1. DIRAC Experiment
2. $\pi^+\pi^-$ atom 2008-2010 data analysis
3. First measurement of the $K\pi$ atom lifetime
4. Observation of long-lived $\pi^+\pi^-$ states
5. Magnetic field influence on $Q_y$ for long-lived $\pi^+\pi^-$ atom measurements
6. Preshower within DIRAC setup
7. T8 proton halo beam influence evaluation
8. K$^+$K$^-$ pairs distributions
9. Publications, presentations and outreach
10. DIRAC – perspectives
1. DIRAC experiment
**DIRAC – Test of nonperturbative QCD**

Quantum Chromodynamics (QCD) is the general accepted strong interaction theory. It has successfully been tested only in the perturbative region of high momentum transfer \((Q > 2 \text{ GeV})\) or equally, at short relative distance \(\Delta x \sim h/Q\) \((\Delta x < 0.1 \text{fm})\). But it has not appropriate answers for non-perturbative processes.

Chiral Perturbation Theory (ChPT), the non-perturbative candidate of QCD, is replacing the QCD quark degrees of freedom by the pion ones.

By measuring *dimeson hadronic atoms lifetime*, DIRAC will determine in a model-independent way the difference \(|a_0 - a_2|\) between the S-wave \(\pi\pi\) scattering lengths \(a_0\) and \(a_2\). ChPT predicts the scattering lengths with high accuracy \(\sim 2\%\). Therefore such a measurement will be a sensitive check in understanding *Chiral symmetry breaking* of QCD, giving an indication about the size of the quark condensate - an order parameter of QCD.
- In the absence of strong interaction between $\pi^+$ and $\pi^-$ there exist the Coulomb bound states

  momentum: $k_n = i\kappa_n = \frac{i}{na_B}$

  energy: $E_n = -\frac{\kappa_n^2}{2m_r} = -\frac{m_r\alpha^2}{2n^2}$

- In the presence of strong interactions, the energies will be shifted.

  The real part of the energy shift $\Delta E_n$:

  $\text{Re}(\Delta E_n) \rightarrow \text{level shift}$

  The imaginary part of the energy shift:

  $-2\text{Im}(\Delta E_n) = \Gamma_n \rightarrow \text{decay width}$

$$\Gamma_0(\pi^+\pi^-) \equiv \frac{1}{\tau_0} = \frac{16\pi}{9} \sqrt{\frac{2\Delta m_\pi}{m_\pi}} (a_0 - a_2)^2 |\psi_C(0)|^2$$

  $\Delta m_\pi$ isospin symmetry breaking
  strong decay
  electromagnetic binding
Test some previsions of the CHPT as the nonperturbative QCD theory

Problem 1:  
DIRAC experimental setup design and construction

- DIRAC spectrometer  
  B. Adeva, ..., M. Pentia et al.  
  NIM A515 (2003) 467-496

- Preshower detector  
  M. Pentia et al.  
  NIM A603 (2009) 309-318

Problem 2:  
Observation of $\pi^+\pi^-$ and $\pi K$ atoms

- Detection of $\pi^+\pi^-$ atoms with the DIRAC spectrometer at CERN.  
  B. Adeva, ..., M. Pentia et al.  

Problem 3:  
Lifetime measurement of $\pi^+\pi^-$ and $\pi K$ atoms

- First measurement of the $\pi^+\pi^-$ atom lifetime.  
  B. Adeva, ..., M. Pentia et al.  

Problem 4:  
Determination of the $\pi^+\pi^-$ and $\pi K$ scattering lengths

- Determination of $\pi\pi$ scattering lengths from measurement of $\pi^+\pi^-$ atom lifetime.  
  B. Adeva, ..., M. Pentia et al.  

Next steps

- DIRAC II setup to be processed and published
- Preshower for DIRAC II setup to be processed and published
- Evidence for $\pi K$ atoms with DIRAC.  
  B. Adeva, ..., M. Pentia et al.  

- Lifetime measurement of $\pi^+\pi^-$ metastable atom to be processed and published

- Lambda shift determination in $\pi^+\pi^-$ atoms to be processed and published

- Lifetime measurement of $\pi^+\pi^-$ and $\pi K$ atom PS data to be processed to be done at SPS

- Determination of $\pi^+\pi^-$ and $\pi K$ scattering length PS data to be processed to be done at SPS

- Lifetime measurement of $K^+K^-$ atom to be done at SPS

- Determination of $K^+K^-$ scattering length to be done at SPS

New DIRAC setup to design and construct

01-Nov-13

M. Pentia IFIN-HH
Target Ni 98 μm

Production point

$p_{24 \text{ GeV/c}}$

Target – two functions:
1. $A_{2\pi}$ production
2. $A_{2\pi}$ ionization

Coincidence events measured with DIRAC detector.

Atomic pairs

$A_{2\pi}$ production

Coulomb pairs

Non-Coulomb pairs

Accidental pairs

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

$\eta, \eta', \ldots$

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

Coulomb + Non-Coulomb + Atomic Pairs (time correlated)

$\sigma_{\Delta t} = 190 \text{ ps}$

time window $= \pm 500 \text{ ps}$

accidental background
1 Target station with Ni foil; 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
2. $\pi^+\pi^-$ atom 2008-2010 data analysis
### $\pi^+\pi^-$ pairs analysis - run 2008-2010

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2008-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_A(Q_L)$</td>
<td>13141±129</td>
<td>19774±153</td>
<td>19474±155</td>
<td>52389±253</td>
</tr>
<tr>
<td>$N_A(Q_L-Q_T)$</td>
<td>13245±114</td>
<td>20072±137</td>
<td>19732±138</td>
<td>53048±225</td>
</tr>
<tr>
<td>$n_A(Q_L)$</td>
<td>6140±352</td>
<td>9769±419</td>
<td>9397±420</td>
<td>25306±690</td>
</tr>
<tr>
<td>$n_A(Q_L-Q_T)$</td>
<td>5537±233</td>
<td>8384±284</td>
<td>8033±284</td>
<td>21954±465</td>
</tr>
<tr>
<td>$P_{br}(Q_L)$</td>
<td>0.467±0.030</td>
<td>0.494±0.024</td>
<td>0.483±0.024</td>
<td>0.483±0.0148</td>
</tr>
<tr>
<td>$P_{br}(Q_L-Q_T)$</td>
<td>0.418±0.020</td>
<td>0.418±0.016</td>
<td>0.407±0.016</td>
<td>0.414±0.010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{br}(2001-2003)=0.446±0.0093$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. First measurement of the $K\pi$ atom lifetime
# $K^-\pi^+$ and $K^+\pi^-$ pair analysis – run 2008-2010

<table>
<thead>
<tr>
<th></th>
<th>$K^-\pi^+$ pairs 2008-2010</th>
<th>$K^+\pi^-$ pairs 2008-2010</th>
<th>$K^-\pi^+$ and $K^+\pi^-$ pairs sum 2008-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_A(Q_L)$</td>
<td>206±25</td>
<td>431±44</td>
<td>638±50</td>
</tr>
<tr>
<td>$N_A(Q_L-Q_T)$</td>
<td>188±21</td>
<td>465±37</td>
<td>653±42</td>
</tr>
<tr>
<td>$n_A(Q_L)$</td>
<td>60±39</td>
<td>140±66</td>
<td>200±76</td>
</tr>
<tr>
<td>$n_A(Q_L-Q_T)$</td>
<td>82±26</td>
<td>96±41</td>
<td>178±49</td>
</tr>
<tr>
<td>$P_{br}(Q_L)$</td>
<td>0.29±0.22</td>
<td>0.325±0.18</td>
<td>0.31±0.14</td>
</tr>
<tr>
<td>$P_{br}(Q_L-Q_T)$</td>
<td>0.44±0.18</td>
<td>0.207±0.101</td>
<td>0.27±0.09</td>
</tr>
<tr>
<td>$P_{br}$ theor</td>
<td></td>
<td></td>
<td>$0.278 \pm 0.012$</td>
</tr>
</tbody>
</table>

M. Pentia IFIN-HH

01-Nov-13
The first $K\pi$ atom lifetime measurement (preliminary results)

The ionization probability ($P_{br}$) dependence on the lifetime ($\tau$) of the $K\pi$ atom in ground state

The lifetime ($\tau$) dependence on the scattering length difference $|a_{1/2} - a_{3/2}|$ of the $K\pi$ atom

The total number of the produced $K\pi$ atoms: 653±42

$\tau^{\text{th}} = (3.5 \pm 0.4) \times 10^{-15}$ s

$\tau^{\text{exp}} = \left(3.2 \pm \frac{3.6}{2.1}\right) \times 10^{-15}$ s

$\frac{1}{3} \cdot |a_{1/2} - a_{3/2}|^{\text{exp}} = 0.095 \pm 0.067 - 0.035$

$\frac{1}{3} \cdot |a_{1/2} - a_{3/2}|^{\text{th}} = 0.09 \pm 0.005$

DIRAC
4. Observation of long-lived $\pi^+\pi^-$ states
**Observation of long-lived $\pi^+\pi^-$ atoms**

$Q_L$ ($Q_T$) longitudinal (transversal) component of the $\pi^+\pi^-$ CMS relative momentum. $Q_T < 1.5\text{MeV/c}$ cut can separate the $\pi^+\pi^-$ pairs produced by atom breakup in $Pt$ foil and $\pi^+\pi^-$ pairs produced in $Be$ target.

The $Q_L$ distribution shows an excess of events above background with a significance of $5\sigma$, which is a possible signal of long-lived $\pi^+\pi^-$ atoms breaking into $ns-np$ states.

**Experimental $\pi^+\pi^-$ pair $Q_L$ distribution and background fit**

Observation of long-lived $\pi^+\pi^-$ state opens the possibility to measure the energy split $\Delta E(ns-np)$ between $ns$ and $np$ states and also the $\pi\pi$ scattering lengths combination $|2a_0+a_2|$.
5. Magnetic field influence on $Q_y$ for long-lived $\pi^+\pi^-$ atom measurements
$Q_y$ distribution for $e^+e^-$ pairs

<table>
<thead>
<tr>
<th>Be target 100 μm</th>
<th>Magnetic Field</th>
<th>Pt foil 2 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$Q_y \approx 12.5\text{MeV/c}$

$Q_y < 2.5\text{MeV/c}$

2.5 MeV/c

12.5 MeV/c

01-Nov-13

M. Pentia IFIN-HH
6. Preshower within DIRAC setup
Preshower $\pi$-detection and $e$-rejection efficiency

Two layers preshower $\pi$-detection efficiency

Two layers preshower $e$-rejection efficiency
7. T8 proton halo beam influence evaluation
Measurement of the proton beam halo interaction with Pt foil (located at $\Delta y = 7.5\, \text{mm}$ from the beam axis). The counting rate of the secondaries produced in Pt foil is measured by IHA7 and IHA8 strips of the Ionization Hodoscope.

Figure shows the beam mean $y$-position (50% probability) at $\mu=8.6\, \text{mm}$ and for $\mu-\sigma_y$, a probability 16% which corresponds to an estimate

$$\sigma_y \approx 1.75\, \text{mm}$$
8. \( K^+K^- \) pairs distributions
2010 data: distribution of pairs on $(t_+ + t_-)/2$ for $p = (1800,2000)$ MeV/c

$P = (1800,2000)$ MeV/c

$\pi^+\pi^-$ pairs

$K^+K^-$ pairs

$\bar{p}p$ pairs

entries vs $(t_+ + t_-)/2$ [ps]
9. Publications, presentations and outreach


4. B.Adeva, et all. “Updated DIRAC spectrometer at CERN PS for investigation of $\pi^+\pi^-$ and $K\pi$ atoms” (in progress).


6. CERN Courier: Outreach - “DIRAC observes dimeson atoms and measures their lifetime” http://cerncourier.com/cws/article/cern/48623

7. Outreach - DIRAC presentation of the “CERN OpenDays 2013” 28-29 September 2013, within Experiments carried at CERN.
10. DIRAC – perspectives
Test some previsions of the CHPT as the nonperturbative QCD theory

**Problem 1:**
DIRAC experimental setup design and construction

**Problem 2:**
Observation of $\pi^+\pi^-$ and $\pi K$ atoms

**Problem 3:**
Lifetime measurement of $\pi^+\pi^-$ and $\pi K$ atoms

**Problem 4:**
Determination of the $\pi^+\pi^-$ and $\pi K$ scattering lengths

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**DIRAC spectrometer**
B. Adeva, ..., M. Pentia *et al.*
*NIM A515* (2003) 467-496
Preshower detector
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*NIM A603* (2009) 309-318

Detection of $\pi^+\pi^-$ atoms with the DIRAC spectrometer at CERN.
B. Adeva, ..., M. Pentia *et al.*

First measurement of the $\pi^+\pi^-$ atom lifetime.
B. Adeva, ..., M. Pentia *et al.*

Determination of $\pi\pi$ scattering lengths from measurement of $\pi^+\pi^-$ atom lifetime.
B. Adeva, ..., M. Pentia *et al.*

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**To be processed and published existing PS data**

**DIRAC II setup**
Preshower for DIRAC II setup

Observation of $\pi^+\pi^-$ metastable atom

Lifetime measurement of $\pi^+\pi^-$ metastable atom

Lamb shift determination in $\pi^+\pi^-$ atoms

Determination of $\pi^+\pi^-$ and $\pi K$ scattering lengths to be done also at SPS

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**New DIRAC setup**
to design and construct

Detection of $K^+K^-$ atom

Lifetime measurement of $K^+K^-$ atom to be done also at SPS

Determination of $K^+K^-$ scattering length to be done at SPS
Based on enormous existing experimental data, in the next two years they will be analyzed and processed as follows:


3. Run 2012 data analysis for metastable $\pi^+\pi^-$ hadronic atom detection.

4. Determination of $\pi^+\pi^-$ and $\pi K$ hadronic atom lifetime based on existing data.

5. Determination of metastable $\pi^+\pi^-$ atom lifetime.

6. Determination of the $\pi^+\pi^-$ and $\pi K$ scattering lengths.
DIRAC demonstrated for the first time, the existence of the $\pi K$ hadronic atom*).

For the first time we measured the lifetime of the $\pi K$ hadronic atom. Next, we will try to study the properties and to evaluate the $\pi K$ scattering lengths to test the Chiral Perturbation Theory predictions with three quarks.

The DIRAC Collaboration will send a new proposal to the CERN Scientific Council.

Thank you
L’expérience n_TOF mesure le temps de vol des particules. Ces résultats sont utiles à différentes disciplines comme l’astrophysique ou le traitement des déchets radioactifs.

The n_TOF experiment measures particles’ time of flight. Its results are useful for many disciplines, from astrophysics to the treatment of radioactive waste.

Les chercheurs de DIRAC veulent mieux comprendre la “force forte”. Elle est cruciale car elle assure la cohésion des plus petits composants de la matière.

The goal of DIRAC is to improve our understanding of the “strong force” which plays a crucial role in holding the smallest components of matter together.

Alors on pourrait dire que la force forte est un peu comme la Super Gue de l’Univers?

Oui c’est un peu ça...

Oui, you could say that.

Des, you could say that.

"Les physiciens ont de l’humour. Comme cette hypothétique particule qui pourrait dissoudre le monde Standard..."

"Physicists have a good sense of humour. This hypothetical particle has the potential to dissolve some of the problems of the Standard Model, so they decided to call it something that sounds like a washing powder: DIRAC!"

"Mais c'est un peu ça..."
### Experimental conditions (run 2008-2010)

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary proton beam</strong></td>
<td>24 GeV/c</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>((10.5 \div 12) \cdot 10^{10}) proton/spill</td>
</tr>
<tr>
<td><strong>Single count of one IH plane</strong></td>
<td>((5 \div 6) \cdot 10^6) particle/spill</td>
</tr>
<tr>
<td><strong>Spill duration</strong></td>
<td>450 ms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ni target</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purity</strong></td>
<td>99.98%</td>
</tr>
<tr>
<td><strong>Target thickness (year)</strong></td>
<td>(98 \pm 1) μm (2008)</td>
</tr>
<tr>
<td><strong>Radiation thickness</strong></td>
<td>(6.7 \cdot 10^{-3} X_0)</td>
</tr>
<tr>
<td><strong>Probability of inelastic proton interaction</strong></td>
<td>(6.4 \cdot 10^{-4})</td>
</tr>
</tbody>
</table>
\[ Q_L \] distribution analysis on \( |Q_L| \) for \( Q_T < 4 \text{ MeV/c} \)

\[ N_x = 52389 \pm 253, \quad n_x = 25306 \pm 690, \quad P_{\text{br}} = 0.483 \pm 0.015 \]

\[ N_x = 53048 \pm 225, \quad n_x = 21954 \pm 465, \quad P_{\text{br}} = 0.414 \pm 0.010 \]
$Q_T$ distribution analysis on $|Q_L|$, $Q_T$ for $|Q_L| < 2$ MeV/c

$Q_T$ distribution analysis on $|Q_L|$, $Q_T$ for $|Q_L| > 2$ MeV/c
**|Q_L| distribution analysis on |Q_L| for Q_T < 4 MeV/c**

**|Q_L| distribution analysis on |Q_L|, Q_T for Q_T < 4 MeV/c**

N_A = 206. ± 25.

n_A = 60. ± 39.

P_{Br} = 0.29 ± 0.22

N_A = 188. ± 21.

n_A = 82. ± 26.

P_{Br} = 0.44 ± 0.18
**|Q_L| distribution analysis on |Q_L| for Q_T < 4 MeV/c**

- **Atomic pairs**
  - Coulomb pairs
  - non-Coulomb pairs

**|Q_L| distribution analysis on |Q_L|, Q_T for Q_T < 4 MeV/c**

- **N_A = 432. ±44.**
- **n_A = 140. ±66.**
- **P_{Br} = 0.32 ± 0.18**

01-Nov-13

M. Pentia IFIN-HH
**K^-\pi^+ and K^+\pi^- atoms – run 2008-2010**

**Atomic pairs**

- Coulomb pairs
- non-Coulomb pairs

**|Q_L| distribution analysis on |Q_L| for Q_T < 4 MeV/c**

- N_A = 638. ±50.
- n_A = 200. ±76.
- P_{Br} = 0.31 ±0.14

**|Q_L| distribution analysis on |Q_L|, Q_T for Q_T < 4 MeV/c**

- N_A = 653. ±42.
- n_A = 178. ±49.
- P_{Br} = 0.27 ±0.09