Status Report of the DIRAC Experiment - PS 212

L. Nemenov (CERN – JINR)

SPSC – 21 October 2014

DIRAC Collaboration

CERN
Geneva, Switzerland

Czech Technical University
Prague, Czech Republic

Institute of Physics ASCR
Prague, Czech Republic

Nuclear Physics Institute ASCR
Rez, Czech Republic

INFN-Laboratori Nazionali di Frascati
Frascati, Italy

University of Messina
Messina, Italy

KEK
Tsukuba, Japan

Kyoto University
Kyoto, Japan

Kyoto Sangyo University
Kyoto, Japan

Tokyo Metropolitan University
Tokyo, Japan

IFIN-HH
Bucharest, Romania

JINR
Dubna, Russia

SINP of Moscow State University
Moscow, Russia

IHEP
Protvino, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
Bern, Switzerland

Zurich University
Zurich, Switzerland

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7. $K^+\pi^-$, $K^-\pi^+$, $\pi^+\pi^-$, K^+K^- atom production analysis at p_p=24GeV/c and p_p=450GeV/c
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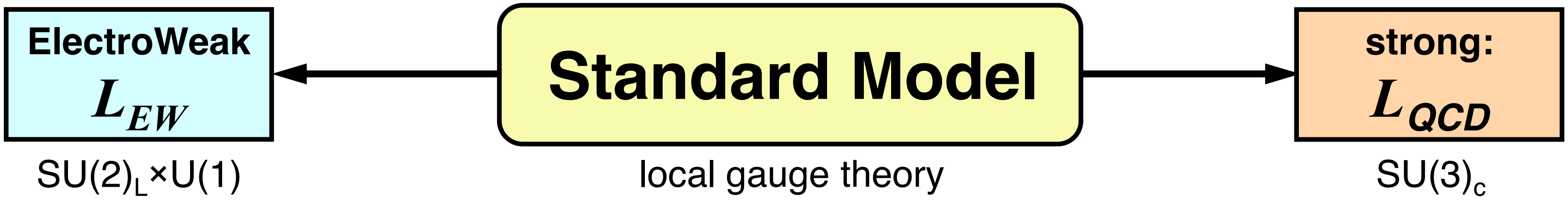
Theoretical motivation



ElectroWeak

L_{EW}

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

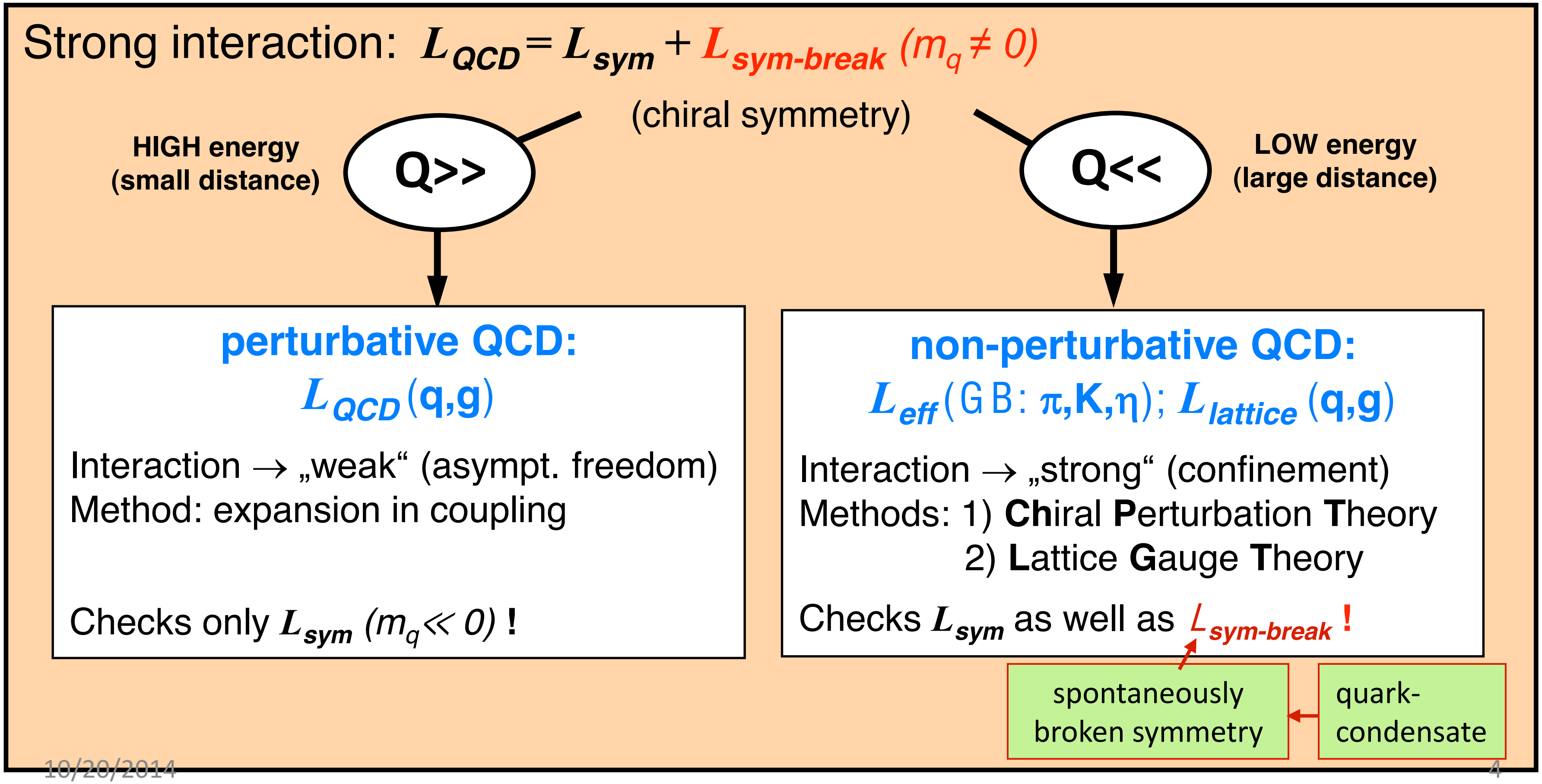
Standard Model

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>>

LOW energy
(large distance)

Q<<

perturbative QCD:

$L_{QCD}(q,g)$

Interaction → „weak“ (asympt. freedom)
Method: expansion in coupling

Checks only $L_{sym}\ (m_q \ll 0)$ **!**

non-perturbative QCD:

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

Interaction → „strong“ (confinement)
Methods: 1) **Chi**ral **P**erturbation **T**heory
2) **L**attice **G**auge **T**heory

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

spontaneously broken symmetry

quark-condensate

1. π^+K^- and π^-K^+ atoms

Published paper: First **πK** atom lifetime and **πK** scattering length measurements, *Physics Letters B* 735 (2014) 288

In this paper, characteristic πK pairs from πK atom breakup in the Ni target have been observed, as many as

178±**49 (3.6σ)** πK atomic pairs as well as
653±42 produced πK atoms

Based on these results, the first measurement of the πK atom lifetime has been deduced

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

and the first measurement of the S-wave isospin-odd πK 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.

π^+K^- and π^-K^+ atoms

The procedure to process and analyse pairs with high background (in the remaining 1/3 of total statistics) has been developed using large statistics of $\pi^+\pi^-$ pairs.

The same analysis will be used for $K\pi$-atoms because the multiplicity in all detectors is the same for $\pi\pi$ and $K\pi$ triggers.

To enlarge the $K\pi$ atomic pair statistics, the 2007 $K^-\pi^+$ and $K^+\pi^-$ atom data, collected on *Pt* target, will be reprocessed. The expected significance of the expected number of atomic pairs measured in 2007 and 2009-2010 runs will be around 5 standard deviations. This work and dedicated publication will be finished in October 2015.

2. *Long-**lived** $\pi^+\pi^-$ atom analysis*

Theoretical motivation

ππ scattering length

In ChPT the effective Lagrangian, which describes the ππ interaction, is an expansion in terms:

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

G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B603 (2001) 125, using ChPT (2-loop) & Roy equations:

$$\left.\begin{array}{l} a_0 = \quad 0.220 \pm 2.3\% \\ a_2 = -0.0444 \pm 2.3\% \end{array}\right\} \quad a_0 - a_2 = 0.265 \pm 1.5\%$$

These results (precision) depend on the low-energy constants (LEC) l_3 and l_4:
Lattice gauge calculations from **2006** provided values for these l_3 and l_4.

Theoretical motivation

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

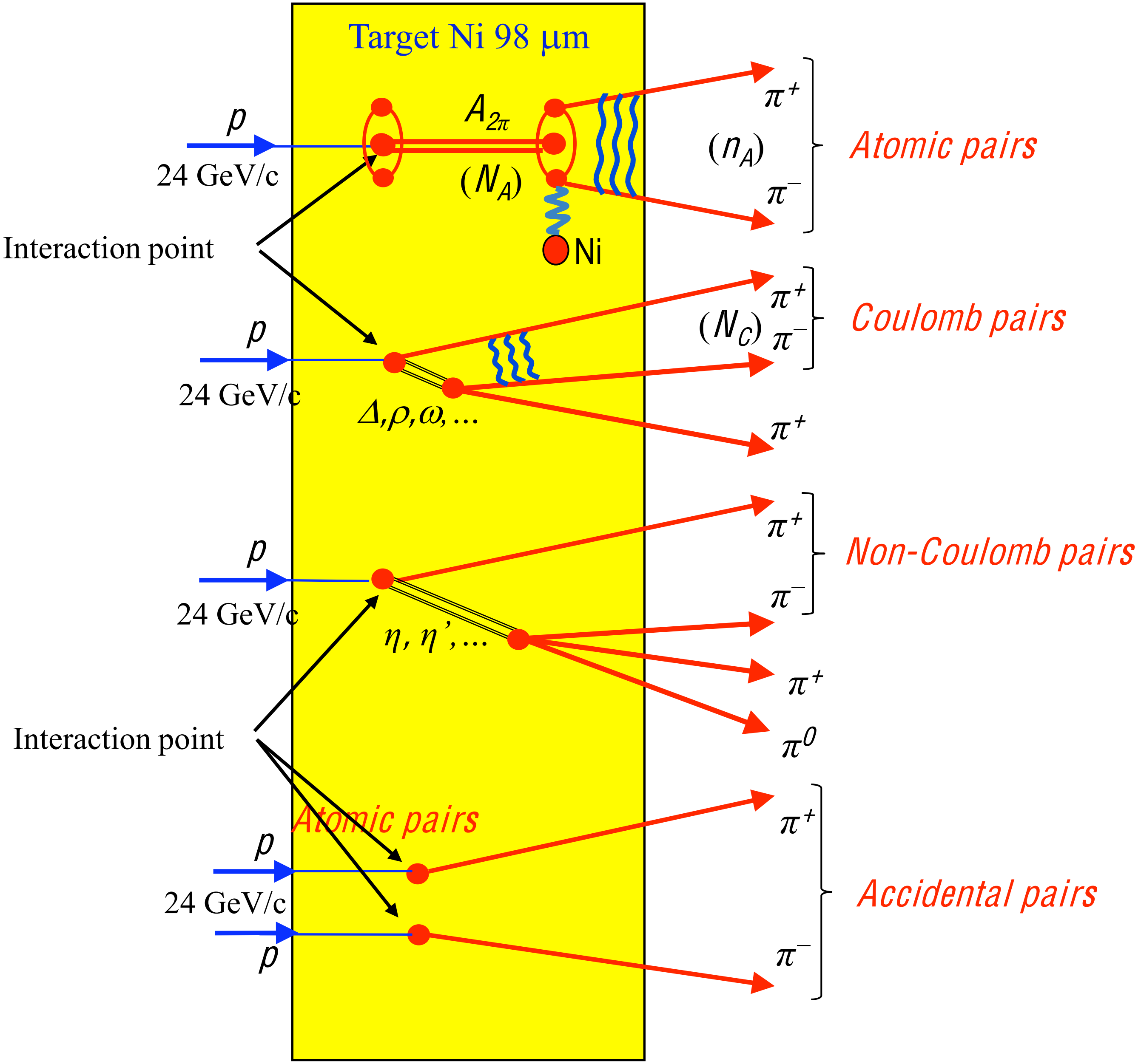
- 2006: $\bar{l}_3, \bar{l}_4$ First lattice calculations
- 2012: 10 collaborations: 3 USA, 5 Europe, 2 Japan
- J. Gasser, H. Leutwyler: Model calculation (1985)
  $\bar{l}_3 = 2.9 \pm 2.4$, $\bar{l}_4 = 4.3 \pm 0.9$

- Lattice calculations of these constants were done in 20 works.

The best result(BMW) is $\bar{l}_3 = 2.6 \pm 0.5\text{st} \pm 0.4\text{syst}$, $\bar{l}_4 = 3.8 \pm 0.4\text{st} \pm 0.2\text{syst}$

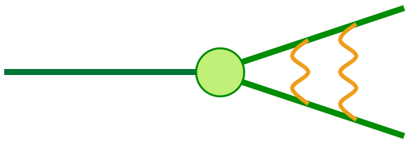
Therefore the theoretical pion-pion scattering length precision can be improved.
The best experimental results on the scattering length have precision more than 4%.

Method of $A_{2\pi}$ observation and measurement



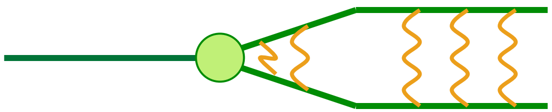
Coulomb pairs and atoms

For the charged pairs from the short-lived sources and small relative momentum Q there is strong Coulomb interaction in the final state.
This interaction increases the production yield of the free pairs with Q decreasing and creates atoms.



$\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$,
K^+K^-, $\pi^+\mu^-$, $\pi^-\mu^+$

Coulomb pairs



$(\pi^+\pi^-)$, $(K^+\pi^-)$, $(K^-\pi^+)$,
(K^+K^-), $(\pi^+\mu^-)$, $(\pi^-\mu^+)$

Atoms

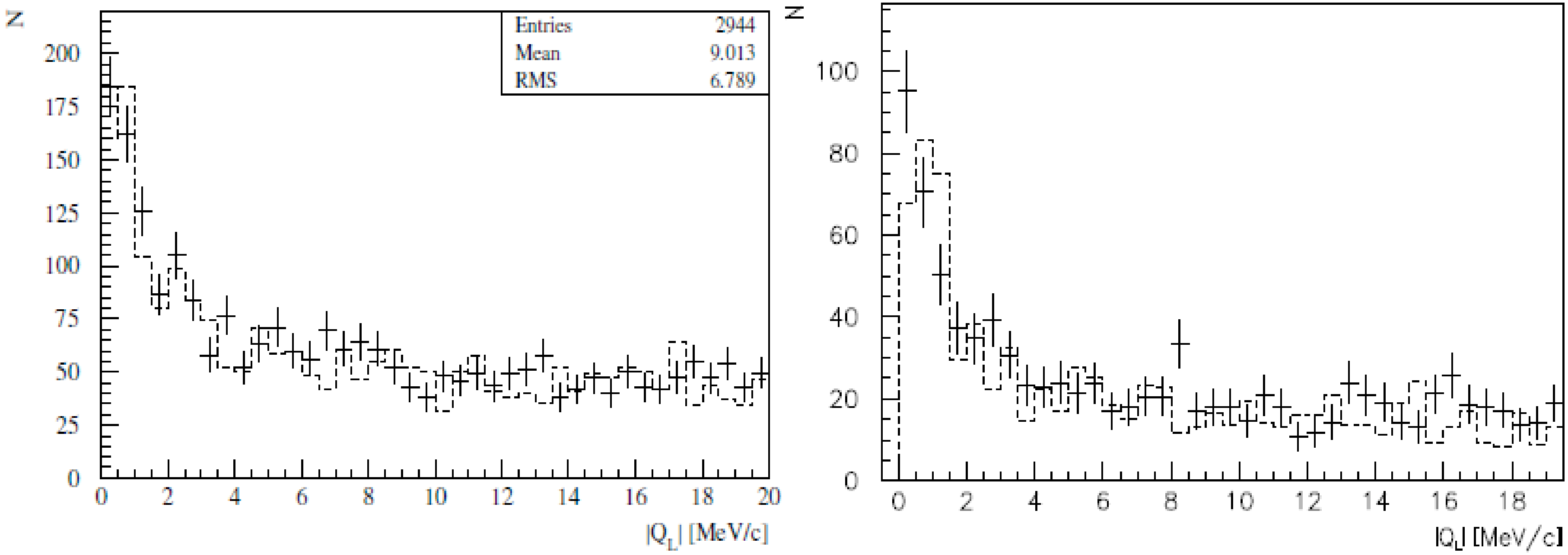
There is precise ratio between the number of produced Coulomb pairs (N_C) with small Q and the number of atoms (N_A) produced simultaneously with these Coulomb pairs:

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

$$\boxed{n_A \text{ - atomic pairs number}, \quad P_{br} = \frac{n_A}{N_A}}$$

Measurement of $A_{2\pi}$ production rate in p-Be interactions

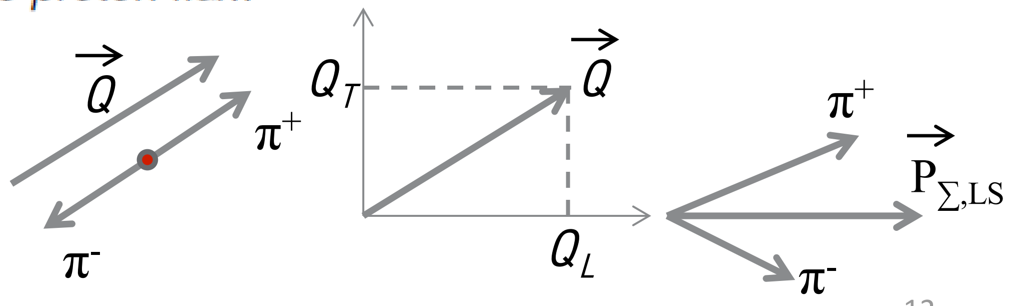
Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of "Coulomb" and "non-Coulomb" pairs (dashed line).



Produced atom numbers normalized on the proton flux:

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

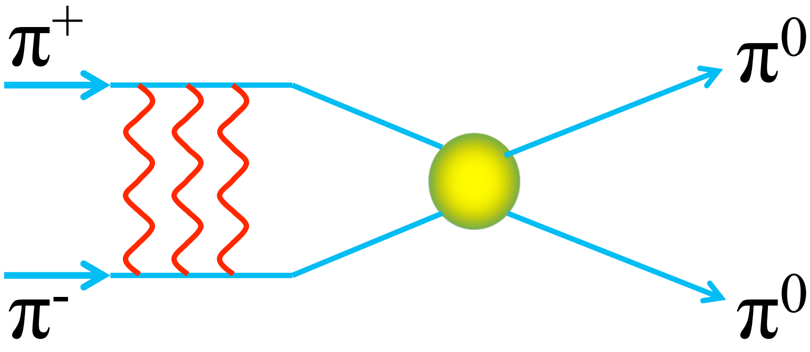
$N_{A_{2\pi}}/p = (5.9 \pm 0.5) \times 10^{-14}$ *(2011)*



$\pi^+\pi^-$ atom lifetime

$\pi^+\pi^-$ atom (pionium) is a hydrogen-like atom consisting of π^+ and π^- mesons:

$E_B = -1.86$ keV, $r_B = 387$ fm, $p_B \approx 0.5$ MeV/c



The lifetime of $\pi^+\pi^-$ atom is dominated by the decay into $\pi^0\,\pi^0$ mesons:

$$\boxed{\Gamma = \frac{1}{\tau} = \Gamma_{2\pi^0} + \Gamma_{2\gamma}} \qquad \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4\times 10^{-3}$$

$$\boxed{\Gamma_{ns\to 2\pi^0} = R\left|\psi_{ns}(0)\right|^2 \left|a_0 - a_2\right|^2} \qquad \boxed{\tau_{1s} = \left(2.9 \pm 0.1\right)\times 10^{-15}\, s}$$

a_0 and a_2 are the $\pi\pi$ s-wave scattering lengths for isospin I=0 and I=2.

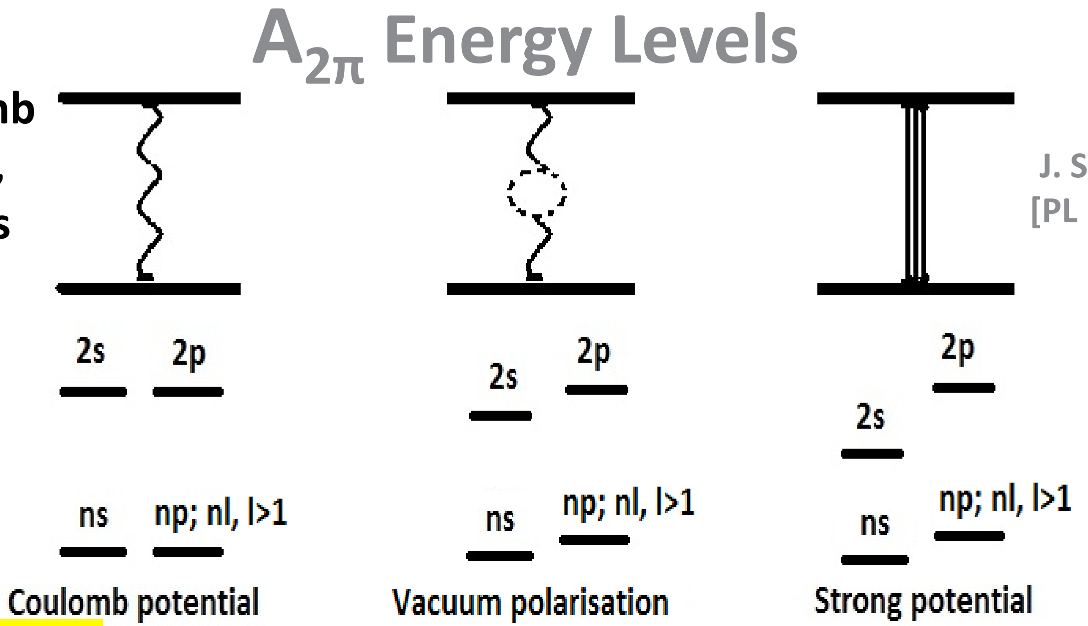
$$\psi_{nl}(0)\begin{cases} \neq 0 \text{ for } \ l = 0 & A_{2\pi}(1s, 2s,\ldots,ns) \longrightarrow \pi^0\pi^0 \\ = 0 \text{ for } \ l \neq 0 & A_{2\pi}(np) \xrightarrow{\gamma} A_{2\pi}(1s, 2s,\ldots(n\text{-}1)s) \longrightarrow \pi^0\pi^0 \end{cases}$$

The lifetime of np states depends on transition $np \longrightarrow 1s, 2s,\ldots,(n\text{-}1)s$ probability

This probability is about three orders less than $ns \longrightarrow \pi^0\pi^0$

Energy splitting measurement

For Coulomb
potential,
E depends
only on n



J. Schweizer
[PL B (2004)]

higher order QED

Notation:

$E_{2s} - E_{2p} = \Delta_{2s-2p}$

$\Delta^{vac}_{2s-2p} = -0.111\,\text{eV}$ $\Delta^{str}_{2s-2p} = -0.47 \pm 0.01\,\text{eV}$ $\Delta^{em}_{2s-2p} = -0.012\,\text{eV}$

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

$$\Delta^{str}_{2s-2p} = -\frac{\alpha^3 m_\pi}{8}\frac{1}{6}\left(2a_0 + a_2\right) + \cdots$$

G.V.Efimov et al.
Sov.J.Nucl.Phys.
(1986)

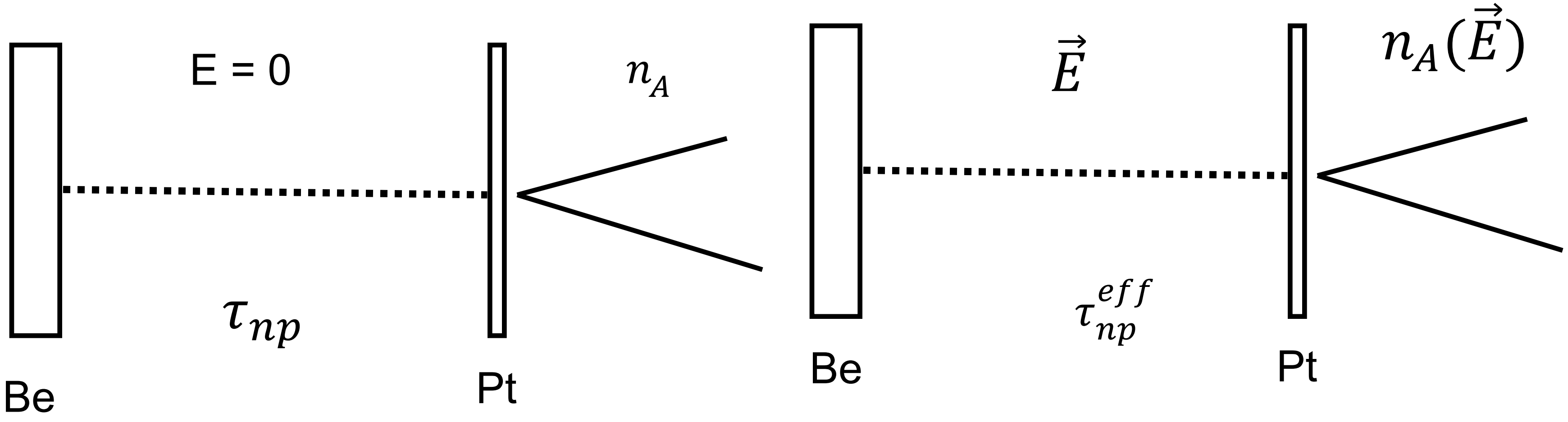
$$\Delta^{str}_{ns-np} = -\frac{\Delta^{str}_{2s-2p}}{n^3} \cdot 8$$

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

Energy splitting measurement

In the static electric field there will be Stark mixing between the ns and the np wave functions.

$$\tau_{np} = \tau_{np}^{eff}\left(\left|\vec{E}\right|, \Delta E_{ns-np}\right), \qquad \tau_{np}^{eff} < \tau_{np}$$

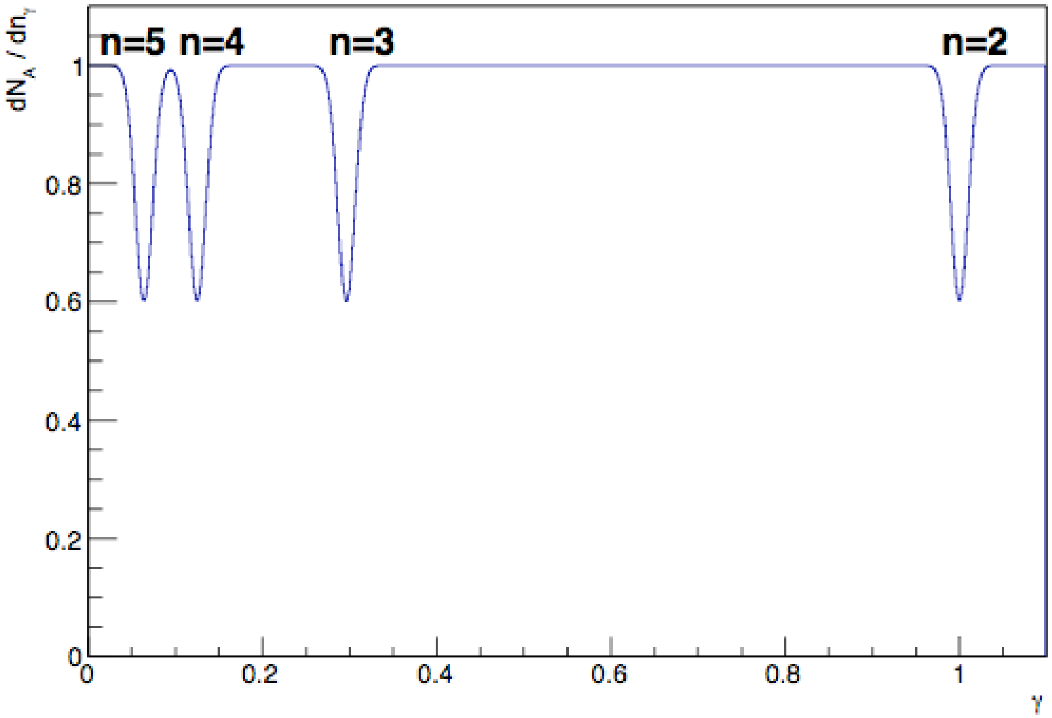


$$n_A - n_A\left(\left|\vec{E}\right|\right) = \Delta n\left(\left|\vec{E}\right|, \Delta E_{ns-np}\right)$$

Only relative abundances of different atomic quantum states are taken from theory

Energy splitting measurement

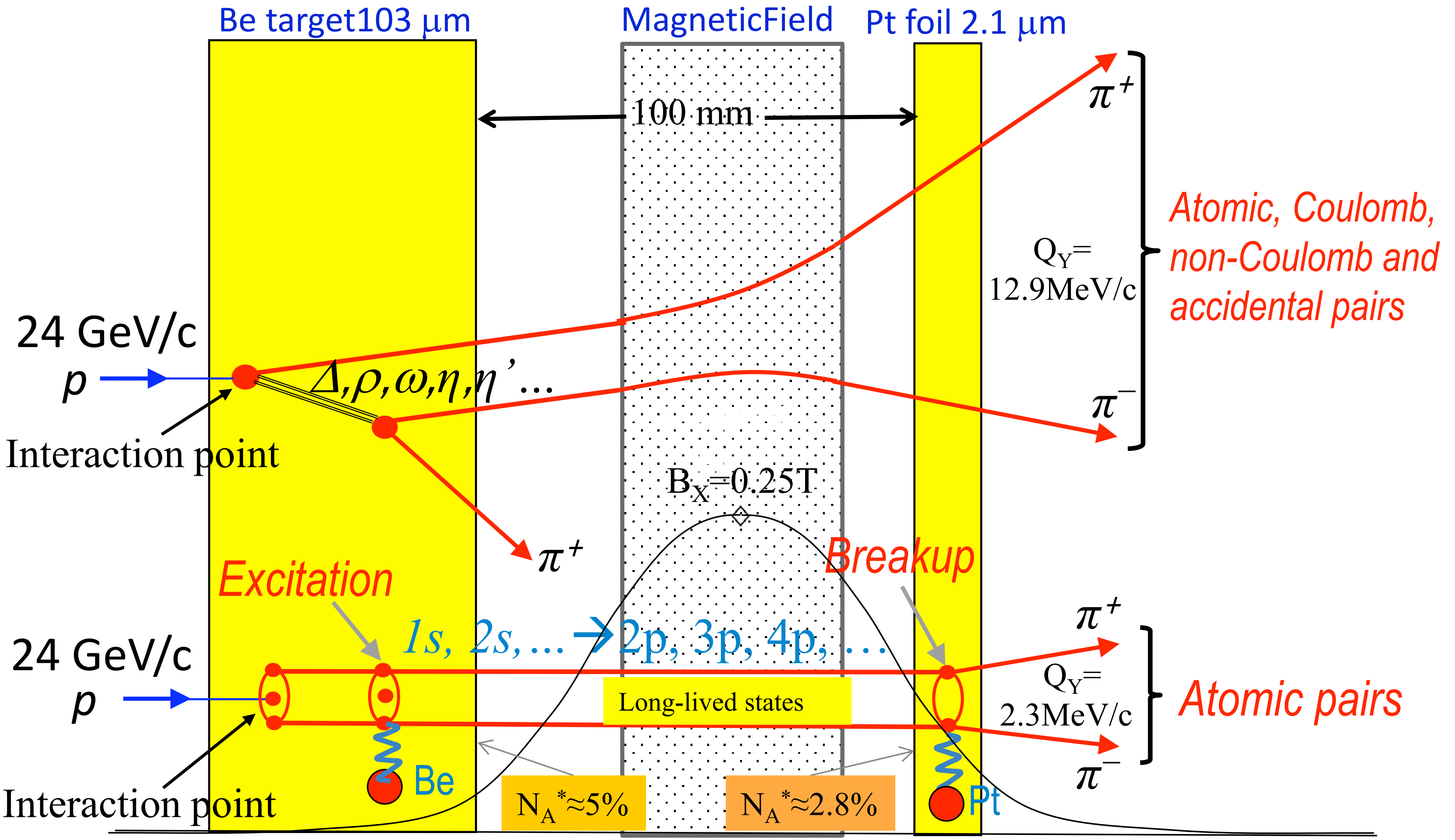
In the periodic electric field there will be oscillations between ns and np states if the external field frequency will coincide with ns-np frequency.



$$\omega_{ns-np} = \gamma_n \omega_{lab}$$

No theoretical input!

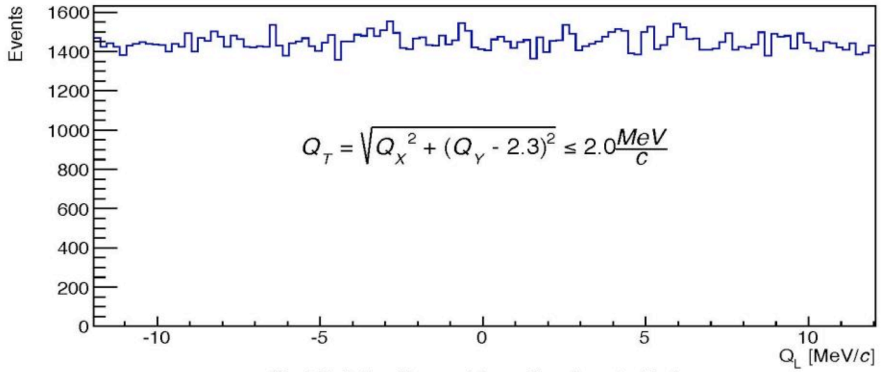
Method for observing long-lived $\pi^+\pi^-$ atom with breakup Pt foil



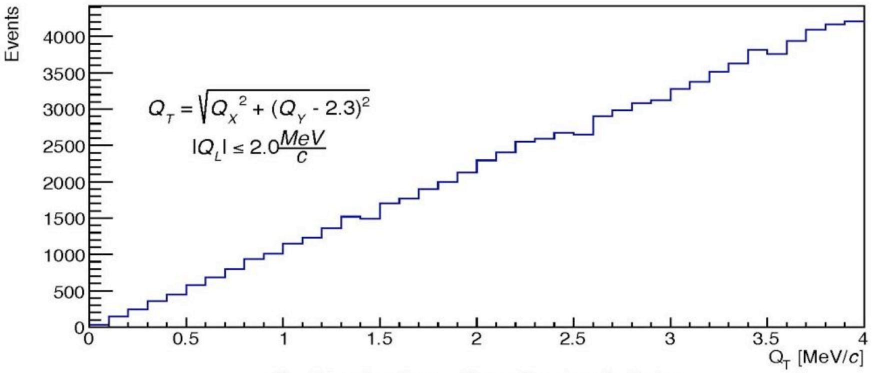
for $\gamma = 16$

$l(2p) = 5.6$ cm, $l(3p) = 19$ cm, $l(4p) = 43$ cm, $l(5p) = 84$ cm, $l(6p) = 144$ cm
$l(2s) = 0.11$ mm, $l(3s) = 0.38$ mm, $l(4s) = 0.89$ mm, $l(5s) = 1.74$ mm, $l(6s) = 3$ mm

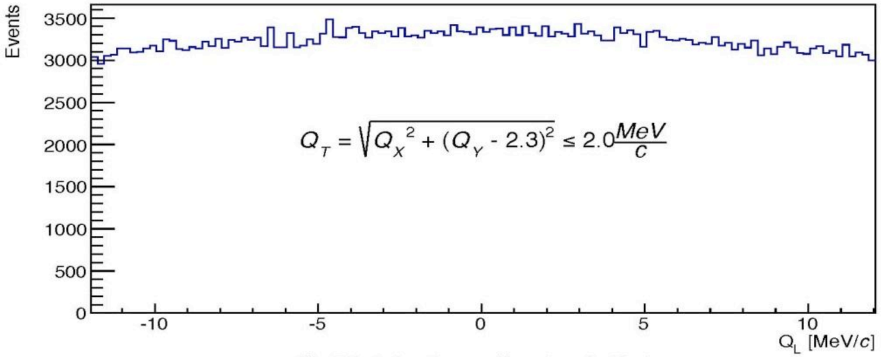
Simulation of $\pi^+\pi^-$ pairs for long-lived $A_{2\pi}$ observation



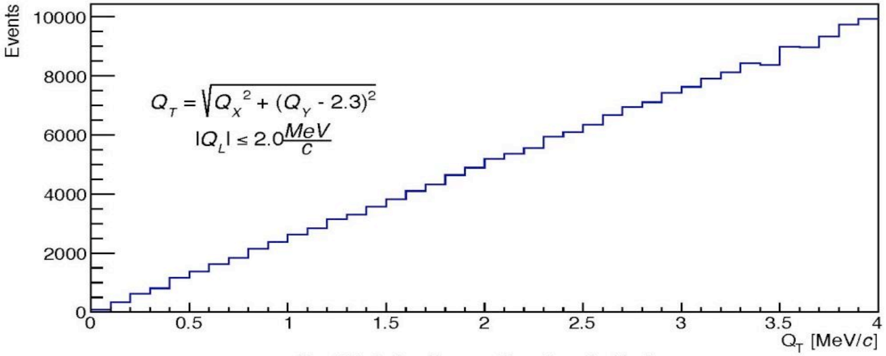
Q_l Distribution - Non-Coulomb Pairs



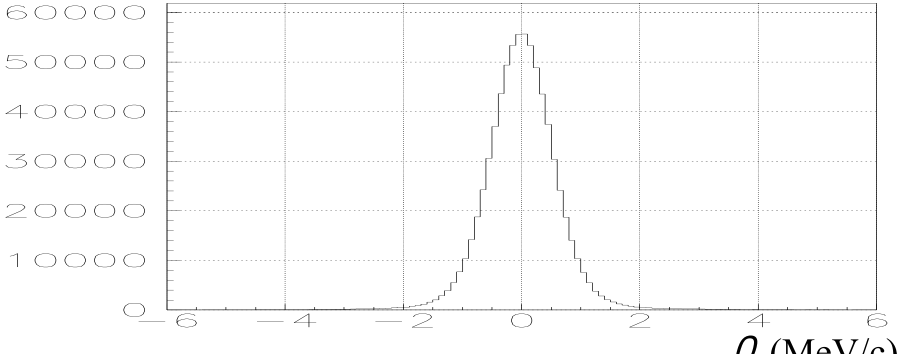
Q_T Distribution - Non-Coulomb Pairs



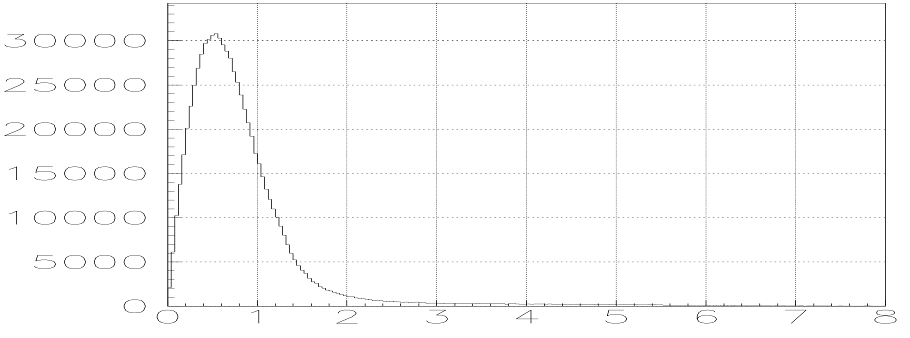
Q_L Distribution - Coulomb Pairs



Q_T Distribution - Coulomb Pairs



Atomic pairs



Atomic pairs

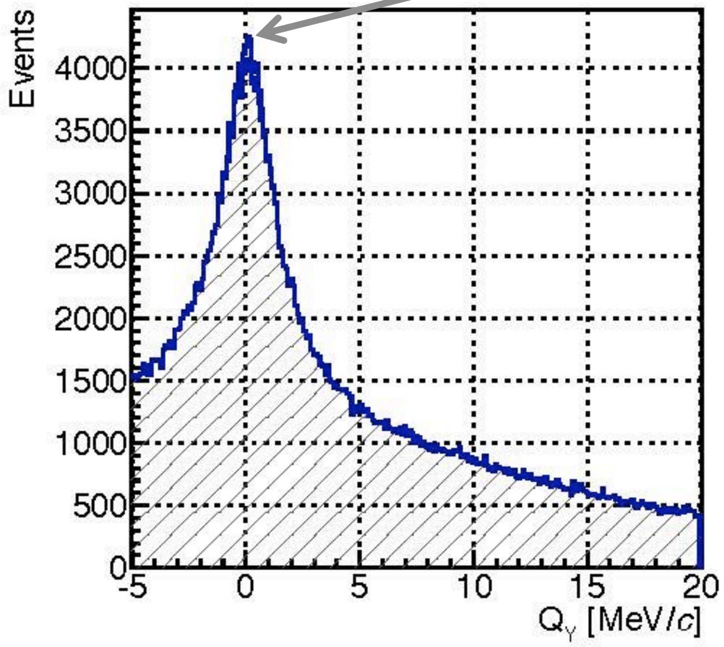
The background reduction with magnetic field for long-lived $A_{2\pi}$ observation

V. Yazkov

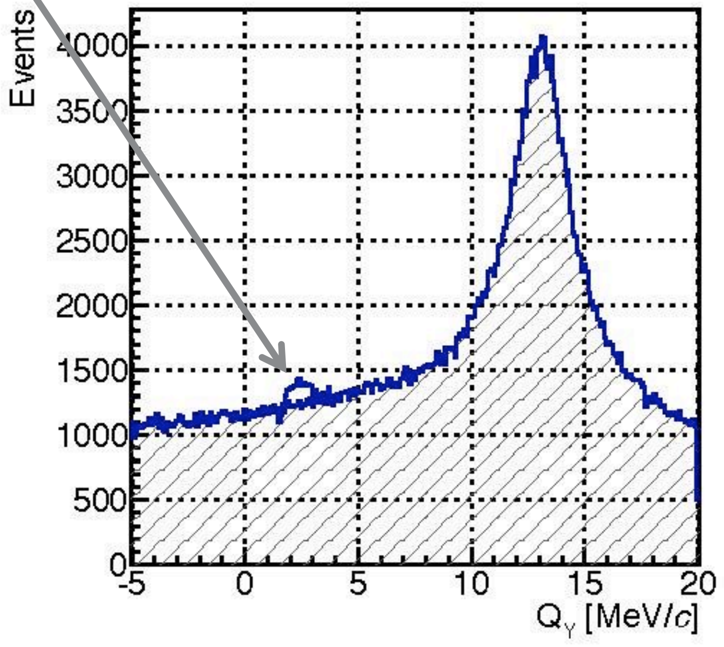
Q_y distribution of “atomic pairs” (signal) above the background of $\pi^+\pi^-$ Coulomb pairs produced in Beryllium target, without (left) and with (right) magnet used in 2012 run.

Selected events with the cut: $\sqrt{Q_X^2 + Q_L^2} < 2\,MeV/c$

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

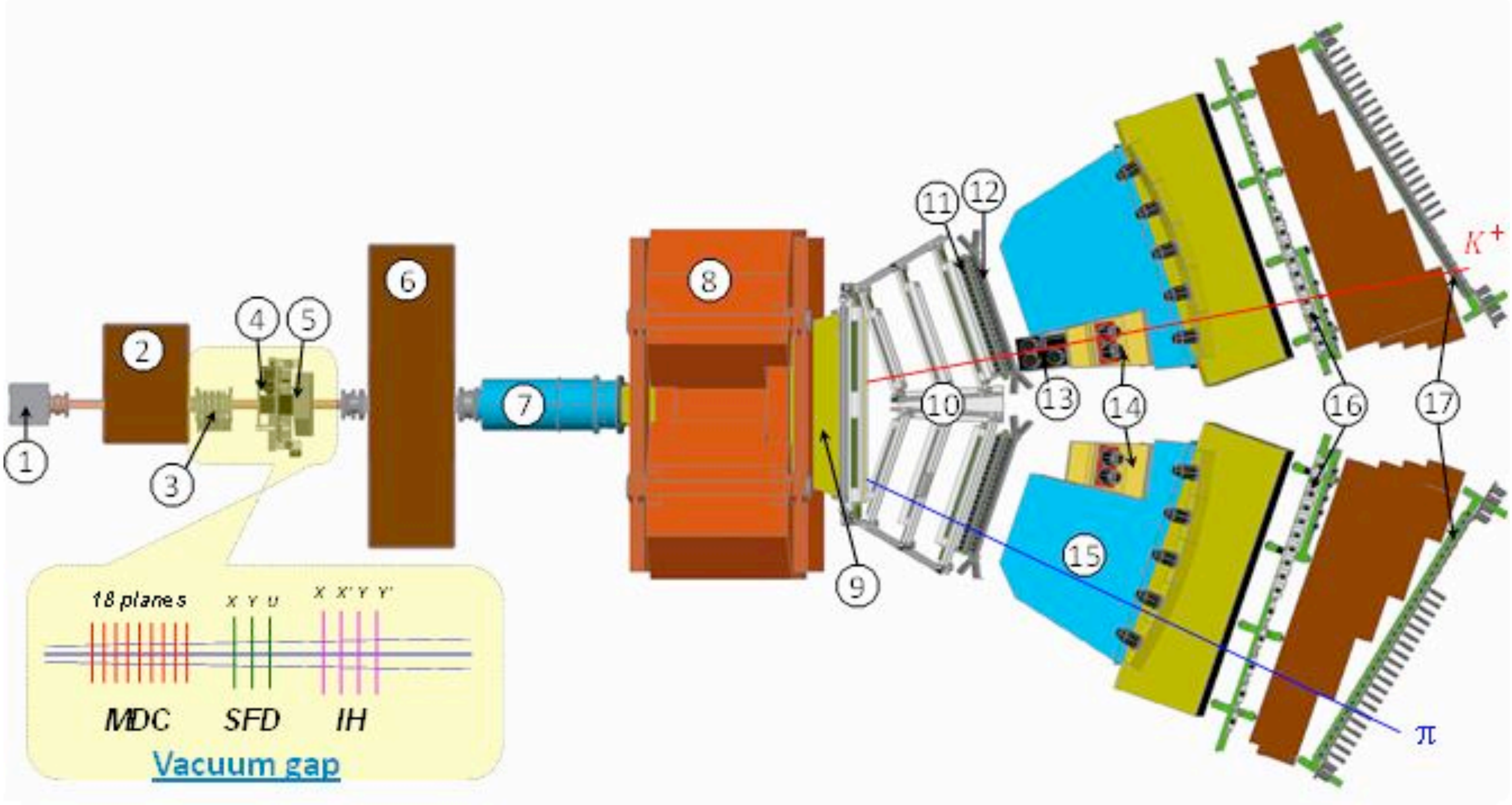


Simulation without magnet



Simulation with magnet

DIRAC upgraded Experimental setup



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

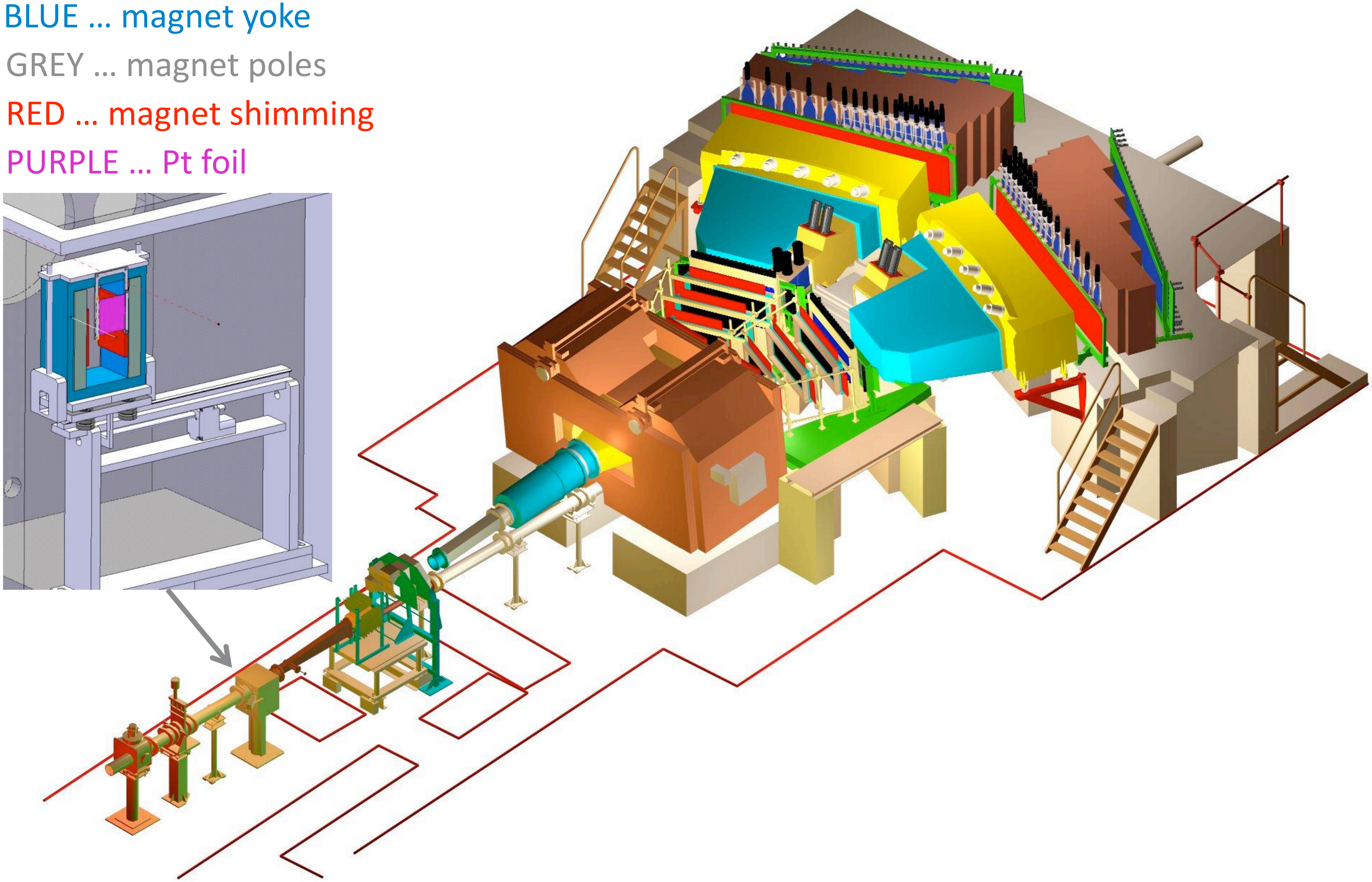
DIRAC upgraded Experimental setup

BLUE … magnet yoke

GREY … magnet poles

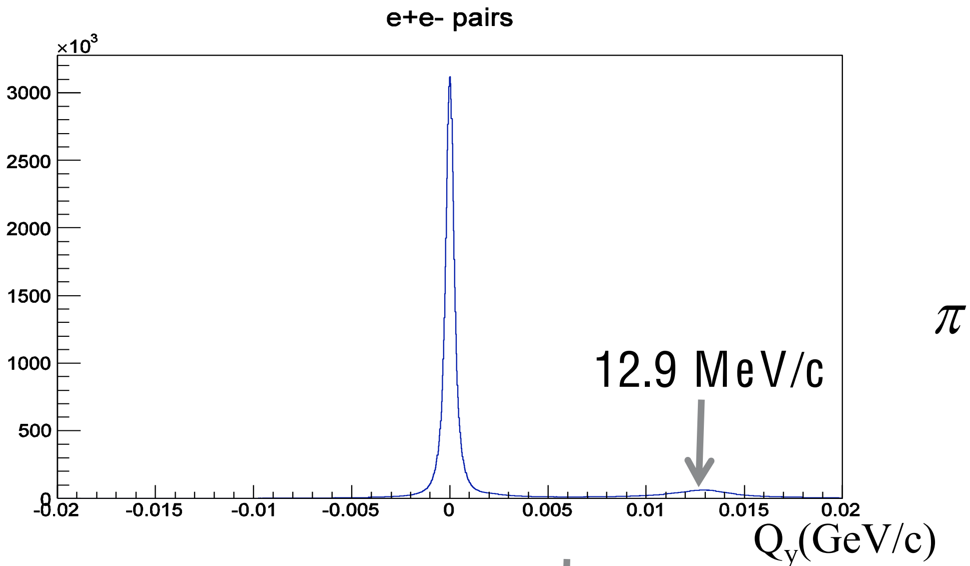
RED … magnet shimming

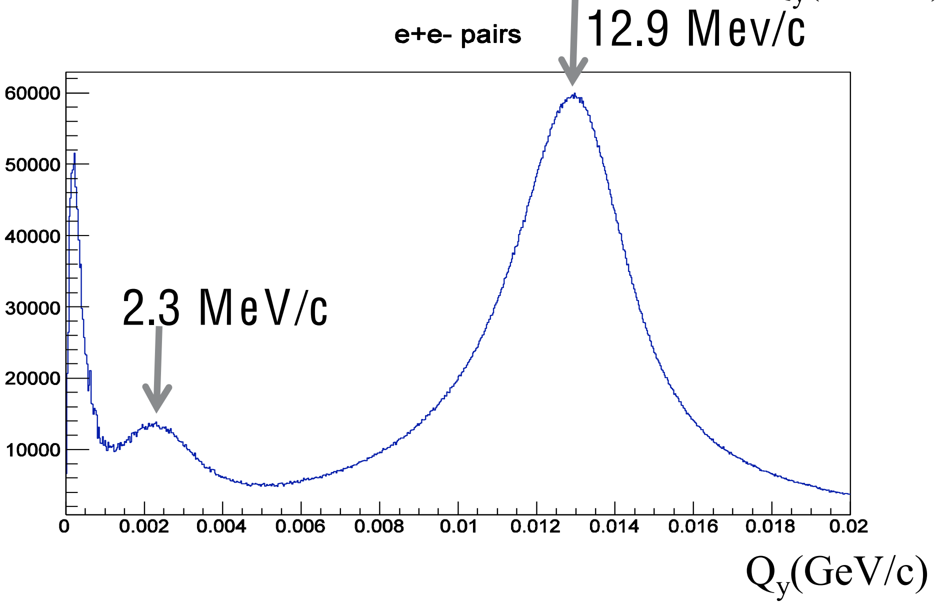
PURPLE … Pt foil

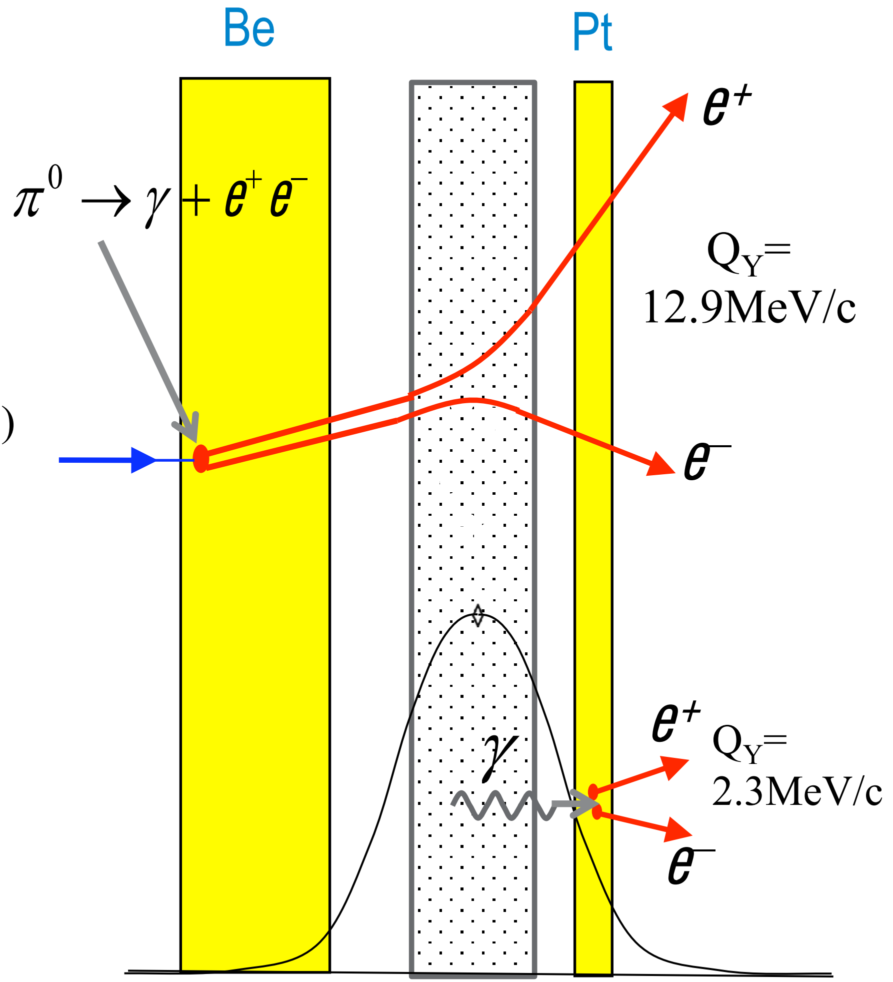


Magnet impact on Q_y distribution for e^+e^- pairs

Real data

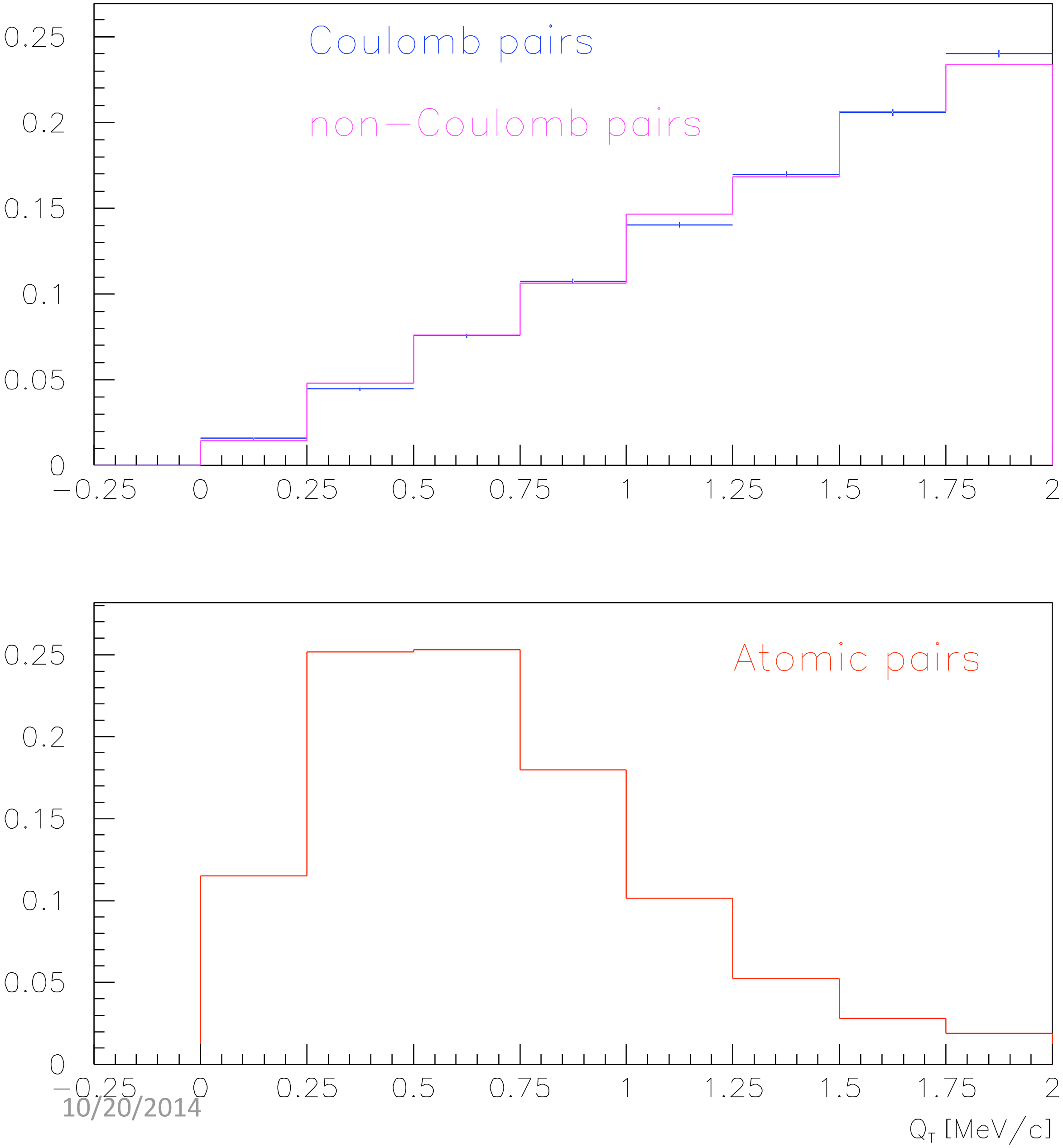






Peak at Q_y=2.3MeV/c evaluated after subtraction of the mirrored left side part.

Long-lived $\pi^+\pi^-$ atoms

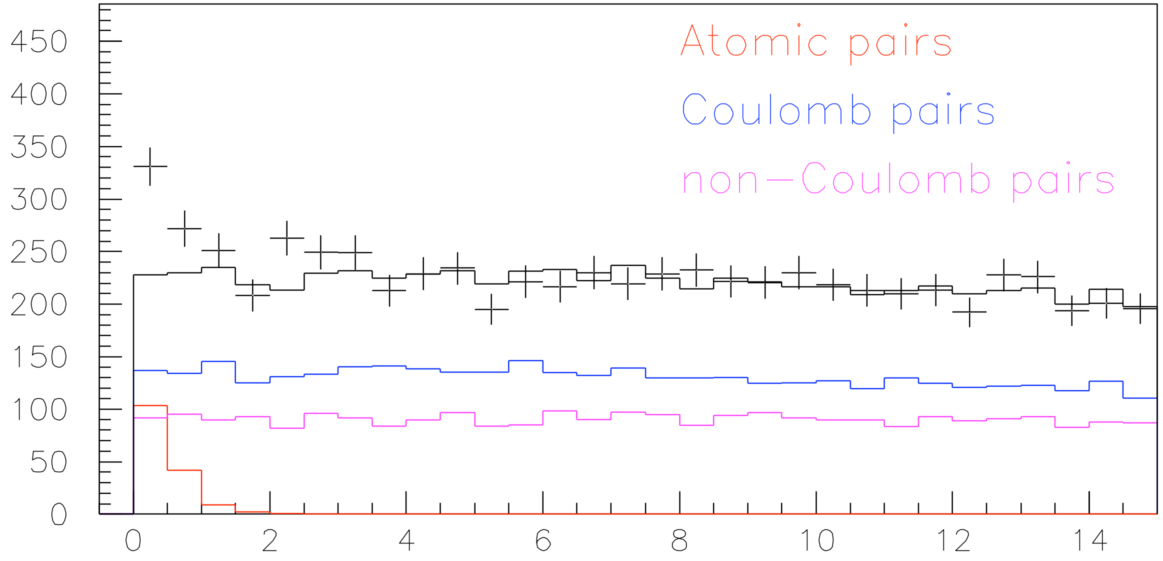


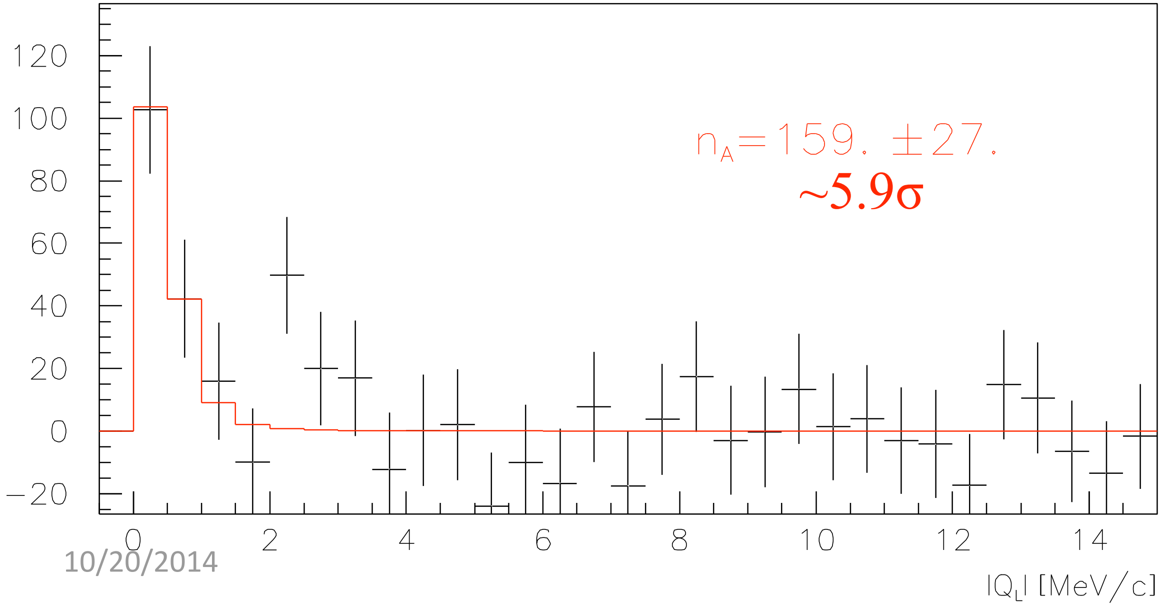
Simulated distributions of "Coulomb", "non-Coulomb" and atomic pairs over Q_T

for $|Q_L|<2$ MeV/c

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

Long-lived $\pi^+\pi^-$ atoms



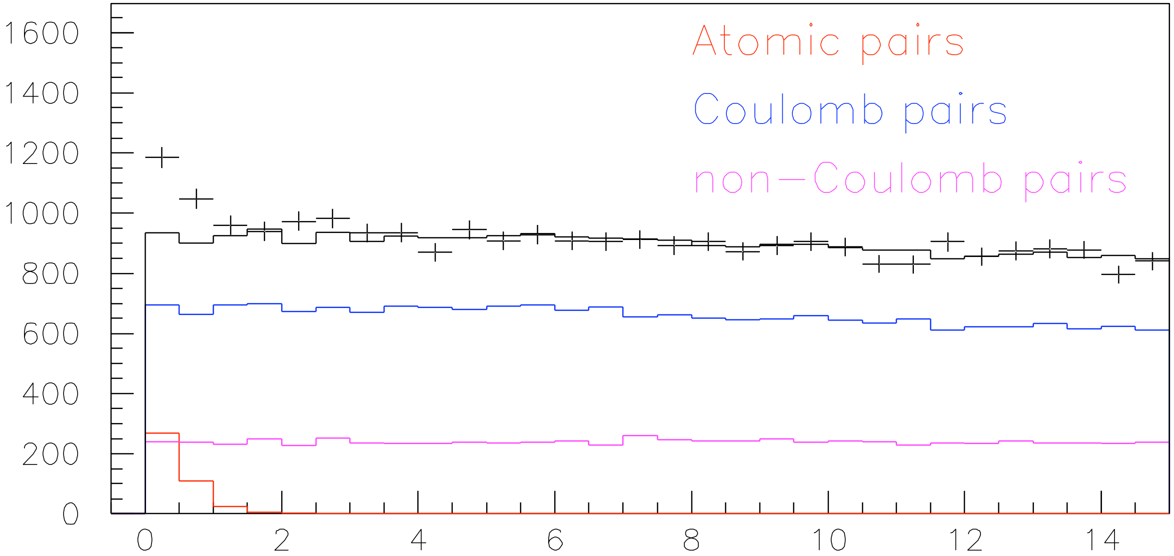


Experimental (real data) and simulated distributions over |Q_L|

for Q_T<0.5 MeV/c

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

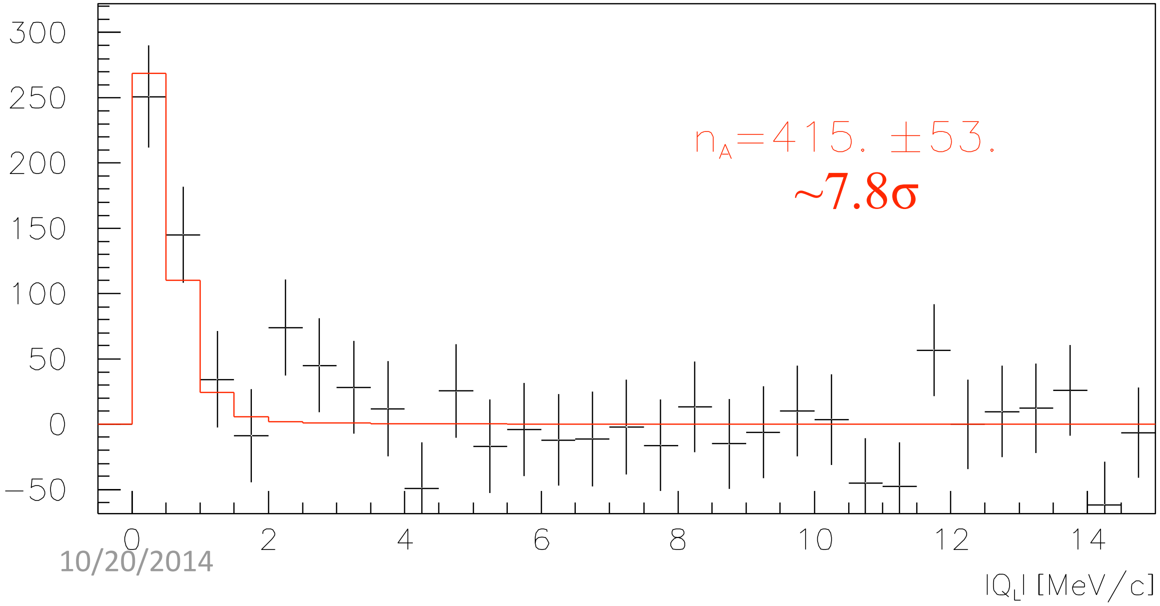
Long-lived $\pi^+\pi^-$ atoms



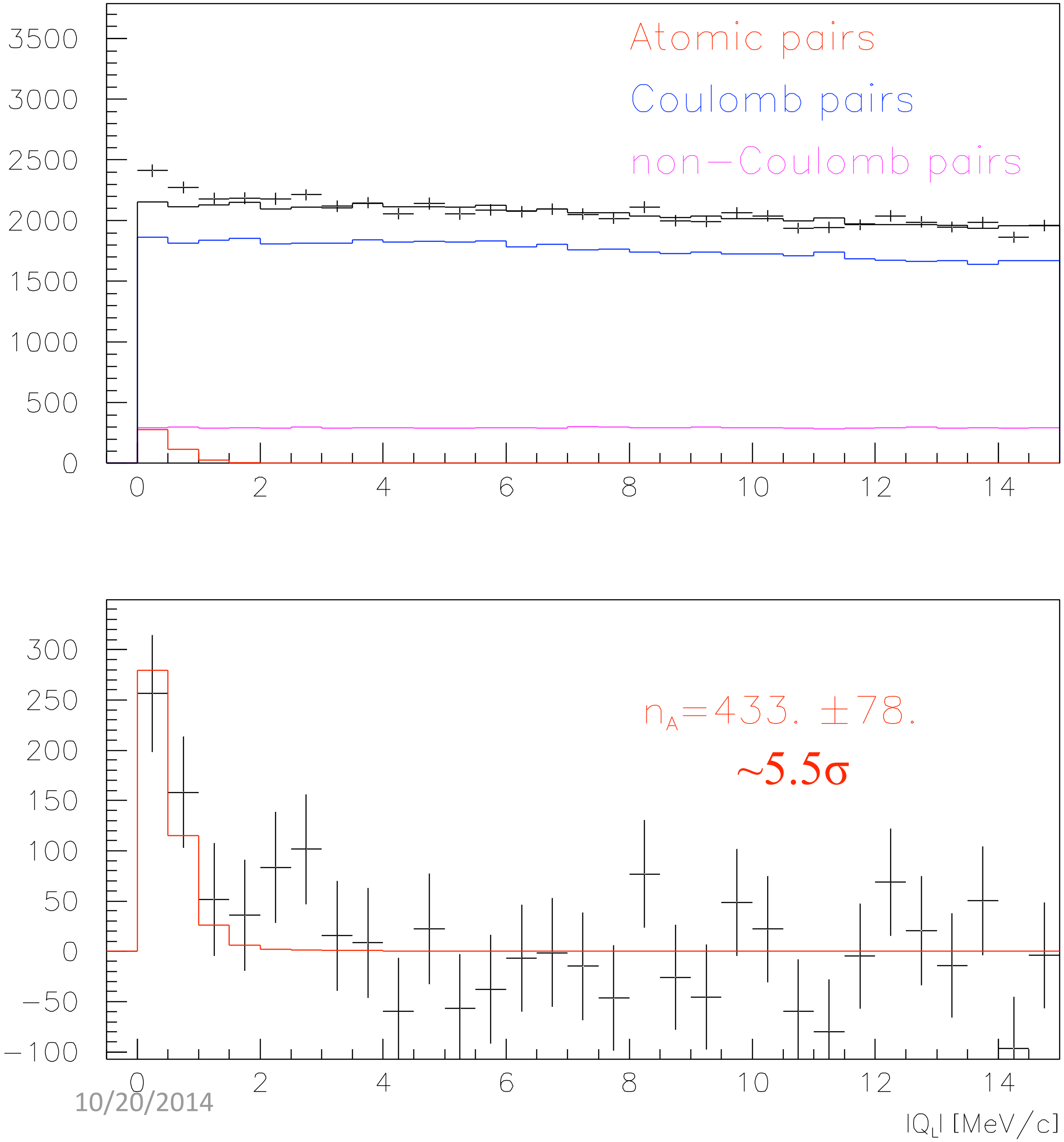
Experimental (real data) and simulated distributions over $|Q_L|$

for Q_T<1.0 MeV/c

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



Long-lived $\pi^+\pi^-$ atoms



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

for Q_T<1.5 MeV/c

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

Long-lived $\pi^+\pi^-$ atoms

The results of the data with low and medium background (2/3 of existing data) are presented in the Table. The experimental distributions of events on Q_L were analysed at 3 values of Q_T cuts (column 1), where Q_L (Q_T) is the longitudinal (transversal) component of the relative momentum Q in the $\pi\pi$ c.m.s. In this analysis the distributions are fitted with a sum of Coulomb and non-Coulomb pairs generated in the *Be* target and atomic pairs originating from the breakup of long-lived atoms in the *Pt* foil placed at 100mm distance from the *Be* target. The numbers of detected atomic pairs as well as total atomic pairs are shown in columns 2 and 4. The last column presents the sum of the Coulomb and non-Coulomb pairs (background) in the signal region: $Q_L < 1.5$MeV/c.

Q_T cut	n_A	Selection efficiency	n_A^{tot}	Background for $Q_L \leq 1.5$ MeV/c
$Q_T<0.5$ MeV/c	159±27 (~5.9σ)	0.365	436±74	690
$Q_T<1.0$ MeV/c	415±53 (~7.8σ)	0.795	522±67	2775
$Q_T<1.5$ MeV/c	433±78 (~5.5σ)	0.945	458±83	6360

Long-lived $\pi^+\pi^-$ atoms (cont.)

- The DIRAC Collaboration aims to finish this analysis and to publish a corresponding preprint

  "*First observation of the long-**lived** $\pi^+\pi^-$ atoms*" in February 2015.

- In 2015, we will study the possibility to evaluate a lowest limit for the Lamb shift based on the existing data.

- In 2015 we intend to process the 2011 data.

3. $\pi^+\pi^-$ atom analysis

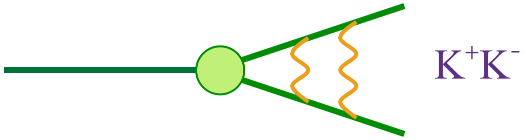
- The $\pi^+\pi^-$ atom data analysis will be finished in 2015 using statistics with low, medium and high background (about 30000 atomic pairs).

  The evaluated atom lifetime measurement will be submitted for publication before July 2016.

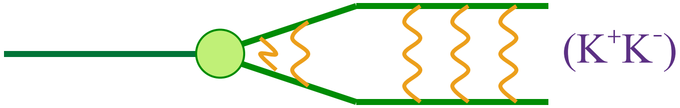
- The measurement of the multiple scattering in *Be*, *Ni* and *Pt* targets with about 0.5% accuracy will be accomplished and published before July 2016.

K^+K^- Coulomb pairs and K^+K^- atoms

For the charged pairs from the short-lived sources and small relative momentum Q there is strong Coulomb interaction in the final state.



Coulomb pairs



Atoms

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

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

$$n_A \text{ - atomic pairs number}, \quad P_{br} = \frac{n_A}{N_A}$$

From K^+K^- pair analysis the Coulomb pair distribution on Q will be obtained, allowing to extract the total number of produced K^+K^- atoms.

4. K^+K^- pair analysis

- A search for K^+K^- Coulomb pairs in the RUN 2010 data will be performed, and the number of K^+K^- atoms, produced simultaneously with these Coulomb pairs, will be extracted.
- In the first part of the work until July 2015, will be analyse about
- 8000 K^+K^- pairs with a total momentum in the laboratory system from 2.8 GeV/c up to 6.0 GeV/c. It is 1/3 of the existing total statistics.
- By occurrence of a signal, Coulomb pairs will also be searched for in the higher momentum region(about 2400 pairs) from 6.0 GeV/c up to 9.6 Gev/c.

5. Proton – antiproton pair analysis

- DIRAC will perform a search for proton−antiproton Coulomb pairs and thus proton−antiproton atoms with the same strategy as in the K^+K^- case (see previous section).
- The search for the proton−antiproton Coulomb pairs in the lower momentum region will be finished before May 2016.

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

- Analogously the 2010 experimental data will be investigated with respect to $\pi^+\mu^-$ and $\pi^-\mu^+$ Coulomb pairs aiming to extract the number of πμ atoms, produced simultaneously with these Coulomb pairs. The analysis will be finished in January 2015.
- If a signal will be observed, the 2011 and 2012 data will be processed in order to improve statistics.

7. $K^+\pi^-$,$K^-\pi^+$, $\pi^+\pi^-$, K^+K^- atom production, in p-nucleus interaction at proton momentum 24 GeV/c and 450 GeV/c

- A DIRAC note will be presented in January 2015 on the simulation of the inclusive production of K^+, K^-, π^+ and π^- in p-nucleus interaction at 24GeV/c and 450GeV/c, to be compared with dedicated experimental data.

- The yield of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms in p-nucleus interaction at proton momenta 24 and 450GeV/c will then be calculated.

The atom yields for DIRAC at 24 GeV/c and 450 GeV/c

p_p at θ_{lab}	$\pi^+\pi^-$ atom	$K^-\pi^+$ atom	$K^+\pi^-$ atom
p_p=24 GeV/c at θ_{lab}=5.7°	$190\cdot10^{-11}$	$22\cdot10^{-11}$	$52\cdot10^{-11}$
p_p=450 GeV/c at θ_{lab}=4.0°	$3400\cdot10^{-11}$	$810\cdot10^{-11}$	$850\cdot10^{-11}$
p_p=24 GeV/c at θ_{lab}=5.7° DIRAC Acceptance	$120\cdot10^{-11}$	$1.3\cdot10^{-11}$	$3.1\cdot10^{-11}$
p_p=24 GeV/c at θ_{lab}=4.0° DIRAC Acceptance	$1900\cdot10^{-11}$	$88\cdot10^{-11}$	$97\cdot10^{-11}$
The ratio of yields DIRAC Acceptance	16	68	31

8. Letter of Intent

- Preparation of a Letter of Intent about the investigation of dimesoatoms at SPS energy before November 2015.

9. Further works

- $\mu^+\mu^-$ pairs analysis: Monte-Carlo simulations will be used to study - before the end of 2015 - the possibility to observe $\mu^+\mu^-$ Coulomb pairs. If the calculated results are promising, DIRAC will analyze the existing experimental data (2001-2003 and 2007-2012) to search for $\mu^+\mu^-$ Coulomb pairs. These pairs allow to evaluate the number of $\mu^+\mu^-$ atoms, produced simultaneously with Coulomb pairs.
- Cross sections evaluation:
  Use of experimental data from 2007-2012 to measure production cross-sections of $K^+\pi^-$, $K^-\pi^+$, $\pi^+\pi^-$ atoms in proton interaction with Be, Ni and Pt nuclei in 2016.
- Instrumental publication:
  DIRAC intends to submit a preprint "Updated DIRAC spectrometer at CERN PS for the investigation of ππ and Kπ atoms" before the end of the year 2014. This paper covers all the details of the detectors and discusses the overall performance of the spectrometer.

Thank you

Additional slides

Physics motivation

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

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

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

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

... published by DIRAC, Physics Letters B 704 (2011), 24.

Experimental results

$\left(\text{scattering length in } m_\pi^{-1}\right)$

$K \to 3\pi$:

2009 NA48/2 (EPJ C64, 589)

$$\Rightarrow a_0 - a_2 = 0.2571 \pm 0.0048\big|_{stat} \pm 0.0025\big|_{syst} \pm 0.0014\big|_{ext} = \ldots \pm 2.2\%$$

plus additional 3.4% theory uncertainty

$Ke4$:

2010 NA48/2 (EPJ C70, 635)

$$\Rightarrow a_0 = 0.2220 \pm 0.0128\big|_{stat} \pm 0.0050\big|_{syst} \pm 0.0037\big|_{theo} = \ldots \pm 6.4\%$$

$$\Rightarrow a_2 = -0.0432 \pm 0.0086\big|_{stat} \pm 0.0034\big|_{syst} \pm 0.0028\big|_{theo} = \ldots \pm 22\%$$

$\pi^+\pi^-$ atom:

2011 DIRAC (PLB 704, 24)

$$\Rightarrow |a_0 - a_2| = 0.2533 \begin{matrix}+0.0078\\-0.0080\end{matrix}\Big|_{stat} \begin{matrix}+0.0072\\-0.0077\end{matrix}\Big|_{syst} = \ldots \begin{matrix}+4.2\%\\-4.4\%\end{matrix}$$

Experimental results with additional theoretical constraints

$K\to 3\pi$:

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

$$\Rightarrow a_0 - a_2 = 0.2633 \pm 0.0024\big|_{stat} \pm 0.0014\big|_{syst} \pm 0.0019\big|_{ext} = \ldots \pm 1.3\%$$

plus additional 2% theory uncertainty

$Ke4$:

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

$$\Rightarrow a_0 = 0.2206 \pm 0.0049\big|_{stat} \pm 0.0018\big|_{syst} \pm 0.0064\big|_{theo} = \ldots \pm 3.7\%$$

$Ke4$ & $K\to 3\pi$:

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

$$\Rightarrow a_0 - a_2 = 0.2639 \pm 0.0020\big|_{stat} \pm 0.0015\big|_{syst} = \ldots \pm 0.9\%$$

$\pi^+\pi^-$ atom lifetime and decay lengths

n	$\tau_{2\pi}$ (10^{-11}sec)		Decay length $A_{2\pi}$ in L.S. (cm) for $\gamma=16$ $(\lambda_{ns}=c\cdot\gamma\cdot\tau_{nl})$	
	s ($l=0$) $\tau_{ns}=\tau_{1s}\cdot n^3$	p ($l=1$)	s ($l=0$)	p ($l=1$)
1	$2.9\cdot10^{-4}$	-	$1.39\cdot10^{-3}$	-
2	$2.32\cdot10^{-3}$	1.17	$1.11\cdot10^{-2}$	5.6
3	$7.83\cdot10^{-3}$	3.94	$3.76\cdot10^{-2}$	19
4	$1.86\cdot10^{-2}$	9.05	$8.91\cdot10^{-2}$	43
5	$3.63\cdot10^{-2}$	17.5	$1.74\cdot10^{-1}$	84
6	$6.26\cdot10^{-2}$	29.9	$3.01\cdot10^{-1}$	144
7	$9.95\cdot10^{-2}$	46.8	$4.77\cdot10^{-1}$	225
8	$1.48\cdot10^{-1}$	69.3	$7.13\cdot10^{-1}$	333

Breakup foil	Thick (μm)	2p	3p	4p	5p	6p	7p
Pt (Z=78)	1.0	0.4147	0.6895	0.8553	0.9324	0.9667	0.9828
	1.5	0.6084	0.8526	0.9446	0.9765	0.9889	0.9944
	2.0	0.7422	0.9244	0.9743	0.9895	0.9951	0.9975

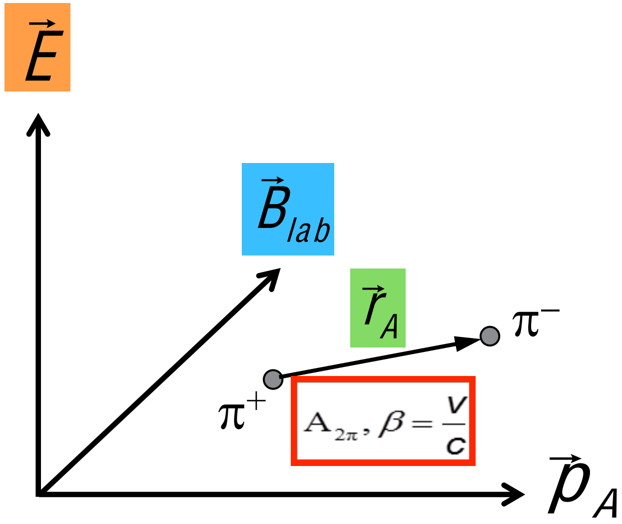
Platinum foils:

The breakup probability for *np* states and different thicknesses ($A_{2\pi}$ momentum P_A=4.5GeV /c and $A_{2\pi}$ lifetime $\tau = 3.0\cdot10^{-15}$s)

Lamb shift measurement with external magnetic field

See: L. Nemenov, V. Ovsiannikov, Physics Letters B 514 (2001) 247.

Impact on atomic beam by
external magnetic field $\underline{B_{lab}}$ and Lorentz factor $\underline{\gamma}$



$\vec{r}_A$ …. relative distance between π^+ and π^- in $A_{2\pi}$ system

$\vec{B}_{lab}$ …. laboratory magnetic field

$\vec{E}$ …electric field in $A_{2\pi}$ system

$$\boxed{\left|\vec{E}\right| = \beta\gamma\, B_{lab} \approx \gamma\, B_{lab}}$$

Dependence of $A_{2\pi}$ lifetime τ_{eff} for 2p-states of the electric field E strength

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

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

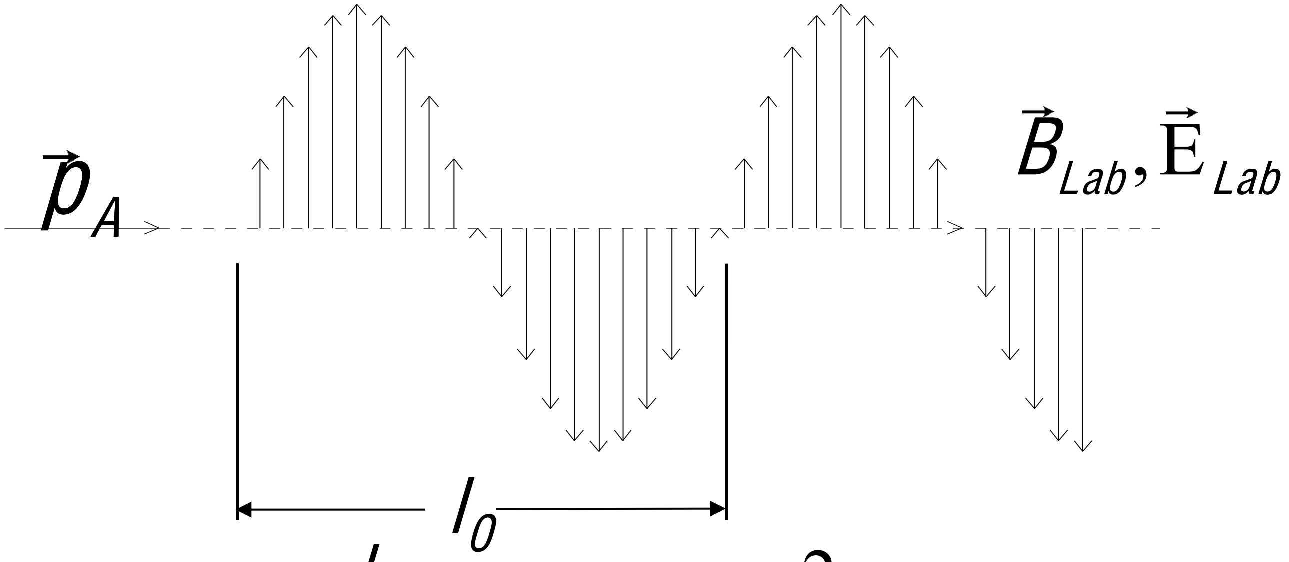
where: $|\xi|^2 \approx \frac{|\vec{E}|^2}{(E_{2p} - E_{2s})^2}$

$\mathrm{B_{Lab}} = 2$ Tesla

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

Resonant enhancement of the annihilation rate of $A_{2\pi}$

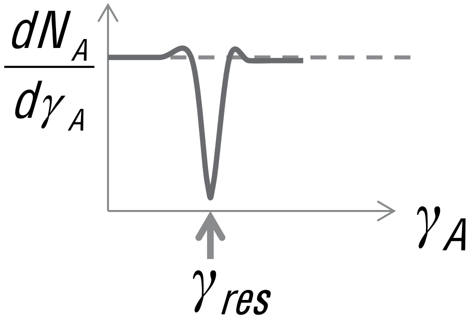
L.Nemenov, V.Ovsiannikov, E.Tchaplyguine, Nucl. Phys. (2002)



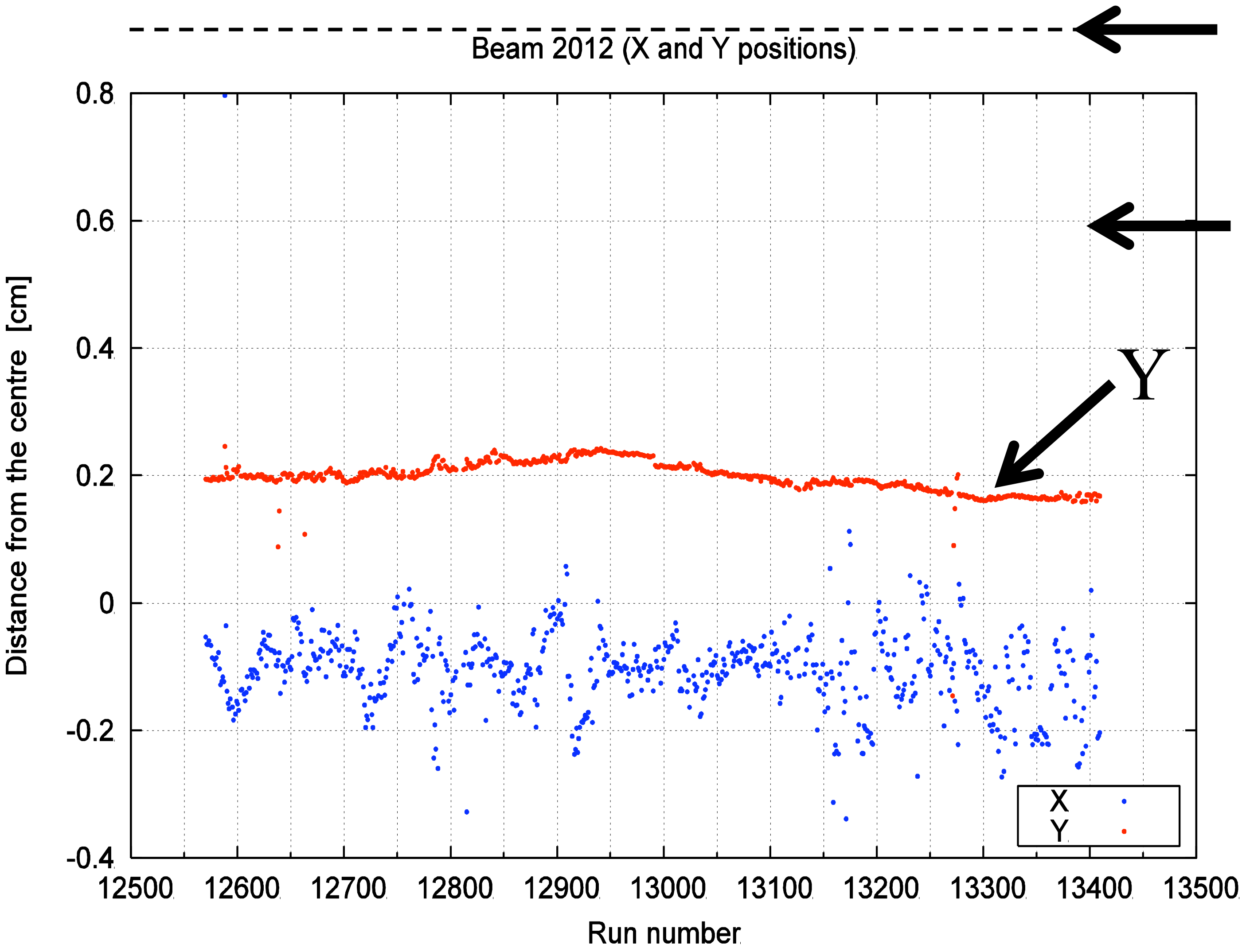
In Lab. System: $T_{Lab} = \frac{l_0}{\beta c}$, $\omega_{Lab} = \frac{2\pi}{T_{Lab}}$

In CM System: $\tilde{\omega} = \gamma \cdot \omega_{Lab}$, $\tilde{\vec{E}} = \gamma \cdot \vec{E}_{Lab} \cdot \cos \tilde{\omega} t$, $\tilde{\Omega} = \frac{E_{2p} - E_{2s}}{\hbar}$

at resonance: $\tilde{\Omega} = \tilde{\omega} = \gamma_{res} \cdot \omega_{Lab}$



y-beam position (run 2012)



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).

DIRAC setup characteristics and experimental conditions

The relative angle of the secondary channel relative to proton beam	$5.7 \pm 1^\circ$
Solid angle	$1.2 \cdot 10^{-3}$ sr
Dipole magnet	$B_{max} = 1.65$ T BL = 2.2 Tm

Spectrometer		
Relative resolution on the particle momentum in L.S.		$3 \cdot 10^{-3}$
Precision on Q-projections (experimental measurement)	$\sigma_{QX} = \sigma_{QY} = 0.5$ MeV/c	$\sigma_{QL} = 0.5$ MeV/c ($\pi\pi$) $\sigma_{QL} = 0.9$ MeV/c (πK)

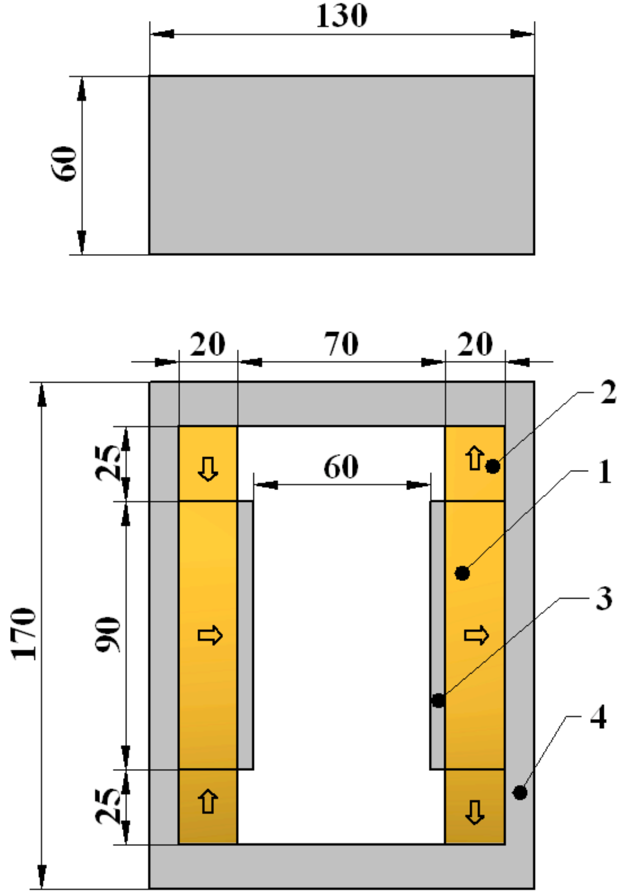
Experimental conditions (run 2012)

Primary proton beam	24 GeV/c
Beam intensity	$(3.0 \div 3.3)\cdot 10^{11}$ proton/spill
Spill duration	450 ms
Secondary particles intensity (single count of one IH plane)	$\approx 7\cdot 10^{6}$ particle/spill

Be target	
Target thickness	103 μm
Radiation thickness	$2.93\cdot 10^{-4}\, X_0$
Probability of inelastic proton interaction	$2.52\cdot 10^{-4}$

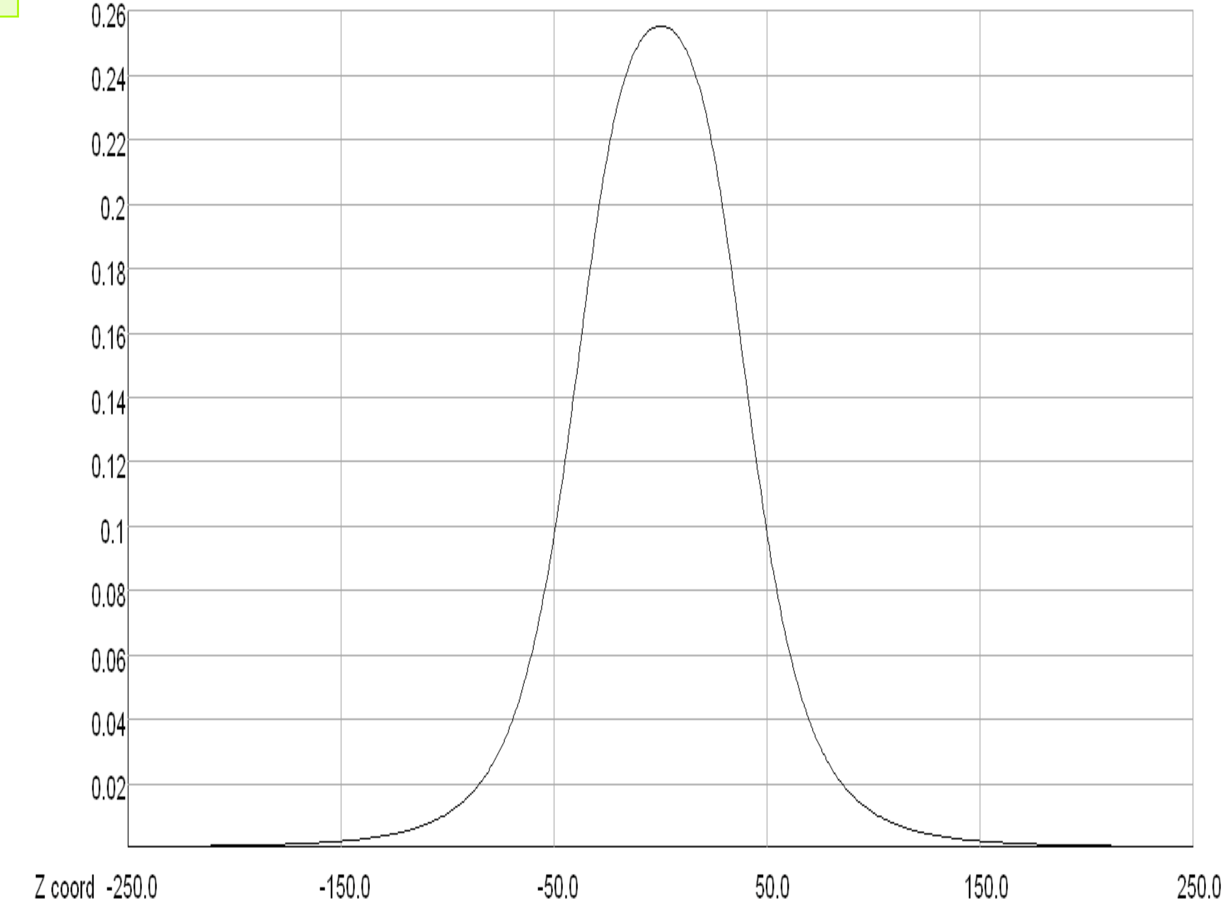
Magnet

Layout of the dipole magnet (arrows indicate the direction of magnetization)



1- PM block Sm2Co17
2- PM block Sm2Co17

Horizontal field distribution along z-axis at X=Y=0mm
$\int Bx(0,0,z)dz = 24.6 \times 10^{-3}$ [Tm]



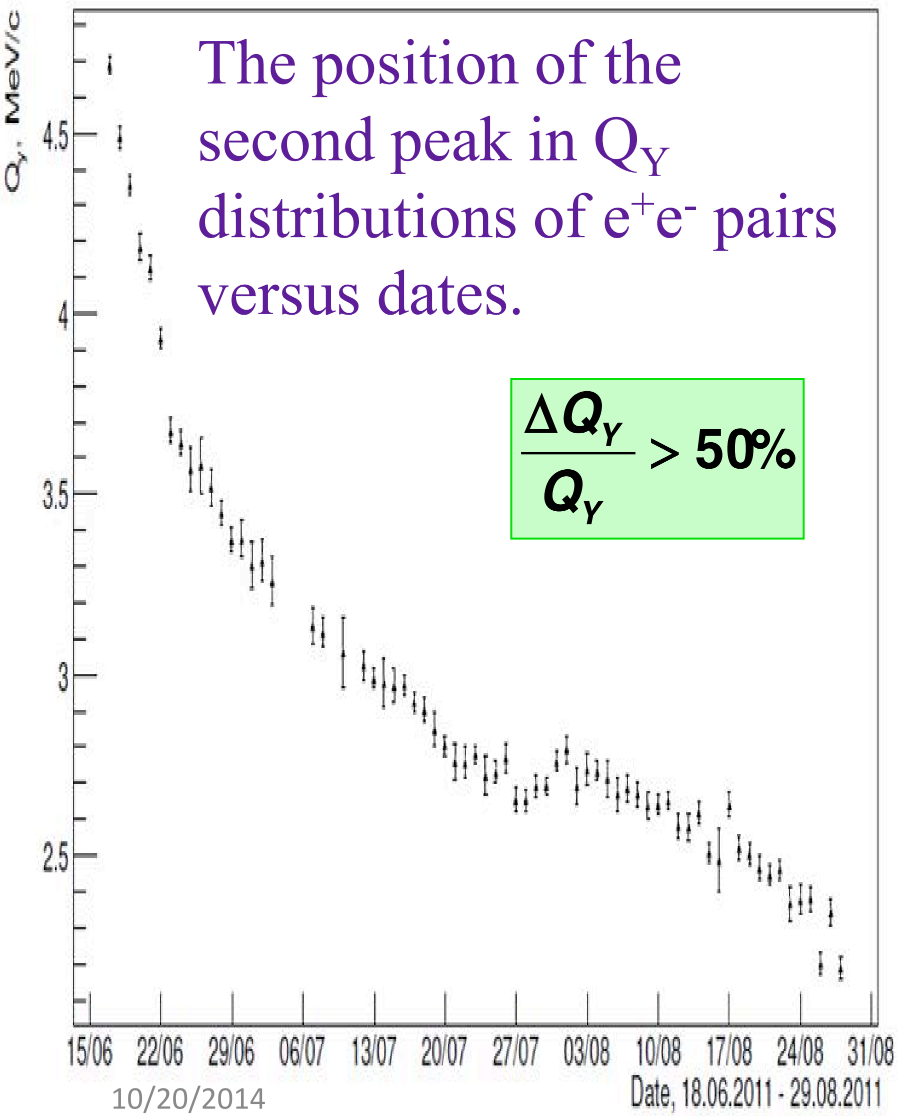
– Component: Bx [T], Integral = 24.6426 [mTm]

Opera

Degradation of old magnet

New magnet behaviour

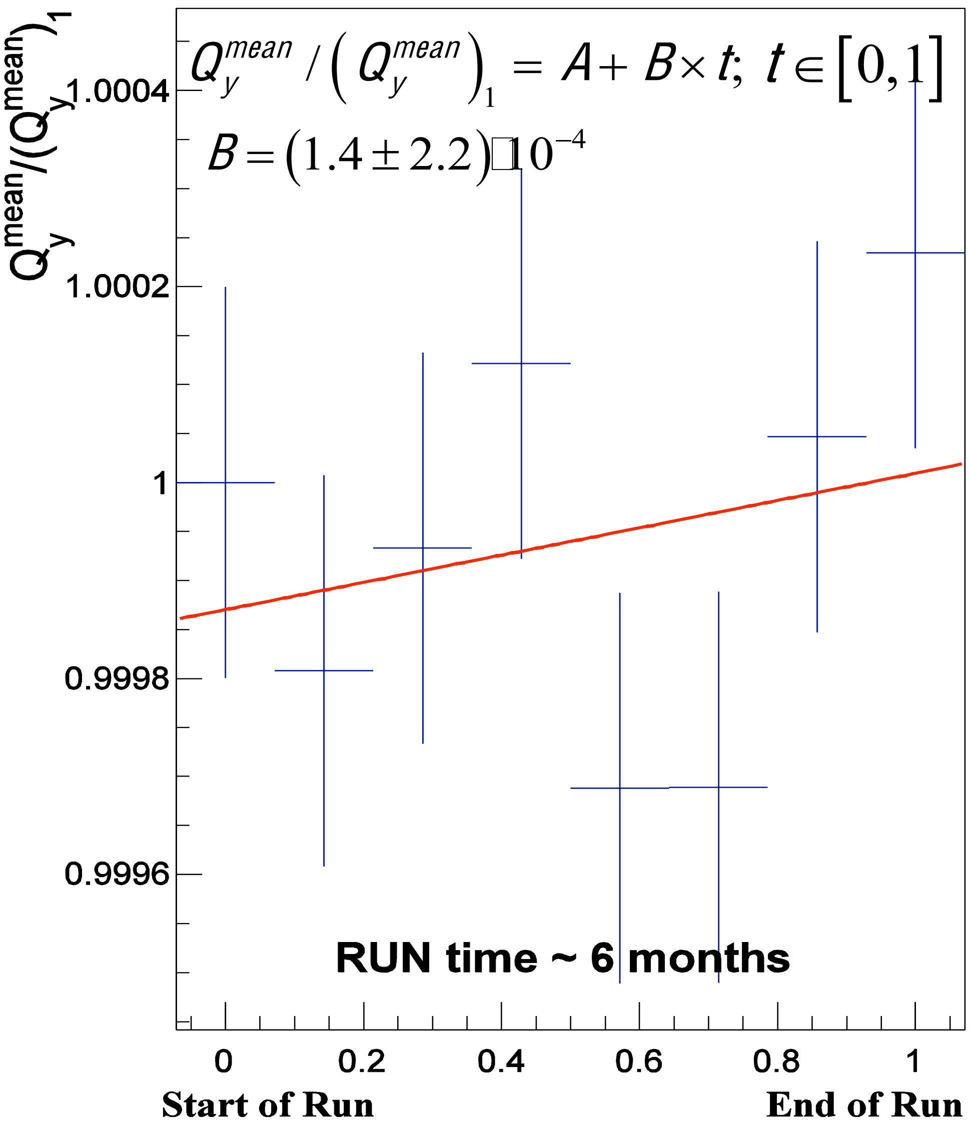
Old magnet (Nd-Fe-B), 2011



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

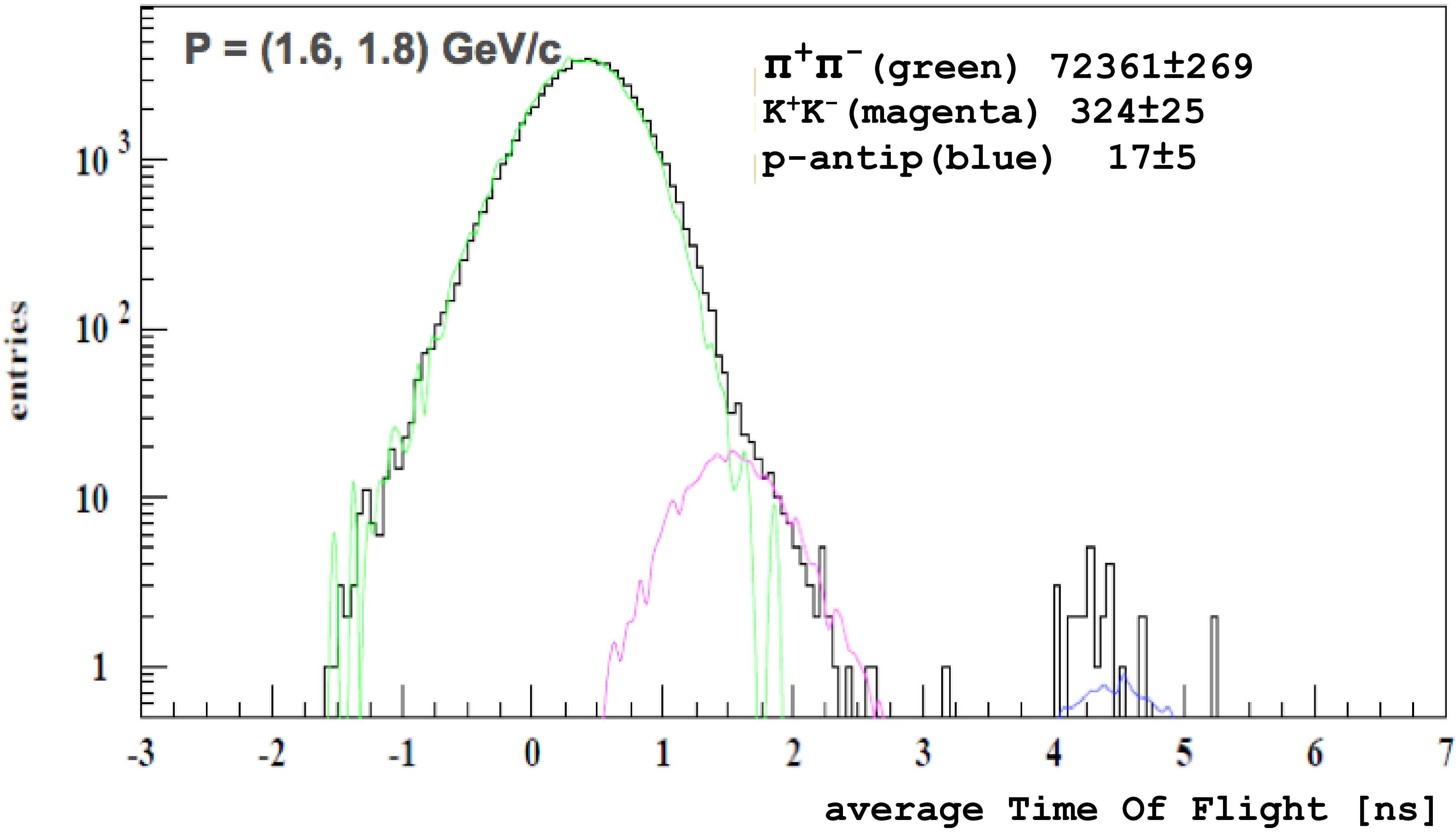


$$Q_y^{mean} / \left(Q_y^{mean}\right)_1 = A + B \times t;\ t \in [0,1]$$

$$B = (1.4 \pm 2.2)\cdot 10^{-4}$$

RUN time ~ 6 months

Search of K^+K^- and p-antiproton pair using Time Of Flight. Low momentum range



$\pi^+\pi^-$ (green) 72361±269

K^+K^- (magenta) 324±25

p-antip (blue) 17±5

$A_{2\pi}$ and $A_{\pi K}$ production

$$\frac{d\sigma^{A}_{nlm}}{d\vec{P}_A} = (2\pi)^3 \frac{E}{M} \left|\psi^{(C)}_{nlm}(0)\right|^2 \left.\frac{d\sigma^{0}_{s}}{dp_1 dp_2}\right|_{\vec{v}_1=\vec{v}_2} \propto \frac{d\sigma}{dp_1}\cdot\frac{d\sigma}{dp_2}\cdot R(\vec{p}_1,\vec{p}_2;s)$$

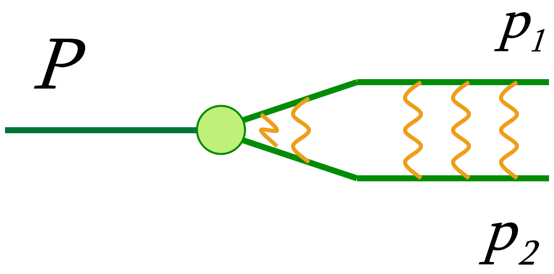
$$\vec{P}_A = \vec{p}_1 + \vec{p}_2$$

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

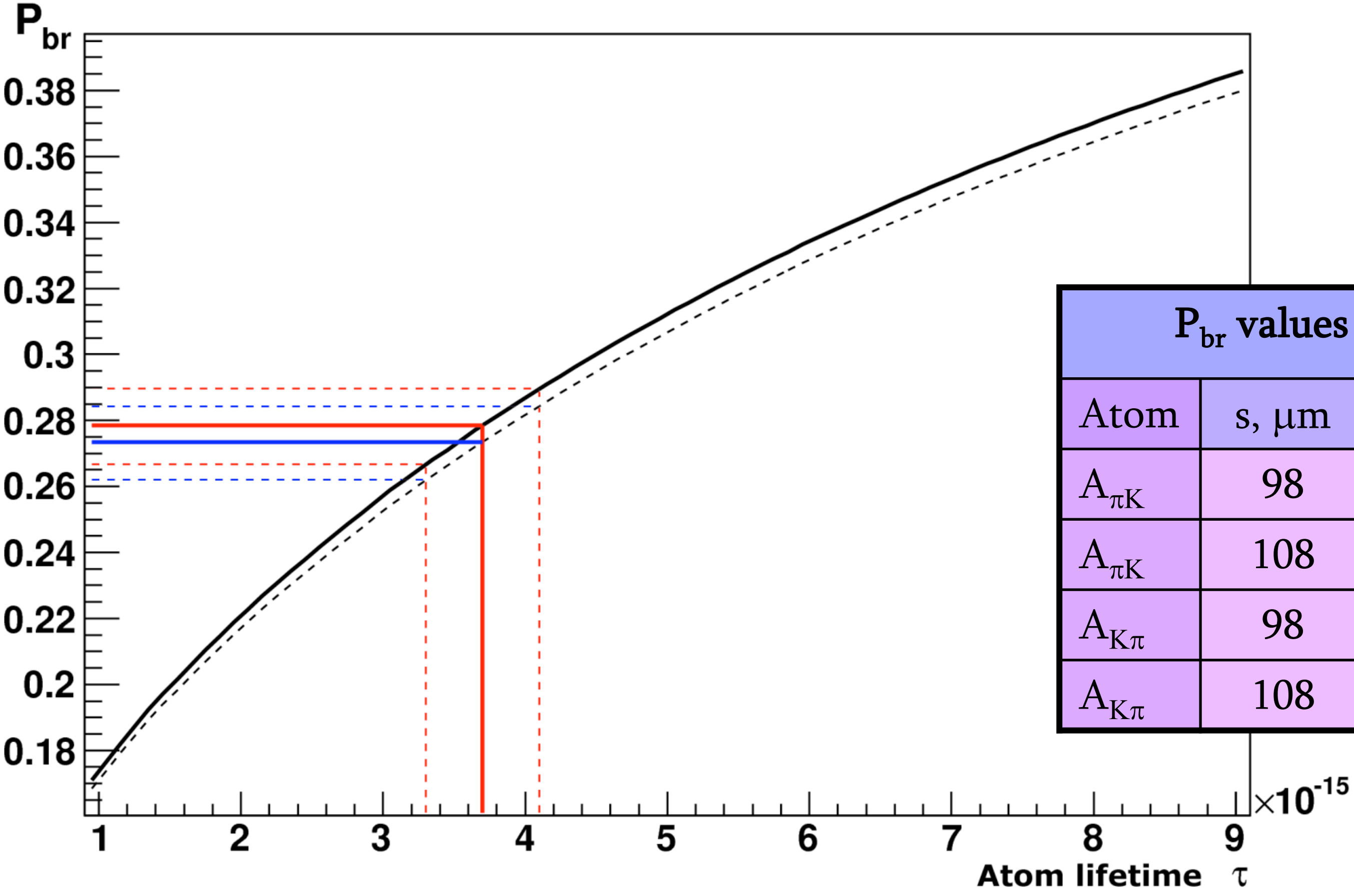
for $A_{2\pi}$ *production* $\vec{p}_1 = \vec{p}_2$

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*

Break-up dependencies P_{br} from atoms lifetime for $K^+\pi^-$ atom ($A_{K\pi}$) and $K^-\pi^+$ atom ($A_{\pi K}$)



P_{br} values corresponding to τ_{1S}^{th}				
Atom	s, μm	P_{br}	P_{br}-σ	P_{br}+σ
$A_{\pi K}$	98	0.274	0.263	0.285
$A_{\pi K}$	108	0.278	0.267	0.290
$A_{K\pi}$	98	0.269	0.258	0.280
$A_{K\pi}$	108	0.273	0.262	0.284

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 μm.
Average momentum of $A_{K\pi}$ and $A_{\pi K}$ are 6.4 GeV/c and 6.5 GeV/c accordingly.

K^+K^- atom and its lifetime

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^-).

K^+K^- interaction complexity ↓

τ ($A_{2K} \rightarrow \pi\pi,\pi\eta$)	K^+K^- interaction
1.2×10^{-16} s [1]	Coulomb-bound
8.5×10^{-18} s [3]	momentum dependent potential
3.2×10^{-18} s [2]	+ one-boson exchange (OBE)
1.1×10^{-18} s [2]	+ f_0' (I=0) + $\pi\eta$-channel (I=1)
2.2×10^{-18} s [4]	ChPT

References: [1] S. Wycech, A.M. Green, Nucl. Phys. A562 (1993), 446;
[2] S. Krewald, R. Lemmer, F.P. Sasson, Phys. Rev. D69 (2004), 016003;
[3] Y-J Zhang, H-C Chiang, P-N Shen, B-S Zou, PRD74 (2006) 014013;
[4] S.P. Klevansky, R.H. Lemmer, PLB702 (2011) 235.