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Light meson decays:

low energy QCD

Chiral Symmetry
Nambu-Goldstone bosons
Breaking patterns + theory

...fundamental symmetries

light $q\bar{q}$ mesons: π^0, η

Andrzej Kupsc, Uppsala University

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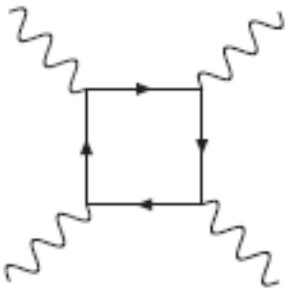
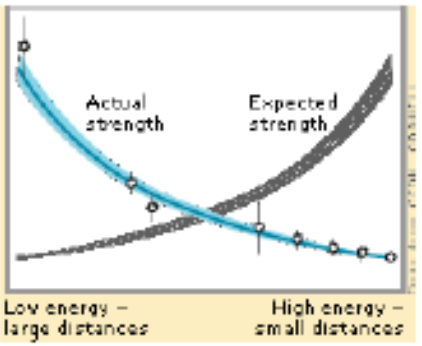
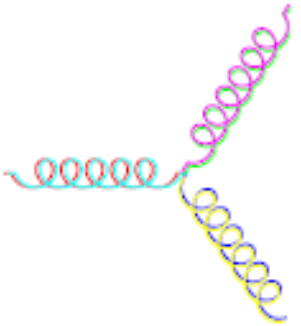
Quantum Chromodynamics (QCD)

Electrodynamics		Chomodynamics
electric charge U(1)		color $SU(3)$
photon		8 gluons
neutral		have color
		
$\alpha = 1/137$	at low energy	α_S large
$\alpha = 1/128$	at 100 GeV	$\alpha_S = 0.12$
$V(r) = -\alpha/r$	potential	$V(r) = -4/3\alpha_s/r + kr$

Perturbation theory – expansion in α:

$$\sigma \propto |A_1\alpha + A_2\alpha^2 + ...|^2$$

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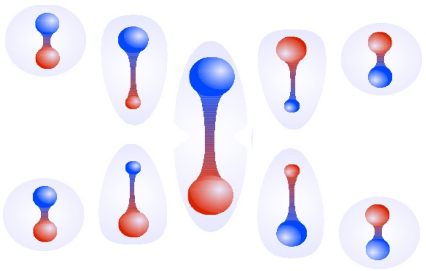
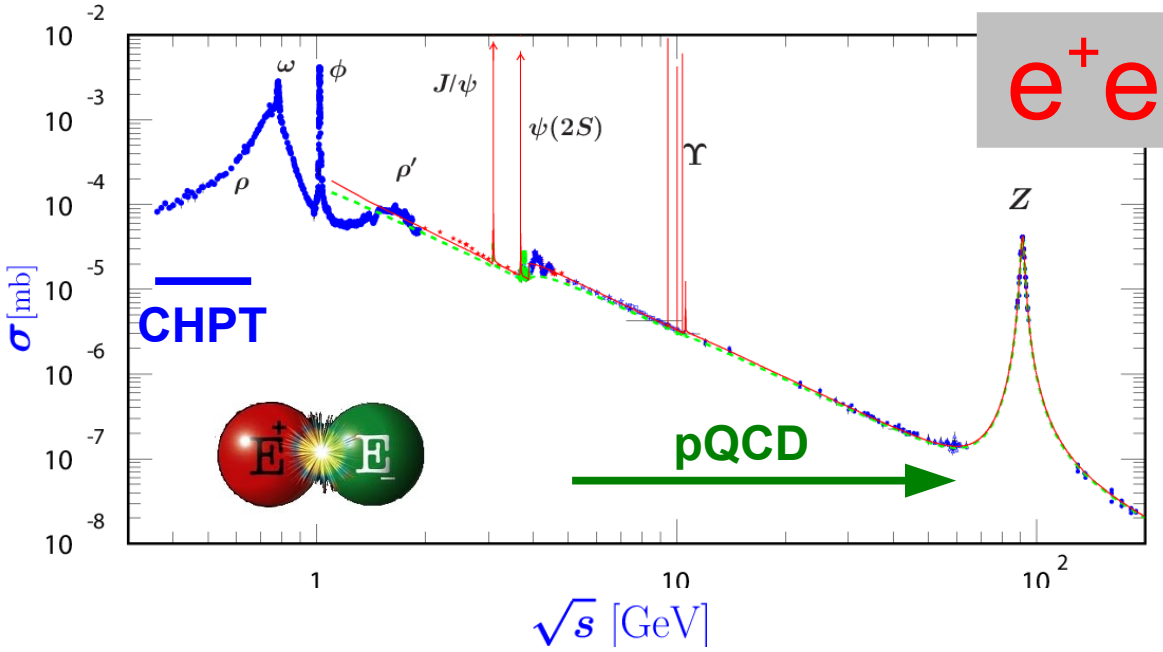
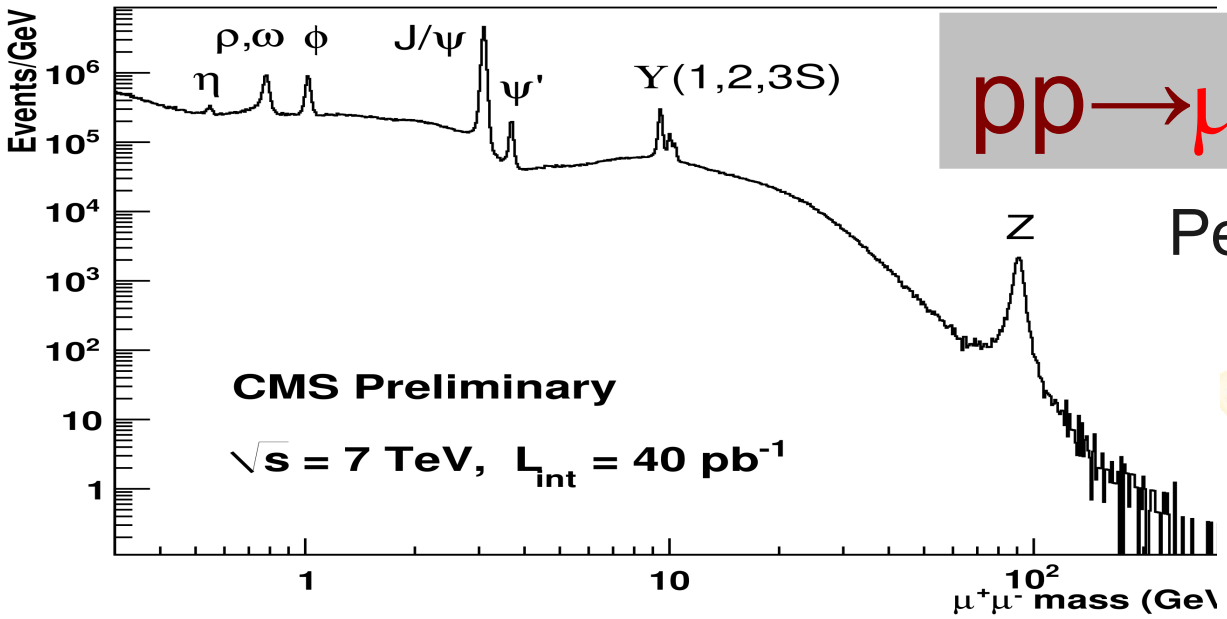
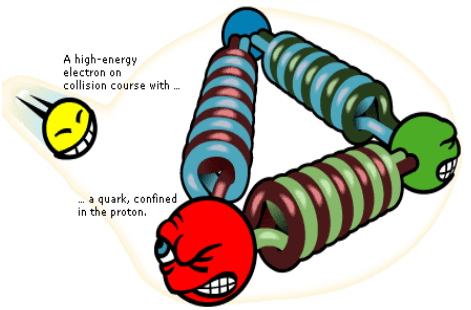
SM spectrum





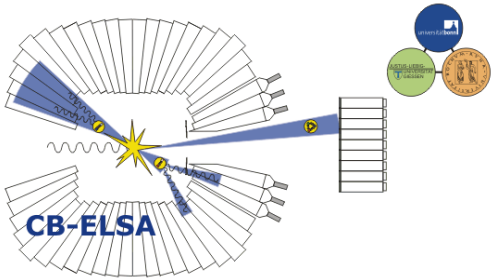


Perturbative QCD



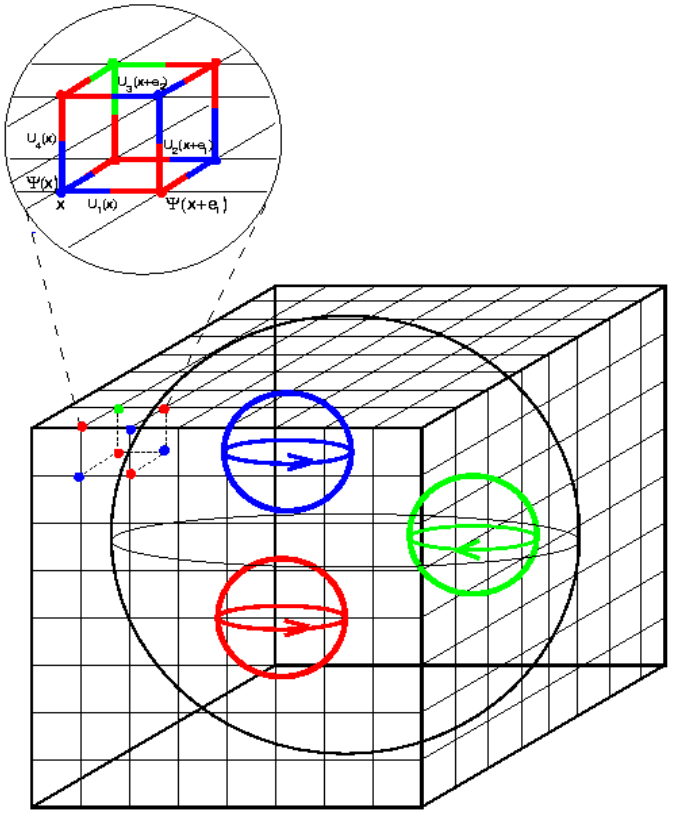
Experiments

WASA-at-COSY



Low energy

QCD



Lattice QCD

Theory

- **Symmetries**
- **Effective theories**
  =>Chiral Perturbation Theory
- **Dispersion relations**

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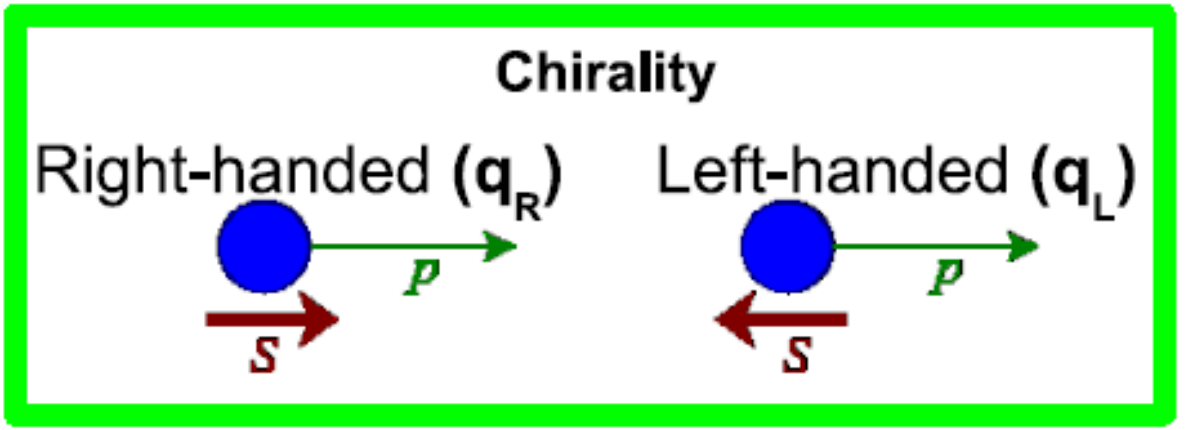
Global Symmetries of QCD

- $SU(2)_{flavor}$ isospin symmetry: $m_u \approx m_d$
- $SU(3)_{flavor}$ symmetry Eightfold way: $m_u \approx m_d \approx m_s$



- Chiral symmetry

(independent rotations of q_L, q_R components)

$\Rightarrow$ $SU(2)_{flavor,L} \times SU(2)_{flavor,R}$ $\quad m_u, m_d \approx 0$

$\Rightarrow$ $SU(3)_{flavor,L} \times SU(3)_{flavor,R}$ $\quad m_u, m_d, m_s \approx 0$

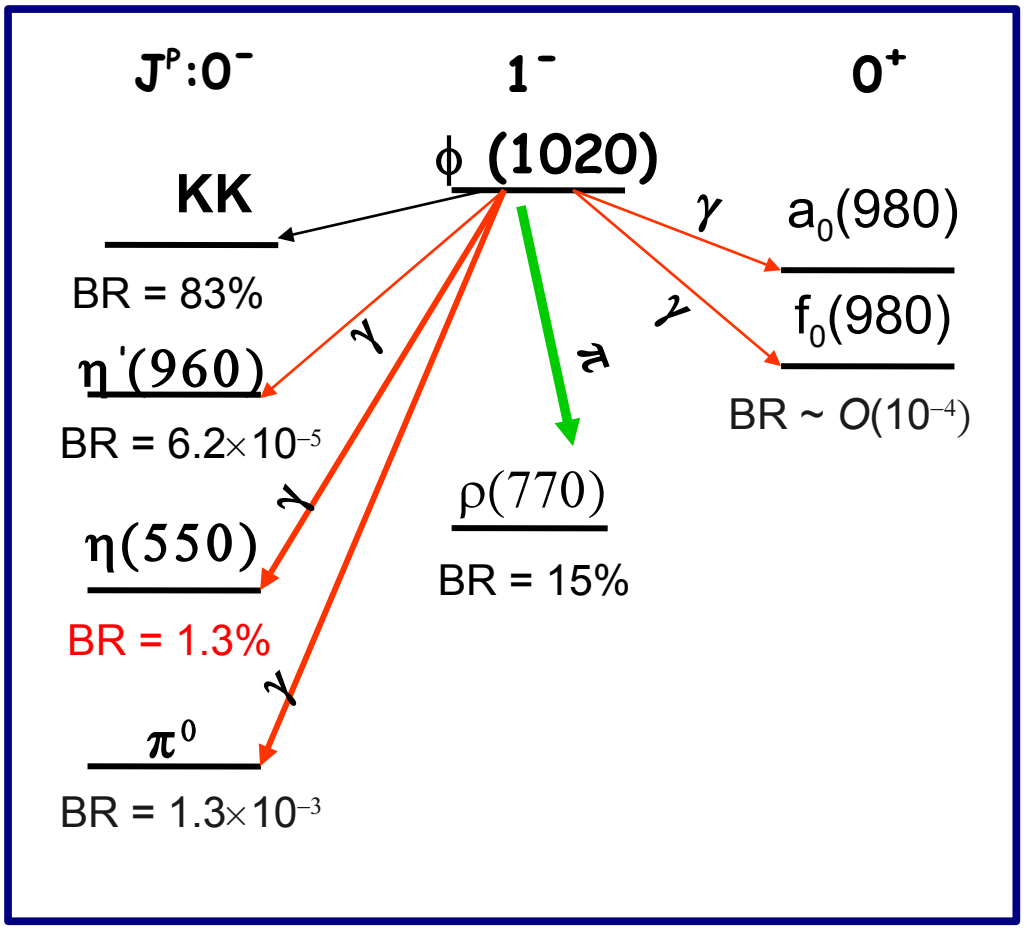
$SU(3)_V \times SU(3)_A$

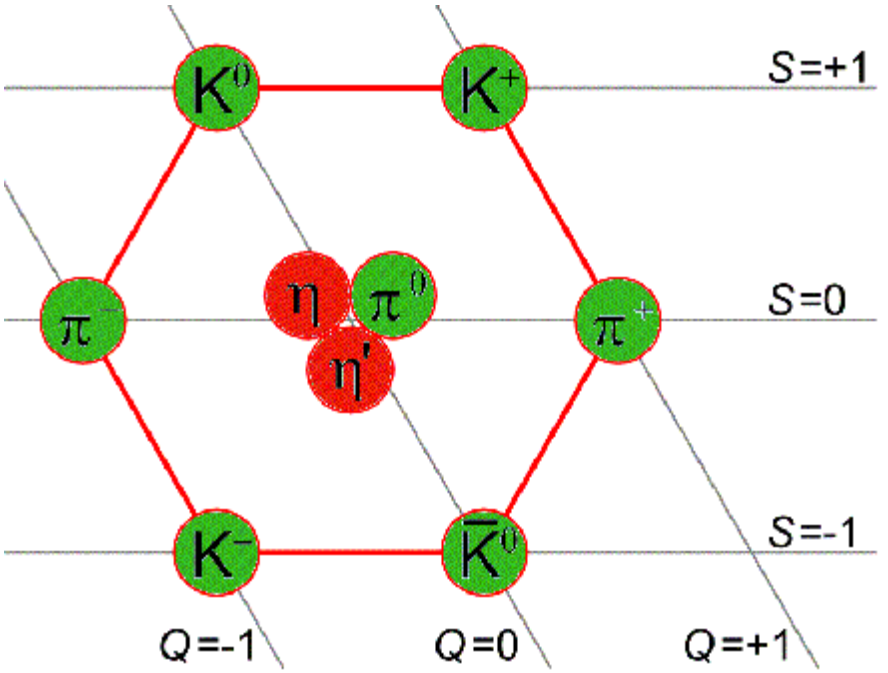
$\Rightarrow$ Symmetries in particle spectrum

Light mesons

$q\bar{q}'$ mesons

Mass < nucleon mass





- Parity $P(q\bar{q}) = (-1)^{L+1}$
- $J^{PC} = 0^{-+}$ mesons (π, K, η): $q \downarrow \bar{q} \uparrow, L = 0\ (^1S_0)$
- $J^{PC} = 0^{++}$ mesons (a_0, K_0^*, f_0): $q \uparrow \bar{q} \uparrow, L = 1\ (^3P_0)$

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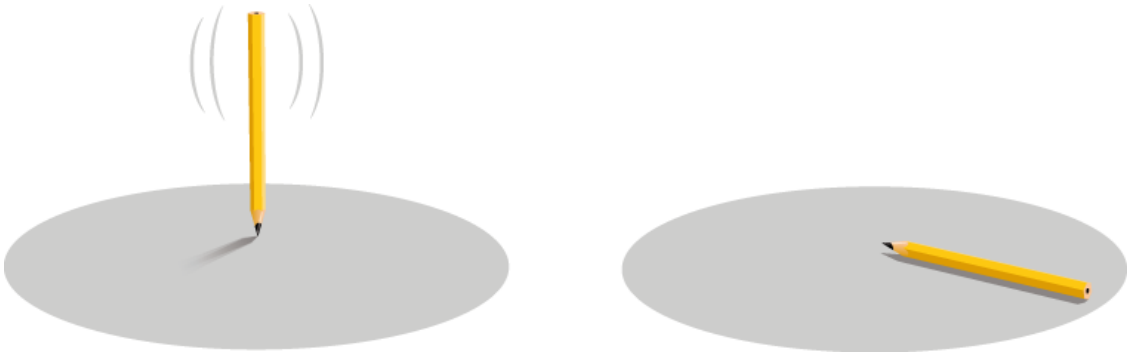
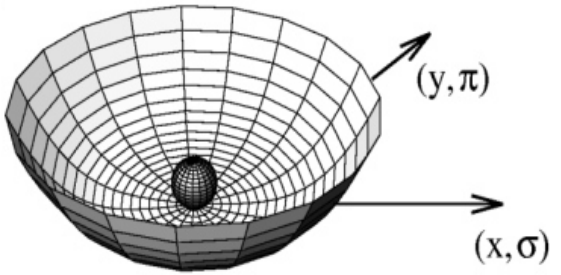
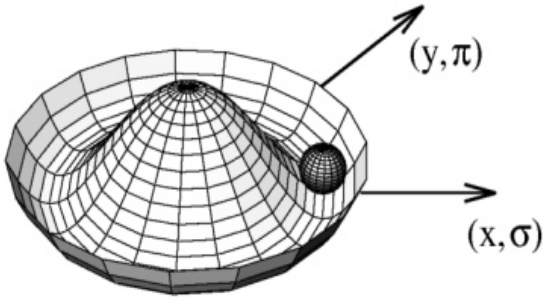
Spontaneous symmetry breaking

- Concept from solid state physics:

  Ferromagnets, superconductors







Nambu 1960: *implementation in subatomic physics*

Ground state not symmetric ⇒ the symmetry is *hidden*:

Global symmetry ⇒ massless particles (Nambu-Goldstone bosons)

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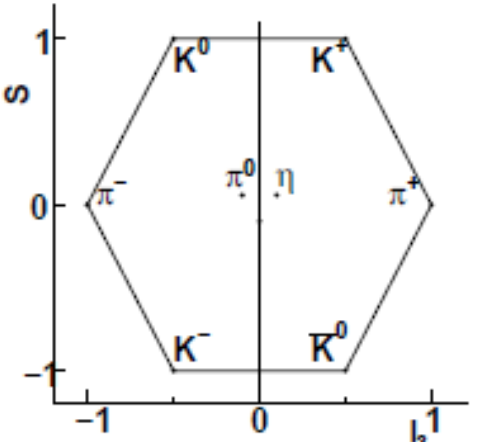
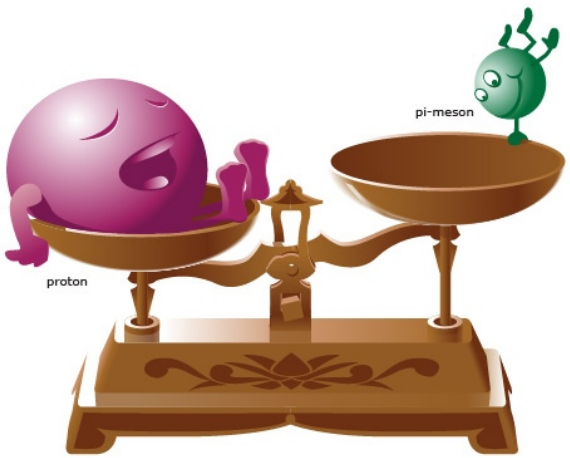
Consequences of hidden Chiral Symmetry

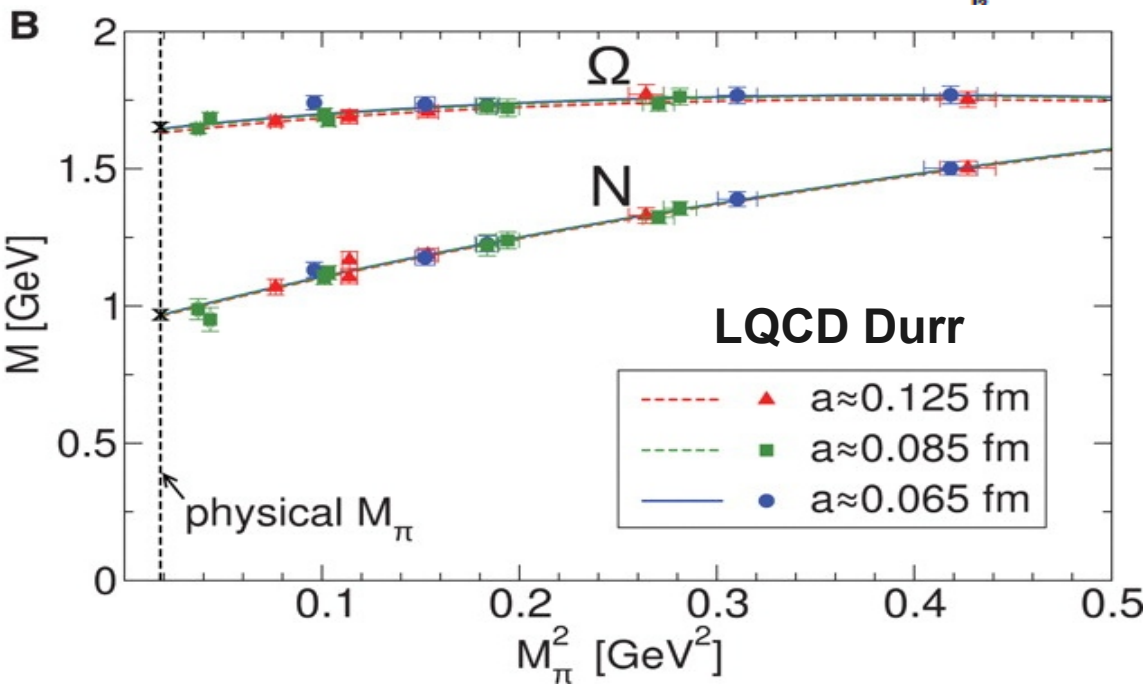
QCD with $m_u, m_d, m_s \approx 0 \Rightarrow$ 8 NG bosons:

⇒ Identified as pseudoscalar mesons

- Quark masses as perturbation: $M_\pi^2 = B(m_u + m_d) + \ldots$
- At vanishing momenta NG bosons do not interact







Hadrons: Mass from QCD vacuum

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Chiral Perturbation Theory (CHPT)

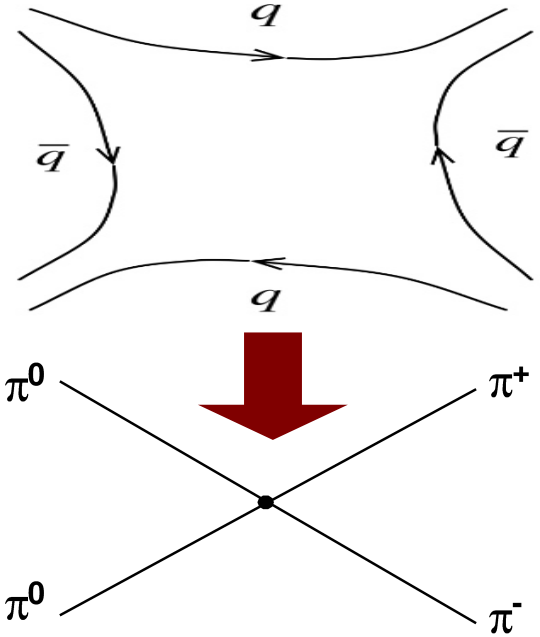
A recipe for theory for $p < \Lambda$:

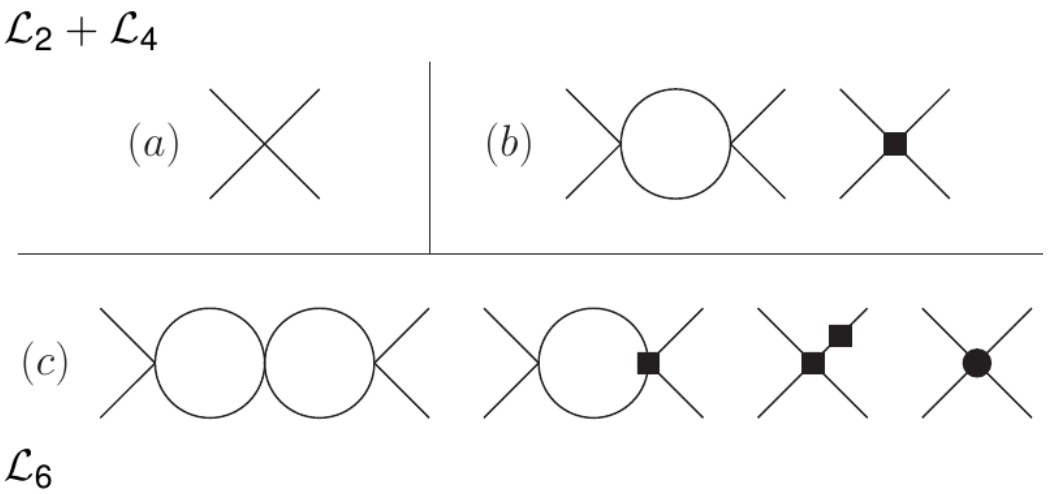
- Chiral Symmetry + NG bosons: $J^{PC} = 0^{-+}$ octet
- Order by powers of $(p/\Lambda)^2$ and (m_q/Λ)
- Unknown couplings: (# 2,10,100,...)

$\Rightarrow \sigma \propto |A_2(B, F_\pi)(p/\Lambda)^2 + A_4(L_1, ..., L_{10})(p/\Lambda)^4 + ...|^2$

- Simplest process $\pi\pi$ scattering:

Chiral Perturbation Theory: Gasser, Leutwyler 1984





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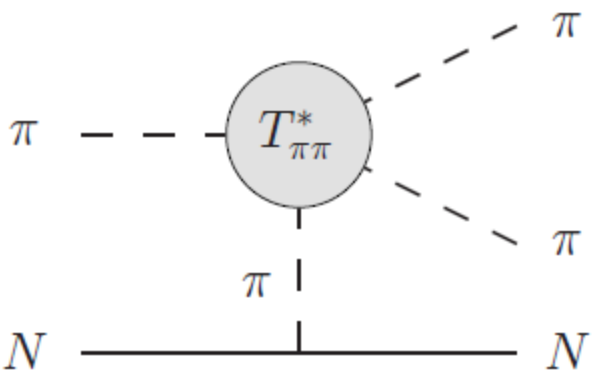
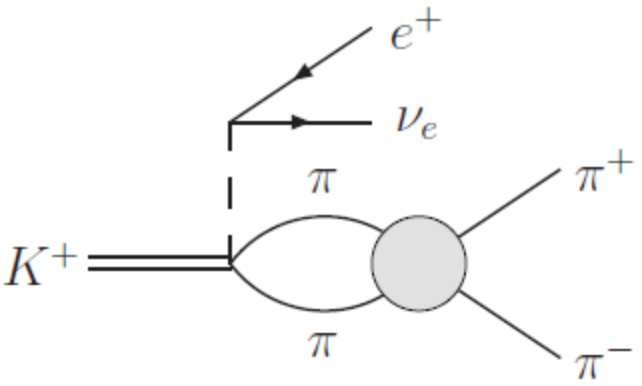
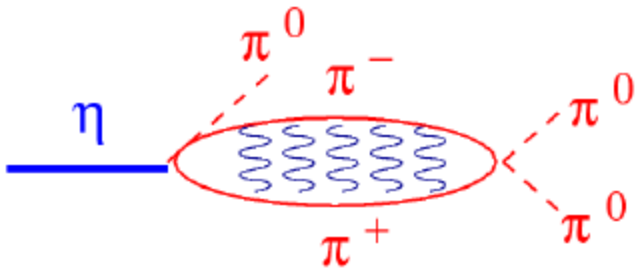
Experimental studies of $\pi\pi \to \pi\pi$

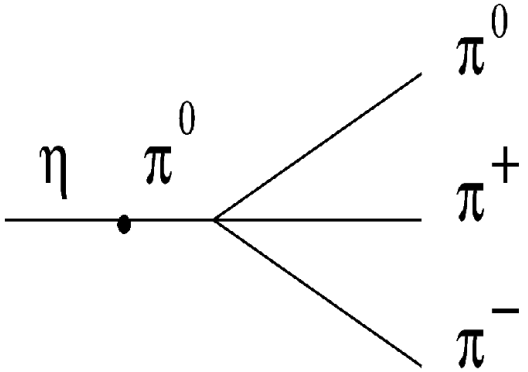
- $\pi N \to \pi\pi N$
- $K^+ \to \pi^+\pi^- e^+ \nu_e$
- $\eta \to 3\pi$ decays
- Cusp in $K^+ \to \pi^+\pi^0\pi^0$, $K_L \to \pi^0\pi^0\pi^0$, $\eta \to \pi^0\pi^0\pi^0$
- Pionium





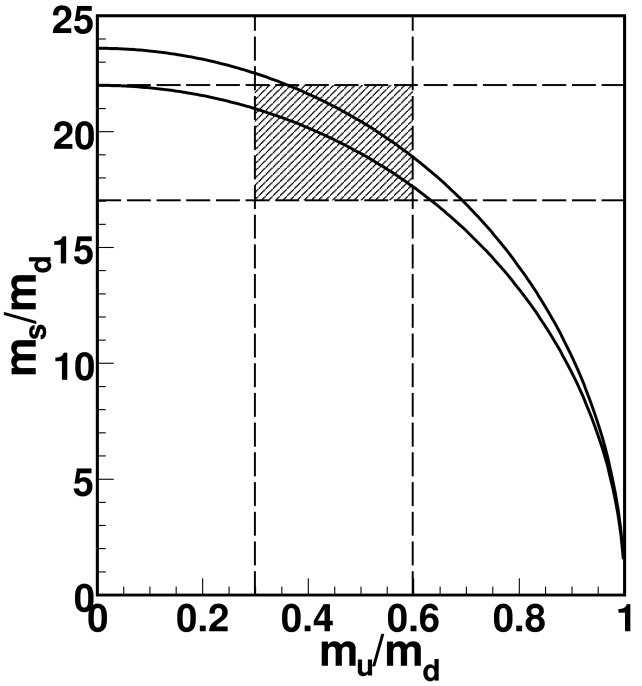


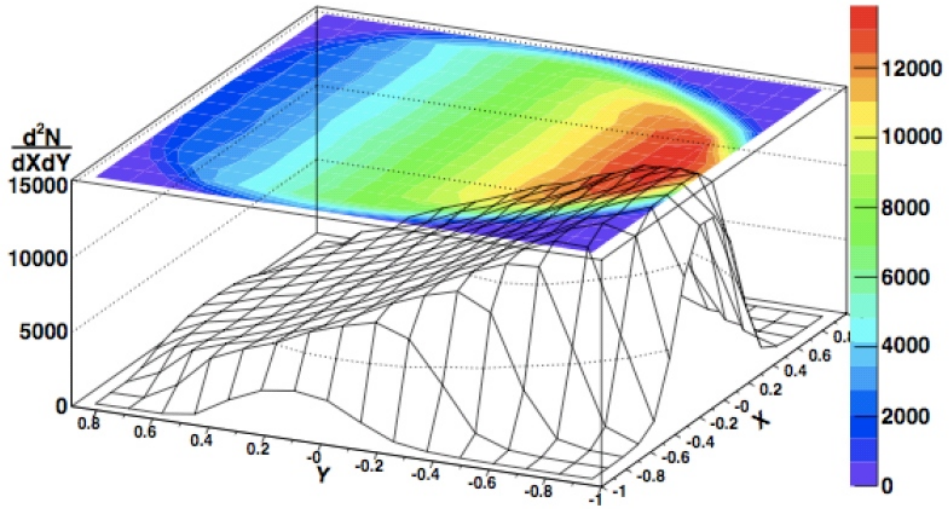
Decay $\eta \to \pi\pi\pi$

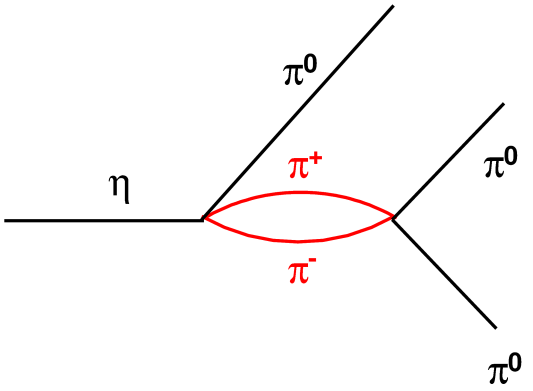


MAMI,KLOE, WASA

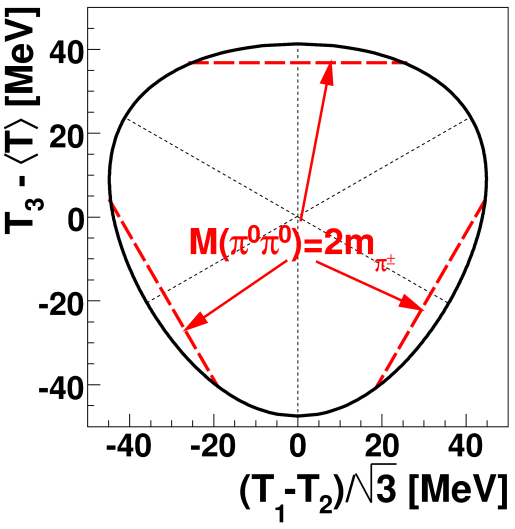
light quark mass ratios
CHPT L_6
+ extensions:
dispersion relations







$\pi^0\pi^0 \to \pi^+\pi^-$ **at treshold**



Meson Transition Form Factors (TFF)

Low energy QCD

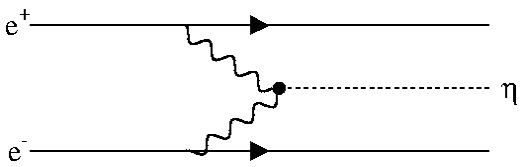
Chiral anomaly

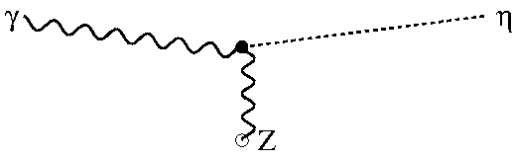
SM contribution to a_μ

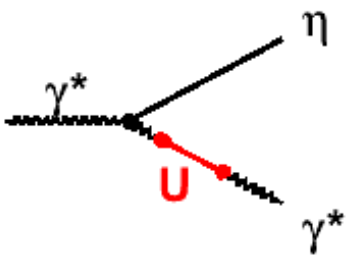
U boson

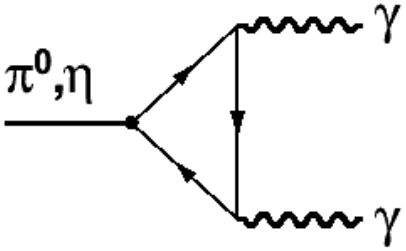
$\Gamma(P \to \gamma\gamma)$

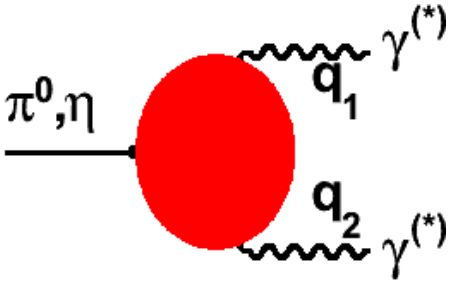
$F_P(q_1^2, q_2^2)$

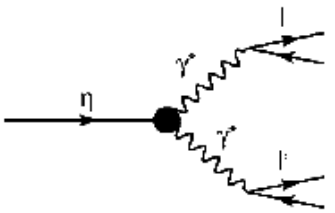


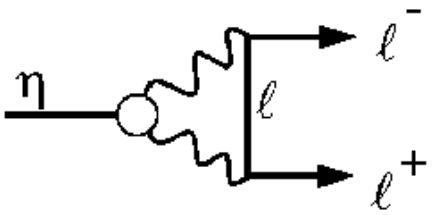


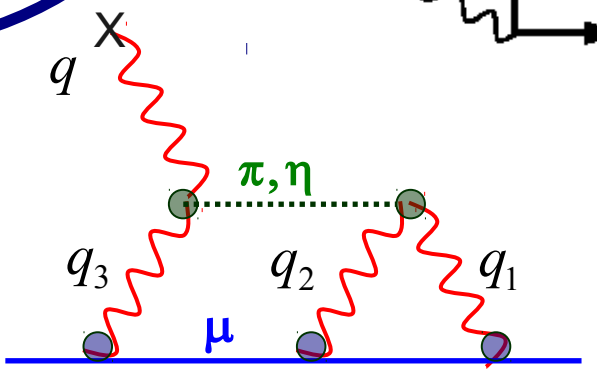






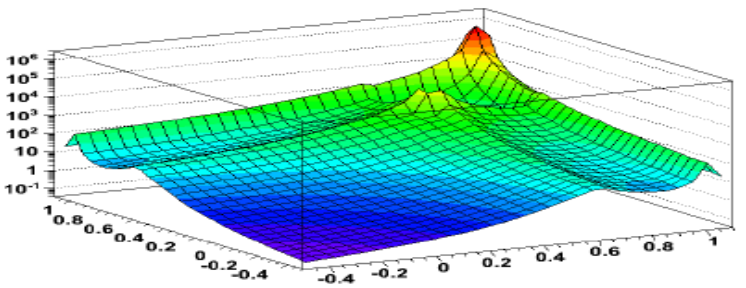






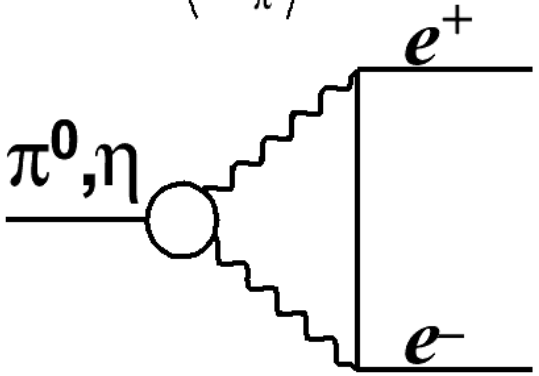
Workshop on Meson Transition Form Factors

May 29-30, 2012 in Cracow, Poland



$\pi^0, \eta \to l^+l^-$

$$BR \approx \alpha^2 \left(\frac{m_e}{m_\pi}\right)^2 \approx O(10^{-8})$$



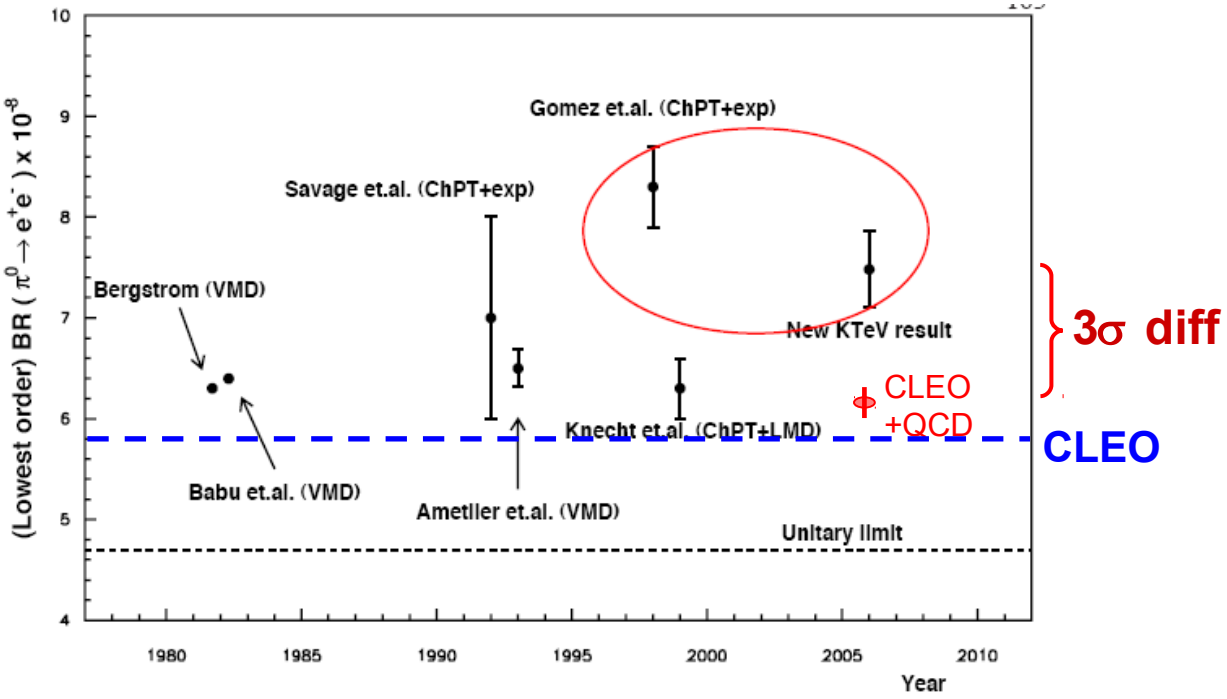


TABLE II. Values of the branchings $B(P \to l^+l^-)$ obtained in our approach and compared with the available experimental results.

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	...

Dorokhov,2007

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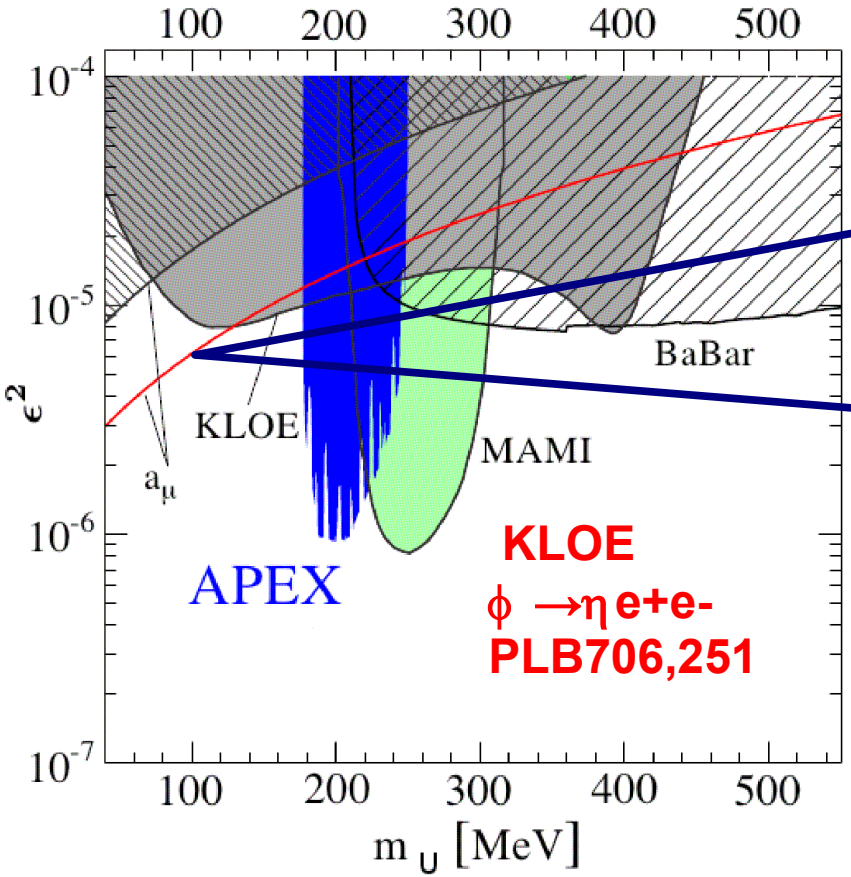
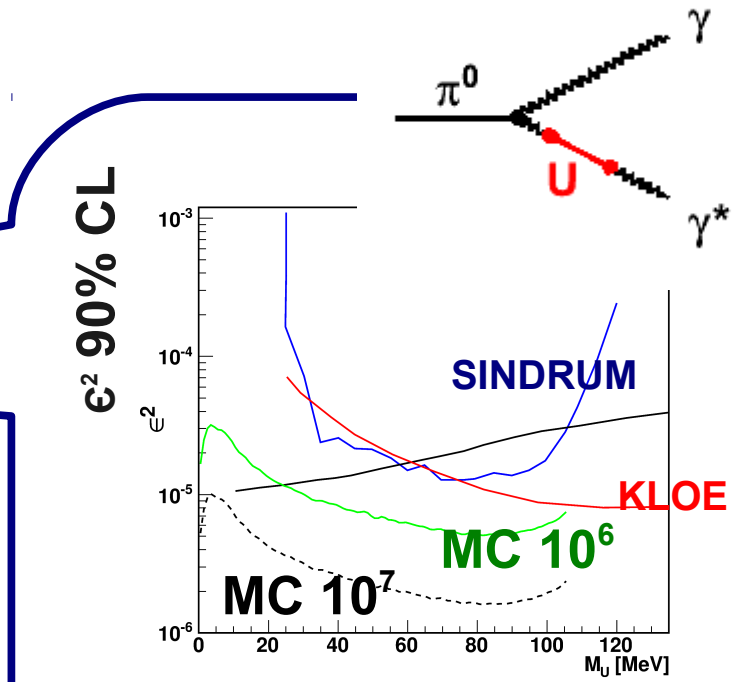
Dark photon searches





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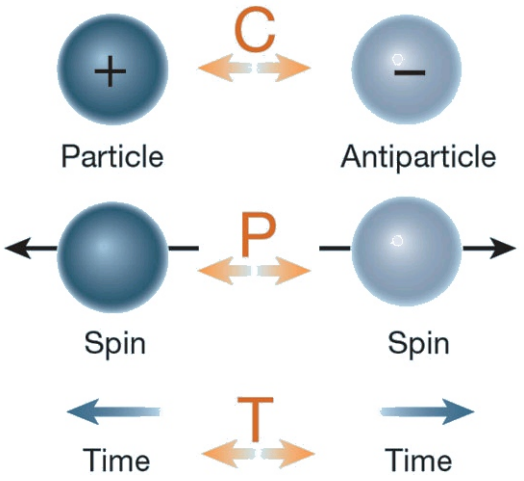
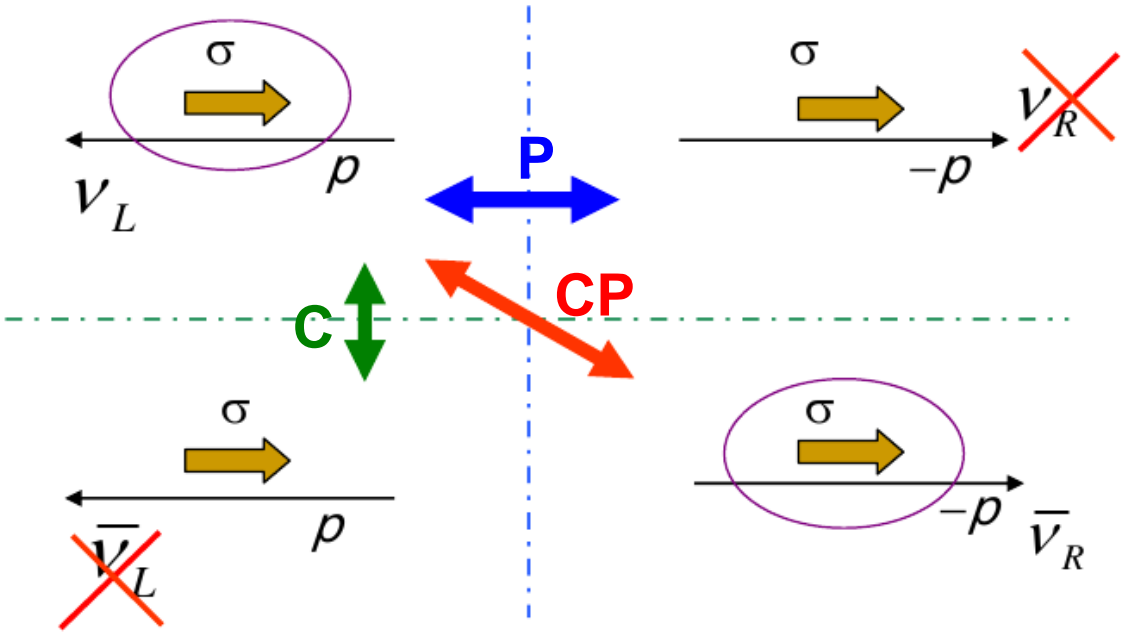
C, P and T symmetries in SM

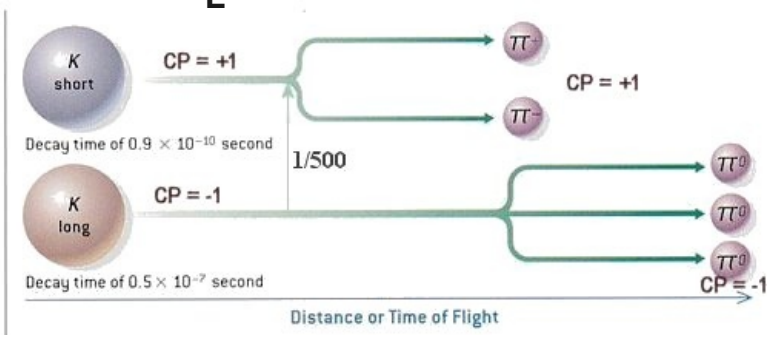




C, P violated in weak interactions

Standard Model (SM): V-A coupling

CP violation: $K_L \rightarrow 2\pi$ (Cronin, Fitch 1964)



SM: CKM matrix

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Tests of discrete symmetries in π^0, η decays

- CPV due to C invariance in em interactions of hadrons

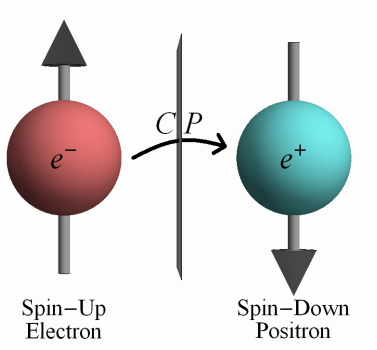
  Bernstein,Feinberg,Lee PR139,B1650,1965

- The π^0, η mesons:
  - $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ mixtures – *"light quarkonia"*

  $\Rightarrow$ C,CP eigenstates
  - pseudo Goldstone bosons of the Chiral Symmetry

  $\Rightarrow$ light and long lived
  - tests complementary to K_L decays

  $+$ π^0, η abundantly produced



- Two ways of testing:

$\Rightarrow$ Rare decays

$\Rightarrow$ Symmetries of the decay distributions

η: 5×10^{-19} s; Γ=1.3 keV	$\eta \to \gamma\gamma$
π^0: 8×10^{-17} s; $c\tau$=25 nm	$\pi^0 \to \gamma\gamma$

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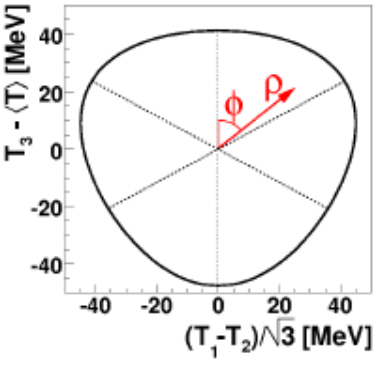
η decays: Tests of fundamental symmetries

η

$I^G(J^{PC}) = 0^+(0^{-+})$

Mass $m = 547.853 \pm 0.024$ MeV
Full width $\Gamma = 1.30 \pm 0.07$ keV

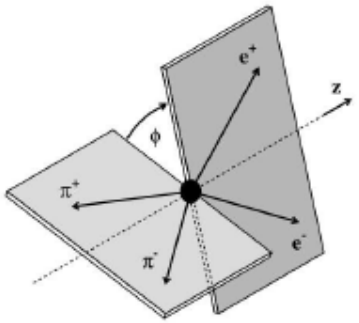


C-nonconserving decay parameters

$\pi^+\pi^-\pi^0$	left-right asymmetry	$= (0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$	sextant asymmetry	$= (0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$	quadrant asymmetry	$= (-0.09 \pm 0.09) \times 10$
$\pi^+\pi^-\gamma$	left-right asymmetry	$= (0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$	β (D-wave)	$= -0.02 \pm 0.07$ (S = 1.3)

CP-nonconserving decay parameters

$\pi^+\pi^- e^+ e^-$ decay-plane asymmetry $A_\phi = (-0.6 \pm 3.1) \times 10^{-2}$



Charge conjugation (C), Parity (P), Charge conjugation × Parity (CP), or Lepton Family number (LF) violating modes

$\pi^0\,\gamma$	C		$<9 \times 10^{-5}$
$\pi^+\,\pi^-$	CP,P		$<1.3 \times 10^{-5}$
$2\pi^0$	CP,P		$<3.5 \times 10^{-4}$
$2\pi^0\,\gamma$	C		$<5 \times 10^{-4}$
$3\pi^0\,\gamma$	C		$<6 \times 10^{-5}$
3γ	C		$<1.6 \times 10^{-5}$
$4\pi^0$	CP,P		$<6.9 \times 10^{-7}$
$\pi^0\,e^+\,e^-$	C	[a]	$<4 \times 10^{-5}$
$\pi^0\,\mu^+\,\mu^-$	C	[a]	$<5 \times 10^{-6}$
$\mu^+\,e^- + \mu^-\,e^+$	LF		$<6 \times 10^{-6}$

PDG 2010

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CP tests in η decays

- $\eta \to \pi\pi$
- predictions:

  Jarlskog, Shabalin PRD52,248;PRD52,6327

  $BR(CKM) \leq 2\times10^{-27}$ ($G_F^2 \sin^2\theta_C$ + dynamical suppr.)
  $BR(QCD\theta) \leq 3\times10^{-17}$ (from d_n)
  $BR(ExtrHiggs) \leq 1.2\times10^{-15}$
- Exp $BR(\eta \to \pi^+\pi^-) \leq 1.3\times10^{-5}$

  KLOE PLB606,276(05)
- Exp $BR(\eta \to \pi^0\pi^0) \leq 3.5\times10^{-4}$

  GAMS YF70,693(07)

  Background from direct 2π production

- $\eta \to 4\pi^0$

  $BR \leq 6.9\times10^{-7}$

  CBall(BNL) PRL 84,4802

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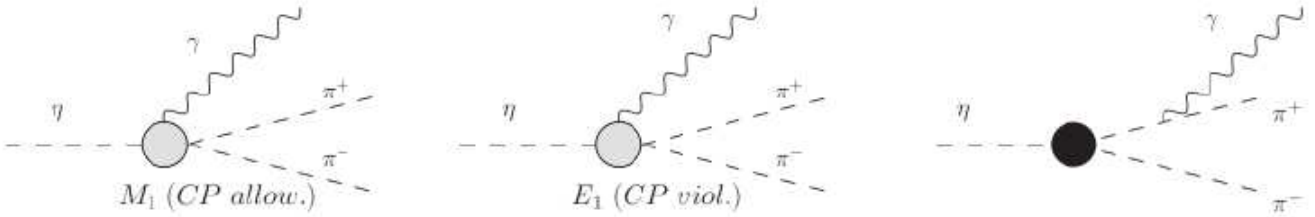
CP test in $\eta \to \pi^+\pi^- e^+ e^-$

- $\eta \to \pi^+\pi^-\gamma^{(*)}$ (γ polarization)

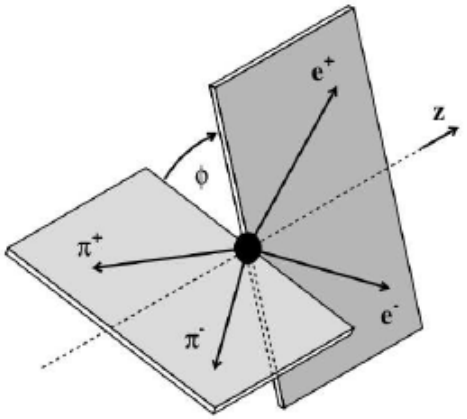
  Geng, Ng, Wu MPL A17:1489(02)

- not constrained by d_n



- Angle between decay planes in $\eta \to \pi^+\pi^- e^+ e^-$

  Gao MPL A17:1583(02)



$$A \equiv \frac{N(0 < \phi < 90) - N(90 < \phi < 180)}{N(0 < \phi < 180)}$$

$A \leq 0.02$ (from $\eta \to \pi^+\pi^-$)

$A = (-0.6 \pm 2.5 \pm 1.8) \times 10^{-2}$

KLOE PLB675,283(09)

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η decays: Tests of C invariance

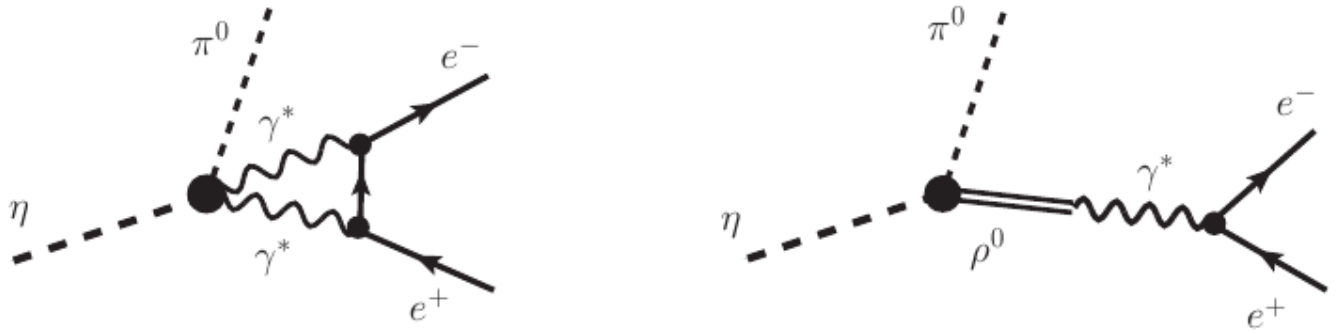
- final states with odd $\#\gamma$ C-violating
  $BR(\eta \to 3\gamma) < 1.6 \times 10^{-5}$

  KLOE PLB591,49

  $BR(\eta \to \pi^0\pi^0\gamma) < 5 \times 10^{-4}$
  $BR(\eta \to \pi^0\pi^0\pi^0\gamma) < 6 \times 10^{-5}$

  CBall(BNL) PRL94,041601

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



- Test C up to $BR \approx 10^{-8}$ (decay via $\pi^0\gamma^*\gamma^*$)
- PDG limit $BR < 4 \times 10^{-5}$ but $M(e^+e^-) > 140$ MeV cut

  PLB59,99(75)

$\Rightarrow$ First limit for $M(e^+e^-) < 120$ MeV

WASA-at-COSY A. Winnemöller PhD 2011

Summary and outlook

- Low energy QCD

  CHPT ($E < M_\rho$) + dispersion relations

  + η' ($N_c \to \infty$), vector mesons

- Tests of SM in decays of π^0, η, η'

  KLOE,MAMI,WASA,ELSA,HADES,CLAS,

  BESIII (10^{10} π^0, 10^9 η, 10^6 η', 10^{10} ϕ)

  MesonNet

http://www2.fz-juelich.de/ikp/mesonnet

→ Talk Ankhi Roy (Friday)

Study of Strongly Interacting Matter

HadronPhysics