Results and scientific plans of the DIRAC experiment at CERN

Leonid Nemenov

11 November  2010
1. Request for data taking in 2011 to observe the $A_{2\pi}$ long-lived states. These will permit to measure the Lamb shift and the new combination $2a_0 + a_2$ of the $\pi^+\pi^-$ scattering lengths.

2. Data processing of the 2008 – 2010 runs to observe $K^+\pi^-$ atoms, to measure their lifetime and $|a_{1/2}-a_{3/2}|$ combination of the scattering lengths.

3. The multiple scattering measurement in $Be, Al, Ti, Ni$ and $Pt$ with better than 1% accuracy. The data will permit to obtain the $A_{2\pi}$ lifetime with better than 6% and $|a_0-a_2|$ with better than 3% precisions.

4. The evaluation of the $K^+K^-$ and $\pi\mu$ atom production cross section based on the 2008-2010(2011) experimental data.
DIRAC plan beyond 2011

1. The preparation of the DIRAC Collaboration for the new experiment at SPS

2. Presentation in 2013 of a Letter of Intent:

   “Investigations of the $\pi\pi$, $\pi K$ and other exotic atoms at the SPS proton beam to check the precise low energy QCD predictions”
Upgraded DIRAC experimental setup

MDC, 18 planes

shield1

vacuum

P

single and multilayer targets

shield2

SFD

MDC

IH

vacuum

magnet

heavy gas Cherenkov

aerogel

1 meter

T1

T2

π⁺, K⁺, p

π⁻, K⁻, \bar{\rho}

π⁺, p, K⁺

π⁻, \bar{\rho}, K⁻

Ch

PSh

Mu
1. Request for data taking in 2011 to observe the $A_{2\pi}$ long-lived states. These will permit to measure the Lamb shift and the new combination $2a_0 + a_2$ of the $\pi^+\pi^-$ scattering lengths.
1.1 Energy splitting between np - ns states in $\pi^+ \pi^-$ atom

\[ \Delta E_n \equiv E_{ns} - E_{np} \]

\[ \Delta E_n \approx \Delta E_{n}^{\text{vac}} + \Delta E_n^s \]

\[ \Delta E_n^s \sim 2a_0 + a_2 \]

For \( n = 2 \)

\[ \Delta E_2^{\text{vac}} = -0.107 \text{ eV} \quad \text{from QED calculations} \]

\[ \Delta E_2^s \approx -0.45 \text{ eV} \quad \text{numerical estimated value from ChPT} \]

\[ a_0 = 0.220 \pm 0.005 \]

\[ a_2 = -0.0444 \pm 0.0010 \]

\[ (2001) \quad G. \ Colangelo, \ J. \ Gasser \ and \ H. \ Leutwyler \]

\[ \Rightarrow \quad \Delta E_2 \approx -0.56 \text{ eV} \]

(1979) A. Karimkhodzhaev and R. Faustov

(1983) G. Austen and J. de Swart

(1986) G. Efimov et al.

(1999) A. Gashi et al.

(2000) D. Eiras and J. Soto


A. Rusetsky, priv. comm.
For \( p_A = 4.5 \) GeV/c and \( \gamma = 16.1 \)

\[
\begin{align*}
\tau_{1s} &= 2.9 \times 10^{-15} \text{ s} , & \lambda_{1s} &= 1.4 \times 10^{-3} \text{ cm} \\
\tau_{2s} &= 2.3 \times 10^{-14} \text{ s} , & \lambda_{2s} &= 1.1 \times 10^{-2} \text{ cm} \\
\tau_{2p} &= 1.17 \times 10^{-11} \text{ s} , & \lambda_{2p} &= 5.7 \text{ cm} , \lambda_{3p} \approx 19 \text{ cm} , \lambda_{4p} \approx 43 \text{ cm}
\end{align*}
\]

Observation of the \( A_{2\pi} \) long-lived states using the breaking-up foil.
1.3 Metastable Atoms

Probabilities of the $A_{2\pi}$ breakup (Br),
Total production yield of the long-lived states: $\Sigma(l \geq 1)$ and
Production yields of the long-lived $p_0$ states by different targets

<table>
<thead>
<tr>
<th>Target Z</th>
<th>Thickness $\mu$m</th>
<th>Br</th>
<th>$\Sigma$ $(l \geq 1)$</th>
<th>2$p_0$</th>
<th>3$p_0$</th>
<th>4$p_0$</th>
<th>$\Sigma$ $(l=1, m=0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be 04</td>
<td>100</td>
<td>4.45%</td>
<td>6.01%</td>
<td>1.18%</td>
<td>0.46%</td>
<td>0.15%</td>
<td>1.90%</td>
</tr>
<tr>
<td>C 06</td>
<td>50</td>
<td>5.00%</td>
<td>6.92%</td>
<td>1.46%</td>
<td>0.51%</td>
<td>0.16%</td>
<td>2.52%</td>
</tr>
<tr>
<td>Al 13</td>
<td>20</td>
<td>5.28%</td>
<td>7.84%</td>
<td>1.75%</td>
<td>0.57%</td>
<td>0.18%</td>
<td>2.63%</td>
</tr>
<tr>
<td>Ni 28</td>
<td>5</td>
<td>9.42%</td>
<td>9.69%</td>
<td>2.40%</td>
<td>0.58%</td>
<td>0.18%</td>
<td>3.29%</td>
</tr>
<tr>
<td>Pt 78</td>
<td>2</td>
<td>18.8%</td>
<td>10.5%</td>
<td>2.70%</td>
<td>0.54%</td>
<td>0.16%</td>
<td>3.53%</td>
</tr>
</tbody>
</table>
1.3 Metastable Atoms
### 1.4 Metastable Atoms

Breakup probability for \( np \) states and for different thickness of the Pt foils.

\( (A_{2\pi} \text{momentum } P_A = 4.5 \text{ GeV/c and } A_{2\pi} \text{ lifetime } \tau = 3 \times 10^{-15}\text{s}) \)

<table>
<thead>
<tr>
<th>Thickness (( \mu \text{m} ))</th>
<th>2p</th>
<th>3p</th>
<th>4p</th>
<th>5p</th>
<th>6p</th>
<th>7p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.0251</td>
<td>0.0520</td>
<td>0.0858</td>
<td>0.1327</td>
<td>0.2035</td>
<td>0.3219</td>
</tr>
<tr>
<td>0.2</td>
<td>0.0559</td>
<td>0.1175</td>
<td>0.1978</td>
<td>0.3001</td>
<td>0.4185</td>
<td>0.5392</td>
</tr>
<tr>
<td>0.5</td>
<td>0.1784</td>
<td>0.3595</td>
<td>0.5537</td>
<td>0.7176</td>
<td>0.8323</td>
<td>0.9043</td>
</tr>
<tr>
<td>1.0</td>
<td>0.4147</td>
<td>0.6895</td>
<td>0.8553</td>
<td>0.9324</td>
<td>0.9667</td>
<td>0.9828</td>
</tr>
<tr>
<td>1.5</td>
<td>0.6084</td>
<td>0.8526</td>
<td>0.9446</td>
<td>0.9765</td>
<td>0.9889</td>
<td>0.9944</td>
</tr>
<tr>
<td>2.0</td>
<td>0.7422</td>
<td>0.9244</td>
<td>0.9743</td>
<td>0.9895</td>
<td>0.9951</td>
<td>0.9975</td>
</tr>
<tr>
<td>3.0</td>
<td>0.8844</td>
<td>0.9739</td>
<td>0.9918</td>
<td>0.9967</td>
<td>0.9985</td>
<td>0.9992</td>
</tr>
<tr>
<td>4.0</td>
<td>0.9415</td>
<td>0.9882</td>
<td>0.9964</td>
<td>0.9986</td>
<td>0.9993</td>
<td>0.9997</td>
</tr>
<tr>
<td>5.0</td>
<td>0.9651</td>
<td>0.9934</td>
<td>0.9980</td>
<td>0.9992</td>
<td>0.9996</td>
<td>0.9998</td>
</tr>
<tr>
<td>10.0</td>
<td>0.9862</td>
<td>0.9975</td>
<td>0.9993</td>
<td>0.9997</td>
<td>0.9999</td>
<td>0.9999</td>
</tr>
</tbody>
</table>
1.5 Metastable Atoms

Atomic pairs from $A_{2n}$ p–st. breakup in 1μ Pt / dist. at 100μ Be production

$n_A^* (\%)

$\Sigma all$

$\Sigma 2p$

$2p$

$3p$

$4p$

$>4p$

$L(cm)$
1.6 Metastable Atoms

Atomic pairs from $A_{2\pi}$ p–st. breakup in $2\mu$ Pt / dist. at $100\mu$ Be production

Graph showing $n_A^*$ (% vs $L$ (cm)) with lines for $\Sigma_{all}$, $\Sigma_p$, $2p$, $3p$, $4p$, and $>4p$. The graph indicates the percentage of metastable atoms as a function of distance ($L$).
1.7 Measurements of the Lamb shift using external magnetic and electric fields


Atom beams are influenced by external magnetic field and the relativistic Lorentz factor

\[ \vec{r} \equiv \text{relative distance between } \pi^+ \text{ and } \pi^- \text{ mesons in } A_{2\pi} \text{ atom} \]

\[ \vec{B}_{\text{Lab}} \equiv \text{laboratory magnetic field} \]

\[ \vec{F} \equiv \text{electric field in the CM system of an } A_{2\pi} \text{ atom} \]

\[ F = \beta \gamma B_{\text{Lab}} \approx \gamma B_{\text{Lab}} \]
1.8 The dependence of $A_{2\pi}$ life time $\tau_{\text{eff}}$ for $2p$-states of the electric field $F$ strength

$$N_A = N_A(0) \cdot e^{-\frac{t}{\tau_{2p}}}$$

$$N_A = N_A(0) \cdot e^{-\frac{t}{\tau_{\text{eff}}}}$$

$$\tau_{\text{eff}} = \frac{\tau_{2p}}{1 + \frac{\left|\xi\right|^2}{4} \cdot \frac{\tau_{2p}}{\tau_{2s}} = \frac{\tau_{2p}}{1 + 120 \left|\xi\right|^2}$$

$$\left|\xi\right|^2 \approx \frac{F^2}{(E_{2p} - E_{2s})^2}$$

where:

$\gamma = 20$, $\left|\xi\right| = 0.025 \Rightarrow \tau_{\text{eff}} = \frac{\tau_{2p}}{1.3}$

$\gamma = 40$, $\left|\xi\right| = 0.05 \Rightarrow \tau_{\text{eff}} = \frac{\tau_{2p}}{2.25}$

$B_{\text{Lab}} = 2$ Tesla
1.9 Resonant enhancement of the annihilation rate of $A_{2\pi}$


In CM System:

\[ \tilde{\omega} = \gamma \omega_{Lab}, \quad \tilde{F} = \gamma \tilde{F}_{Lab} \cdot \cos \tilde{\omega}t, \quad \tilde{\Omega} = \frac{E_{2p} - E_{2s}}{\hbar} \]

at resonance:

\[ \tilde{\Omega} = \tilde{\omega} = \gamma_{res} \cdot \omega_{Lab} \quad \Rightarrow \quad \gamma_{res} = \frac{\tilde{\Omega}}{\omega_{Lab}} \]

In Lab. System:

\[ T_{Lab} = \frac{l_0}{\beta c}, \quad \omega_{Lab} = \frac{2\pi}{T_{Lab}} \]
1.10 Resonant enhancement

The graph shows the variation of $P_d(\gamma)$ with $\gamma$ for different magnetic fields $B_0$.

- $B_0=0.6T$ (dashed line)
- $B_0=0.3T$ (dotted line)
- $B_0=0.1T$ (solid line)

Key markers include $\Omega_1/10$, $\Omega_1/20$, and $\Omega_1/40$. The peaks in the graph correspond to these markers, indicating resonant enhancement effects at specific values of $\gamma$. The $x$-axis represents $\gamma$, and the $y$-axis represents $P_d(\gamma)$.
1.11 Resonant method

Charged secondary

Proton beam

Resonators

$A^{*}_{2\pi}$, $A^{*}_{\pi\mu, \mu}$, $A^{*}_{\pi K}$

$\pi^{0}$, $\pi^{0}$, $\pi^{0}$, $\pi^{0}$

$\gamma_{res1}$, $\gamma_{res2}$, $\gamma_{res3}$, $\gamma_{res4}$

Pt foil

$p$
1.12 Be 2010 \( Q_T < 1 \text{ MeV/c} \)

The page contains three graphs showing data distributions with histograms. Each graph has a title indicating the type of data (Real + Accidental or Accidental) and the number of entries (2844, 1870, and 2719) for each set of data points. The x-axis represents the range of \(|Q_L|\) values, while the y-axis represents the number of entries (N). The graphs provide visual representations of the data distributions under the specified conditions.
1.13 Be 2010 $Q_t < 1$ MeV/c
1.14 The background events in $A_{2\pi}$ measurements with different targets

$N_A$ – Number of produced atoms, $N_{bckg}$ – Number of background events in the region F<2.5 (~85% of atomic pairs) are presented. $Q_L \times Q_X \times Q_Y$ – semi-axes of the ellipsoid for F<2.5

<table>
<thead>
<tr>
<th>Data set</th>
<th>$N_A$ (($A_{2\pi}$ atoms)</th>
<th>$N_{bckg}$ (Coulomb and non-Coulomb pairs)</th>
<th>Ellipsoid extension $Q_L \times Q_X \times Q_Y$ (MeV/c)</th>
<th>Ratio $N_A/N_{bckg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni 2001 (94 μm)</td>
<td>10000±400</td>
<td>18240</td>
<td>1.625 x 2.5 x 2.5</td>
<td>0.55</td>
</tr>
<tr>
<td>Ni 2009 (108 μm)</td>
<td>16000±250</td>
<td>27350</td>
<td>1.625 x 2.5 x 2.5</td>
<td>0.59</td>
</tr>
<tr>
<td>Be 2010 (100 μm)</td>
<td>736±75</td>
<td>266</td>
<td>1.5 x 0.9 x 0.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Be 2010 (100 μm) + Pt (2 μm)</td>
<td>736±75</td>
<td>510</td>
<td>1.5 x 1.35 x 1.35</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The 736 ±75 $A_{2\pi}$ atoms has been detected during 7.5 days of data taking
2. Data processing of the 2008 – 2010 runs to observe $K^+\pi$ atoms, to measure their lifetime and the $|a_{1/2}-a_{3/2}|$ combination of the scattering lengths.
What new will be known if $\pi K$ scattering length will be measured?

The measurement of the $s$-wave $\pi K$ scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD ($u$, $d$ and $s$ quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking ($u$, $d$ quarks).

This is the principal difference between $\pi\pi$ and $\pi K$ scattering!

Experimental data on the $\pi K$ low-energy scattering are absent
2.2 $\pi K$ scattering lengths

I. ChPT predicts s-wave scattering lengths:

\[ a_0^{1/2} = 0.19 \pm 0.2 \quad a_0^{3/2} = -0.05 \pm 0.02 \]

\[ L^{(2)}, L^{(4)} \text{ and } 1\text{-loop} \]

\[ a_0^{1/2} - a_0^{3/2} = 0.23 \pm 0.01 \]

\[ a_0^{1/2} - a_0^{3/2} = (0.220 - (-0.047)) = 0.267 \]

\[ L^{(2)}, L^{(4)}, L^{(6)} \text{ and } 2\text{-loop} \]

II. Roy-Steiner equations:

\[ a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015 \]


A. Rossel. – 1999

J. Bijnens, P. P. Donthe

P. Talavera. – 2004

P. Büttiker et al. – 2004
## 2.3 Accuracy of $|a_{1/2} - a_{3/2}|$ measurement

<table>
<thead>
<tr>
<th>Accuracy of the measurement</th>
<th>$5\sigma$ (20%)</th>
<th>$6\sigma$ (17%)</th>
<th>$6.5\sigma$ (15%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ (s)</td>
<td>$(3.7 \pm 60%, - 43%) \cdot 10^{-15}$</td>
<td>$(3.7 \pm 51%, - 38%) \cdot 10^{-15}$</td>
<td>$(3.7 \pm 46%, - 32%) \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$\delta_{averge}</td>
<td>a_{1/2} - a_{3/2}</td>
<td>$</td>
<td>26 %</td>
</tr>
</tbody>
</table>
3. The multiple scattering measurement in \textit{Be, Al, Ti, Ni} and \textit{Pt} with better than 1\% accuracy. The data will permit to obtain the $A_{2\pi}$ lifetime with better than 6\% and $|a_0-a_2|$ with better than 3\% precisions.
4. The evaluation of the $K^+K^-$ and $\pi\mu$ atom production cross section based on the 2008-2010(2011) experimental data.
The production yield strongly increases for smaller $Q$

For small $Q$ there are Coulomb pairs:

- $pp$, $pK$, $K^+K^-$, $\pi\mu$ C-pairs
- $pp$, $pK$, $K^+K^-$, $\pi\mu$ atoms

4.1 Coulomb pairs and atoms

Strong interaction

$p \rightarrow \pi^+ K^+ \pi^- K^- \mu^+ \pi^-$

$nucleus$
5. The preparation of the DIRAC Collaboration extension and the setup upgrade.
5.1 $A_{2\pi}$ and $A_{\pi K}$ production

$$\frac{d\sigma_{nlm}^A}{d\vec{P}} = (2\pi)^3 \frac{E}{M} \left| \psi_{nlm}^{(C)}(0) \right|^2 \frac{d\sigma_s^0}{dp_1dp_2} \propto \frac{d\sigma_s}{dp_1} \cdot \frac{d\sigma_s}{dp_2}$$

for atoms $v_1 = v_2$ where $v_1, v_2$ — velocities of particles in the L.S. for all types of atoms

for $A_{2\pi}$ production $\vec{p}_1 = \vec{p}_2$

for $A_{\pi K}$ production $\vec{p}_\pi = \frac{m_\pi}{m_K} \vec{p}_K$
5.2 Inclusive cross-sections for $\pi^+$, $\pi^-$ - mesons generation

$$E_p = 450 GeV \quad \theta_L = 0^\circ$$
5.3 $A_{2\pi}$ momentum distributions (5.7°)

$\theta_L = 5.7° \pm 1.3° \ E_p = 24 GeV$

$\theta_L = 5.7° \pm 1.3° \ E_p = 450 GeV$
\[ \theta_L = 2^\circ \pm 1.3^\circ \quad E_p = 450\text{GeV} \]

\[ \theta_L = 0^\circ \pm 1.3^\circ \quad E_p = 450\text{GeV} \]
5.5 Inclusive cross-sections for $K^+, K^-$ - mesons generation

\[ E_p = 450 \text{GeV} \quad \theta_L = 0^\circ \]
### 5.6 DIRAC prospects at SPS CERN

#### Yields of atoms at PS and SPS

Yield of meson atoms per one proton-Ni interaction, detectable by DIRAC upgrade setup at $\Theta_L = 5.7^{\circ}$

<table>
<thead>
<tr>
<th></th>
<th>$E_p$</th>
<th>$W_A$</th>
<th>$W_A^N$</th>
<th>$W_A/W_\pi$</th>
<th>$W_A^N/W_\pi^N$</th>
<th>Total gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_{2\pi}$</td>
<td>$A_{K^+\pi^-}$</td>
<td>$A_{\pi^+K^-}$</td>
<td>$A_{2\pi}$</td>
<td>$A_{K^+\pi^-}$</td>
<td>$A_{\pi^+K^-}$</td>
</tr>
<tr>
<td>24 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1·10^{-9}</td>
<td>0.52·10^{-10}</td>
<td>0.29·10^{-10}</td>
<td>0.13·10^{-7}</td>
<td>0.10·10^{-8}</td>
<td>0.71·10^{-9}</td>
</tr>
<tr>
<td>450 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.4·10^{-8}</td>
<td>16·10^{-10}</td>
<td>9·10^{-10}</td>
<td>1.3·10^{-7}</td>
<td>1·10^{-8}</td>
<td>7.1·10^{-9}</td>
</tr>
<tr>
<td></td>
<td>1.</td>
<td>1.</td>
<td>1.</td>
<td>3.8</td>
<td>6.2</td>
<td>8.</td>
</tr>
</tbody>
</table>

A multiplier due to different spill duration $\sim 4$

Total gain

1. 1. 1. 15. 25. 32.
### 5.7 DIRAC prospects at SPS CERN

**Present low-energy QCD theoretical predictions for ππ scattering lengths**

<table>
<thead>
<tr>
<th></th>
<th>δ$a_0$ (%)</th>
<th>δ$a_2$ (%)</th>
<th>δ($a_0-a_2$) (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ChPT</td>
<td>2.3</td>
<td>2.3</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

Will be improved by Lattice calculations

#### DIRAC Expected results

<table>
<thead>
<tr>
<th>τ($A_{2π}$)PS 2008-2010 (2011)</th>
<th>δ$a_0$ (%)</th>
<th>δ$a_2$ (%)</th>
<th>δ($a_0-a_2$) (%)</th>
<th>δ(2$a_0$+$a_2$) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ($A_{2π}$) SPS beyond 2013</td>
<td></td>
<td></td>
<td>≤ 2</td>
<td></td>
</tr>
</tbody>
</table>

2011: Observation of metastable π⁺π⁻ atoms and study the possibility to measure its Lamb shift
Study the possibility to observe at SPS the K⁺K⁻ and πμ atoms based on 2008-2010(2011) data

($E_{np}$ - $E_{ns}$)_{ππ} SPS beyond 2013 Possible higher precision order relative to present methods
## 5.8 DIRAC prospects at SPS CERN

### Present theoretical predictions for $\pi K$ scattering lengths

<table>
<thead>
<tr>
<th></th>
<th>$\delta a_{1/2}$ (%)</th>
<th>$\delta a_{3/2}$ (%)</th>
<th>$\delta(a_{1/2}-a_{3/2})$ (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChPT</td>
<td>11</td>
<td>40</td>
<td>10</td>
<td>Will be significantly improved by ChPT</td>
</tr>
<tr>
<td>Roy-Steiner</td>
<td>10</td>
<td>17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### DIRAC expected results

<table>
<thead>
<tr>
<th></th>
<th>$\delta(a_{1/2}-a_{3/2})$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau(A_{\pi K})$ PS 2008-2010 (2011)</td>
<td>26</td>
</tr>
<tr>
<td>$\tau(A_{\pi K})$ SPS beyond 2013</td>
<td>5 (stat)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\delta(2a_{1/2}+a_{3/2})$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(E_{np}-E_{ns})_{\pi K}$ SPS beyond 2013</td>
<td></td>
</tr>
</tbody>
</table>
6. Presentation in 2013 of a Letter of Intent:

“Investigations of the $\pi\pi$, $\pi K$ and other exotic atoms at the SPS proton beam to check the precise low energy $QCD$ predictions”
Thank you for your attention
Method of $A_{2\pi}$ observation and measurement

Target Ni 98 $\mu$m

Atomic pairs

Coulomb correlated pairs

Non-Coulomb pairs

Accidental pairs

Interaction point

$\Delta, \rho, \omega, \ldots$

$\pi^+, \pi^-, \pi^0$

$\eta, \eta', \ldots$

$\pi^+, \pi^-$

$\pi^+$

$\pi^-$

$\pi^0$

$\pi^+$

$\pi^-$

Method of observation and measurement

Method of observation and measurement
\[ Q = \sqrt{Q_x^2 + Q_y^2 + Q_L^2} \]

\[ F = \sqrt{\frac{Q_x^2}{\sigma_{Q_x}^2} + \frac{Q_y^2}{\sigma_{Q_y}^2} + \frac{Q_L^2}{\sigma_{Q_L}^2}} \]

\[ \sigma_{Q_x} = \sigma_{Q_y} = 1\text{MeV/c} \]

\[ \sigma_{Q_L} = 0.65\text{MeV/c} \]

\[ N_a(F < 2.3) > N_a(Q < 2.0\text{MeV/c}) \]

\[ N_b(F < 2.3) \approx N_b(Q < 2.0\text{MeV/c}) \]
Comparision with other experimental results

$K \rightarrow 3\pi$

2009 NA48/2 (EPJ C64, 589)

\[ a_0 - a_2 = 0.2571 \pm 0.0048_{\text{stat}} \pm 0.0029_{\text{syst}} \]

...without constraint between $a_0$ and $a_2$: and $\pm 0.0088$ theory uncertainty

Ke4:

2010 NA48/2 (CERN-PH-EP-2010-036)

Submitted for publication in EPJ C

\[ a_0 = 0.2220 \pm 5.8\%_{\text{stat}} \pm 2.3\%_{\text{syst}} \pm 1.7\%_{\text{theo}} = \ldots \pm 6.4\% \]

\[ a_2 = -0.0432 \pm 20\%_{\text{stat}} \pm 7.9\%_{\text{syst}} \pm 6.5\%_{\text{theo}} = \ldots \pm 22\% \]

...without constraint between $a_0$ and $a_2$: ...with ChPT constraint between $a_0$ and $a_2$:

\[ a_0 = 0.2206 \pm 2.2\%_{\text{stat}} \pm 0.8\%_{\text{syst}} \pm 2.9\%_{\text{theo}} = \ldots \pm 3.7\% \]
Be 2010

$Q_r < 1 \text{ MeV/c}$

$n_A(|Q_L| < 0.5) = 24.2 \pm 43.3$

$n_A(|Q_L| < 1.0) = 2.4 \pm 85.3$

$n_A(|Q_L| < 1.5) = 23.7 \pm 99.3$

$n_A(|Q_L| < 2.0) = 30.0 \pm 108.8$
Upgraded DIRAC experimental setup
Target Ni 98 μm

$\pi^+ \pi^- \pi^+ \pi^- \pi^0 \pi^0 \Delta, \rho, \omega, \ldots$

Atomic pairs

Coulomb correlated pairs

Non-Coulomb pairs

Accidental pairs

Interaction point

$24$ GeV/c

$N_A$

$N_C$

$\text{Atomic pairs}$

$\text{Coulomb correlated pairs}$

$\text{Non-Coulomb pairs}$

$\text{Accidental pairs}$
$\pi^−p$ mass & $\pi^+\pi^−$ signal in 2007

Observation of $\pi^+\pi^−$ atoms with the Platinum target

Setup calibration with $\Lambda$ decays
1.7 DIRAC prospects at SPS CERN

Present low-energy QCD predictions for $\pi\pi$ and $\pi K$ scattering lengths

$\pi\pi \quad \delta a_0 = 2.3\% \quad \delta a_2 = 2.3\% \quad \delta(a_0 - a_2) = 1.5\% \quad \ldots\text{will be improved by Lattice calculations}$

$\pi K \quad \delta a_{1/2} = 11\% \quad \delta a_{3/2} = 40\% \quad \delta a_{1/2} = 10\% \quad \delta a_{3/2} = 17\% \quad \text{ChPT, Roy-Steiner}$

Expected results of DIRAC ADDENDUM at PS CERN after 2008-2010

$\tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 2\% (\text{stat}) \pm 1\% (\text{syst}) \pm 1\% (\text{theor})$

$\tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 10\% (\text{stat}) \pm \ldots \ldots \pm 1.5\% (\text{theor})$

2011 Observation of metastable $\pi^+\pi^-$ atoms and study of a possibility to measure its Lamb shift.

Study of the possibility to observe $K^+K^-$ and $\pi^+\mu^+\bar{\nu}$ atoms using 2008-2010 data.

DIRAC at SPS CERN beyond 2011

$\tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 0.5\% (\text{stat}) \quad \tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 2.5\% (\text{stat})$

$(E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2) \quad (E_{np} - E_{ns})_{\pi K} \rightarrow \delta(2a_{1/2} + a_{3/2})$