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.

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 $|\boldsymbol{a_{1/2}}\text{-}\boldsymbol{a_{3/2}}|$ with an average precision of 34% (*Phys.Rev.D* 2017).

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

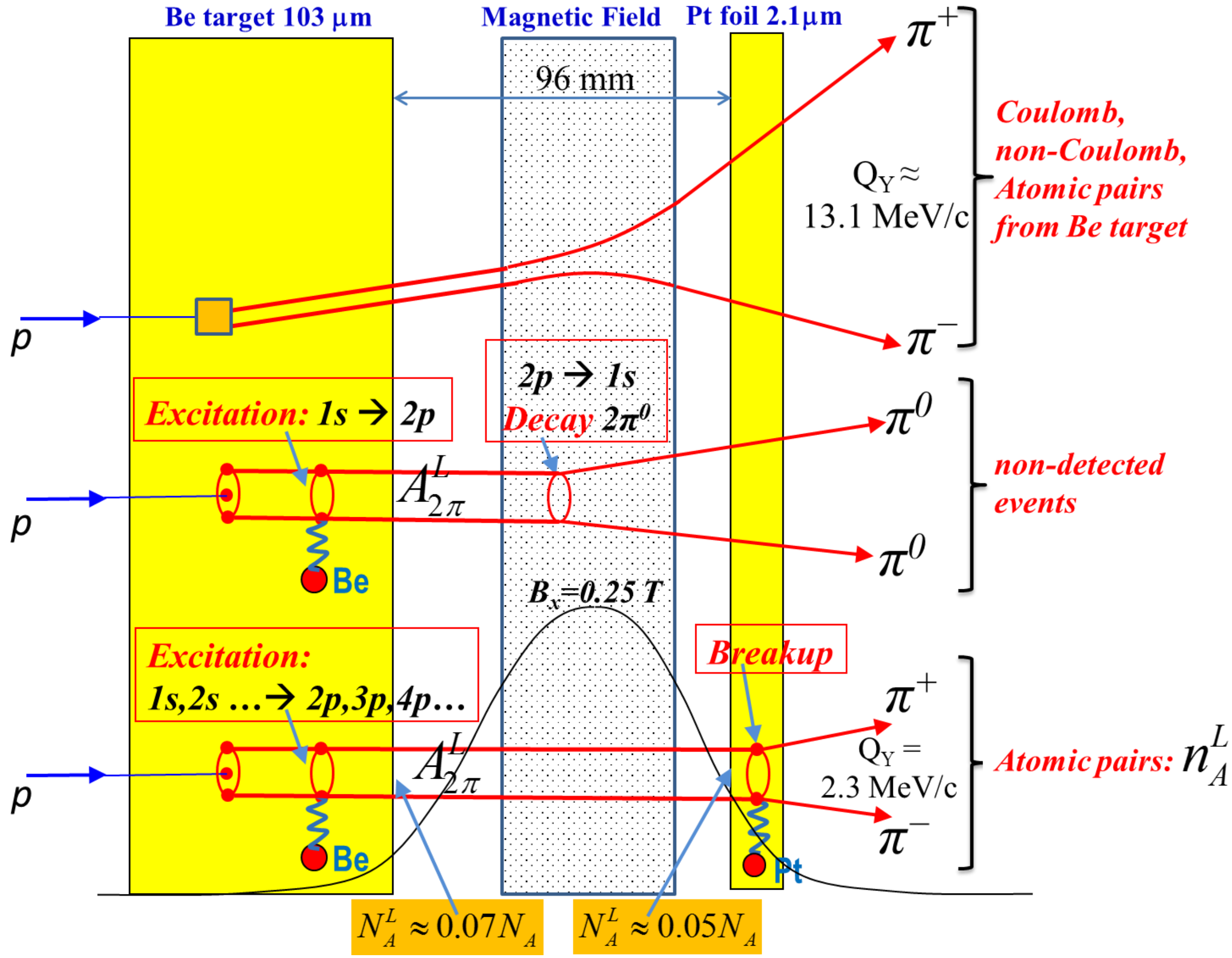


Fig. 1 Method to observe long-lived $A^L{}_{2\pi}$ by means of a breakup foil (*Pt*). The most of the produced $\pi^+\pi^-$ atoms decay (~70%) or are ionized (~6%) in the *Be* target. The excited (long lived) atoms (~24%) are investigated here.

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: $n_A = 436^{+157}_{-61}|_{\text{tot}}$

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

$$\tau_{2p} = 0.22^{+1.6}_{-0.18}|_{\text{tot}} \times 10^{-11}\text{s}$$

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

The measured ground state lifetime is:

$$\tau_{1s} = 3.15^{+0.28}_{-0.26}|_{\text{tot}} \times 10^{-15}\text{s}$$

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).

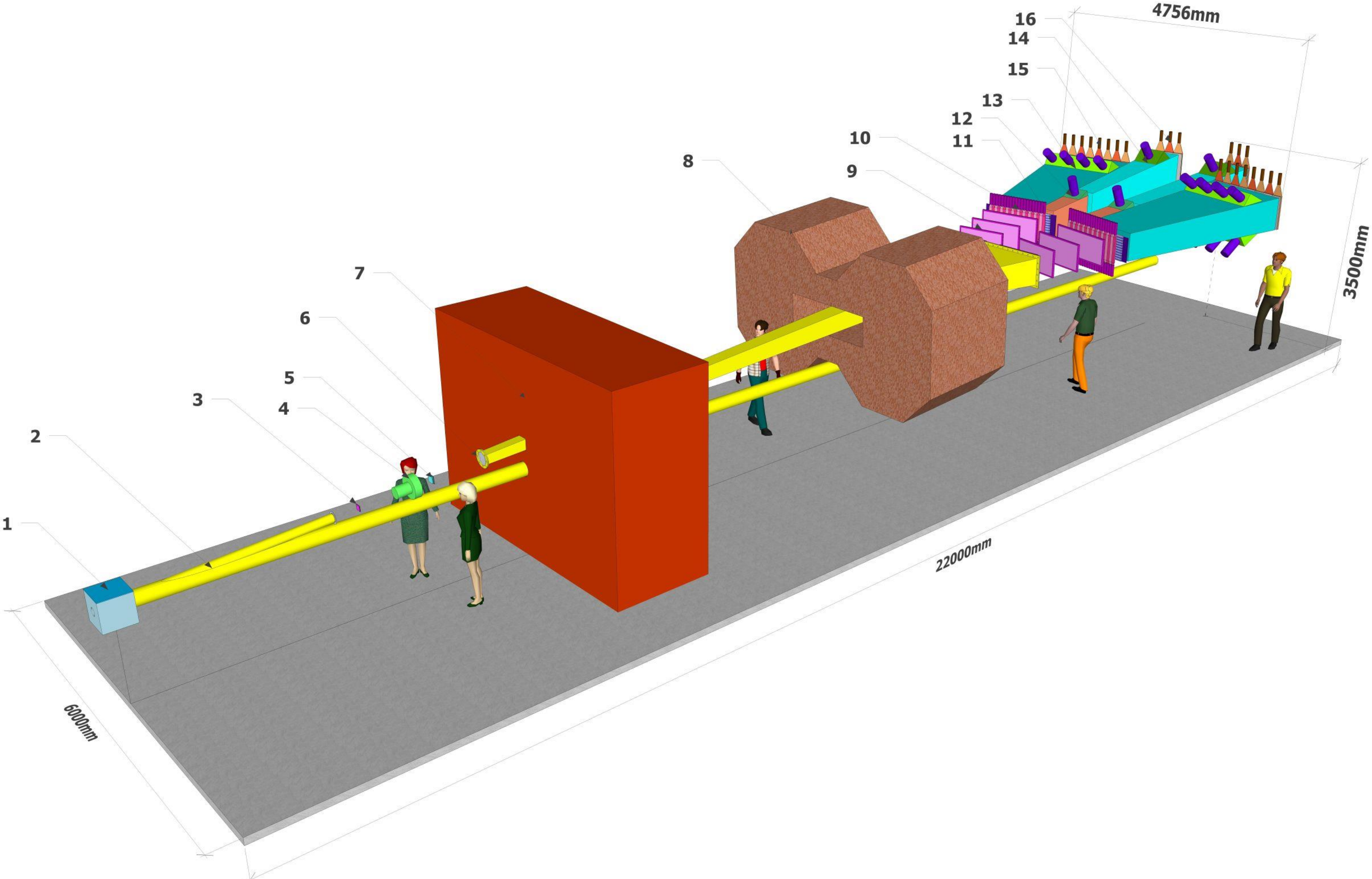
The short-lived atoms lifetime measurement allowed to evaluate $\pi\pi$ scattering length combination $a_0 - a_2$.
The study of the long-lived atoms will allow to measure the Lamb shift depending on another $\pi\pi$ scattering length combination: $2a_0+a_2$ and to evaluate the a_0, a_2 separately.

Atom yield for DIRAC at 24 and 450 GeV/c

per 1 proton-nucleus interaction

p_p θ_{lab}	$\pi^+\pi^-$ atom	$K^-\pi^+$ atom	$K^+\pi^-$ atom
p_p=24 GeV/c , θ_{lab}=5.7^o	$194\cdot10^{-11}$	$22\cdot10^{-11}$	$52\cdot10^{-11}$
p_p=450 GeV/c , θ_{lab}=4.0^o	$3400\cdot10^{-11}$	$810\cdot10^{-11}$	$850\cdot10^{-11}$
p_p=24 GeV/c , θ_{lab}=5.7^o (DIRAC acceptance)	$125\cdot10^{-11}$	$1.3\cdot10^{-11}$	$3.1\cdot10^{-11}$
p_p=450 GeV/c, θ_{lab}=4.0^o (DIRAC acceptance)	$1900\cdot10^{-11}$	$88\cdot10^{-11}$	$97\cdot10^{-11}$
yield ratio per time unit taking in to account the beam conditions and single particles generation at PS & SPS (DIRAC acceptance)	12 ± 2	53 ± 11	24 ± 5

DIRAC++ (Setup Isometric view)



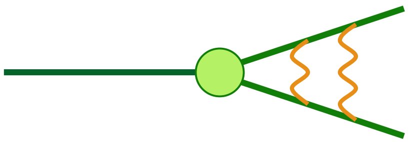
$\mathcal{L}(3)$,$\mathcal{L}(2)$ and Chiral Lagrangian predictions check with $K\pi$ and $\pi^+\pi^-$ atoms

The Lattice calculations: for the πK scattering lengths $a_{1/2}$ and $a_{3/2}$ the precision is~ 5% and will be improved in the near future. The experimental precision for $a_{1/2}$ - $a_{3/2}$ from the πK atom lifetime measurement is 34%. For the proton beam intensity $3\text{x}10^{11}$ protons/s, 3000 spills per day and running time 5 months the expected accuracy will be 5%. At the same running time the $\pi\pi$ scattering lengths a_0 , a_2 measurement will be improved.

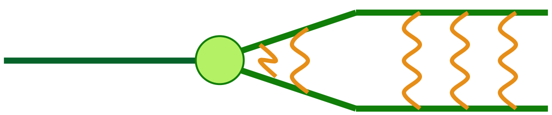
Lattice calculations	a_0 a_2	4-10% precision ~1% precision	K.Sasaki et al., Phys.Rev. 2014, Z.Fu, Phys.Rev.(2013), C.Lang et al.,Phys.Rev.(2012), Feng et al., Phys. Lett.(2010), T.Yagy at al., arXiv:1108.2970, S.Beame et al. Phys.Rev(2008)
ChPT	a_0 and a_2 a_0-a_2	2.3% precision 1.5% precision	Colangelo et al. Nucl.Phys.(2001)
Experimental values	a_0-a_2	~ 4% precision	J.R.Bateley at al., Eur. Phys. J. (2009), K decay, cusp-effect. Adeva et al., Phys. Lett. (2011) $\pi\pi$ atom lifetime measurement
	a_0 a_2	~ 6% precision ~22% precision	J.R.Bateley at al., Eur. Phys. J. (2009), *Ke4 decay* J.R.Bateley at al., Eur. Phys. (2010) *Ke4 decay*
Expected Experimental values on SPS	a_0-a_2 $2a_0 + a_2$	0.7% (~2%) Statistical(systematic) Errors Will de estimated	DIRAC-NOTE-2016-05

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

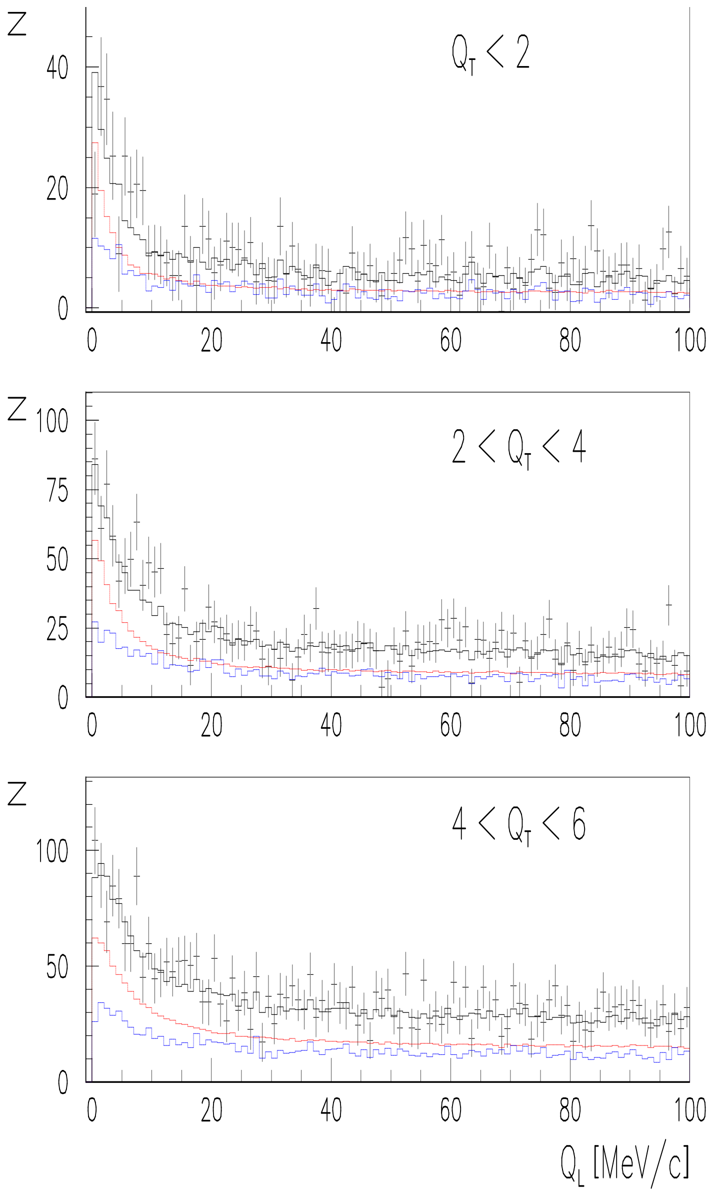
Coulomb pair

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:

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

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



Experimental distributions of K^+K^- pairs on the longitudinal component Q_L of Q, the relative momentum in the pair c.m.s., for the three transverse momentum intervals:

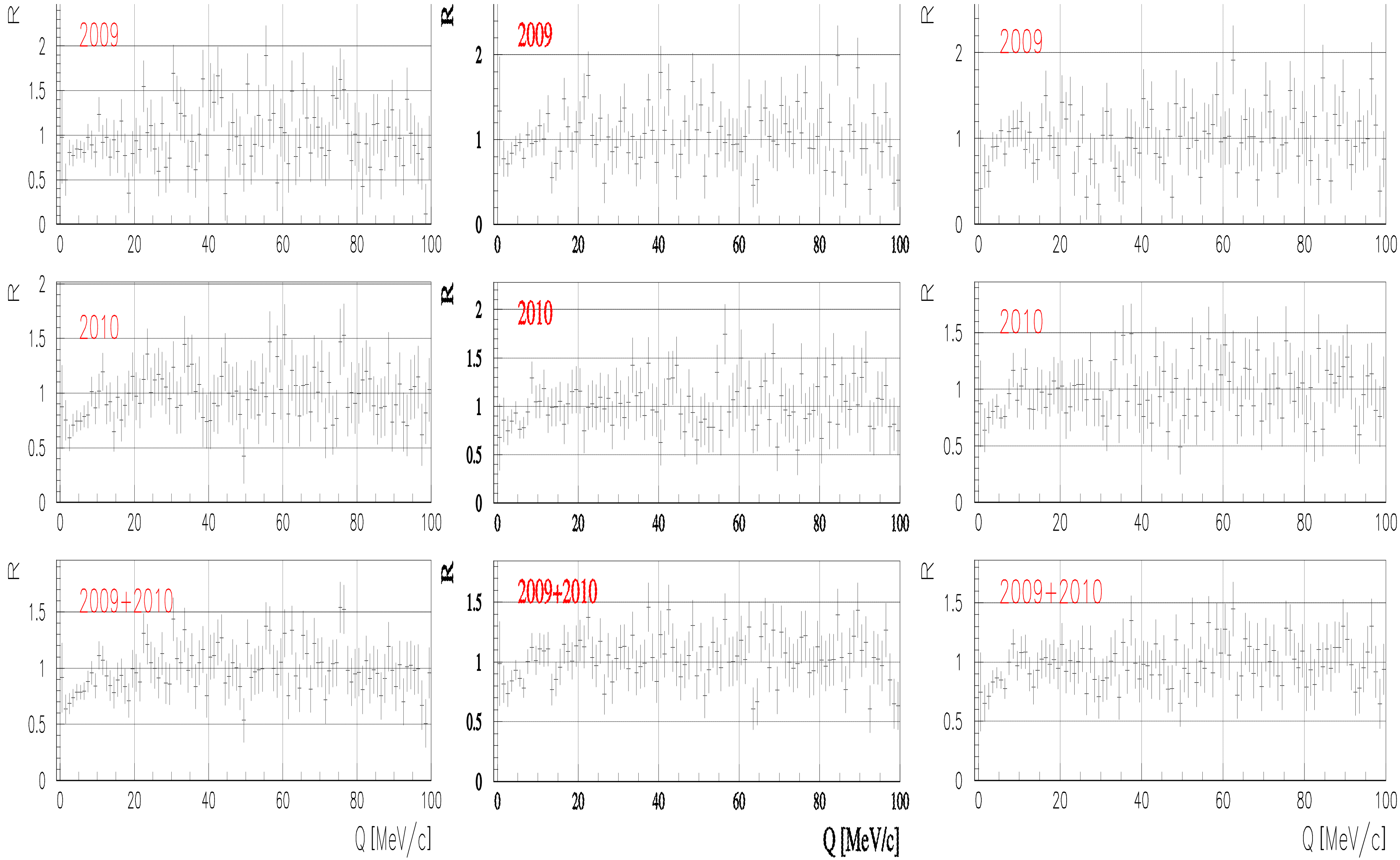
$0 < Q_T < 2$MeV/c,

$2 < Q_T < 4$MeV/c,

$4 < Q_T < 6$MeV/c.

These distributions were obtained after subtracting from the experimental K^+K^- and $\pi^+\pi^-$ distributions the background of $\pi^+\pi^-$ pairs. The part of the K^+K^- pairs in the initial distributions was 70%. In each Q_T interval, the yield of pairs is increasing with decreasing Q_L. This effect is caused by the Coulomb interaction between K^+ and K^- in the final state. To confirm this interpretation, the distributions were fitted by simulated K^+K^- distributions (red) and the experimental distributions of $\pi^+\pi^-$ pairs processed as K^+K^- (blue). It is obvious that the experimental distributions cannot be described without K^+K^- final state interaction.

The analysis of the detected Coulomb pairs allows to evaluate model-independently the total number of produced K^+K^- atoms and to formulate the experimental conditions for the K^+K^- atom observation and its lifetime measurement at the CERN SPS.



30%

50%

70
%

Proton-antiproton pair analysis

In 2018, DIRAC will perform a search for an proton-antiproton Coulomb pairs and thus proton- antiproton atoms with the same strategy as in the K^+K^- case.

Coulomb pairs as a possible new physical method to investigate the particles production in the coordinate space will be studied.

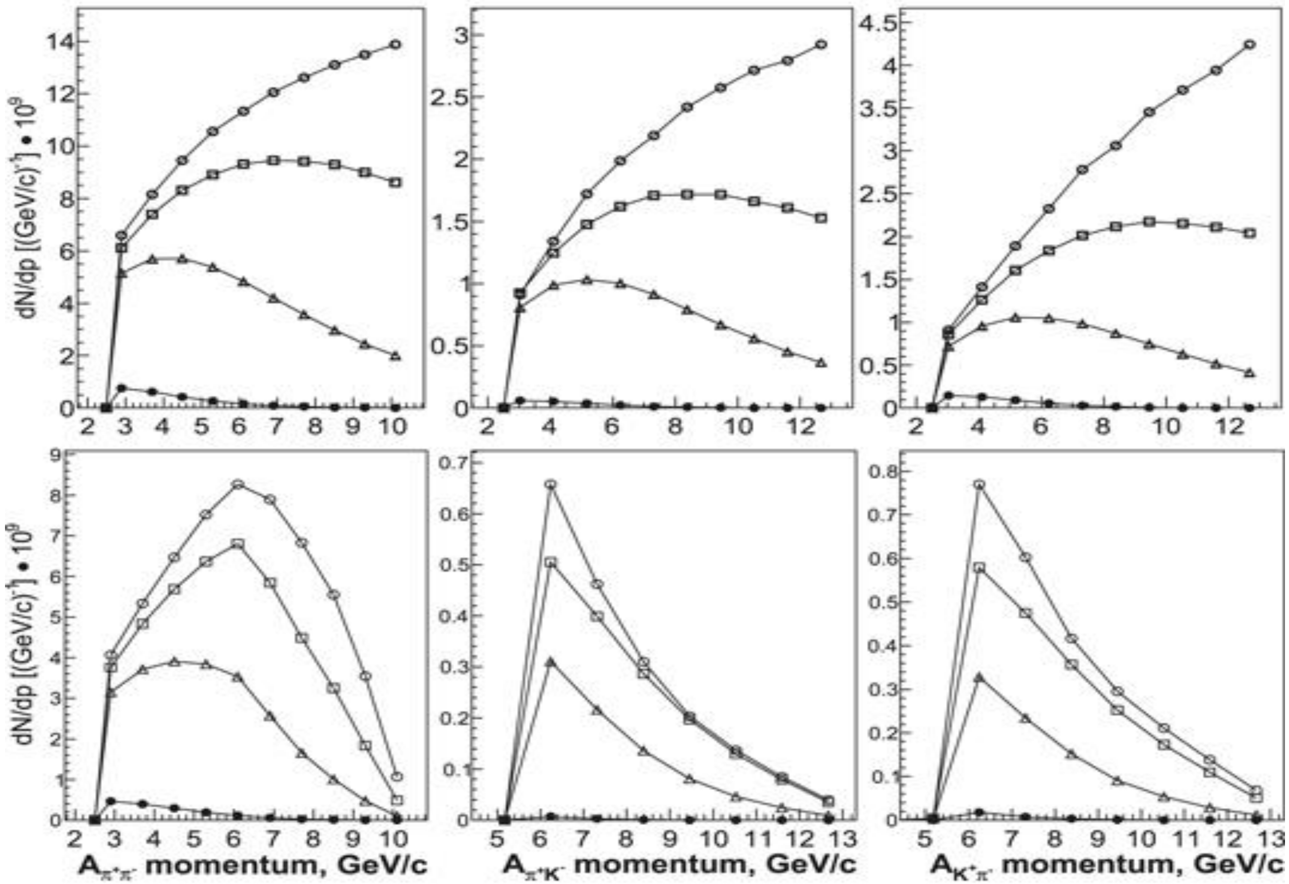
Coulomb correlations

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.

Thank you

Yields of $A_{2\pi}$, $A_{\pi K}$ and $A_{K\pi}$ per 10^9 pNi interactions



Yields of $A_{2\pi}$, $A_{\pi K}$ and $A_{k\pi}$ per 10^9 *pNi* interaction as a function of the atom momentum in l.s. for a solid angle of 10^{-3} sr at p = 450 GeV c^{-1} and emission angles θ_{lab} = 0°, 2°, 4° and at p = 24 GeV c^{-1} and θ_{lab} = 5.7°.

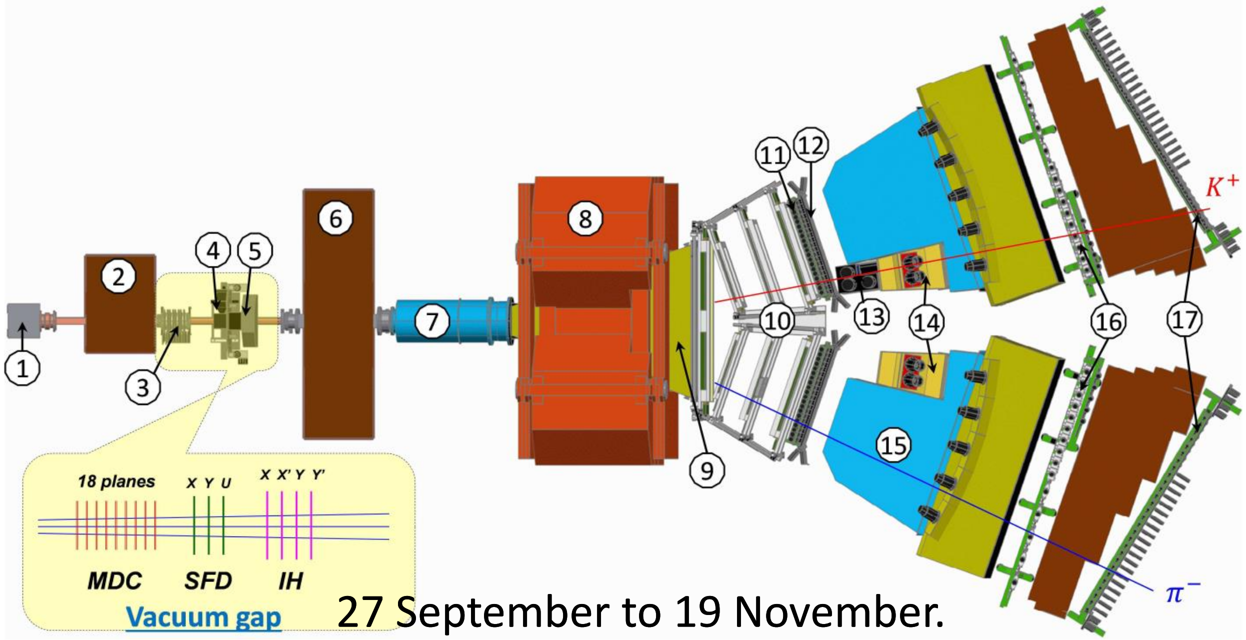
Top: DIRAC setup acceptance and pion & kaon decays not included.

Bottom: DIRAC setup acceptance and pion & kaon decays taken into account.

24 GeV c^{-1}: θ_{lab} = 5.7° (filled circle ●)

450 GeV c^{-1}: θ_{lab} = 0° (open circle ○), 2°(open box □), 4° (open triangle Δ).

DIRAC setup, experimental and theoretical data



27 September to 19 November.

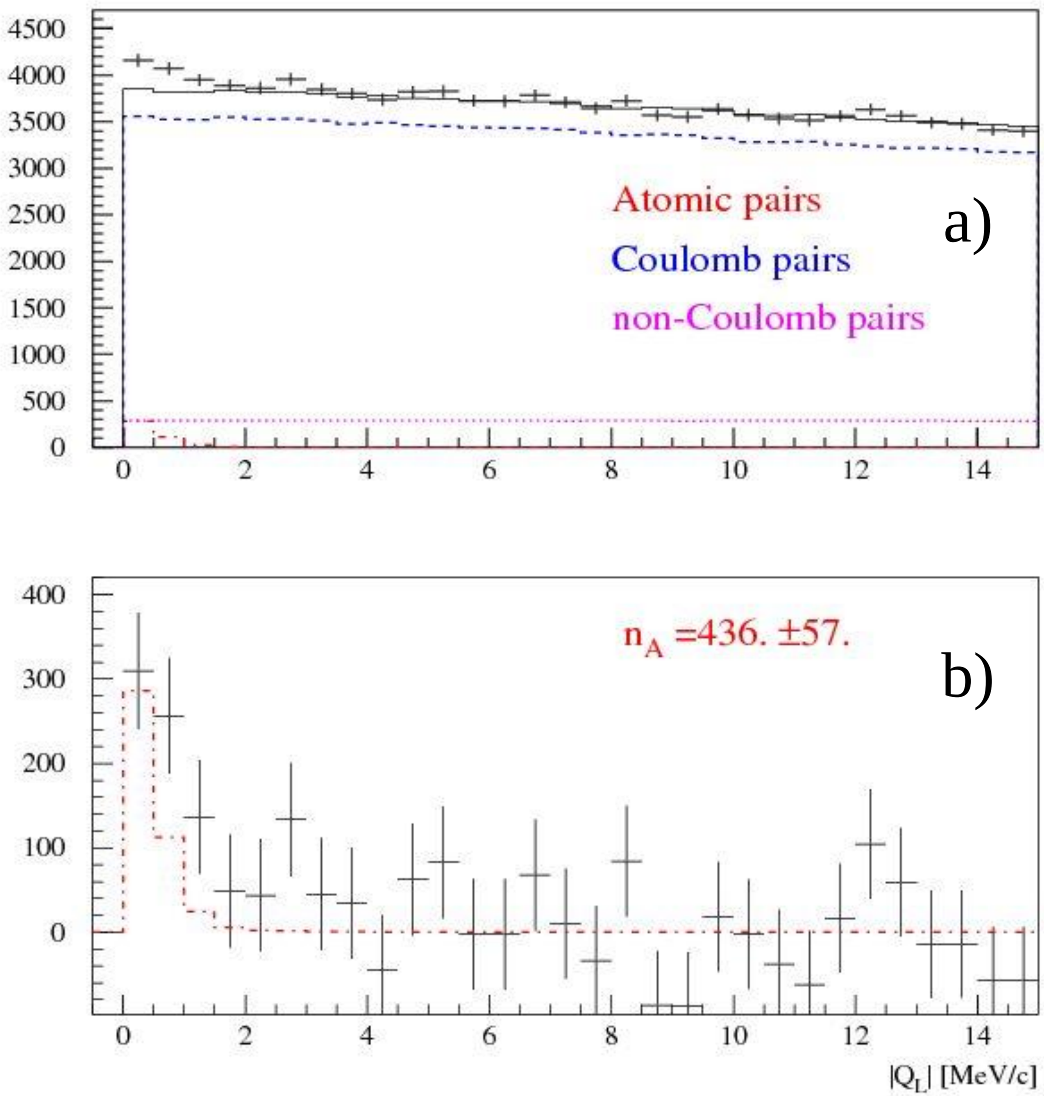
Experiment	Detected atomic pairs (n_A)	τ (10^{-15} sec)	$a^- = \frac{1}{3}(a_{1/2}-a_{3/2})$	Average error
DIRAC	349±61(stat)±9(syst) =349±62(tot) (5.6σ)	$5.5^{+5.0}_{-2.8}$	$0.072^{+0.031}_{-0.020}$	34%

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

$\pi^+\pi^-$ 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	$2.9 \cdot 10^{-4}$	-	$1.39 \cdot 10^{-3}$	-
2	$2.32 \cdot 10^{-3}$	1.17	$1.11 \cdot 10^{-2}$	5.6
3	$7.83 \cdot 10^{-3}$	3.94	$3.76 \cdot 10^{-2}$	19
4	$1.86 \cdot 10^{-2}$	9.05	$8.91 \cdot 10^{-2}$	43
5	$3.63 \cdot 10^{-2}$	17.5	$1.74 \cdot 10^{-1}$	84
6	$6.26 \cdot 10^{-2}$	29.9	$3.01 \cdot 10^{-1}$	144
7	$9.95 \cdot 10^{-2}$	46.8	$4.77 \cdot 10^{-1}$	225
8	$1.48 \cdot 10^{-1}$	69.3	$7.13 \cdot 10^{-1}$	333

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



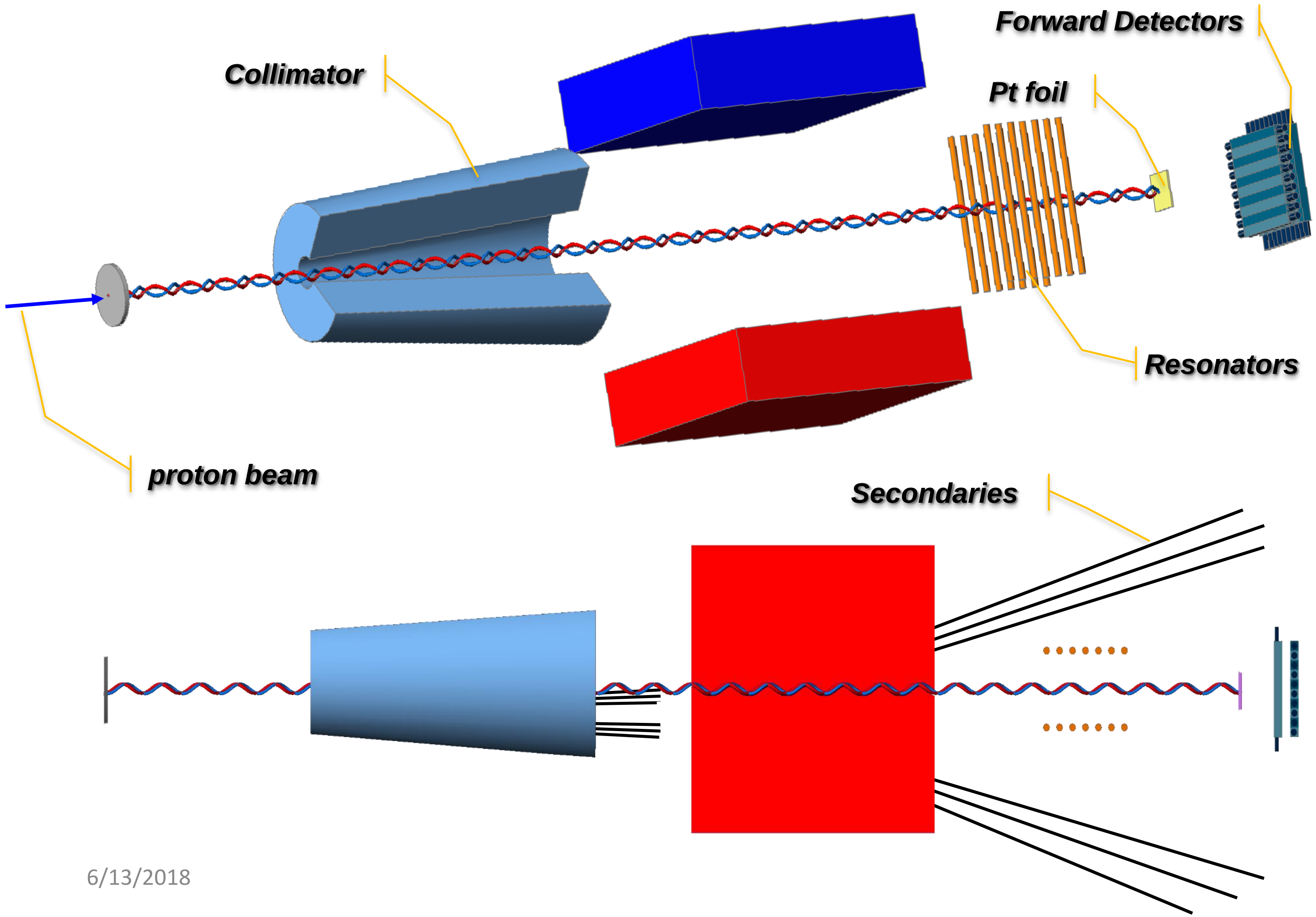
<u>$|Q_L|$ distribution of $\pi^+\pi^-$ pairs for Q_T <2.0 MeV/c</u>

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.

DIRAC future Experimental setup



K^+K^- atom and its lifetime

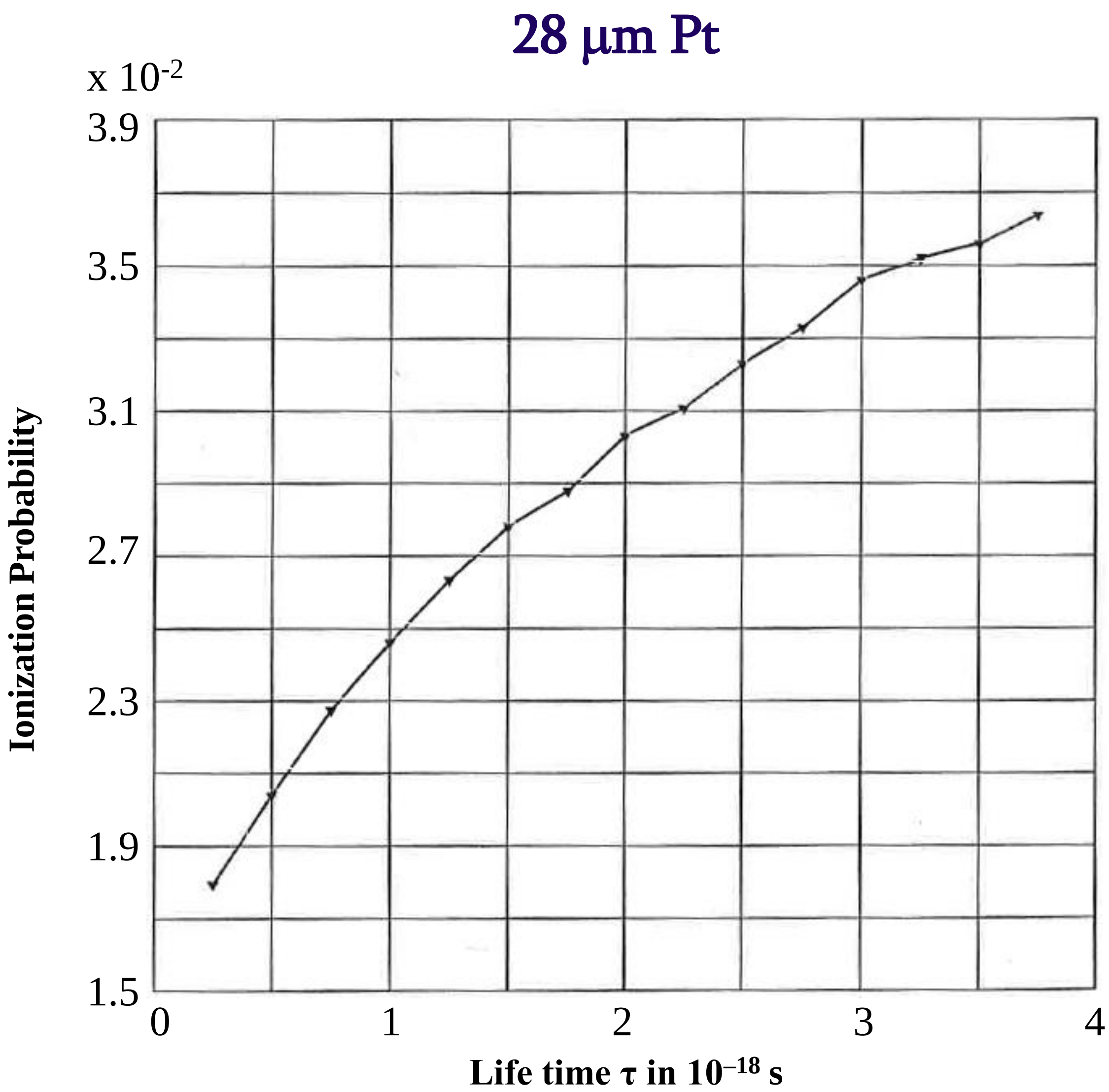
The A_{2K} lifetime is strongly reduced by strong interaction (OBE, scalar meson f_0 and a_0) as compared to the annihilation of a purely Coulomb-bound system (K^+K^-).

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.

K^+K^- atoms ionization probability



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

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	

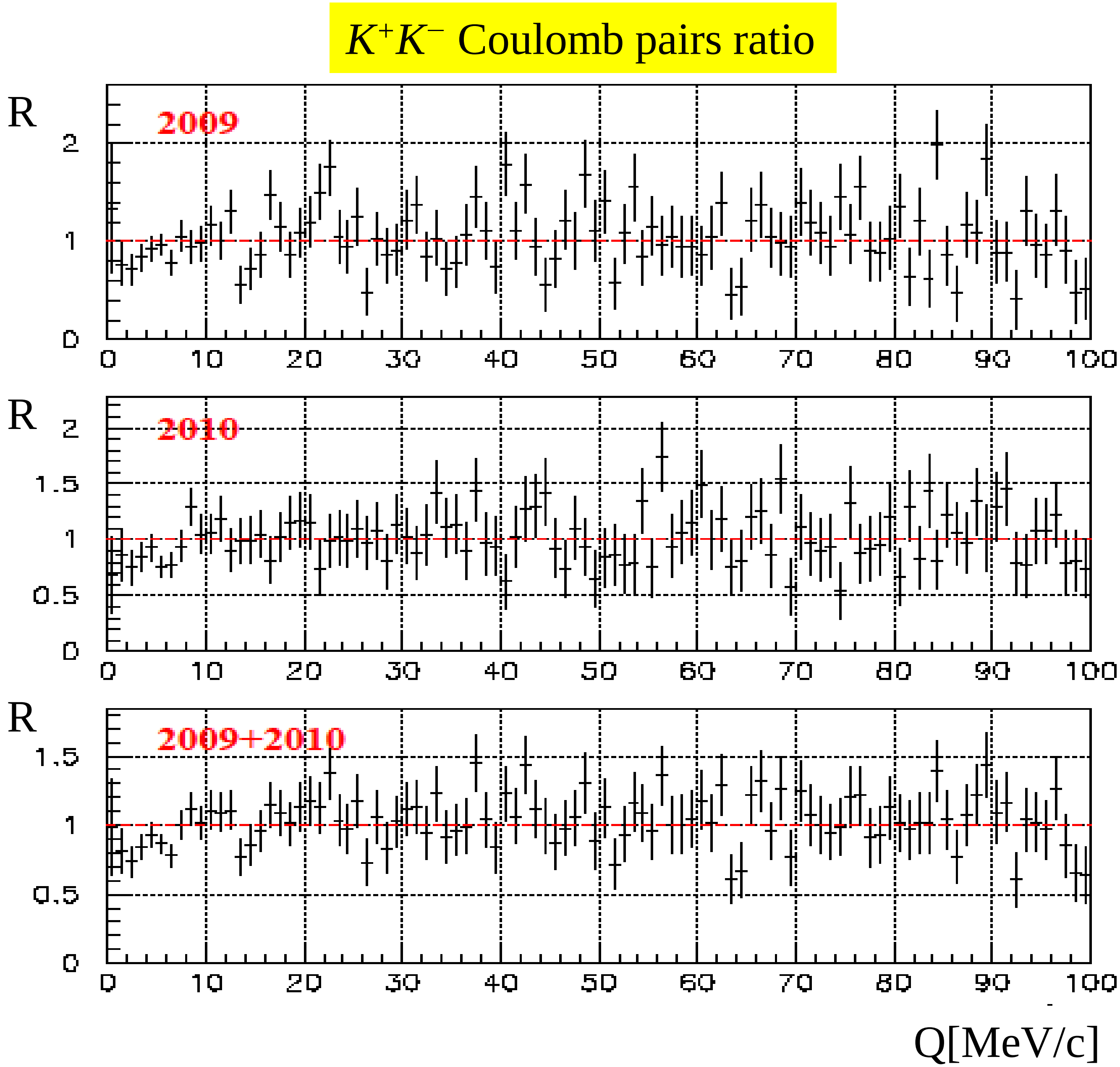
	Z	A	Nublear radius [fm]
Be	04	9.012	2.56
Ni	28	58.69	4.78
Pt	78	195.08	7.13

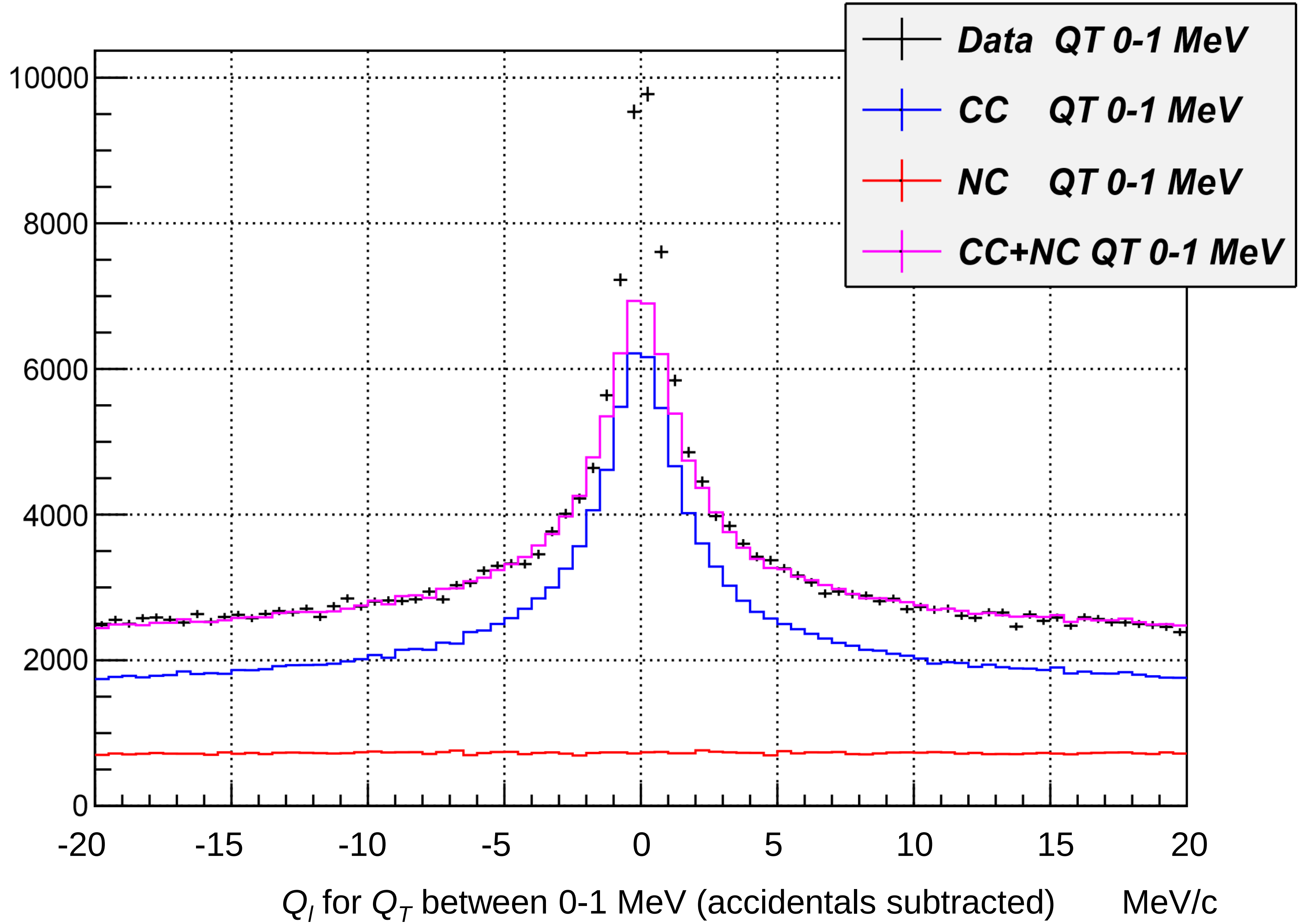
Coulomb correlation with account of size of pair production region r^*

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

Point-like Coulomb correlation

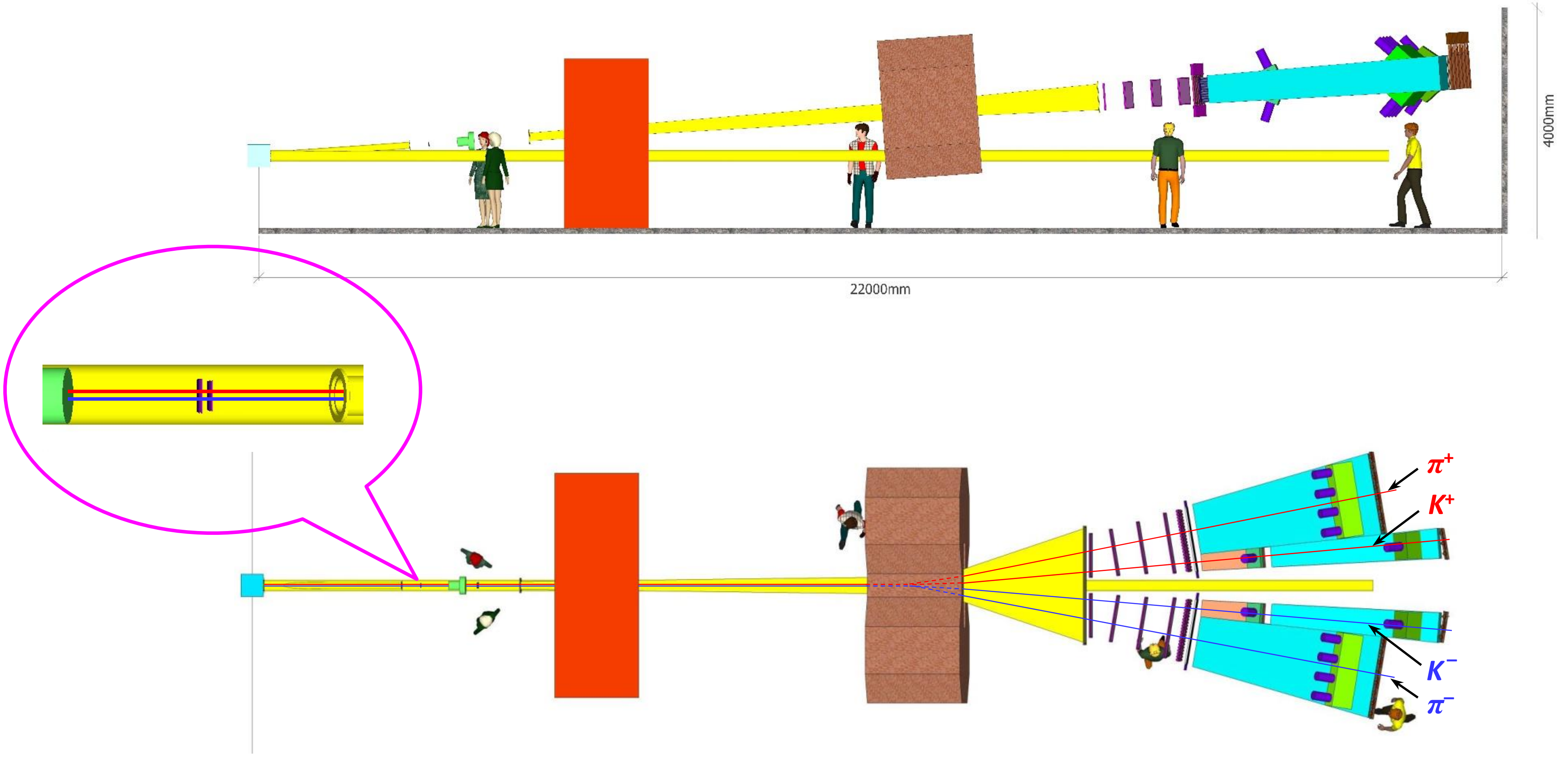
K^+K^- pair analysis





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

DIRAC++ Setup (top view)



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%