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

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(for the KLOE/KLOE-2 Collaborations)

PHI PSI 13 **Roma**, September 9 - 12, 2013

Outline

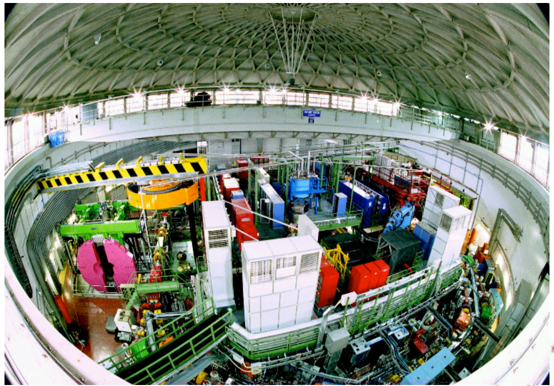
- DAΦNE & KLOE

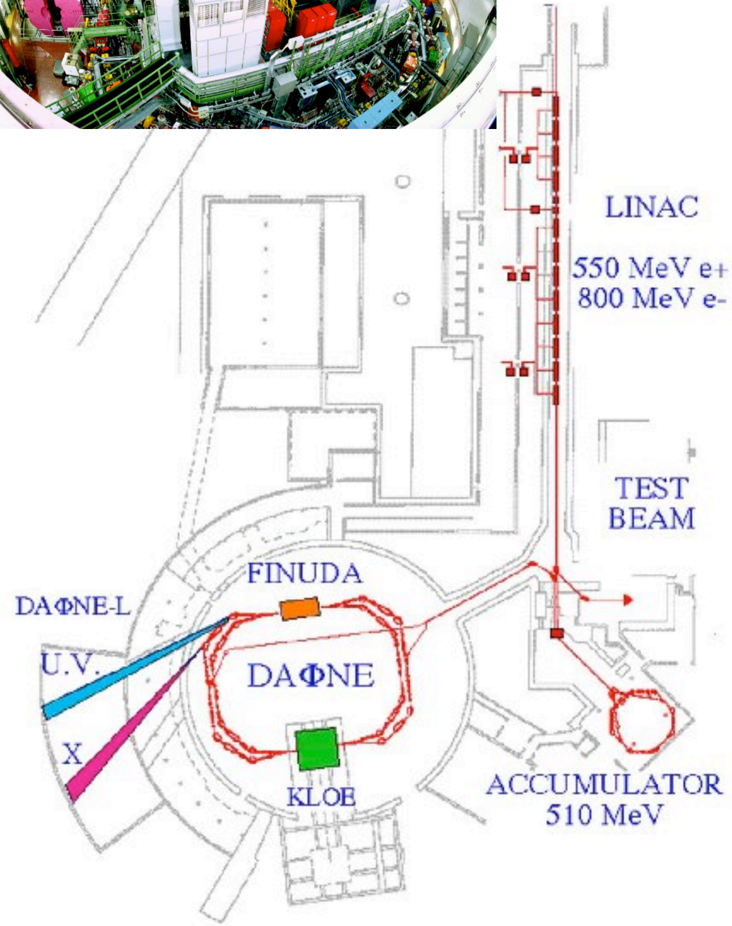
- $\gamma\gamma$–physics at KLOE (no tagging)
  - $\gamma\gamma \to \eta$
  - $\gamma\gamma \to \pi^0\pi^0$

- $\gamma\gamma$–physics at KLOE-2 (tagging)
  - **HET** and **LET** detectors
  - $\gamma\gamma \to \pi^0\pi^0$, Γ ($\pi^0 \to \gamma\gamma$) and TFF meas.

- Conclusions

DAΦNE @ LNF



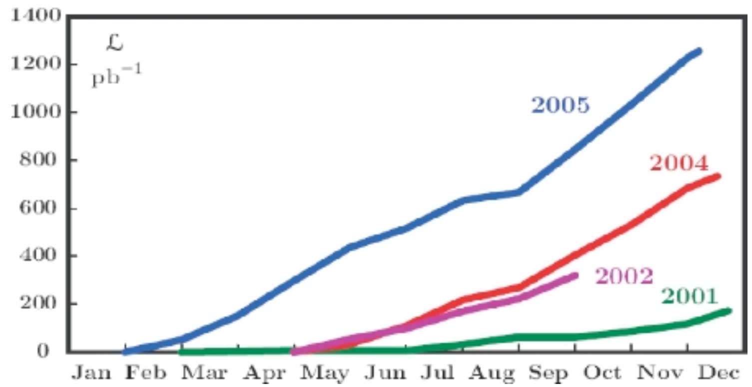


DAΦNE features

- $e^+ e^-$ collider @ $\sqrt{s} = M_\Phi \approx 1020$ MeV
- Separate rings for $e^+ e^-$ circulating beams
- 100 + 100 bunches (2.7 ns spacing)

KLOE Data Set (1999/2006)

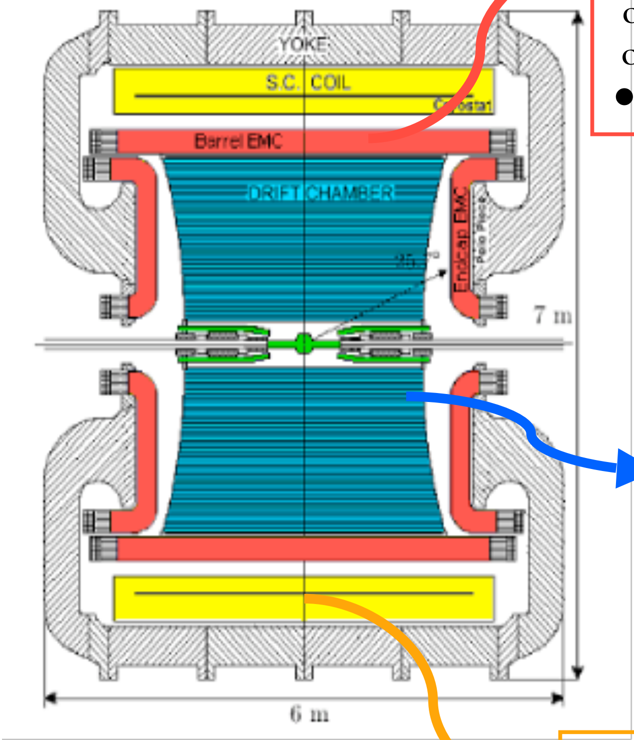
- On Peak ($\sqrt{s} \approx 1.02$ GeV)
  2.5 fb^{-1} (8×10^9 Φ produced)
- Off-Peak ($\sqrt{s} = 1.0$ GeV)
  250 pb^{-1}



Best performance (2005)

$L_{peak} = 1.4 \times 10^{32}$ cm^{-2} s^{-1}
$L_{int} = 8$ pb^{-1} / day

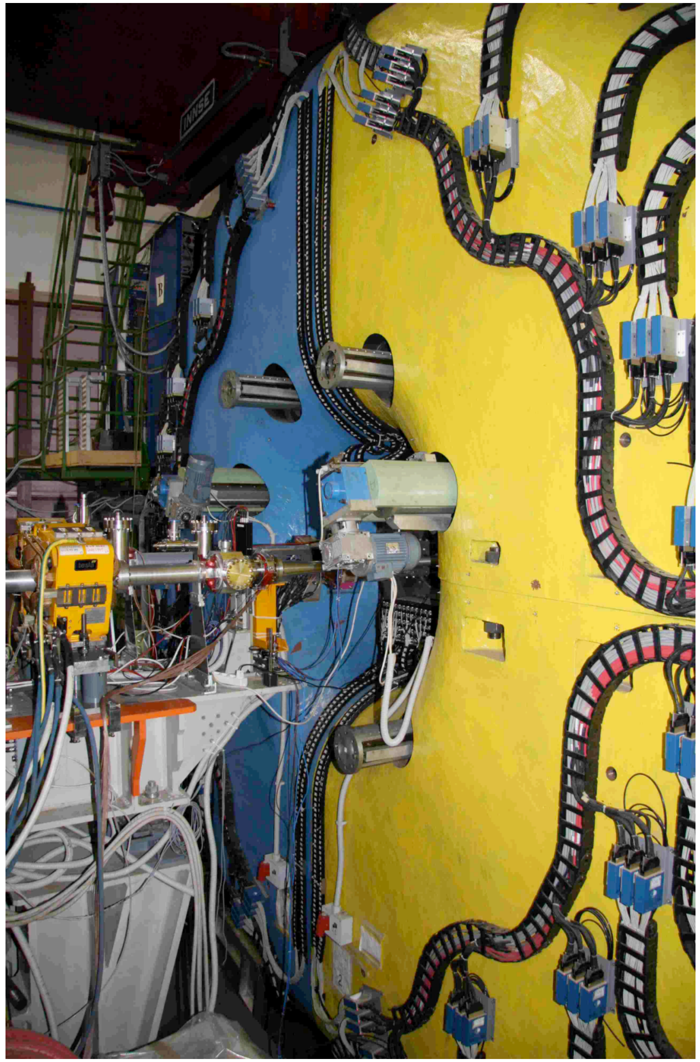
KLOE @ LNF



Calorimeter
- Pb/scintillating fiber
- 98 % of 4π
- Energy resolution:
  $\sigma_E / E = 5.7\% / \sqrt{E(GeV)}$
  $\sigma_\tau / E = 57ps / \sqrt{E(GeV)} + 100$ ps
- PID capabilities

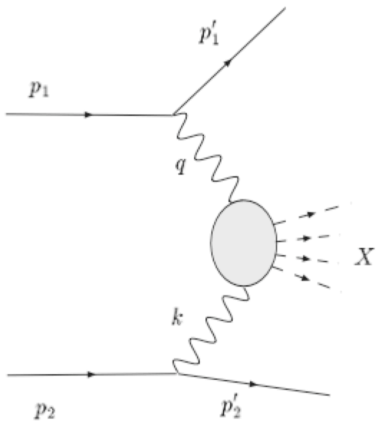
Drift Chamber
- Dim: Ø = 4m; L = 3.3m
- # wires = 52140
- Gas mix: $0.9He + 0.1C_4H_{10}$
- $\delta p / p = 0.4\% \ (\theta > 45°)$
- $\sigma_{xy} = 0.15mm; \sigma_z = 2mm$

Magnetic Field
- Superconducting coil
- Axial B Field
- B = 0.52 T



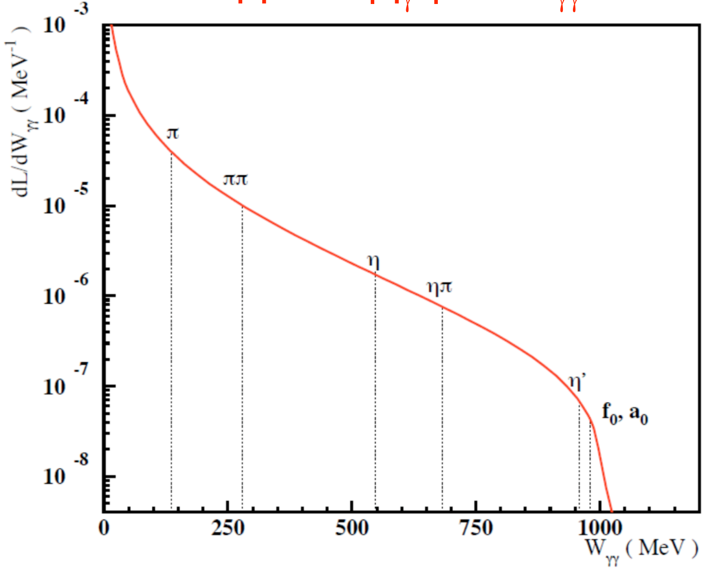
$\gamma\gamma$ – physics

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



$$\dot{N}_X = L_{ee} \int \mathrm{d}W_{\gamma\gamma} \frac{\mathrm{d}L}{\mathrm{d}W_{\gamma\gamma}} \sigma(\gamma\gamma \to X)$$

Weizsäcker-Williams approx. $|q_\gamma^2| << W_{\gamma\gamma}^2$



quasi-real photons

↓

J^{PC} (X) = $0^{\pm+}$, $2^{\pm+}$

(vs. J^{PC} = 1^{--} in 1γ case)

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

L = 242.5 pb^{-1} off-peak data ($\sqrt{s}$ = 1 GeV)

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

- 6γ only w/ E > 15 MeV, $\theta \in$ (23, 157) deg, |t-r/c| < 3 σ_t
- no tracks in DC
- $\gamma\gamma$ pairing for π^0s

$$\chi^2_{\text{pair}} = \sum_{ij} \left[\frac{m_{\gamma_i \gamma_j} - m_{\pi^0}}{\sigma(m_{\gamma_i \gamma_j})} \right]^2$$

- kin. fit requiring $M_{6\gamma} = m_\eta$

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

- 2γ only w/ E > 15 MeV, $\theta \in$ (23, 157) deg, |t-r/c| < 3 σ_t
- 2 tracks w/ opposite curvature from IP; $|p_1| + |p_2| < 700$ MeV; e/π likelihood
- $\gamma\gamma$ pairing for π^0
- kin. fit requiring $M_{\pi\pi\gamma} = m_\eta$

main bckg: $e^+e^- \to \eta\gamma$

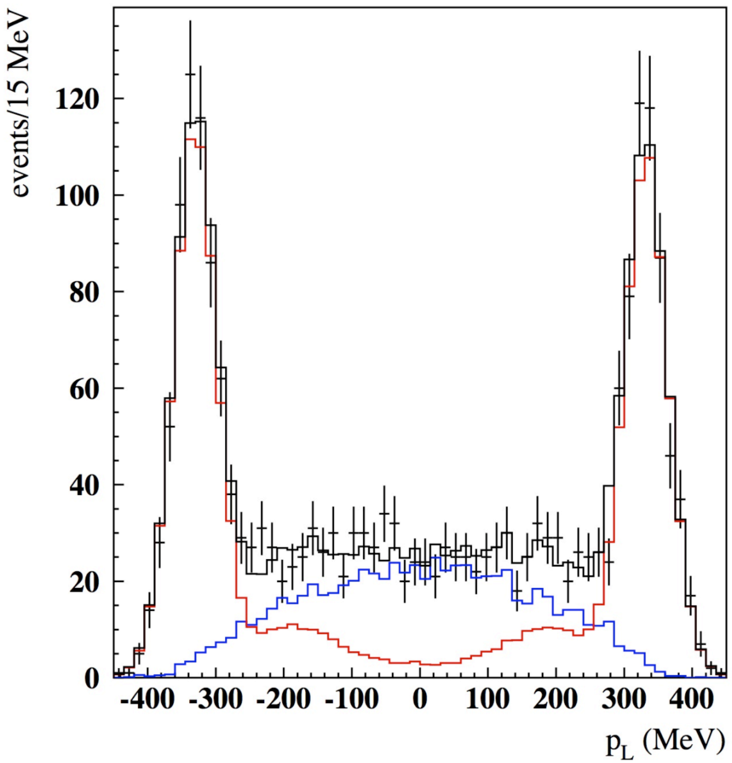
$e^+e^- \to e^+e^- \eta$

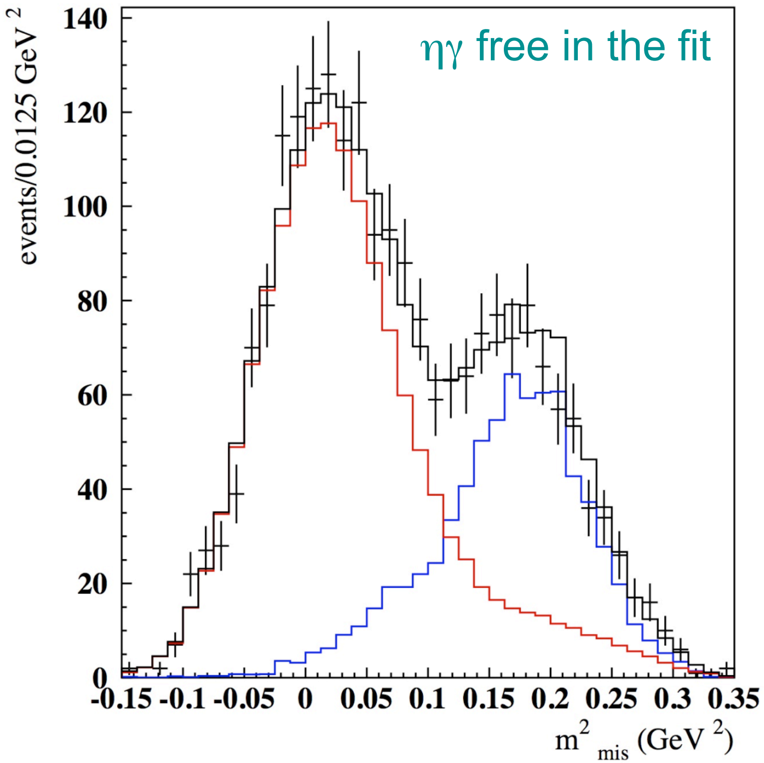
2-dim. fits

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

variables: P_L, M^2_{miss}

MC signal
MC ηγ





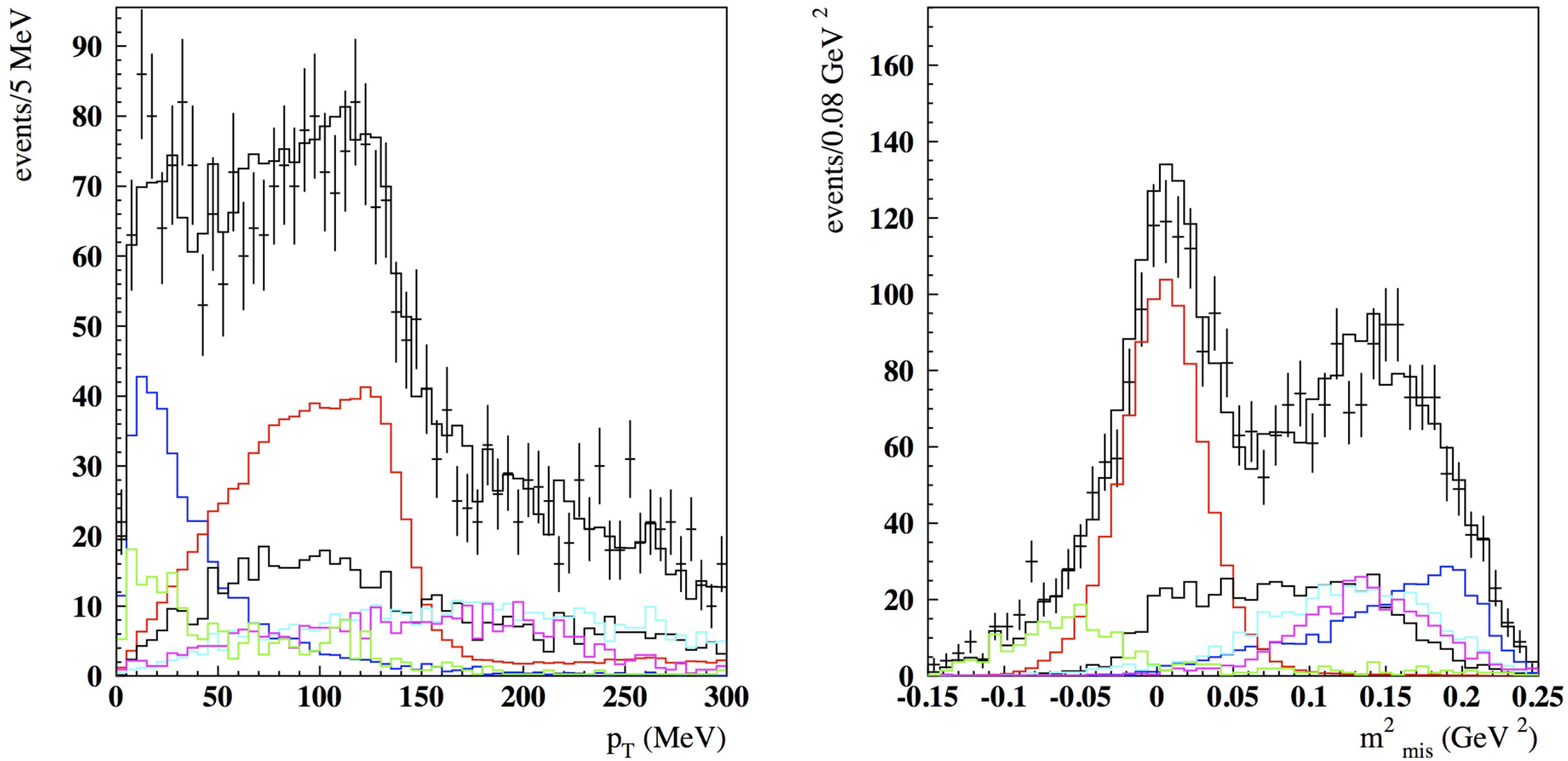
$e^+e^- \rightarrow e^+e^- \eta$

2-dim. fits

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

variables: P_T, M^2_{miss}

MC signal
MC $\eta\gamma$
MC K^+K^-
MC $\omega\pi^0$
MC $K_S K_L$
MC $e^+e^-\gamma$



bckg weights checked in a control region

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

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$$\sigma(\sqrt{s} = 1\ \mathrm{GeV})$$

$\eta \to \pi^0\pi^0\pi^0$ (≈ 720 evs)

$$(32.0 \pm 1.5_{\mathrm{st.}} \pm 0.9_{\mathrm{sys.}} \pm 0.2_{\mathrm{FF}} \pm 0.2_{\mathrm{BR}})\ \mathrm{pb}$$

$\eta \to \pi^+\pi^-\pi^0$ (≈ 390 evs)

$$(34.5 \pm 2.5_{\mathrm{st.}} \pm 1.0_{\mathrm{sys.}} \pm 0.7_{\mathrm{FF}} \pm 0.4_{\mathrm{BR}})\ \mathrm{pb}$$

$$\longrightarrow \quad (32.7 \pm 1.3_{\mathrm{st.}} \pm 0.7_{\mathrm{sys.}})\ \mathrm{pb}$$

$\eta \to 2\gamma$ width deduced from both chs. → combined result:

$$\Gamma(\eta \to \gamma\gamma) = (520 \pm 20_{\mathrm{st.}} \pm 13_{\mathrm{sys.}})\ \mathrm{eV}$$

(PDG value: 510 ± 26 eV)

$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

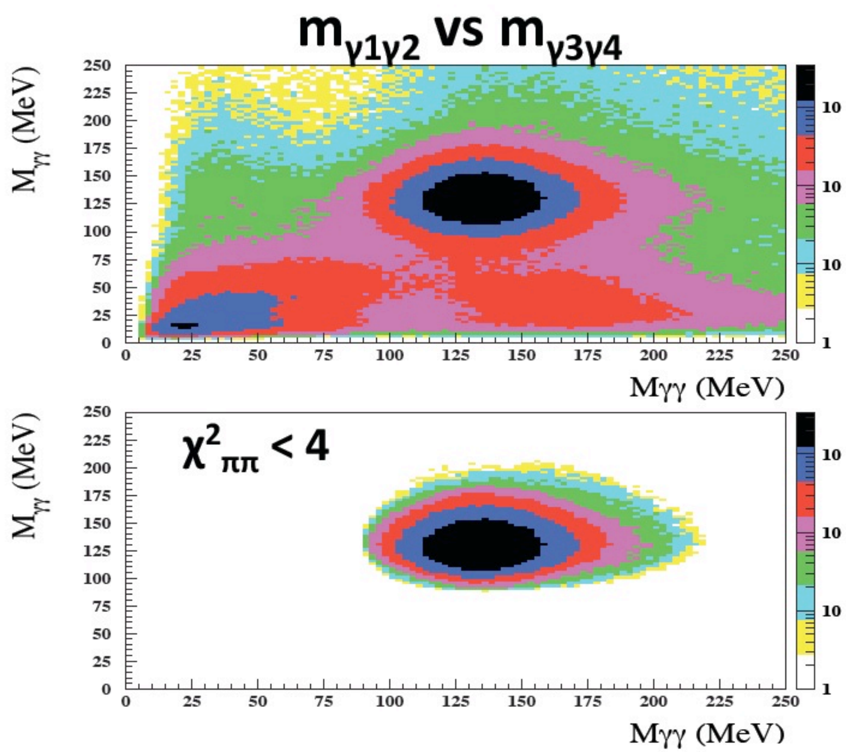
combination of a cut-based and multivariate (MV) analysis

✓ (main) analysis cuts

- no tracks in DC
- 4γ only w/ E > 15 MeV, $\theta \in (23, 157)$ deg, $|t-r/c| < 5\ \sigma_t$
- no late clusters (reject K_SK_L bckg)
- γγ pairing

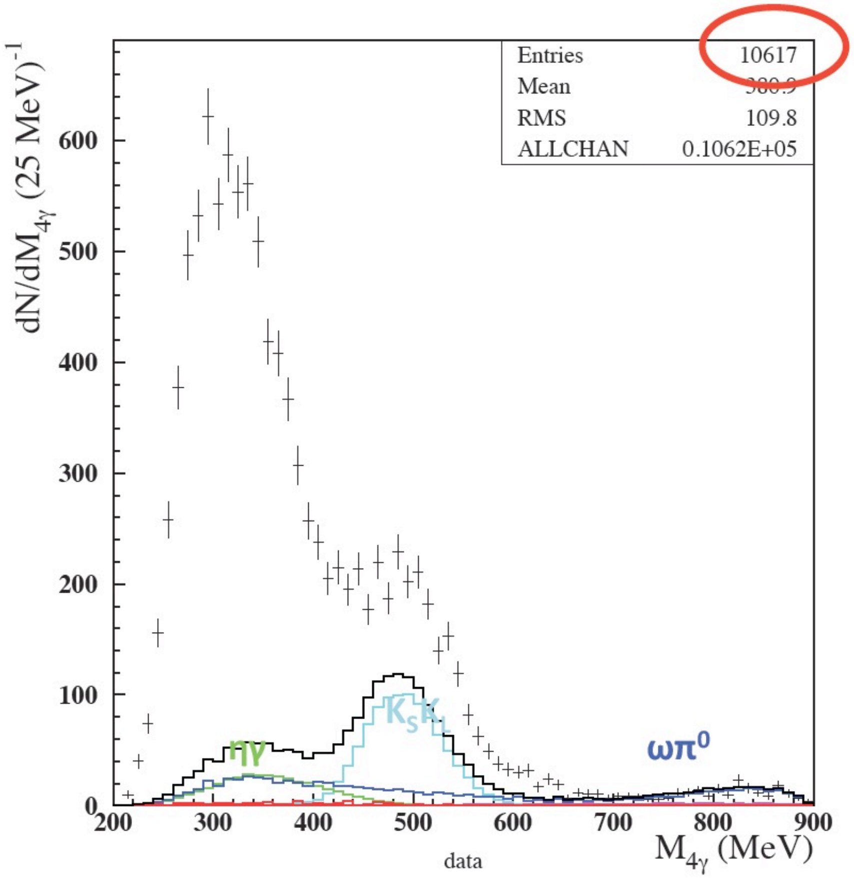
$$\chi^2_{\pi\pi} = \frac{(m_{\pi^0} - m_{ij})^2}{\sigma^2_{ij}} + \frac{(m_{\pi^0} - m_{kl})^2}{\sigma^2_{kl}}$$

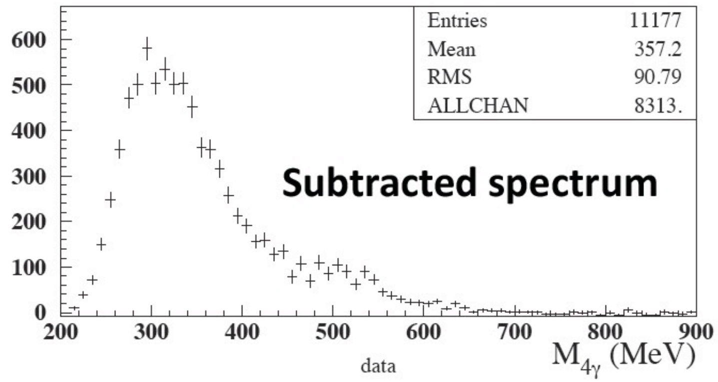
- cut on photons energy spread

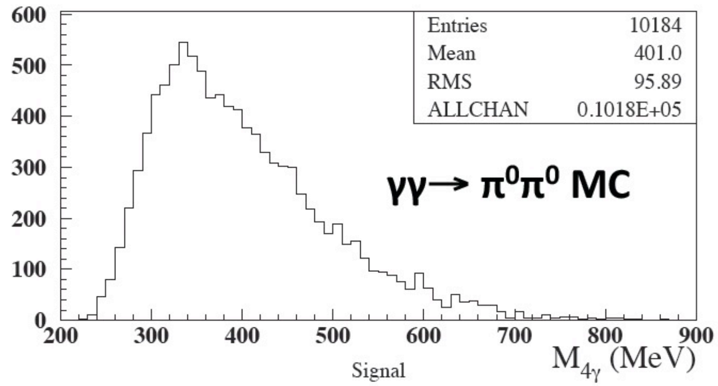


$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

4γ invariant mass



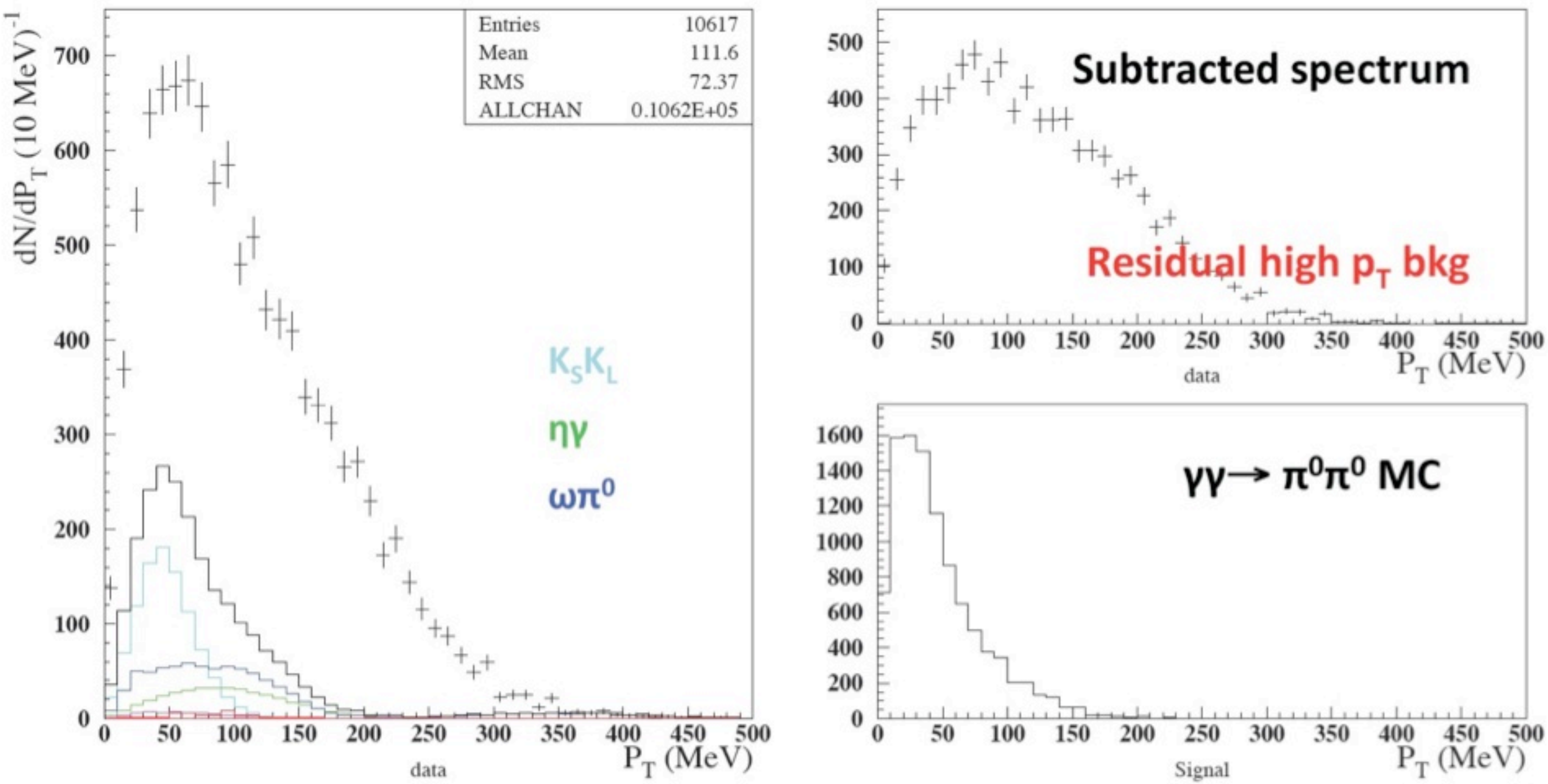




MC: full 4-body   Nguyen, Piccinini, Polosa – EPJ C**47**, 65 (2006)

$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

P_T



$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

selected sample contaminated by a residual low mass, high-P_T bckg

→ P_L asimmetry → hint of machine bckg

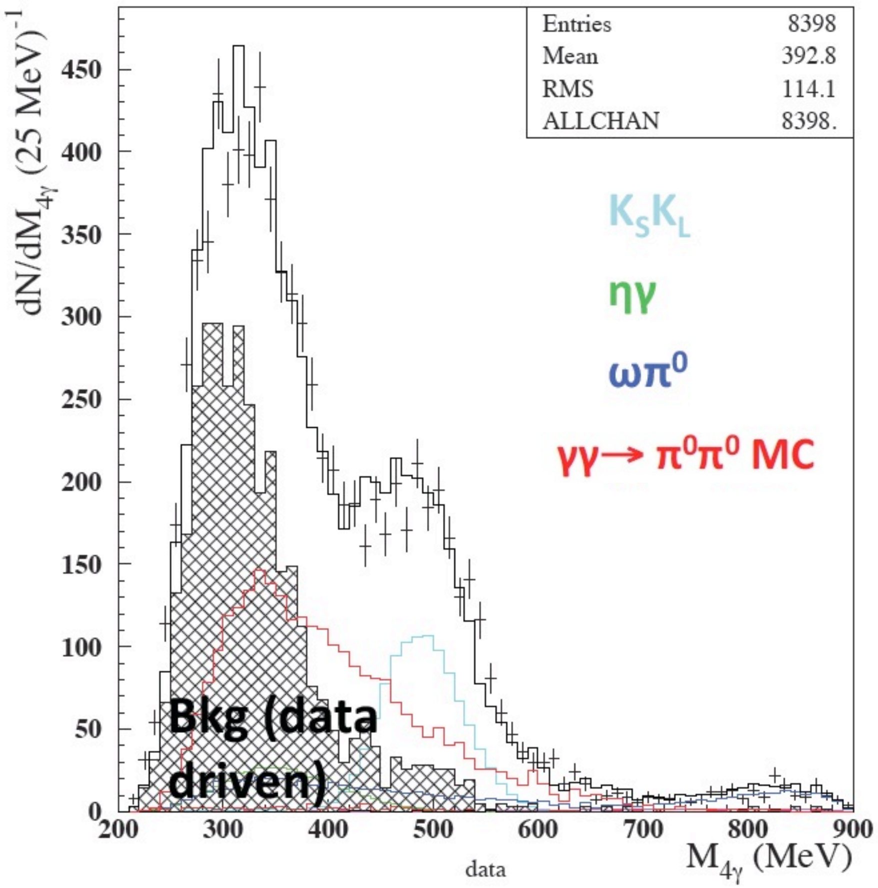
new strategy: select pathological bckg directly from data and use it in a multivariate analysis → cut on MVA output

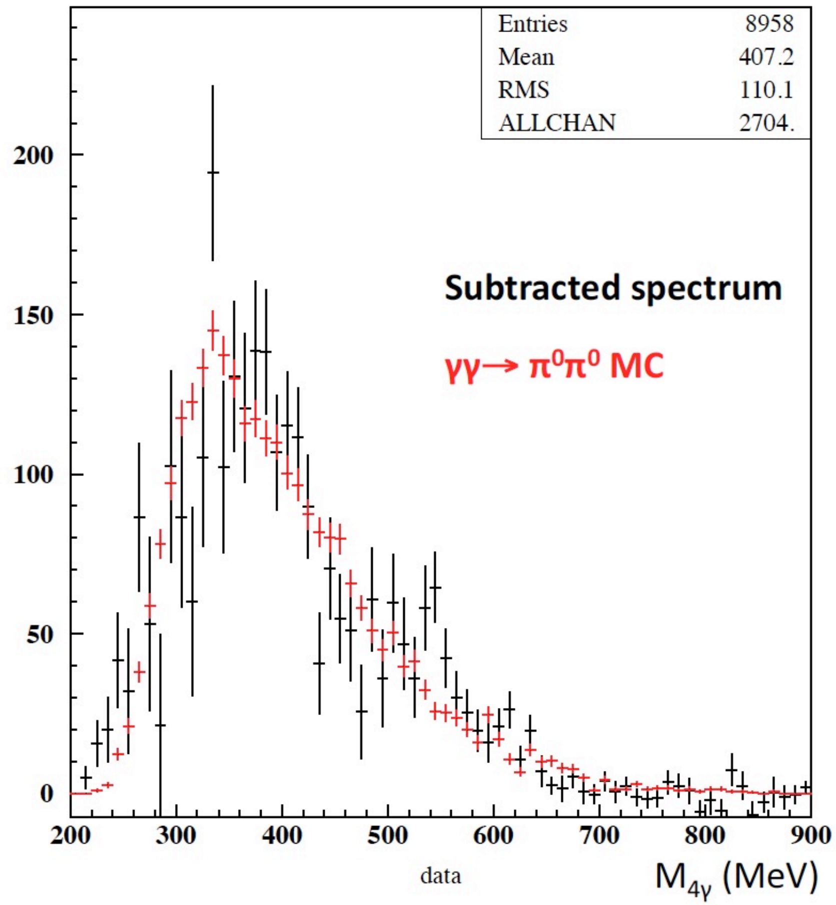
✓ multivariate analysis

- machine bckg selected from poorly prompt events ($|t - r/c| > 5\ \sigma_t$)
- bckg sample & MC sample used to train a MVA analysis to discriminate bckg from signal
- application to data: (for each event) likelihood for signal *vs* bckg
- cut on likelihood and subtract from data

$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

TMVA package used

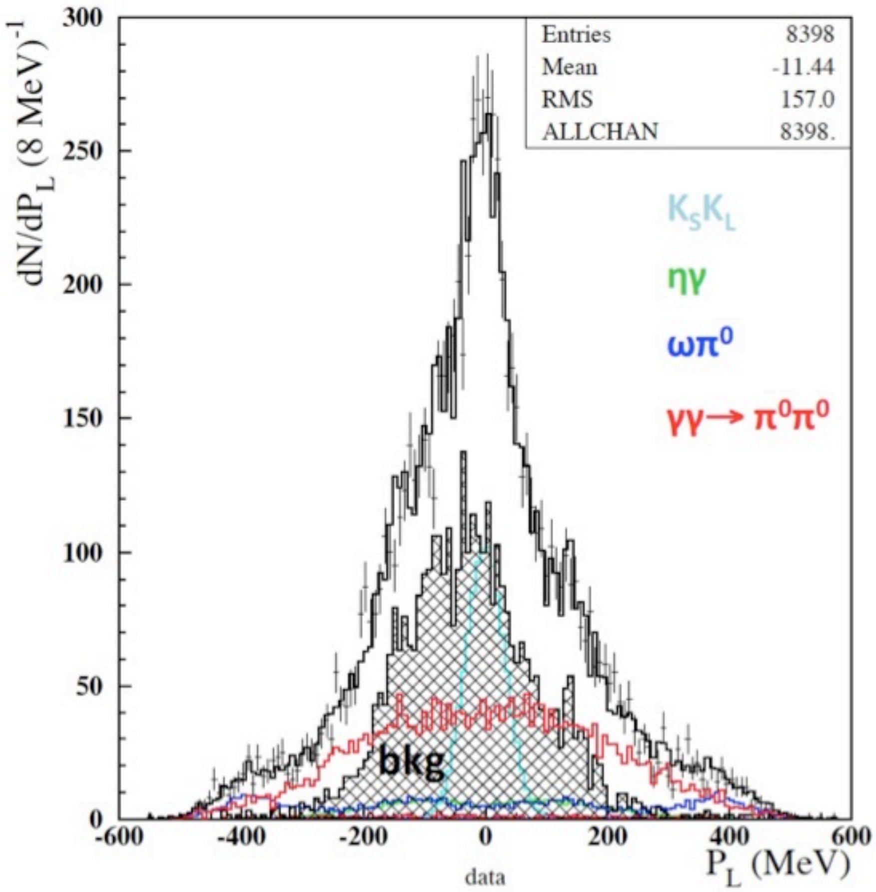


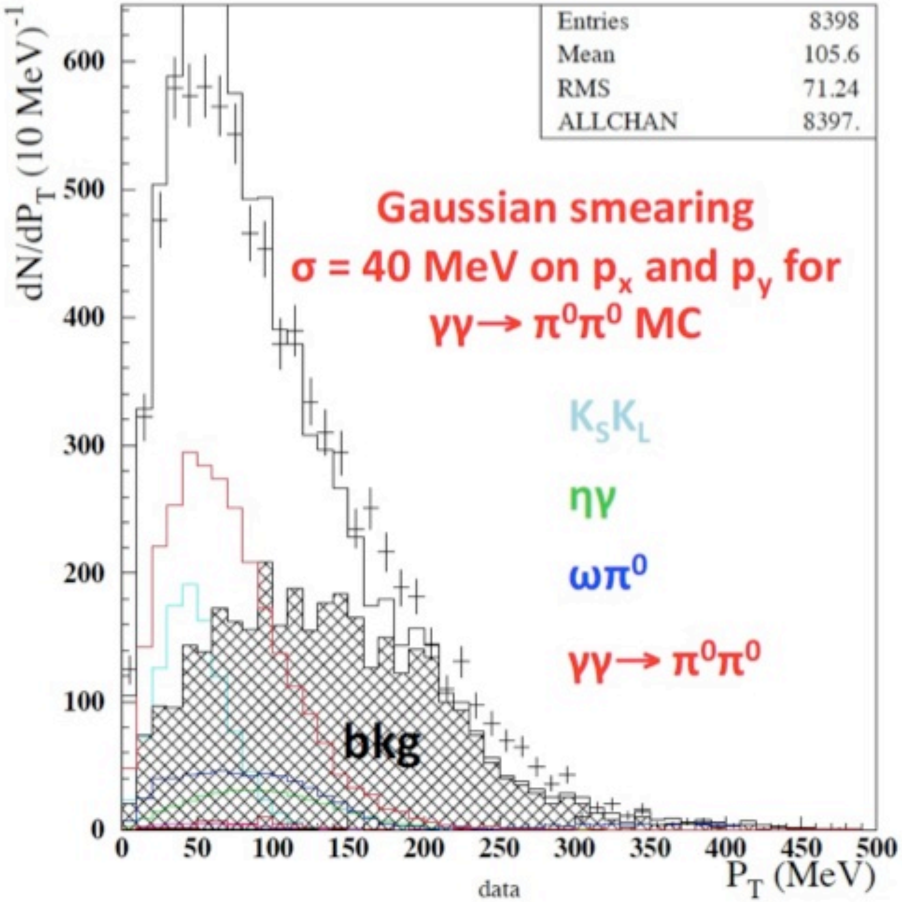


quite good agreement

$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

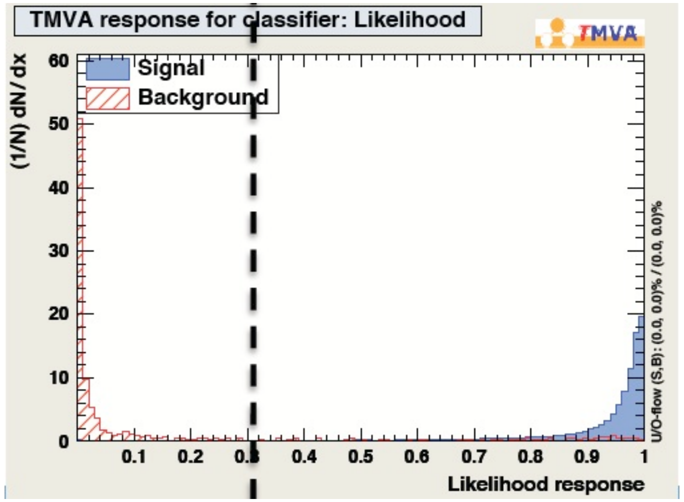
weights from $M_{4\gamma}$ fit





P_L asimmetry mainly due to bckg

$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

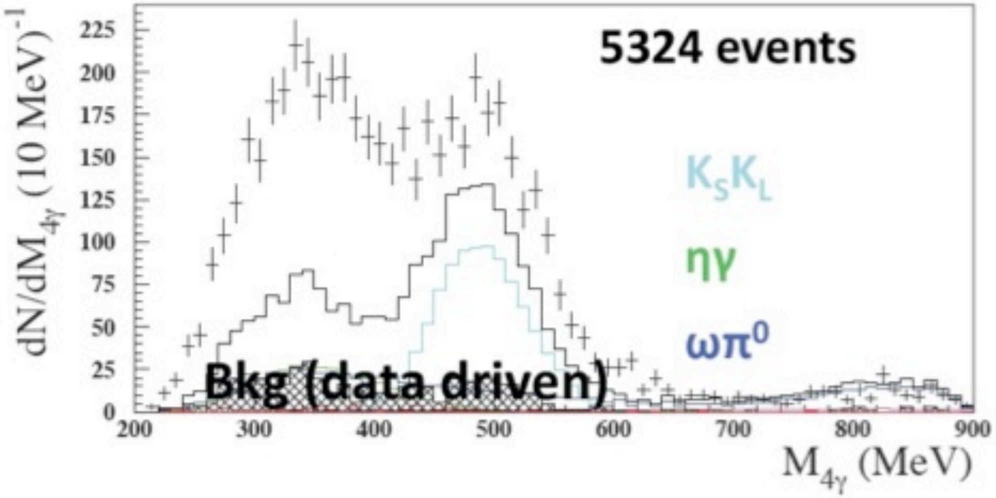


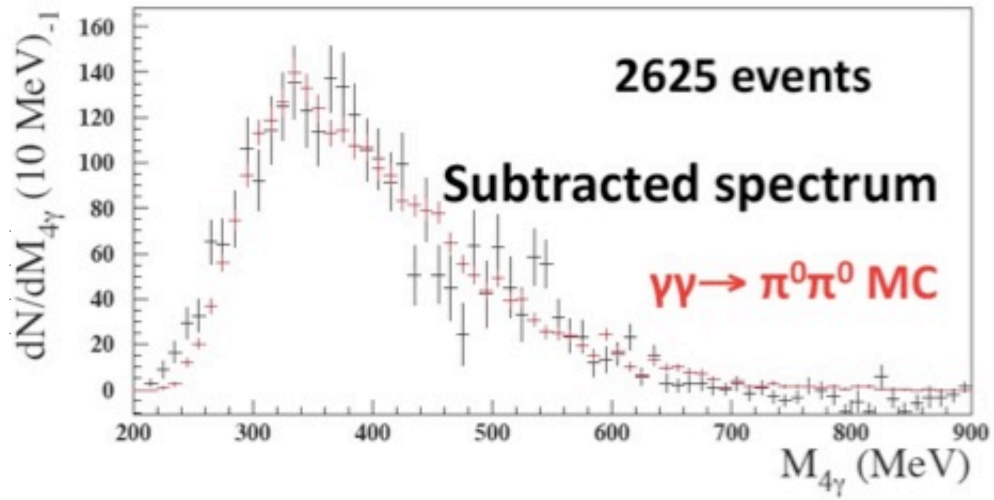
likelihood > 0.3

	ε	σ (nb)	n = Lσε
K_SK_L	0.003	1.28	953
ηγ	0.005	0.284	374
$\omega\pi^0$	0.006	0.550	774
$f_0\gamma$, $a_0\gamma$, γγ	≈ 0	-	110

Bkg (data driven)	492
$\gamma\gamma \rightarrow \pi^0\pi^0$	**2625**

$M_{4\gamma}$ spectra





$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

✓ quite good data – MC agreement
✓ results quite stable respect to the cut on TMVA output (still some discrepancy between ε_{MC} & ε_{data})

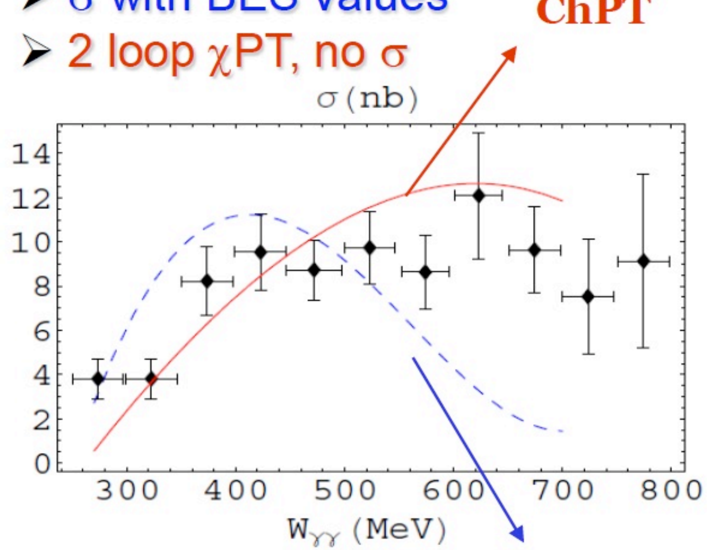
Work in progress:

• efficiency for the signal
• luminosity function

↓

$$\sigma(\gamma\gamma \rightarrow \pi^0\pi^0)$$

● Crystal Ball, PRD41 (1990) 3324
➢ σ with BES values
➢ 2 loop χPT, no σ



Resonant contribution $\gamma\gamma \rightarrow \sigma \rightarrow \pi^0\pi^0$

KLOE-2 @ LNF

i.e. **$\gamma\gamma$-physics at ϕ-peak**

$\gamma\gamma$ process

channel	Total Production (L = 10 fb^{-1})
$e^+e^- \to e^+e^-\pi^0$	4×10^6
$e^+e^- \to e^+e^-\eta$	10^6
$e^+e^- \to e^+e^-\pi^+\pi^-$	2×10^6
$e^+e^- \to e^+e^-\pi^0\pi^0$	2×10^4

ϕ decays

decay mode	esc.particle	events	bckg to:
$K_S(\pi^0\pi^0)\,K_L$	K_L	$\sim 10^9$	$\pi^0\pi^0$
$K_S(\pi^+\pi^-)\,K_L$	K_L	$\sim 2 \times 10^9$	$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$	π^0	$\sim 10^9$	
$\eta(\gamma\gamma)\,\gamma$	γ	$\sim 10^8$	η
$\pi^0(\gamma\gamma)\,\gamma$	γ	$\sim 5 \times 10^8$	π^0

- additional (sizable) bckgs from non ϕ decays (ISR and continuum processes)
- kinematics cut (mainly from p_T) $\to$ rejection factor < 100

hopeless w/o tagging of the scattered $e^\pm$

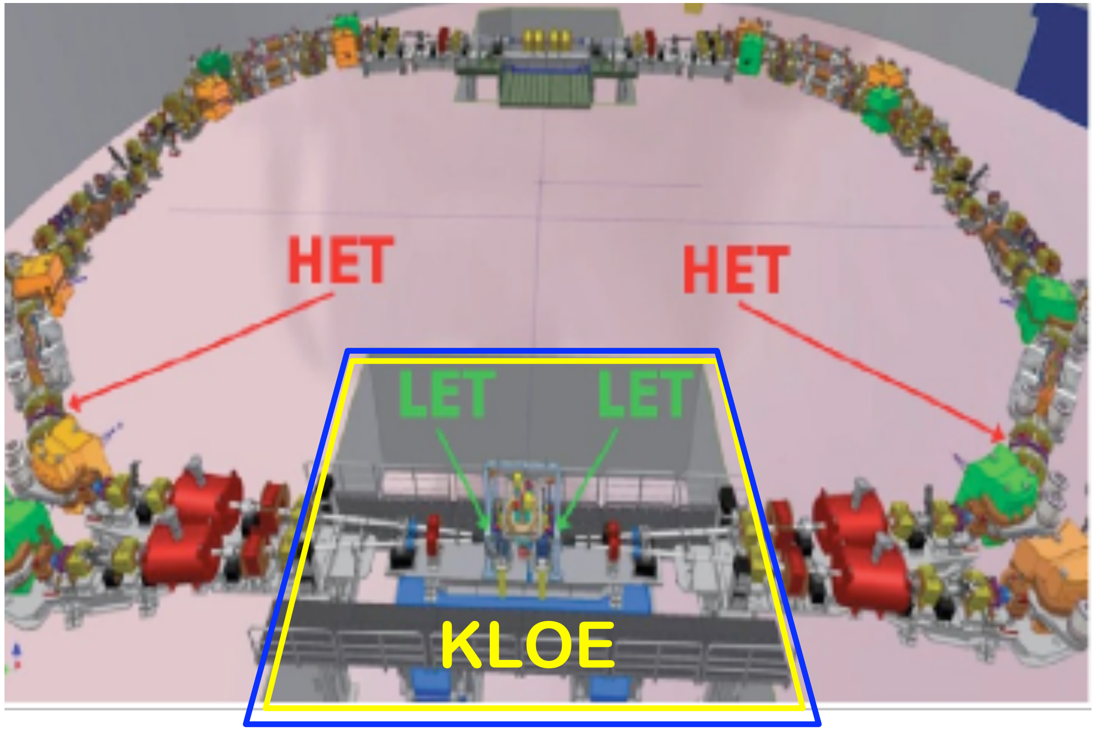
Tagging

scattered $e^{\pm}$

✓ small $\theta \rightarrow$ escape KLOE detection

✓ $E_e < 510$ MeV $\rightarrow$ deviate from equilibrium orbit while propagating along machine optics after IP

off-energy particles tracked along machine optics w/ BDSIM package (Geant4 toolkit)



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

taggers → LET / HET; X → KLOE

LET (Low Energy tagger)

- inside KLOE (1 m from IP)
- energy range = 160-400 MeV

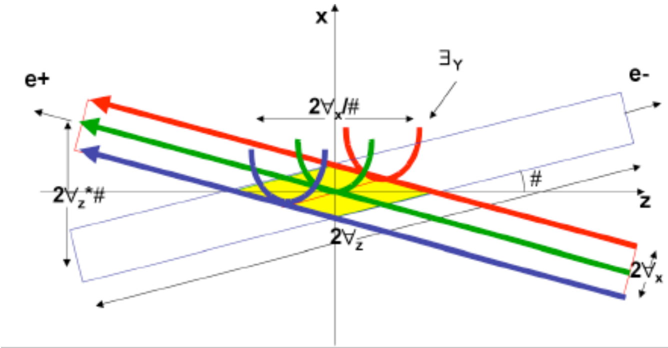
HET (High Energy tagger)

- after 1st dipole (11 m from IP)
- energy range = 420-495 MeV

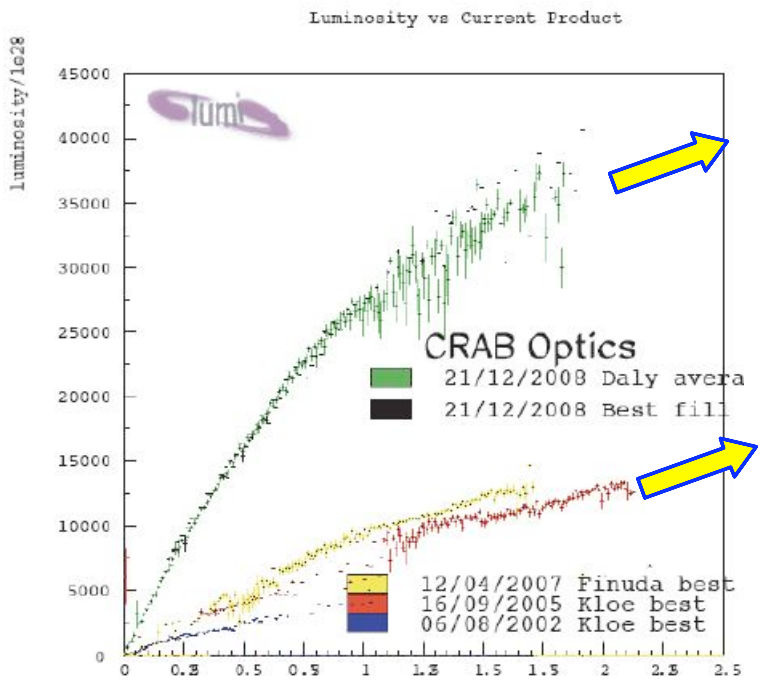
DAΦNE upgrade

new interaction scheme implemented

- Large beam crossing angle at IP (2 x 25.64 mrad)
- Reduced beam size at crossing point
- Sextupoles for crab-waist configuration at IP



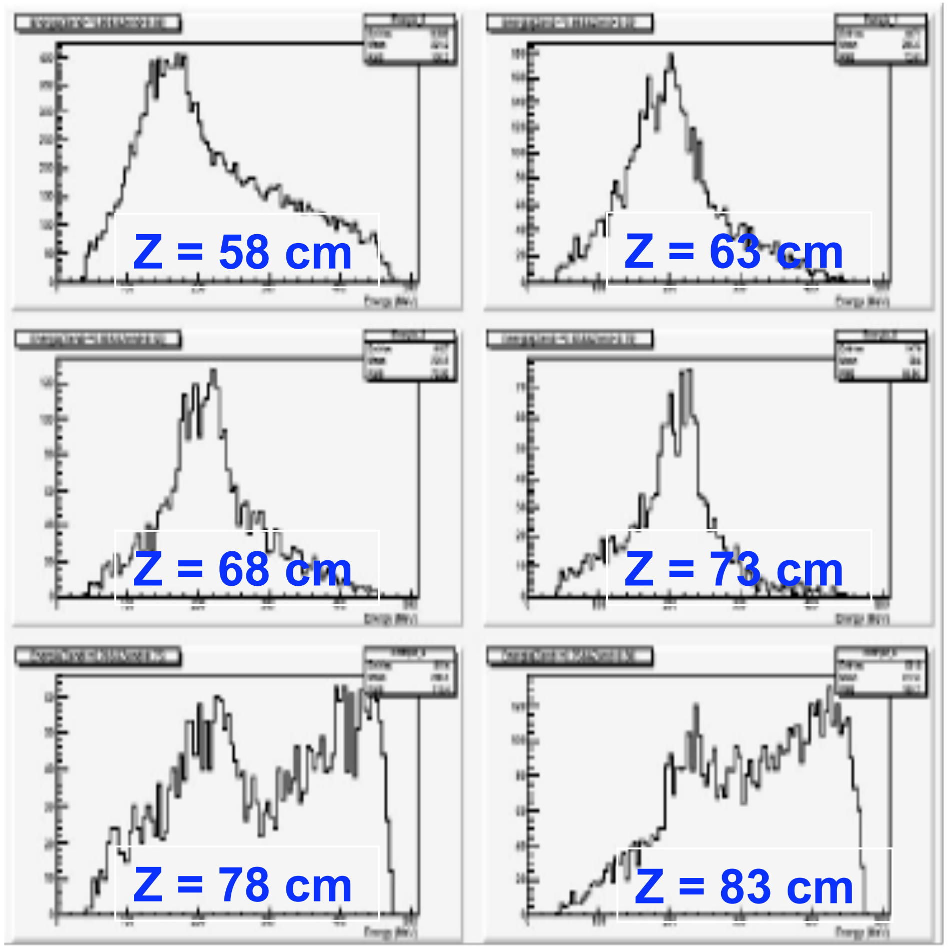
$L_{int} \approx 1\ pb^{-1}/hour$



NEW SCHEME
SIDDHARTA
Run 2008/09

OLD SCHEME
KLOE & FINUDA
Runs 2002/05

LETs

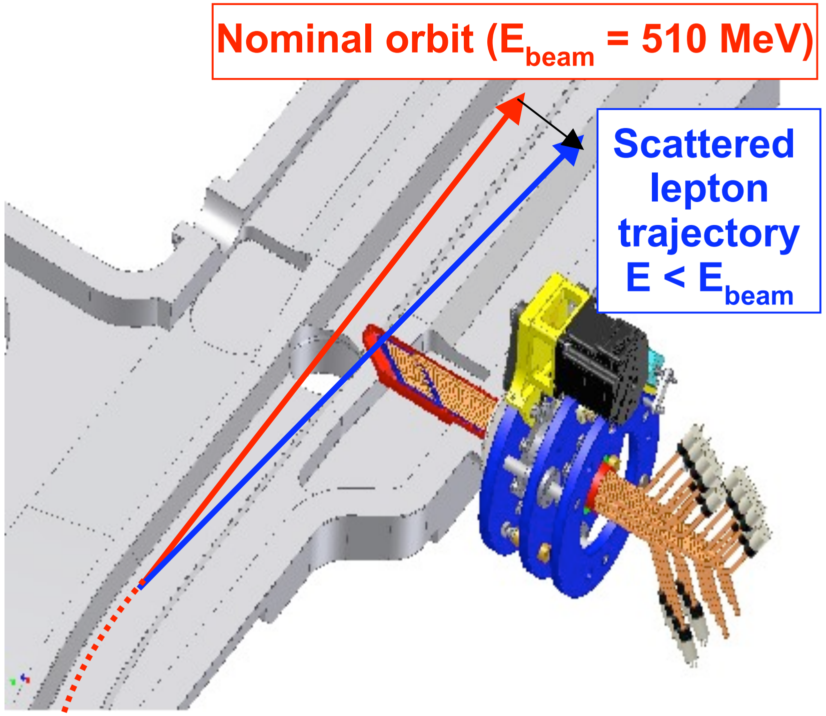


NO correlation between E and θ of final leptons → Calorimetric detector

- ✓ Inside KLOE detector (~ 1m)
- ✓ 20 LYSO Crystals read by SiPM (not sensitive to KLOE B field) → (7.5 x 6 x 12) cm^3
- ✓ σ_E < 10% @ E > 150MeV

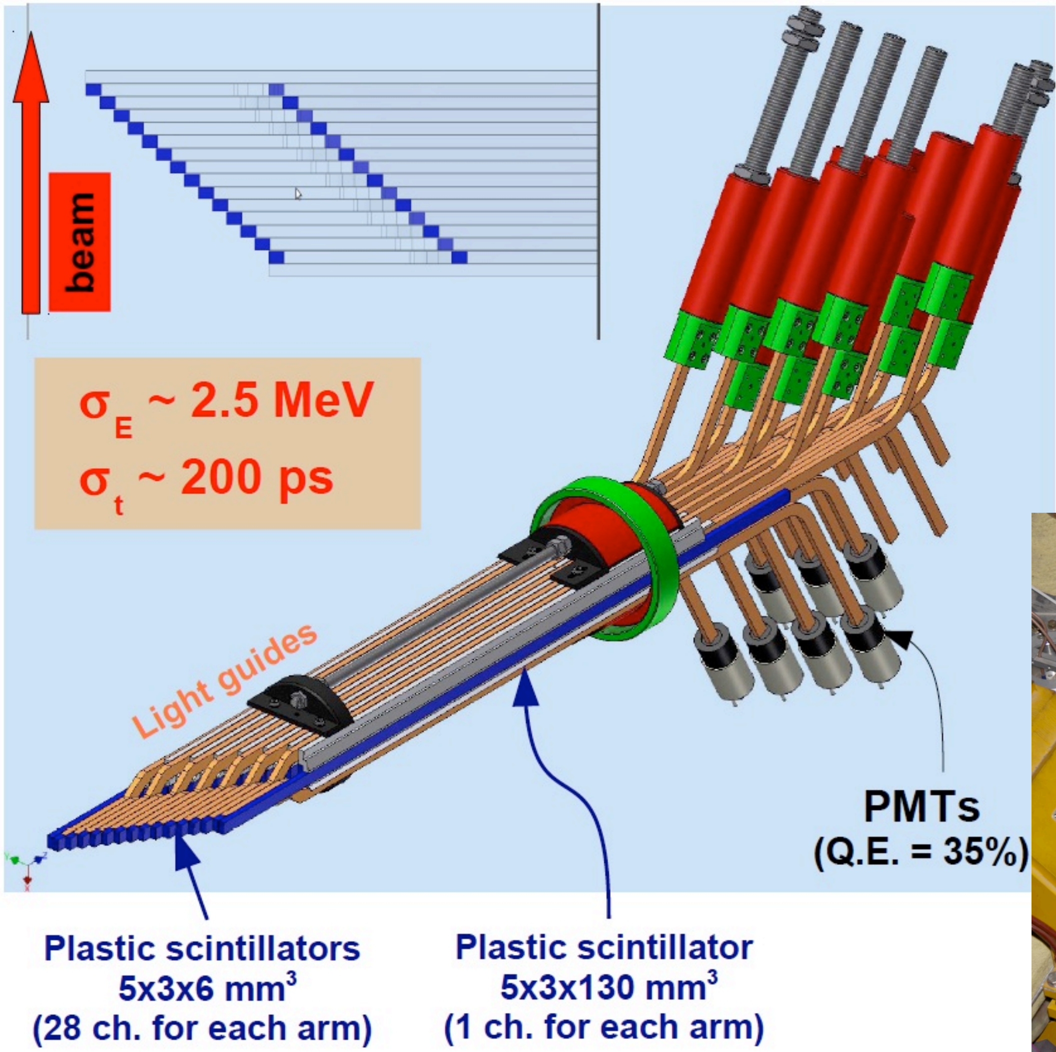
HETs

1st bending dipole after IP acts as a spectrometer, separating particles of different energy in the range (420 – 495) MeV

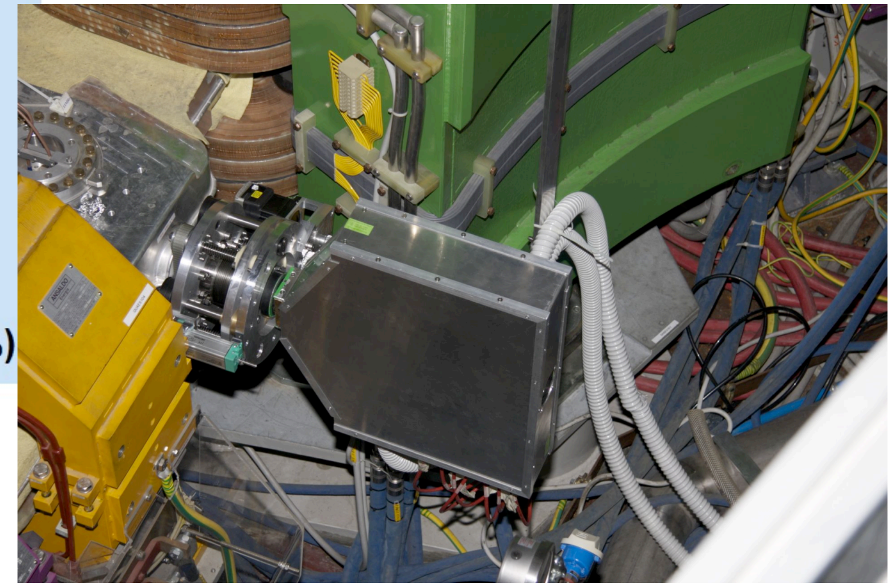


Strong correlation between E and deviation from nominal orbit for final leptons → Position detector

HETs

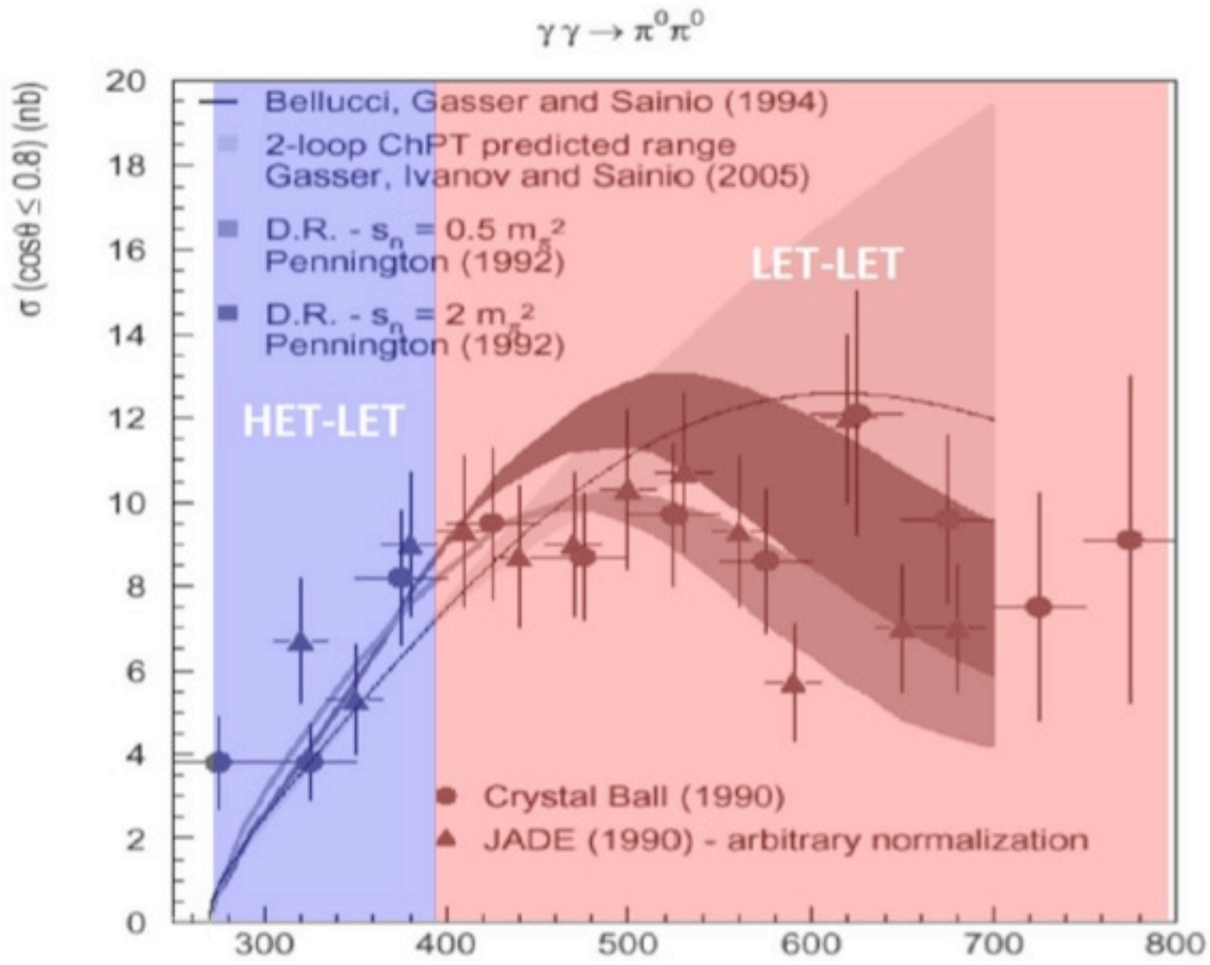


beam
σ_E ~ 2.5 MeV
σ_t ~ 200 ps
Light guides
PMTs
(Q.E. = 35%)
Plastic scintillators
5x3x6 mm^3
(28 ch. for each arm)
Plastic scintillator
5x3x130 mm^3
(1 ch. for each arm)



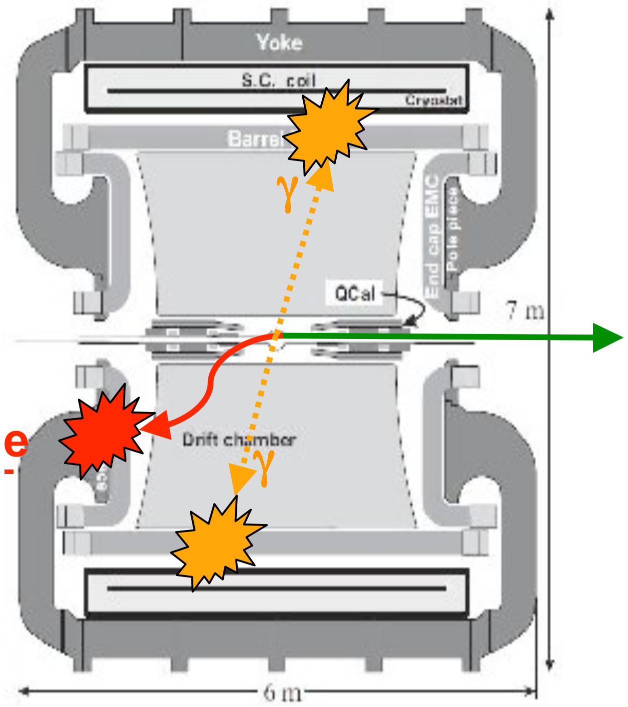
$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

$\gamma\gamma$ events tagged by the coincidence of 2 tagging stations



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

HET-KLOE coincidence

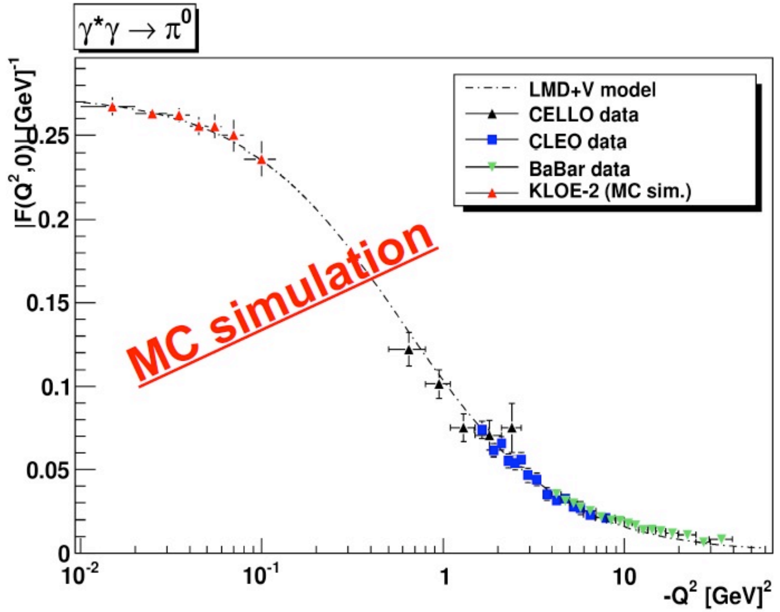


$e^+ \to$ $q_\gamma^2 \lesssim 10^{-3}$ GeV^2

$e^- \to$ $q_\gamma^2 \sim 0.01 - 0.1$ GeV^2

$$\mathcal{F}_{\pi^0\gamma*\gamma*}(q_1^2, 0)$$

measured only for space-like $q^2 > 0.5$ GeV^2



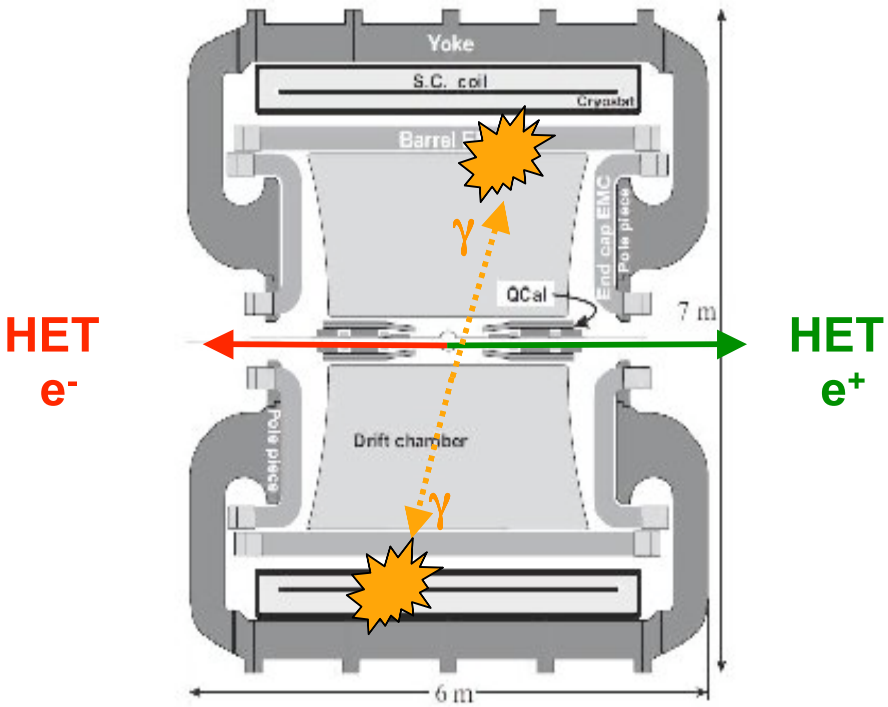
$L_{int} = 5$ fb^{-1} $\to$ 6% stat. error in each bin

EPJ C72, 1917 (2012)

(Kloe2 + Czyż, Ivashyn, Nyffeler)

$e^+e^- \rightarrow e^+e^- \pi^0$

HET-HET coincidence



e^+, e^- → $q_\gamma^2 \lesssim 10^{-3}$ GeV^2

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$

theoretical uncertainty = 1%
best experimental result from PrimEx @ JLAB → 2.8%

$\sigma_{tot}^{e^+e^-\rightarrow e^+e^-\pi^0} \simeq 0.28\ nb$ $\quad L = 5\ fb^{-1}$

$\sigma_{vis}^{x_0=30} \approx 1.90\ pb \Rightarrow N_{events} \approx 9500$

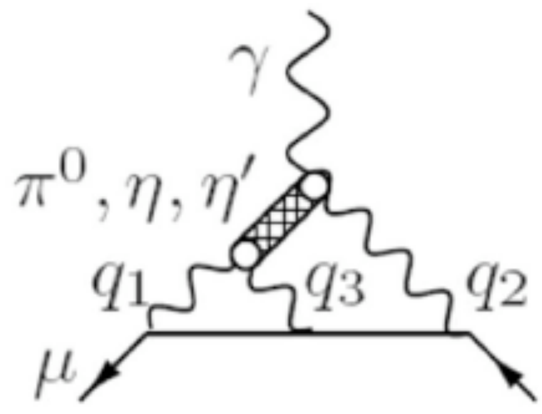
$\sigma_{vis}^{x_0=40} \approx 1.79\ pb \Rightarrow N_{events} \approx 9000$

$\sigma_{vis}^{x_0=50} \approx 1.68\ pb \Rightarrow N_{events} \approx 8500$

stat. error ~ 1%

$e^+e^- \rightarrow e^+e^- \pi^0$

Experimental measurements (and theoretical constraints) of relevant $\pi\gamma*\gamma*$ FF can help to constrain the models and reduce the uncertainties in $a_\mu^{had.\ LbL}$



KLOE-2 data → reduction by a factor ~ 2 in the uncertainty affecting the (dominant) π^0 contribution (details in EPJ C**72**, 1917 (2012))

Conclusions

KLOE $(\sqrt{s} = 1\ \mathrm{GeV})$

1. $e^+e^- \rightarrow e^+e^-\eta$

published

- studied in $\eta \rightarrow \pi^+\pi^-\pi^0$ & $\eta \rightarrow 3\pi^0$ chs
- X-sect. evaluated and $\eta \rightarrow \gamma\gamma$ width extracted

2. $e^+e^- \rightarrow e^+e^-\pi^0\pi^0$

work in progress

- excess of events just above threshold
- contamination from machine bckg handled using MVA
- $\approx$ 2600 $\gamma\gamma \rightarrow \pi^0\pi^0$ candidate events sample

Conclusions

KLOE - 2 (ϕ-peak)

- ✓ detector upgrades (taggers, inner tracker,…) completed
- ✓ expect to collect O(10 fb^{-1}) in the next 3 years
- ✓ $\gamma\gamma \to \pi^0\pi^0$ (tagged)
- ✓ promising $\gamma\gamma \to \pi^0$ analysis w/ 5-6 fb^{-1}
  - 2γ width at 1% (stat.) accuracy, better than current world av.
  - First measurement of TFF in the space-like low Q^2 region (0.01 – 0.1) GeV^2 w/ statistical error < 6% in each bin

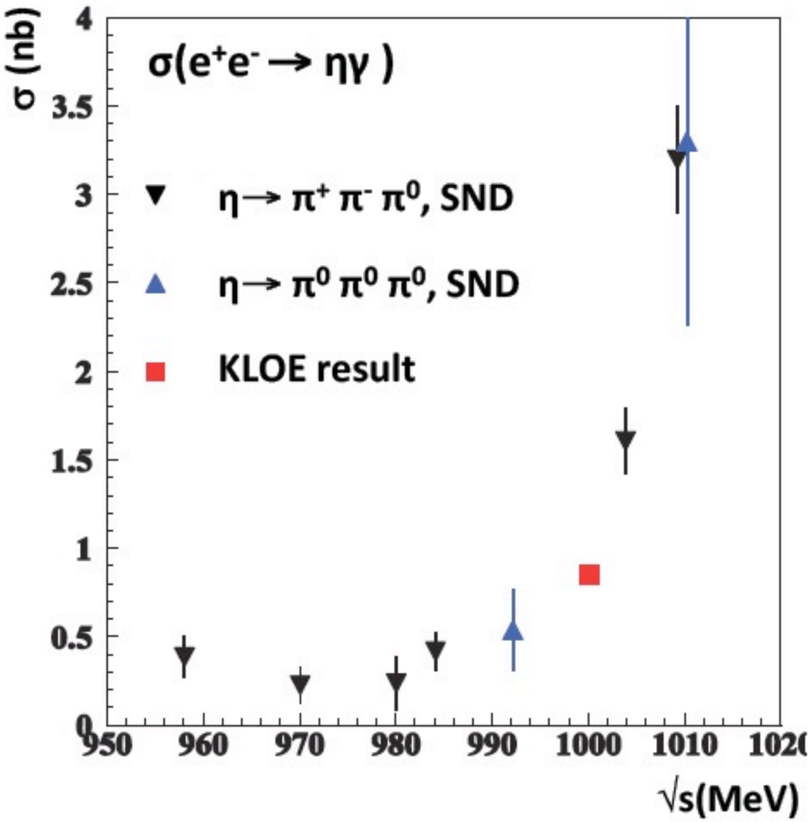
↳
- consistency check for TFF parametrizations
- model dependence reduction of a_μ^{LbL}
- factor ~2 error improvement on a_μ^{LbL}

SPARE SLIDES

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

used as a constraint in the fit for $\eta \to \pi^+\pi^-\pi^0$ analysis

$$\sigma(\sqrt{s} = 1\ \mathrm{GeV}) = (856 \pm 8_{\mathrm{st.}} \pm 12_{\mathrm{sys.}} \pm 11_{\mathrm{BR}})\ \mathrm{pb}$$



NB – as a (independent) by-product of $\eta \to 3\pi^0$ analysis:

$$(853 \pm 25_{\mathrm{st.}} \pm 5_{\mathrm{sys.}} \pm 6_{\mathrm{BR}})\ \mathrm{pb}$$

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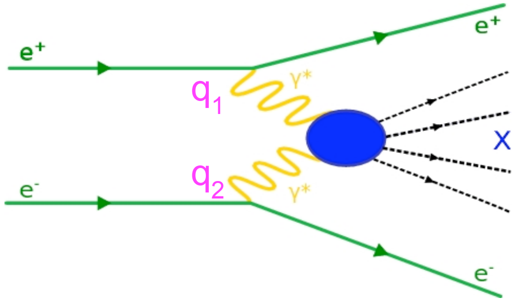
The π^0 case: width and TFF

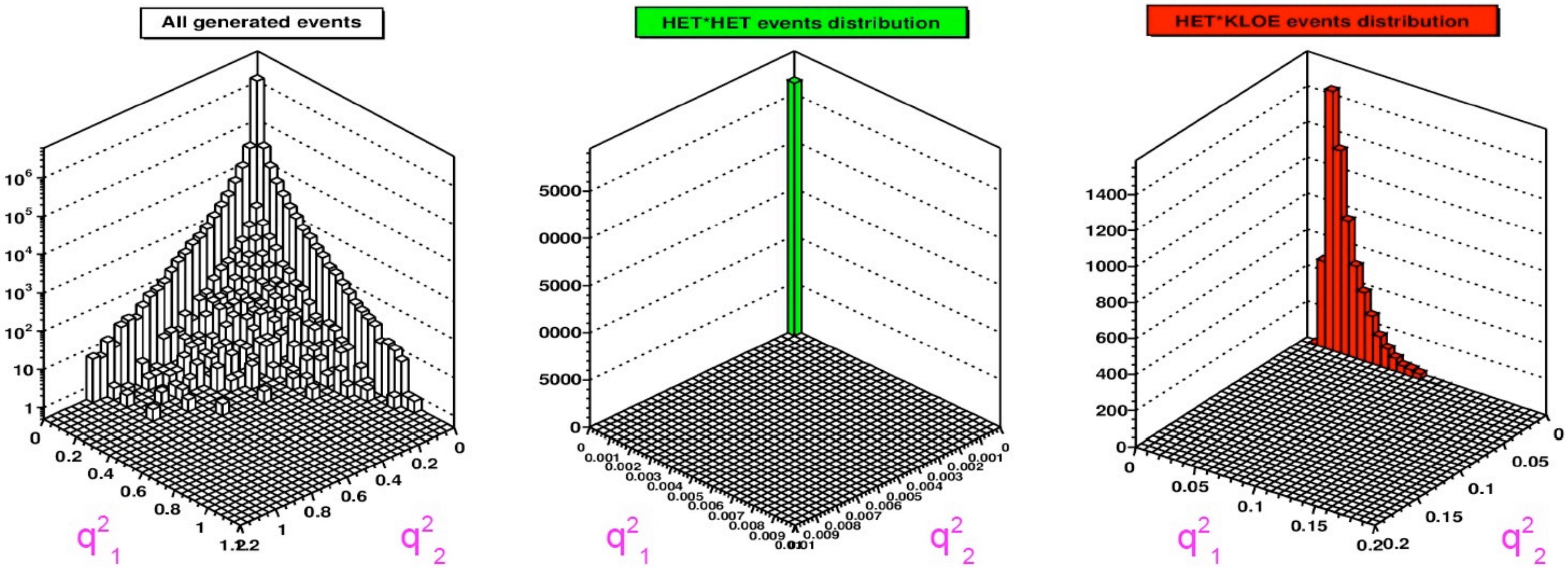


$e^+ \to$ HET
$e^- \to$ HET
$\pi^0 \to \gamma\gamma \to$ KLOE

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

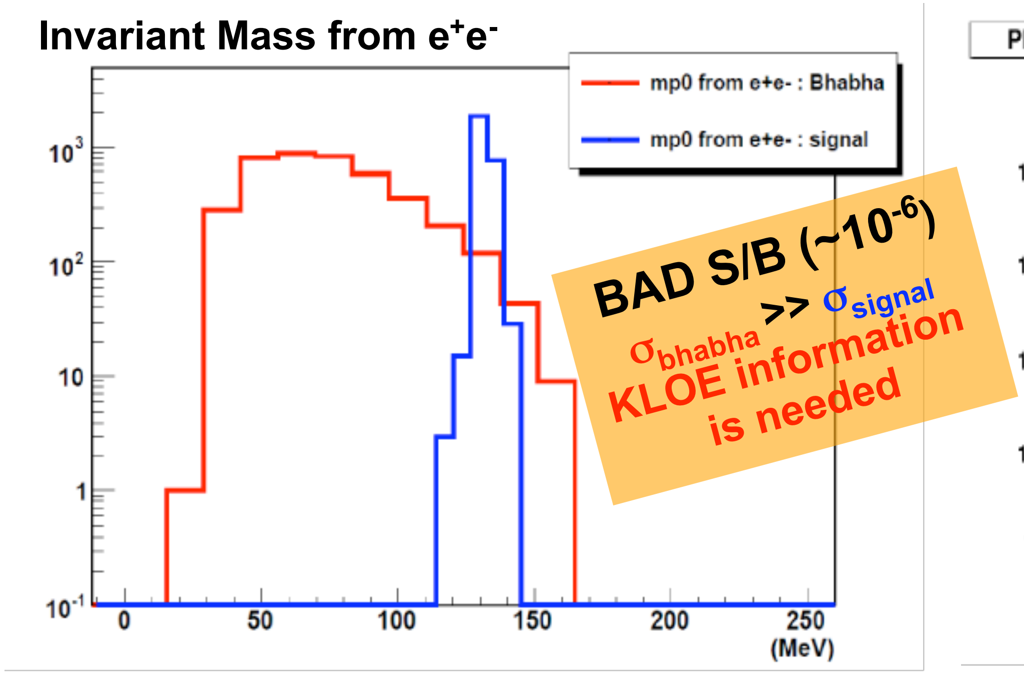
$e^+ \to$ HET
$e^- \to$ KLOE
$\pi^0 \to \gamma\gamma \to$ KLOE

access to $F(m^2_{\pi 0}, q^2, 0)$



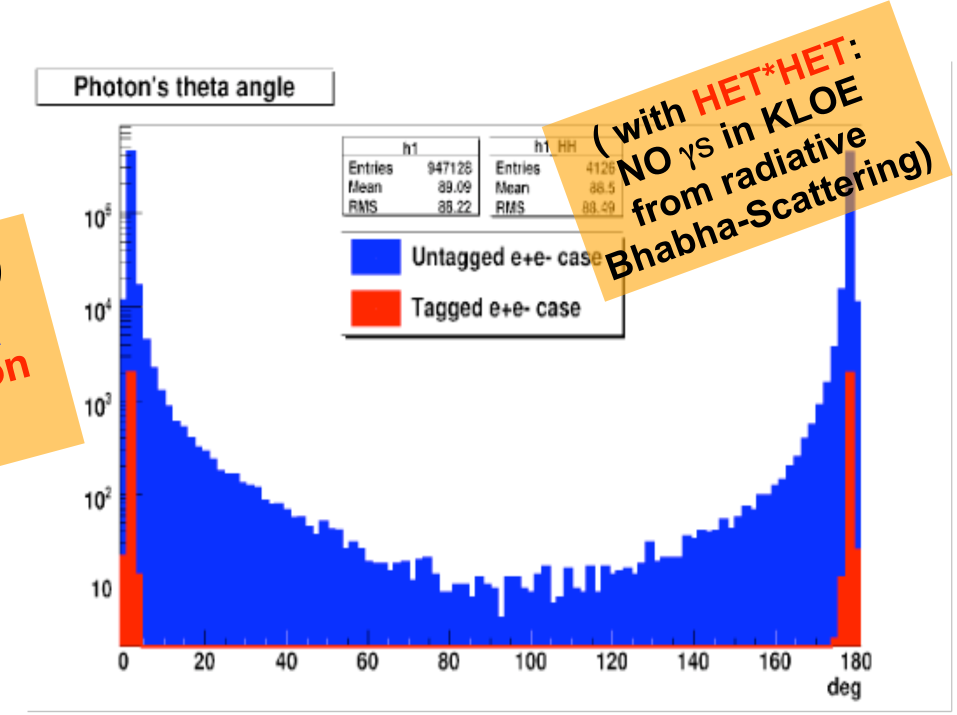
π^0 case: width measurement

Width extraction $\Gamma(\pi^0 \to \gamma\gamma) = \frac{N_{\pi^0}}{\epsilon L} \frac{\tilde{\Gamma}(\pi^0 \to \gamma\gamma)}{\tilde{\sigma}(e^+e^- \to e^+e^-\pi^0)}$ ➡ $F^2_{\pi^0\gamma^*\gamma^*}(q_1^2 = 0, q_2^2 = 0) = \frac{4}{\pi\alpha^2 m_\pi^3}\Gamma(\pi^0 \to \gamma\gamma)$



Bhabha
$e^+e^- \to e^+e^-\gamma\gamma$; $e^+e^- \to e^+e^-\gamma$

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

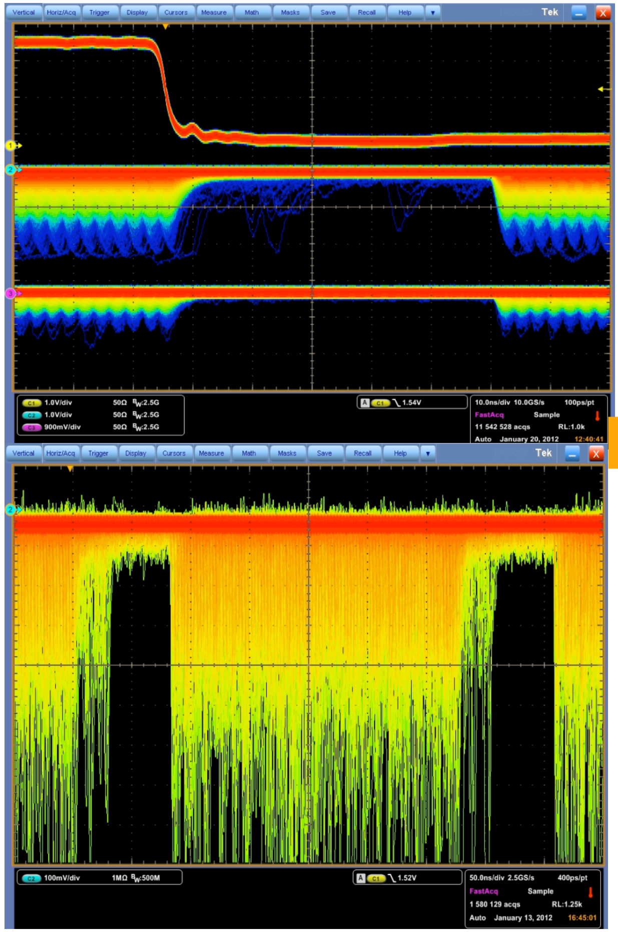


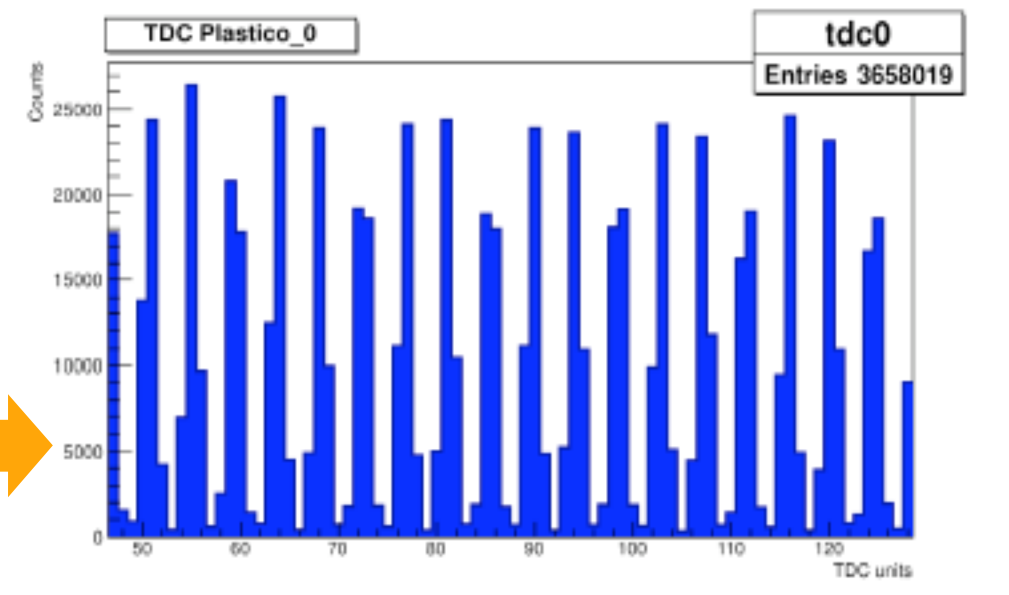
Untagged Bhabha

Tagged Bhabha H*H

HET detectors: beam tests

Main purpose: distinguish signals coming from two consecutives bunch-crossings → 2.7 ns spacing





The whole electronic chain is properly working

→ Double Threshold system is OK
→ TDC resolution is ~ 300 ps < 2.7 ns
→ HET calibration is ongoing

→ **THE DETECTOR IS READY FOR DATA ACQ. WAITING FOR DAΦNE COMMISSIONING !**