<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN</td>
<td>Geneva, Switzerland</td>
</tr>
<tr>
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</tr>
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<td>Institute of Physics ASCR</td>
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<td>Nuclear Physics Institute ASCR</td>
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<td>INFN-Laboratori Nazionali di Frascati</td>
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<td>Bern, Switzerland</td>
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<td>Zurich University</td>
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</table>
1. Theoretical motivation
2. Long-lived $\pi^+\pi^-$ atom analysis
3. $\pi^+K^-$ and $\pi^-K^+$ atom analysis
4. Short-lived $\pi^+\pi^-$ atom analysis
6. $K^+\pi^-, K^-\pi^+, \pi^+\pi^-, K^+K^-$ atom production analysis at pp=24GeV/c and pp=450GeV/c
7. Letter of Intent
8. Further works
Electroweak

$L_{EW}$

SU(2)$_L \times$ U(1)

Standard Model

local gauge theory

Strong:

$L_{QCD}$

SU(3)$_c$

Strong interaction: $L_{QCD} = L_{sym} + L_{sym\text{-break}} (m_q \neq 0)$

(chiral symmetry)

HIGH energy (small distance)

Q$\gg$

perturbative QCD:

$L_{QCD}(q,g)$

Interaction $\to$ „weak“ (asympt. freedom)

Method: expansion in coupling

Checks only $L_{sym}$!

LOW energy (large distance)

Q$\ll$

non-perturbative QCD:

$L_{eff}(GB: \pi, K, \eta); L_{lattice}(q,g)$

Interaction $\to$ „strong“ (confinement)

Methods: 1) Chiral Perturbation Theory

2) Lattice Gauge Theory

Checks $L_{sym}$ as well as $L_{sym\text{-break}}$!

spontaneously broken symmetry

quark-condensate
In ChPT the effective Lagrangian, which describes the $\pi\pi$ interaction, is an expansion in terms:

$$L_{\text{eff}} = L^{(2)}_{\text{(tree)}} + L^{(4)}_{\text{(1-loop)}} + L^{(6)}_{\text{(2-loop)}} + \cdots$$


$$a_0 = 0.220 \pm 2.3\%$$
$$a_2 = -0.0444 \pm 2.3\%$$

$$a_0 - a_2 = 0.265 \pm 1.5\%$$

These results precision depends on the low-energy constants (LEC) $\bar{I}_3$ and $\bar{I}_4$: Lattice gauge calculations from 2006 provided values for these $\bar{I}_3$ and $\bar{I}_4$ which allows to improve the scattering length precision. Lattice calculation are giving also the scattering length values.
Method of $A_{2\pi}$ observation and measurement

Target Ni 98 µm

$A_{2\pi}$

$(N_A)$

$\pi^+$

$\pi^-$

$q_A$

$\pi^+$

$\pi^-$

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

$\eta, \eta', \ldots$

$\pi^+$

$\pi^0$

$\pi^+$

$\pi^-$

$\pi^-$

Interaction point

24 GeV/c

Atomic pairs

Coulomb pairs

Non-Coulomb pairs

Accidental pairs

Q – relative momentum in $\pi^+\pi^-$ c.m.s.

$Q_L$, $Q_T$

Q – relative momentum in $\pi^+\pi^-$ c.m.s.

$Q_L$, $Q_T$
For charged pairs from short-lived sources and with small relative momenta $Q$, Coulomb final state interaction has to be taken into account. This interaction increases the production yield of the free pairs with $Q$ decreasing and creates atoms.

There is a precise ratio between the number of produced Coulomb pairs ($N_C$) with small $Q$ and the number of atoms ($N_A$) produced simultaneously with Coulomb pairs:

$$N_A = K(Q_0)N_C(Q \leq Q_0), \frac{\delta K(Q_0)}{K(Q_0)} \leq 10^{-2}$$

$n_A$ - atomic pair number, $P_{br} = \frac{n_A}{N_A}$
\[ \pi^+\pi^- \text{ atom (pionium) is a hydrogen-like atom consisting of } \pi^+ \text{ and } \pi^- \text{ mesons:} \]

\[ E_B = -1.86 \text{ keV}, \quad r_B = 387 \text{ fm}, \quad p_B \approx 0.5 \text{ MeV/c} \]

The \( \pi^+\pi^- \) atom lifetime is dominated by the decay into \( \pi^0\pi^0 \) mesons:

\[ \Gamma = \frac{1}{\tau} = \Gamma_{2\pi^0} + \Gamma_{2\gamma} \]

\[ \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4 \times 10^{-3} \]

\[ \tau_{1s} = (2.9 \pm 0.1) \times 10^{-15} \text{ s} \]

\[ \tau_{2p} = 1.17 \times 10^{-11} \text{ s} \]

\[ \Delta R \approx 1.2 \times 10^{-2} \]

\[ \Gamma_{ns \rightarrow 2\pi^0} = R \left| \psi_{ns} (0) \right|^2 \left| a_0 - a_2 \right|^2 \]

\[ a_0 \text{ and } a_2 \text{ are the } \pi\pi \text{ S-wave scattering lengths for isospin } I=0 \text{ and } I=2. \]

\[ \psi_{nl} (0) \begin{cases} 
\neq 0 \text{ for } l = 0 \\
= 0 \text{ for } l \neq 0
\end{cases} \]

\[ A_{2\pi} (1s, 2s, \ldots, ns) \rightarrow \pi^0\pi^0 \]

\[ A_{2\pi} (np) \gamma \rightarrow A_{2\pi} (1s, 2s, \ldots, (n-1)s) \rightarrow \pi^0\pi^0 \]

The \( np \) state lifetime depends on the transition \( np \rightarrow 1s, 2s, \ldots, (n-1)s \) probability. This probability is about 3 orders of magnitude less than for \( ns \rightarrow \pi^0\pi^0 \).
A\textsubscript{2\pi} Energy Levels

For Coulomb potential, E depends only on n

\[
\begin{align*}
\Delta^{\text{vac}}_{2s-2p} &= -0.111 \text{eV} \\
\Delta^{\text{str}}_{2s-2p} &= -0.47 \pm 0.01 \text{eV} \\
\Delta^{\text{em}}_{2s-2p} &= -0.012 \text{eV} 
\end{align*}
\]

\[
\Gamma = \frac{\alpha^3 m_e}{8} \frac{1}{6} \left( 2a_0 + a_2 \right) + \cdots
\]

\[
\Delta^{\text{str}}_{ns-np} = -\frac{\Delta^{\text{str}}_{2s-2p}}{n^3} \cdot \frac{1}{8}
\]

CONCLUSION: one parameter \((2a_0 + a_2)\) allows to calculate all \(\Delta^{\text{str}}_{ns-np}\) values

\[
E_{2s} - E_{2p} = \Delta_{2s-2p}
\]

Notation:

\[
\Gamma = \frac{\alpha^3 m_e}{8} \frac{1}{6} \left( 2a_0 + a_2 \right) + \cdots
\]

\[
\Delta^{\text{vac}+\text{str}+\text{em}}_{2s-2p} = -0.59 \pm 0.01 \text{eV}
\]

\[\Delta^{\text{str}}_{2s-2p} = -0.47 \pm 0.01 \text{eV}\]

\[\Delta^{\text{em}}_{2s-2p} = -0.012 \text{eV}\]

\[\Delta^{\text{vac}}_{2s-2p} = -0.111 \text{eV}\]
1. Paper “First observation of long-lived $\pi^+\pi^-$ atoms” accepted for publication in Physics Letters B. The number of atomic pairs from long-lived $\pi^+\pi^-$ atoms breakup in the Pt foil is:

$$n_A = 436 \pm 57 |_{\text{stat}} \pm 23 |_{\text{syst}} = 436 \pm 61 |_{\text{tot}} (7.1 \sigma).$$

2. The preliminary value of the long-lived $\pi^+\pi^-$ atom lifetime will be presented in April 2016.

3. In 2016, we will study the possibility to evaluate a lower limit for the Lamb shift of $\pi^+\pi^-$ atom based on the existing data.

4. In 2016 we intend to process the 2011 data.
Method for observing long-lived $\pi^+\pi^-$ atom with breakup Pt foil

Be target 103 µm

Magnetic Field
B_x = 0.25 T

Pt foil 2.1 µm

24 GeV/c
p

Interaction point

Excitation

$\Delta, \rho, \omega, \eta, \eta'$ ...

Breakup

Long-lived states

Atomic, Coulomb, non-Coulomb and accidental pairs
Coulomb pairs $\rightarrow N_A$

Atomic pairs

$N_A = 17043 \pm 410, n_A L = 436 \pm 61$

$\tau_{1s} = (2.9 \pm 0.1) \cdot 10^{-15} s$

$\tau_{2p} = 1.2 \cdot 10^{-11} s$

<table>
<thead>
<tr>
<th>n</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>$\geq 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_n(\text{Be}) \times 10^2$</td>
<td>$2.48 \pm O(10^{-3})$</td>
<td>$1.54 \pm 0.01$</td>
<td>$0.86 \pm 0.03$</td>
<td>$0.56 \pm 0.06$</td>
<td>$6.8 \pm 0.6$</td>
</tr>
<tr>
<td>$\varepsilon_n(\text{Pt}) \times 10^2$</td>
<td>$0.52 \pm O(10^{-4})$</td>
<td>$1.10 \pm O(10^{-3})$</td>
<td>$0.78 \pm 0.03$</td>
<td>$0.54 \pm 0.06$</td>
<td>$4.3 \pm 0.6$</td>
</tr>
<tr>
<td>$P_{br}$</td>
<td>$0.72 \pm 0.03$</td>
<td>$0.89 \pm 0.03$</td>
<td>$0.94 \pm 0.02$</td>
<td>$0.96 \pm 0.02$</td>
<td>$0.97 \pm 0.02$</td>
</tr>
</tbody>
</table>

11/6/2015
$Q_y$ distribution of “atomic pairs” (signal) above the background of $\pi^+\pi^-$ Coulomb pairs produced in Beryllium target, without (left) and with (right) magnet used in 2012 run.

**Selected events with the cut:** \[\sqrt{Q_x^2 + Q_L^2} < 2\text{MeV}/c\]

Expected signal (atomic pairs) from broken up long-lived $\pi^+\pi^-$ atoms

Simulation without magnet  
Simulation with magnet
1 Target station; 2 First shielding; 3 Micro Drift Chambers; 4 Scintillating Fiber Detector; 5 Ionization Hodoscope; 6 Second Shielding; 7 Vacuum Tube; 8 Spectrometer Magnet; 9 Vacuum Chamber; 10 Drift Chambers; 11 Vertical Hodoscope; 12 Horizontal Hodoscope; 13 Aerogel Čerenkov; 14 Heavy Gas Čerenkov; 15 Nitrogen Čerenkov; 16 Preshower; 17 Muon Detector
BLUE ... magnet yoke
GREY ... magnet poles
RED ... magnet shimming
PURPLE ... Pt foil

\[ \sigma_{Q_X} = \sigma_{Q_Y} = 0.5 \text{ MeV/c} \]
\[ \sigma_{Q_L} = 0.5 \text{ MeV/c (}\pi\pi\text{)} \]
\[ \sigma_{Q_L} = 0.9 \text{ MeV/c (}\pi\text{K)} \]
\[ |Q_L| \text{ distribution of } \pi^+\pi^- \text{ pairs for } Q_T < 2.0 \text{ MeV/c} \]

a) The experimental distribution (points with statistical error) and the simulated background (solid line).

b) The experimental distribution after background subtraction (points with statistical error) and the simulated distribution of atomic pairs (dot-dashed line).

The fit procedure has been applied to the 2-dimensional \(|Q_L|, Q_T\) distribution.
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!
Method of $K\pi$ atom observation and investigation

Q – relative momentum in $\pi^+\pi^-$ c.m.s.
$Q_L, Q_T$

Atomic pairs
$K^+(K^-), \pi^-(\pi^+)$

Coulomb pairs
$K^+(K^-), \pi^-(\pi^+)$

Non-Coulomb pairs
$K^+(K^-), \pi^-(\pi^+), \eta, \eta', \ldots$

Accidental pairs
$K^+(K^-), \pi^-(\pi^+)$
In this paper, characteristic $\pi K$ pairs from $\pi K$ atom breakup in the Ni target have been observed, as many as

$$178 \pm 49 \ (3.6\sigma) \ \text{\piK atomic pairs as well as} \ 653 \pm 42 \ \text{produced \piK atoms}$$

Based on these results, the first measurement of the $\pi K$ atom lifetime has been deduced

$$\tau = \left(2.5^{+3.0}_{-1.8}\right) \text{fs}$$

and the first measurement of the S-wave isospin-odd $\pi K$ scattering length

$$\left|a_0^-\right| = \frac{1}{3} \left|a_{1/2} - a_{3/2}\right| = \left(0.11^{+0.09}_{-0.04}\right) M_{\pi}^{-1}$$

The result was obtained using 2/3 of the existing statistics with low and medium background in the scintillation fiber detector.
Run 2008-2010, statistics with low and medium background (2/3 of all statistics).

- Atomic pairs
- Coulomb pairs
- non-Coulomb pairs

\[ N_A = 638. \pm 50. \]
\[ n_A = 200. \pm 76. \]
\[ P_{Br} = 0.31 \pm 0.14 \]

\[ N_A = 653. \pm 42. \]
\[ n_A = 178. \pm 49. \]
\[ P_{Br} = 0.27 \pm 0.09 \]

\[ |Q_L| \text{ distribution analysis on } |Q_L| \text{ for } Q_T < 4 \text{ MeV/c} \]

\[ |Q_L| \text{ distribution analysis on } |Q_L| \text{ and } Q_T \text{ for } Q_T < 4 \text{ MeV/c} \]

$N_A = 886. \pm 48$

$n_A = 322. \pm 57$

$P_{Br} = 0.36 \pm 0.08$
Number of “atomic pairs” \((n_A)\) with statistical error and ratio signal-to-error \((r_A)\) for \(\pi K\) atoms collected with **Nickel** target in 2008, 2009 and 2010. Selection criteria: \(|Q_L| < 20\) MeV/c, \(Q_T < 4\) MeV/c.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(n_A^{K^+\pi^-}(r_A))</th>
<th>(n_A^{\pi^+K^-}(r_A))</th>
<th>(n_A^{\pi K}(r_A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q)</td>
<td>175. ± 46. (3.8)</td>
<td>85. ± 29. (3.0)</td>
<td>260. ± 54. (4.8)</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>)</td>
<td>93. ± 70. (1.3)</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>,Q_T)</td>
<td>158. ± 44. (3.6)</td>
</tr>
</tbody>
</table>

Number of “atomic pairs” \((n_A)\) with statistical error and ratio signal-to-error \((r_A)\) for \(\pi K\) atoms collected with **Platinum** target in 2007. Selection criteria: \(|Q_L| < 20\) MeV/c, \(Q_T < 4\) MeV/c.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(n_A^{K^+\pi^-}(r_A))</th>
<th>(n_A^{\pi^+K^-}(r_A))</th>
<th>(n_A^{\pi K}(r_A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q)</td>
<td>46. ± 17. (2.8)</td>
<td>16. ± 10. (1.5)</td>
<td>62. ± 19. (3.2)</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>)</td>
<td>55. ± 25. (2.2)</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>,Q_T)</td>
<td>55. ± 16. (3.5)</td>
</tr>
</tbody>
</table>

Number of “atomic pairs” \((n_A)\) with statistical error and ratio signal-to-error \((r_A)\) for \(\pi K\) atoms collected with **Platinum and Nickel** target in 2007, 2008, 2009 and 2010. Selection criteria: \(|Q_L| < 20\) MeV/c, \(Q_T < 4\) MeV/c.

<table>
<thead>
<tr>
<th>Variable</th>
<th>(n_A^{K^+\pi^-}(r_A))</th>
<th>(n_A^{\pi^+K^-}(r_A))</th>
<th>(n_A^{\pi K}(r_A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q)</td>
<td>222. ± 48. (4.6)</td>
<td>101. ± 30. (3.3)</td>
<td>322. ± 57. (5.6)</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>)</td>
<td>148. ± 75. (2.0)</td>
</tr>
<tr>
<td>(</td>
<td>Q_L</td>
<td>,Q_T)</td>
<td>213. ± 47. (4.5)</td>
</tr>
</tbody>
</table>
The procedure of matching the downstream tracks with SFD hits will be modified accounting a dependence of the expected hits region on particle momenta. The main aim of this procedure is to improve the quality of the statistics with the low and medium background and to process the part of the statistics with high background (1/3 of the total data).

The preliminary results on $K^+\pi^-$ and $K^-\pi^+$ atoms investigation using all the data available from 2007, 2008, 2009 and 2010 runs and with the improved analysis will be ready in April 2016.
1. At present time the $\pi^+\pi^-$ pairs are using as calibration process for the $\pi K$ pairs analysis. Preliminary results on the $\pi^+\pi^-$ atom lifetime measurement based on all available data will be ready at the end of 2016.

2. The current systematical error in the $\pi^+\pi^-$ atom lifetime measurement is equal to statistical uncertainty. The main part of systematical error arise due to the multiple scattering in the Ni target. To reduce this error we continue experimental study of the multiple scattering of our targets: Ni: 50, 109 and 150 microns; Be: 100 and 2000 microns; Pt: 2 and 30 microns and Ti: 250 microns.
Multiple scattering evaluation

The Ratio RMS(exp)/RMS(Mol) evaluated for intervals

\[ \pm 1 \text{ RMS(Mol)}, \pm 2 \text{ RMS(Mol)}, \pm 3 \text{ RMS(Mol)} \]

<table>
<thead>
<tr>
<th>SCATTER RER</th>
<th>RMS(Mol)</th>
<th>( \pm 1 ) RMS(Mol)</th>
<th>( \pm 2 ) RMS(Mol)</th>
<th>( \pm 3 ) RMS(Mol)</th>
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</thead>
<tbody>
<tr>
<td>Ni-50</td>
<td>0.7913E-03</td>
<td>1.01217</td>
<td>0.95509</td>
<td>0.99187</td>
</tr>
<tr>
<td>Ni-100</td>
<td>0.1118E-02</td>
<td>0.98192</td>
<td>0.96447</td>
<td>0.95943</td>
</tr>
<tr>
<td>Ni-150</td>
<td>0.1369E-02</td>
<td>0.97556</td>
<td>0.96181</td>
<td>0.95436</td>
</tr>
<tr>
<td>Ti-250</td>
<td>0.1113E-02</td>
<td>1.00850</td>
<td>0.98617</td>
<td>0.99082</td>
</tr>
<tr>
<td>Ni-109</td>
<td>0.1167E-02</td>
<td>0.99661</td>
<td>0.97571</td>
<td>0.95421</td>
</tr>
<tr>
<td>Pt-30</td>
<td>0.1361E-02</td>
<td>0.98962</td>
<td>0.95817</td>
<td>0.94733</td>
</tr>
<tr>
<td>Be-2mm</td>
<td>0.9705E-03</td>
<td>1.00103</td>
<td>0.94648</td>
<td>0.93091</td>
</tr>
</tbody>
</table>

Ni-109 Drift Chamber Resolution

Ni-109 Scatter

Ni-109 Reconstructed Distribution

Ni-109 Multiple Scattering Simulation
For charged pairs from short-lived sources and with small relative momenta \( Q \), Coulomb final state interaction has to be taken into account.

There is a precise ratio between the number of produced Coulomb pairs \((N_C)\) with small \( Q \) and the number of atoms \((N_A)\) produced simultaneously with Coulomb pairs:

\[
N_A = K(Q_0)N_C(Q \leq Q_0), \quad \frac{\delta K(Q_0)}{K(Q_0)} \leq 10^{-2}
\]

\( n_A \) - atomic pairs number, \( P_{br} = \frac{n_A}{N_A} \)

From \( K^+K^- \) pairs analysis the Coulomb pair distribution on \( Q \) will be obtained, allowing to extract the total number of produced \( K^+K^- \) atoms.
The $A_{2\pi}$ lifetime is strongly reduced by strong interaction (OBE, scalar meson $f_0$ and $a_0$) as compared to the annihilation of a purely Coulomb-bound system ($K^+K^-$).

<table>
<thead>
<tr>
<th>$\tau (A_{2K} \rightarrow \pi\pi,\pi\eta)$</th>
<th>$K^+K^-$ interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.2 \times 10^{-16}$ s [1]</td>
<td>Coulomb-bound</td>
</tr>
<tr>
<td>$8.5 \times 10^{-18}$ s [3]</td>
<td>momentum dependent potential</td>
</tr>
<tr>
<td>$3.2 \times 10^{-18}$ s [2]</td>
<td>+ one-boson exchange (OBE)</td>
</tr>
<tr>
<td>$1.1 \times 10^{-18}$ s [2]</td>
<td>+ $f_0'$ (I=0) + $\pi\eta$-channel (I=1)</td>
</tr>
<tr>
<td>$2.2 \times 10^{-18}$ s [4]</td>
<td>ChPT</td>
</tr>
</tbody>
</table>

References:  
1. A search for $K^+K^-$ Coulomb pairs in the 1/3 of 2010 data will be performed. The number of $K^+K^-$ atoms, which are produced together with these Coulomb pairs, will be extracted.

2. In the first part of the work we will analyse about 7000 $K^+K^-$ pairs with total lab momenta 2.8 to 6.0 GeV/c, corresponding to 1/3 of the statistics.

- If a signal is observed, Coulomb pairs will also be searched for in the higher momentum range from 6.0 to 9.6 GeV/c (about 2400 pairs).
- The total statistics of $K^+K^-$ pairs produced on Ni and Pt targets is about 100000.
1. DIRAC note (September 2015) presented simulation of the inclusive production of $K^+$, $K^-$, $\pi^+$ and $\pi$ in p-nucleus interaction at 24 GeV/c and 450 GeV/c. The simulated results compared with dedicated experimental data.

2. The yields of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms in p-nucleus interaction at proton momenta 24 GeV/c and 450 GeV/c are calculated. Minimum values of this yields evaluated with the errors obtained from the experiments.
\[
\frac{d\sigma^A_{nlm}}{d\vec{P}_A} = (2\pi)^3 \frac{E}{M} \left| \psi_n^{(C)}(0) \right|^2 \frac{d\sigma^0_{s}}{dp_1dp_2} \bigg|_{\vec{v}_1=\vec{v}_2} \propto \frac{d\sigma}{dp_1} \cdot \frac{d\sigma}{dp_2} \cdot R(\vec{p}_1, \vec{p}_2; s)
\]

\[\vec{P}_A = \vec{p}_1 + \vec{p}_2\]

for atoms \(\vec{v}_1 = \vec{v}_2\) where \(\vec{v}_1, \vec{v}_2\) - 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 \(\vec{p}_\pi = \frac{m_\pi}{m_K} \vec{p}_K\)

\[R(\vec{p}_1, \vec{p}_2; s)\] - correlation function
The yield of $\pi^+\pi^-$, $\pi^+K^-$ and $K^+\pi^-$ atoms

<table>
<thead>
<tr>
<th>$\theta_{\text{lab}}$</th>
<th>$5.7^\circ$</th>
<th>$4^\circ$</th>
<th>$2^\circ$</th>
<th>$0^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$</td>
<td>24 GeV/c</td>
<td>450 GeV/c</td>
<td>450 GeV/c</td>
<td>450 GeV</td>
</tr>
</tbody>
</table>

The yield of $\pi^+\pi^-$ atoms

<table>
<thead>
<tr>
<th>$W_A$</th>
<th>$1.25 \cdot 10^{-9}$</th>
<th>$1.9 \cdot 10^{-8}$</th>
<th>$3.5 \cdot 10^{-8}$</th>
<th>$4.5 \cdot 10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_A^N$</td>
<td>1</td>
<td>15 (9.7±1.5)</td>
<td>28 (17.5±2.8)</td>
<td>36 (22.7±3.6)</td>
</tr>
<tr>
<td>$(W_A/W_{\text{ch}})^N$</td>
<td>1</td>
<td>2.4 (1.55±0.20)</td>
<td>1.2 (0.77±0.13)</td>
<td>0.27 (0.17±0.03)</td>
</tr>
</tbody>
</table>

The yield of $\pi^+K^-$ atoms

<table>
<thead>
<tr>
<th>$W_A$</th>
<th>$1.3 \cdot 10^{-11}$</th>
<th>$8.8 \cdot 10^{-10}$</th>
<th>$1.7 \cdot 10^{-9}$</th>
<th>$2.0 \cdot 10^{-9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_A^N$</td>
<td>1</td>
<td>67 (45 ± 8)</td>
<td>131 (87 ± 15)</td>
<td>154 (104 ± 18)</td>
</tr>
<tr>
<td>$(W_A/W_{\text{ch}})^N$</td>
<td>1</td>
<td>10.6 (7.0±1.0)</td>
<td>5.8 (3.9±0.7)</td>
<td>1.2 (0.79±0.13)</td>
</tr>
</tbody>
</table>

The yield of $K^+\pi^-$ atoms

<table>
<thead>
<tr>
<th>$W_A$</th>
<th>$3.1 \cdot 10^{-11}$</th>
<th>$9.7 \cdot 10^{-10}$</th>
<th>$2.1 \cdot 10^{-9}$</th>
<th>$2.7 \cdot 10^{-9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_A^N$</td>
<td>1</td>
<td>31 (18.6±4.1)</td>
<td>68 (41±9)</td>
<td>87 (52±11)</td>
</tr>
<tr>
<td>$(W_A/W_{\text{ch}})^N$</td>
<td>1.</td>
<td>4.9 (2.9±0.6)</td>
<td>3.0 (1.9±0.4)</td>
<td>0.66 (0.40±0.09)</td>
</tr>
</tbody>
</table>

SPS duty cycle add factor 5 relative to PS

11/6/2015
In the static electric field there will be Stark mixing between the $ns$ and the $np$ wave functions.

$$\tau_{np} \Rightarrow \tau_{np}^{\text{eff}} (|\vec{E}|, \Delta E_{ns-np}) < \tau_{np}$$

Only relative abundances of different atomic quantum states are taken from theory.
Resonant enhancement of the annihilation rate of $A_{2\pi}$


In CM System:

\[ \omega_{\text{Lab}} = \frac{2\pi}{T_{\text{Lab}}} \]

In Lab. System:

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

In CM System:

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

at resonance:

\[ \tilde{\Omega} = \tilde{\omega} = \gamma_{\text{res}} \cdot \omega_{\text{Lab}} \]
In a periodic electric field, there will be oscillations between ns and np states, if the external field frequency will coincide with ns - np frequency.

\[ \omega_{ns-np} = \gamma_n \omega_{lab} \]
Preparation of a *Letter of Intent* about
the investigation of $\pi^+\pi^-$, $\pi^+K^-$, $K^+\pi^-$
and $K^+K^-$ atoms at SPS energy
before November 2016
Instrumental publication

The paper “Updated DIRAC spectrometer at CERN PS for the investigation of $\pi\pi$ and $K\pi$ atoms” has been submitted to NIM

Measurement of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms production cross sections in proton interaction with Be, Ni and Pt nuclei based on 2007-2012 experimental data, will be done in 2017.

Dedicated measurements of the proton flux and the dead time of electronics and of DAQ were done for these purposes. Estimation of systematic biases in our cross sections can be done basing on extrapolation of single particle production cross sections available for 32 GeV/c protons.

$\pi^+\mu^-$ and $\pi^-\mu^+$ pair analysis

The 2010 experimental data has been searched for $\pi^+\mu^-$ and $\pi^-\mu^+$ Coulomb pairs with the aim of extracting the number of $\pi\mu$ atoms produced simultaneously with the Coulomb pairs. An upper limit on the atom production will be calculated and published as DIRAC note before the end of 2017.
Thank you
Hit regions in SFD
Theoretical motivation

Lattice calculations of $\tilde{l}_3$, $\tilde{l}_4$

- 2006: $\tilde{l}_3$, $\tilde{l}_4$ ... first lattice calculations
- 2012: 10 collaborations: 3 in USA, 5 in Europe and 2 in Japan
  
  $\tilde{l}_3 = 2.9 \pm 2.4$, $\tilde{l}_4 = 4.3 \pm 0.9$

- Lattice calculations of these constants have been done in 20 works.
  
  Best result (BMW): $\tilde{l}_3 = 2.6 \pm 0.5_{st} \pm 0.4_{sys}$, $\tilde{l}_4 = 3.8 \pm 0.4_{st} \pm 0.2_{sys}$

Therefore, the theoretical pion-pion scattering length precision can be improved. The best experimental results on the scattering length have a precision not better than 4%.
Analysis of data collected in 2012 for different $Q_T$ cuts. The detected numbers $n_A^L$ of atomic pairs and the corresponding total numbers $n_A^{L,\text{tot}}$ (via selection efficiency) are presented together with the background contribution (Coulomb, non-Coulomb and accidental pairs) and the fit quality $\chi^2 / n$ ($n$ - degrees of freedom). Errors are only statistical.

<table>
<thead>
<tr>
<th>$Q_T$ cut (MeV/c)</th>
<th>$n_A^L$</th>
<th>$n_A^{L,\text{tot}}$</th>
<th>Background</th>
<th>$\chi^2 / n$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fit over $Q_L$, $Q_T$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>436±57</td>
<td>488±64</td>
<td>16790</td>
<td>138/140</td>
</tr>
<tr>
<td><strong>Fit over $Q_L$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>152±29</td>
<td>467±88</td>
<td>971</td>
<td>29/27</td>
</tr>
<tr>
<td>1.0</td>
<td>349±53</td>
<td>489±75</td>
<td>3692</td>
<td>19/27</td>
</tr>
<tr>
<td>1.5</td>
<td>386±78</td>
<td>454±91</td>
<td>9302</td>
<td>22/27</td>
</tr>
<tr>
<td>2.0</td>
<td>442±105</td>
<td>495±117</td>
<td>16774</td>
<td>22/27</td>
</tr>
</tbody>
</table>
Experimental $Q_T$ distributions of $\pi^+\pi^-$ pairs

$Q_T$-distribution of $\pi^+\pi^-$ pairs for $|Q_L| < 2$ MeV/c

a) The experimental distribution (points with statistical error) and the simulated background (solid line).

b) The experimental distribution after background subtraction (points with statistical error) and the simulated distribution of atomic pairs (dot-dashed line).

The fit procedure has been applied to the 2-dimensional ($|Q_L|$, $Q_T$) distribution.
Magnet impact on $Q_y$ distribution for $e^+e^-$ pairs

Peak at $Q_y=2.3\text{MeV}/c$ evaluated after subtraction of the mirrored left side part.
The $\pi^+\pi^-$, $K^+K^-$, and $p\bar{p}$ pair numbers

- $\pi^+\pi^-$ pairs in high momenta
- $K^+K^-$ pairs in high momenta
- $p\bar{p}$ pairs in high momenta
Analogously, the 2010 data will be investigated with respect to $\pi^+\mu^-$ and $\pi\mu^+$ Coulomb pairs, to extract the number of $\pi\mu$ atoms, produced together with these Coulomb pairs. The analysis will be finished in January 2015.

In presence of a signal, the 2011 and 2012 data will be processed in order to improve statistics.
Search of $K^+K^-$ and $\bar{p}p$ pair with TOF (low momentum)

$P = (1.6, 1.8) \text{ GeV/c}$

- $\pi\pi$ (green): $72361 \pm 269$
- $K\bar{K}$ (magenta): $324 \pm 25$
- $p$-antip (blue): $17 \pm 5$

the average TOF (ns)
Search of $K^+K^-$ and $p\bar{p}$ pair with TOF (high momentum)

$P = (4.2, 4.4)$ GeV/c

- $K^+K^-$ (magenta) 190±38
- p-antip (blue) 32±14

The average TOF (ns)
DIRAC will perform a search for proton–antiproton Coulomb pairs, thus proton–antiproton atoms, with the same strategy as in the $K^+K^-$ case (see previous section).

The search for proton–antiproton Coulomb pairs in the lower momentum region will be finished before May 2016.
Additional slides
Physics motivation

$\pi^+\pi^-$ atom: lifetime & scattering length

$\Rightarrow \tau_{1s} \left(10^{-15} \text{ s}\right) = 3.15^{+0.20}_{-0.19} \text{ stat} +0.20 -0.18 \text{ syst} = 3.15^{+0.28}_{-0.26} \text{ tot}$

$\Gamma_{1s} = \frac{1}{\tau_{1s}} \approx \frac{2}{9} \alpha^3 p_{\pi^0} (a_0 - a_2)^2 m_{\pi}^2$

$\Rightarrow |a_0 - a_2| \left(m_{\pi}^{-1}\right) = 0.2533^{+0.0078}_{-0.0080} \text{ stat} +0.0072 -0.0077 \text{ syst} = 0.2533^{+0.0106}_{-0.0111} \text{ tot}$

Experimental results

\[ K \rightarrow 3\pi \]

\((\text{scattering length in } m^{-1})\)

2009 NA48/2 (EPJ C64, 589)

\[ a_0 - a_2 = 0.2571 \pm 0.0048 \pm 0.0025 \pm 0.0014 \text{ ext} = \ldots \pm 2.2\% \]

plus additional 3.4\% theory uncertainty

Ke4:

2010 NA48/2 (EPJ C70, 635)

\[ a_0 = 0.2220 \pm 0.0128 \pm 0.0050 \pm 0.0037 \text{ theo} = \ldots \pm 6.4\% \]

\[ a_2 = -0.0432 \pm 0.0086 \pm 0.0034 \pm 0.0028 \text{ theo} = \ldots \pm 22\% \]

π⁺π⁻ atom:

2011 DIRAC (PLB 704, 24)

\[ |a_0 - a_2| = 0.2533 \pm 0.0078 \pm 0.0072 + \pm 4.2\% \]

\[ -0.0080 \pm 0.0077 \text{ syst} = \ldots -4.4\% \]
Experimental results with additional theoretical constraints

\( K \rightarrow 3\pi \):

2009 NA48/2 (EPJ C64, 589) ...with ChPT constraint between \( a_0 \) and \( a_2 \):

\[
\Rightarrow a_0 - a_2 = 0.2633 \pm 0.0024 \left| \begin{array}{c} \text{stat} \\ \text{syst} \\ \text{ext} \end{array} \right| = ... \pm 1.3\%
\]

plus additional 2% theory uncertainty

Ke4:

2010 NA48/2 (EPJ C70, 635) ...with ChPT constraint between \( a_0 \) and \( a_2 \):

\[
\Rightarrow a_0 = \ 0.2206 \pm 0.0049 \left| \begin{array}{c} \text{stat} \\ \text{syst} \\ \text{theo} \end{array} \right| = ... \pm 3.7\%
\]

Ke4 & \( K \rightarrow 3\pi \):

2010 NA48/2 (EPJ C70, 635) Remark: the results didn’t include theory uncertainty

\[
\Rightarrow a_0 - a_2 = 0.2639 \pm 0.0020 \left| \begin{array}{c} \text{stat} \\ \text{syst} \end{array} \right| = ... \pm 0.9\%
\]
### Table: \( \tau_{2\pi} \) and Decay Lengths

<table>
<thead>
<tr>
<th>( n )</th>
<th>( \tau_{2\pi} ) (10(^{-11}) sec)</th>
<th>Decay length ( A_{2\pi} ) in L.S. (cm) for ( \gamma=16 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s (( l=0 ))</td>
<td>p (( l=1 ))</td>
</tr>
<tr>
<td>( \tau_{ns}=\tau_{1s} \cdot n^3 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.9 \cdot 10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2.32 \cdot 10^{-3}</td>
<td>1.17</td>
</tr>
<tr>
<td>3</td>
<td>7.83 \cdot 10^{-3}</td>
<td>3.94</td>
</tr>
<tr>
<td>4</td>
<td>1.86 \cdot 10^{-2}</td>
<td>9.05</td>
</tr>
<tr>
<td>5</td>
<td>3.63 \cdot 10^{-2}</td>
<td>17.5</td>
</tr>
<tr>
<td>6</td>
<td>6.26 \cdot 10^{-2}</td>
<td>29.9</td>
</tr>
<tr>
<td>7</td>
<td>9.95 \cdot 10^{-2}</td>
<td>46.8</td>
</tr>
<tr>
<td>8</td>
<td>1.48 \cdot 10^{-1}</td>
<td>69.3</td>
</tr>
</tbody>
</table>

**Platinum foils:**

The breakup probability for \( np \) states and different thicknesses (\( A_{2\pi} \) momentum \( P_A=4.5\text{GeV}/c \) and \( A_{2\pi} \) lifetime \( \tau = 3.0 \cdot 10^{-15}\text{s} \))

<table>
<thead>
<tr>
<th>Breakup foil</th>
<th>Thick (( \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>Pt (Z=78)</td>
<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></td>
<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></td>
<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>
</tbody>
</table>
Impact on atomic beam by external magnetic field $B_{\text{lab}}$ and Lorentz factor $\gamma$

.... relative distance between $\pi^+$ and $\pi^-$ in $A_{2\pi}$ system

.... laboratory magnetic field

...electric field in $A_{2\pi}$ system

$$\left| \vec{E} \right| = \beta \gamma B_{\text{lab}} \approx \gamma B_{\text{lab}}$$
Dependence of $A_{2\pi}$ lifetime $\tau_{\text{eff}}$ for 2p-states of the electric field $E$ strength

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

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

\[
\tau_{\text{eff}} = \frac{\tau_{2p}}{1 + \frac{\xi^2}{4} \frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1 + 120 \xi^2}
\]

where:

\[
|\xi|^2 \approx \frac{|\overrightarrow{E}|^2}{(E_{2p} - E_{2s})^2}
\]

\[
\begin{aligned}
\gamma = 20 & , \quad |\xi| = 0.025 \quad \Rightarrow \quad \tau_{\text{eff}} = \frac{\tau_{2p}}{1.3} \\
\gamma = 40 & , \quad |\xi| = 0.05 \quad \Rightarrow \quad \tau_{\text{eff}} = \frac{\tau_{2p}}{2.25}
\end{aligned}
\]

$B_{\text{Lab}} = 2$ Tesla
Pt foil edge position 7.5 mm from the beam axis

Proton beam position when the IH slabs single counts increase on factor 2 due to the halo beam interaction with the Pt foil (no Be target).
### Experimental conditions (run 2012)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary proton beam</td>
<td>24 GeV/c</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>$(3.0 \div 3.3) \cdot 10^{11}$ proton/spill</td>
</tr>
<tr>
<td>Spill duration</td>
<td>450 ms</td>
</tr>
<tr>
<td>Secondary particles intensity (single count of one IH plane)</td>
<td>$\approx 7 \cdot 10^6$ particle/spill</td>
</tr>
<tr>
<td>Be target</td>
<td></td>
</tr>
<tr>
<td>Target thickness</td>
<td>103 μm</td>
</tr>
<tr>
<td>Radiation thickness</td>
<td>$2.93 \cdot 10^{-4} X_0$</td>
</tr>
<tr>
<td>Probability of inelastic proton interaction</td>
<td>$2.52 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>
Layout of the dipole magnet (arrows indicate the direction of magnetization)

Horizontal field distribution along z-axis at X=Y=0mm
\[ \int B_x(0,0,z) dz = 24.6 \times 10^{-3} \text{ [Tm]} \]
Degradation of old magnet

Old magnet (Nd-Fe-B), 2011

The position of the second peak in $Q_Y$ distributions of $e^+e^-$ pairs versus dates.

$\frac{\Delta Q_Y}{Q_Y} > 50\%$

New magnet (Sm-Co), 2012

$\frac{Q^\text{mean}_Y}{\left(Q^\text{mean}_Y\right)_0} = A + B \times t; \ t \in [0, 1]$

$B = (1.4 \pm 2.2) \times 10^{-4}$
Break-up dependencies $P_{br}$ from atom lifetime for $K^+\pi^-$ and $\pi^+K^-$ atom.

Probability of break-up as a function of lifetime in the ground state for $A_{\pi K}$ (solid line) and $A_{K\pi}$ atoms (dashed line) in Ni target of thickness 108 $\mu$m. Average momentum of $A_{K\pi}$ and $A_{\pi K}$ are 6.4 GeV/c and 6.5 GeV/c accordingly.

<table>
<thead>
<tr>
<th>Atom</th>
<th>s, $\mu$m</th>
<th>$P_{br}$</th>
<th>$P_{br}-\sigma$</th>
<th>$P_{br}+\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\pi K}$</td>
<td>98</td>
<td>0.274</td>
<td>0.263</td>
<td>0.285</td>
</tr>
<tr>
<td>$A_{\pi K}$</td>
<td>108</td>
<td>0.278</td>
<td>0.267</td>
<td>0.290</td>
</tr>
<tr>
<td>$A_{K\pi}$</td>
<td>98</td>
<td>0.269</td>
<td>0.258</td>
<td>0.280</td>
</tr>
<tr>
<td>$A_{K\pi}$</td>
<td>108</td>
<td>0.273</td>
<td>0.262</td>
<td>0.284</td>
</tr>
</tbody>
</table>
Simulation of $\pi^+\pi$ pairs for long-lived $A_{2\pi}$ observation.

\[ Q_T = \sqrt{Q_X^2 + (Q_Y - 2.3)^2} \leq 2.0 \text{MeV/c} \]

\[ Q_T = \sqrt{Q_X^2 + (Q_Y - 2.3)^2} \leq 2.0 \text{MeV/c} \]

\[ Q_L = \sqrt{Q_X^2 + (Q_Y - 2.3)^2} \leq 2.0 \text{MeV/c} \]

\[ Q_T = \sqrt{Q_X^2 + (Q_Y - 2.3)^2} \leq 2.0 \text{MeV/c} \]
Experimental (real data) and simulated distributions over $|Q_L|$ for $Q_T < 0.5$ MeV/c

$n_A = 159 \pm 27$

$\sim 5.9\sigma$

$Q_T = \sqrt{Q_x^2 + (Q_y - 2.3\text{MeV}/c)^2}$
Long-lived $\pi^+\pi^-$ atoms

Experimental (real data) and simulated distributions over $|Q_L|$

For $Q_T < 1.0$ MeV/c

$$Q_T = \sqrt{Q_X^2 + (Q_Y - 2.3 \text{MeV}/c)^2}$$

$n = 415 \pm 53$

$\sim 7.8\sigma$
Experimental (real data) and simulated distributions over $|Q_L|$ for $Q_T < 1.5$ MeV/c

$$Q_T = \sqrt{Q_X^2 + (Q_Y - 2.3\text{MeV/c})^2}$$

$n_a = 433. \pm 78.$

$\sim 5.5\sigma$
Multiple scattering measurement
Multiple scattering measurement

- Be 100 mkm
- Pt 2 mkm
- Be 200 mkm
- 50mm X 50mm
- Ni 50 mkm
- Ni 100 mkm
- Ni 150 mkm
- Ni 98 mkm - old target
- Pt 30 mkm
- Ti 200 mkm
- 100mm X 25mm
Measurement of $A_{2\pi}$ production rate in $p$-Be interactions

Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of “Coulomb” and “non-Coulomb” pairs (dashed line).

Produced atom numbers normalized on the proton flux:

$N_{A_{2\pi}} / p = (5.1 \pm 0.5) \times 10^{-14}$ (2010)

$N_{A_{2\pi}} / p = (5.9 \pm 0.5) \times 10^{-14}$ (2011)
### Spectrometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The angle of the secondary channel relative to proton beam</td>
<td>5.7 ± 1°</td>
</tr>
<tr>
<td>Solid angle</td>
<td>1.2 \cdot 10^{-3} \text{ sr}</td>
</tr>
<tr>
<td>Dipole magnet</td>
<td>$B_{\text{max}} = 1.65 \text{ T}$</td>
</tr>
<tr>
<td></td>
<td>$BL = 2.2 \text{ Tm}$</td>
</tr>
<tr>
<td>Relative resolution on the particle momentum in L.S.</td>
<td>$3 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Precision on Q-projections (experimental measurement)</td>
<td>$\sigma_{QX} = \sigma_{QY} = 0.5 \text{ MeV/c}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{QL} = 0.5 \text{ MeV/c (}\pi\pi)$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{QL} = 0.9 \text{ MeV/c (}\pi\text{K)}$</td>
</tr>
</tbody>
</table>