

# An extraction of $\bar{K}$ - nucleon subthreshold amplitude

from  
Kaonic atoms

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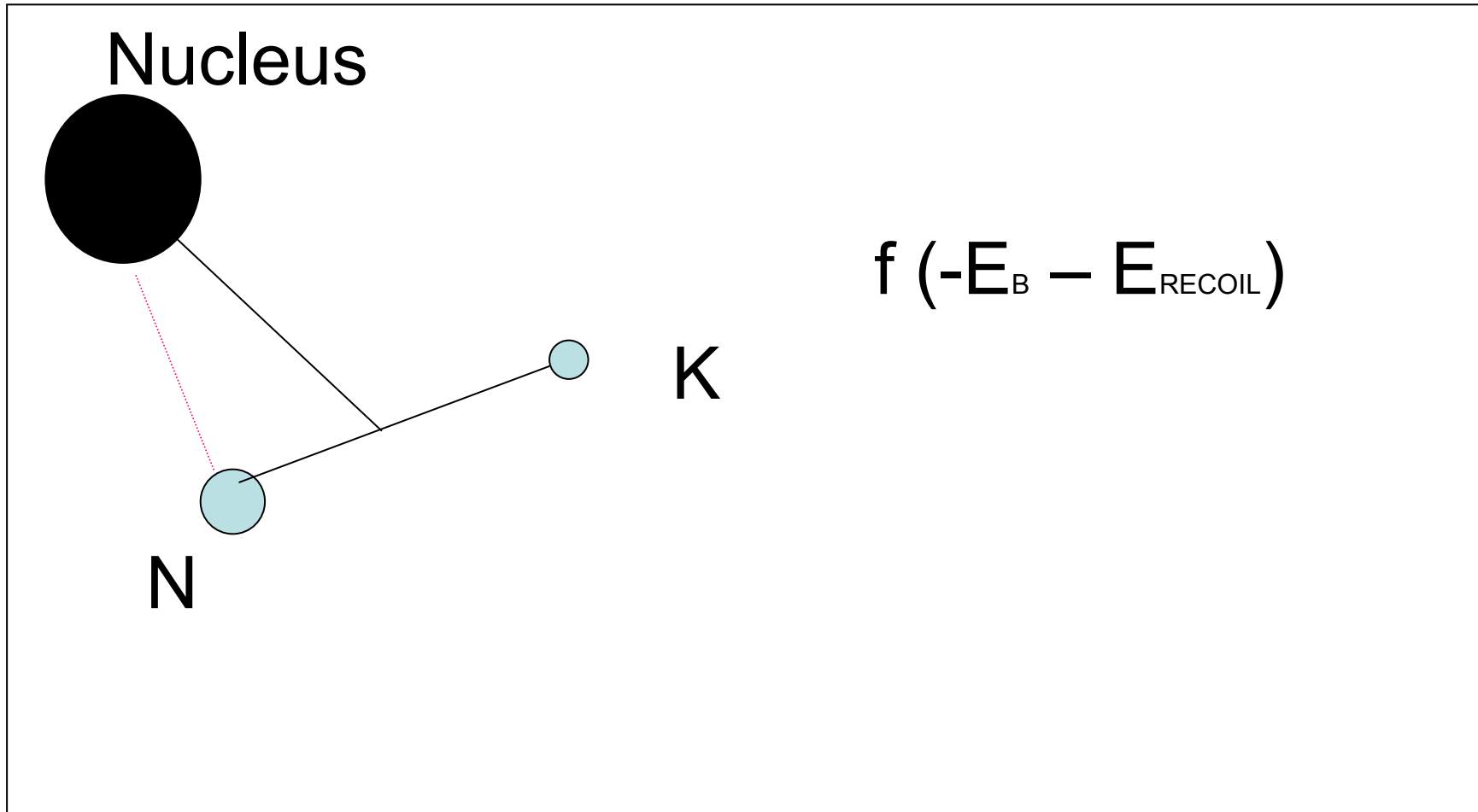
# Motivation

Hadronic atoms involve subthreshold  
H-N scattering amplitudes

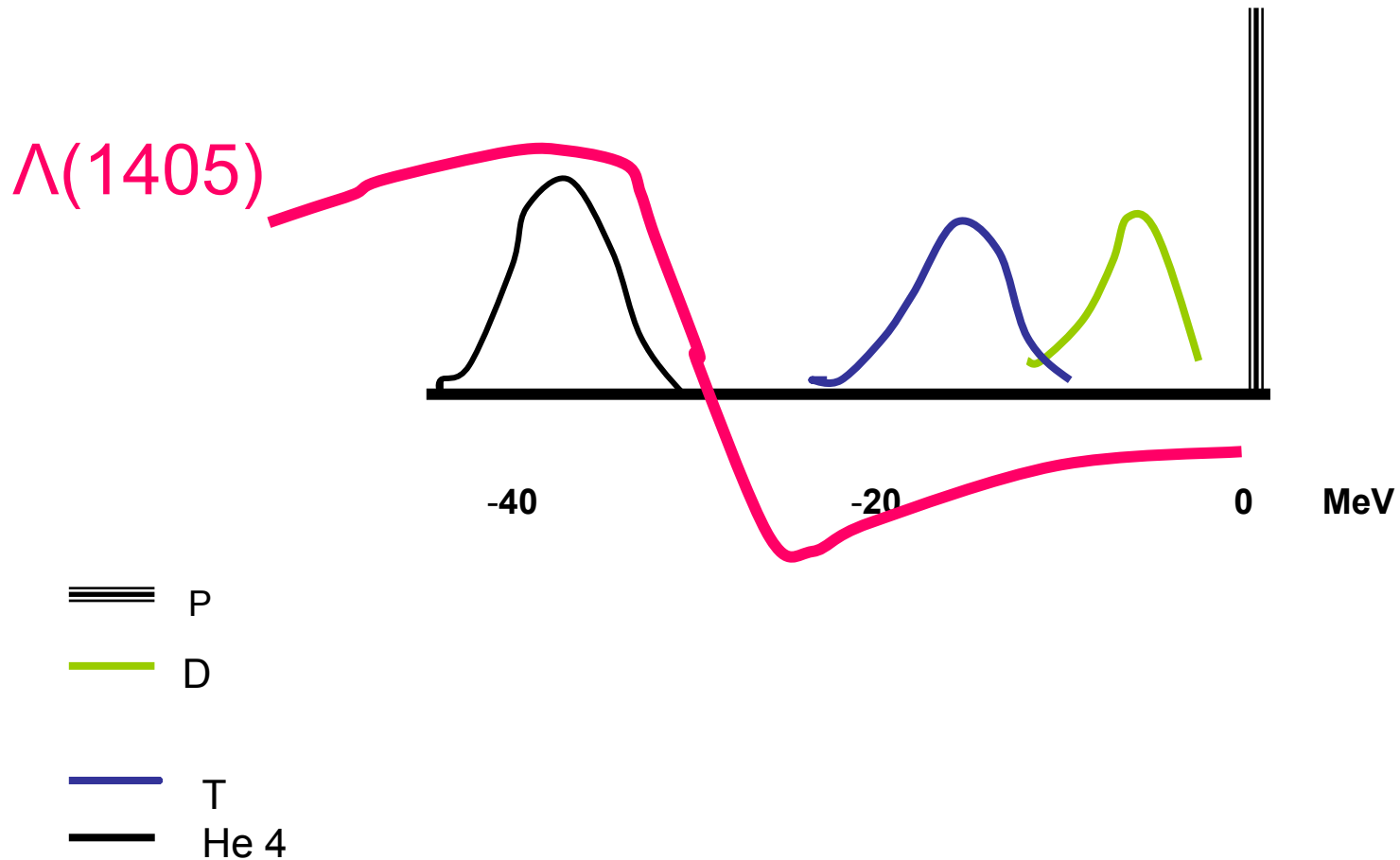
In this region, there may be  
bound states, baryonia, quark states.

- $\bar{N} N$  : baryonia , quasi-bound states
- $\bar{K} N$  :  $\Lambda(1405)$ ,  $\Sigma(1385)$

# Energy in KN c.m.system



# $\bar{K} N$ subthreshold energies involved in p-bar atoms



# Average subthreshold energy (spread)

| Atom | 1S     | 2P     | 3D     |
|------|--------|--------|--------|
| 1H   | 0      | 0      | 0      |
| 2H   | 13(5)  | 8(3)   | 6(2)   |
| 3H   | 19(7)  | 17(6)  | 16(6)  |
| 3He  | 20(7)  | 18(6)  | 17(6)  |
| 4He  | 37(10) | 37(10) | 36(10) |

# Atomic level shifts $\approx$ zero energy *nuclear* scattering parameters

S waves

$$\Delta E - i \Gamma/2 = 2\pi / M |\Psi_A(0)|^2 A_0 (1 + 3.154 A_0/B); \text{ Tueman}$$

$$= 2\pi / M |\Psi_A(0)|^2 A (1 + X A/B)$$

$A_0$ - hadron-nucleus scattering length  
„inner Coulomb corrected”

$A$ - „bare” scattering length,  $X$

$B$  - atomic radius

$\Psi_A$ - atomic wave function

Higher  $L$  atomic states

$$\Delta E_L - i \Gamma/2 = \text{constant}_L A_L$$

# K-p lengths

[fm]

$$A_0 = -0.47(9) + i 0.31(12) \quad \text{Trueman}$$

$$A = -0.45(9) + i 0.27(12) \quad \text{Chiral (U-G.M.)}$$

$$A = -0.49(9) + i 0.34(12) \quad \text{T.O.E.}$$

# Low energy expansion for scattering amplitudes

$$F_{\text{SCATTERING}} = A_0 + 3 \mathbf{k} \mathbf{k}' A_1 + \dots$$

On a nucleus  $A_i$  ( $E = 0$ )

In  $\bar{K} N$  sub-systems

$a_{(KN)} (-B_{\text{BINDING}} - E_{\text{RECOIL}})$  negative energies

EXTRACT  $a_{(KN)}$

Analogies :

$\bar{K}$  - atoms

$\bar{p}$  - atoms

more data/ but more waves

# Antiprotonic atom data widths and lower level shifts

Hydrogen  $1s, 2p$

CERN -PS- 207

Deuteron  $1s, 2p$

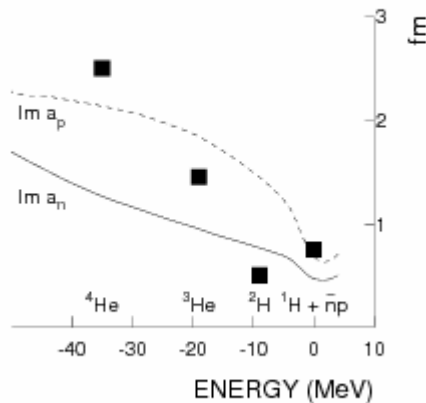
CERN -PS- 207

$^3\text{He}, ^4\text{He}$   $2p, 3d$

M.Schneider

Averaged absorptive parts of S-wave  $\bar{p}N$   
amplitude  
obtained from light atoms

Continuation both ways ?  
What partial wave ?



# S wave ( $\bar{p} p$ ) state

Two experiments select  $^1S_0$  partial waves :

$J/\psi \rightarrow (\bar{p} p), \gamma$  BES

$J/\psi \rightarrow (\pi\pi\eta'), \gamma$  BES X(1835)

Non-selective

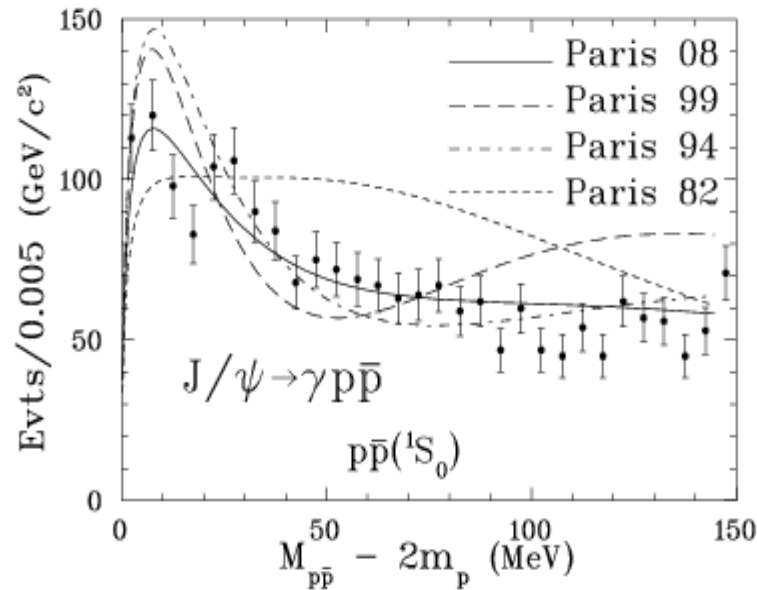
$\bar{p}$  - atomic level widths  
without fine structure

PS 209, PS 207

# Enhancement in $^1S$ wave

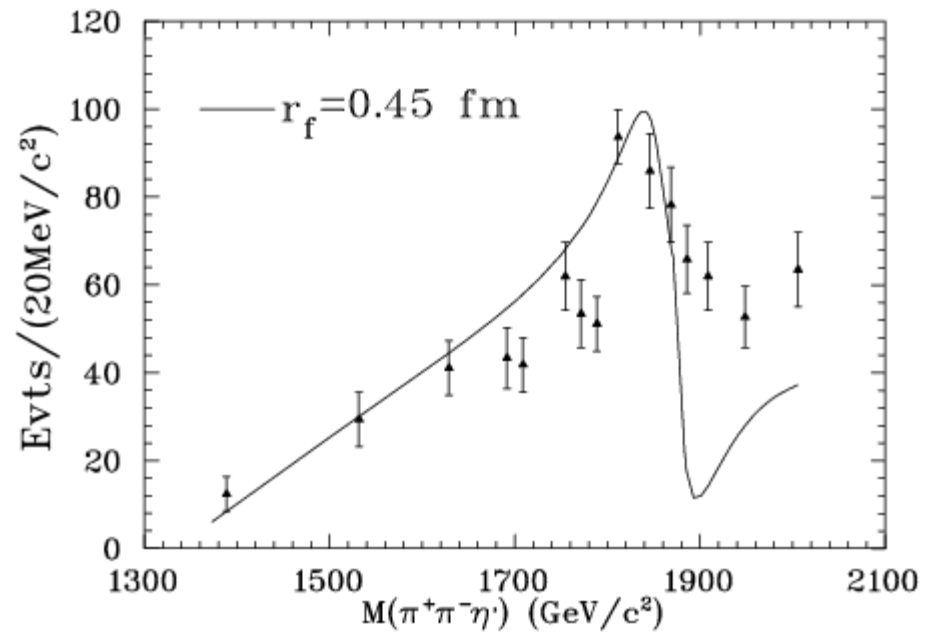
## BES experiment

reproduced by Paris and Juelich models



$J/\psi \rightarrow (\pi\pi\eta')$ ,  $\gamma$   
by BES

Named  $X(1835)$

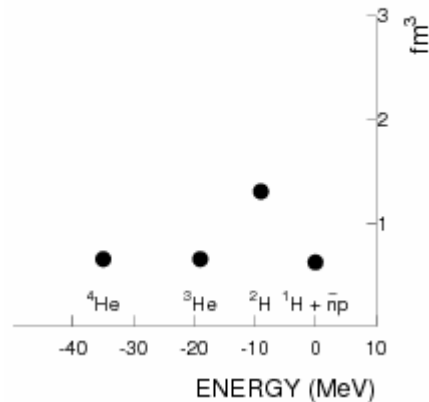


# $^{11}\text{S}$ summary evidence

- The X(1835) peak can be generated by **conventional  $N\bar{N}$**  potential model [7].
- Structure stems from broad and weakly **bound state** in the  $^{11}\text{S}_0$  wave: meson exchange + G-parity.
- Same state: peaks in  $J/\Psi \rightarrow \gamma pp'$  and  $J/\Psi \rightarrow \gamma \pi^+ \pi^- \eta'$ .
- Additional confirmation in level widths of **anti-protonic** atoms.

# Imaginary part of P-wave $\bar{p}$ -bar amplitude from light atoms

- Paris : 9 MeV wide state beyond atoms  
„seen „ in radiochemical studies



- Kaonic Helium

# KAONIC ${}^4\text{He}$ atom KEK

3d  $\rightarrow$  2p transition

$$\text{Shift} = -2(2) \text{ eV} \quad \textit{attractive} \quad \text{S.Okada..}$$

$$\text{Width} = 7(5) \text{ eV} \quad \textit{unofficial}$$

Extracted

$$A_1(\text{K } {}^4\text{He}) = 3.4(3.4) + i 6.0(4) \text{ fm}^3 \quad \textit{attractive}$$

$$A_1(\bar{\text{p}} {}^4\text{He}) = 3.5 - i 4.4 \text{ fm}^3 \quad \textit{repulsive}$$

**different sign conventions !**

P – wave K-  $\alpha$

quasi -bound state due to  $\Sigma(1385)$

contributes little

$$A_1 (K \ ^4\text{He}) = -.2 + i \ 1.0 \text{ fm}^3$$

# Method of calculation

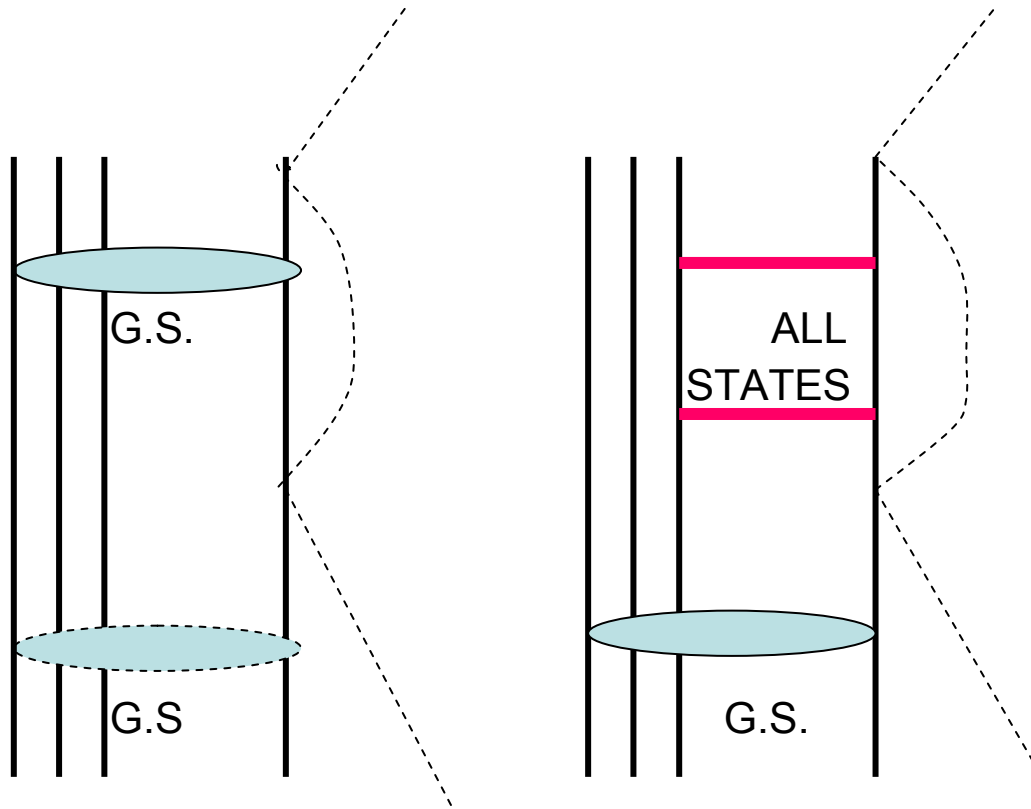
Partial sums of multiple scattering series

$$A = a + \langle aGa \rangle \dots = a / (1 - \langle aGa \rangle / a) \dots$$

$$\begin{aligned} A &= a + \langle aGa \rangle + \langle aGaGa \rangle \dots = \\ &= a / \{ 1 - \langle aGa \rangle / a - \langle aGaGa \rangle / a + \\ &\quad + [\langle aGa \rangle / a]^2 \dots \} \end{aligned}$$

Two steps ~ 1% precision in deuteron, S-wave

# Method of calculation-propagator

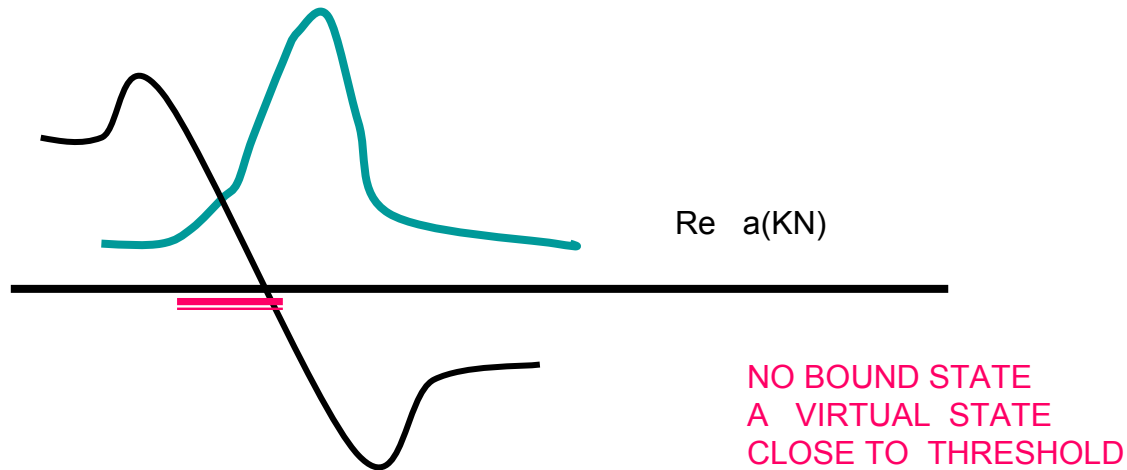


OPTICAL  
Slow convergence

MODEL 3+1  
Fast convergence

# A(K <sup>4</sup>He) scattering volume as a function of „ attraction strength”

- — Re A
- — Im A
- error



Average KN amplitude at – 37 MeV

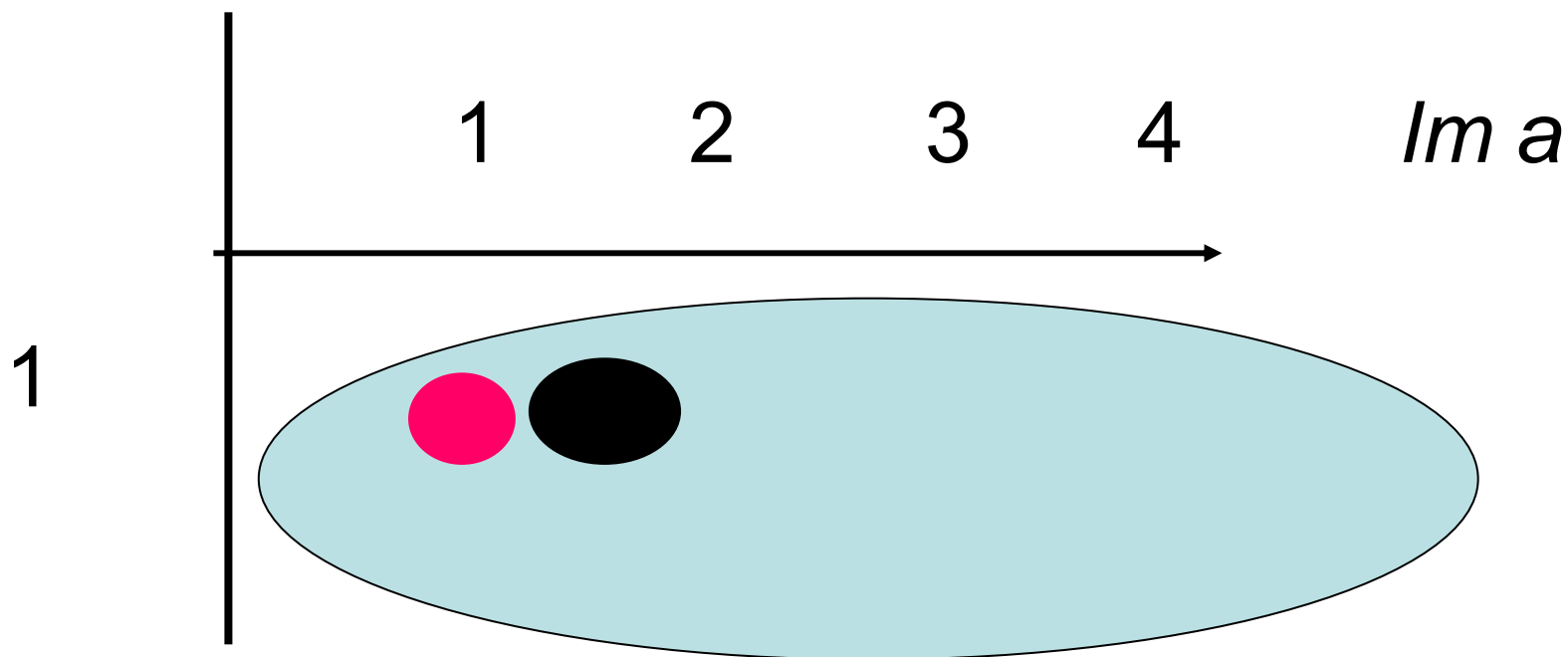
$a(-37\text{MeV}) \sim 1.2 + i \quad 1.3 \text{ fm}$   
phenomenological

$a(-37\text{MeV}) \sim 0.8 + i \quad 0.8 \text{ fm}$   
chiral

$a(-37\text{MeV}) \sim 2.3 + i \quad 2.5 \text{ fm}$   
best fit      atom



$Re a$  [fm]



# CONCLUSION

Ask / press experimental friends  
for

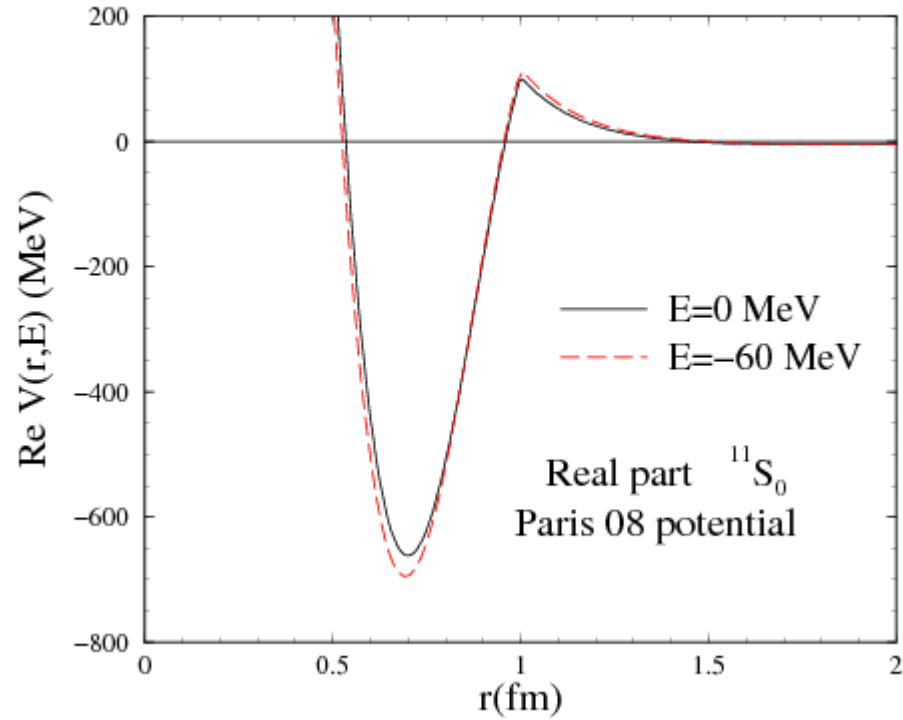
Hydrogen      1s , 2p

Deuteron      1s, 2p

$^3\text{He}$  ,  $^4\text{He}$       2p, 3d

Intensity - loss measurements

# Potential in $^{11}\text{S}$

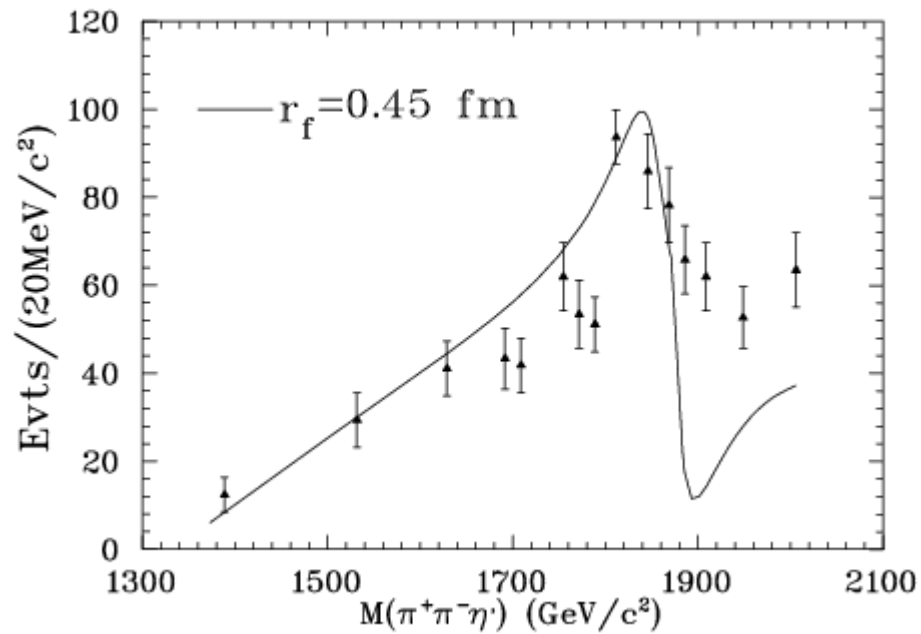




# $J/\psi \rightarrow (\pi\pi\eta'), \gamma$

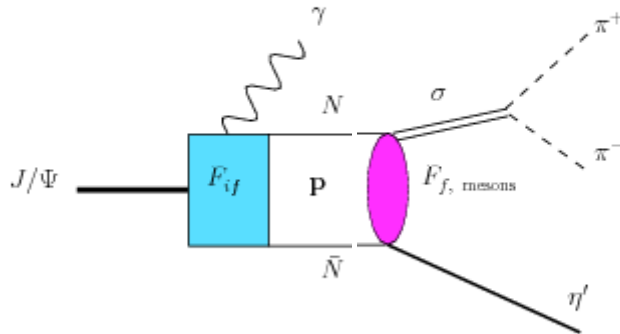
## BES experiment

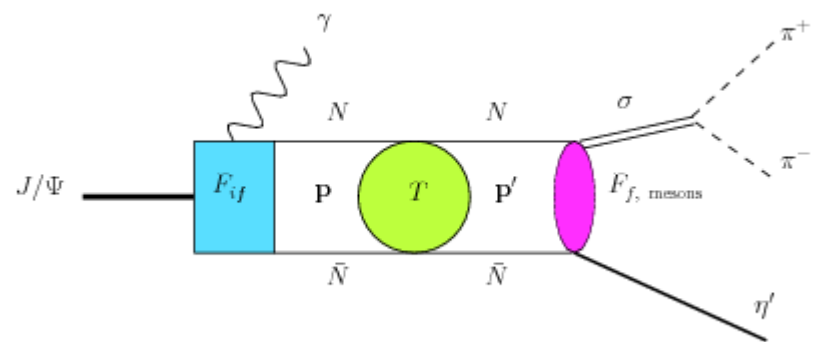
### Paris model understanding



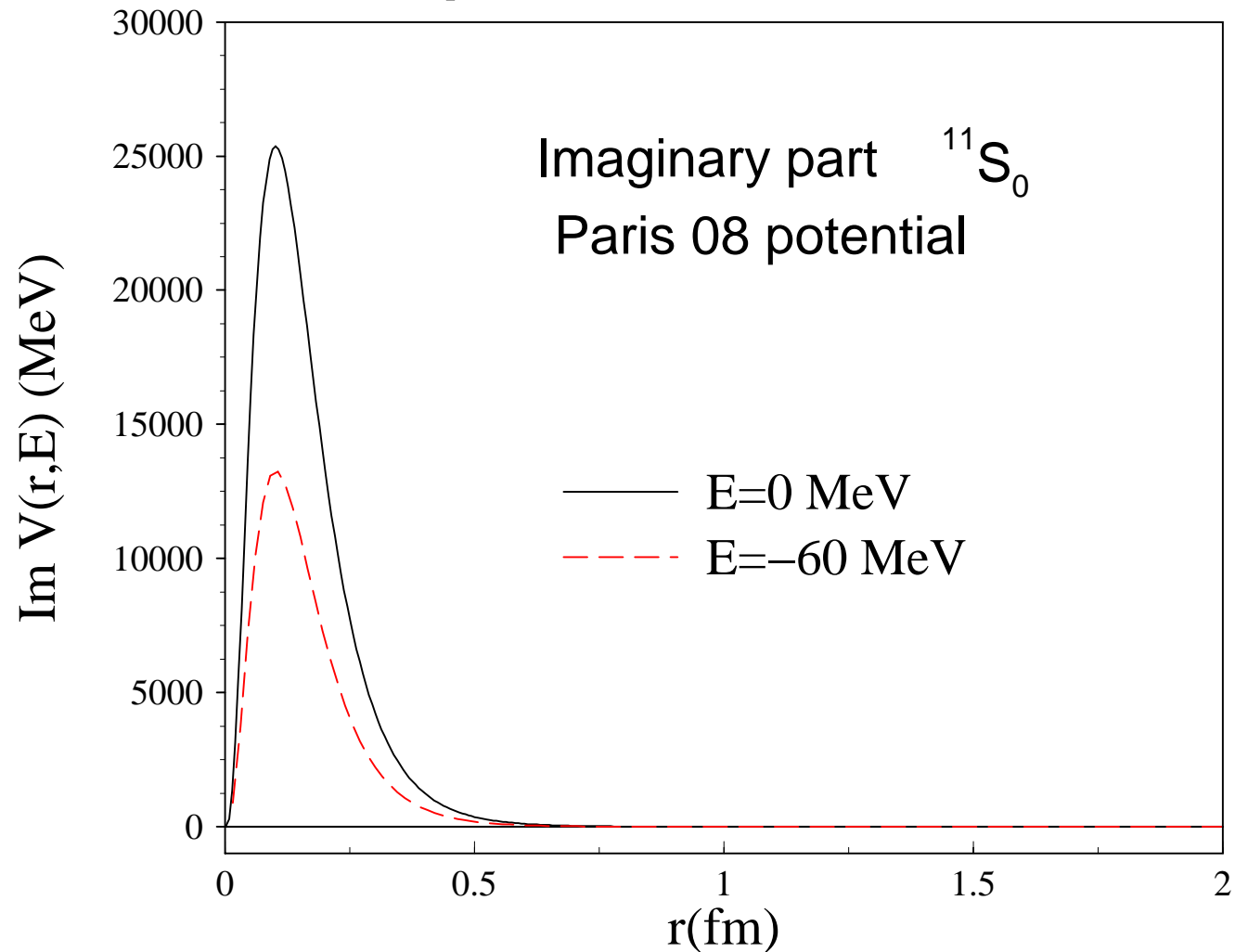
# Direct decay

- $F_{if}$  used before –free range parameter,
- $F_f$  -  $f_r$





# An effect of energy dependent potential

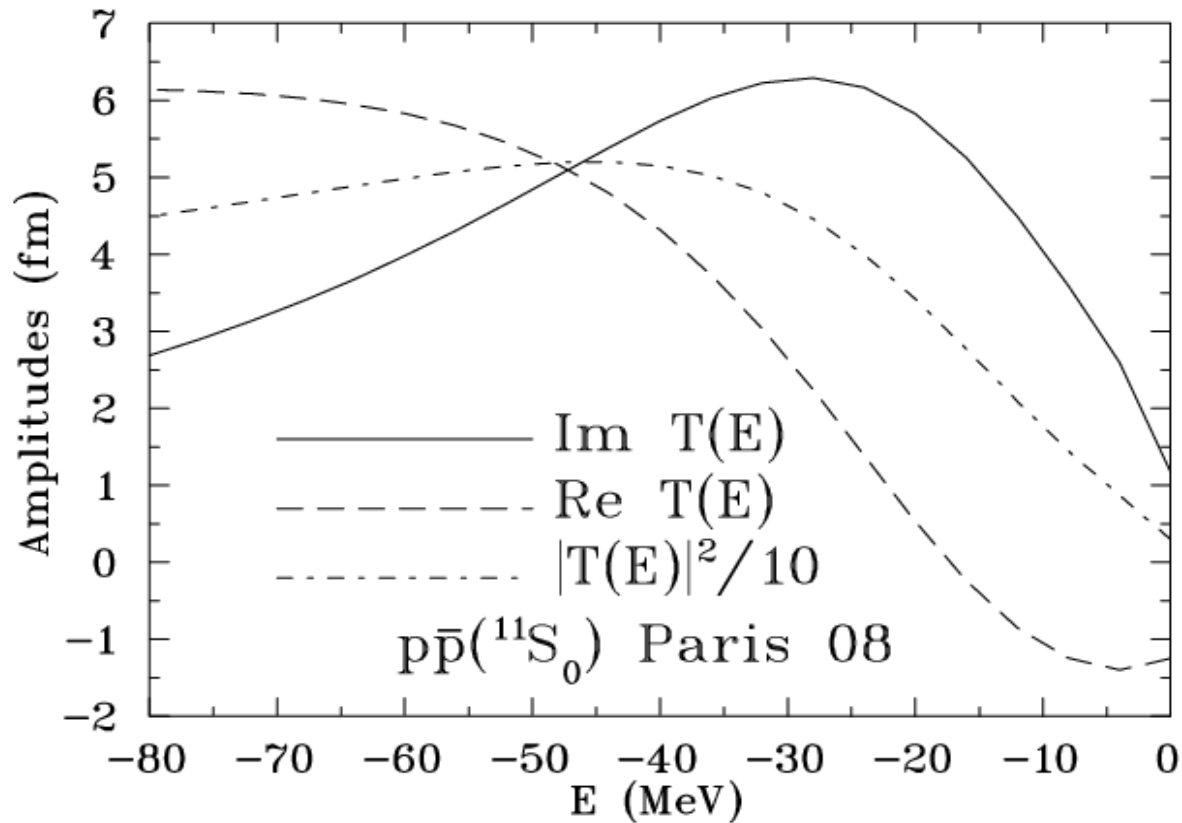


Subthreshold enhancement  
what partial wave is involved ?

An additional evidence needed

# Nature of X(1835)

11S amplitude below threshold



# 25 year search

- baryonium =  $2 q + 2 \bar{q}$  ?
- $\bar{N} - N$  quasi-bound states !

# New clarifying experiments

Fine structure resolution in  
deuterium, helium atoms

PAX – polarized beam proposal

$$\bar{p} p \rightarrow (\bar{p} p), \gamma$$

# P wave exotics

# Guidelines : Paris N-Nbar potential model 2009

TABLE III: Binding energy in MeV of the close to threshold quasi-bound states of the present model and of the Paris 99 potential [8].

| $2T+1 \ 2S+1 \ L_J$ | Present work | Paris 99 |
|---------------------|--------------|----------|
| $^{11}S_0$          | -4.8-i26     |          |
| $^{33}P_1$          | -4.5-i9.0    | -17-i6.5 |

- But no bound state in  $^{11}S$  Juelich potential
- Paris potential : M. Lacombe, B. Loiseau, S.W. . . .

- Ratio  $\sigma(\bar{p}n)/\sigma(\bar{p}p)$

- 

- ↓                   ↓                   ↓

- Lower level ,   Upper level ,   cold capture

- 96 Zr       1.61(6)               1.91(6)               2.6(3)
- 116 Cd     2.60(35)              3.33(37)             5.6(5)
- 124 Sn     3.09(7)              3.43(25)             5.4(7)

- 

- Anomalies ( 4 cases)

- =====

- 106 Cd     1.65(80)               5.13(80)               0.5(1)

- weakly bound proton , strongly bound neutron

# K-mesic atom data

lower shifts + widths

Hydrogen      1s

$^4\text{He}$       2p

# Chiral KN amplitude

Weise, Borasoy

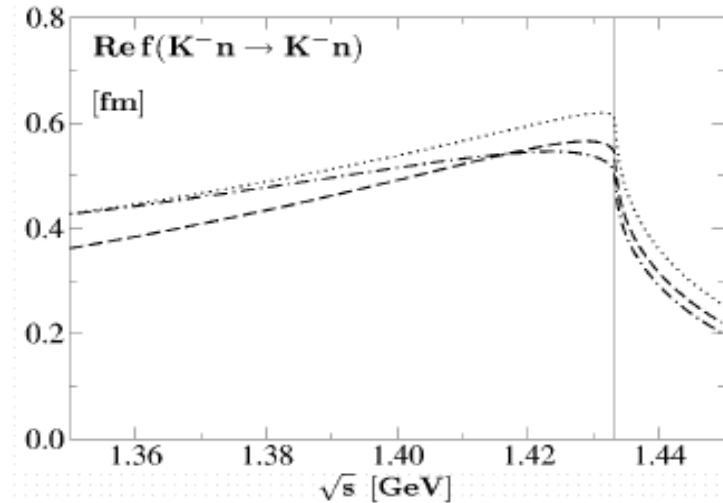
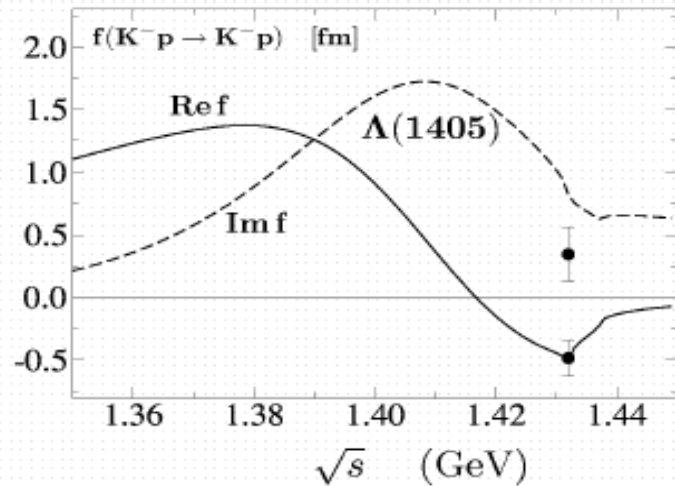
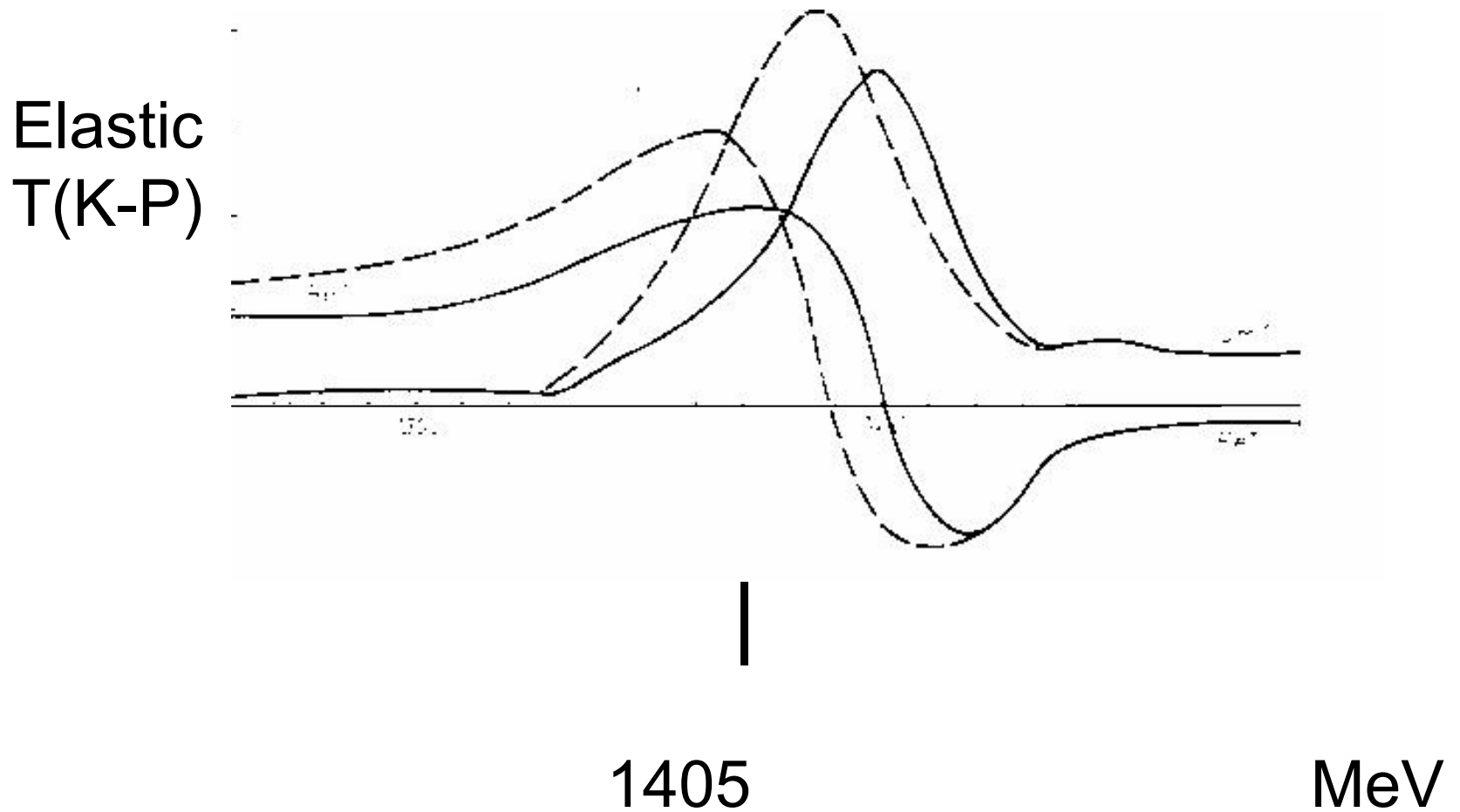


Figure 2: Left: Real and imaginary parts of the  $K^-p$  forward elastic scattering amplitude calculated in the Chiral SU(3) Coupled Channels approach [13]. Real and imaginary parts of the scattering length deduced from the DEAR kaonic hydrogen measurements [15] are also shown. Right: Predicted real part of the  $K^-n$  forward elastic scattering amplitude calculated in the same approach [13]. In both figures  $\sqrt{s}$  is the invariant  $\bar{K}N$  center-of-mass energy.

# Main uncertainty - position of $\Lambda(1405)$



For hard cores, absorbtive spheres

$$|A_1| \sim R^3 / 3 \sim 3 \text{ fm}^3$$

$$A_1 (\text{K } ^4\text{He}) = 0 (10) + i 14.5 \text{ fm}^3$$

$\text{K- } ^4\text{He}$  quasi-bound state  
close to threshold

# Conclusions

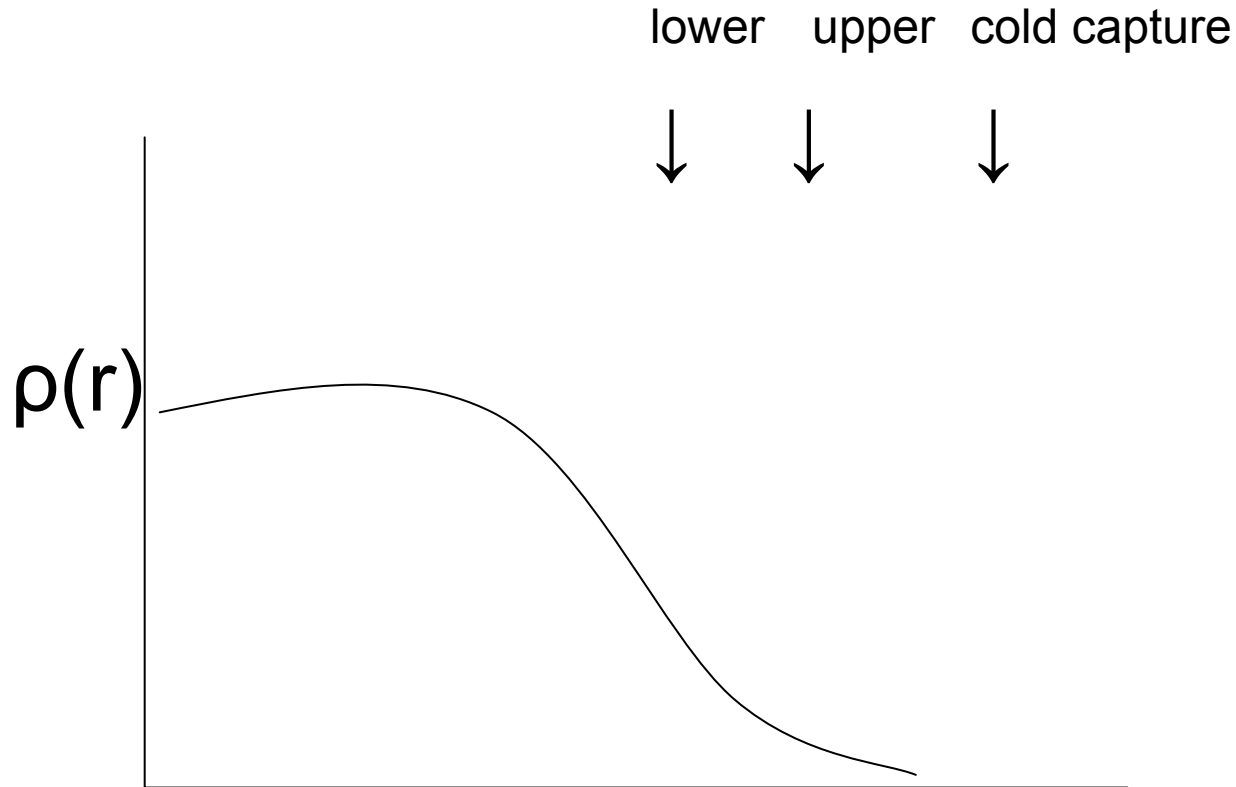
- Consistent evidence of  $^{11}\text{S}$  q. b. state  
(the structure is less certain)
- Indications of  $^{33}\text{P}$  q.b.s.
- Quasibound K-He state close to threshold  
(not well understood )



$$A(\text{K He}) \rightarrow \quad a(\text{KN}) \sim 3 + 0.5 i \text{ fm}$$

??

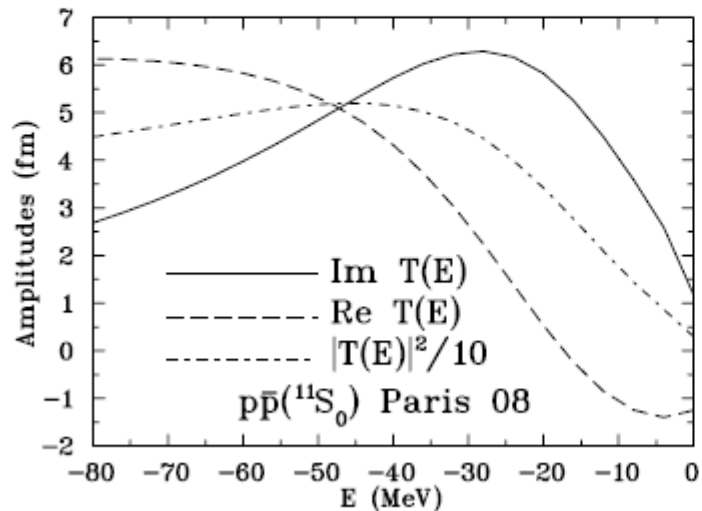
# Nuclear regions studied in atoms



# Subthreshold amplitude in $^{11}\text{S}$

$$T(E) = \int dr T(r, E)$$

Normalized to the scattering length at threshold



$$T(k, E) = \int dr T(r, E) \frac{\sin(kr)}{kr}$$

Fourier transform of  $T(r, E)$

- Resonance behavior for  $Im T(E)$
- $^{11}\text{S}_0$  bound state:  
pole at  $E = -4.8 - i26$  MeV
- Maximum of  $Im T(E)$ ,  $E \simeq -2.7$  MeV or  
 $M_{p\bar{p}} = 2m_p - |E| \sim 1850$  MeV
- $M(\pi^+\pi^-\eta')$  distribution peaks at  
 $M_{p\bar{p}} = 1835$  MeV  
 $\Rightarrow$  interpretation of X(1835) more involved

# Heavier atoms

PS 209

Optical potential  $U = V(r) - i W(r)$

$$T = a + 3 b \mathbf{P} \cdot \mathbf{P}'$$

$$U = 2 \pi / \mu \left[ a \rho(r) + 3 b \frac{\partial \rho(r)}{\partial r} \right]$$

$a(E)$  yields better fit to  $\sim 100$  data

$$\chi^2 / N \text{ (2.25-2.11)}$$

# Origin of the potential

~4000 data + hydrogen p-bar atom

2

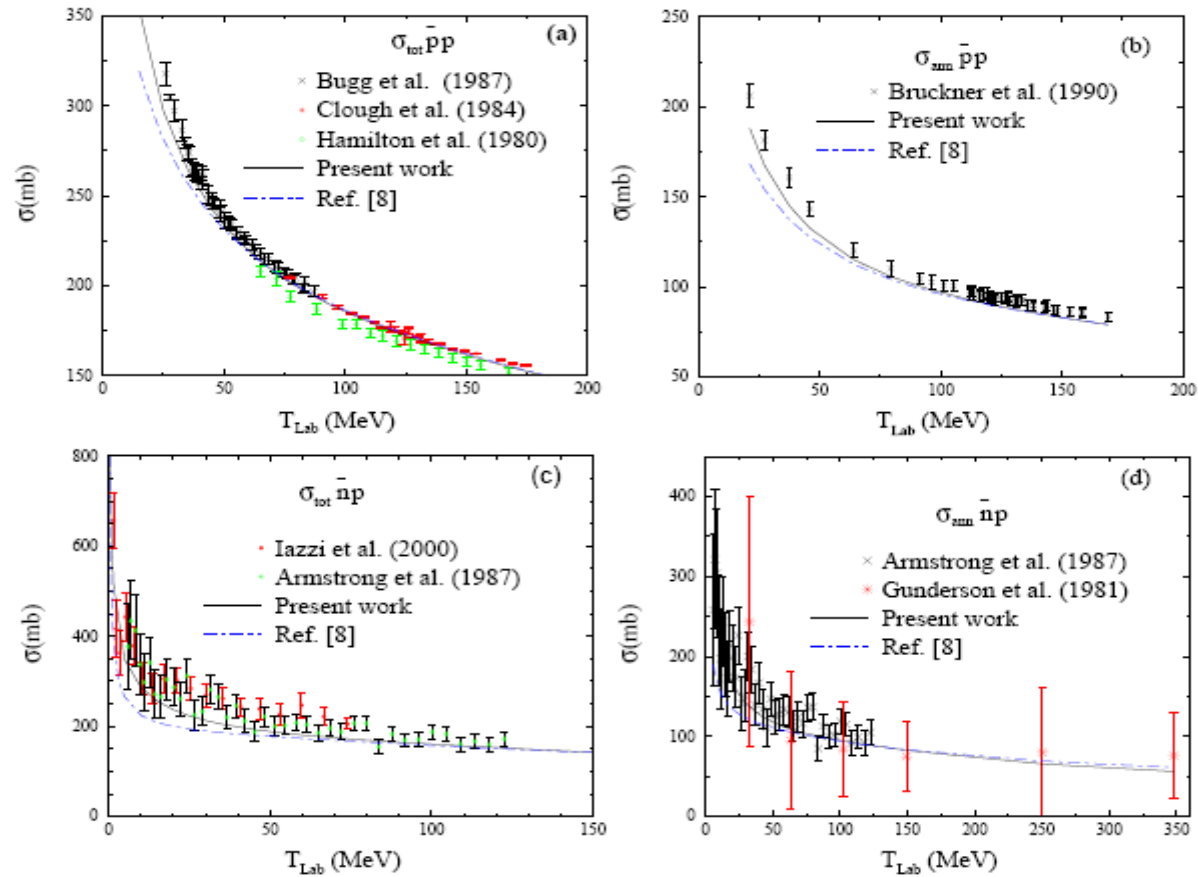


FIG. 1: Total and annihilation cross sections for the  $\bar{p}p$  and  $\bar{n}p$  systems. The references of the experimental data can be found in Ref. [7]. The data of Iazzi et al. in Fig. 1(c) are from Ref. [9].

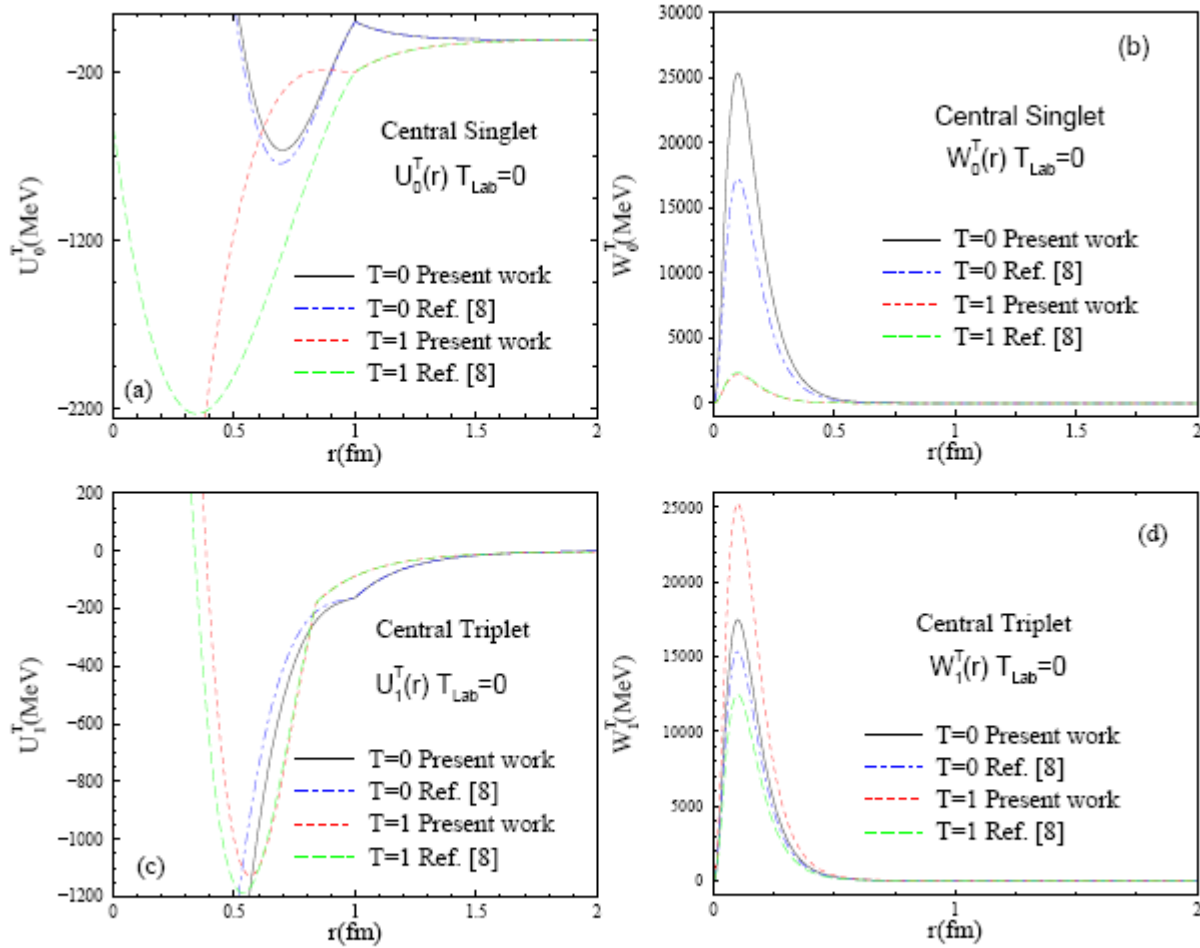


FIG. 2: Resulting real  $U(r)$  and imaginary  $W(r)$  potentials compare with those of Paris 99 [8]. The  $NN$  optical potential is defined as  $U(r) - iW(r)$  [7].

# P wave quasi-bound state indications

## Evidence

- $\bar{p}$  atomic level widths in H,  $^2\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$  PS 207
- Radiochemical studies of N-1, Z-1 nuclei in nuclear  $\bar{p}$  capture PS 203, 208

# Resonances

$^{13}P_0$

- Paris model resonances

TABLE IV: Close to threshold resonances of the present model. The numbers in parenthesis correspond to the  $^{11}P_1$  resonance of Paris 99. The  $^{13}P_0$  and  $^{13}P_1$  resonances have identical positions in the Paris 99 model. There is no  $^{33}P_0$  resonance in the Paris 99 potential.

| $^{2T+1} 2S+1 L_J$ | $^{11}P_1$  | $^{13}P_0$ | $^{13}P_1$ | $^{33}P_0$ |
|--------------------|-------------|------------|------------|------------|
| Mass (MeV)         | 1877 (1872) | 1876       | 1872       | 1871       |
| Width (MeV)        | 26 (12)     | 10         | 20         | 21         |

- „atomic”  $^{13}P_0$  disagrees with all models
- may give nuclear states of antiproton

