Rare decay $\pi_0 \to e^+ e^-$ as a filter for low mass dark matter

A.E. Dorokhov (JINR, Dubna),
In collaboration with M. Ivanov, E. Kuraev, Yu. Bystrytsky

Introduction

Model Independent Approach to $\pi^0 \to e^+e^-$ Decay and KTeV Data

Other $P \to l^+ l^-$ decays

$\pi^0 \to e^+e^-$ Decay and Dark Matter

Conclusions

Introduction

Abnormal people are looking for traces of Extraterrestrial Guests
Abnormal Educated people are looking for hints of New Physics

Cosmology tell us that 95% of matter was not described in text-books yet

Two search strategies:
1) High energy physics to excite heavy degrees of freedom.
No any evidence till now. LHC era has started on 10.09.08.

2) Low energy physics to produce Rare processes in view of huge statistics.

There are some rough edges of SM.

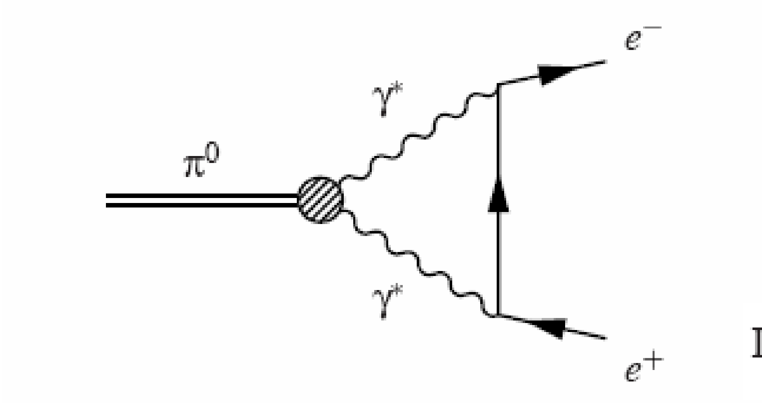
$(g-2)_\mu$ is very famous example

$\pi_0 \to e^+e^-$ is in the list of SM test after new exp. and theor. results

That's intriguing

Rare Pion Decay $\pi^0 \to e^+e^{--}$ *from KTeV*

PRD (2007)



Lowest order diagram

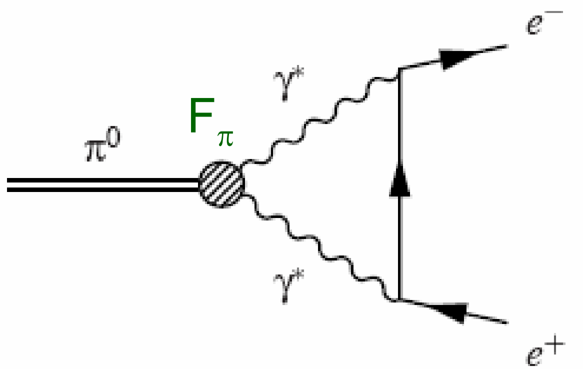
One of the simplest process for THEORY

From KTeV E799-II EXPERIMENT at Fermilab experiment (1997-2007)

$$B^{\mathrm{KTeV}}_{\pi\to e^+e^-} = (7.49 \pm 0.29 \pm 0.25) \bullet 10^{-8}$$

The result is based on observation of 794 candidate π_0 → e+e- events using K_L → $3\pi_0$ as a source of tagged π_0s.

Classical theory of $\pi^0 \to e^+e^-$ decay



Drell (59'), Berman,Geffen (60'),
Quigg,Jackson (68')

Bergstrom,et.al. (82') dispersion approach
Savage, Luke, Wise (92') χPT

$$R\left(\pi^0 \to e^+e^-\right) = \frac{B\left(\pi^0 \to e^+e^-\right)}{B\left(\pi^0 \to \gamma\gamma\right)} = 2\beta\left(m_\pi^2\right)\left(\frac{\alpha}{\pi}\frac{m_e}{m_\pi}\right)^2\left[\left(\mathrm{Re}\,\mathcal{A}\left(m_\pi^2\right)\right)^2 + \left(\mathrm{Im}\,\mathcal{A}\left(m_\pi^2\right)\right)^2\right]$$

$$\beta\left(q^2\right) = \sqrt{1 - 4\frac{m_e^2}{q^2}}$$

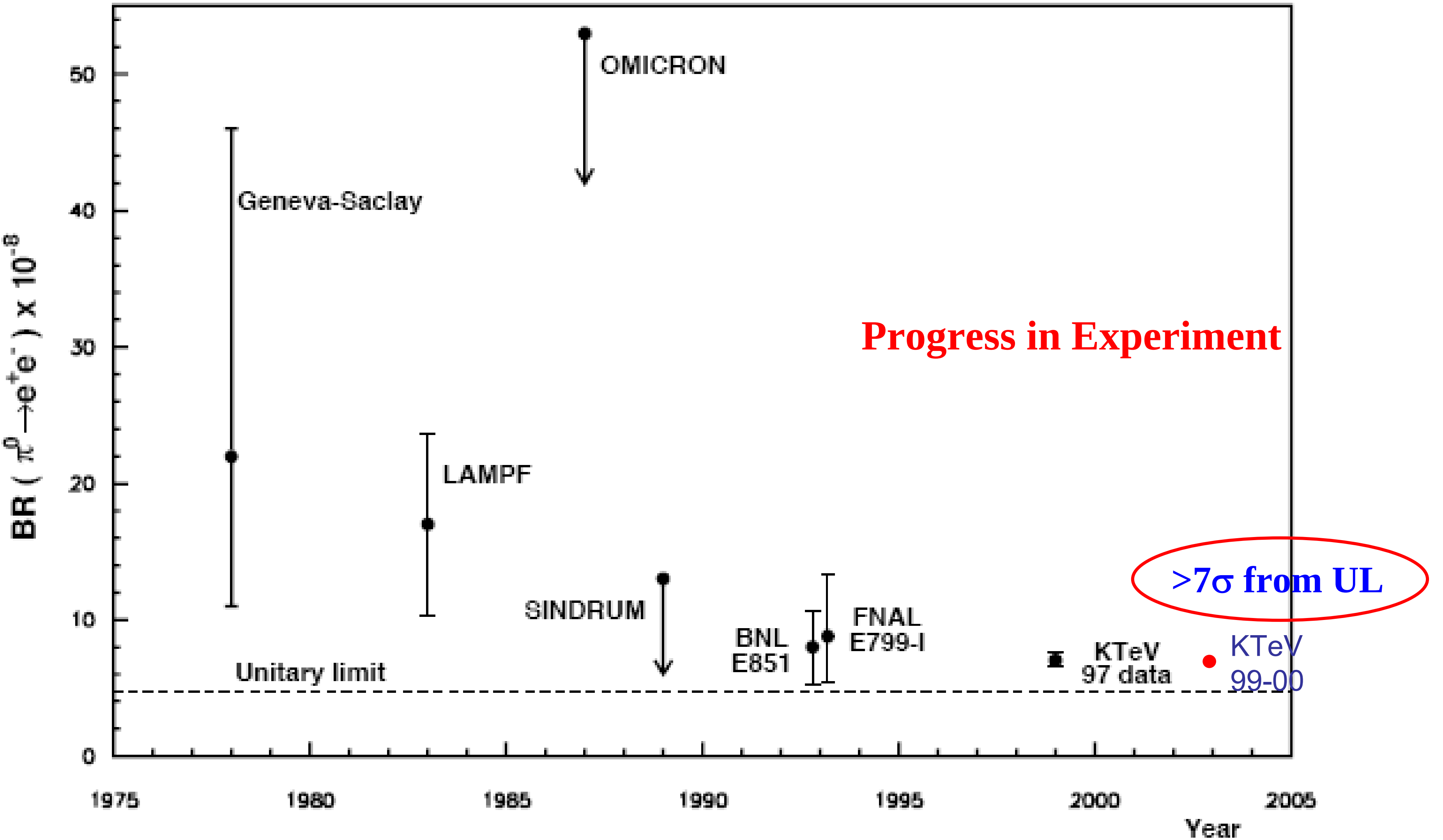
$$\mathcal{A}\left(q^2\right) = \frac{2i}{q^2}\int \frac{d^4k}{\pi^2}\frac{q^2k^2 - (qk)^2}{\left(k^2 + i\varepsilon\right)\left((k-q)^2 + i\varepsilon\right)\left((k-p)^2 - m_e^2 + i\varepsilon\right)}F_\pi\left(k^2, (k-q)^2\right)$$

$$\mathrm{Im}\,\mathcal{A}\left(q^2\right) = \frac{\pi}{2\beta\left(q^2\right)}\ln\left(\frac{1 - \beta\left(q^2\right)}{1 + \beta\left(q^2\right)}\right)$$

The Imaginary part is Model Independent;
Unitary limit

From condition $|\mathcal{A}|^2 \geq (\mathrm{Im}\,\mathcal{A})^2$ **one has the *unitary limit***

$$R\left(\pi^0 \to e^+e^-\right) \geq R^{\mathrm{unitary}}\left(\pi^0 \to e^+e^-\right) = 4.75 \cdot 10^{-8}.$$



Still no intrigue

I. The Decay Amplitude in Soft limit $q^2 \to 0$

A.D., M.A.Ivanov PRD 07'

$$\mathrm{Re}\,A\left(m_\pi^2\right) = \ln^2\left(\frac{m_e}{m_\pi}\right) + \frac{\pi^2}{12} + 3\ln\left(\frac{m_e}{\mu}\right) + \chi_P\left(\mu\right) + O\left(\frac{m_e^2}{\Lambda^2}\ln\left(\frac{\Lambda^2}{m_e^2}\right), \frac{m_\pi^2}{\Lambda^2}\right)$$

$$\chi_P\left(\mu\right) = -\frac{5}{4} - \frac{3}{2}\left[\int_0^{\mu^2} dt\,\frac{F_\pi\left(t,t\right)-1}{t} + \int_{\mu^2}^{\infty} dt\,\frac{F_\pi\left(t,t\right)}{t}\right]$$

$$m_e^2 \ll m_\pi^2 \ll \Lambda^2 \sim m_\rho^2$$

$$a_\mu^{(2)\mathrm{hvp}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\,\frac{K(s)}{s}\,R^{(0)}(s)$$

The unknown constant is expressed as inverse moment of Pion Transition FF!!!

The accuracy is of order $O(m_e/m_\rho)^2$.

Thus the amplitude is fully reconstructed!

[1] A. E. Dorokhov and M. A. Ivanov, Phys. Rev. D **75** (2007) 114007

[2] A. E. Dorokhov and M. A. Ivanov, JETP Lett. **87** (2008) 531

[3] A. E. Dorokhov, E. A. Kuraev, Yu. M. Bystritskiy and M. Secansky, Eur. Phys. J. C **55** (2008) 193

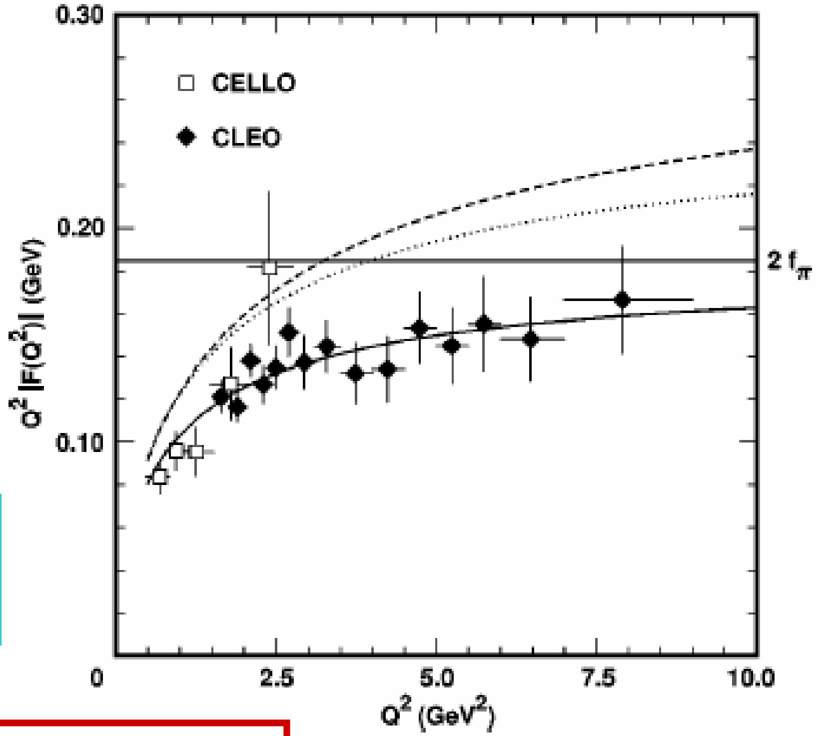
II. CLEO data and Lower Bound on Branching

Use inequality $F_\pi(t,t) < F_\pi(t,0)$ at spacelike $t>0$

and CLEO data (98')

$$F_\pi^{\rm CLEO}(t,0) = \frac{1}{1+t/s_0^{\rm CLEO}}$$

$$s_0^{\rm CLEO} = (776 \pm 22 \quad {\rm MeV})^2$$



$$\mathrm{Re}\,\mathcal{A}(q^2=0) > -\frac{3}{2}\ln\left(\frac{s_0^{\rm CLEO}}{m_e^2}\right) - \frac{5}{4} = -23.2 \pm 0.1$$

$$R\left(\pi^0 \to e^+e^-\right) \geq R^{\rm CLEO}\left(\pi^0 \to e^+e^-\right) = (5.91 \pm 0.02)\cdot 10^{-8}$$

$$R^{\rm KTeV} = (7.58 \pm 0.40) \bullet 10^{-8}$$

$$R\left(\pi^0 \to e^+e^-\right) \geq R^{\rm unitary}\left(\pi^0 \to e^+e^-\right) = 4.75 \cdot 10^{-8}.$$

Intrigue appears

III. $F_\pi(t,t)$ general arguments

Let $$F_\pi(t,t) = \frac{1}{1+t/s_1}$$ **then** $$\mathrm{Re}\,\mathcal{A}^{\mathrm{theory}}(q^2=0) = -\frac{3}{2}\ln\left(\frac{s_1}{m_e^2}\right) - \frac{5}{4}$$

1. From $$-\frac{\partial F_\pi(t,t)}{\partial t}\bigg|_{t=0} = -2\frac{\partial F_\pi(t,0)}{\partial t}\bigg|_{t=0}$$ **one has** $$s_1 = s_0/2$$

2. From OPE QCD (Brodsky, Lepage)

$$F_\pi^{\mathrm{OPE}}(t,0)\big|_{t\to\infty} = 8\pi^2 f_\pi^2 \frac{1}{t},$$

$$F_\pi^{\mathrm{OPE}}(t,t)\big|_{t\to\infty} = \frac{8\pi^2 f_\pi^2}{3}\frac{1}{t}$$

one has $$s_1^{OPE} = s_0^{OPE}/3$$

F(t,0) → F(t,t) reduces to rescaling

It follows $$\mathrm{Re}\,A^{\mathrm{theory}}(q^2=0) = -21.9 \pm 0.3$$

$$B^{\mathrm{KTeV}} = (7.49 \pm 0.39)\bullet 10^{-8}$$

$$B^{\mathrm{theory}}(\pi^0 \to e^+e^-) = (6.2 \pm 0.1)\bullet 10^{-8}$$ **3.3σ below data!!**

It would required change of s_0 scale by factor more then 10!

Now it's intriguing!

B. $F\pi(t,t)$ VMD parametrization *(M.Knecht, A.Nyffeler, EPJC 01')*

$$F_{gVMD}(s,t) = \frac{4\pi^2 f_\pi^2}{3} \frac{(s+t)\,st - h_2 st + h_5 (s+t) + M_V^4 M_{V1}^4 h_7}{(M_V^2+s)(M_V^2+t)(M_{V1}^2+s)(M_{V1}^2+t)}$$

$$\langle r^2 \rangle_{\pi\gamma\gamma^*} = -6 \left.\frac{\partial F(t,0)}{\partial t}\right|_{t=0} = 6\left(\frac{1}{M_V^2} + \frac{1}{M_{V1}^2} - \frac{h_5}{M_V^2 M_{V1}^2}\frac{3}{4\pi^2 f_\pi^2}\right) = 0.39 \quad \mathrm{fm}^2$$

$$\mathrm{Re}\,\mathcal{A}_{g\mathrm{VMD}}(q^2=0) = -3\ln\left(\frac{M_V}{m_e}\right) + \frac{1}{4} + \frac{3r}{(r-1)^2} - \frac{3}{2}\frac{3r-1}{(r-1)^3}\ln r +$$

$$+\frac{4\pi^2 f_\pi^2}{M_V^2 (r-1)^3}\left(\frac{h_2}{2M_V^2}\left((r+1)\ln r - 2(r-1)\right) - \left(1 + \frac{h_5}{M_{V1}^2 M_V^2}\right)\left(r^2 - 1 - 2r\ln r\right)\right) = -21.94$$

$r = (M_{V1}/M_V)^2.$

Nicely confirms general arguments!
Parameters for LbL

$$\mathrm{Re}\,A^{\mathrm{theory}}(q^2=0) = -21.9 \pm 0.3$$

A. $F_\pi(t,t)$ QCD sum rules (V.Nesterenko, A.Radyushkin, YaF 83')

$$F_\pi^{\mathrm{QCDsr}}(t,t) = 2\int_0^{s_0^{\mathrm{QCDsr}}} ds \int_0^1 dx \frac{x(1-x)t^2}{\left[x(1-x)s+t\right]^3} + \text{v.c.},$$

From

$$-\frac{\partial F_\pi(t,t)}{\partial t}\bigg|_{t=0} = -2\frac{\partial F_\pi(t,0)}{\partial t}\bigg|_{t=0}$$

and

$$\langle r^2\rangle^{\mathrm{QCDsr}}_{\pi^0\gamma^*\gamma^*} = -6\frac{\partial F_\pi^{\mathrm{QCDsr}}(t,t)}{\partial t}\bigg|_{t=0} = \frac{12}{s_0^{\mathrm{QCDsr}}}$$

one has

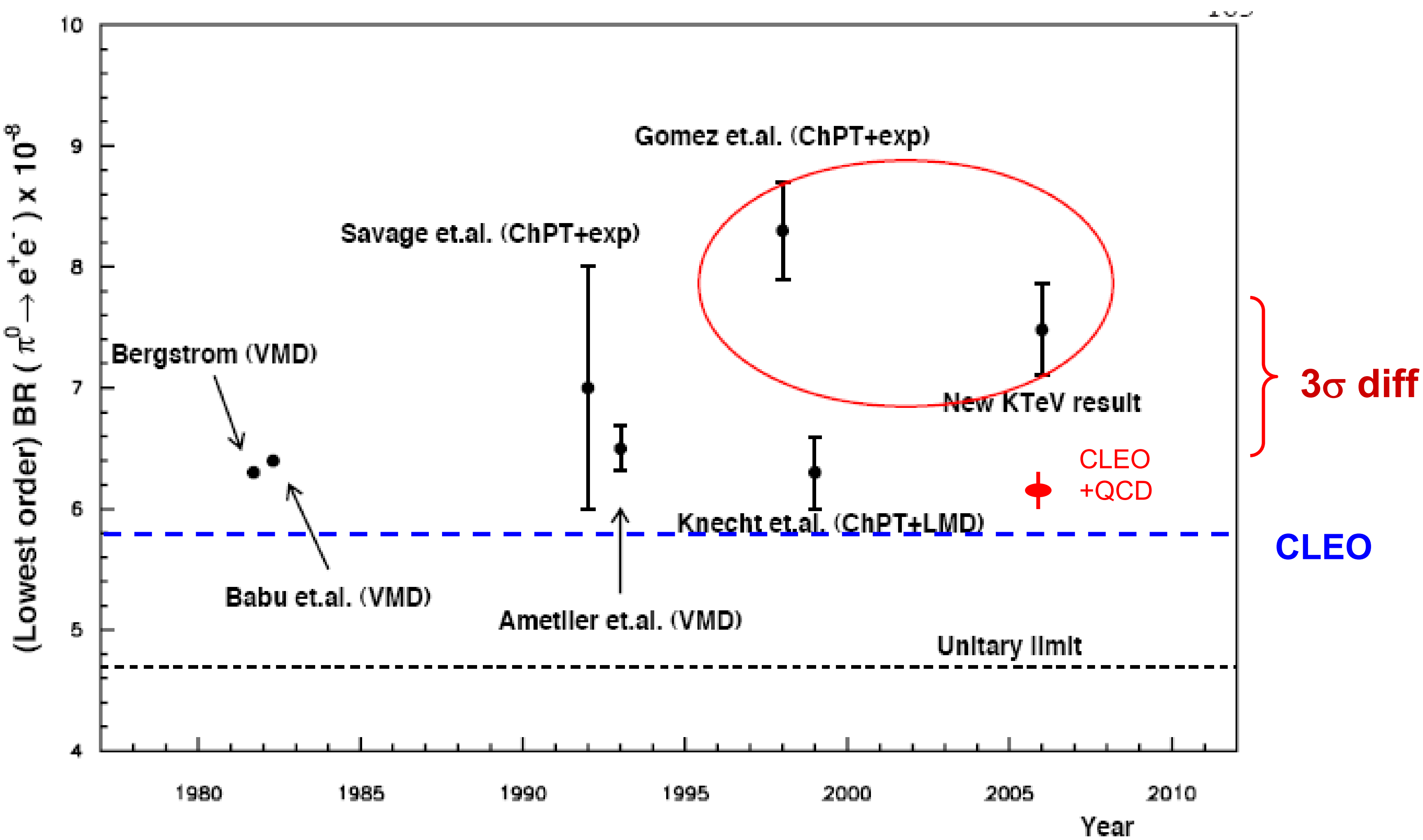
$$s_0^{\mathrm{QCDsr}} = s_0^{\mathrm{CLEO}}$$

$$\operatorname{Re} A^{\mathrm{QCDsr}}\left(q^2=0\right) = -\frac{3}{2}\ln\left(\frac{s_0^{\mathrm{CLEO}}}{\mathrm{m}_e^2}\right) + \frac{1}{4} = -21.7 \pm 0.1,$$

$$s_1^{\mathrm{QCDsr}} = \frac{s_0^{\mathrm{QCDsr}}}{e}$$

Nicely confirms general arguments!

$$\operatorname{Re} A^{\mathrm{theory}}\left(q^2=0\right) = -21.9 \pm 0.3$$



What is next? It would be very desirable if Others will confirm KTeV result
Also, Pion transition FF need to be more accurately measured.

Possible explanations of the effect

1) Radiative corrections

KTeV used in their analysis the results from Bergstrom 83'.

A.D.,Kuraev, Bystritsky, Secansky (EJPC 08') confirmed Numerics.

2) Mass corrections (tiny)

A.D., M.Ivanov (ZhETPh Lett 08')

Dispersion relations are corrected by small power corrections $(m_\pi/m_\rho)^n$

3) New physics

Kahn, Schmidt, Tait 07' Low mass dark matter particles

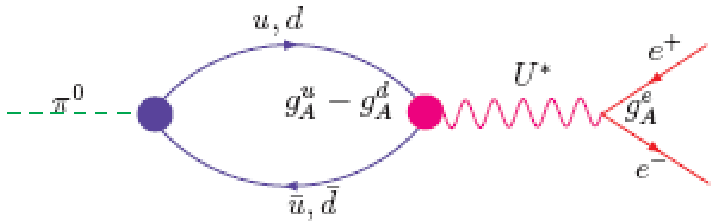
4) Experiment wrong

Waiting for new results from

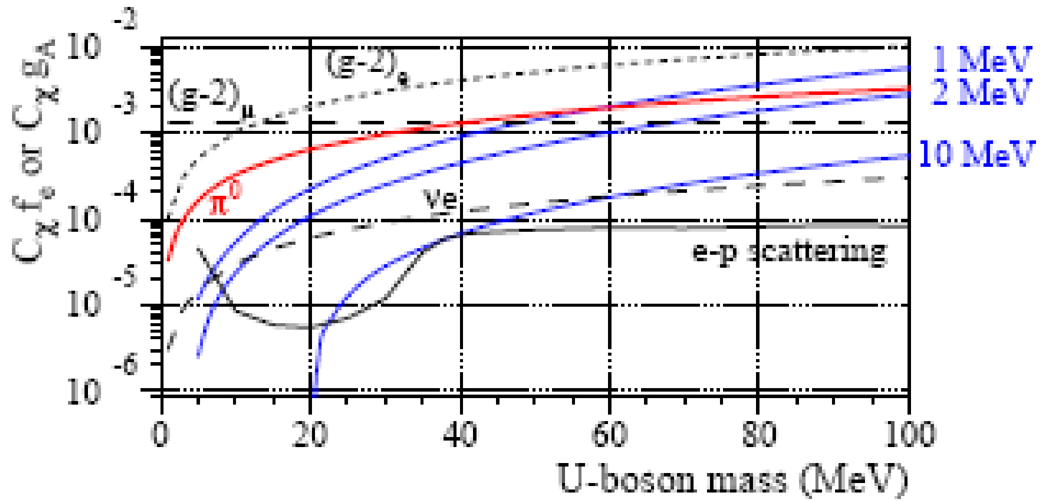
KLOE, NA48, WASA@COSY, BESIII,…

Enhancement in Rare Pion Decays from a Model of MeV Dark Matter (Boehm&Fayet)

was considered by Kahn, Schmitt and Tait (2007)



$$M_{U^*} \sim 10 \text{ MeV}$$



The anomalous 511 keV γ-ray signal from Galactic Center observed by INTEGRAL/SPI (2003) is naturally explained

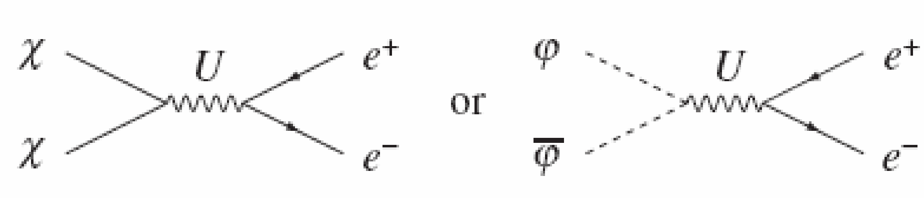


FIG. 1. Dark matter annihilations into e^+e^- pairs [12,13]. The first diagram corresponds to the pair annihilation of spin-$\frac{1}{2}$ LDM particles χ (which may be self-conjugate, or not); and the second one to the case of spin-0 particles φ.

Rare decay $\pi 0 \rightarrow e+e-$ as a sensitive probe of light CP-odd Higgs in Next-to-Minimal SuperSymmetric Model (NMSSM)
(Qin Chang, Ya-Dong Yang, 2008)

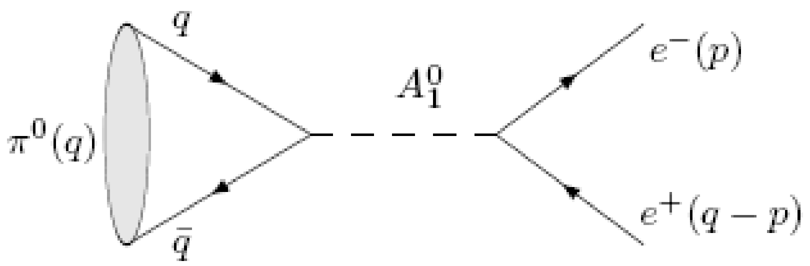


Figure 1: Relevant Feynman diagram within NMSSM.

They find the combined constraints from $\Upsilon \rightarrow \gamma A^0_1$, a_μ and $\pi 0 \rightarrow e+e-$ point to a very light A^0_1 with $m_{A01} \simeq$ 135MeV and $|Xd| = 0.10 \pm 0.08$


VICTORIA

Other $P \to l^+l^-$ decays

$$F_\eta^{\mathrm{CLEO}}\left(k^2, q^2 = 0\right) = \frac{1}{1 + k^2 / s_{0\eta}^{\mathrm{CLEO}}}, \qquad s_{0\eta}^{\mathrm{CLEO}} = (774 \pm 29 \quad \mathrm{MeV})^2,$$

TABLE II. Values of the branchings $B(P \to l^+l^-)$ obtained in our approach and compared with the available experimental results.

B	Unitary bound	CLEO bound	CLEO + OPE	Experiment
$B(\pi^0 \to e^+e^-) \times 10^8$	≥ 4.69	$\geq 5.85 \pm 0.03$	6.23 ± 0.09	7.49 ± 0.38 [1]
$B(\eta \to \mu^+\mu^-) \times 10^6$	≥ 4.36	$\leq 6.23 \pm 0.12$	5.11 ± 0.20	5.8 ± 0.8 [7,32]
$B(\eta \to e^+e^-) \times 10^9$	≥ 1.78	$\geq 4.33 \pm 0.02$	4.60 ± 0.06	...

$B\left(\eta \to e^+e^-\right) \leq 2.7 \times 10^{-5}$ Celsius/Wasa 2008

Summary

1) *The processes P → l+l- are good for test of SM. Radiative and mass corrections are well under control. New measurments of the transition form factors are welcome.*

2) *At present there is 3.3σ disagreemnt between SM and KTeV experiment for π0→e+e-*
CLOE, WASA@COSY, NA48 are interested in new measurments

3) *If effect found persists it might be evidence for the SM extensions with low mass (10-100 MeV) particles (Dark Matter, NSSM)*

Anomalous magnetic moment of muon

From BNL E821 experiment (1999-2006)

$$a_\mu^{BNL} = 11\,659\,208.0(6.3)\bullet 10^{-10}$$

Standard Model $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadr} = 11\,659\,178.5(6.1)\bullet 10^{-10}$

predicts the result which is 3.4σ below the experiment (since 2006)