UNIVERSITAS IAGELLONICA CRACOVIENSIS

FNP Foundation for Polish Science

Symposium on applied nuclear physics and innovative technologies

Precision measurements of hadronic contributions to muon anomaly with KLOE

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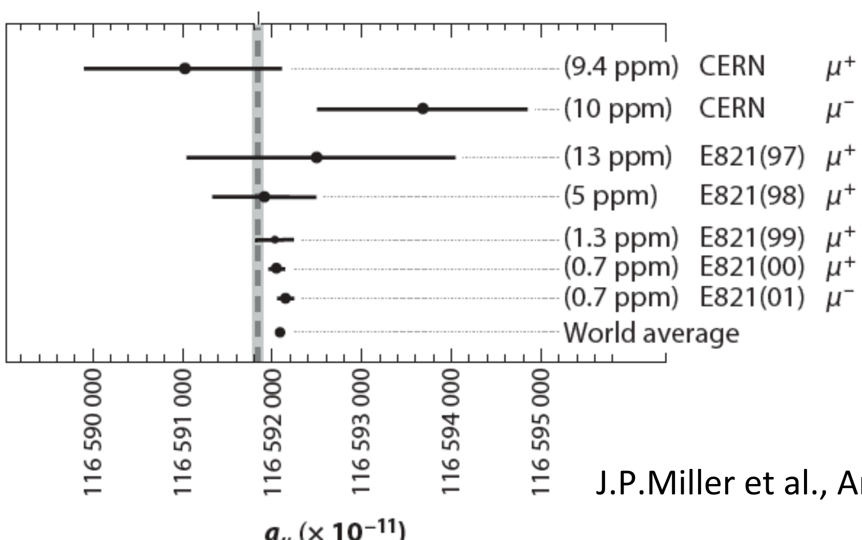
Outline

- Hadronic Vacuum Polarization contribution to a_μ
- The KLOE results on the hadronic cross section
  - from absolute measurements of ISR cross section $\sigma(e^+e^- \rightarrow \pi\pi\gamma(\gamma))$
  - from $\sigma(e^+e^- \rightarrow \pi\pi\gamma(\gamma))/\sigma(e^+e^- \rightarrow \mu\mu\gamma(\gamma))$ ratio
- Search for U-boson with the $\mu\mu\gamma$ sample

The muon anomaly

- Muon anomaly $a_\mu = (g_\mu - 2)/2 = 1.16591790(65)\times 10^{-3}$ is dominated by
  - QED lepton-loop contributions, at 4-loops $1.1658471809\ (15)\mathrm{x}10^{-3}$
- The second-most important term comes for vacuum-hadron contribution
  - at level of $6.9\mathrm{x}10^{-8}$
  - dominant contribution at the error
- The experimental result, from E821 at the BNL, is of 0.5 ppm precision



$$a_\mu = 1.16592089(63)\times 10^{-3}$$

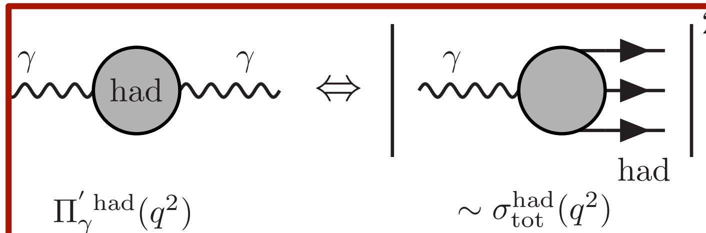
J.P.Miller et al., Annu.Rev.Nucl.Part.Sci. 62(2012)237

Hadron vacuum polarization

- Hadron vacuum polarization, HVP, is relevant for precision tests of the SM

- Prediction of the HVP contribution is obtained from the hadronic cross section weighted by kernel functions, integrated over s (dispersion integrals, DI)

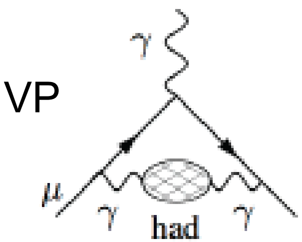
$$\Delta v^{had} = \int_{s_{\min}}^{s_{\max}} \sigma^0_{had}(s) \cdot \mathrm{K}(s)\, ds$$



- Precision σ^0_{had} predictions from pQCD requires $q^2 > 2$ GeV^2. At lower energy, $\sigma^{0,data}_{had}$ is used

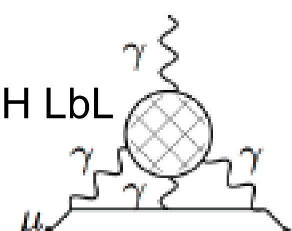
- For $a_\mu = \left(g_\mu - 2\right)/2 = 1.16591790(65) \times 10^{-3}$ theoretical precision, of 6.5 10^{-10} is from HVP (5.6) and hadronic light-by-light scattering (3.9)

HLO VP



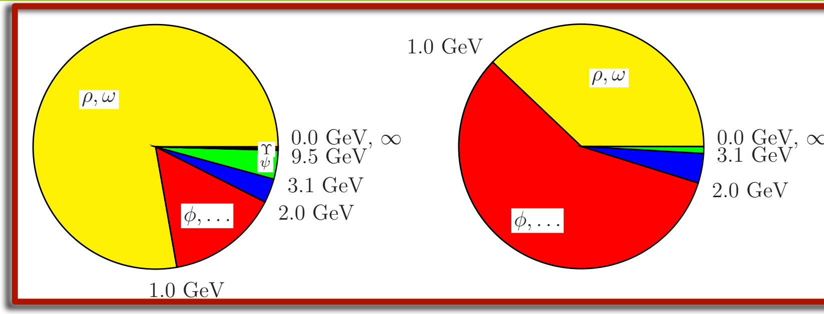
$a_\mu^{HLO} = (692.4 \pm \mathbf{5.6})10^{-10}$
[Jegerlehner, Phys.Rept. 477 (2009) 1]

H LbL

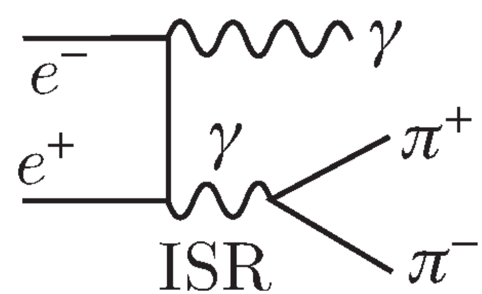


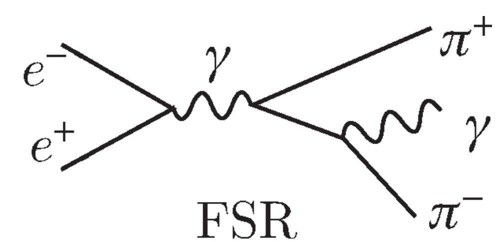
$a_\mu^{HLbL} = (11.6 \pm 3.9)10^{-10}$

Hadronic cross section



- Contributions from the threshold region of hadron production is enhanced by kernel dependence on $1/s^2$ and by the presence of ρ−resonance
- 70% of the contribution from the region below 1 GeV^2
- Most recent hadronic cross section measurements at $s< 1$ GeV^2 have been obtained from
  - energy scan by Novosibirsk experiments, CMD-2 and SND
  - radiative return by experiments at the ϕ and B –factories
- From radiative return it is possible to select hadronic final states of any invariant mass $s_{had} < s_R$
- Angular cuts are effective to obtain ISR-enriched samples. Corrections for residual FSR effects are obtained from precision MonteCarlo generators
- Both, photon-tagged and untagged samples have been used. Photon-tagged samples have been used to reach the dipion threshold running at the ϕ-factory





ISR processes

- The hadronic cross section $\sigma^{0,data}_{had}$ in the DI is obtained from ISR processes and the radiator function H

$$\left.\frac{d\sigma(e^+e^- \to \pi\pi\gamma)}{dM^2_{\pi\pi}}\right|_{ISR} = \frac{\sigma^0_{\pi\pi(\gamma)}(M^2_{\pi\pi})}{s} H\left(M^2_{\pi\pi};s\right)$$

Two KLOE measurements, **PLB670,285** and **PLB700,102**

- Alternatively, from the ratio of the ISR processes, $\pi\pi\gamma$ and $\mu\mu\gamma$,

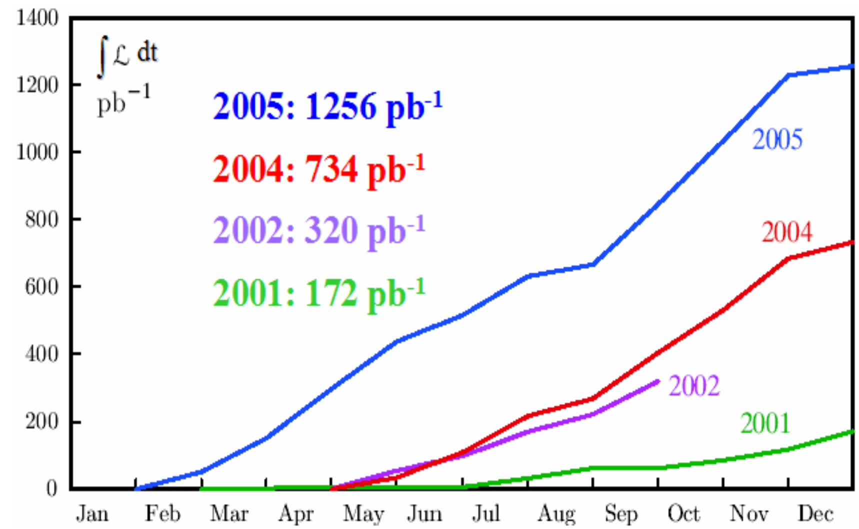
$$\sigma^0_{\pi\pi(\gamma)}(M^2) = \frac{\left.\frac{d\sigma(e^+e^- \to \pi\pi\gamma)}{dM^2}\right|_{ISR}}{\left.\frac{d\sigma(e^+e^- \to \mu\mu\gamma)}{dM^2}\right|_{ISR}} \sigma^0_{\mu\mu}(M^2)$$

PLB720,336

The contribution to the muon anomaly from HVP ($s < 1$ GeV^2) is $\Delta a_\mu^{\pi\pi} = \int_{s_{\min}}^{s_{\max}} \sigma^0_{\pi\pi(\gamma)}(s) \cdot K(s)\, ds$

The KLOE experiment

- The KLOE experiment, at the Daϕne ϕ– factory took data in 2001-2002 and 2004-2006
- 2.5 fb^{-1} integrated at 1.02 GeV; 250 pb^{-1} at 1 GeV
- Excellent-quality data set for precision measurement on
  - CKM unitarity
  - QM, and CPT invariance;
  - CP in kaons;
  - QCD models based on ChPT;
  - isospin-violating decays for the measurement of the light quark masses ratio;
  - **hadronic cross section for the calculation of HVP**
  - $\gamma\gamma$ physics



- New data taking, starting in June, to integrate 5 fb^{-1} during 2013-15
  [G. Amelino-Camelia et al., EPJ C68, 619 (2010)]
- Work in progress for
  - DAFNE consolidation after the IP upgrade
  - the KLOE upgrade with installation of IT, calorimeters at low angle, taggers for $\gamma\gamma$ physics

Event selection: LA-γ sample

PLB700 (2011)102

Pion tracks at large angles

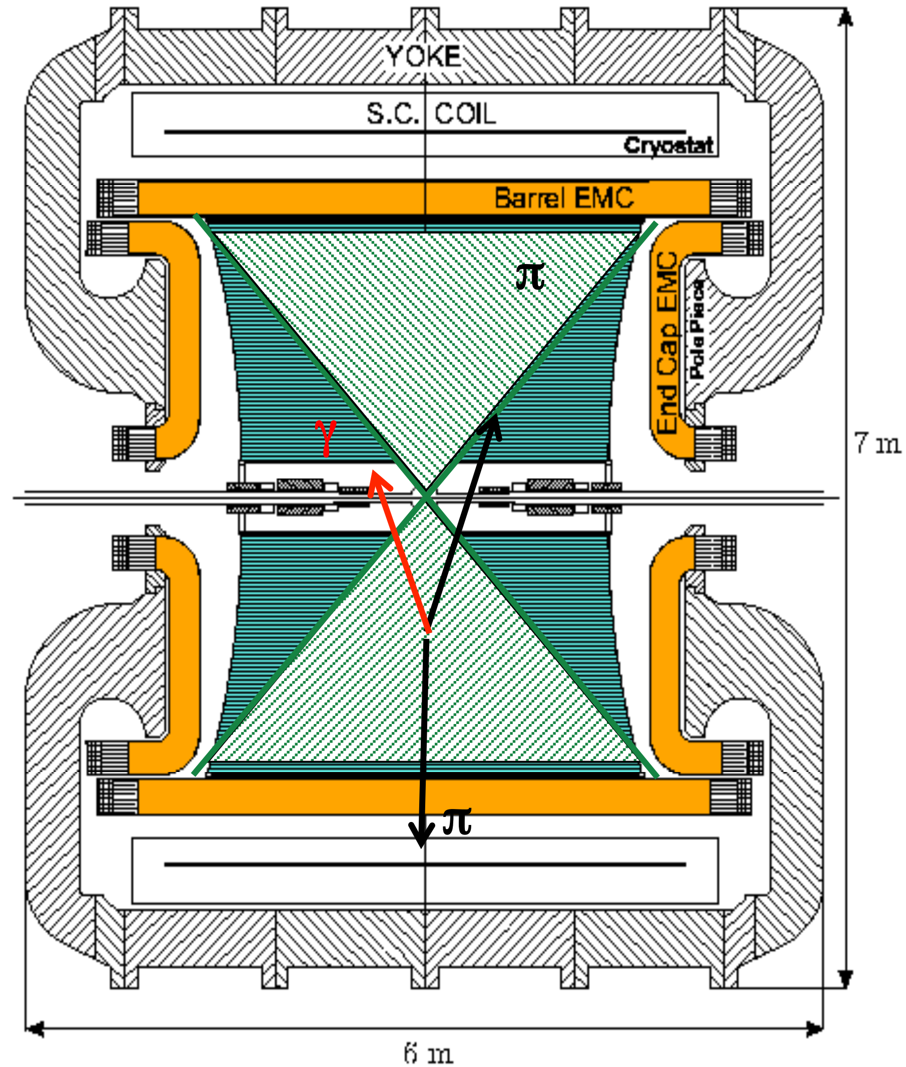
$50^o < \theta_\pi < 130^o$

Photons at large angles

$50^o < \theta_\gamma < 130^o$

➔Photon is explicitly measured in the detector!

- Threshold region accessible
- Sizeable contribution from FSR and $\phi \to \pi^+\pi^-\pi^0$ (use off peak data)



Event selection: SA-γ sample

PLB670 (2009) 285

Pion tracks at large angles

$50^o < \theta_\pi < 130^o$

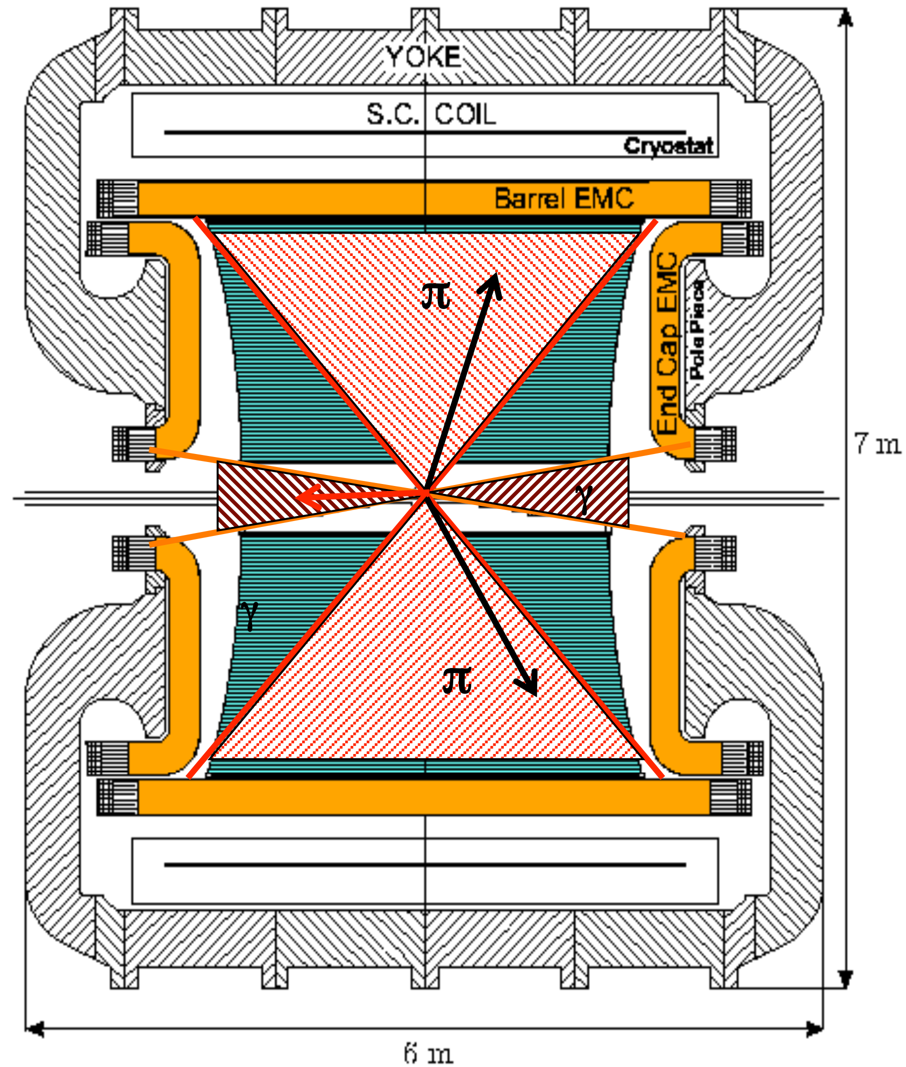
Photons at small angles

$\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$

➔ Photon momentum from kinematics:

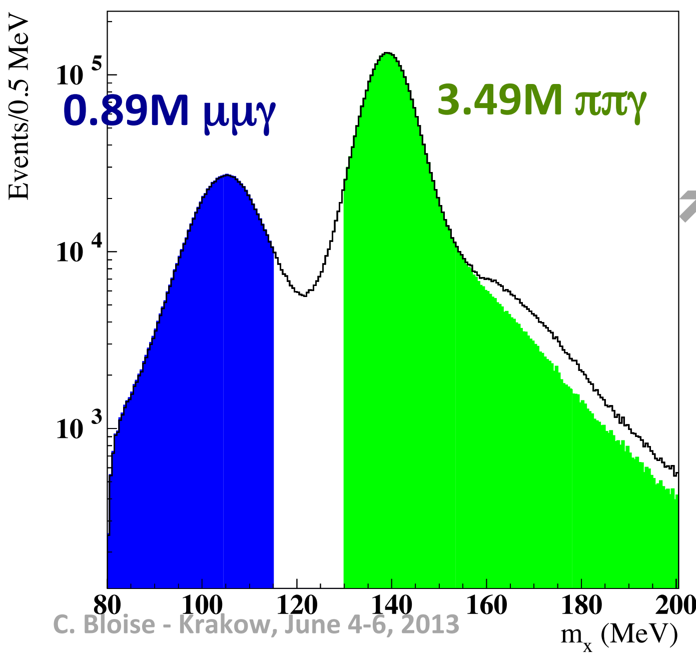
$$\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)$$

- High statistics for ISR photons
- Very small contribution from FSR
- Small background contamination

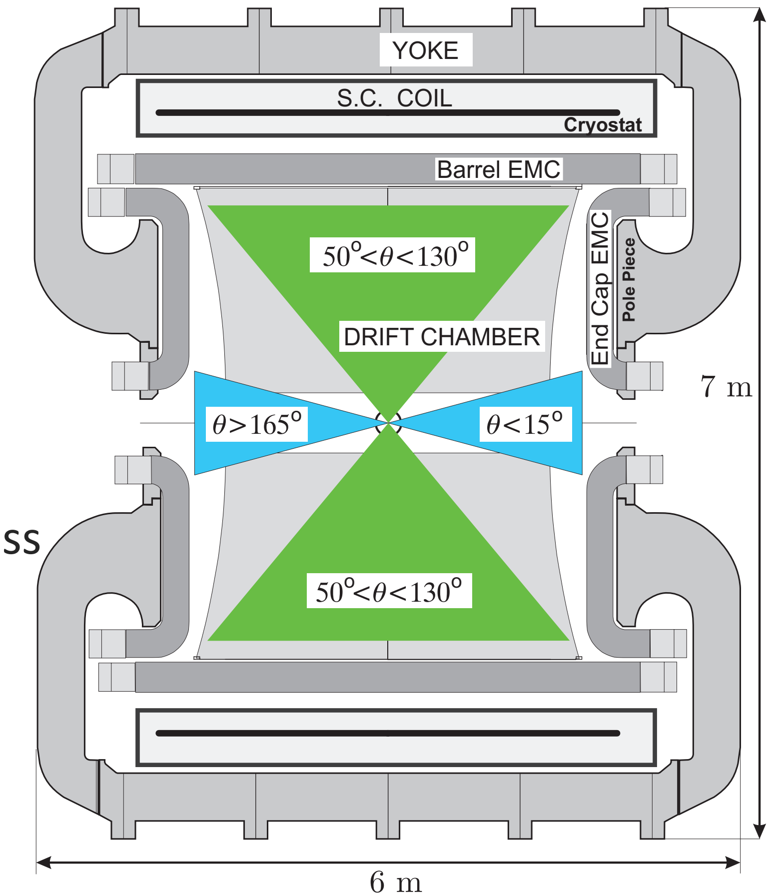


μμγ selection

- Event selection requires two opposite-charge particles at large angle with undetected photon at small angle, $\cos(\theta_{\mu\mu}) > \cos(15°)$
- μμγ, ππγ, eeγ final states are separated by
  - kinematical constraints giving m_x
    $$E - \sqrt{p_+^2 + m_x^2} - \sqrt{p_-^2 + m_x^2} = \left|\vec{P} - (\vec{p}_+ + \vec{p}_-)\right|$$
  - by additional PID based on time-of-flight and energy deposit in the calorimeter



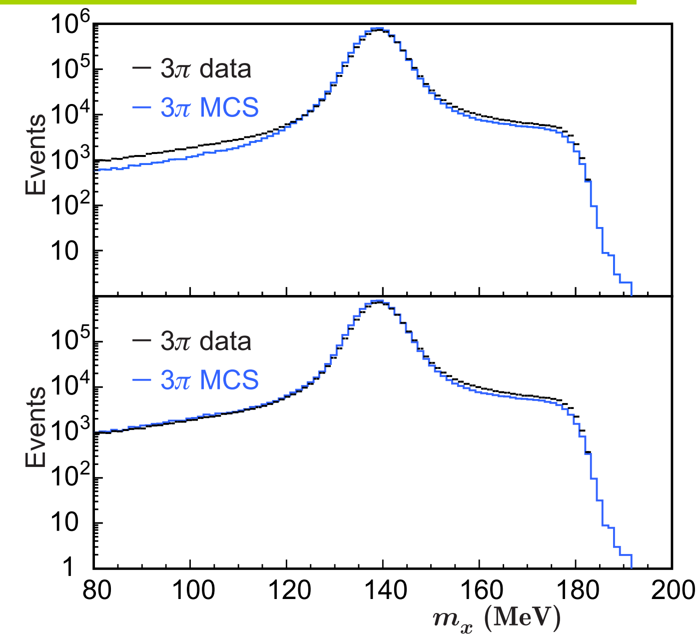
- Absolute ππγ cross section already measured

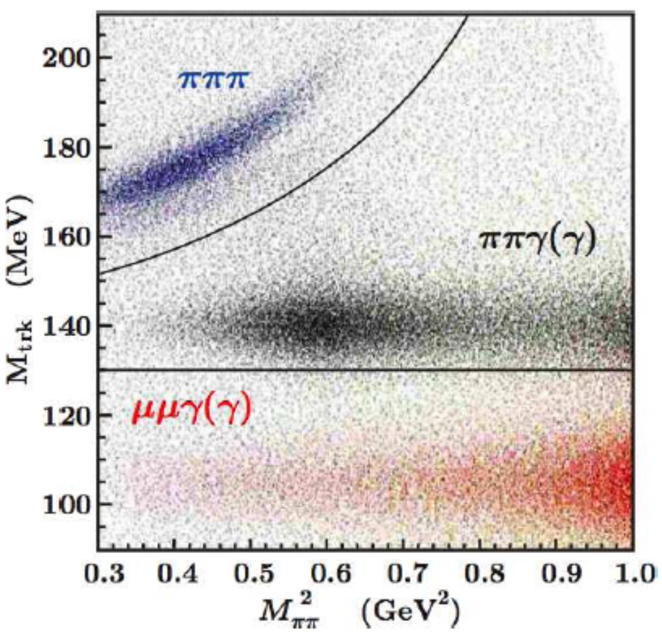


Data analysis

http://www.lnf.infn.it/kloe2/tools/getfile.php?doc_fname=K2PD-6.pdf&doc_ftype=docs

- Correction for Data/MC discrepancy on momentum reconstruction applied as a function of momentum and polar angle
- Pure πππ data sample used; Tails of the m_x distribution correctly predicted
- Residual background is evaluated with a fit to the μμγ, ππγ, πππ relative contributions to the m_x spectrum in the μμγ region and the weights used for background subtraction





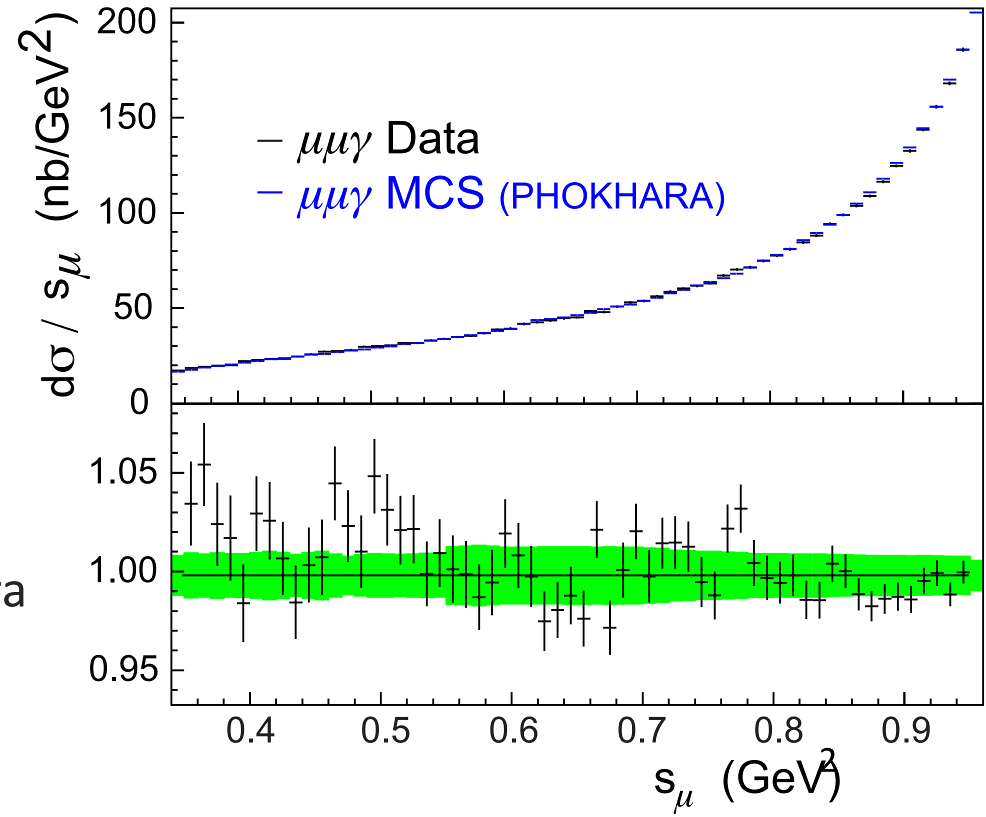
- The worst contamination of the μμγ spectrum is at the ρ peak, from ππγ
- Tail of the m_x distribution checked by two different procedures
  - With track-quality requirements, leading to a factor of two lower contamination
  - With a selection procedure based on the Likelihood instead of m_x

μμγ spectrum

$$\frac{d\sigma^{data}_{\mu\mu\gamma(\gamma)}}{dM^2_{\mu\mu}} = \frac{\Delta N^{sel}_{\mu\mu\gamma(\gamma)} - \Delta N^{fit}_{backg}}{\Delta M^2_{\mu\mu}} \frac{1}{\varepsilon_{sel}\int L\,dt}$$

$$\frac{d\sigma^{data}_{\mu\mu\gamma(\gamma)}}{d\sigma^{MC,NLO}_{\mu\mu\gamma(\gamma)}} = 0.998 \pm 0.001_{stat} \pm 0.011_{syst}$$

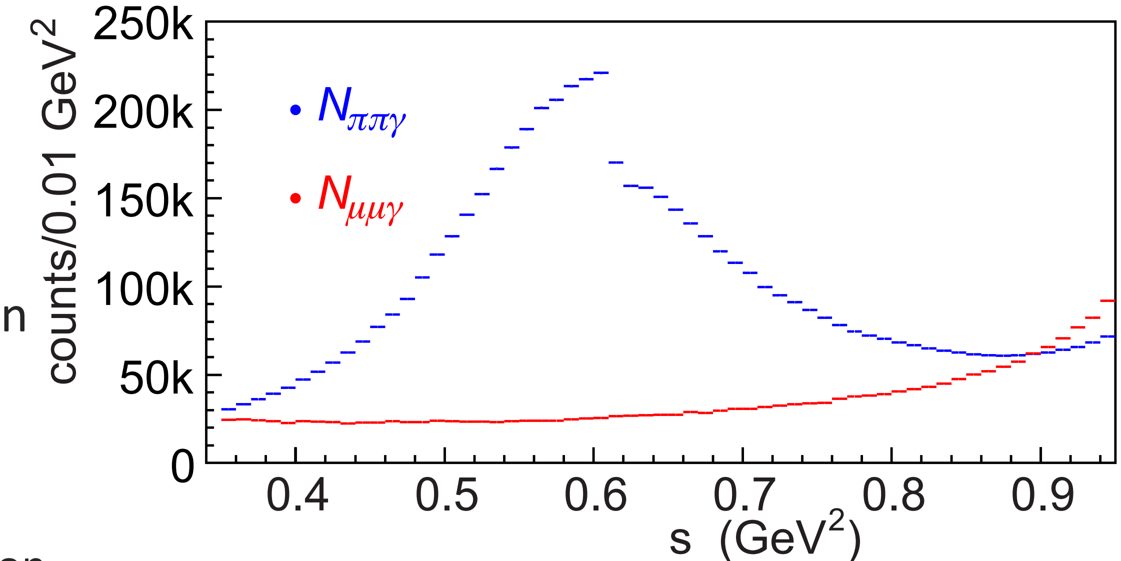
- μμγ spectrum is in agreement with predictions of NLO generator Phokhara [S. Actis et al., Eur.Phys.J. C66 (2010) 585]
- 1% level of accuracy reached

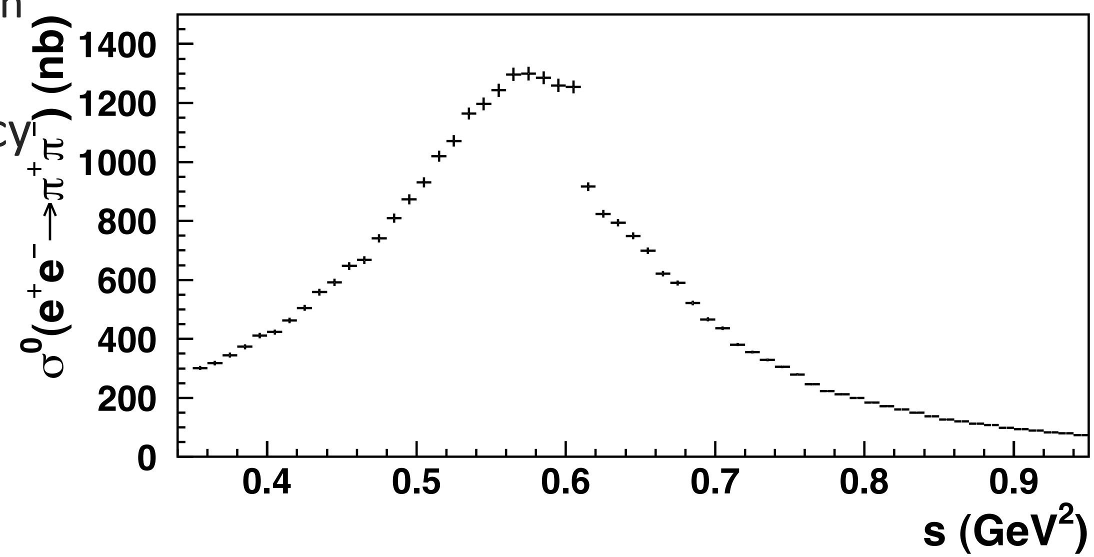


Δs_μ =0.01 GeV^2

$\pi\pi\gamma/\mu\mu\gamma$ spectrum

- $\pi\pi\gamma$ spectrum from previous analysis
- $\sigma^0(e^+e^- \rightarrow \pi\pi)$ from the bin-by-bin ratio is independent from
  - radiator function H
  - vacuum polarization subtraction
- Systematics from global efficiency reduced
- No Luminosity measurement needed





$\Delta^{\pi\pi} a_\mu$ from KLOE

- The results are consistent, all of comparable statistical errors, with systematics from different sources
- The error of the new measurement has negligible contribution from theoretical uncertainty and acceptance
- KLOE result from both, SA and LA measurements, covers ~70% of the total the $\Delta^{had,LO} a_\mu$ with 1% precision,

$$\Delta a_\mu^{\pi\pi}\left[(0.1 < s < 0.95)GeV^2\right] = (488.6 \pm 6.0)10^{-10}$$

Contribution to systematics %	$\Delta^{\pi\pi} a_\mu$, ratio, SA-γ	$\Delta^{\pi\pi} a_\mu$, abs, SA-γ	$\Delta^{\pi\pi} a_\mu$, abs, LA-γ
Background subtraction	0.6	0.3	0.5
$f_0+\rho\pi$	negligible	negligible	0.4
Ω cut	-	-	0.2
Particle mass/PID	0.2	0.2	0.5
Tracking	0.1	0.3	0.3
Trigger	0.1	0.1	0.2
Acceptance	negligible	0.2	0.5
L3 Trigger	0.1	0.1	0.1
Luminosity	-	0.3	0.3
Total experimental	**0.7**	**0.6**	**1.0**
FSR treatment	0.2	0.3	0.8
Radiator H	-	0.5	0.5
Vacuum polarization	-	0.1	0.1
Total theoretical	**0.2**	**0.6**	**0.9**
Total systematics	**0.7**	**0.9**	**1.1**

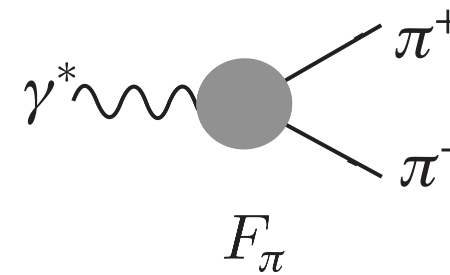
$$\Delta a_\mu^{\pi\pi} = \int^{s_{max}} \sigma^0_{\pi\pi(\gamma)}(s) \cdot K(s)\,ds$$

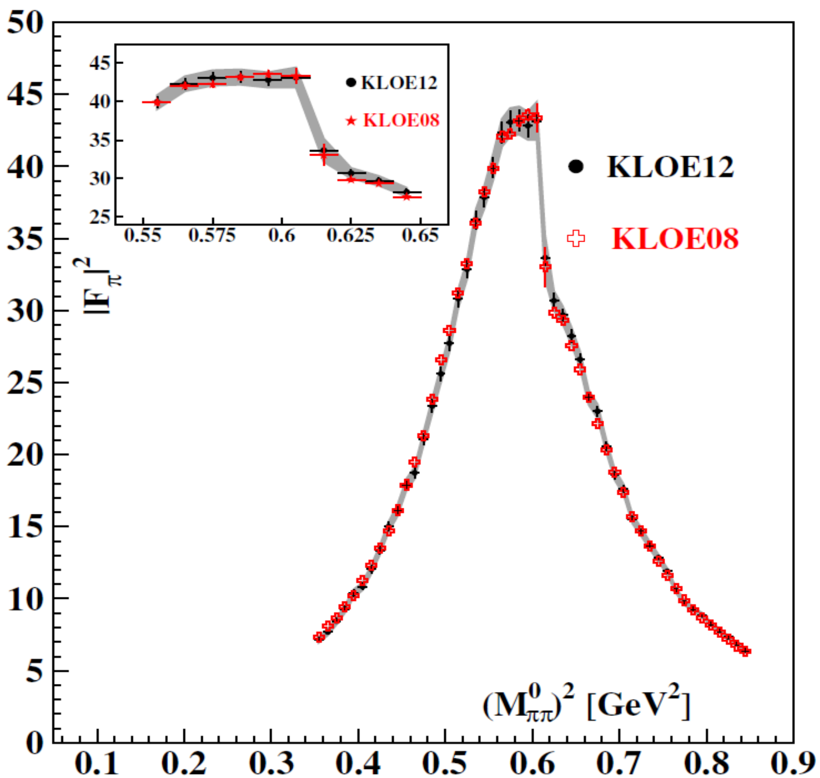
	Data	$\Delta^{\pi\pi} a_\mu \cdot 10^{10}$ 0.35< s < 0.85 GeV^2
PLB 720,336	$\sigma_{\pi\pi(\gamma)} / \sigma_{\mu\mu(\gamma)}$, SA- γ_{ISR}	$377.4 \pm 1.1_{stat} \pm 2.7_{sys+th}$
PLB 670,285	Abs. $\sigma_{\pi\pi(\gamma)}$, SA- γ_{ISR}	$379.6 \pm 0.4_{stat} \pm 3.3_{sys+th}$
PLB 700,102	Abs. $\sigma_{\pi\pi(\gamma)}$, LA- γ_{ISR}	$376.6 \pm 0.9_{stat} \pm 3.3_{sys+th}$

Pion form factor

- Pion form factor measures the dependence on s of the photon coupling to the dipion system, with $F_\pi(0)=1$

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



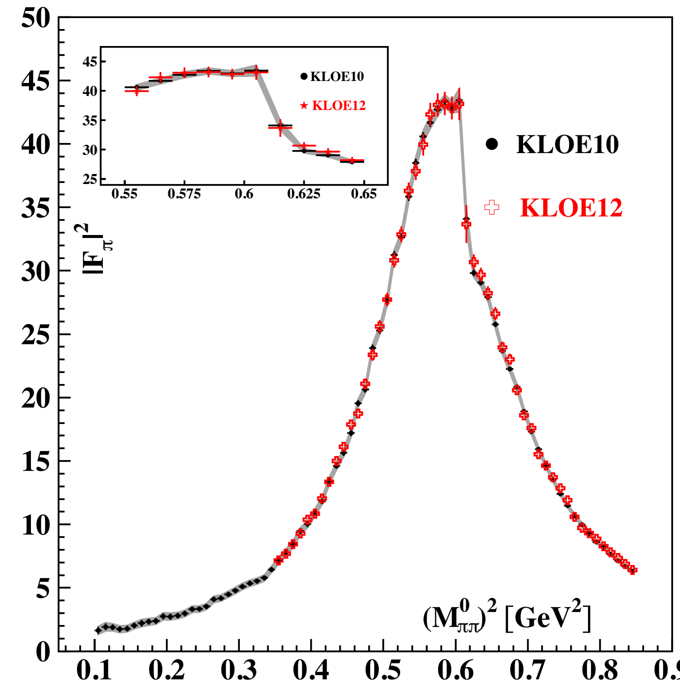


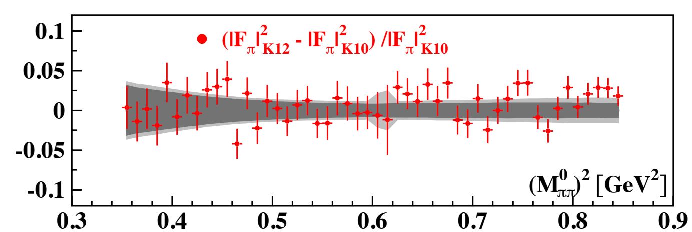
- Pion form factor in agreement with previous measurements, from the absolute hadronic cross section, using both, γ−untagged (SA-γ), and γ−tagged (LA-γ) analyses

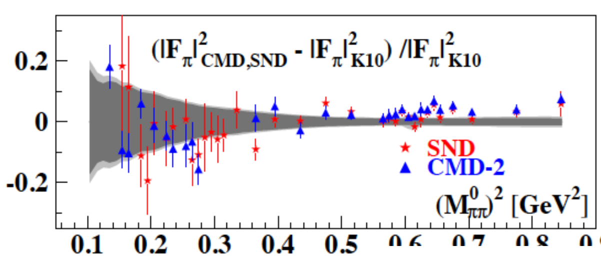
Data comparison

- In the overlap region with the tagged-photon analysis, 0.35<s<0.85, pion form factor results are in full agreement

- The agreement is good also with the other e^+e^- experiments, except for the region above the ρ peak, showing a deficit < 3%, negligible when weighted in the dispersion integral
  [M. Benayoun et al. , arXiv:1210.7184 [hep-ph]]

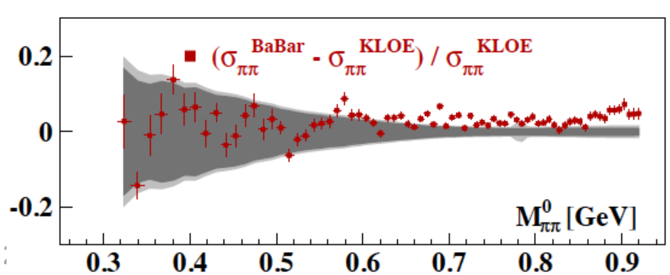






M.N. Achasov et al., J. Exp. Theor. Phys. 103, 480 (2006)

R.R. Akhmetshin et al., Phys.Lett. B648, 28 (2007)

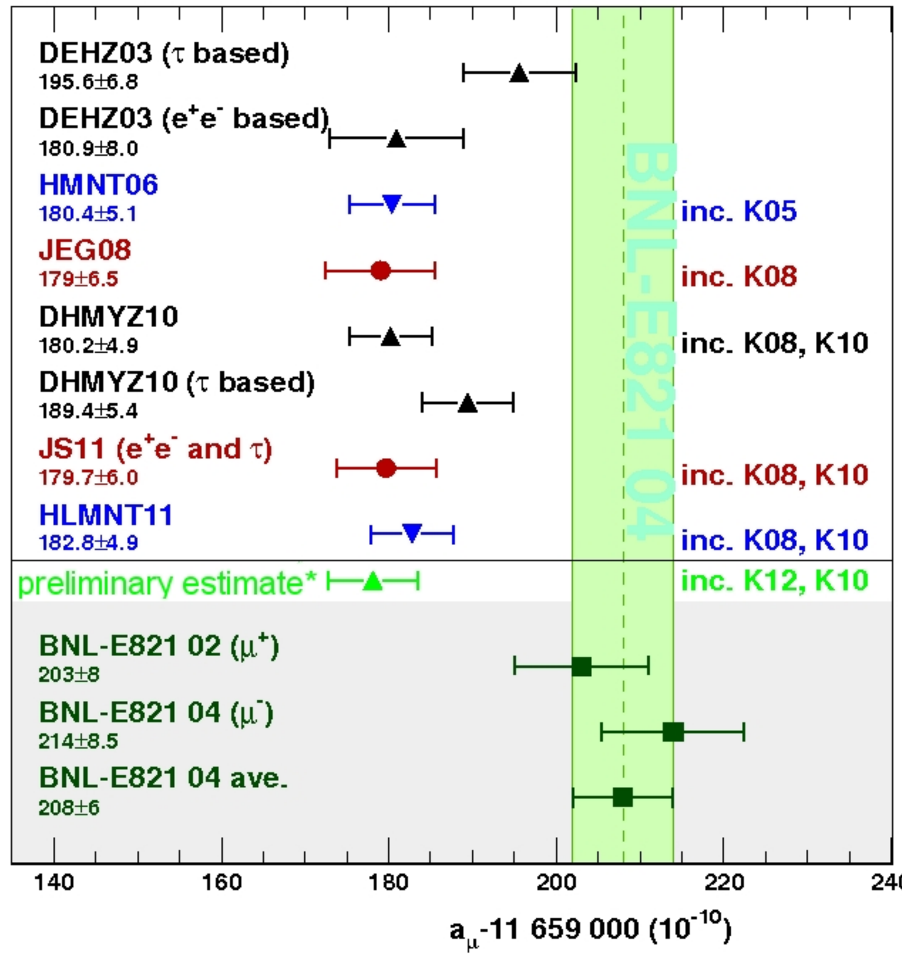


B. Aubert et al, Phys.Rev.Lett. 103, 231801(2009)

Summary on muon anomaly

- Discrepancy with experiment at 3.5σ level confirmed by the KLOE measurement of the ratio of cross sections ππγ / μμγ

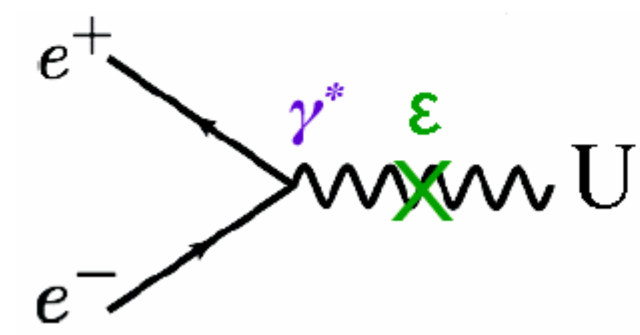
- Previous tension between e^+e^- and τ data reduced by 1σ [F. Jegerlehner et al., Eur.Phys.J. C71 (2011) 1632, ρ−γ treatment]



* Our extrapolation based on DHMYZ10

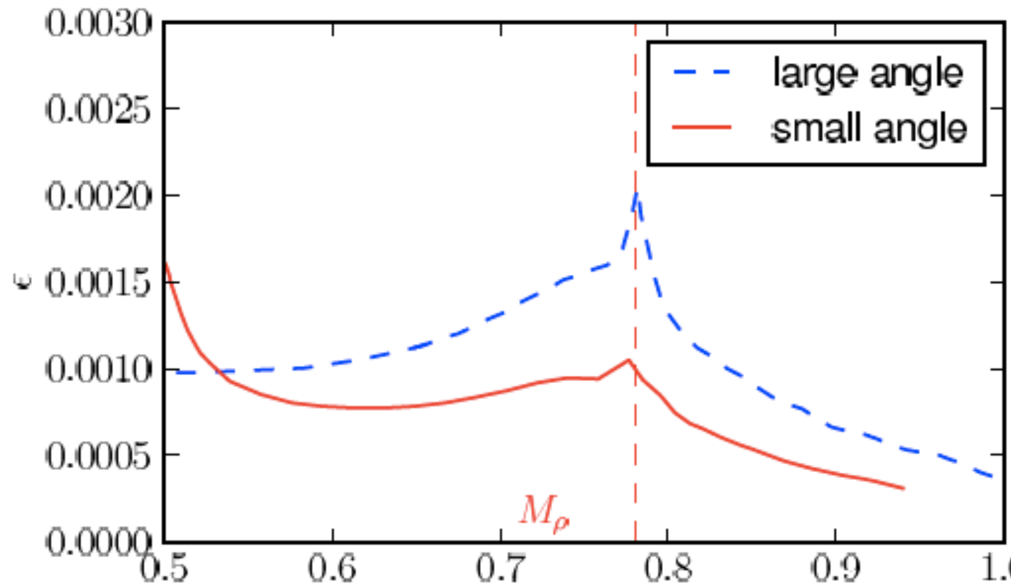
Searching for Dark-photon

- Some models of physics beyond the SM predict the existence of light neutral vector particles, U-boson, mediator of new gauge interactions under which ordinary matter is uncharged
- Motivated by astrophysical arguments, their mass is expected to be of order 1 GeV or lighter
- Coupling of SM particles is possible via kinetic mixing between, regulated by ε, expected to be of 10^{-3} or less



Using μμγ spectrum for Dark-photon searches

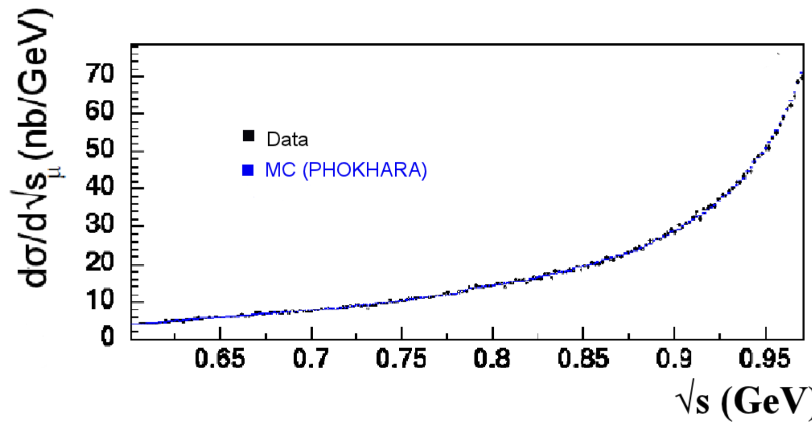
- The spectrum of the μμγ sample has been used to search for low-mass U-boson decaying to μμ pairs
- WIMP Dark matter belonging to a secluded sector could imply the existence of a gauge boson with kinetic coupling to the SM photon, $\varepsilon^2 = \alpha_D/\alpha \leq 10^{-4}$ [N. Arkani-Hamed et al., PR D79, 015014 (2009)]
- At the fixed-target facilities, JLAB and MAMI-C, the U-boson search is based on electron-N scattering and U→ee decay
- At the φ–factory we can study:
  - φ → η U→η ll, → η ππ, → π ll
  - ee→ U γ → llγ

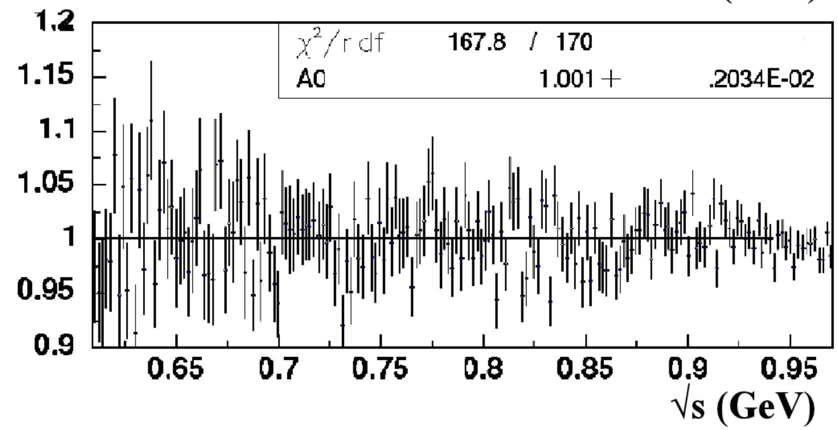


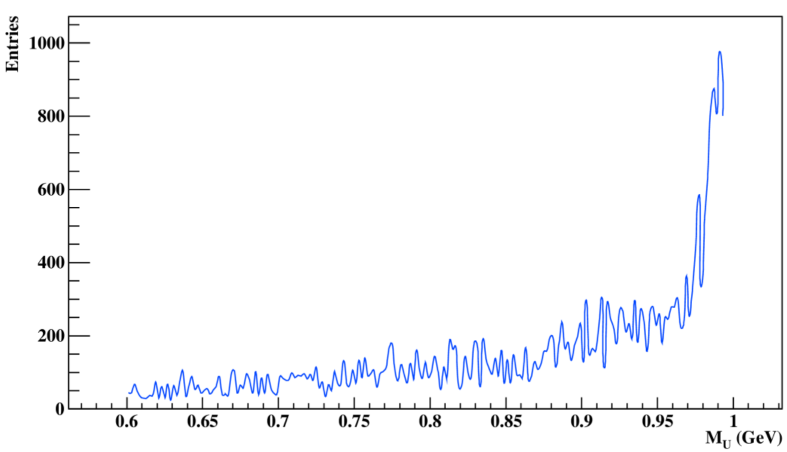
- KLOE-2 discovery potential in the μμγ sample, with 5 fb^{-1} [L.Berze' et al. EPJ C71(2011)1680]

Upper limits from μμγ spectrum

- Exploiting the precision reached on the μμγ spectrum in the region 0.6<√s<1 GeV a sensitivity on $\varepsilon^2 \approx 10^{-6}$ has been reached with a preliminary analysis



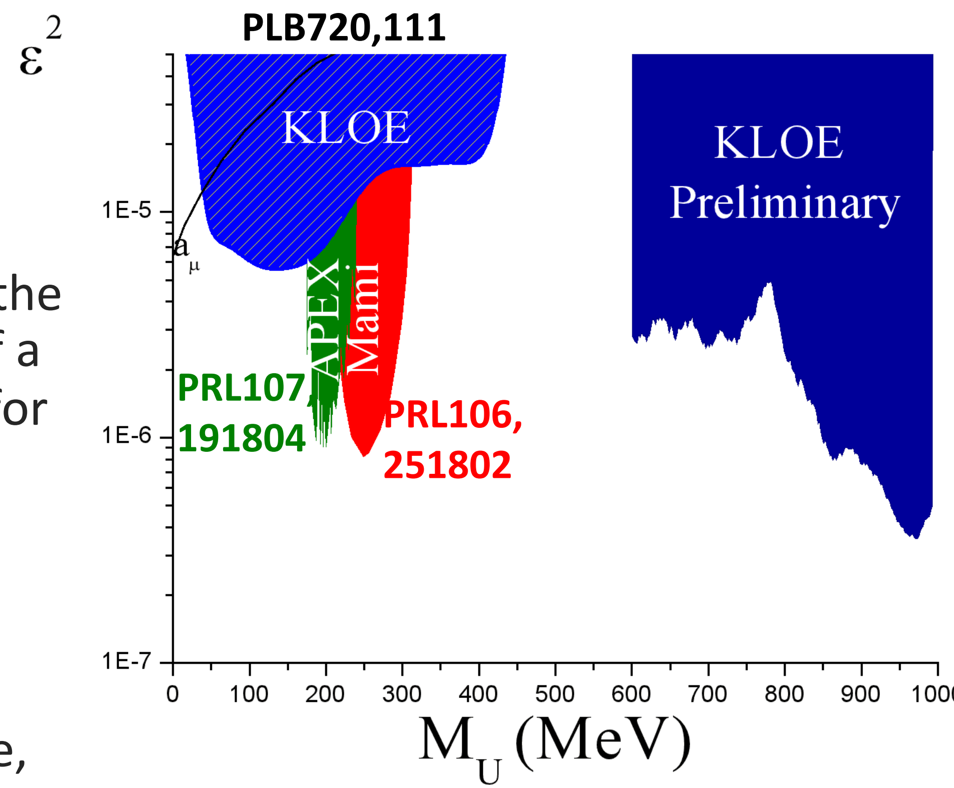




- UL on the events per bin vs M_U using the CL_S distribution

Exclusion plot

- The analysis of $\phi \rightarrow \eta\, ee$ is sensitive to the mass region ($50<M_U< 400$) MeV
- The results are published on PLB 720, 111
- In that region $60<M_U<200$ MeV the results rule out the hypothesis of a Dark-photon as the explanation for the 3.5-σ discrepancy in the magnetic moment of the muon
- Further work is in progress, increasing statistics of the $\mu\mu\gamma$ sample, processing $ee\gamma$ final state, looking at $\mu\mu$+missing energy



Conclusions

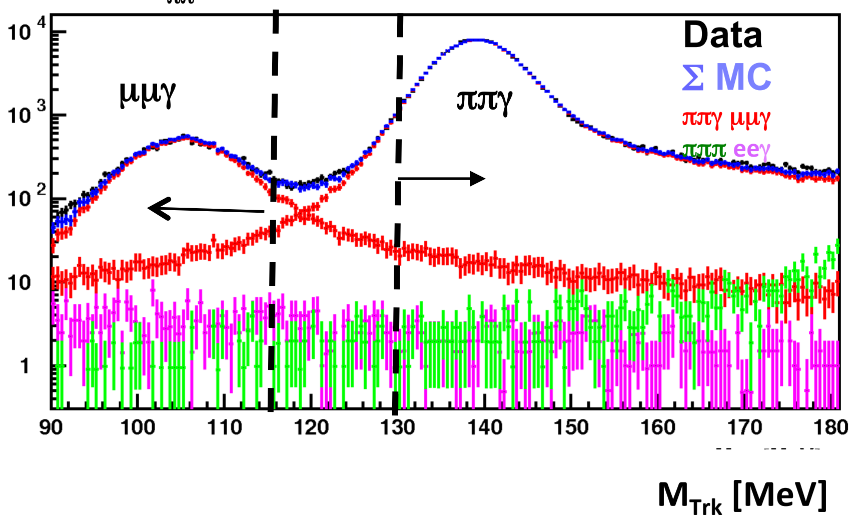
- The $\mu\mu\gamma$ spectrum has been measured with 1% precision
- From the bin-to-bin ratio of the $\pi\pi\gamma/\mu\mu\gamma$ spectra, we obtained a new measurement of the hadronic cross section $\sigma^0_{\pi\pi(\gamma)}$
- The result confirms
  - the KLOE previous measurements and associated systematics, and the calculation of the hadronic vacuum polarization contribution to the magnetic moment of the muon, showing a 3.5-σ discrepancy with the experimental result of BNL-E681
- We have searched for U-boson in the $\mu\mu\gamma$ spectrum. No structures have been observed. The exclusion plot obtained in the region $(0.6<M_U< 1.0)$ GeV, rules out ε^2 in the 10^{-6} range

Spares

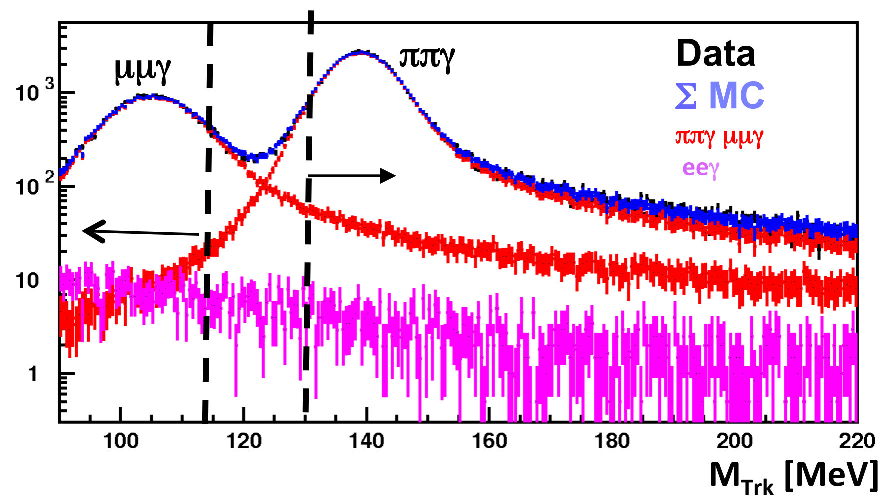
Background:

Main backgrounds estimated from MC shapes fitted to data distribution in M_{Trk} ($\pi\pi\gamma/\mu\mu\gamma$, $\pi\pi\pi$, $ee\gamma$)

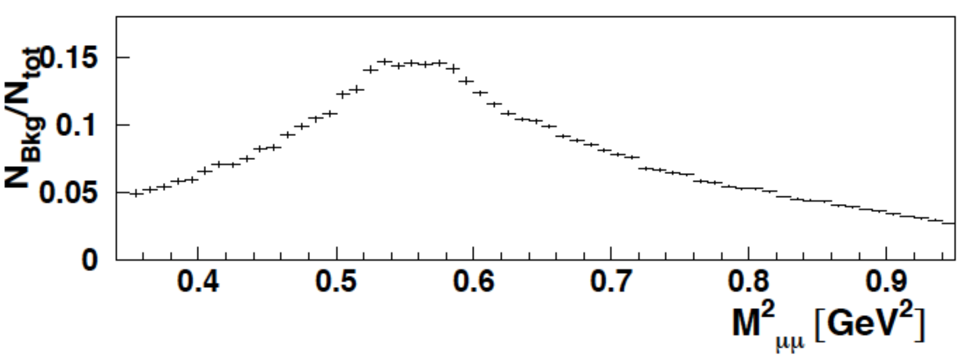
$0.60 < M_{\pi\pi}^2 < 0.62$ GeV^2, χ^2/ndof = 158/180



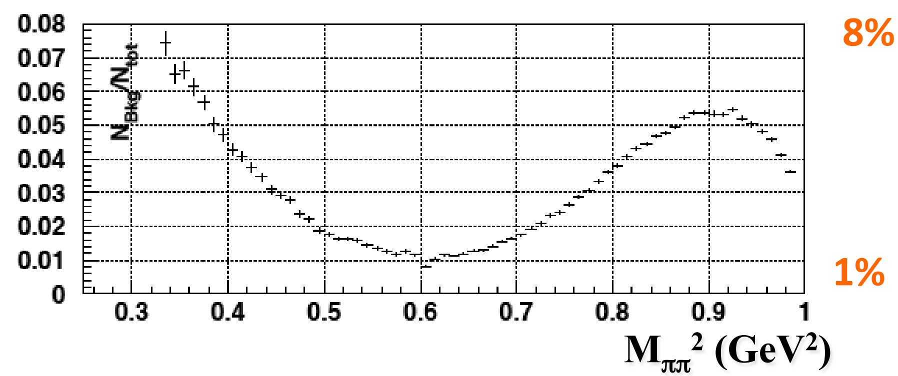
$0.84 < M_{\pi\pi}^2 < 0.86$ GeV^2 χ^2/ndof = 179/258



Tot % bckg to $\mu\mu\gamma$



Tot % bckg to $\pi\pi\gamma$



- Systematic error on $\mu\mu\gamma$ due to background~1% in the ρ peak