Check of QCD predictions at low energy with $K\pi$ and $\pi^+\pi^-$ atoms

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6. Publications and plans.

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

$e^+e^- \to$ 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 $\mathcal{L}(2)$, $\mathcal{L}(3)$ 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.

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:

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

Lattice calculations results

Theory	K.Sasaki et al., Phys.Rev. (2014)	Z.Fu, Phys.Rev. (2013)	S.R.Beane et al. Phys.Rev (2008)	X.Feng et al., Phys.Lett.B (2010)	T.Yagi et al., arXiv:1108.2970 (2011)
a_2	–0.04263(22)(41)	–0.04260(25)(40)	–0.04260(25)	–0.04385(28)(38)	–0.04410(69)(18)

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)**

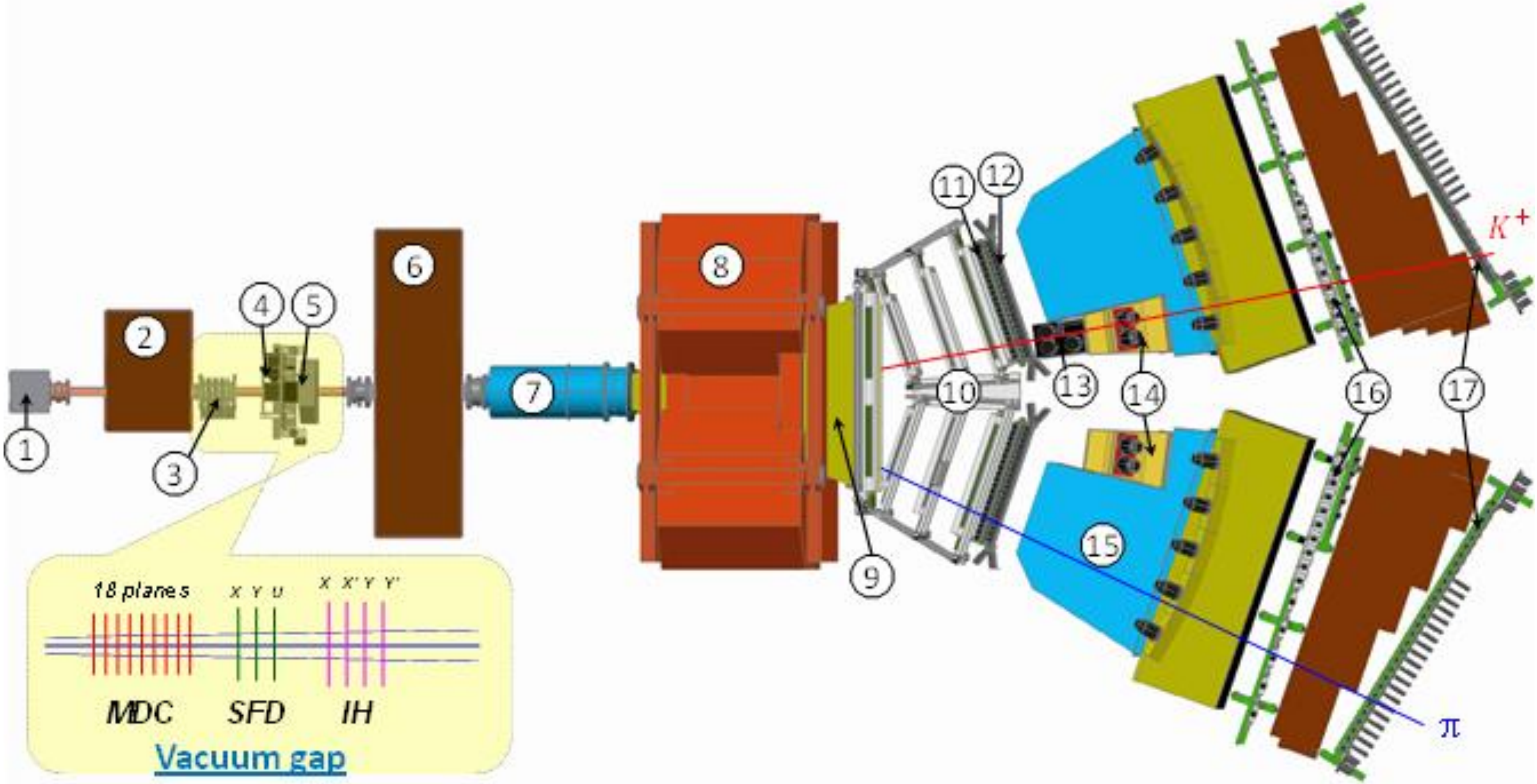
  $\bar{l}_3=2.9\pm2.4$, $\bar{l}_4=4.3\pm0.9$
- Lattice calculations of these constants have been done in 20 works.

  Best result (BMW): $\bar{l}_3=2.6\pm0.5\text{st}\pm0.4\text{sys}$, $\bar{l}_4=3.8\pm0.4\text{st}\pm0.2\text{sys}$

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%.

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

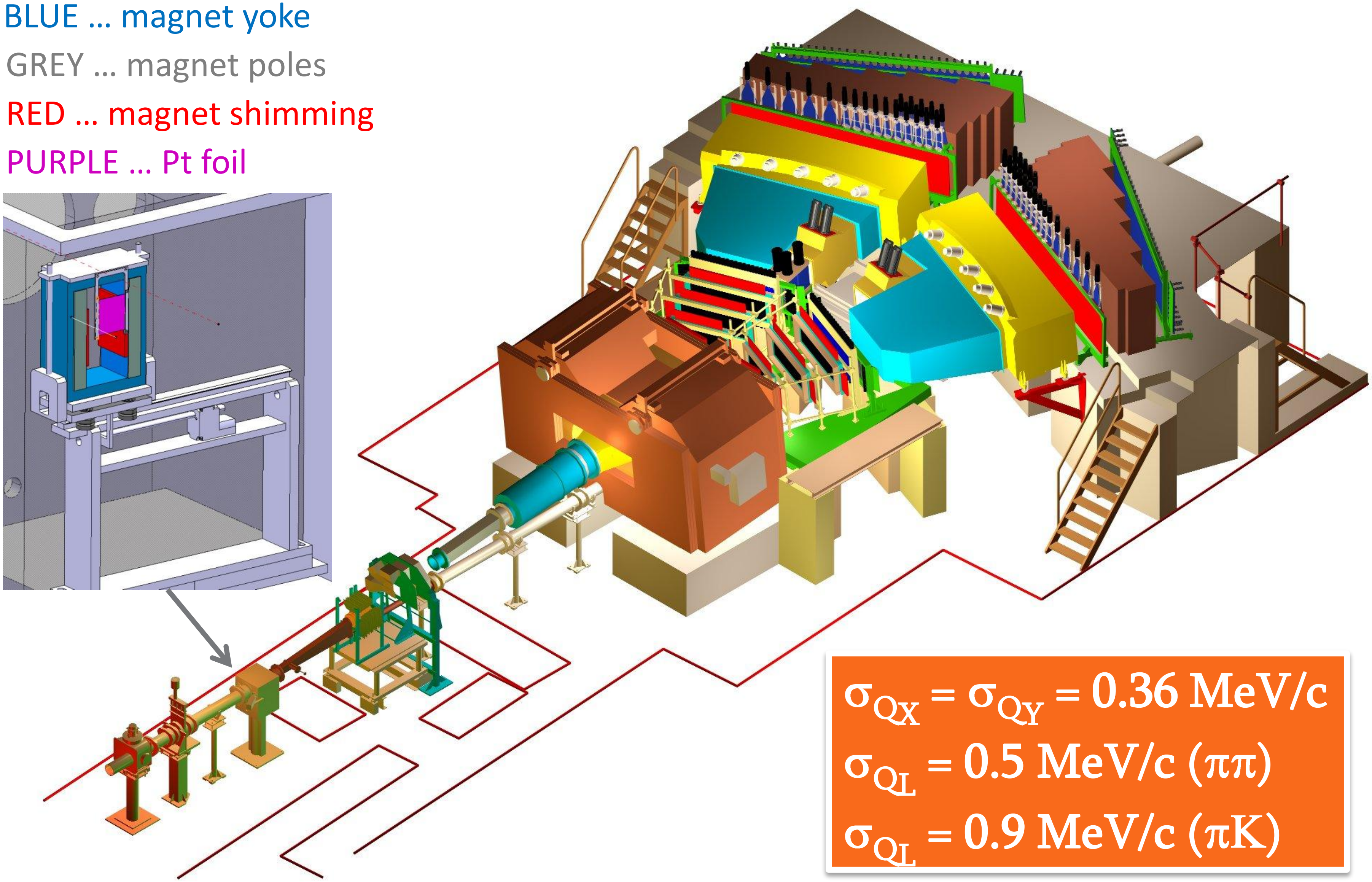
DIRAC upgraded Experimental setup

BLUE … magnet yoke

GREY … magnet poles

RED … magnet shimming

PURPLE … Pt foil

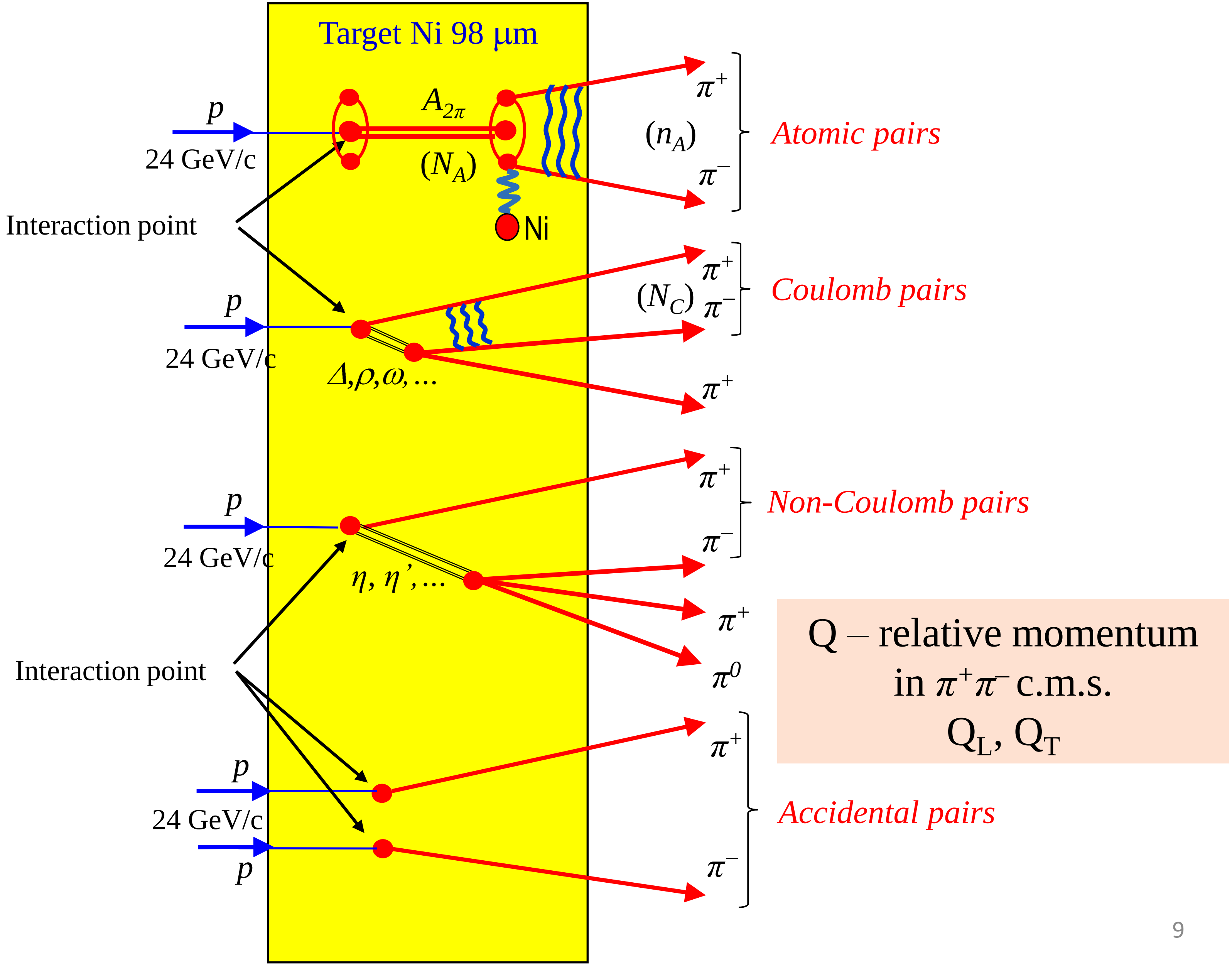


$\sigma_{QX} = \sigma_{QY} = 0.36$ MeV/c

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

$\sigma_{QL} = 0.9$ MeV/c (πK)

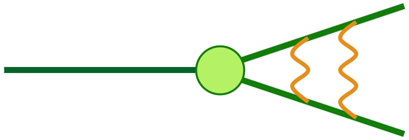
Method of $A_{2\pi}$ observation and measurement



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

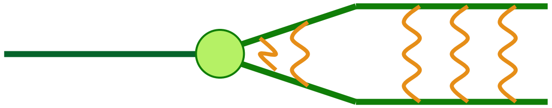
Coulomb pairs and atoms

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:

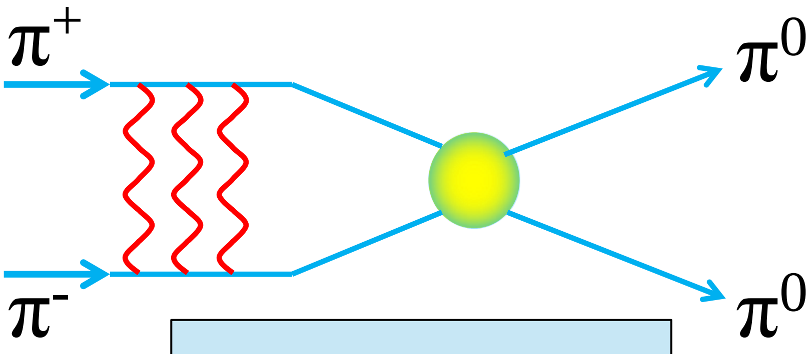
$$\boxed{N_A = K(Q_0)N_C(Q \le Q_0), \frac{\delta K(Q_0)}{K(Q_0)} \le 10^{-2}}$$

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

$\pi^+\pi^-$ 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:

$$\Gamma \quad \frac{1}{\tau} \quad \Gamma_{2\pi^0} \quad \Gamma_{2\gamma}$$

$$\frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4\times10^{-3}$$

$$-$$

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

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

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

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* ⟶ $\pi^0\pi^0$.

Experimental results

$K \to 3\pi$:

scattering length in m_π^{-1}

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)

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

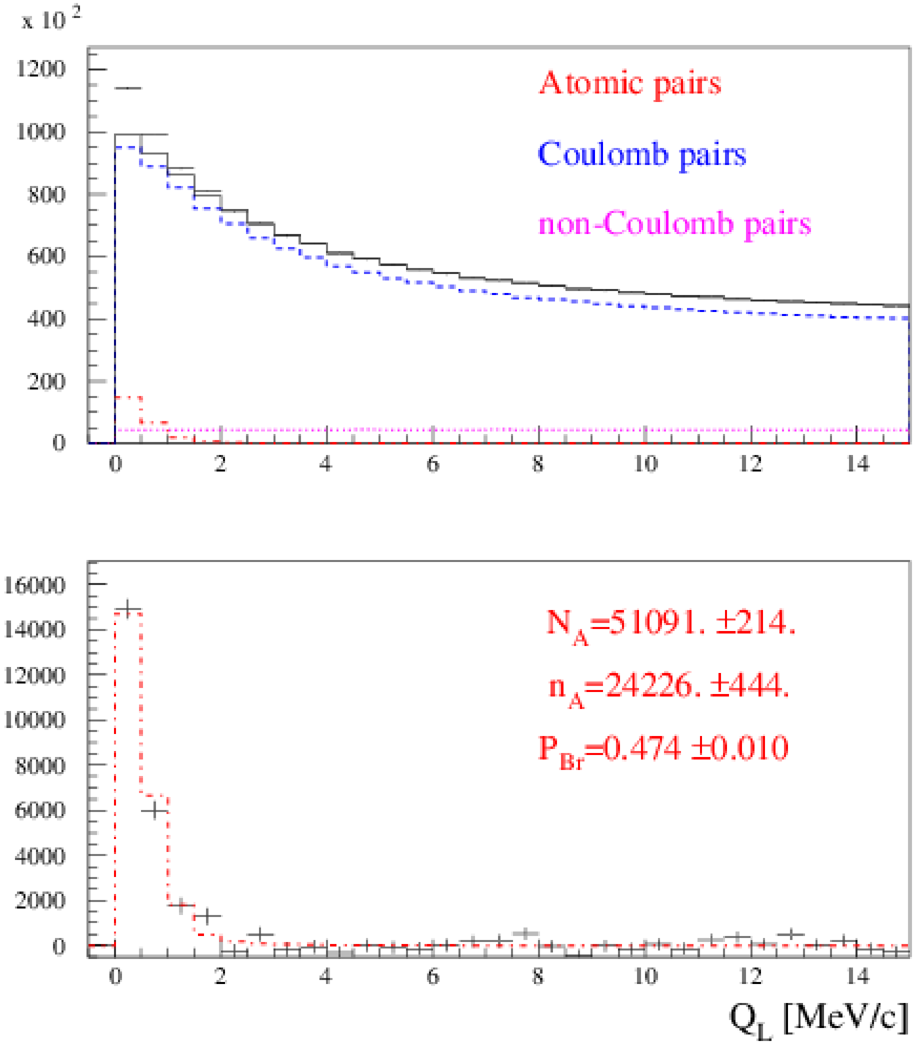
$$\Rightarrow a_2 = -0.0432 \pm 0.0086\Big|_{stat} \pm 0.0034\Big|_{syst} \pm 0.0028\Big|_{theo} = \ldots \pm 22\%$$

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

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

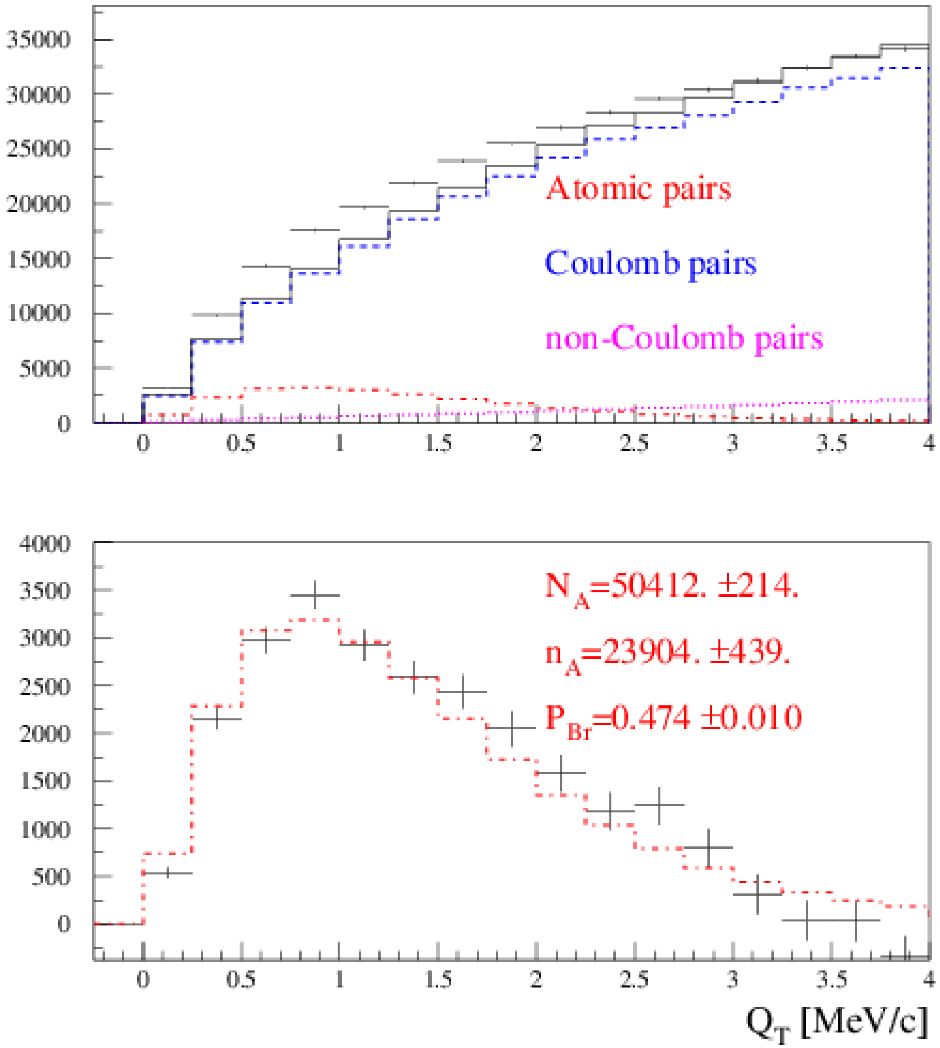
$$\Rightarrow |a_0 - a_2| = 0.2533 {}^{+0.0078}_{-0.0080}\Big|_{stat} {}^{+0.0072}_{-0.0077}\Big|_{syst} = \ldots {}^{+4.2\%}_{-4.4\%}$$

Distribution of $\pi^+ \pi^-$ pairs, collected in 2008-2010



Distribution over $|Q_L|$ of events, selected with criterion $Q_T < 4$ MeV/c. Fractions of atomic, Coulomb and non-Coulomb pairs have been obtained with fit of distribution over $(|Q_L|, Q_T)$ with criteria: $|Q_L| < 15$ MeV/c, $Q_T < 4$ MeV/c

Distribution of $\pi^+ \pi^-$ pairs, collected in 2008-2010



Distribution over Q_T of events, selected with criterion $|Q_L| < 2$ MeV/c. Fractions of atomic, Coulomb and non-Coulomb pairs have been obtained with fit of distribution over $(|Q_L|, Q_T)$ with criteria: $|Q_L| < 15$ MeV/c, $Q_T < 4$ MeV/c

πK scattering

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

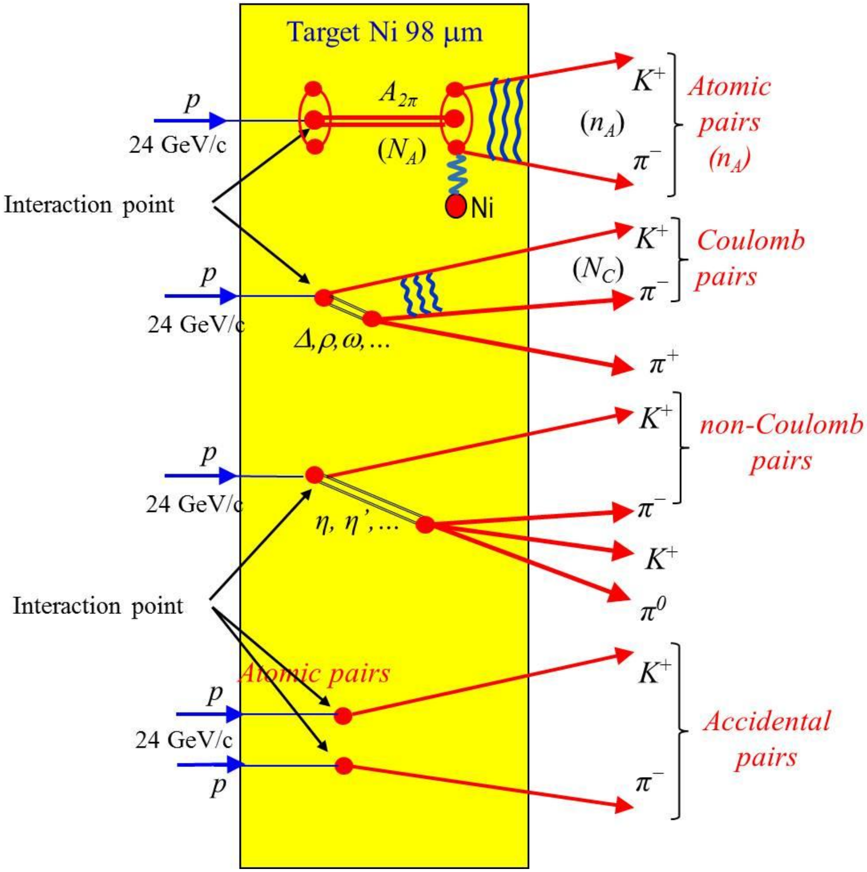
The measurement of the s-wave πK scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking (u, d and s quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u, d quarks).

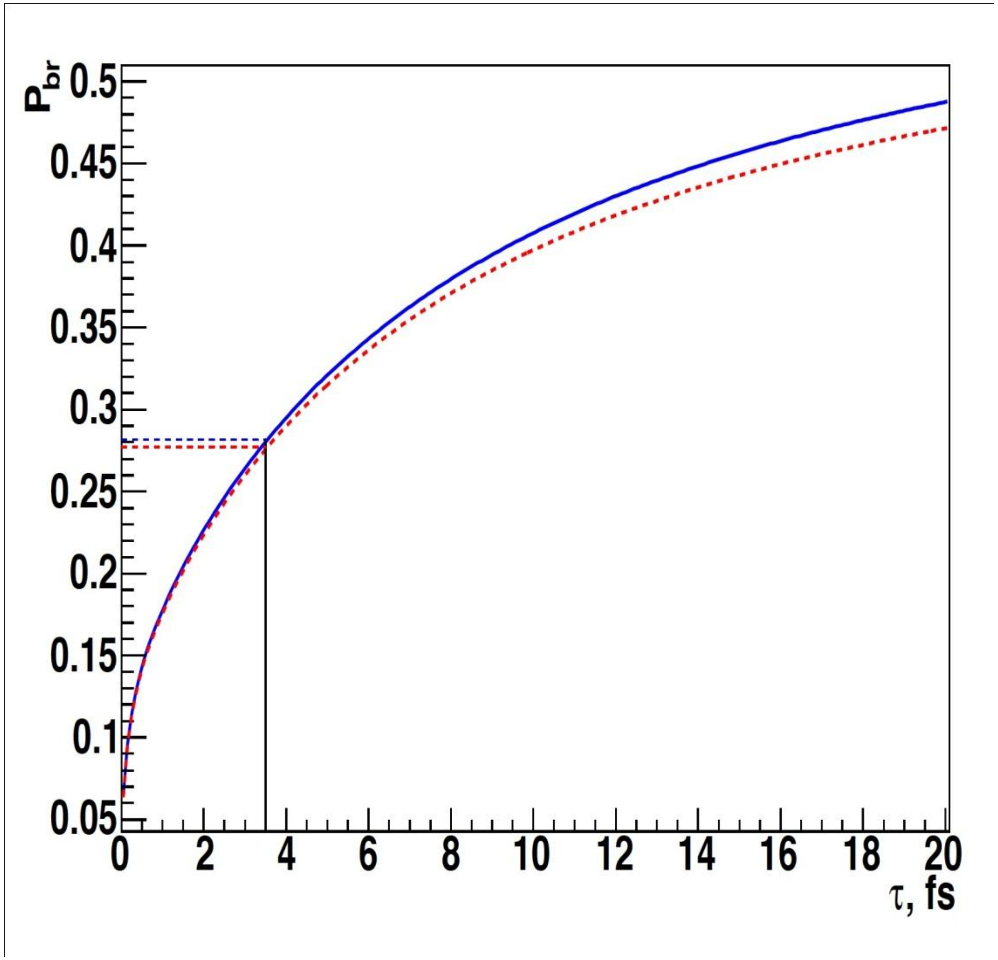
This is the principal difference between $\pi\pi$ and πK scattering!

The πK atom lifetime and πK scattering length

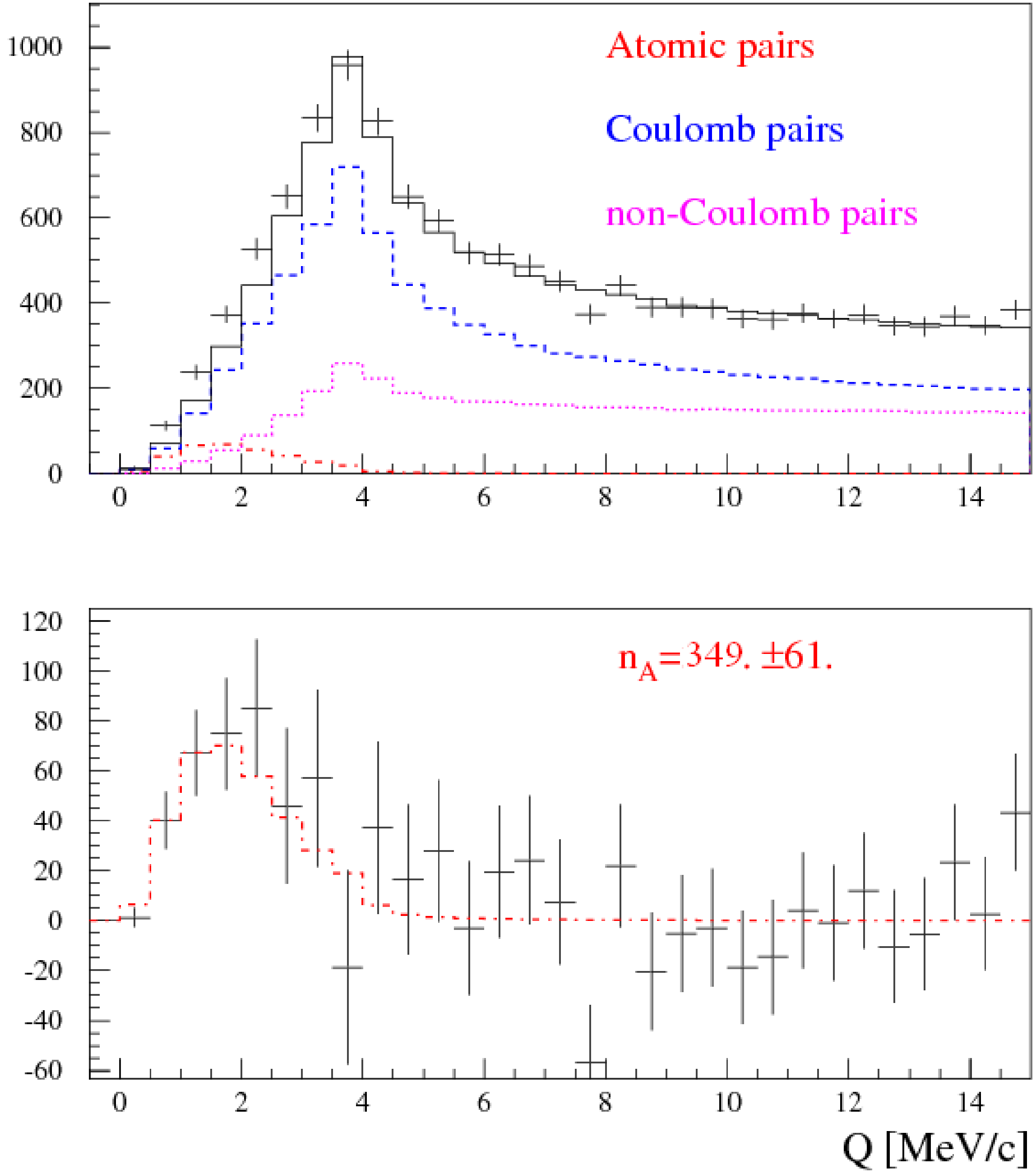
$$- = R\,|\boldsymbol{a}_{1/2}\text{-}\boldsymbol{a}_{3/2}|^2$$

τ_{th} =(3.5 0.4)×10^{-15} s. The evaluation error from this relation for $|a_{1/2}\text{-}a_{3/2}|$ is 1%





Experimental Q distributions of π^-K^+ and π^+K^- pairs



Experimental and theoretical data

Experiment	Detected atomic pairs (n_A)	τ (10^{-15} sec)	$a^{-} = -(a_{1/2}-a_{3/2})$	**Average error**
DIRAC	Phys.Rev.Lett. 117,(2016) =349 62(tot) (5.6σ)			34%

Theory	P.Buttiker et al., Eur.Phys.J. (2004)	K.Sasaki et al., Phys.Rev. (2014)	Z.Fu, Phys.Rev. (2013)	S.R.Beane et al. Phys.Rev (2008)
Method	Roy-Steiner equations	Lattice calculations	Lattice calculations	Lattice calculations
$a_{1/2}$	0.224±0.022	0.183±0.018±0.035	0.1819±0.0035	
$a_{3/2}$	–0.0448±0.0077	–0.0602±0.0031±0.0026	–0.0512±0.0018	

Theory	P.Buttiker et al., Eur.Phys.J. (2004)	K.Sasaki et al., Phys.Rev. (2014)	Z.Fu, Phys.Rev. (2013)	S.R.Beane 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		0.089
Method	Roy-Steiner equations	Lattice calculations	Lattice calculations	Lattice calculations	Lattice calculations	ChPT, two loops

$\pi^+\pi^-$ atom lifetime

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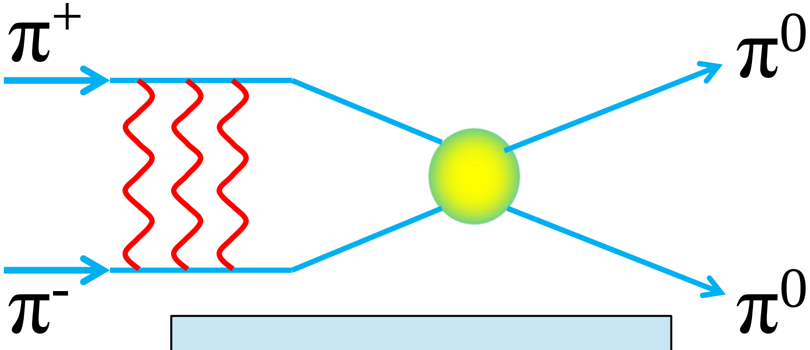

The $\pi^+\pi^-$ atom lifetime is dominated by the decay into $\pi^0\,\pi^0$ mesons:

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$$\frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4\times10^{-3}$$

—

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

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

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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* ⟶ $\pi^0\pi^0$.

$\pi^+\pi^-$ 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	$2.9\cdot10^{-4}$	-	$1.39\cdot10^{-3}$	-
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

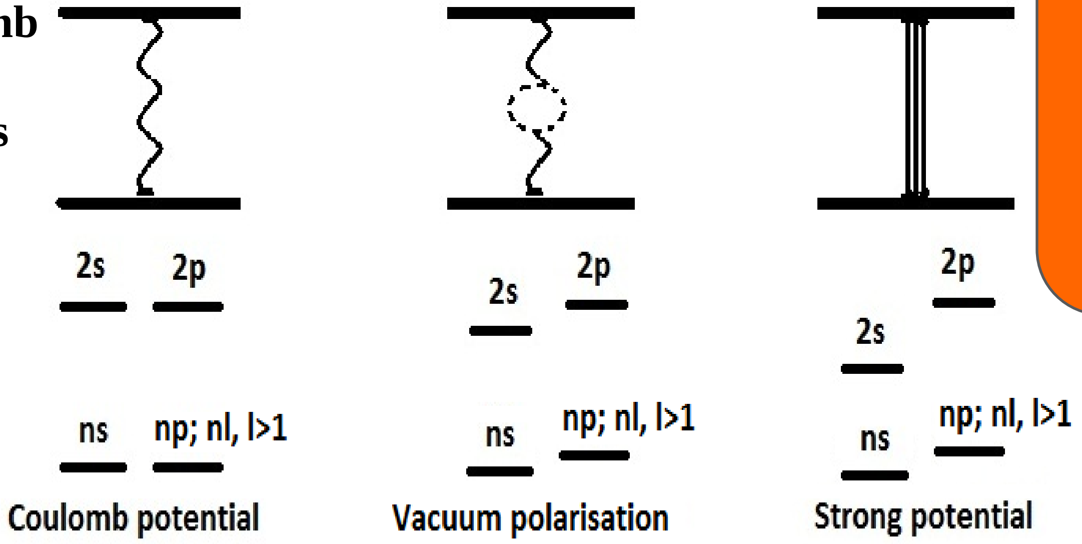
Breakup foil	Thick (μm)	2p	3p	4p	5p	6p	7p
Pt (Z=78)	1.0	0.4147	0.6895	0.8553	0.9324	0.9667	0.9828
	1.5	0.6084	0.8526	0.9446	0.9765	0.9889	0.9944
	2.0	0.7422	0.9244	0.9743	0.9895	0.9951	0.9975

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)

Energy splitting measurement

$A_{2\pi}$ Energy Levels

For Coulomb potential, E depends only on n



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)]

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

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

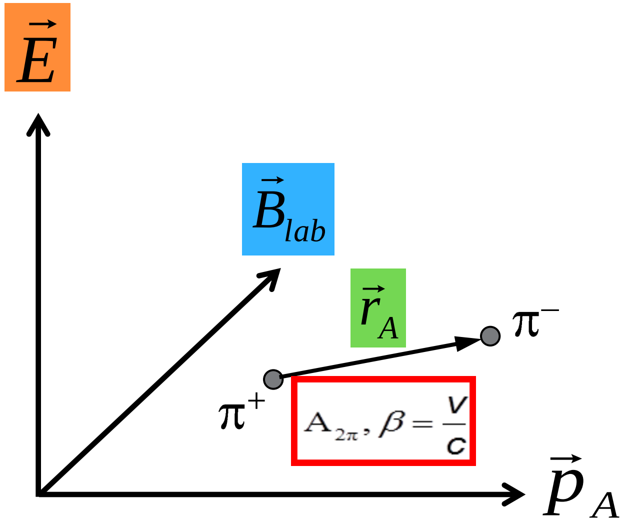
$$\Delta^{str}_{ns-np} = -\frac{\Delta^{str}_{2s-2p}}{n^3}\cdot 8$$

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

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 $\underline{\boldsymbol{B_{lab}}}$ and Lorentz factor $\underline{\boldsymbol{\gamma}}$



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

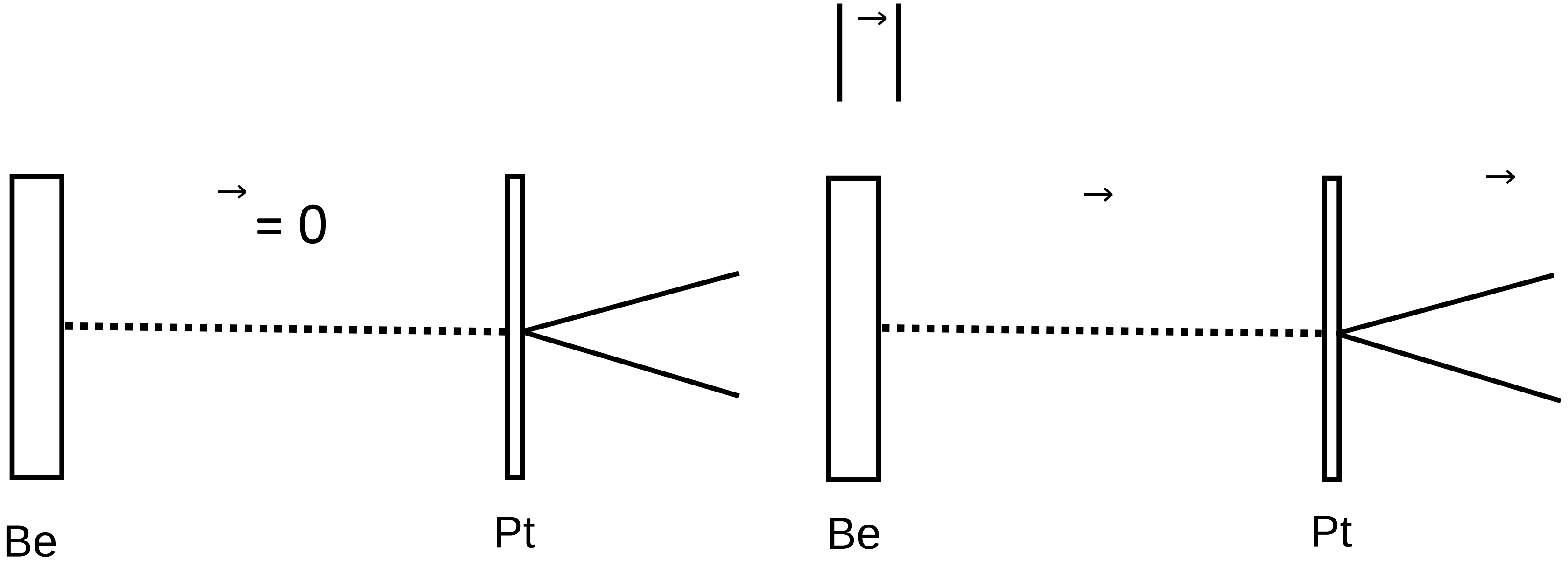
$\vec{B}_{lab}$ …. laboratory magnetic field

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

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

Energy splitting measurement

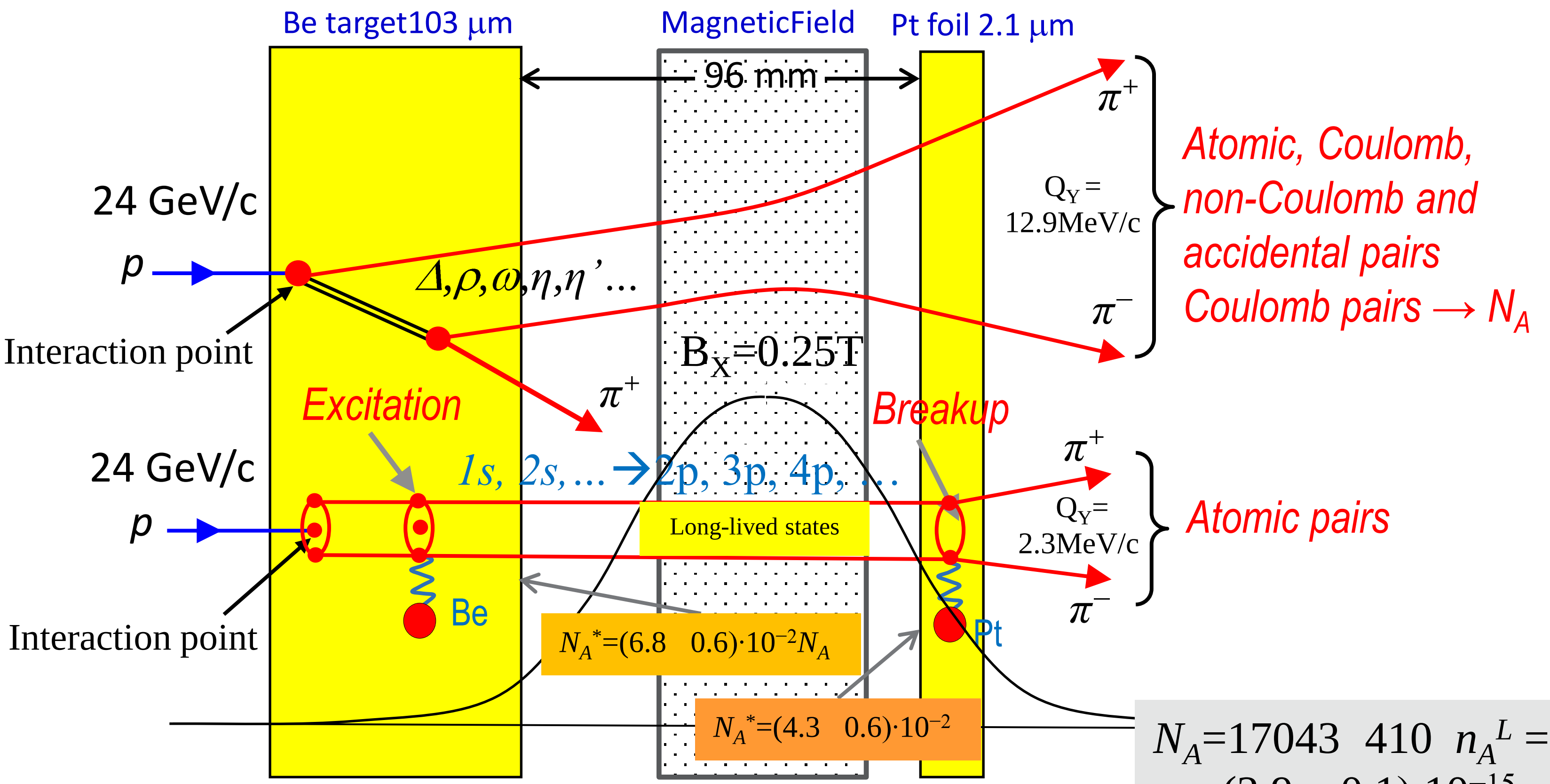
In the static electric field there will be Stark mixing between the *ns* and the *np* wave functions.



$$(|\vec{\ }|) \qquad |\vec{\ }| \qquad)$$

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

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



N_A=17043 410 n_A^L =436 61

τ_{1s}=(2.9   0.1)$\cdot 10^{-15}s$

τ_{2p}=1.2$\cdot 10^{-11}s$

n	2	3	4	5	≥ 2
ε_n(Be) 10^2	2.48 O(10^{-3})	1.54 0.01	0.86 0.03	0.56 0.06	6.8 0.6
ε_n(Pt) 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

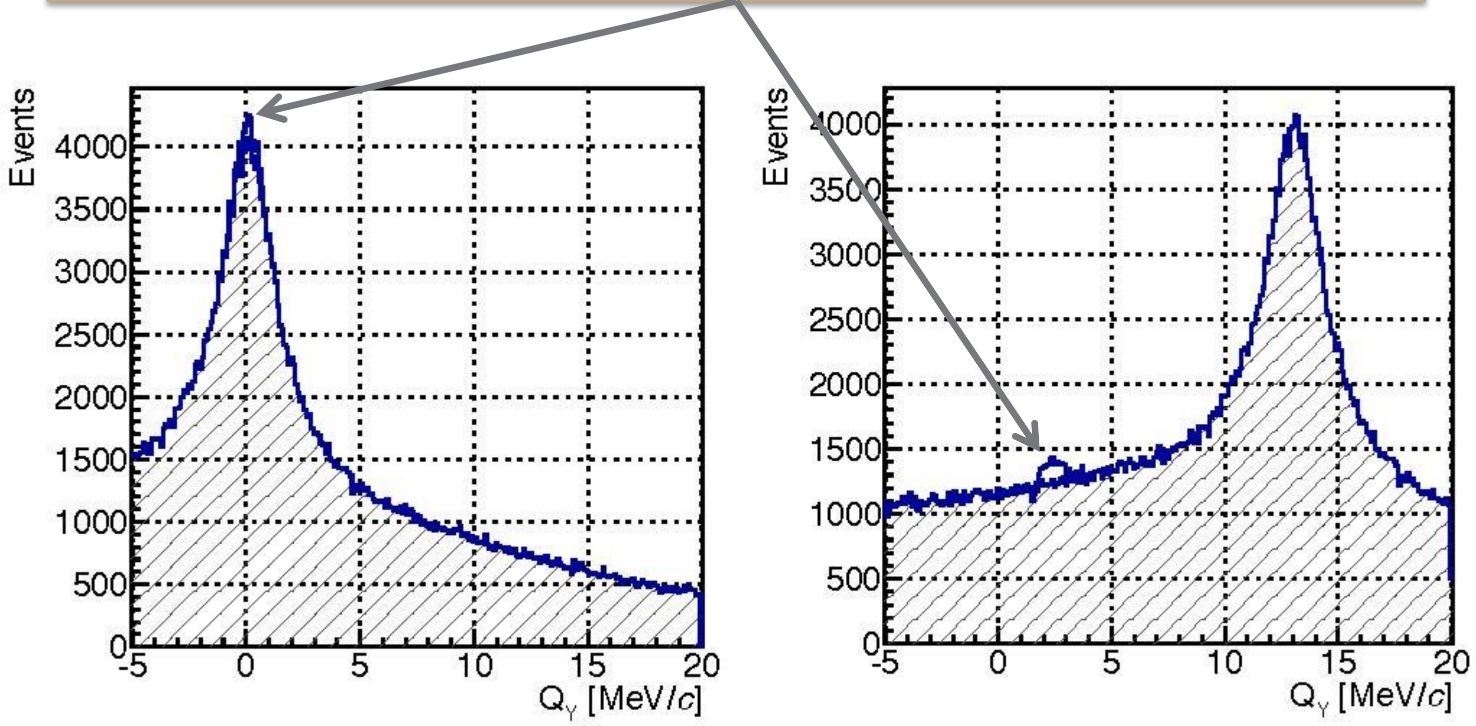
The background reduction with magnetic field for long-lived $A_{2\pi}$ observation

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: $\sqrt{Q_X^2 + Q_L^2} < 2 MeV / c$

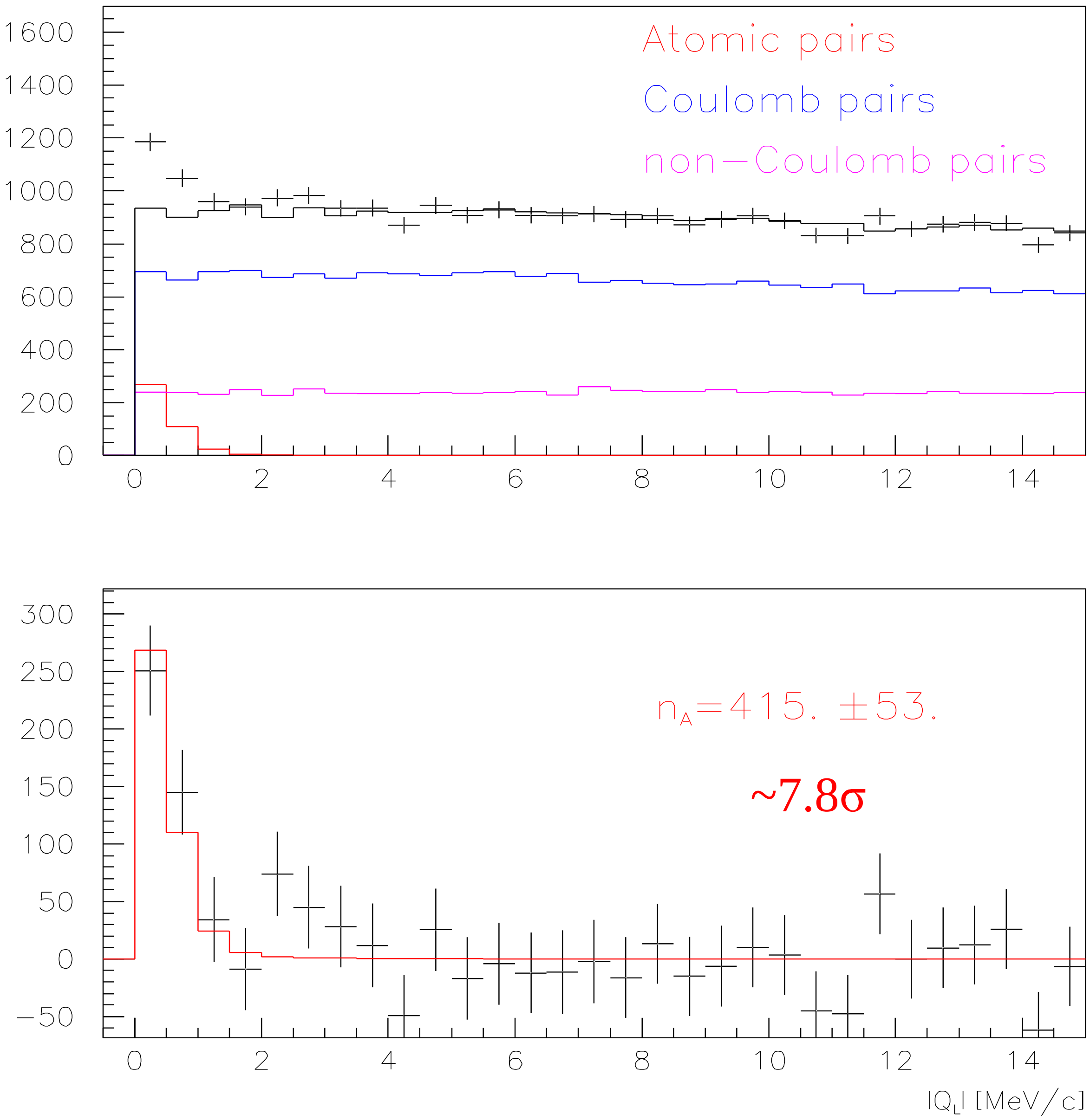
Expected signal (atomic pairs) from broken up long-lived $\pi^+\pi^-$ atoms



Simulation without magnet

Simulation with magnet

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

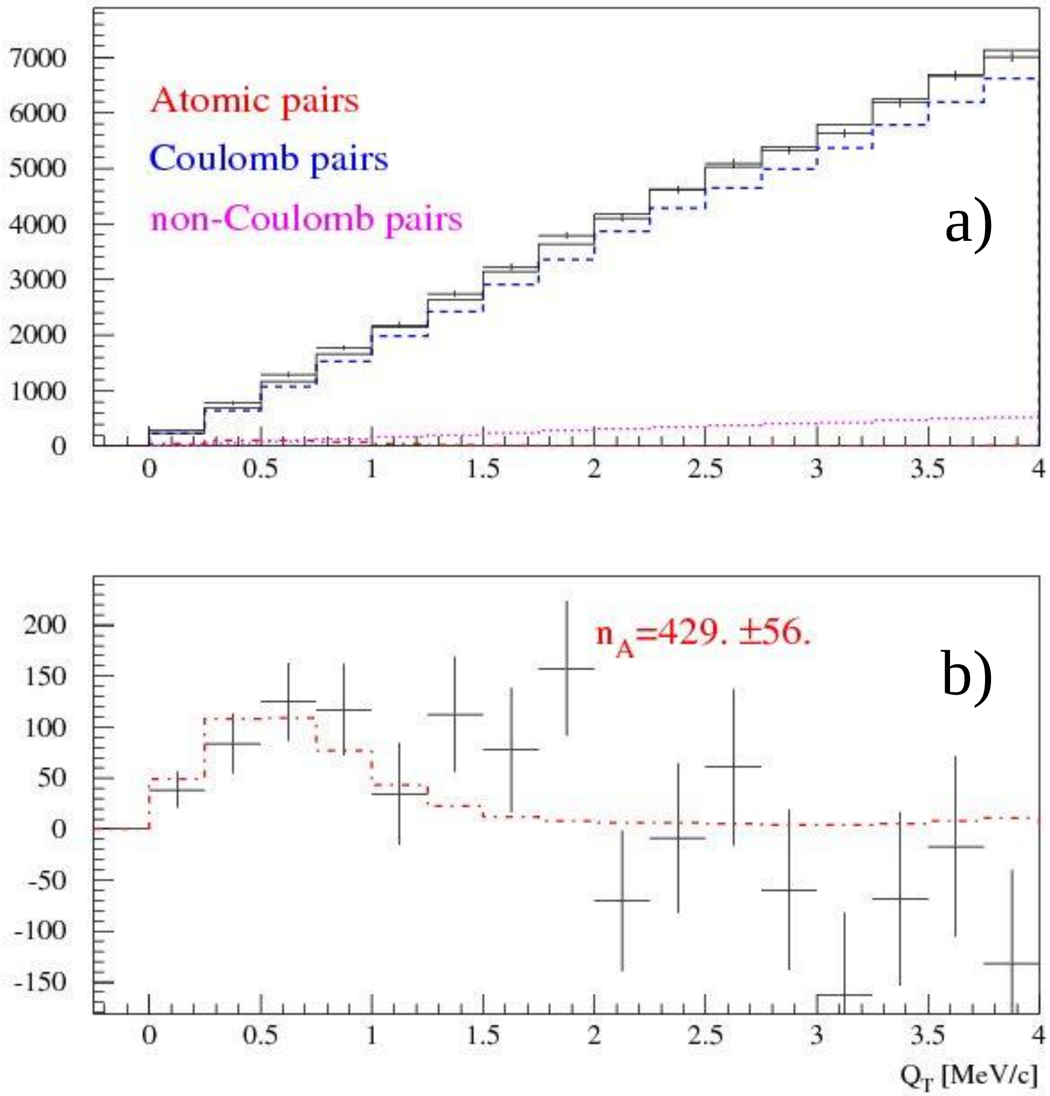


Experimental (real data) and simulated distributions over |Q_L|

for Q_T<1.0 MeV/c

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

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



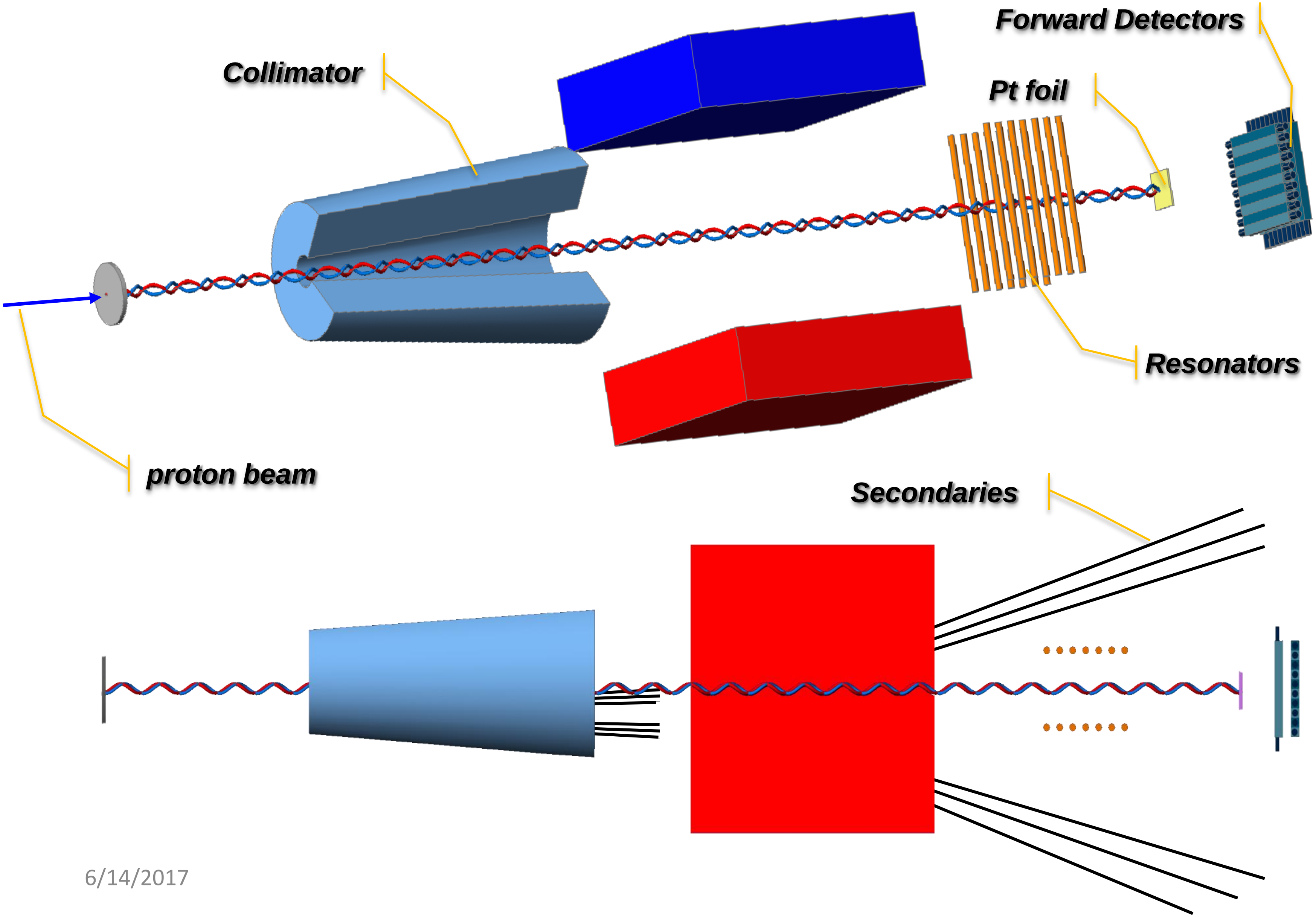
Q_T distribution of $\pi^+\pi^-$ pairs for $|Q_L| < 2$ MeV/c

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).

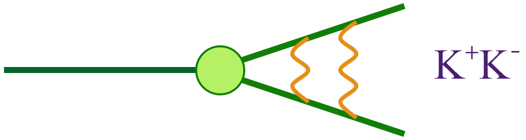
The fit procedure has been applied to the 2-dimensional ($|Q_L|$, Q_T) distribution.

DIRAC future Experimental setup

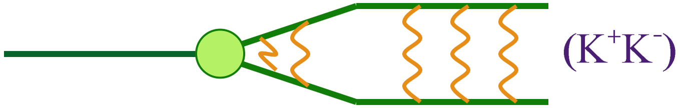


K^+K^- Coulomb pairs and K^+K^- atoms

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:

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

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

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.

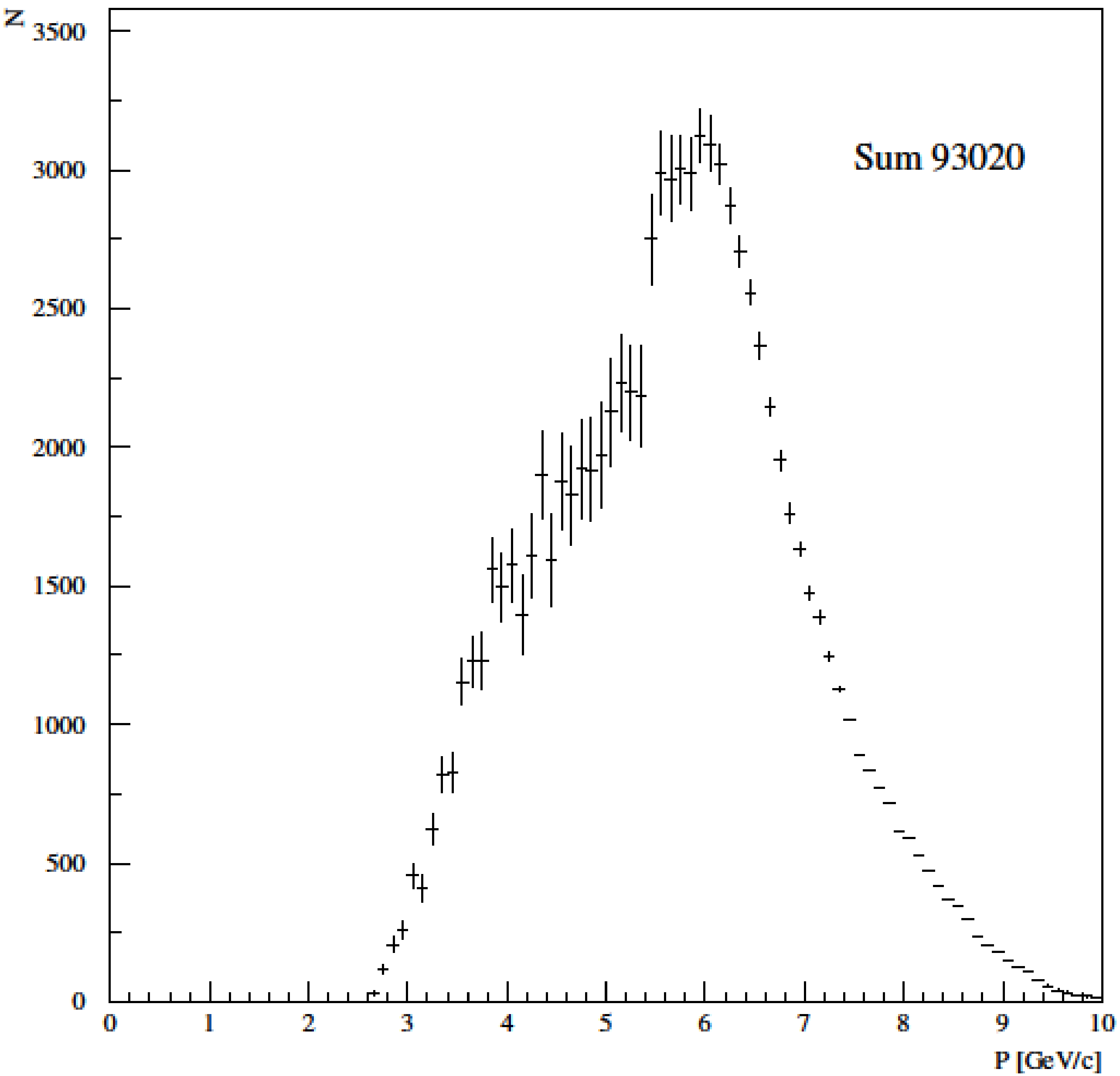
K^+K^- atom and its lifetime

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^-).

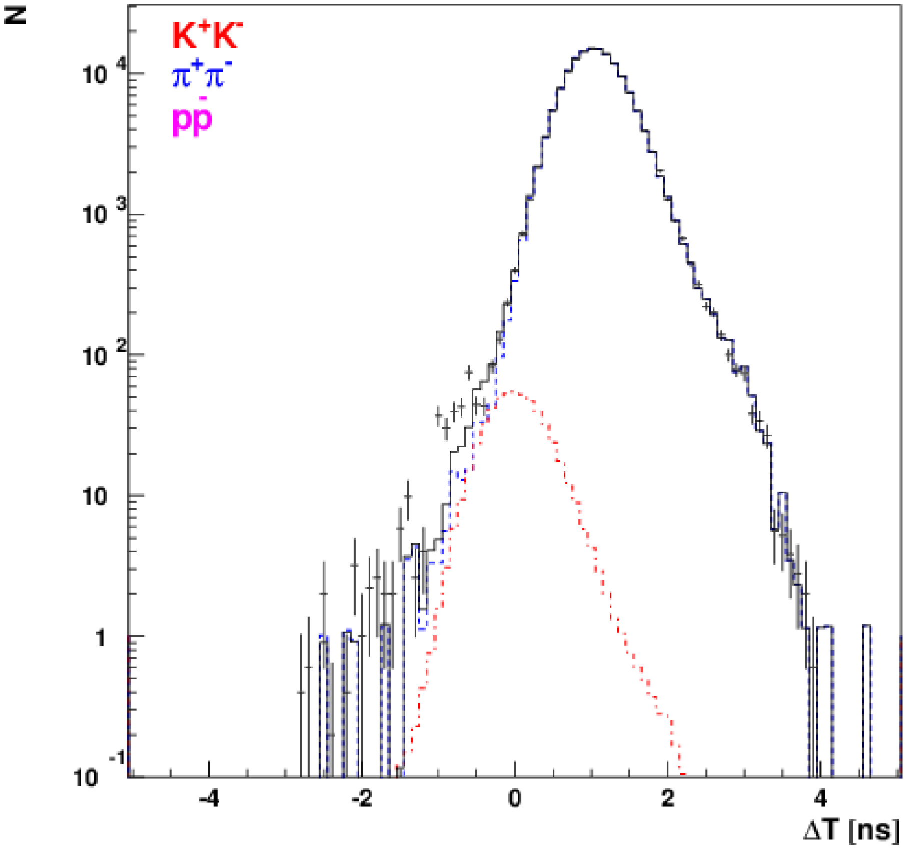
K^+K^- interaction complexity ↓

τ ($A_{2K} \rightarrow \pi\pi, \pi\eta$)	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

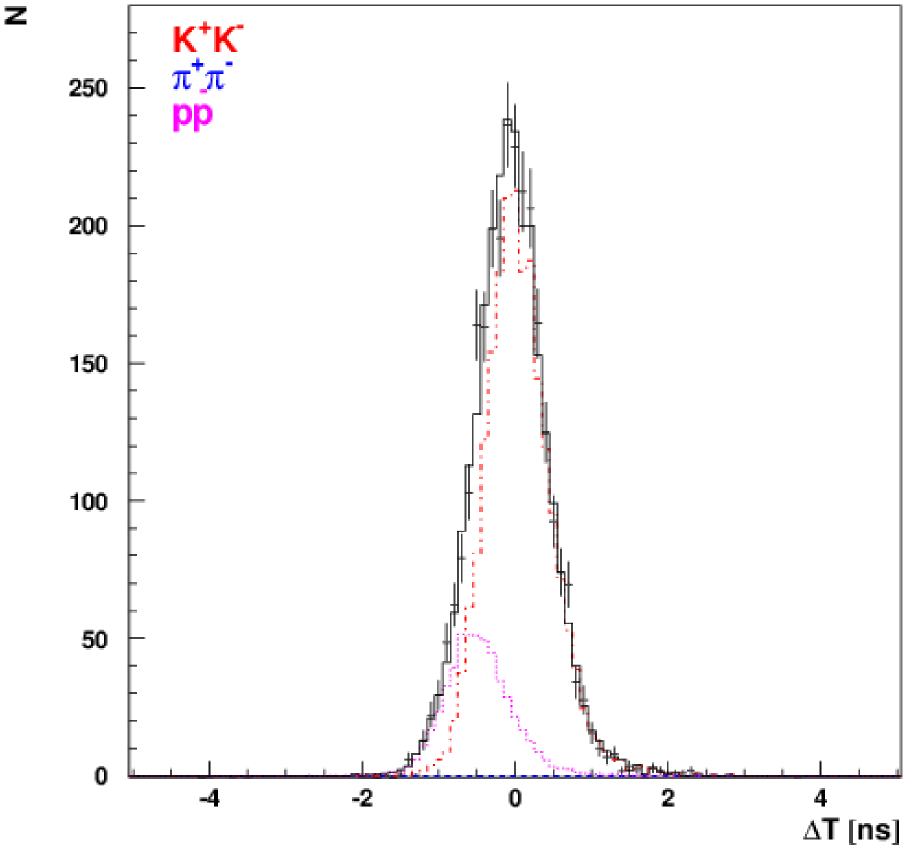
References:
[1] S. Wycech, A.M. Green, Nucl. Phys. A562 (1993), 446;
[2] S. Krewald, R. Lemmer, F.P. Sasson, Phys. Rev. D69 (2004), 016003;
[3] Y-J Zhang, H-C Chiang, P-N Shen, B-S Zou, PRD74 (2006) 014013;
[4] S.P. Klevansky, R.H. Lemmer, PLB702 (2011) 235.


N
3500
3000
2500
2000
1500
1000
500
0
Sum 93020
0
1
2
3
4
5
6
7
8
9
10
P [GeV/c]

Time-of-flight measurements for K+K- pairs

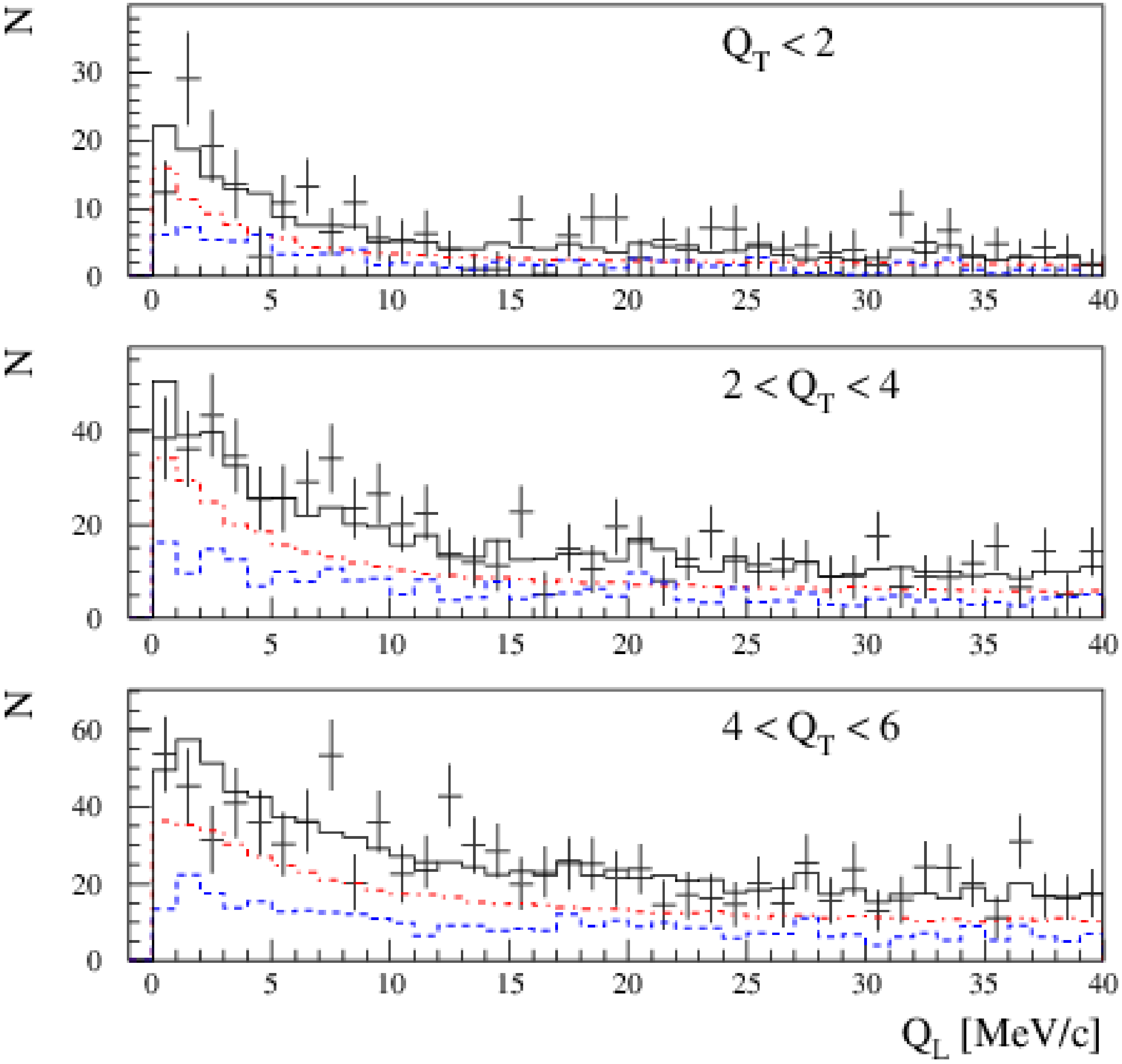


Low momenta



High momenta

Search of K^+K^- pairs in data, collected in 2010



Experimental distribution of events selected to be K^+K^- are fitted to simulated distribution of K^+K^- pairs (red) and experimental distribution of pure $\pi^+ \pi^-$ (blue). Integral number of K^+K^- pairs is 2180 ± 200, number of $\pi^+ \pi^-$ pairs is 1340 ± 200

SPS beam time for πK scattering length measurement

O.Gorchakov , L.Nemenov, J. Phys. G: Nucl. Part. Phys. 2016
The number of $\pi^+\pi^-$, $K^-\pi^+$ and $K^+\pi^-$ atoms generated per time unit on the proton beam of SPS will be 12 2, 53 11 and 24 5 times higher than in the DIRAC experiment.

The expected number of πK atomic pairs: n_A=13000 (In the DIRAC experiment n_A=349 62)

The statistical(systematic)precision of πK scattering length: ~5% (2%). (In the DIRAC experiment 34%)

The expected number of $\pi^+\pi^-$ atomic pairs n_A=400000

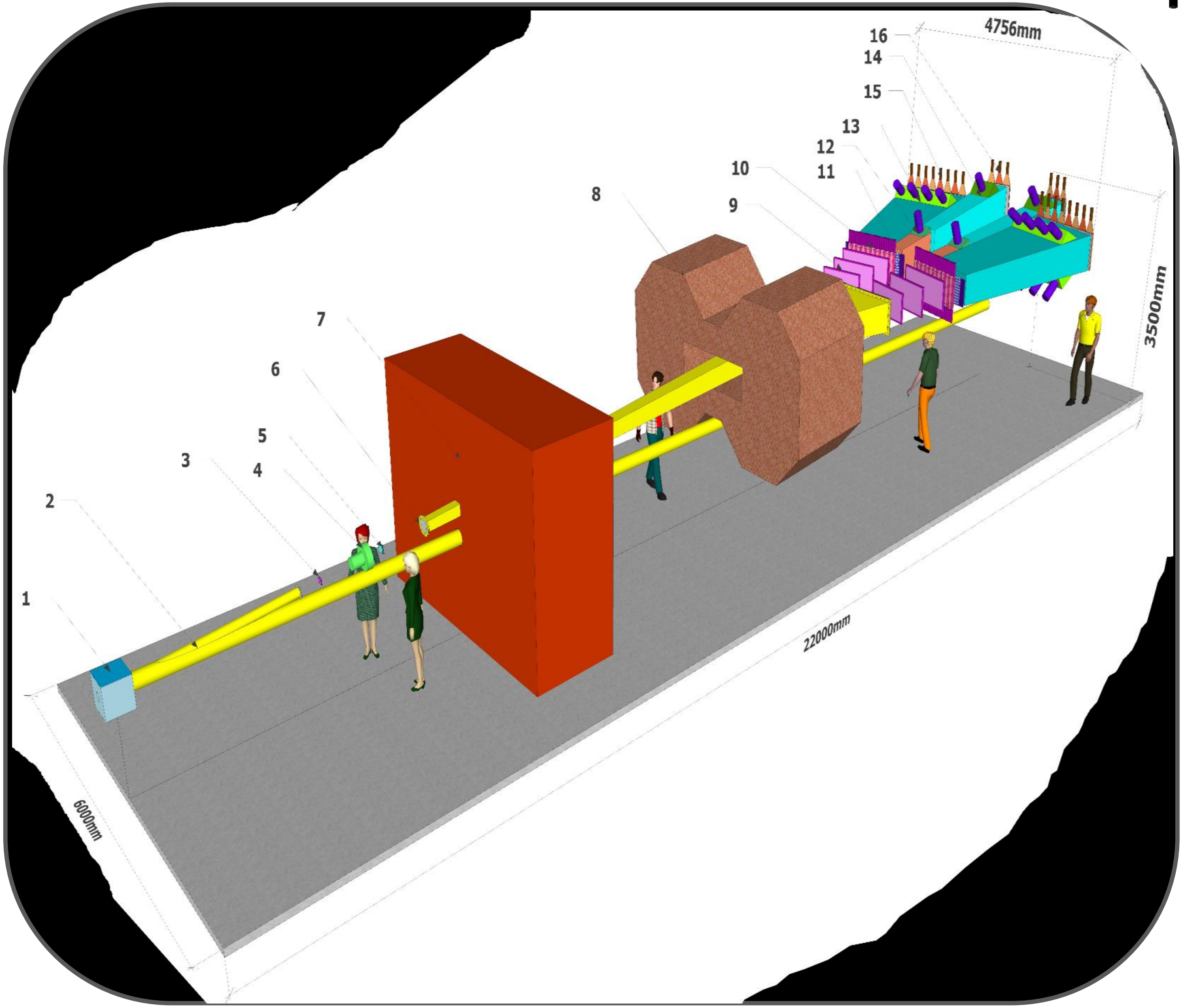
The statistical(systematic)precision of $\pi\pi$ scattering length:

0.7% (2%) V.Yazkov, DIRAC NOTE 2016-05

DIRAC+

Experimental SetUp

+



1. Box with Target Station.
2. Vacuum Tube for Primary and Secondary Proton Beam.
3. Vertex detector.
4. Particle identification detector.
5. Scintillating Fiber detector.
6. Vacuum volume for Secondary beam.
7. Iron Shielding wall.
8. Spectrometer magnet.
9. Downstream Tracker.
10. Vertical Hodoscope.
11. Horizontal Hodoscope.
12. Heavy Gas Cherenkov detector.
13. Nitrogen Cherenkov detector (part 1).
14. Nitrogen Cherenkov detector (part 2).

1. B. Adeva et al., **«First *πK* atom lifetime and *πK* scattering length measurements»**, Physics Letters B 735 (2014) 288.
2. B. Adeva et al., **«First observation of long-lived ππ atoms»**, Physics Letters B 751 (2015) 12.
3. B. Adeva et al., **«Observation of *πK* atoms»**, Physical Review Letters 117, 112001 (2016).
4. B. Adeva et al., **«Upgraded DIRAC spectrometer at CERN PS for the investigation of *ππ* and *πK* atoms»**, Nuclear Instruments and Methods in Physics Research A 839 (2016)
5. O.Gorchakov and L.Nemenov “ Estimation of production rates of $K^{+}\pi^{-}$, $K^{-}\pi^{+}$ and $\pi^{+}\pi^{-}$ atoms in proton-nucleus Interactions at 450GeV/c”, J. Phys. G: Nucl. Part. Phys. 43 (2016) 095004.

πK and $\pi\,\pi$ atoms data analysis

6.The paper "The measurement of πK atom lifetime and πK scattering lengths" submitted for publication in June 2017.

7. The paper " First measurement of the long-lived $\pi^+\pi^-$ atom lifetime" will be submitted for publication before the end of 2017.

8. Preliminary results on the $\pi^+\pi^-$ atom lifetime measurement based on all available data will be ready in 2017 and the paper " Measurement of short-lived $\pi^+\pi^-$ atom lifetime and $\pi\pi$ scattering lengths" will be published before the end of 2018.

9. Analysis of K^+K^- Coulomb pairs will be performed in 2017-2018 . The number of produced K^+K^- atoms and the upper limit of their lifetime will be evaluated and published in 2018.

·10. In 2017 DIRAC will start an investigation of proton-antiproton Coulomb pairs and thus proton-antiproton atoms with the same strategy as in the K^+K^- case . Results of investigation will be published in 2019.

11. 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 started in 2018*.

12. The experimental study of the multiple scattering in Ni: 50 μm, 109 μm and 150 μm; Be: 100 μm and 2000 μm; Pt: 2 μm and 30 μm and Ti: 250 μm. will be continue in 2017-2018 to check the Moliere theory accuracy. The statistical precision in each measurement on the order of magnitude higher than in the published measurements.

13. In 2018-2019 collaboration will study the Coulomb effects in the system of 2 and 3 charge particles.

14.During 2017-2018 collaboration will work with the PBC committee CERN to prepare the LOI for the experiment on SPS.

Thank you

DIRAC setup characteristics and experimental conditions

The angle of the secondary channel relative to proton beam	5.7±1°
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)	$\sigma_{QX} = \sigma_{QY} = 0.36$ MeV/c	$\sigma_{QL} = 0.5$ MeV/c (ππ) $\sigma_{QL} = 0.9$ MeV/c (πK)

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:

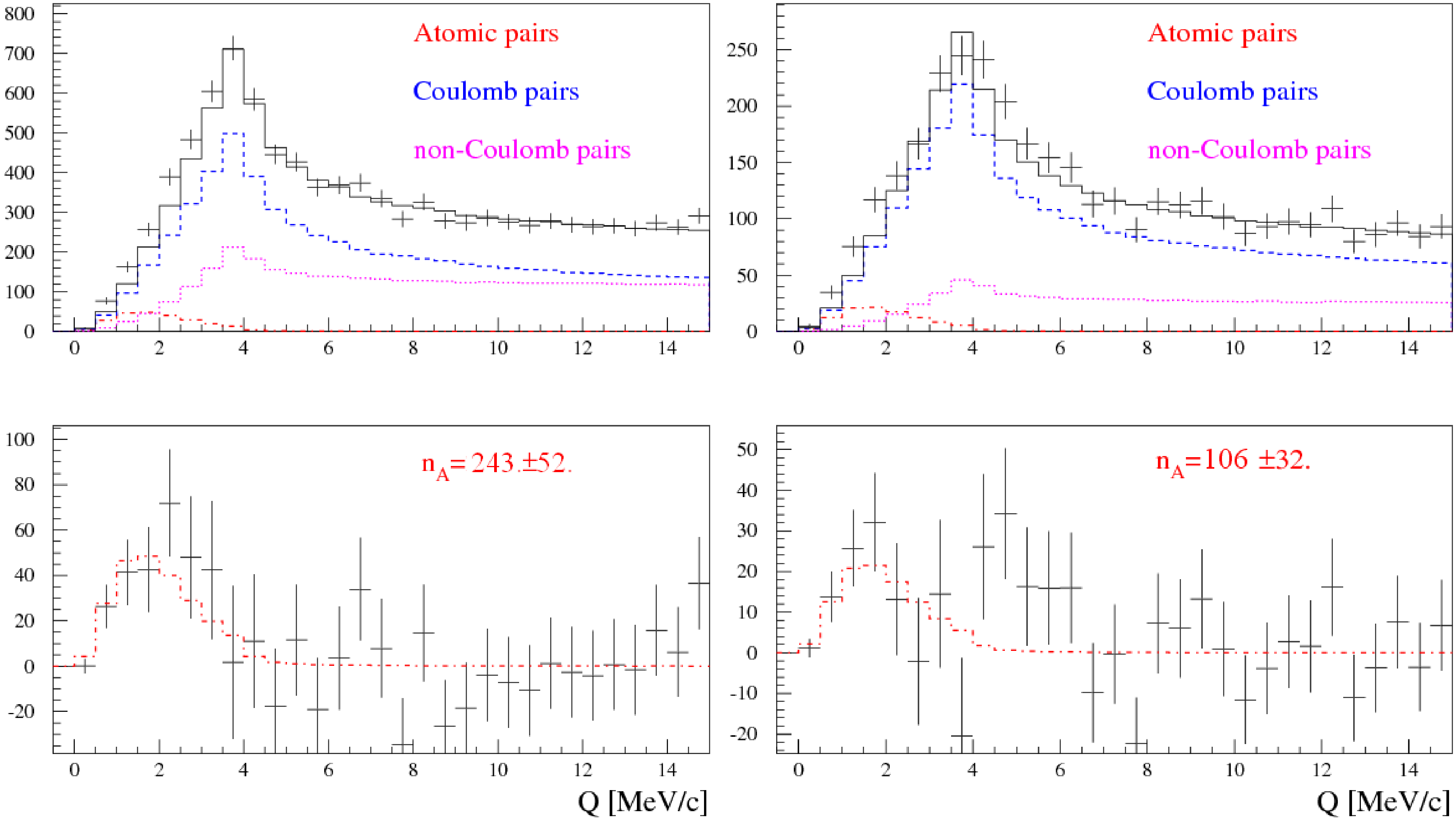
$$\Rightarrow a_0 = 0.2206 \pm 0.0049\Big|_{stat} \pm 0.0018\Big|_{syst} \pm 0.0064\Big|_{theo} = \ldots \pm 3.7\%$$

Ke4 & $K \to 3\pi$:

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

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

Experimental Q distributions of π^-K^+ and π^+K^- pairs



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

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

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

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

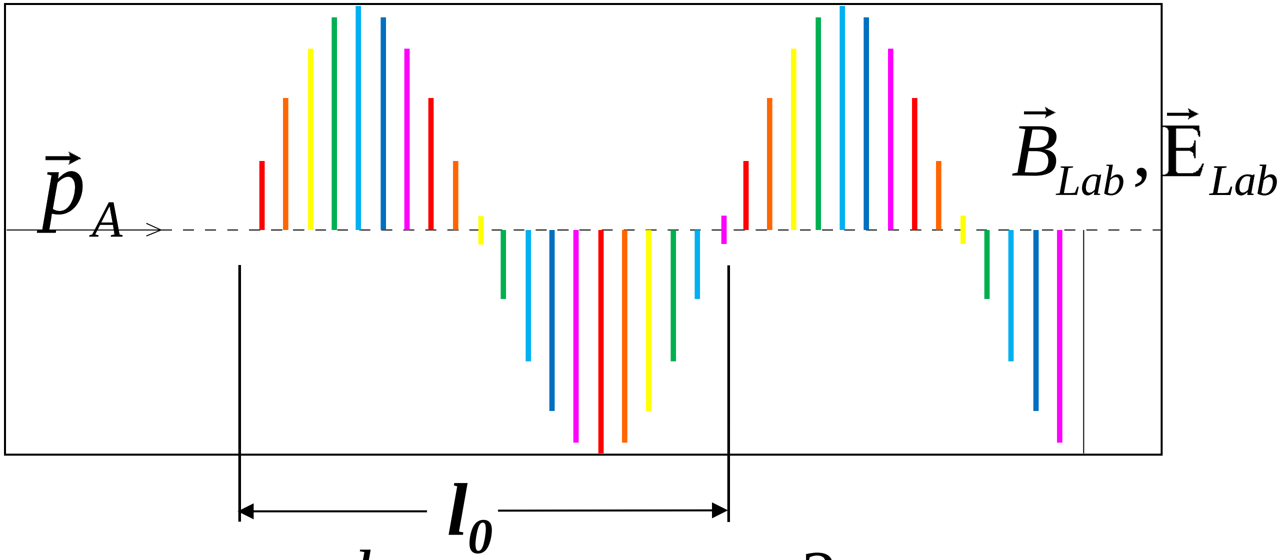
where: $$|\xi|^2 \approx \frac{\left|\vec{E}\right|^2}{E_{2p}-E_{2s}{}^2}$$

B_{Lab} = 2 Tesla

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

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

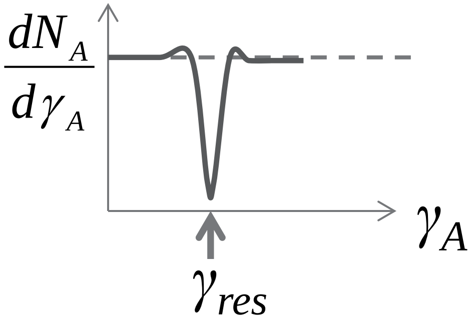
L.Nemenov, V.Ovsiannikov, E.Tchaplyguine, Nucl. Phys. (2002)



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

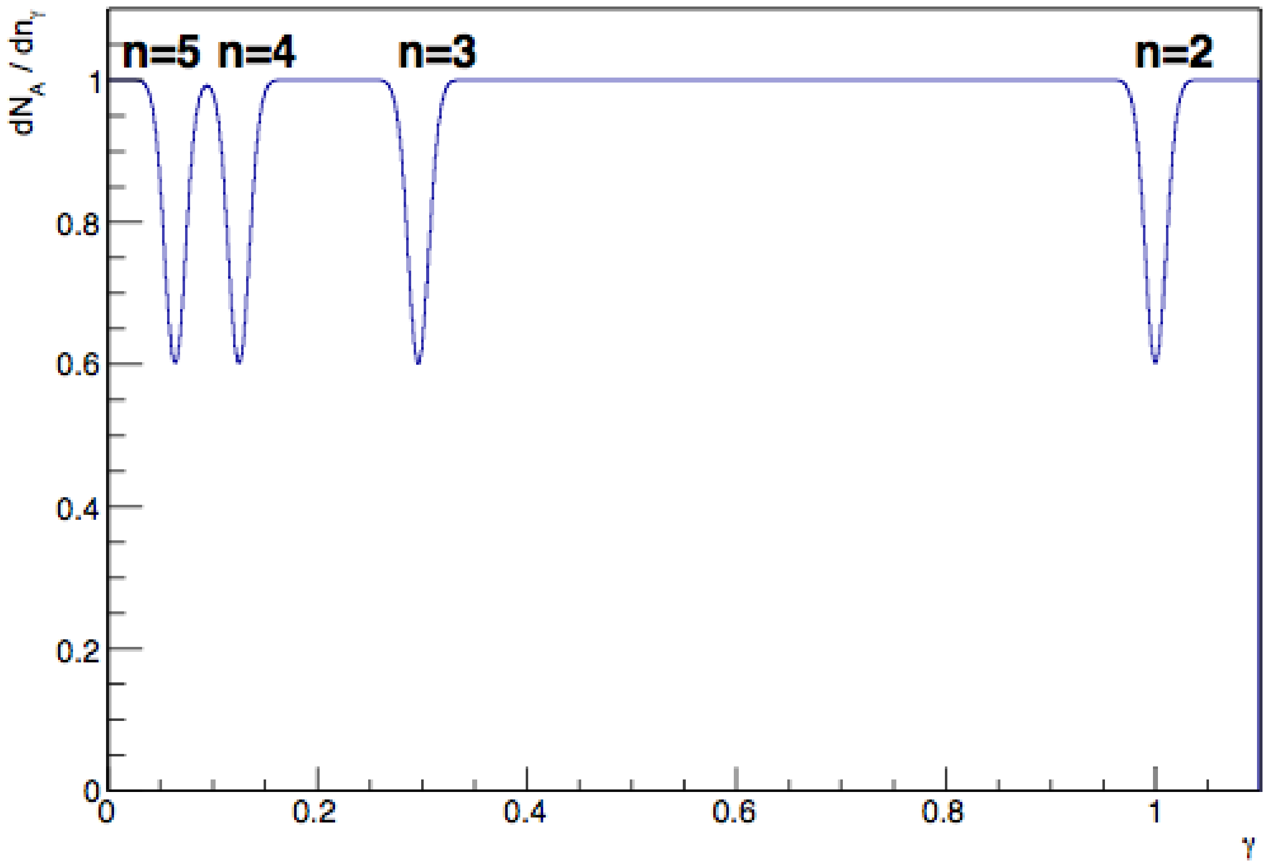
In CM System: $\tilde{\omega} = \gamma \cdot \omega_{Lab}$, $\qquad \tilde{\vec{E}} = \gamma \cdot \vec{E}_{Lab} \cdot \cos \tilde{\omega} t$, $\qquad \tilde{\Omega} = \dfrac{E_{2p} - E_{2s}}{\hbar}$

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.



No theoretical input!

$\pi^+\pi^-$ atom lifetime measurement

1. The $\pi^+\pi^-$ atom lifetime measurement with precision 9% was published (Phys.Lett.2011) The new available data were using for calibration. The analysis of this data will be ready at the end of 2017 and dedicated paper will be published before the end of 2018.

2. The current value of systematical error in the $\pi^+\pi^-$ atom lifetime measurement is equal to statistical uncertainty. The main part of systematical error arises due to an uncertainty in the multiple scattering in the Ni target.

To reduce this error and to study the Moliere theory precision we will study the multiple scattering in 8 scatters: Ni 50 μm, 109 μm and 150 μm; Be 100 μm and 2000 μm; Pt: 2 μm and 30 μm and Ti: 250 μm. For Be (2000 μm) and Ni (109 μm) the difference between theoretical and experimental r.m.s. is 0.4% and 0.8% accordingly. The r.m.s. values were calculated in the interval of $\pm 2\sigma$.

It is expected that systematic errors would be decreased by 2 times. Also we plan to test predictions of Moliere theory.

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 $|\boldsymbol{a}_{1/2}-\boldsymbol{a}_{3/2}|$ with an average precision of 34% (Conference in Chicago, 2016).

QCD and Chiral Lagrangian predictions check with long-lived $\pi^+\pi^-$ atoms

The DIRAC collaboration (Adeva et al., Phys.Lett.(2015)) observed 436 61(7.1 sigma) pion pairs from the long-lived ($\tau \geq 1\times10^{-11}$ sec) $\pi^+\pi^-$ atom breakup (ionisation).
Lifetime of the short-lived $\pi^+\pi^-$ atom is $\tau \geq 3\times10^{-15}$ sec

The study of these excited atoms allows to measure the Lamb shift depending on another $\pi\pi$ scattering length combination: $2a_0+a_2$.

The SPS proton beam and the new experimental arrangements makes this measurement possible.

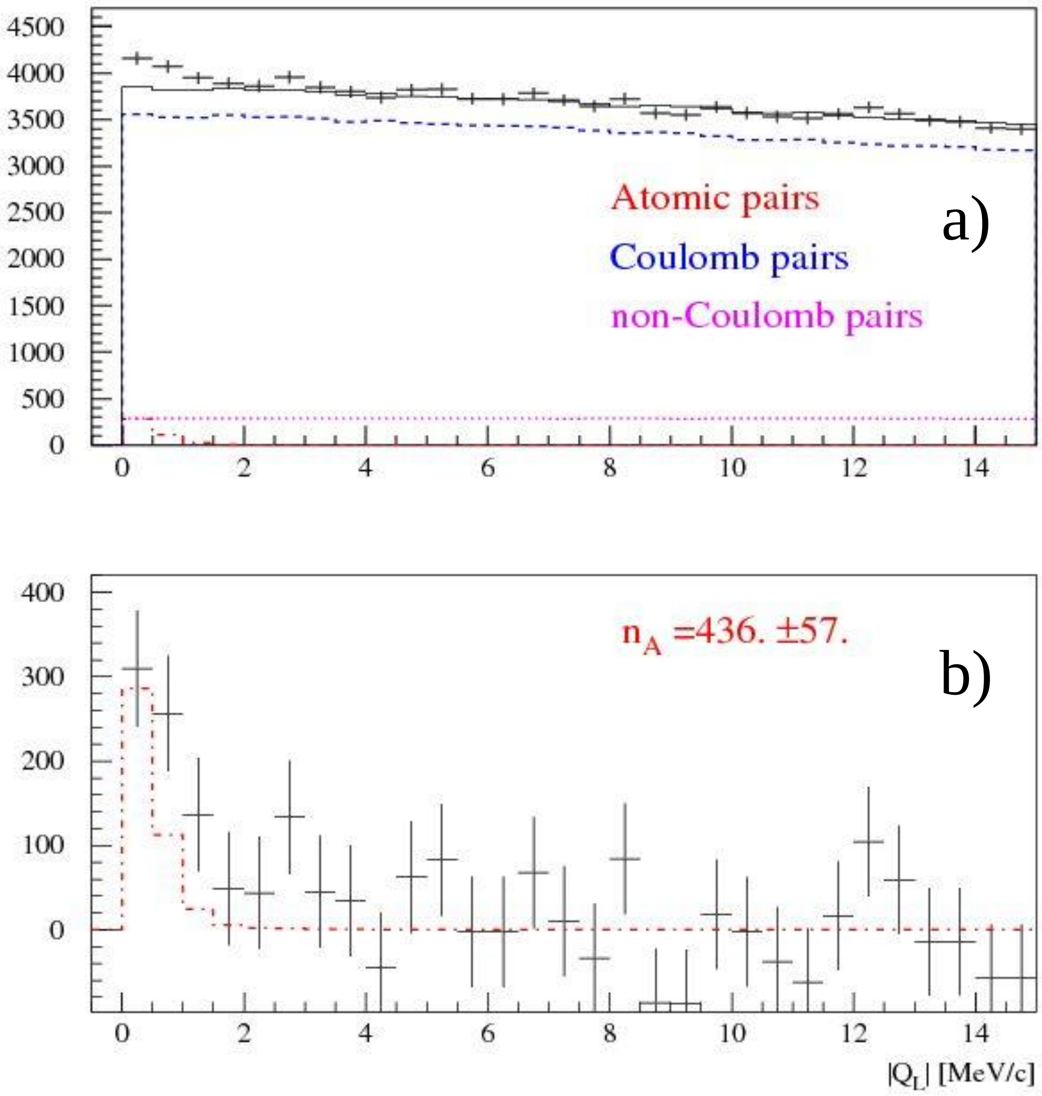
$\mathcal{L}(2)$ and Chiral Lagrangian predictions check with short-lived $\pi^+\pi^-$ atoms

ChPT	a_0 and a_2 a_0-a_2	2.3% precision 1.5% precision	Colangelo et al. Nucl.Phys.(2001)

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)

Experimental values	a_0-a_2	~ 4% precision	J.R.Bateley at al., Eur. Phys. J. (2009), J.R.Bateley at al., Eur. Phys. (2010), Adeva et al., Phys. Lett. (2011)
	a_0 a_2	~ 6% precision ~22% precision	J.R.Bateley at al., Eur. Phys. J. (2009), J.R.Bateley at al., Eur. Phys. (2010)
on SPS	a_0-a_2	~2% precision	DIRAC estimation

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



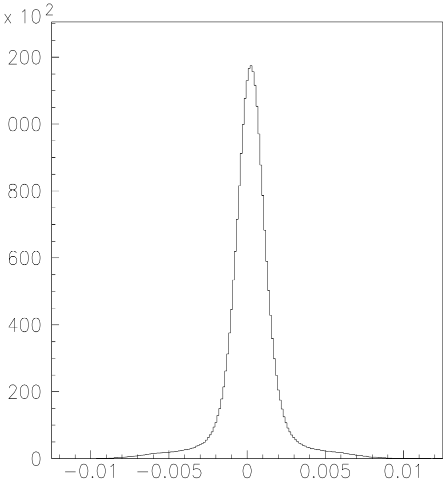
$|Q_L|$ distribution of $\pi^+\pi^-$ pairs
for Q_T <2.0 MeV/c

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

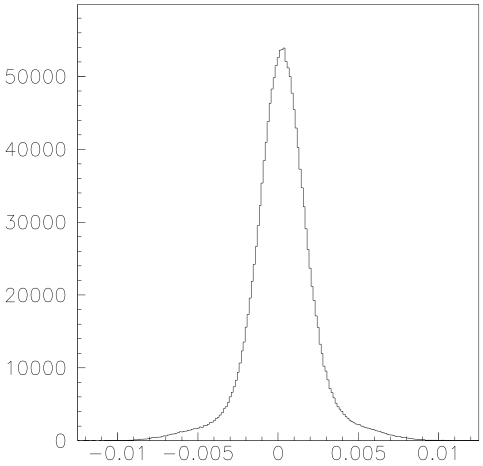
b) The experimental distribution after background subtraction (points with statistical error) and the simulated distribution of atomic pairs (dot-dashed line).

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

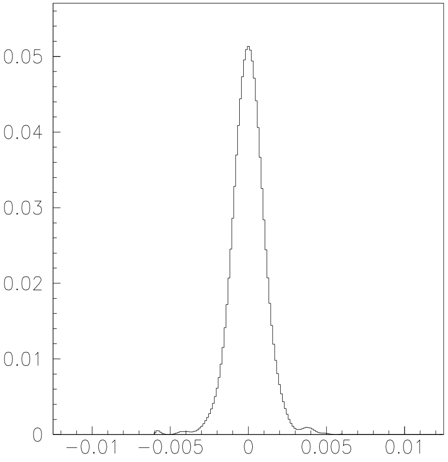
Multiple scattering evaluation



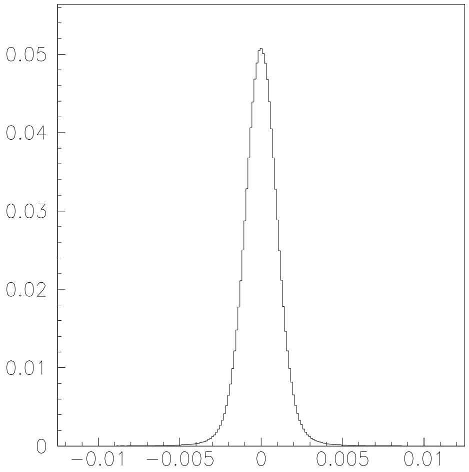
Ni-109 Drift Chamber Resolution



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

$\pi^+\pi^-$ and πK atom production

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

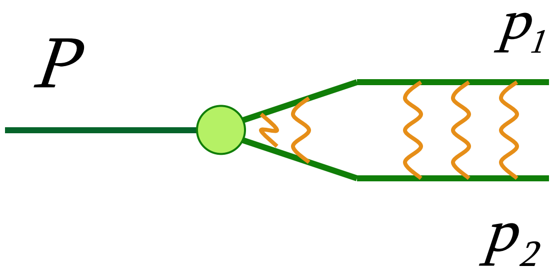
$$\vec{P}_A = \vec{p}_1 + \vec{p}_2$$

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

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 ~ $6 \text{x} 10^{-4}$.

The proton beam can be used for other experiments.

Proton beam intensity: $3 \text{x} 10^{11}$ protons/s (DIRAC worked at $2.7 \text{x} 10^{11}$ protons/s)

Number of spills: $4.5 \text{x} 10^{5}$ 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%

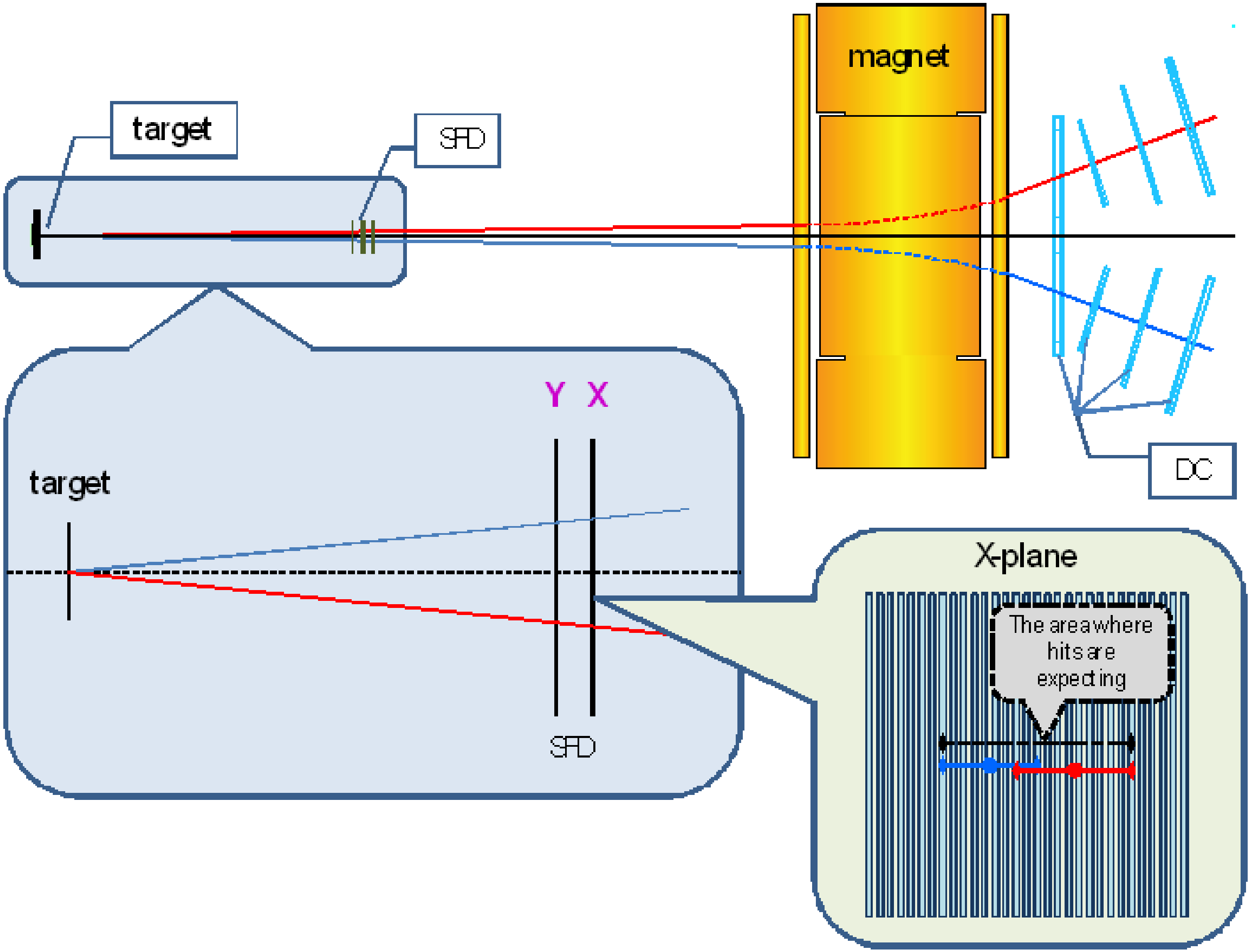
The expected systematic error will be at the level of 2%

The expected number of $\pi^+\pi^-$ atomic pairs n_A=400000

The statistical precision of the $\pi^+\pi^-$ scattering length will be: 0.7%

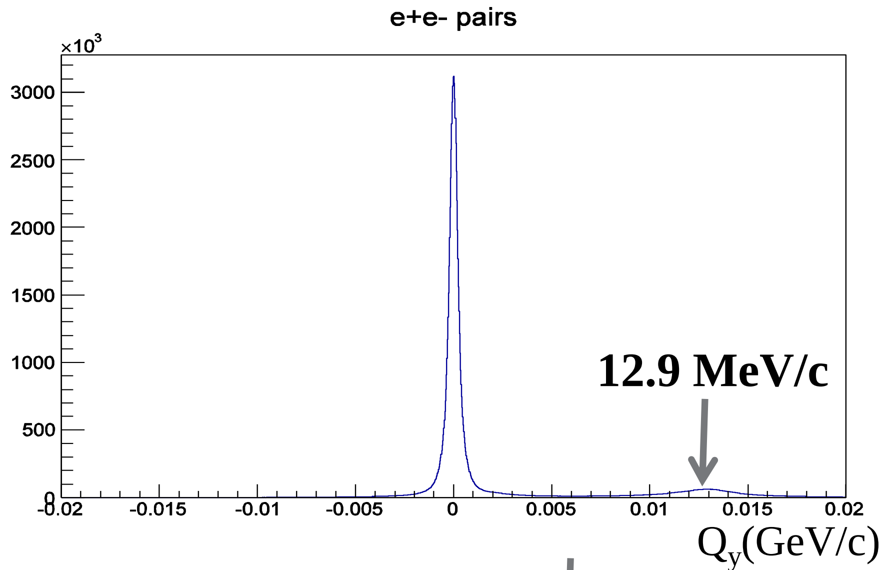
The expected systematic error will be at the level of 2%

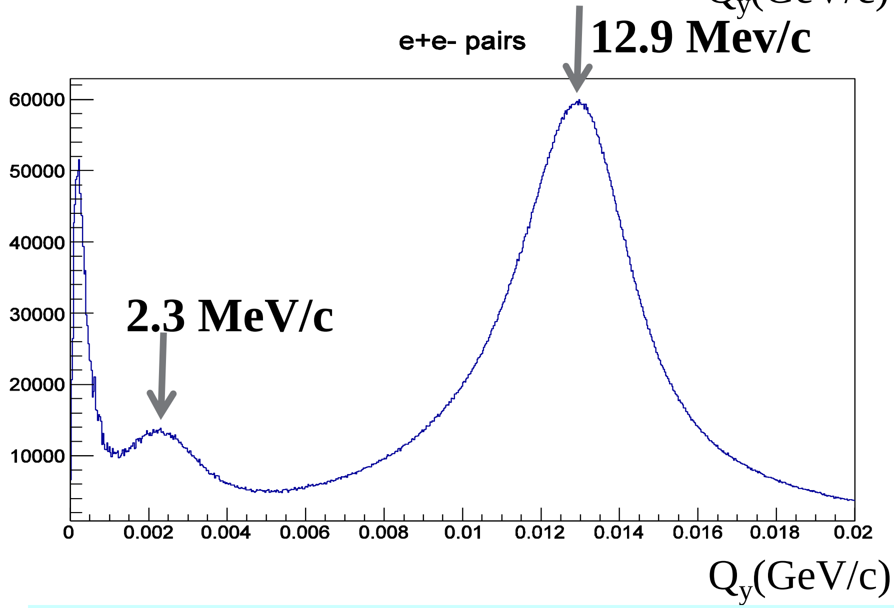
Hit regions in SFD

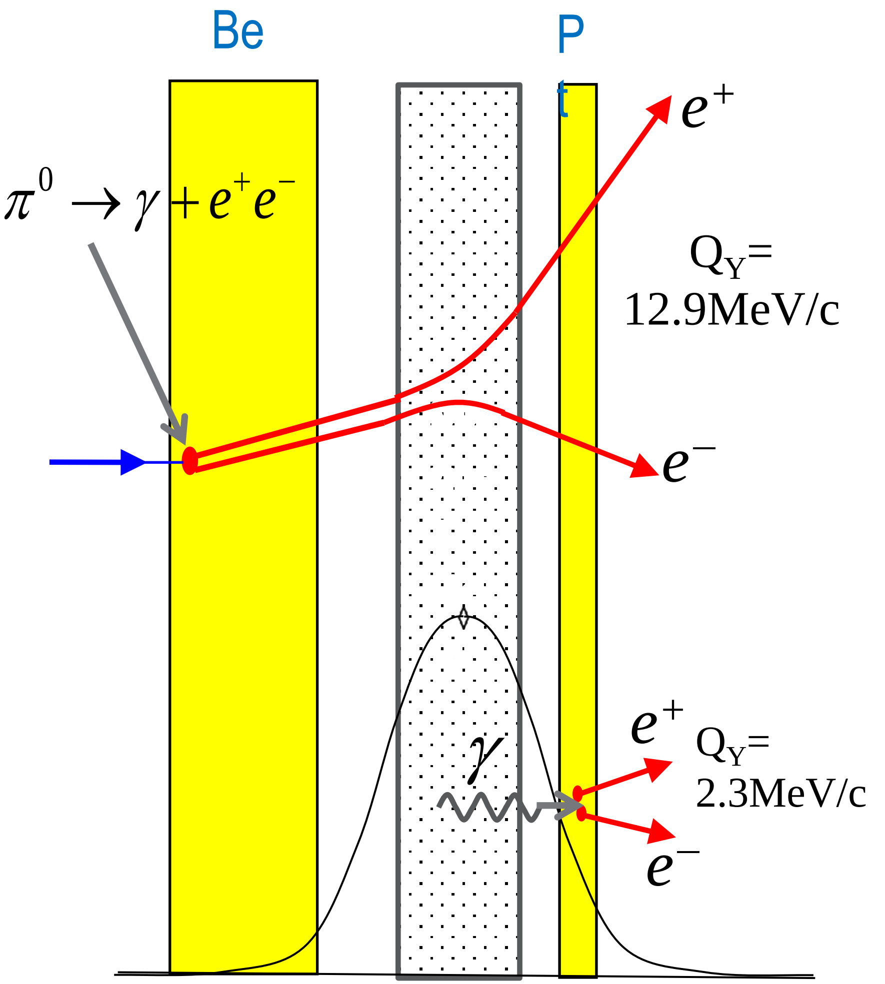


Magnet impact on Q_y distribution for e^+e^- pairs

Real data

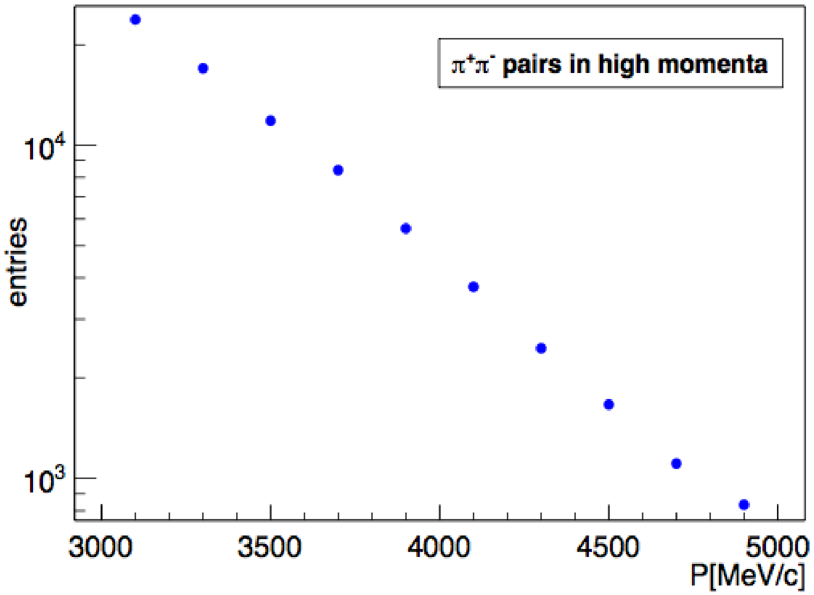


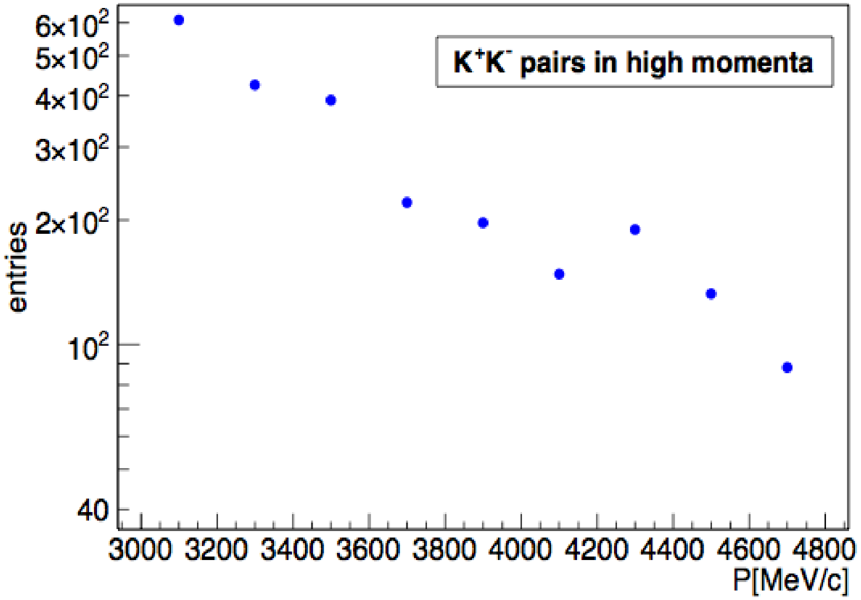


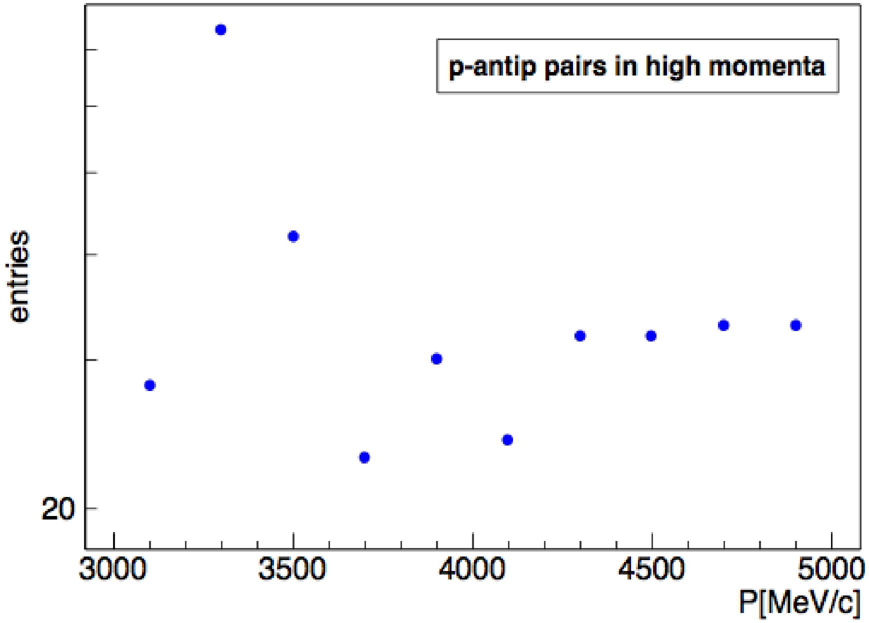


Peak at Q_y=2.3MeV/c evaluated after subtraction of the mirrored left side part.

The $\pi^+\pi^-$, K^+K^- and $p\text{-}\bar{p}$ pair numbers

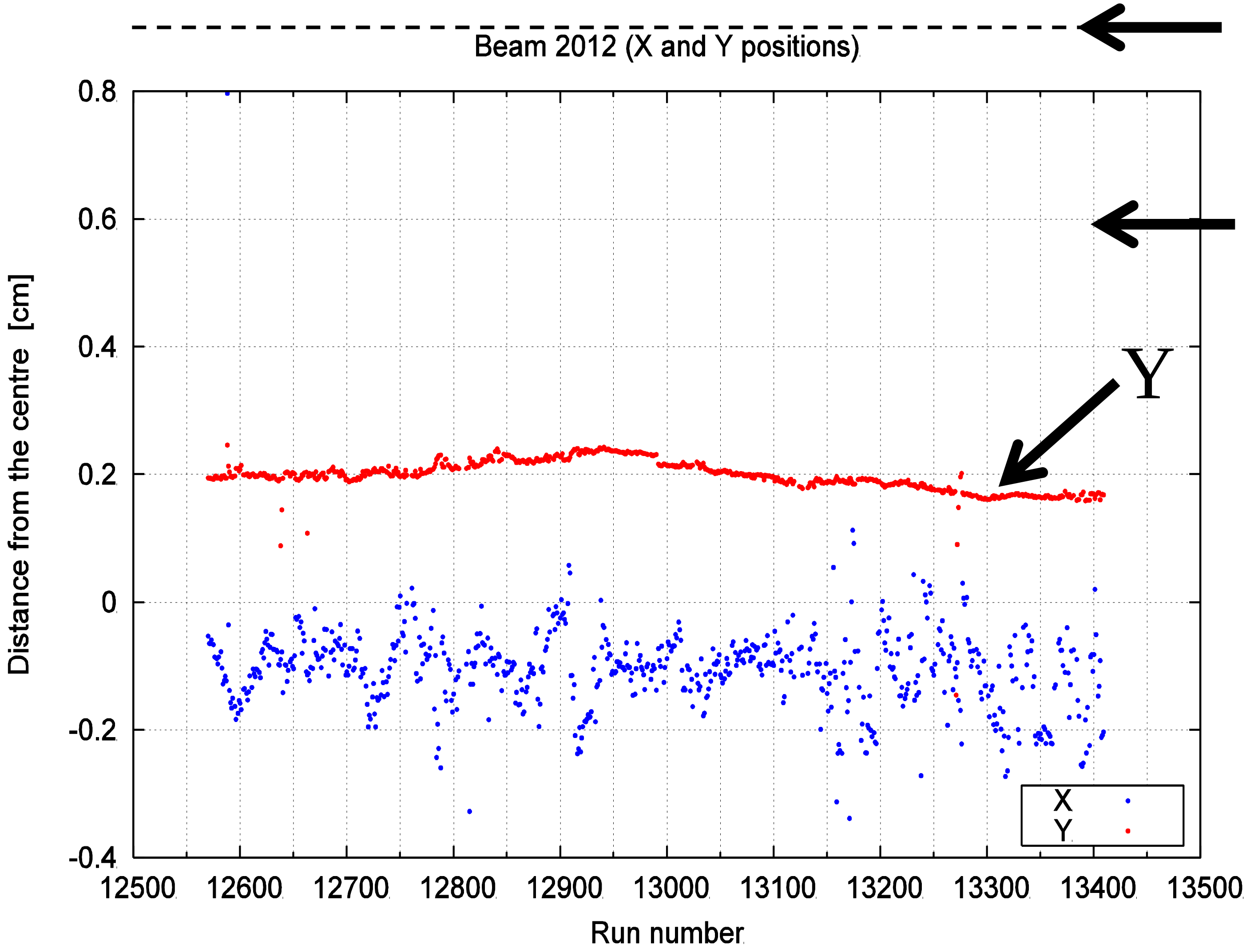






Additional slides

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).

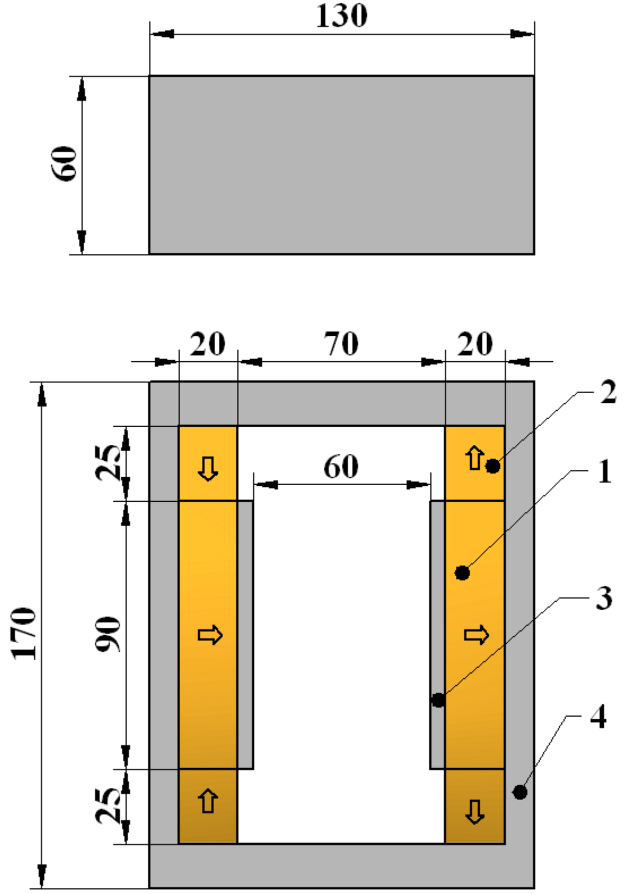
Experimental conditions (run 2012)

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	**$2.52\cdot 10^{-4}$**

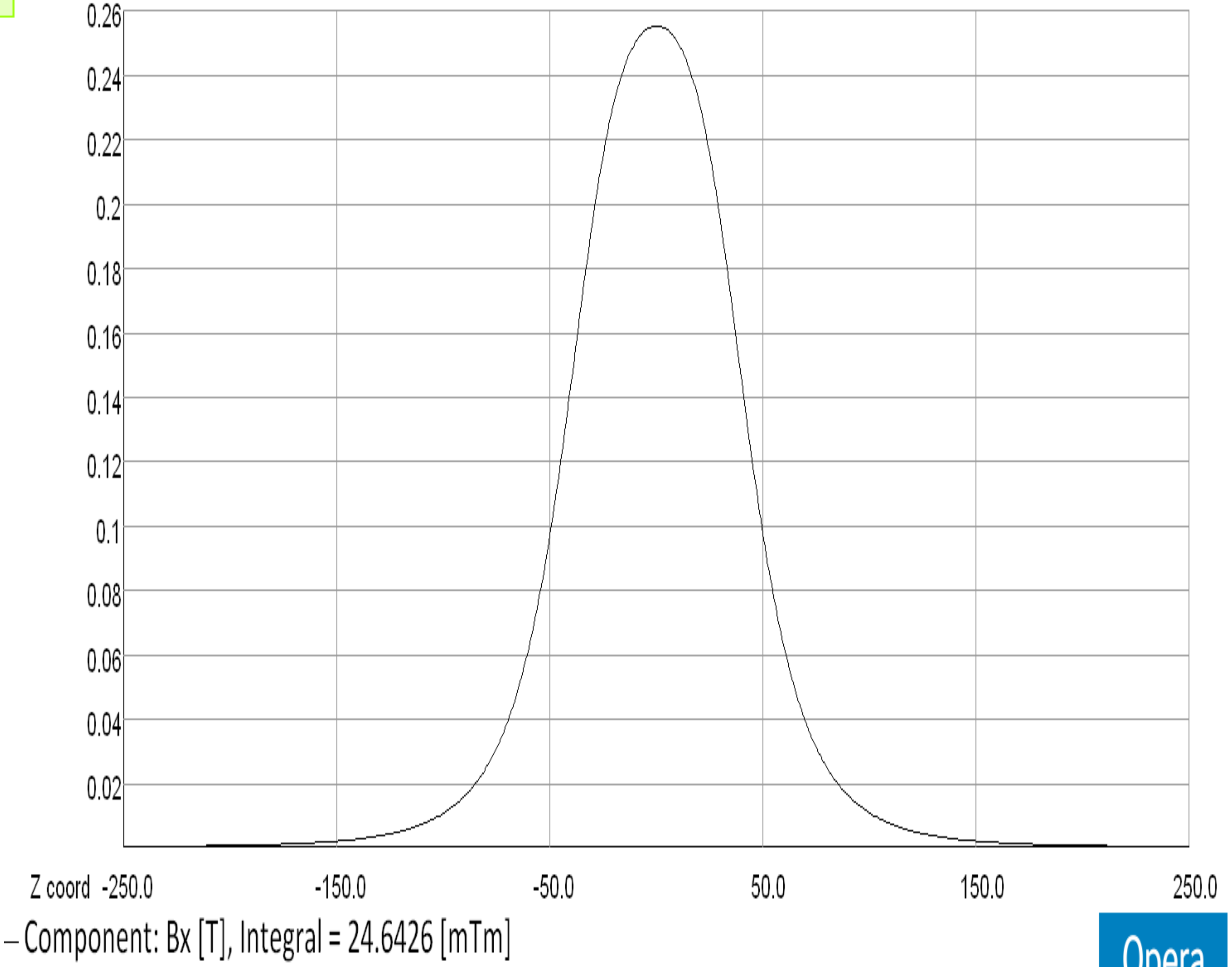
Magnet

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



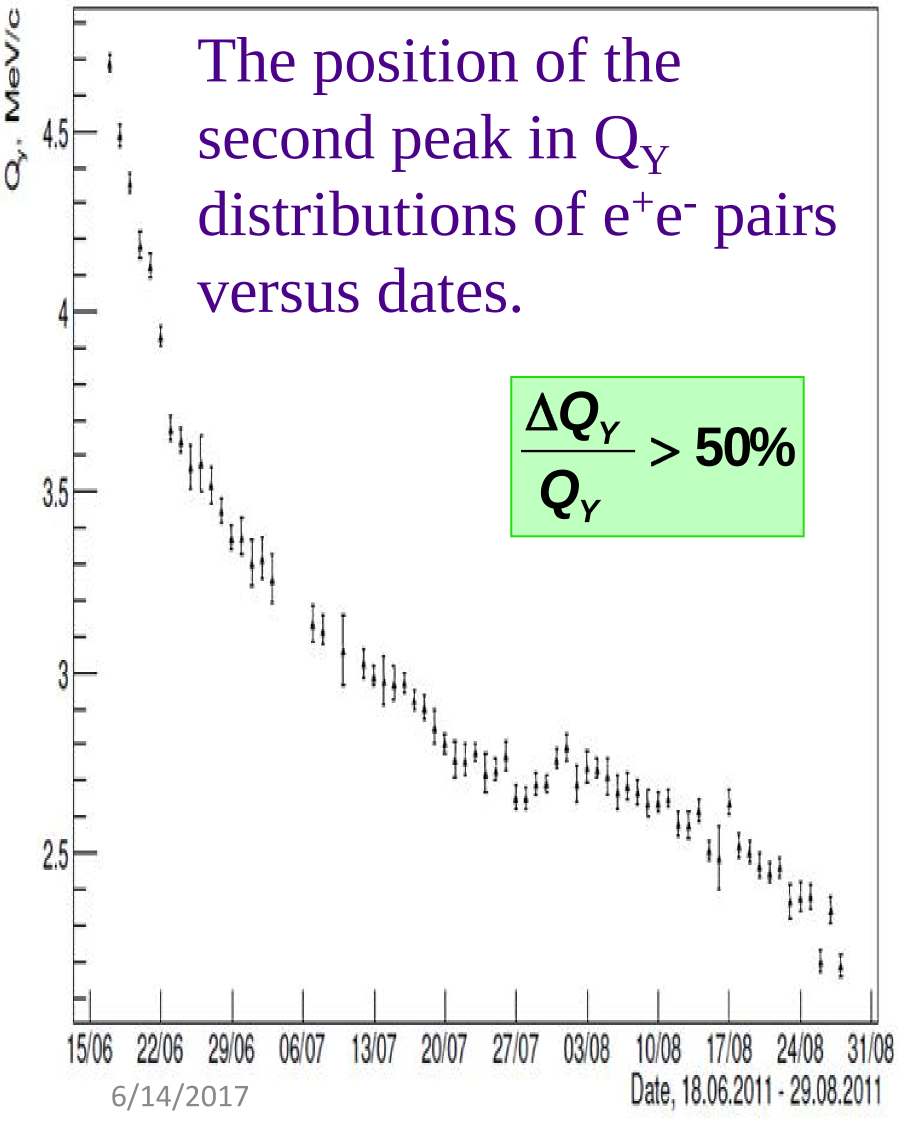
1- PM block Sm2Co17
2- PM block Sm2Co17

Horizontal field distribution along z-axis at X=Y=0mm
$\int Bx(0,0,z)dz = 24.6x10^{-3}$ [Tm]



Degradation of old magnet

Old magnet (Nd-Fe-B), 2011

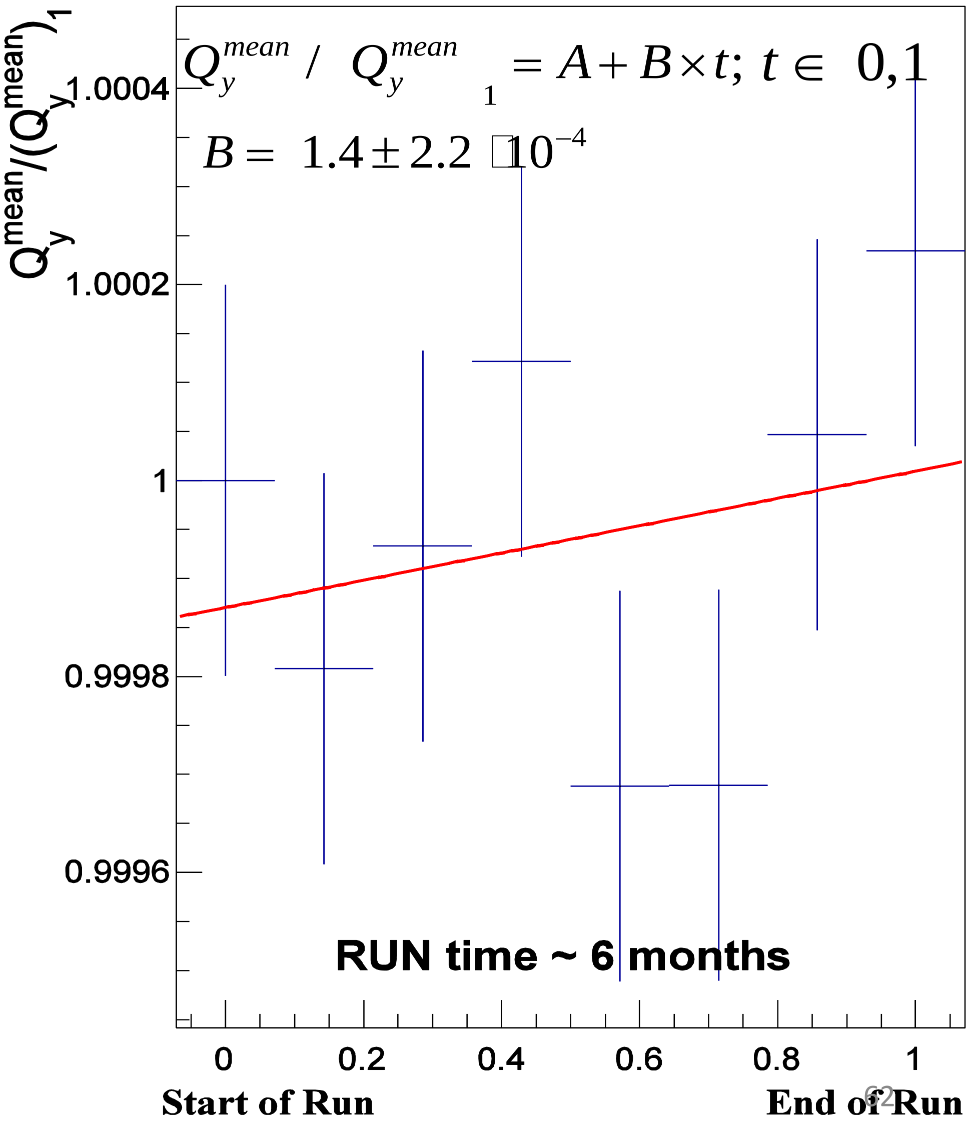


The position of the second peak in Q_Y distributions of e^+e^- pairs versus dates.

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

New magnet behavior

New magnet (Sm-Co), 2012

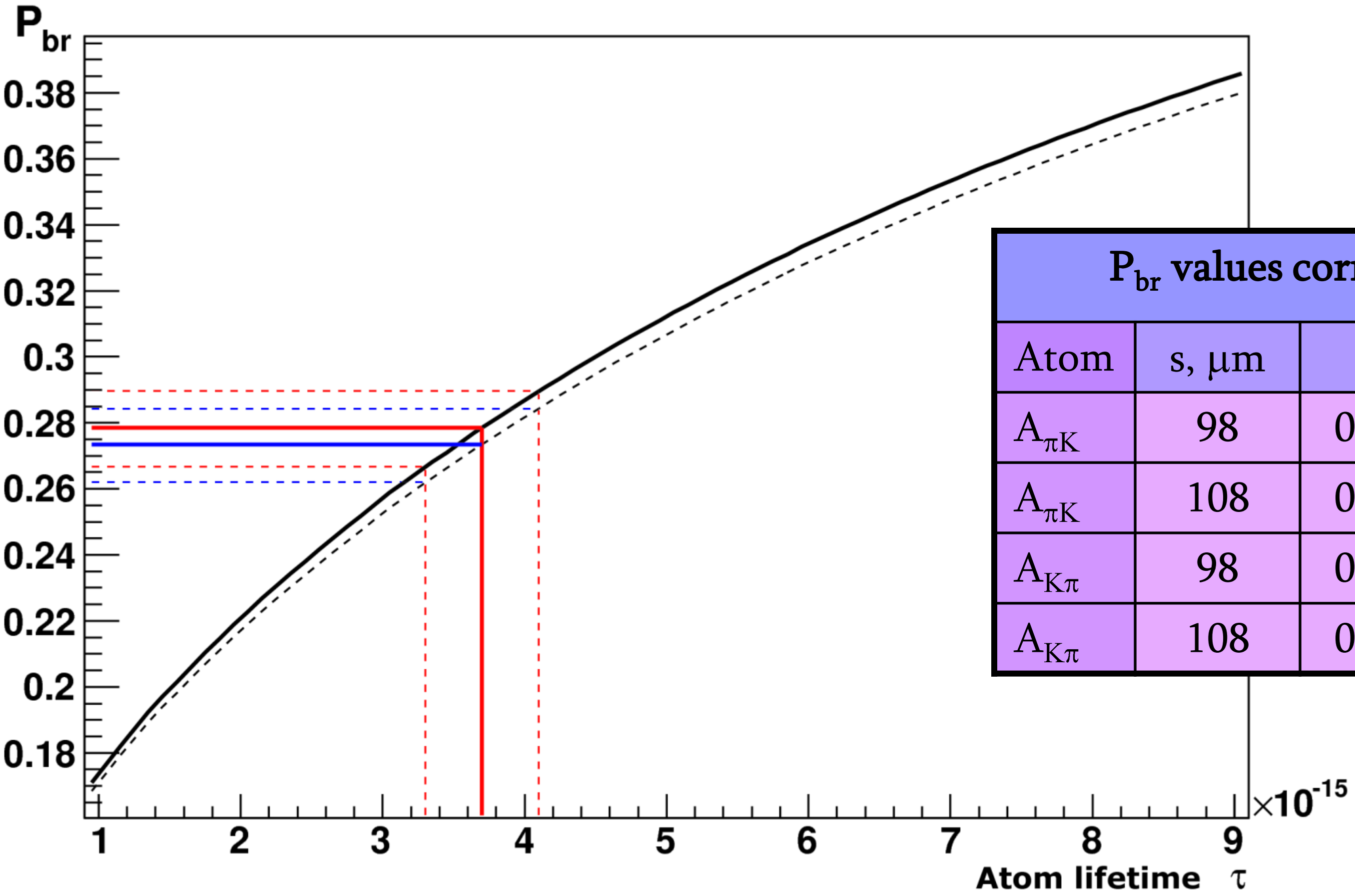


$$Q_y^{mean} / \left(Q_y^{mean}\right)_1 = A + B\times t;\ t \in [0,1]$$

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

RUN time ~ 6 months

Break-up dependencies P_{br} from atom lifetime for $K^+\pi^-$ and π^+K^- atom

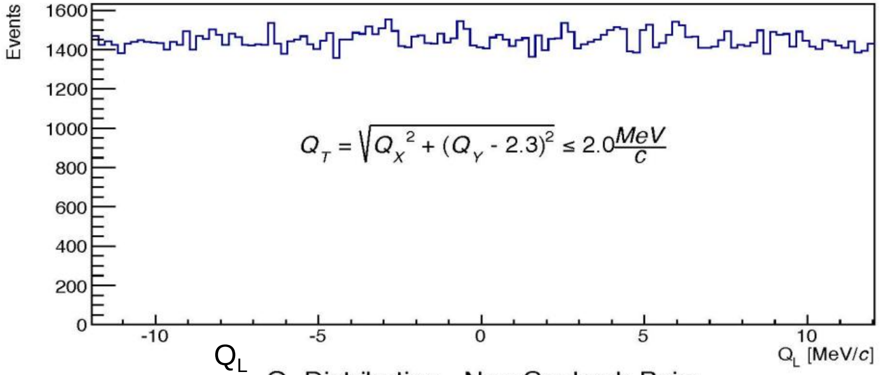


P_{br} values corresponding to τ_{1S}^{th}

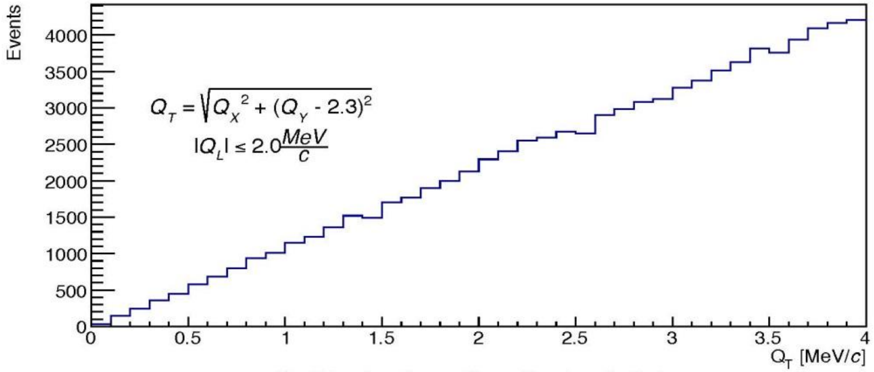
Atom	s, μm	P_{br}	P_{br}-σ	P_{br}+σ
$A_{\pi K}$	98	0.274	0.263	0.285
$A_{\pi K}$	108	0.278	0.267	0.290
$A_{K\pi}$	98	0.269	0.258	0.280
$A_{K\pi}$	108	0.273	0.262	0.284

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.

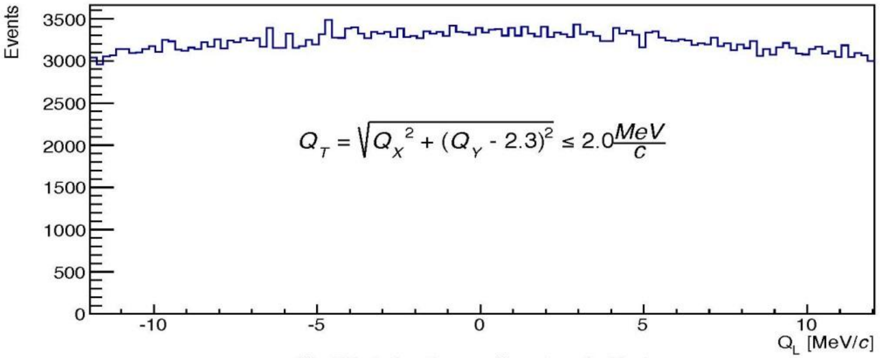
Simulation of $\pi^+\pi^-$ pairs for long-lived $A_{2\pi}$ observation



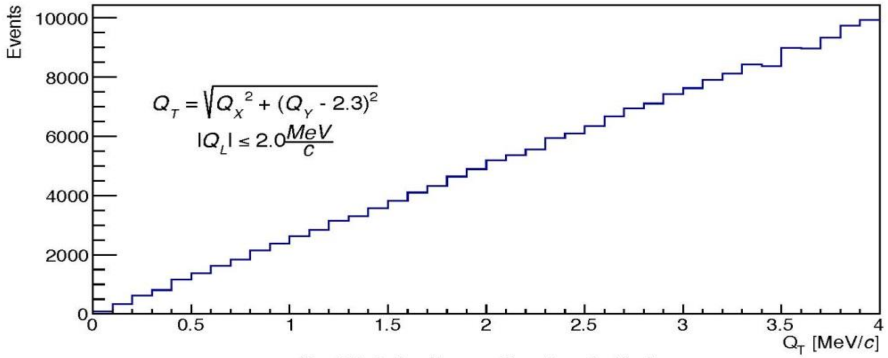
Q_l Distribution - Non-Coulomb Pairs



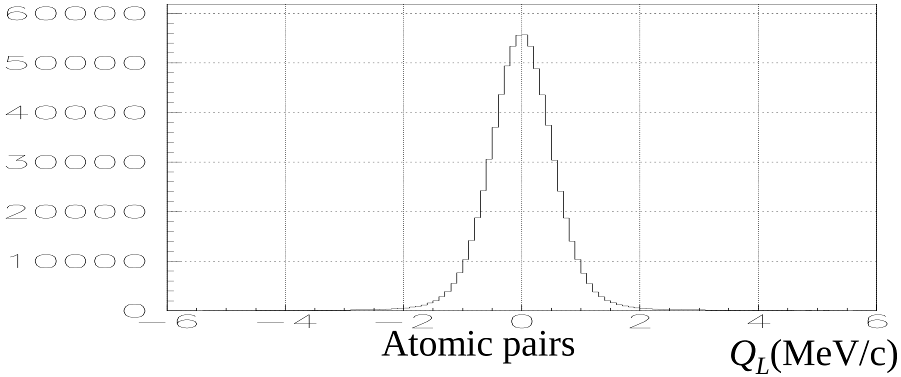
Q_T Distribution - Non-Coulomb Pairs



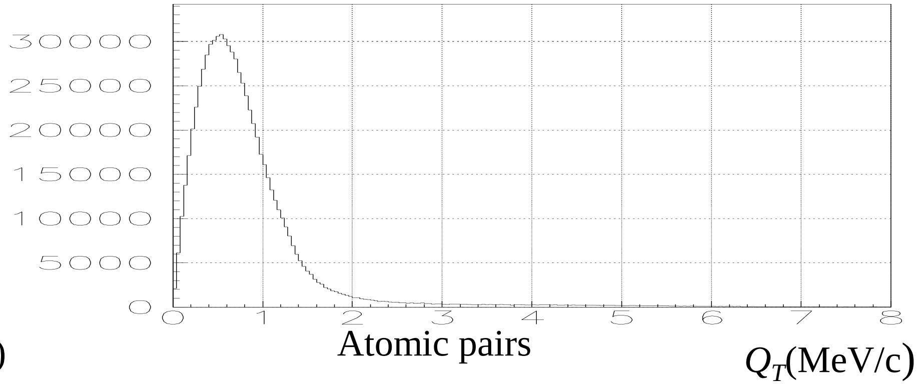
Q_L Distribution - Coulomb Pairs



Q_T Distribution - Coulomb Pairs

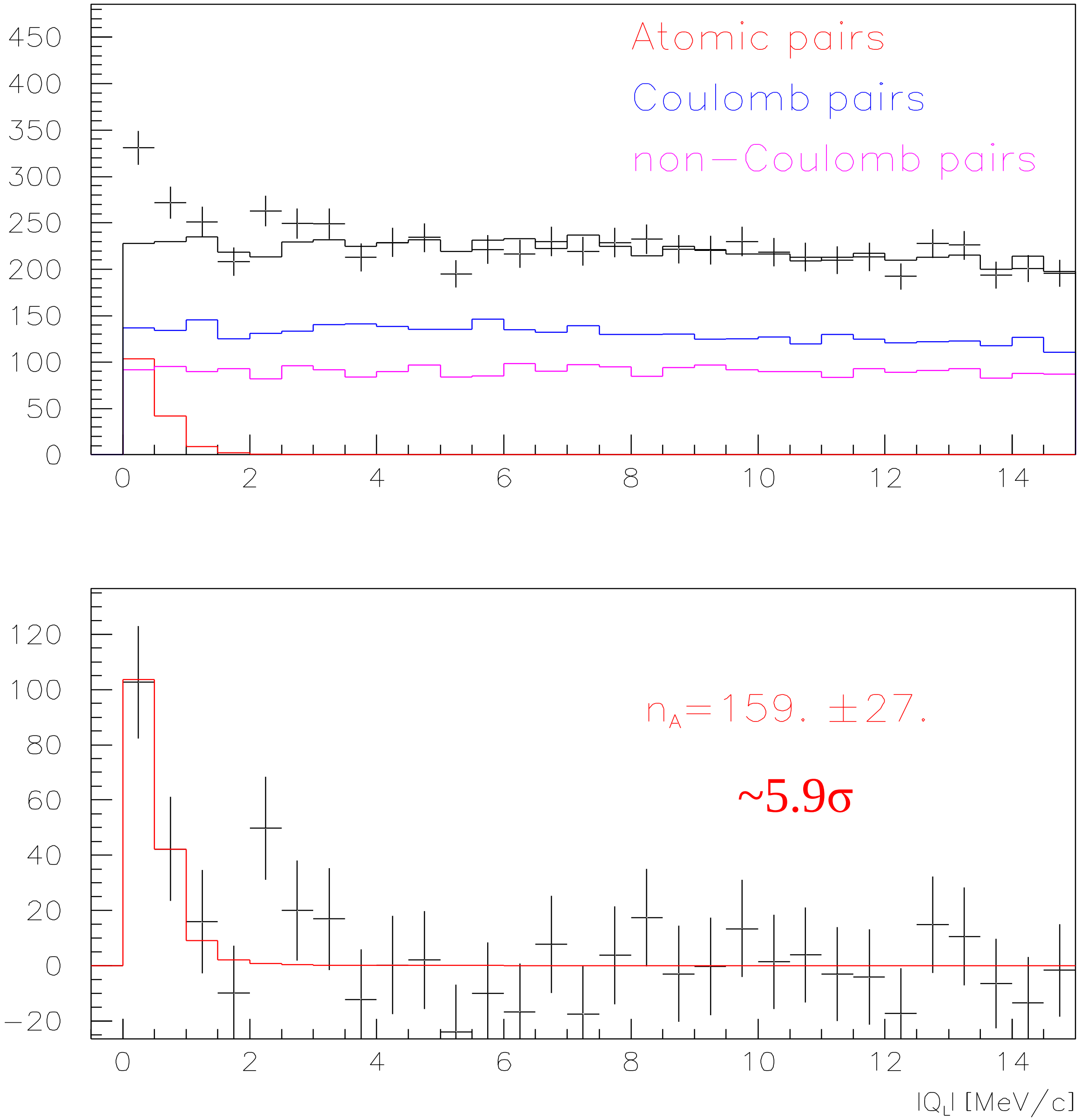


Atomic pairs



Atomic pairs

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

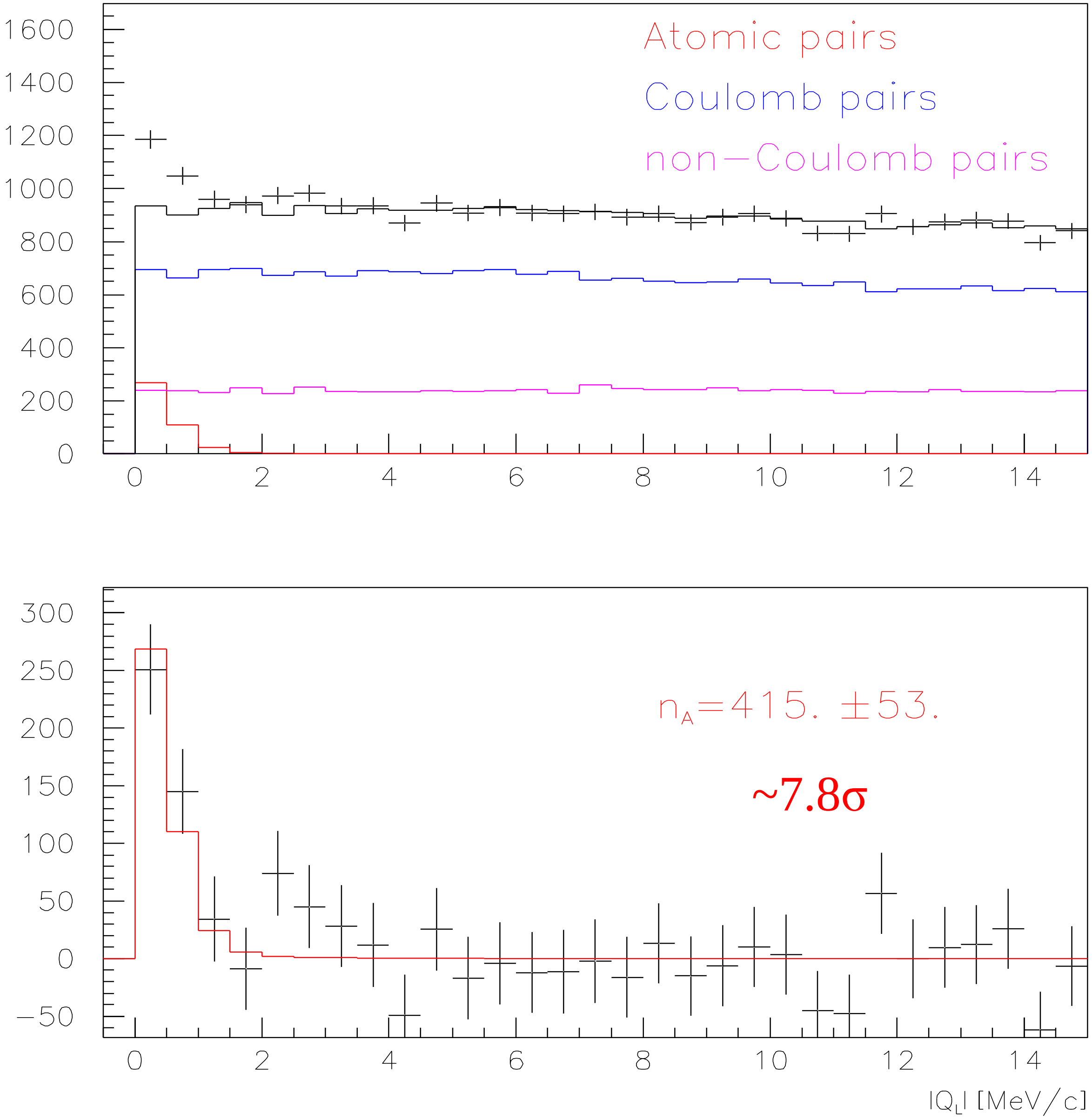


Experimental (real data) and simulated distributions over $|Q_L|$

for Q_T<0.5 MeV/c

$$Q_T = \sqrt{Q_X^2 + \; Q_Y - 2.3MeV/c^{\;2}}$$

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

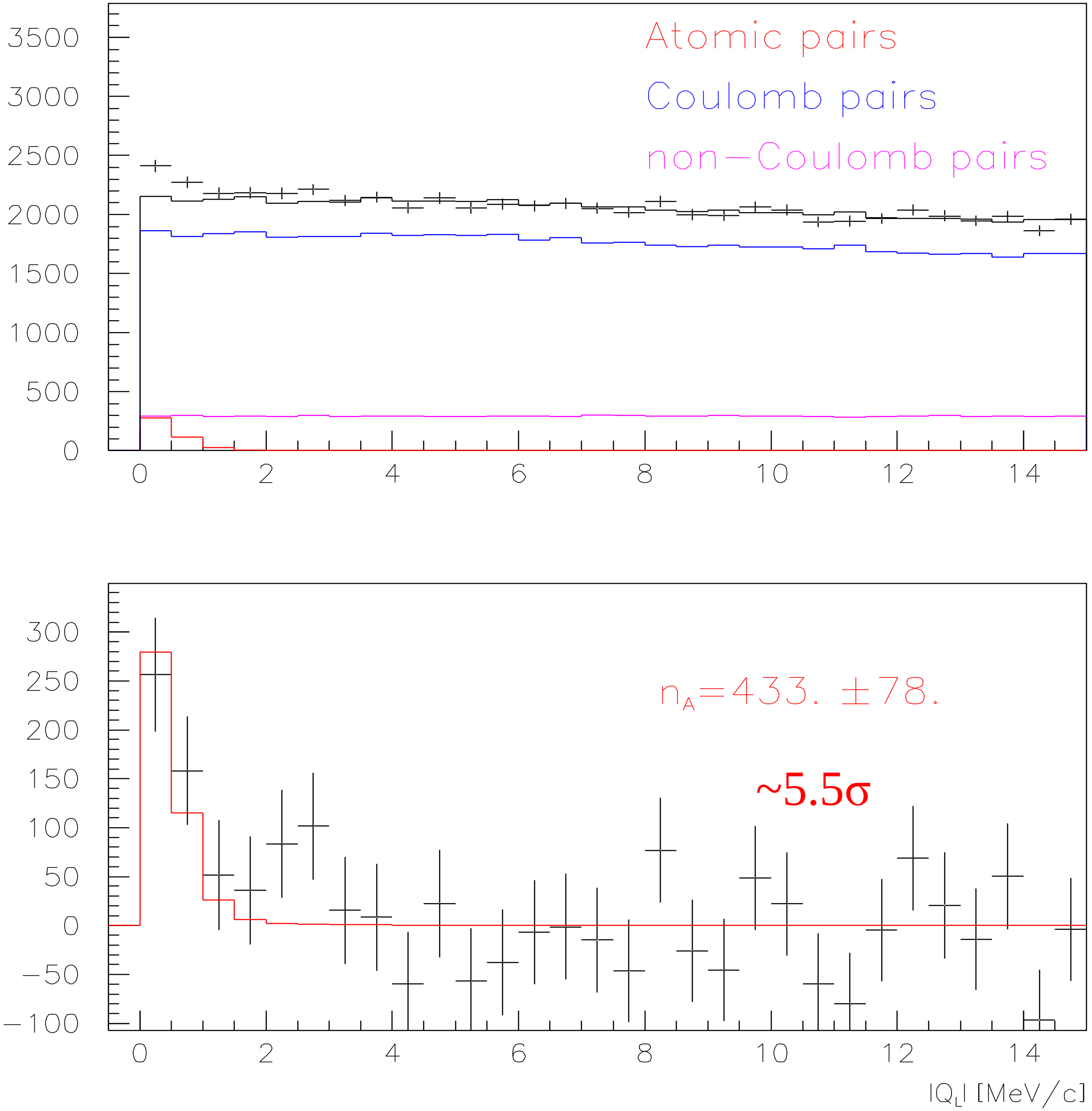


Experimental (real data) and simulated distributions over |Q_L|

for Q_T<1.0 MeV/c

$$Q_T = \sqrt{Q_X^2 + \ Q_Y - 2.3MeV/c^{\,2}}$$

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



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

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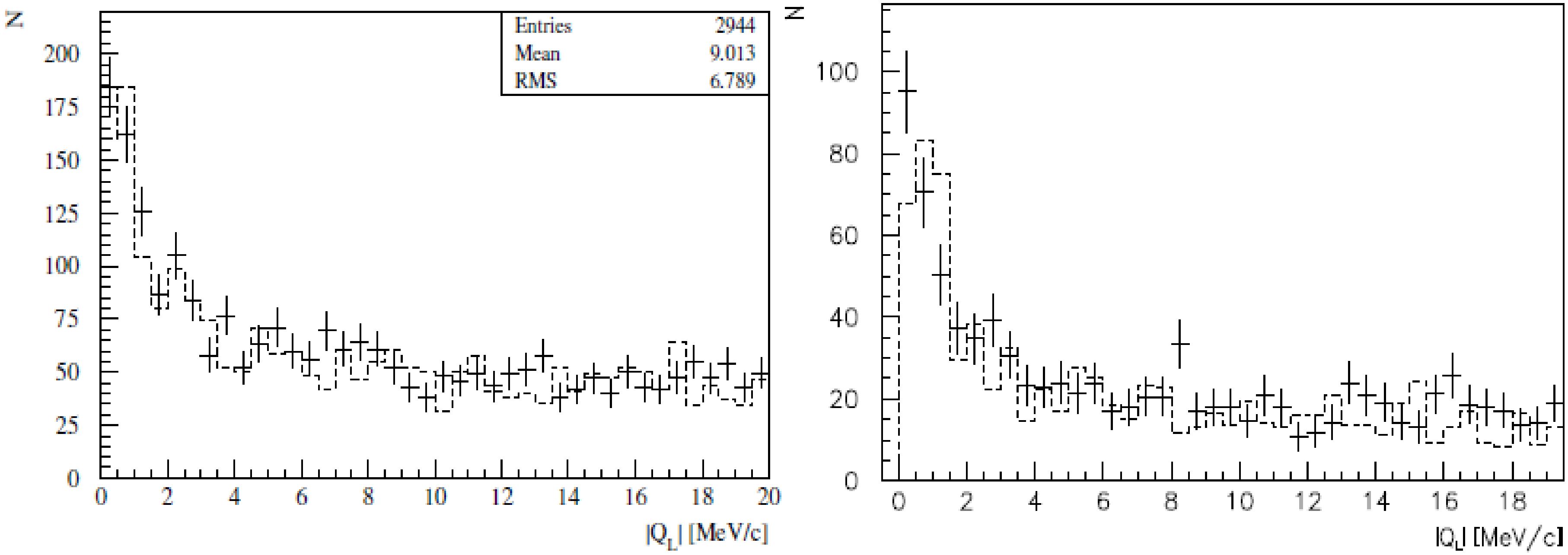
$$Q_T = \sqrt{Q_X^2 + \ Q_Y - 2.3MeV/c\ {}^2}$$

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

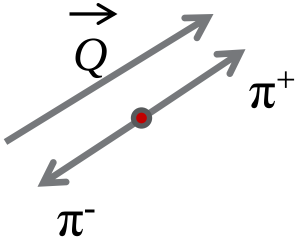
Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of "Coulomb" and "non-Coulomb" pairs (dashed line).

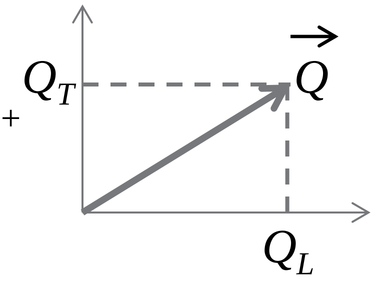


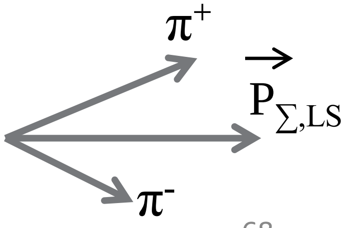
Produced atom numbers normalized on the proton flux:

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

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







DIRAC++

9. Box with Target Station.
   Contains thin (~100 μm) targets.
10. Vacuum Tube for Primary and Secondary Proton Beam.
    Angle between primary proton beam and axis of secondary particle channel is 4 degrees.
11. Vertex detector.
    It could be 2 planes of pixel detectors or 2-4 planes of silicon strip or fiber detectors.
    Distance from the target 301 cm. Size 7.6×7.6 cm^2.
    Coordinate resolution is better than 0.01 cm, ideally is better than 0.005 cm.
    Time resolution is better than 400 ps, ideally is better than 200 ps.
    Rate capability is better than $5.\times10^5$ particles per second per cm2, ideally is better than $2.\times10^6$ particles per second per cm^2.
    Summary radiation thickness is less than $0.015\times X_0$, ideally is less than $0.007\times X_0$.
    Distance from the target to detector could be changed to value from 200 to 320 cm, and size of detectors could be varied from 5.0×5.0 to 8.0×8.0 cm^2, correspondingly.
    Rate capability is to be varied inversely proportional to square of detectors.
12. Particle identification detector.
    It provides separation of kaons from protons for laboratory momenta greater than 5.5 GeV/c (it could be RICH detector).
13. Scintillating Fiber detector.
    Detector similar to fiber detector of experiment DIRAC: X, Y and W planes, size 10×10 cm^2, coordinate resolution 0.006 cm (X and Y planes) and 0.013 cm (W plane). Time resolution 400 ps.
    Distance from the target to fiber detector 402 cm. Radiation length is about 0.9% X_0 per plane.
14. Vacuum volume for Secondary beam.
15. Iron Shielding wall.
    Distance from the target to shielding 540 cm. Thickness is 150 cm.
    Rectangular collimator inside wall define acceptance of secondary beam.
    Opening angles ±0.7 degrees both in horizontal and vertical planes.
16. Spectrometer magnet.
    At the moment it is proposed to use magnet of experiment DIRAC (PS212). But another choice is possible for

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