T_1) from KLOE
- ⋆ The time-depth for the HET data recording has been measured as a function of the delay between KLOE trigger and the Fiducial (DAΦNE radio-frequency signal) and ranges from 660 to 970 ns
- ⋆ The HET do not provide trigger to KLOE
- ⋆ We read the history of the HET in turns of DAΦNE only when a valid KLOE trigger is asserted

The HET DAQ



- ⋆ KLOE and HET acquisition systems are asynchronous: we use the Fiducial provided by DAΦNE which is in phase with respect to the first bunch circulating in DAΦNE
- ⋆ A global delay is used for each TDCV5 in order to shift the Fiducial signal used as common start
- ⋆ We acquire also the KLOE trigger in both HETs for cross-checks and monitoring purposes.
- ⋆ The long plastic scintillator from HETs is also acquired by the TDC of KLOE trigger

- ⋆ KLOE and HET asynchronous Data Acquisition overlapping region.

$\gamma\gamma \to \pi^0$ signal is expected in the red region , events outside the overlapping region are used as control sample