Status Report of the DIRAC Experiment - PS 212

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SPSC – 20 October 2015

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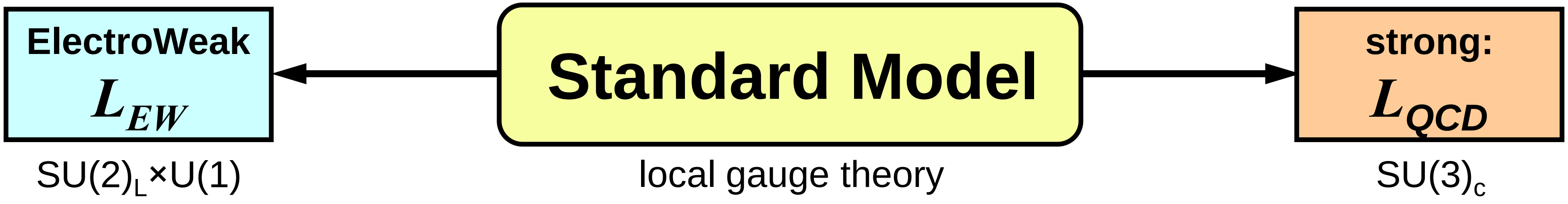
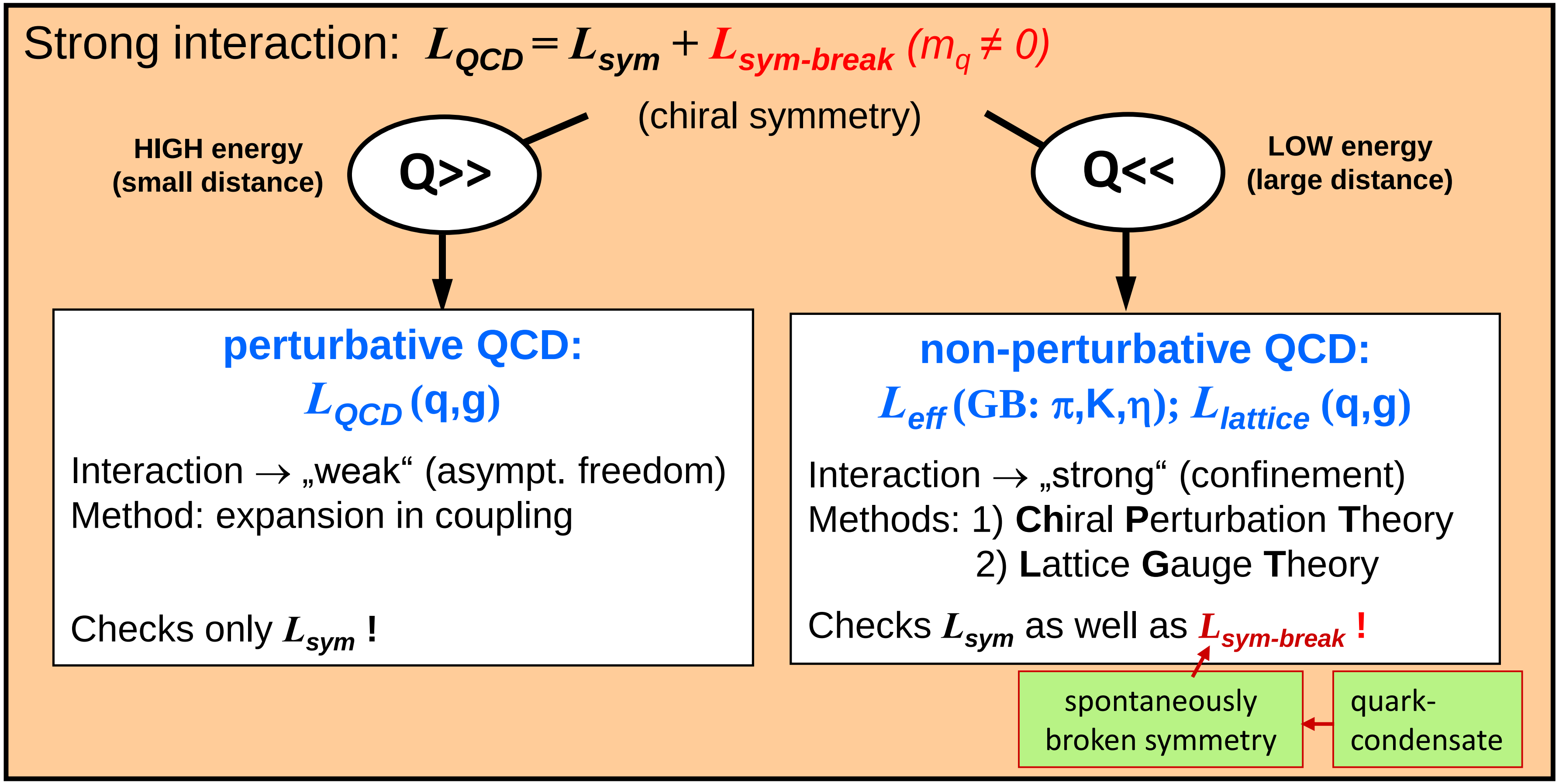
Theoretical motivation



ElectroWeak
L_{EW}
$SU(2)_L \times U(1)$

Standard Model
local gauge theory

strong:
L_{QCD}
$SU(3)_c$



Strong interaction: $L_{QCD} = L_{sym} + L_{sym\text{-}break}\ (m_q \neq 0)$

(chiral symmetry)

HIGH energy
(small distance)

Q>>

LOW energy
(large distance)

Q<<

perturbative QCD:
L_{QCD} **(q,g)**

Interaction → „weak“ (asympt. freedom)
Method: expansion in coupling

Checks only L_{sym} **!**

non-perturbative QCD:
L_{eff} (GB: π,K,η); $L_{lattice}$ **(q,g)**

Interaction → „strong“ (confinement)
Methods: 1) **Ch**iral **P**erturbation **T**heory
2) **L**attice **G**auge **T**heory

Checks L_{sym} as well as $L_{sym\text{-}break}$ **!**

spontaneously broken symmetry

quark-condensate

Theoretical motivation

ππ scattering length

In ChPT the effective Lagrangian, which describes the ππ interaction, is an expansion in terms:

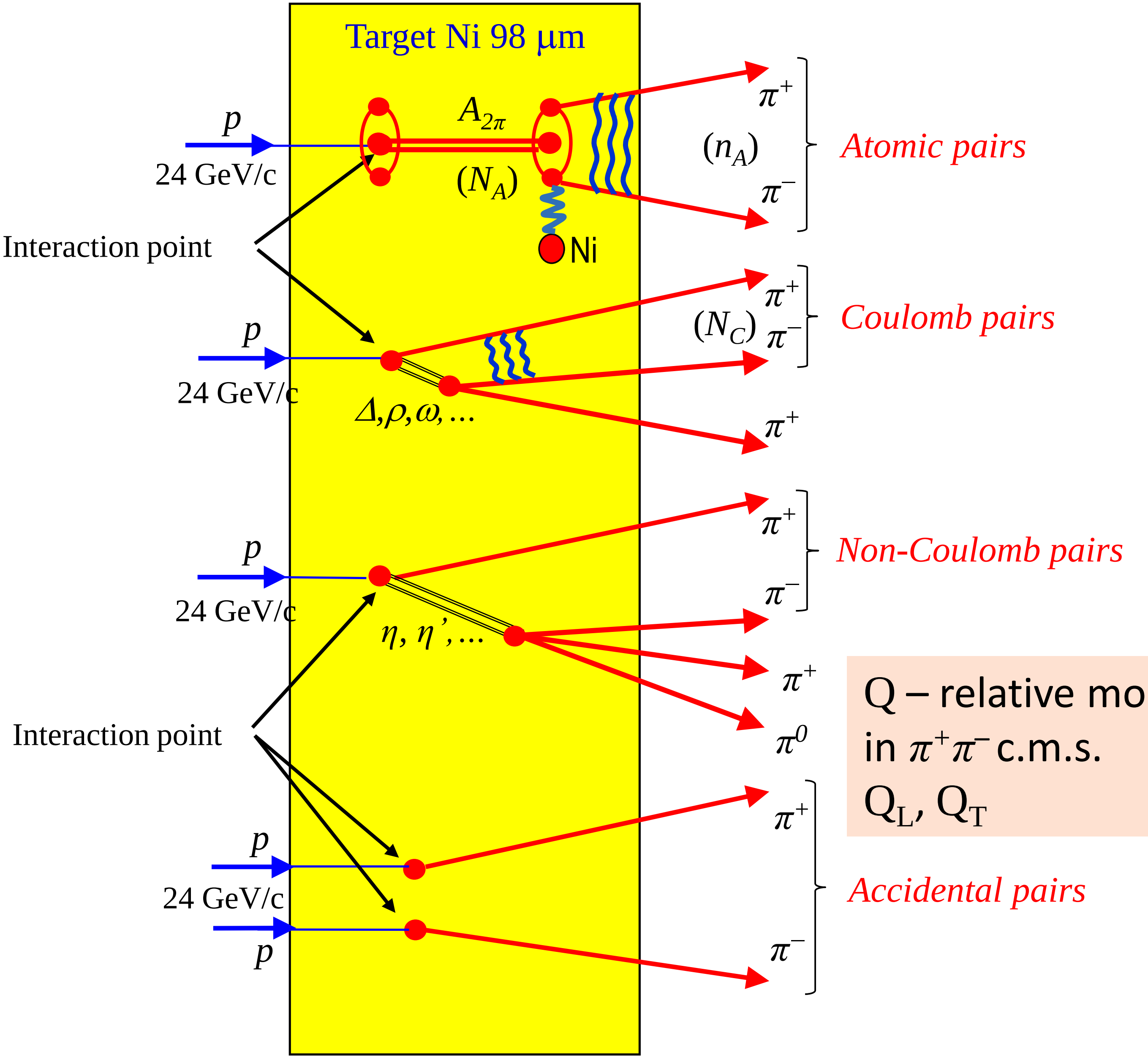
$$L_{eff} = \underset{\text{(tree)}}{L^{(2)}} + \underset{\text{(1-loop)}}{L^{(4)}} + \underset{\text{(2-loop)}}{L^{(6)}} + \cdots$$

G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B603 (2001) 125, using ChPT (2-loop) & Roy equations:

$$\left.\begin{aligned} a_0 &= 0.220 \pm 2.3\% \\ a_2 &= -0.0444 \pm 2.3\% \end{aligned}\right\} \quad a_0 - a_2 = 0.265 \pm 1.5\%$$

These results precision depends on the low-energy constants (LEC) $\bar{l}_3$ and $\bar{l}_4$:
Lattice gauge calculations from **2006** provided values for these $\bar{l}_3$ and $\bar{l}_4$ which allows to improve the scattering length precision.
Lattice calculation are giving also the scattering length values.

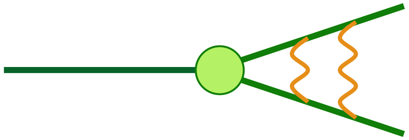
Method of $A_{2\pi}$ observation and measurement



Q – relative momentum
in $\pi^+\pi^-$ c.m.s.
Q_L, Q_T

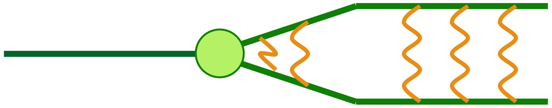
Coulomb pairs and atoms

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

Coulomb pair



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

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:

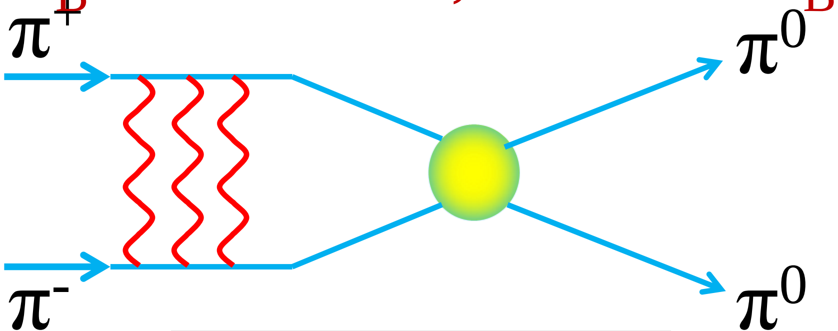
$$N_A = K(Q_0)\,N_C(Q \le Q_0), \quad \frac{\delta K(Q_0)}{K(Q_0)} \le 10^{-2}$$

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

$\pi^+\pi^-$ 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:

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

$$\boxed{\frac{\Delta R}{R} = 1.2\times10^{-2}}$$

$$\boxed{\tau_{1s} = (2.9 \pm 0.1)\times10^{-15}s}$$

$$\boxed{\Gamma_{ns\to2\pi^0} = R\left|\psi_{ns}(0)\right|^2\left|a_0 - a_2\right|^2}$$

$$\boxed{\tau_{2p} = 1.17\times10^{-11}s}$$

a_0 and a_2 are the $\pi\pi$ *S*-wave scattering lengths for isospin I=0 and I=2.

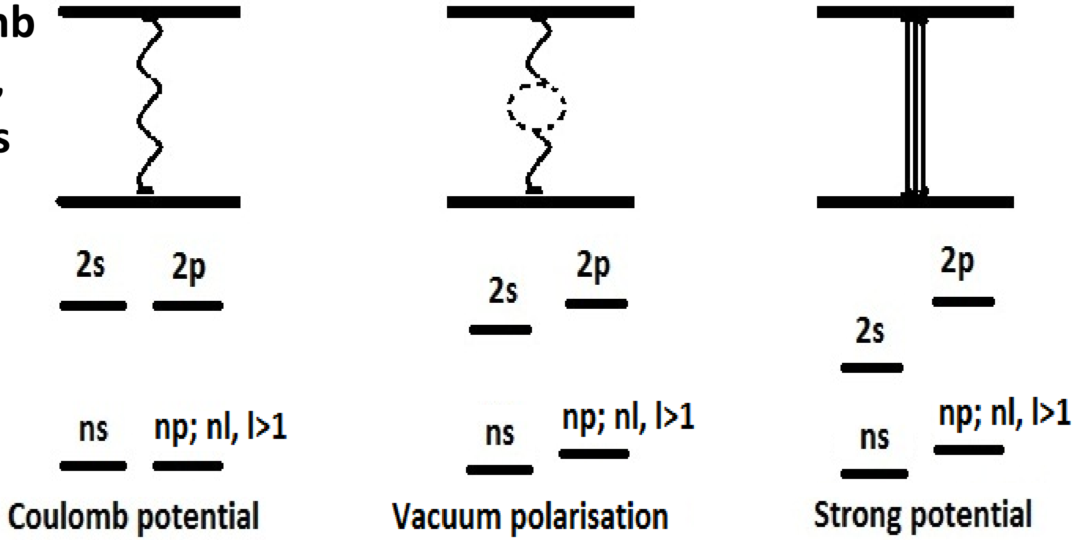
$$\psi_{nl}(0)\begin{cases} \neq 0 \text{ for } \quad l = 0 & A_{2\pi}(1s, 2s,\ldots, ns) \longrightarrow \pi^0\pi^0 \\ = 0 \text{ for } \quad l \neq 0 & A_{2\pi}(np) \xrightarrow{\gamma} A_{2\pi}(1s, 2s,\ldots(n-1)s) \longrightarrow \pi^0\pi^0 \end{cases}$$

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* ⟶ $\pi^0\pi^0$.

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 ≈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)

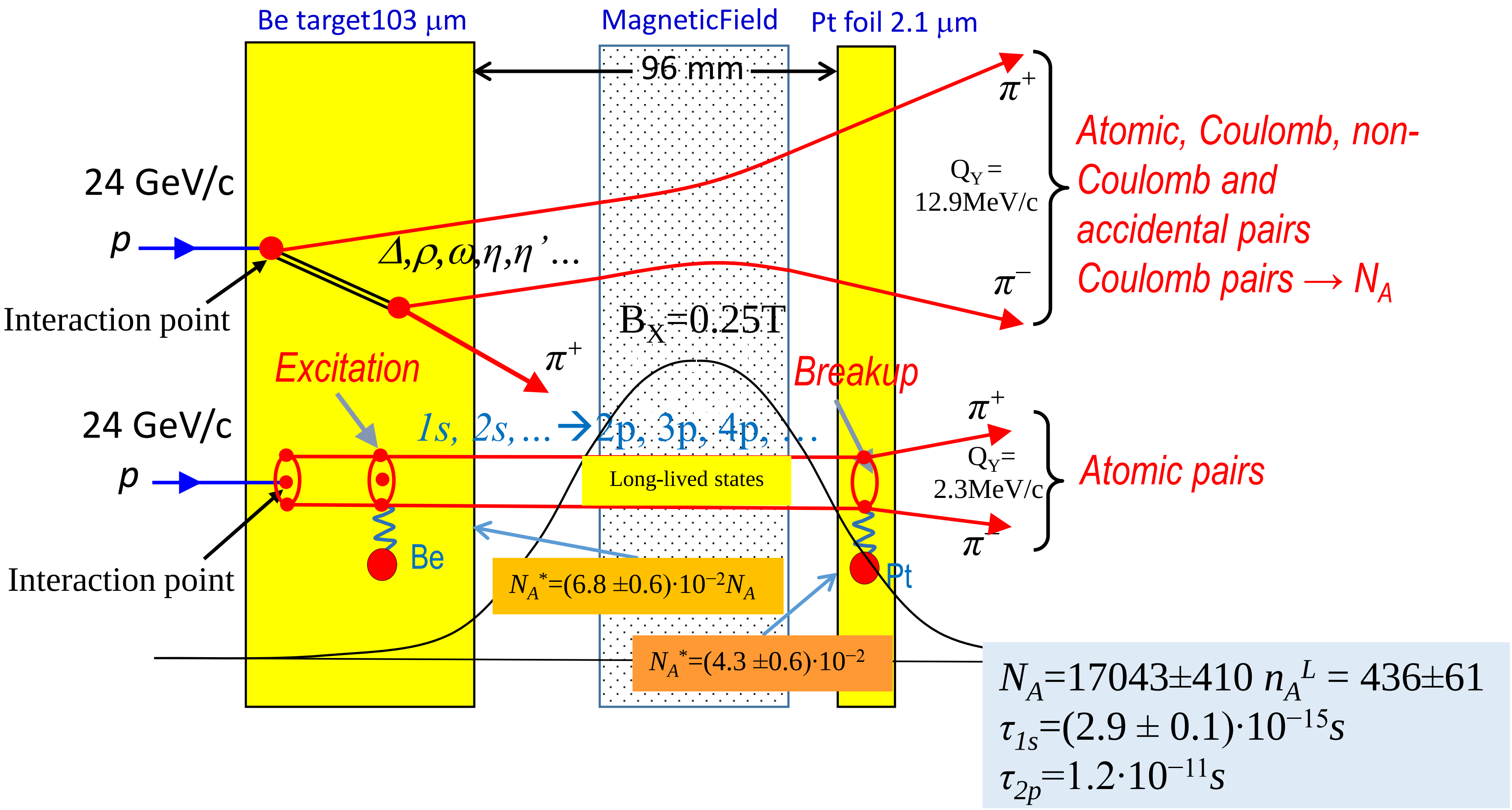
$$\Delta^{str}_{ns-np} = -\frac{\Delta^{str}_{2s-2p}}{n^3} \cdot 8$$

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

Long-lived $\pi^+\pi^-$ atoms (cont.)

1. Paper “First observation of long-lived $\pi^+\pi^-$ atoms” accepted for publication in Physics Letters B.
   The number of atomic pairs from long-lived $\pi^+\pi^-$ atoms breakup in the Pt foil is:
   $$n_A=436\pm57|_{stat}\pm23|_{syst}=436\pm61|_{tot}\ (7.1\ \sigma).$$
2. The preliminary value of the long-lived $\pi^+\pi^-$ atom lifetime will be presented in April 2016.
3. In 2016, we will study the possibility to evaluate a lower limit for the Lamb shift of $\pi^+\pi^-$ atom based on the existing data.
4. In 2016 we intend to process the 2011 data.

Method for observing long-lived $\pi^+\pi^-$ atom with breakup Pt foil



$N_A=17043\pm 410$ $n_A^L = 436\pm 61$

$\tau_{1s}=(2.9 \pm 0.1)\cdot 10^{-15}s$

$\tau_{2p}=1.2\cdot 10^{-11}s$

n	2	3	4	5	≥ 2
$\varepsilon_n(\mathrm{Be})\times 10^2$	2.48 ± O(10^{-3})	1.54 ± 0.01	0.86 ± 0.03	0.56 ± 0.06	6.8 ± 0.6
$\varepsilon_n(\mathrm{Pt})\times 10^2$	0.52 ± O(10^{-4})	1.10 ± O(10^{-3})	0.78 ± 0.03	0.54 ± 0.06	4.3 ± 0.6
P_{br}	0.72 ± 0.03	0.89 ± 0.03	0.94 ± 0.02	0.96 ± 0.02	0.97 ± 0.02

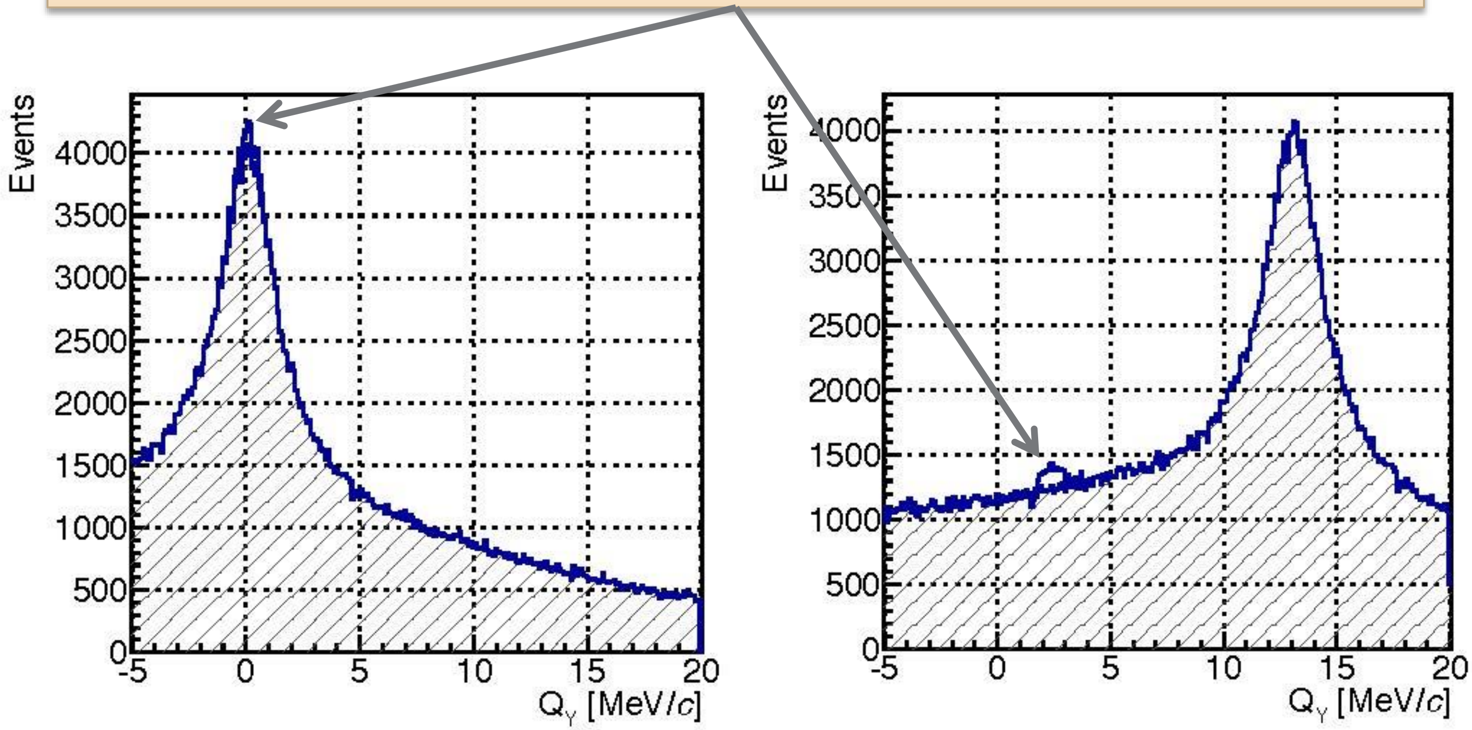
The background reduction with magnetic field for long-lived $A_{2\pi}$ observation

V. Yazkov

Q_y distribution of “atomic pairs” (signal) above the background of $\pi^+\pi^-$ Coulomb pairs produced in Beryllium target, without (left) and with (right) magnet used in 2012 run.

Selected events with the cut: $\sqrt{Q_X^2 + Q_L^2} < 2MeV/c$

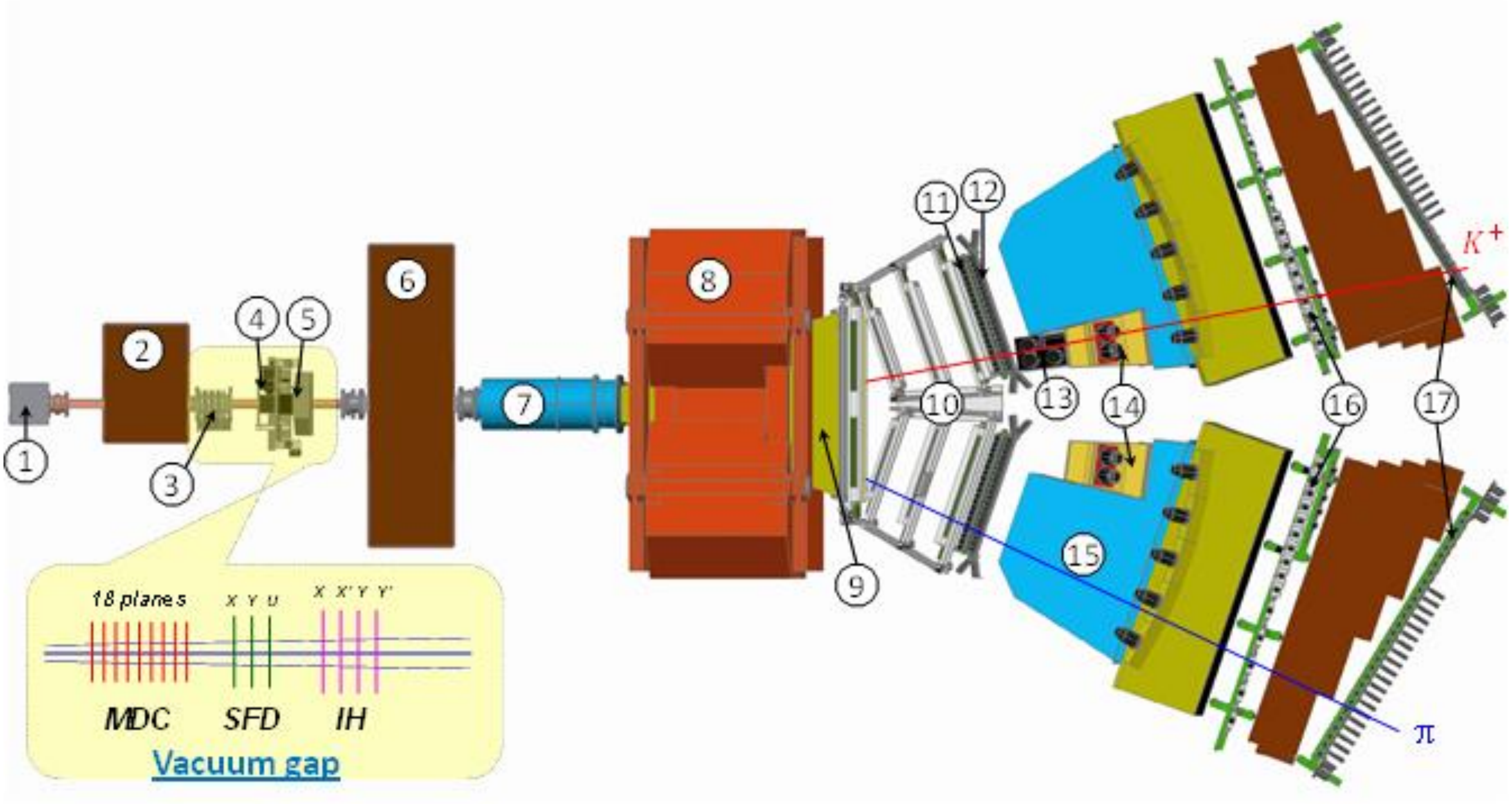
Expected signal (atomic pairs) from broken up long-lived $\pi^+\pi^-$ atoms



Simulation without magnet

Simulation with magnet

DIRAC upgraded Experimental setup



1 Target station ; 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

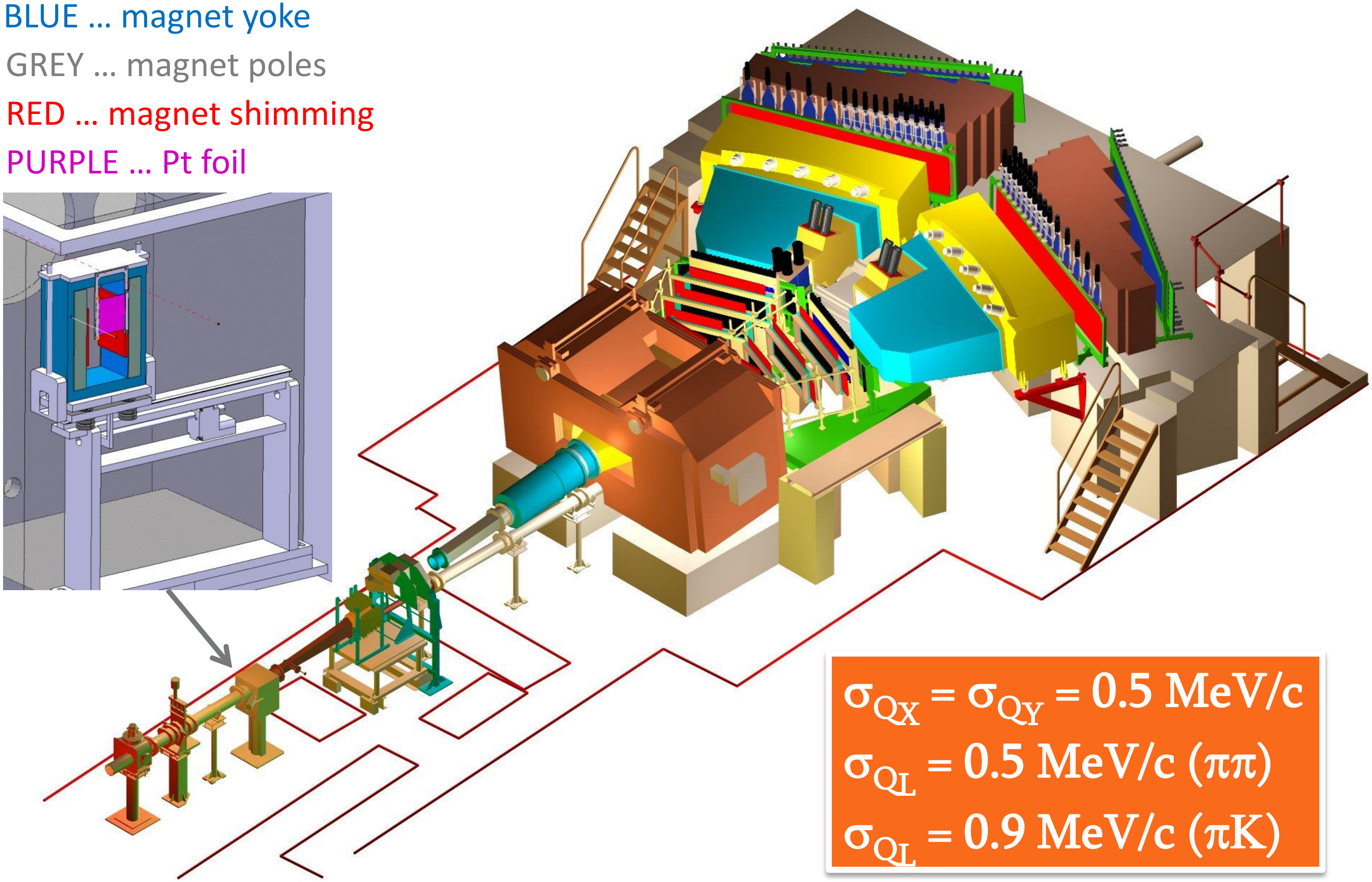
DIRAC upgraded Experimental setup

BLUE … magnet yoke

GREY … magnet poles

RED … magnet shimming

PURPLE … Pt foil

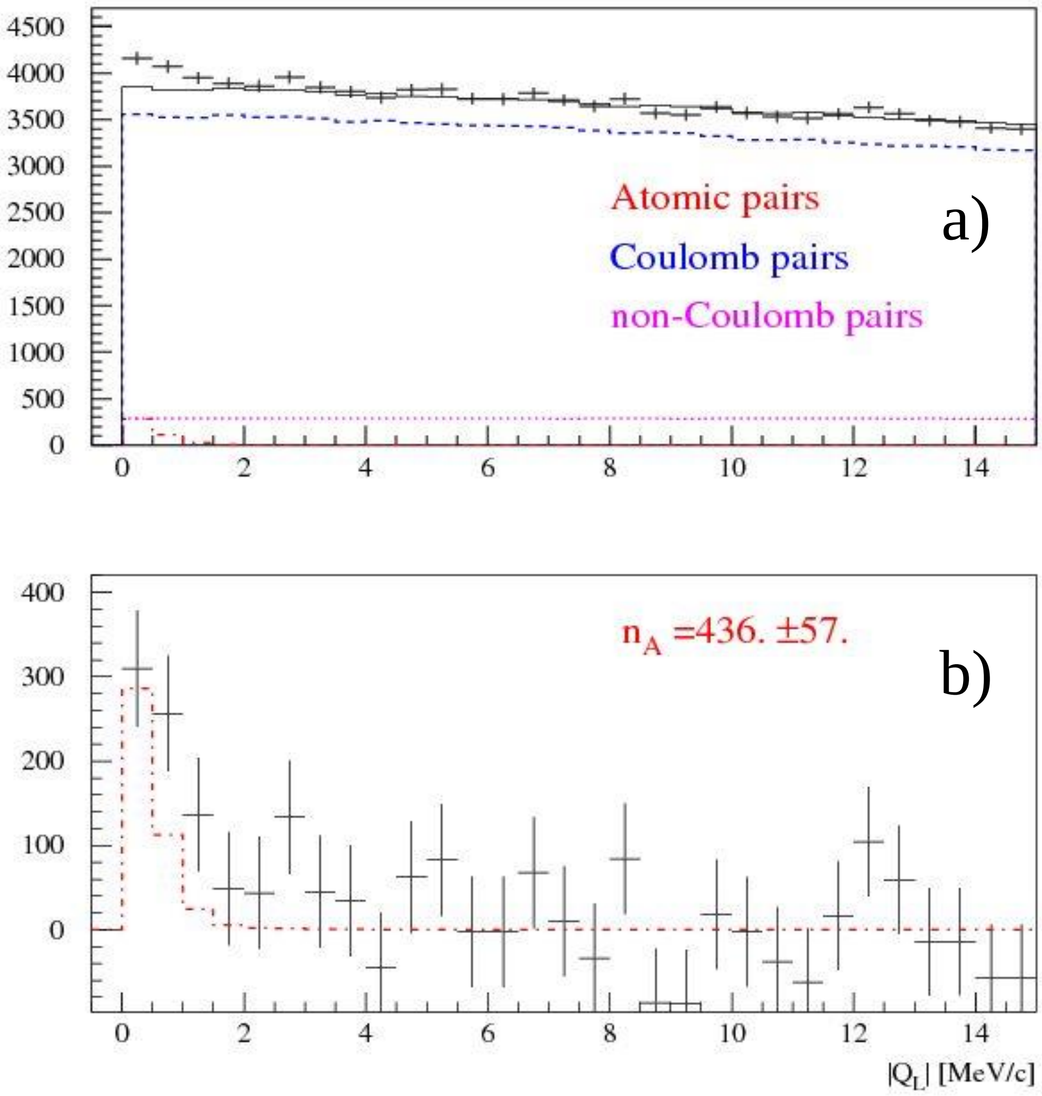


$\sigma_{Q_X} = \sigma_{Q_Y} = 0.5$ MeV/c

$\sigma_{Q_L} = 0.5$ MeV/c ($\pi\pi$)

$\sigma_{Q_L} = 0.9$ MeV/c (πK)

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.

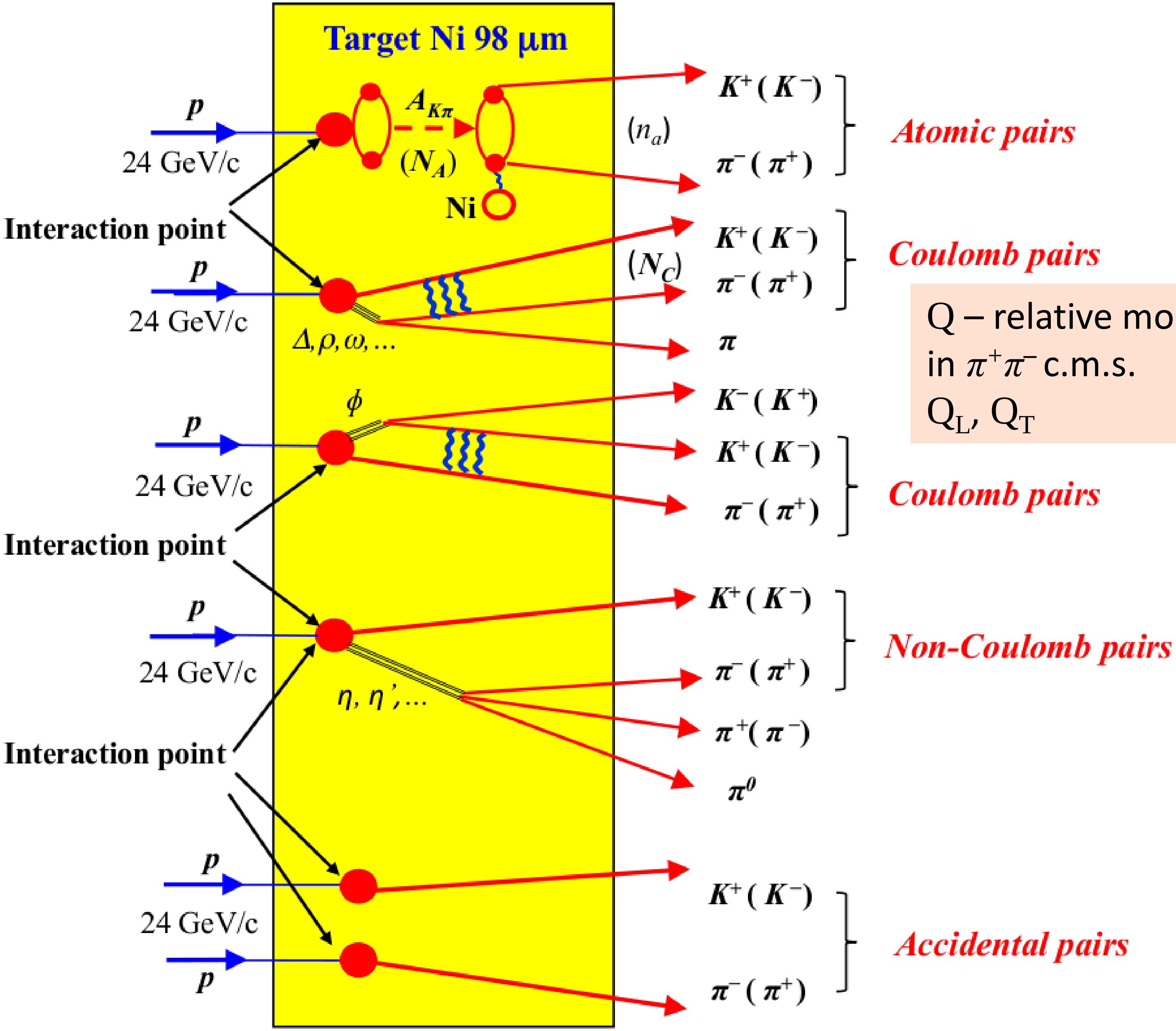
πK *scattering*

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

The measurement of the s-wave πK scattering lengths would test 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).

This is the principal difference between $\pi\pi$ and πK scattering!

Method of Kπ atom observation and investigation



Q – relative momentum
in $\pi^+\pi^-$ c.m.s.
Q_L, Q_T

π^+K^- and π^-K^+ atoms

Published paper: ***Physics Letters B* 735 (2014) 288**

"First **πK** atom lifetime and **πK** scattering length measurements"

In this paper, characteristic πK pairs from πK atom breakup in the Ni target have been observed, as many as

178±49 **(3.6σ)** πK atomic pairs as well as
653±42 produced πK atoms

Based on these results, the first measurement of the πK atom lifetime has been deduced

$$\tau = \left(2.5^{+3.0}_{-1.8}\right)\, fs$$

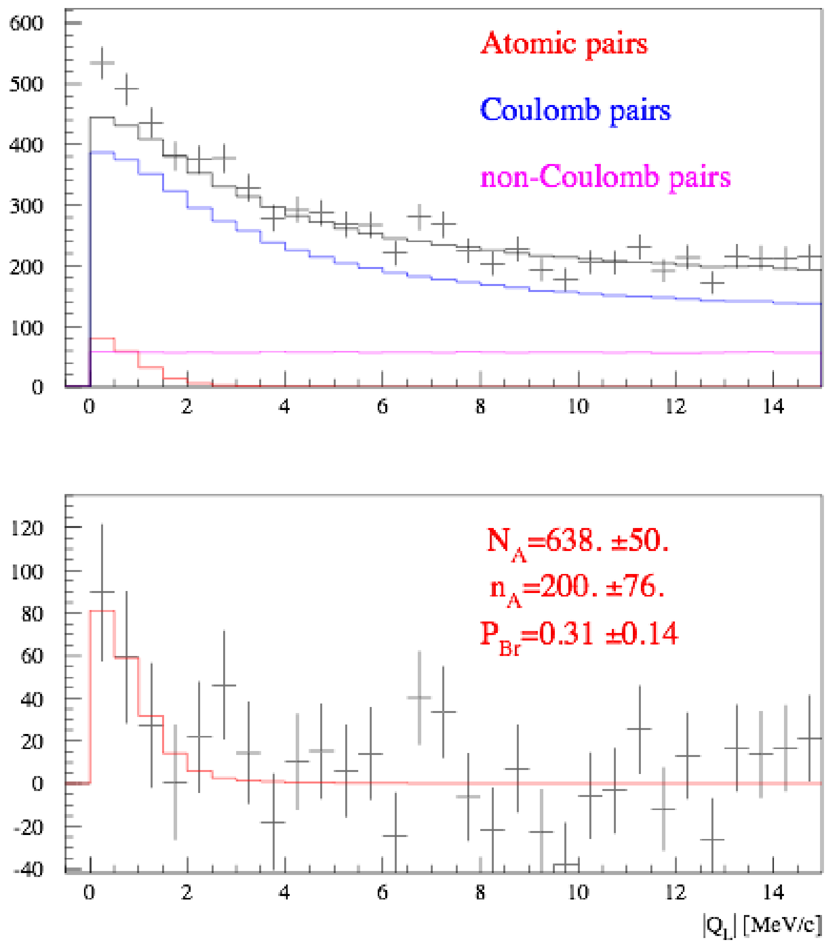
and the first measurement of the S-wave isospin-odd πK scattering length

$$\left|a_0^-\right| = \frac{1}{3}\left|a_{1/2} - a_{3/2}\right| = \left(0.11^{+0.09}_{-0.04}\right) M_\pi^{-1}$$

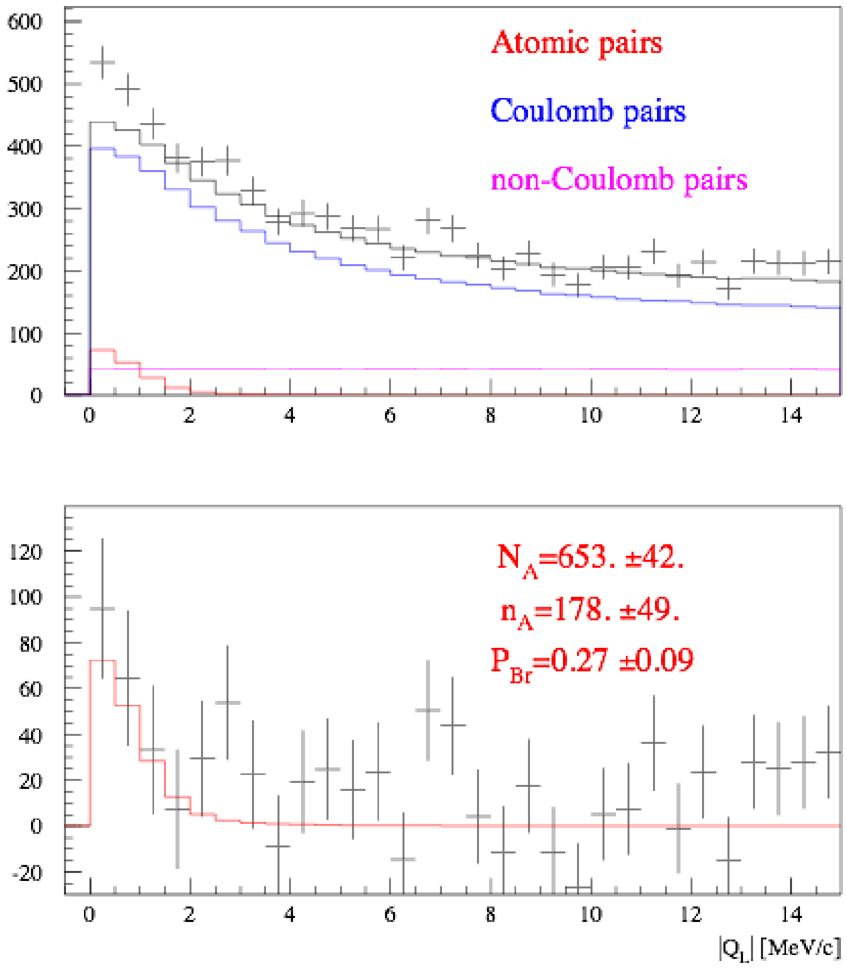
The result was obtained using 2/3 of the existing statistics with low and medium background in the scintillation fiber detector.

π^+K^- and π^-K^+ - run 2008-2010

Run 2008-2010, statistics with low and medium background (2/3 of all statistics).

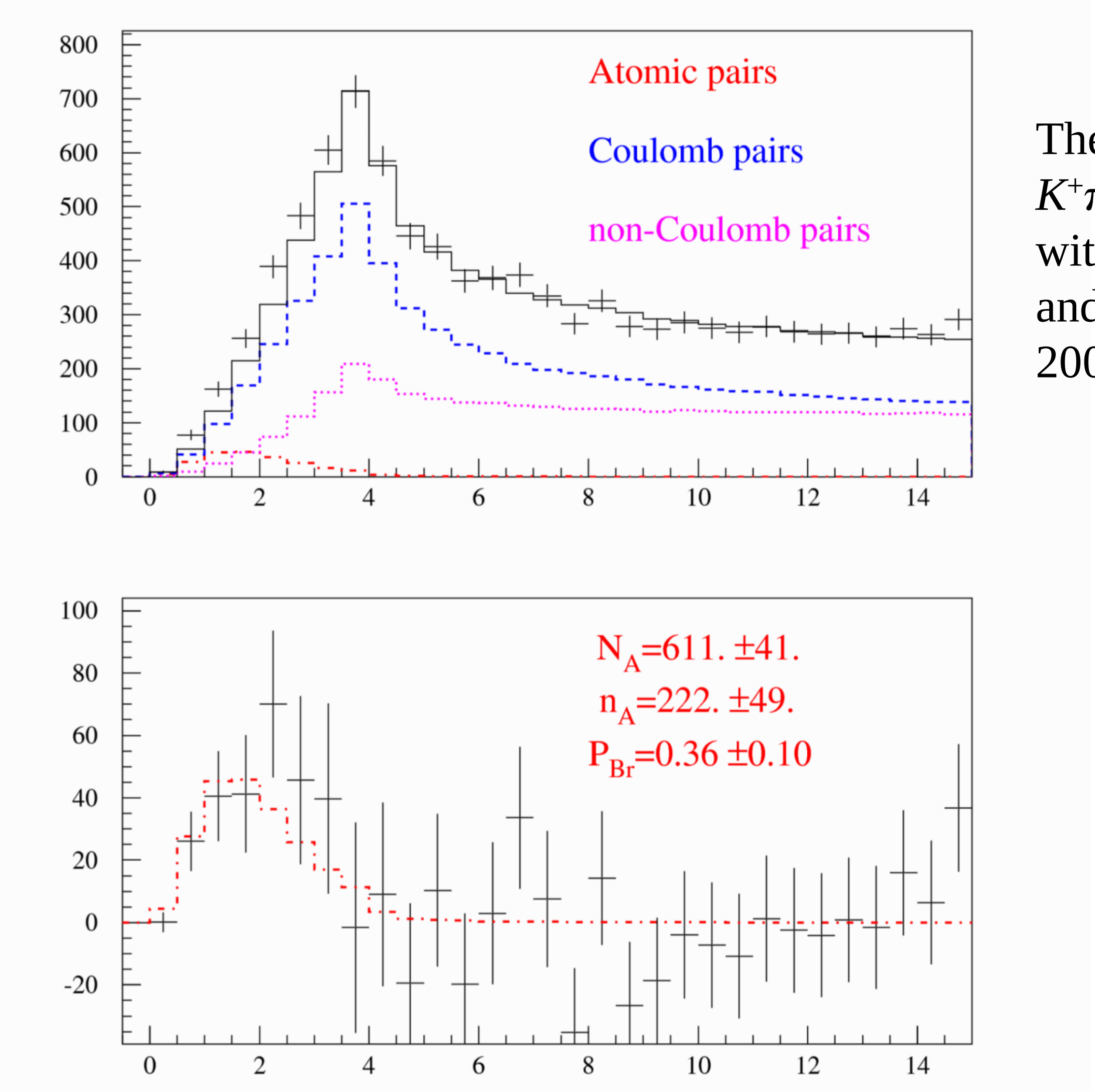


$|Q_L|$ distribution
analysis on $|Q_L|$ for Q_T < 4 MeV/c



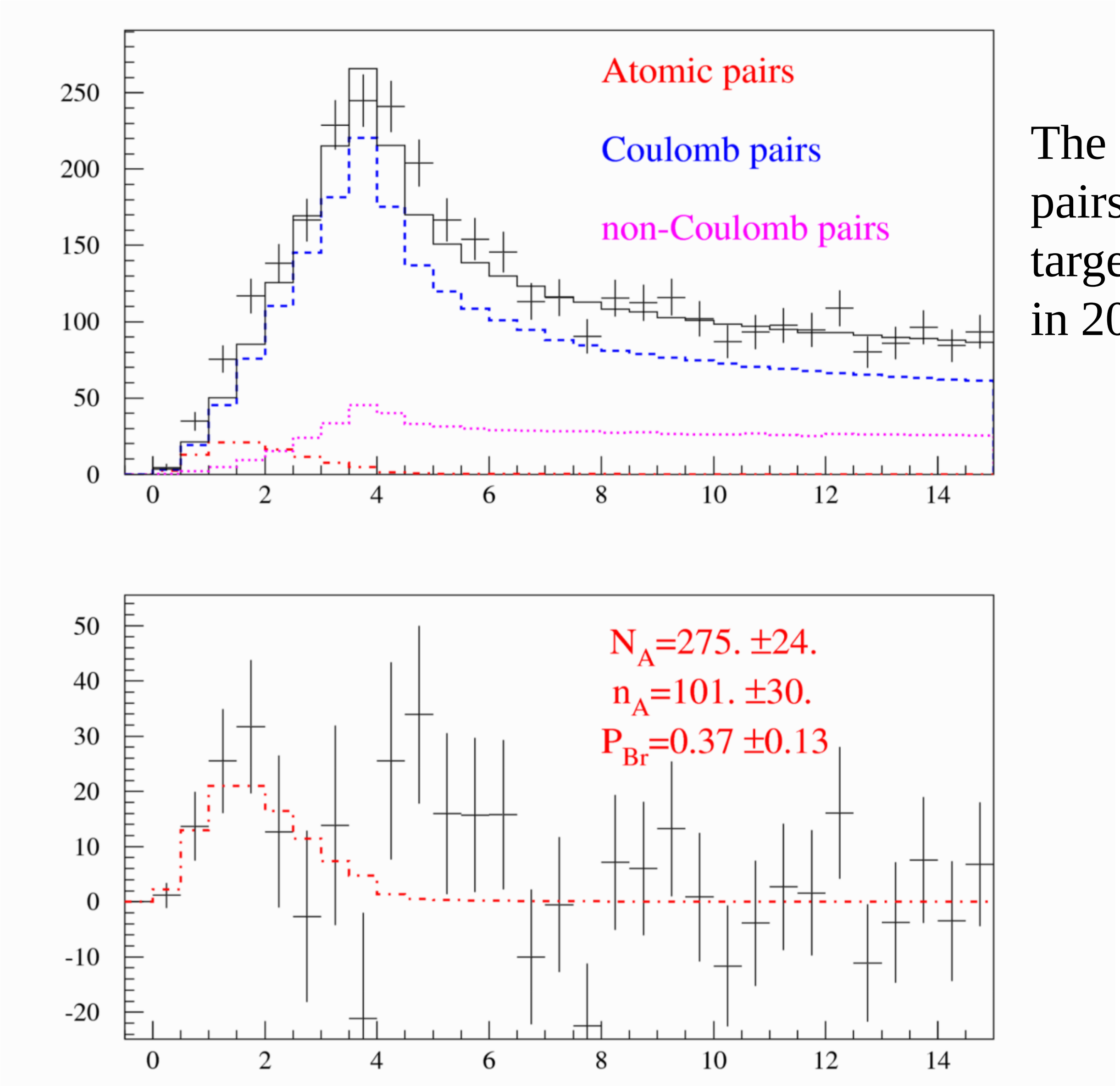
$|Q_L|$ distribution
analysis on $|Q_L|$ and Q_T for Q_T < 4 MeV/c

Experimental Q distributions of $K^+\pi^-$ pairs



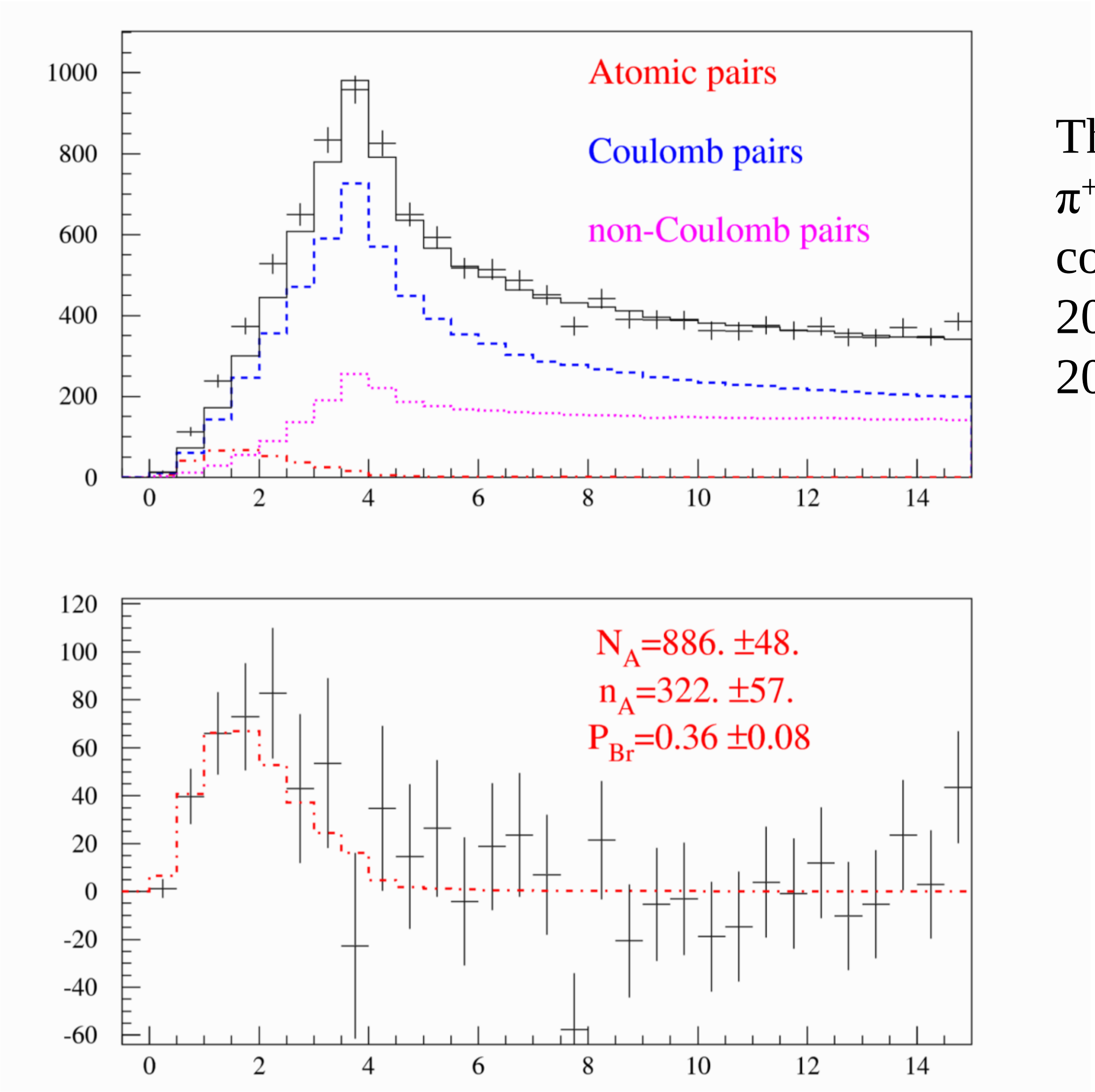
The *Q* distribution of the $K^+\pi^-$ pairs collected with Platinum target in 2007 and Nickel target in 2008, 2009, 2010.

Experimental Q distributions of π^+K^- pairs



The Q distribution of the π^+K^- pairs collected with Platinum target in 2007 and Nickel target in 2008, 2009, 2010.

Experimental *Q* distributions of $K^+\pi^-$ and π^+K^- pairs



The *Q* distribution of the $K^+\pi^-$ and π^+K^- pairs(2/3 of existing statistic) collected with Platinum target in 2007 and Nickel target in 2008, 2009, 2010.

Experimental number of atomic $K^+\pi^-$, π^+K^- pairs

Number of “atomic pairs” (n_A) with statistical error and ratio signal-to-error (r_A) for πK atoms collected with **Nickel** target in 2008, 2009 and 2010. Selection criteria: $|Q_L| < 20$ MeV/c, $Q_T <$ 4 MeV/c.

Variable	$n_A^{K+\pi-}$ (r_A)	$n_A^{\pi+K-}$ (r_A)	$n_A^{\pi K}$ (r_A)
Q	175. ± 46. (3.8)	85. ± 29. (3.0)	260. ± 54. (4.8)
$\|Q_L\|$	93. ± 70. (1.3)	53. ± 42. (1.3)	146. ± 82. (1.8)
$\|Q_L\|,Q_T$	158. ± 44. (3.6)	72. ± 28. (2.6)	230. ± 53. (4.4)

Number of “atomic pairs” (n_A) with statistical error and ratio signal-to-error (r_A) for πK atoms collected with **Platinum** target in 2007. Selection criteria: $|Q_L| < 20$ MeV/c, $Q_T < 4$ MeV/c.

Variable	$n_A^{K+\pi-}$ (r_A)	$n_A^{\pi+K-}$ (r_A)	$n_A^{\pi K}$ (r_A)
Q	46. ± 17. (2.8)	16. ± 10. (1.5)	62. ± 19. (3.2)
$\|Q_L\|$	55. ± 25. (2.2)	16. ± 14. (1.1)	71. ± 29. (2.5)
$\|Q_L\|,Q_T$	55. ± 16. (3.5)	10. ± 10. (1.0)	65. ± 18. (3.5)

Number of “atomic pairs” (n_A) with statistical error and ratio signal-to-error (r_A) for πK atoms collected with **Platinum and Nickel** target in 2007, 2008, 2009 and 2010. Selection criteria:$|Q_L| < 20$ MeV/c, Q_T<4 MeV/c

Variable	$n_A^{K+\pi-}$ (r_A)	$n_A^{\pi+K-}$$(r_A)$)	$n_A^{\pi K}$$(r_A)$
Q	222. ± 48. (4.6)	101. ± 30. (3.3)	322. ± 57. (5.6)
$\|Q_L\|$	148. ± 75. (2.0)	69. ± 45. (1.5)	216. ± 87. (2.5)
$\|Q_L\|,Q_T$	213. ± 47. (4.5)	82. ± 30. (2.7)	295. ± 56. (5.3)

π^+K^- and π^-K^+ atoms Data Process improvement

- The procedure of matching the downstream tracks with SFD hits will be modified accounting a dependence of the expected hits region on particle momenta. The main aim of this procedure is to improve the quality of the statistics with the low and medium background and to process the part of the statistics with high background (1/3 of the total data).

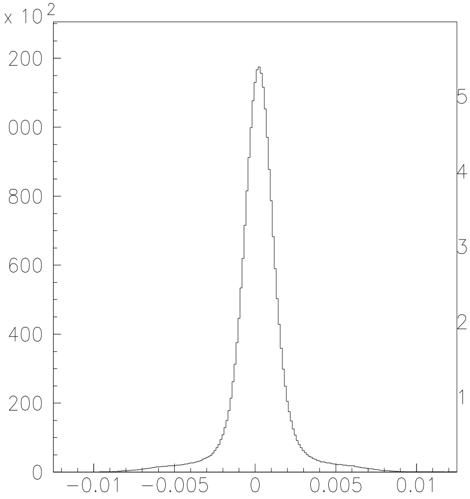
- The preliminary results on $K^+\pi^-$ and $K^-\pi^+$ atoms investigation using all the data available from 2007, 2008, 2009 and 2010 runs and with the improved analysis will be ready in April 2016.

$\pi^+\pi^-$ atom analysis

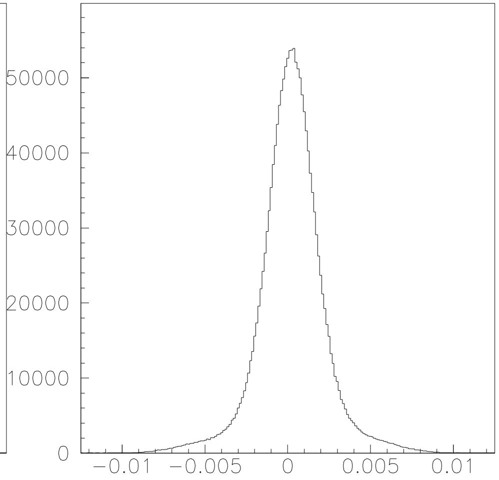
1. At present time the $\pi^+\pi^-$ pairs are using as calibration process for the πK pairs analysis. Preliminary results on the $\pi^+\pi^-$ atom lifetime measurement based on all available data will be ready at the end of 2016.

2. The current systematical error in the $\pi^+\pi^-$ atom lifetime measurement is equal to statistical uncertainty. The main part of systematical error arise due to the multiple scattering in the Ni target. To reduce this error we continue experimental study of the multiple scattering of our targets: Ni: 50, 109 and 150 microns; Be: 100 and 2000 microns; Pt: 2 and 30 microns and Ti: 250 microns.

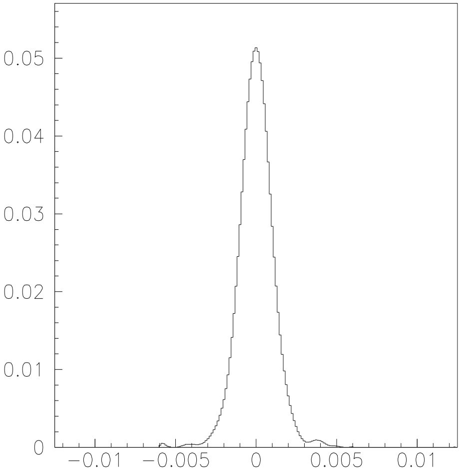
Multiple scattering evaluation



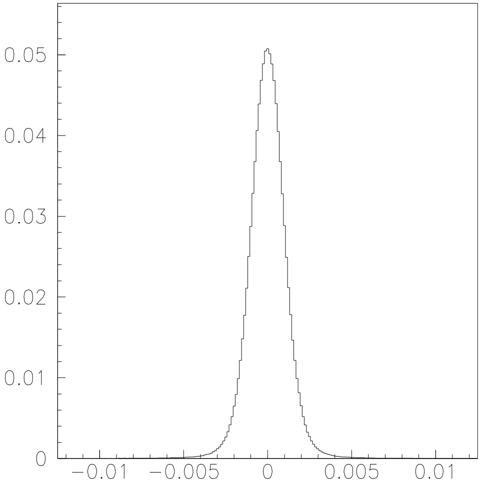
Ni-109 Drift Chamber Resolution



Ni-109 Scatter



Ni-109 Reconstructed Distribution



Ni-109 Multiple Scattering Simulation

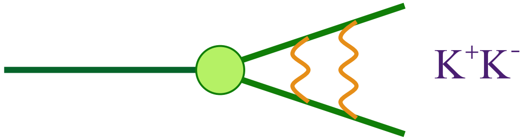
The Ratio RMS(exp)/RMS(Mol) evaluated for intervals

∓1 RMS(Mol), ∓2 RMS(Mol), ∓3 RMS(Mol)

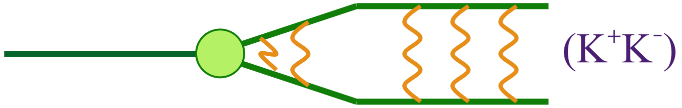
SCATTERER	RMS(Mol)	∓1 RMS (Mol)	∓2 RMS (Mol)	∓3 RMS (Mol)
Ni-50	0.7913E-03	1.01217	0.95509	0.99187
Ni-100	0.1118E-02	0.98192	0.96447	0.95943
Ni-150	0.1369E-02	0.97556	0.96181	0.95436
Ti-250	0.1113E-02	1.00850	0.98617	0.99082
Ni-109	0.1167E-02	0.99661	0.97571	0.95421
Pt-30	0.1361E-02	0.98962	0.95817	0.94733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

K^+K^- Coulomb pairs and K^+K^- atoms

For charged pairs from short-lived sources and with small relative momenta Q , Coulomb final state interaction has to be taken into account.



Coulomb pairs



Atoms

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:

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

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

From K^+K^- pairs$^-$ analysis the Coulomb pair distribution on Q will be obtained, allowing to extract the total number of produced K^+K^- atoms.

K^+K^- atom and its lifetime

The $A_{2\pi}$ 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 ↓

$\tau\ (A_{2K} \rightarrow \pi\pi, \pi\eta)$	**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^- pair analysis and K^+K^- atoms

1. A search for K^+K^- Coulomb pairs in the 1/3 of 2010 data will be performed. The number of K^+K^- atoms, which are produced together with these Coulomb pairs, will be extracted.

2. In the first part of the work we will analyse about 7000 K^+K^- pairs with total lab momenta 2.8 to 6.0 GeV/c, corresponding to 1/3 of the statistics.

- If a signal is observed, Coulomb pairs will also be searched for in the higher momentum range from 6.0 to 9.6 GeV/c (about 2400 pairs).
- The total statistics of K^+K^- pairs produced on Ni and Pt targets is about 100000.

$K^+\pi^-$, $K^-\pi^+$, $\pi^+\pi^-$ and K^+K^- atom production in p-nucleus interaction at proton momentum 24 GeV/c and 450 GeV/c

1. DIRAC note (September 2015) presented simulation of the inclusive production of K^+, K^-, π^+ and π^- in p-nucleus interaction at 24 GeV/c and 450 GeV/c. The simulated results compared with dedicated experimental data.

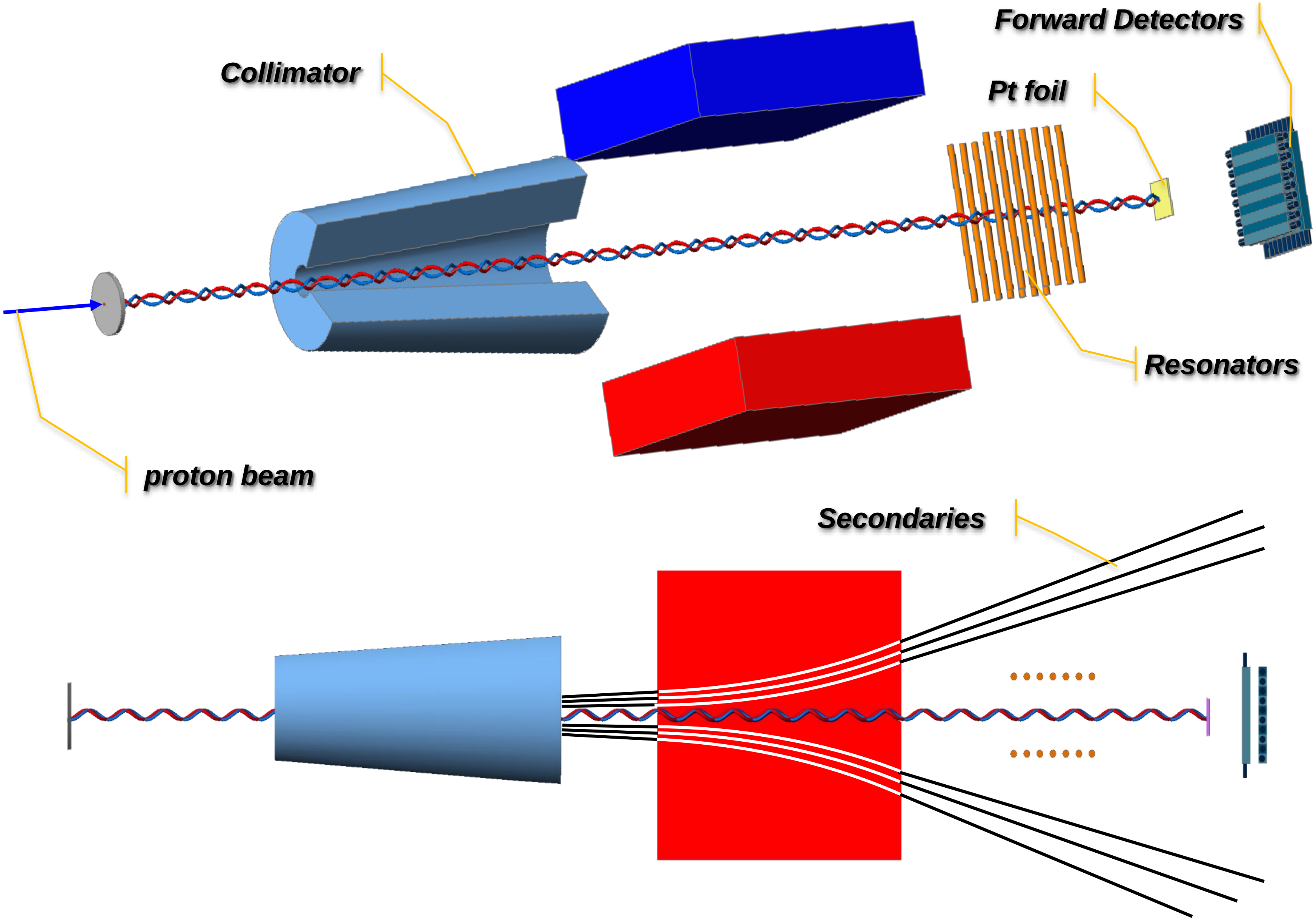
2. The yields of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms in p-nucleus interaction at proton momenta 24 GeV/c and 450 GeV/c are calculated. Minimum values of this yields evaluated with the errors obtained from the experiments.

The yield of $\pi^+\pi^-$, π^+K^- and $K^+\pi^-$ atoms

θ_{lab}	5.7°	4°	2°	0°
E_p	24 GeV/c	450 GeV/c	450 GeV/c	450 GeV
The yield of $\pi^+\pi^-$ atoms				
W_A	$1.25\cdot10^{-9}$	$1.9\cdot10^{-8}$	$3.5\cdot10^{-8}$	$4.5\cdot10^{-8}$
W_A^N	1	15 (9.7±1.5)	28 (17.5±2.8)	36 (22.7±3.6)
$(W_A/W_{ch})^N$	1	2.4 (1.55±0.20)	1.2 (0.77±0.13)	0.27 (0.17±0.03)
The yield of π^+K^- atoms				
W_A	$1.3\cdot10^{-11}$	$8.8\cdot10^{-10}$	$1.7\cdot10^{-9}$	$2.0\cdot10^{-9}$
W_A^N	1	67 (45 ± 8)	131 (87 ± 15)	154 (104 ± 18)
$(W_A/W_{ch})^N$	1	10.6 (7.0±1.0)	5.8 (3.9±0.7)	1.2 (0.79±0.13)
The yield of $K^+\pi^-$ atoms				
W_A	$3.1\cdot10^{-11}$	$9.7\cdot10^{-10}$	$2.1\cdot10^{-9}$	$2.7\cdot10^{-9}$
W_A^N	1	31 (18.6±4.1)	68 (41±9)	87 (52±11)
$(W_A/W_{ch})^N$	1.	4.9 (2.9±0.6)	3.0 (1.9±0.4)	0.66 (0.40±0.09)

SPS duty cycle add factor 5 relative to PS

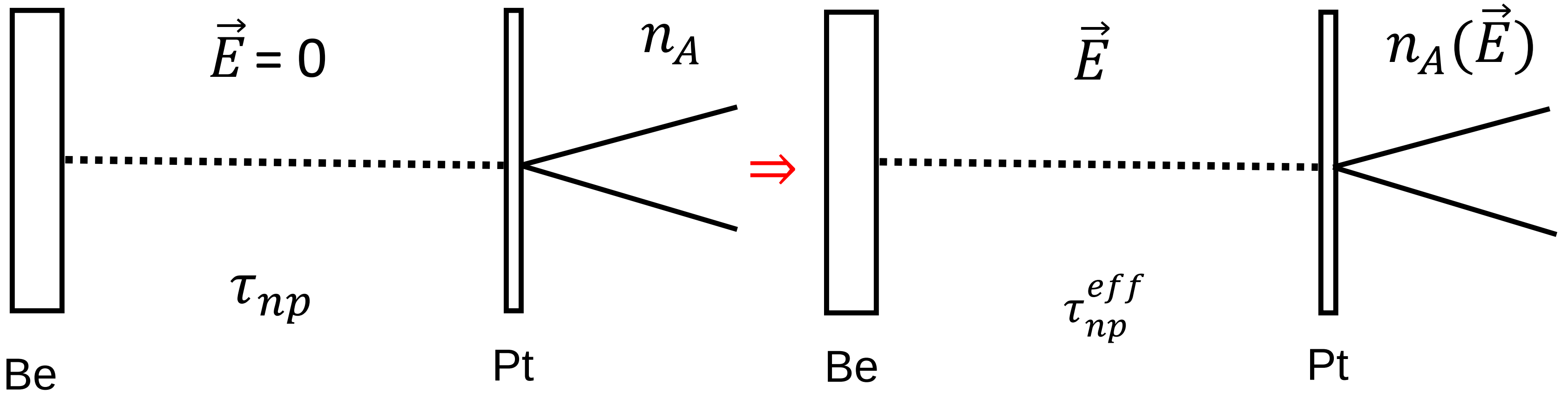
DIRAC future Experimental setup



Energy splitting measurement

In the static electric field there will be Stark mixing between the ns and the np wave functions.

$$\tau_{np} \quad \Rightarrow \quad \tau_{np}^{eff}\left(|\vec{E}|, \Delta E_{ns-np}\right) < \tau_{np}$$

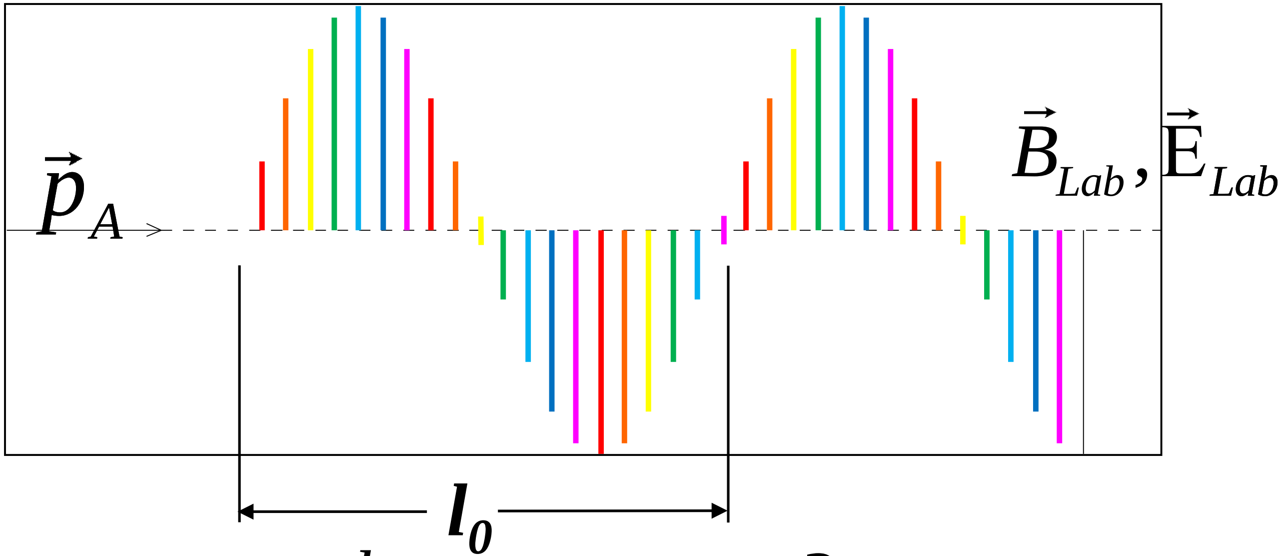


$$n_A - n_A\left(|\vec{E}|\right) = \Delta n\left(|\vec{E}|, \Delta E_{ns-np}\right)$$

Only relative abundances of different atomic quantum states are taken from theory.

Resonant enhancement of the annihilation rate of $A_{2\pi}$

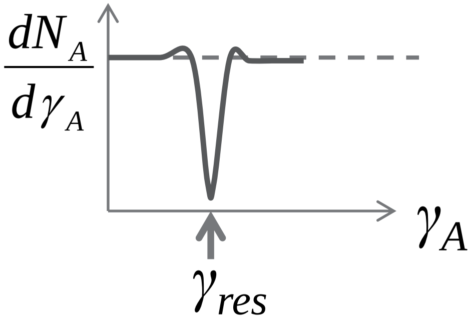
L.Nemenov, V.Ovsiannikov, E.Tchaplyguine, Nucl. Phys. (2002)



In Lab. System: $T_{Lab} = \dfrac{l_0}{\beta c}$, $\quad \omega_{Lab} = \dfrac{2\pi}{T_{Lab}}$

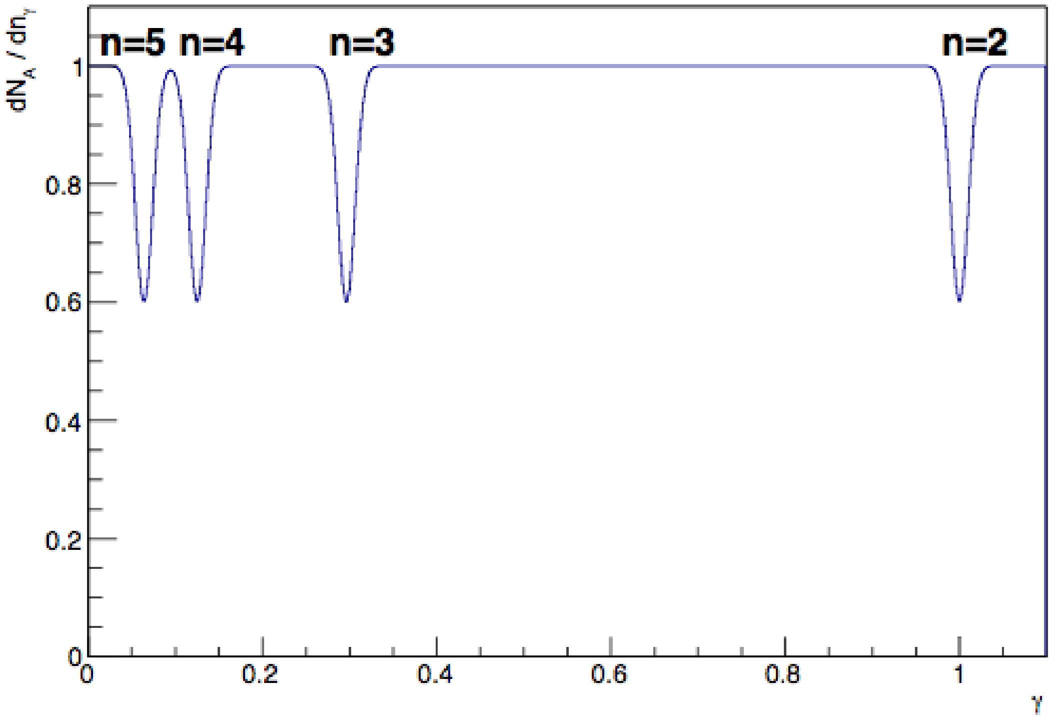
In CM System: $\tilde{\omega} = \gamma \cdot \omega_{Lab}$, $\quad \tilde{\vec{E}} = \gamma \cdot \vec{E}_{Lab} \cdot \cos \tilde{\omega} t$, $\quad \tilde{\Omega} = \dfrac{E_{2p} - E_{2s}}{\hbar}$

at resonance: $\tilde{\Omega} = \tilde{\omega} = \gamma_{res} \cdot \omega_{Lab}$



Energy splitting measurement

In a periodic electric field, there will be oscillations between ns and np states, if the external field frequency will coincide with ns – np frequency.



$$\omega_{ns-np} = \gamma_n \omega_{lab}$$

No theoretical input!

Letter of Intent

Preparation of a *Letter of Intent* about the investigation of $\pi^+\pi^-$, π^+K^-, $K^+\pi^-$ and K^+K^- atoms at SPS energy before November 2016

Instrumental publication

The paper “Updated DIRAC spectrometer at CERN PS for the investigation of $\pi\pi$ and $K\pi$ atoms” has been submitted to NIM

Measurement of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms production cross sections in proton interaction with Be, Ni and Pt nuclei basing of 2007-2012 experimental data will be done in 2017.

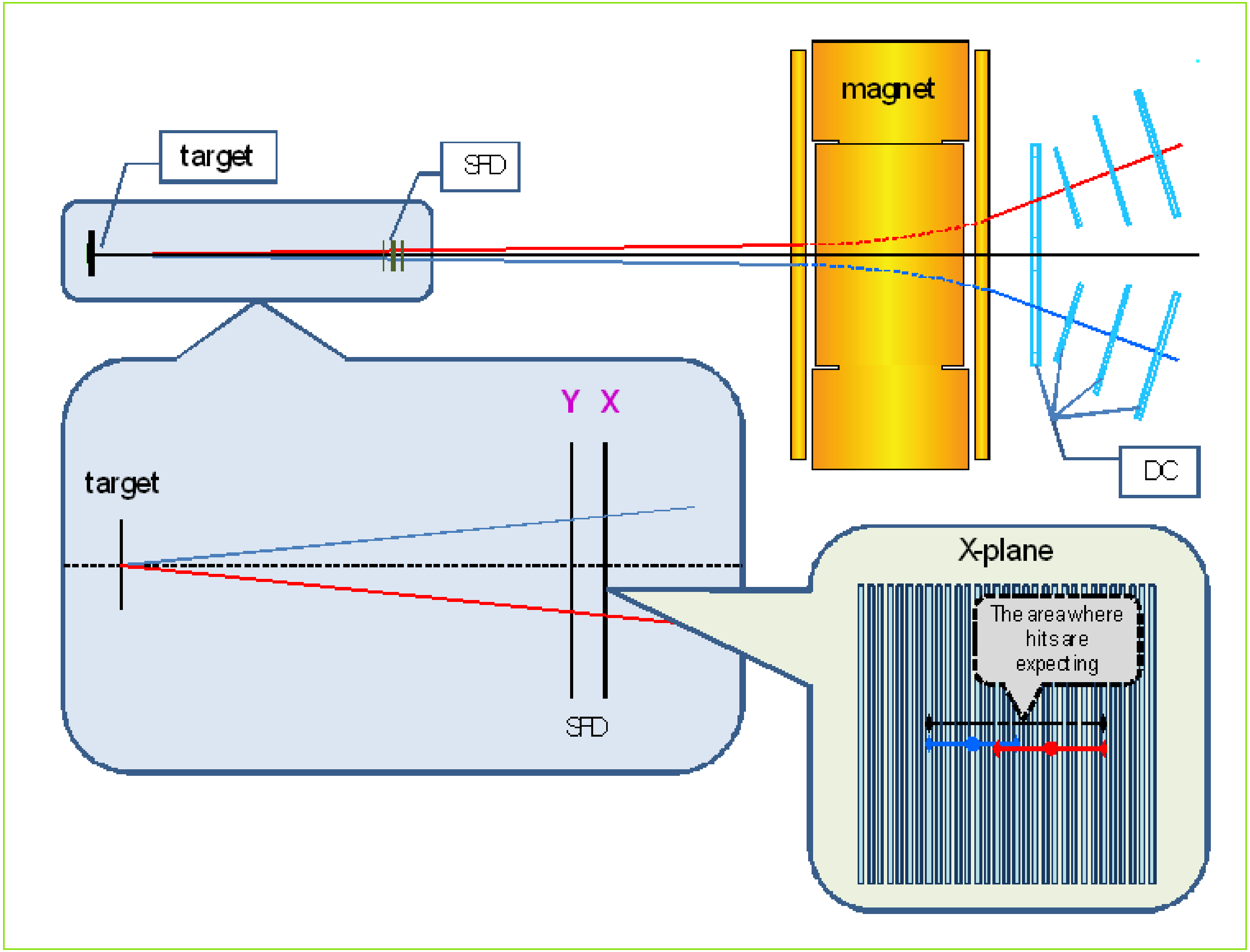
Dedicated measurements of the proton flux and the dead time of electronics and of DAQ were done for these purposes. Estimation of systematic biases in our cross sections can be done basing on extrapolation of single particle production cross sections available for 32 GeV/c protons.

$\pi^+\mu^-$ and $\pi^-\mu^+$ pair analysis

The 2010 experimental data has been searched for $\pi^+\mu^-$ and $\pi^-\mu^+$ Coulomb pairs with the aim of extracting the number of $\pi\mu$ atoms produced simultaneously with the Coulomb pairs. An upper limit on the atom production will be calculated and published as DIRAC note before the end of 2017.

Thank you

Hit regions in SFD



Theoretical motivation

Lattice calculations of $\bar{l}_3$, $\bar{l}_4$

- 2006: $\bar{l}_3$, $\bar{l}_4$ … first lattice calculations
- 2012: 10 collaborations: 3 in USA, 5 in Europe and 2 in Japan
- J. Gasser, H. Leutwyler: model calculation (1985)
  $\bar{l}_3 = 2.9 \pm 2.4$, $\bar{l}_4 = 4.3 \pm 0.9$
- **Lattice calculations of these constants have been done in 20 works.**
  Best result (BMW): $\bar{l}_3 = 2.6 \pm 0.5\text{st} \pm 0.4\text{sy}$, $\bar{l}_4 = 3.8 \pm 0.4\text{st} \pm 0.2\text{sy}$

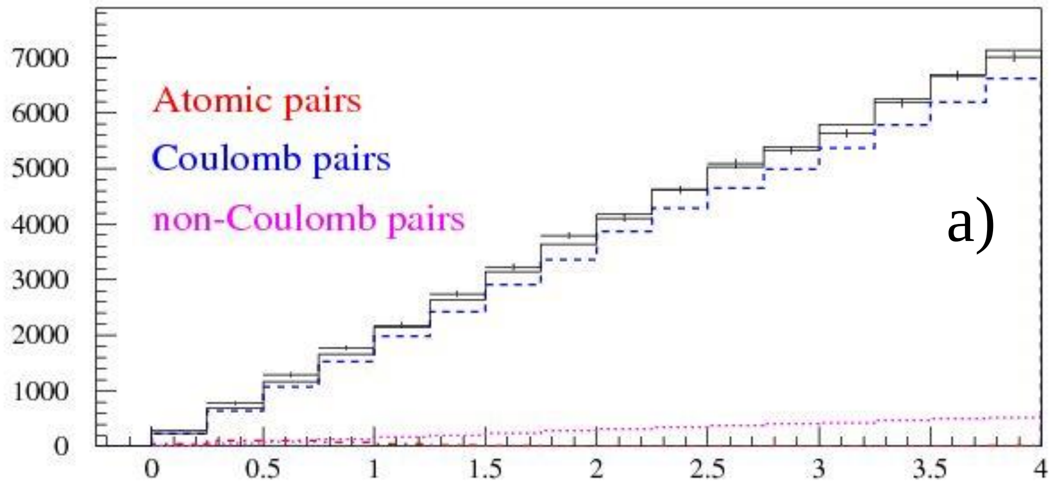
Therefore, the theoretical pion-pion scattering length precision can be improved.
The best experimental results on the scattering length have a precision not better than 4%.

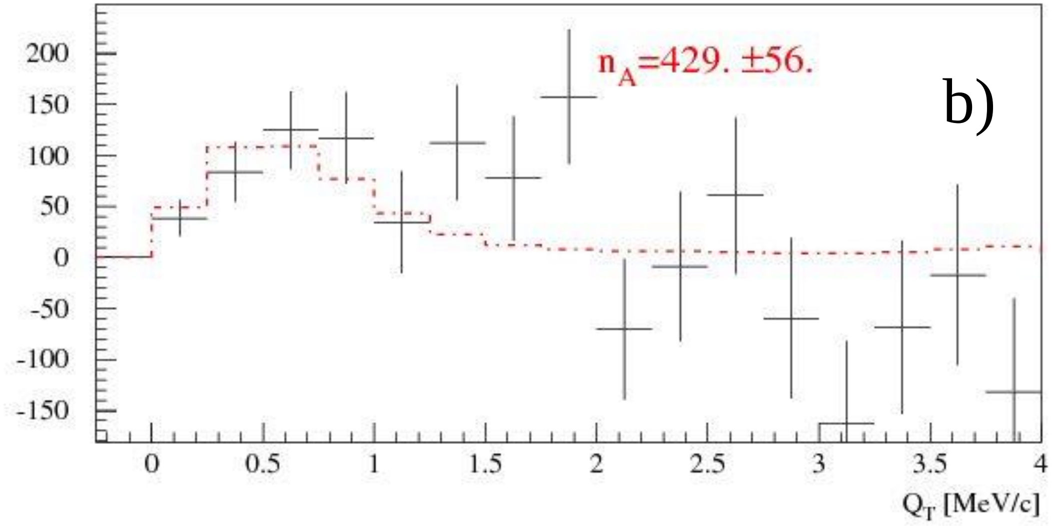
Experimental $|Q_L|$ distributions of $\pi^+\pi^-$ pairs

Analysis of data collected in 2012 for different Q_T cuts. The detected numbers n_A^L of atomic pairs and the corresponding total numbers $n_A^{L,tot}$ (via selection efficiency) are presented together with the background contribution (Coulomb, non-Coulomb and accidental pairs) and the fit quality χ^2 / n (n - degrees of freedom). Errors are only statistical.

Q_T cut (MeV/c)	n_A^L	$n_A^{L,tot}$	Background	χ^2 / n
Fit over Q_L, Q_T				
2.0	436±57	488±64	16790	138/140
Fit over Q_L				
0.5	152±29	467±88	971	29/27
1.0	349±53	489±75	3692	19/27
1.5	386±78	454±91	9302	22/27
2.0	442±105	495±117	16774	22/27

Experimental Q_T distributions of $\pi^+\pi^-$ pairs





Q_T distribution of $\pi^+\pi^-$ pairs
for $|Q_L| < 2$ MeV/c

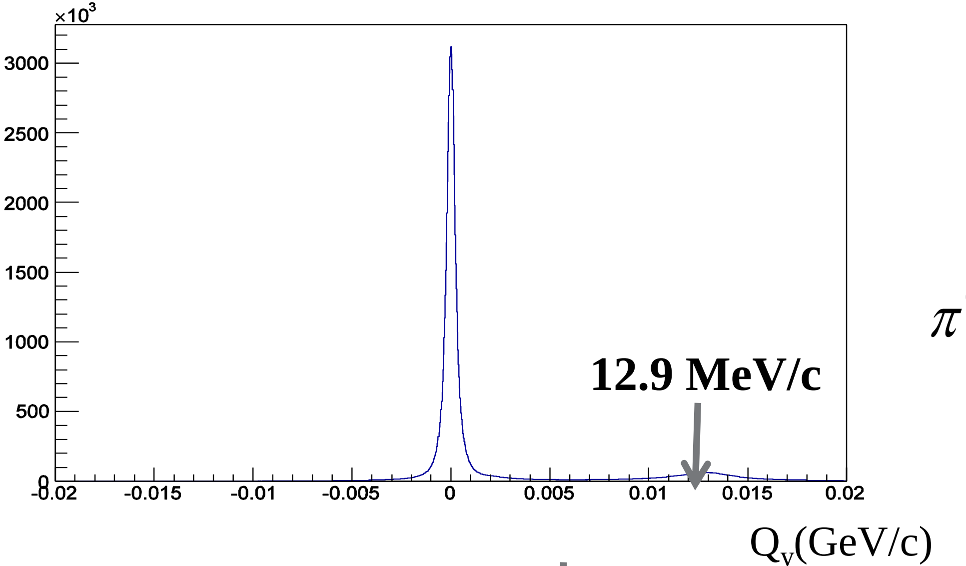
a) The experimental distribution (points with statistical error) and the simulated background (solid line).

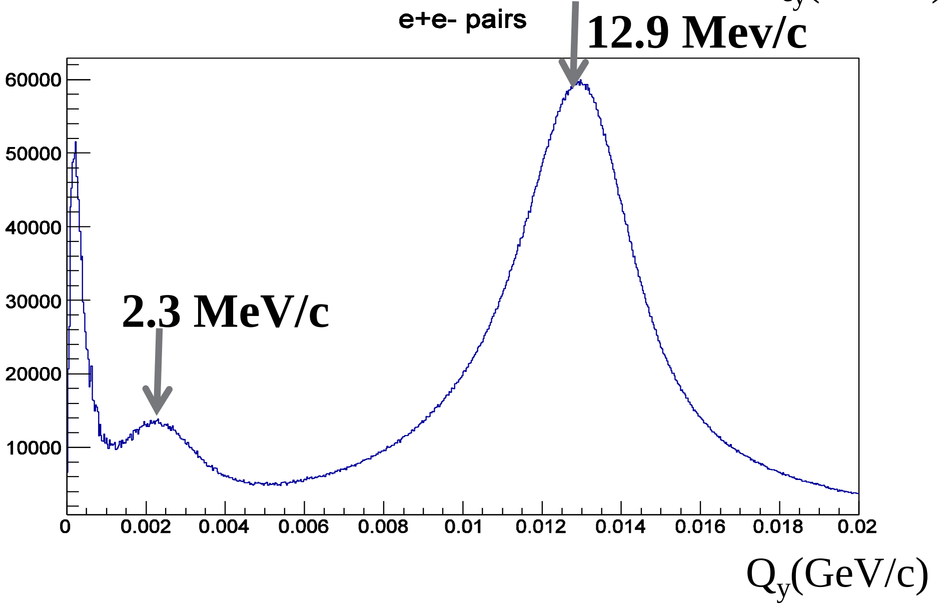
b) The experimental distribution after background subtraction (points with statistical error) and the simulated distribution of atomic pairs (dot-dashed line).

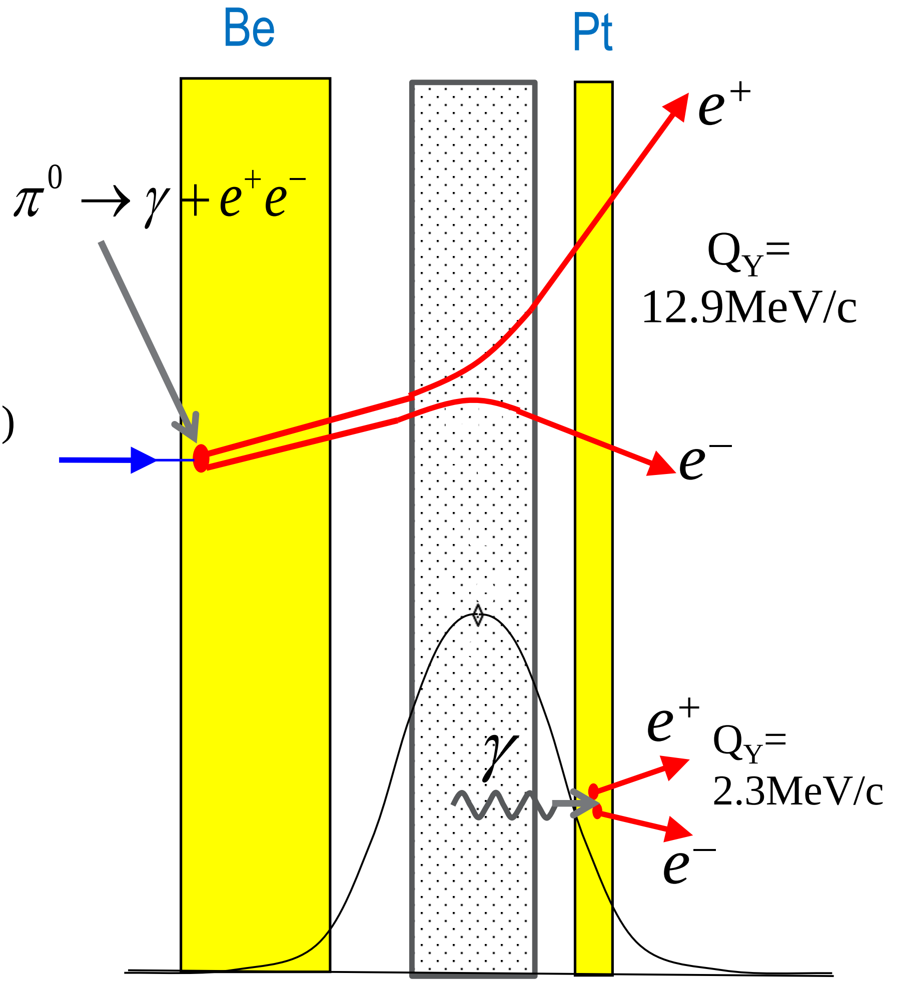
The fit procedure has been applied to the 2-dimensional ($|Q_L|$, Q_T) distribution.

Magnet impact on Q_y distribution for e^+e^- pairs

Real data

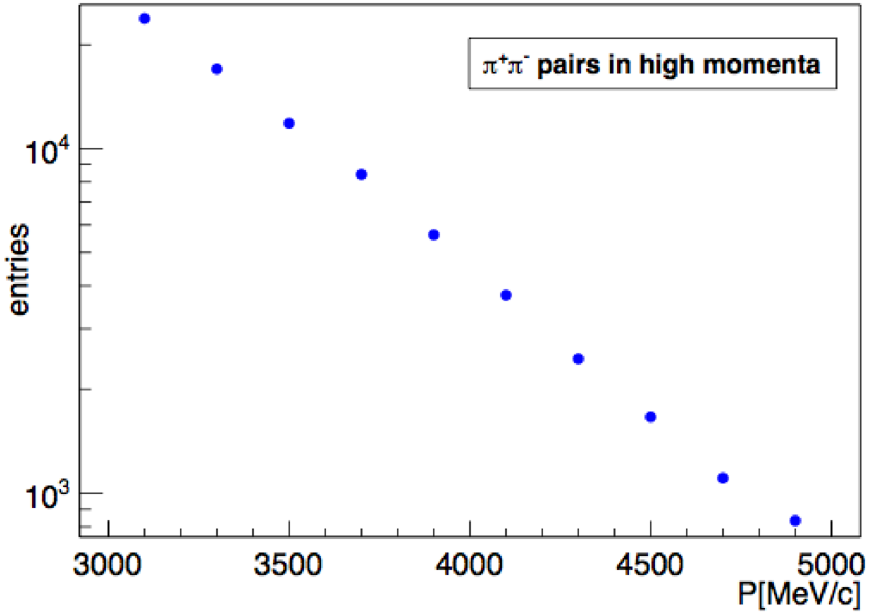


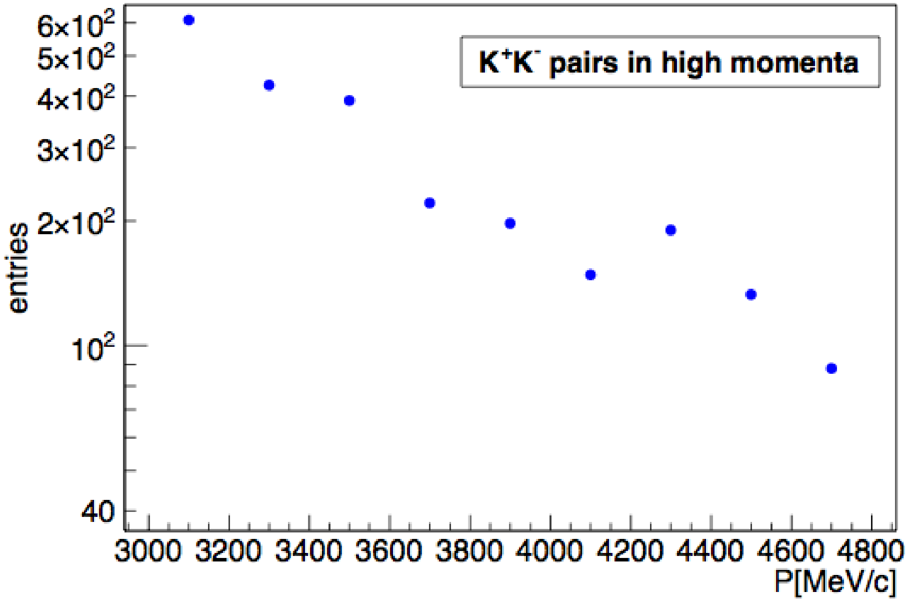


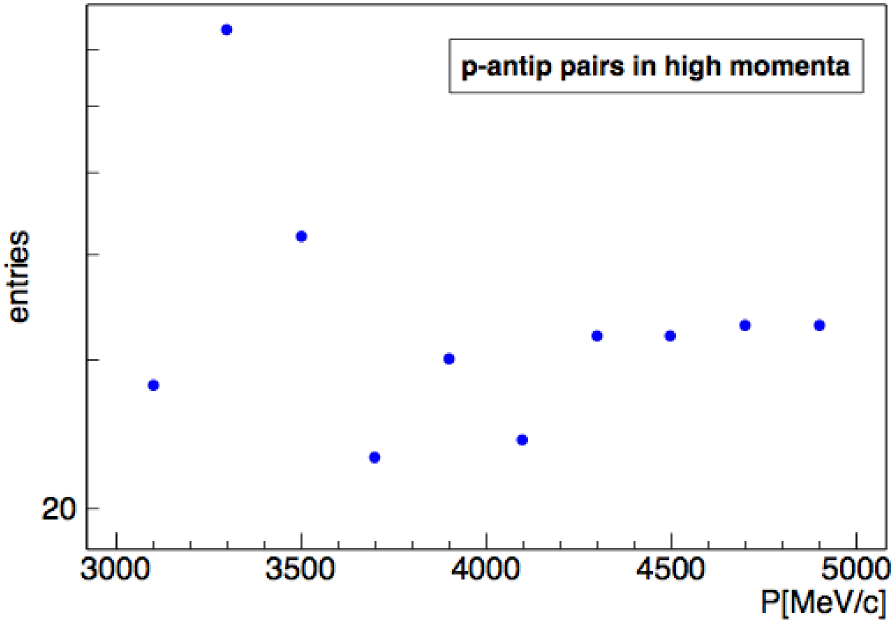


Peak at Q_y=2.3MeV/c evaluated after subtraction of the mirrored left side part.

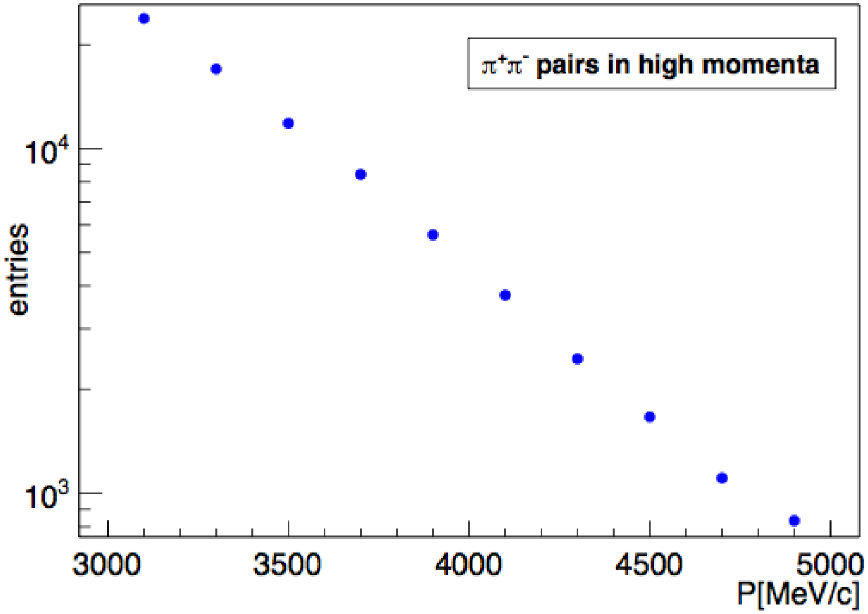
The $\pi^+\pi^-$ K^+K^- and p-antiproton numbers of pairs as a function of their momentum (high momentum)

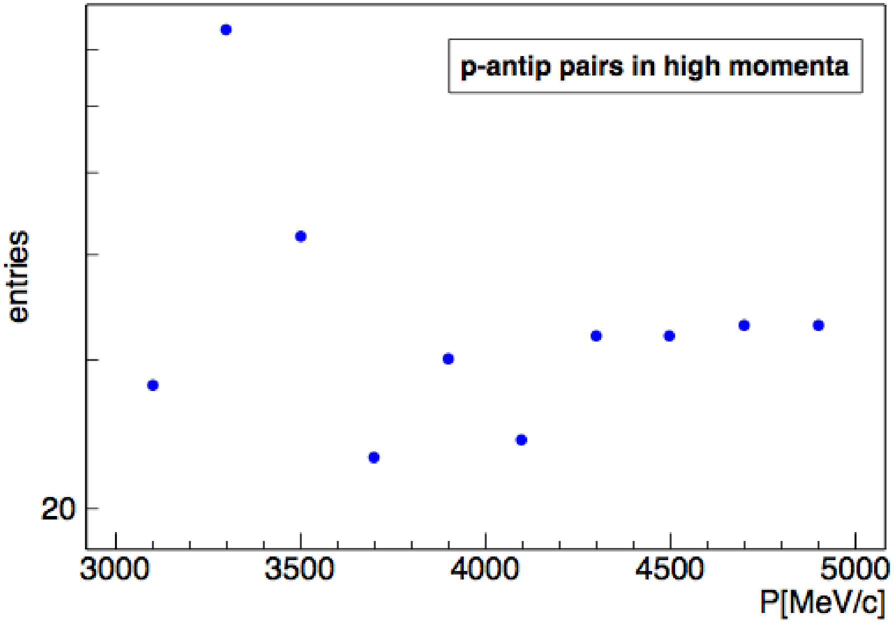


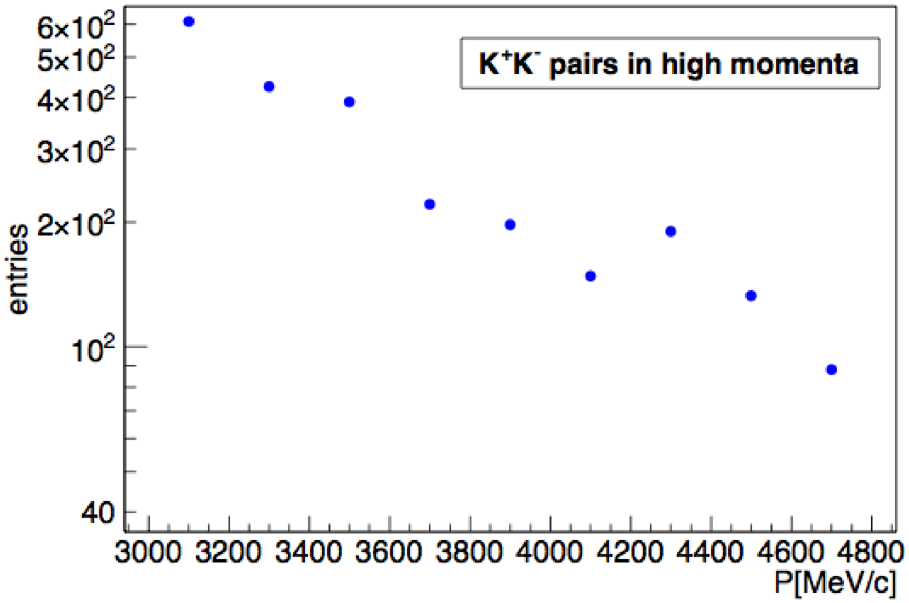




The $\pi^+\pi^-$ K^+K^- and p-antiproton numbers of pairs as a function of their momentum (high momentum)



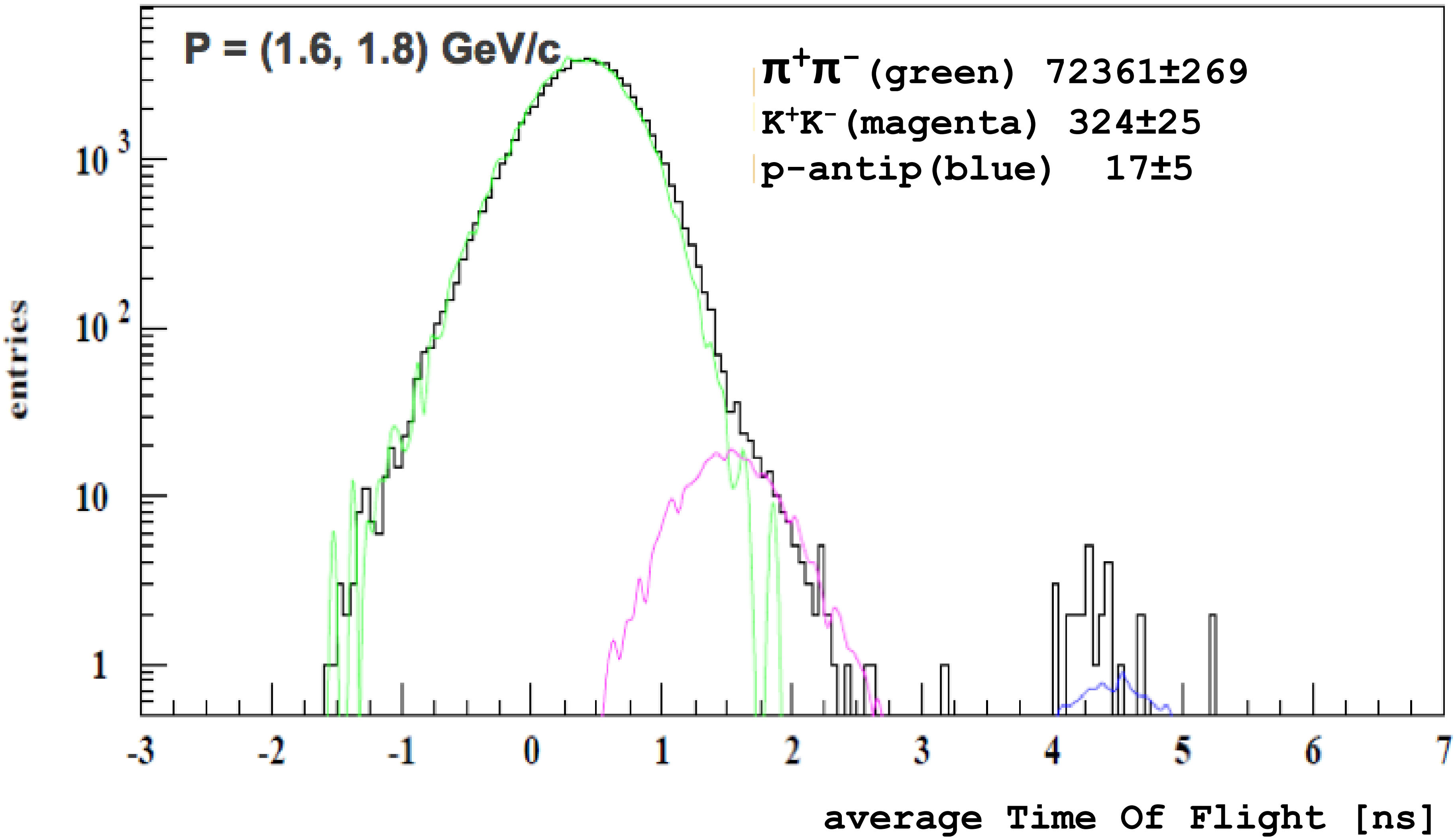




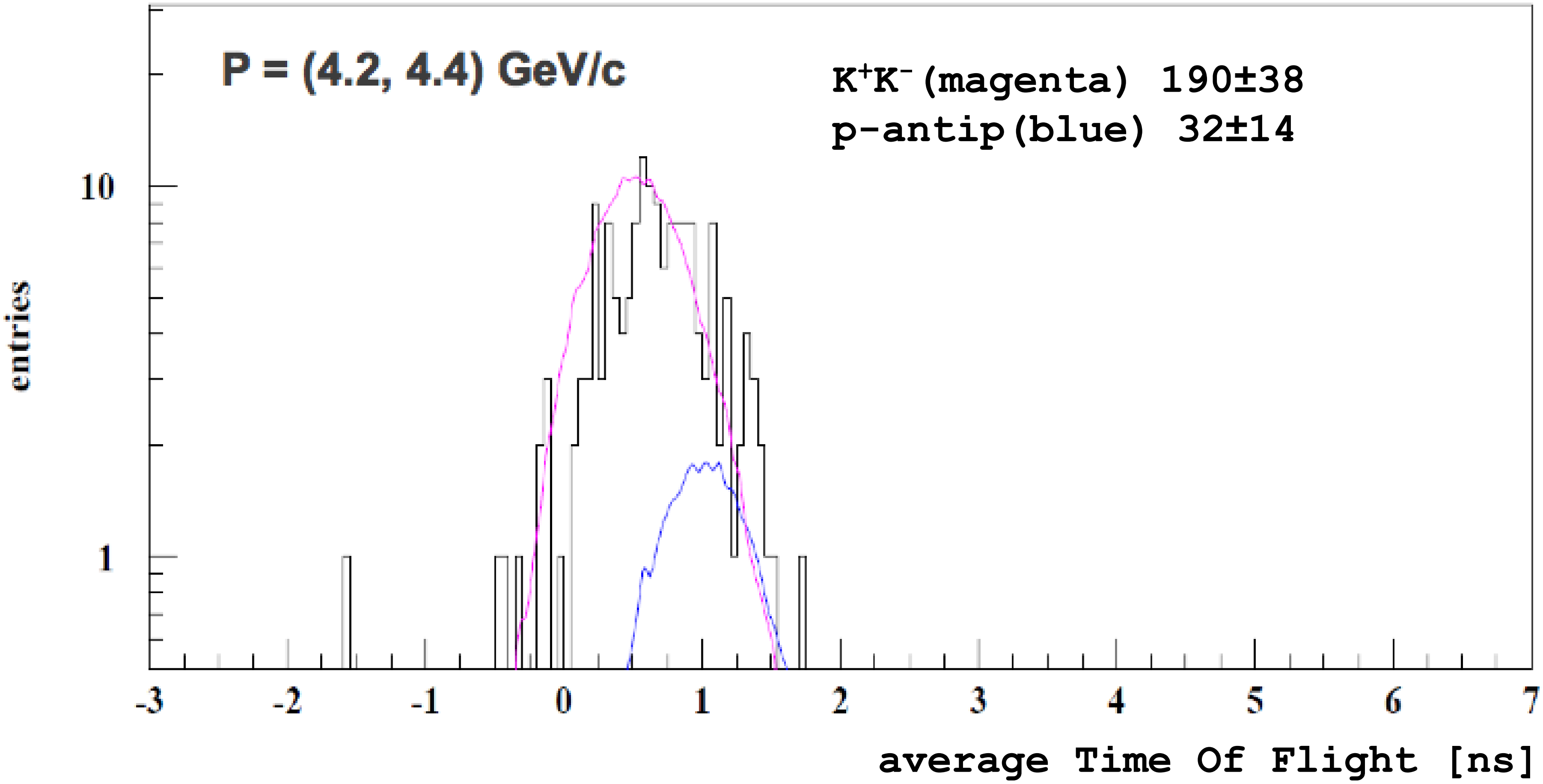
6. $\pi^+\mu^-$ and $\pi^-\mu^+$ pair analysis

- Analogously, the 2010 data will be investigated with respect to $\pi^+\mu^-$ and $\pi^-\mu^+$ Coulomb pairs, to extract the number of πμ atoms, produced together with these Coulomb pairs. The analysis will be finished in January 2015.
- In presence of a signal, the 2011 and 2012 data will be processed in order to improve statistics.

Search of K^+K^- and p-antiproton pair using Time Of Flight. Low momentum range



Search of K^+K^- and p-antiproton pair using Time Of Flight. High momentum range



5. Proton – antiproton pair analysis

- DIRAC will perform a search for proton–antiproton Coulomb pairs, thus proton–antiproton atoms, with the same strategy as in the K^+K^- case (see previous section).
- The search for proton–antiproton Coulomb pairs in the lower momentum region will be finished before May 2016.

Additional slides

Physics motivation

$\pi^+\pi^-$ atom: lifetime & scattering length

$$\Rightarrow \tau_{1s}\left(10^{-15}\,s\right) = 3.15\left.^{+0.20}_{-0.19}\right|_{stat} \quad \left.^{+0.20}_{-0.18}\right|_{syst} = 3.15\left.^{+0.28}_{-0.26}\right|_{tot}$$

$$\Gamma_{1s} = \frac{1}{\tau_{1s}} \approx \frac{2}{9}\alpha^3 p_{\pi^0}\left(a_0 - a_2\right)^2 m_\pi^2$$

$$\Rightarrow \left|a_0 - a_2\right|\left(m_\pi^{-1}\right) = 0.2533\left.^{+0.0078}_{-0.0080}\right|_{stat} \quad \left.^{+0.0072}_{-0.0077}\right|_{syst} = 0.2533\left.^{+0.0106}_{-0.0111}\right|_{tot}$$

... published by DIRAC, Physics Letters B 704 (2011), 24.

Experimental results

$$\left(\text{scattering length in } m_\pi^{-1}\right)$$

K→3π:

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)

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

Experimental results with additional theoretical constraints

$K \to 3\pi$:

2009 **NA48/2** (EPJ C64, 589) ...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 - a_2 = 0.2633 \pm 0.0024\Big|_{stat} \pm 0.0014\Big|_{syst} \pm 0.0019\Big|_{ext} = \ldots \pm 1.3\%$$

plus additional 2% theory uncertainty

Ke4:

2010 **NA48/2** (EPJ C70, 635) ...with ChPT constraint between a_0 and a_2:

$$\Rightarrow a_0 = 0.2206 \pm 0.0049\Big|_{stat} \pm 0.0018\Big|_{syst} \pm 0.0064\Big|_{theo} = \ldots \pm 3.7\%$$

Ke4 & $K \to 3\pi$:

2010 **NA48/2** (EPJ C70, 635) Remark: the results didn't include theory uncertainty

$$\Rightarrow a_0 - a_2 = 0.2639 \pm 0.0020\Big|_{stat} \pm 0.0015\Big|_{syst} = \ldots \pm 0.9\%$$

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

n	$\tau_{2\pi}$ (10^{-11}sec)		Decay length $A_{2\pi}$ in L.S. (cm) for $\gamma=16$ ($\lambda_{ns}=c\cdot\gamma\cdot\tau_{nl}$)	
	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

Breakup foil	Thick (μm)	2p	3p	4p	5p	6p	7p
Pt (Z=78)	1.0	0.4147	0.6895	0.8553	0.9324	0.9667	0.9828
	1.5	0.6084	0.8526	0.9446	0.9765	0.9889	0.9944
	2.0	0.7422	0.9244	0.9743	0.9895	0.9951	0.9975

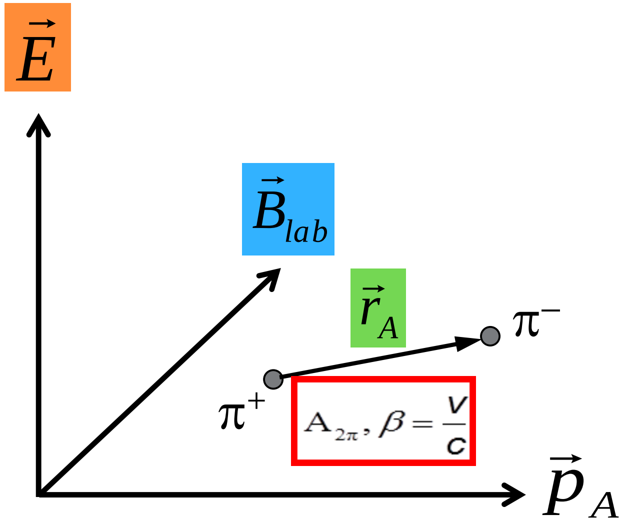
Platinum foils:

The breakup probability for *np* states and different thicknesses ($A_{2\pi}$ momentum P_A=4.5GeV /c and $A_{2\pi}$ lifetime $\tau = 3.0\cdot10^{-15}$s)

Lamb shift measurement with external magnetic field

See: L. Nemenov, V. Ovsiannikov, Physics Letters B 514 (2001) 247.

Impact on atomic beam by
external magnetic field $\boldsymbol{B_{lab}}$ and Lorentz factor $\boldsymbol{\gamma}$



$\vec{r}_A$ …. relative distance between π^+ and π^- in $A_{2\pi}$ system

$\vec{B}_{lab}$ …. laboratory magnetic field

$\vec{E}$ …electric field in $A_{2\pi}$ system

$$\boxed{\left|\vec{E}\right| = \beta\gamma\, B_{lab} \approx \gamma\, B_{lab}}$$

Dependence of $A_{2\pi}$ lifetime τ_{eff} for 2p-states of the electric field E strength

$$N_A = N_A(0)\cdot e^{-\frac{t}{\tau_{2p}}} \qquad N_A = N_A(0)\cdot e^{-\frac{t}{\tau_{eff}}}$$

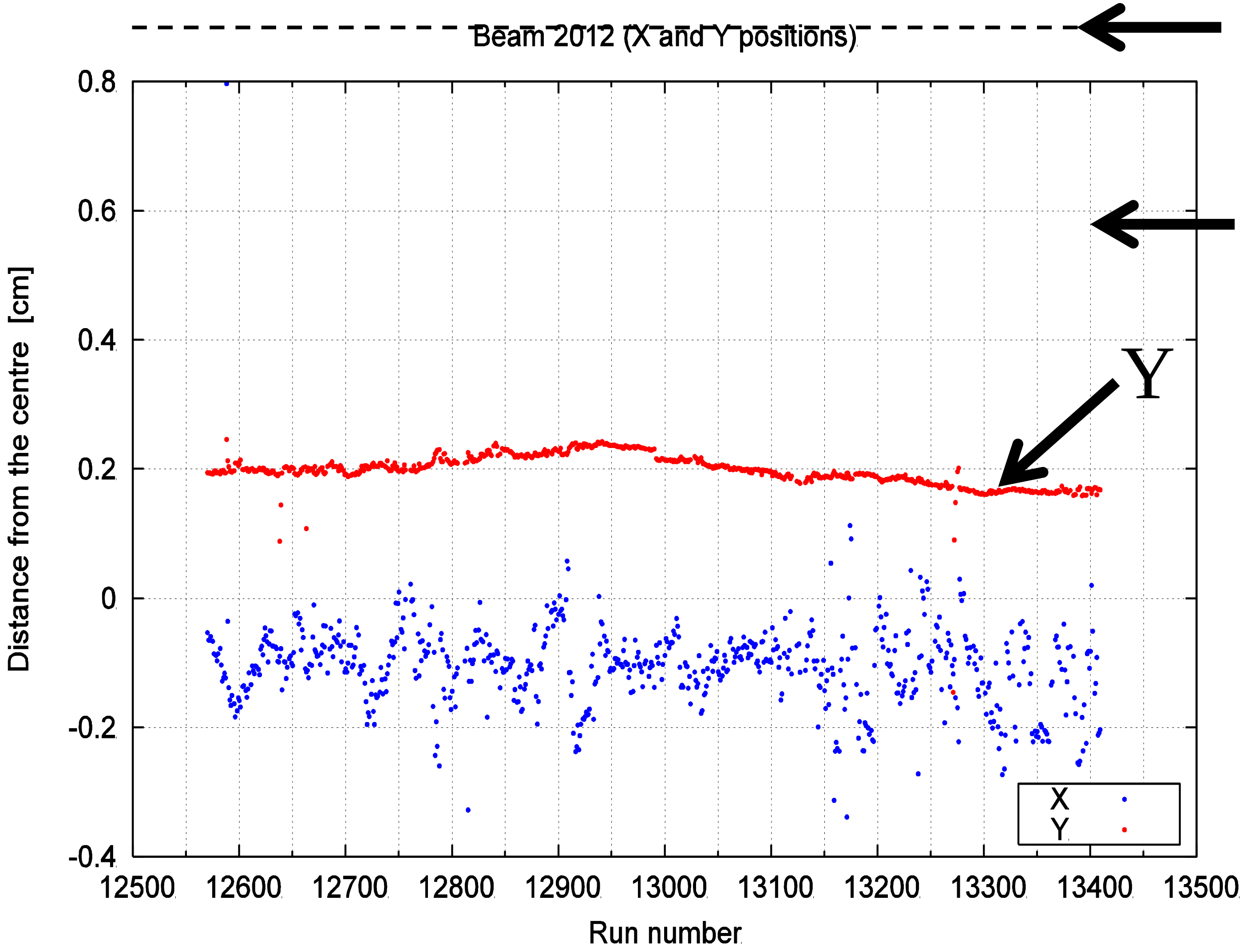
$$\tau_{eff} = \frac{\tau_{2p}}{1+\frac{|\xi|^2}{4}\frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1+120\,|\xi|^2}$$

where: $$|\xi|^2 \approx \frac{|\vec{E}|^2}{\left(E_{2p}-E_{2s}\right)^2}$$

B_{Lab} = 2 Tesla

$$\begin{cases} \gamma = 20\ , & |\xi| = 0.025 \Rightarrow \tau_{eff} = \dfrac{\tau_{2p}}{1.3} \\ \gamma = 40\ , & |\xi| = 0.05 \Rightarrow \tau_{eff} = \dfrac{\tau_{2p}}{2.25} \end{cases}$$

y-beam position (run 2012)



Pt foil edge position 7.5 mm from the beam axis

Proton beam position when the IH slabs single counts increase on factor 2 due to the halo beam interaction with the *Pt* foil (no *Be* target).

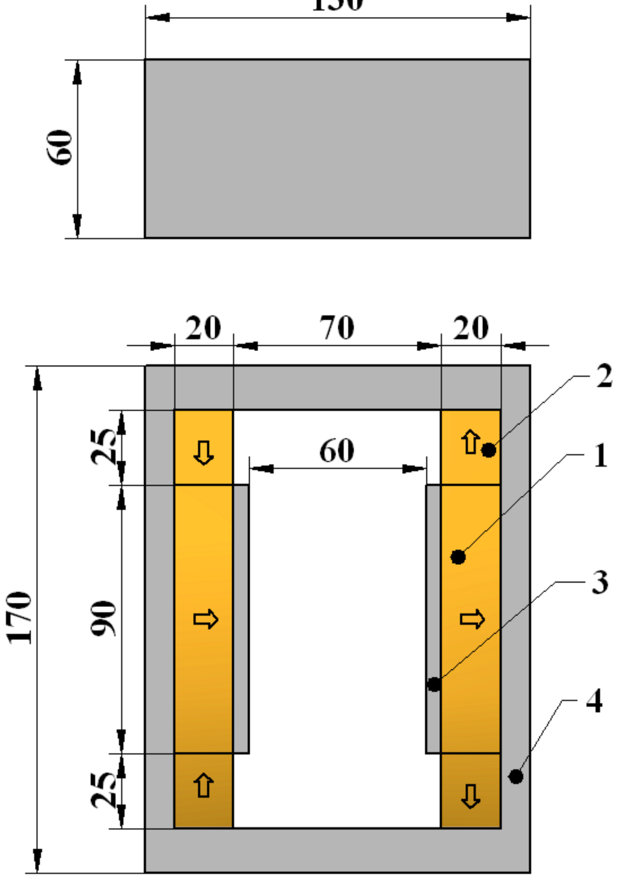
Experimental conditions (run 2012)

Primary proton beam	24 GeV/c
Beam intensity	$(3.0 \div 3.3)\cdot 10^{11}$ proton/spill
Spill duration	450 ms
Secondary particles intensity (single count of one IH plane)	$\approx 7\cdot 10^{6}$ particle/spill

Be target	
Target thickness	103 μm
Radiation thickness	$2.93\cdot 10^{-4}\,X_0$
Probability of inelastic proton interaction	$2.52\cdot 10^{-4}$

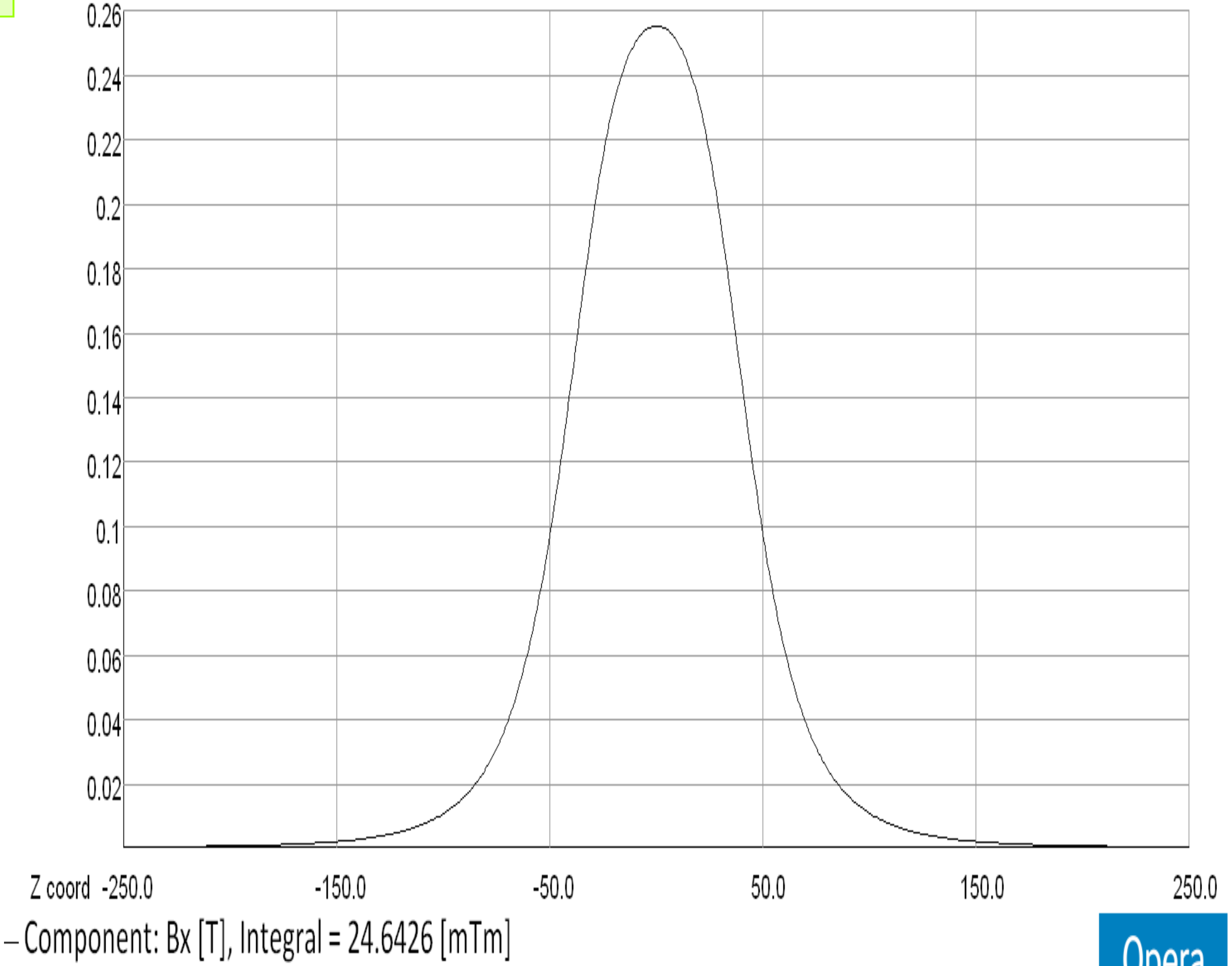
Magnet

Layout of the dipole magnet (arrows indicate the direction of magnetization)



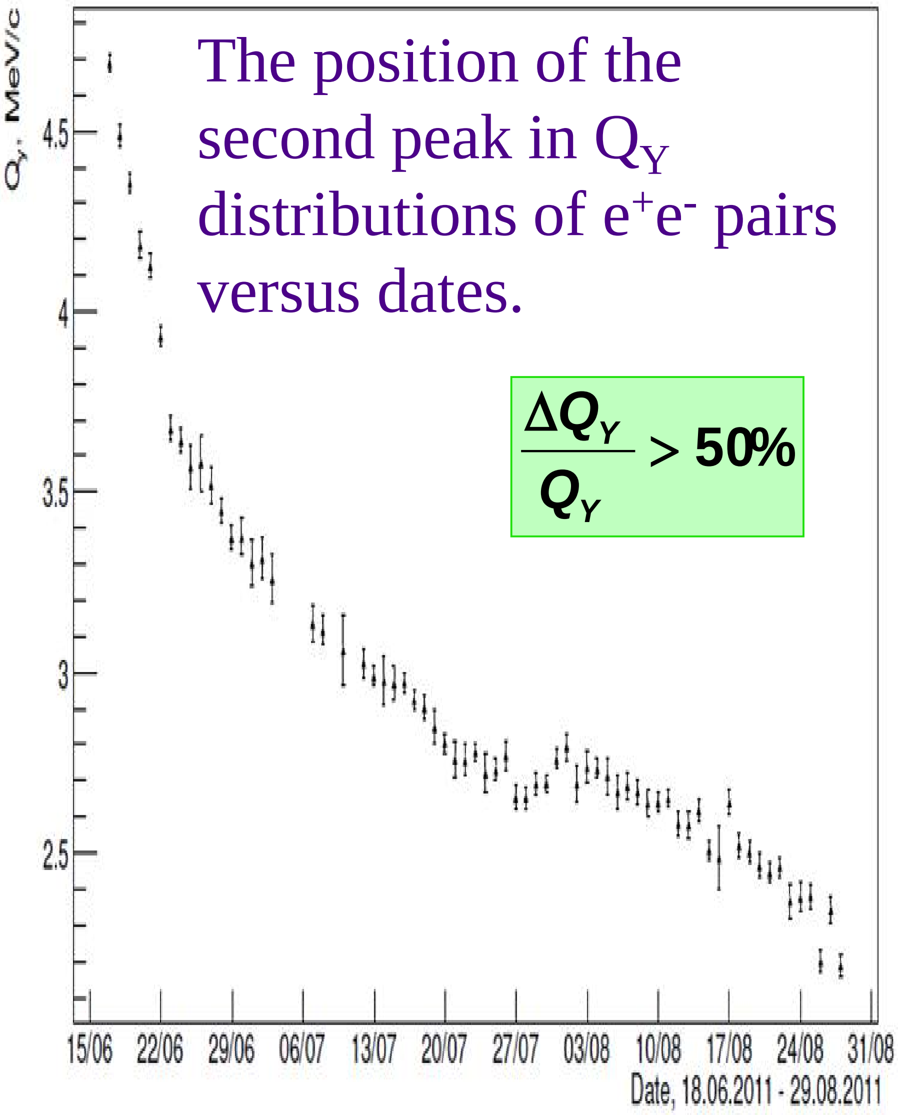
1- PM block Sm2Co17
2- PM block Sm2Co17

Horizontal field distribution along z-axis at X=Y=0mm
$\int B_x(0,0,z)dz = 24.6\times10^{-3}$ [Tm]



Degradation of old magnet

Old magnet (Nd-Fe-B), 2011

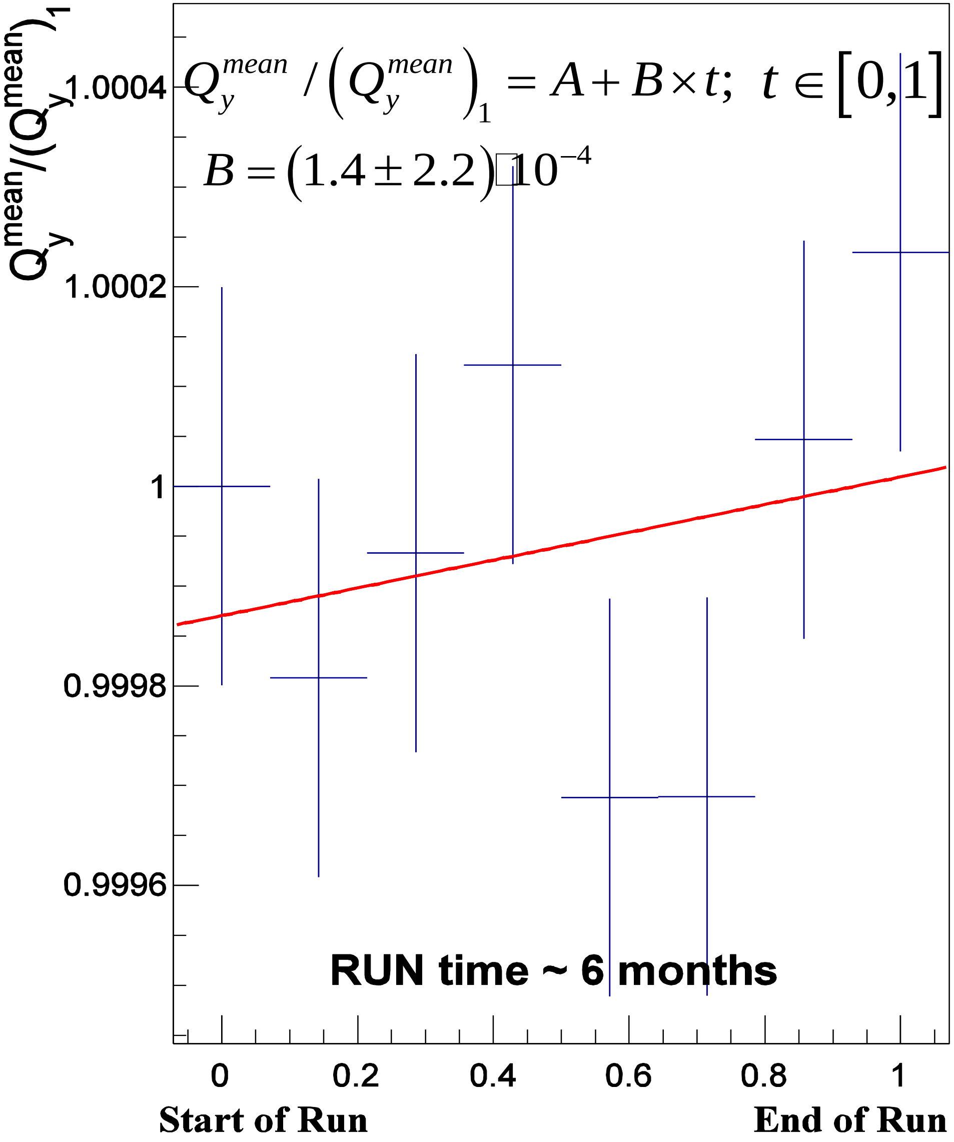


The position of the second peak in Q_Y distributions of e^+e^- pairs versus dates.

$$\frac{\Delta Q_Y}{Q_Y} > 50\%$$

New magnet behaviour

New magnet (Sm-Co), 2012

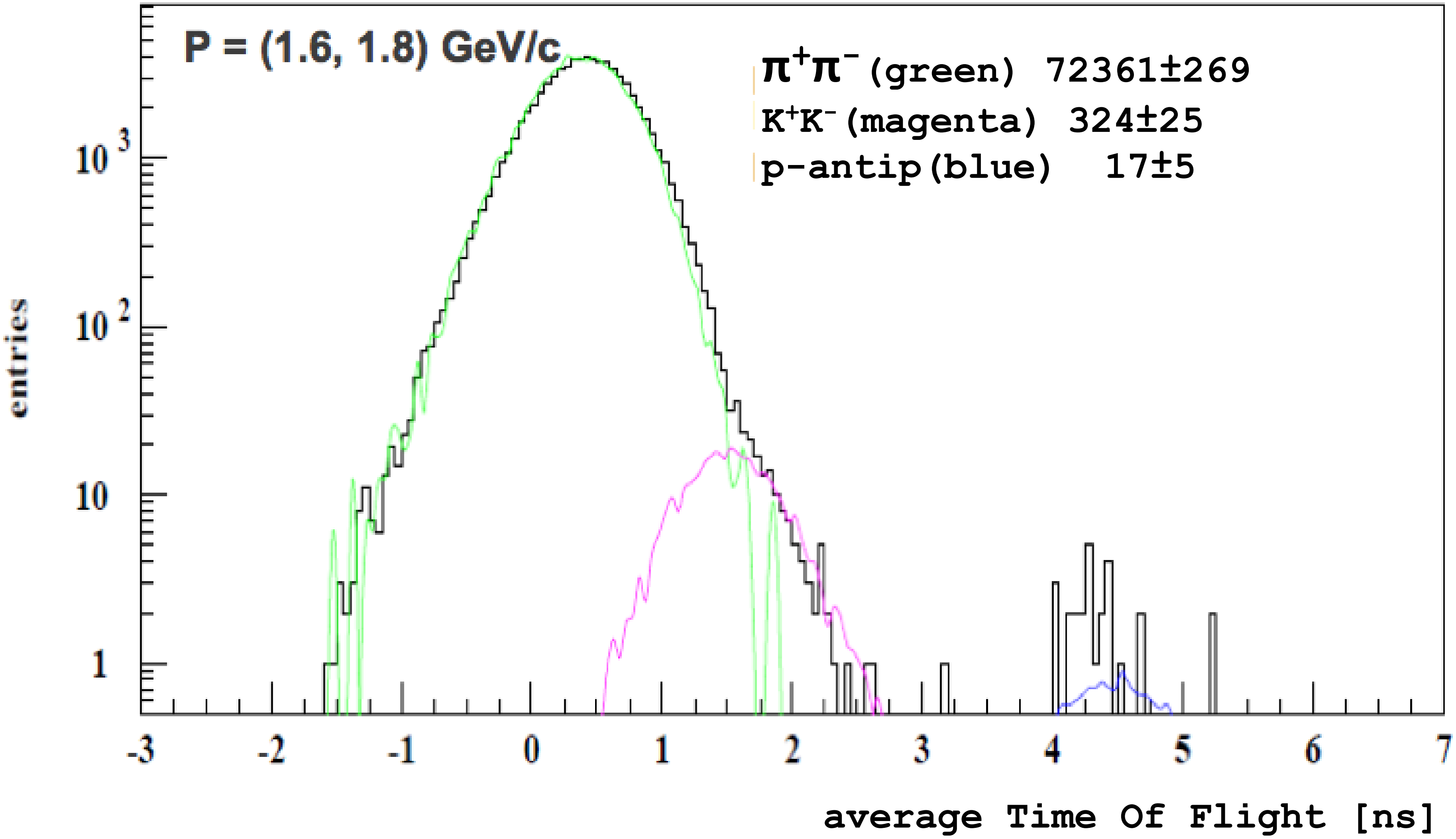


$$Q_y^{mean} / \left(Q_y^{mean}\right)_1 = A + B\times t;\ \ t\in\left[0,1\right]$$

$$B = \left(1.4 \pm 2.2\right)\cdot 10^{-4}$$

RUN time ~ 6 months

Search of K^+K^- and p-antiproton pair using Time Of Flight. Low momentum range



$A_{2\pi}$ and $A_{\pi K}$ production

$$\frac{d\sigma^{A}_{nlm}}{d\vec{P}_A} = (2\pi)^3 \frac{E}{M} \left|\psi^{(C)}_{nlm}(0)\right|^2 \frac{d\sigma^0_s}{dp_1 dp_2}\bigg|_{\vec{v}_1=\vec{v}_2} \propto \frac{d\sigma}{dp_1}\cdot\frac{d\sigma}{dp_2}\cdot R(\vec{p}_1,\vec{p}_2;s)$$

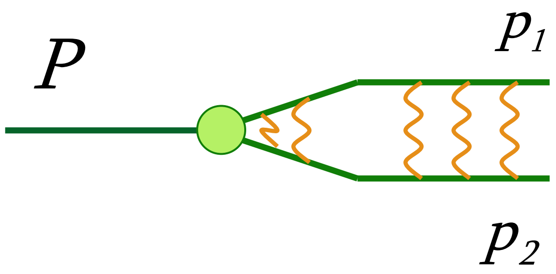
$$\vec{P}_A = \vec{p}_1 + \vec{p}_2$$

for atoms $\vec{v}_1 = \vec{v}_2$ *where* $\vec{v}_1, \vec{v}_2$ *- velocities of particles in the L.S.*

for all types of atoms

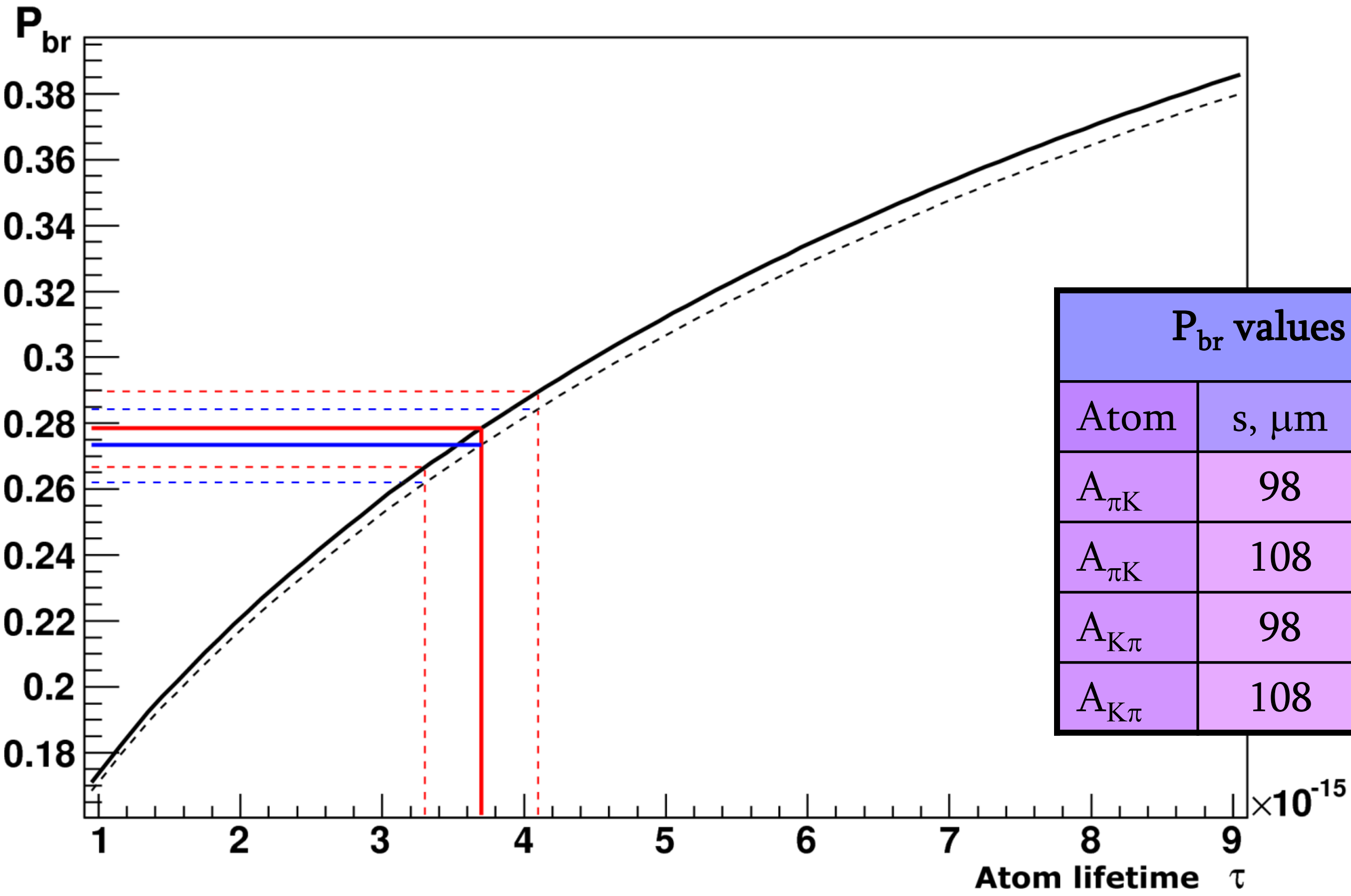
for $A_{2\pi}$ *production* $\vec{p}_1 = \vec{p}_2$

for $A_{\pi K}$ *production* $\vec{p}_\pi = \frac{m_\pi}{m_K}\vec{p}_K$



$R(\vec{p}_1,\vec{p}_2;s)$ *- correlation function*

Break-up dependencies P_{br} from atoms lifetime for $K^+\pi^-$ atom ($A_{K\pi}$) and $K^-\pi^+$ atom ($A_{\pi K}$)



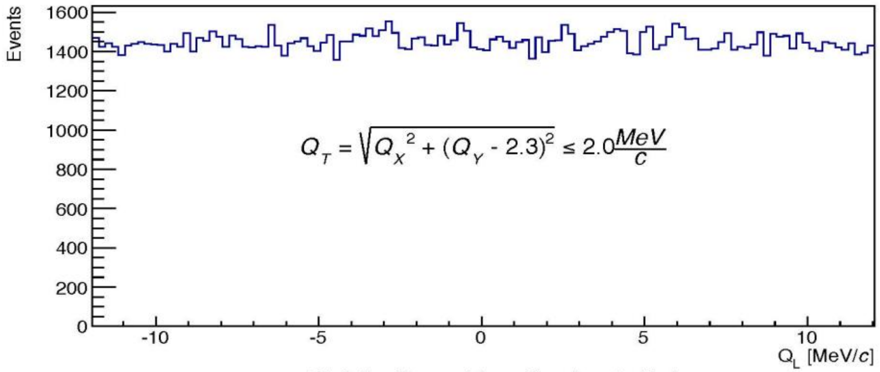
P_{br} values corresponding to τ_{1S}^{th}

Atom	s, μm	P_{br}	$P_{br}-\sigma$	$P_{br}+\sigma$
$A_{\pi K}$	98	0.274	0.263	0.285
$A_{\pi K}$	108	0.278	0.267	0.290
$A_{K\pi}$	98	0.269	0.258	0.280
$A_{K\pi}$	108	0.273	0.262	0.284

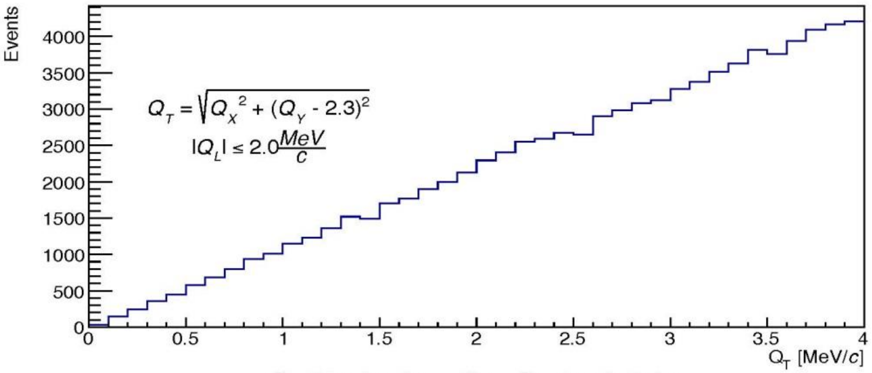
Probability of break-up as a function of lifetime in the ground state for $A_{\pi K}$ (solid line) and $A_{K\pi}$ atoms (dashed line) in Ni target of thickness 108 μm.

Average momentum of $A_{K\pi}$ and $A_{\pi K}$ are 6.4 GeV/c and 6.5 GeV/c accordingly.

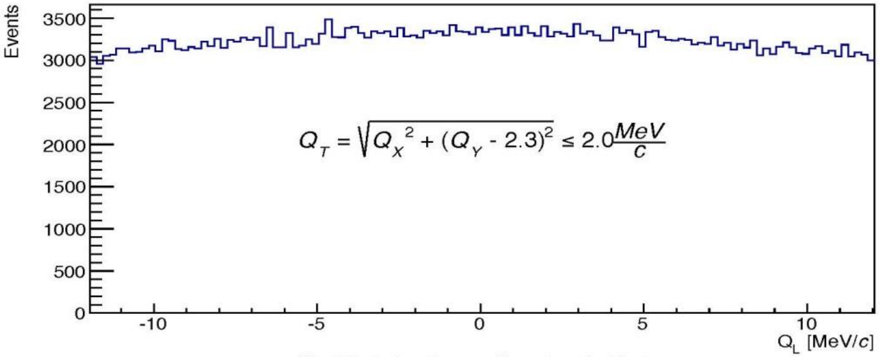
Simulation of $\pi^+\pi^-$ pairs for long-lived $A_{2\pi}$ observation



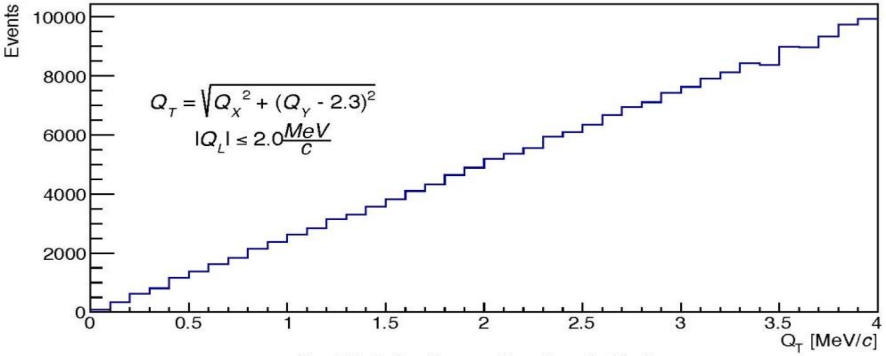
Q_L Distribution - Non-Coulomb Pairs



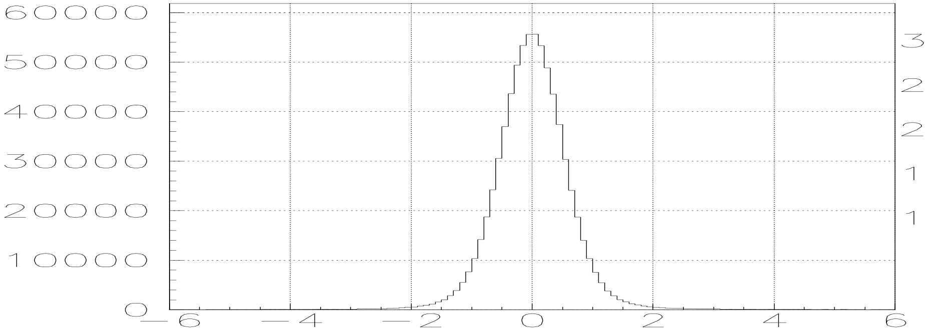
Q_T Distribution - Non-Coulomb Pairs



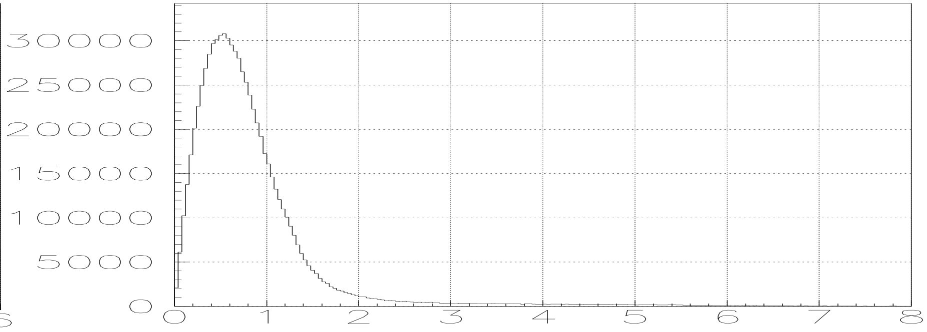
Q_L Distribution - Coulomb Pairs



Q_T Distribution - Coulomb Pairs

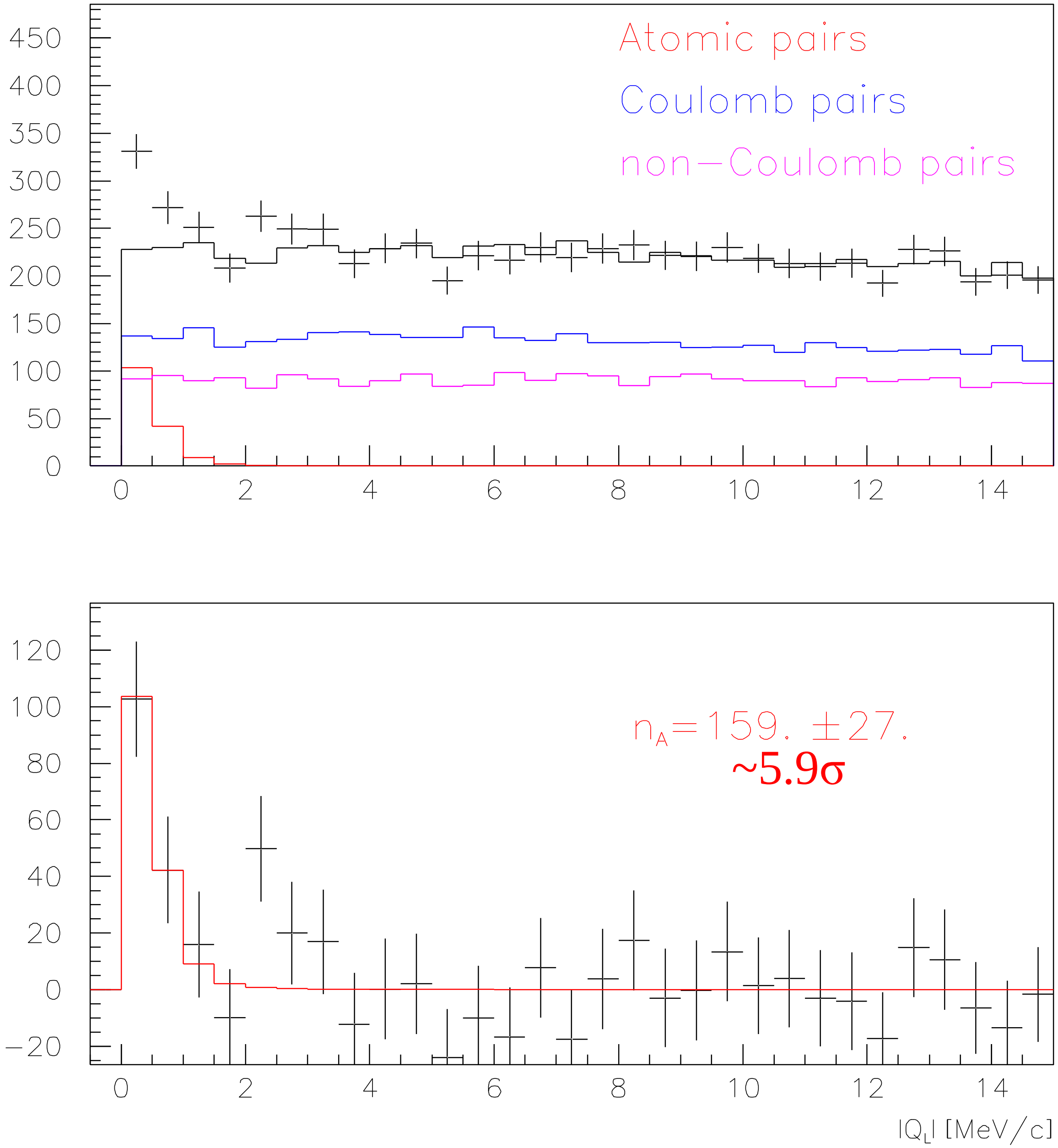


Atomic pairs Q_L(MeV/c)



Atomic pairs Q_T(MeV/c)

Long-lived $\pi^+\pi^-$ atoms

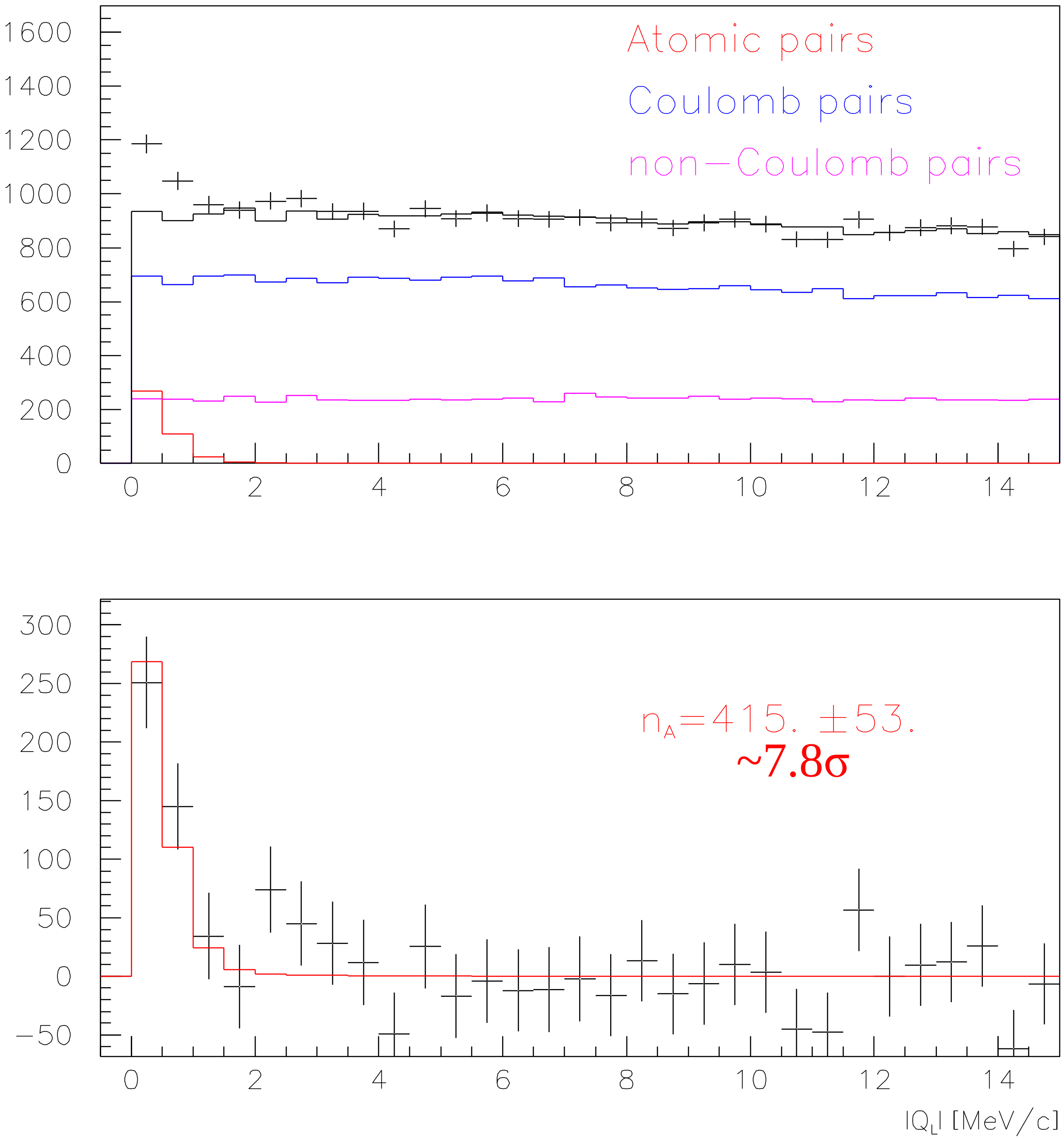


Experimental (real data) and simulated distributions over $|Q_L|$

for Q_T<0.5 MeV/c

$$Q_T = \sqrt{Q_X^2 + \left(Q_Y - 2.3 MeV / c\right)^2}$$

Long-lived $\pi^+\pi^-$ atoms

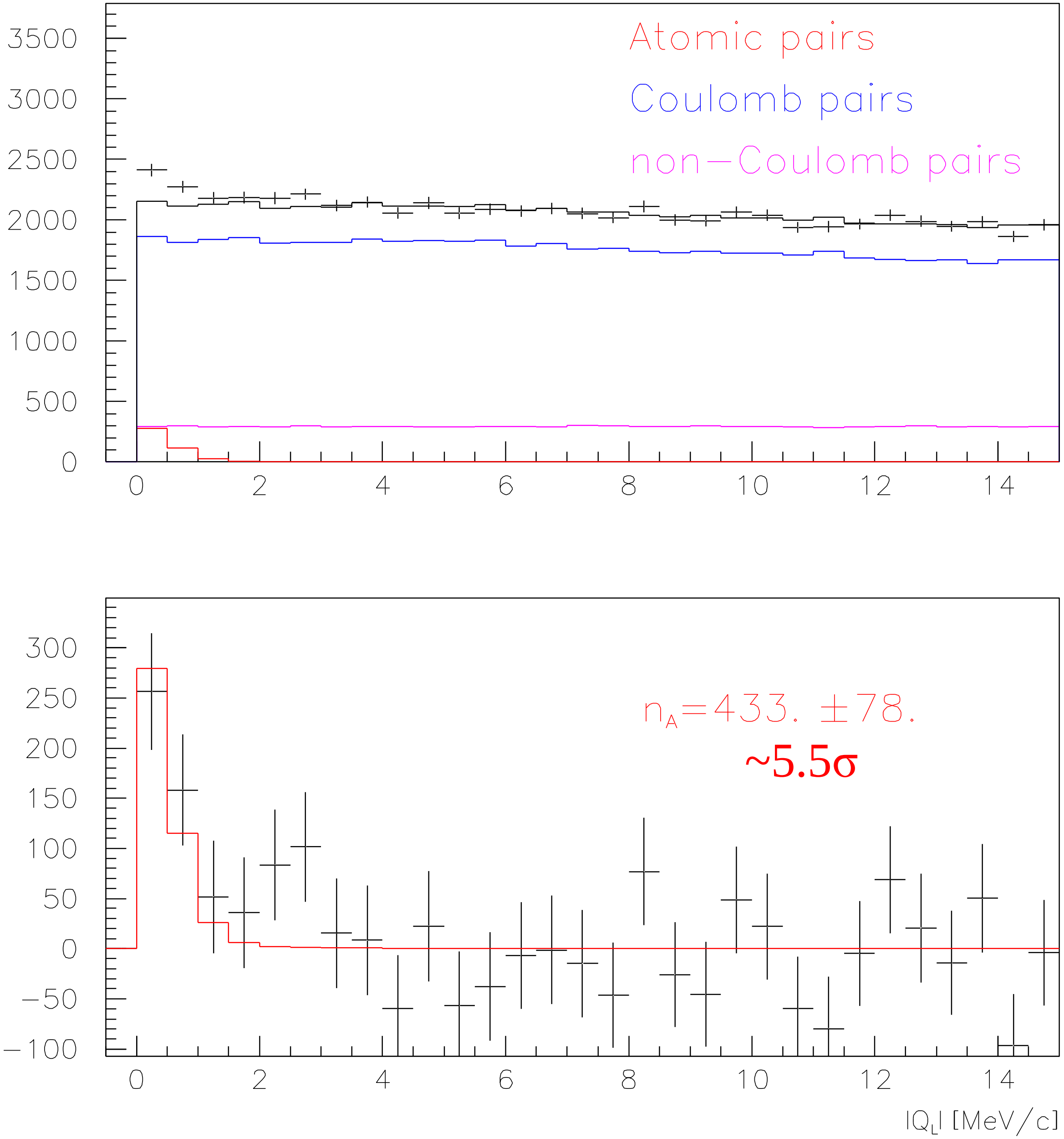


Experimental (real data) and simulated distributions over $|Q_L|$

for Q_T<1.0 MeV/c

$$Q_T = \sqrt{Q_X^2 + \left(Q_Y - 2.3MeV/c\right)^2}$$

Long-lived $\pi^+\pi^-$ atoms

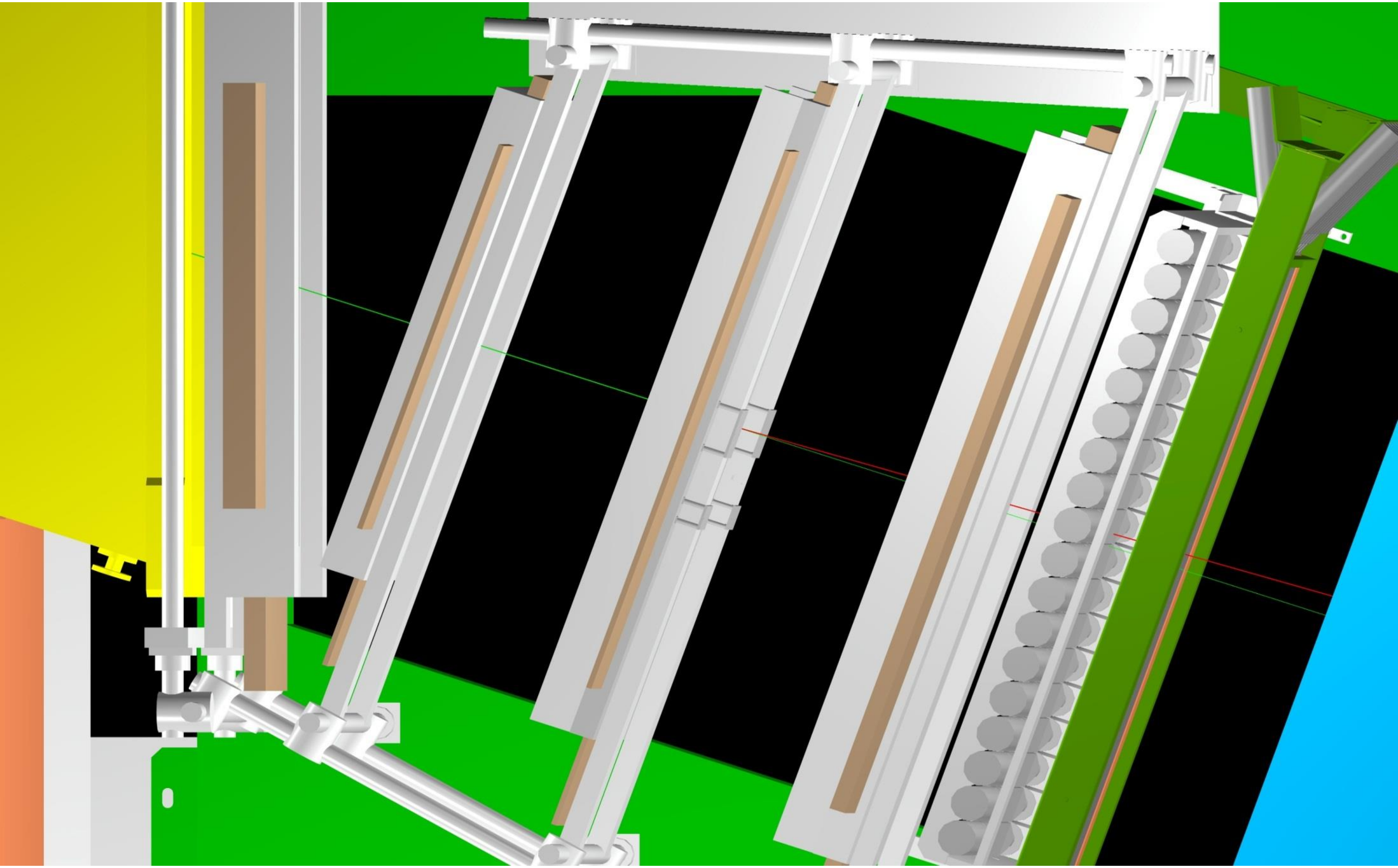


Experimental (real data) and simulated distributions over $|Q_L|$

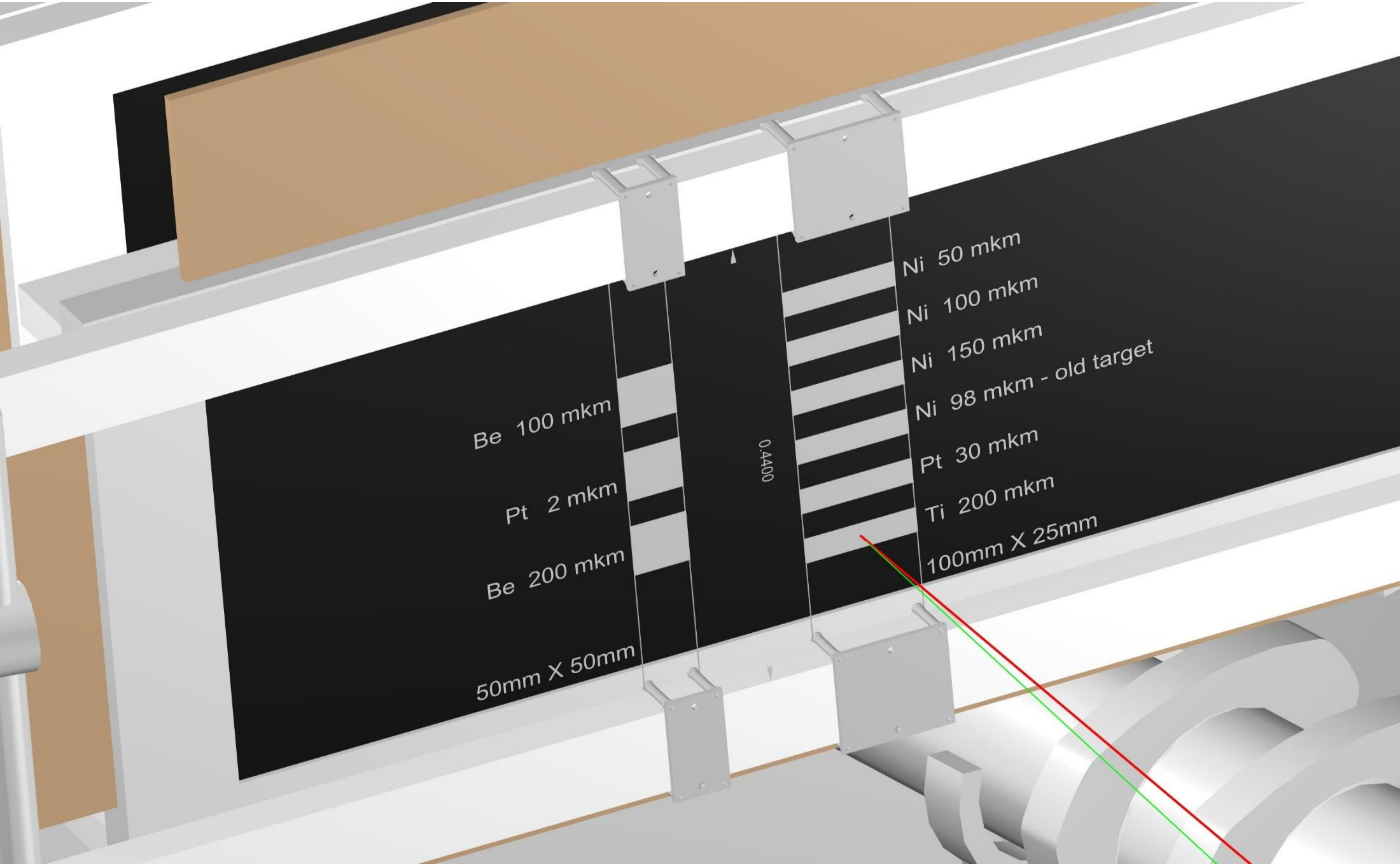
for Q_T<1.5 MeV/c

$$Q_T = \sqrt{Q_X^2 + \left(Q_Y - 2.3MeV/c\right)^2}$$

Multiple scattering measurement

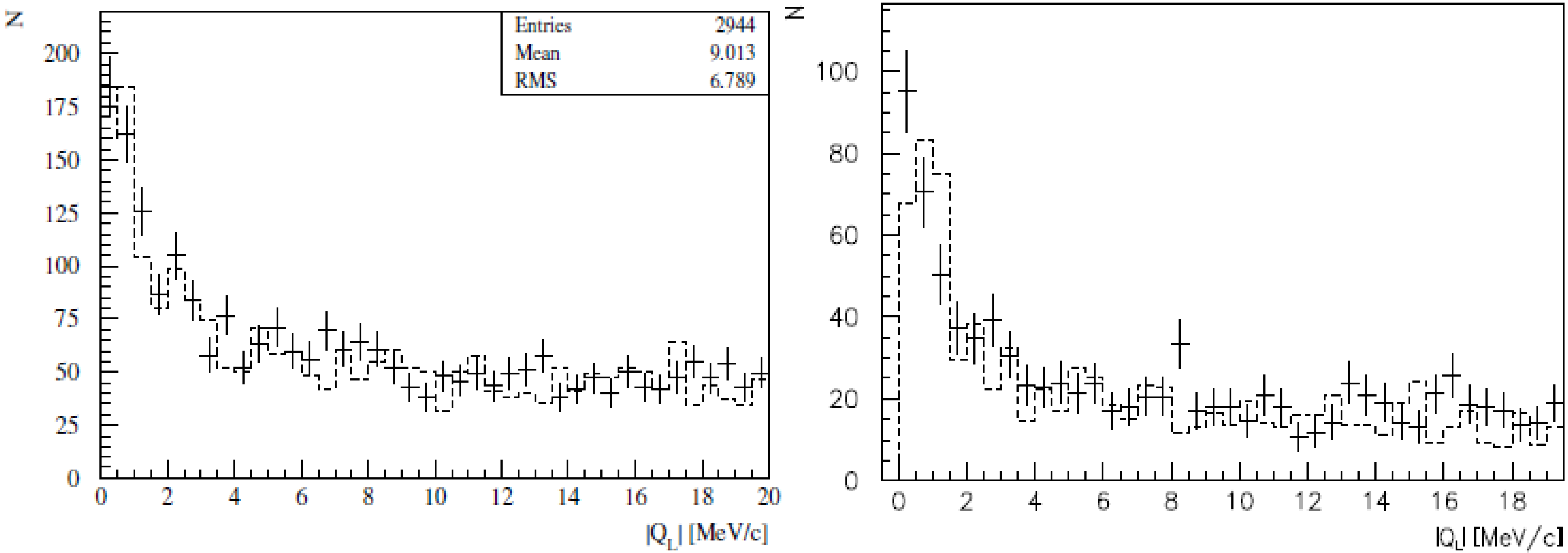


Multiple scattering measurement



Measurement of $A_{2\pi}$ production rate in p-Be interactions

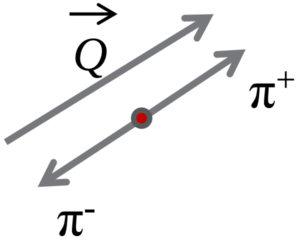
Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of "Coulomb" and "non-Coulomb" pairs (dashed line).

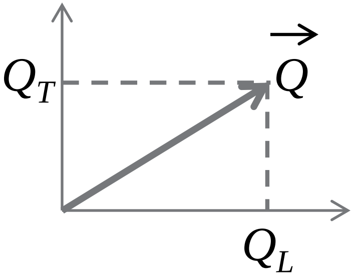


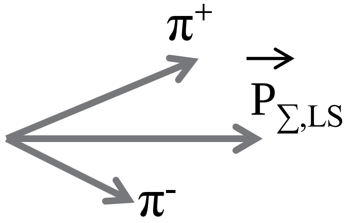
Produced atom numbers normalized on the proton flux:

$N_{A_{2\pi}}/p = (5.1 \pm 0.5) \times 10^{-14}$ *(2010)*

$N_{A_{2\pi}}/p = (5.9 \pm 0.5) \times 10^{-14}$ *(2011)*







DIRAC setup characteristics and experimental conditions

The angle of the secondary channel relative to proton beam	$5.7 \pm 1^\circ$
Solid angle	$1.2 \cdot 10^{-3}$ sr
Dipole magnet	$B_{max} = 1.65$ T BL = 2.2 Tm

Spectrometer		
Relative resolution on the particle momentum in L.S.		$3 \cdot 10^{-3}$
Precision on Q-projections (experimental measurement)	$\sigma_{QX} = \sigma_{QY} = 0.5$ MeV/c	$\sigma_{QL} = 0.5$ MeV/c ($\pi\pi$) $\sigma_{QL} = 0.9$ MeV/c (πK)