KLOE-2 results on hadron physics

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Result: UL $\eta \to \pi^+\pi^-$

Prel. result: $\eta \to \pi^0\gamma\gamma$

Status: $\Gamma(\pi^0 \to \gamma\gamma)$ in $\gamma\gamma \to \pi^0$, search for leptophobic B boson

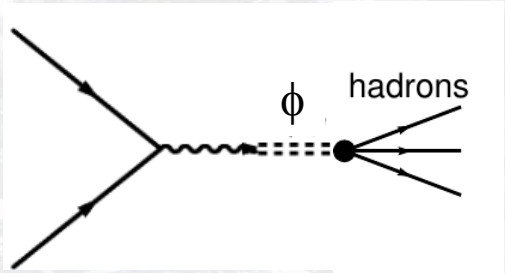
$e^+e^- \to \pi^+\pi^-\pi^0\gamma,\ \eta\pi^+\pi^-,\ \eta\mu^+\mu^-$

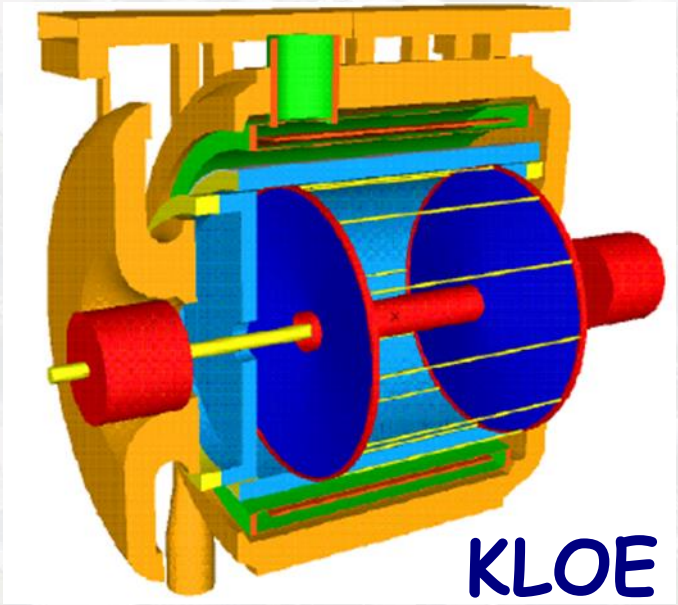
PANIC Lisbon (online) 2021-09-05

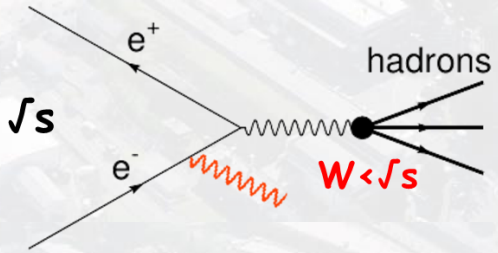
DAΦNE

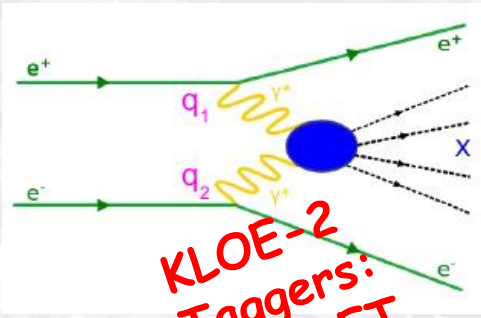
Frascati φ-factory

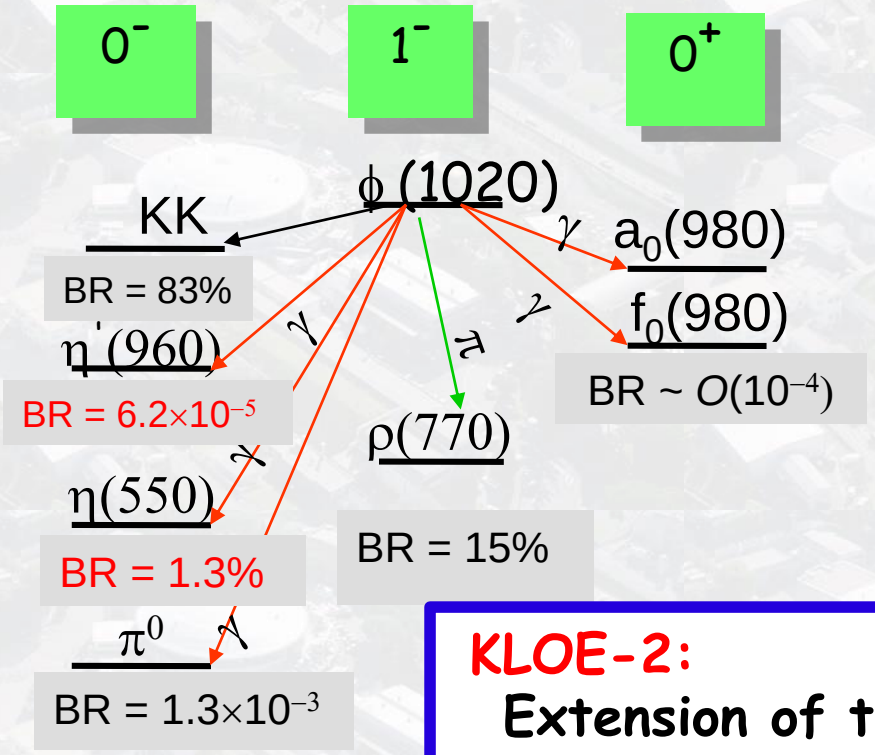
e^+e^- collider $\sqrt{s} = M\phi$











KLOE: 2001-2005

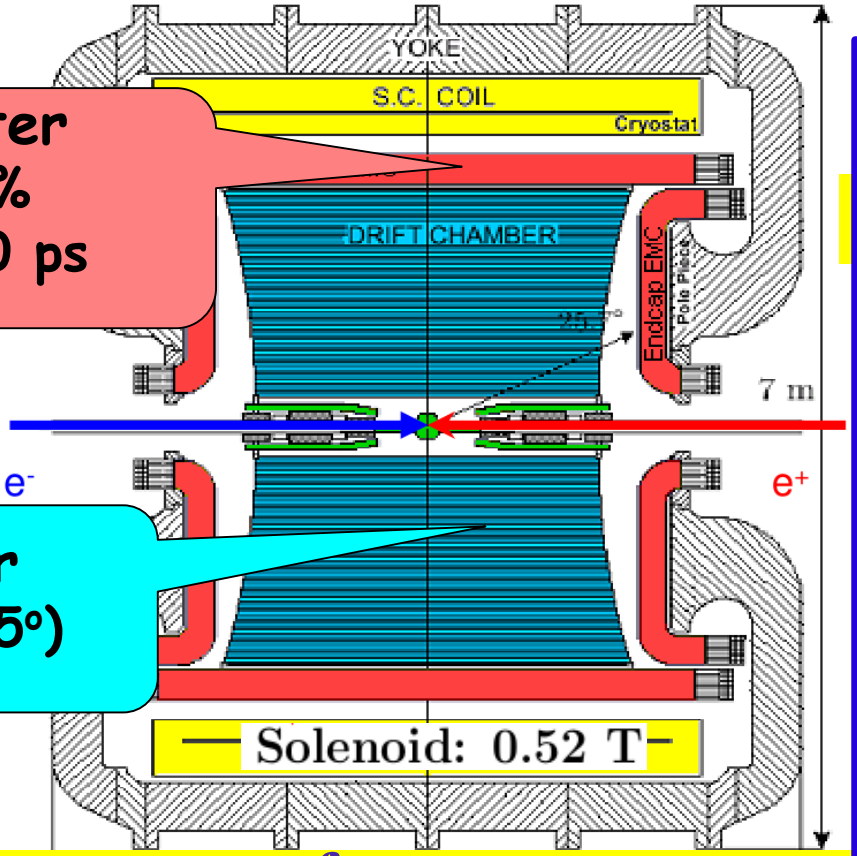
1.7 fb^{-1} @ ϕ meson
240 pb^{-1} @ 1 GeV (off-peak data)

KLOE-2:
Extension of the KLOE physics program at upgraded DAΦNE

KLOE → KLOE-2

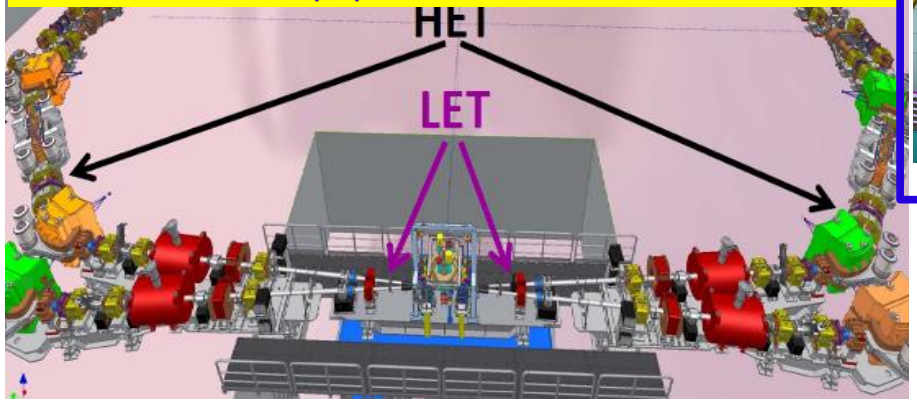
EM Calorimeter
$\delta E/E = 5.7/\sqrt{E}$ %
$\delta t = 57/\sqrt{E} \oplus 100$ ps

Drift Chamber
$\delta p_T \sim 0.4\%$ ($\theta < 45^\circ$)



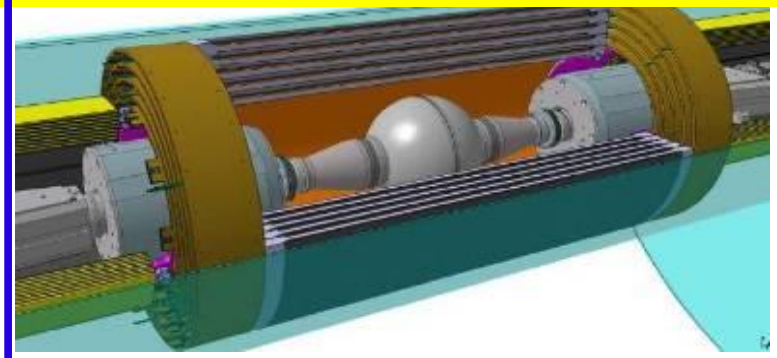
2+2 taggers for:

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

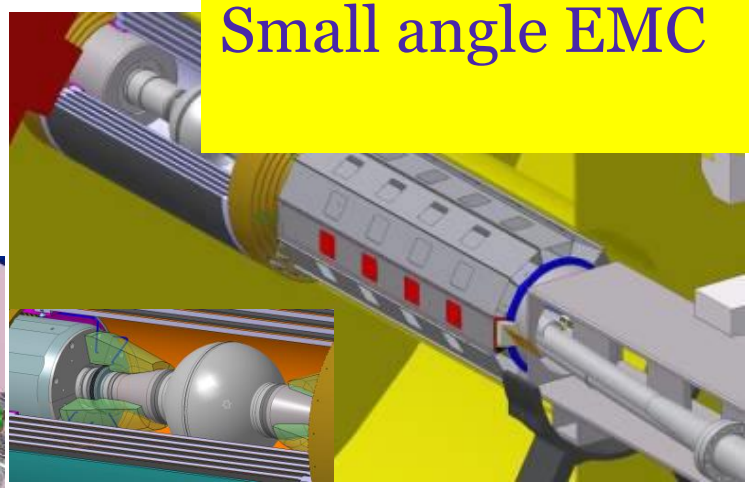


Upgrades

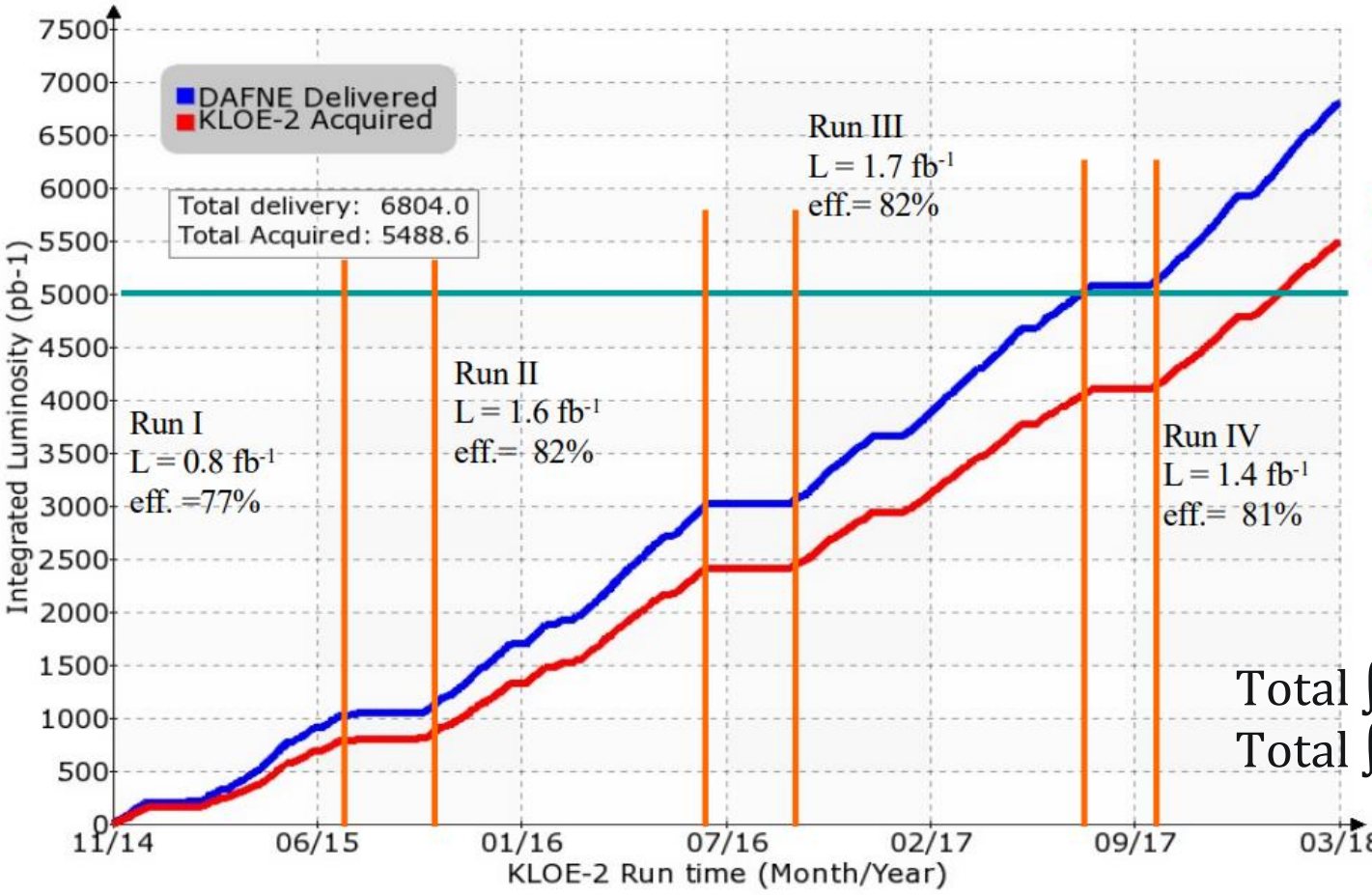
Inner Tracker: cyl. GEM



Small angle EMC



KLOE-2 data taking



Total $\int L$ Delivered: 6.8 fb^{-1}
Total $\int L$ Acquired: 5.5 fb^{-1}

KLOE+KLOE-2 data sample: 8 fb^{-1} $\Rightarrow 2.4 \times 10^{10}$ $\phi(1020)$ mesons
The world's largest data sample at the $\phi(1020)$ peak

KLOE-2 physics

KLOE-2 coll. EPJC (2010) 68, 619

Dark forces:

- Improve limits on:

Uγ associate production

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

- Higgstrahlung

$e^+e^- \to Uh' \to \mu^+\mu^-$ + missing enegy

- **Leptophobic B boson search**

$\phi \to \eta B$, $B \to \pi 0\gamma$, $\eta \to \gamma\gamma$

$\eta \to B\gamma$, $B \to \pi 0\gamma$

- Search for U invisible decay

Hadronic cross sections

- ISR: 2π,**3π**, 4π final states
- Measurement of a_μ

HLO in the space-like region using Bhabha proces

Light meson Physics:

- η decays, ω decays
- Transition Form Factors
- C,P,CP violation: improve limits on

$\boldsymbol{\eta \to \pi^+\pi^-}, \pi^0\pi^0, \gamma\gamma\gamma, \pi^0\pi^0\gamma$

- improve $\eta \to \pi^+\pi^-e^+e^-$
- ChPT : $\boldsymbol{\eta \to \pi^0\gamma\gamma}$
- Light scalars: $f_0(500)$ in $\Phi \to K_S K_S\, \gamma$
- **$\gamma\,\gamma \to \pi^0$ and π^0 TFF**
- Search for axion-like particles

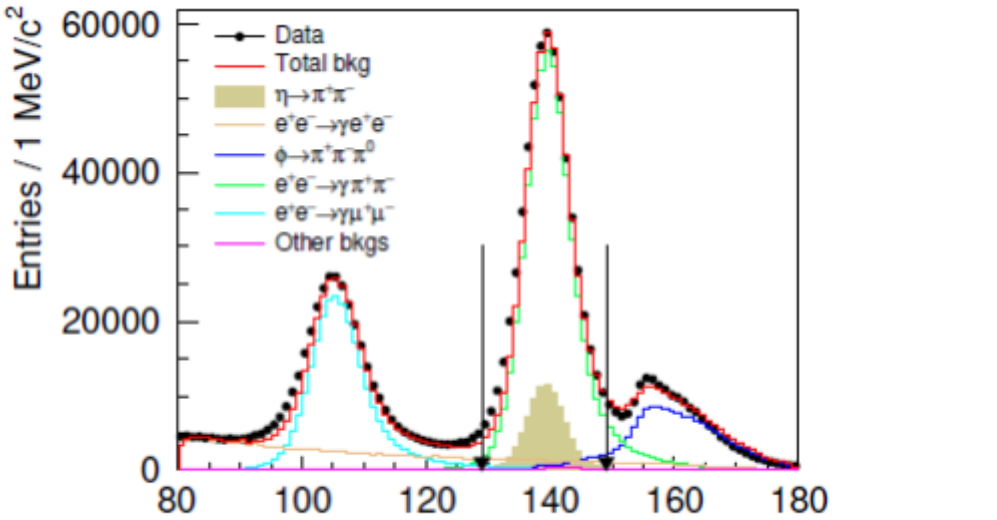
$\eta \to \pi^+\pi^-$

P, CP-violating process: CKM mechanism BR $\mathcal{O}(10^{-27})$

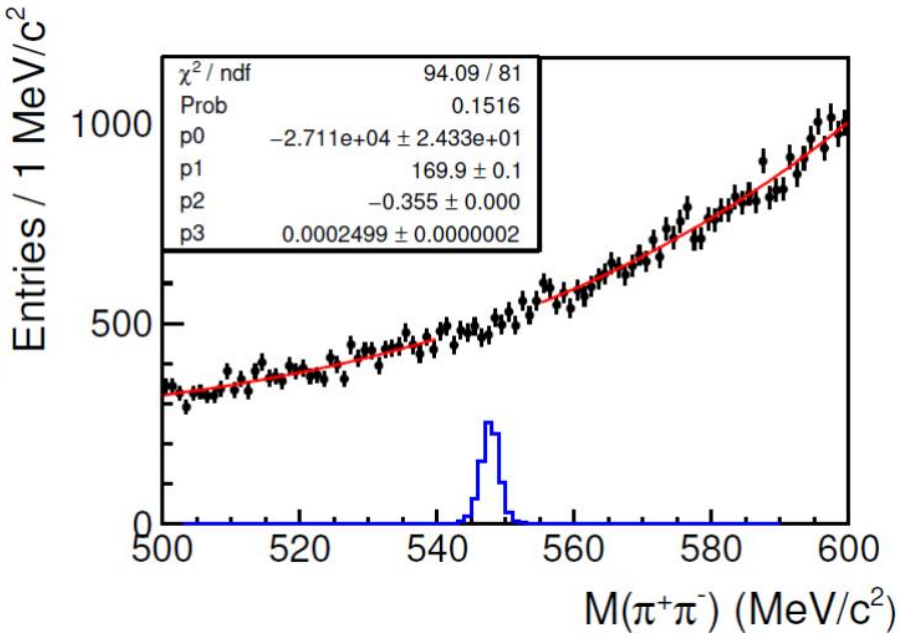
Previous results

KLOE (0.4 fb-1): $< 1.3 \times 10^{-5}$ 90% CL [PLB 606 (2005) 276]

LHCb: $< 1.6 \times 10^{-5}$ 90% CL [PLB 764 (2017) 233]



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



New analysis: independent 1.6 fb^{-1} of KLOE data

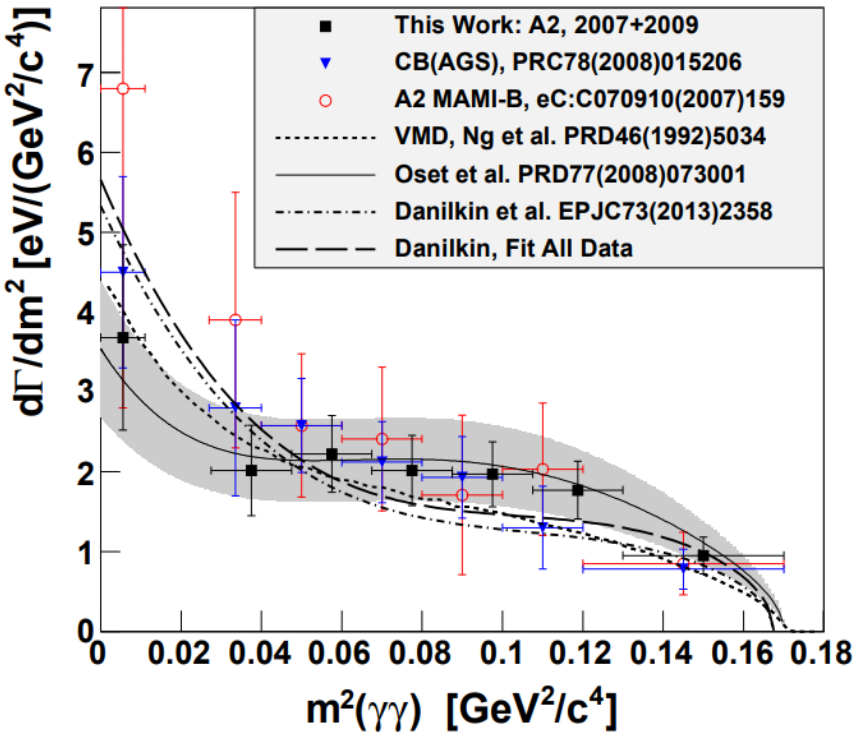
Null signal: limit extracted using CLs technique

$\boldsymbol{BR(\eta \to \pi^+\pi^-) < 4.9 \times 10^{-6}}$ **90% CL**

Combined with previous KLOE result: $< 4.4 \times 10^{-6}$ @ 90% CL

Published in JHEP10 (2020) 047

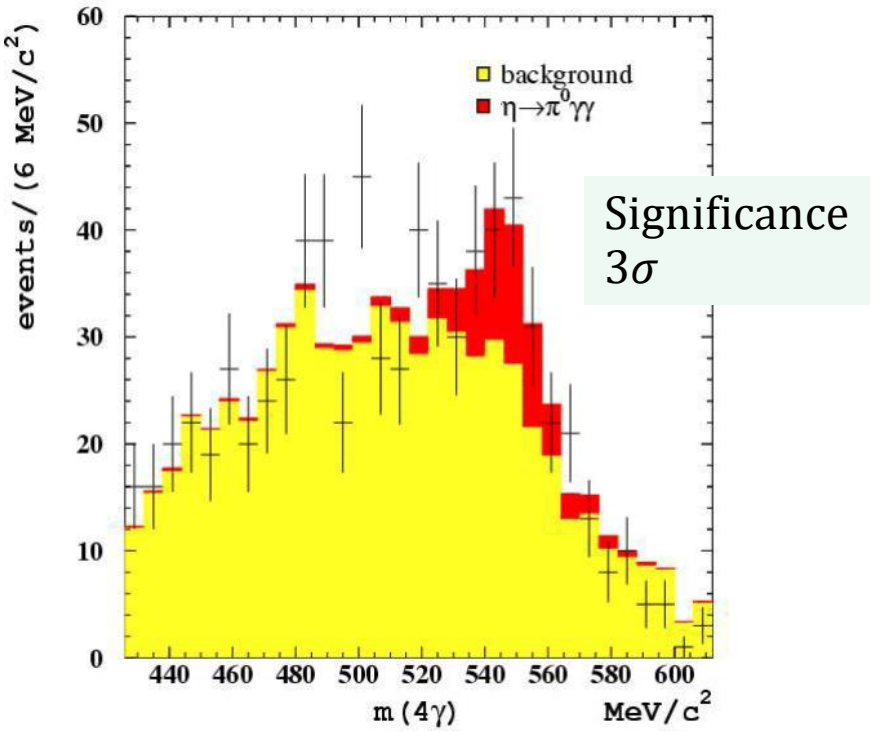
$\eta \to \pi^0\gamma\gamma$ long time controversy



BR = (22.1 ± 2.4 ± 4.7)×10^{-5} CB@AGS (2008)
BR = (25.2±2.5)×10^{-5} A2 MAMI (2014)

A2 MAMI PRC 90 (2014) 025206

KLOE (2006)prel. :
(8.4±2.7±1.4)×10^{-5}



Significance 3σ

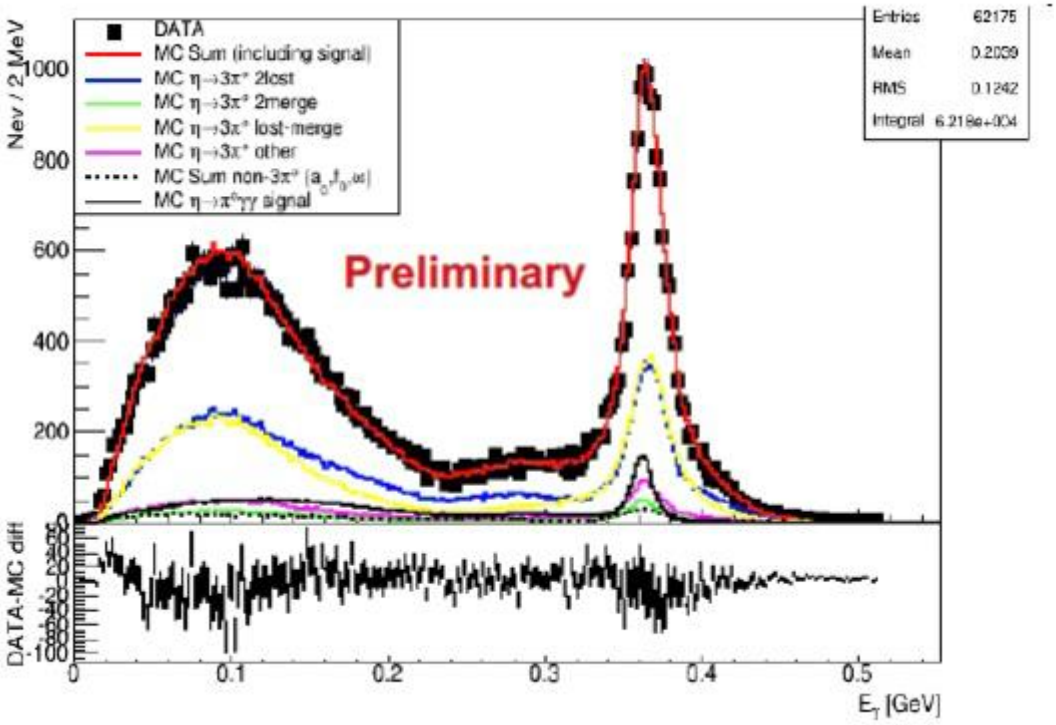
Most recent Theory evaluation

$BR = 1.35(8) \times 10^{-4}$

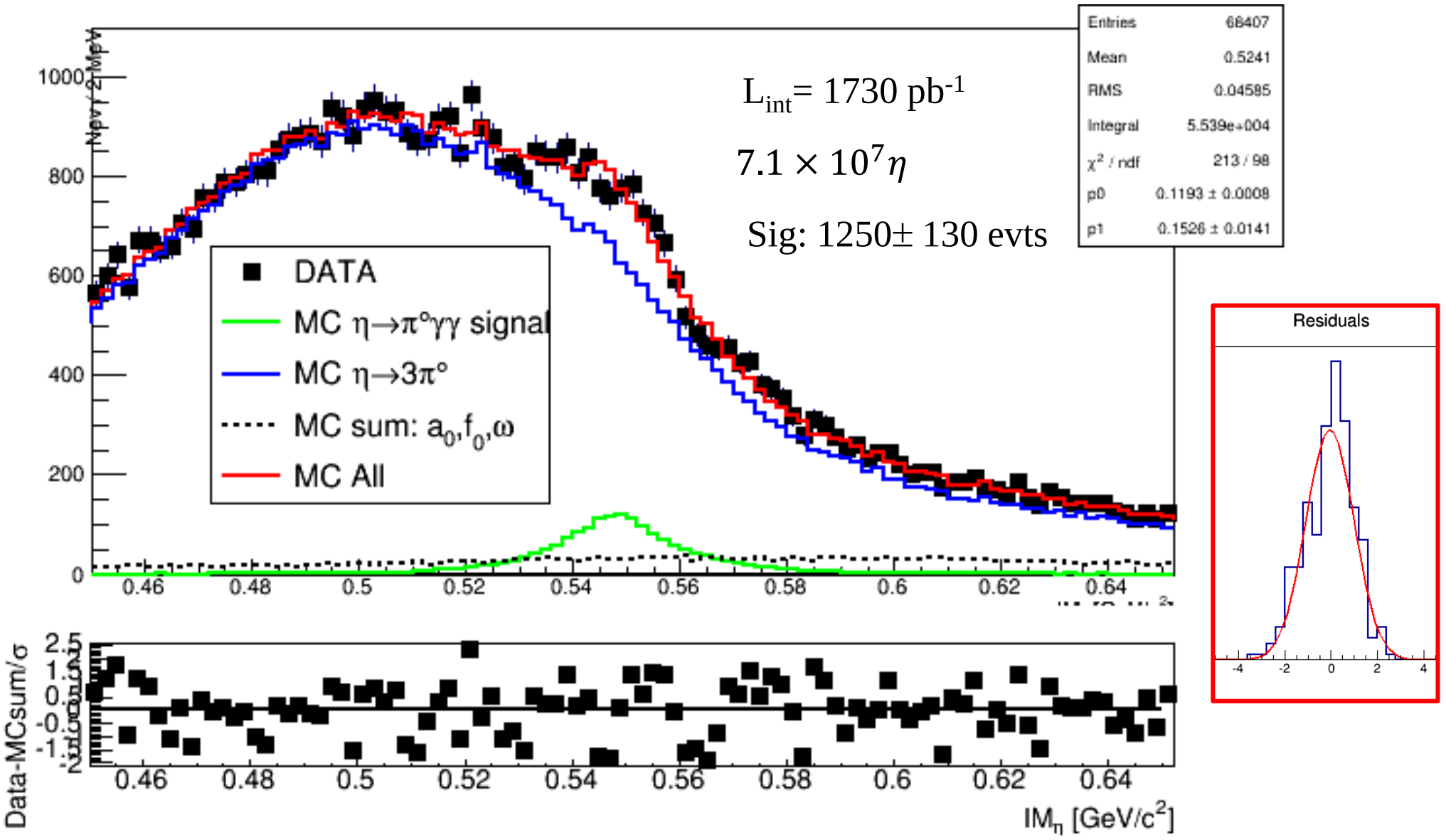
R.Escribano et al. PRD 102 (2020) 034026

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

New analysis using 4× larger data sample (~ 1.7 fb^{-1})
Similar strategy to the B-boson analysis
Energy resolution of all variables improved using kinematic fit
Kinematic fit with η and π^0 hypothesis to reject a_0
$\pi^0\pi^0$ events removed
Main background $\boldsymbol{\eta \rightarrow 3\pi^0}$ with merged γs suppressed using MVA-BDT method using cluster shapes as an input



$KLOE$: $\eta \to \pi^0\gamma\gamma$ signal



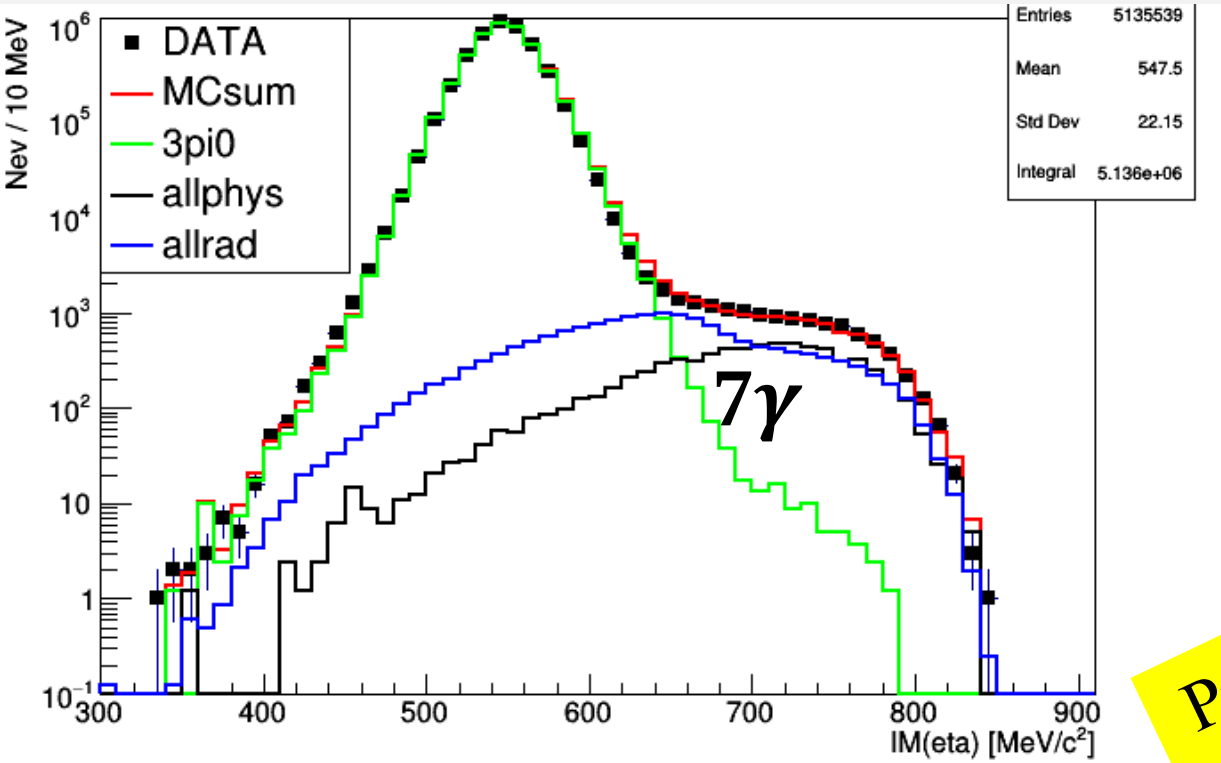
L_{int}= 1730 pb^{-1}

$7.1 \times 10^7 \eta$

Sig: 1250± 130 evts

- Very good agreement of data-MC sum of signal + all background components
- Clear evidence of the signal, 10% stat. error

BR normalization: $\eta \to 3\pi^0$



Preliminary KLOE result:

$$\frac{BR(\eta\to\pi^\circ\gamma\gamma)}{BR(\eta\to3\pi^\circ)} = \frac{N_S/\varepsilon_S}{N_{3\pi^\circ}/\varepsilon_{3\pi^\circ}}$$

$$BR=(1.23 \pm 0.14_{stat})\times 10^{-4}$$

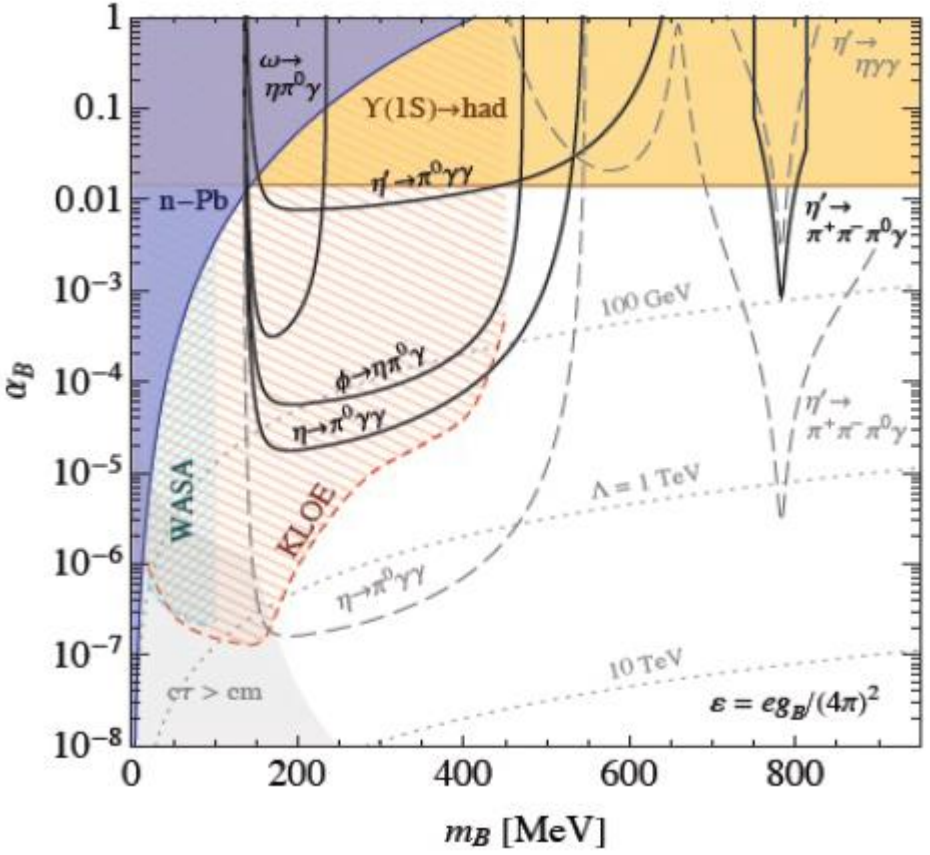
- Robust normalization based on $\eta \to 3\pi^0$ with 7 photons reconstructed
  few % stability on the counting if integrating 6-8 photon events
- **Result agrees with latest theory prediction and with old KLOE prel. value**
- **Work on systematics is well progressed (Kin fit, TVMA, Chi2 cut)**
- **Work on M(gg) spectrum is also on-going**

Search for a Leptophobic B boson

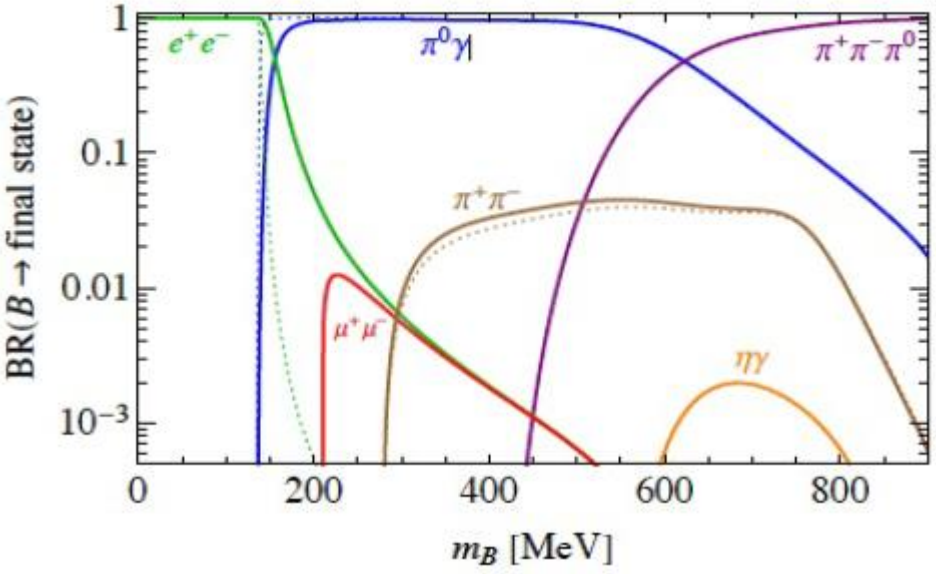
Tulin, PRD89(2014)114008]

•Dark Force mediator coupled to baryon number (B-boson)
has ω(782) quantum numbers
it couples mostly to quarks
Can have an impact on (g-2)mu anomaly

$$\mathcal{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu \quad \alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\text{MeV})$$



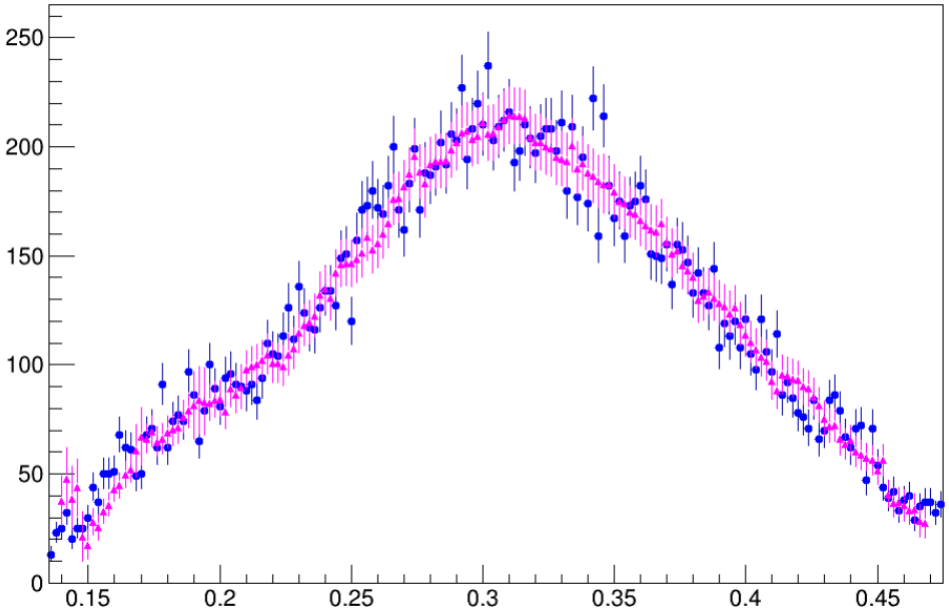
• For (m_B< 600 MeV): B→π⁰γ decay dominant:
ϕ→ηB -> ηπ0 γ⇒5 prompt γs with η and π0
ϕ→ηγ -> η→Bγ⇒π0 γγγ, one π0



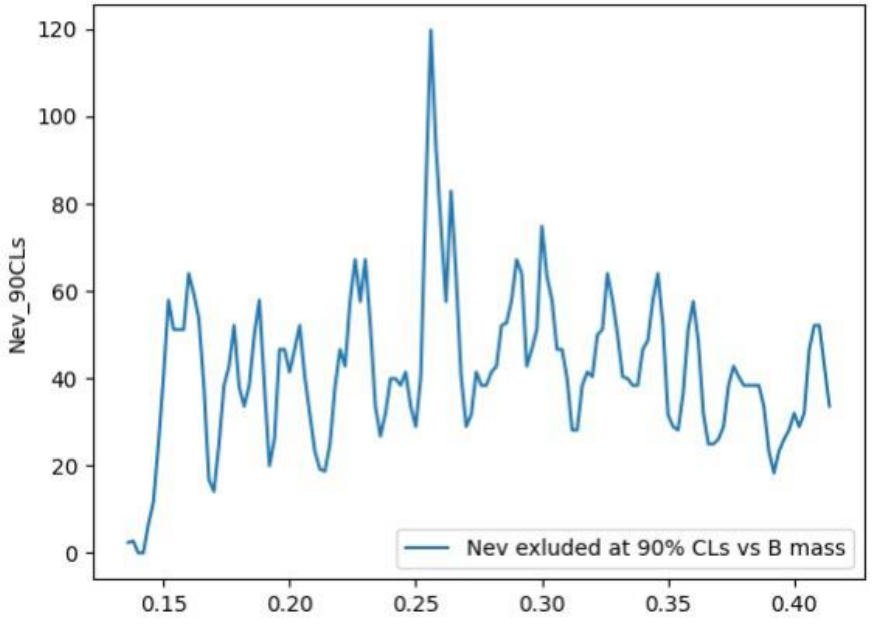
Present constraints from ϕ→a0 γ KLOE measurement with 400 pb^{-1}
and KLOE A' dark photon search exclusion using BR(B-> e+e-) as a function of mixing parameter

Search for a Leptophobic B boson

- KLOE full stat., 5γ final state (with η and π^0)
- Kinematic fit to improve energy resolution
- Main background from
  $\phi \to a_0\gamma \to \eta\pi^0\gamma$
  $\phi \to \eta\gamma \to 3\pi^0\gamma \to 7\gamma$ with 2 γ lost or merged
- Signal: narrow peak in the $M(\pi^0\gamma)$ distribution
- Background is estimated from fitting to the side-bands excluding the signal region
- Correction for reconstruction efficiency and luminosity underway to set BR UL
- **Expect much improvement over existing limits on α_B**

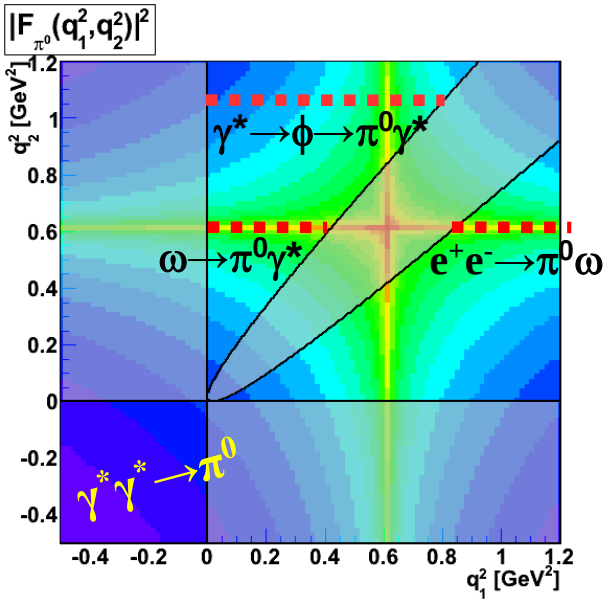


$M(\pi^0\gamma)$ [GeV]

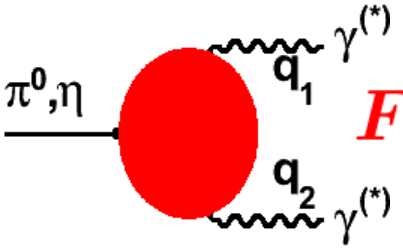


$M(\pi^0\gamma)$ [GeV]

π^0 Transition Form Factor (TFF)



$$\Gamma(P \to \gamma\gamma)$$



$$F_P(q_1^2, q_2^2)$$

KLOE-2:

Access to all phys regions

$|q^2|<1$ GeV^2

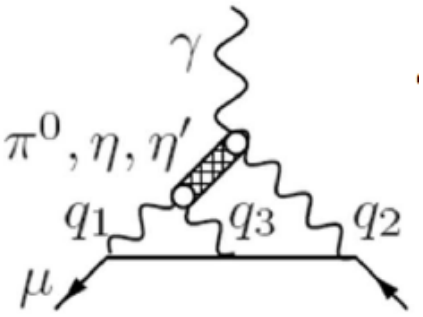
$$\Gamma(\pi^0 \to \gamma\gamma)$$

Prediction from chiral anomaly

$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{\alpha^2 M_{\pi^0}^3}{64\pi^3 F_\pi^2} = 7.750(16)\,\text{eV}$$

Primakoff type measurement
PrimEx-I and PrimEx-II

$$\Gamma(\pi^0 \to \gamma\gamma) = 7.802(52)_{\text{stat}}(105)_{\text{syst}}\,\text{eV} = 7.802(117)\,\text{eV}$$



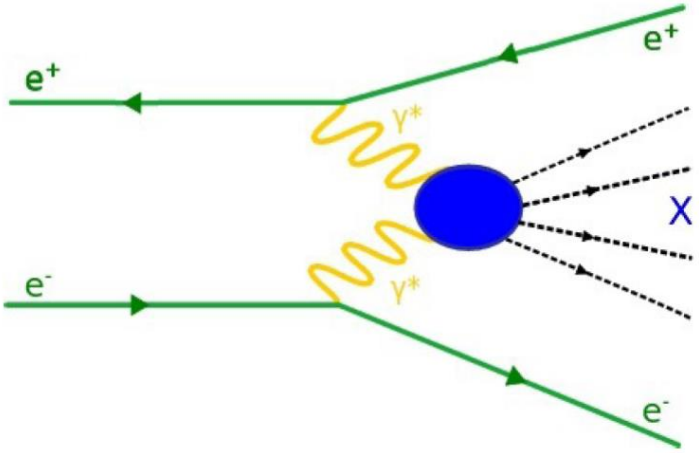
Dominant HLbL contribution to $(g-2)_\mu$

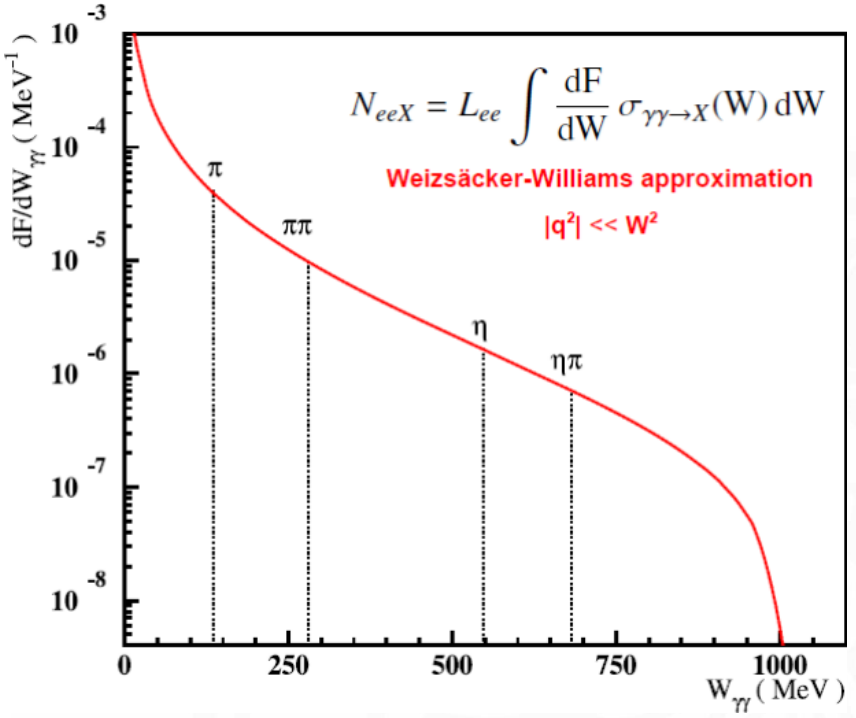
$\Gamma(\pi^0 \to \gamma\gamma)$ and π^0 TFF measurement at KLOE – 2

$\gamma^*\gamma^* \to \pi^0$ @KLOE-2

use taggers:
HET-HET coincidence + 2 γ's in EMC

$\sigma_{TOT}(e^+e^- \to e^+e^-\pi^0) \approx 0.28$ nb



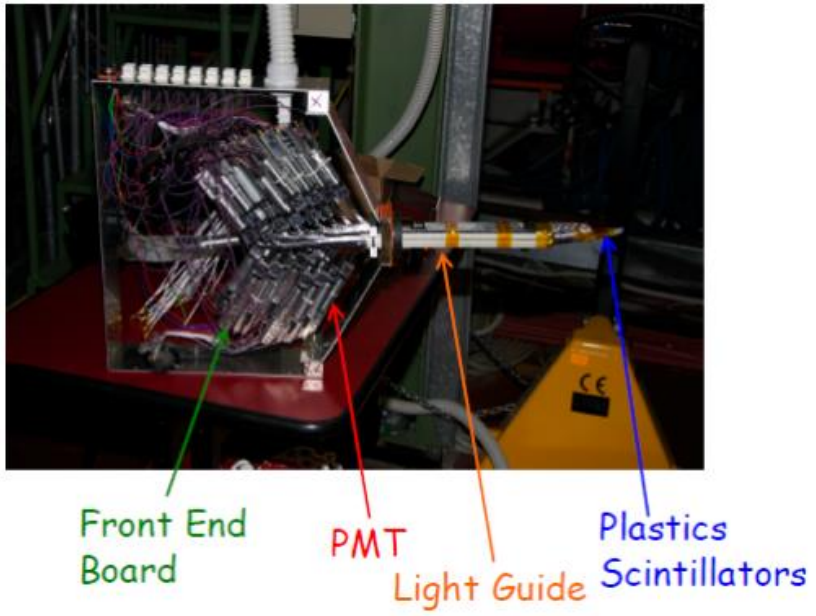


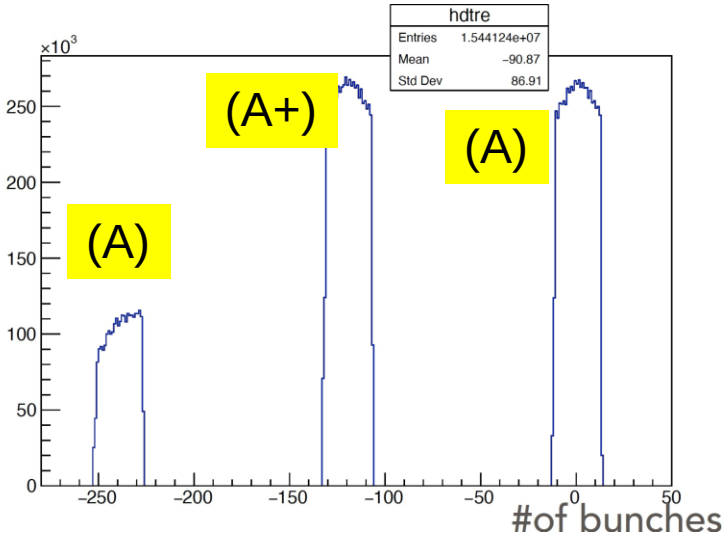
Low angle tagging system in KLOE–2 (HET)

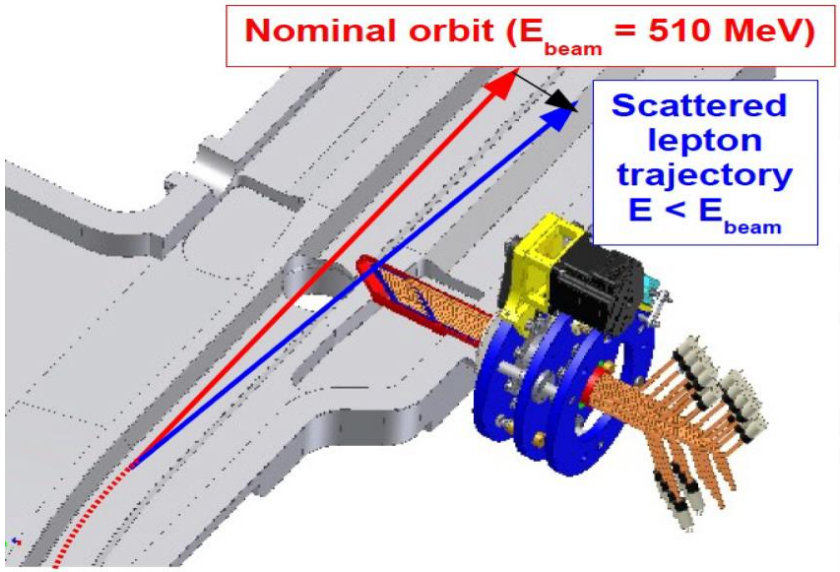
HET (High Energy Tagging) 2 stations
Spectrometer for the scattered leptons
HET data synchronized with DAϕNE (each 325 ns) and the KLOE trigger.
HET acquisition window = 2.5 DAϕNE revolutions for a KLOE trigger

Analysis uses the following samples:

- **accidental pure (A)** for background modeling
- **accidental + HET*KLOE coincidences (A+)**





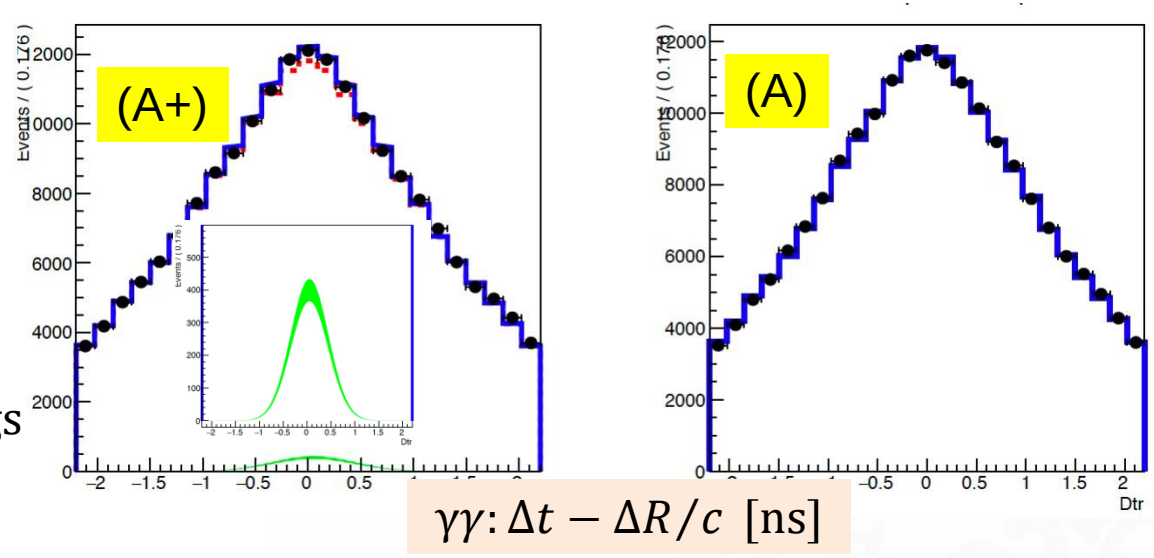


Status of search for $\gamma\gamma \to \pi^0$ signal with 1.5/fb

(reconstruction of 3 fb^{-1}completed)

Single-arm selection:

-2 photons from the same bunch crossing
-Select bunch crossing and
HET signal (+/- 40 ns KLOE trigger)



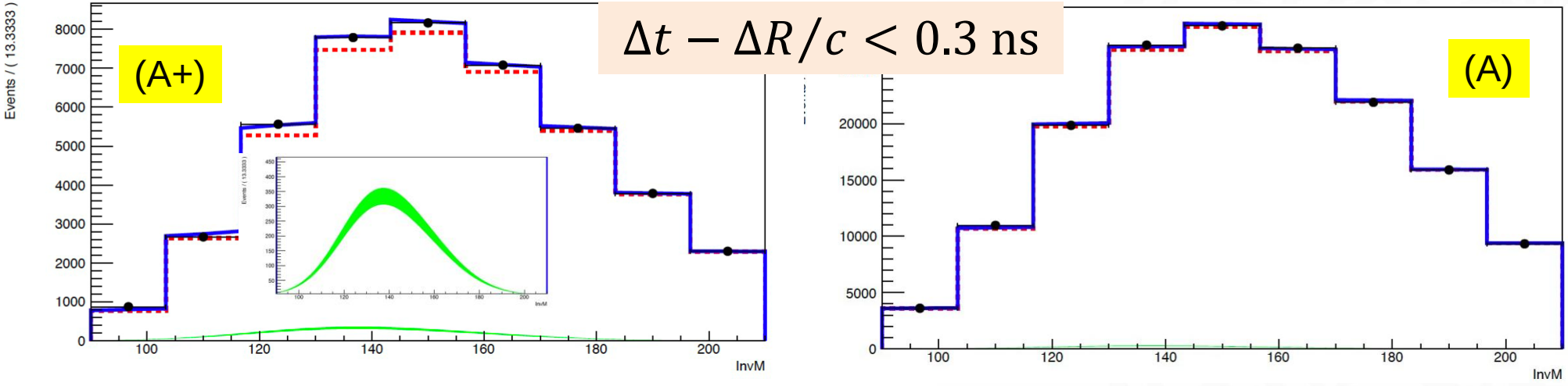
$\gamma\gamma$: $\Delta t - \Delta R/c$ [ns]

Simultaneous fits of (A+)/(A) samples

Fit to (A) samples used to determine number of accidentals in A+
-Time coincidence window: 4 bunch crossings

-Sample (A) -> background p.d.f.
-Signal p.d.f. : EKHARA, control samples and BDSIM transport of the leptons through the beamline.
-Acceptance: low angle radiative Bhabha cross section measurement (in progress)

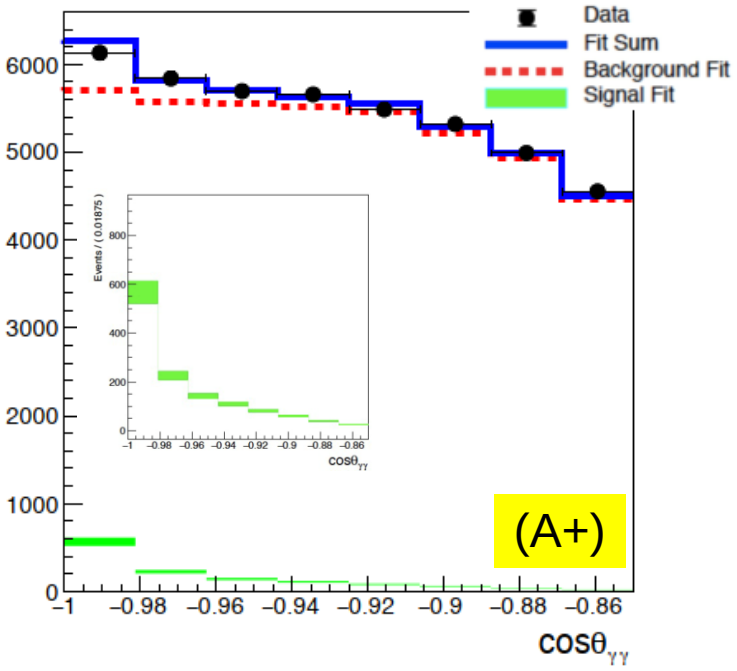
$\Delta t - \Delta R/c < 0.3$ ns

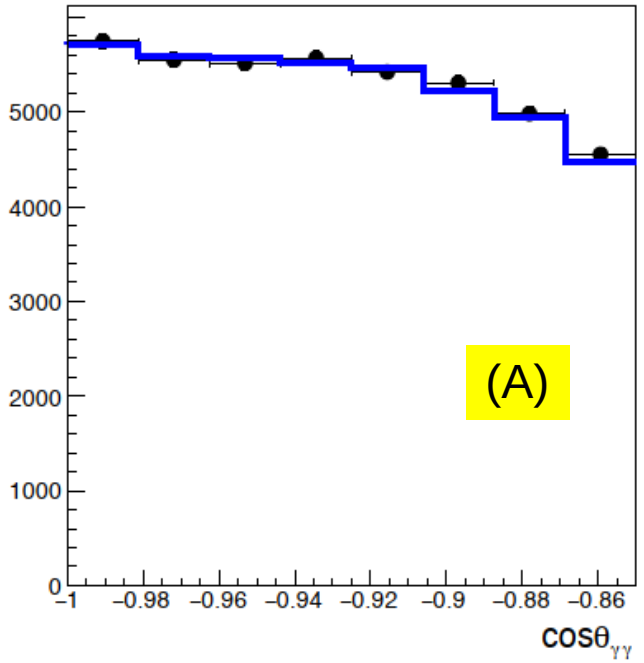


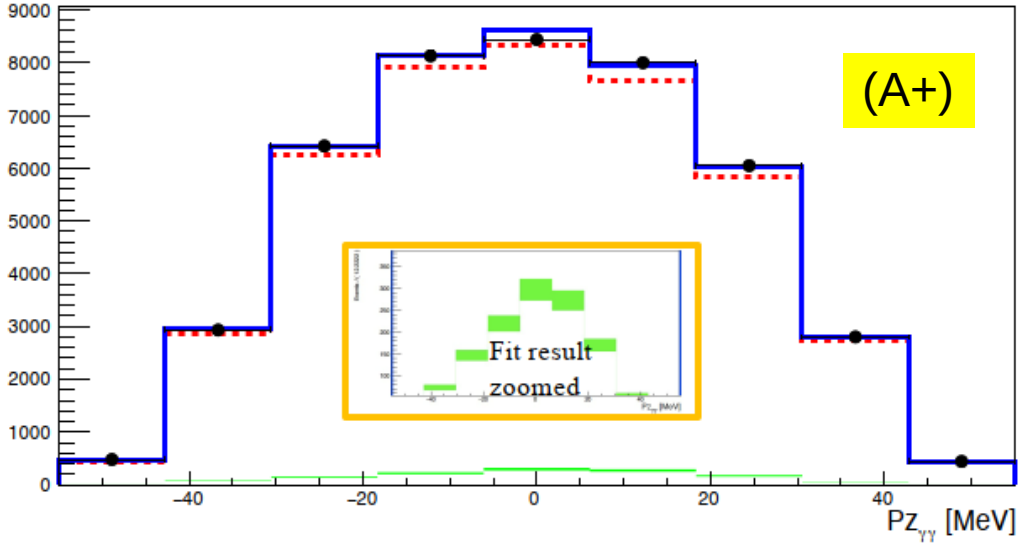
Selected data: ($\Delta T\gamma\gamma$-$\Delta R\gamma\gamma/c$ < 0.3 ns)

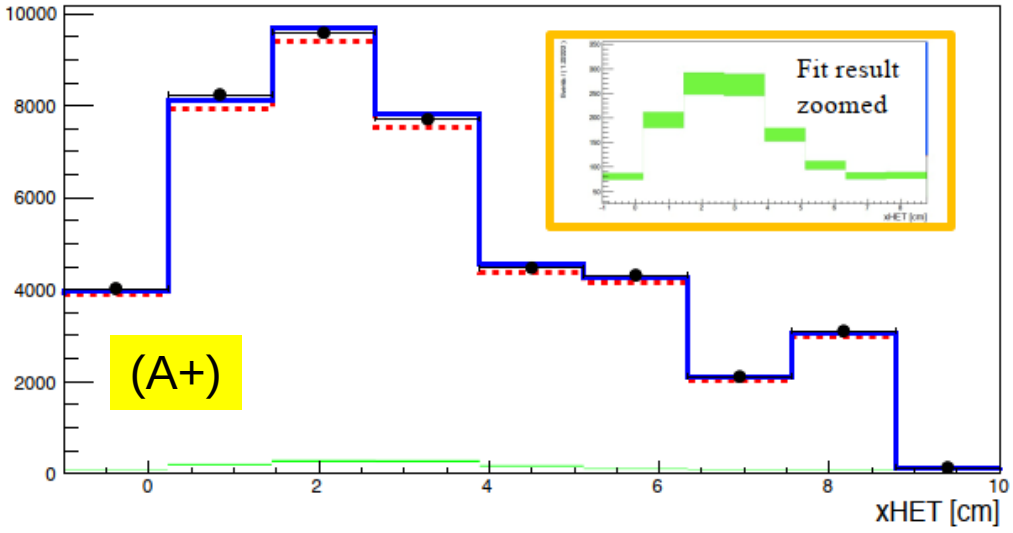
Fit Sig+Bkg

- $M(\gamma\gamma)$, $\cos\theta_{\gamma\gamma}$
- 2D: Pz vs x-HET position
- checks ongoing





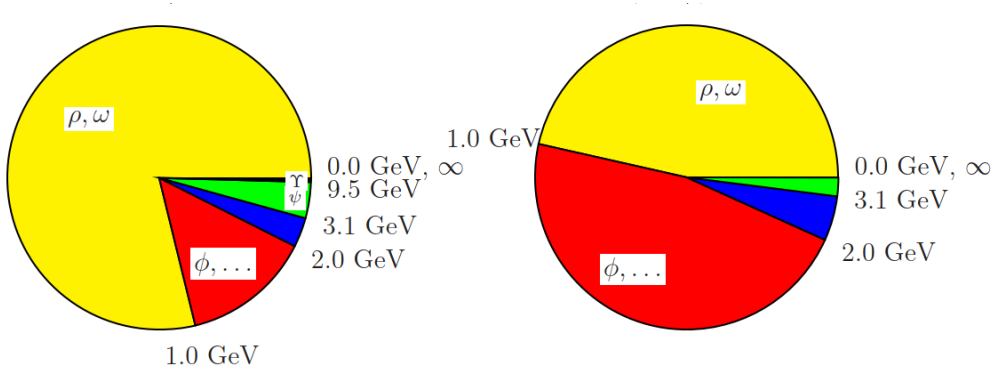




$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$

- $e^+e^- \to \pi^+\pi^-\pi^0$ is 2nd largest HVP contribution to $(g-2)_\mu$: both absolute value and uncertainty

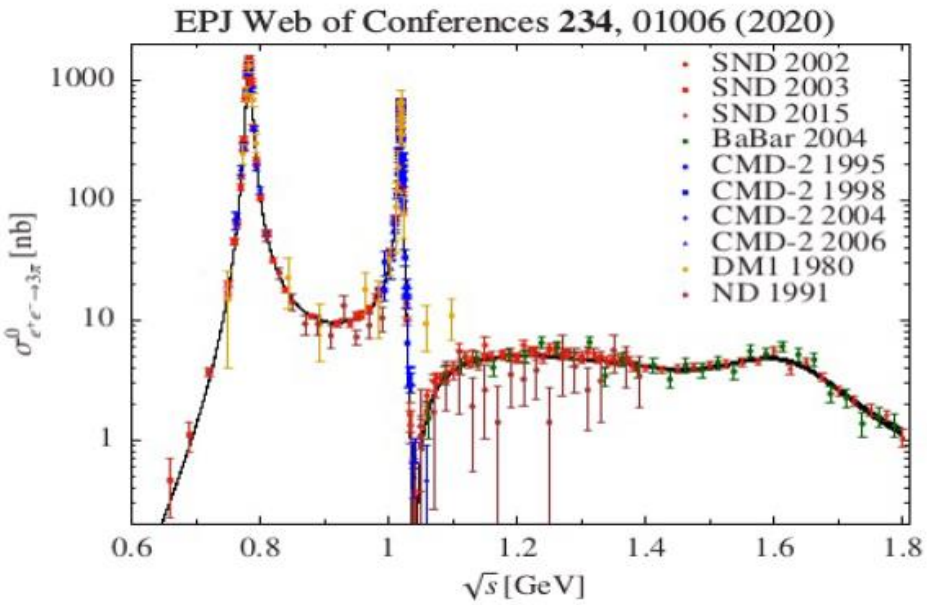
Channel	HLMNT 11
$\eta\pi^+\pi^-$	0.88 ± 0.10
K^+K^-	22.09 ± 0.46
$K^0_S K^0_L$	13.32 ± 0.16
$\omega\pi^0$	0.76 ± 0.03
$\pi^+\pi^-$	505.65 ± 3.09
$2\pi^+2\pi^-$	13.50 ± 0.44
$3\pi^+3\pi^-$	0.11 ± 0.01
$\pi^+\pi^-\pi^0$	47.38 ± 0.99
$\pi^+\pi^-2\pi^0$	18.62 ± 1.15



value error^2

Cross section measurements:
CMD-2/SND (energy scan)
BaBar/BESIII (ISR)

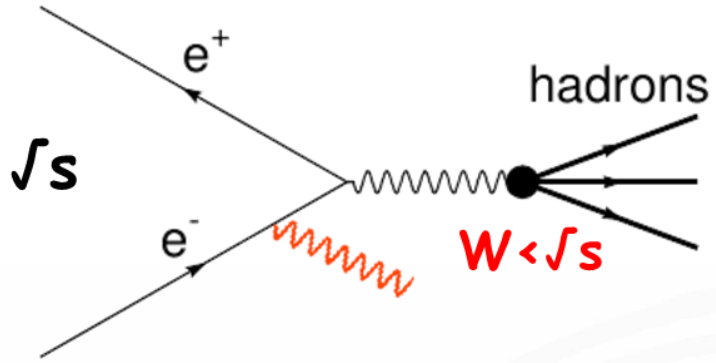
- **KLOE/KLOE-2: ISR for $\sqrt{s} < 1$ GeV,**



Extract the ω peak cross section and measure product of branching fractions
B($\omega \to$e+e-) B($\omega \to 3\pi$)

$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$

Ongoing analysis: 1.7 fb^{-1} KLOE on-peak
• MC signal: PHOKHARA 5



Event selection:
- At least two tracks with opposite curvature
- Three neutral clusters:
  $|\cos\theta|<0.92$, Eclu>15 MeV,
  $|t - R/c| < \min(2, 5\sigma_t)$ ns
- Two tracks with opposite curvature originating from a cylinder

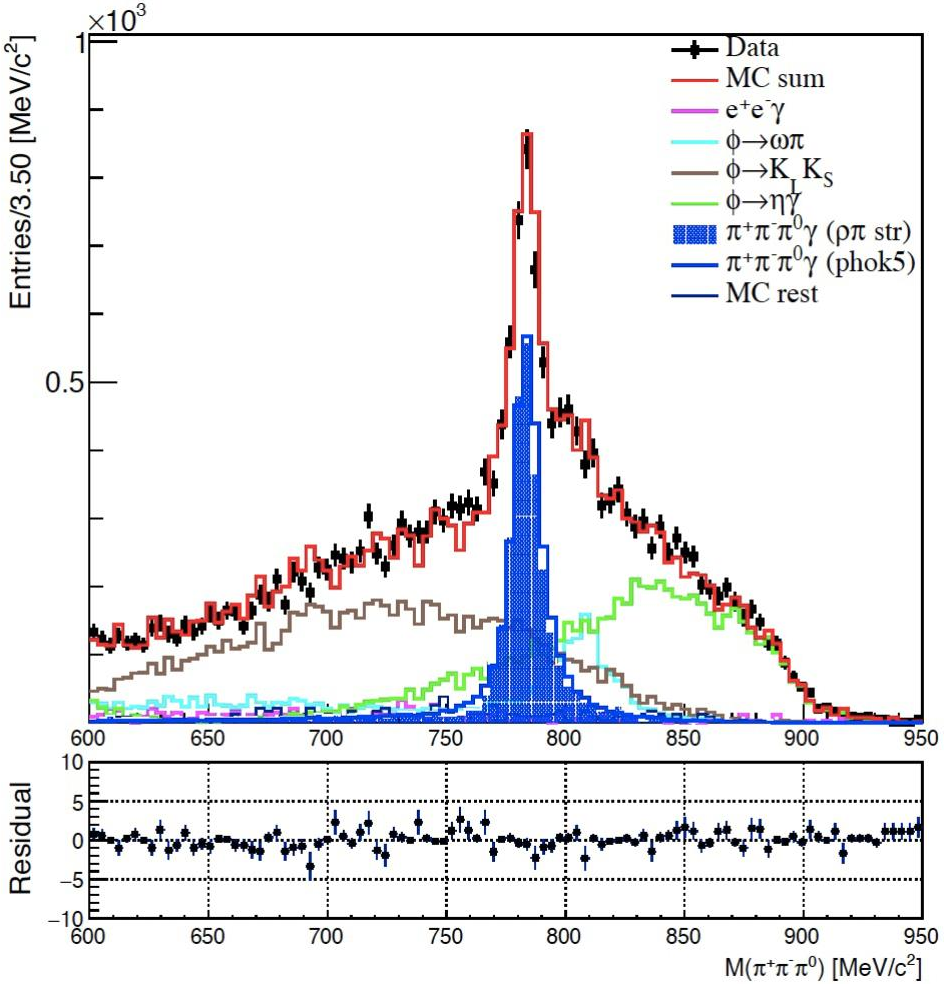
$$\rho = \sqrt{x^2 + y^2} < 4 \text{ cm and } |z| < 10$$

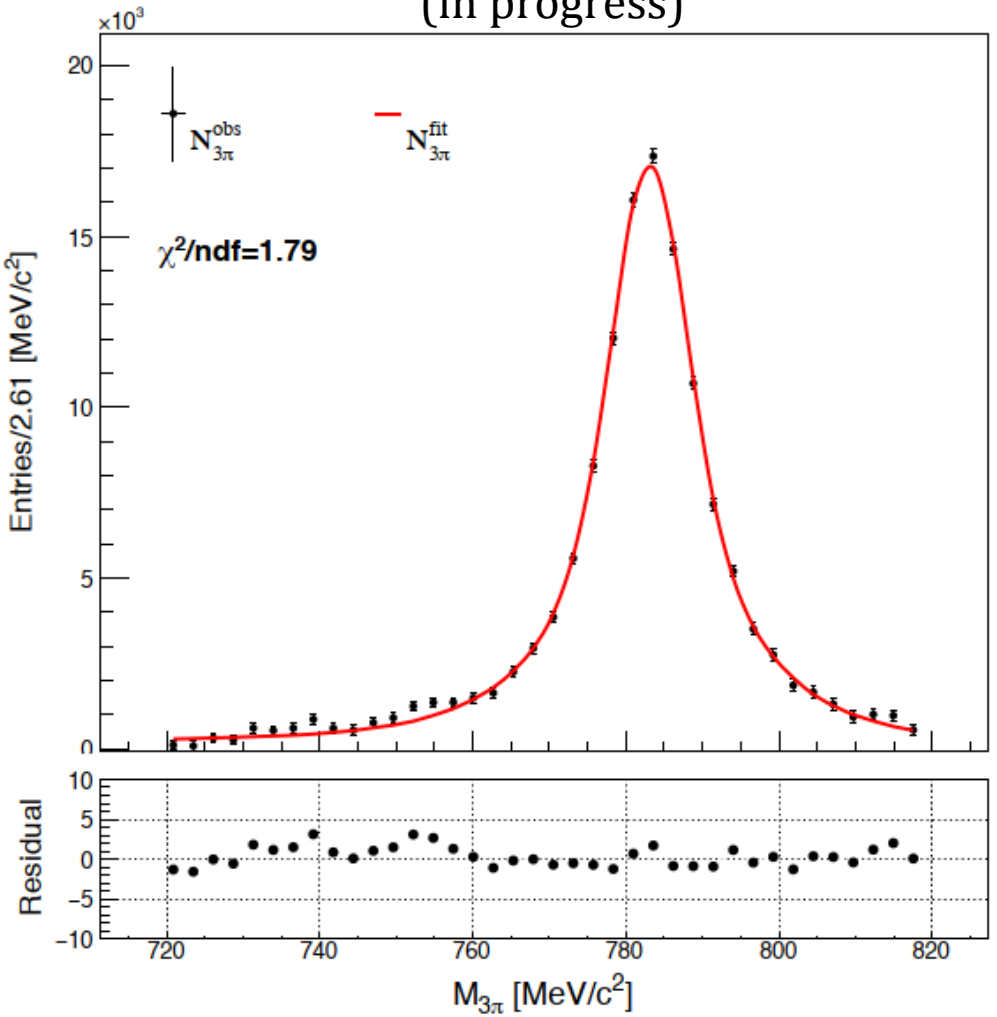
Additional selection:
- 7C Kinematic fit with $\chi^2 < 26$ to reject kaons
- $\cos \sphericalangle(\gamma\gamma)$ to reject Bhabha events
- Eγ< 207 MeV to reject $\rho\pi$

$$E_\gamma = |\bar{p}_{\pi+} + \bar{p}_{\pi-}| - \left(\sqrt{s} - \sqrt{m_\pi^2 + p_{\pi-}^2} - \sqrt{m_\pi^2 + p_{\pi+}^2}\right)$$

$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$

Extraction of the cross section in the ω region (in progress)

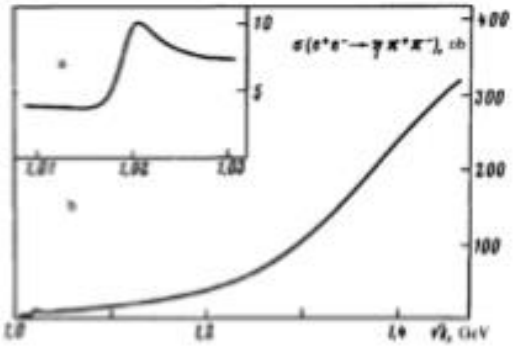




Data fit with single BW ⊗ (ISR radiator) ⊗ (mass resolution smearing)
Improving fit quality with better mass resolution description (2 gausians)
Stat. uncertainties on omega parameters promising
Analysis of systematic effects ongoing
Theory fit model being refined

$\phi \to \eta\pi^+\pi^-, \eta\mu^+\mu^-$

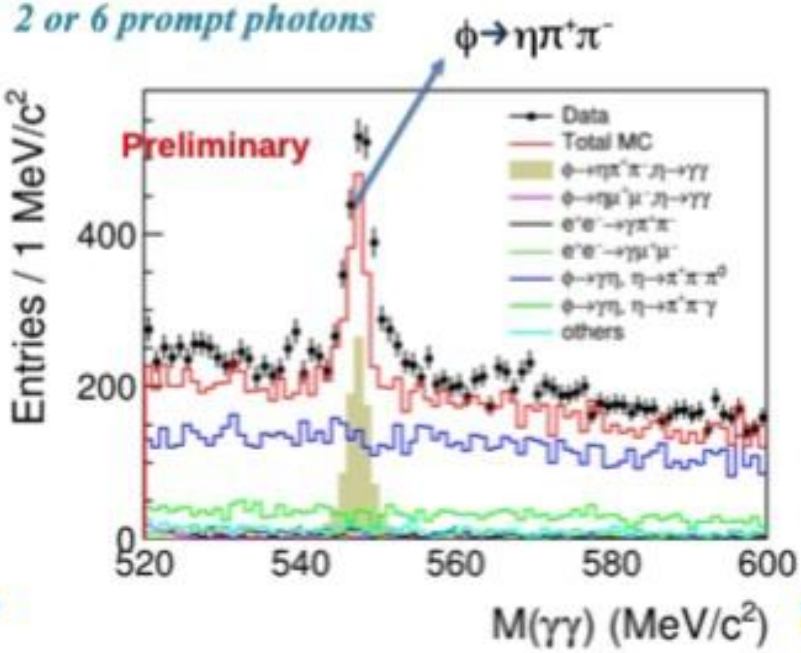
- In VMD model, $e^+e^- \to \eta\pi^+\pi^-$ is proceed via ρ resonances, mainly via ρη intermediate state. KLOE/KLOE-2 data allow to measure the line shape around φ
- $\phi \to \eta\pi^+\pi^-$ violates the OZI rule and G-parity, VMD predicts the Br~ 0.35×10^{-6}. Br<1.8×10^{-5} @ 90% CL @ CMD-2 PLB491(2000)81
- The same sample can be also used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$, Br<0.94×10^{-5} @ 90% CL @ CMD-2 PLB501(2001)191

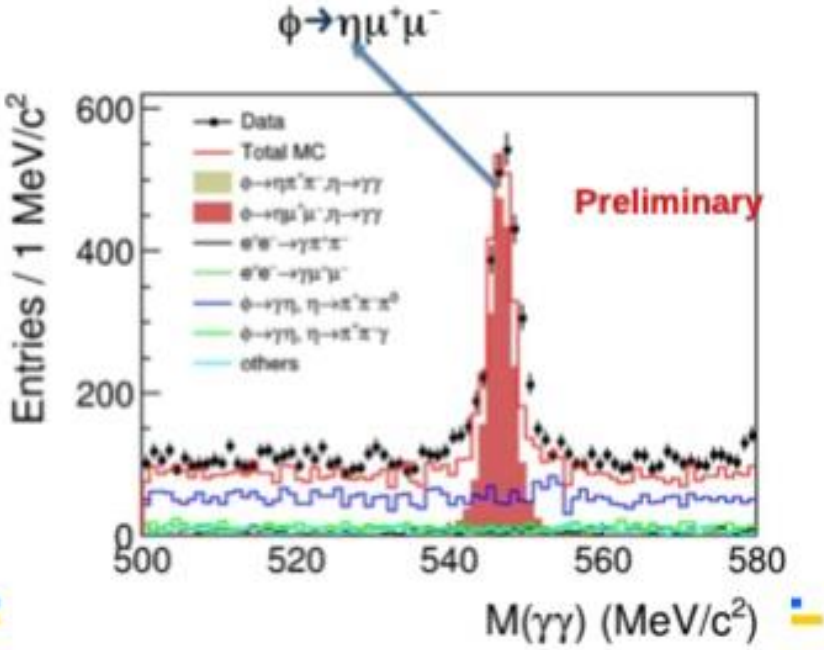


With ~700 pb^{-1} KLOE data, analysis procedure for $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ is established:

- *$\eta \to \gamma\gamma/\pi^0\pi^0\pi^0$*
- *2 charged tracks*
- *2 or 6 prompt photons*

clear $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ signals





Conclusions

KLOE and KLOE-2 have collected in total 8fb^{-1} high quality data for kaon and light energy hadron physics

- Limit on $BR(\eta \to \pi^+\pi^-) < 4.9 \times 10^{-6}$ 90% CL, 3× improvement
- Studies of 5γ final states:
  - search for leptophobic B-boson in $\phi \to \eta B \to \eta\pi^0\gamma$
  - study the ChPT suppressed $\eta \to \pi^0\gamma\gamma$
    prel. BR ~1/2 of A2 value
- $\gamma\gamma \to \pi^0$ and tagged with HET to determine $\Gamma(\pi^0 \to \gamma\gamma)$:
  using first 1.5 fb^{-1} 8% stat. error reached
  calibration of the remaining data sets
  Investigation effect of kinematic fit procedure on reconstructed

- Clean signal $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$ in the ω region.
  Stat. uncertainty looks very promising
- First observation of $\phi \to \eta\pi^+\pi^-, \eta\mu^+\mu^-$