Physics from 1-2 GeV

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What next LNF: Perspectives of fundamental physics at the Frascati Laboratory

Frascati, November 10–11, 2014

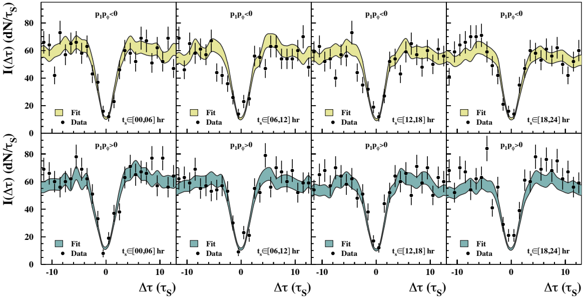
Three classes of measurements

- Kaon physics: Interference in the neutral kaon system
- Hadronic cross sections and γ–γ physics
- Searches for particle production from a secluded sector

from recent papers

- CP, FCNC, LFV, Test of fundation principles of QFT
- HVP and hadronic LbL contributions to a_μ and $\Delta\alpha_{em}(Q^2)$
- Hidden symmetries for explaining Dark Matter

KLOE Phys Lett B 730(2014)89



- Running at the ϕ resonance, neutral kaon pairs ($\sigma_{K_S K_L} \sim \mu$barn) are in a pure, antisymmetric quantum state

- The neutral kaon interference, as in $\phi \rightarrow \mathrm{K_S K_L} \rightarrow \pi^+\pi^-\pi^+\pi^-$:

$$I(\pi^+\pi^-, \pi^+\pi^-; \Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t}\cos(\Delta m \Delta t)$$

is the most sensitive probe in the quark sector of CPT invariance

CPT and Lorentz invariance tests are considered a probe for physics at the Planck scale

Space–time modifications from QG at M_P naturally lead to CPT/Lorentz–invariance breaking

In the low–energy regime accessible to experiments, the SME is widely used, from atomic to particle physics, to cosmology

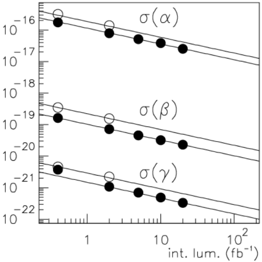
At present, the distribution of the decay distance of the two neutral kaons is sensitive to SME CPT–violating parameters of the $O(10^{-18})$GeV

Kostelecky and Russell RMP 83(2011)11

Table D26. Quark sector, $d \geq 3$

Combination	Result	System	Ref.
Δa_0^K	$(-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18}$ GeV	K oscillations	[164]
Δa_X^K	$(0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18}$ GeV	"	[164]
Δa_Y^K	$(-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18}$ GeV	"	[164]
Δa_Z^K	$(3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18}$ GeV	"	[164]
$N^D(\Delta a_0^D - 0.6\Delta a_Z^D)$	$(-2.8$ to $4.8) \times 10^{-16}$ GeV	D oscillations	[170]
$N^D \Delta a_X^D$	$(-7$ to $3.8) \times 10^{-16}$ GeV	"	[170]
$N^D \Delta a_Y^D$	$(-7$ to $3.8) \times 10^{-16}$ GeV	"	[170]
$N^B(\Delta a_0^B - 0.30\Delta a_Z^B)$	$(-3.0 \pm 2.4) \times 10^{-15}$ GeV	B_d oscillations	[171]
$N^B \Delta a_X$	$(-22 \pm 7) \times 10^{-15}$ GeV	"	[171]
$N^B \Delta a_Y$	$(-27$ to $-4) \times 10^{-15}$ GeV	"	[171]
$N^B(\Delta a_0^B - 0.3\Delta a_Z^B)$	$-(5.2 \pm 4.0) \times 10^{-15}$ GeV	"	[172]
$N^B\sqrt{(\Delta a_X^B)^2 + (\Delta a_Y^B)^2}$	$(37 \pm 16) \times 10^{-15}$ GeV	"	[172]
$(\Delta a^{B_s})_T$	$(3.7 \pm 3.8) \times 10^{-12}$ GeV	B_s oscillations	[169]*

KLOE EPJ C68(2010)619



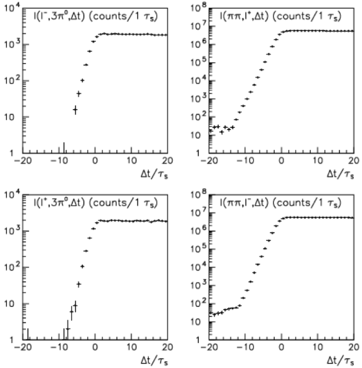
- First evidence for T-violation using non–CPT conjugate states obtained by Babar in 2012 Babar PRL 109(2012)211801

- At the ϕ factory, the final states are:

Reference		$\mathcal{T}$-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$

Table 1: Possible comparisons between $\mathcal{T}$-conjugated transitions and the associated time-ordered decay products in the experimental ϕ-factory scheme.

J.Bernabeu *et al* NP B868(2013)102



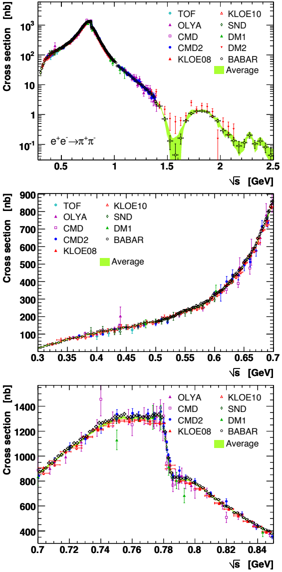
Hadronic cross section at low energy obtained at the e^+e^- collider through:

- Scan in energy at Novosibirsk
- Radiative return working at the resonance by Babar, Kloe, Belle

Most combined data on the $e^+e^- \to \pi\pi$ cross section have reached a relative precision of $O(10^{-2})$ below the ϕ resonance

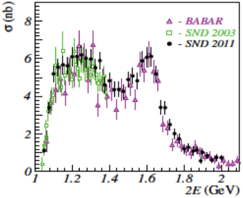
VEPP-2000 is expected to publish soon results from the scan of the 0.32-2 GeV region, with $\sim 60\ \mathrm{pb}^{-1}$ of integrated luminosity

M. Davier *et al* EPJ C71 (2011) 1515

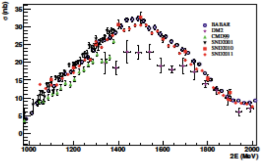


The relative uncertainty on the cross sections of multi–pions and final states with kaons is at the level of 10%, with some missing channel

SND 2011, unpublished

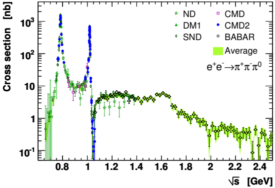


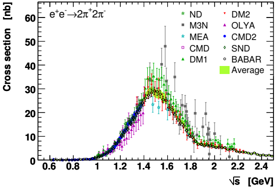
$\pi\pi\pi^0$

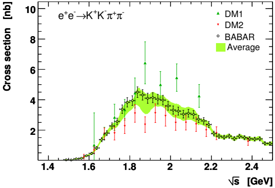


$\pi\pi\pi^0\pi^0$

M. Davier *et al* EPJ C71 (2011) 1515



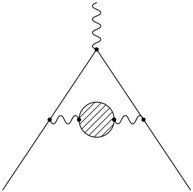




- Hadronic cross section from $\pi\pi$ threshold to 1.8 GeV is the experimental input for the theoretical evaluation of the Hadron Vacuum Polarization at leading order, HLO.

- Data are used in dispersion integrals al low energy where pQCD cannot be applied

- The uncertainty on HLO limits the theoretical precision for a_μ, $\alpha(M_Z^2)$, and several QCD observables including $\alpha_S(s)$



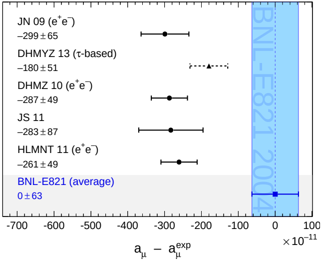
- The SM prediction of a_μ includes QED, EW, HLO and HHO contributions

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLO} + a_\mu^{HHO}$$

- The dominant QED term and the suppressed EW contribution do not contribute significantly to the total error

$a_\mu^{SM} - a_\mu^{exp} =$

$(-287 \pm 63_{exp} \pm 49_{pred}) \times 10^{-11}$



$$a_\mu^{QED} + a_\mu^{EW} = (\,116584718.95(8) + 153.6(1.0))\times 10^{-11}$$

The uncertainty on the HLO is due to the experimental input

$a_\mu^{HLO} = (6923 \pm 42 \pm 4_{QCD})\times 10^{-11}$ Z. Zhang arXiv:1312.7549

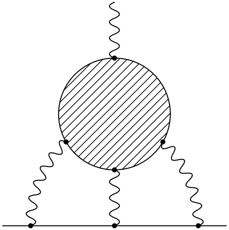
$a_\mu^{HLO} = (6909.6 \pm 46.5)\times 10^{-11}$ F. Jegerlehner, R. Szafron EPJ C71(2011)1632

HHO uncertainty dominated by LBL contribution

$a_\mu^{HHO} = (\text{-}98(1)_{vp} + 116(39)_{LBL})\ \times 10^{-11}$

M. Davier *et al* EPJ C71 (2011) 1515

Channel	$a_\mu^{\rm had,LO}$ $[10^{-10}]$	$\Delta\alpha_{\rm had}(M_Z^2)$ $[10^{-4}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$	$0.36 \pm 0.01 \pm 0.01 \pm 0.01$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$	$0.08 \pm 0.00 \pm 0.00 \pm 0.00$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$	$34.43 \pm 0.07 \pm 0.17 \pm 0.04$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$	$4.58 \pm 0.04 \pm 0.11 \pm 0.09$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$	$3.49 \pm 0.03 \pm 0.12 \pm 0.08$
$\pi^+\pi^-2\pi^0$	$18.01 \pm 0.14 \pm 1.17 \pm 0.40$	$4.43 \pm 0.03 \pm 0.29 \pm 0.10$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.72 \pm 0.04 \pm 0.07 \pm 0.03$	$0.22 \pm 0.01 \pm 0.02 \pm 0.01$
$\pi^+\pi^-3\pi^0$ (η excl., from isospin)	$0.36 \pm 0.02 \pm 0.03 \pm 0.01$	$0.11 \pm 0.01 \pm 0.01 \pm 0.00$
$3\pi^+3\pi^-$	$0.12 \pm 0.01 \pm 0.01 \pm 0.00$	$0.04 \pm 0.00 \pm 0.00 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.70 \pm 0.05 \pm 0.04 \pm 0.09$	$0.25 \pm 0.02 \pm 0.02 \pm 0.03$
$\pi^+\pi^-4\pi^0$ (η excl., from isospin)	$0.11 \pm 0.01 \pm 0.11 \pm 0.00$	$0.04 \pm 0.00 \pm 0.04 \pm 0.00$
$\eta\pi^+\pi^-$	$1.15 \pm 0.06 \pm 0.08 \pm 0.03$	$0.33 \pm 0.02 \pm 0.02 \pm 0.01$
$\eta\omega$	$0.47 \pm 0.04 \pm 0.00 \pm 0.05$	$0.15 \pm 0.01 \pm 0.00 \pm 0.02$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$\eta\pi^+\pi^-2\pi^0$ (estimated)	$0.02 \pm 0.01 \pm 0.01 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.89 \pm 0.02 \pm 0.06 \pm 0.02$	$0.18 \pm 0.00 \pm 0.02 \pm 0.00$
$\omega\pi^+\pi^-, \omega 2\pi^0$ ($\omega \to \pi^0\gamma$)	$0.08 \pm 0.00 \pm 0.01 \pm 0.00$	$0.03 \pm 0.00 \pm 0.00 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.36 \pm 0.00 \pm 0.01 \pm 0.00$	$0.03 \pm 0.00 \pm 0.00 \pm 0.00$
K^+K^-	$21.63 \pm 0.27 \pm 0.58 \pm 0.36$	$3.13 \pm 0.04 \pm 0.08 \pm 0.05$
$K_S^0K_L^0$	$12.96 \pm 0.18 \pm 0.25 \pm 0.24$	$1.75 \pm 0.02 \pm 0.03 \pm 0.03$
ϕ (non-$K\overline{K}, 3\pi, \pi\gamma, \eta\gamma$)	$0.05 \pm 0.00 \pm 0.00 \pm 0.00$	$0.01 \pm 0.00 \pm 0.00 \pm 0.00$
$K\overline{K}\pi$ (partly from isospin)	$2.39 \pm 0.07 \pm 0.12 \pm 0.08$	$0.76 \pm 0.02 \pm 0.04 \pm 0.02$
$K\overline{K}2\pi$ (partly from isospin)	$1.35 \pm 0.09 \pm 0.38 \pm 0.03$	$0.48 \pm 0.03 \pm 0.14 \pm 0.01$
$K\overline{K}3\pi$ (partly from isospin)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$	$-0.01 \pm 0.00 \pm 0.01 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$	$0.13 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega K\overline{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$
J/ψ (Breit-Wigner integral)	6.22 ± 0.16	7.03 ± 0.18
$\psi(2S)$ (Breit-Wigner integral)	1.57 ± 0.03	2.50 ± 0.04
$R_{\rm data}$ [3.7 − 5.0 GeV]	$7.29 \pm 0.05 \pm 0.30 \pm 0.00$	$15.79 \pm 0.12 \pm 0.66 \pm 0.00$
$R_{\rm QCD}$ $[1.8 - 3.7\ {\rm GeV}]_{uds}$	33.45 ± 0.28	24.27 ± 0.19
$R_{\rm QCD}$ $[5.0 - 9.3\ {\rm GeV}]_{udsc}$	6.86 ± 0.04	34.89 ± 0.18
$R_{\rm QCD}$ $[9.3 - 12.0\ {\rm GeV}]_{udscb}$	1.21 ± 0.01	15.56 ± 0.04
$R_{\rm QCD}$ $[12.0 - 40.0\ {\rm GeV}]_{udscb}$	1.64 ± 0.01	77.94 ± 0.12
$R_{\rm QCD}$ $[> 40.0\ {\rm GeV}]_{udscb}$	0.16 ± 0.00	42.70 ± 0.06
$R_{\rm QCD}$ $[> 40.0\ {\rm GeV}]_{t}$	0.00 ± 0.00	-0.72 ± 0.01
Sum	$692.3 \pm 1.4 \pm 3.1 \pm 2.4 \pm 0.2_\psi \pm 0.3_{\rm QCD}$	$274.97 \pm 0.17 \pm 0.78 \pm 0.37 \pm 0.18_\psi \pm 0.52_{\rm QCD}$



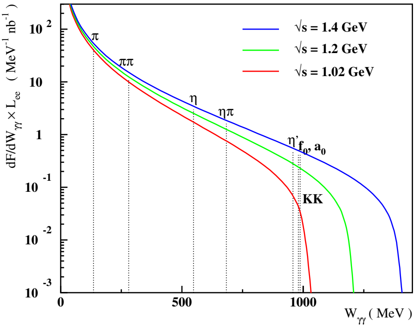
- The uncertainty on HHO is dominated by the LBL scattering diagrams. It limits the theoretical precision for a_μ,

$$\sigma(a_\mu^{HLO}) \sim \sigma(a_\mu^{LBL})$$

- Dispersive methods for the precision evaluation of the contributions to LBL are being developed

- Experimental inputs are the radiative pseudoscalar widths and the transition form factors

- They can be obtained with several measurements of γ–γ processes



$e^+e^- \to \gamma\gamma \to e^+e^-$ X processes for studying hadron production $\to$ X internal structure

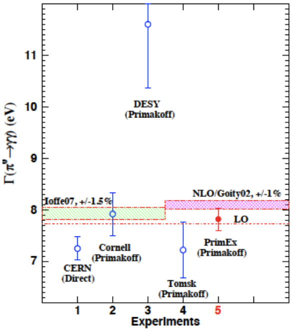
The measurements of the transition form factors, $F_X(q_1^{(*)2}, q_2^{(*)2})$, in different q_i^{*2} regimes/ranges relating with taggers and detector acceptance

Measurement of the $\Gamma_{\pi^0}(\gamma\gamma)$ at 1% precision level could improve by a factor of two the precision of the relating contribution to a_μ^{HHO}

D. Babusci *et al* Eur.Phys.J. C72 (2012) 1917

Model	Data	$a_\mu^{\text{LbyL};\pi^0} \times 10^{11}$
VMD	A0	$(57.2 \pm 4.0)_{JN}$
VMD	A1	$(57.7 \pm 2.1)_{JN}$
VMD	A2	$(57.3 \pm 1.1)_{JN}$
VMD	B0	—
VMD	B1	—
VMD	B2	—
LMD+V, $h_1 = 0$	A0	$(72.3 \pm 3.5)^*_{JN}$
		$(79.8 \pm 4.2)_{MV}$
LMD+V, $h_1 = 0$	A1	$(73.0 \pm 1.7)^*_{JN}$
		$(80.5 \pm 2.0)_{MV}$
LMD+V, $h_1 = 0$	A2	$(72.5 \pm 0.8)^*_{JN}$
		$(80.0 \pm 0.8)_{MV}$
LMD+V, $h_1 = 0$	B0	—
LMD+V, $h_1 = 0$	B1	—
LMD+V, $h_1 = 0$	B2	—
LMD+V, $h_1 \neq 0$	A0	$(72.4 \pm 3.8)^*_{JN}$
LMD+V, $h_1 \neq 0$	A1	$(72.9 \pm 2.1)^*_{JN}$
LMD+V, $h_1 \neq 0$	A2	$(72.4 \pm 1.5)^*_{JN}$
LMD+V, $h_1 \neq 0$	B0	$(71.9 \pm 3.4)^*_{JN}$
LMD+V, $h_1 \neq 0$	B1	$(72.4 \pm 1.6)^*_{JN}$
LMD+V, $h_1 \neq 0$	B2	$(71.8 \pm 0.7)^*_{JN}$

Phys.Rev.Lett. 106 (2011)162303

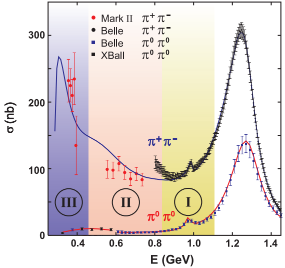


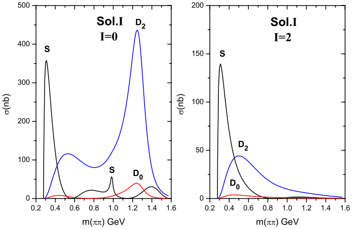
Recent work to establish dispersive relations for LbL calculation G. Colangelo *et al* JHEP 1409(2014)091

Results of a complete amplitude analysis as experimental inputs

Cross section measurements of the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, full angular acceptance

L.Y. Dai, M.R. Pennington PRD 90(2014)036004

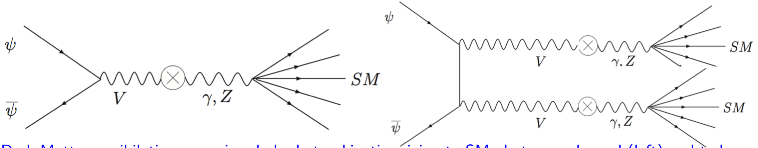




– New gauge symmetry $U_S(1)$ advocated to realize a dark sector for DM

– SM allows three portals to the secluded sector

– Such portals comprise couplings with the Higgs sector, to right–handed neutrinos and to photon/Z through the kinetic mixing with $U_Y(1)$, $\epsilon F^S_{\mu\nu} F^Y_{\mu\nu}$ B. Batell et al. PRD 79(2009)115008



Dark Matter annihilation assuming dark photon kinetic mixing to SM photon: s-channel (left) and t-channel (right)

– Cosmic ray positron fraction increases with the energy

– The effect was measured by HEAT, PAMELA, Fermi, AMS-02

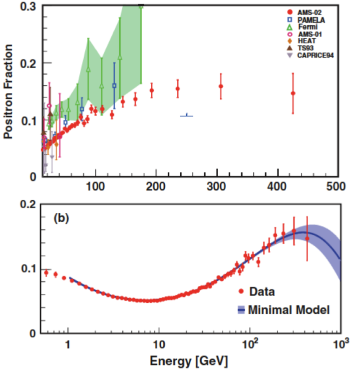
– High–energy cosmic ray interactions with interstellar medium only ruled out

– If one of the additional sources is DM annihilation, $\sigma_{DMannihi}$ should be larger than for thermalized WIMPS

– The existence of a dark force could enhance the cross section at the right level Arkani–Hamed et al. PR D79(2009)015014

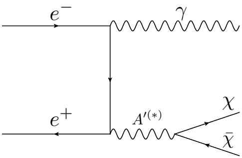
Cosmic rays: positron fraction

AMS Collab. PRL 113(2014)121101



Searches for Light DM

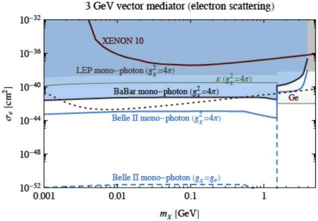
– Kinetic mixing can be studied at ϕ and B–factories by a rich experimental program of light dark photon (U–boson) searches



– Minimally suppressed (by ϵ^2) channels are:

- scattering: $e^+e^- \to U\gamma$; $e^+e^- \to U\ P(\pi^0, \eta, ...)$
- higgs'-strahlung: $e^+e^- \to U\ h'$

– The signature depends on masses, m_U, m_χ, $m_{h'}$, dark coupling α_D, kinetic mixing, ϵ



– A particularly sensitive signature at the collider should be the analysis of mono–photon events, for constraining LDM production when the dark photon is on–shell and can decay in a LDM pair R. Essig *et al.* JHEP

- A High luminosity collider running at $\sqrt{s} \sim$ 1-2 GeV provides a unique data sample for

- new, more sensitive tests of QM and CPT invariance,
- the study of K_S rare decays,
- improving on the accuracy of the hadronic cross section,
- precision measurements of the pseudoscalar, $\pi\pi$ and KK production through γ–γ scattering
- to search for LDM and light dark photons

- With plans at Fermilab and JPARC for new experiments on the anomalous moment of the muon, hadronic cross section measurements and the program on γ–γ physics are needed to limit the theoretical uncertainties at the level of 20×10^{-11}