Status Report of the DIRAC Experiment - PS 212

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PBC COMMITTEE, November 2017

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Measurement of the πK and ππ scattering length on SPS CERN

The number of produced $A_{2\pi}$, $A_{\pi^+K^-}$ and $A_{\pi^-K^+}$ per time unit at SPS CERN at p_p = 450*Gev/c*, will be 12±2, 53±11 and 24±5 times higher than in the DIRAC experiment [J.Phys. G: Nucl. Phys. 43 (2016)]

For the setup with the same parameters as in the DIRAC experiment and running time 5 months the expected statistical (sysematic) precision for πK scattering length $|a_{1/2}\text{-}a_{3/2}|$ is ~5% (2%). (The DIRAC error is 34%). It allows to check with the same accuracy predictions of the total $\mathcal{L}$(3) QCD Lagrangian based on the chiral $SU(3)_L{*}SU(3)_R$ symmetry breaking.

Simultaneously the expected number of $\pi^+\pi^-$ atomic pairs n_A=400000 .
The statistical (systematic) precision of the $\pi^+\pi^-$ scattering length $|a_0\text{-}a_2|$ will be: 0.7% (2%).

The $\pi^+\pi^-$ atoms production in Be target

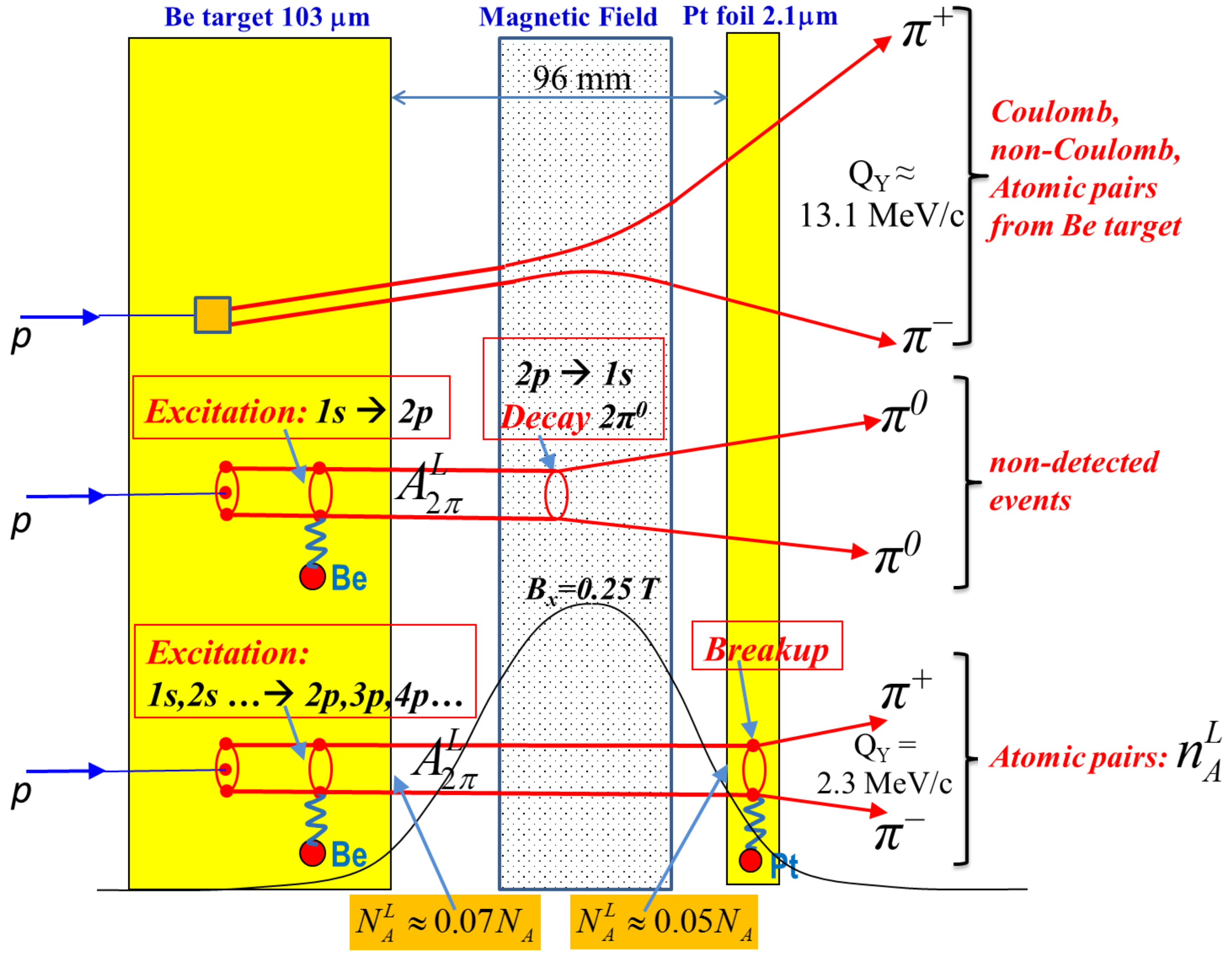


Fig. 1 Method to observe long-lived $A^L_{2\pi}$ by means of a breakup foil (*Pt*). The most of the produced $\pi^+\pi^-$ atoms decay (~70%) or are ionized (~6%) in the *Be* target. The excited (long lived) atoms (~24%) are investigated here.

Lifetime of long-lived $\pi^+\pi^-$ atoms

Number of atoms generated on Be target: $N_A = 16960 \pm 290|_{\text{tot}}$

Number of long-lived atoms after Be target: $N_A^{L,\text{Be}} = 1153 \pm 104|_{\text{tot}}$

Number of atoms entered Pt foil: $N_A^{L,\text{Pt}} = 501^{+184}_{-80}|_{\text{tot}}$

Number of atomic pairs after Pt foil: $n_A = 436 \pm 157|_{\text{tot}}$

The lifetime of long-lived atom in simple approach:

$$\tau_L = \left(1.21 \pm 0.19|_{\text{stat}}\ {}^{+0.75}_{-0.18}|_{\text{syst}}\right) \times 10^{-11} = 1.21^{+0.77}_{-0.26}|_{\text{tot}} \times 10^{-11}\text{s}$$

QED: $\tau_{2p} = 1.17 \times 10^{-11}\text{s}$

The measured ground state lifetime: $\tau_{1s} = 3.15^{+0.28}_{-0.26}|_{\text{tot}} \times 10^{-15}\text{s}$

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

n	$\tau_{2\pi}$ (10^{-11}sec)		Decay length $A_{2\pi}$ in L.S. (cm) for γ=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

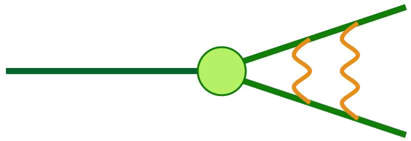
QCD and Chiral Lagrangian predictions check with long-lived $\pi^+\pi^-$ atoms

The DIRAC collaboration Phys.Lett.(2015) observed 436±61 pion pairs from the long-lived ($\tau \geq 1\times10^{-11}$ sec) $\pi^+\pi^-$ atom breakup in Pt foil(Phys.Lett.(2015).

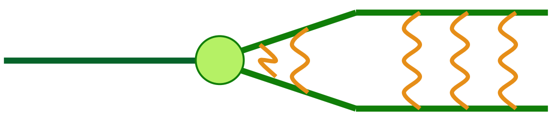
The short-lived atoms lifetime measurement allowed to evaluate $\pi\pi$ scattering length combination $a_0 - a_2$.
The study of the long-lived atoms will allow to measure the Lamb shift depending on another $\pi\pi$ scattering length combination: $2a_0+a_2$ and to evaluate the a_0, a_2 separately.

Coulomb pairs and atoms

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.



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



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

Coulomb pair

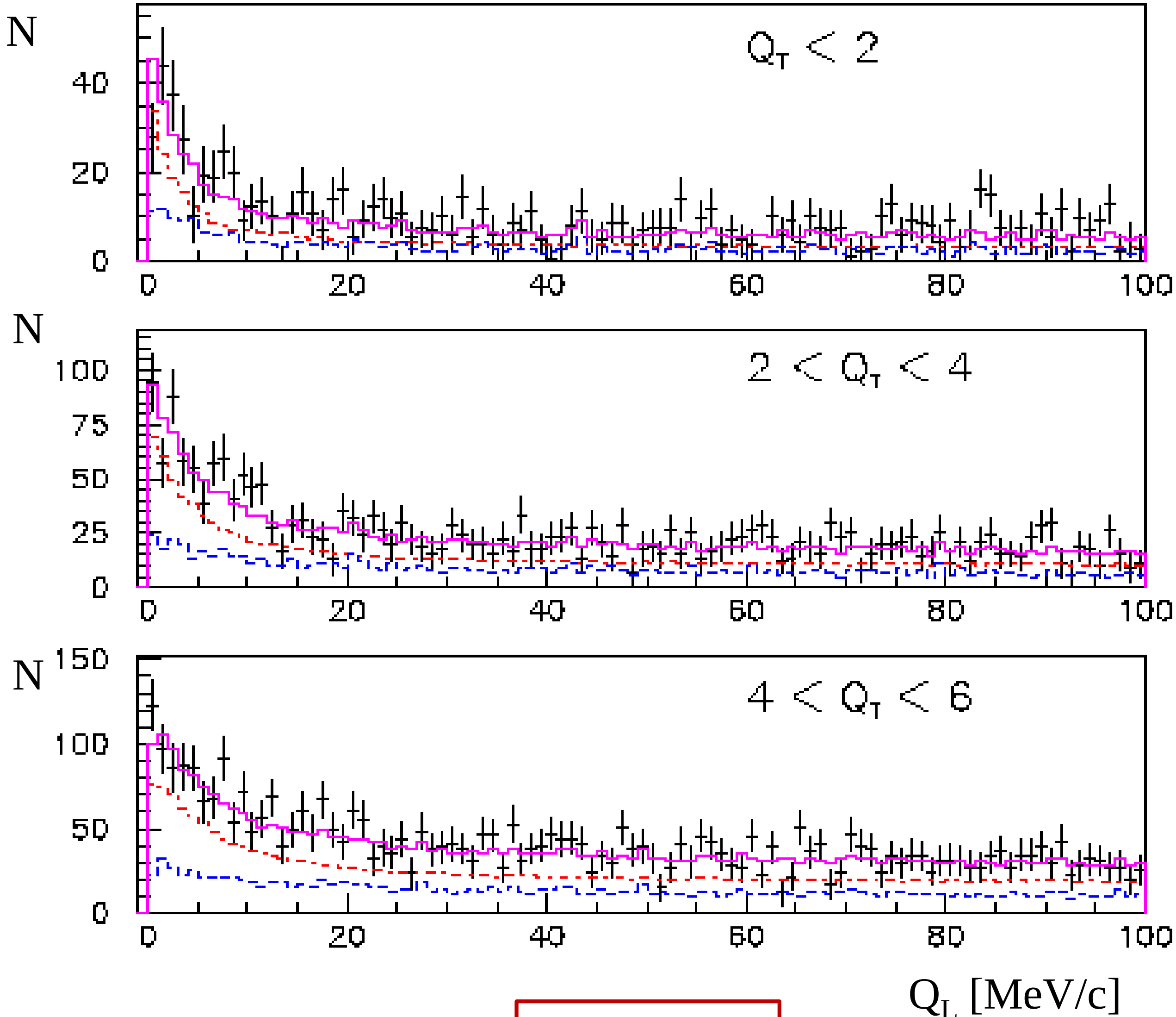
Atom

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:

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

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

K^+K^- pair analysis

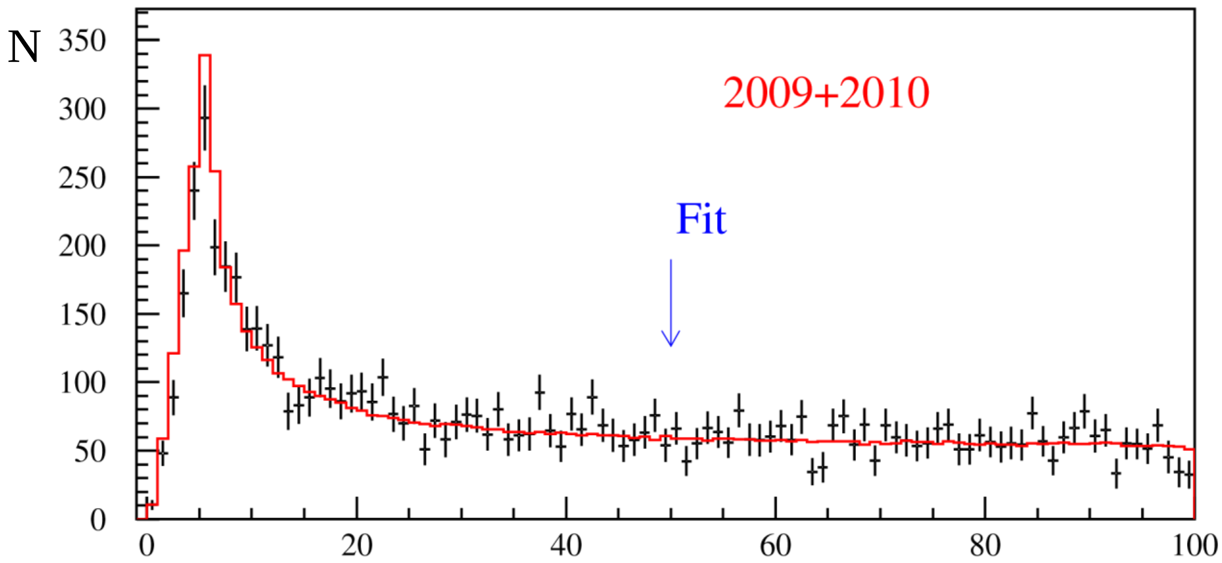


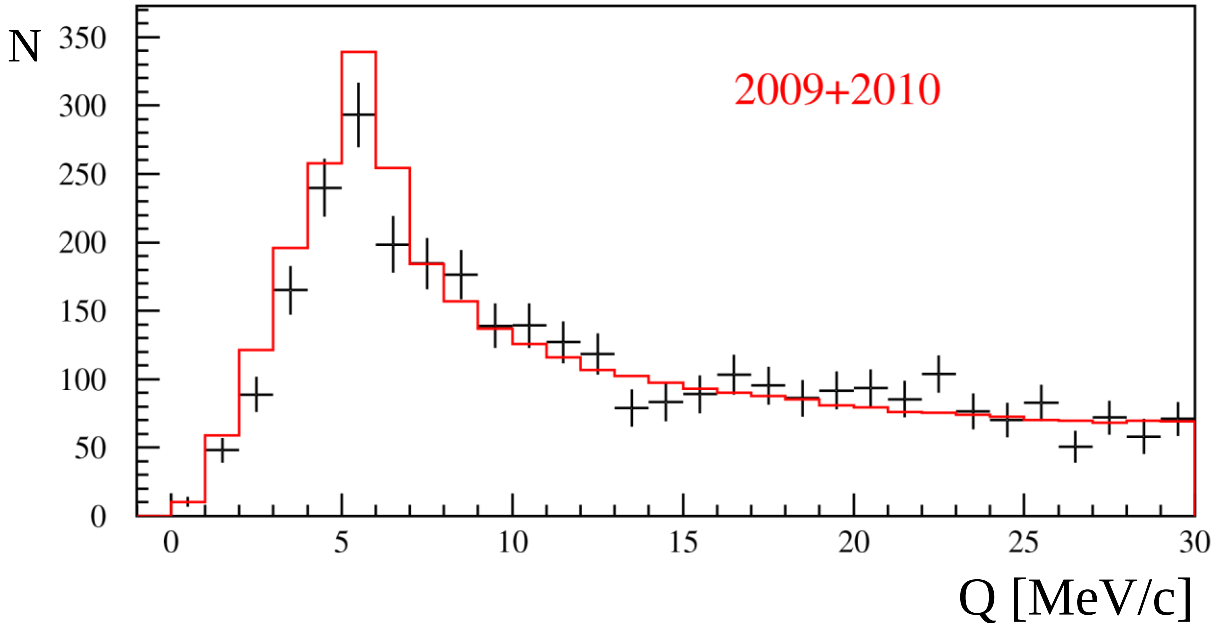
Experimental distributions of selected events. Events are fitted by the simulated distribution of K^+K^- pairs (red) and experimental distribution of pure $\pi^+\pi^-$ (blue) processed with kaon masses.

2009 + 2010

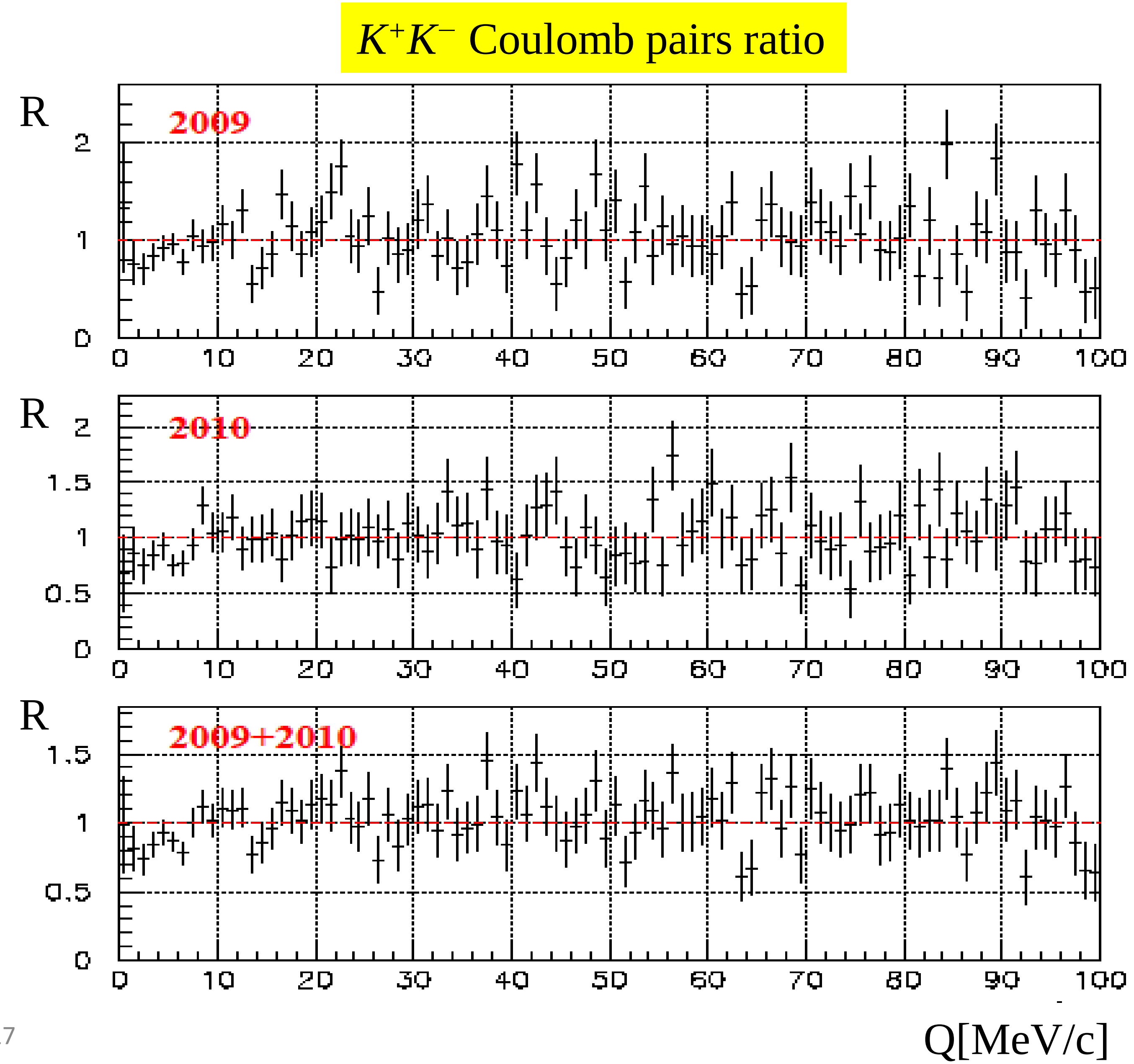
$K^+K^- = 4534 \pm 364$; $\pi^+\pi^- = 2635 \pm 366$

K^+K^- pair analysis



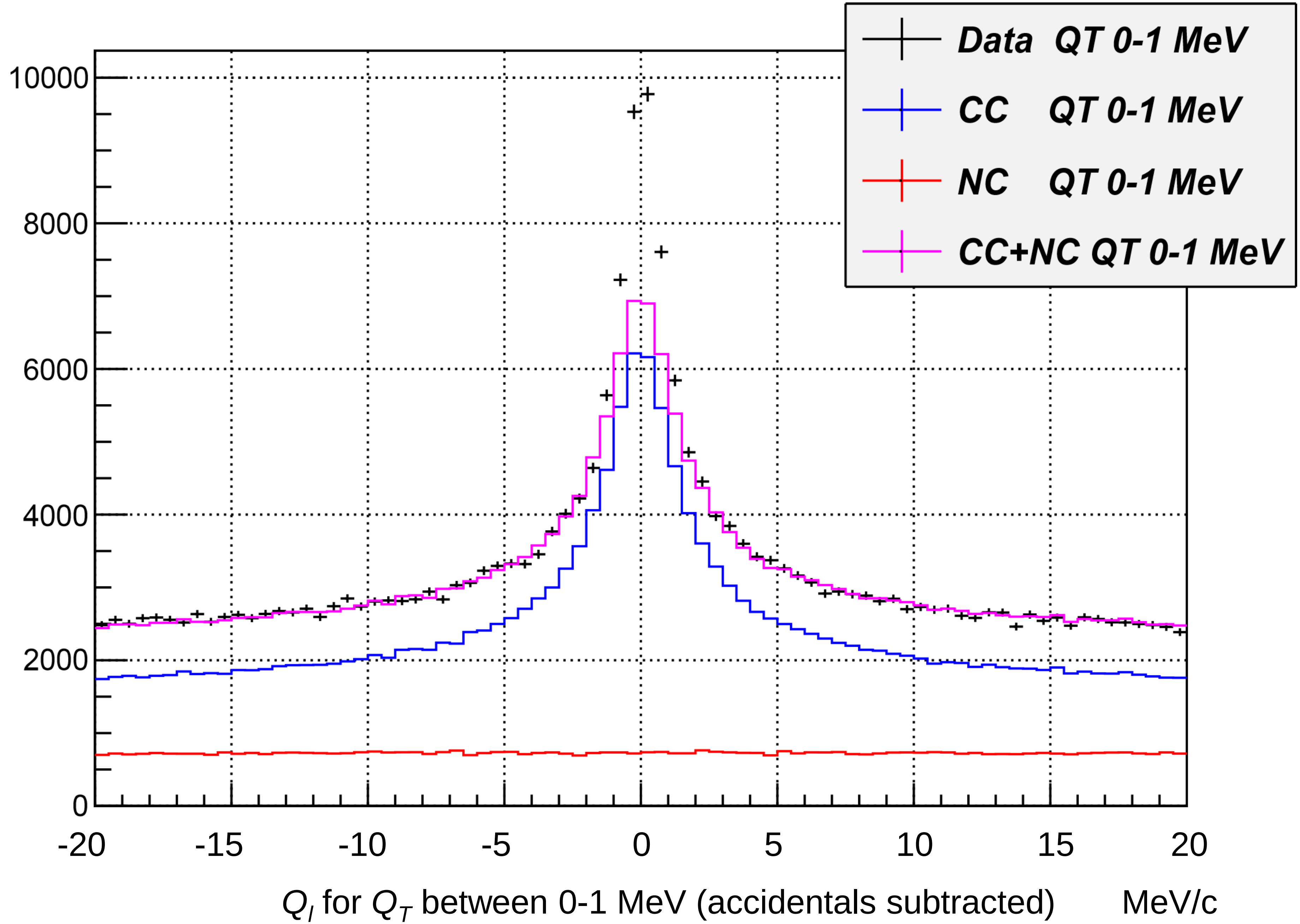


K^+K^- pair analysis



Proton-antiproton pair analysis

In 2018, 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.



Data QT 0-1 MeV
CC QT 0-1 MeV
NC QT 0-1 MeV
CC+NC QT 0-1 MeV
10000
8000
6000
4000
2000
0
-20
-15
-10
-5
0
5
10
15
20
Q_l for Q_T between 0-1 MeV (accidentals subtracted) MeV/c

Coulomb correlations

Atom	Borh radius a_B [fm]	Resonance cτ [fm]
$\pi^+\pi^-$	387	ω(782) 23
πK	248	ω(782) + ϕ(1020)
K^+K^-	109	ϕ(1020) 46
$p\bar{p}$	58	

	Z	A	Nublear radius [fm]
Be	04	9.012	2.56
Ni	28	58.69	4.78
Pt	78	195.08	7.13

Coulomb correlation with account of size of pair production region r^*

$$A_c(r^*, a_B) = A_c(0)\left[1 - \frac{2r^*}{a_B} + \cdots\right], \quad A_c(0) \sim \frac{1}{q}$$

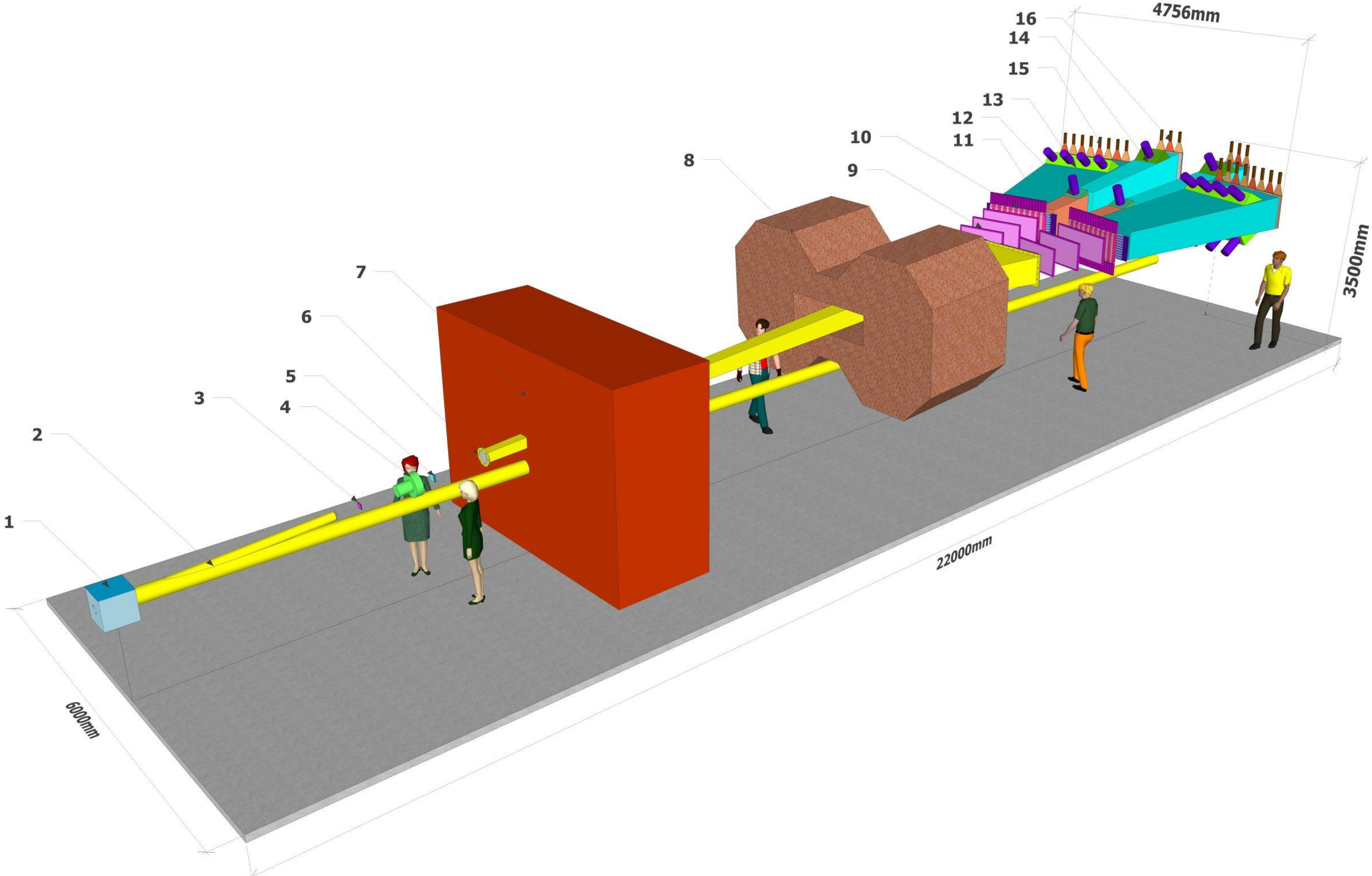
Point-like Coulomb correlation

Coulomb correlations

Coulomb correlations as a possible new physical method to investigate the particles production in the coordinate space.

The shape of Coulomb correlation curve for $K^{+}K^{-}$ and proton-antiproton pairs is expected to be much sensitive to the size of particle production region compared to the case of $\pi^{+}\pi^{-}$ pairs. Thus, detailed study of this shape could open a possibility to evaluate the size of production region for such pairs. The investigation is planned for 2018.

DIRAC++ (Setup Isometric view)



Thank you

QCD Lagrangian and its prediction

The QCD Lagrangians use the $SU(3)_L*SU(3)_R$ and $SU(2)_L*SU(2)_R$ chiral symmetry breaking.

$$\mathcal{L}(u,d,s) = \mathcal{L}(3) = \mathcal{L}_{sym}(3) + \mathcal{L}_{sym.br.}(3)$$

$$\mathcal{L}(u,d) = \mathcal{L}(2) = \mathcal{L}_{sym}(2) + \mathcal{L}_{sym.br.}(2)$$

$\mathcal{L}_{sym.br.}$ is proportional to m_q

$e^+e^- \rightarrow$ hadrons QCD provides cross sections with 1% precision

1. Perturbation theory is working at high momentum transfer Q.
2. Unitarity condition.

At large Q, contribution of $\mathcal{L}_{sym.br.}$ to the cross section is proportional to $1/Q^4$. Therefore these experiments checked only the $\mathcal{L}_{sym}$ prediction precision.

To check the total $\mathcal{L}(3)$ Lagrangian predictions, we must study the low momentum transfer Q processes.

Tools: Lattice calculations and Chiral Perturbation Theory (ChPT)

Lattice----- $\mathcal{L}(3)$, $\mathcal{L}(2)$ ChPT------Effective Lagrangians.

K^+K^- atom and its lifetime

The A_{2K} 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 ↓

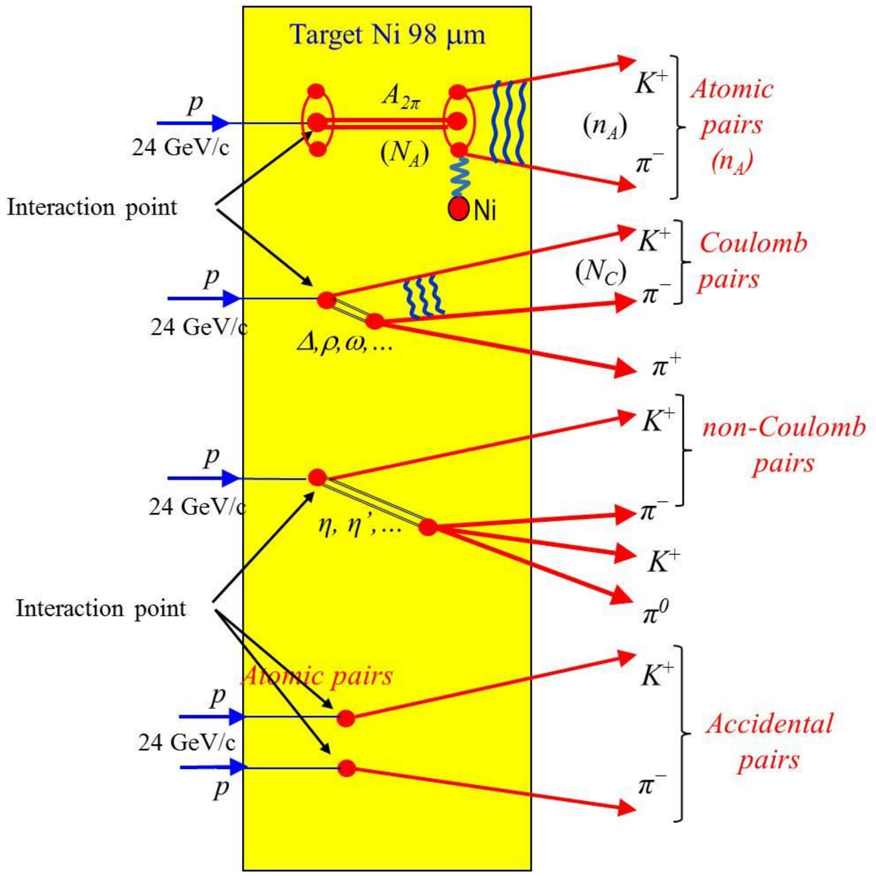
$\tau\ (A_{2K} \to \pi\pi, \pi\eta)$	K^+K^- interaction
1.2×10^{-16} s [1]	Coulomb-bound
8.5×10^{-18} s [3]	momentum dependent potential
3.2×10^{-18} s [2]	+ one-boson exchange (OBE)
1.1×10^{-18} s [2]	+ f'_0 (I=0) + $\pi\eta$-channel (I=1)
2.2×10^{-18} s [4]	ChPT

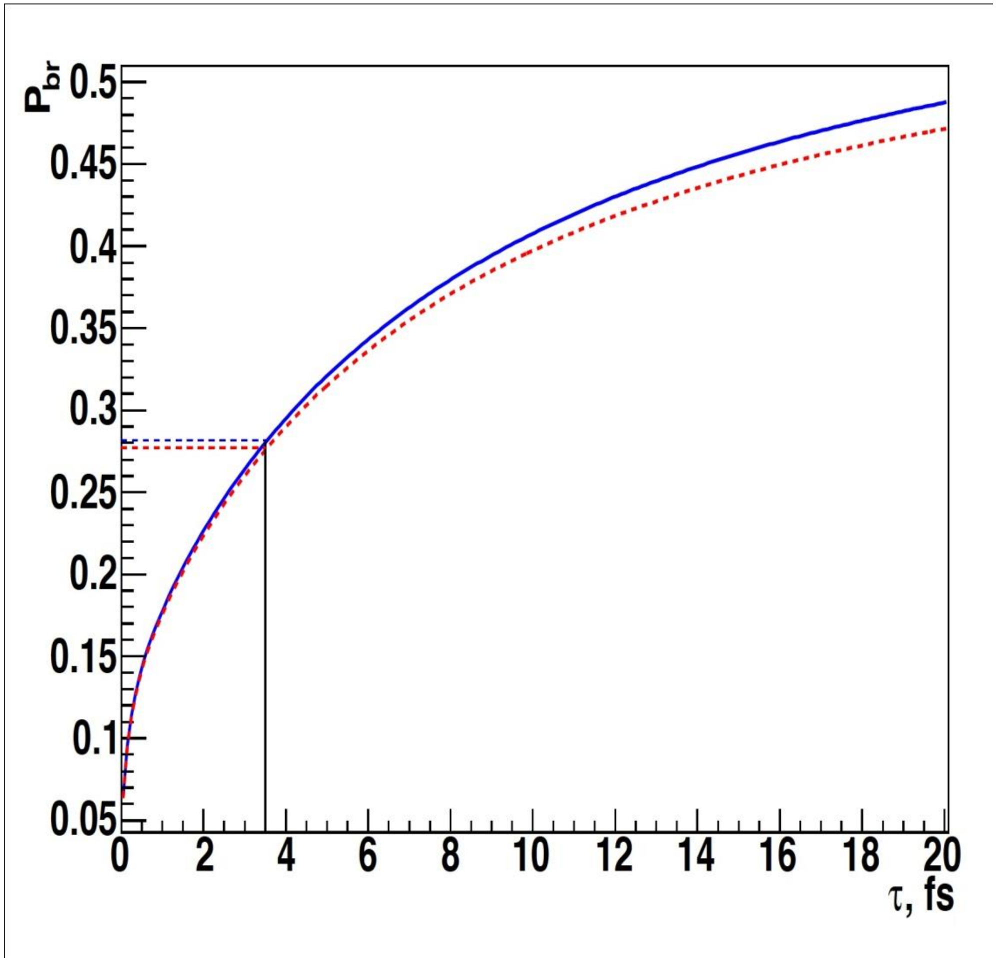
References: [1] S. Wycech, A.M. Green, Nucl. Phys. A562 (1993), 446;
[2] S. Krewald, R. Lemmer, F.P. Sasson, Phys. Rev. D69 (2004), 016003;
[3] Y-J Zhang, H-C Chiang, P-N Shen, B-S Zou, PRD74 (2006) 014013;
[4] S.P. Klevansky, R.H. Lemmer, PLB702 (2011) 235.

The πK atom lifetime and πK scattering length

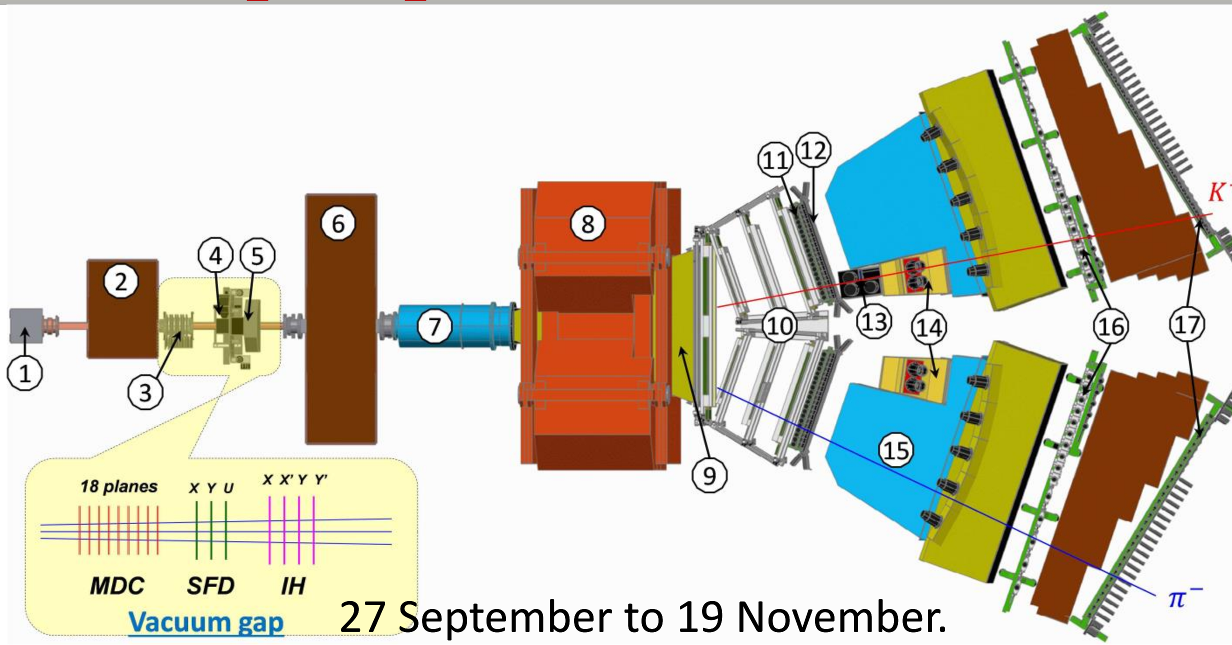
$$\frac{1}{\tau} = R\ |a_{1/2} - a_{3/2}|^2$$

$\tau_{th} = (3.5 \pm 0.4) \times 10^{-15}$ s. The evaluation error from this relation for $|a_{1/2}-a_{3/2}|$ is 1%





DIRAC setup, experimental and theoretical data



27 September to 19 November.

Experiment	Detected atomic pairs (n_A)	τ (10^{-15} sec)	$a^- = \frac{1}{3}(a_{1/2}-a_{3/2})$	Average error
DIRAC	349±61(stat)±9(syst) =349±62(tot) (5.6σ)	$5.5^{+5.0}_{-2.8}$	$0.072^{+0.031}_{-0.020}$	34%

Theory	P.Buttiker et al., Eur.Phys.J. (2004)	K.Sasaki et al., Phys.Rev. (2014)	Z.Fu, Phys.Rev. (2013)	S.R.Beame et al. Phys.Rev (2008)	C.Lang et al.,Phys.Rev. (2012)	J.Bijnens et al., J. High Energy Phys. (2004)
a^-	0.090±0.005	0.081	0.077	0.077	0.10	0.089
Method	Roy-Steiner equations	Lattice calculations	Lattice calculations	Lattice calculations	Lattice calculations	ChPT, two loops

I. Long-lived states of $\pi^+\pi^-$ atoms

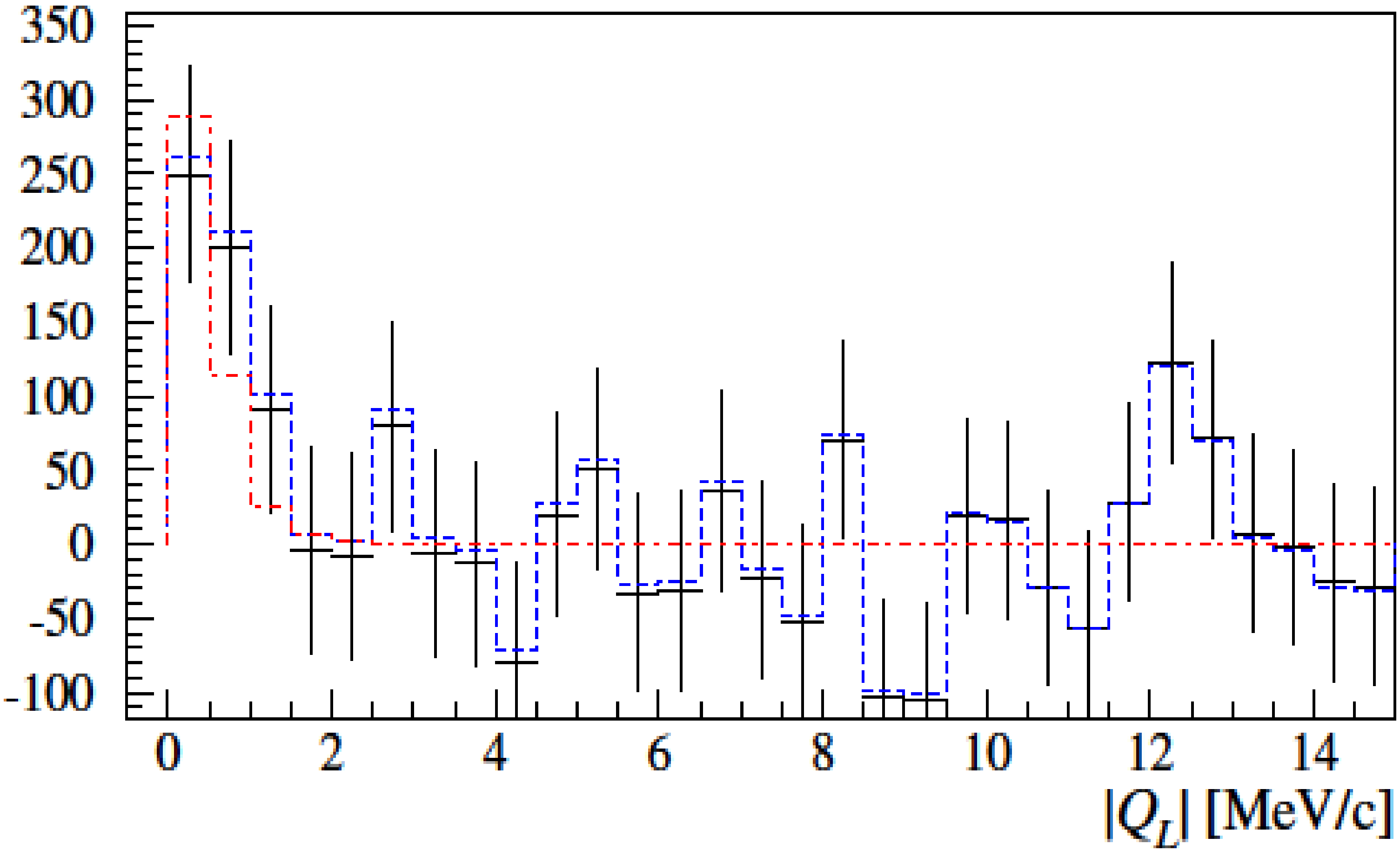
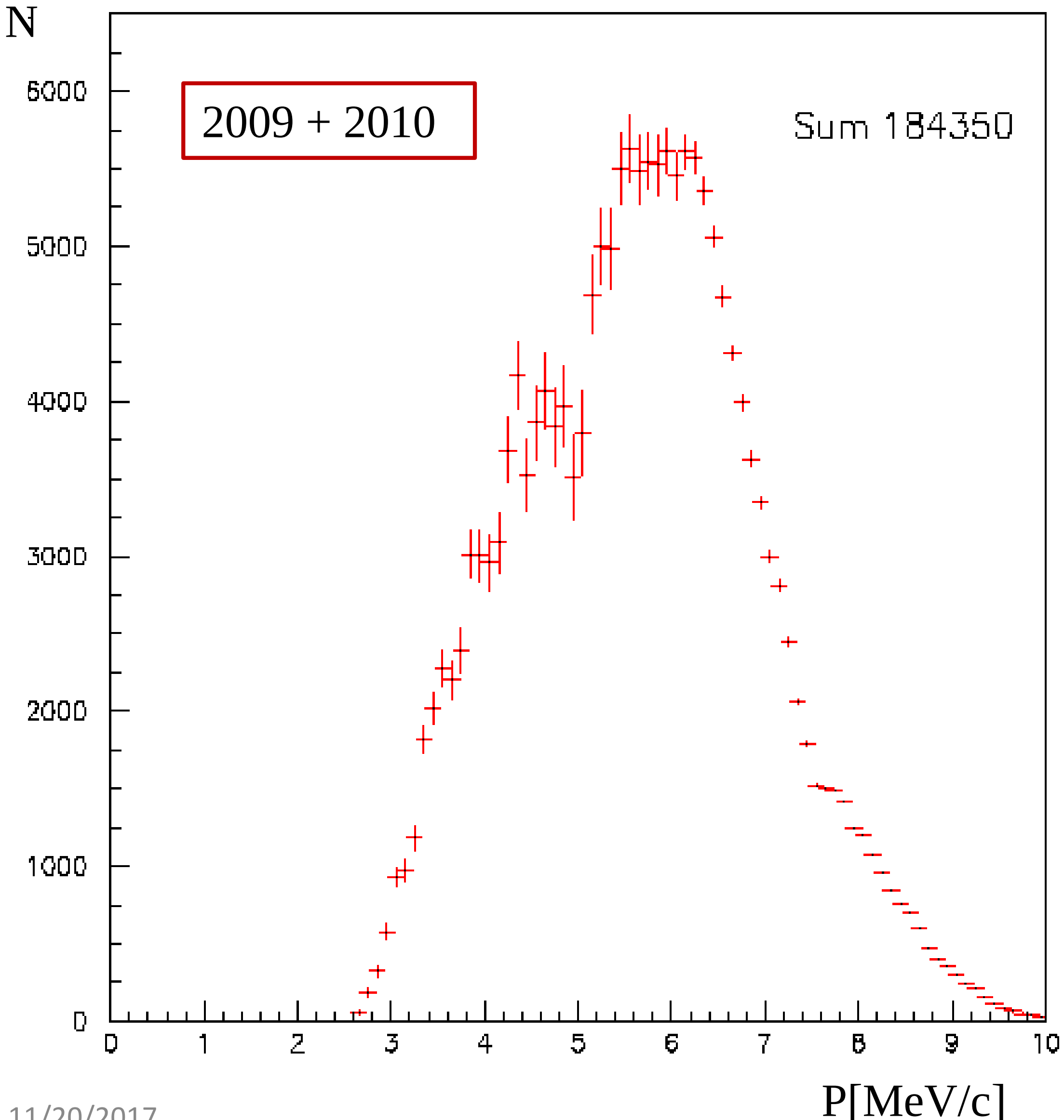


Fig. 8. $|Q_L|$ experimental distribution after subtraction of background obtained with 3 parameter fit (black points with statistical error) and after subtraction of background obtained with 2 parameter fit (blue dashed line), comparing to the simulated distribution of atomic pairs (red dotted-dashed line).
The fit procedures have been applied to the 1-dimensional $|Q_L|$ distribution.
The atomic pairs number in the region $|Q_L| < 2$, $Q_T < 4$ MeV/c obtained with 3 parameter fit is $n_A^L = 435 \pm 03$ and with 2 parameter fit is $n_A^L = 579 \pm 64$.

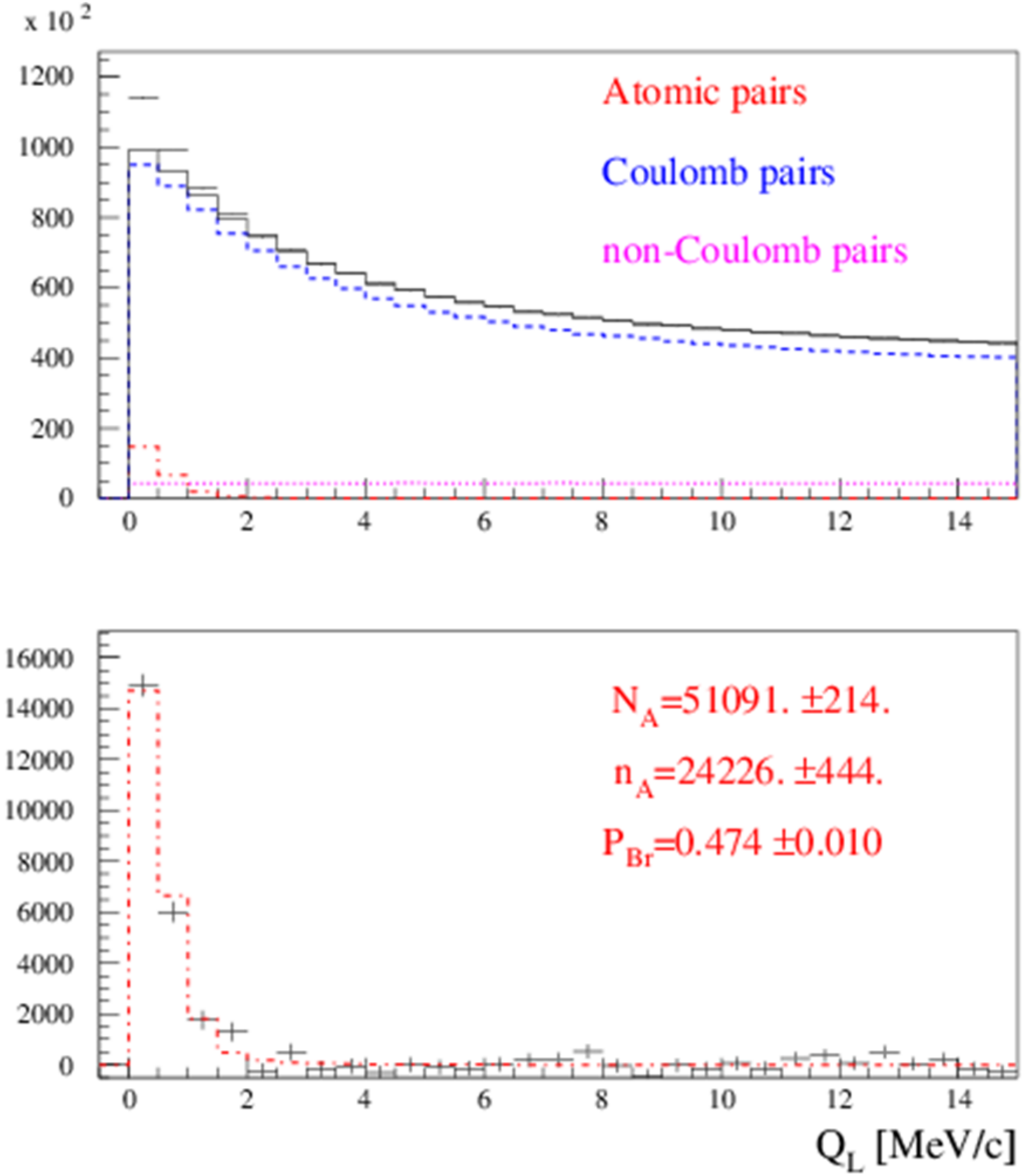
K^+K^- pair analysis

K^+K^- Coulomb pairs signal



Distribution of K^+K^- pairs in the RUN 2009 + 2010 over the full pair momentum in laboratory system.

III. The short-lived $\pi^+\pi^-$ atom lifetime measurement



Preliminary results on the short-lived atom lifetime measurement based on all available 2008-2010 data are presented in Fig. 1 and 2.

Fig.1. Distribution over $|Q_L|$ for events, selected with criterion $Q_T < 4$ MeV/c. Fractions of atomic, Coulomb and non-Coulomb pairs were obtained by fitting the distri-bution over $(|Q_L|, Q_T)$ with criteria: $|Q_L|<15$ MeV/c, $Q_T < 4$ MeV/c.
N_A, n_A and P_{br}. are the number of produced atoms, detected atomic pairs and probability of the atoms breaking in the target respectively.

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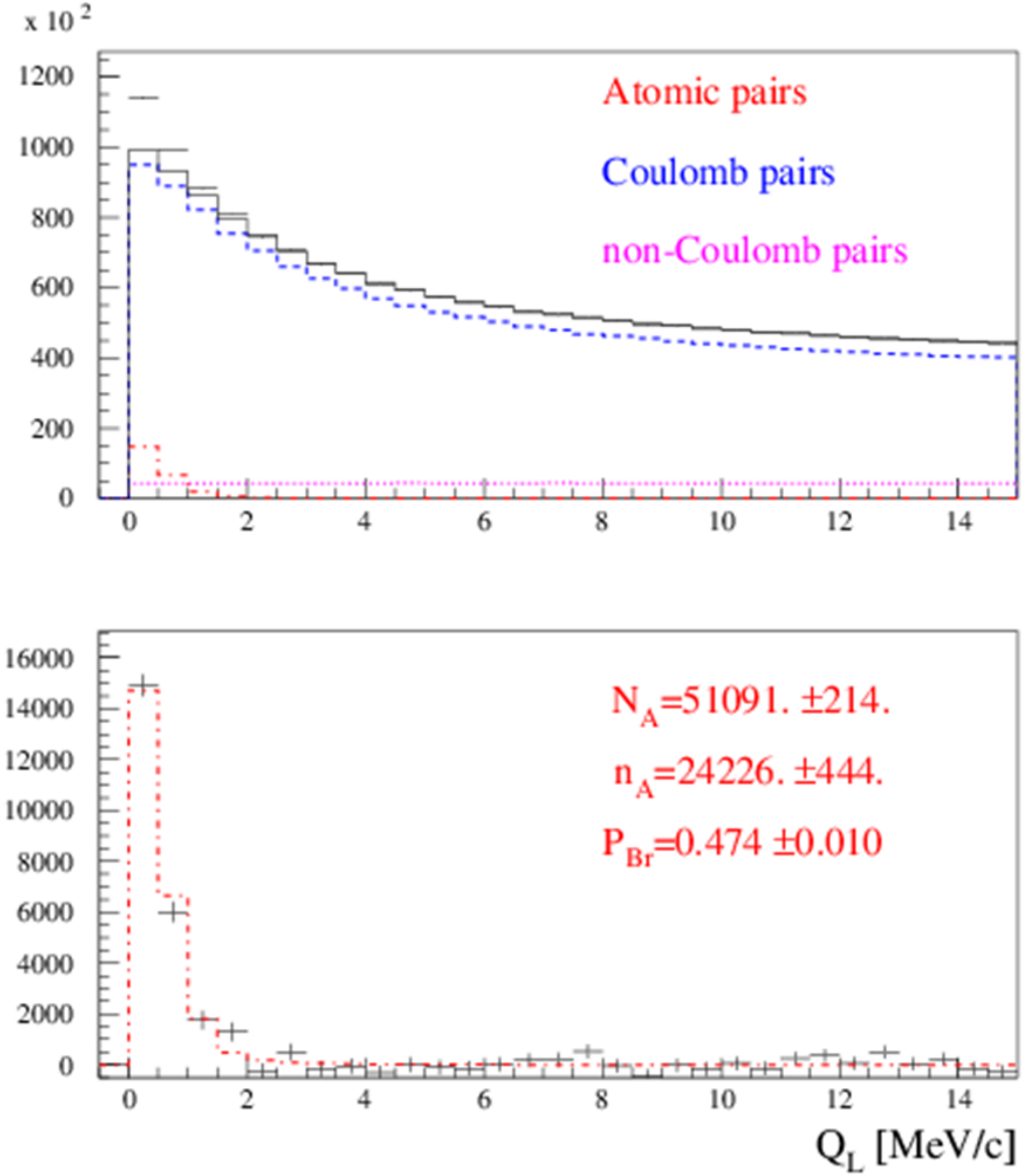

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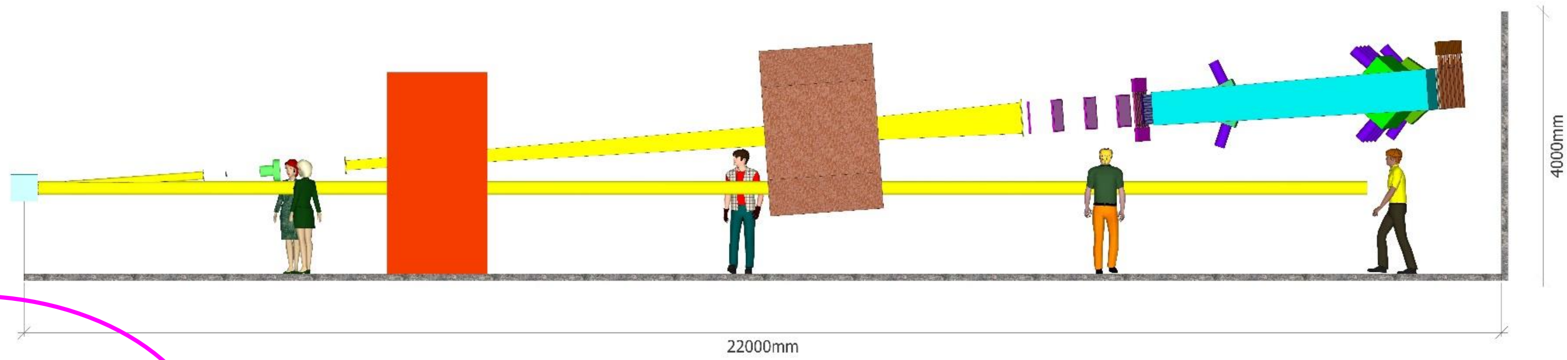
Fig.1. Distribution over $|Q_L|$ for events, selected with criterion Q_T < 4 MeV/c. Fractions of atomic, Coulomb and non-Coulomb pairs were obtained by fitting the distri-bution over ($|Q_L|$,Q_T) with criteria: $|Q_L|$<15 MeV/c, Q_T < 4 MeV/c.
N_A, n_A and P_{br}. are the number of produced atoms, detected atomic pairs and probability of the atoms breaking in the target respectively.

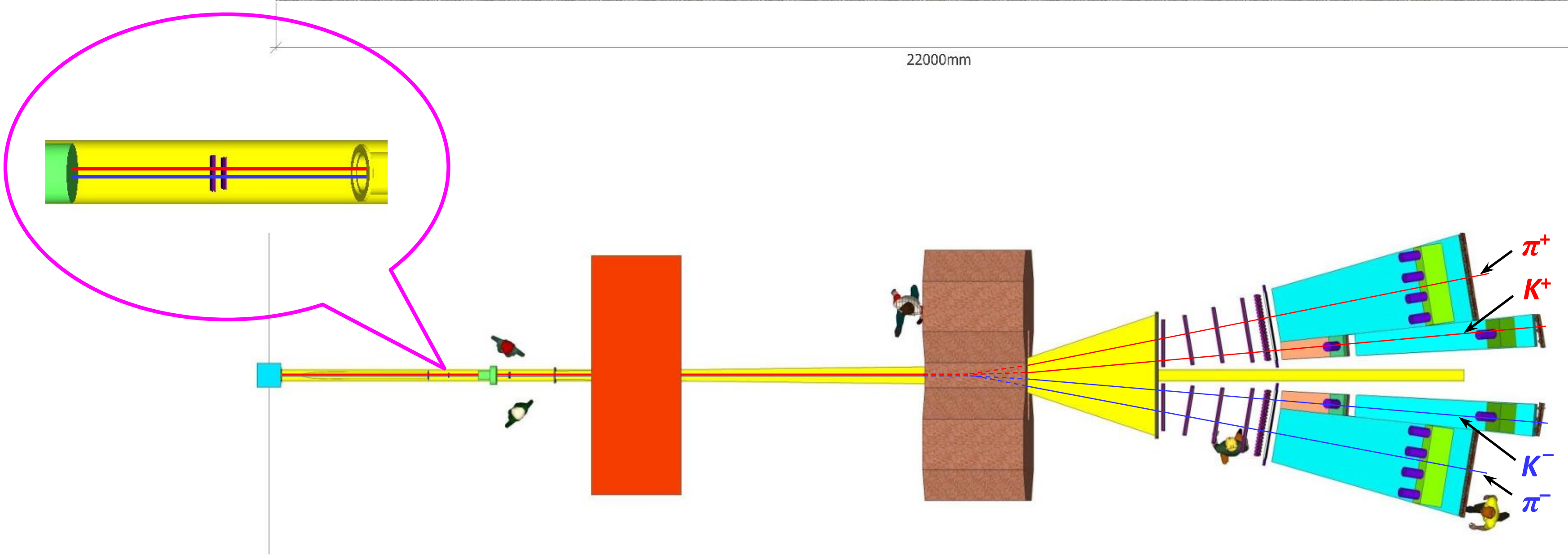
III. The short-lived $\pi^+\pi^-$ atom lifetime measurement

1. The average probability of $\pi^+\pi^-$ atom breakup for the Ni targets of 98 μm thickness (RUN 2008) and 109 μm (RUNS 2009-2010) was evaluated as $P_{br} = 0.474 \pm 0.01$. It is in agreement with the value $P_{br} = 0.46 \pm 0.013$ obtained for the 98 μm target and published in 2011.
In the final data analysis, the new measurements of multiple scattering will be included.
The dedicated paper will be ready before June of 2018.

2. The current value of systematical error in the $\pi^+\pi^-$ atom lifetime measurement is equal to the statistical uncertainty. The main part of the systematical error arises due to an uncertainty in the multiple scattering in the Ni target.
To reduce this error, we did an experimental study of the multiple scattering in the targets:
Be: 100 and 2000 μm; Ti: 250 μm ; Ni: 50, 109 and 150 μm and Pt: 2 and 30 μm.
For Be (2000 μm), Ni (109 μm) the difference between theoretical and experimental r.m.s. is 0.4% and 0.8% accordingly. The r.m.s. values were calculated in the interval of $\pm 2\sigma$.
The achieved precision of multiple scattering investigation is better by one order of magnitude than in the previous experiments.

DIRAC++ Setup (top view)





DIRAC++ (Detectors)

Setup element (number planes)	Aperture (cm)	Occupancy ($s^{-1} \cdot cm^{-2}$)	X_0 %	Resolution	
				Coordinate (μm)	Time (ns)
1. Target Station (*) 2. Vacuum system (*) 3. Vertex detector (2 ÷ 4 planes)	7.6 × 7.6	$(5 \div 20) \cdot 10^5$	0.7 ÷ 1.5	50	0.2
4. RICH?	9.0 × 9.0	$(4 \div 16) \cdot 10^5$	< 5		< 1
5. SFD (3 planes) (*)	10. × 10.	$(3 \div 12) \cdot 10^5$	2.7	60	0.3
6. Vacuum system (*) 7. Iron shielding wall (*) 8. Spectrometer magnet (*)	155 × 50				
9. Downstream Tracker (2 × 8)	75 ÷ 110×44	$(1 \div 10) \cdot 10^4$	4 ÷ 8	< 80	
10. Vertical Hodoscope (2 × 1 ÷ 2) (*)	112 × 44	$(1 \div 8) \cdot 10^4$			< 0.7
11. Horizontal Hodoscope (2) (*)	115 × 44	$(1 \div 8) \cdot 10^4$			< 0.5
12. Heavy Gas Cherenkov detector (2) (*)	30 × 49	$(1 \div 8) \cdot 10^4$			< 1.0
13. Nitrogen Cherenkov detector (2)	90 × 50	$(1 \div 10) \cdot 10^3$			< 1.0
14. Nitrogen Cherenkov detector (2)	37 × 53	$(1 \div 8) \cdot 10^4$			< 1.0
15. PreShower detector (2)	148 × 60	$(1 \div 8) \cdot 10^3$			< 1.0
16. PreShower detector (2)	56 × 60	$(5 \div 40) \cdot 10^3$			< 1.0
--. Ionisation Hodoscope (4 planes)	10. × 10.	$(4 \div 16) \cdot 10^5$	3		

*** - Existing parts of the Setup**   **? - Micro-Pattern Gas Detectors (MPGD)**

SPS beam time for πK scattering length measurement

The data at p_p = 24*GeV/c* and 450*Gev/c* were simulated, processed and analysed (V.Yazkov, DIRAC note, 2016 05).

Experimental conditions on SPS with Ni target

Thin *Ni* target, nuclear efficiency ~ 6×10^{-4}.

The proton beam can be used for other experiments.

Proton beam intensity: 3×10^{11} protons/s

(DIRAC worked at 2.7×10^{11} protons/s)

Number of spills: 4.5×10^5 with spill duration 4.5 s

Data taking: 3000 spills per 24 hours.

Running time: 5 months

The expected number of πK atomic pairs: n_A=13000

(In the DIRAC experiment was n_A=349±62)

The statistical precision in these conditions for πK scattering length will be: ~5%

The expected systematic error will be at the level of 2%

The expected number of $\pi^+\pi^-$ atomic pairs n_A=400000

The statistical precision of the $\pi^+\pi^-$ scattering length will be: 0.7%

The expected systematic error will be at the level of 2%

$\mathcal{L}(2)$ and Chiral Lagrangian predictions check with short-lived $\pi^+\pi^-$ atoms

- The QCD Lagrangian $\mathcal{L}(2)$ and Chiral Lagrangian describe processes with *u* and *d* quarks, using $SU(2)_L * SU(2)_R$ chiral symmetry breaking.
- From the ChPT prediction for a_0 and a_2, the $\pi^+\pi^-$ atom lifetime in the ground state, given by $1/\tau = R|a_0 - a_2|^2$, is $\tau_{th} = (2.9 \pm 0.1) * 10^{-15}$ s.
- The evaluation error for $|a_0 - a_2|$ from this relation is 0.6%.
- These Lagrangians predict the S-wave $\pi^+\pi^-$ scattering lengths a_0 and a_2.

$\mathcal{L}(2)$ and Chiral Lagrangian predictions check with short-lived $\pi^+\pi^-$ atoms

ChPT	a_0 and a_2 a_0-a_2	2.3% precision 1.5% precision	Colangelo et al. Nucl.Phys.(2001)

Lattice calculations	a_0 a_2	4-10% precision ~1% precision	K.Sasaki et al., Phys.Rev. 2014, Z.Fu, Phys.Rev.(2013), C.Lang et al.,Phys.Rev.(2012), Feng et al., Phys. Lett.(2010), T.Yagy at al., arXiv:1108.2970, S.Beame et al. Phys.Rev(2008)

Experimental values	a_0-a_2	~ 4% precision	J.R.Bateley at al., Eur. Phys. J. (2009), J.R.Bateley at al., Eur. Phys. (2010), Adeva et al., Phys. Lett. (2011)
	a_0 a_2	~ 6% precision ~22% precision	J.R.Bateley at al., Eur. Phys. J. (2009), J.R.Bateley at al., Eur. Phys. (2010)
on SPS	a_0-a_2	~2% precision	DIRAC estimation