PANIC11

Hadron Physics at KLOE/KLOE-2

Focus on

- measurements of $\sigma(e^+e^-\to\pi^+\pi^-(\gamma))$ and evaluation of $a_\mu^{\pi\pi}$
- η meson electromagnetic processes: $\eta\to e^+e^-e^+e^-(\gamma)$ and $\gamma^*\gamma^*\to\eta$
- searches for exotic phenomena with the η meson: the U boson in $\phi\to\eta U$ and test of the box anomaly with $\eta\to\pi^+\pi^-\gamma$

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MIT, *Cambridge, MA - July, 28th 2011*

$$\sigma(e^+e^- \to \pi^+\pi^-) = \frac{\pi\alpha^2}{3s}|F_\pi|^2\beta_\pi^3$$

measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ and contribution to a_μ with

$d\sigma(e^+e^- \to \pi^+\pi^-\gamma)/d\sigma(e^+e^- \to \mu^+\mu^-\gamma)$:

comparison with past KLOE measurements

$\sigma(e^+e^- \to \text{hadrons})$ with Initial State Radiation

- ~ 3 σ discrepancy between $a_\mu^{SM} - a_\mu^{exp}$ $[a_\mu = (g_\mu - 2)/2]$
- $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$ → main contribution to the uncertainty on a_μ^{SM}

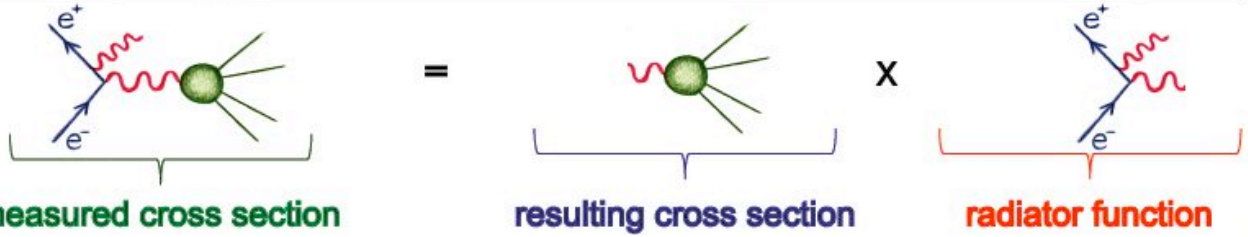
$$a_\mu^{had,LO} = 1/(4\pi^3)\int_{4m_\pi^2}^{\infty} \sigma(e^+e^- \to \text{hadr.})K(s)ds \quad ; \quad K(s) \sim 1/s$$

$\pi^+\pi^-$ accounts for 70% of a_μ^{had} and 60% of δa_μ^{had}

Neglecting final state radiation (FSR):

at DAΦNE, with fixed √s

$$\frac{d\sigma(e^+e^- \to hadrons + \gamma)}{dM^2_{hadr}} = \frac{\sigma(e^+e^- \to hadrons, M^2_{hadr})}{s} H(s, M^2_{hadr})$$



Two different selections:

(1) photon emitted at Small Angle (S.A. analysis) irreducible backgrounds free

[PLB606(2005)12, PLB670(2009)285]

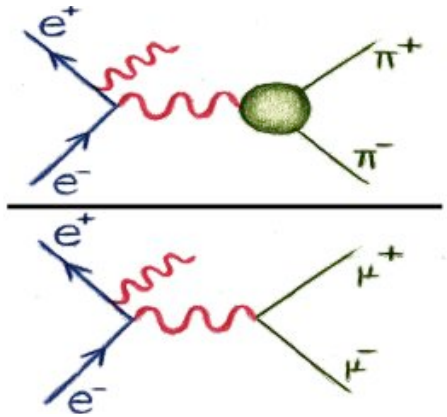
(2) photon emitted at Large Angle (L.A. analysis) $\pi^+\pi^-$ threshold accessed

[PLB700(2011)102]

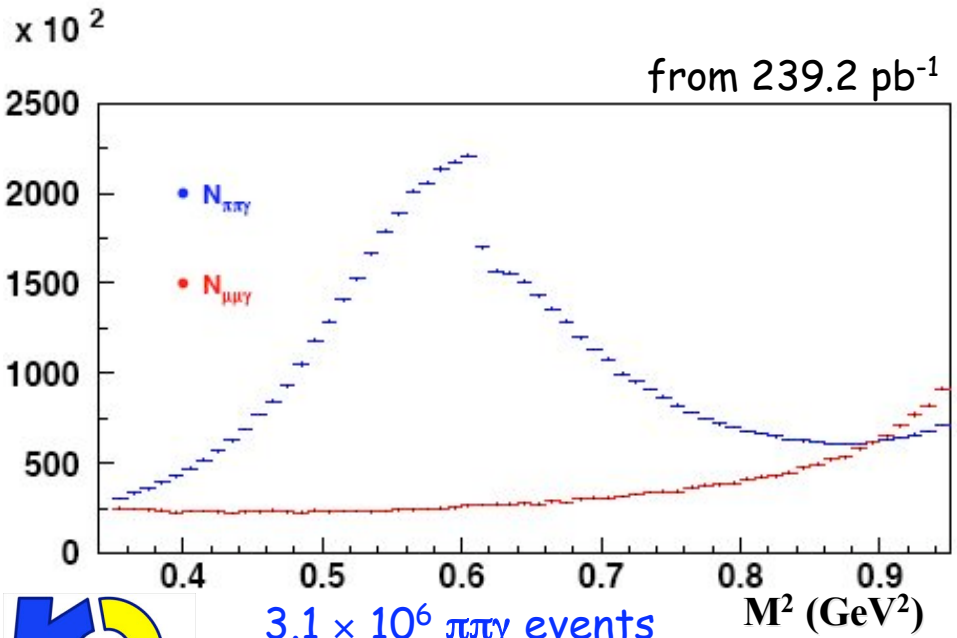
The ratio $d\sigma(e^+e^-\to\pi^+\pi^-\gamma)/d\sigma(e^+e^-\to\mu^+\mu^-\gamma)$

past results based on the H function, provided with 0.5% error → alternative:
$|F_\pi|^2$ from the bin-by-bin ratio of pion over muon yields

$$|F_\pi(s_{\gamma^*})|^2 \sim \frac{4(1+2m_\mu^2/s_{\gamma^*})\beta_\mu}{\beta_\pi^3}\frac{d\sigma_{\pi\pi\gamma}/ds_{\gamma^*}}{d\sigma_{\mu\mu\gamma}/ds_{\gamma^*}}$$

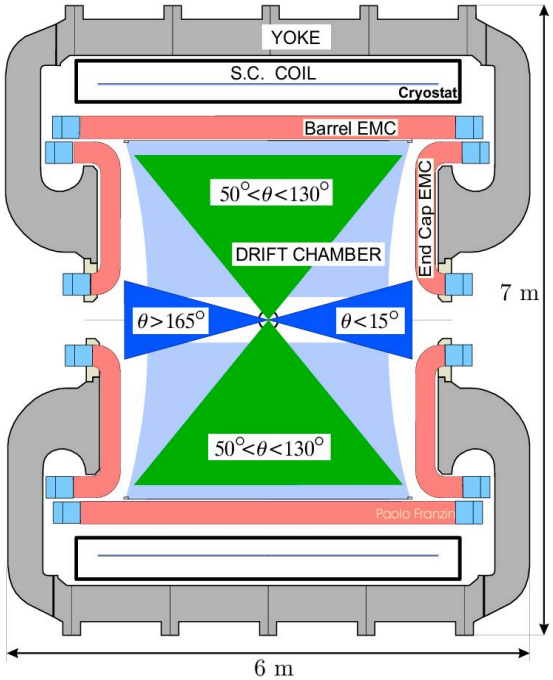


radiator function H, vacuum polarization corrections and
- with the same data sample - luminosity cancel out



3.1 × 10^6 ππγ events
0.9 × 10^6 μμγ events

μμγ selection with Photon at Small Angle, same as the ππγ in PLB670(2009)285



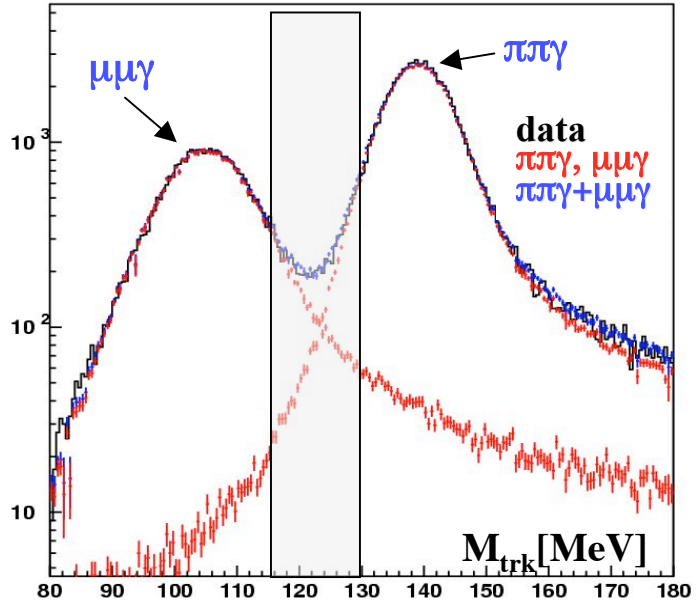
Federico Nguyen
07-28-2011

Measurement of $d\sigma(e^+e^- \to \mu^+\mu^-\gamma)$

the challenge is $\pi\pi\gamma/\mu\mu\gamma$ separation with ~ 1% accuracy, not trivial *in the ρ region $\sigma_{\pi\pi\gamma}/\sigma_{\mu\mu\gamma}$ ~ 10*

π vs.μ accomplished at the event selection level

$$\left(\sqrt{s} - \sqrt{p_1^2 + M_{trk}^2} - \sqrt{p_2^2 + M_{trk}^2}\right)^2 - (p_1 + p_2)^2 = 0$$

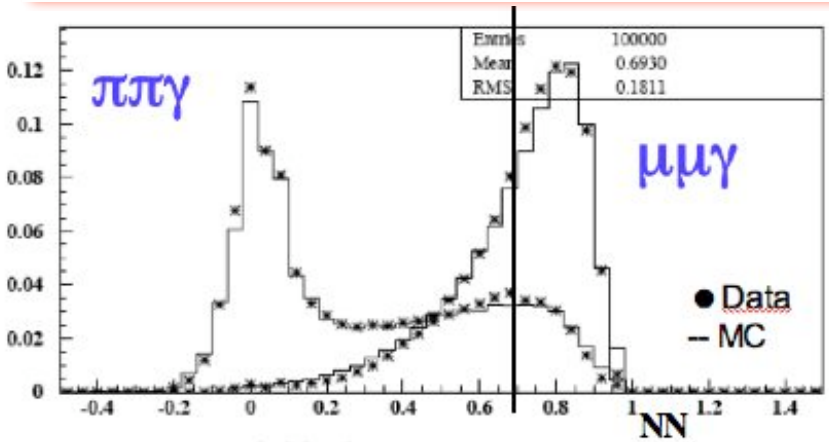


✓ selection checked against 2 other different methods (kinematic fit, tighter cuts on the quality of the charged tracks)

π vs. μ accomplished per single track: crucial for single track efficiency on data

✓ trigger, tracking and PID efficiencies evaluated on control samples from data

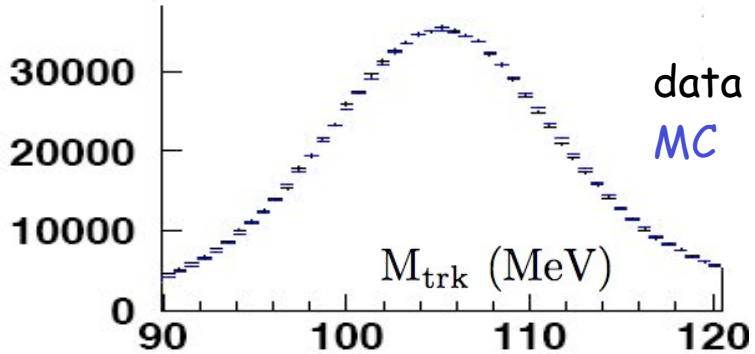
✓ PID (π,μ vs. e and π vs. μ) based on calorimeter information

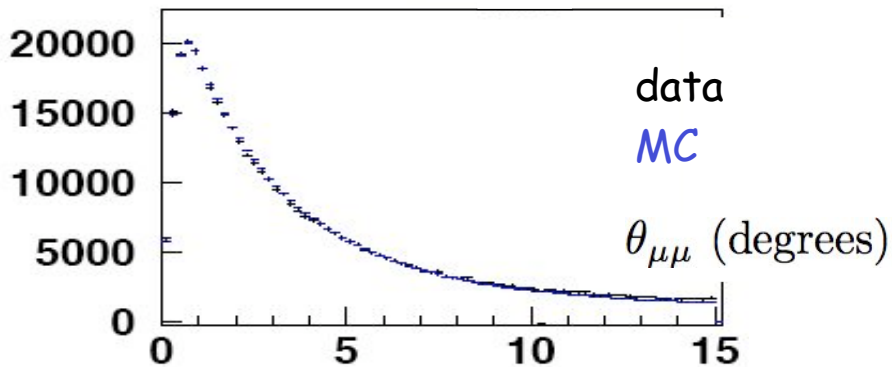


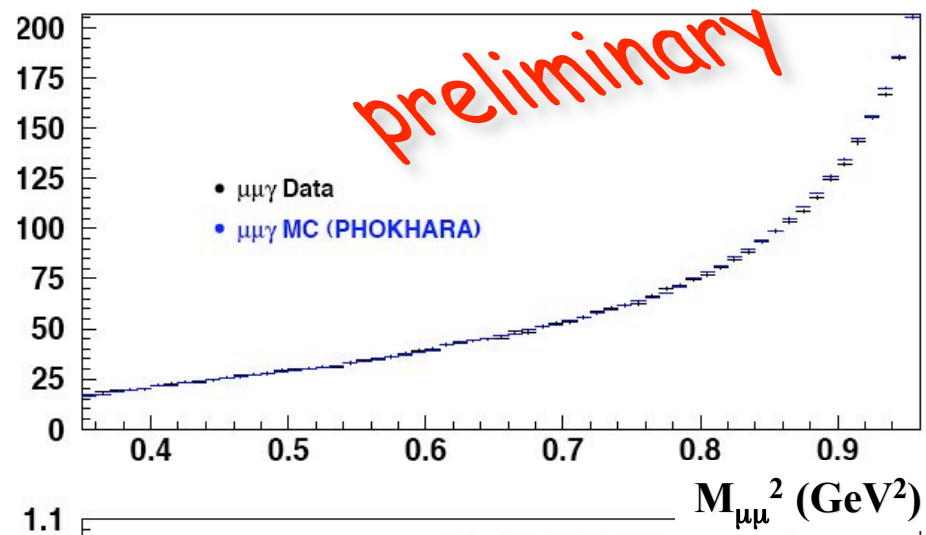
Test of the ISR method with $\mu^+\mu^-\gamma$ events

MC PHOKHARA: $\mu\mu\gamma$ @ NLO, EPJC39(2005)411

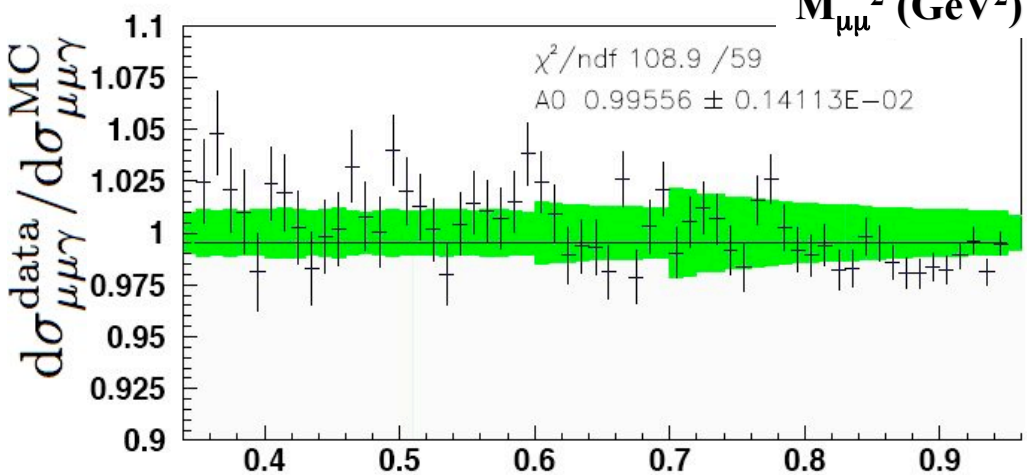
$$\frac{d\sigma_{\mu\mu\gamma}}{dM^2_{\mu\mu}} = \frac{N^{obs} - N^{bkg}}{\Delta M^2_{\mu\mu}} \cdot \frac{1}{\varepsilon_{sel}} \cdot \frac{1}{L}$$







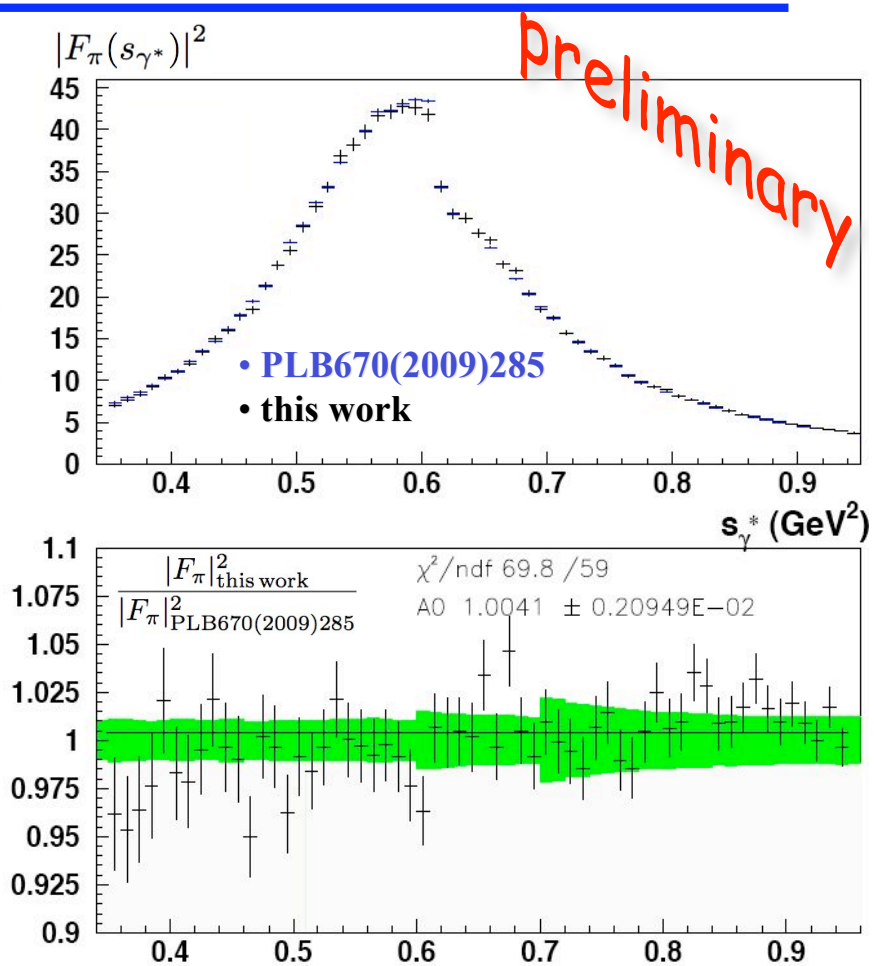
$$\frac{d\sigma^{data}_{\mu\mu\gamma}}{d\sigma^{MC}_{\mu\mu\gamma}} = 0.996 \pm 0.001_{stat} \pm 0.011_{syst}$$



consistency check of the H radiator function (PHOKHARA) and luminosity measurement

This work vs. PLB670(2009)285

Syst. errors (%)	PLB670(2009)285 $\Delta^{\pi\pi}a_\mu$ abs	this work $\Delta^{\pi\pi}a_\mu$ ratio
Reconstruction Filter	negligible	negligible
Background subtraction	0.3	0.8 $(0.3_{\pi\pi\gamma} \oplus 0.7_{\mu\mu\gamma})$
Trackmass	0.2	0.4 $(0.2_{\pi\pi\gamma} \oplus 0.4_{\mu\mu\gamma})$
Particle ID	negligible	negligible
Tracking	0.3	0.6 $(0.3_{\pi\pi\gamma} \oplus 0.5_{\mu\mu\gamma})$
Trigger	0.1	0.1 $(0.1_{\pi\pi\gamma})$
Unfolding	negligible	negligible
Acceptance $(\theta_{\pi\pi})$	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	0.1	0.1 $(0.1_{\pi\pi\gamma} \oplus 0.1_{\mu\mu\gamma})$
Luminosity	0.3 $(0.1_{th} \oplus 0.3_{exp})$	-
$\sqrt{s}$ dep. of H	0.2	-
Total exp systematics	0.6	1.0
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.3
Rad. function H	0.5	-
Total theory systematics	0.6	0.3
Total systematic error	0.9	1.1



this work agrees with PLB670(2009)285 and halves the theory correlated error

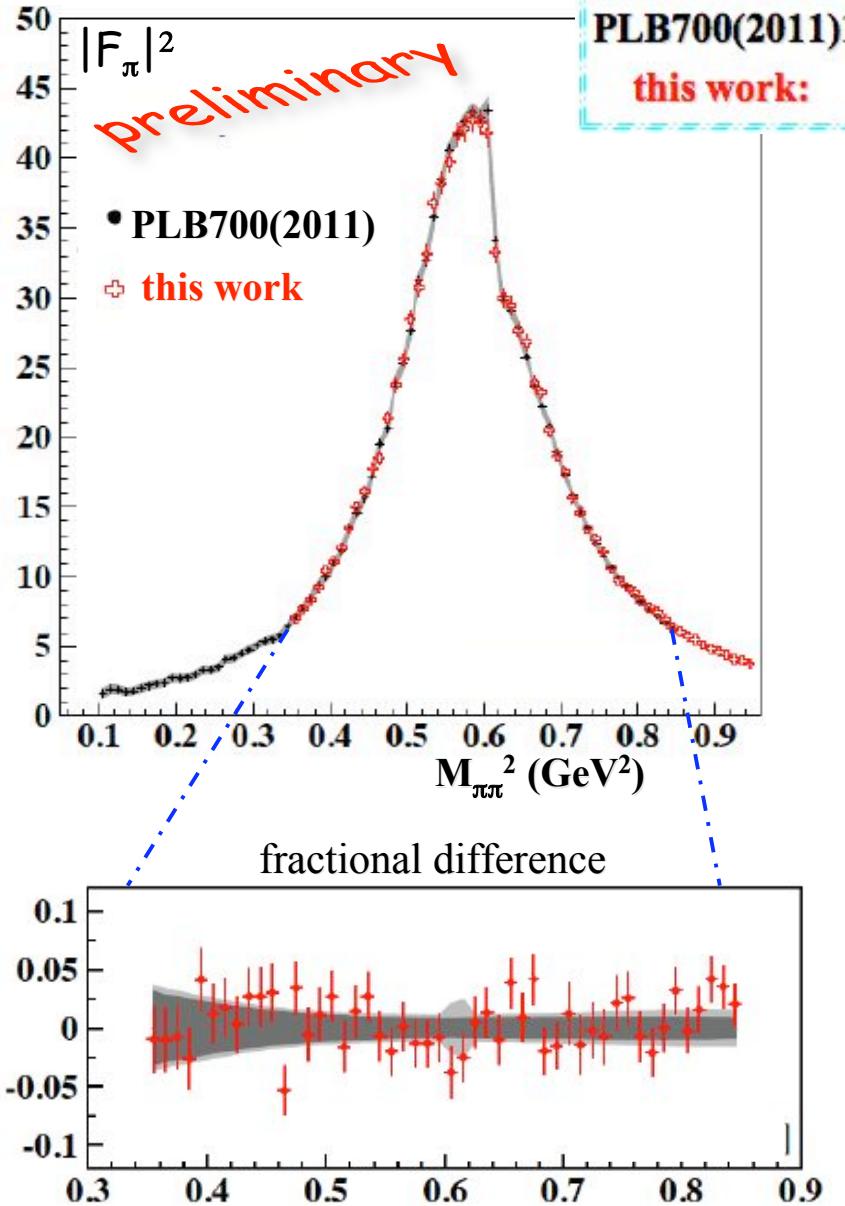
PLB670(2009)285: $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \text{GeV}^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{syst} \pm 2.3_{th}) \times 10^{-10}$

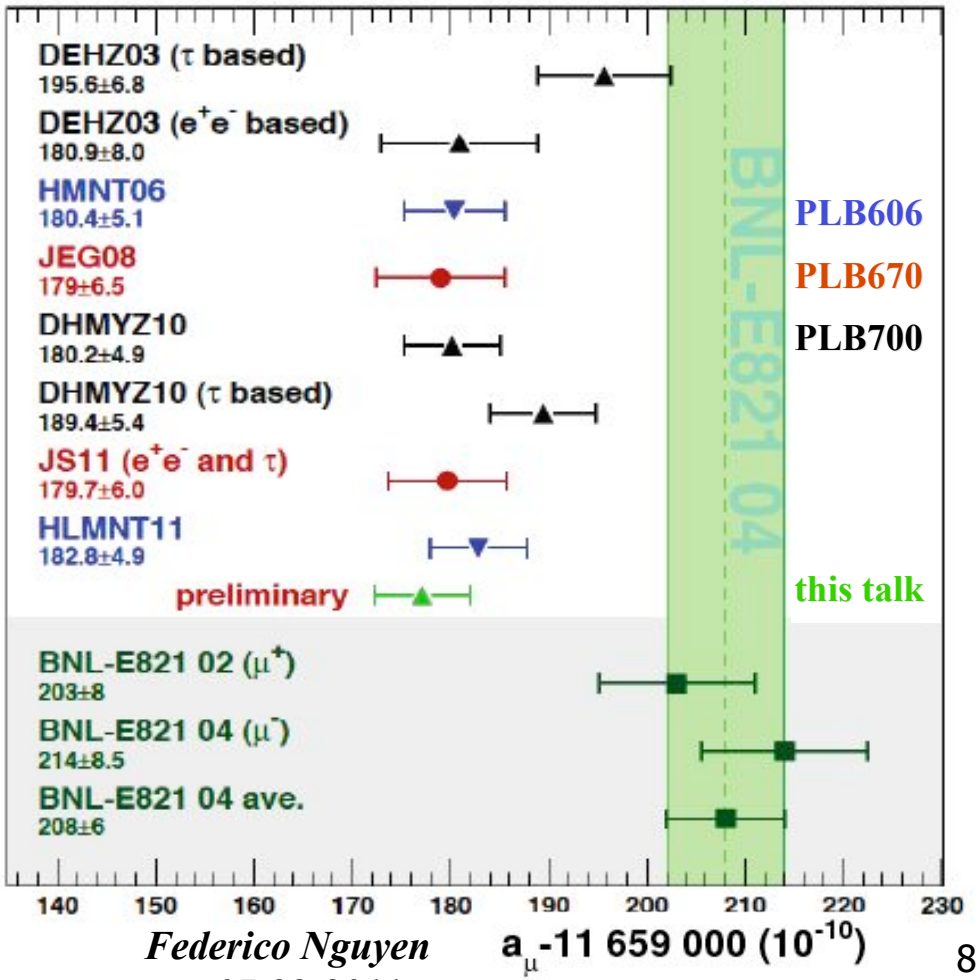
this work: $a_\mu^{\pi\pi}(0.35\text{-}0.95\ \text{GeV}^2) = (384.1 \pm 1.2_{stat} \pm 4.0_{syst} \pm 1.2_{th}) \times 10^{-10}$

This work vs. PLB700(2011)102

PLB700(2011)102: $a_\mu^{\pi\pi}(0.35\text{-}0.85\ \mathrm{GeV}^2) = (376.6 \pm 0.9_{stat} \pm 3.3_{syst+th}) \times 10^{-10}$

this work: $a_\mu^{\pi\pi}(0.35\text{-}0.85\ \mathrm{GeV}^2) = (376.4 \pm 1.2_{stat} \pm 4.1_{syst+th}) \times 10^{-10}$





η meson: electromagnetic and exotic dynamics

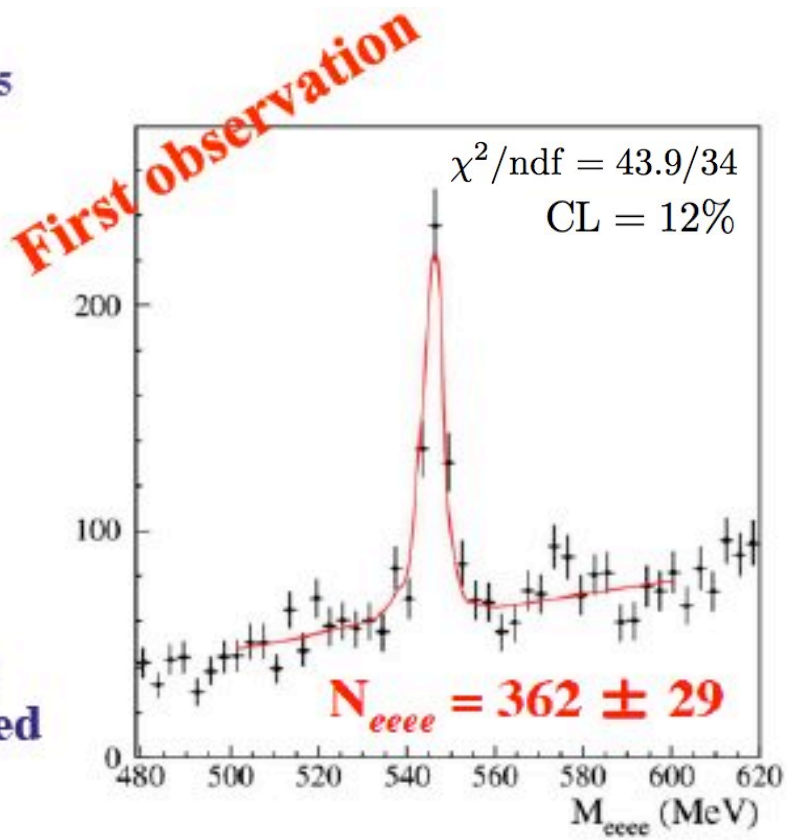
Observation of the $\eta \to e^+e^-e^+e^-$ decay

- Theoretical predictions: BR ~ 2.4 – 2.6 $\times 10^{-5}$

- BR < 6.9×10^{-5} @90%C.L. (CMD-2, 2001)
  BR < 9.7×10^{-5} @90%C.L. (WASA, 2008)
  (2 evts, with 1.3 bckg)

- Data sample: 1.7 fb^{-1}
- MC simulation according to
  Bijnens and Persson [hep-ph/0106130]
- e^+e^- pairs from photon conversions in the beam pipe and Drift Chamber wall rejected

- Fit with signal + background from continuum ($e^+e^- \to e^+e^-\gamma$ with γ conversion)



accepted by PLB [arXiv: 1105.6067]

$$BR(\eta \to e^+e^-e^+e^-(\gamma)) = (2.4 \pm 0.2_{stat} \pm 0.1_{syst}) \times 10^{-5}$$

Observation of $e^+e^- \to e^+e^-\eta$ @ 1 GeV

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

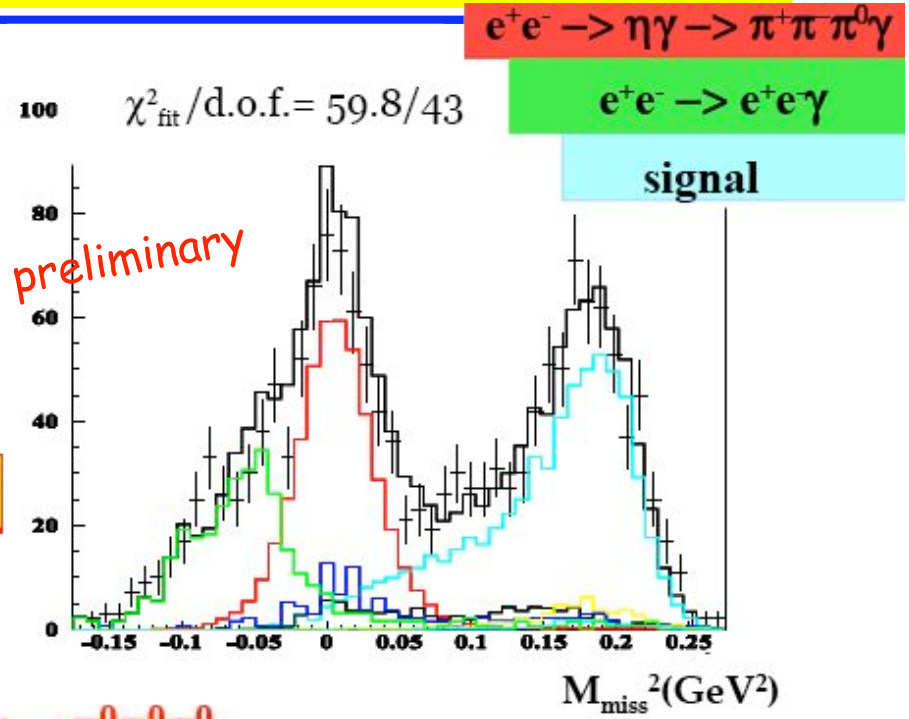
$$\sigma_{\gamma\gamma\to X}(q_1,q_2) \propto \Gamma_{X\to\gamma\gamma}\frac{8\pi^2}{M_X}\delta((q_1+q_2)^2 - M_X^2)\left|F(q_1^2,q_2^2)\right|^2$$

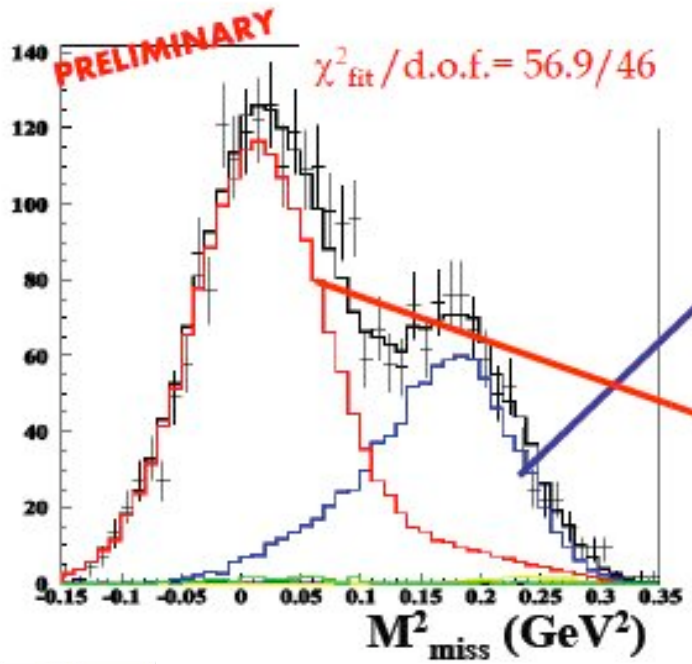
Data sample: 240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV)

Main bckg: $e^+e^- \to \eta\gamma$ with γ lost

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

$\Rightarrow$ 650 signal events





- **$\gamma\gamma\to\eta$; $\eta\to\pi^0\pi^0\pi^0$**
- **Fit to the missing mass distribution:**

$\Rightarrow$ 921 signal events

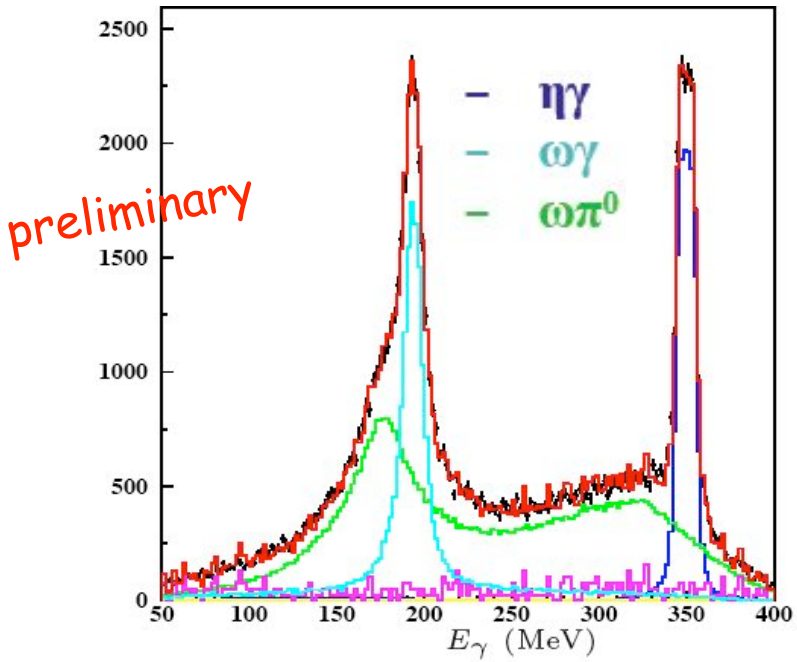
1760 $e^+e^- \to \eta\gamma$ events

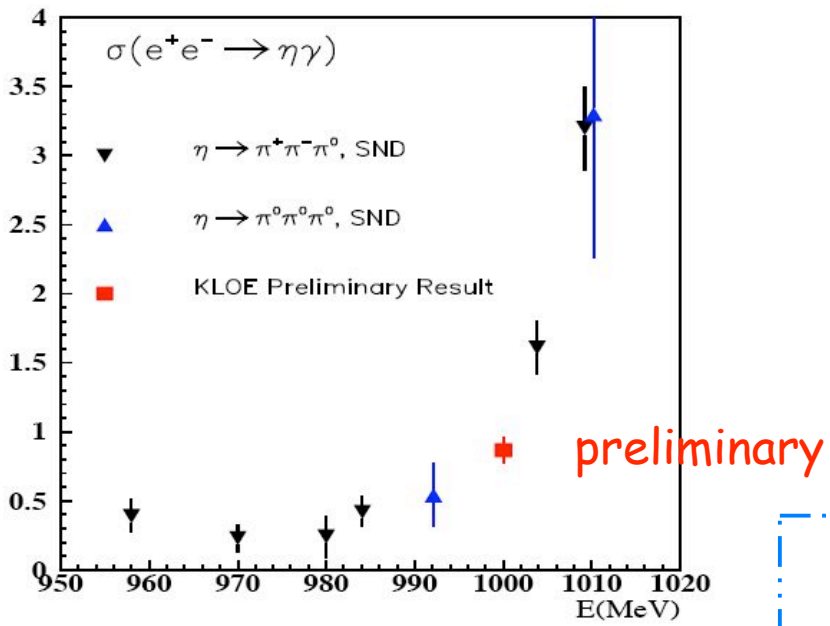
extraction of $\Gamma_{\eta\gamma\gamma}$ is in progress

Measurement of $\sigma(e^+e^- \to \eta\gamma)$ @ 1 GeV

- $e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$: 3 photons + 2 tracks
  - pion ID
  - kinematic cuts to suppress background from kaons
  - kinematic fit

$\sigma(e^+e^- \to \eta\gamma, 1\ \text{GeV}) = (0.866 \pm 0.009 \pm 0.093)$ nb





- In agreement with the result from $\eta \to \pi^0\pi^0\pi^0$:

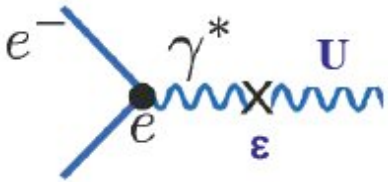
$\sigma(e^+e^- \to \eta\gamma, 1\ \text{GeV}) = (0.875 \pm 0.018 \pm 0.035)$ nb

background for $\gamma\gamma \to \eta$ most accurately measured from the same data sample

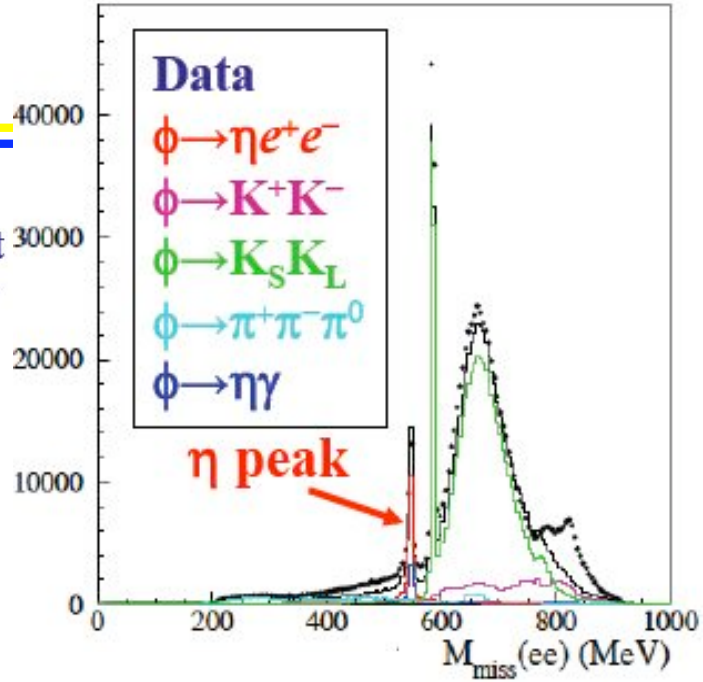
[arXiv: 1107.3782]

Search for the $\phi \to \eta U$ decay

Recent astrophysical observations (PAMELA, ATIC, INTEGRAL, DAMA/LIBRA) can be interpreted by assuming the existence of a light dark sector that interacts with SM particles through a mixing of a new gauge boson, U with *O*(1 GeV) mass, with the photon



[Arkani-Hamed et al. PRLD79(2009), 015014
Essig et al., PRD80(2009)015003]



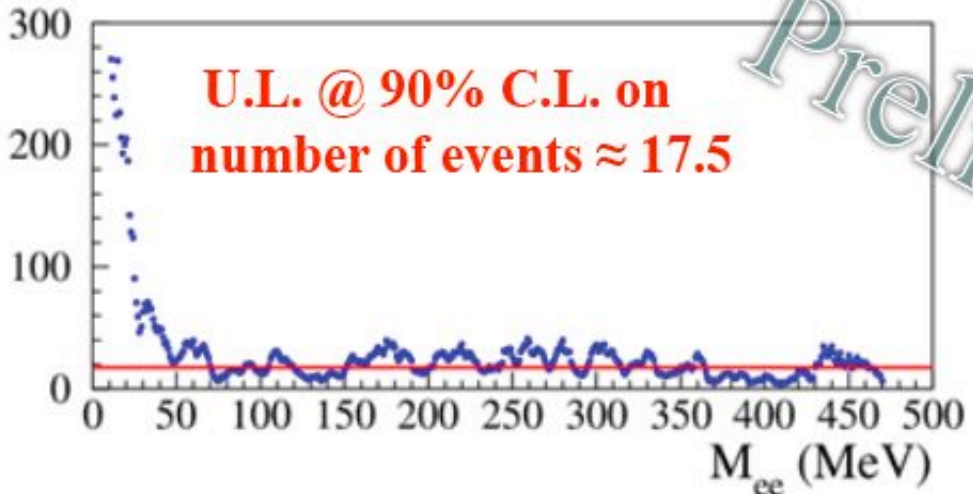
Signature: $\phi \to \eta U$, $U \to \ell^+\ell^-$

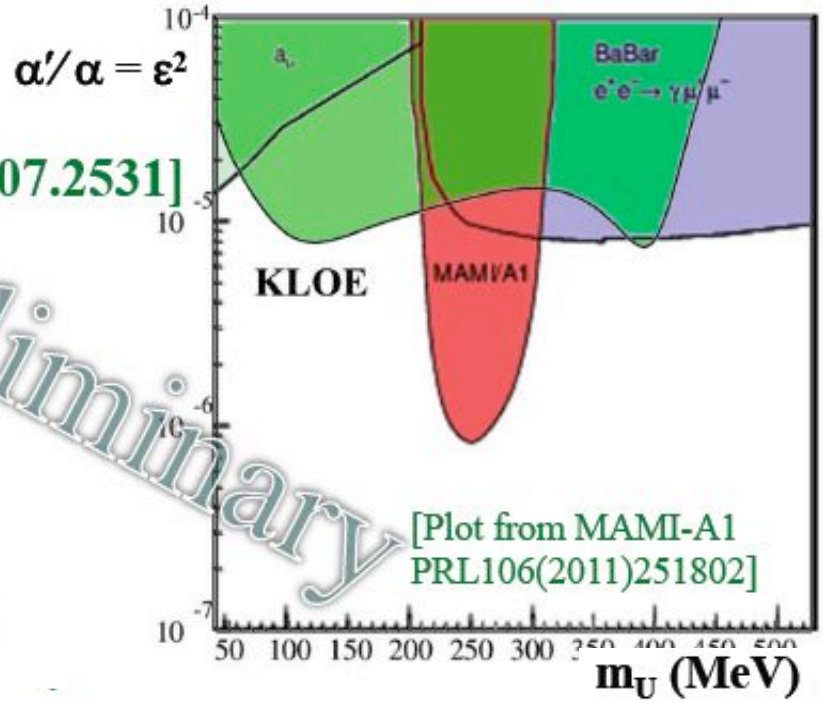
$\Rightarrow \phi \to \eta e^+e^-$ $\eta \to \pi^+\pi^-\pi^0$

Main bckg: $\phi \to \eta\gamma^* \to \eta e^+e^-$

Analyzed sample: 1.5 fb^{-1}

[arXiv:1107.2531]

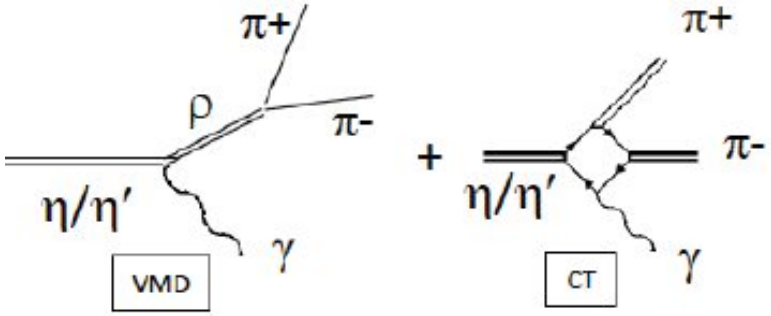




[Plot from MAMI-A1 PRL106(2011)251802]

Preliminary

Study of the $\eta \to \pi^+\pi^-\gamma$ decay



$$\left.\frac{\Gamma_{\eta\to\pi^+\pi^-\gamma}}{\Gamma_{\eta\to\pi^+\pi^-\pi^0}}\right|_{\text{preliminary}} = 0.1838(5)_{\text{stat}}(30)_{\text{syst}}$$

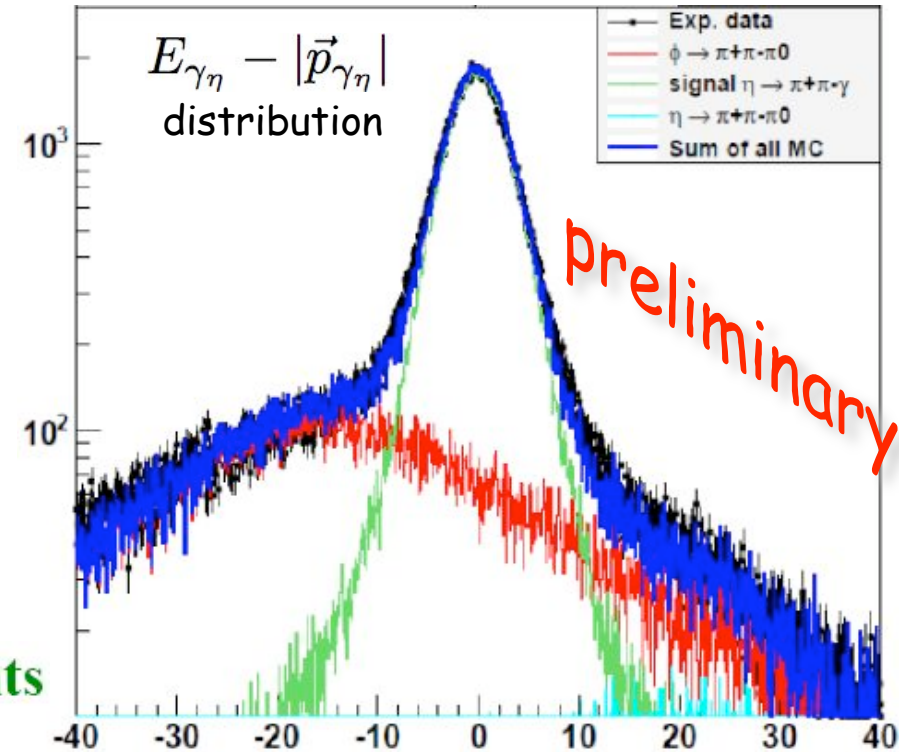
- consistent with CLEO
- fit parameters of the ππ invariant mass in progress

A. Contact Term, CT, due to box anomaly, contribution expected both in $\Gamma_{\eta\to\pi\pi\gamma}/\Gamma_{\eta\to\pi\pi\pi}$ and in the ππ invariant mass

B. the CLEO $\Gamma_{\eta\to\pi\pi\gamma}/\Gamma_{\eta\to\pi\pi\pi}$ result (2007) is 2-3 σ away from previous measurements

$$E_{\gamma_\eta} = \sqrt{s} - E_{\pi^+} - E_{\pi^+} - E_{\gamma_\phi}$$
$$|\vec{p}_{\gamma_\eta}| = |\vec{p}_{\pi^+} + \vec{p}_{\pi^+} + \vec{p}_{\gamma_\phi}|$$

value	events	author	year
0.203 ± 0.008	PDG average		
0.175 ± 0.007 ± 0.006	859	Lopez	2007
0.209 ± 0.004	18 k	Thaler	1973
0.201 ± 0.006	7250	Gormley	1970



$\phi\to\eta\gamma$, $\eta\to\pi^+\pi^-\gamma$: L = 558 pb^{-1}

Main background: $\phi\to\pi^+\pi^-\pi^0$

~ 205 × 10^3 signal events

Conclusions

✓ KLOE published more than 20 papers on hadron physics: scalar mesons studies, η/η' dynamics and decays, hadron cross section measurements…

✓ KLOE keeps on analysing the high statistics collected at DAΦNE featuring: new $|F_\pi|^2$ measurement with the ratio $\pi\pi\gamma/\mu\mu\gamma$ in excellent agreement with past results, 1st evidence of $\eta\to e^+e^-e^+e^-$ and $\gamma\gamma\to\eta$ at $\sqrt{s}$=1 GeV, 1st upper limit on ηU production and study of $\eta\to\pi^+\pi^-\gamma$ decay

✓ KLOE-2, with the plan of > 20 fb^{-1} in the next 3-4 years and upgraded detectors, will provide with opportunities in: precision study of the η/η' dynamics, the search for extremely rare phenomena (dark forces, $f_0(980)\to K\bar{K}$, etc…) and $\gamma\gamma$ physics (transition form factors and scalar mesons)

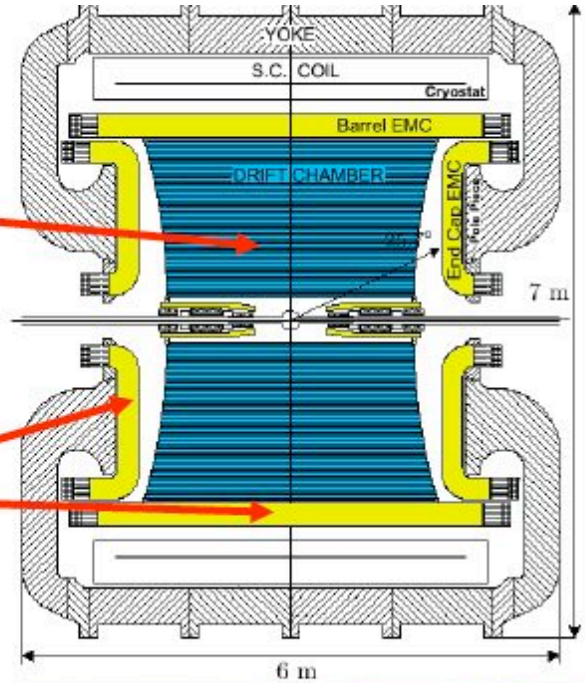
[Eur.Phys.J.C68(2010),619]

KLOE and KLOE-2

Drift chamber:
- gas: 90% He-10% iC_4H_{10}
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 1$ mm

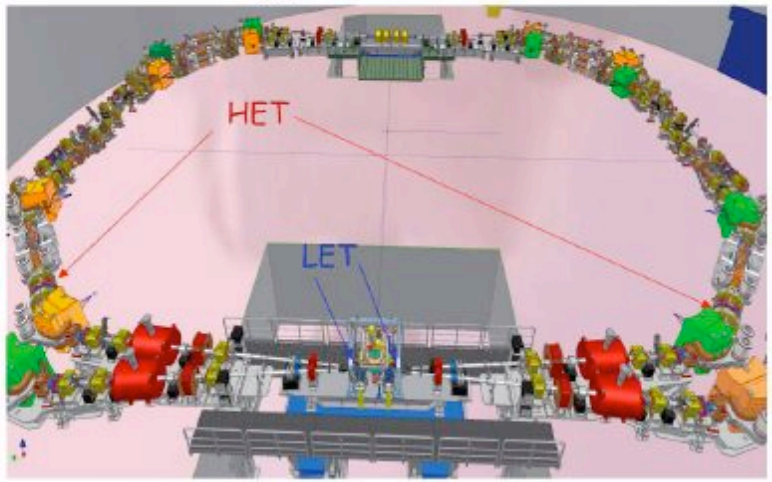
E.m. calorimeter (Pb-Sci.Fi.):
- $\sigma_E/E = 5.7\% / \sqrt{(E(GeV))}$
- $\sigma_t = 55\ ps/\sqrt{(E(GeV))} \oplus 100$ ps
- 98% of 4π

Magnetic field: 0.52 T



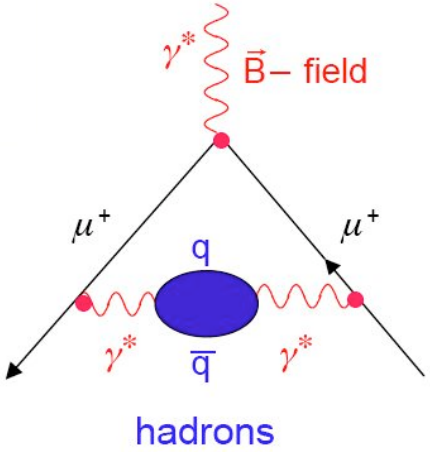
- KLOE-2: a two step upgrade

1) First run (~ 5 fb^{-1} @ ϕ peak)
   $e^{\pm}$ taggers for $\gamma\gamma$ physics (already installed)
2) Major upgrades (Summer 2012) (L>20 fb^{-1})
   inner tracker +
   new small angle calorimeters

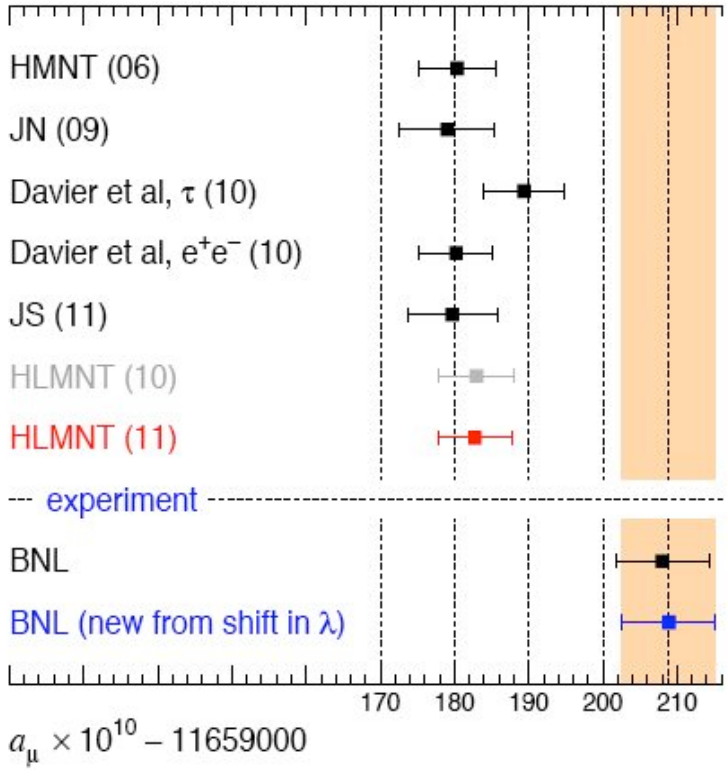


The $(g\text{-}2)_\mu$: brief status

$$\vec{\mu} = g_\mu \frac{e}{2m_\mu}\,\vec{s} \qquad \underbrace{g_\mu = 2}_{\text{Dirac}}(1 + a_\mu)$$



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{EW}$$



$$a_\mu^{exp} = (11\ 659\ 208.9 \pm 6.3) \times 10^{-10}$$

$$\text{new } \lambda = \frac{\mu_\mu}{\mu_p} \text{ value (2009)}$$

$$a_\mu^{exp} - a_\mu^{SM} = (26.1 \pm 8.0) \times 10^{-10}$$

3.3 standard deviations

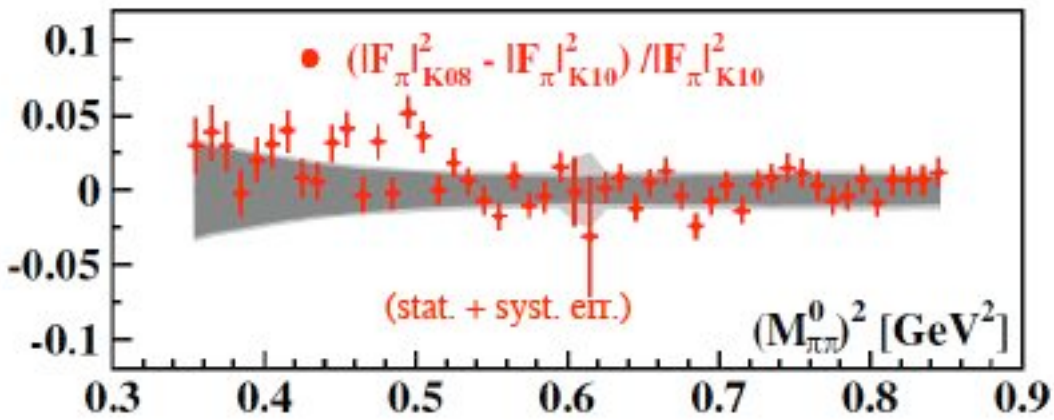
$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int \sigma(e^+e^- \to \pi^+\pi^-)K(s)\,ds$$

Measurements of the $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$

Normalized to luminosity

- KLOE measurements of $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$:
  - Small (photon) angle measurements (KLOE05, KLOE08)
  - Large (photon) angle measurement (KLOE10)
  - Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND/BaBar

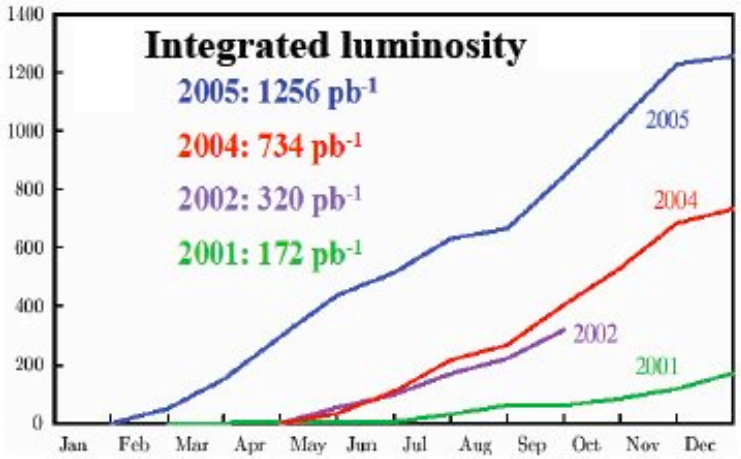
fractional difference btw KLOE08 and KLOE10



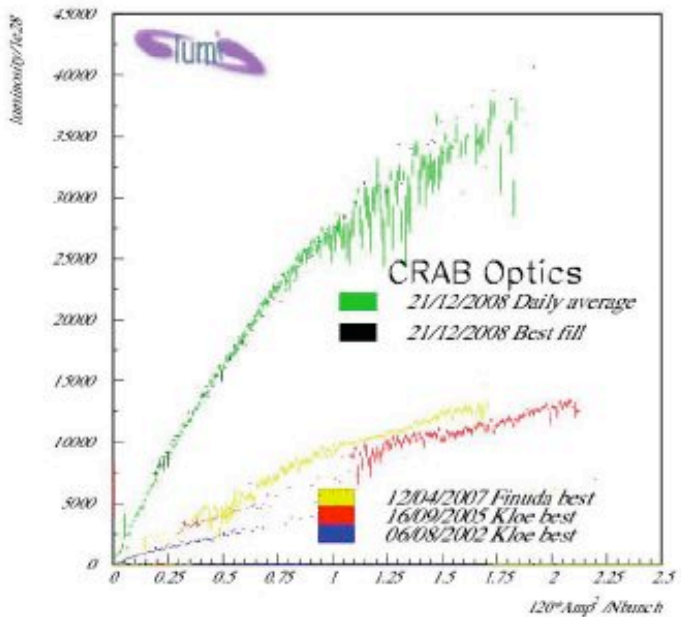
DAΦNE

- Frascati ϕ-factory: e^+e^- collider @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$; $\sigma_{peak} \approx 3.1\ \mu b$

- Best performances in 2005:
  - $L_{peak} = 1.4 \times 10^{32}\ cm^{-1}s^{-1}$
  - $\int Ldt = 8.5\ pb^{-1}/day$
- KLOE: 2.5 fb^{-1} @ $\sqrt{s}=M_\phi$ ($\Rightarrow 8\times10^9\ \phi$ produced) + 250 pb^{-1} off-peak @ $\sqrt{s}=1000$ MeV



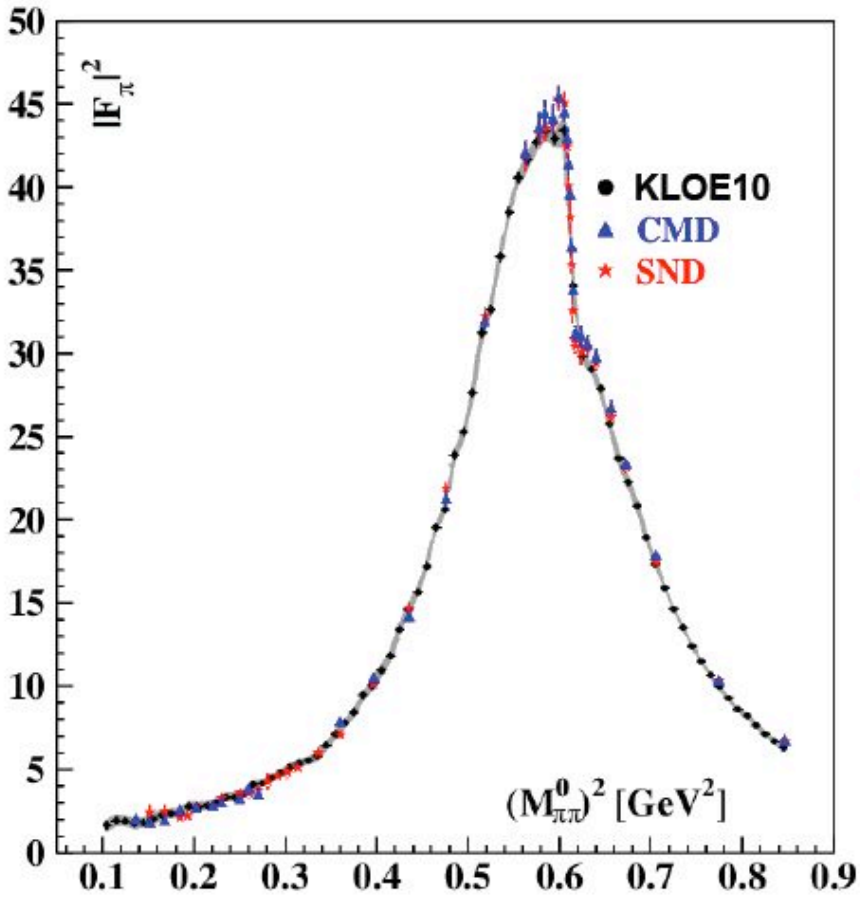
- DAΦNE upgrade:
  New interaction scheme implemented, large beam crossing angle + crabbed waist optics

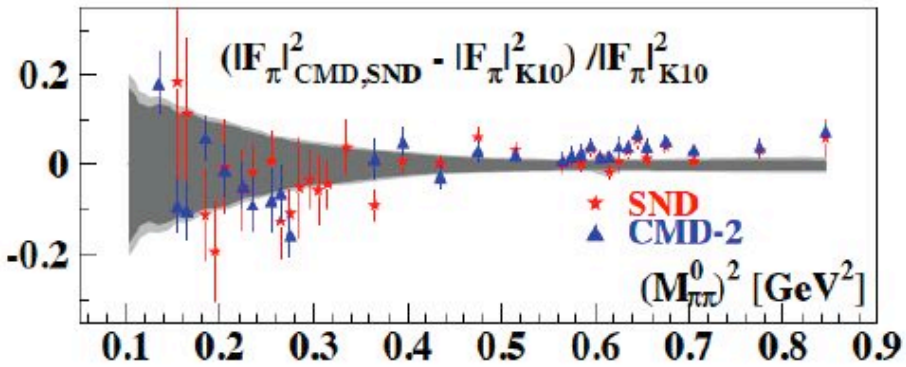


$\Rightarrow$ Luminosity increase expected: factor ~ 3
$\int Ldt \approx 1\ pb^{-1}/hour$

- DAΦNE commissioning will restart in October 2011

Spare 1

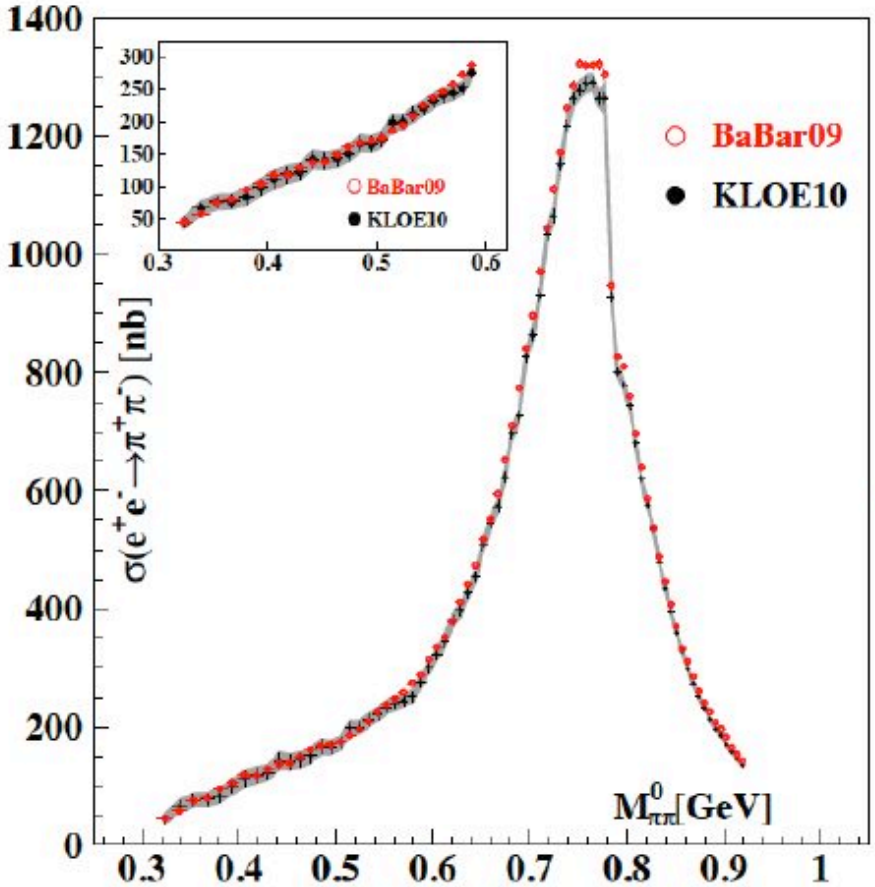


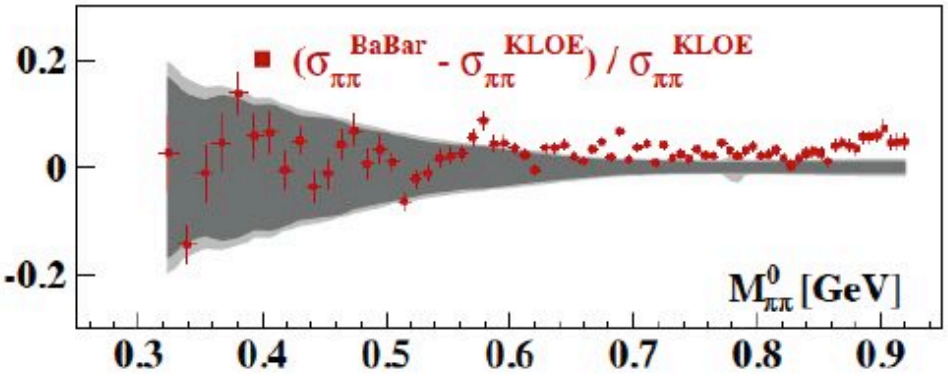


band: KLOE10 error

Below the ρ peak good agreement with CMD-2/SND.
Above the ρ peak KLOE10 slightly lower (as KLOE08)

Spare 2





band: KLOE10 error

Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above