DIRAC Report

SPSC – October 2019

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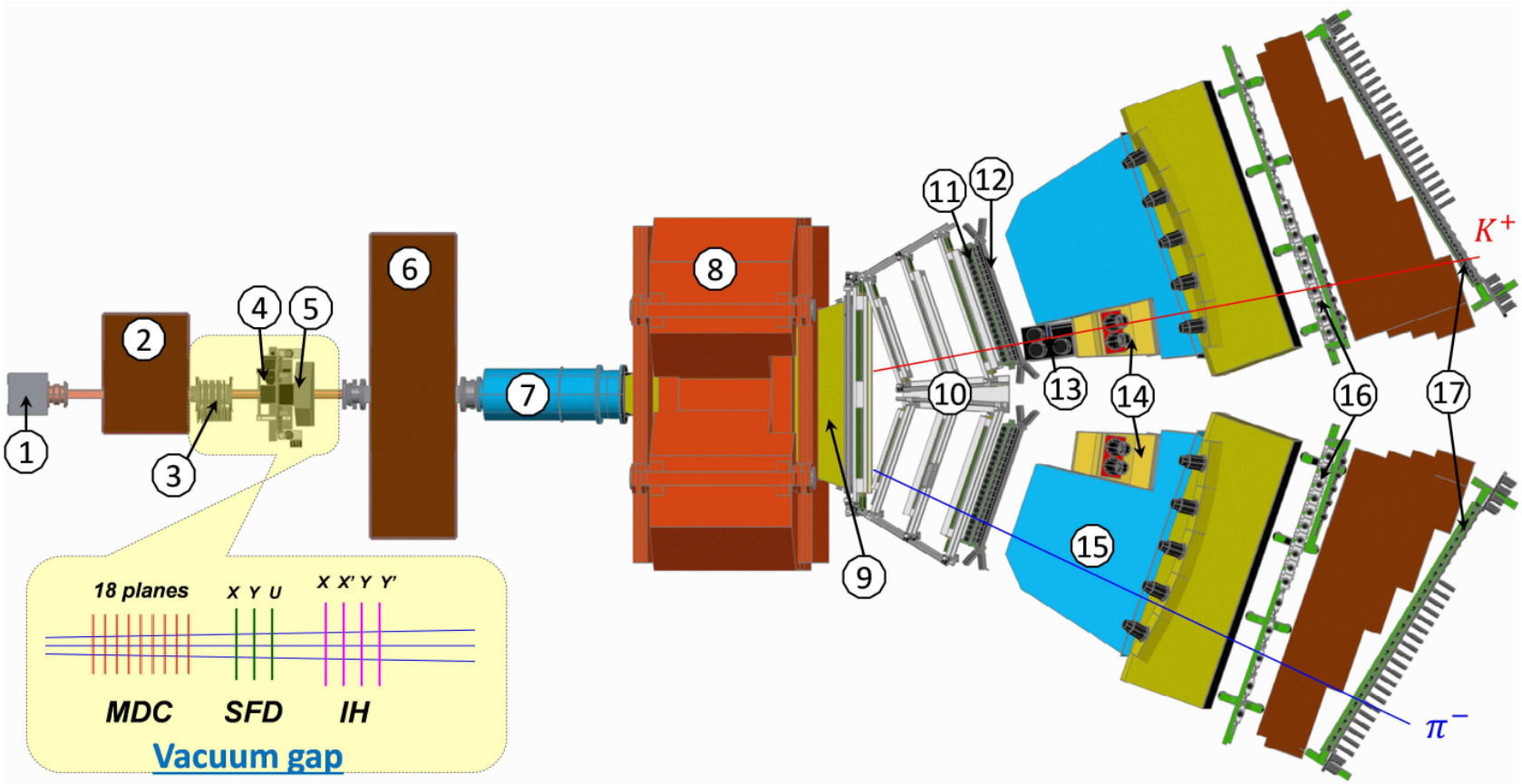
Content

1. Long-lived $\pi^+\pi^-$ atoms
2. K^+K^- pair investigation near threshold
3. Short-lived $\pi^+\pi^-$ atom lifetime measurement
4. Proton-antiproton pair analysis
5. High precision investigation of multiple scattering in Be, Ti, Ni and Pt

DIRAC setup, experimental and theoretical data



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

The lifetime of the long-lived atom in 2p state is:

$$\tau_{2p} = 0.45^{+1.08}_{-0.30}\big|_{\text{tot}} 10^{-11}\text{s}$$

QED: $\tau_{2p} = 1.17\times10^{-11}\text{s}$

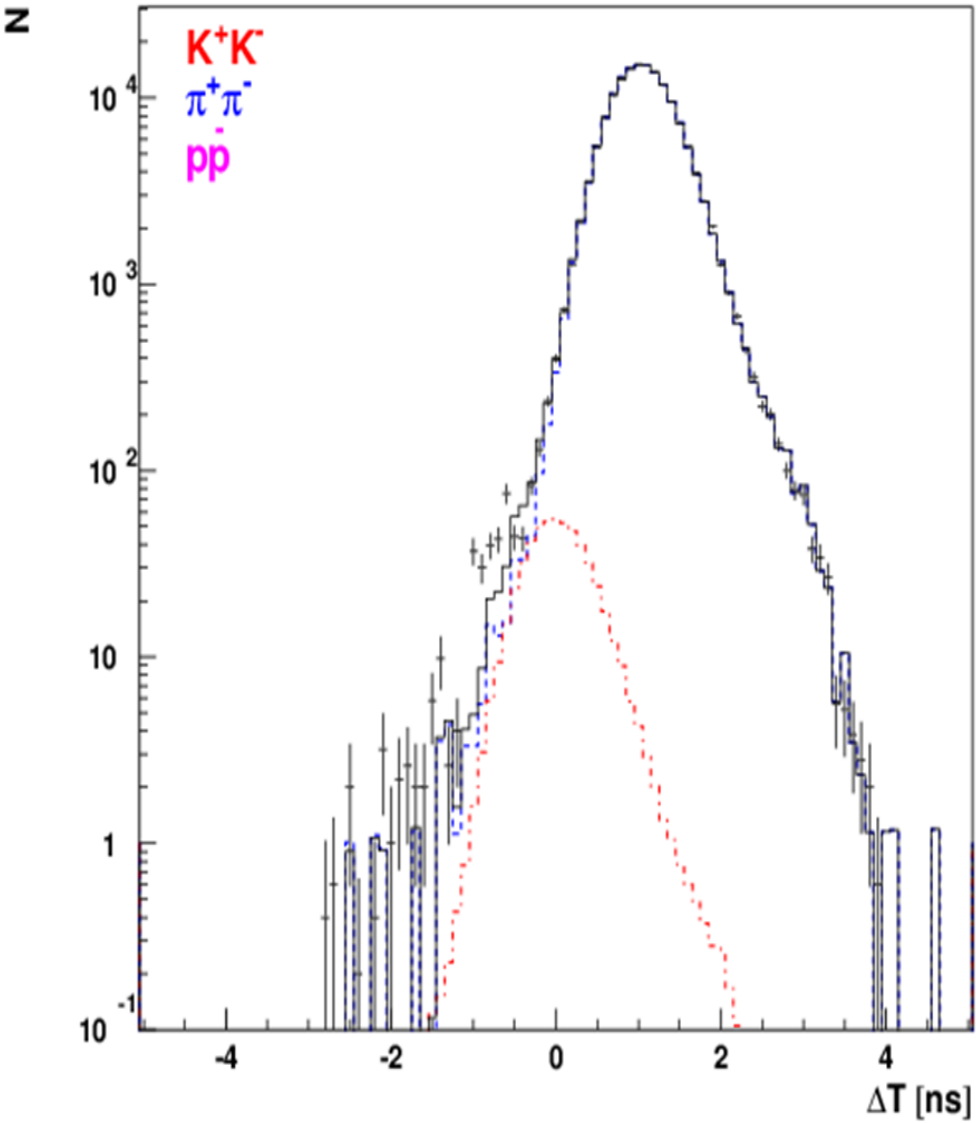
The measured ground state lifetime is: $\tau_{1s} = 3.15^{+0.28}_{-0.26}\big|_{\text{tot}}\times10^{-15}\text{s}$

$$\tau_{2p} = 0.60^{+1.34}_{-0.30}\big|_{\text{tot}} 10^{-11}\text{s}$$

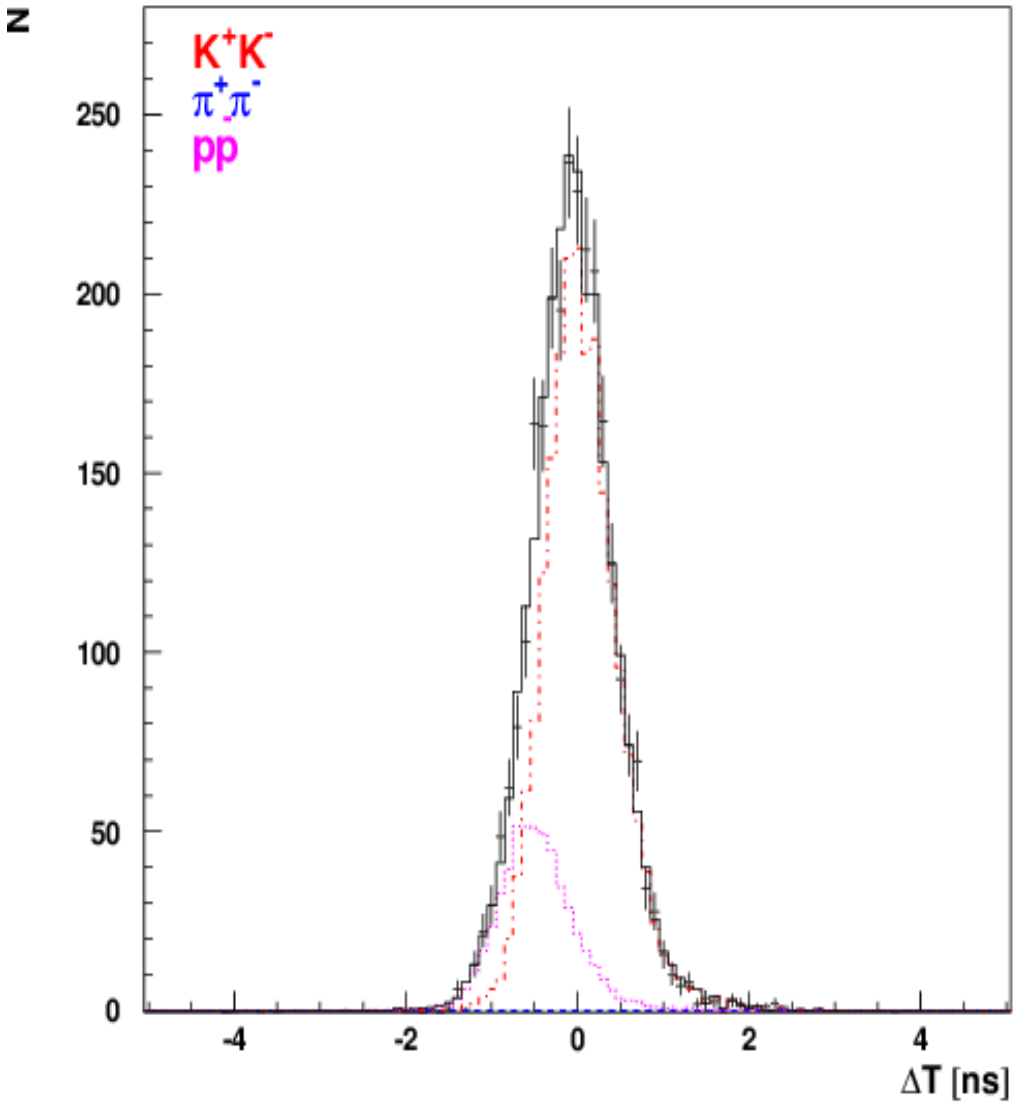
One-third of the long-lived atoms have a lab. decay length of 40 – 140cm. It opens the possibility to measure the Lamb shift and $\boldsymbol{\pi\pi}$ scattering lengths. The experimental results were published :

Phys.Rev.Lett., 122, 082003(2019)

K^+K^- pair analysis



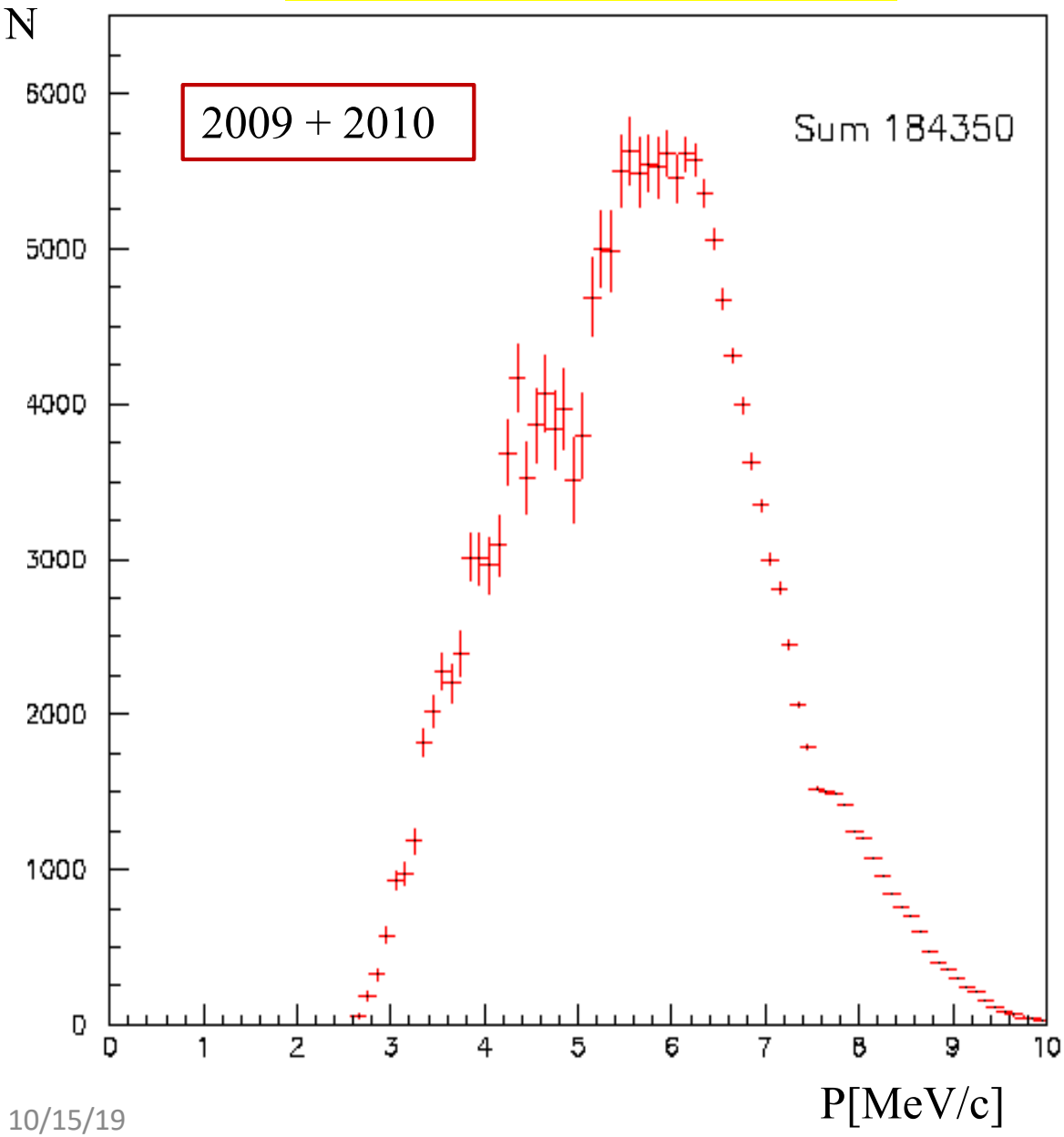
The time-of-flight distribution for the low momentum interval



The time-of-flight distribution for the high momentum interval

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.

Experimental data

Experimental distributions 2009, 2010 years evaluated with different (30%, 50%, 70%) cuts on the Time of Flight spectra for K^+K^- separation and $\pi^+\pi^-$, $p\bar{p}$ background suppression (with Q_T cuts on the trigger only)

2009	Experimental data				Correction ratios		
Sample	all	30%	50%	70%	30%/all	50%/all	70%/all
$\pi^+\pi^-$	7.77E+06	17290	3540	620	0.22%	0.05%	0.008%
K^+K^-	90840	25660	15040	8210	28.2%	16.6%	9.0%
$p\bar{p}$	7670	2960	1930	880	38.6%	25.2%	11.5%

2010	Experimental data				Correction ratios		
Sample	all	30%	50%	70%	30%/all	50%/all	70%/all
$\pi^+\pi^-$	7.96E+06	15230	2970	80	0.19%	0.04%	0.001%
K^+K^-	92960	25550	15910	8330	27.5%	17.1%	9.0%
$p\bar{p}$	7200	2950	1780	770	41.0%	24.7%	10.7%

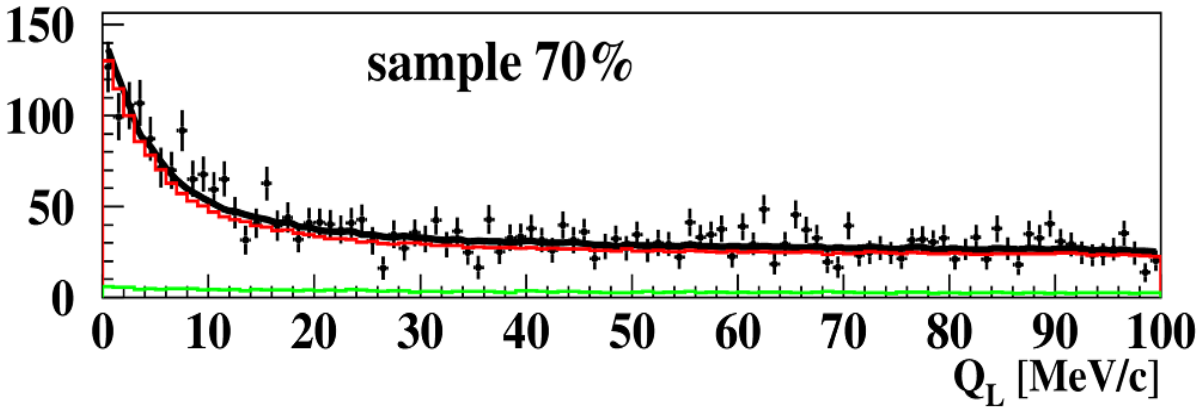
Experimental data

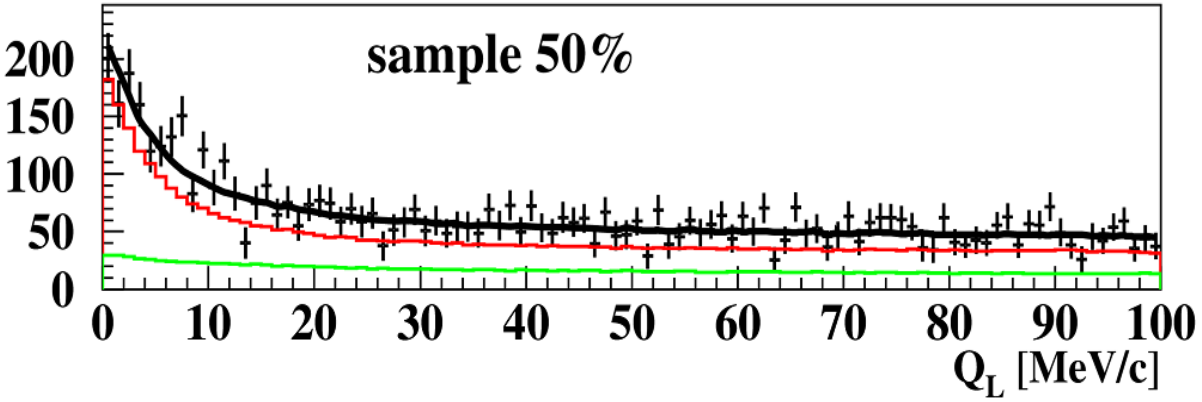
Experimental distributions 2009, 2010 years evaluated with different (30%, 50%, 70%) cuts on the Time of Flight spectra for K^+K^- separation and $\pi^+\pi^-$, $p\bar{p}$ background suppression (with $Q_T < 8$MeV/c)

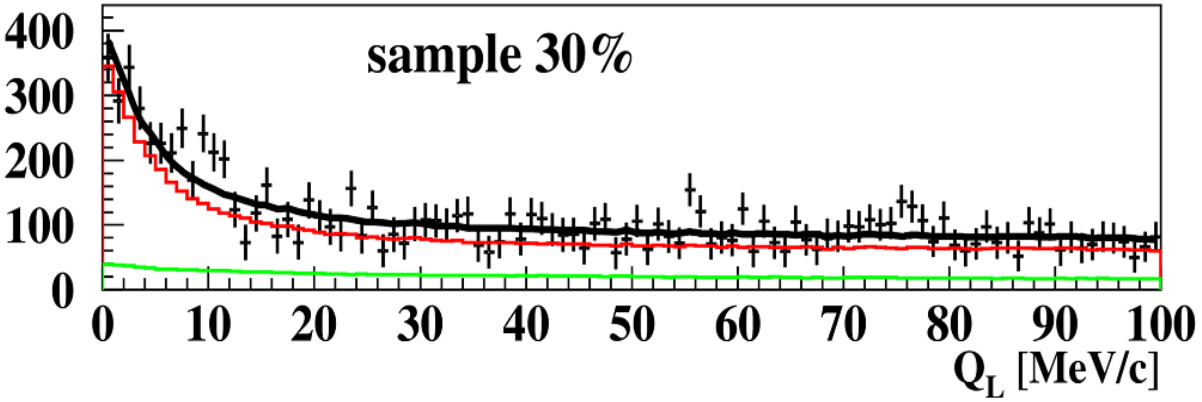
2009	Experimental data				Correction ratios		
Sample	all	30%	50%	70%	30%/all	50%/all	70%/all
$\pi^+\pi^-$	4.59E+06	9970	2030	380	0.22%	0.04%	0.008%
K^+K^-	50500	14470	8350	4510	28.7%	16.5%	8.9%
$p\bar{p}$	3730	1520	990	450	40.8%	26.5%	12.1%

2010	Experimental data				Correction ratios		
Sample	all	30%	50%	70%	30%/all	50%/all	70%/all
$\pi^+\pi^-$	4.69E+06	8590	1660	90	0.18%	0.04%	0.002%
K^+K^-	50200	14140	8750	4510	28.2%	17.4%	9.0%
$p\bar{p}$	3180	1470	880	390	46.2%	27.7%	12.3%

Experimental Q_L distributions 2009 + 2010







The experimental distributions fitted in the interval $0 < Q_L < 100$MeV/c by simulated distributions of K^+K^- pairs (red line) and $\pi^+\pi^-$ pairs (green line). The black line is the sum of K^+K^- and $\pi^+\pi^-$ pairs.

K^+K^- and $\pi^+\pi^-$ experimental Q_L distribution 2009 and 2010 data

Analysis of the 2009, 2010 years experimental Q_L distributions evaluated by different (30%, 50%, 70%) cuts on the Time of Flight pair spectra .
The Q_L spectra fitted in $0 < Q_L < 100$ MeV/c interval by the simulated distributions of K^+K^- and $\pi^+\pi^-$ pairs.

year	cut on ToF	total events	$(K^+K^-) \pm \sigma_{K^+K^-}$	$(\pi^+\pi^-) \pm \sigma_{\pi^+\pi^-}$	χ^2 /DF
2009	70%	1870	1820 ± 240	-40 ± 230	1.016
	50%	3340	2260 ± 360	990 ± 370	0.931
	30%	6080	3970 ± 660	2040 ± 680	0.770
2010	70%	1920	1460 ± 210	370 ± 210	1.016
	50%	3080	2320 ± 360	700 ± 360	0.931
	30%	4960	4740 ± 630	180 ± 650	0.770
2009 + 2010	70%	3790	3280 ± 320	330 ± 310	
	50%	6420	4580 ± 510	1690 ± 510	
	30%	11050	8720 ± 910	2220 ± 940	

K^+K^- and $\pi^+\pi^-$ experimental Q distribution 2009 and 2010 data

Analysis of the 2009, 2010 years experimental ***Q*** distributions evaluated by different (30%, 50%, 70%) cuts on the Time of Flight pair spectra .
The ***Q*** spectra fitted in $0 < Q < 100$ *MeV/c* interval
by the simulated distributions of K^+K^- and $\pi^+\pi^-$ pairs.

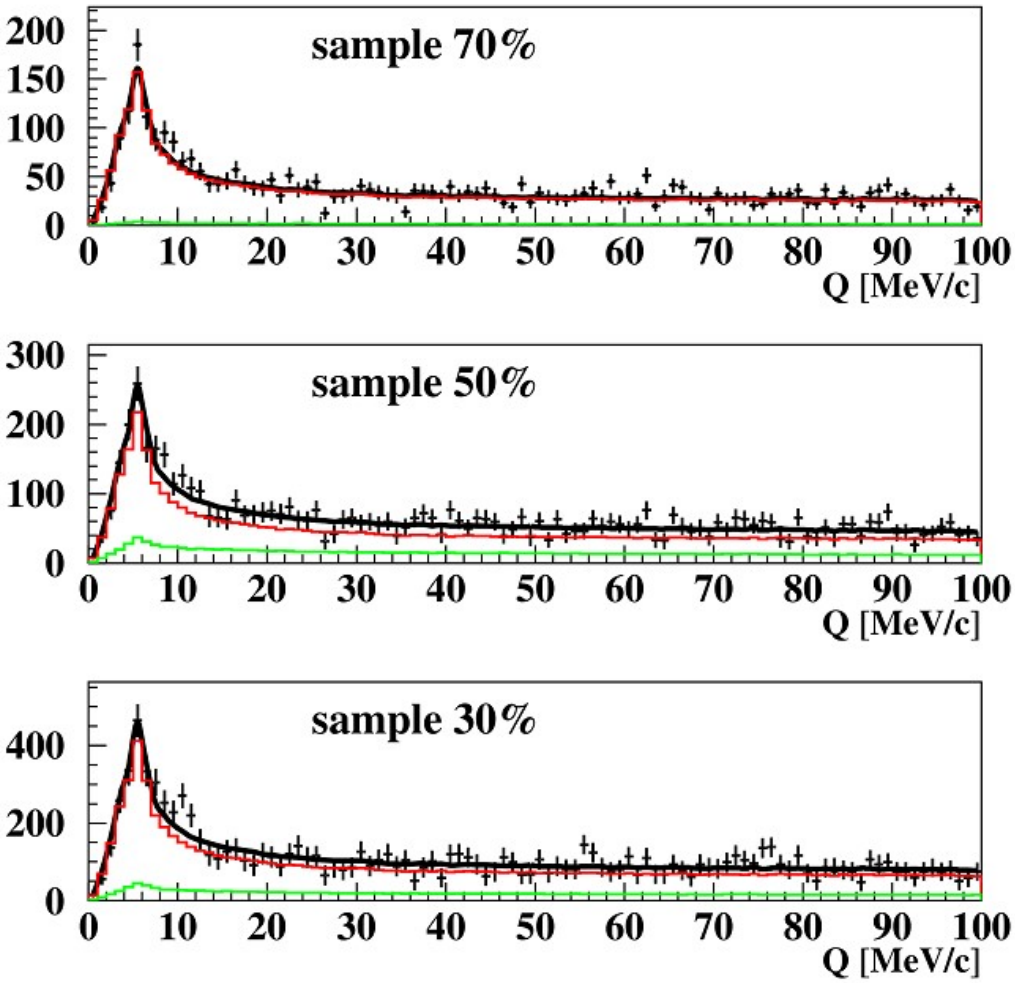
year	cut on ToF	total events	$(K^+K^-) \pm \sigma_{K^+K^-}$	$(\pi^+\pi^-) \pm \sigma_{\pi^+\pi^-}$	χ^2 /DF
2009	70%	1870	1840 ± 240	-70 ± 240	1.180
	50%	3340	2310 ± 380	950 ± 380	1.129
	30%	6070	4150 ± 680	1860 ± 710	0.928
2010	70%	1920	1620 ± 220	220 ± 220	0.962
	50%	3080	2470 ± 370	550 ± 370	0.790
	30%	4960	4910 ± 650	0 ± 670	0.688
2009 + 2010	70%	3790	3460 ± 330	150 ± 320	
	50%	6420	4780 ± 530	1490 ± 530	
	30%	11030	9060 ± 940	1860 ± 980	

K^+K^- and $\pi^+\pi^-$ experimental Q distribution 2009 and 2010 data

Analysis of the 2009, 2010 years experimental ***Q*** distributions evaluated by different (30%, 50%, 70%) cuts on the Time of Flight pair spectra .
The ***Q*** spectra fitted in $0 < Q < 30$ *MeV/c* interval
by the simulated distributions of K^+K^- and $\pi^+\pi^-$ pairs.

year	cut on ToF	total events	$(K^+K^-) \pm \sigma_{K^+K^-}$	$(\pi^+\pi^-) \pm \sigma_{\pi^+\pi^-}$	χ^2 /DF
2009	70%	1870	1880 ± 290	-140 ± 330	1.324
	50%	3340	2300 ± 450	930 ± 540	1.124
	30%	6070	4830 ± 830	780 ± 1030	1.124
2010	70%	1920	1560 ± 260	280 ± 290	1.067
	50%	3080	2420 ± 440	620 ± 530	0.504
	30%	4960	4640 ± 780	410 ± 960	0.831
2009 + 2010	70%	3790	3440 ± 380	140 ± 440	
	50%	6420	4720 ± 630	1550 ± 760	
	30%	11030	9470 ± 1140	1190 ± 1410	

Experimental Q distributions 2009 + 2010

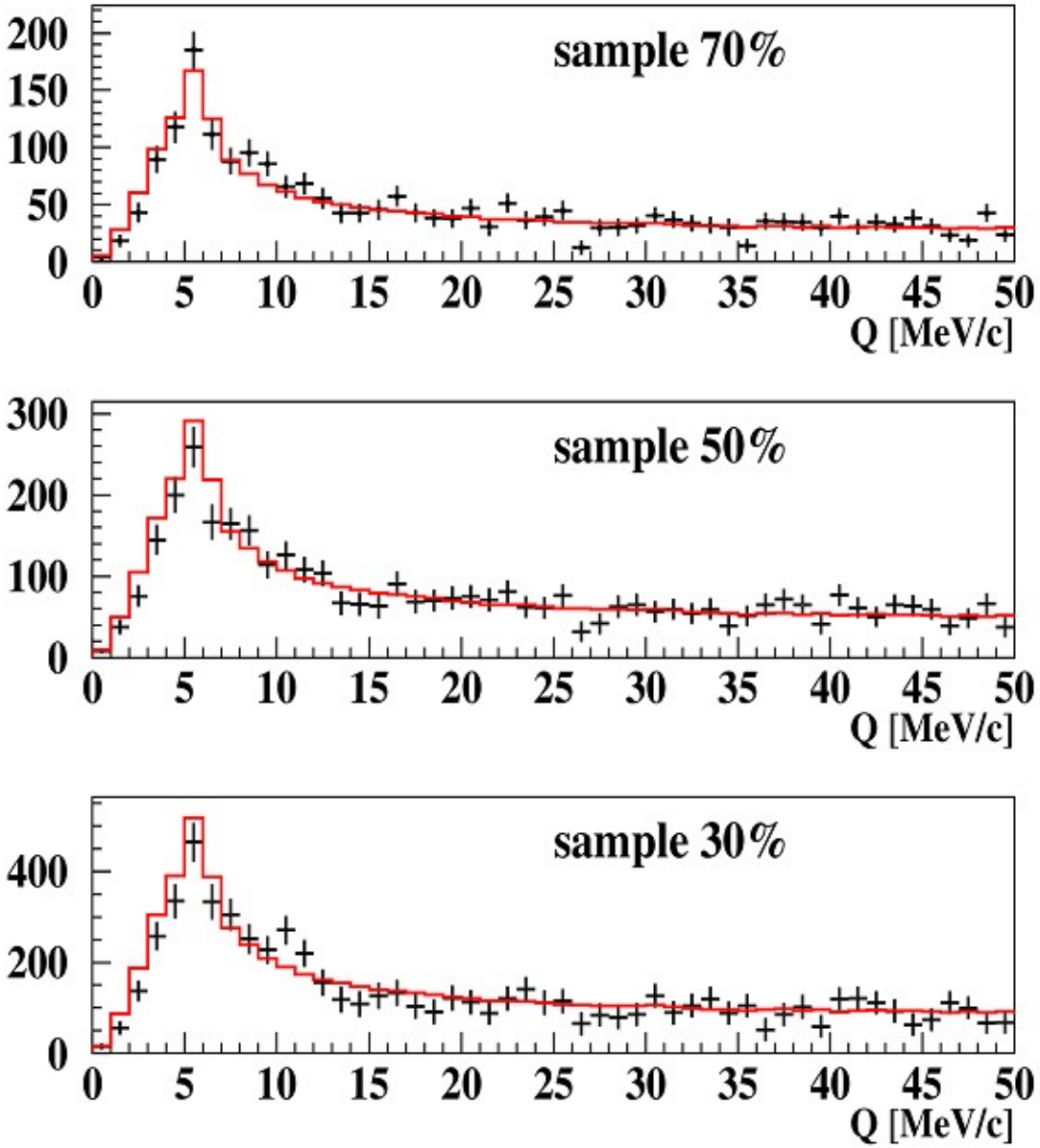


The experimental distributions fitted in the interval $0 < Q < 100$ MeV/c by simulated distributions of K^+K^- pairs (red line) and $\pi^+\pi^-$ pairs (green line). The black line is the sum of K^+K^- and $\pi^+\pi^-$ pairs.

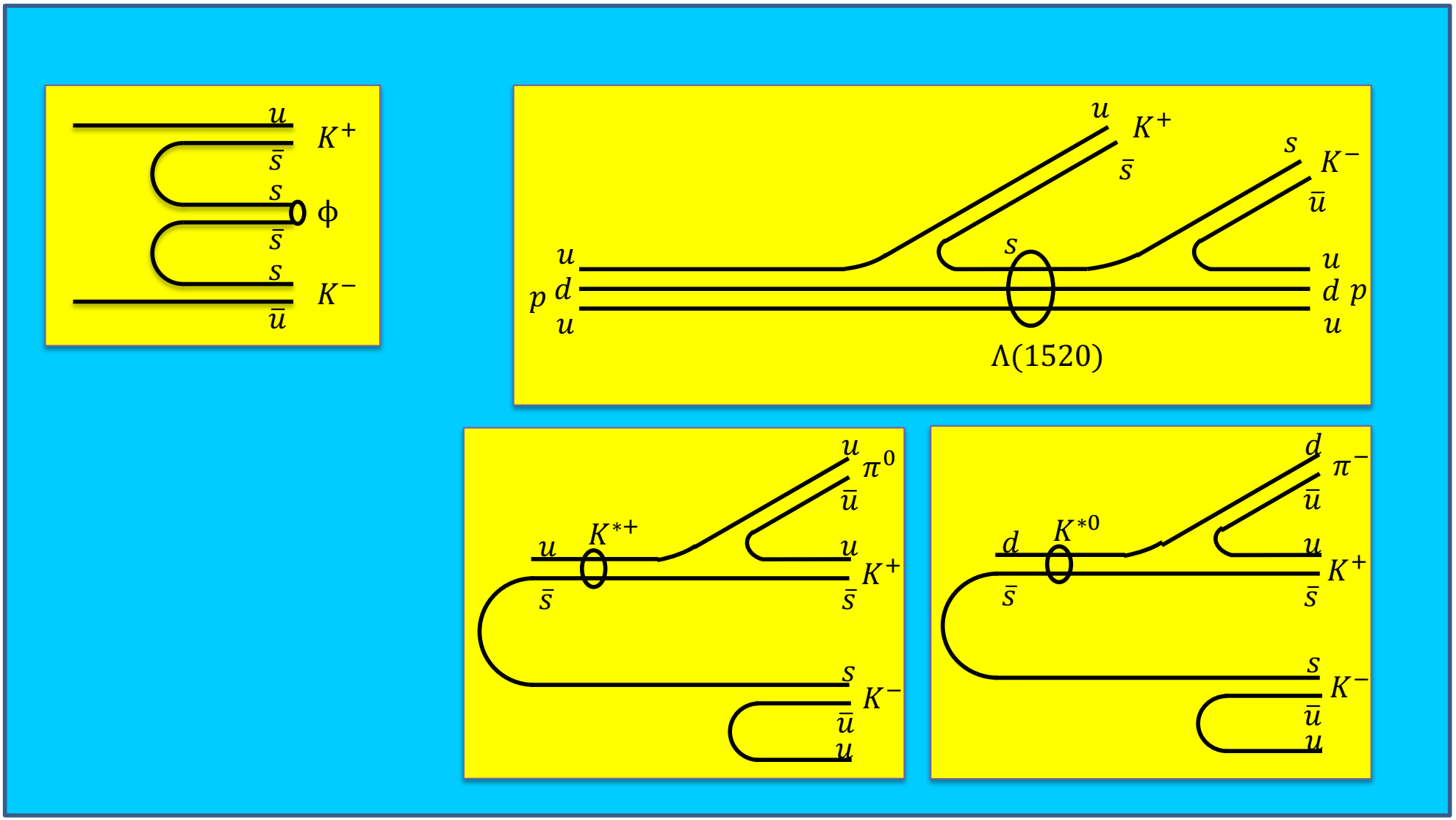
Similarities of the Q and Q_L distribution analysis

Year	cut on ToF	total events	$(K^+K^-) \pm \sigma_{K^+K^-}$	$(\pi^+\pi^-) \pm \sigma_{\pi^+\pi^-}$
2009 + 2010	70%	Q	3460 ± 330	150 ± 320
		Q_L	3280 ± 320	330 ± 310
	50%	Q	4780 ± 530	1490 ± 530
		Q_L	4580 ± 510	1690 ± 510
	30%	Q	9060 ± 940	1860 ± 980
		Q_L	8720 ± 910	2220 ± 940

Experimental Q distributions 2009 + 2010 K^+K^- data



The experimental distributions fitted by simulated distributions of K^+K^- pairs (red line).
The simulated distributions are normalized to the experimental one in the interval $50 < Q < 100$ MeV/c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K^{*0}
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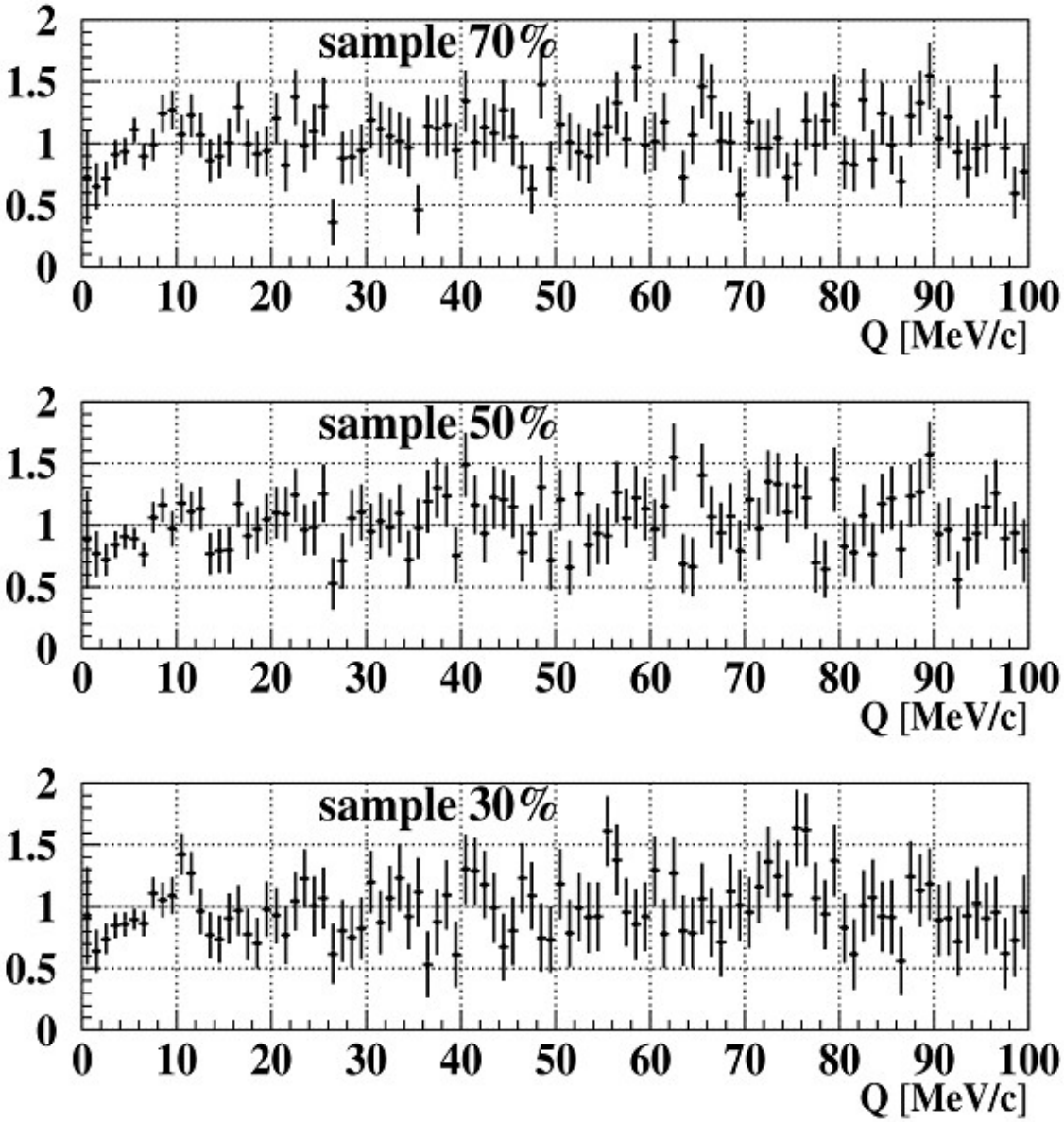
Ratio experimental/simulated 2009 + 2010 K^+K^- data



The fitted Q spectra in $0 < Q < 100$ *MeV/c* interval without subtraction of $\pi^+\pi^-$ background

KK Coulomb pairs and KK 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.

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:

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

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

K^+K^- atom and its lifetime

Properties of the K^+K^- atom (kaonium or A_{2K}) [1]:

$a_B = [\alpha m_K/2]^{-1} = 109.6$ fm … Bohr radius
$p_B = \alpha m_K/2 = 1.80$ MeV … Bohr momentum
$|E_{1s}| = \alpha^2 m_K/4 = 6.57$ keV … binding energy
$\tau(A_{2K}) = [\Gamma(A_{2K})]^{-1} =$? … lifetime

The A_{2K} lifetime is strongly reduced by strong interaction (OBE, scalar f_0 and a_0) as compared to the annihilation of a purely Coulomb-bound system (K^+K^-).

K^+K^- interaction complexity ↓

τ ($A_{2K} \to \pi\pi,\pi\eta$)	K^+K^- interaction
1.2×10^{-16} s [2]	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, NPA562 (1993) 446;
[2] S. Krewald, R. Lemmer, F.P. Sasson, PRD69 (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.

Total number of K^+K^- atoms

The number of K^+K^- pairs evaluated in the Q analysis

year	cut on ToF	$(K^+K^-) \pm \sigma_{K^+K^-}$	Ratio	total number of K^+K^-
2009	70%	1840 ± 240	9.0 ± 0.7%	20400 ± 3110
	50%	2310 ± 380	16.6 ± 1.4%	13950 ± 2540
	30%	4150 ± 680	28.2 ± 2.8%	14680 ± 2820
2010	70%	1620 ± 220	9.0 ± 0.7%	18050 ± 2830
	50%	2470 ± 370	17.4 ± 1.4%	14160 ± 2410
	30%	4910 ± 650	28.2 ± 2.7%	17440 ± 2850

The number of evaluated K^+K^- atoms

cut on ToF	$(K^+K^-) \pm \sigma_{K^+K^-}$ (Q < 4 MeV/c)	Ratio	Total N_C	N(K^+K^- atoms)
30%	420 ± 40	28 %	1490 ± 150	2080 ± 210
50%	230 ± 30	17 %	1330 ± 150	1860 ± 210
70%	150 ± 20	9 %	1690 ± 180	2360 ± 250

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)

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

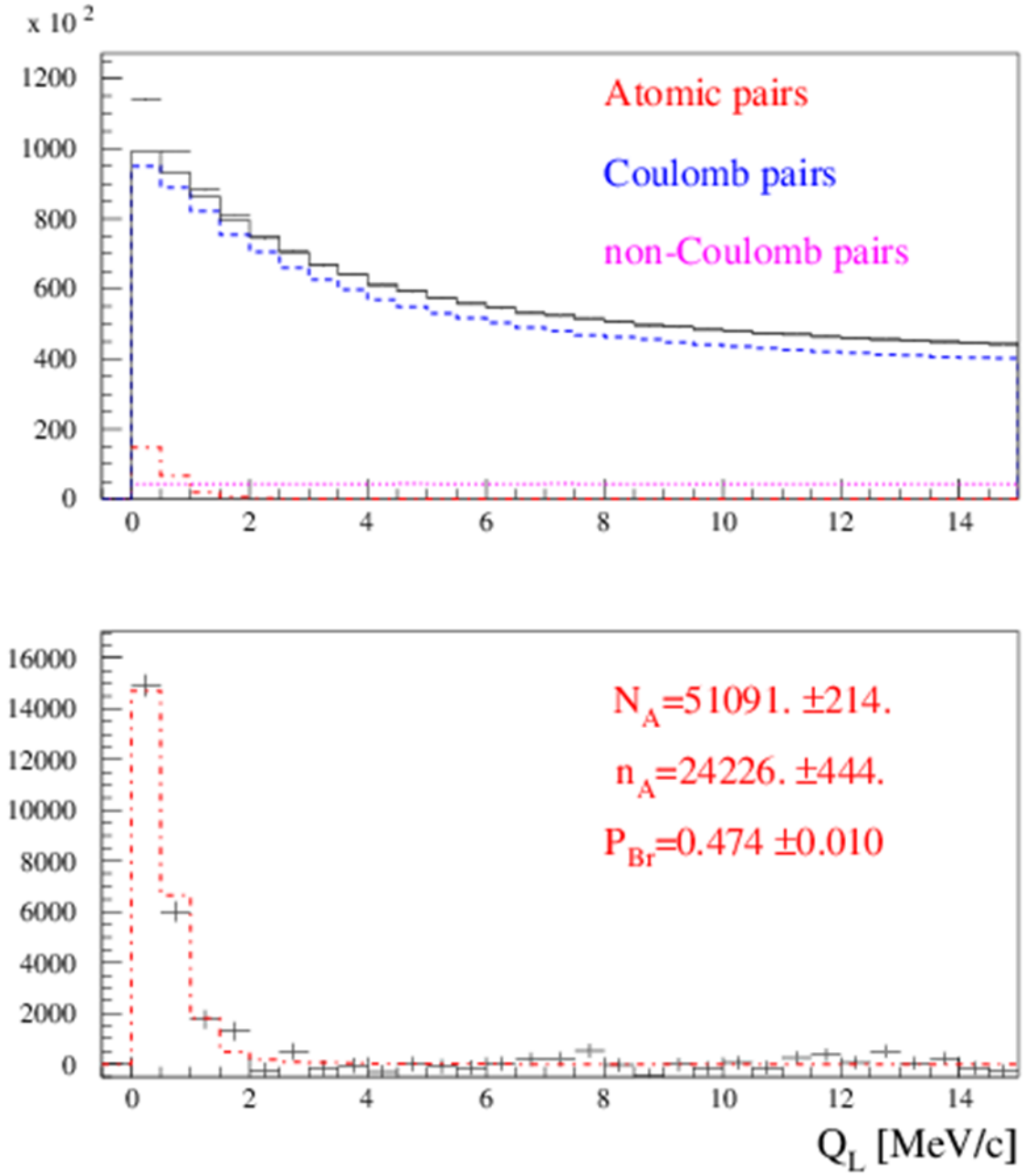
$$\Rightarrow a_2 = -0.0432 \pm 0.0086\big|_{stat} \pm 0.0034\big|_{syst} \pm 0.0028\big|_{theo} = \ldots \pm 22\%$$

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

2011 **DIRAC** (PLB 704, 24)

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

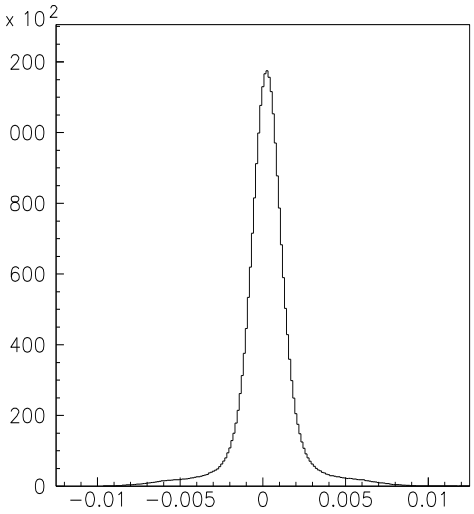
III. The short-lived $\pi^+\pi^-$ atom lifetime measurement



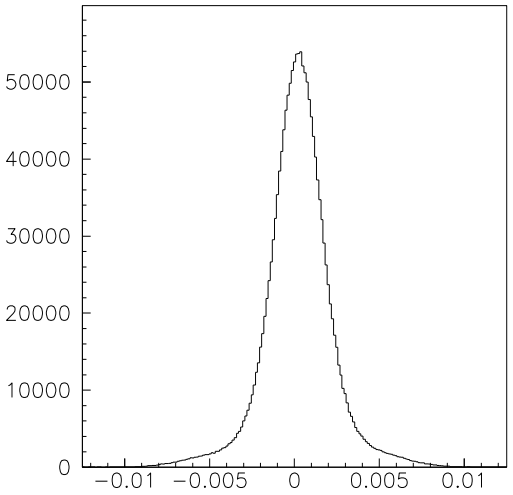
Preliminary results on the short-lived atom lifetime measurement based on all available 2008-2010 data are presented in Fig. 1 and 2.

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.

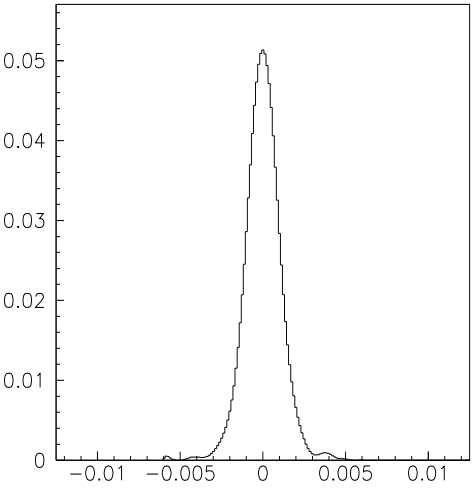
Multiple scattering evaluation



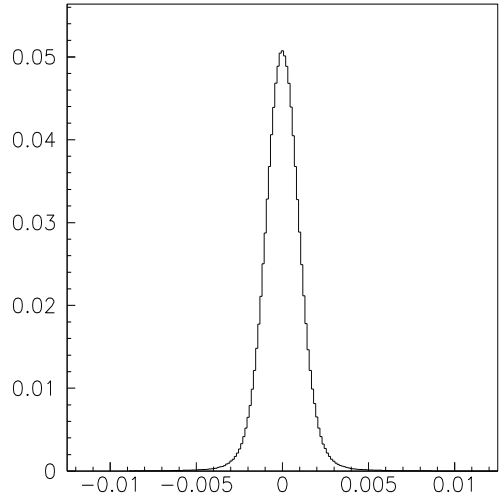
Ni-109 Drift Chamber Resolution



Ni-109 Scatter



Ni-109 Reconstructed Distribution



Ni-109 Multiple Scattering Simulation

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

∓1 RMS(Mol), ∓2 RMS(Mol), ∓3 RMS(Mol)

SCATTERER	RMS(Mol)	∓1 RMS (Mol)	∓2 RMS (Mol)	∓3 RMS (Mol)
Ni-50	0.7913E-03	1.01217	0.95509	0.99187
Ni-100	0.1118E-02	0.98192	0.96447	0.95943
Ni-150	0.1369E-02	0.97556	0.96181	0.95436
Ti-250	0.1113E-02	1.00850	0.98617	0.99082
Ni-109	0.1167E-02	0.99661	0.97571	0.95421
Pt-30	0.1361E-02	0.98962	0.95817	0.94733
Be-2mm	0.9705E-03	1.00103	0.94648	0.93091

Plan for 2020

1. The theoretical paper about the influence of a magnetic field on long-lived np states for any n will be published in 2020.
2. The preprint about the K^+K^- pair investigation will be submitted in the beginning of 2020.
3. The evaluation of the short-lived atom lifetime and $\pi\pi$ scattering lengths, based on all available data, will be finished in 2020.
4. The proton-antiproton pair analysis, using the same strategy as for KK, will be finished soon and the corresponding preprint be submitted in fall 2020.
5. The multiple scattering study will be fully accomplished.

Thank you