Experimental check of precise predictions of QCD using π^+K^-, $K^+\pi^-$ and $\pi^+\pi^-$ atoms

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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.

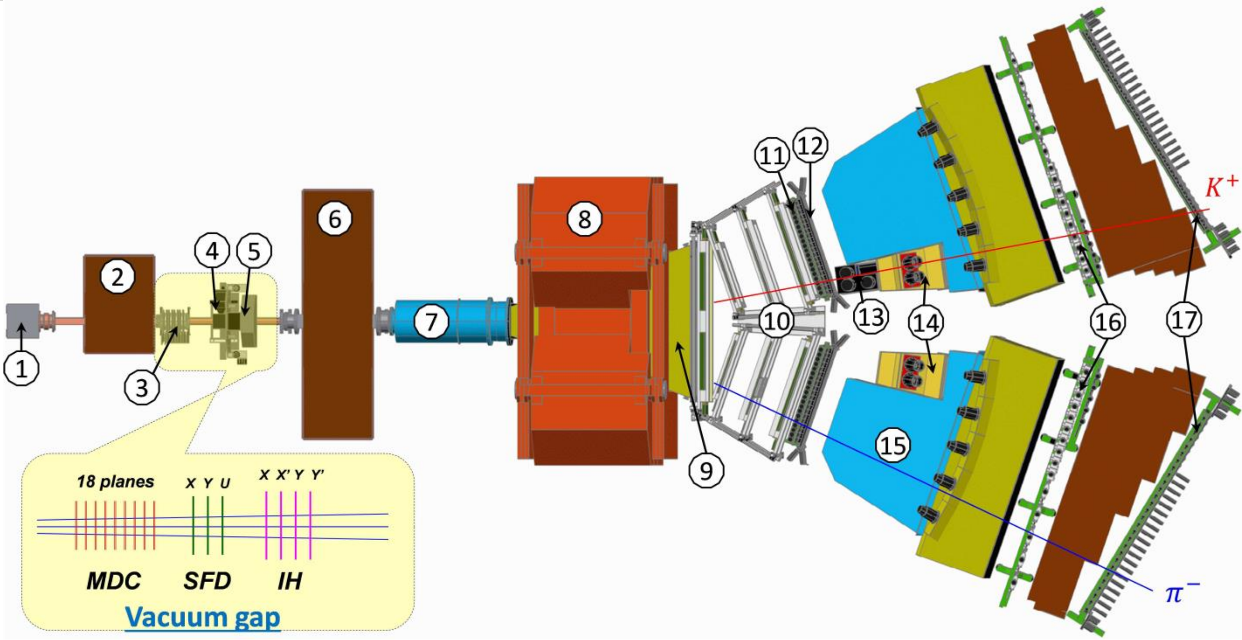
At large Q, contribution of $\mathcal{L}_{sym.br.}$ to the cross section is proportional to $1/Q^4$. Therefore these experiments checked only the $\mathcal{L}_{sym}$ prediction precision.

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.

DIRAC setup, experimental and theoretical data



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

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 ππ scattering length combination $a_0 - a_2$.

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

At present time:

a_0 precision is 6% (experiment), 4-10%(Lattice), 2.3%(ChPT)

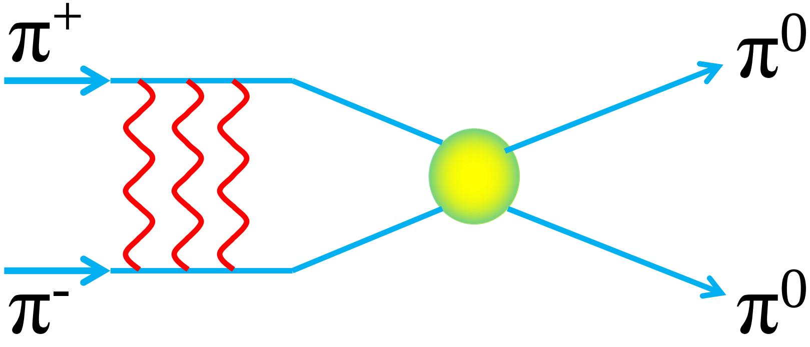
a_2 precision is 22% (experiment), **1% (Lattice),** 2.3% (ChPT)

$a_0 - a_2$ precision is ≈4% (experiment), 1.5%(ChPT)

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

$$\boxed{\Gamma = \frac{1}{\tau} = \Gamma_{2\pi^0} + \Gamma_{2\gamma}} \qquad \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4\times10^{-3}$$

$$\boxed{\Gamma_{ns\to 2\pi^0} = R\left|\psi_{ns}(0)\right|^2 \left|a_0 - a_2\right|^2}$$

$$\boxed{\tau_{1s} = \left(2.9\pm0.1\right)\times10^{-15}\,s}$$

a_0 and a_2 are the ππ 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 *np* state lifetime depends on the transition *np* ⟶ 1*s*, 2*s*,…, (*n*-1)*s* probability. This probability is about 3 orders of magnitude less than for *ns* ⟶ $\pi^0\pi^0$.

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

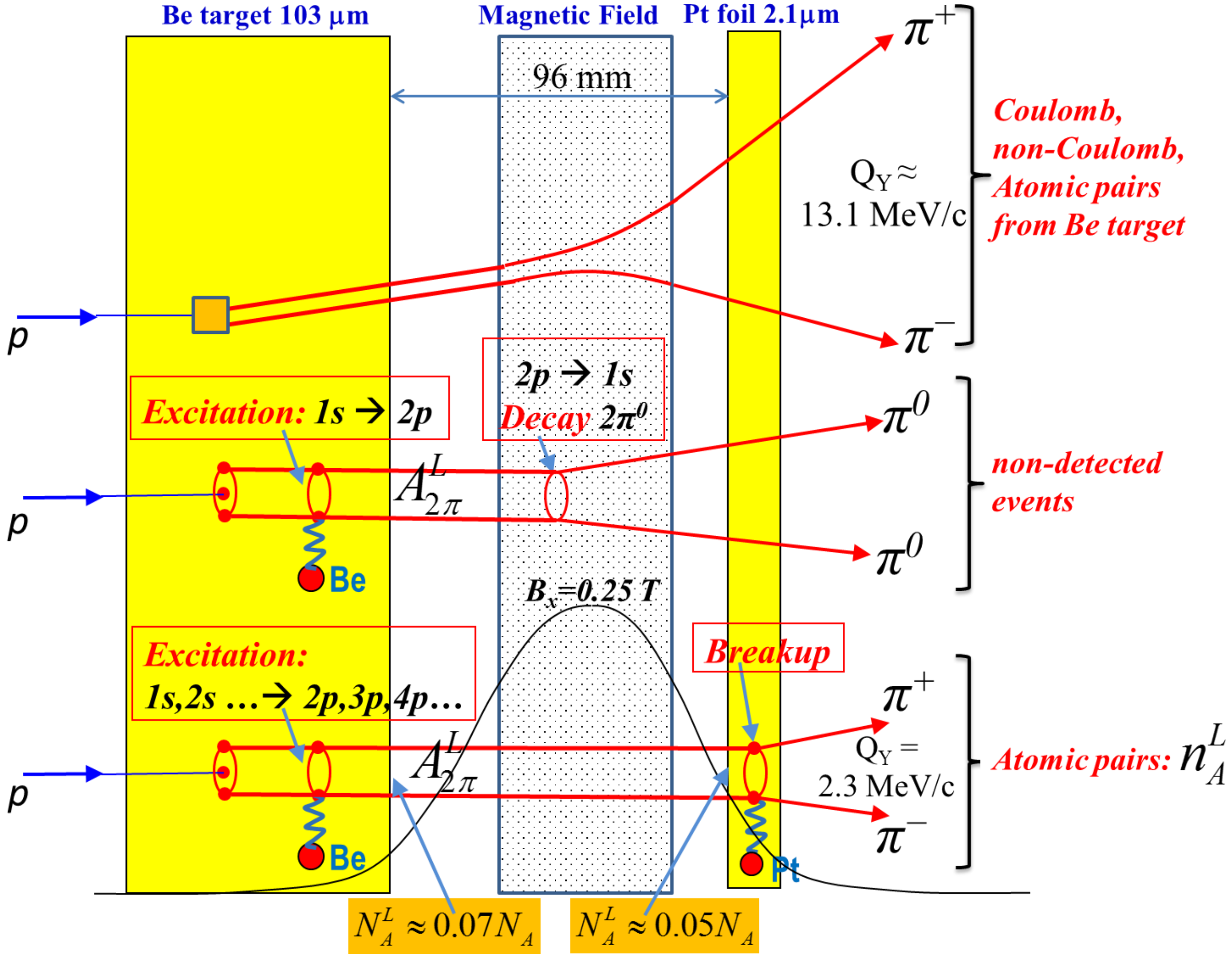
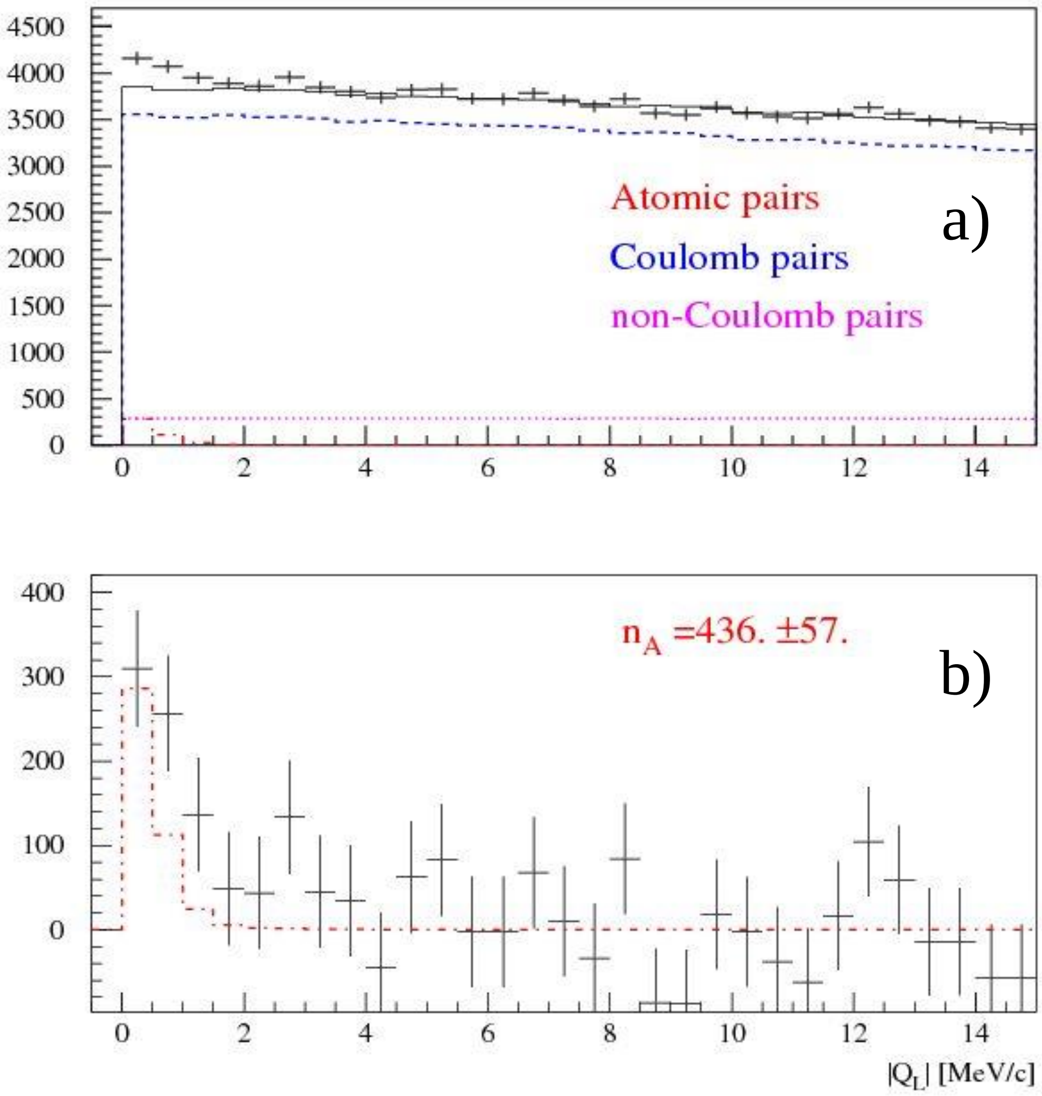


Fig. 1 Method to observe long-lived $A^L_{2\pi}$ by means of a breakup foil (*Pt*). Most (70%) of the produced $\pi^+\pi^-$ atoms decay and 6% are ionized in the *Be* target. 6% are long-lived and 18% are short-lived atoms.

Experimental $|Q_L|$ distributions of $\pi^+\pi^-$ pairs



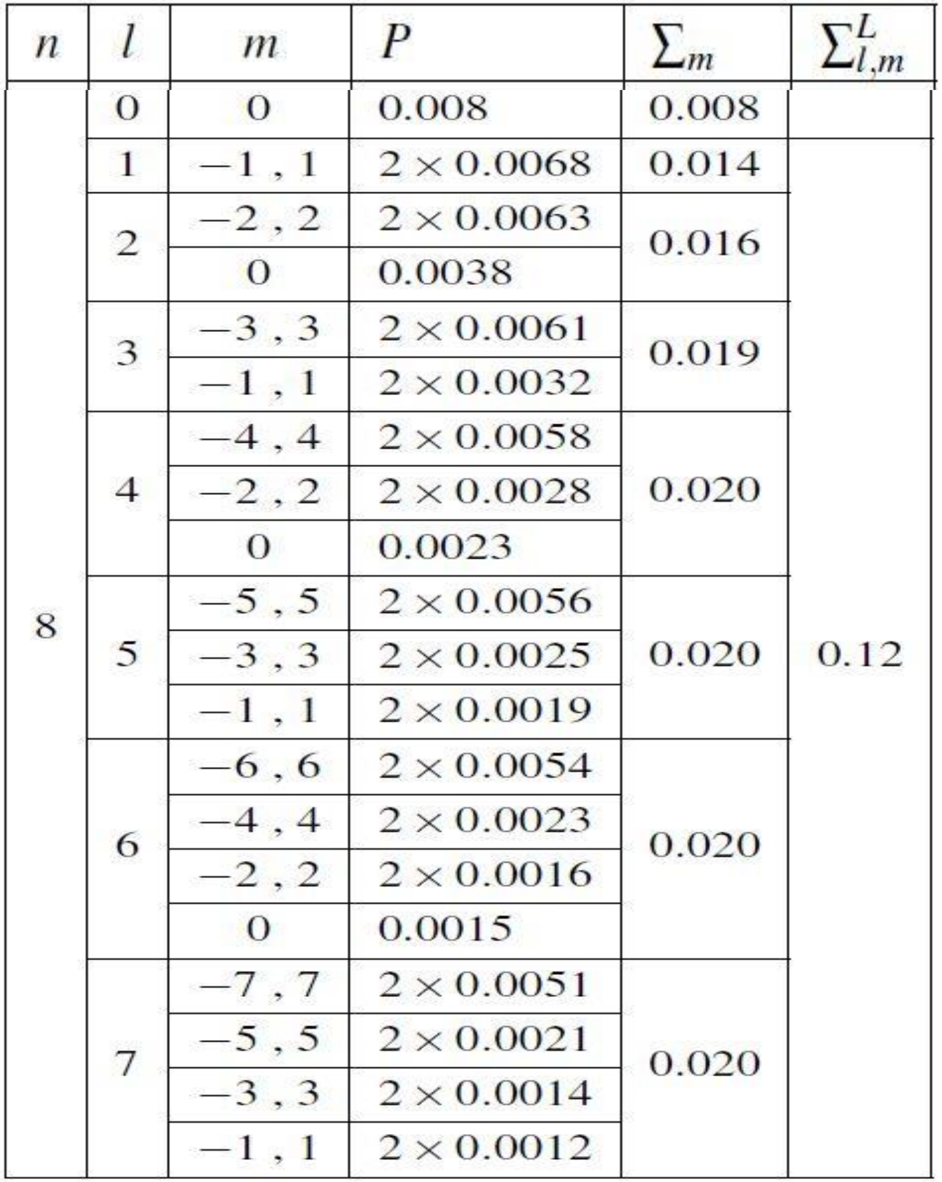
$|Q_L|$ distribution of $\pi^+\pi^-$ pairs
for Q_T <2.0 MeV/c

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).

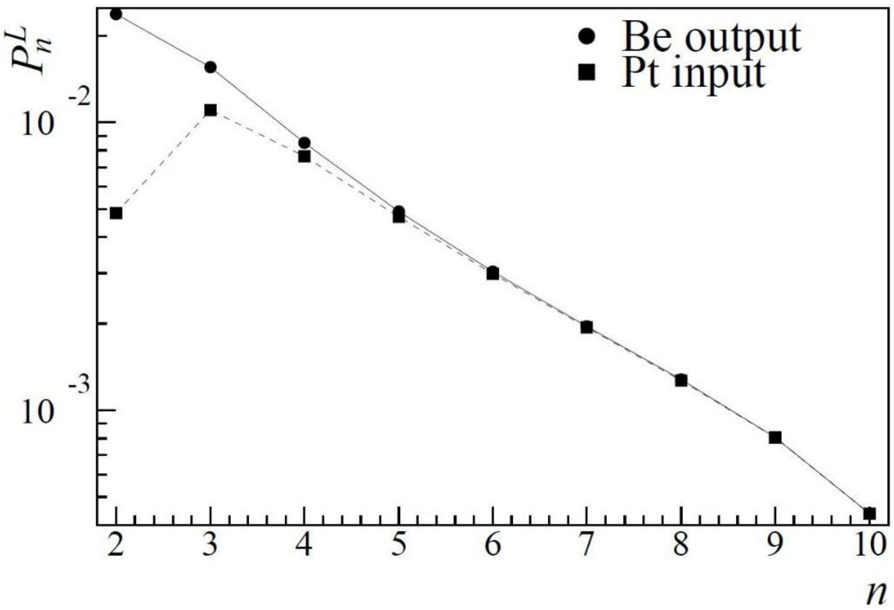
The fit procedure has been applied to the 2-dimensional ($|Q_L|$, Q_T) distribution.

Atomic states population for n=8

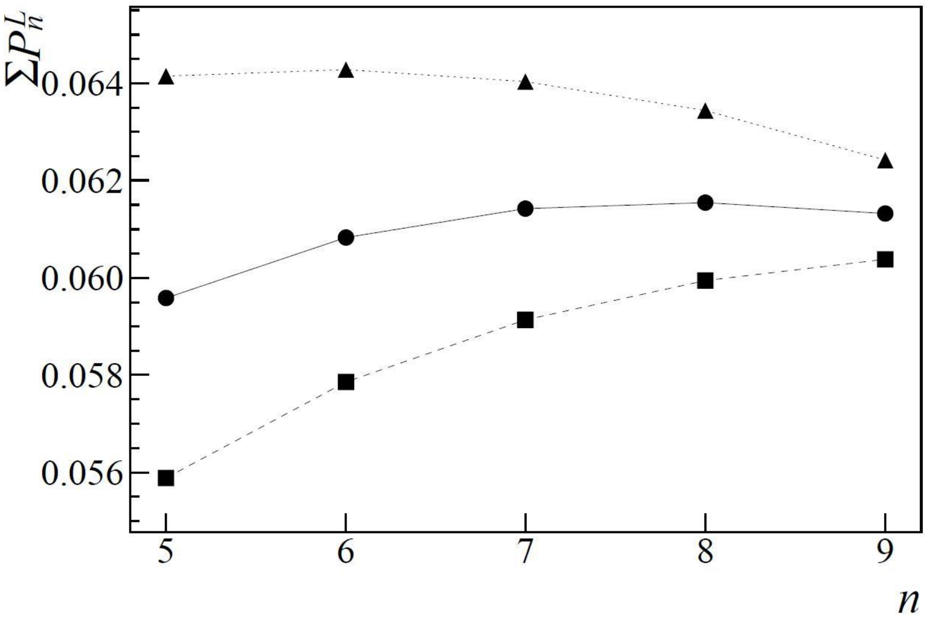


n	l	m	P	$\sum_m$	$\sum_{l,m}^L$
8	0	0	0.008	0.008	
	1	-1 , 1	2×0.0068	0.014	0.12
	2	-2 , 2	2×0.0063	0.016	
		0	0.0038		
	3	-3 , 3	2×0.0061	0.019	
		-1 , 1	2×0.0032		
	4	-4 , 4	2×0.0058	0.020	
		-2 , 2	2×0.0028		
		0	0.0023		
	5	-5 , 5	2×0.0056	0.020	
		-3 , 3	2×0.0025		
		-1 , 1	2×0.0019		
	6	-6 , 6	2×0.0054	0.020	
		-4 , 4	2×0.0023		
		-2 , 2	2×0.0016		
		0	0.0015		
	7	-7 , 7	2×0.0051	0.020	
		-5 , 5	2×0.0021		
		-3 , 3	2×0.0014		
		-1 , 1	2×0.0012		

Population of long-lived states

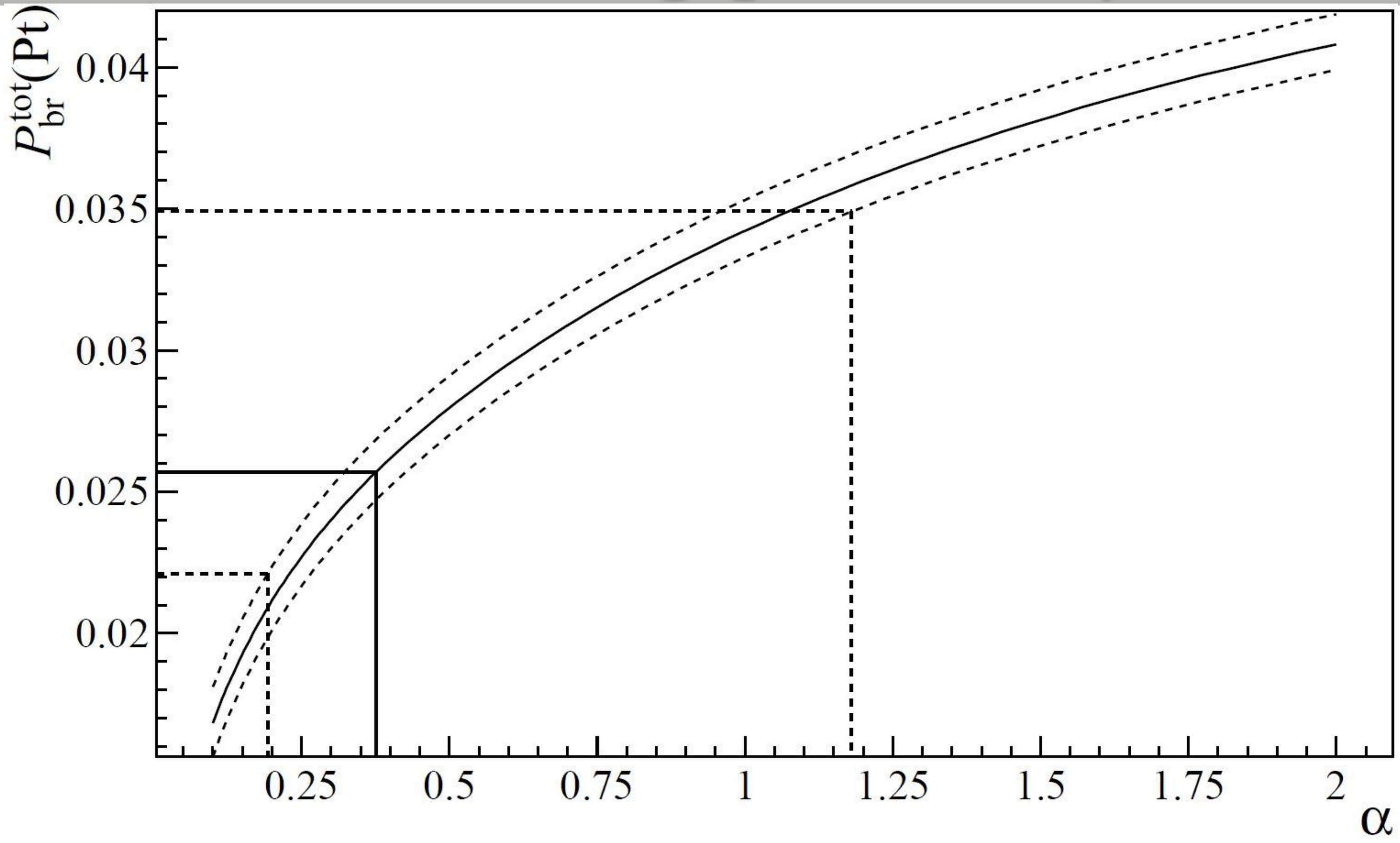


Populations P_n^L of long-lived states $A_{2\pi}^L$ versus *n*, summed over *l* and *m*, at the exit of the *Be* target (●) and at the *Pt* foil entry (■).



Summed populations $\sum P_n^L$ of all long-lived atomic states at the exit of the Be target as a function of *n* used for “tail” estimation. For each *n*, the two upper curves show the sum of state populations for the given *n* plus different “tail” estimations calculated from populations for *n* and *n*-1 (exponential “tail” – ●, hyperbolic “tail” – ▲). The lower curve (■) presents the sum of the population for the given *n* plus the population for *n*+1 instead of the “tail”.

Breakup probability



Probability $P_{br}^{tot}(Pt)$ calculated as a function of α . The horizontal lines correspond to the measured value $P_{br}^{tot}(Pt) = 0.0257^{+0.0097}_{-0.0036}\Big|_{tot} \cdot 10^{-11}\,s$ together with the total errors. The value α = 1, which corresponds to pure QED calculations, is within the error band of the measurement.

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

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

Number of atomic pairs after Pt foil: $n_A = 436^{+157}_{-61}|_{\text{tot}}$

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

$\tau_{2p} = 0.45^{+1.08}_{-0.30}|_{\text{tot}} 10^{-11}\text{s}$ (1), $\tau_{2p} = 0.22^{+1.42}_{-0.18}|_{\text{tot}} 10^{-11}\text{s}$ (2)

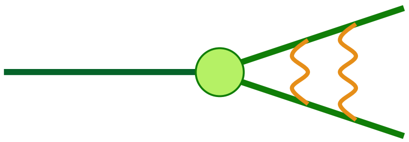
QED: $\tau_{2p} = 1.17 \times 10^{-11}\text{s}$

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

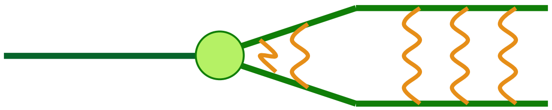
The 90% of the long-lived atoms have decay length in l.s. from 40 cm. up to 140 cm. It opens the possibility to measure the Lamb shift and ***ππ*** scattering lengths. The experimental results were presented as section report on the Rochester 2018, submitted as CERN preprint and in

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.



K^+K^-



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^- 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^-).

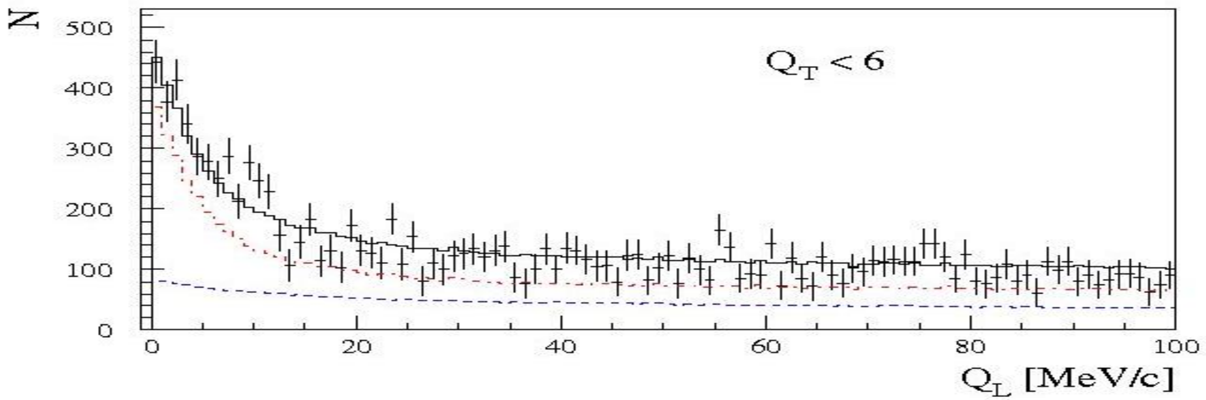
K^+K^- interaction complexity ↓

$\tau\ (A_{2K} \to \pi\pi,\pi\eta)$	**K^+K^- interaction**
1.2×10^{-18} 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) + πη-channel (I=1)
2.2×10^{-18} s [4]	ChPT

References:

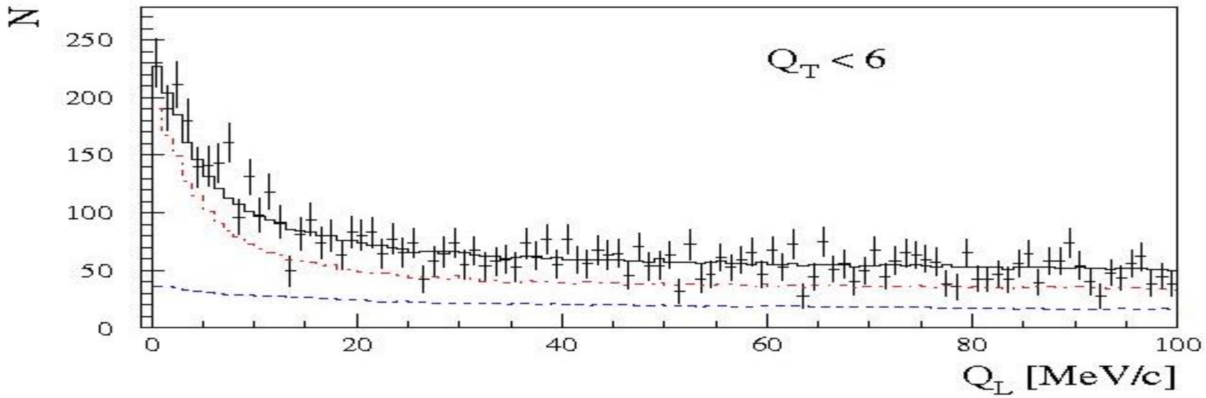
[1] S. Wycech, A.M. Green, Nucl. Phys. A562 (1993), 446;
[2] S. Krewald, R. Lemmer, F.P. Sasson, Phys. Rev. D69 (2004), 016003;
[3] Y-J Zhang, H-C Chiang, P-N Shen, B-S Zou, PRD74 (2006) 014013;
[4] S.P. Klevansky, R.H. Lemmer, PLB702 (2011) 235.

K^+K^- Coulomb pairs.



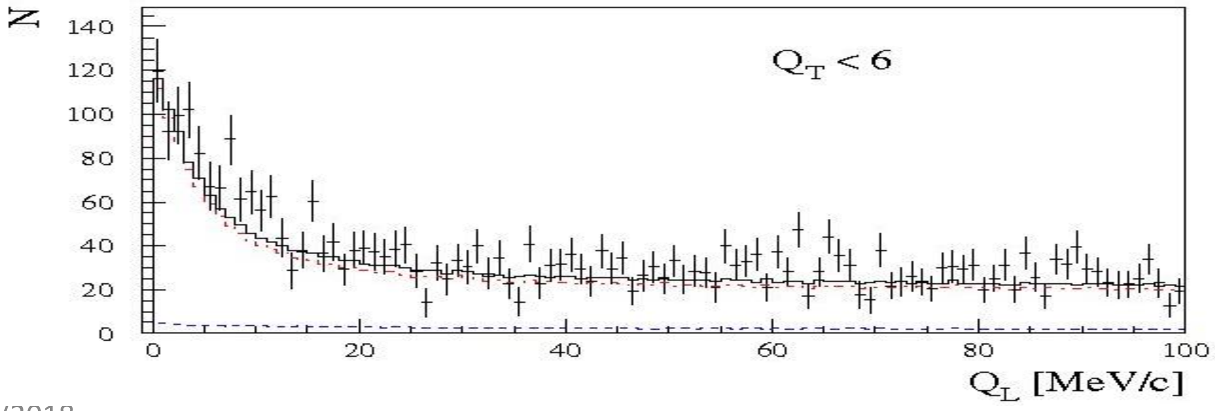
30%

K^+K^- pairs



50%

K^+K^- pairs



70%

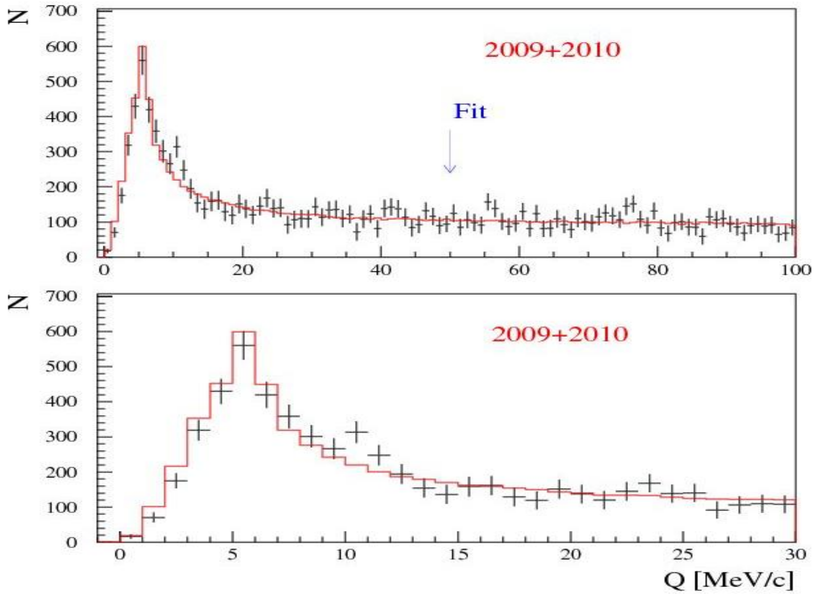
K^+K^- pairs

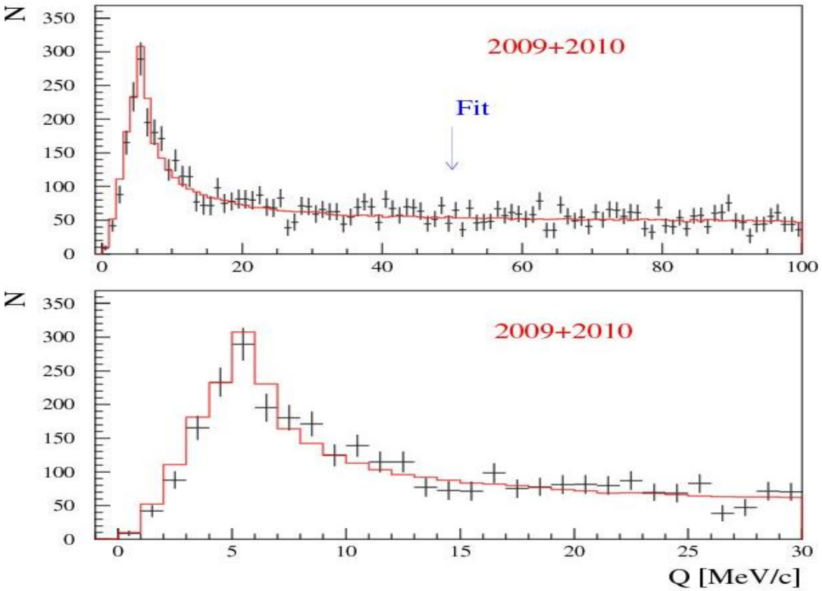
Predicted number of K^+K^- pairs with $Q_t < 4$ MeV/c and $Q_t < 6$ MeV/c according to fits of Q_l distributions of given samples

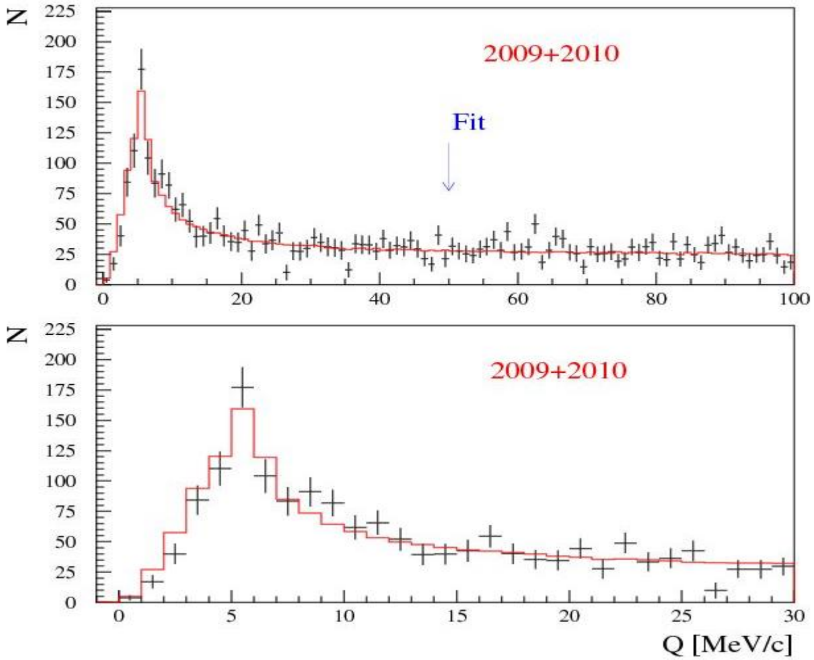
	$Q_t < 4$ MeV/c	$Q_t < 6$ MeV/c
k70:	13906	31457
k50:	12666	28653
k30:	14834	33556
average:	13802	31222

k70, k50, k30 – samples with ratio of at least 70%, 50%, 30% of K^+K^- pairs in individual momentum and time intervals

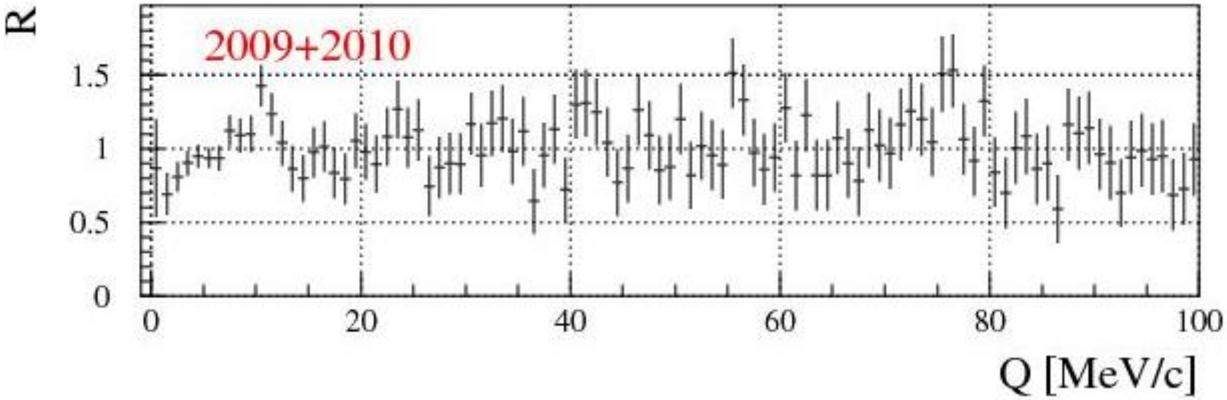
DIRAC Collaboration

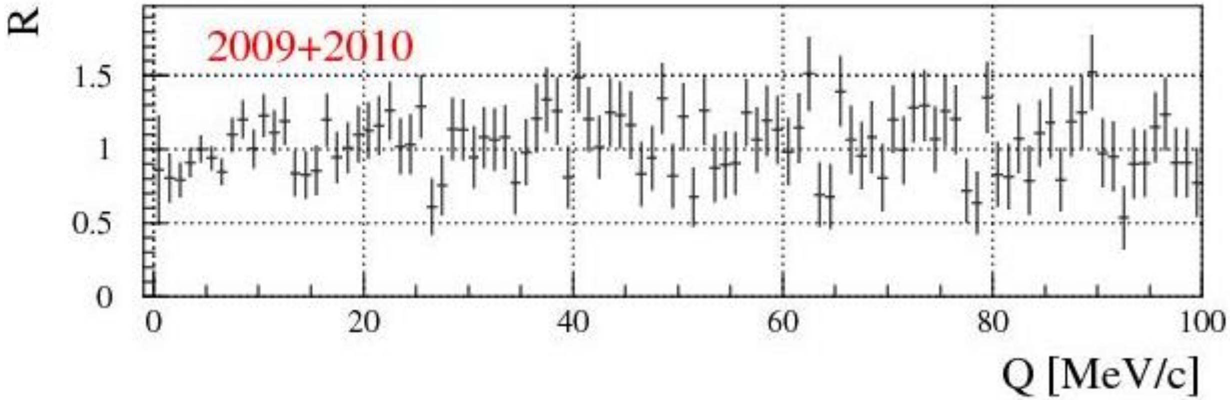


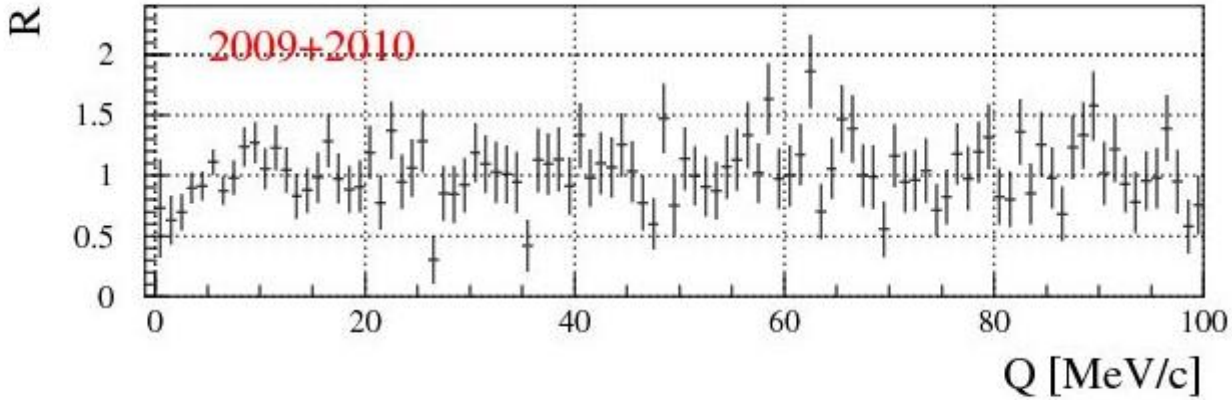


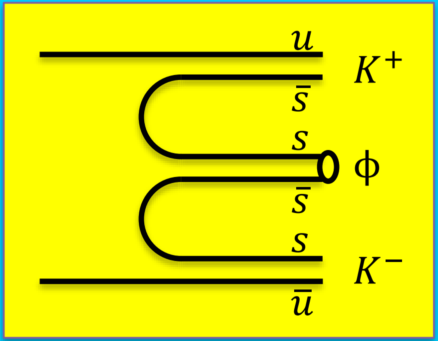


DIRAC Collaboration





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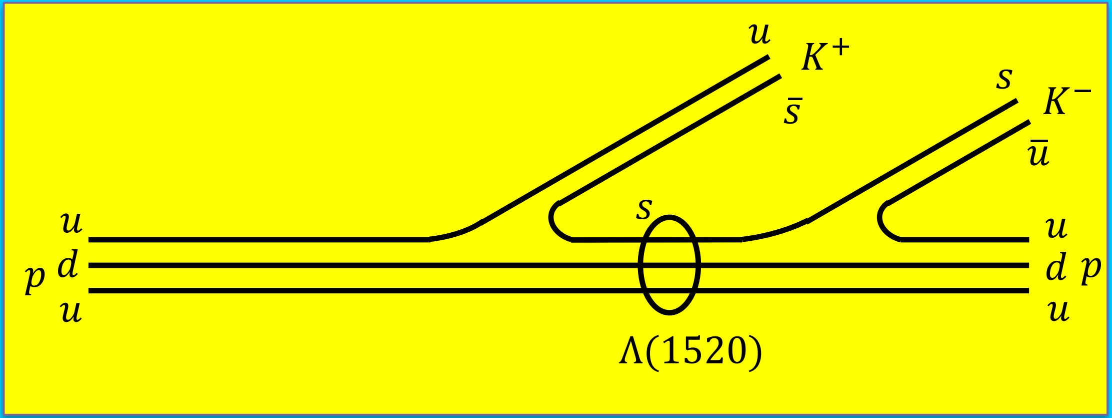
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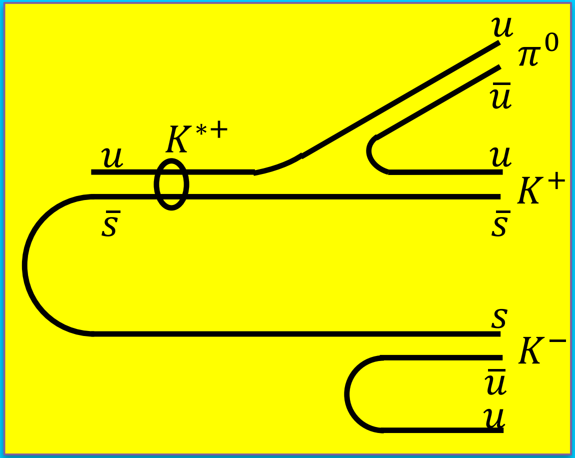
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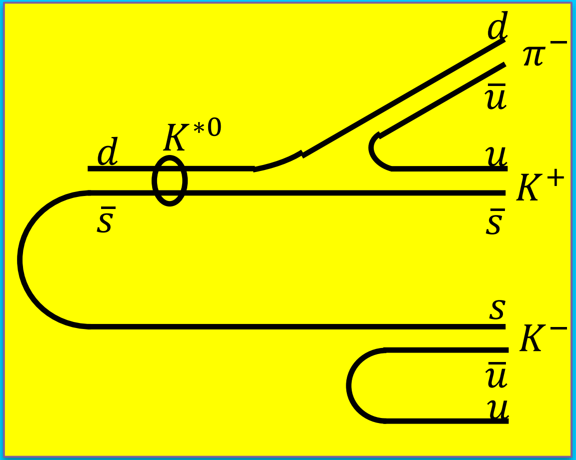
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Coulomb correlations

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	

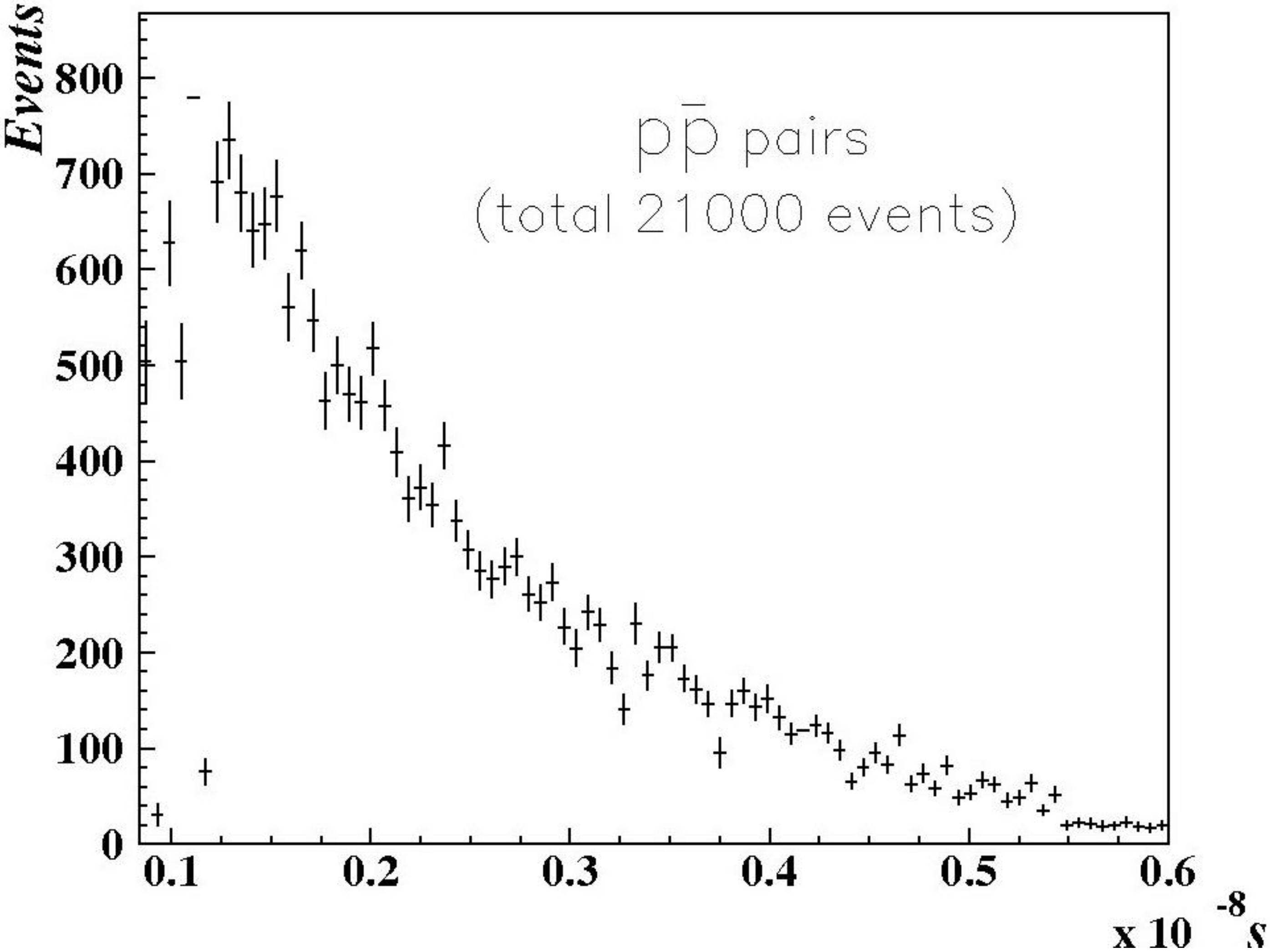
	Z	A	Nublear radius [fm]
Be	04	9.012	2.56
Ni	28	58.69	4.78
Pt	78	195.08	7.13

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

Number of p-antiproton pairs



KK Coulomb pairs, KK atoms and proton-antiproton pairs.

1. In April 2019 the theoretical investigation of KK pairs and KK atoms production will be finished.
2. In June 2019 the preliminary measurement of the KK atoms number generated simultaneously with detected KK pairs will be evaluated.
3. In October 2019 the dedicated paper will be submitted.
4. The experimental conditions needed for the KK atoms lifetime measurement on SPS and LHC will be formulated.
5. The proton-antiproton Coulomb pairs investigation will be done in June 2019.

Thank you

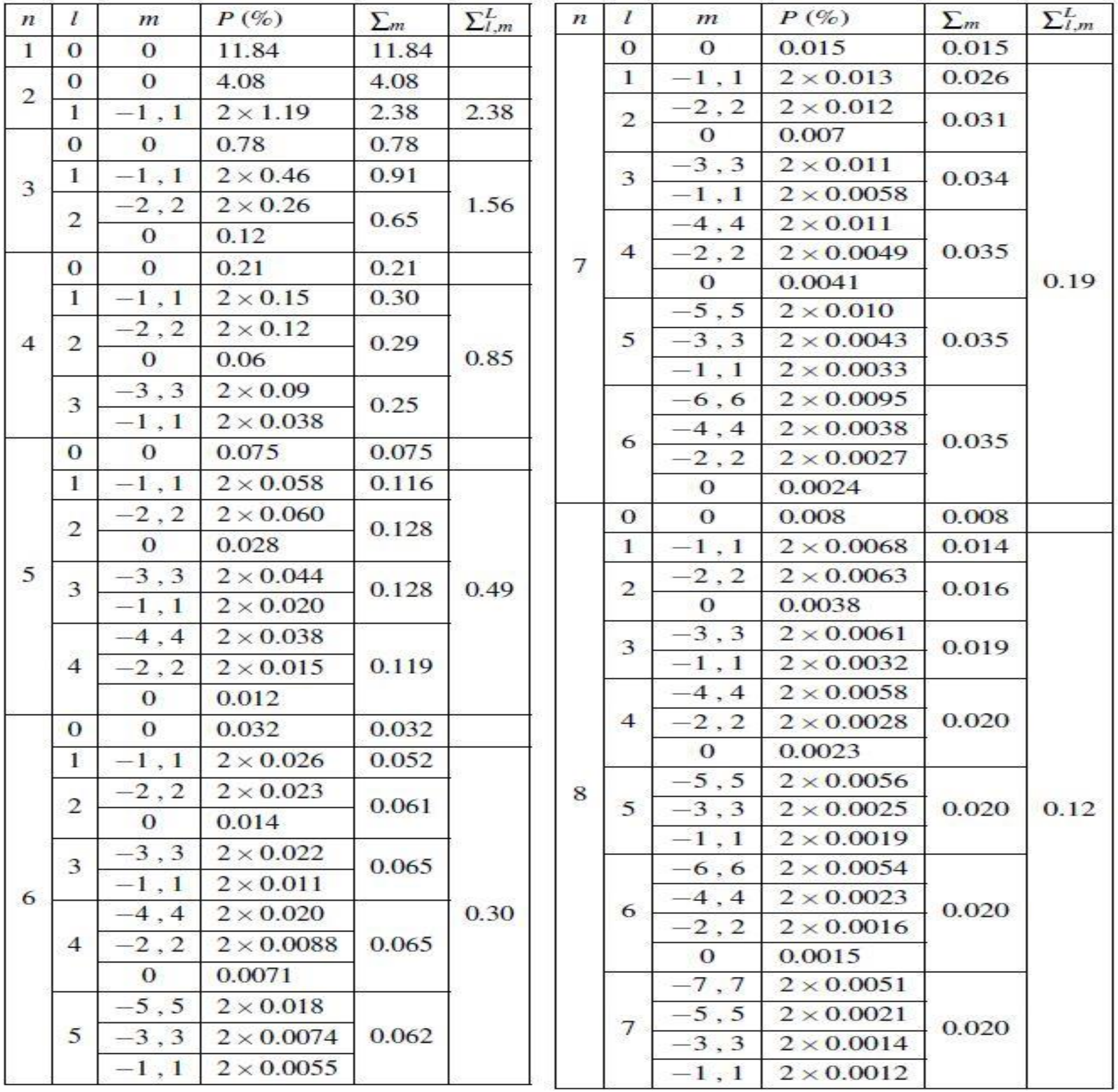
Measurement of the πK scattering length

The *S*-wave πK scattering lengths $a_{1/2}$ and $a_{3/2}$ in the chiral symmetry world are zero. Therefore the scattering length values $a_{1/2}$ and $a_{3/2}$ are very sensitive to the $\mathcal{L}_{\text{sym.br.}}(3)$.

For Lattice QCD the πK interaction at threshold is a relatively simple process. It gives πK scattering length values with an average precision of 5%.
This precision will be improved in the near future.

There is only one experimental data: DIRAC collaboration observed 349±62 πK atomic pairs (*Phys.Rev.Lett*. 2016) and measured $|\boldsymbol{a_{1/2}-a_{3/2}}|$ with an average precision of 34% (*Phys.Rev.D* 2017).

Atomic states population



n	l	m	P (%)	Σ_m	$\Sigma^L_{l,m}$
1	0	0	11.84	11.84	
2	0	0	4.08	4.08	
	1	−1 , 1	2 × 1.19	2.38	2.38
3	0	0	0.78	0.78	
	1	−1 , 1	2 × 0.46	0.91	1.56
	2	−2 , 2	2 × 0.26	0.65	
		0	0.12		
4	0	0	0.21	0.21	
	1	−1 , 1	2 × 0.15	0.30	0.85
	2	−2 , 2	2 × 0.12	0.29	
		0	0.06		
	3	−3 , 3	2 × 0.09	0.25	
		−1 , 1	2 × 0.038		
5	0	0	0.075	0.075	
	1	−1 , 1	2 × 0.058	0.116	0.49
	2	−2 , 2	2 × 0.060	0.128	
		0	0.028		
	3	−3 , 3	2 × 0.044	0.128	
		−1 , 1	2 × 0.020		
	4	−4 , 4	2 × 0.038	0.119	
		−2 , 2	2 × 0.015		
		0	0.012		
6	0	0	0.032	0.032	
	1	−1 , 1	2 × 0.026	0.052	0.30
	2	−2 , 2	2 × 0.023	0.061	
		0	0.014		
	3	−3 , 3	2 × 0.022	0.065	
		−1 , 1	2 × 0.011		
	4	−4 , 4	2 × 0.020	0.065	
		−2 , 2	2 × 0.0088		
		0	0.0071		
	5	−5 , 5	2 × 0.018	0.062	
		−3 , 3	2 × 0.0074		
		−1 , 1	2 × 0.0055		
7	0	0	0.015	0.015	
	1	−1 , 1	2 × 0.013	0.026	0.19
	2	−2 , 2	2 × 0.012	0.031	
		0	0.007		
	3	−3 , 3	2 × 0.011	0.034	
		−1 , 1	2 × 0.0058		
	4	−4 , 4	2 × 0.011	0.035	
		−2 , 2	2 × 0.0049		
		0	0.0041		
	5	−5 , 5	2 × 0.010	0.035	
		−3 , 3	2 × 0.0043		
		−1 , 1	2 × 0.0033		
	6	−6 , 6	2 × 0.0095	0.035	
		−4 , 4	2 × 0.0038		
		−2 , 2	2 × 0.0027		
		0	0.0024		
8	0	0	0.008	0.008	
	1	−1 , 1	2 × 0.0068	0.014	0.12
	2	−2 , 2	2 × 0.0063	0.016	
		0	0.0038		
	3	−3 , 3	2 × 0.0061	0.019	
		−1 , 1	2 × 0.0032		
	4	−4 , 4	2 × 0.0058	0.020	
		−2 , 2	2 × 0.0028		
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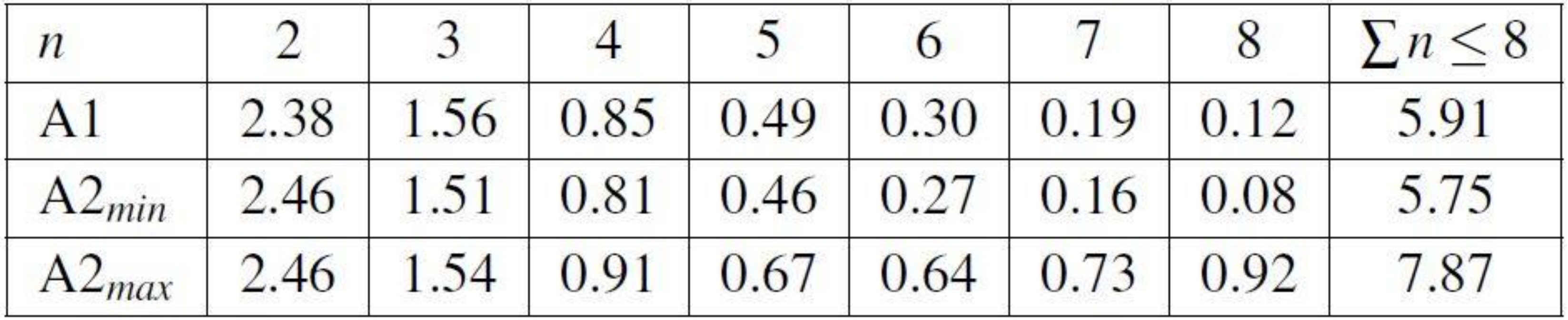
		−2 , 2	2 × 0.0016		
		0	0.0015		
	7	−7 , 7	2 × 0.0051	0.020	
		−5 , 5	2 × 0.0021		
		−3 , 3	2 × 0.0014		
		−1 , 1	2 × 0.0012		

Table 1: Population P of atomic states with the quantum numbers n, l and m at the exit of the 103 μm thick *Be* target. The calculations are performed for the average atom momentum 4.44 GeV/c and the ground state lifetime $\tau = 3.15 \cdot 10^{-15} s$. $\sum_m$ is the population summed over the quantum number m, and $\sum^L_{l,m}$ the long-lived state population summed over l and m. All numbers are given in % of the total number N_A of produced atoms.

Table 2: Summed populations of long-lived atomic states versus n given in % of the total number of produced $A_{2\pi}$ in the *Be* target. The values are calculated in approach 1 (A1) and minimum/maximum values in approach 2 ($A2_{min}/A2_{max}$).



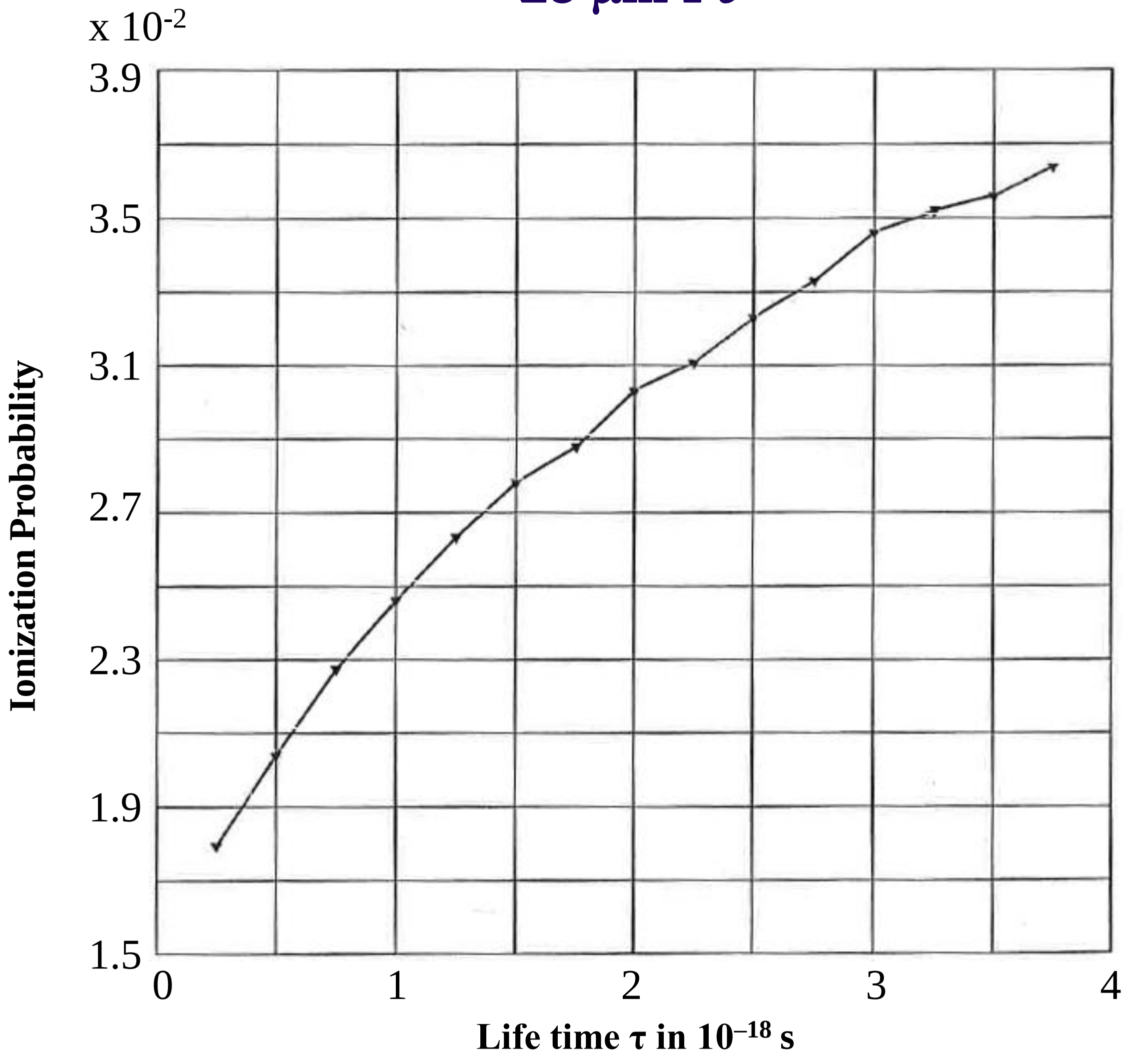
n	2	3	4	5	6	7	8	$\sum n \leq 8$
A1	2.38	1.56	0.85	0.49	0.30	0.19	0.12	5.91
$A2_{min}$	2.46	1.51	0.81	0.46	0.27	0.16	0.08	5.75
$A2_{max}$	2.46	1.54	0.91	0.67	0.64	0.73	0.92	7.87

Table 3: P_n (in %) is the population of long-lived atomic states versus *n* (summed over *l* and *m*) at the entry in the *Pt* foil. $P_{br}(np)$ is the breakup probability of the $A_{2\pi}$ *np* states in the 2.1μm thick *Pt* foil. The values are calculated in approach 1 for the average atom momentum 4.44 GeV/c and the ground state lifetime $\tau = 3.15 \cdot 10^{-15}$ s.

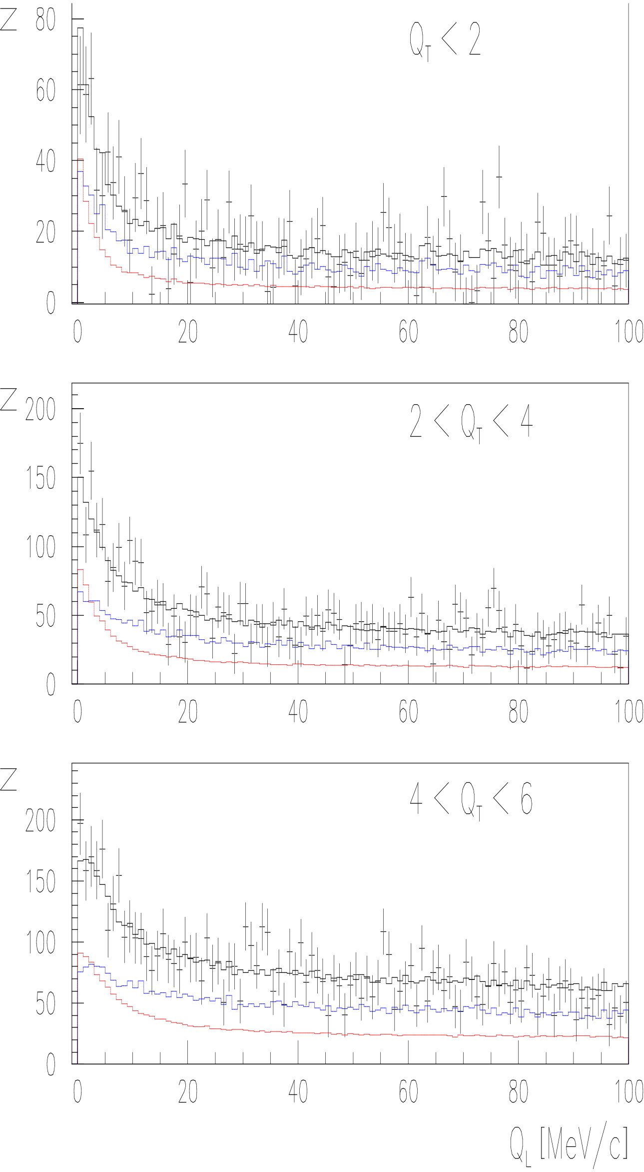
n	2	3	4	5	6	7
P_n	0.48	1.10	0.76	0.47	0.30	0.19
$P_{br}(np)$	0.763	0.933	0.978	0.991	0.996	0.998

K^+K^- atoms ionization probability

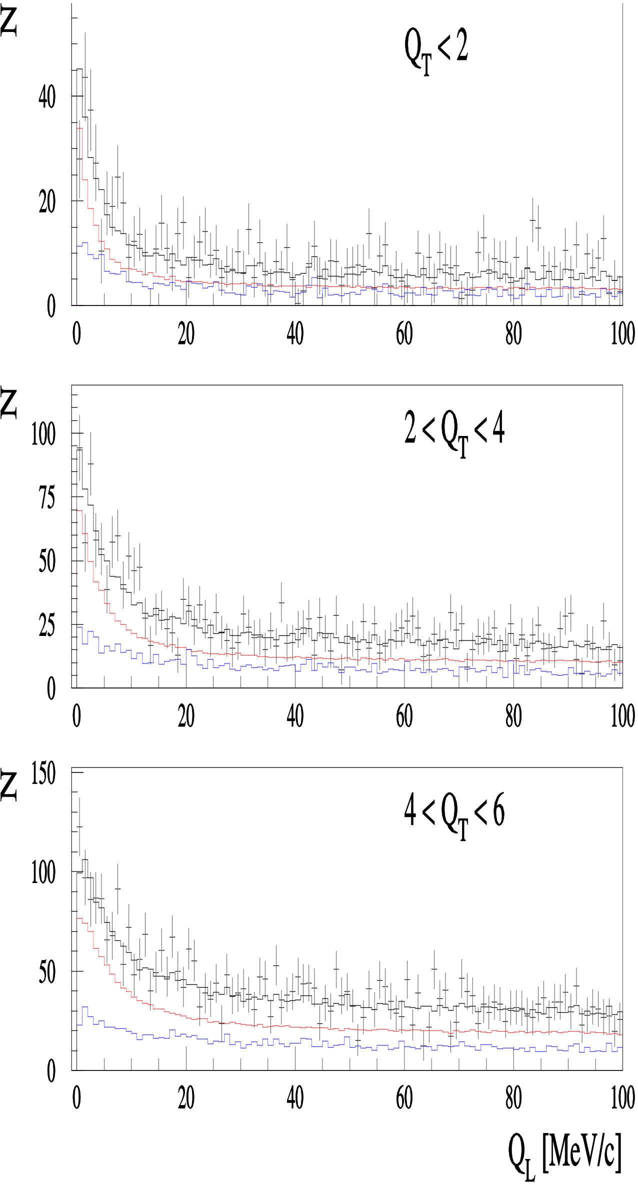
28 μm Pt



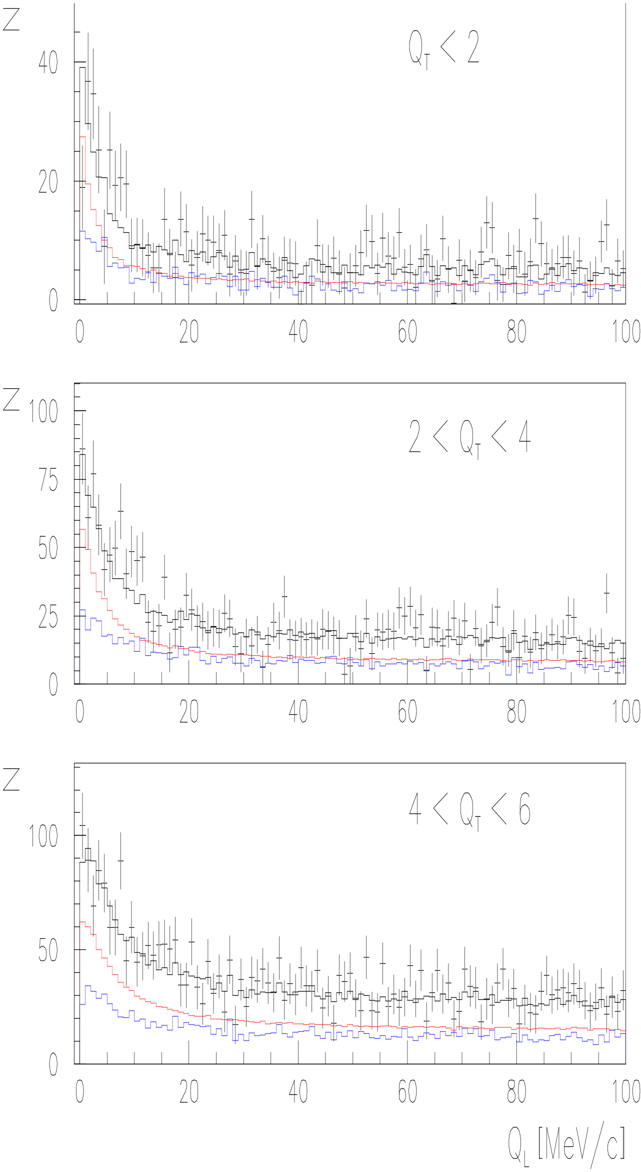
K^+K^- atoms Lorentz factor is $\gamma = 18$


Z
Q_T < 2
2 < Q_T < 4
4 < Q_T < 6
0 20 40 60 80 100
Q_L [MeV/c]

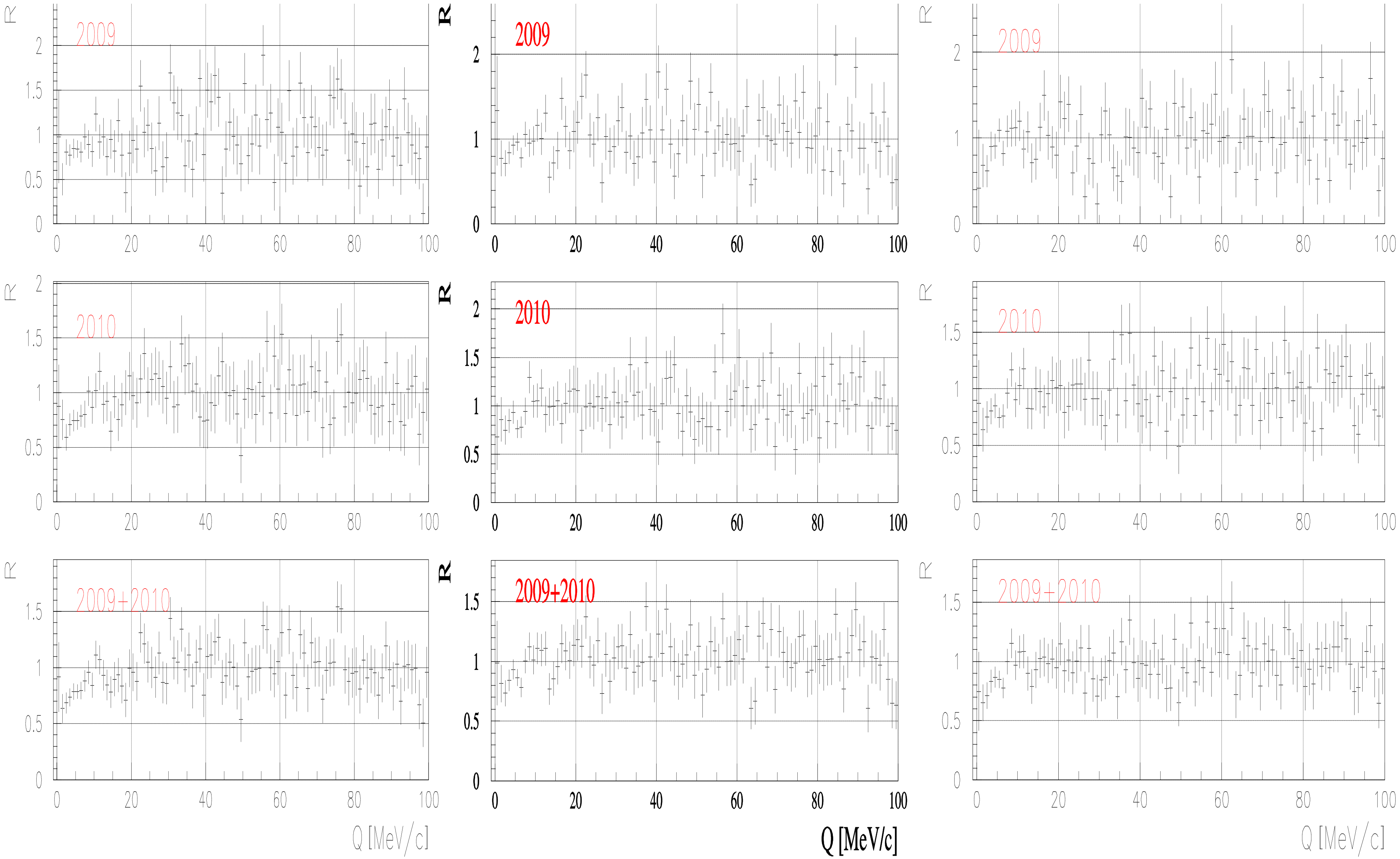
30%


Z
Q_T < 2
2 < Q_T < 4
4 < Q_T < 6
0 20 40 60 80 100
Q_L [MeV/c]

50%


Z
Q_T < 2
2 < Q_T < 4
4 < Q_T < 6
0 20 40 60 80 100
Q_L [MeV/c]

70%

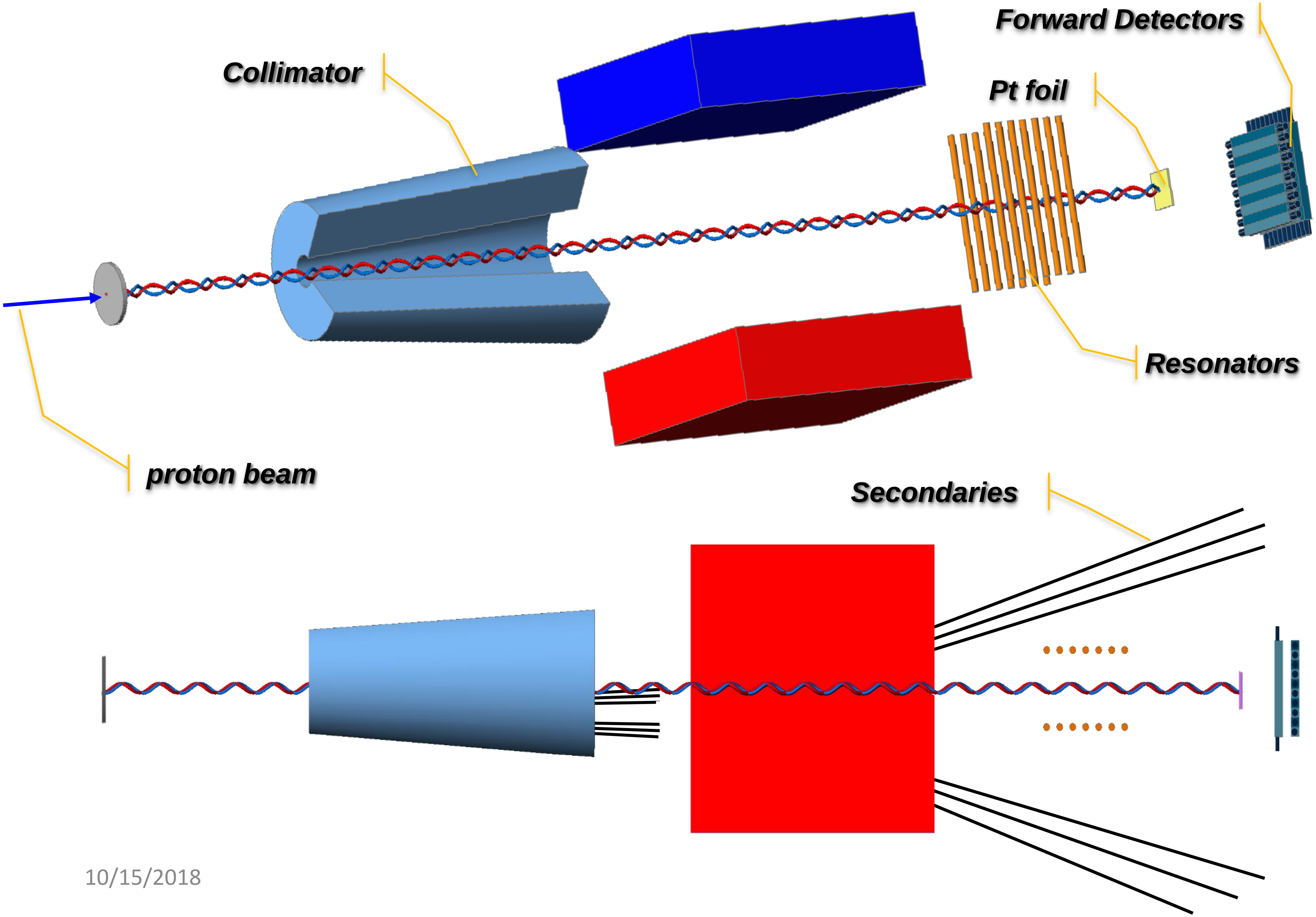


30%

50%

70
%

DIRAC future Experimental setup



Forward Detectors

Collimator

Pt foil

Resonators

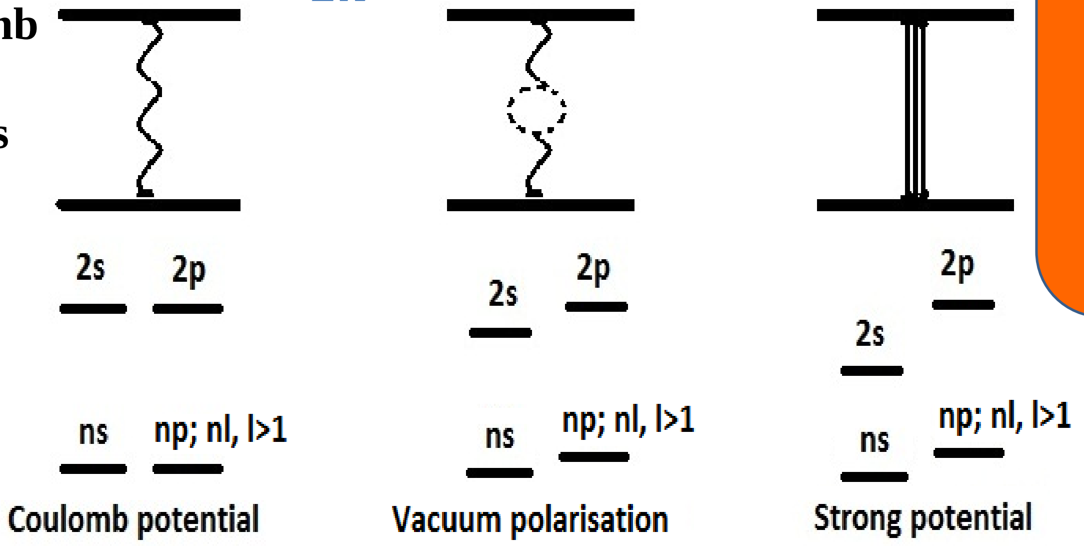
proton beam

Secondaries

Energy splitting measurement

$A_{2\pi}$ Energy Levels

For Coulomb potential, E depends only on n



Δ^{vac}_{2s-2p} can be calculated with relative precision $\approx 10^{-5}$ (S. Karshtenbom)

higher order QED

Notation:

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

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

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

J. Schweizer [PL B (2004)]

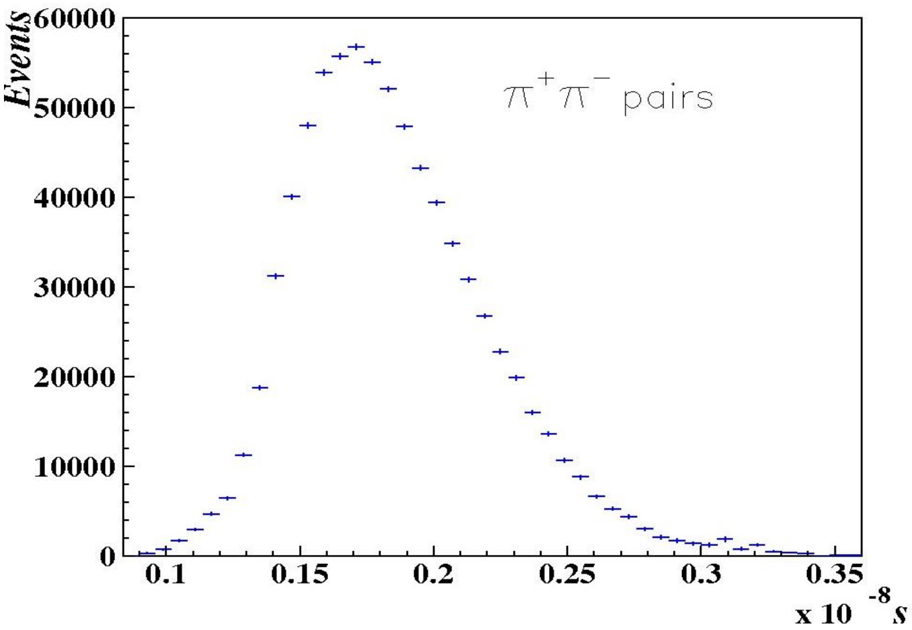
$$\Delta^{str}_{2s-2p} = -\frac{\alpha^3 m_\pi}{8}\frac{1}{6}\left(2a_0 + a_2\right) + \cdots$$

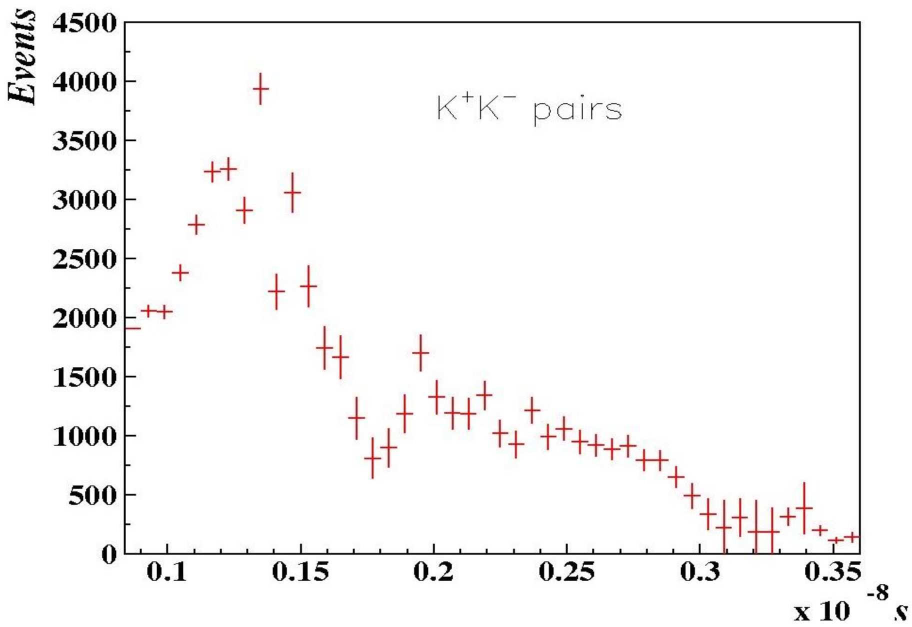
G.V.Efimov et al. Sov.J.Nucl.Phys. (1986)

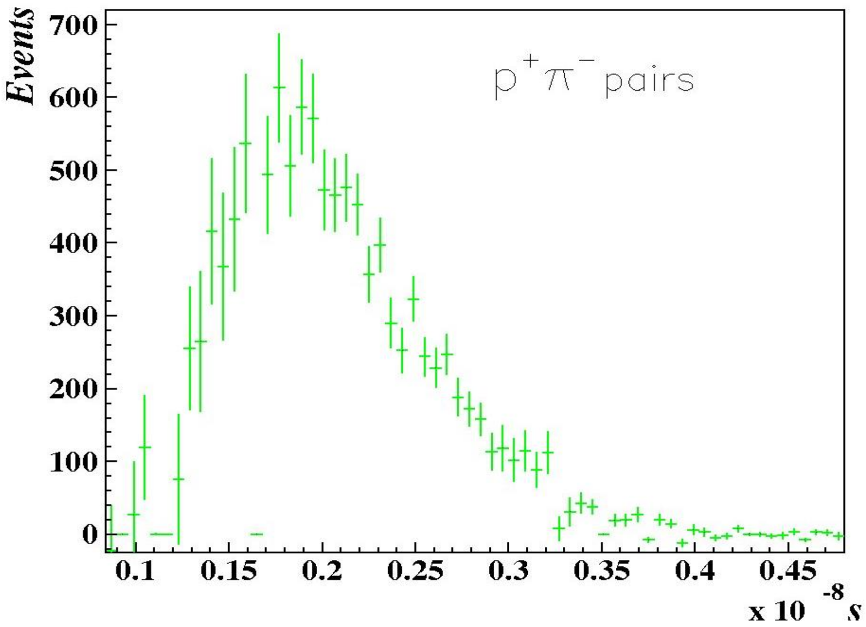
$$\Delta^{str}_{ns-np} = -\frac{\Delta^{str}_{2s-2p}}{n^3} \cdot 8$$

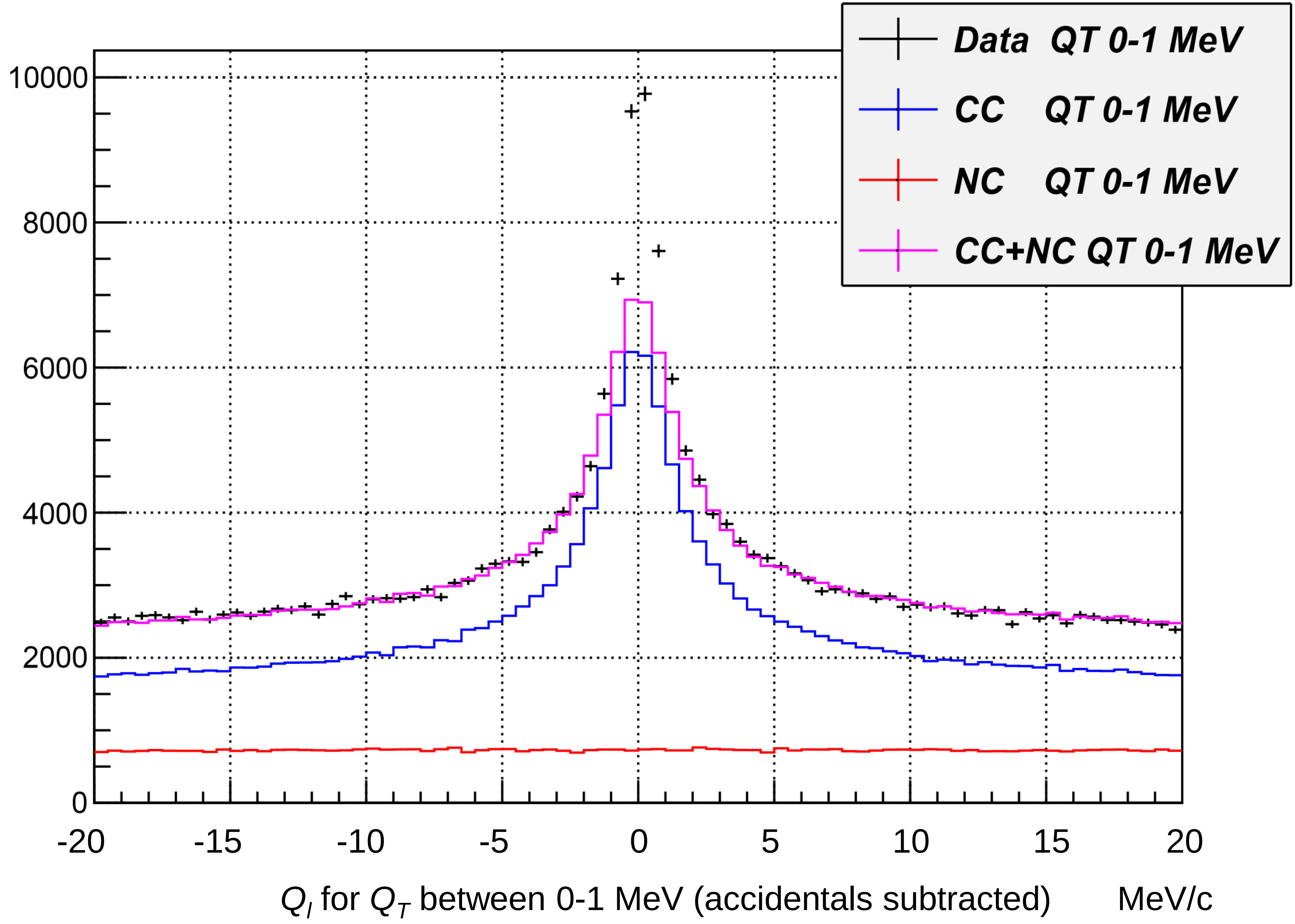
CONCLUSION: one parameter ($2a_0$+a_2) allows to calculate all Δ^{str}_{ns-np} values

Number of atomic pairs





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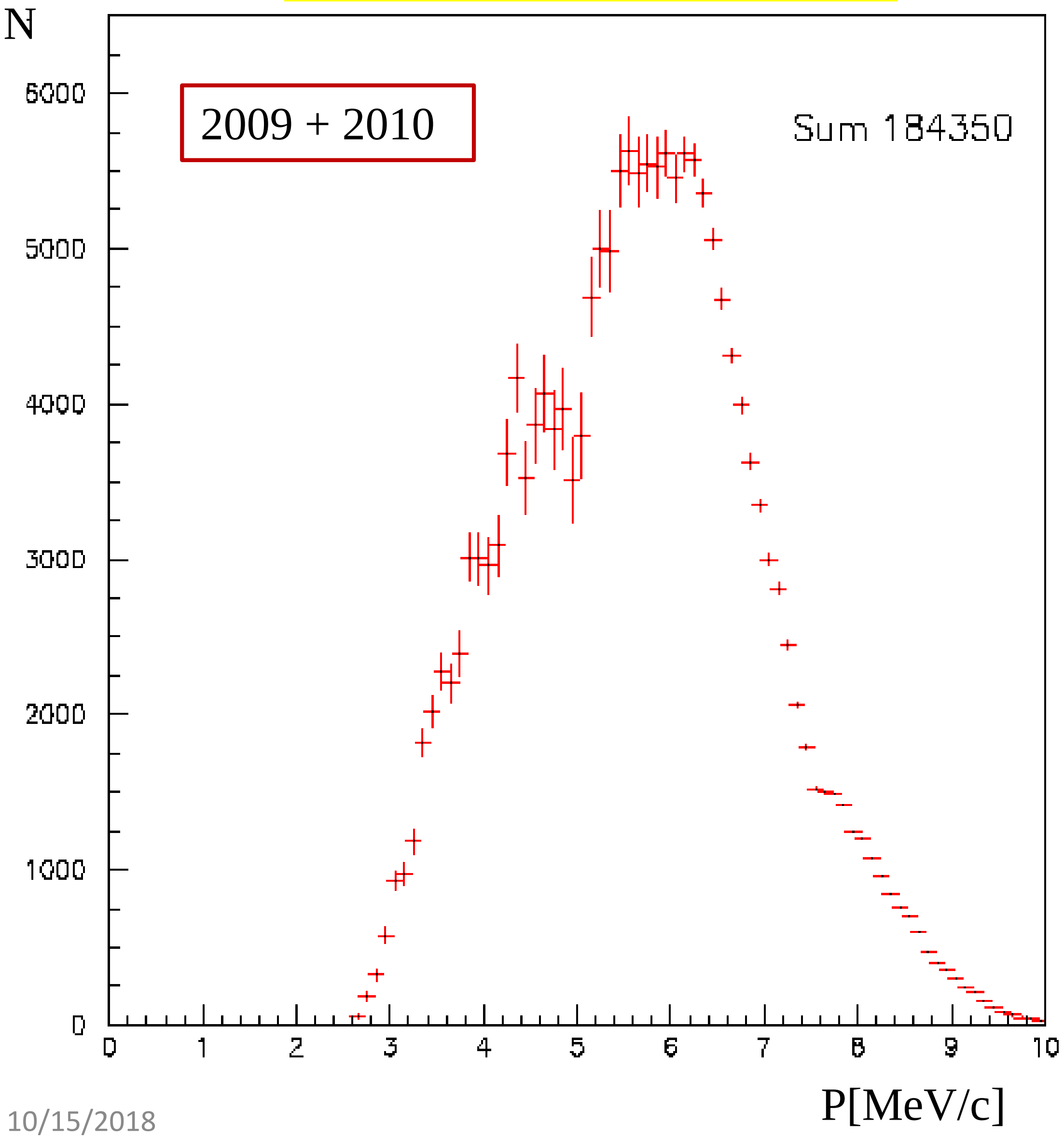
CC QT 0-1 MeV
NC QT 0-1 MeV
CC+NC QT 0-1 MeV
10000
8000
6000
4000
2000
0
-20
-15
-10
-5
0
5
10
15
20
Q_l for Q_T between 0-1 MeV (accidentals subtracted)
MeV/c

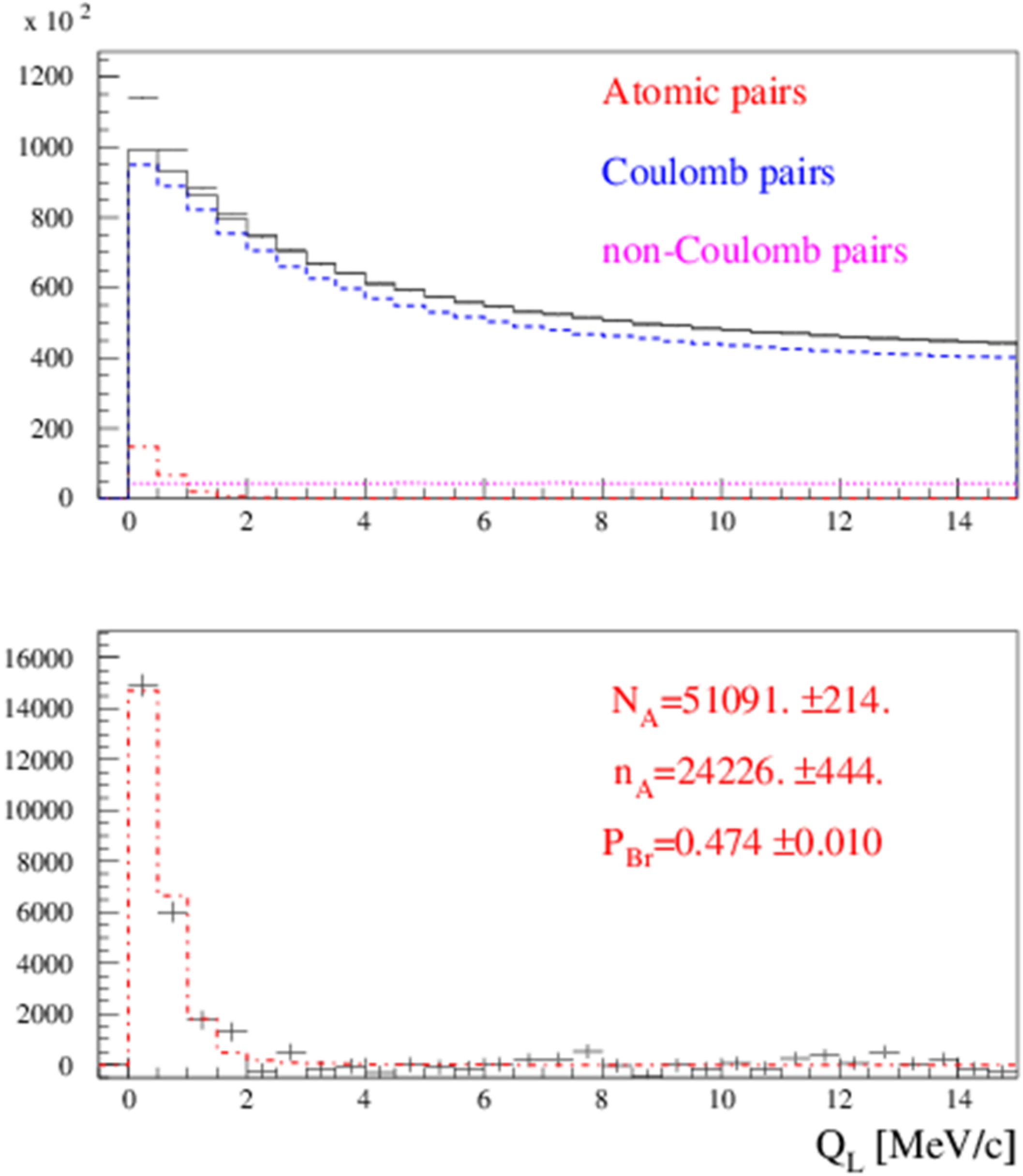
K^+K^- pair analysis

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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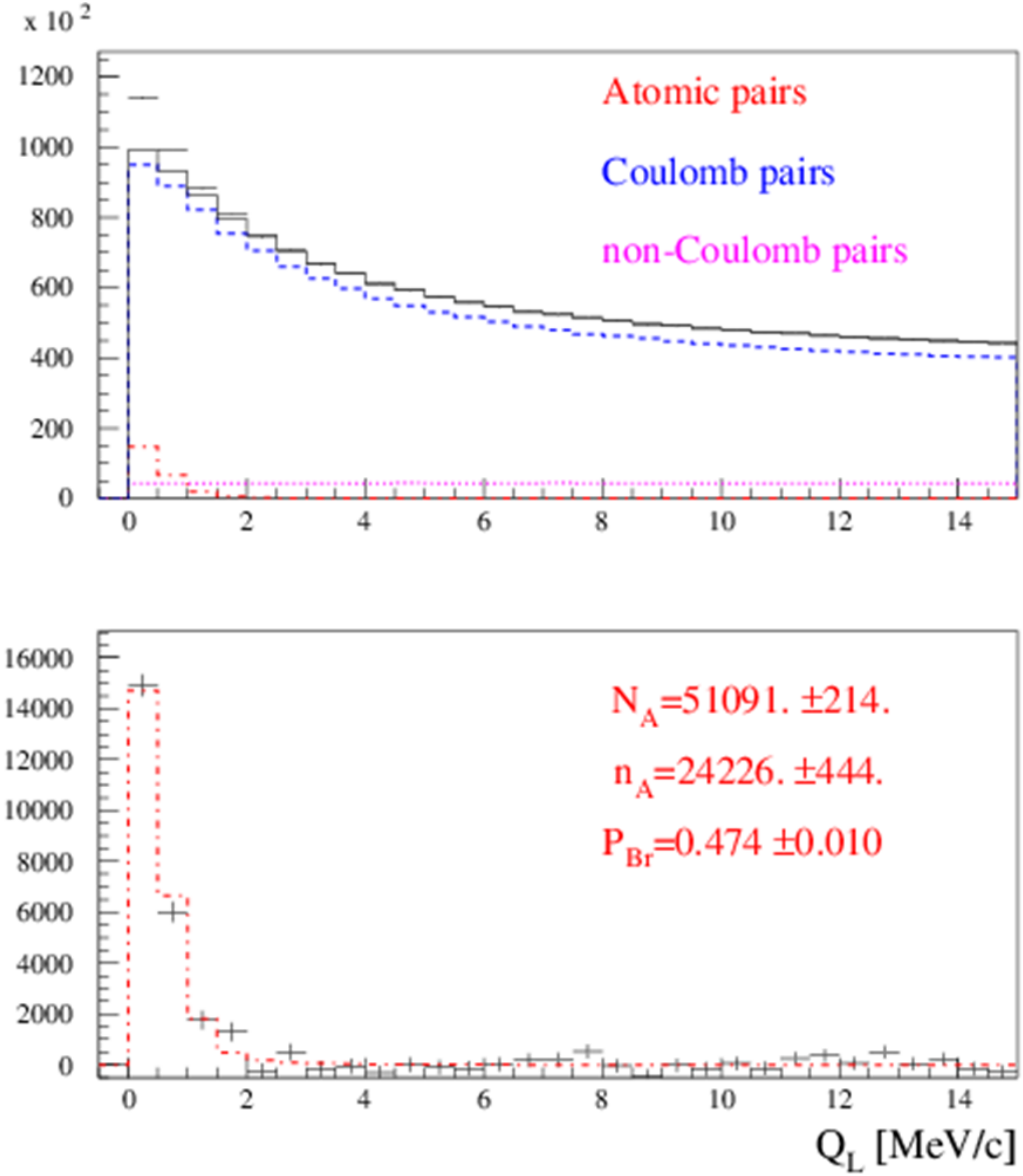

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