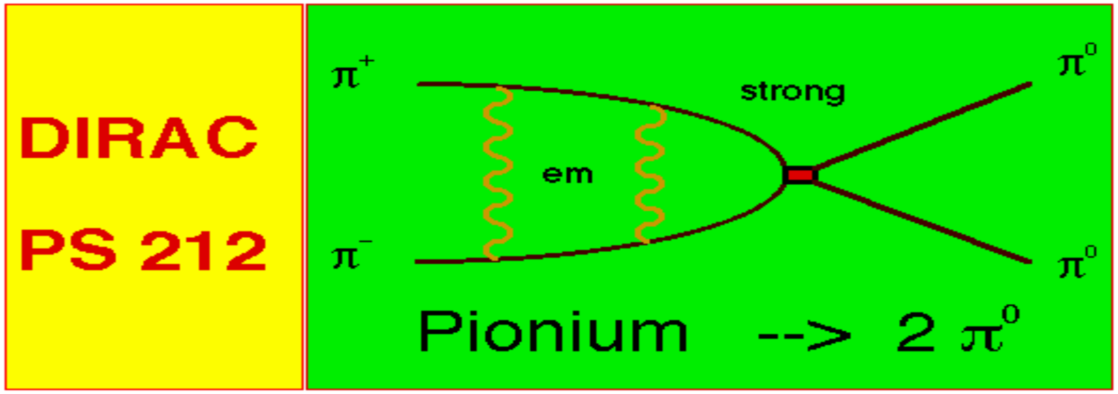
Double-exotic dimeson atoms and low-energy QCD

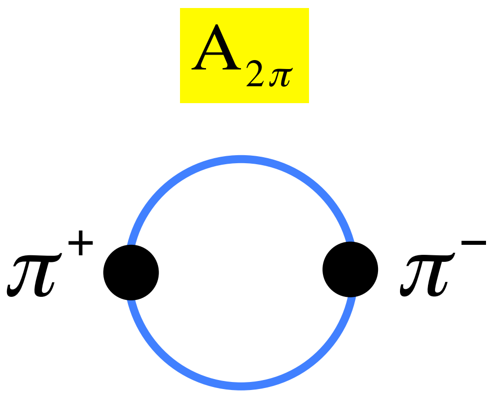
LIFETIME MEASUREMENT OF MESONIUM



Collaboration DIRAC (DImeson Relativistic Atom Complex) → cern.ch/DIRAC
(~70 people from Czechia, Italy, Japan, Romania, Russia, Spain, Switzerland)

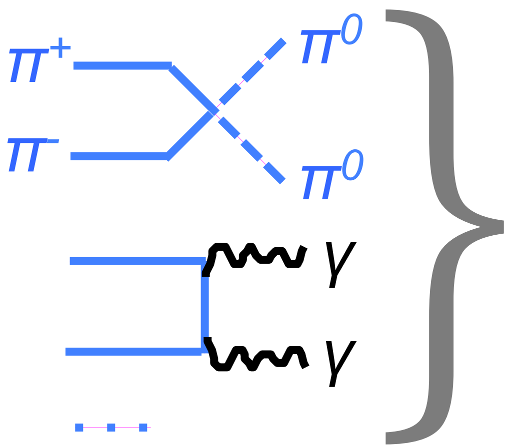
- Mesonium & lifetime of O(femtosecond)
- Mesonium detection / lifetime measurement
- Magnetic double-arm spectrometer @ CERN PS
- $\pi\pi$ & πK atom lifetime / scattering length measurement
- Long-lived $\pi\pi$ atom

Mesonium / pionium



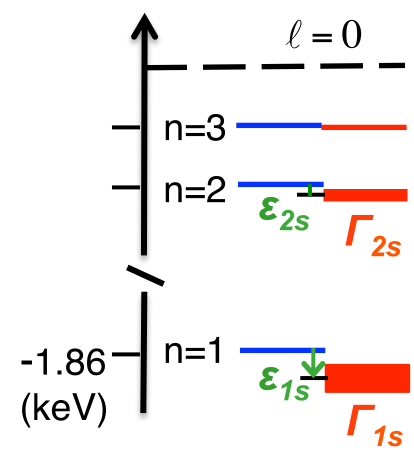
- Reduced mass: $\mu = \frac{1}{2} M_\pi \approx 70\,\text{MeV}$
- Bohr radius: $r_B = (\alpha\mu)^{-1} = 387\,\text{fm}$
- Bohr momentum: $p_B = (\alpha\mu) \approx 0.5\,\text{MeV}$
- Binding energy: $E_B^C = -\frac{1}{2}\alpha^2\mu = -1.86\,\text{keV}$

Decay modes:

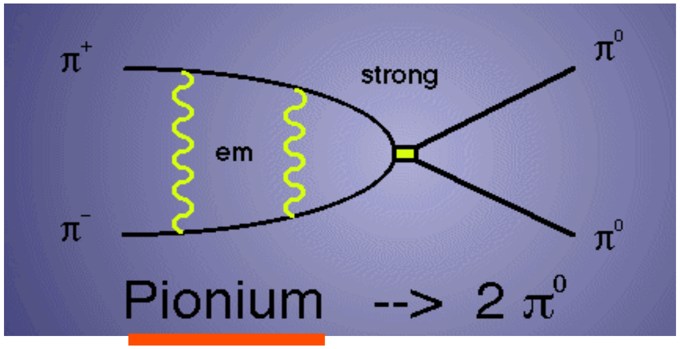


$$\Gamma_{1S} \approx 0.2\,\text{eV} \approx (3\,\text{fs})^{-1}$$

STRONG => level shift ε and width Γ



Mesonium lifetime



$$\downarrow$$

$$A_{2\pi}(J^{PC} = 0^{++})$$

$$\tau^{-1} \propto \underbrace{\left[a_0 - a_2\right]}_{\Delta}{}^2$$

$$\frac{\delta\tau}{\tau} = 10\% \quad \Rightarrow \quad \frac{\delta\Delta}{\Delta} = 5\%$$

Motivation for DIRAC

Experimental aspects	Theoretical aspects
♦ atomic physics @ high energy ♦ measure lifetime @ order of 10^{-15} s	♦ study of QCD @ low energy ♦ $\pi\ \pi$ scattering: theory ahead experiment

QCD @ low energy

QCD @ low energy (non-perturbative/confinement):

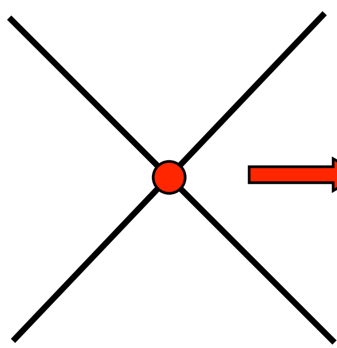
→ other DOF: **(q, g)** => (**meson**, baryon)

⬇

Goldstone Boson physics

EFT / ChPT with precise predictions !

ππ scattering



„Coupling constant“:

$M_\pi^2 \sim m_q \cdot \langle 0|\bar{q}_R q_L|0\rangle$

explicit *spontaneous* ***symmetry breaking***

$m_q \rightarrow 0 \Rightarrow$

no reaction

$\langle 0|\bar{q}_R q_L|0\rangle \rightarrow 0 \Rightarrow$

QCD @ low energy

Physics behind DIRAC:
$\pi^+\pi^-$ atom (pionium) ⇔ QCD & EM ⊕ interplay

- ♦ non-perturbative QCD
- ♦ QCD ground state / QCD vacuum?
- ♦ Γ(pionium) $= f(a_i)$, a_i =«scattering» lengths

Pionium lifetime

...in the framework „**QCD including photons**“:

- Workshops „HadAtom01“, hep-ph/0112293 and „HadAtom02“, hep-ph/0301266
- J.Gasser, V.Lyubovitskij, A.Rusetsky, A.Gall, „Decays of the $\pi^+\pi^-$ atom“, PR D64 (2001) 016008:

$$\Gamma_{2\pi^0} = \frac{2}{9}\alpha^3 p^* A^2 (1+K) = \Gamma_{2\pi^0}^{\text{Deser}} (1+\delta_\Gamma)$$

DIRAC ↓

$$A = \underbrace{(a_0 - a_2)}_{\text{DIRAC}} + \varepsilon$$

$p^* \ldots \pi^0$ momentum

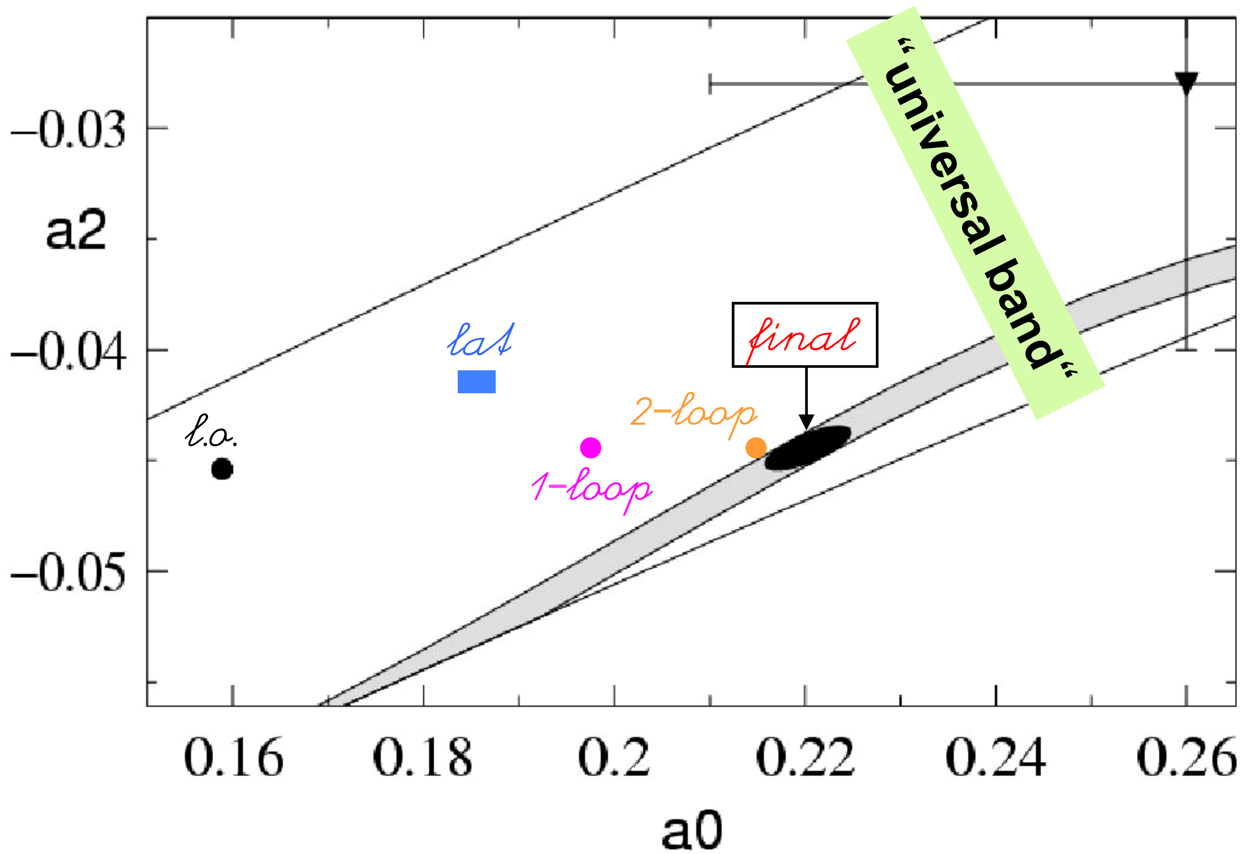
$$\left.\begin{array}{l} \text{For } a_0 - a_2 = 0.265 \pm 0.004 \\ \text{and } \varepsilon = (6.1 \pm 1.6)\cdot 10^{-3} \\ \text{and } K = (1.15 \pm 0.03)\cdot 10^{-2} \end{array}\right\} \rightarrow \delta_\Gamma = 0.058 \pm 0.012$$

$$\Longrightarrow \tau = (2.9 \pm 0.1)\, fs$$

$$\rightarrow c\tau \approx 1\,\mu m$$

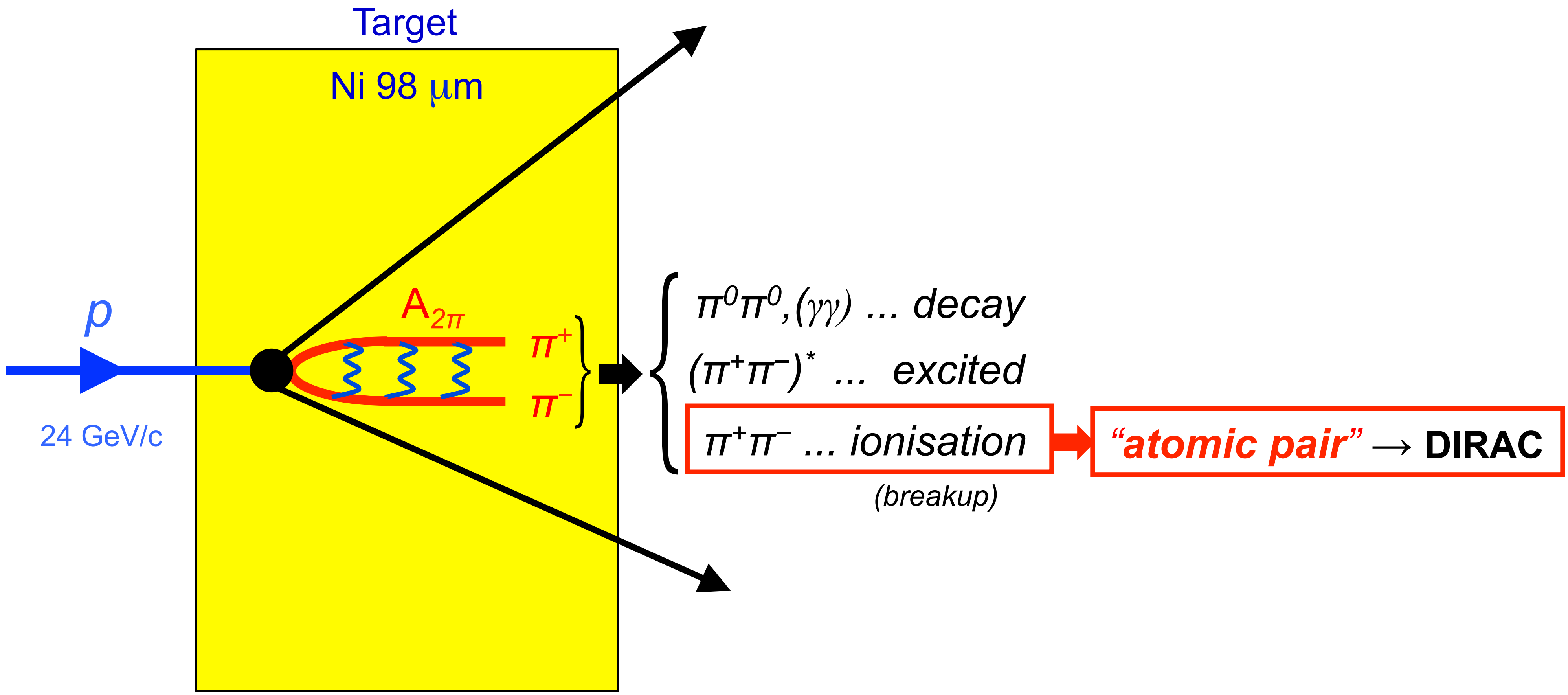
S-wave scattering lengths: (a_0, a_2) plane

- Roy equations only admit solutions in the „universal band“.
- ● ... *tree* result (Weinberg)
- ▭ ... low energy theorem for scalar radius
- black ellipse represents *final* result: Roy+ChPT.
- ■ ... *lattice* QCD result



Reference: G.Colangelo, J.Gasser and H.Leutwyler, Nucl.Phys. B603 (2001) 125

Production of pionium ($A_{2\pi}$)



$A_{2\pi}$ generated in nS-states: $|\Psi_{nS}(0)|^2 \propto \frac{1}{n^3}$ [1S: 83%; 2S: 10%, ...]

Detection of pionium

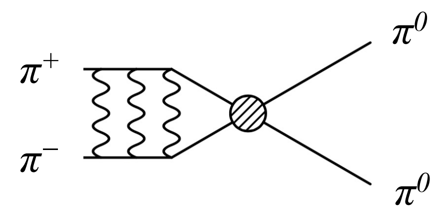
Fate of produced relativistic $A_{2\pi}$ $[\gamma \approx 17]$

Use thin & dense target ⇒ ~100μm Ni:

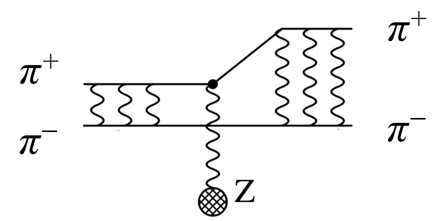
1) **Annihilation** $A_{2\pi} \rightarrow \pi^0\pi^0 \; (\tau \approx 3\,fs)$:

→ decay length $\lambda_{1s} \approx 17\mu m \sim \lambda_{int}(1s)$:

$P_{ann} \approx 0.38$

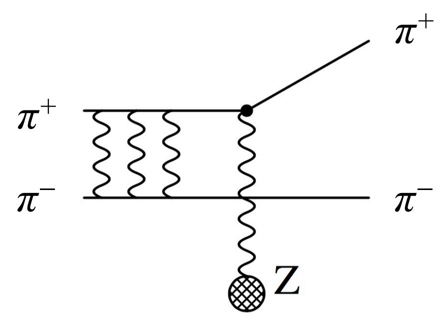


2) **Excitation** . . . . . discrete states

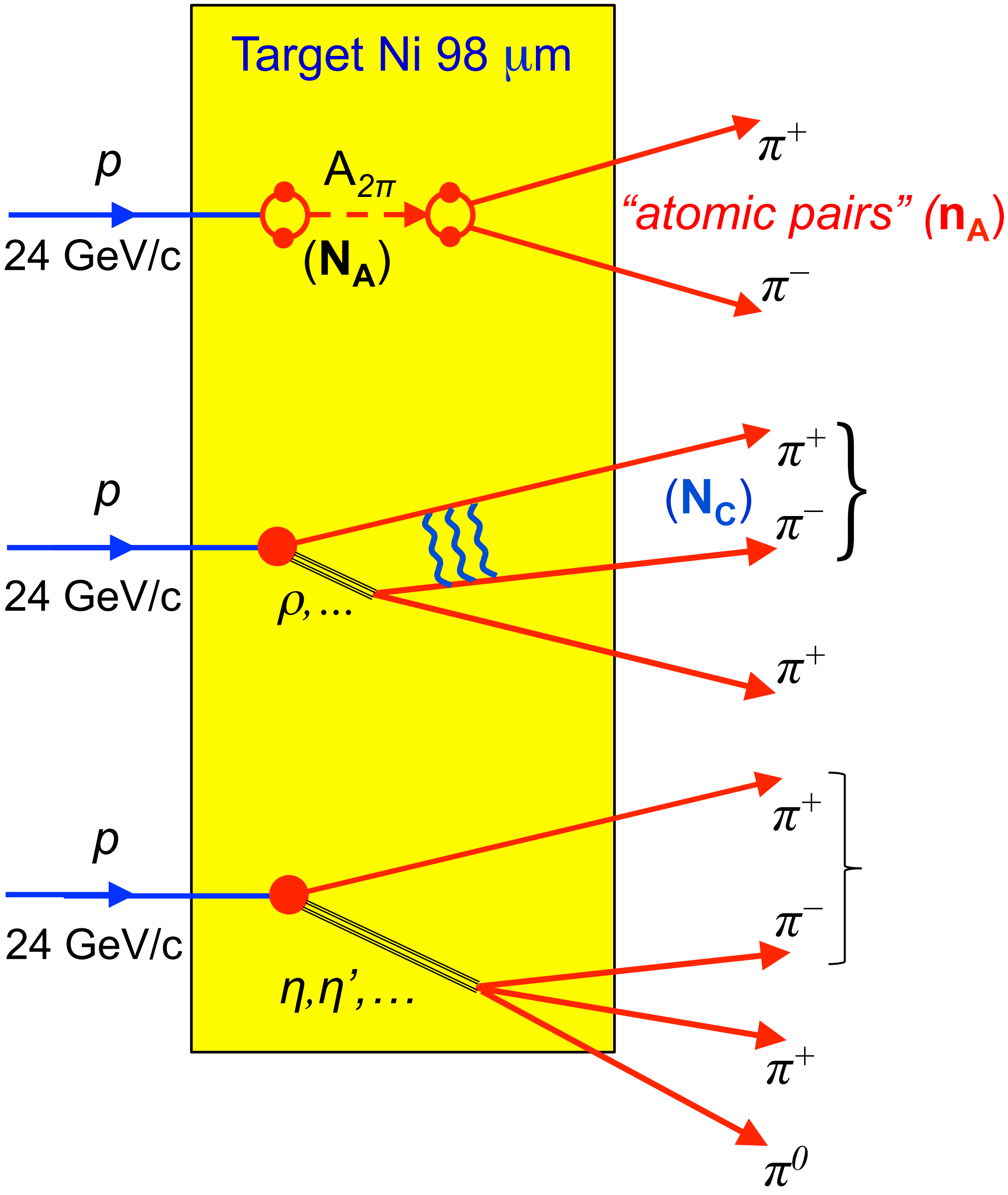


3) **Ionisation** → ***„atomic pairs"*** : $P_{br} \approx 0.47$

- Q(CM) < 3 MeV/c
- $E_+ = E_-$ (3‰) & Θ_{+-} (mrad) ~ $6/\gamma \approx 0.35$



Scheme: Atom observation / lifetime measurement



($\tau_{A2\pi}$ ... *too small to be measured directly*)

E. m. interaction of $A_{2\pi}$ in target:

$A_{2\pi} \rightarrow \pi^+\pi^-$

$Q < 3$ MeV/c, $\Theta_{lab} < 3$ mrad

Coulomb *from short-lived sources:*

$N_C(Q<Q_0) \Rightarrow N_A$ $\Rightarrow$ Breakup probability: $P_{br}(\tau) = n_A / N_A$

non-Coulomb *from long-lived sources*

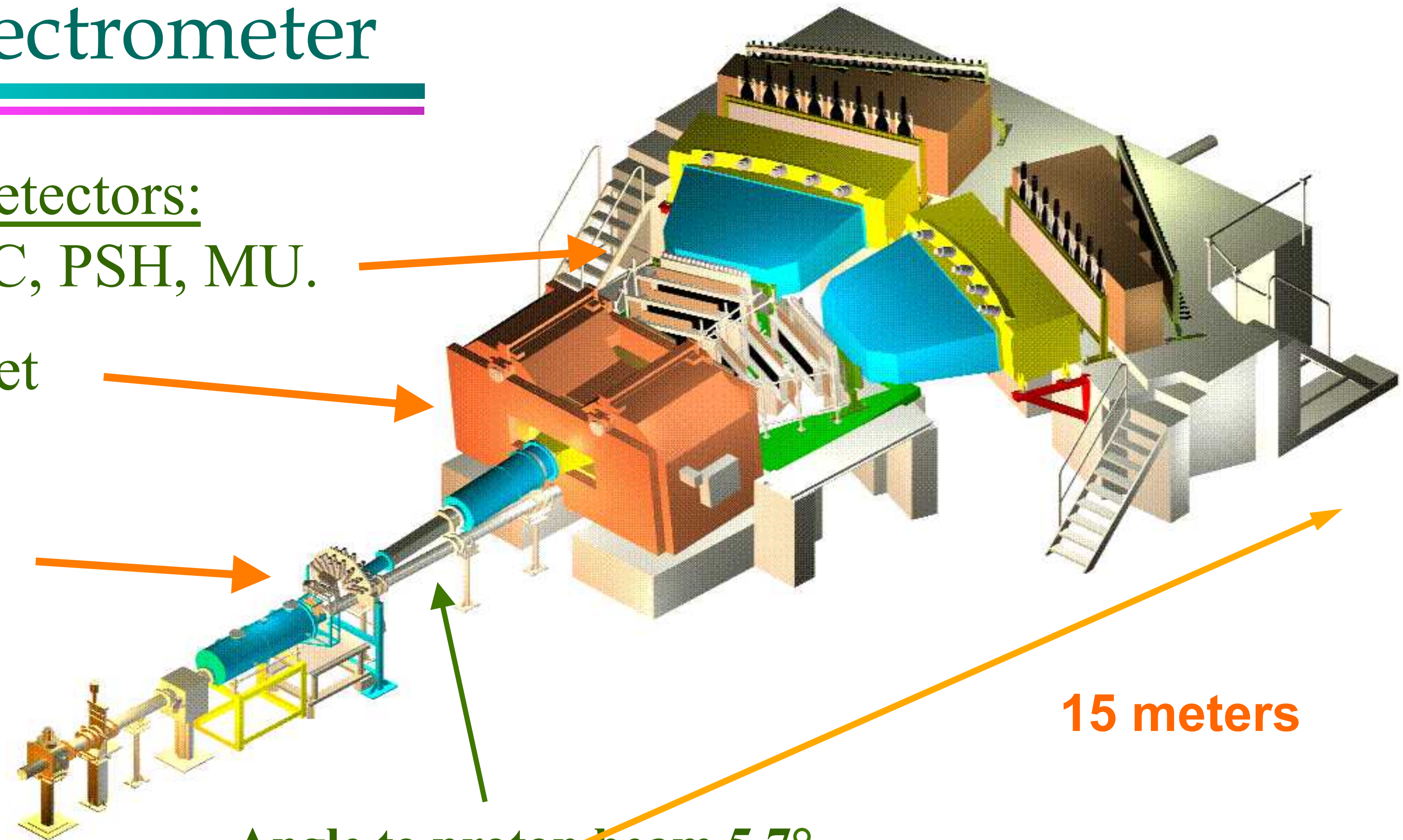
Double-arm spectrometer

[CERN-PH-EP-2015-147]

Downstream detectors:
DC, VH, HH, C, PSH, MU.

Bending magnet

Upstream detectors:
MSGC, SFD, IH.



15 meters

Angle to proton beam 5.7°

Proton beam

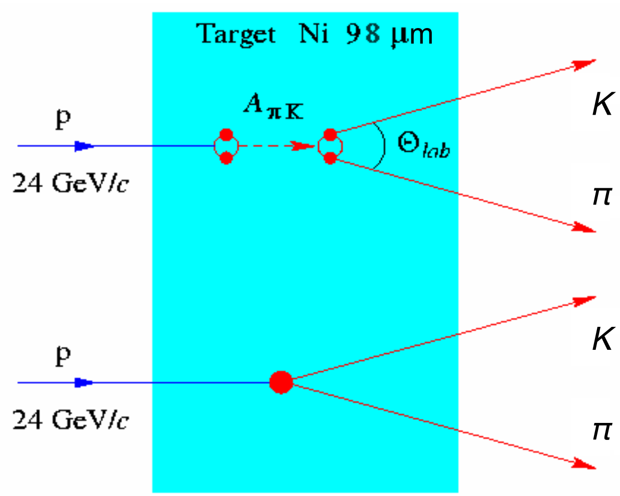
Setup features:

angle to proton beam:	$\Theta = 5.7^{\circ}$
channel aperture:	$\Omega = 1.2 \cdot 10^{-3}$ sr
dipole magnet:	1.65T & 2.2 Tm
momentum range:	$1.2 \leq p \leq 7$ GeV/c
rel. mom. resolution:	$\sigma_{QT} = 0.10$ MeV/c
	$\sigma_{QL} = 0.55$ MeV/c

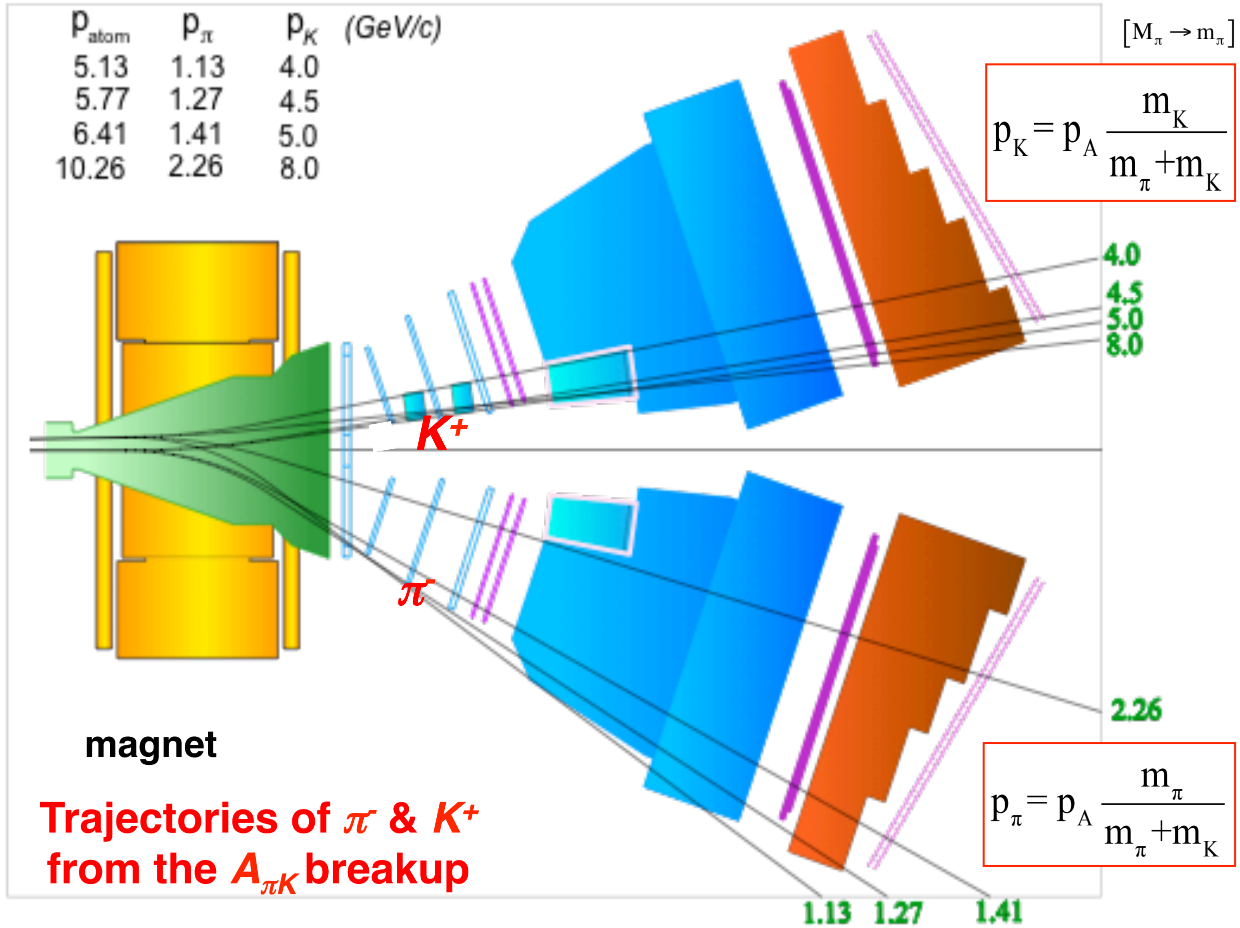
DIRAC setup

πK atom

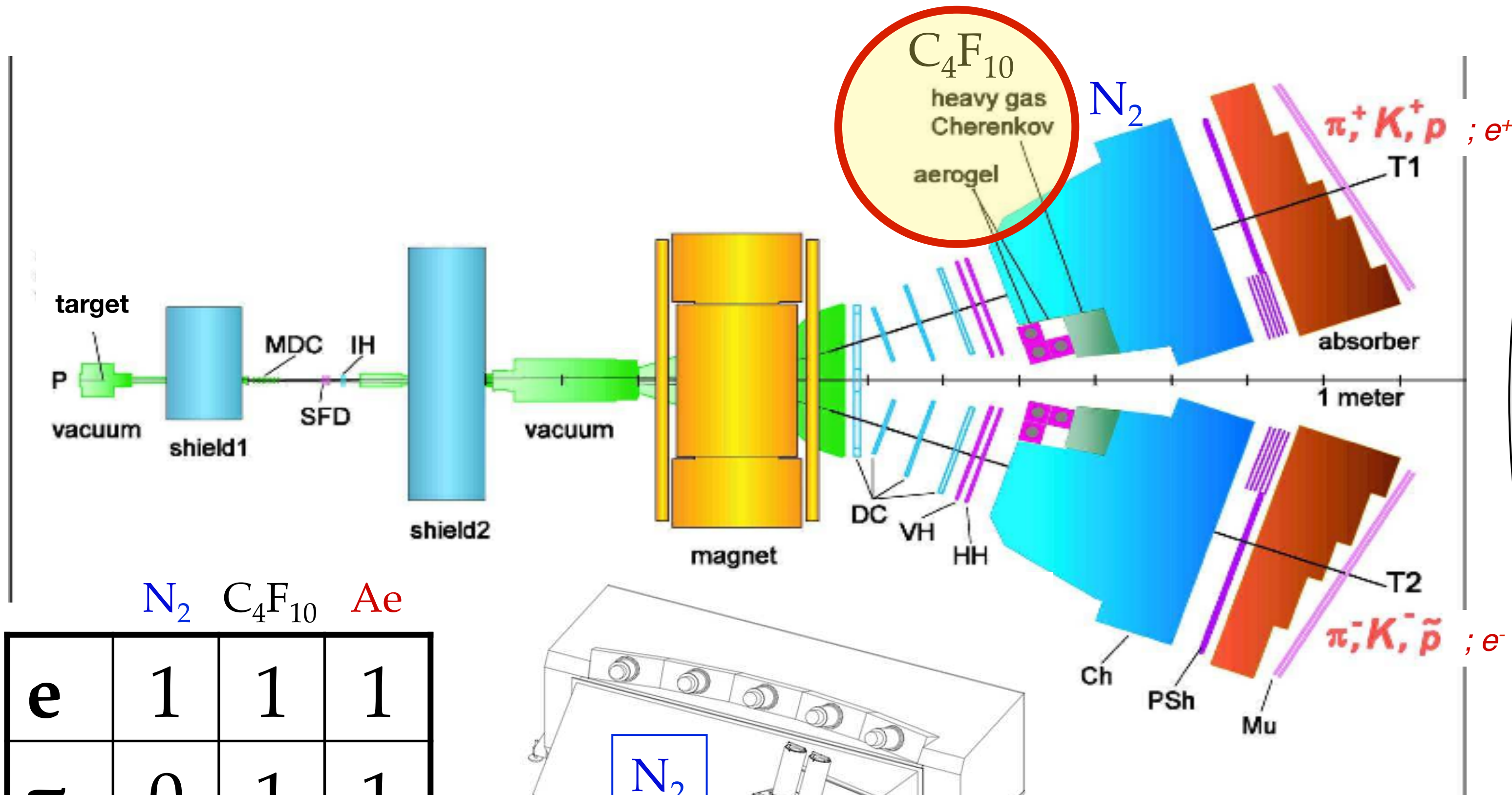
(asymmetric system)

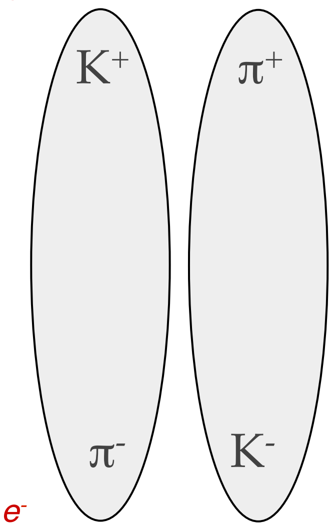


- kaon detection
- phase space modification
- *e – π separation*
- *π – K separation*
- *K – p separation*

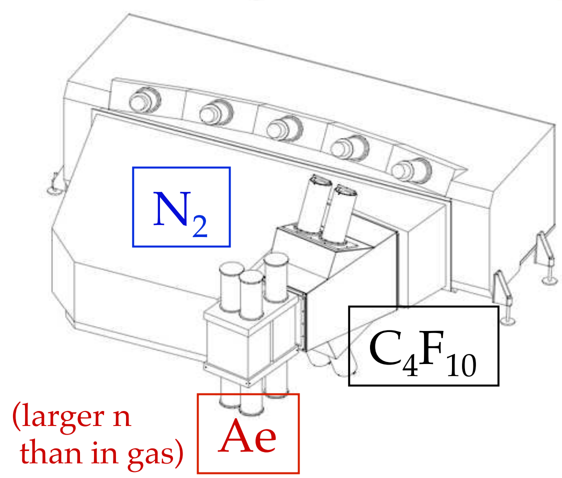


DIRAC setup

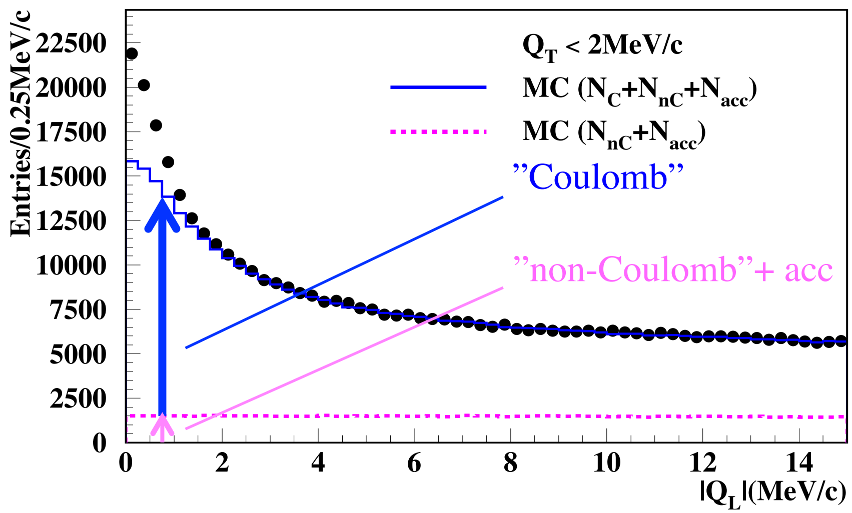


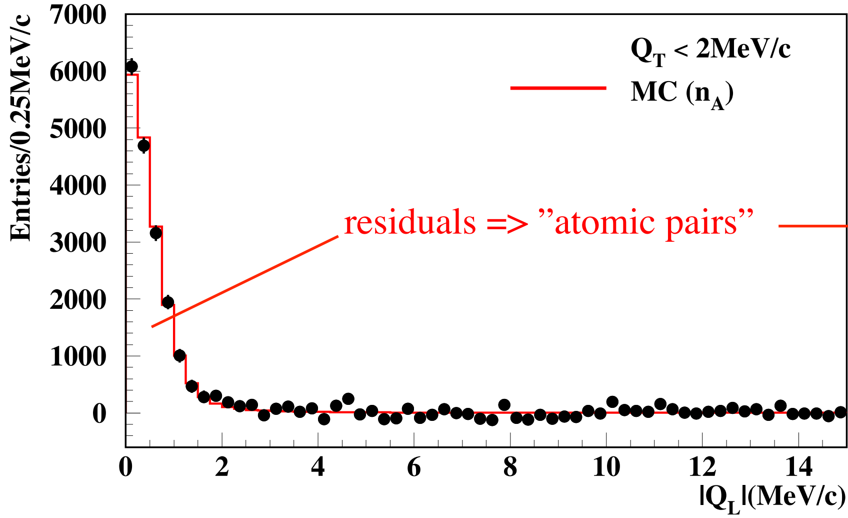


	N_2	C_4F_{10}	Ae
e	1	1	1
π	0	1	1
K	0	0	1
p	0	0	0



Data analysis ⇒ "atomic pairs"





Selection and analysis:

- prompt $\pi^+\pi^-$ pairs: $|\Delta t_{left\text{-}right}| < 0.5$ ns
- simulation:
  - · parametrization of nC (phase space) and C (Gamow-Sommerfeld-Sakharov factor A_C)
  - · MC of detector response
- χ^2-analysis in (Q_T,Q_L) plane

$$A_C(Q) = \frac{\frac{2\pi\alpha m_\pi}{Q}}{1 - e^{-\frac{2\pi\alpha m_\pi}{Q}}}$$

Result (Nickel 2001-2003)**:**

$n_A = 21227 \pm 407$

$N_C \big|_{Q_T < 5\ \mathrm{MeV/c}} = 1‘871‘377 \pm 8613$

⇒ $\mathbf{P_{br} \approx 0.46}$ (± < 3%) ... breakup

(see next slide)

Pionium lifetime measurement

$$P_{br}^{exp}\left(\tau_{A_{2\pi}}\right) = \frac{n_A}{N_A}$$

$\leftarrow$ # $A_{2\pi}$ ionized $|_{measured}$

$\leftarrow$ # $A_{2\pi}$ produced $|_{calculated}$

There exists a precise relation between **N_A** (bound state) and the total number N_C of Coulomb pairs (free state) with small Q:

$$N_A = K(Q_0)\ N_C(Q<Q_0)$$

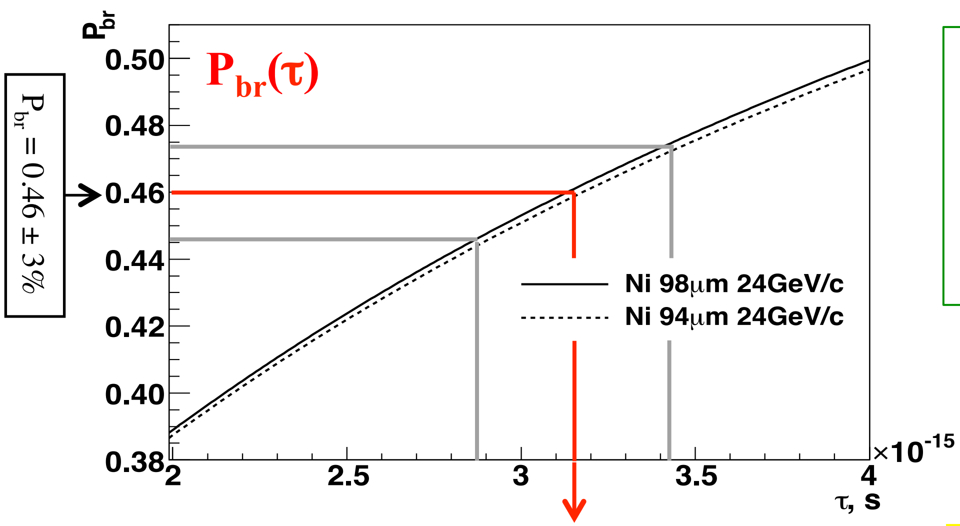
$\{K^{th} \approx 0.6 \ldots Q < 2\text{MeV/c}\}$

[L.Nemenov, SJNP 41 (1985) 629]

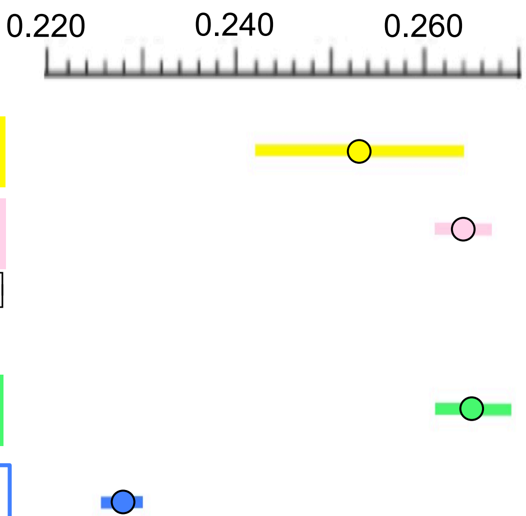
$\Rightarrow$ $P_{br}^{exp}\left(\tau_{A_{2\pi}}\right)$ is compared to $P_{br}^{th}\left(\ell, Z, \rho; p_{A_{2\pi}}, \tau_{A_{2\pi}}\right)$:

Pionium lifetime measurement

Breakup probability → lifetime τ (→ scattering length):



The solution of the transport equations provides a 1-to-1 dependence of the measured breakup probability P_{br} on the pionium lifetime τ.



DIRAC, PLB704 (2011) 24: $\tau = (3.15 \pm 0.28)\, fs$ → $|a_0 - a_2| = (0.253 \pm 0.011)\, m_\pi^{-1}$

NA48/2, EPJC70 (2010) 635 [K_{e4} and $K_{3\pi}$ decay]: → $a_0 - a_2 = (0.264 \pm 0.003)\, m_\pi^{-1}$

$[0.2639 \pm 0.0020|_{stat} \pm 0.0015|_{syst}]$

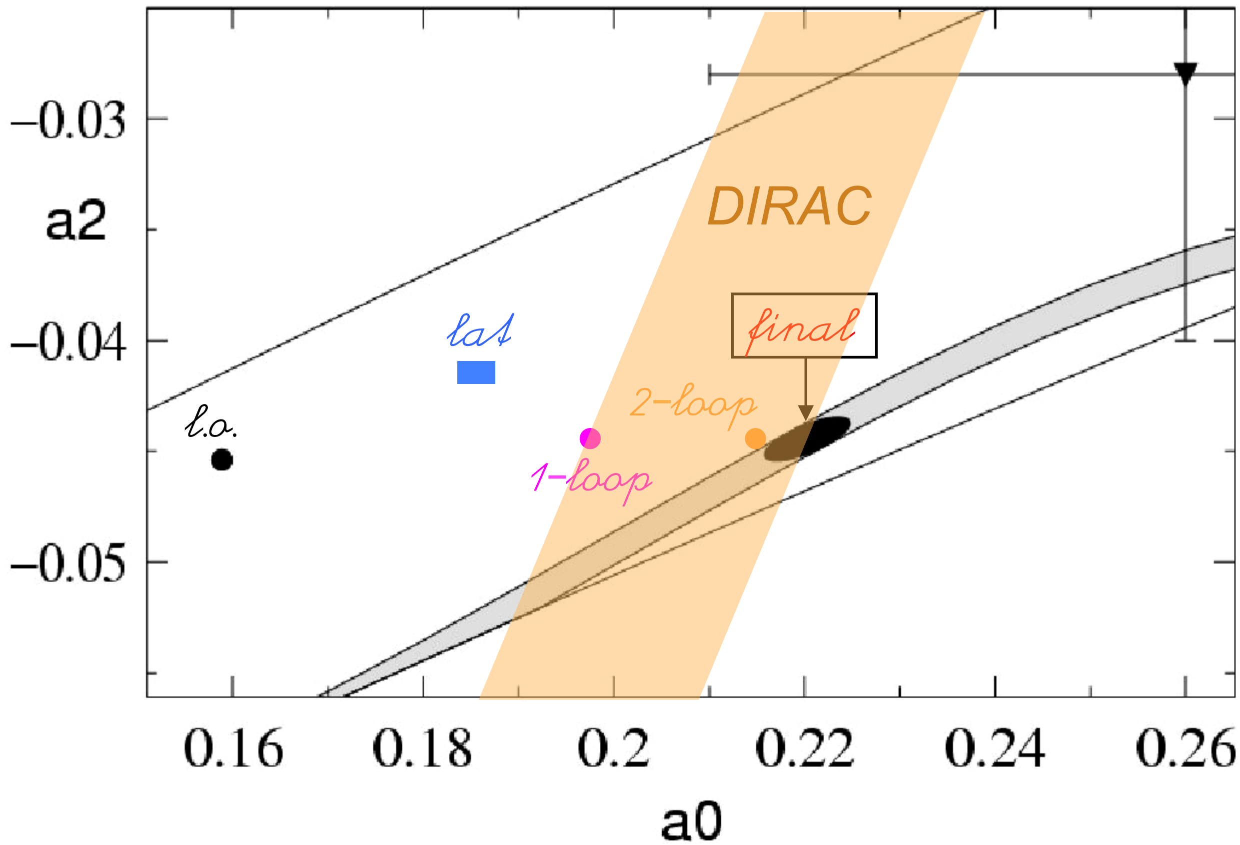
ChPT (J. Gasser et al., PRD64 (2001) 016008)**:**

$\Gamma = \tau^{-1} \propto |a_0 - a_2|^2 \rightarrow \tau = (2.9 \pm 0.1)\, fs$ ← $a_0 - a_2 = (0.265 \pm 0.004)\, m_\pi^{-1}$

Lattice (Z. Fu, Com. Theor. Phys. 57 (2012) 78): → $a_0 - a_2 = (0.228 \pm 0.002)\, m_\pi^{-1}$

S-wave scattering lengths: (a_0 , a_2) plane

- Roy equations only admit solutions in the „universal band“.
- ● ... *tree* result (Weinberg)
- ▭ ... low energy theorem for scalar radius
- black ellipse represents *final* result: Roy+ChPT.
- ▬ ... *lattice* QCD result



Reference: G.Colangelo, J.Gasser and H.Leutwyler, Nucl.Phys. B603 (2001) 125

πK atom

Electromagnetic force:

$E_B = E(1S) = -\alpha^2\mu / 2 = -2.9$ keV

$r_B = r(1S) = 1 / \alpha\mu = 248$ fm

↓

μ = reduced mass = 109 MeV

Strong force:

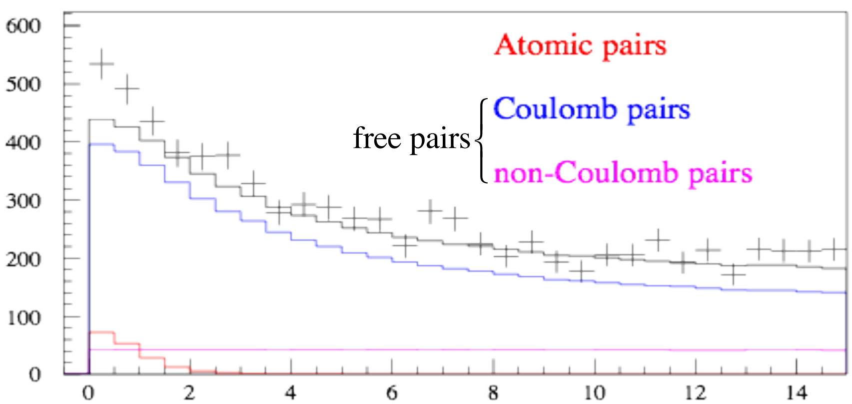
- $\Delta E \approx -10$ eV … stronger binding
- $\pi^- K^+$ ***decays*** => $\pi^0 K^0$: $\tau = (3.5 \pm 0.4)$fs

($\pi^+ K^-$ ***decays*** => $\pi^0 \overline{K^0}$)

[For details: J. Schweizer, PLB587 (2004) 33]

First evidence for πK-atom ***observation*** in DIRAC: PLB674 (2009) 11

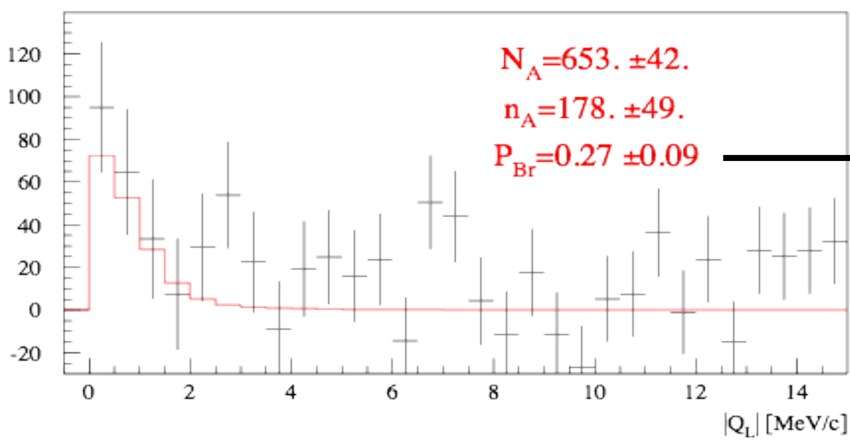
$\pi^{+-}K^{-+}$ atom lifetime



$|Q_L|$ distribution

[Ni target (≈100 μm), run 2008-2010]

2-dimensional (Q_T,Q_L) fit of data ($Q_T < 4$ MeV/c)



Difference: experimental / free pair distribution

$$\tau = \left(2.5\,^{+3.0}_{-1.8}\Big|_{tot}\right) fs \rightarrow \left|a_0^-\right| m_\pi = \tfrac{1}{3}\left|a_{1/2} - a_{3/2}\right| m_\pi = 0.11^{+0.09}_{-0.04}$$

DIRAC, PLB735 (2014) 288

Roy-Steiner dispersion:
P. Buettiker et al.,
EPJ C33 (2004) 409

$$\rightarrow a_0^- m_\pi = 0.090 \pm 0.005$$

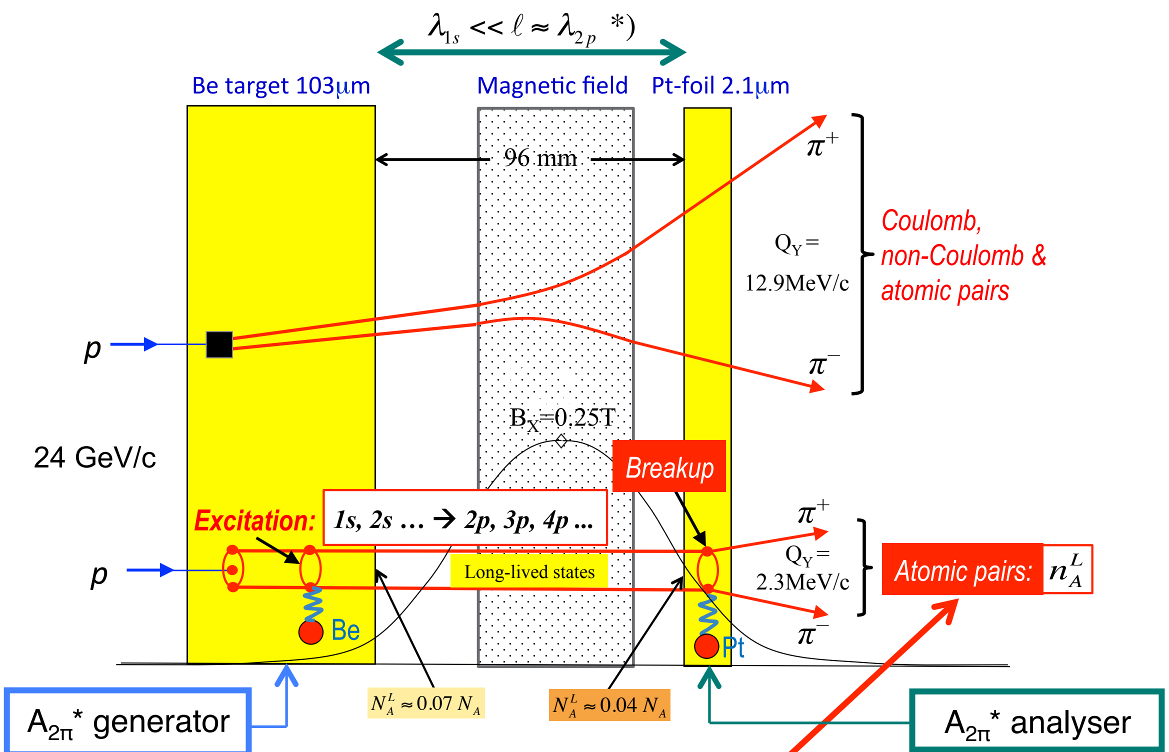
Long-lived $\pi^+\pi^-$ atom ($A_{2\pi}{}^*$ or $A_{2\pi}{}^L$)

DIRAC also aims to investigate $A_{2\pi}$ level splitting ("Lamb shift") and therewith to determine – besides $|a_0 - a_2|$ already measured – another combination of $\pi\pi$ scattering lengths $2a_0 + a_2$.

According to Nemenov (PLB 2001, NPA 2002), there exists a method to extract an experimental value for $E_{2s} - E_{2p} = f(2a_0 + a_2)$ (in general terms: $E_{ns} - E_{np}$) by tracking the dependence of the long-lived $A_{2\pi}$* ($l \geq 1$) decay probability on an applied electromagnetic field.

$A_{2\pi}{}^{*}$ observation

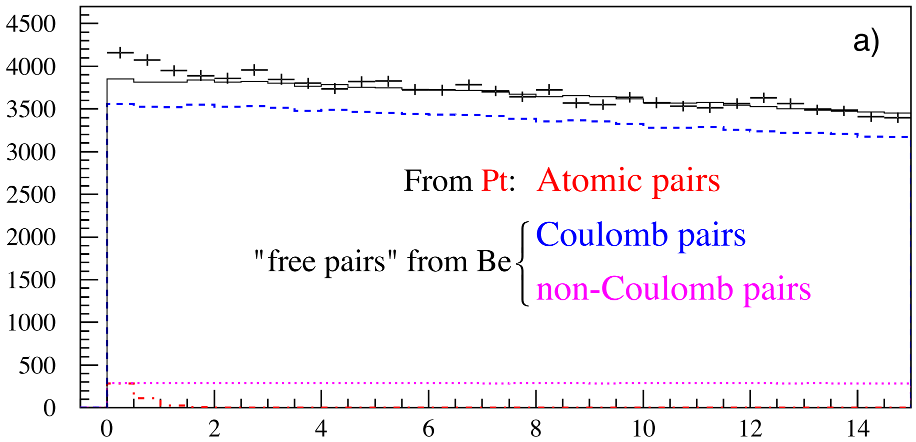
The decay $A_{2\pi}$***(np) → 2π⁰** is forbidden by angular momentum conservation. The lifetime of $A_{2\pi}$* in the 2p-state is given by the 2p–1s radiative transition (τ_{2p}≈12ps) with the subsequent annihilation from the 1s-state into $2\pi^0$ (τ_{1s}≈3fs).



Long-lived $A_{2\pi}$* mostly break up in **Pt**, yielding additional "atomic pairs" **$\pi^+\pi^-$**.

*) For $\gamma(A_{2\pi}) \approx 17$: decay lengths $\lambda_{1s} \approx 17\mu m$ and $\lambda_{2p} \approx 59mm$

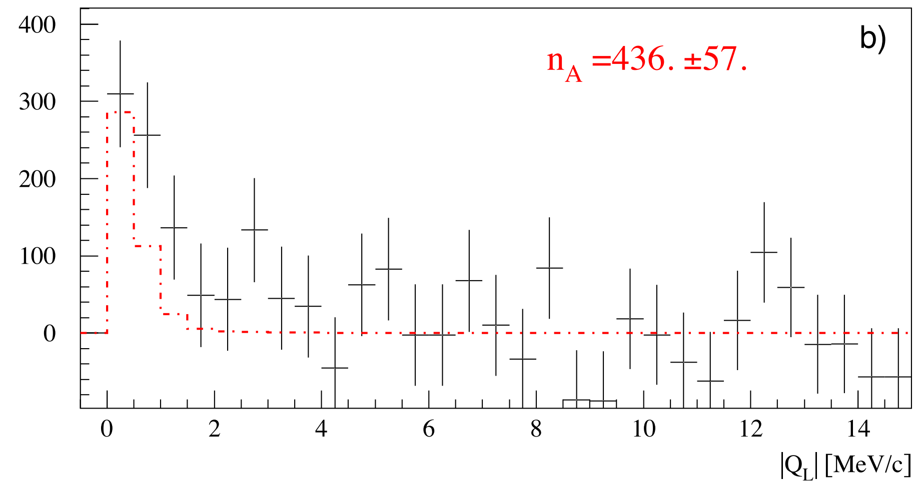
Long-lived $A_{2\pi}{}^*$



$|Q_L|$ distribution

[Be target (≈100 μm), run 2012]

2-dimensional (Q_T,Q_L) fit of data ($Q_T < 2$ MeV/c)



Difference: experimental / free pair distribution:

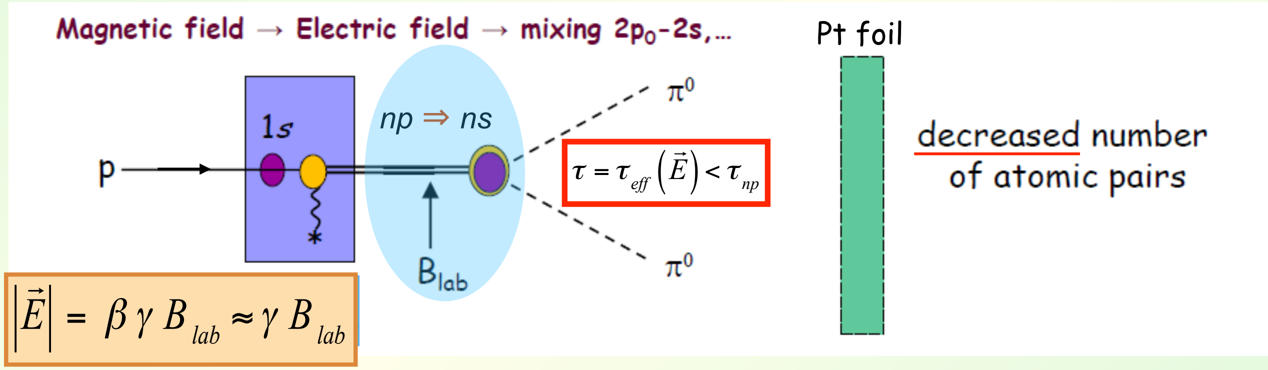
atomic pairs from $A_{2\pi}{}^*$ breakup: $n_A^L = 436 \pm 61|_{tot}$

(7σ)

DIRAC, PLB751 (2015) 12

Long-lived $A_{2\pi}{}^*$

The exertion of a **magnetic field** (=> **electric field** => **Stark effect**) on the $A_{2\pi}$* atom opens the possibility to measure the **2*s* – 2*p* energy splitting** by tracking the field dependence of the annihilation or decay probability.



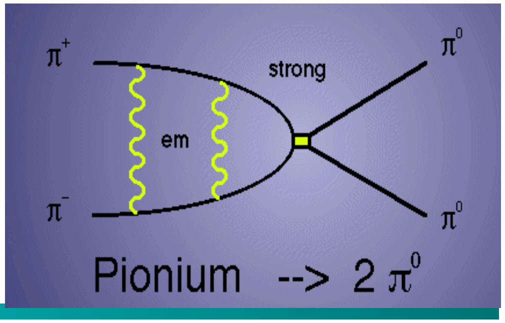
$$|\vec{E}| = \beta \gamma B_{lab} \approx \gamma B_{lab}$$

Electric field controlled $A_{2\pi}$* lifetime $\boldsymbol{\tau_{eff}}$ => "Lamb shift" $\boldsymbol{\Delta E_{2s\text{-}2p}}$:
=> S-wave pion-pion scattering length combination $\boldsymbol{2a_0 + a_2}$

DIRAC PS212

Results from DIRAC

- summary -



- The DIRAC 2-arm spectrometer provides a pair relative momentum (Q) resolution of < 1 MeV/c for Q < 30 MeV/c.

- The extracted signal sample consists of >40000 dissociated $\pi^+\pi^-$ (atomic pairs) from $\pi^+\pi^-$ atoms $A_{2\pi}$.

- The ππ analysis of Ni (2001−2003) data leads to

  → pionium ($A_{2\pi}$) lifetime: $\tau = \left(3.15^{+0.20}_{-0.19}\left[stat\right] \pm^{+0.20}_{-0.18}\left[syst\right]\right) fs$ th: $\left(2.9 \pm 0.1\right)$

  → ππ scattering length: $\left|a_0 - a_2\right| = \left(0.253 \pm 0.011\right) m_\pi^{-1}$ 0.265 ± 0.004

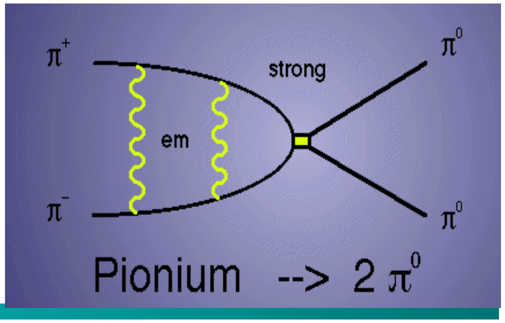
- The πK analysis of Ni data (178±49 atomic pairs) leads to

  → πK atom ($A_{\pi K}$) lifetime: $\tau = \left(2.5^{+3.0}_{-1.8}\right) fs$ th: $\left(3.5 \pm 0.4\right)$

  → πK scattering length: $\left|a_0^-\right| = \left(0.11^{+0.09}_{-0.04}\right) m_\pi^{-1}$ 0.090 ± 0.005

Results from DIRAC

- summary -



- First observation of long-lived $\pi^+\pi^-$ atoms ($A_{2\pi}$*):

  → number of atomic pairs from $A_{2\pi}$* breakup: 436±61 (7σ)
  [→ study of „Lamb shift“ in $A_{2\pi}$* → scattering length $\mathbf{2a_0+a_2}$]

- Our future goals:
  1. improve on statistics → analyse full $\pi^+\pi^-$ sample ($n_A \sim 45000$)
  2. improve on systematics:
     → different analysis procedures
     → detailed study of multiple scattering
  3. $A_{2\pi}$ & $A_{\pi K}$ investigation at CERN SPS (letter of intent?):
     → yield ↑ at p momentum 450 GeV/c (4^0) cf. to 24 GeV/c (5.7^0):

$A_{2\pi}$	17
$A_{\pi K}$	∼30