école Joliot-Curie school

STRONG INTERACTION IN THE NUCLEAR MEDIUM: NEW TRENDS

"INTERACTION FORTE DANS LA MATIÈRE NUCLÉAIRE : NOUVELLES TENDANCES"

27 SEPT–03 OCT 2009, LACANAU (FRANCE)

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"PROPERTIES OF LIGHT MESONS IN THE NUCLEAR MEDIUM"

LECTURE ONE

-Description of ordinary matter, QCD, Chiral Symmetry and hadron masses

-Any experimental "evidence" for partial restoration of Chiral Symmetry ?

Meson-Nucleon interaction in the medium

- -pionic states in nuclei;
- -low energy π-nucleus elastic scattering,
- -"sigma" channel in 2π production in nuclei
- -kaons in nuclei

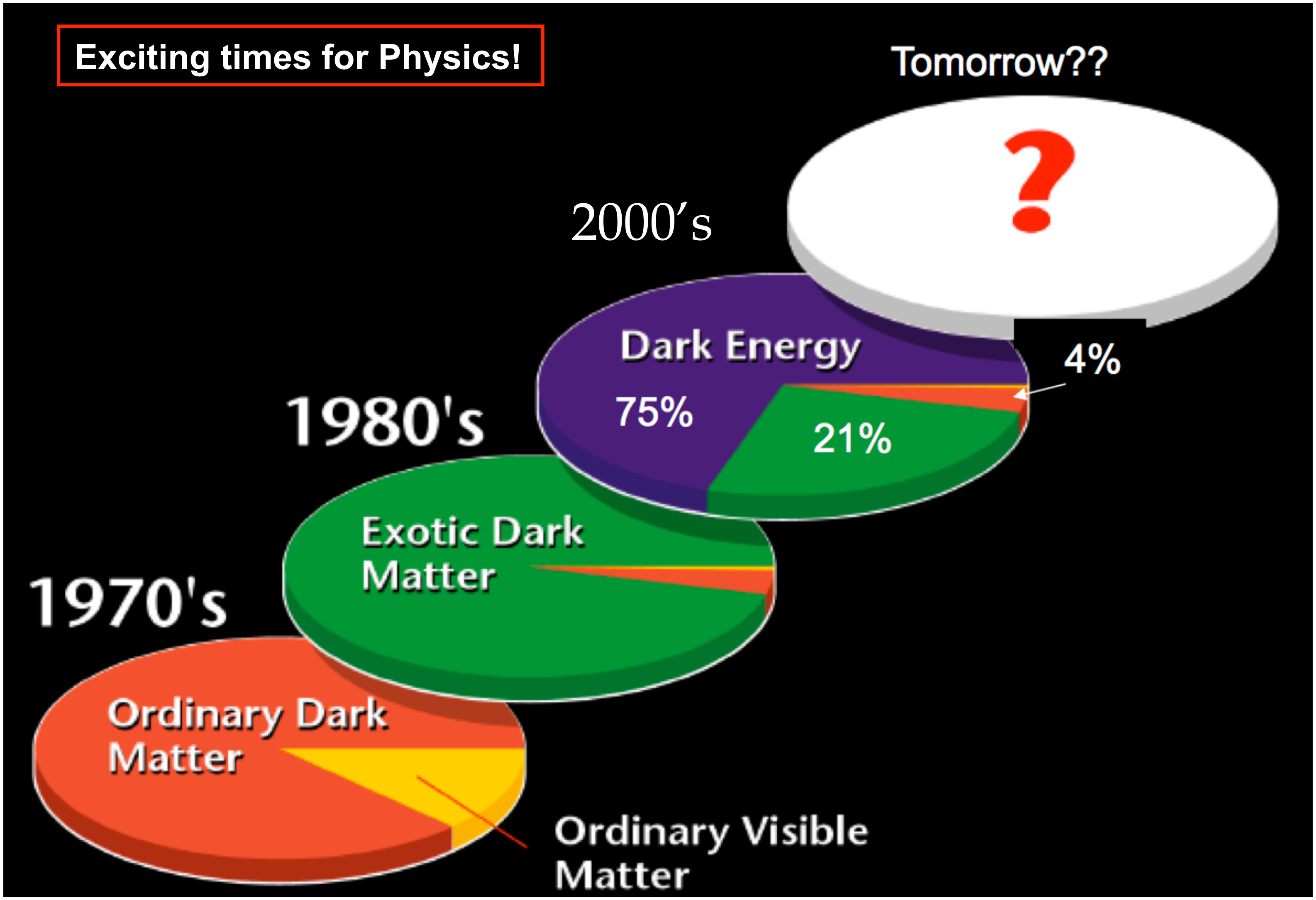
LECTURE TWO

Vector Meson in the medium (di-lepton decay)

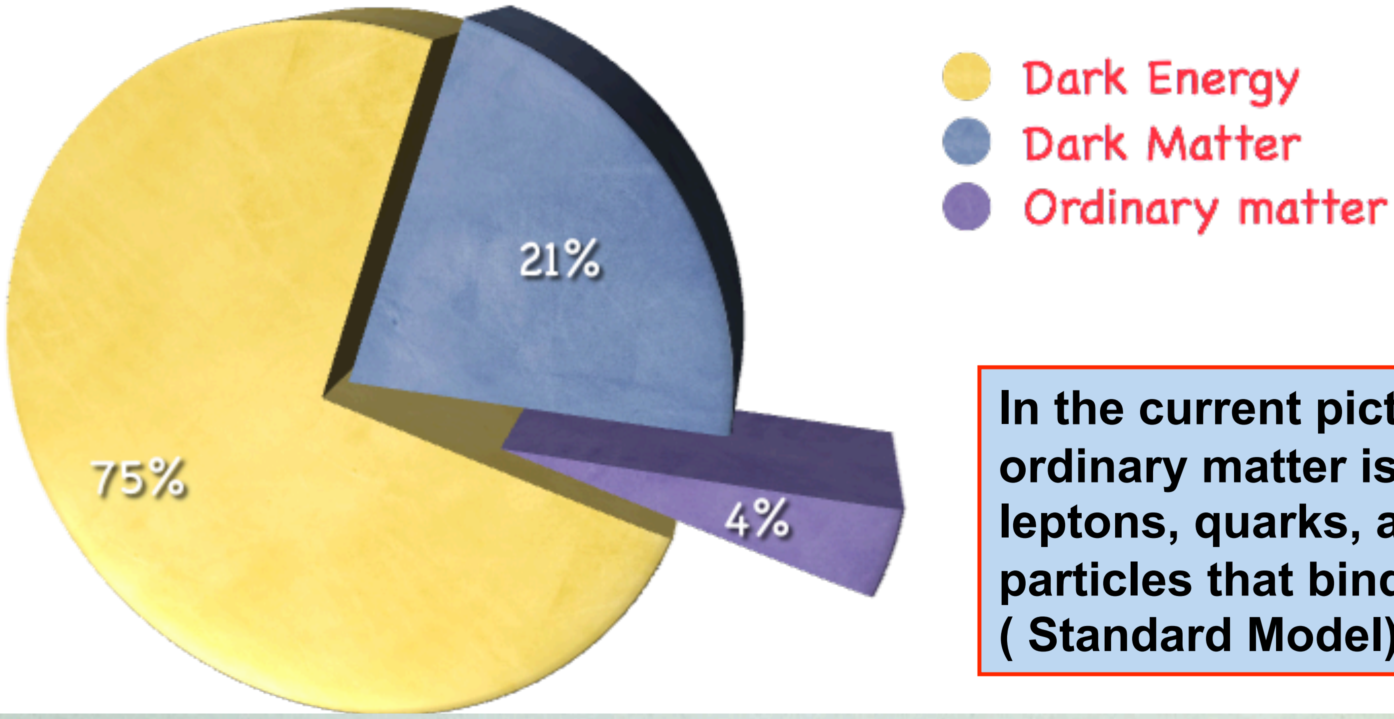
- -In relativistic heavy ion collisions
- -In nuclei

-Summary-Conclusions-Outlook

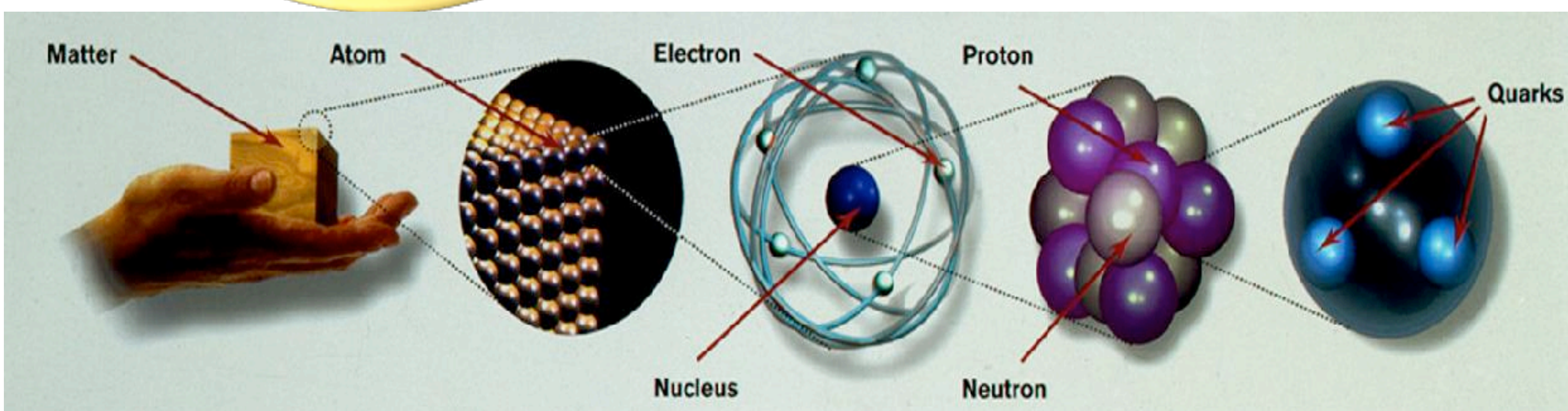
Changing View of What makes the Universe



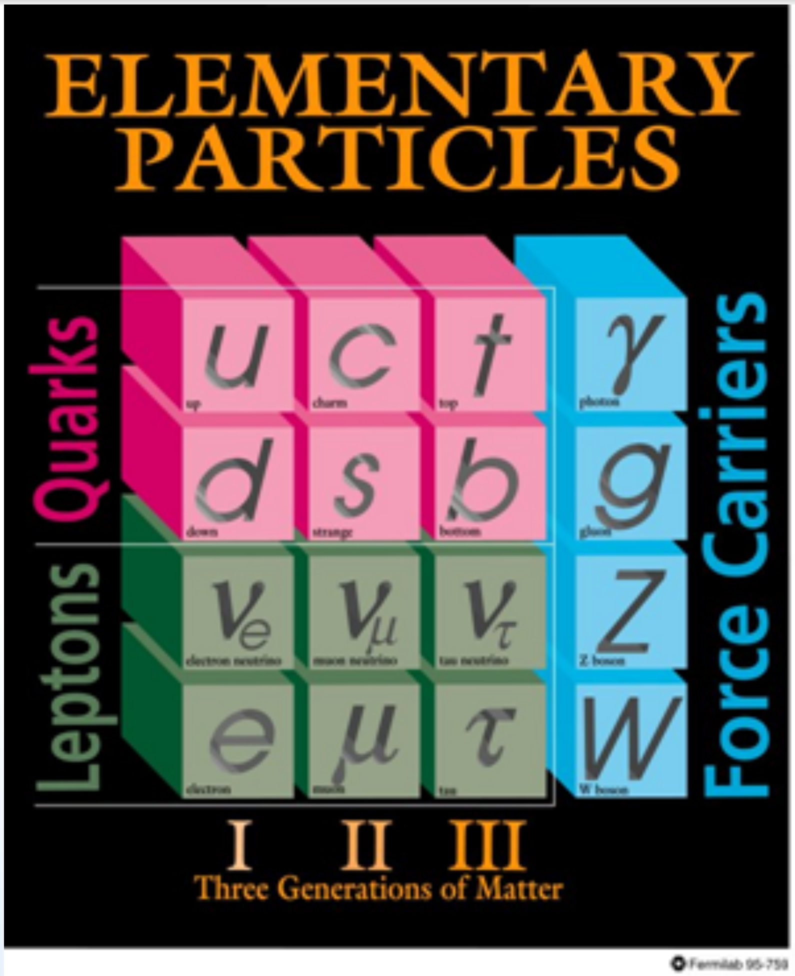
Ordinary Matter (only 4%)

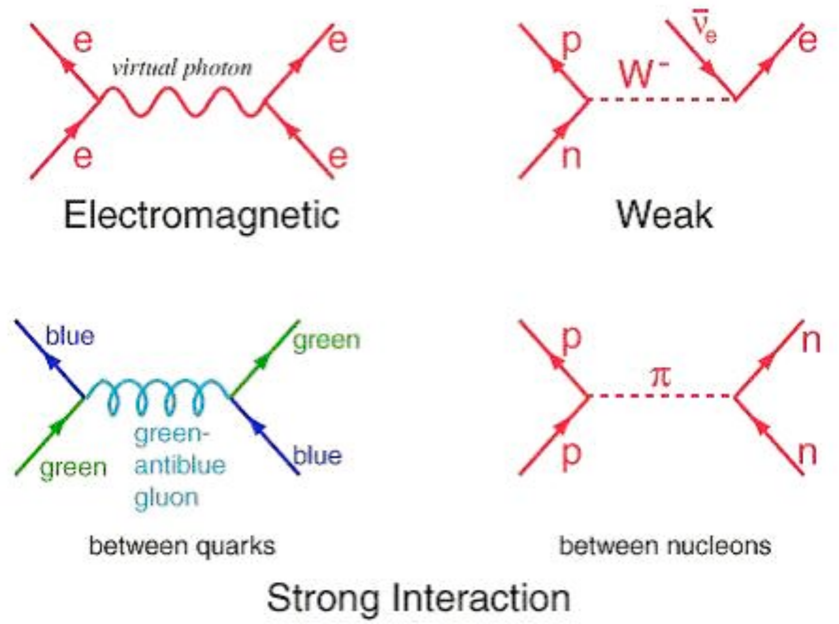


In the current picture, ordinary matter is made of leptons, quarks, and the particles that bind them (Standard Model).



Current Theory: Standard Model





<u>The Standard Model WORKS !</u>

- ★ Highly predictive theory - tested to high precision at an energy scale of $\sqrt{s} = 100$ GeV
- ★ ALL particles of SM have been discovered with the exception of the Higgs.

Origin of fermion masses (The Higgs)

Particle masses - Higgs Boson

There is one final ingredient to the Standard Model - the Higgs Boson.

The Standard Model requires the existence of a new neutral SCALAR (i.e. spin-0) particle - the HIGGS boson.

Higgs Boson and Mass

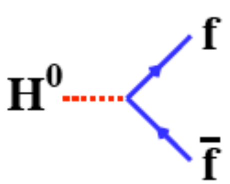
★ The Higgs Boson (if it exists) is the particle responsible for the MASS of ALL particles (including the $W^{\pm}$ and Z^0).

★ The Higgs Field has a non-zero vacuum expectation value, it is a property of the vacuum. **Spontaneous breaking of Symmetry**

★ As particles move through the vacuum they interact with the non-zero Higgs field

★ It is this interaction that gives fermions mass

★ The strength of the Higgs coupling to fermions is proportional to mass



$$g_{Hff} = (\sqrt{2}G_F)^{\frac{1}{2}} m_f$$

Quark masses – PDG 2008

u $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.5$ to 3.3 MeV [a] Charge $= \frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

$m_u/m_d = 0.35$ to 0.60

d $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 3.5$ to 6.0 MeV [a] Charge $= -\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

$m_s/m_d = 17$ to 22

$\overline{m} = (m_u+m_d)/2 = 2.5$ to 5.0 MeV

s $I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 104^{+26}_{-34}$ MeV [a] Charge $= -\frac{1}{3}\,e$ Strangeness $= -1$

$(m_s - (m_u + m_d)/2)/(m_d - m_u) = 30$ to 50

c $I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 1.27^{+0.07}_{-0.11}$ GeV Charge $= \frac{2}{3}\,e$ Charm $= +1$

b $I(J^P) = 0(\frac{1}{2}^+)$

Charge $= -\frac{1}{3}\,e$ Bottom $= -1$

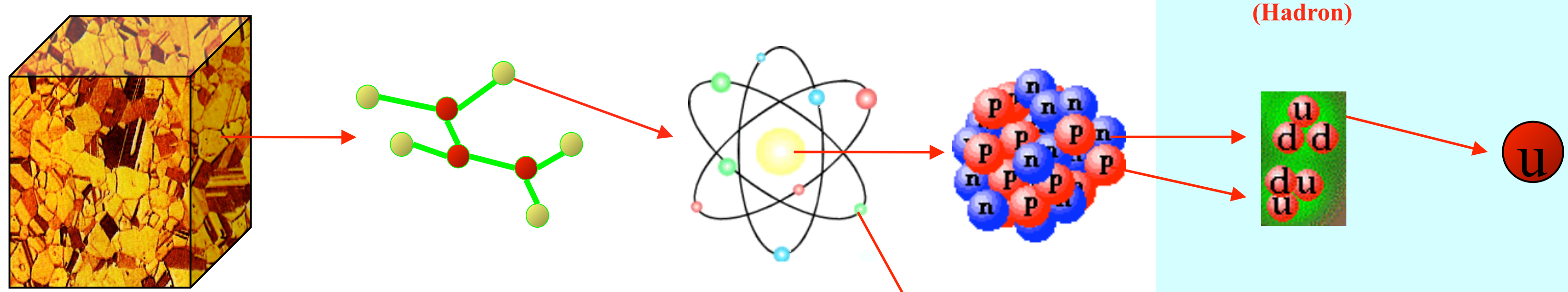
Mass $m = 4.20^{+0.17}_{-0.07}$ GeV ($\overline{\text{MS}}$ mass)

t $I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\,e$ Top $= +1$

Mass $m = 171.2 \pm 2.1$ GeV [b] (direct observation of top event

Mass of composite systems



For most composite systems $M \approx \Sigma\, m_i$

$BE_{Atom} \approx 10^{-8}$ $BE_{Nuclei} \approx 10^{-3}$

The proton mass and the electron mass (almost) add up to the hydrogen-atom mass.
Likewise, masses of two protons and two neutrons (almost) add up to the alpha-particle mass.

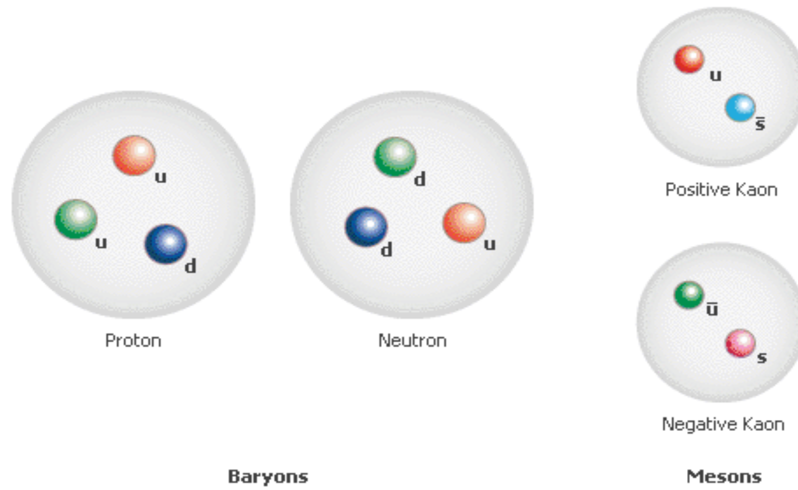
However, this is not the case for Hadrons!!

Hadrons are made of quarks, anti-quarks (+gluons)

Under normal conditions, quarks are confined in Hadrons.

m_u, m_d <10 MeV so naively one might expect $m_{p,n}$ ~20-50 MeV

Observed $m_{p,n}$ ~ 1000 MeV



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

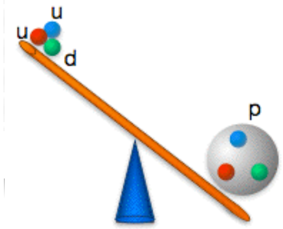
Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0



Why is the proton so heavy?

Do masses of two u (up) quarks and a d (down) quark add up to the proton mass?

Not at all!. **Adding the u,d quark masses(≈5 MeV/c²) fall very short of the proton mass, which is 938 MeV/c².** **Why?**

- **Condensation in vacuum**

Right after the Big Bang, quarks and leptons were massless. With expansion:

- **the temperature of the Universe dropped below ≈100 GeV, Higgs particles condense in the vacuum, and quarks and leptons acquire masses through the "Higgs mechanism".**
- **the temperature reached ≈100 MeV, quarks (and gluons) became confined in protons and neutrons. The vacuum structure changes again; quarks and anti-quarks condense in the vacuum (called chiral condensate), and this condensate is considered to be responsible for giving each u, d quark in the proton an "effective" mass of some 300 MeV/c².**

Higgs generates ~2% and QCD generates 98% of the mass of ordinary matter !!!

The nucleon mass is almost entireley dynamically generated.

- **How can we experimentally prove this scenario?**

- **Experiments at the large hadron collider (LHC) at CERN will search the Higgs particle, the missing piece in the Standard Model.**
- **However, the chiral condensate cannot be studied this way, it is not an observable. Theoretical models are used to link observables to the quark-condensate.**

From Ryugo lectureHayano

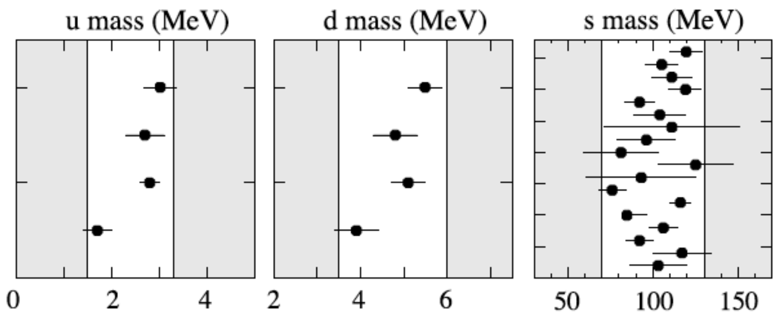
QCD: The theory of Strong Interactions

Light quarks u,d, s (j,k = 1,2,3 refer to color; q = u,d,s refers to flavor; a = 1,..,8 to gluon fields)

$$\mathsf{L}_{qcd} = i\sum_q \overline{\psi}_q^{\,j} \gamma^\mu (\mathsf{D}_\mu)_{jk} \psi_q^k - \sum_q m_q \overline{\psi}_q^{\,j} \psi_q^k - \tfrac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

mass of "free" quarks

PDG2008, PLB667



At high momenta (short distances) Asymptotic freedom . Perturbative QCD

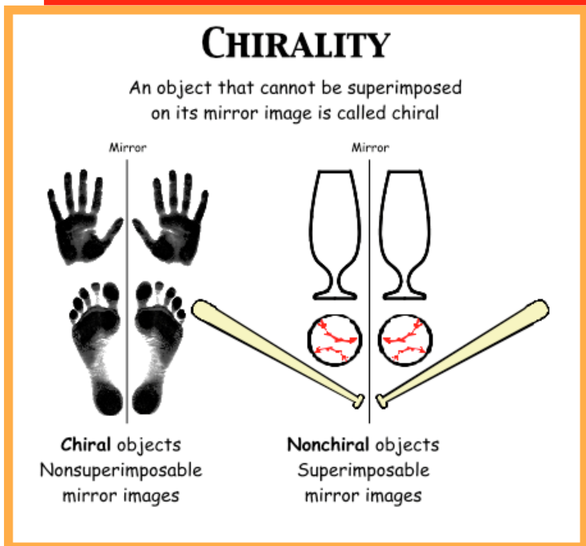
At small momenta (large distances), QCD highly non perturbative. Spontaneous breaking of Chiral Symmetry.

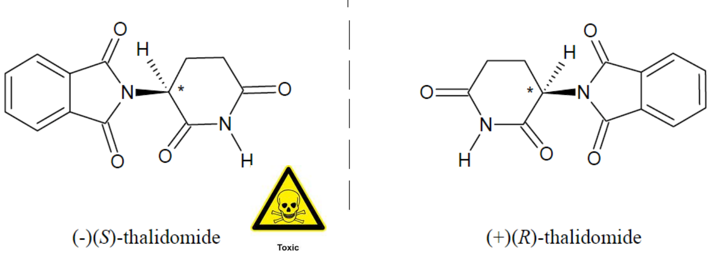
•**If m_q=0** ⇒ **exact chiral $SU(n_f)_L$x$SU(n_f)_R$ symmetry** ⇒ RH and LH quarks "don't talk to each other" and we expect chiral partners degenerate in mass. (pseudoscalar-scalar; vector-axial,.)

•**If we restrict ourselves to only u and d quarks, m_u, m_d (< 10 MeV) being relatively small ⇒ approximate chiral $SU(n_f)_L$ x $SU(n_f)_R$ symmetry ⇒ successful Chiral Effective Theories**

Chirality: Concept of "handedness"

"I call any geometrical figure, or group of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself." *Lord Kelvin in 1904*





All amino acid molecules are chiral
Aspartame (only one χ is sweet)
DNA components all one χ

For massless spin 1/2 particles

the HELICITY operator.

$$\hat{H} = \frac{\vec{\sigma}.\hat{\mathrm{p}}}{|p|}$$

with Eigenvalues $+1$ and -1 respectively.

HELICITY is the projection of a particle's SPIN onto its flight direction.

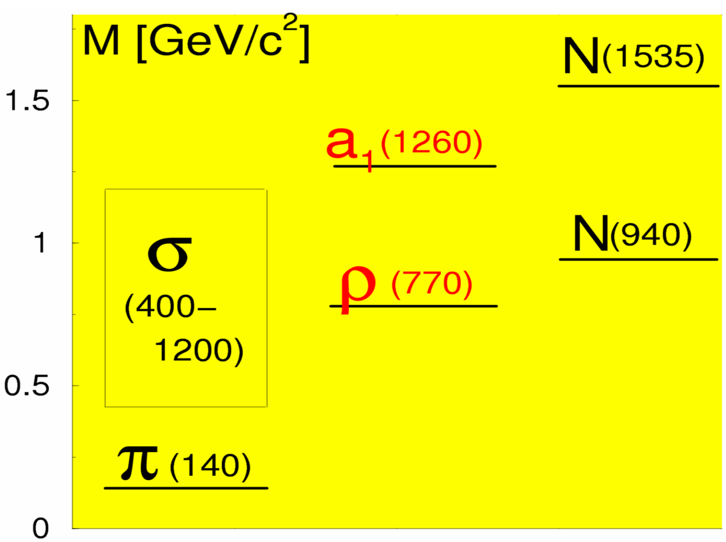
Chiral (χ) symmetry breaking mixes RH and LH quarks

Chiral symmetry (χ_s) is broken in vacuum

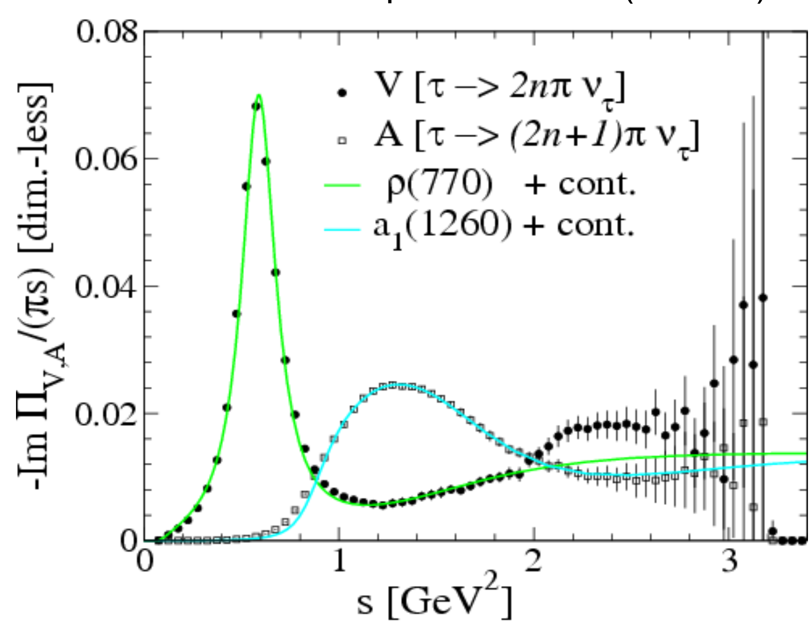
Spectral evidence of χ_s breaking: we have non degenerate chiral partners:

π (J^P=0^-) m=140 MeV ←→ σ (J^P=0^+) m =400-1200 MeV
ρ (J^P = 1^-) m=770 MeV ←→ a_1 (J^P = 1^+) m=1260 MeV

N (1/2$^+$) m=940 MeV ←→ (N* (1/2$^-$) m=1535 MeV) ?



hep-ex/0506072 (ALEPH):



Order Parameters $<0|q\bar{q}|> \text{ and } f_\pi$

In the light quark sector (u, d,.) χ_s is a very good symmetry of the QCD Lagrangian,
However, QCD vacuum doesn't possess the symmetry of the Lagrangian,

Chiral symmetry is spontaneously broken in the vacuum.

(non zero order parameters "measure" how much the symmetry is broken).

-quark condensate $\langle 0|q\bar{q}|0\rangle \approx -(250\text{MeV})^3 \pm 10\%$

-pion decay constant f_π ~ 93 MeV

The (almost massless) pions are the Nambu-Goldstone bosons.

Symmetry Breaking Scale (i.e. Mass Gap Λ_χ):

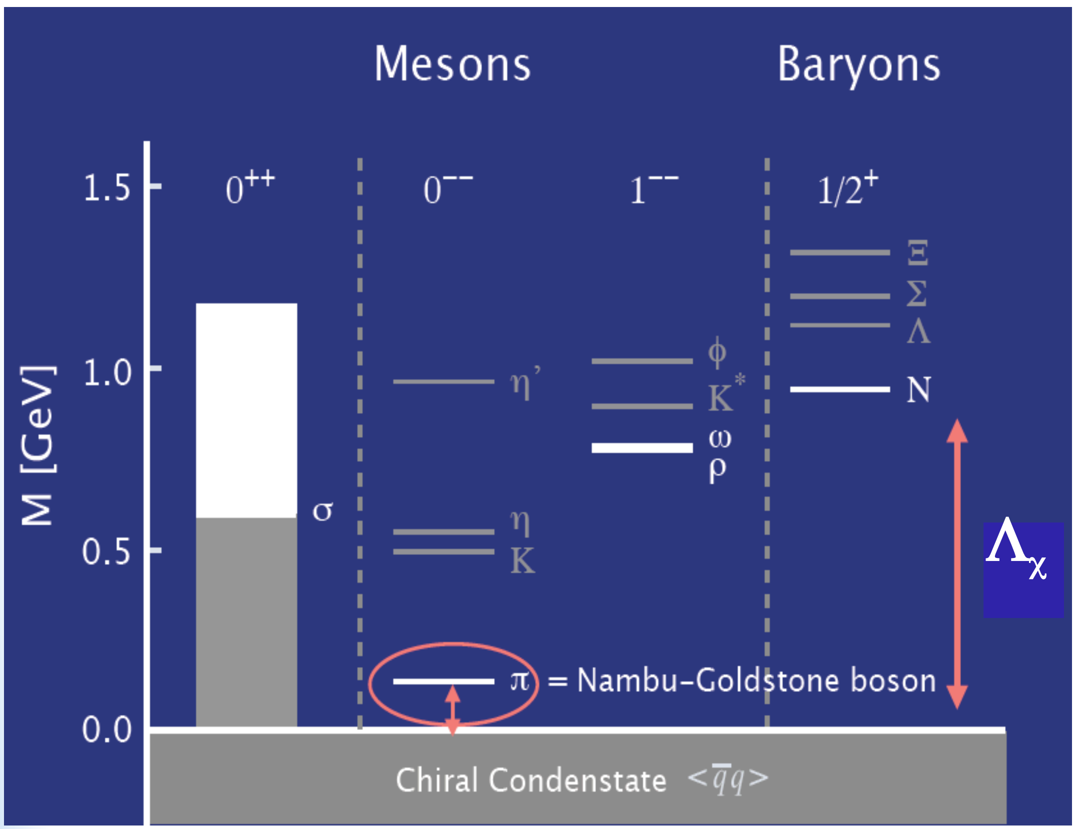
$\Lambda_\chi = 4\pi f_\pi$ ~ 1. GeV

Gell-Mann- Oakes – Renner (GOR) relation

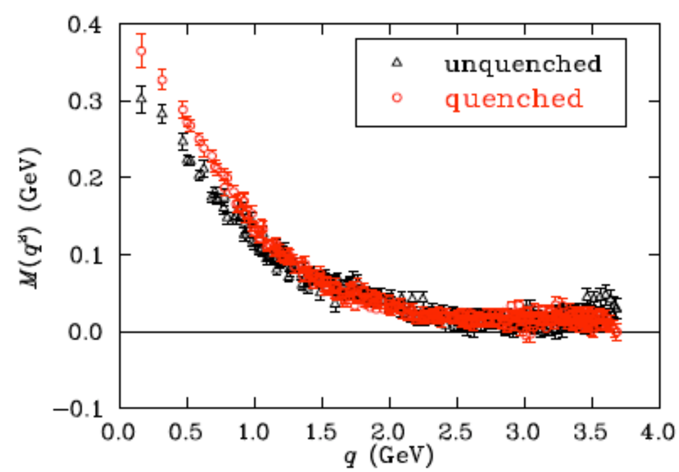
$$m_\pi^2 f_\pi^2 = -2(m_u + m_d) < 0|q\bar{q}|0 > + O(m_q^q)$$

Light mesons and baryons

-QCD vacuum as a Bose-Einstein condensate of quark-anti-quarks.
-All states (particles) are created out of the vacuum state, ("excitations of the QCD vacuum") → the ground-state structure influences the particles properties
-Pion mass ≠ 0, explicit breaking of chiral symmetry because of small m_q



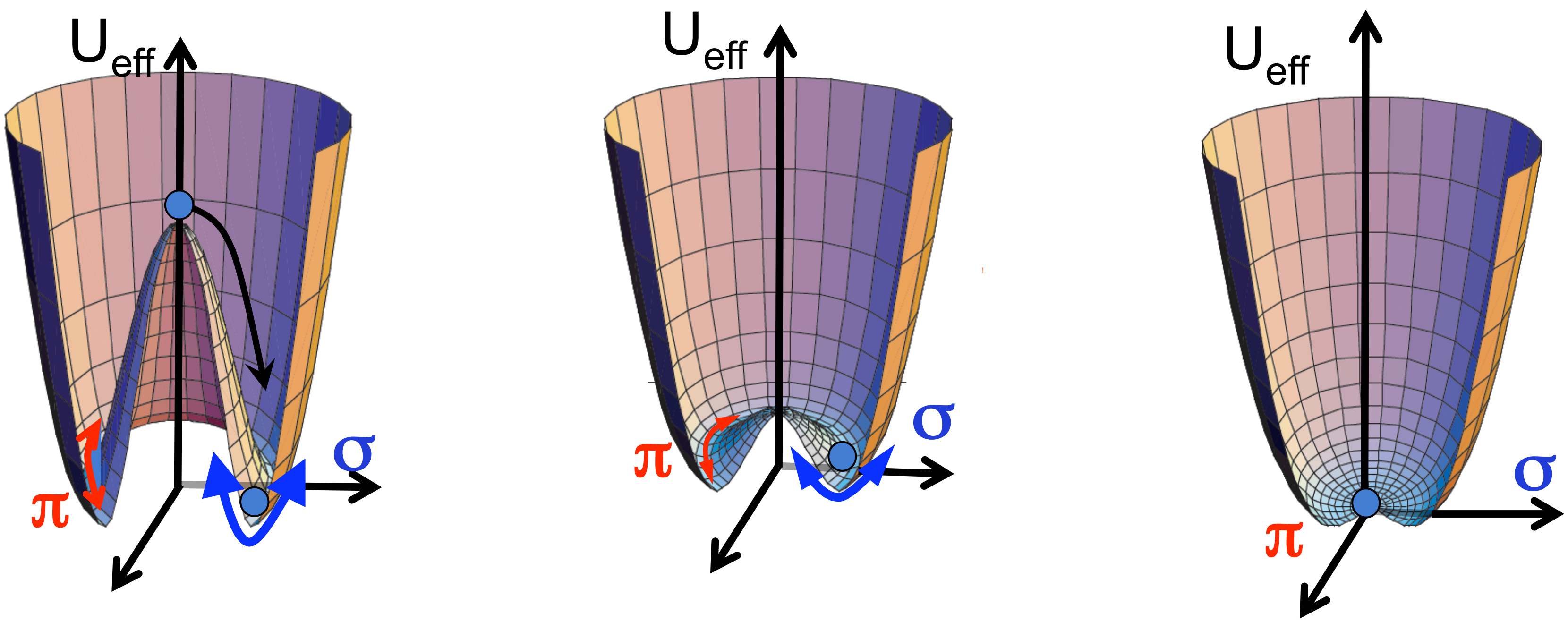
The coupling to the quark condensates gives the "constituent mass" of ~ 300 MeV to the u and d quarks.



PRD71(2005)054507

Spontaneous Breaking of Chiral Symmetry (χ_s)

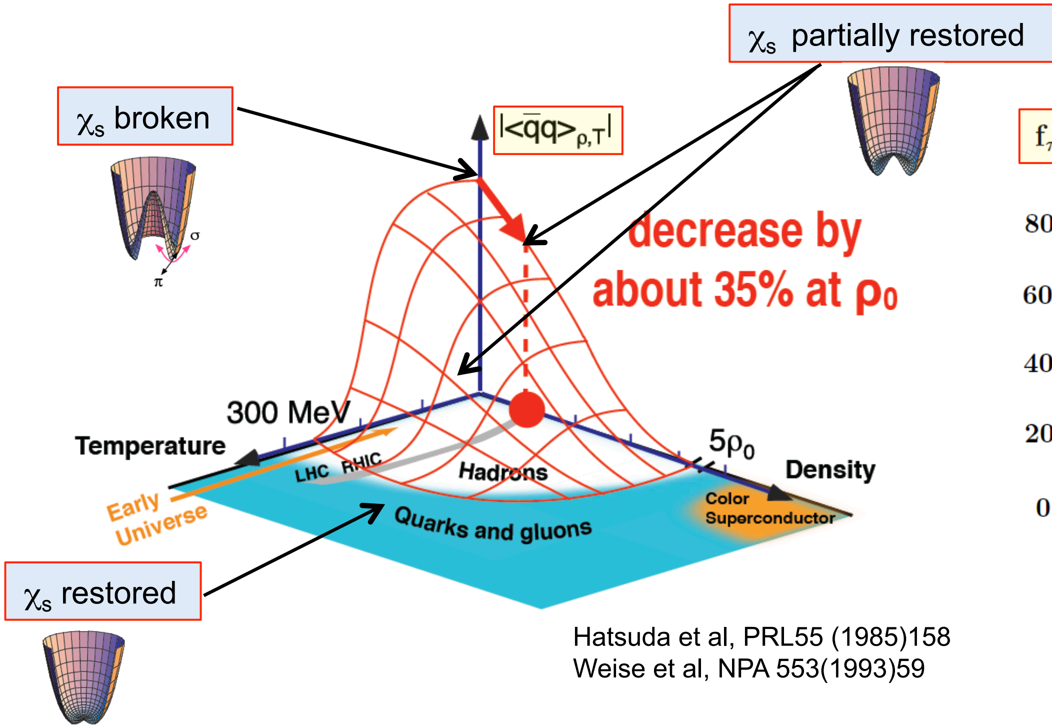
- Effective potential in terms of π and σ (effective dof)
- χ_s broken, "Mexican hat shape" potential
- χ_s restored, paraboloid potential
- π as "phase fluctuation " and σ as "amplitude fluctuation"



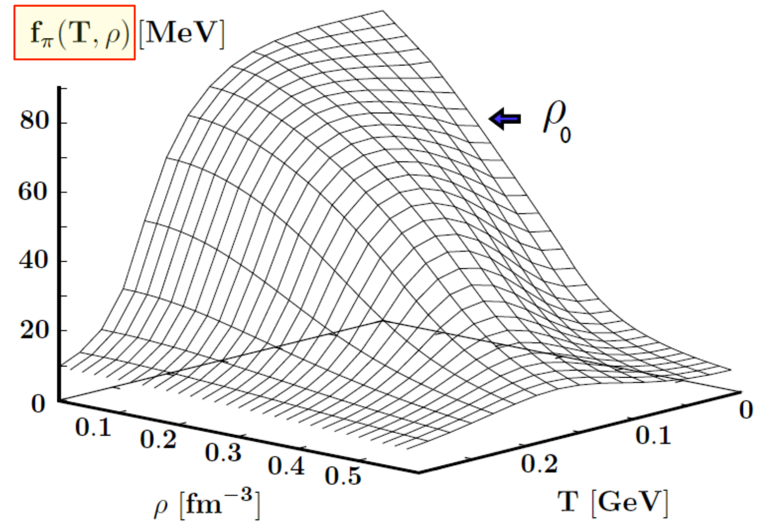
χ_s highly broken $m_\sigma > m_\pi$ ($m_\pi \sim 0$)	χ_s lightly broken m_σ -->m_π	χ_s valid(or restored) $m_\sigma \sim m_\pi$

Properties of $< 0 | q\bar{q} | 0 >$ and f_π in medium

As temperature (T) and/or density (ρ) increases in the medium, Both order parameter drop and χ_s is restored. LQCD calculations show that χ_s restoration and deconfinement coincide (not fully understood).



Hatsuda et al, PRL55 (1985)158
Weise et al, NPA 553(1993)59



Ratti et al, PRD73(2006)014019
S. Klimt et al, PLB249(1990)386

With T and ρ dependence of the type:

$$\frac{f_\pi^2(T,\rho)}{f_\pi^2(0)} \approx \frac{< 0 | q\bar{q} | 0 >_{T,\rho}}{< 0 | q\bar{q} | 0 >_0} = 1 - \frac{T^2}{8 f_\pi^2} - \frac{\sigma_N}{m_\pi^2 f_\pi^2}\rho + \ldots$$

NPB 321 (1989) 387.
PRC 45 (1992) 1881.
PLB 357(1995)199

How to study the changes in $<0|q\bar{q}|0>$ and f_π ?

Contrary to the Higgs Boson, the quark condensate is not an observable. We need theoretical models to relate the quark condensate to actual experimental observations.

Experimentally: Properties of hadrons in the vacuum (such as mass, width, spectral functions, etc…) are compared to those measured in the medium looking for changes. Media created in heavy ion collisions or even inside a normal nucleus are ruled by complex dynamics.

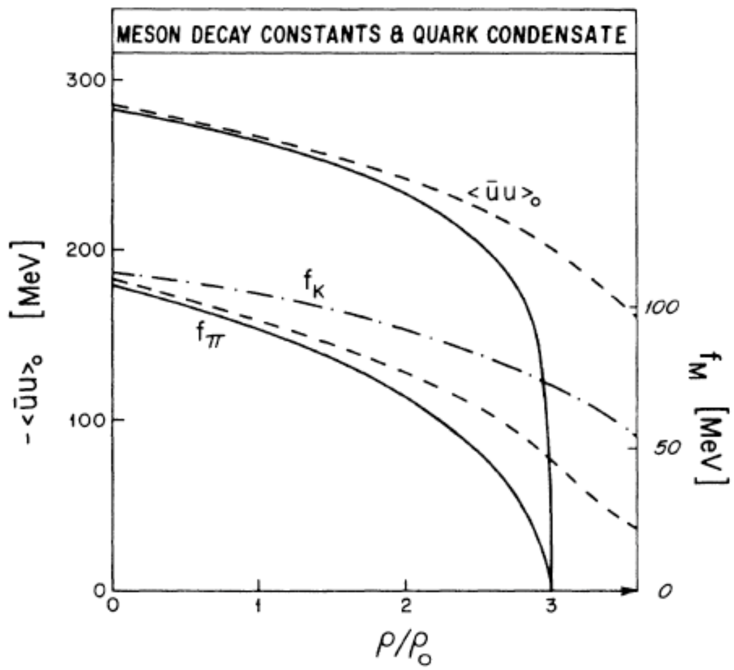
Theoretically: Understand the properties of hadrons in the medium. If possible, separate "standard many body effects" from those related to QCD underlying symmetries (in this case Chiral symmetry). Unambiguous links between in medium hadronic properties and $<0|q\bar{q}|0>$ or f_π are not yet fully established.

Many models with different degrees of sophistication!

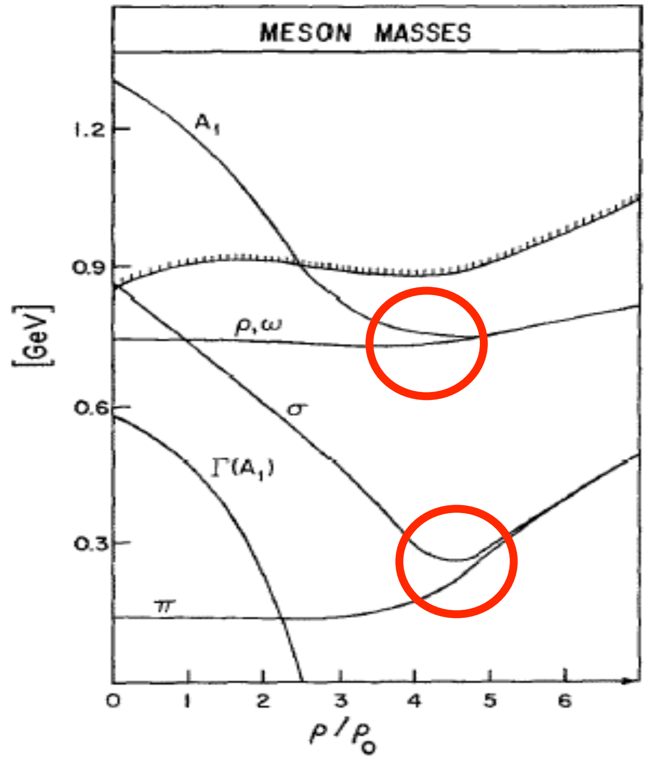
Nambu-Jona-Lasinio model at finite T and ρ

Dynamical treatment of mass generation and meson properties

V. Bernard et al,PRL. 59 (1987) 966 and PRD38 (1988) 1551, NPA489 (1988) 647
T. Hatsuda et al, PRL55 (1985) 158 and PLB185 (1987) 304
U. Vogl et al,, Prog. PNP 27 (1991)195.



$< 0 | q\bar{q} | >$ and f_π as a function of ρ



As density increases, $m_{\pi,\rho,\omega}$ ~ constant
Degeneracy of chiral partners

QCD Sum Rules (QCDSR)

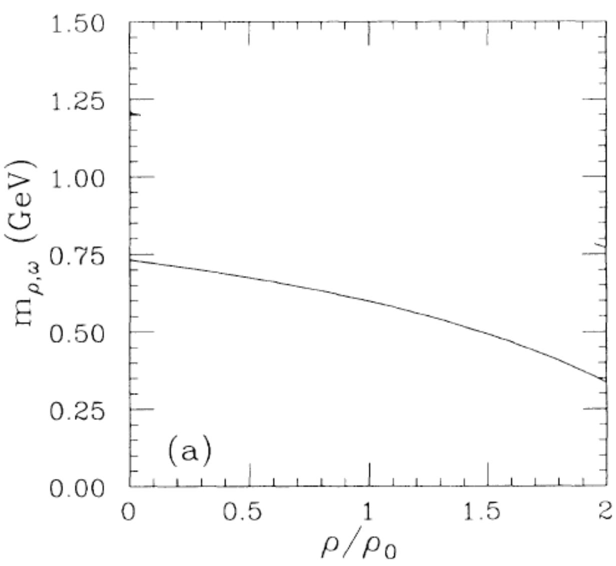
-In medium QCDSR give useful constraints, evaluating the weighted average of the spectral functions. QCDSR try to relate hadronic spectral functions to the QCD condensates. Only averages not detail shapes of spectral functions.

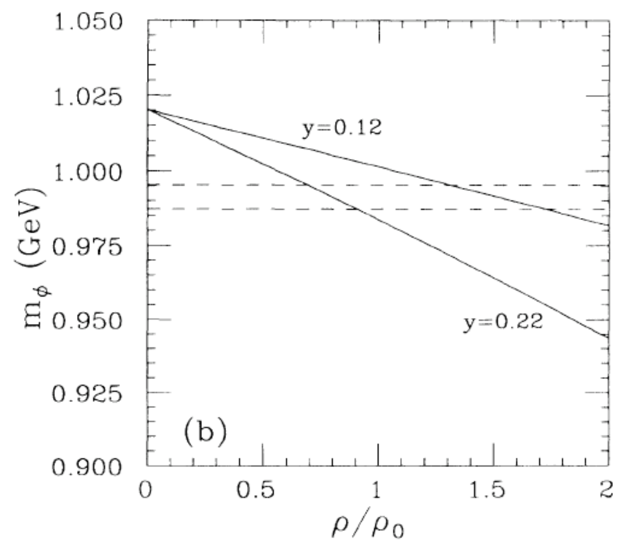
-Vector meson masses are predicted to change with density (Hatsuda and Lee)

M. A. Shifman et al., NPB147 (1979)385, 448
T. Hatsuda et al, PRC46 (1992) R34; NPB394 (1993) 221
Y. Kwon et al, PRC78 (2008) 055

$$\frac{m_V^*}{m_V} = (1 - \alpha \frac{\rho}{\rho_0})$$

ρ_0 is normal nuclear density 0.17 fm^{-3}
α~0.18±0.06 for V= ρ ,ω
α~0.15y for V= ϕ (y nucleon stangeness content)





Mass Scaling

Conjecture: Masses of light vector mesons scale universally as a function of density and/or temperature. Effective chiral Lagrangians with scaling properties of QCD lead to approximate in-medium scaling law.

Brown and Rho, PRL66 (1991) 2720

Theoretical foundations for such scaling:

T. Harada et al, PRD66, (2002)016003 ; PLB537 (2002)280; PRD73, (2006)036001.

$$\frac{m_\rho^{\;*}}{m_\rho} \approx \frac{m_\omega^{\;*}}{m_\omega} \approx \frac{\left\langle \bar{q}q \right\rangle^*}{\left\langle \bar{q}q \right\rangle_0}$$

near the chiral restoration point

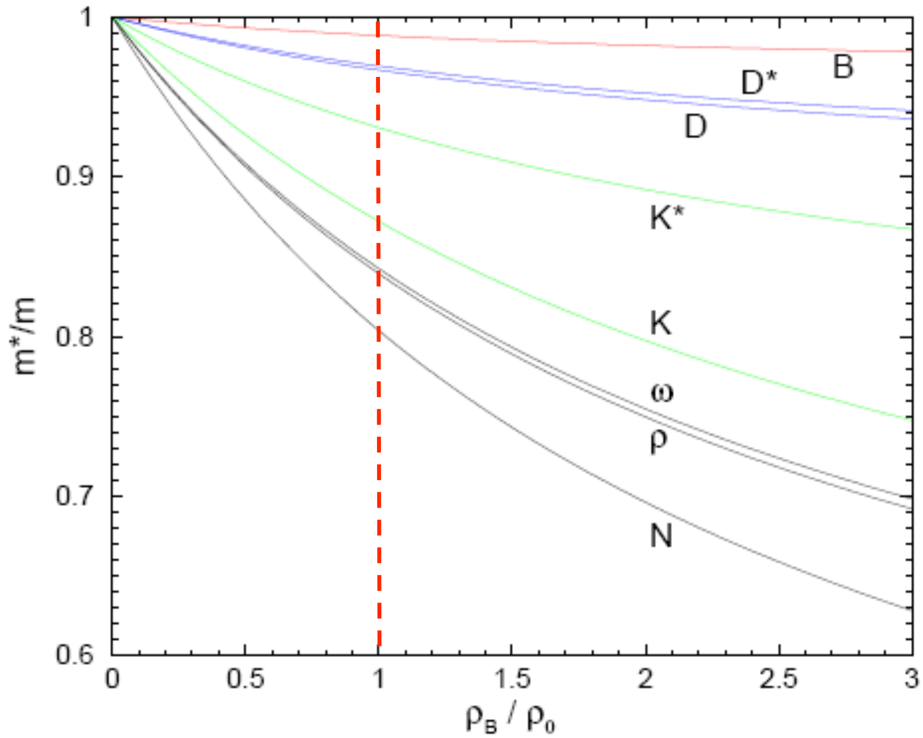
"Brown-Rho Scaling"

$$\frac{m_\sigma^{\;*}}{m_\sigma} \approx \frac{m_N^{\;*}}{m_N} \approx \frac{m_\rho^{\;*}}{m_\rho} \approx \frac{m_\omega^{\;*}}{m_\omega} \approx \frac{f_\pi^*}{f_\pi} \approx 0.8 \left(\rho \approx \rho_0 \right)$$

Quark-meson coupling model (QMC)

Phenomenological theory confining quarks and gluons in a "bag". In-medium mesons feel a scalar potential → universal scaling law.

K. Saito et al, PRC55 (1997) 2637



At normal nuclear density (ρ_0):

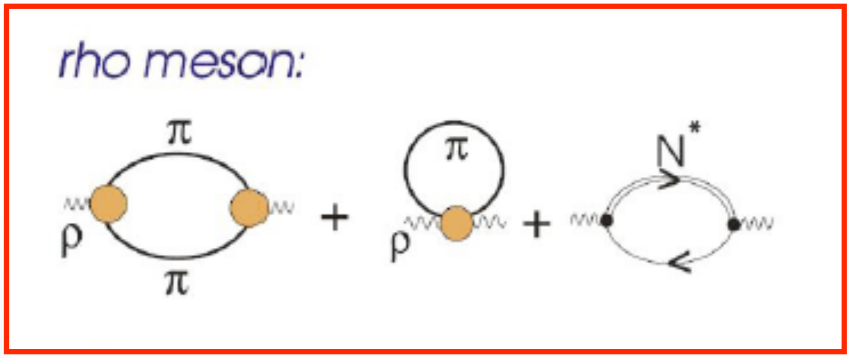
The ρ and ω -masses have dropped by ≈ 15%;
The N-mass has dropped by ≈ 20%;
The D-mass has dropped by ≈ 3%

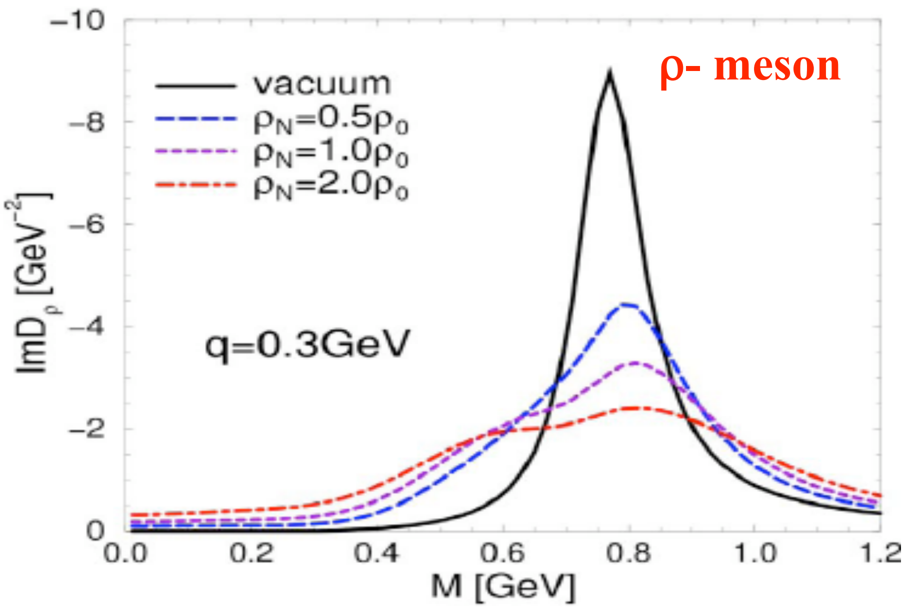
Hadronic models

-Contrary to the models described so far (which gave average constraints), hadronic models calculate the spectral function of the mesons in the medium.. Mesons are propagating in medium and coupling to resonances → "richer predictions" (spectral shift, broadening, new spectral peaks, etc…)

-Not easy to relate spectral functions to actual measured mass spectra

Many body effects such as coupling to baryon resonances gives infromation beyong just the mass

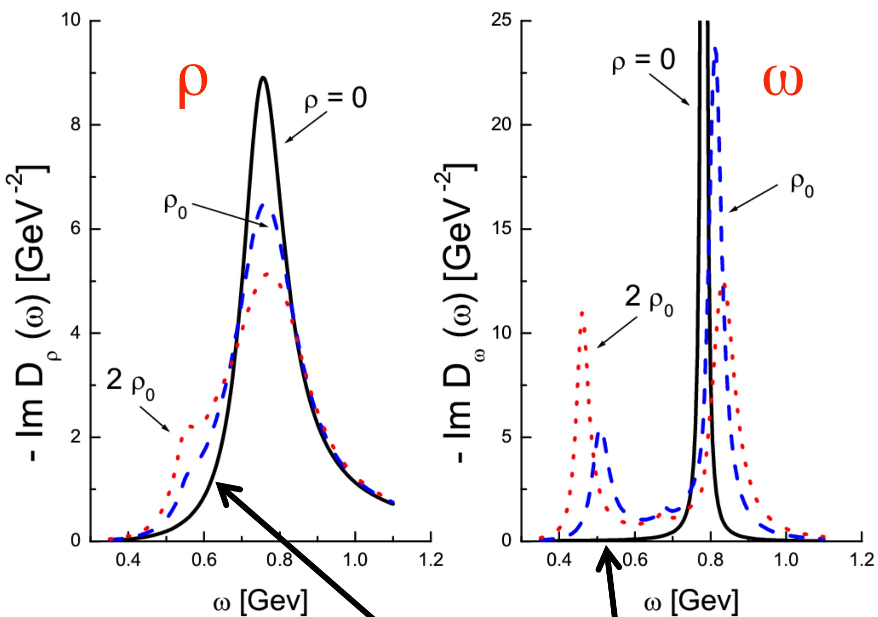




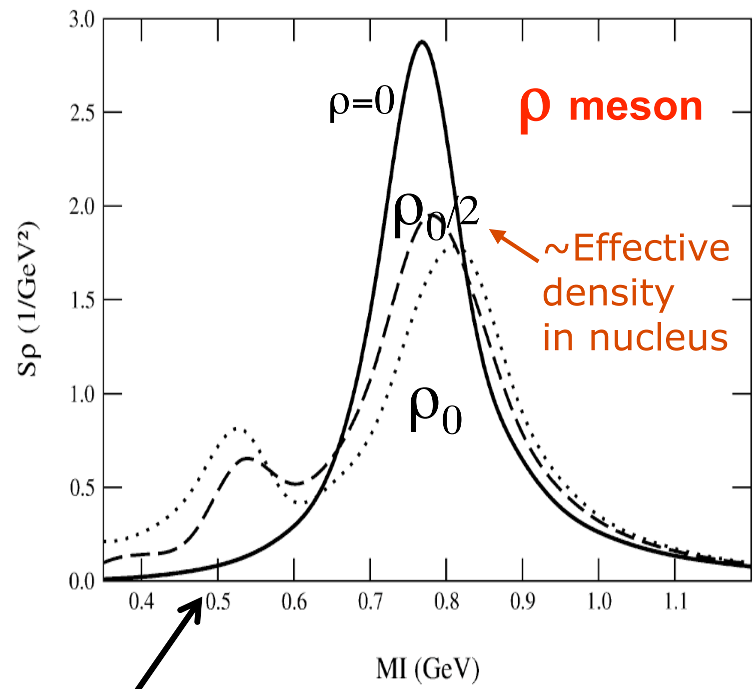
Rapp, Wambach, EPJA 6 (1999) 415
B Friman et al, *NPA617 (1997) 496*
R. Rapp et al, *NPA617 (1997) 472*

Spectral Functions in Medium

M. Lutz et. al. , Nucl. Phys. A 705 (2002) 431



D. Cabrera et. al. , Nucl. Phys. A 705 (2002) 90



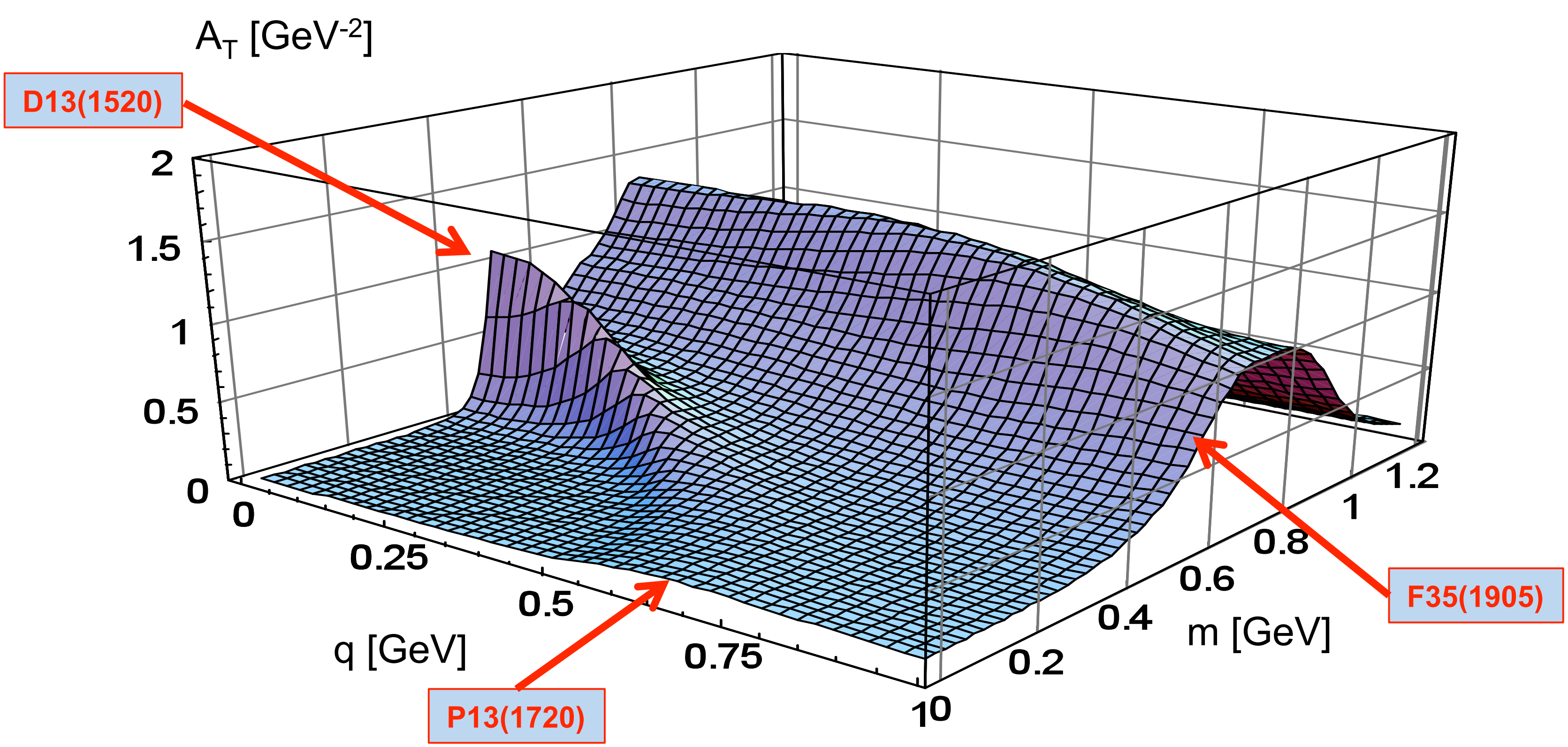
structures in spectral functions due to coupling to baryon resonances

Spectral Functions in Medium

Momentum dependence should be measured

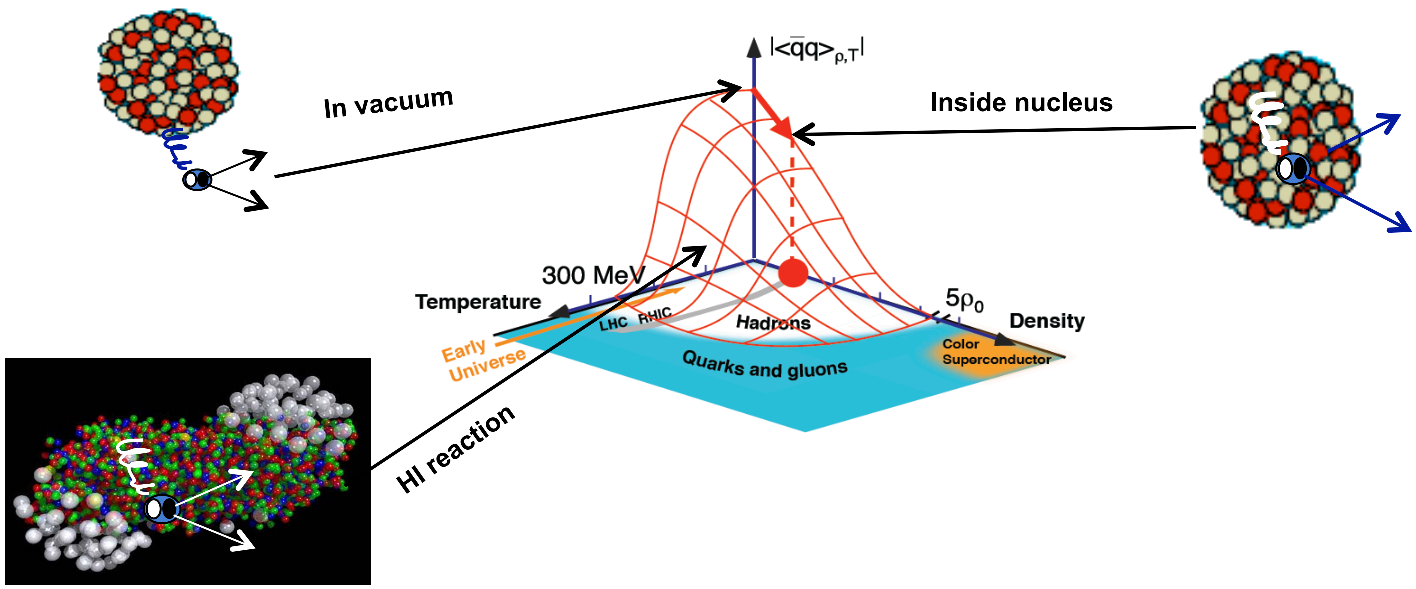
ρ-meson

M. Post et al., nucl-th/0309085



Lot of predictions, now what?

Many different predictions of modification of hadron properties in the medium (mass shift, change in interaction, widening, extra peaks, etc..). Experimentally, one needs to measure and <u>compare the properties of these hadrons in the vacuum and in different media</u> (T and/or $\rho \neq 0$).



- **Extensive programs to look at changes in properties of Baryons (p, n,..) not covered in these lectures.**
- **We will only mention some experiments looking at changes of properties of light mesons (π, σ, K, ρ, ω and ϕ,..) in the medium.**

Mesons as probe of Chiral Symmetry restoration

Experiments roughly fall under two categories

1) Looking at the modification of the meson-nucleon interaction in medium:

   -pionic states in nuclei (capture and nuclear reaction),

   -elastic pion-nucleus scattering at low energy,

   -Double pion production in nuclei and the σ.

   -Kaon production in nuclei

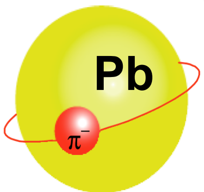
2) Mass and width changes of light vector mesons ρ, ω and ϕ:

   -in relativistic heavy ion collisions

   -in nuclei

Disclaimer: only few experiments covered (might not be your favorite one)

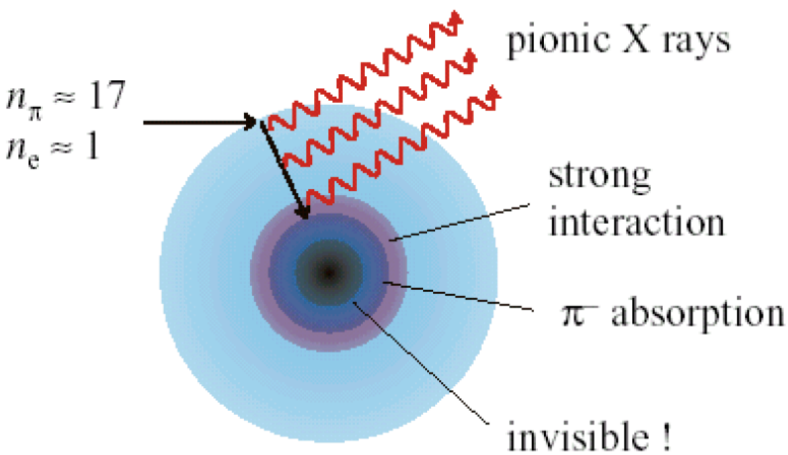
Pionic Atoms (stopped π^- captured in atomic orbit)

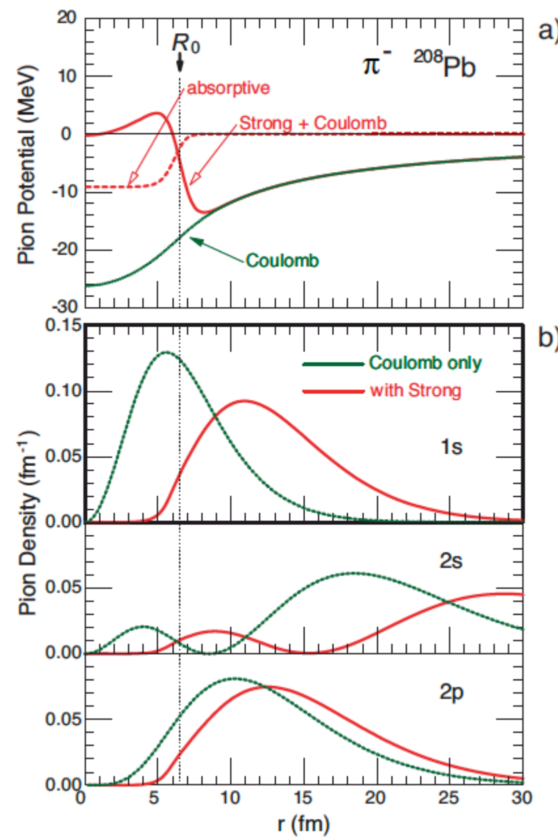


π^- bound by attractive Coulomb and repulsive Strong interactions
Ericson (1966): π-nucleus potential has s-wave and p-wave parts.

$$V_{opt} = b_0\rho(r) + b_1[\rho_n(r) - \rho_p(r)] + B_0\rho^2(r) \quad + \text{P-wave part}$$

b_0 (b_1): isoscalar (isovector) scattering length
ρ_n (ρ_p): neutron (proton) density
B_0 : s-wave absorption parameter



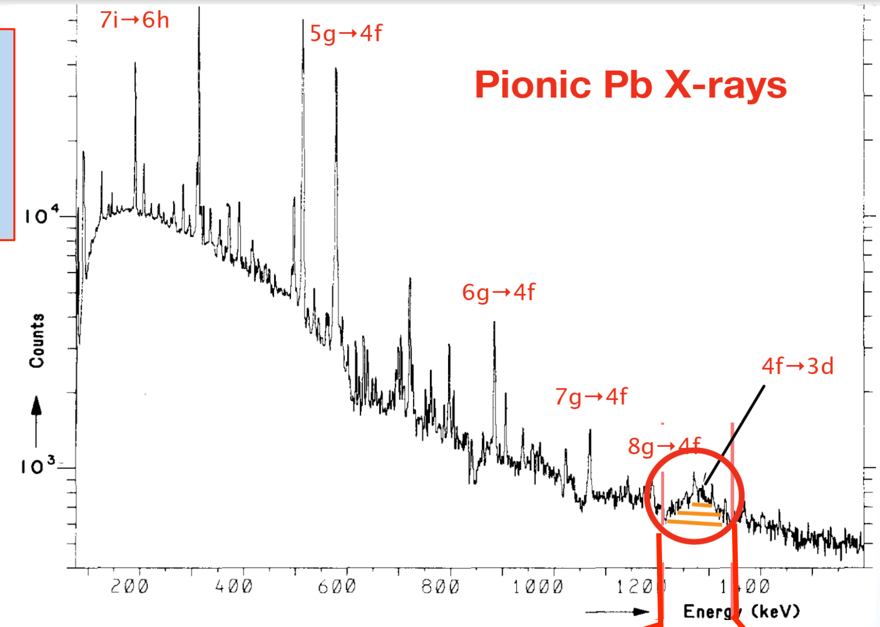


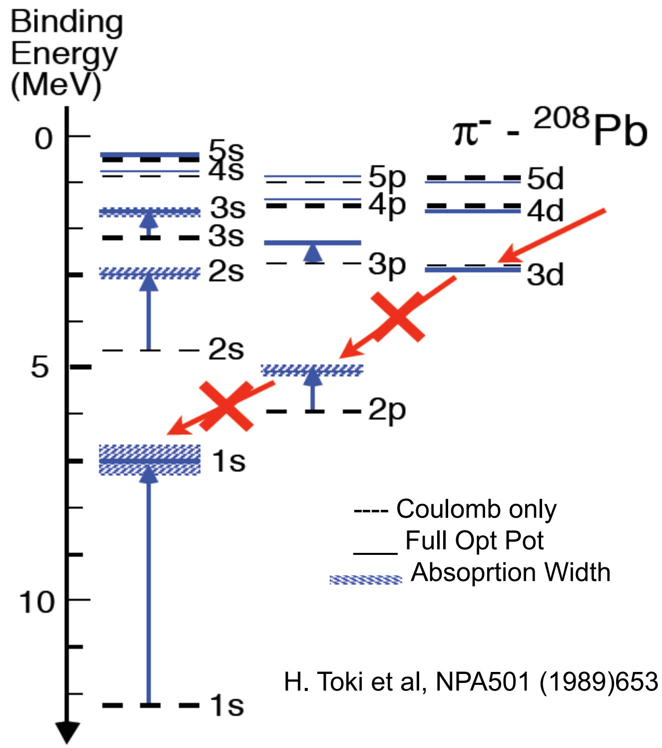
Precise measurement for H done at PSI to derive the isovector scattering length b_1 in "vacuum". Measurements on heavier nuclei harder. π are absorbed before reaching lower orbits.

Schroder et al, EJPC21(2001),473

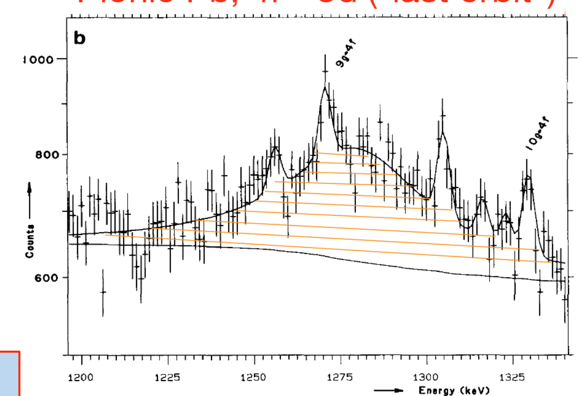
Limitation of pionic atom X-ray spectroscopy

To "feel the medium", the π needs to be in lowest orbits. In Pb that is not possible. The last observed transition is: 4f → 3d !!
PLB162 (1985) 81



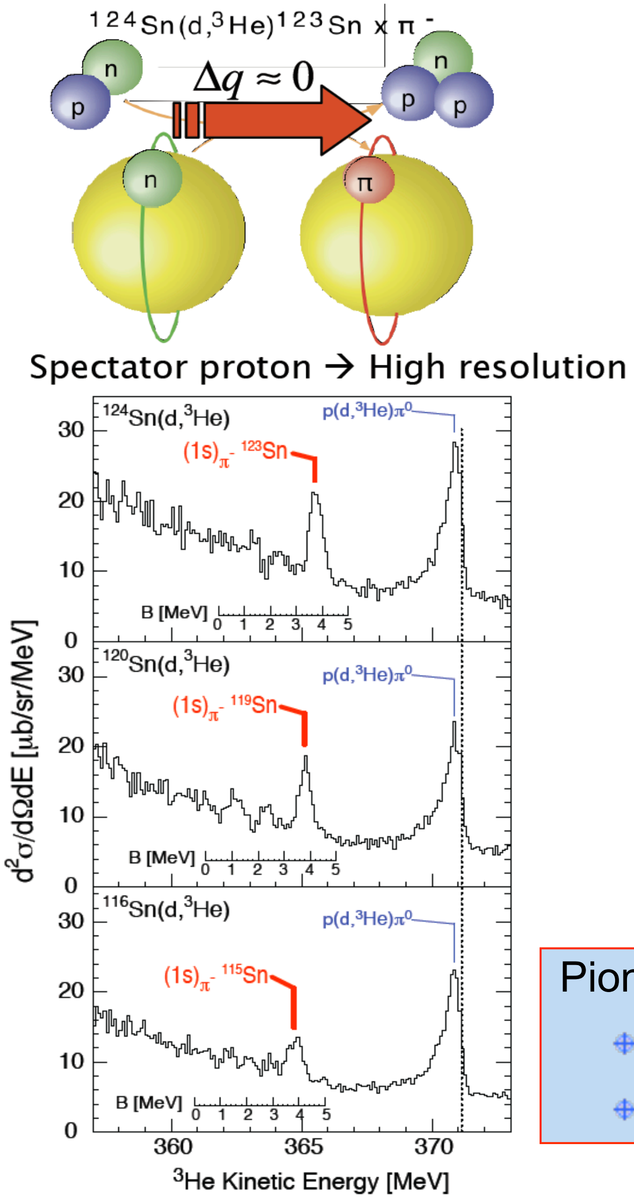


Pionic Pb, 4f→3d ("last orbit")



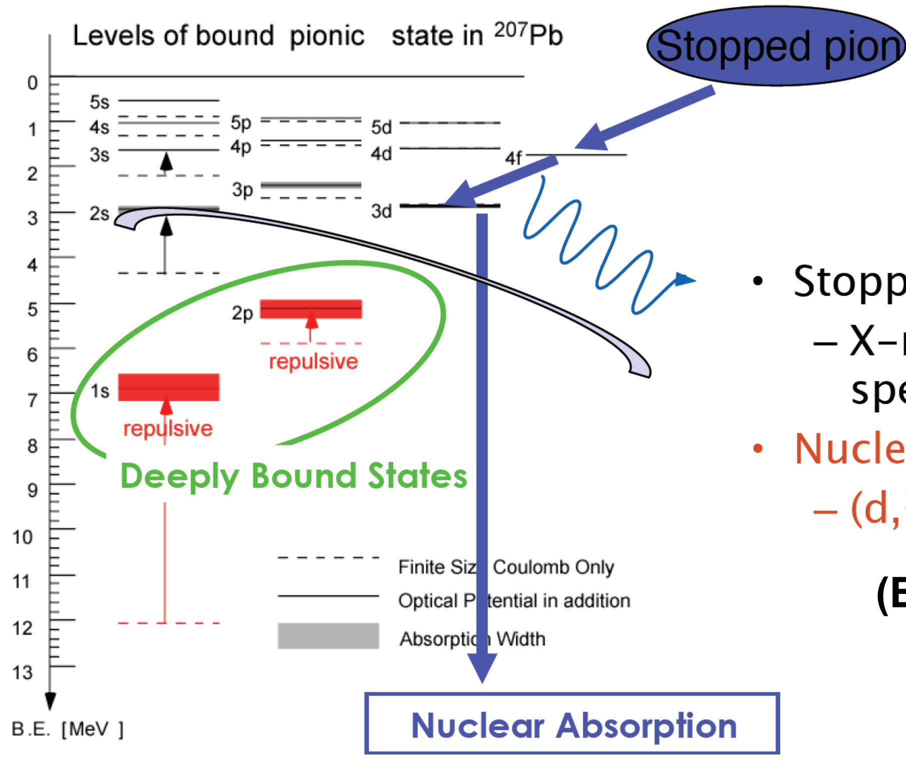
Solution: "deposit" the π in 1s orbit by nuclear reaction

Deeply bound pionic state spectroscopy (GSI-FRS)



(d,³He) transfer successful to form deeply bound pionic atoms:

Pionic 1s states now seen in 5 nuclei (missing mass spectra)



- Stopped pion
  - X-ray spectroscopy
- Nuclear reaction
  - (d,³He) reaction

(E_d~503 MeV)

Pionic 1s states in Sn isotopes: **[Suzuki et al, PRL 92 (2004) 072302]**

- $(1s)_\pi$ peak seen in ^{115,119,123}**Sn**
- Isotope shift seen for the first time in deeply bound states

Link to quark condensate

Following Suzuki and Hayano:

from symmetric nuclei: ^{16}O, ^{20}Ne, ^{28}Si

from isotopes heavy N>>Z nuclei
GSI (d,3He) reactions on Sn isotopes

Precise X-ray spectroscopy on H (PSI)

1) Pionic-atom 1s binding energy

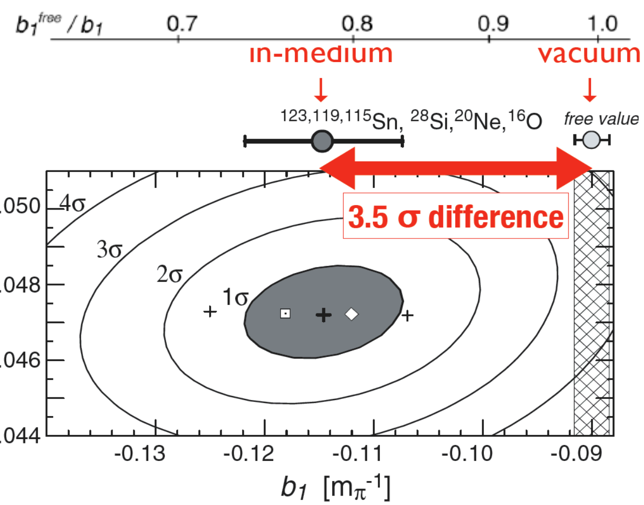
2) $b_0(\rho_n + \rho_p) + b_1^{\text{in-medium}}(\rho_n - \rho_p)$ s-wave optical potential

3) Compare $b_1^{\text{in-medium}}$ with b_1^{vacuum} obtained from pionic hydrogen

4) Tomozawa-Weinberg $b_1^{\text{vacuum}} \propto \frac{m_\pi}{f_\pi^2(\rho)}$, $\frac{b_1^{\text{vacuum}}}{b_1^{\text{in-medium}}} = \frac{f_\pi^2(\rho)}{f_\pi^2}$

5) Gell-Mann - Oakes - Renner $f_\pi^2(\rho) m_\pi^2 \approx -m_q \langle \bar{q}q \rangle_\rho$

$$\begin{aligned} b_0 &= -0.0233 \pm 0.0038\ m_\pi^{-1}, \\ b_1 &= -0.1149 \pm 0.0074\ m_\pi^{-1}, \\ \mathrm{Re}B_0 &= -0.019 \pm 0.017\ m_\pi^{-4}, \\ \mathrm{Im}B_0 &= 0.0472 \pm 0.0013\ m_\pi^{-4}. \end{aligned}$$



Issues: uncertainties on neutron radii in Sn isotopes

At an effective density of ~ 0.6 ρ_0

$$R = \frac{b_1^{\text{free}}}{b_1} = \frac{f_\pi^*(\rho_\varepsilon)^2}{f_\pi^2} = 0.78 \pm 0.05$$

$$\Rightarrow \frac{<0|q\bar{q}|0>_{\rho_0}}{<0|q\bar{q}|0>_0} \approx 0.67$$

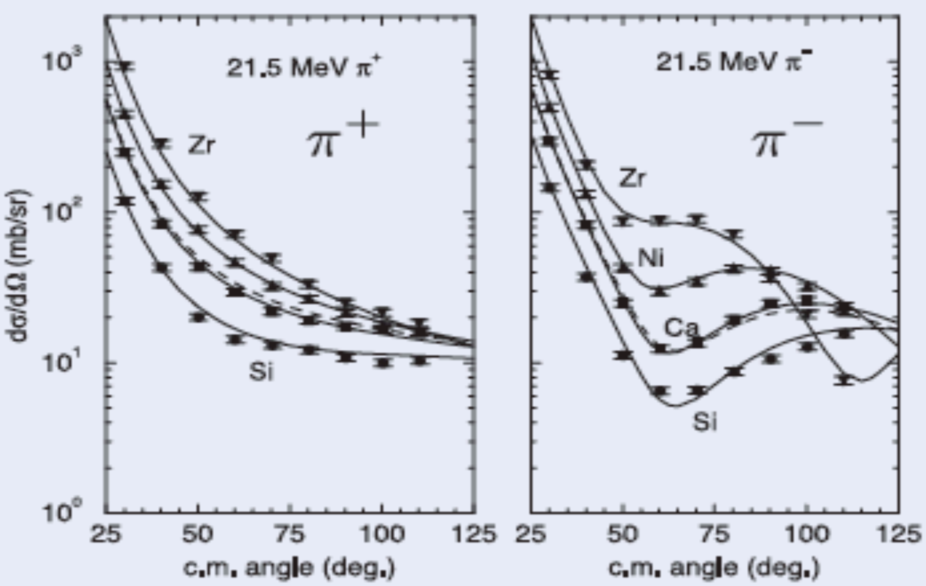
=> Evidence of partial restoration of chiral symmetry

Low energy π−nucleus elastic scattering

Elastic π-nucleus scattering at low energy

Classical approach to investigate optical potentials
Complementary experiments to pionic atom

19.5 and 30 MeV on Ca
(LAMPF, Wright et al. PRC37 (88))
21.5 MeV on Si, Ca, Ni, Zr
(PSI, Friedman et al. PRL93 (04))



Elastic scattering (Friedman et al.)

$b_1^{\text{free}}/b_1 \sim 0.69$

reduction f_π^2 by 22%(at 0.6ρ_0) →37% (at ρ_0)

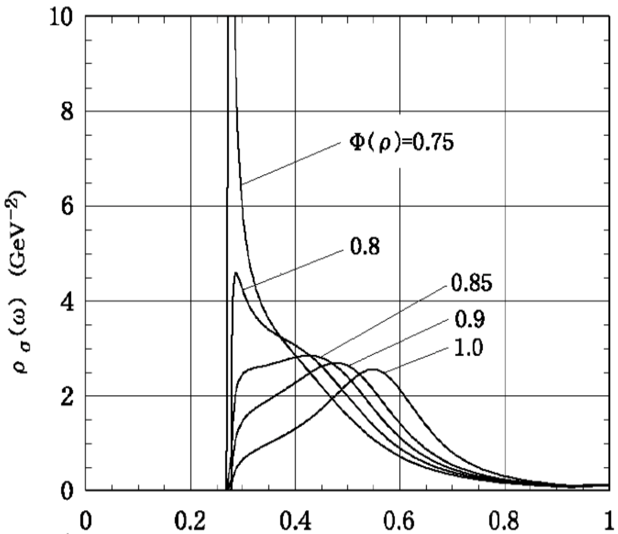
Consistent with the evidence for partial restoration of chiral symmetry found in pionic bound states

The "σ" and low mass $\pi^+\pi^-$ enhancement in nuclei

Predictions as we increase the density:

-Chiral symmetry is restored (the quark condensate decreases).
-The σ mass drops (σ-π degenerate in chiral limit).
-Phase space for σ →2π closes, σ "becomes narrower" as if shifts to lower masses.

Hatsuda, Kunihiro, Shimizu PRL82(1999)2840



Studying ππ channel

Invariant mass of ππ in:

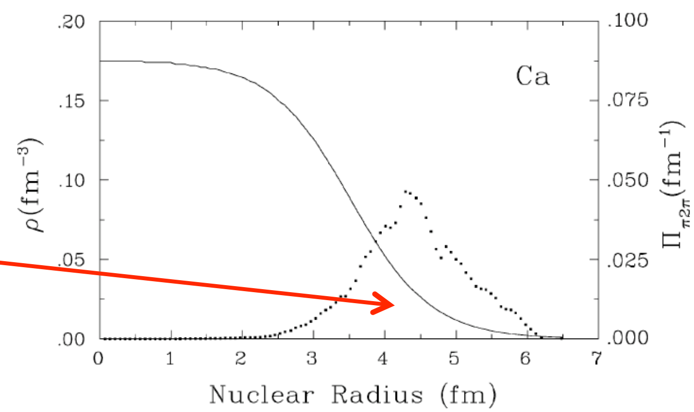
πA →ππX (CHAOS and CB)

γA →ππX (TAPS)

$\pi^+\pi^-$ (I=0, J=0, quantum # of σ and vacuum)

$\pi^+\pi^-$ and $\pi^0\pi^0$ compared to $\pi^+\pi^+$ and $\pi^-\pi^-$

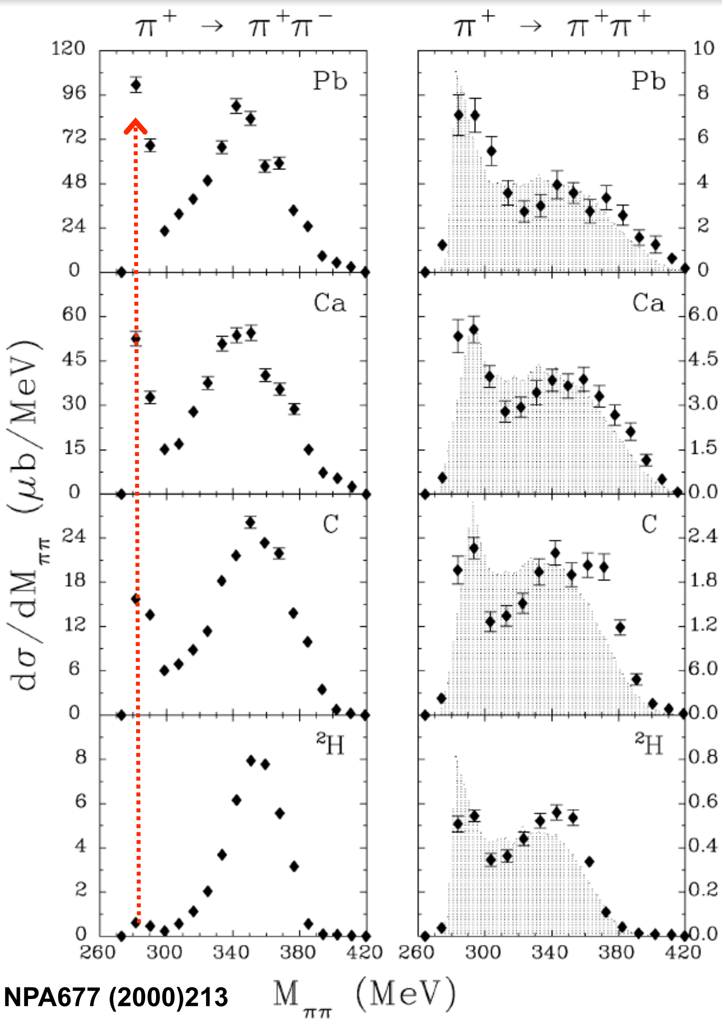
F. Bonutti et al. / Nuclear Physics A 677 (2000) 213–240



In π reactions: effective density ~ (1/3) ρ_0

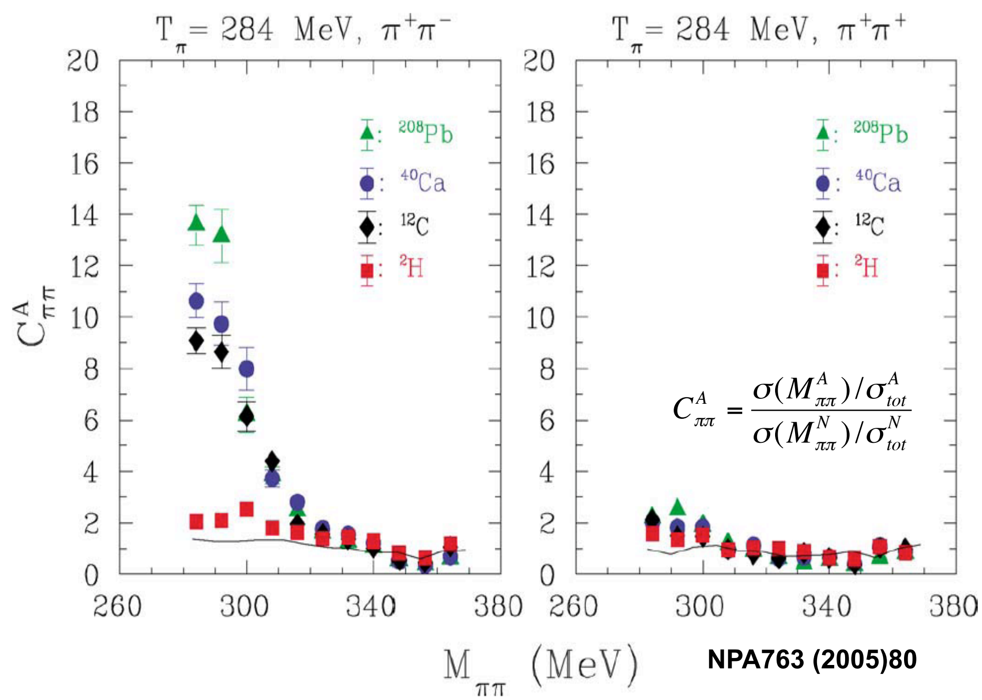
In γ reactions: effective density ~(2/3) ρ_0

Low mass $\pi^+\pi^-$ enhancement in nuclei (CHAOS@TRIUMF)



NPA677 (2000)213

A(π,$\pi\pi$)X [E_π = 243-305 MeV] observes:
-enhancement of correlated pions with I=0 close to $2m_\pi$ threshold.
-no enhancement in $\pi^+\pi^+$



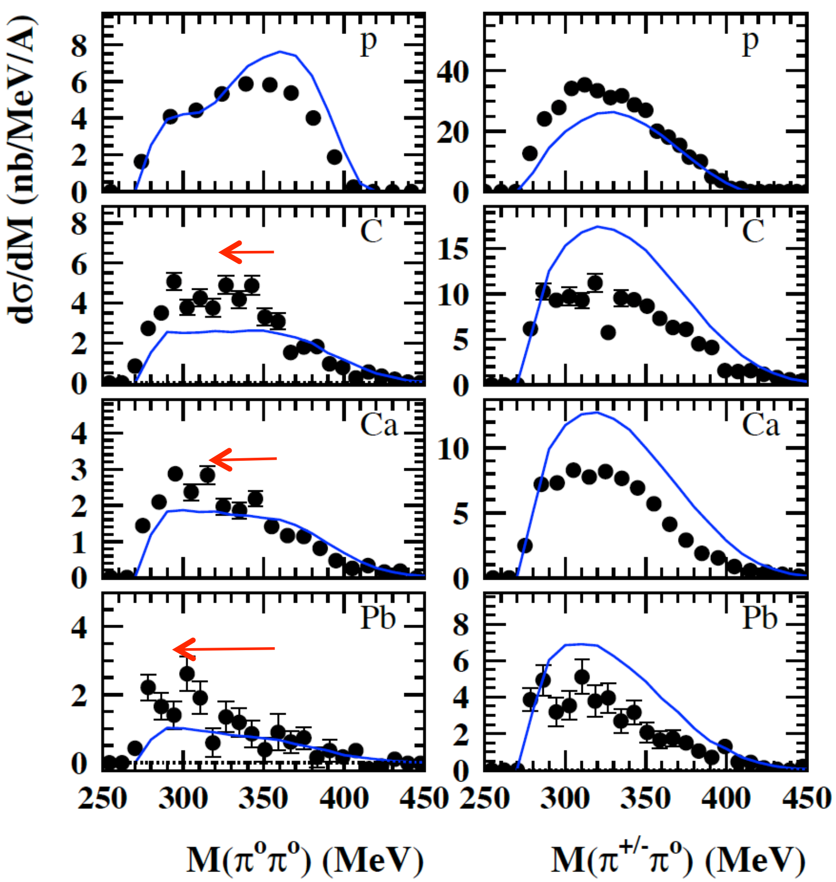
NPA763 (2005)80

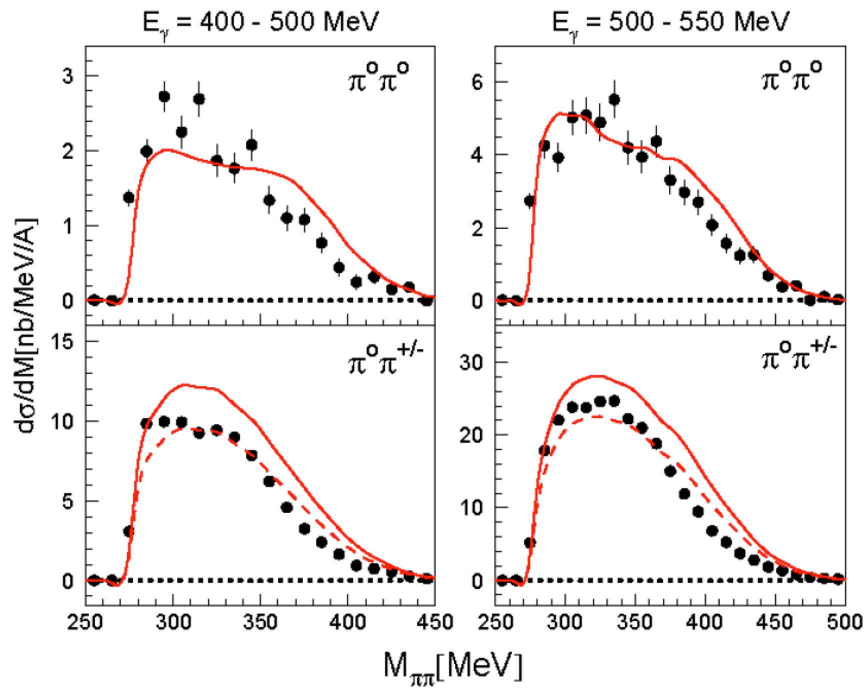
-First explanation: Chiral restoration, f_π has dropped. HOWEVER:
-Recent Final State Interactions (FSI) calculations can explain the enhancement (rescattering).
-However questions remain? NO EVIDENCE OF CHIRAL RESTORATION

Low mass $\pi^+\pi^-$ enhancement in nuclei (TAPS)

A(γ, $\pi^0\pi^0$)X and A(γ, $\pi^0\pi^\pm$) X [A=(H,C, Ca and Pb) & Eγ=400-500 MeV]

Metag, PPNP55 (2005)35





Ca data explained by FSI calculations.

Buss et al, EPJA32 (2007)219

Medium effects YES!

NO EVIDENCE OF CHIRAL RESTORATION!

With hadrons, BEWARE OF FSI, before any conclusions!

What have we learned from pions in medium?

1) Studies of Pionic atoms with X-ray spectroscopy) and deep bound states populated in (d,^{3}He) reactions seem to **require a ~30% drop in f_π at normal nuclear density**. precise r_n measurements needed
1) Low energy scattering of pions is also consistent with this drop.
2) In two pions production on nuclei, the $\pi^+\pi^-$ and $\pi^0\pi^0$ yields increase close to $2m_\pi$. Drop in σ mass as suggested by chiral restoration scenarios? Originally thought so BUT correct FSI calculations of the two pions explains it.

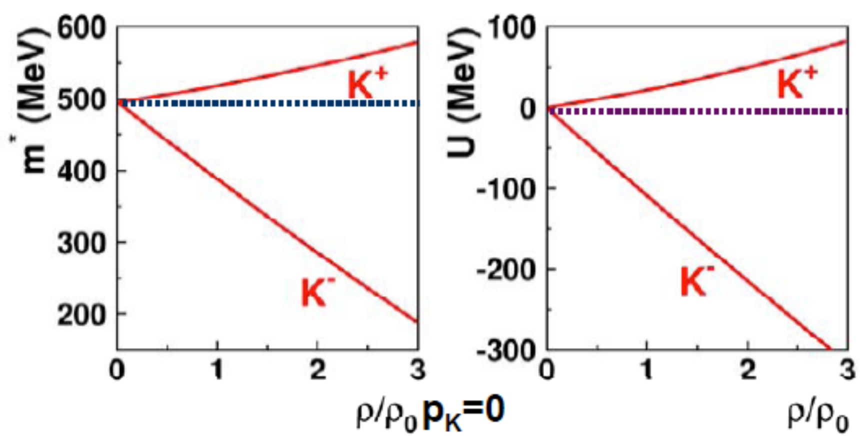
BEWARE OF FSI WITH HADRONS

So far only "solid evidence" for partial chiral restoration" comes from pionic atom studies.

Kaons in Medium(addition of s quark)

Theoretical models [NPA567(19940937; NPA610(1996)35c; NPA625(1997)372] predict modifications of masses and coupling constants for kaons and antikaons.

As density increases, $m_{eff}(K^+)$ rises slightly while $m_{eff}(K^-)$ drops "fast".



Kaons (K^+,K^0) feel a weak repulsive potential, while anti-Kaons (K^-,K^0) feel a strong attractive potential. Condensation of anti-Kaons in dense baryonic matter such as in neutron stars [PLB175(1986)57]

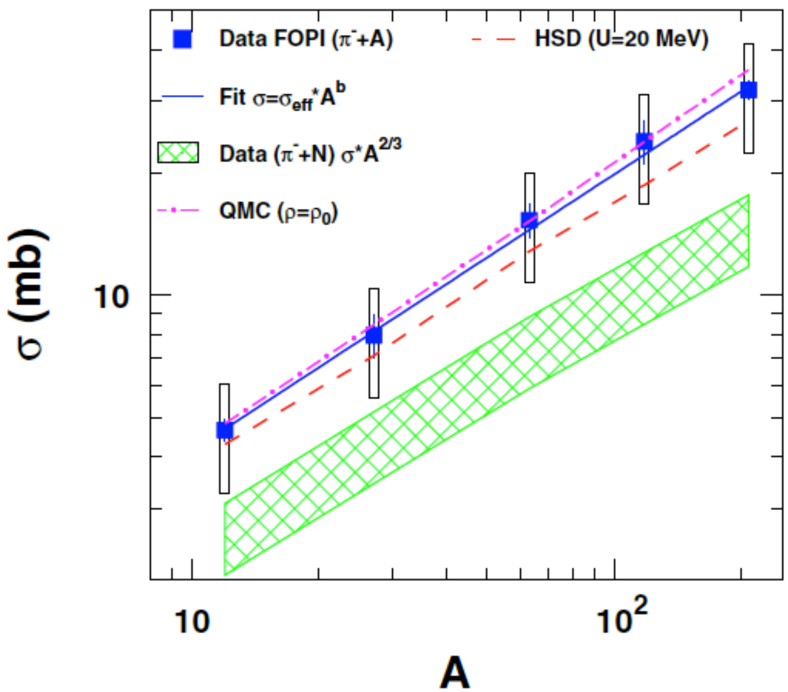
QMC calculations [PRC62(2000)064904] predict that Kaons (K^+, K^0) and hyperons (Λ,Σ) are produced via the formation of intermediate Δ and N* resonances which are modified in the medium → substantial changes of the kaon production cross sections at normal nuclear matter density.

The FOPI collaboration at GSI has measured the in-medium K^0 inclusive cross sections in $A(\pi^-, \pi^+\pi^-)X$, [A=C, Al, Cu, Sn, Pb; p_π=1.15 GeV/c]
PRL102, (2009)182501

The ANKE collaboration at COSY has measured the in-medium K^+ inclusive cross sections in $A(p, K^+)X$, [A=Cu, Au; E_p=2.3 GeV]
EJPA15, (2004)301

Kaons in the medium (FOPI @ GSI)

In-Medium K^0 inclusive cross sections in $A(\pi^-, \pi^+\pi^-)X$, [A=C, Al, Cu, Sn, Pb; p_π=1.15 GeV/c]



λ_π(1GeV/c)~1 fm → surface production expected
Indeed fit is: $\sigma = \sigma_{eff} * A^b$
With σ_{eff}=0.87± 0.13 mb and b=0.67±0.03 (~2/3)

Simple scaling ansatz underestimates data by 2

$$\sigma_{eff} = \frac{Z}{A}\left[\sigma(\pi + p \to K^0 + \Lambda) + \sigma(\pi + p \to K^0 + \Sigma^0)\right] + \frac{N}{A}\left[\sigma(\pi + n \to K^0 + \Sigma^-)\right]$$

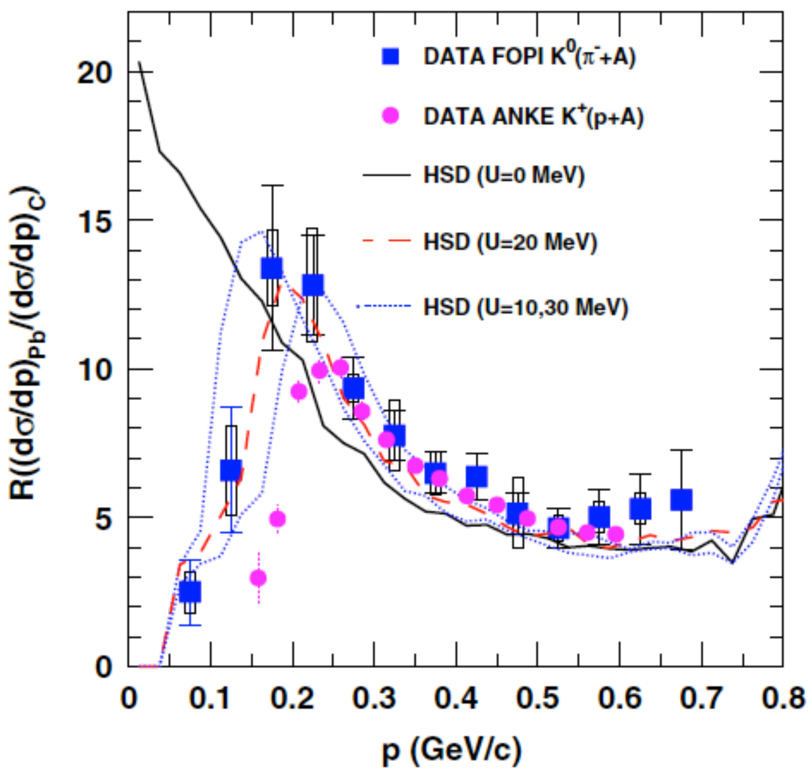
→ medium effects on production of Kaons

QMC model fits the trend, BUT QMC is for $\rho=\rho_0$
Here ρ_{eff} ~0.5-0.6
HSD transport code [PR308(1999)308;NPA614(1997)415]
Can be directly compared to data.

However, the inclusive total cross section is not sensitive to the modification of K-N in the medium. The ratio of Kaons yields as a function of momentum in the lab shows sensitivity.

Kaons in the medium

Ratio of yields for K0 (K+) produced by pions (protons) on Pb and C seen in FOPI (ANKE)



At p > 250 MeV/c, FOPI and ANKE ratios agree. K^0_S with p<170 MeV/c are suppressed in Pb with respect to C.
Same pattern for K^+ below p~250 MeV/c

A repulsive KN potential in the nuclear medium can explain this observation. The Kaons are accelerated before getting out of the nucleus. The larger the nucleus , the longer they feel the potential

Coulomb repulsion accelerated the depletion for K^+

HSD transport model calculations show sensitivity to these ratios

A <u>repulsive KN potential of 20 ± 5 MeV</u> (at normal nuclear density) explains the FOPI and ANKE results

END OF LECTURE ONE