Observation and investigation of πK atoms

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Low-energy QCD precise predictions

πK scattering lengths

I . ChPT predicts s-wave scattering lengths:

$L^{(2)}$, $L^{(4)}$ and 1-loop

$$a_0^{1/2} = 0.19 \pm 0.02,\ a_0^{3/2} = -0.05 \pm 0.02$$

$$a_0^{1/2} - a_0^{3/2} = 0.24 \pm 0.03$$

V. Bernard, N. Kaiser, U. Meissner - 1991

$$a_0^{1/2} - a_0^{3/2} = 0.23 \pm 0.01$$

A. Roessl - 1999

$L^{(2)}$, $L^{(4)}$, $L^{(6)}$ and 2-loop

$$a_0^{1/2} - a_0^{3/2} = 0.267$$

J. Bijnens, P. Dhonte, P. Talavera - April 2004

II . Roy-Steiner equations:

$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015$$

P. Büttiker et al. - 2004

πK scattering lengths

III . S-wave πK scattering has also been studied extensively in the framework of lattice QCD

Recently predictions for πK scattering have been obtained:

$$a_0^{1/2} = 0.1725^{+0.0026}_{-0.0157}, a_0^{3/2} = -0.0574^{+0.0029}_{-0.0060}$$

S.R. Beane et al, Phys. Rev. D77 (2008) 094507

$$a_0^{1/2} = 0.183 \pm 0.039, a_0^{3/2} = -0.0602 \pm 0.0040$$

C.B. Lang et al., Phys. Rev. D86 (2012) 054508

$$a_0^- = \frac{1}{3}(a_0^{1/2} - a_0^{3/2}) = 0.0811 \pm 0.0143$$

K. Sasaki et al., Phys. Rev. D89 (2014) 054502

$$a_0^- = \frac{1}{3}(a_0^{1/2} - a_0^{3/2}) = 0.0745 \pm 0.00020$$

T. Janowski et al., PoS LATTICE2014 (2015) 080

Gain of πK scattering length measurement

What new will be known if πK scattering lengths will be measured?

The measurement of the s-wave πK scattering lengths sensitively checks QCD (LQCD) predictions for process at low energy and, as result, our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (u, d and s quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u,d quarks). Contribution of chiral symmetry breaking part of Lagrangian to processes with high energy is very small.

At present πK scattering length measurement is only source of experimental data for checking chiral symmetry breaking for processes with s quarks.

Published results on πK scattering lengths

Experimental data on the πK low-energy phases are absent.

DIRAC data	$\tau_{1s}(10^{-15}s)$ value stat syst tot	$\mid a_0^- \mid$ value tot	Reference
2008-10	$2.5^{+3.0+0.3}_{-1.8-0.1} \begin{bmatrix} +3.0 \\ -0.18 \end{bmatrix}$	$0.11^{+0.09}_{-0.04}$	PL B 735 (2014) 288

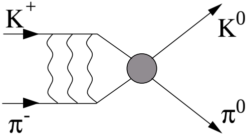
Method of πK atom observation and investigation

$K^+\pi^-$ and π^+K^- atoms lifetime

πK-atom ($A_{\pi K}$) is a hydrogen-like atom consisting of $K^\pm$ and $\pi^\mp$ mesons:

$$E_B = -2.9\,keV,\ r_B = 248\,fm, p_B \approx 0.8\,MeV/c$$

The πK-atom lifetime (ground state 1S), $\tau = \frac{1}{\Gamma}$ is dominated by the annihilation process into $\pi^0 K^0$:



$$A_{K^+\pi^-} \to \pi^0 K^0,\ A_{\pi^+K^-} \to \pi^0 \bar{K}^0$$

$$\Gamma_{1S,\pi^0K^0} = R_K \mid a_0^{1/2} - a_0^{3/2} \mid^2 \text{ with } \frac{\Delta R}{R} \approx 2\%$$

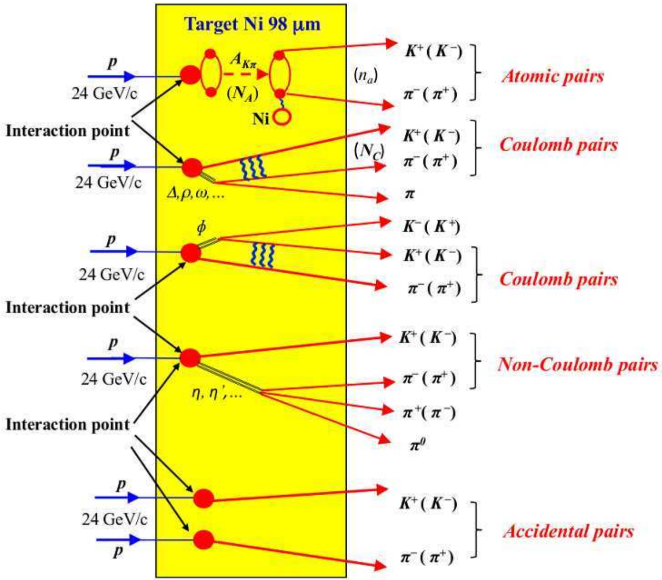
J. Schweizer - 2004

From Roy-Steiner equations:

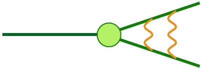
$$a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015 \to \tau = (3.5 \pm 0.4)10^{-15}s$$

$$\text{If} \quad \frac{\Delta\Gamma}{\Gamma} = 10\% \quad \Rightarrow \quad \frac{\Delta|a_0^{1/2}-a_0^{3/2}|}{|a_0^{1/2}-a_0^{3/2}|} = 5\%$$

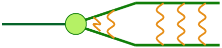
Method of and πK atom observation



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



Coulomb pairs



Atoms

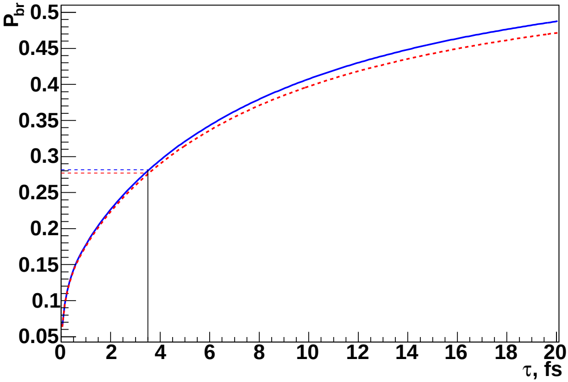
There is precise ratio between the number of produced Coulomb pairs (N_C) with small Q and the number of atoms (N_A) produced simultaneously with these Coulomb pairs:

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

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

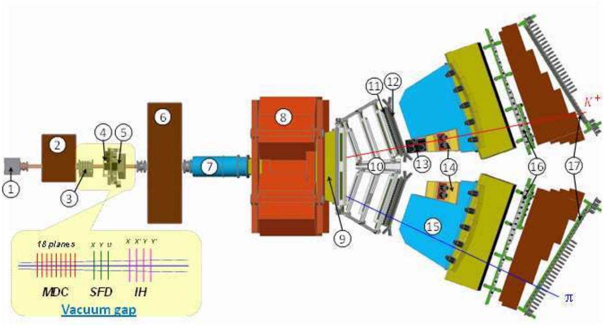
Break-up probability

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on πK atom lifetime for Nickel target with thicknesses $108\mu m$ and $98\mu m$



DIRAC setup

Experimental setup



1 Target station with Ni foil; 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

Setup properties

SFD			
Coordinate precision	$\sigma_X = 60\mu m$	$\sigma_Y = 60\mu m$	$\sigma_W = 120\mu m$
Time precision	$\sigma^t_X = 380ps$	$\sigma^t_Y = 512ps$	$\sigma^t_W = 522ps$

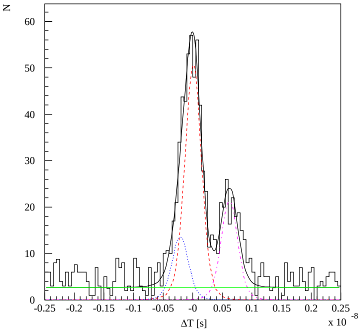
DC	
Coordinate	$\sigma = 85\mu m$

VH	
Time precision	$\sigma = 100ps$

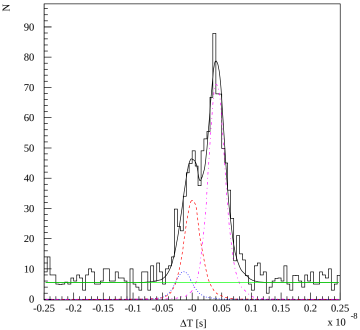
Spectrometer		
Relative resolution on the particle momentum in L.S.		$3 \cdot 10^{-3}$
Precision on Q-projections	$\sigma_{Q_X} = \sigma_{Q_Y} = 0.5\ MeV/c$	$\sigma_{Q_L} = 0.9\ MeV/c\ (\pi K)$

Trigger efficiency 98%	for pairs with	$Q_L < 28\ MeV/c$
		$Q_X < 6\ MeV/c$
		$Q_Y < 4\ MeV/c$

Observation of πK atoms

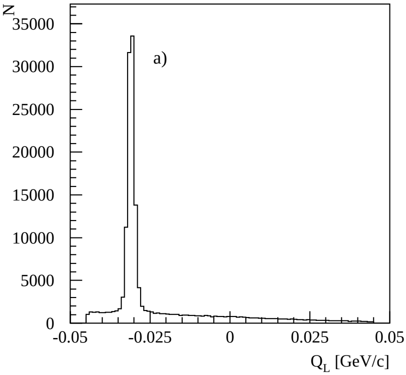


Momentum of positive particle in a range $4.4 \div 4.5$ GeV/c



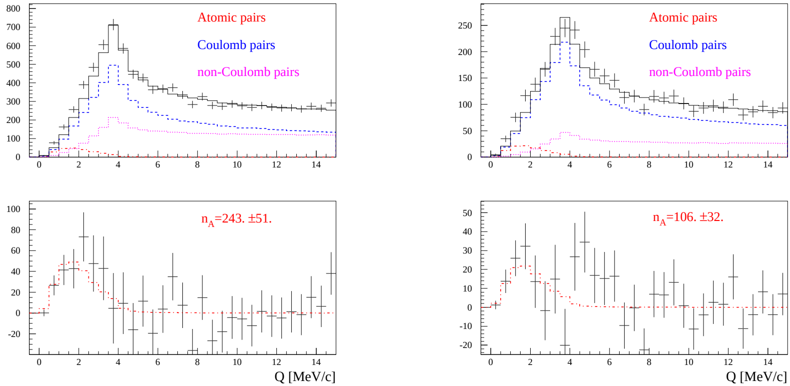
Momentum of positive particle in a range $5.4 \div 5.5$ GeV/c

Background suppression for $K^+\pi^-$



$K^+\pi^-$ and π^+K^- atoms - run 2007-2010

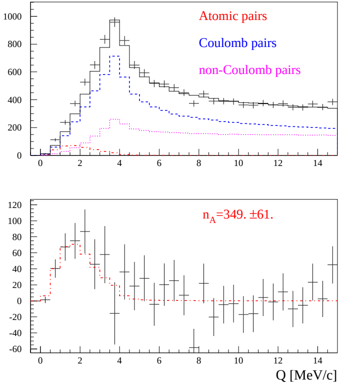
Statistics with Platinum (2007) and Nickel (2008-2010) targets



Criterion $Q_T < 4MeV/c$. $\chi^2/ndf = 36/37$.
In absence of "atomic pairs" $\chi^2/ndf = 56/38$

Criterion $Q_T < 4MeV/c$. $\chi^2/ndf = 42/37$.
In absence of "atomic pairs" $\chi^2/ndf = 53/38$

Statistics with Platinum (2007) and Nickel (2008-2010) targets



Criterion $Q_T < 4MeV/c$. $\chi^2/ndf = 41/37$. In absence of "atomic pairs" $\chi^2/ndf = 73/38$

Statistics πK atomic pairs

Analysis	$\pi^- K^+$	$\pi^+ K^-$	$\pi^- K^+$ and $\pi^+ K^-$?
Q	243 ± 52 (4.7σ)	106 ± 32 (3.3σ)	349 ± 61 (5.7σ)
$\lvert Q_L \rvert$	164 ± 79 (2.1σ)	67 ± 47 (1.4σ)	230 ± 92 (2.5σ)
$\lvert Q_L \rvert, Q_T$	237 ± 50 (4.7σ)	78 ± 32 (2.5σ)	314 ± 59 (5.3σ)

Systematic errors

Sources of systematic errors	σ_Q^{syst}	$\sigma_{Q_L}^{syst}$	$\sigma_{\lvert Q_L \rvert, Q_T}^{syst}$
Uncertainty in Λ width correction	0.8	3.0	2.0
Uncertainty of multiple scattering in Ni target	4.4	0.7	2.7
Accuracy of SFD simulation	0.2	0.0	0.1
Correction of Coulomb correlation function on finite size production region	0.0	0.2	0.1
Uncertainty in πK pair laboratory momentum spectrum	3.3	5.4	7.8
Uncertainty in laboratory momentum spectrum of background pairs	6.6	1.6	5.4
Total	8.6	6.4	10.1

Observation of πK atoms

Analysis with Q_L, Q_T:

$$n_A = 314 \pm 59(stat) \pm 10(syst) = 314 \pm 60(tot)$$

5.2 standard deviations

Analysis with Q:

$$n_A = 349 \pm 61(stat) \pm 9(syst) = 349 \pm 62(tot)$$

5.6 standard deviations

B.Adeva, PRL 117, (2016) 112001

Break-up probability of πK atoms

Year	Q	Q_L	$\|Q_L\|, Q_T$
		$K^+\pi^-$	
2007	1.09 ± 0.52	1.42 ± 0.95	1.44 ± 0.59
2008	0.32 ± 0.20	0.41 ± 0.34	0.44 ± 0.22
2009	0.23 ± 0.16	0.04 ± 0.22	0.16 ± 0.15
2010	0.41 ± 0.17	0.15 ± 0.20	0.33 ± 0.16
		π^+K^-	
2007	1.2 ± 1.3	0.9 ± 1.6	0.27 ± 0.56
2008	0.52 ± 0.39	0.50 ± 0.62	0.42 ± 0.38
2009	0.29 ± 0.20	0.49 ± 0.37	0.33 ± 0.24
2010	0.33 ± 0.22	-0.13 ± 0.20	0.21 ± 0.20

Systematic errors for break-up probability

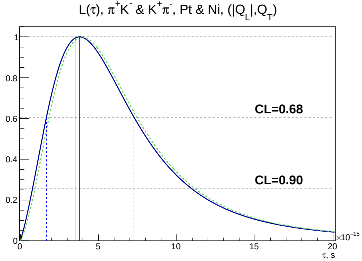
Sources of systematic errors	Nickel target		
	σ_{Q}^{syst}	$\sigma_{Q_L}^{syst}$	$\sigma_{\|Q_L\|,Q_T}^{syst}$
Uncertainty in Λ width correction	0.0006	0.0013	0.0006
Uncertainty of multiple scattering in Ni target	0.0051	0.0006	0.0036
Accuracy of SFD simulation	0.0002	0.0001	0.0003
Correction of Coulomb correlation function on finite size production region	0.0001	0.0000	0.0000
Uncertainty in πK pair laboratory momentum spectrum	0.0052	0.0031	0.0050
Uncertainty in laboratory momentum spectrum of background pairs	0.0011	0.0010	0.0011
Uncertainty in the $P_{\rm br}(\tau)$ relation	0.0055	0.0055	0.0055
Total	0.0092	0.0066	0.0084

Systematic errors for break-up probability

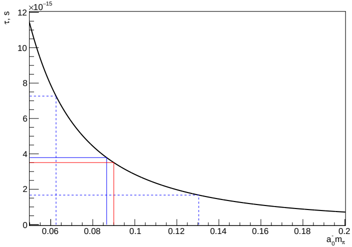
Sources of systematic errors	Platinum target		
	σ_{Q}^{syst}	$\sigma_{Q_L}^{syst}$	$\sigma_{\|Q_L\|,Q_T}^{syst}$
Uncertainty in Λ width correction	0.011	0.099	0.073
Uncertainty of multiple scattering in Ni target	0.0087	0.0086	0.014
Accuracy of SFD simulation	0.	0.	0.
Correction of Coulomb correlation function on finite size production region	0.0001	0.0002	0.0002
Uncertainty in πK pair laboratory momentum spectrum	0.089	0.27	0.25
Uncertainty in laboratory momentum spectrum of background pairs	0.22	0.068	0.21
Uncertainty in the $P_{\rm br}(\tau)$ relation	0.01	0.01	0.01
Total	0.24	0.29	0.34

πK atom lifetime estimation

Analysis with Q_L, Q_T.



Likelihood function for πK atom lifetime measurement



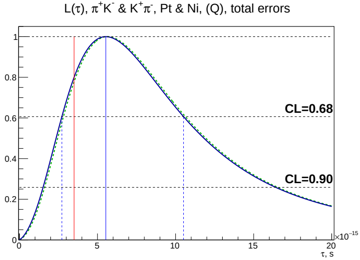
Relation between measured value πK atom lifetime (τ) and a S-wave isospin-odd πK scattering length $|a_0^-|$

$$\tau = (3.8^{+3.3}_{-2.0}|_{stat}\ {}^{1.0}_{-0.6}|_{syst})\ fs = (3.8^{+3.5}_{-2.1}|_{tot})\ fs$$

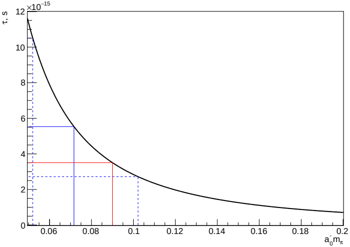
$$|a_0^-|M_\pi = 0.087^{+0.043}_{-0.024}$$

πK atom lifetime estimation

Analysis with Q.



Likelihood function for πK atom lifetime measurement



Relation between measured value πK atom lifetime (τ) and a S-wave isospin-odd πK scattering length $|a_0^-|$

$$\tau = (5.5^{+4.9}_{-2.8}|_{stat} \ {}^{+0.9}_{-0.5}|_{syst})\ fs = (5.5^{+5.0}_{-2.8}|_{tot})\ fs$$

$$|a_0^-|M_\pi = 0.072^{+0.031}_{-0.020}$$

CERN-EP-2017-137
To be sent to Phys. Rev. D

Increasing of statistic with 450 GeV/c proton beam

The yield w of charged particles, and $\pi^+\pi^-$-,π^+K^-- and $K^+\pi^-$- atoms into DIRAC setup acceptance.

θ_{lab}	5.7°	4°	2°	0°
E_p	24 GeV	450 GeV	450 GeV	450 GeV
Yield charged particles				
W_{ch}	0.022	0.14	0.50	2.9
W_{ch}^N	1	6.4	22.7	132
Yield of $\pi^+\pi^-$ atoms				
$W_A \times 10^9$	1.94	34.	69.	89.
W_A^N	1.	17.3	35.4	45.9
$(W_A/W_{ch})^N$	1.	2.4	1.2	0.27
Yield of π^+K^- atoms				
$W_A \times 10^9$	0.217	8.1	16.3	23
W_A^N	1.	37.5	75.	106.
$(W_A/W_{ch})^N$	1.	10.6	5.8	1.2
Yield of $K^+\pi^-$ atoms				
$W_A \times 10^9$	0.52	8.5	19.	30.
W_A^N	1.	16.4	37.6	57.4
$(W_A/W_{ch})^N$	1.	4.9	3.0	0.66

Accuracy of a_0^- measurement with 450 GeV beam

On the base of experimental data, estimation of time needed for measurement a_0^- with statistical accuracy $\delta_{a_0^-}$ for present DIRAC setup and beam condition (Nickel target only); Mod1 is for DIRAC setup at $E_p = 450$ GeV beam (small modification due to another geometry of secondary particle beam); Mod2 is for essentially modified DIRAC setup at 450 GeV beam with higher intensity (I_B). It is assumed that at 450 GeV beam setup would obtain 3000 spills (4.5s) per day.

Setup	E_p GeV	I_b p/s	θ_{lab}	Solid angle sr	Beam time s	Run time months	$\delta_{a_0^-}$ %
Present	24	$2.7 \cdot 10^{11}$	5.7	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{6}$	14.5	43.
Mod1	450	$1.0 \cdot 10^{11}$	4.0	$0.6 \cdot 10^{-3}$	$5.5 \cdot 10^{6}$	13.6	5.
Mod2	450	$1.0 \cdot 10^{12}$	4.0	$0.6 \cdot 10^{-3}$	$6.5 \cdot 10^{5}$	1.6	5.

Expected statistic with 450 GeV beam

- Expected statistic of πK atomic pairs: $n_A \approx 13000$.
- Statistical accuracy of πK scattering length difference: $\sim 5\%$.
- Expected systematic error: $\sim 2\%$.
- Expected statistic of $\pi^+\pi^-$ atomic pairs: $n_A \approx 400000$.
- Statistical accuracy of $\pi^+\pi$ scattering length difference : $\sim 0.7\%$.
- Expected systematic error: $\sim 2\%$.

These result have been presented on Physics Beyond Colliders Workshop.
Work under LOI for experiment at 450 Gev proton beam is started.

Conclusion

- In the experiment DIRAC at CERN, the $K^+\pi^-$ and π^+K^- atoms have been observed with reliable statistics. The analysis distributions over Q yields $349 \pm 62(tot)$ atomic pairs (5.6 σ). Analysis distributions over $|Q_L|$, Q_T yields 314 ± 60 events (5.2 σ).

- The breakup probabilities for each atom type and each target are determined. By means of these probabilities, the lifetime of the πK atom in the ground state is evaluated to be:

$$\tau_{\text{tot}} = (5.5^{+5.0}_{-2.8}\big|_{\text{tot}}) \cdot 10^{-15}\text{s}\,,$$

  and the S-wave isospin-odd πK scattering length deduced: $\left|a_0^-\right| = \frac{1}{3}\left|a_{1/2} - a_{3/2}\right| = (0.072^{+0.031}_{-0.020}\big|_{\text{tot}})M_\pi^{-1}\,.$

- Simulation, based on results of experiment DIRAC, shoes that a S-wave isospin-odd πK scattering length $|a_0^-|$ could be measured with accuracy 5% in a reasonable time, using 450 GeV proton beam.

Thank you for your attention!

Supplementary slides

Experimental conditions

Primary proton beam	$24\ GeV/c$
Beam intensity	$(10.5 \div 12) \cdot 10^{10}\ proton/spill$
Single count of one IH plane	$(5 \div 6) \cdot 10^{6}\ particle/spill$
Spill duration	$450\ ms$

Ni target		
Purity	99.98%	
Target thickness (year)	$98 \pm 1\ \mu m$ (2008)	$108 \pm 1\ \mu m$ $(2009-2010)$
Radiation thickness	$6.7 \cdot 10^{-3}\ X_0$	$7.4 \cdot 10^{-3}\ X_0$
Probability of inelastic proton interaction	$6.4 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$

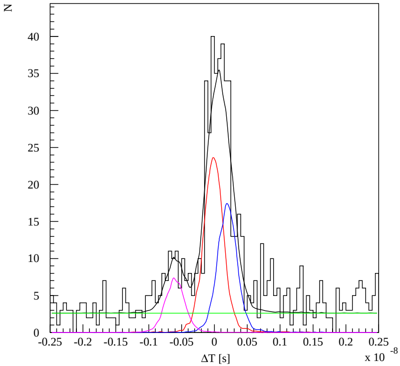
Experimental conditions

Secondary particles channel (relative to the proton beam)	5.7^o
Angular divergence in vertical and horizontal planes	$\pm 1^o$
Solid angle	$1.2 \cdot 10^{-3}\ sr$
Dipole magnet	$B_{max} = 1.65\ T,\ BL = 2.3\ Tm$

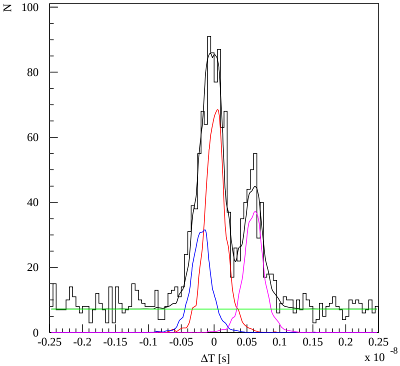
Time resolution [ps]								
	VH	IH				SFD		
plane	1	1	2	3	4	X	Y	W
2008	112	713	728	718	798	379	508	518
2010	113	907	987	997	1037	382	517	527

Admixtures in distributions of $\pi^+ K^-$ and $\pi^- K^+$ pairs

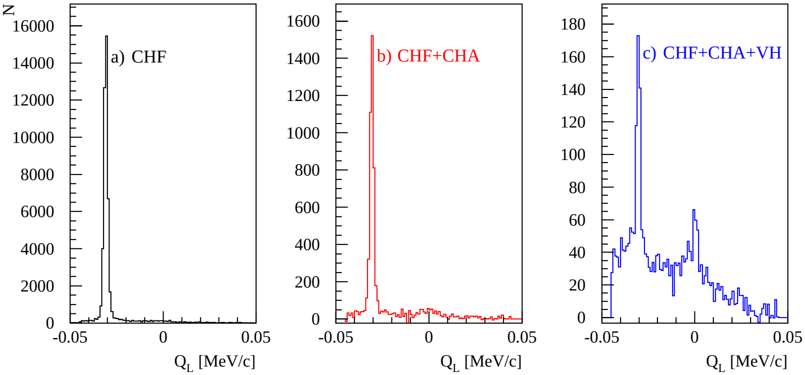
$\pi^+ K^-$



$\pi^- K^+$



Background suppression for $K^+\pi^-$



Background suppression for $\pi^+ K^-$