

*Status Report of the
DIRAC Experiment - PS-212*

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SPSC, October 2016

DIRAC Collaboration



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QCD Lagrangian and its prediction

The QCD Lagrangians use the $SU(3)_L^*SU(3)_R$ and $SU(2)_L^*SU(2)_R$ chiral symmetry breaking.

$$\mathcal{L}(u,d,s) = \mathcal{L}(3) = \mathcal{L}_{\text{sym}}(3) + \mathcal{L}_{\text{sym.br.}}(3)$$

$$\mathcal{L}(u,d) = \mathcal{L}(2) = \mathcal{L}_{\text{sym}}(2) + \mathcal{L}_{\text{sym.br.}}(2)$$

$\mathcal{L}_{\text{sym.br.}}$ is proportional to m_q

$e^+e^- \rightarrow \text{hadrons}$

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

To check the total $\mathcal{L}(3)$ Lagrangian predictions, we must study the
low momentum transfer Q processes.

Tools: Lattice calculations and Chiral Perturbation Theory (ChPT)

Lattice----- $\mathcal{L}(3), \mathcal{L}(2)$

ChPT-----Effective Lagrangians.

Measurement of the πK scattering length

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

For Lattice QCD the πK interaction at threshold is a relatively simple process. It gives πK scattering length values with an average precision of **5%**.

This precision will be improved in the near future.

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

πK scattering

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

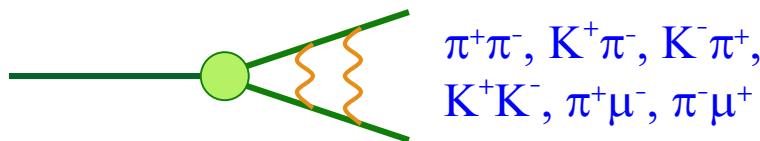
The measurement of the s -wave πK scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (u, d and s quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u, d quarks).

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

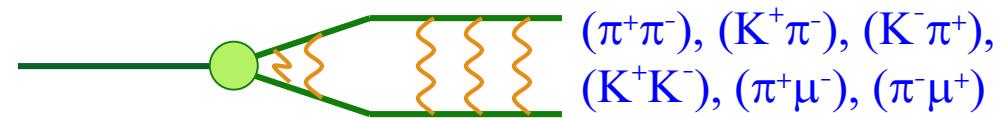
Coulomb pairs and atoms

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.



Coulomb pair



Atom

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

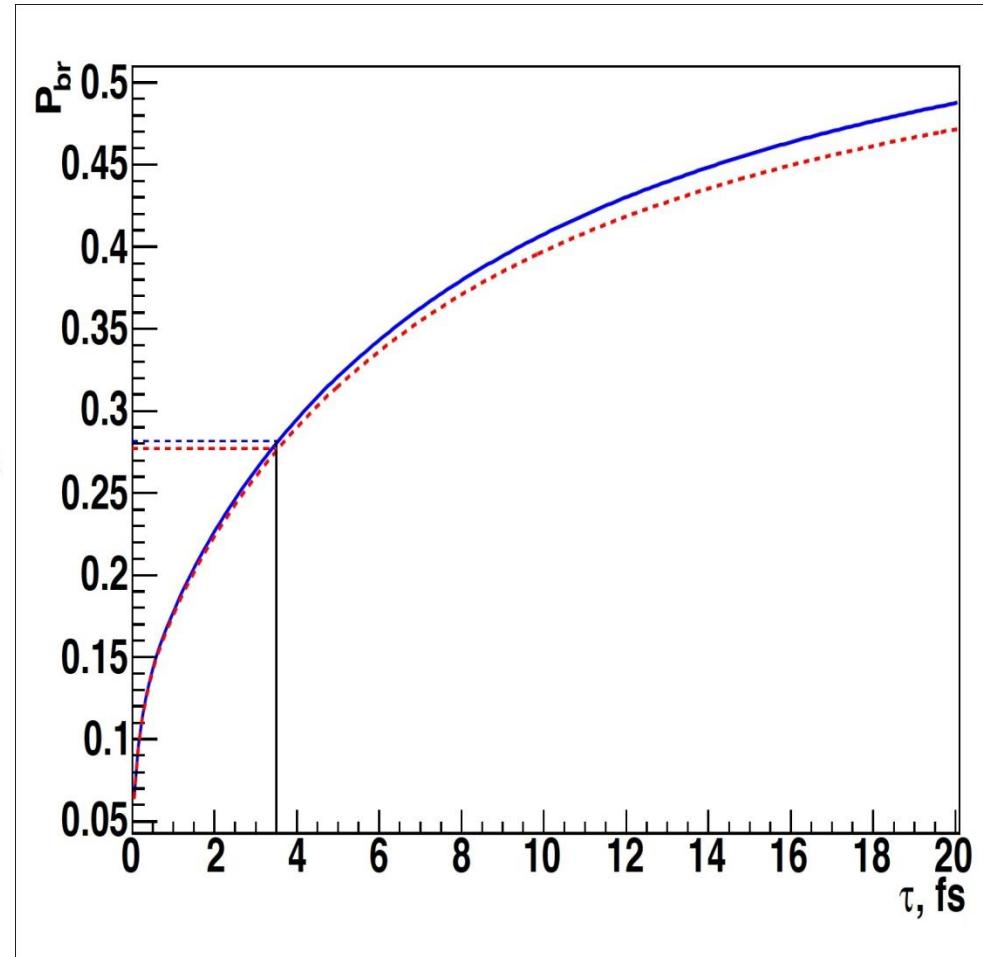
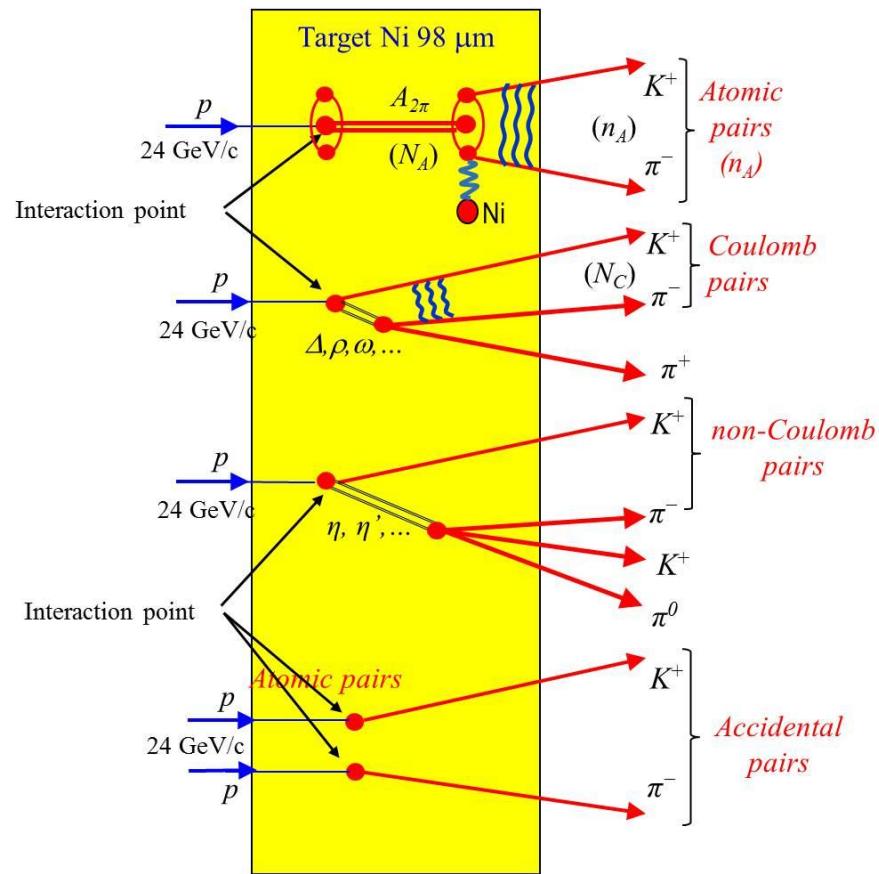
$$N_A = K(Q_0)N_C(Q \leq Q_0), \frac{\delta K(Q_0)}{K(Q_0)} \leq 10^{-2}$$

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

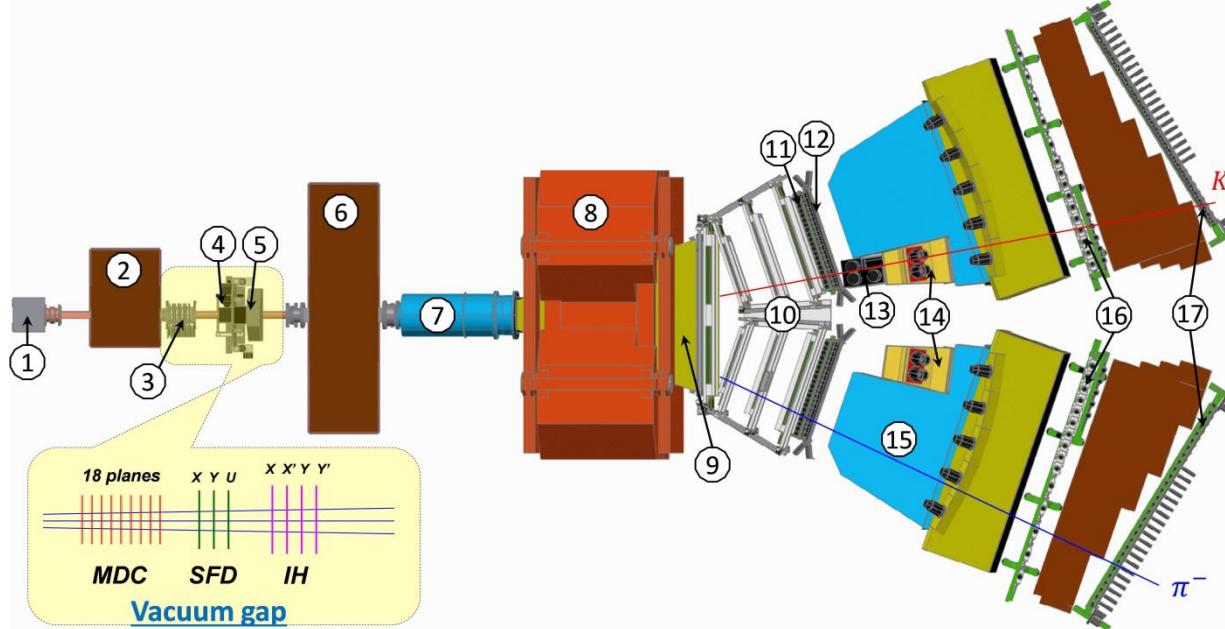
The πK atom lifetime and πK scattering length

$$\frac{1}{\tau} = R |a_{1/2} - a_{3/2}|^2$$

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



DIRAC setup, experimental and theoretical data

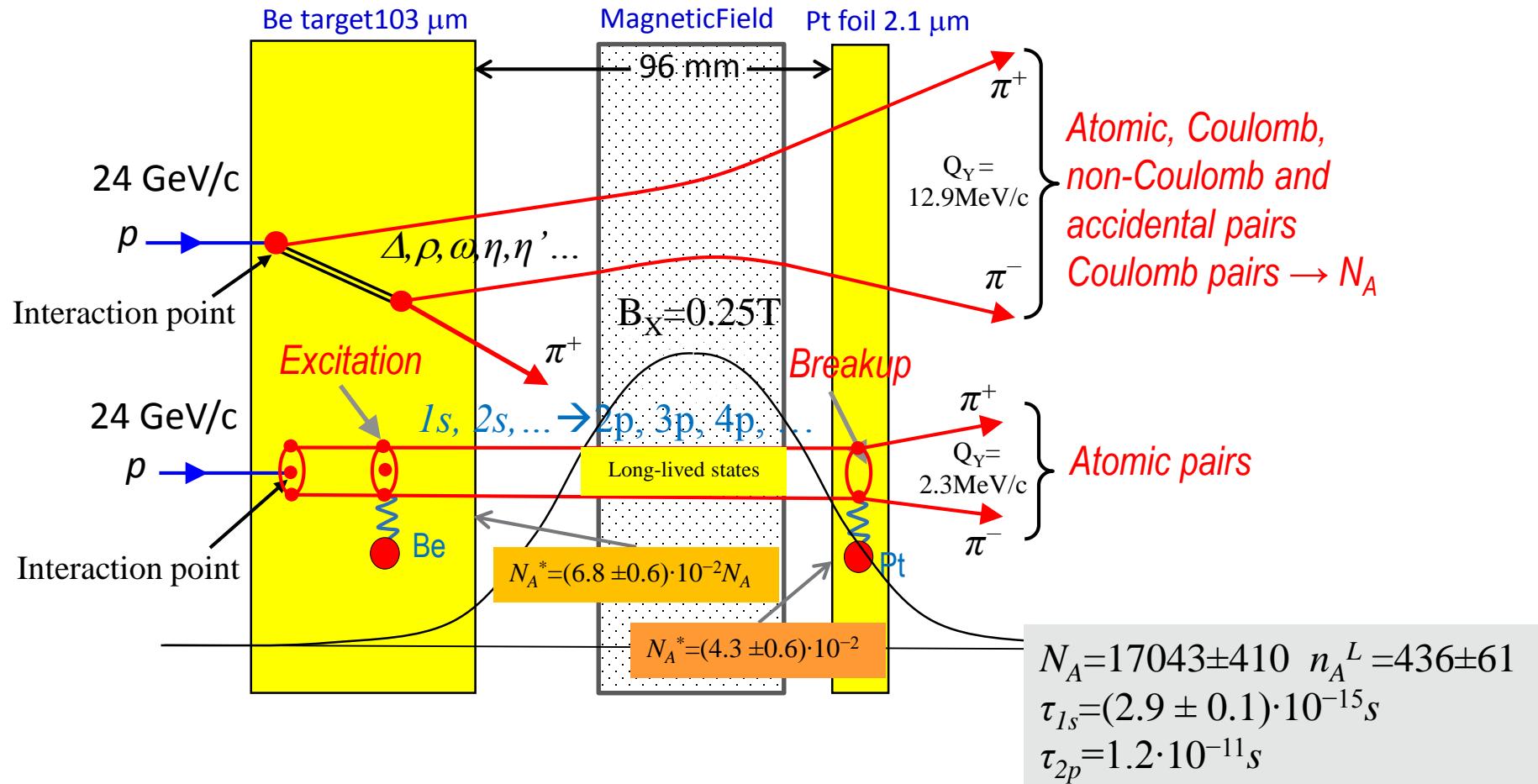


Experiment	Detected atomic pairs (n_A)	τ (10^{-15} sec)	$a^- = \frac{1}{3} (a_{1/2} - a_{3/2})$	Average error		
DIRAC	Phys.Rev.Lett. 117,(2016) =349±62(tot) (5.6 σ)	$5.5^{+5.0}_{-2.8}$	$0.072^{+0.031}_{-0.020}$	34%		
Theory	P.Buttiker et al., Eur.Phys.J. (2004)	K.Sasaki et al., Phys.Rev. (2014)	Z.Fu, Phys.Rev. (2013)	S.R.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

π^+K^- and π^-K^+ atoms data analysis

1. The paper “Observation of π^+K^- and π^-K^+ atoms“ is published: Phys.Rev.Lett., 117,112001(2016).
- 2.The paper “Updated DIRAC spectrometer at CERN PS for the investigation of $\pi\pi$ and $K\pi$ atoms” approved for publication in NIM
- 3.The paper “The measurement of πK atom lifetime and πK scattering lengths” will be submitted for publication before the end of 2016.

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

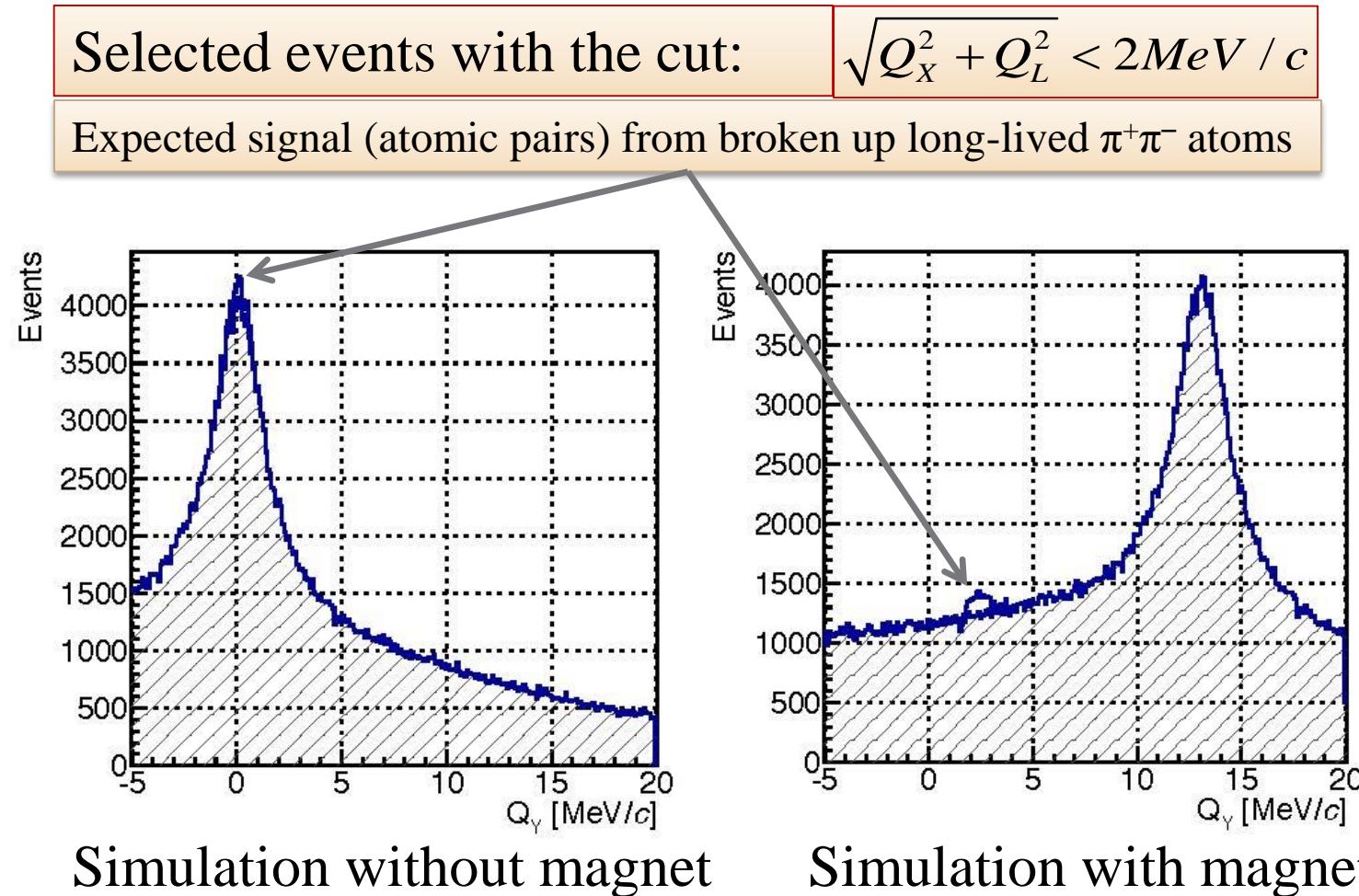


n	2	3	4	5	≥ 2
$\epsilon_n(\text{Be}) \times 10^2$	$2.48 \pm 0(10^{-3})$	1.54 ± 0.01	0.86 ± 0.03	0.56 ± 0.06	6.8 ± 0.6
$\epsilon_n(\text{Pt}) \times 10^2$	$0.52 \pm 0(10^{-4})$	$1.10 \pm 0(10^{-3})$	0.78 ± 0.03	0.54 ± 0.06	4.3 ± 0.6
P_{br}	0.72 ± 0.03	0.89 ± 0.03	0.94 ± 0.02	0.96 ± 0.02	0.97 ± 0.02

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.



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 ($\tau \geq 1 \times 10^{-11}$ sec) $\pi^+\pi^-$ atom breakup (ionisation).

Lifetime of the short-lived $\pi^+\pi^-$ atom is $\tau \geq 3 \times 10^{-15}$ 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.

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

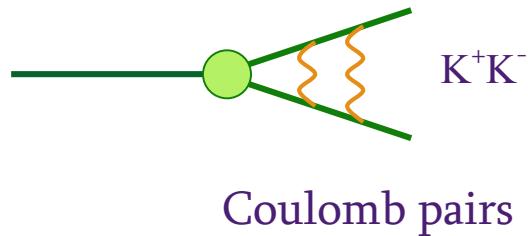
1. The $\pi^+\pi^-$ atom lifetime measurement with precision 9% was published (Phys.Lett.2011) The new available data were used for calibration. The analysis of this data will be ready in the beginning of 2017 and dedicated paper will be published before the end of 2017.
2. The current value of systematical 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 $\pm 2\sigma$.

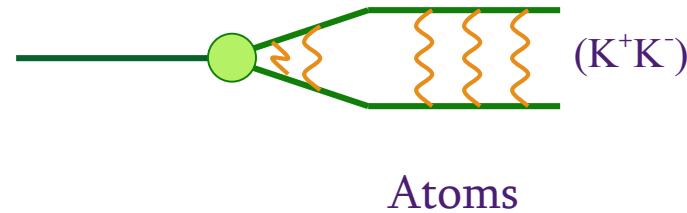
It is expected that systematic errors would be decreased by 2 times. Also we plan to test predictions of Moliere theory.

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:

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

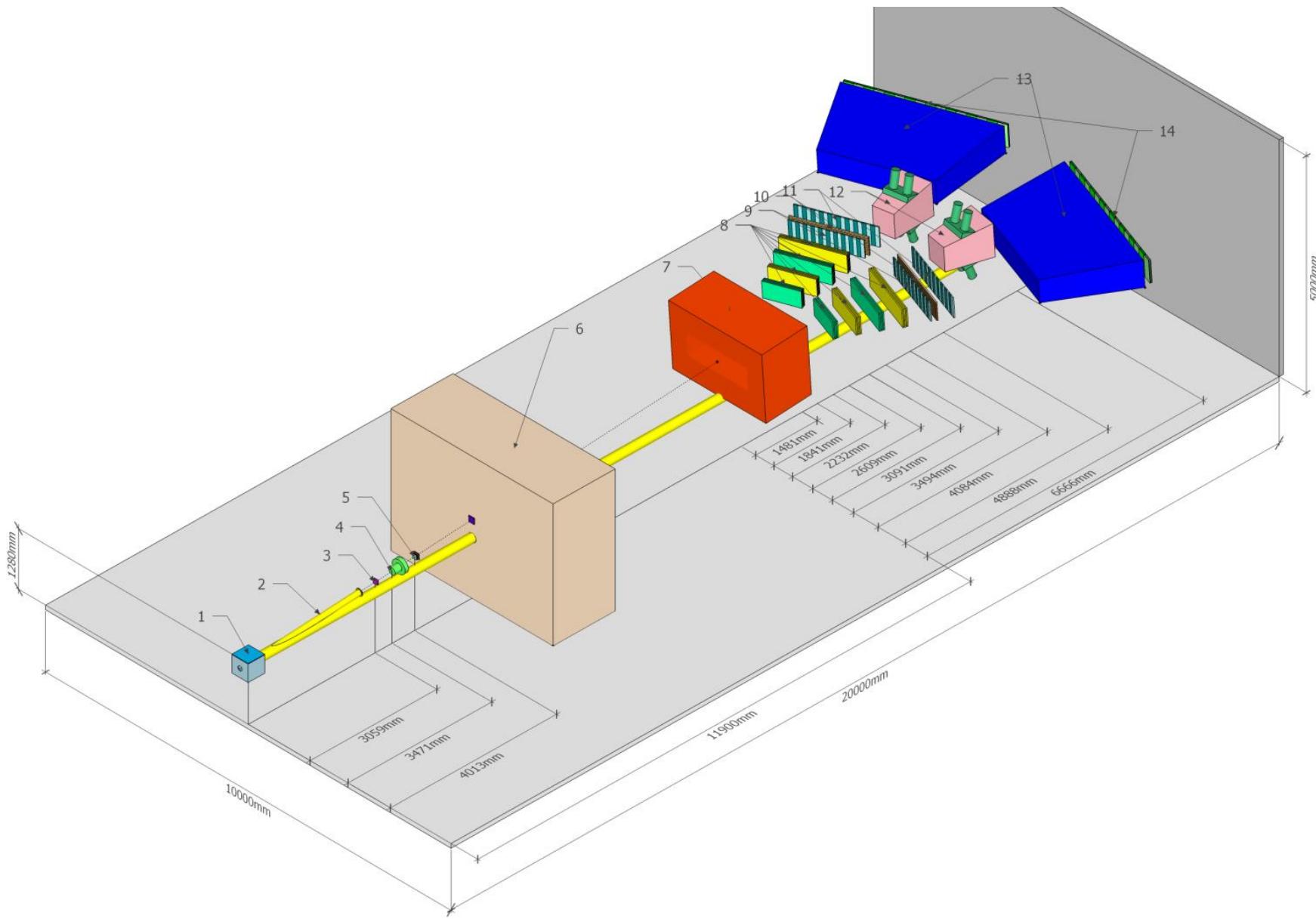
$$n_A - \text{atomic pairs number}, \quad P_{br} = \frac{n_A}{N_A}$$

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^- pairs analysis

1. Search for K^+K^- Coulomb pairs will be performed in 2016-2017 with improved procedure of the particles identification using time-of-flight technique. The number of produced K^+K^- atoms can be evaluated from the number of about 7000 K^+K^- pairs with a total momentum in the lab. system between 2.8 GeV/c and 6.0 GeV/c. If the signal from the Coulomb pairs will be seen, then analysis will continue to the higher momentum region 6.0 - 9.6 GeV/c. where we have 2400 K^+K^- pairs. The total existing statistics of K^+K^- pairs on Ni target is expected to be about 80000.
2. The possibility of KK scattering lengths evaluation will be studied in 2017.
3. Simulation of the K^+K^- pairs and the K^+K^- atoms production for proton momentum 24 GeV/c and 450 GeV/c using CERN version of FRITIOF generator is finished (DIRAC note 2016-7).
4. The results of investigation will be published in the beginning of 2018.

The possible scheme of the setup and detectors



SPS beam time for πK scattering length measurement

The data at $p_p = 24\text{GeV}/c$ and $450\text{Gev}/c$ were simulated, processed and analysed (V.Yazkov, DIRAC note, 2016- 05).

Thin Ni target, nuclear efficiency $\sim 6 \times 10^{-4}$.

The proton beam can be used for other experiments.

Proton beam intensity: 3×10^{11} protons/s (DIRAC worked at 2.7×10^{11} protons/s). Running time: 5 months

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

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%)

$\mathcal{L}(2)$ 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 et al., Eur. Phys. J. (2009), J.R.Bateley et al., Eur. Phys. (2010), Adeva et al., Phys. Lett. (2011)
	a_0	~ 6% precision	J.R.Bateley et al., Eur. Phys. J. (2009), J.R.Bateley et al., Eur. Phys. (2010)
	a_2	~22% precision	
on SPS	a_0-a_2	~2% precision	DIRAC estimation

Conclusion

1. The paper “Observation of π^+K^- and π^-K^+ atoms” is published.
2. The paper “ Measurement of πK atom lifetime and πK scattering lengths” will be submitted for publication before the end of 2016.
3. The paper “ First measurement of the long-lived $\pi^+\pi^-$ atom lifetime” will be submitted for publication before June 2017.
4. Search for K^+K^- Coulomb pairs will be performed in 2016-2017 . If these pairs would be observed than the number of produced K^+K^- atoms will be evaluated.

Conclusion

5. 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 submitted for publication before the end of 2017.
6. 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 to check the Moliere theory accuracy. The statistical precision in each measurement on the order of magnitude higher than in the published measurements.

Conclusion

7. The number of produced $A_{2\pi}$, $A_{\pi^+K^-}$ and $A_{\pi^-K^+}$ per time unit at $p_p = 450 \text{Gev}/c$, will be 12 ± 2 , 53 ± 11 and 24 ± 5 times higher than in the DIRAC experiment(J.Phys. G: Nucl. Phys. 43 (2016) 095004.)

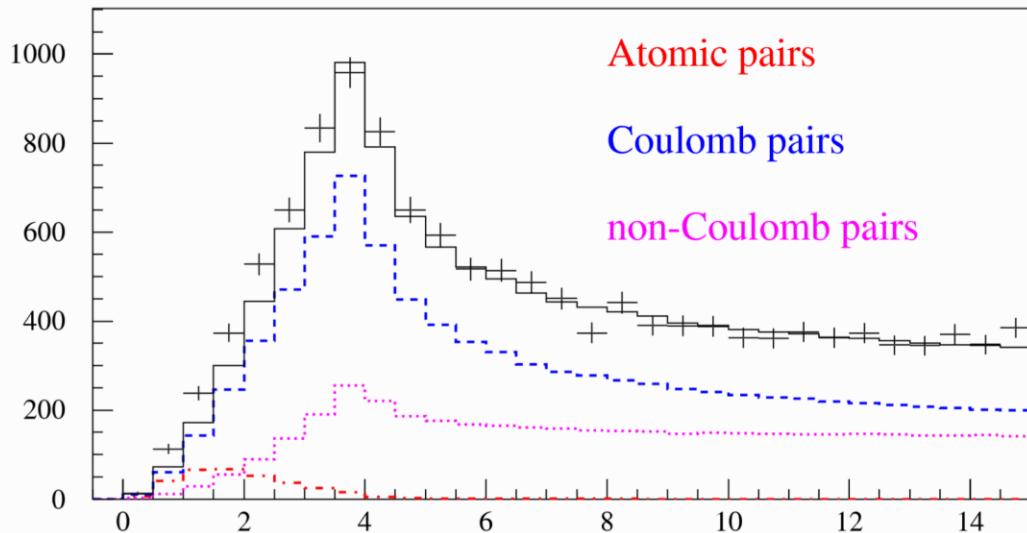
At proton beam intensity 3×10^{11} protons/s. and running time **5 months** the expected number of πK atomic pairs: $n_A = 13000$. The statistical(systematic) precision in these conditions for πK scattering length is $\sim 5\%$ (2%).(The DIRAC error is 34%)
The expected number of $\pi^+\pi^-$ atomic pairs $n_A = 400000$
The statistical(systematic) precision of the $\pi^+\pi^-$ scattering length will be: 0.7% (2%).

Conclusion

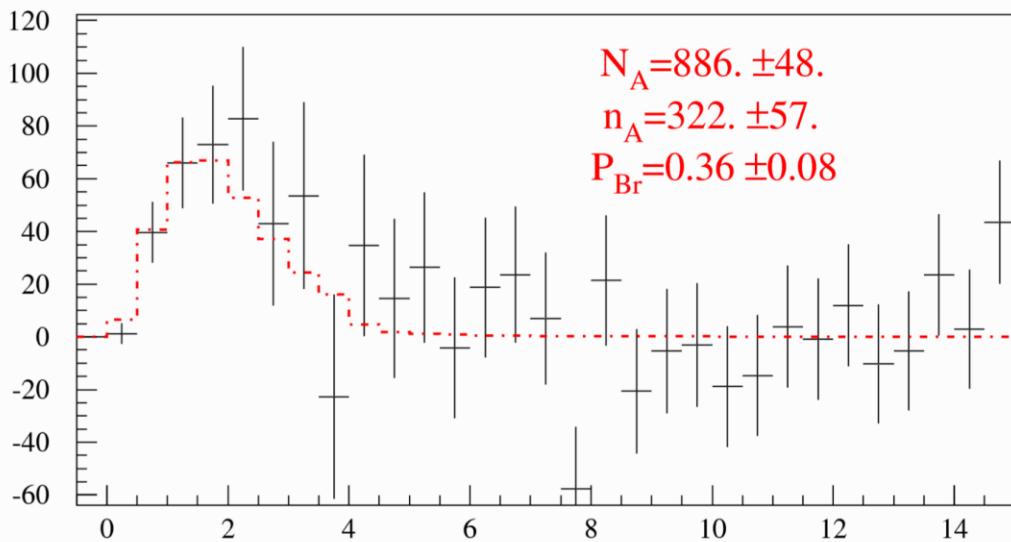
8. In the DIRAC experiment were observed $436 \pm 57(\text{stat}) \pm 23(\text{syst})$ long-lived $\pi^+\pi^-$ atoms. The higher energy of proton beam and the simple change of the experiment scheme open a possibility for the measurement of the Lamb shift and evaluation of the new combination of $\pi\pi$ scattering lengths $2a_0 + a_2$.
9. The Letter of Intent about investigation of $K\pi$ and $\pi^+\pi^-$ atoms will be submitted to SPSC at April 2017.

Thank you

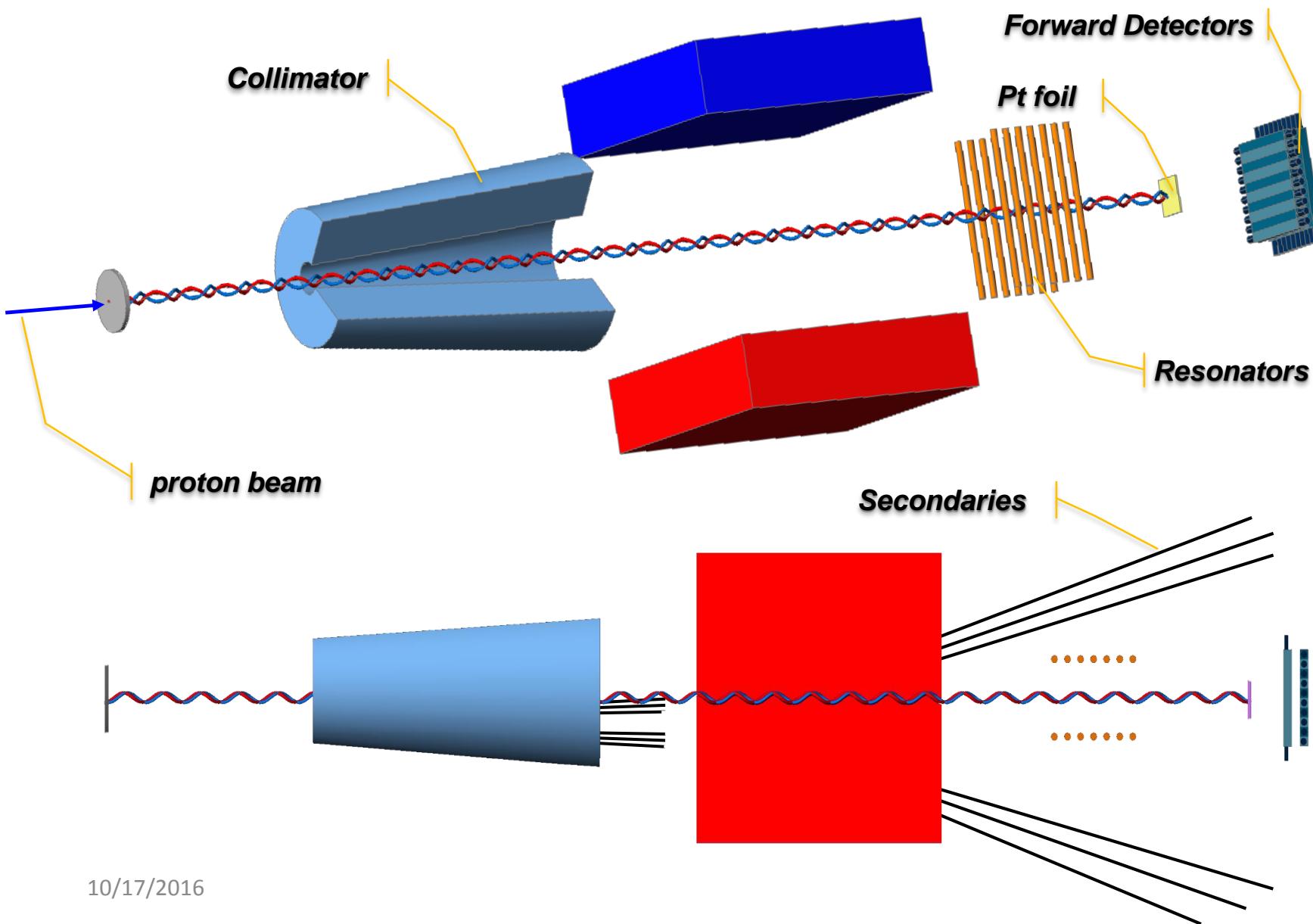
Experimental Q distributions of $K^+\pi^-$ and π^+K^- pairs



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.



DIRAC future Experimental setup

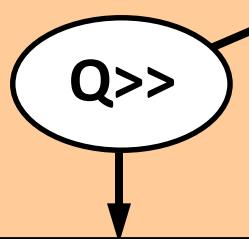


Theoretical motivation



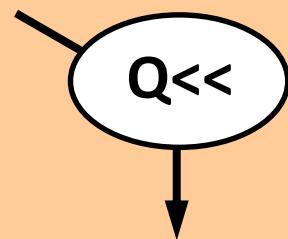
Strong interaction: $L_{QCD} = L_{sym} + L_{sym-break}$ ($m_q \neq 0$)

HIGH energy
(small distance)



(chiral symmetry)

LOW energy
(large distance)



perturbative QCD:

$$L_{QCD}(q,g)$$

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

Checks only L_{sym} !

non-perturbative QCD:

$$L_{eff}(\text{GB: } \pi, K, \eta); L_{lattice}(q, g)$$

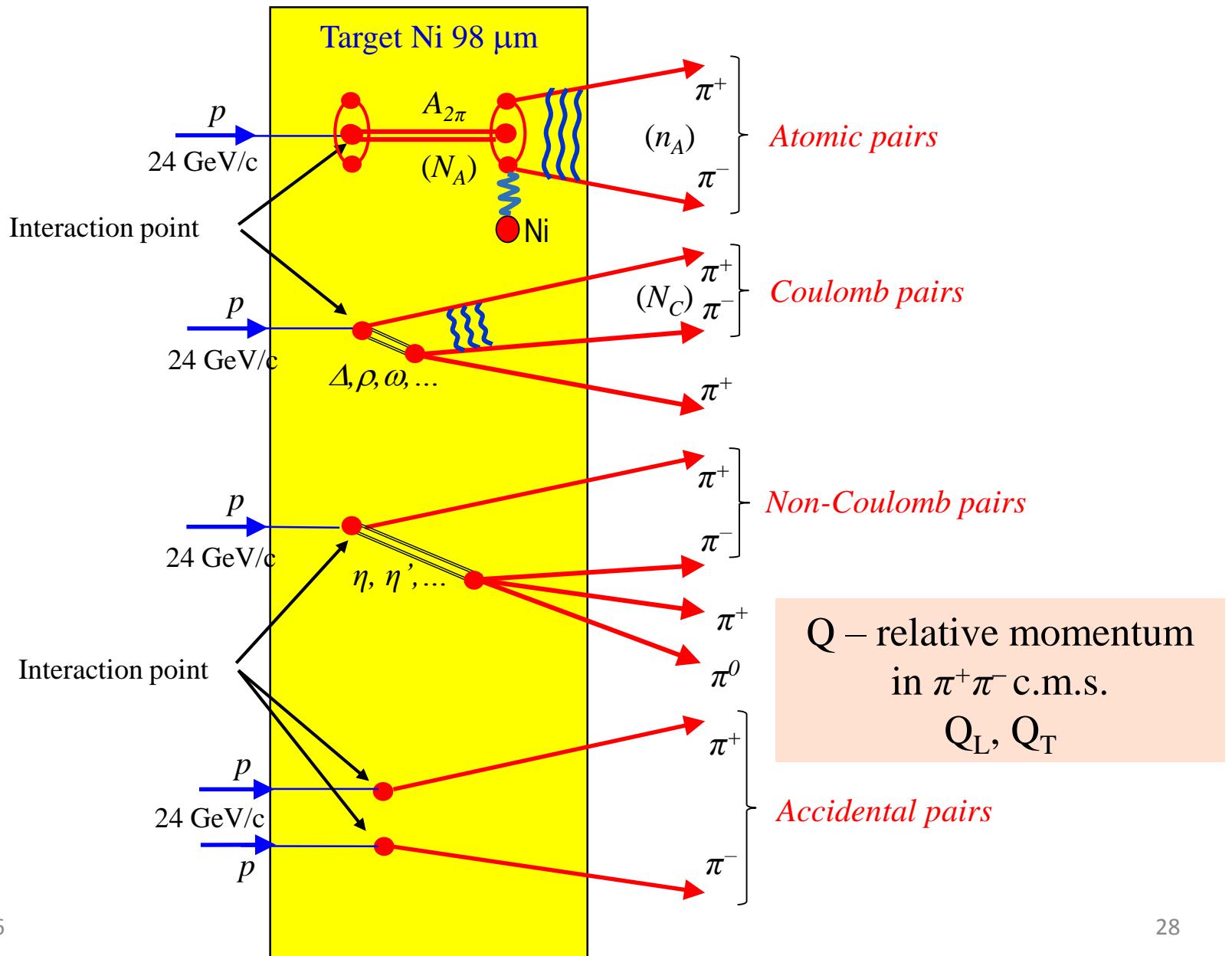
Interaction → „strong“ (confinement)
Methods: 1) Chiral Perturbation Theory
2) Lattice Gauge Theory

Checks L_{sym} as well as $L_{sym-break}$!

spontaneously broken symmetry

quark-condensate

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



Theoretical motivation

$\pi\pi$ scattering length

In ChPT the effective Lagrangian, which describes the $\pi\pi$ interaction, is an expansion in terms:

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

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

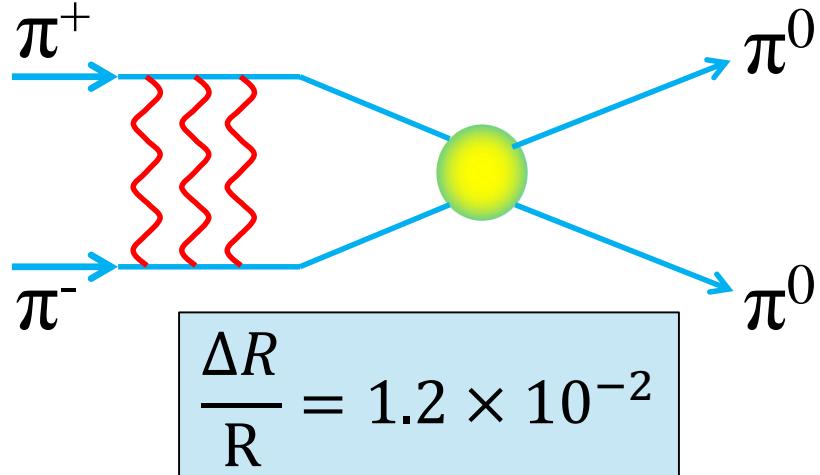
$$\left. \begin{array}{l} a_0 = 0.220 \pm 2.3\% \\ a_2 = -0.0444 \pm 2.3\% \end{array} \right\} \quad a_0 - a_2 = 0.265 \pm 1.5\%$$

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

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

$\pi^+ \pi^-$ atom (pionium) is a hydrogen-like atom consisting of π^+ and π^- mesons:

$$E_B = -1.86 \text{ keV}, \quad r_B = 387 \text{ fm}, \quad p_B \approx 0.5 \text{ MeV/c}$$



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

$$\Gamma = \frac{1}{\tau} = \Gamma_{2\pi^0} + \Gamma_{2\gamma} \quad \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4 \times 10^{-3}$$

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

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

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

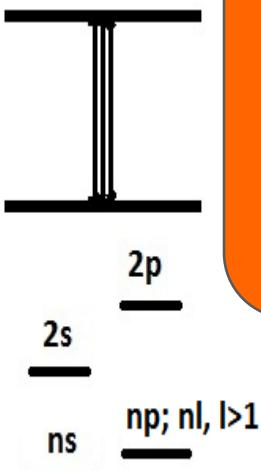
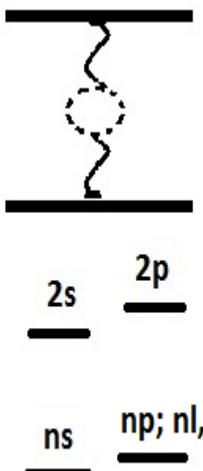
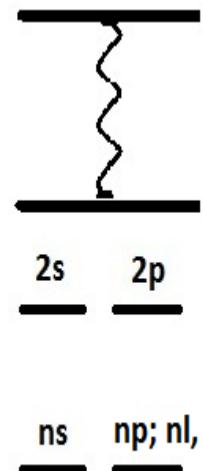
$$\psi_{nl}(0) \begin{cases} \neq 0 \text{ for } l=0 & A_{2\pi}(1s, 2s, \dots, ns) \rightarrow \pi^0 \pi^0 \\ = 0 \text{ for } l \neq 0 & A_{2\pi}(np) \xrightarrow{\gamma} A_{2\pi}(1s, 2s, \dots, (n-1)s) \rightarrow \pi^0 \pi^0 \end{cases}$$

The np state lifetime depends on the transition $np \rightarrow 1s, 2s, \dots, (n-1)s$ probability. This probability is about 3 orders of magnitude less than for $ns \rightarrow \pi^0 \pi^0$.

Energy splitting measurement

A_{2π} Energy Levels

For Coulomb potential, E depends only on n



Coulomb potential

Vacuum polarisation

Strong potential

higher order QED

Notation:

$$\Delta_{2s-2p}^{vac} = -0.111 \text{ eV}$$

$$\Delta_{2s-2p}^{str} = -0.47 \pm 0.01 \text{ eV}$$

$$\Delta_{2s-2p}^{em} = -0.012 \text{ eV}$$

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

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

J. Schweizer
[PL B (2004)]

$$\Delta_{2s-2p}^{str} = -\frac{\alpha^3 m_\pi}{8} \frac{1}{6} (2a_0 + a_2) + \dots$$

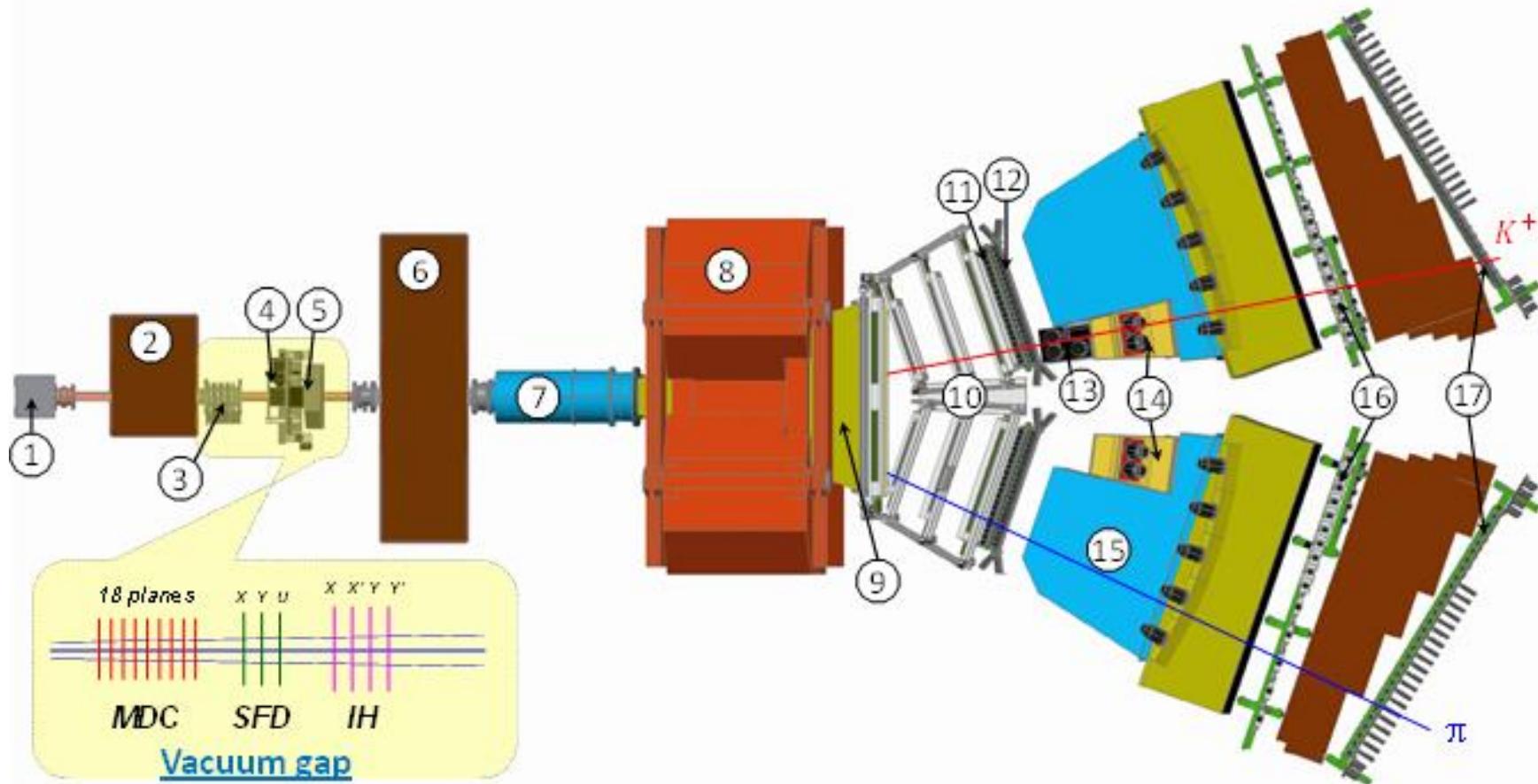
G.V.Efimov et al.
Sov.J.Nucl.Phys.
(1986)

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

CONCLUSION: one parameter (2a₀+a₂) allows to calculate all Δ_{ns-np}^{str} values

Δ_{2s-2p}^{vac} can be calculated with relative precision ≈ 10⁻⁵
(S. Karshtenbom)

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

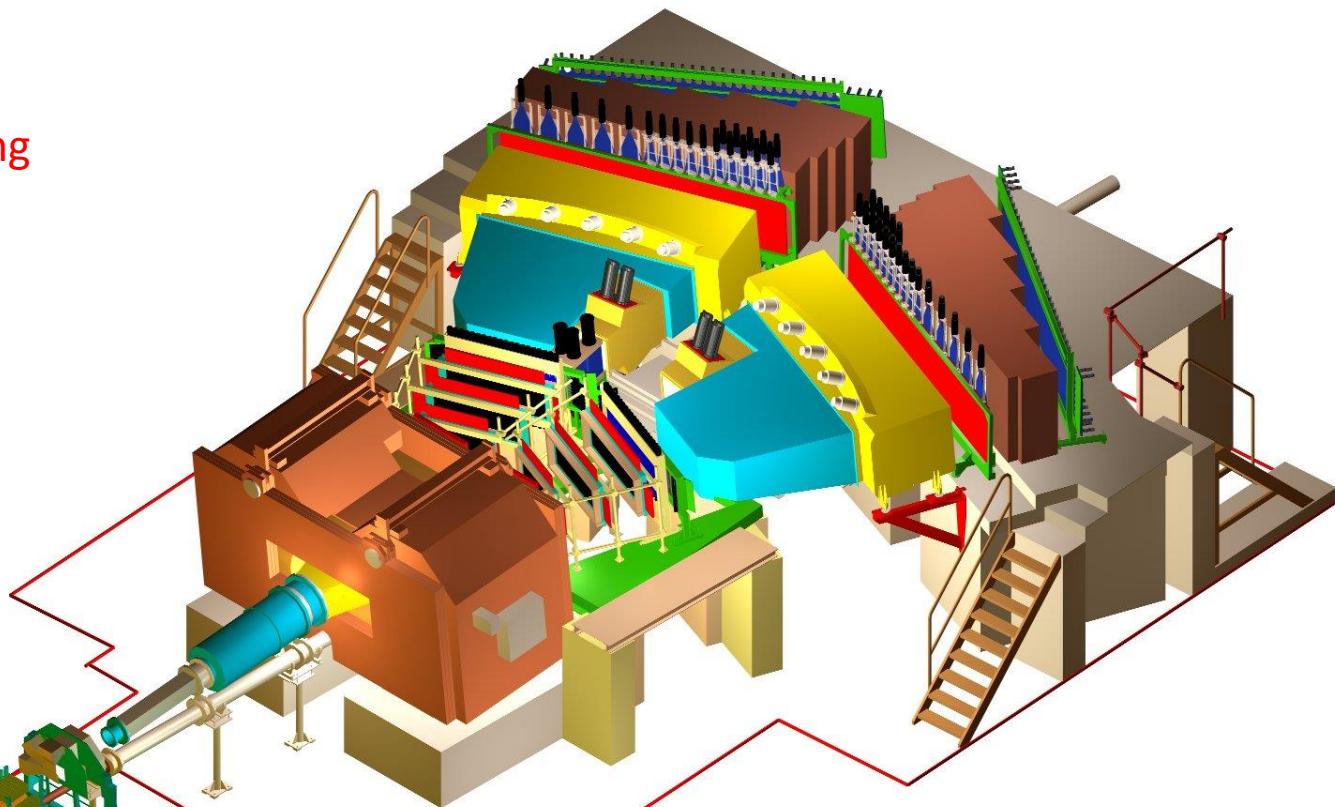
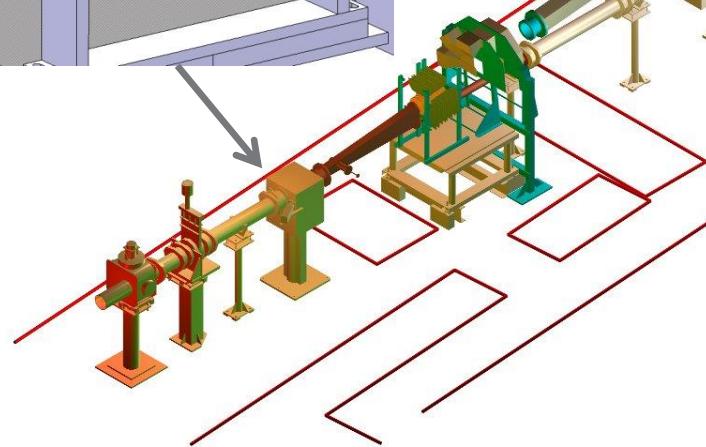
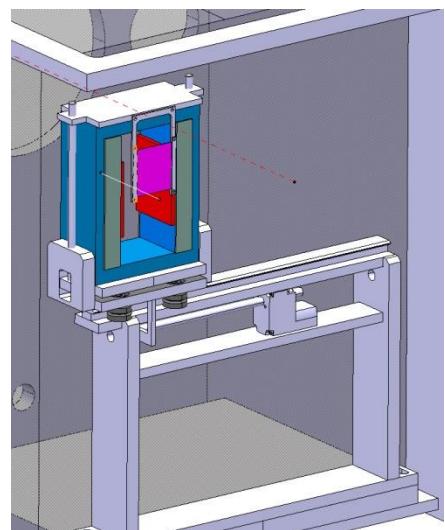
DIRAC upgraded Experimental setup

BLUE ... magnet yoke

GREY ... magnet poles

RED ... magnet shimming

PURPLE ... Pt foil

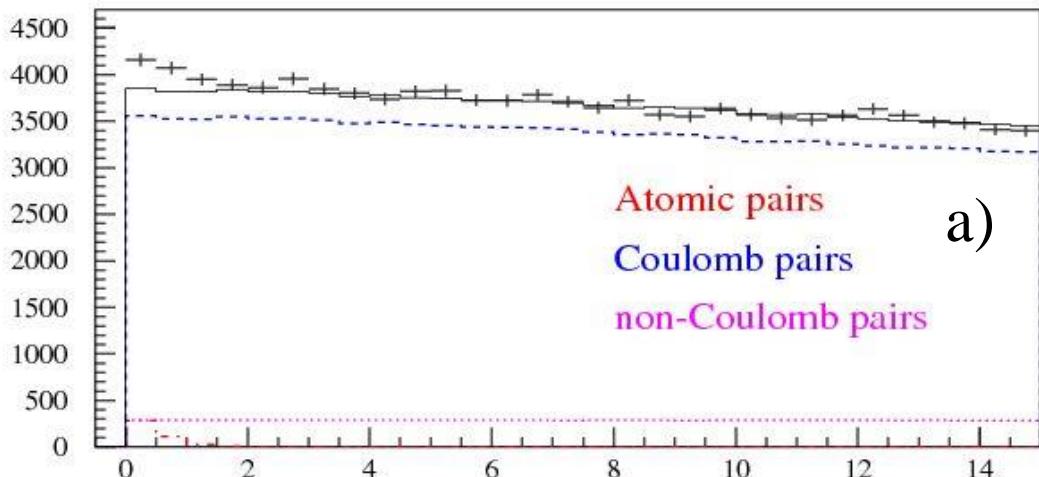


$$\sigma_{QX} = \sigma_{QY} = 0.5 \text{ MeV/c}$$

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

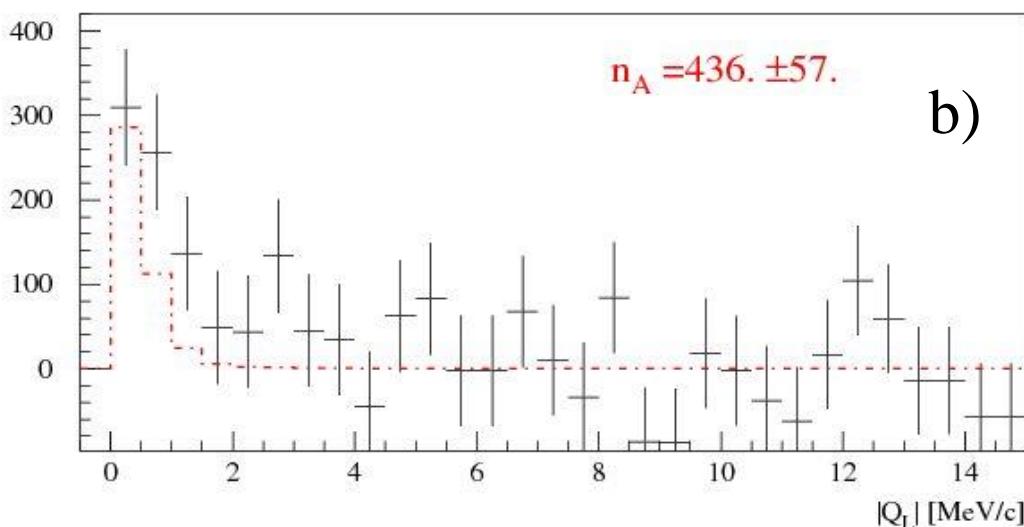
$$\sigma_{QL} = 0.9 \text{ MeV/c } (\pi K)$$

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).

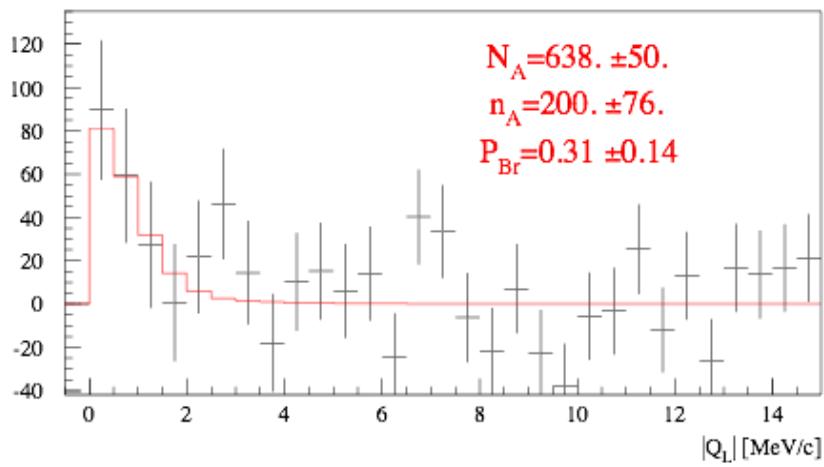
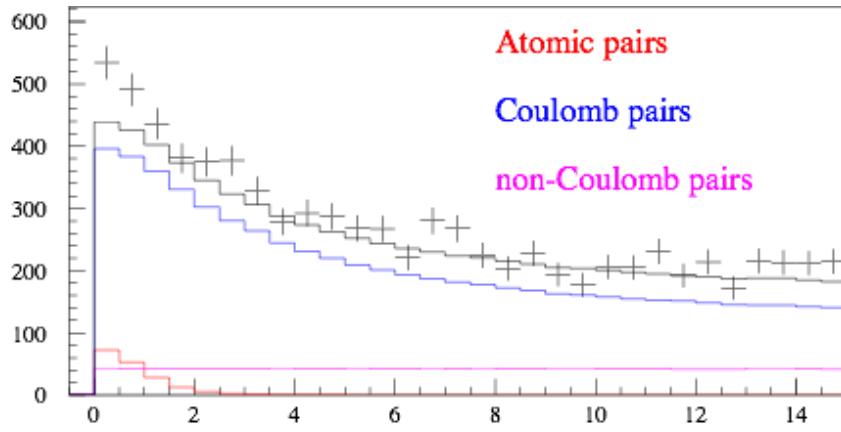
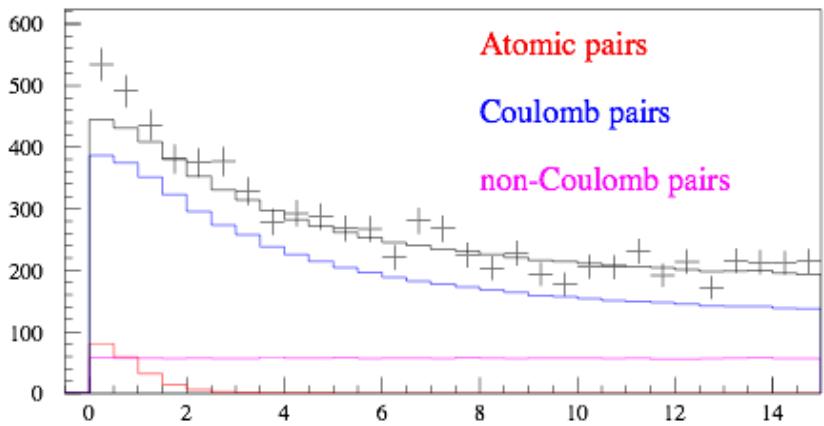


b) The experimental distribution after background subtraction (points with statistical error) and the simulated distribution of atomic pairs (dot-dashed line).

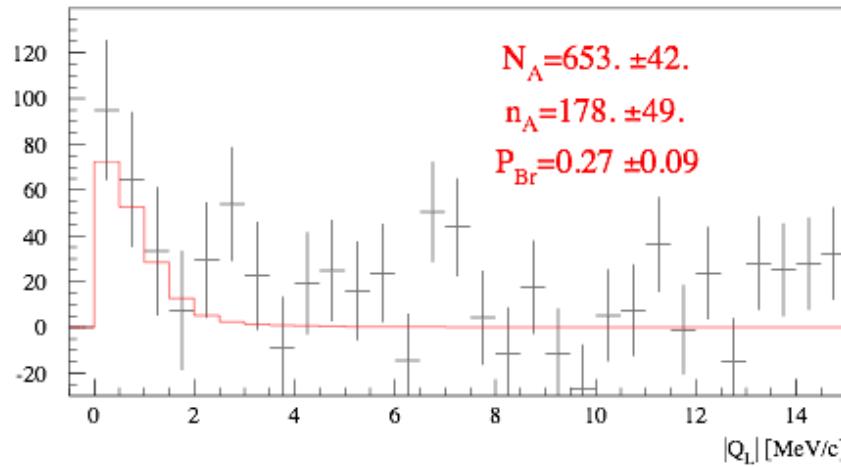
The fit procedure has been applied to the 2-dimensional ($|Q_L|$, Q_T) distribution.

π^+K^- and π^-K^+ - run 2008-2010

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

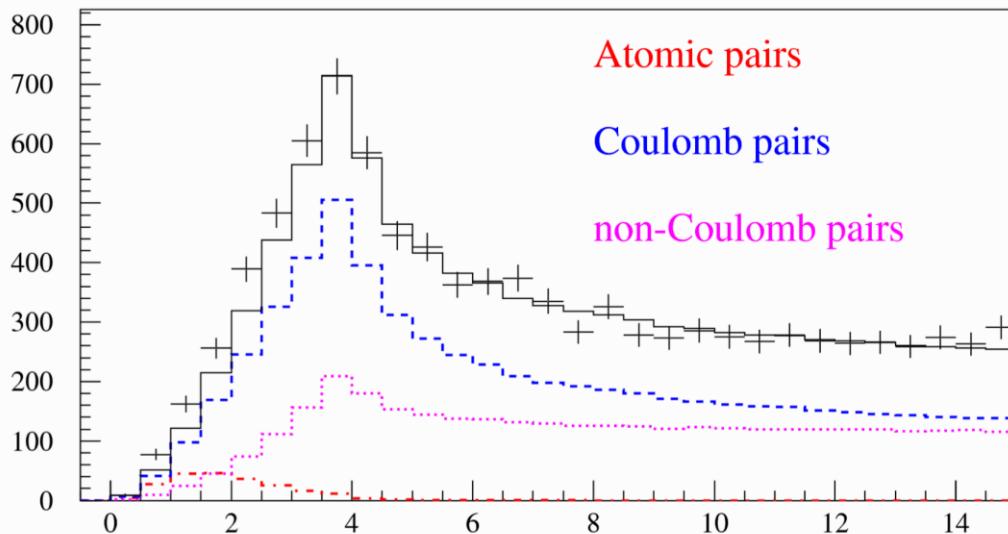


$|Q_L|$ distribution
analysis on $|Q_L|$ for $Q_T < 4$ MeV/c

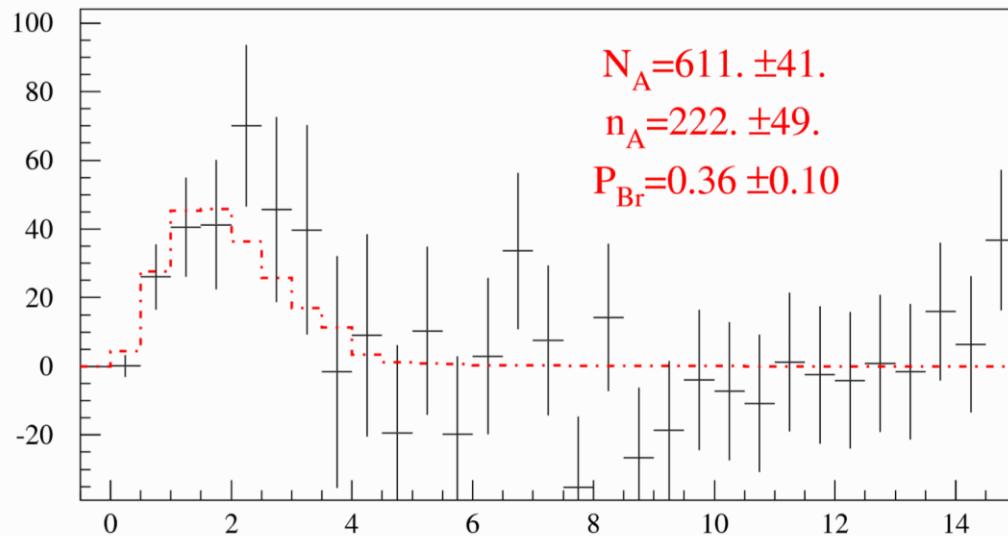


$|Q_L|$ distribution
analysis on $|Q_L|$ and Q_T for $Q_T < 4$ MeV/c

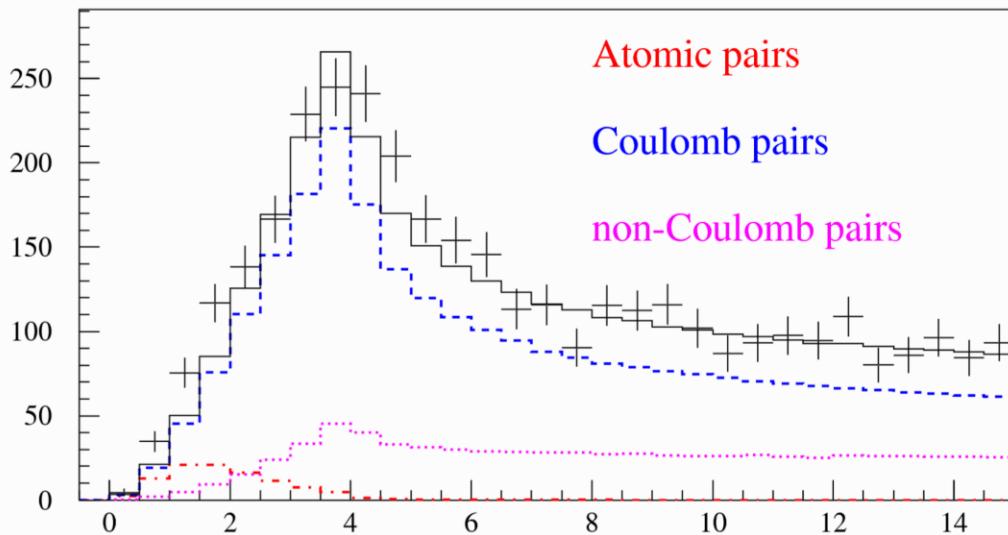
Experimental Q distributions of $K^+\pi^-$ pairs



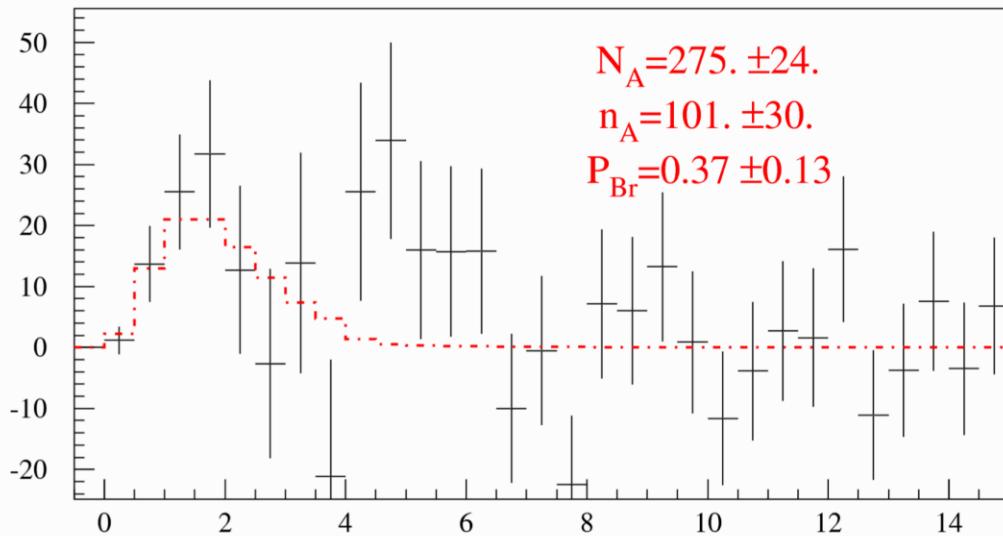
The Q distribution of the $K^+\pi^-$ pairs collected with Platinum target in 2007 and Nickel target in 2008, 2009, 2010.



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 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: $|Q_L| < 20 \text{ MeV/c}$, $Q_T < 4 \text{ MeV/c}$.

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

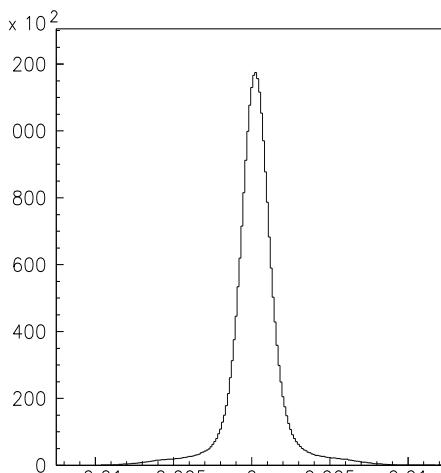
Number of “atomic pairs” (n_A) with statistical error and ratio signal-to-error (r_A) for πK atoms collected with **Platinum** target in 2007. Selection criteria: $|Q_L| < 20 \text{ MeV/c}$, $Q_T < 4 \text{ MeV/c}$.

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

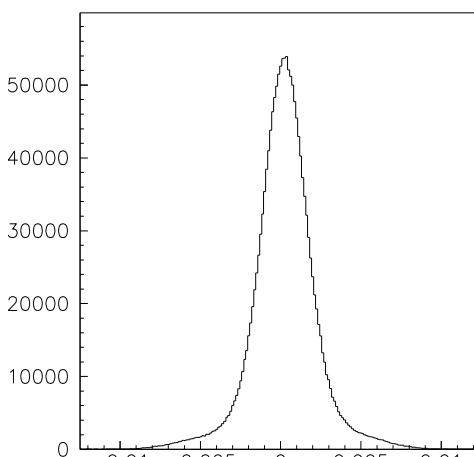
Number of “atomic pairs” (n_A) with statistical error and ratio signal-to-error (r_A) for πK atoms collected with **Platinum and Nickel** target in 2007, 2008, 2009 and 2010. Selection criteria: $|Q_L| < 20 \text{ MeV/c}$, $Q_T < 4 \text{ MeV/c}$

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

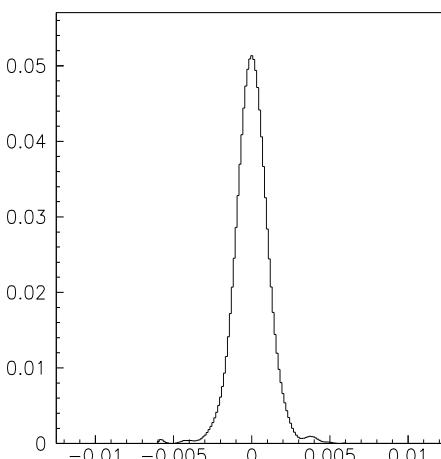
Multiple scattering evaluation



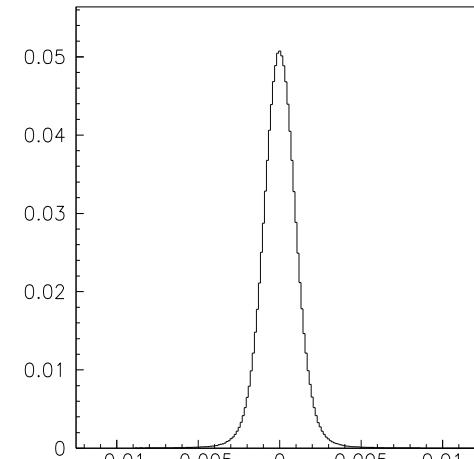
Ni-109 Drift Chamber Resolution



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⁻ atom and its lifetime

The A_{2π} lifetime is strongly reduced by strong interaction (OBE, scalar meson f₀ and a₀) as compared to the annihilation of a purely Coulomb-bound system (K⁺K⁻).

τ (A _{2K} → ππ, πη)	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) + πη-channel (I=1)
2.2×10^{-18} s [4]	ChPT

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

$\pi^+ \pi^-$ and πK atom production

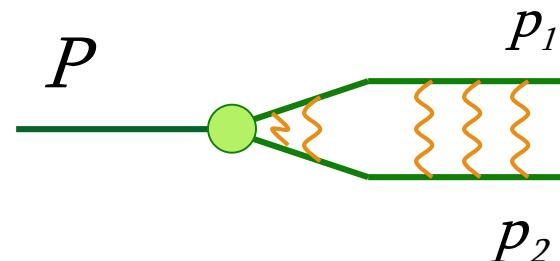
$$\frac{d\sigma_{nlm}^A}{d\vec{P}_A} = (2\pi)^3 \frac{E}{M} \left| \psi_{nlm}^{(C)}(\theta) \right|^2 \frac{d\sigma_s^0}{dp_1 dp_2} \Bigg|_{\vec{v}_1 = \vec{v}_2} \propto \frac{d\sigma}{dp_1} \cdot \frac{d\sigma}{dp_2} \cdot R(\vec{p}_1, \vec{p}_2; s)$$

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

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

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

- The QCD Lagrangian $\mathcal{L}(2)$ and Chiral Lagrangian describe processes with u and d quarks, using $SU(2)_L * SU(2)_R$ chiral symmetry breaking.
- From the ChPT prediction for a_0 and a_2 , the $\pi^+\pi^-$ atom lifetime in the ground state, given by $1/\tau = R|a_0 - a_2|^2$, is $\tau_{\text{th}} = (2.9 \pm 0.1) * 10^{-15}$ s.
- The evaluation error for $|a_0 - a_2|$ from this relation is 0.6%.
- These Lagrangians predict the S-wave $\pi^+\pi^-$ scattering lengths a_0 and a_2 .

SPS beam time for πK scattering length measurement

The data at $p_p = 24\text{GeV}/c$ and $450\text{Gev}/c$ were simulated, processed and analysed (V.Yazkov, DIRAC note, 2016 05).

Experimental conditions on SPS with Ni target

Thin Ni target, nuclear efficiency $\sim 6 \times 10^{-4}$.

The proton beam can be used for other experiments.

Proton beam intensity: 3×10^{11} protons/s (DIRAC worked at 2.7×10^{11} protons/s)

Number of spills: 4.5×10^5 with spill duration 4.5 s

Data taking: 3000 spills per 24 hours.

Running time: 5 months

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

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%

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 (3.6 σ) 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

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

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

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

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

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

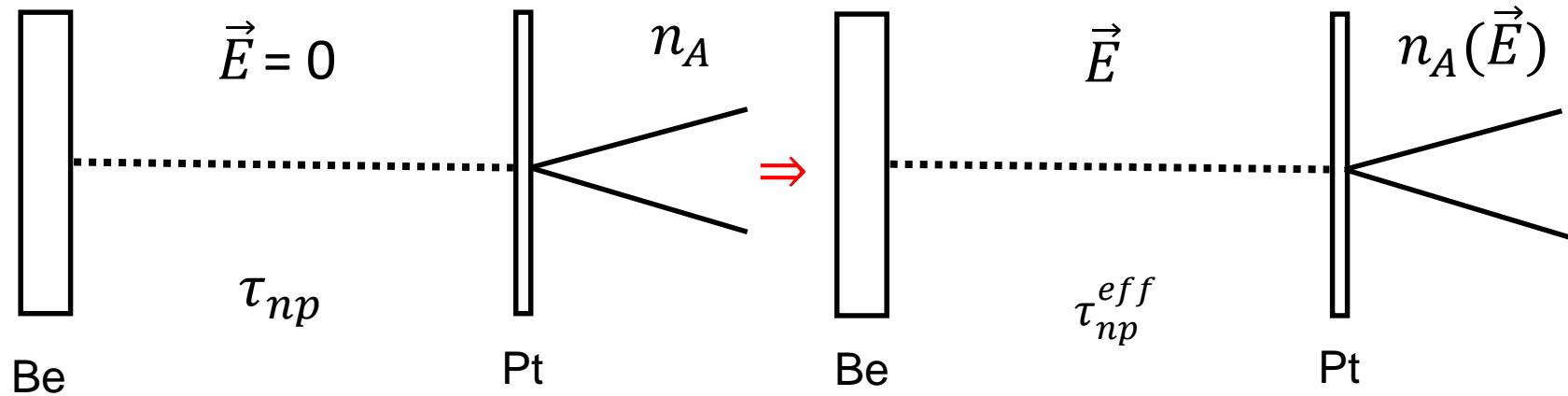
θ_{lab}	5.7°	4°	2°	0°
E_p	24 GeV/c	450 GeV/c	450 GeV/c	450 GeV
The yield of $\pi^+\pi^-$ atoms				
W_A	$1.25 \cdot 10^{-9}$	$1.9 \cdot 10^{-8}$	$3.5 \cdot 10^{-8}$	$4.5 \cdot 10^{-8}$
W_A^N	1	15 (9.7 ± 1.5)	28 (17.5 ± 2.8)	36 (22.7 ± 3.6)
$(W_A/W_{\text{ch}})^N$	1	2.4 (1.55 ± 0.20)	1.2 (0.77 ± 0.13)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

Energy splitting measurement

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

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

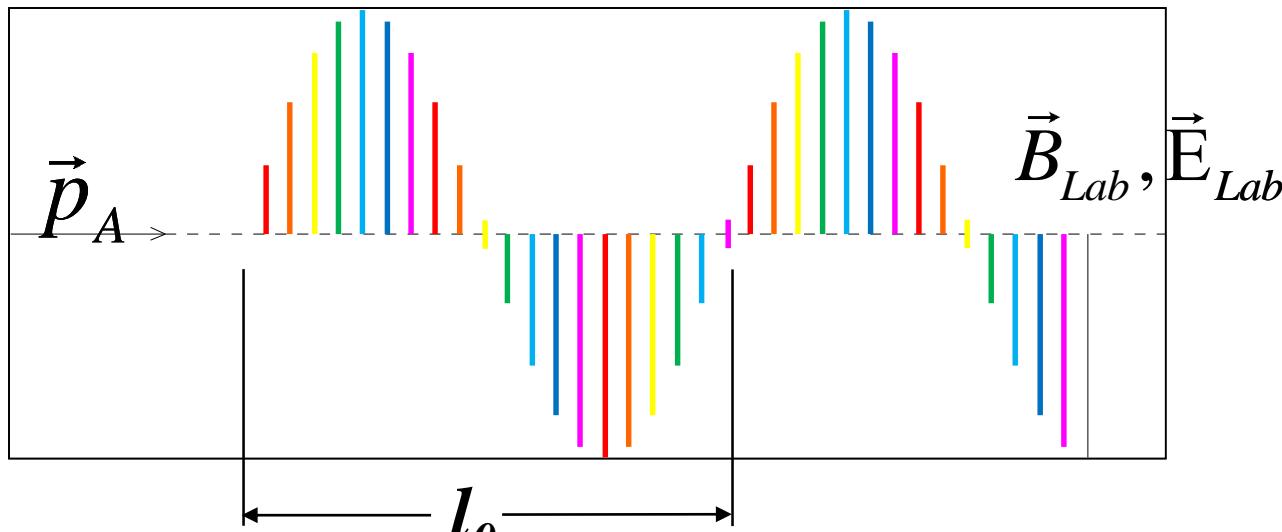


$$n_A - n_A(|\vec{E}|) = \Delta n(|\vec{E}|, \Delta E_{ns-np})$$

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

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

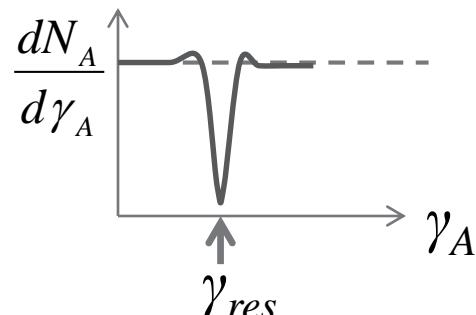
L.Nemenov, V.Ovsiannikov, E.Tchaplyguine, Nucl. Phys. (2002)



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

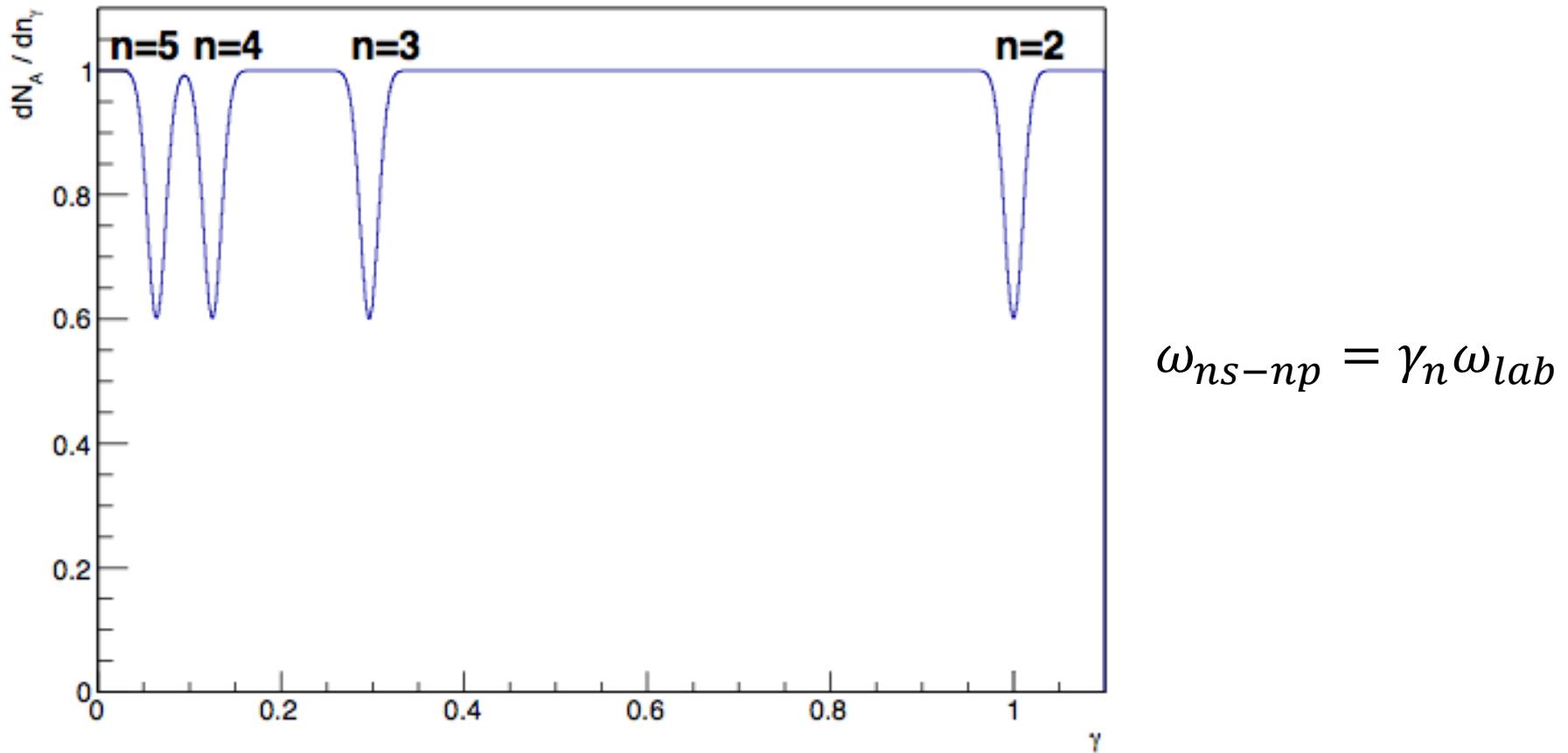
$$\text{In CM System: } \tilde{\omega} = \gamma \cdot \omega_{Lab}, \quad \tilde{\vec{E}} = \gamma \cdot \vec{E}_{Lab} \cdot \cos \tilde{\omega}t, \quad \tilde{\Omega} = \frac{E_{2p} - E_{2s}}{\hbar}$$

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



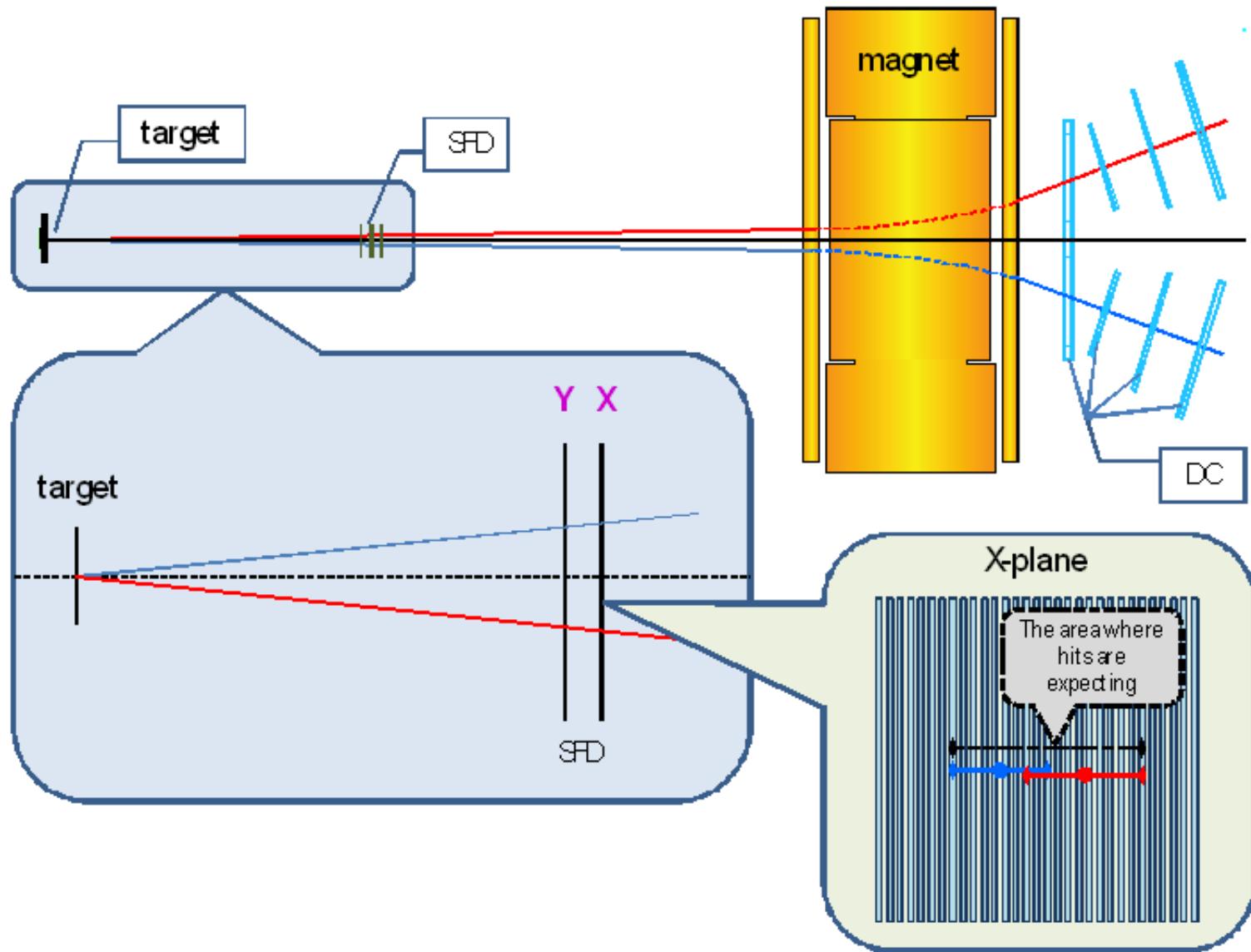
Energy splitting measurement

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!

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): $\bar{l}_3 = 2.6 \pm 0.5\text{st} \pm 0.4\text{sys}, \bar{l}_4 = 3.8 \pm 0.4\text{st} \pm 0.2\text{sys}$

Therefore, the theoretical pion-pion scattering length precision can be improved.

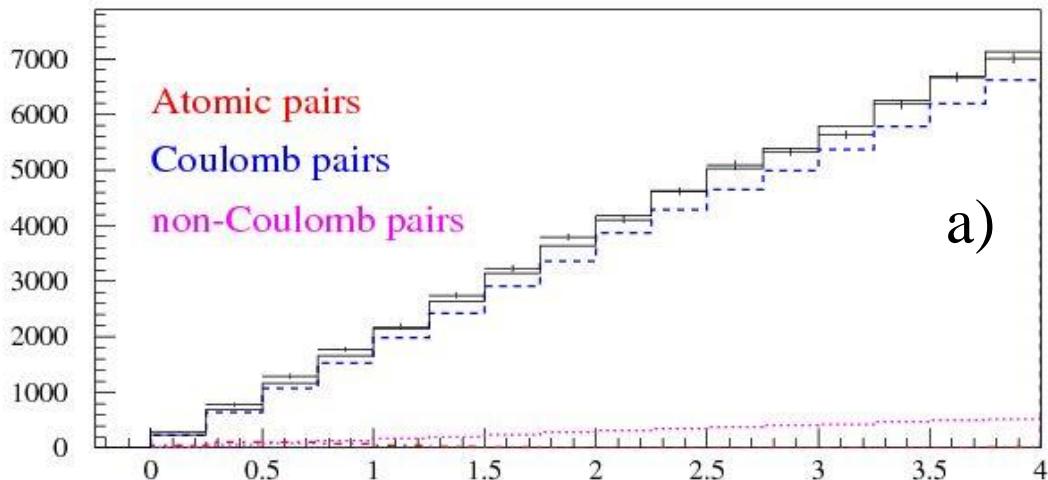
The best experimental results on the scattering length have a precision not better than 4%.

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.

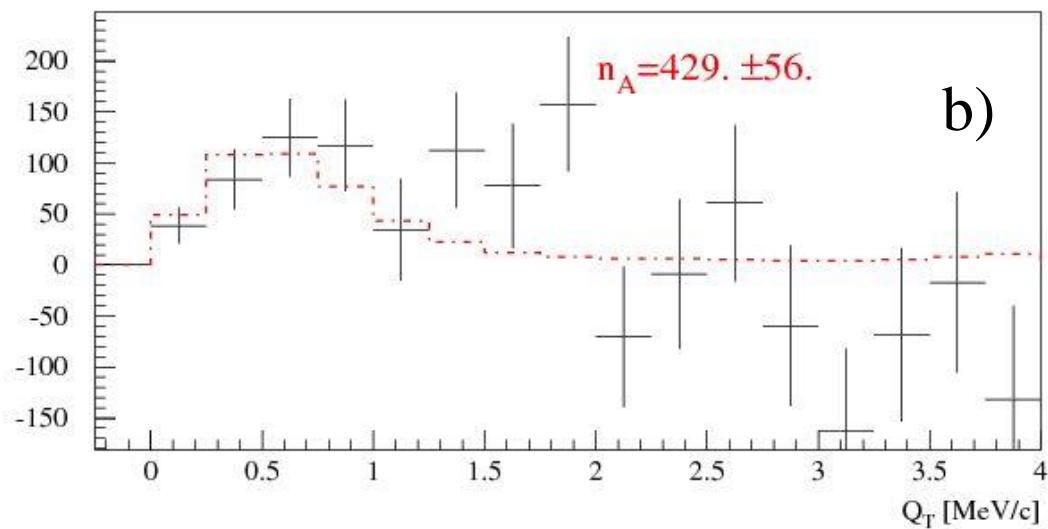
Q_T cut (MeV/c)	n_A^L	$n_A^{L,tot}$	Background	χ^2 / n
Fit over Q_L, Q_T				
2.0	436±57	488±64	16790	138/140
Fit over Q_L				
0.5	152±29	467±88	971	29/27
1.0	349±53	489±75	3692	19/27
1.5	386±78	454±91	9302	22/27
2.0	442±105	495±117	16774	22/27

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).

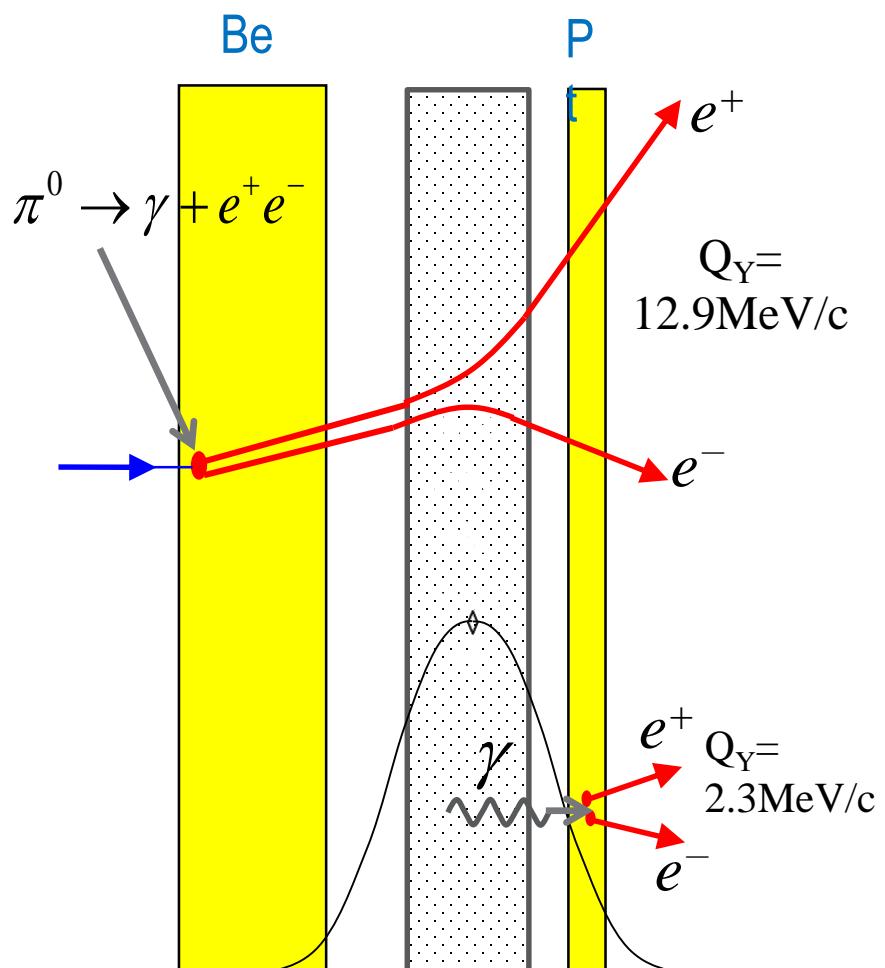
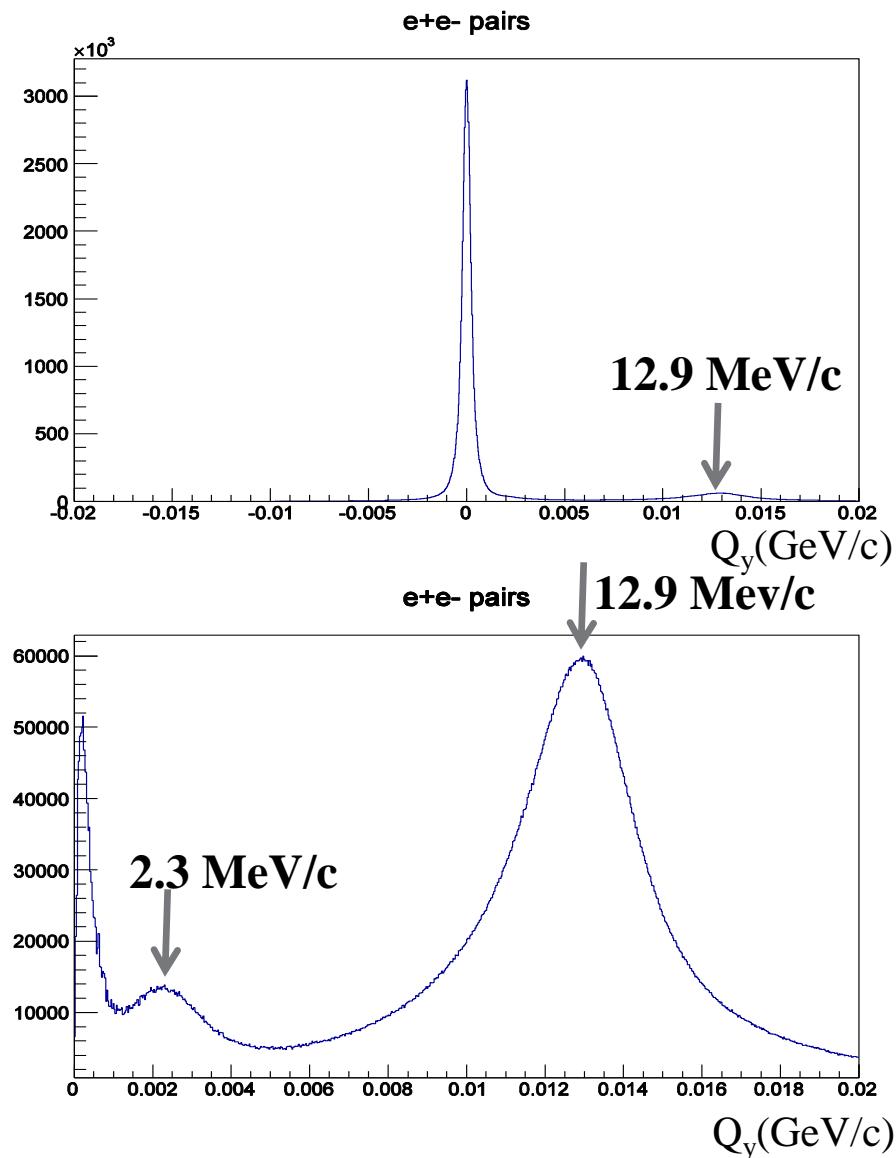


b) The experimental distribution after background subtraction (points with statistical error) and the simulated distribution of atomic pairs (dot-dashed line).

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

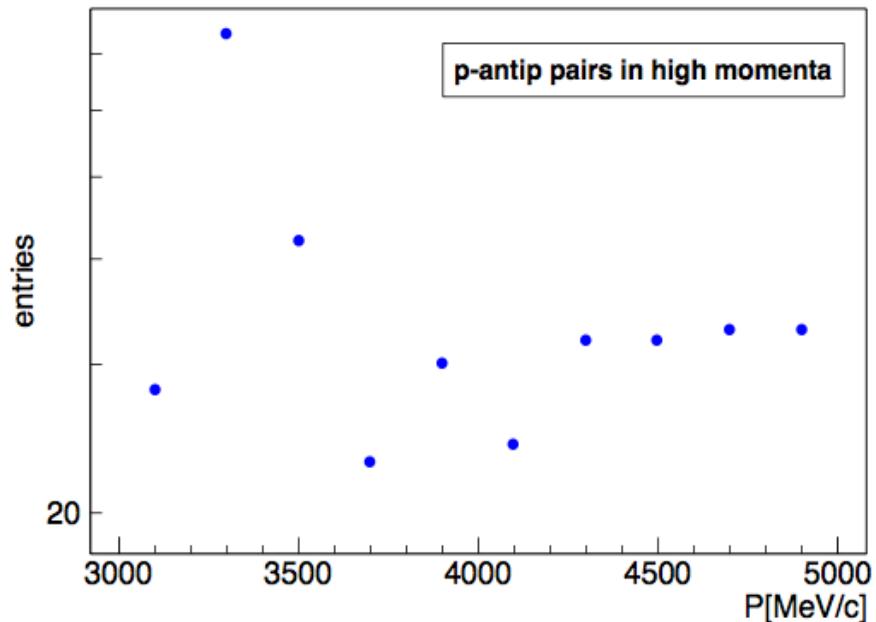
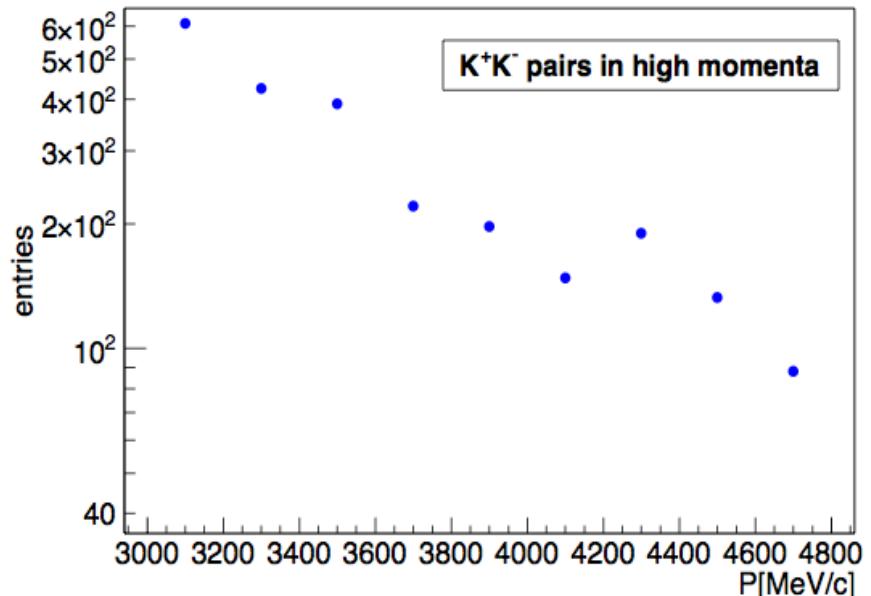
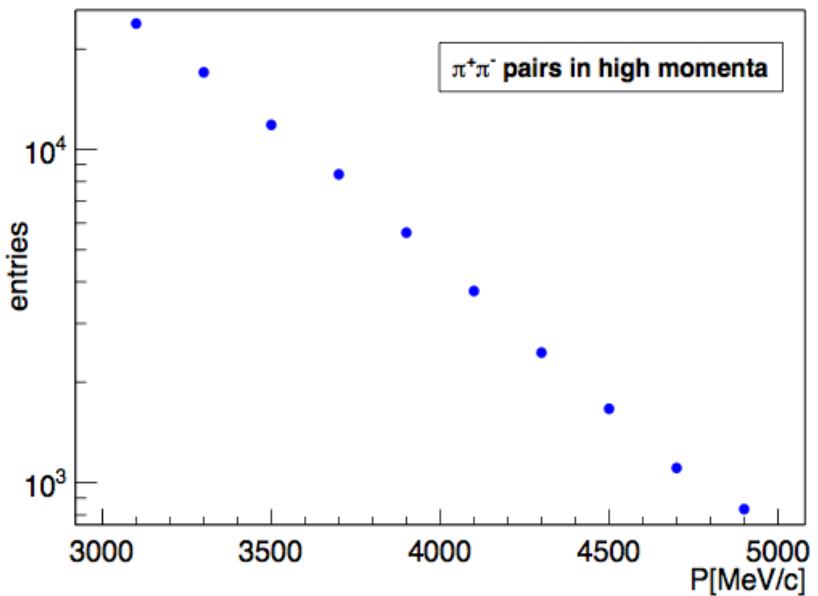
Magnet impact on Q_y distribution for e^+e^- pairs

Real data



Peak at $Q_y=2.3\text{MeV}/c$ evaluated after subtraction of the mirrored left side part.

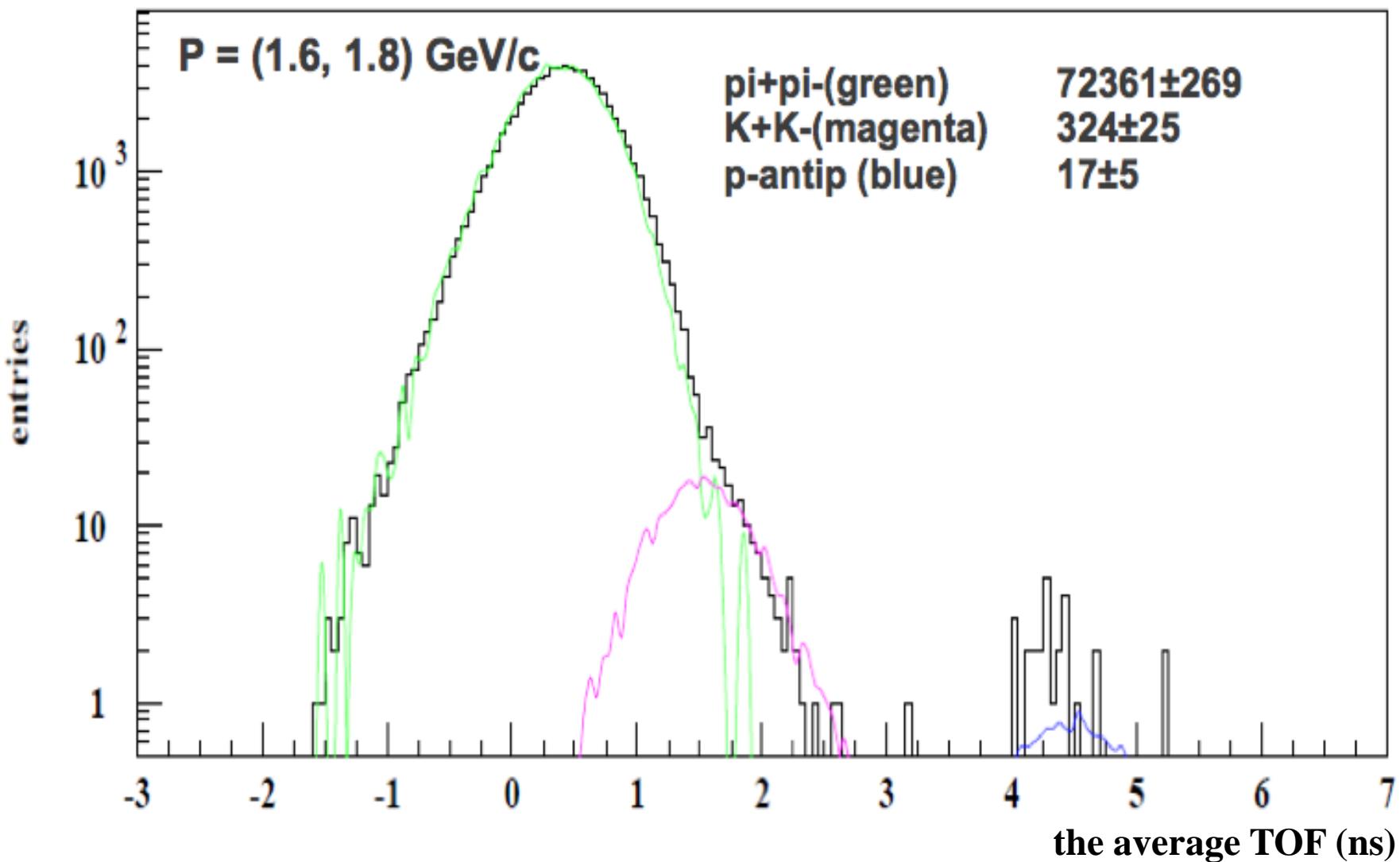
The $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ pair numbers



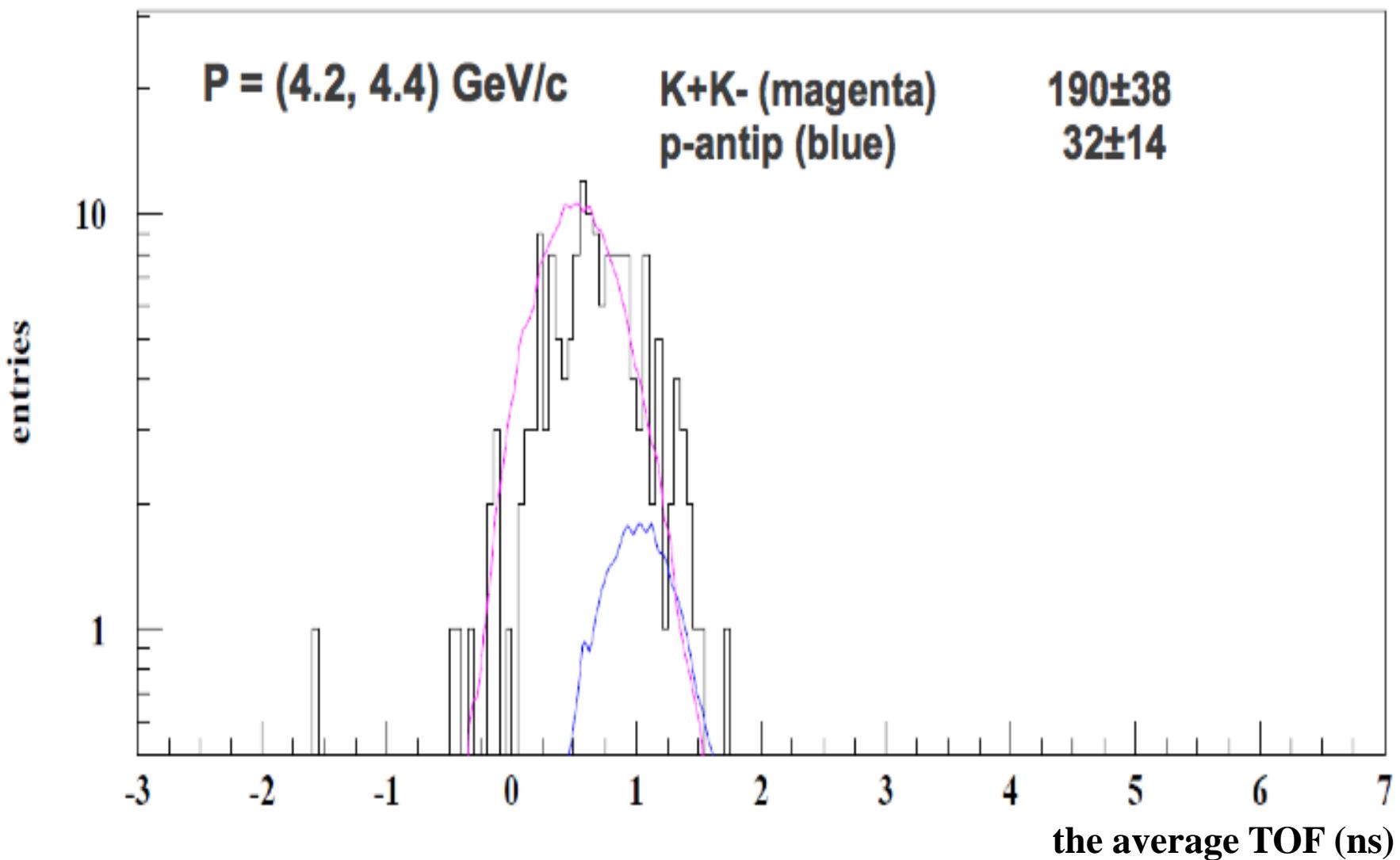
$\pi^+\mu^-$ and $\pi^-\mu^+$ pair analysis

- Analogously, the 2010 data will be investigated with respect to $\pi^+\mu^-$ and $\pi^-\mu^+$ Coulomb pairs, to extract the number of $\pi\mu$ 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 $p\bar{p}$ pair with TOF (low momentum)



Search of K^+K^- and $p-\bar{p}$ pair with TOF (high momentum)



Additional slides

Physics motivation

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

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

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

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

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

Experimental results

K \rightarrow 3 π :

(scattering length in m_π^{-1})

2009 **NA48/2** (EPJ C64, 589)

$$\Rightarrow a_0 - a_2 = 0.2571 \pm 0.0048 \Big|_{stat} \pm 0.0025 \Big|_{syst} \pm 0.0014 \Big|_{ext} = \dots \pm 2.2\%$$

plus additional 3.4% theory uncertainty

Ke4:

2010 **NA48/2** (EPJ C70, 635)

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

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

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

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

$$\Rightarrow |a_0 - a_2| = 0.2533 \begin{array}{l} +0.0078 \\ -0.0080 \end{array} \Big|_{stat} \begin{array}{l} +0.0072 \\ -0.0077 \end{array} \Big|_{syst} = \dots \begin{array}{l} +4.2\% \\ -4.4\% \end{array}$$

Experimental results with additional theoretical constraints

K→3π:

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

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

plus additional 2% theory uncertainty

Ke4:

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

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

Ke4 & K→3π:

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

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

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

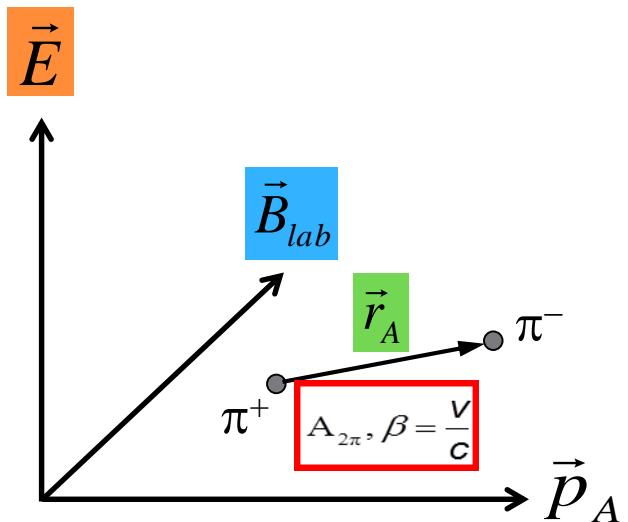
n	$\tau_{2\pi}$		Decay length $A_{2\pi}$ in L.S. (cm) for $\gamma=16$	
	(10^{-11}sec)		$(\lambda_{ns}=c \cdot \gamma \cdot \tau_{nl})$	
	s ($l=0$) $\tau_{ns}=\tau_{1s} \cdot n^3$	p ($l=1$)	s ($l=0$)	p ($l=1$)
1	$2.9 \cdot 10^{-4}$	-	$1.39 \cdot 10^{-3}$	-
2	$2.32 \cdot 10^{-3}$	1.17	$1.11 \cdot 10^{-2}$	5.6
3	$7.83 \cdot 10^{-3}$	3.94	$3.76 \cdot 10^{-2}$	19
4	$1.86 \cdot 10^{-2}$	9.05	$8.91 \cdot 10^{-2}$	43
5	$3.63 \cdot 10^{-2}$	17.5	$1.74 \cdot 10^{-1}$	84
6	$6.26 \cdot 10^{-2}$	29.9	$3.01 \cdot 10^{-1}$	144
7	$9.95 \cdot 10^{-2}$	46.8	$4.77 \cdot 10^{-1}$	225
8	$1.48 \cdot 10^{-1}$	69.3	$7.13 \cdot 10^{-1}$	333

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

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 \vec{B}_{lab} and Lorentz factor γ



\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

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

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

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

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

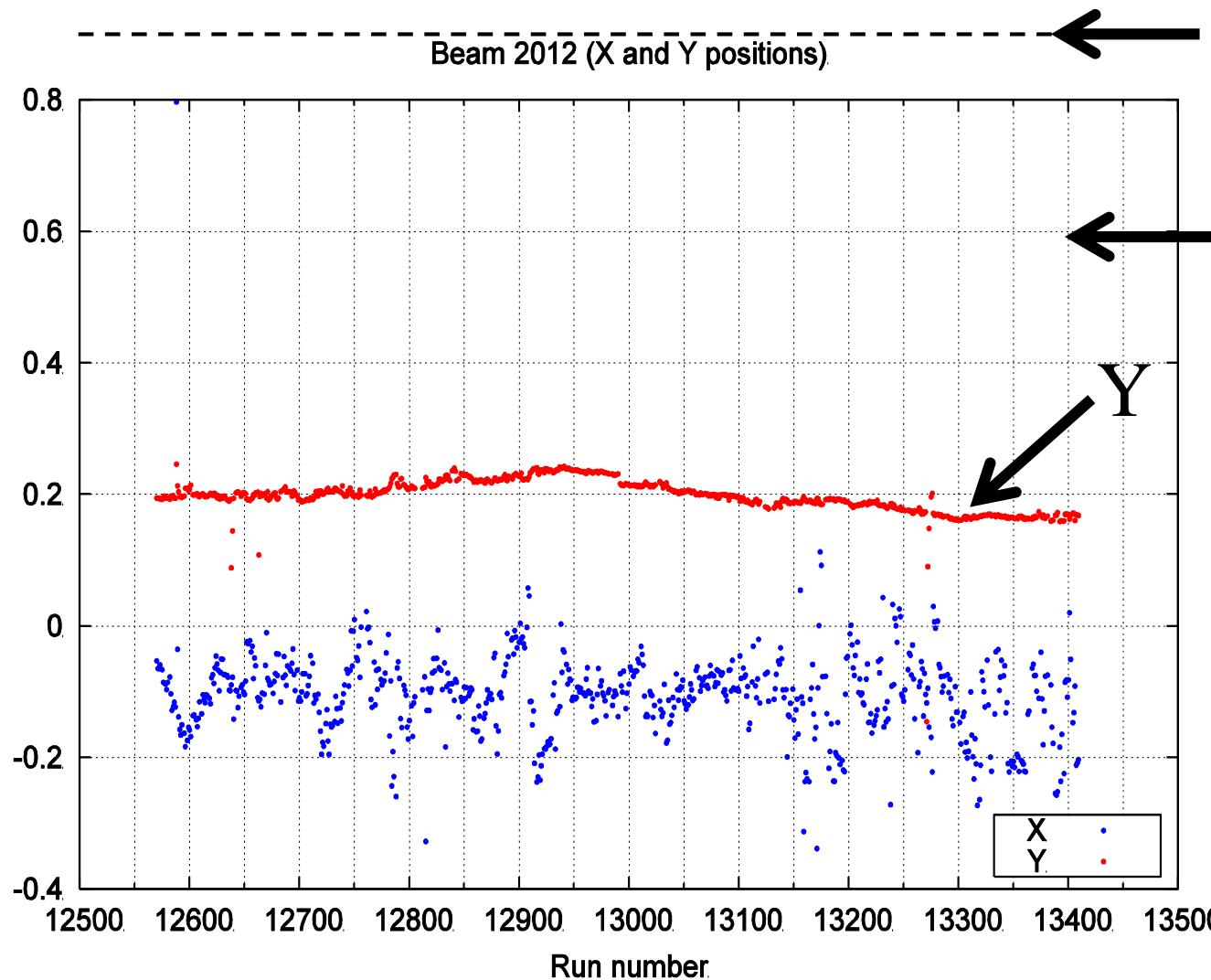
$$\tau_{eff} = \frac{\tau_{2p}}{1 + \frac{|\xi|^2}{4} \frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1 + 120 |\xi|^2}$$

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

$$B_{Lab} = 2 \text{ Tesla}$$

$$\left\{ \begin{array}{l} \gamma = 20 , \quad |\xi| = 0.025 \Rightarrow \tau_{eff} = \frac{\tau_{2p}}{1.3} \\ \gamma = 40 , \quad |\xi| = 0.05 \Rightarrow \tau_{eff} = \frac{\tau_{2p}}{2.25} \end{array} \right.$$

y-beam position (run 2012)



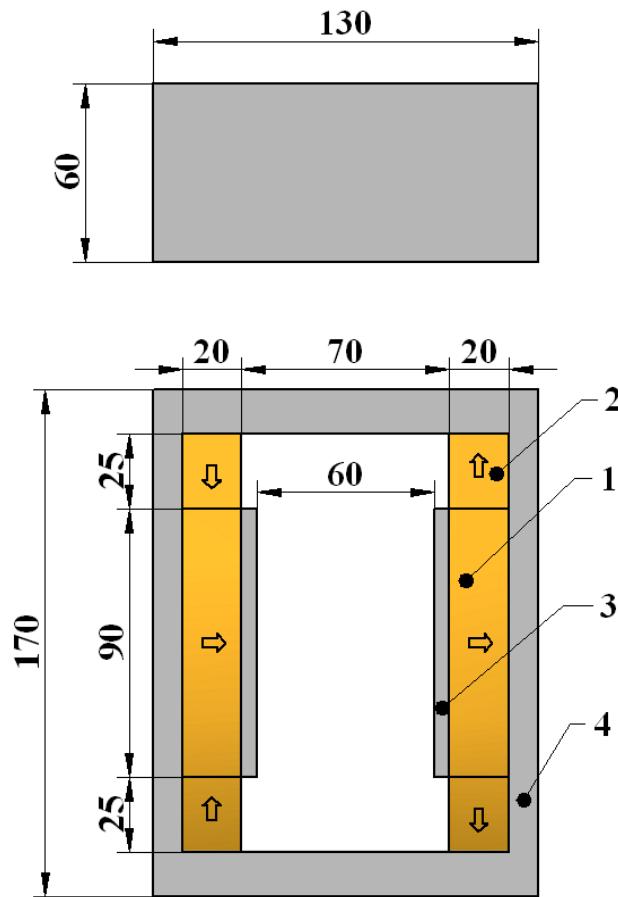
Experimental conditions (run 2012)

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	$2.52 \cdot 10^{-4}$

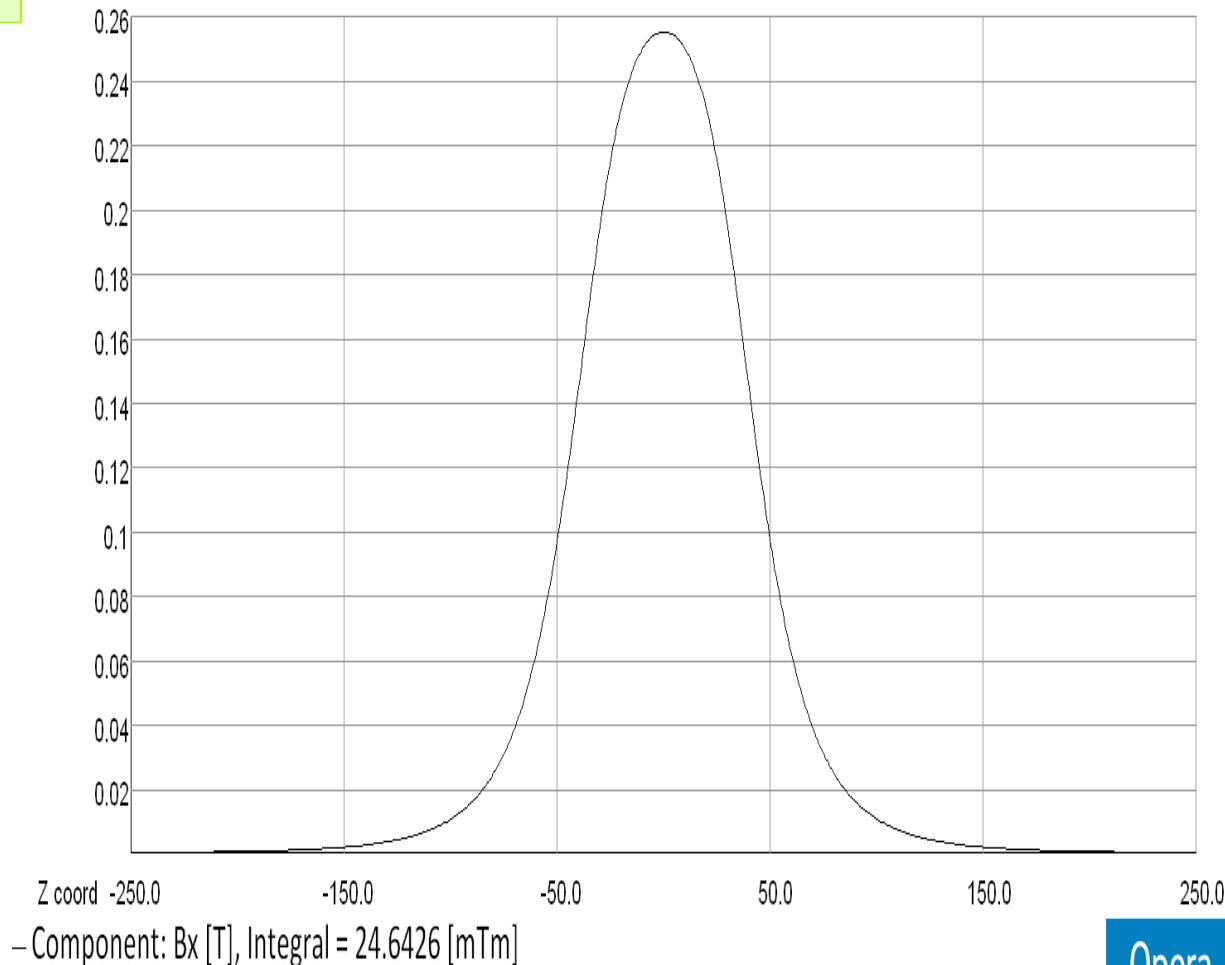
Magnet

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



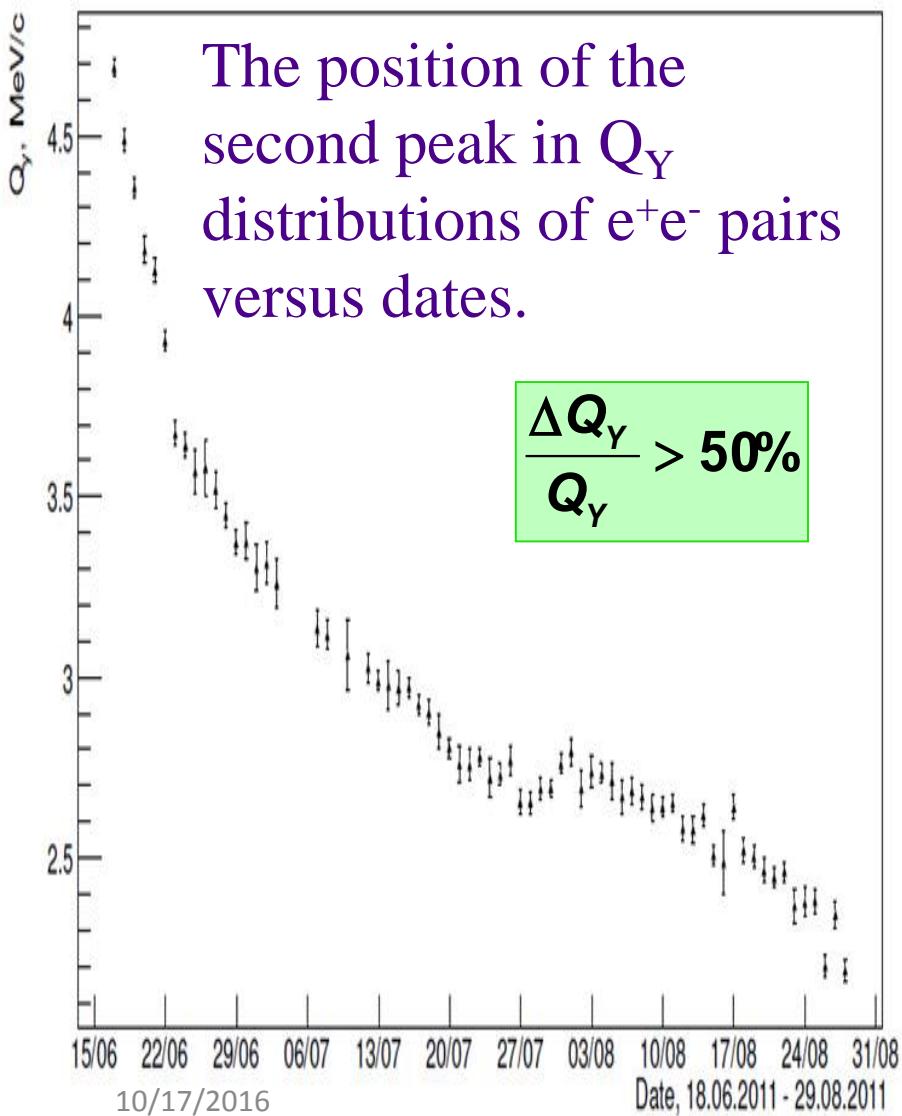
10/17/2016

Horizontal field distribution along z-axis at X=Y=0mm
 $\int B_x(0,0,z)dz = 24.6 \times 10^{-3}$ [Tm]



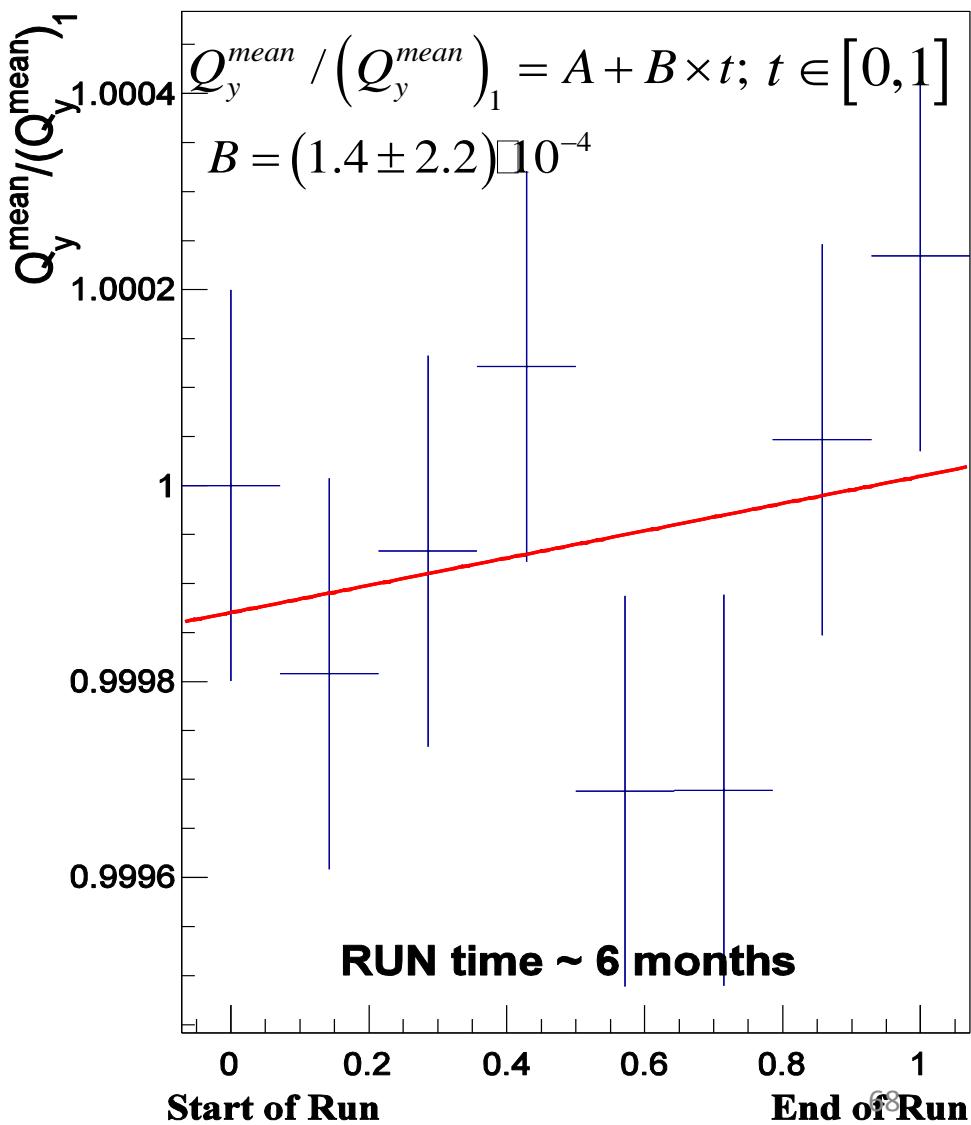
Degradation of old magnet

Old magnet (Nd-Fe-B), 2011

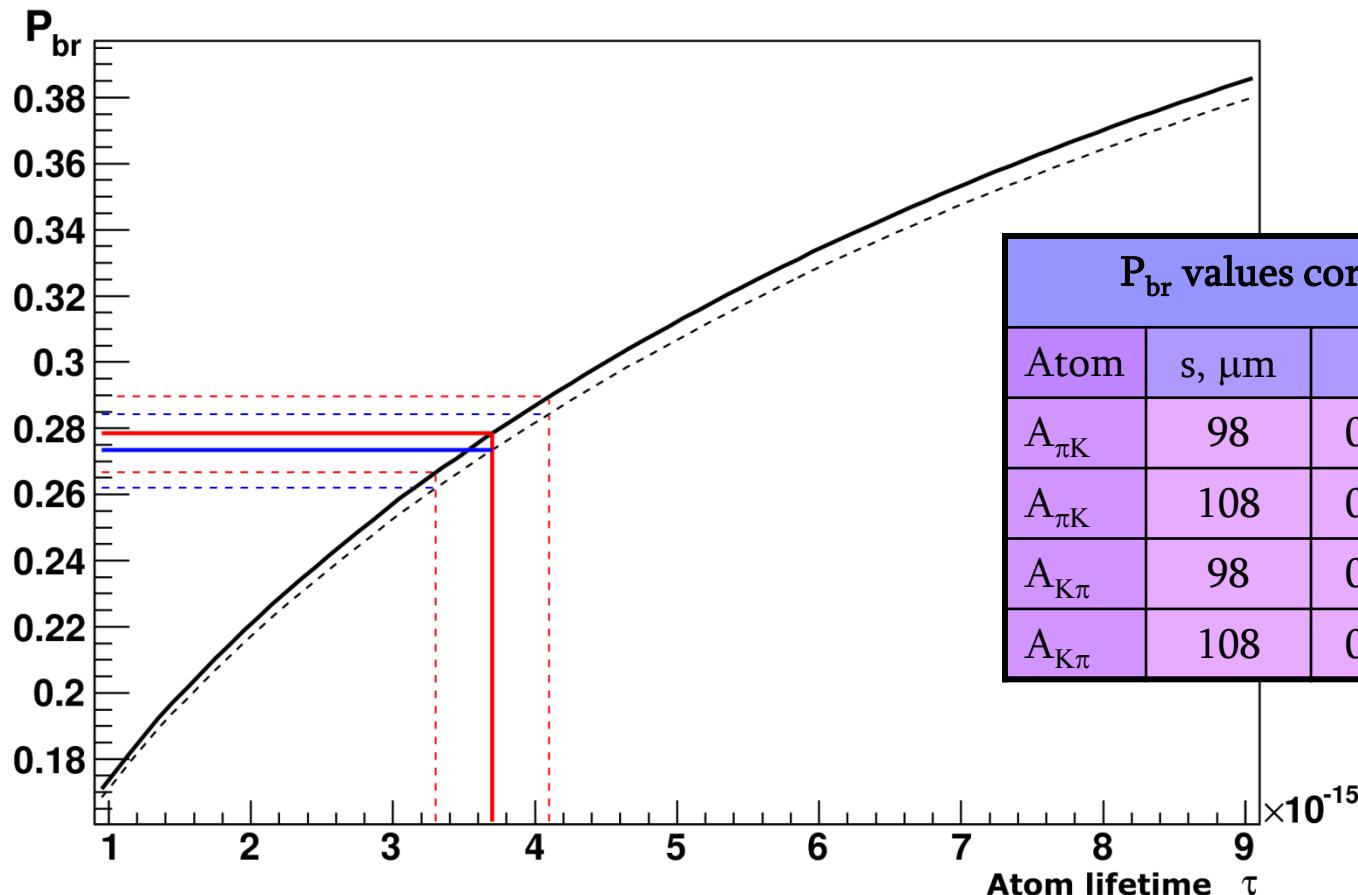


New magnet behavior

New magnet (Sm-Co), 2012

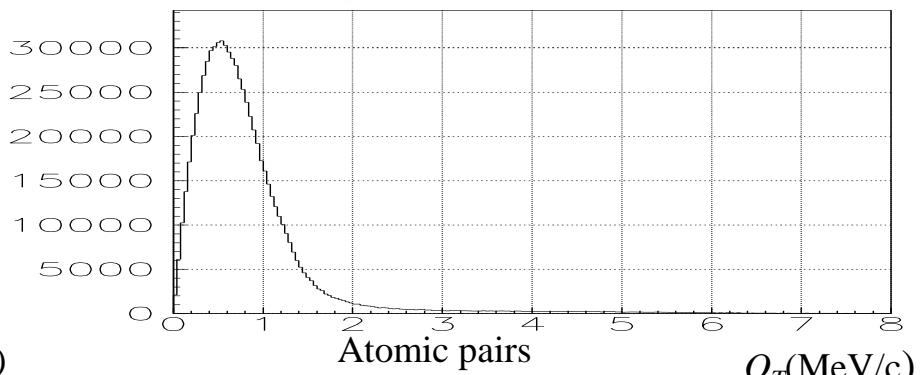
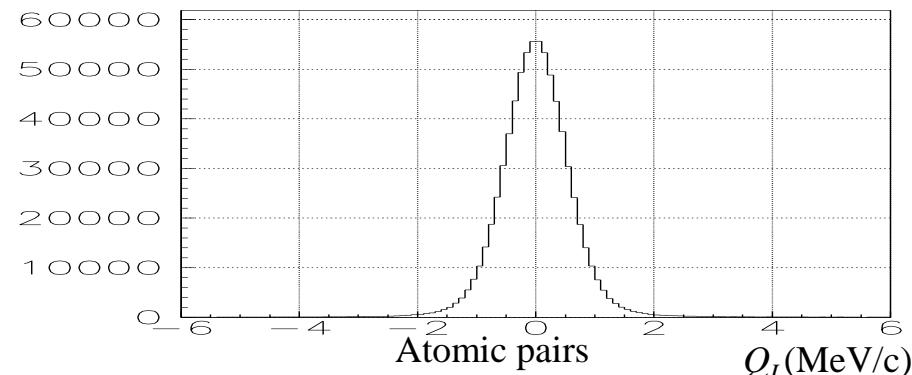
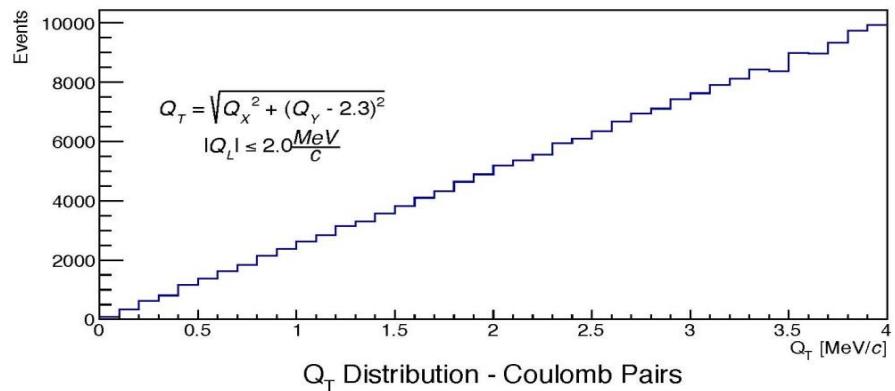
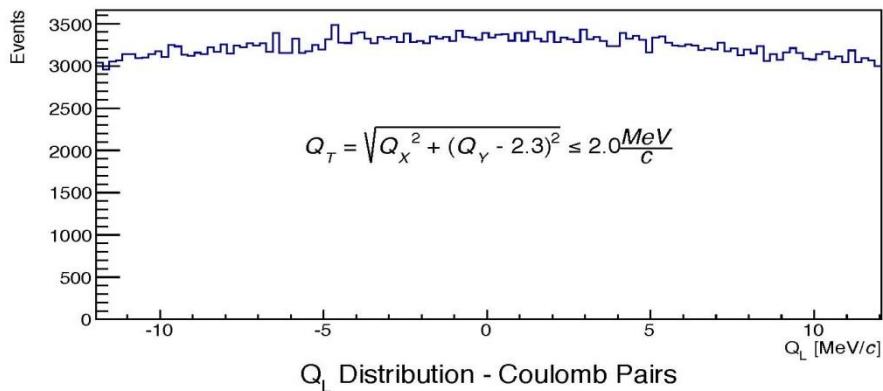
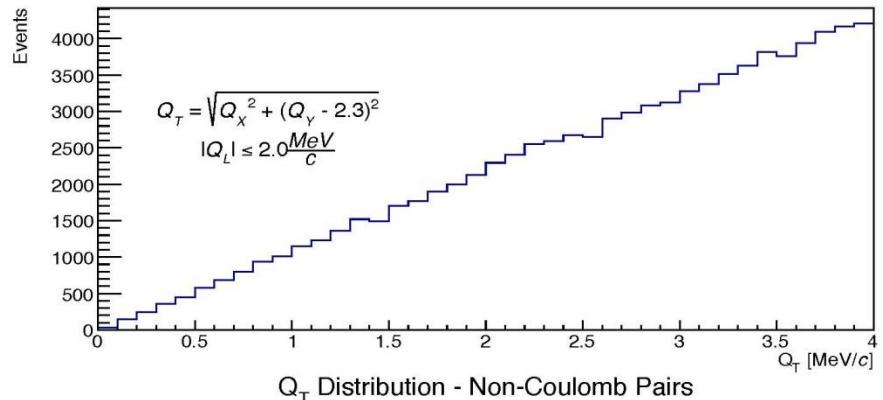
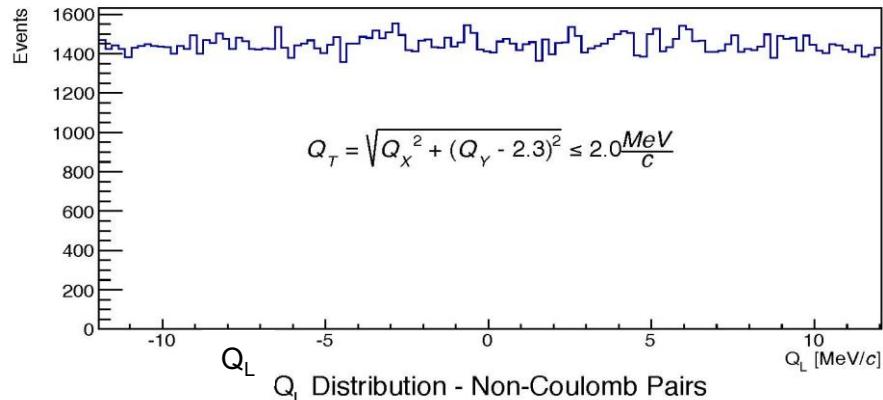


Break-up dependencies P_{br} from atom lifetime for $K^+\pi^-$ and π^+K^- atom

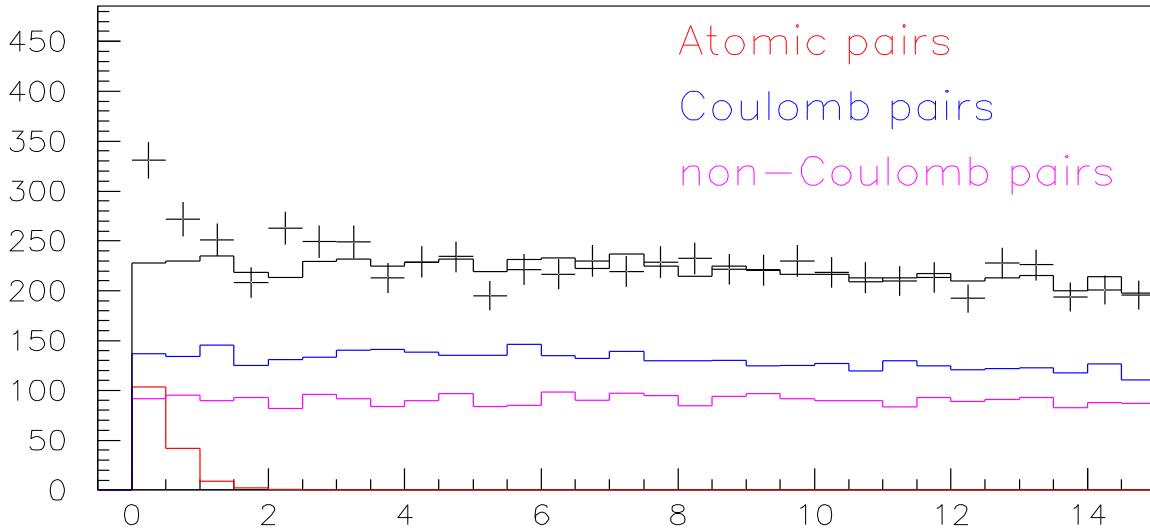


Probability of break-up as a function of lifetime in the ground state for $A_{\pi K}$ (solid line) and $A_{K\pi}$ atoms (dashed line) in Ni target of thickness 108 μm .
 Average momentum of $A_{K\pi}$ and $A_{\pi K}$ are 6.4 GeV/c and 6.5 GeV/c accordingly.

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

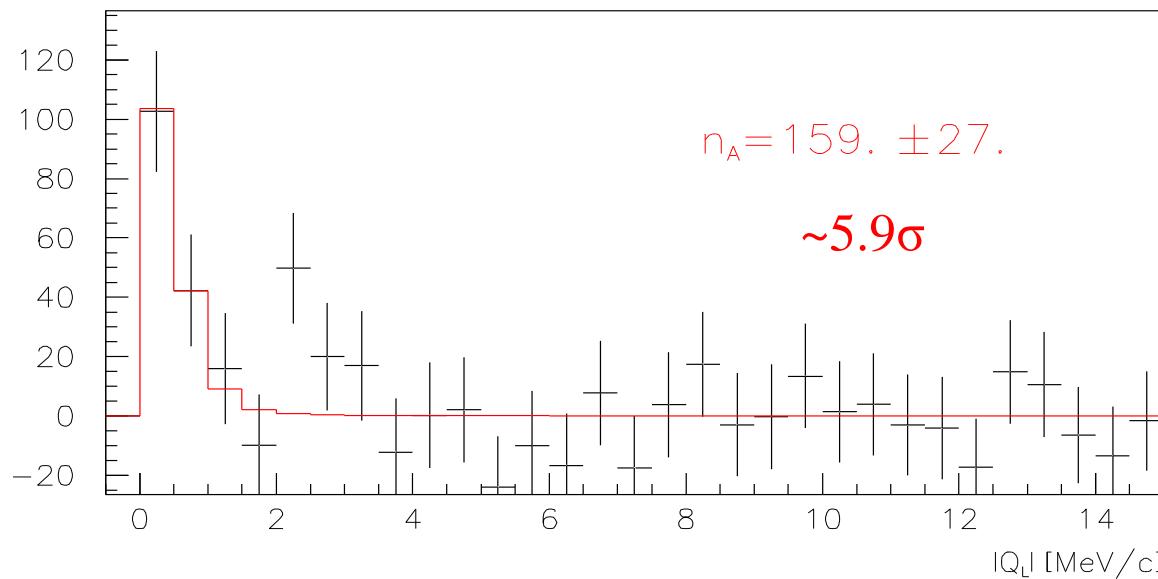


Long-lived $\pi^+\pi^-$ atoms



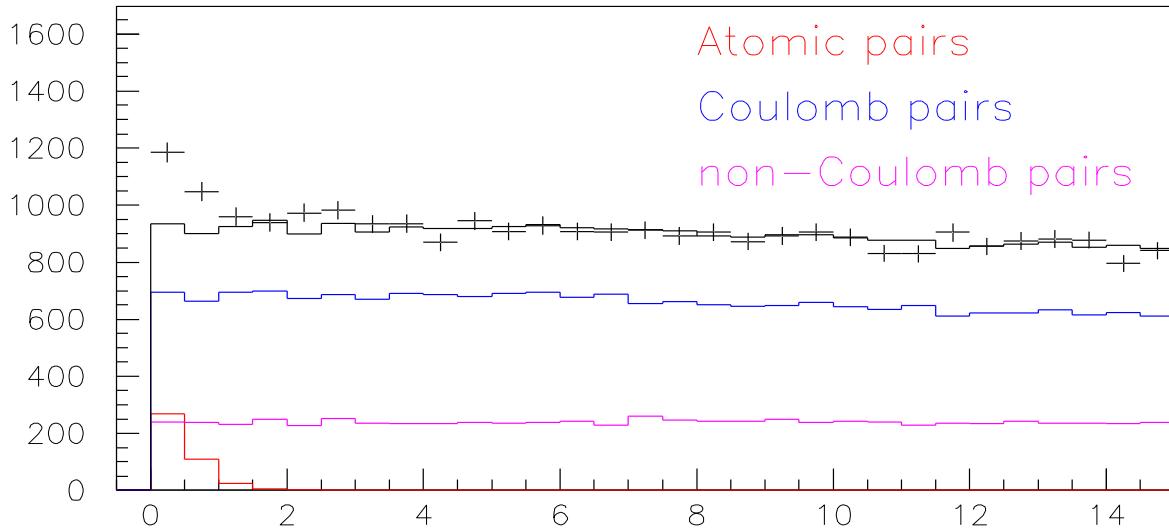
Experimental (real data) and simulated distributions over $|Q_L|$

for $Q_T < 0.5 \text{ MeV}/c$



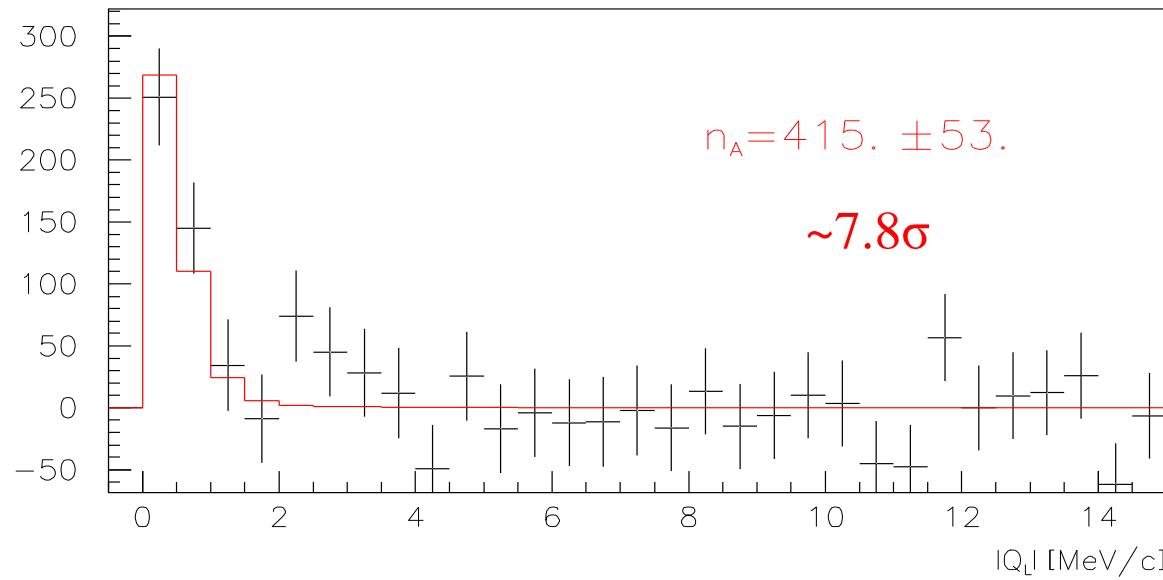
$$Q_T = \sqrt{Q_x^2 + (Q_y - 2.3 \text{ MeV}/c)^2}$$

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



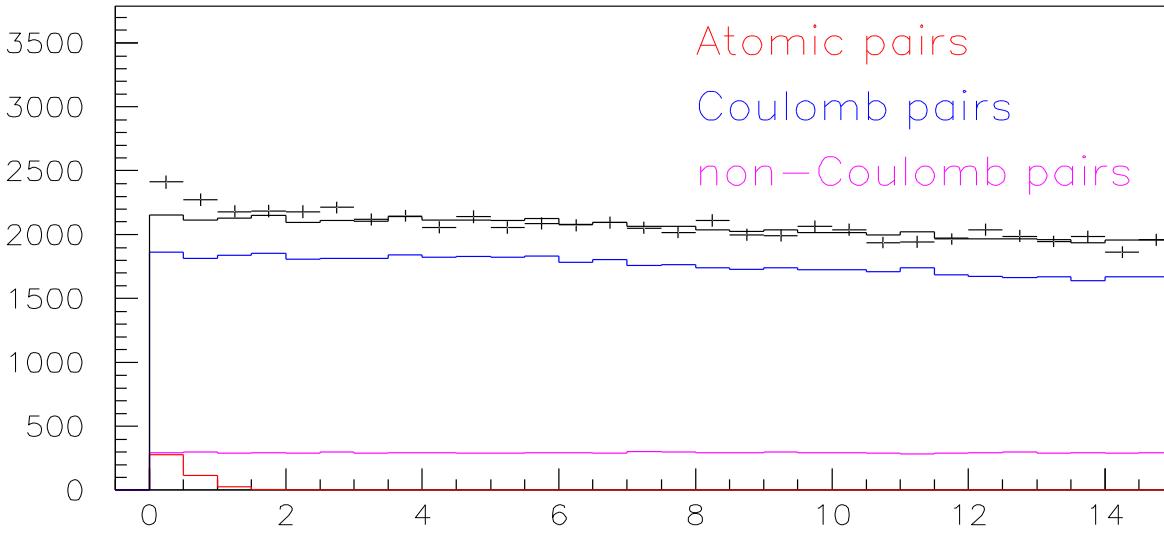
Experimental (real data) and simulated distributions over $|Q_L|$

for $Q_T < 1.0 \text{ MeV}/c$



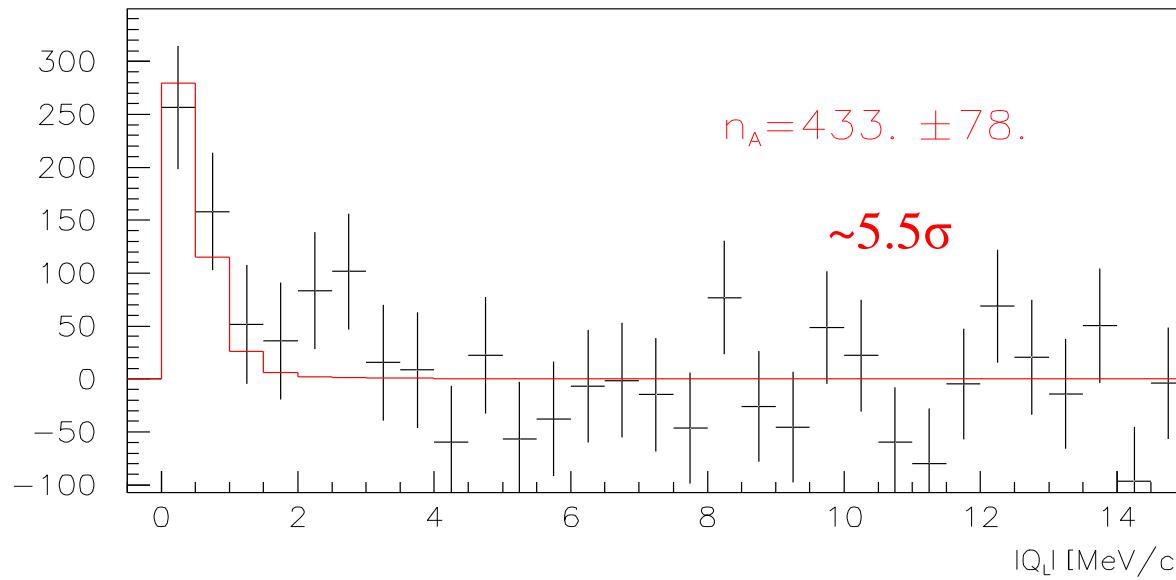
$$Q_T = \sqrt{Q_x^2 + (Q_y - 2.3 \text{ MeV}/c)^2}$$

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



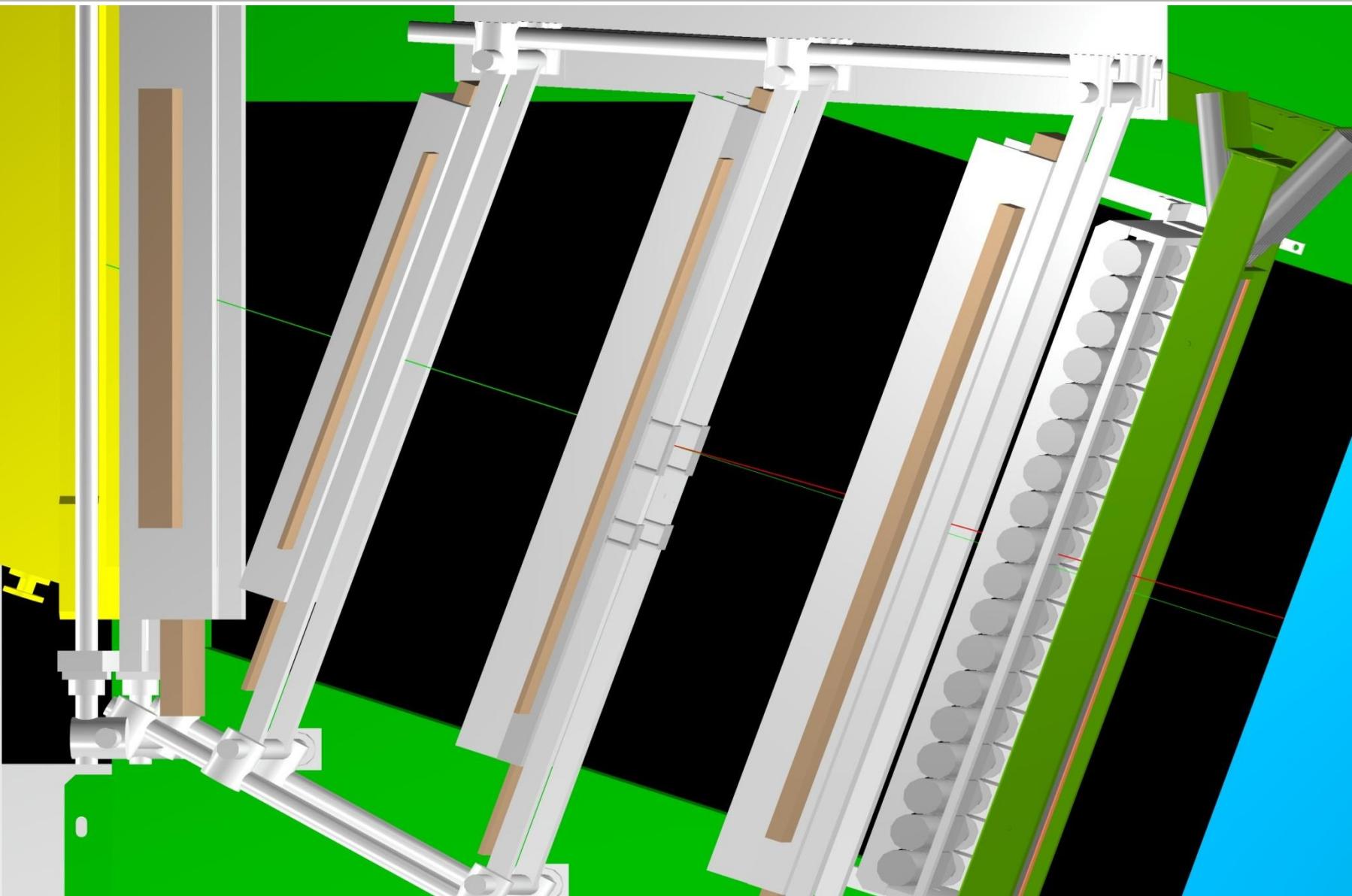
Experimental (real data) and simulated distributions over $|Q_L|$

for $Q_T < 1.5 \text{ MeV}/c$

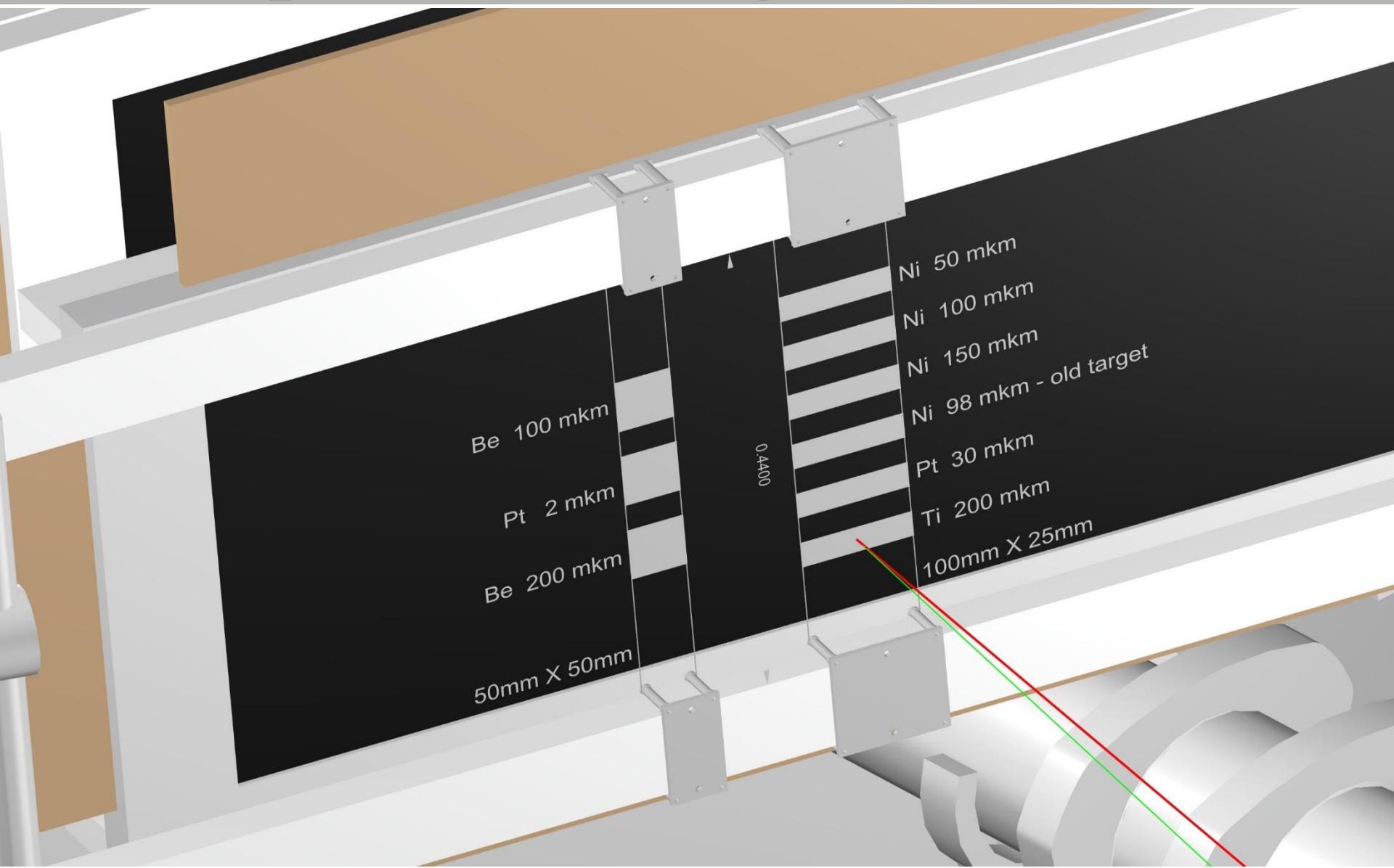


$$Q_T = \sqrt{Q_x^2 + (Q_y - 2.3 \text{ MeV}/c)^2}$$

Multiple scattering measurement

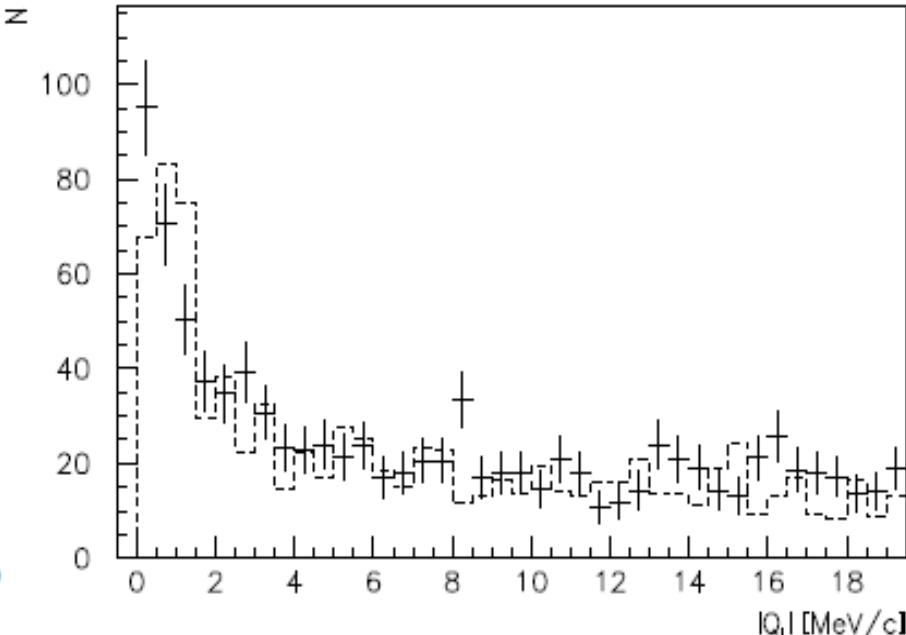
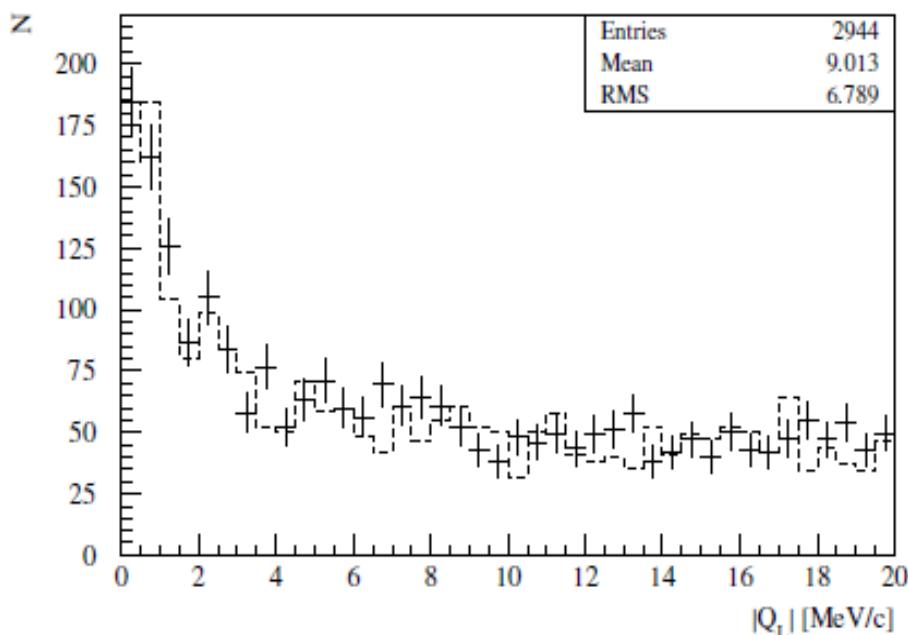


Multiple scattering measurement



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

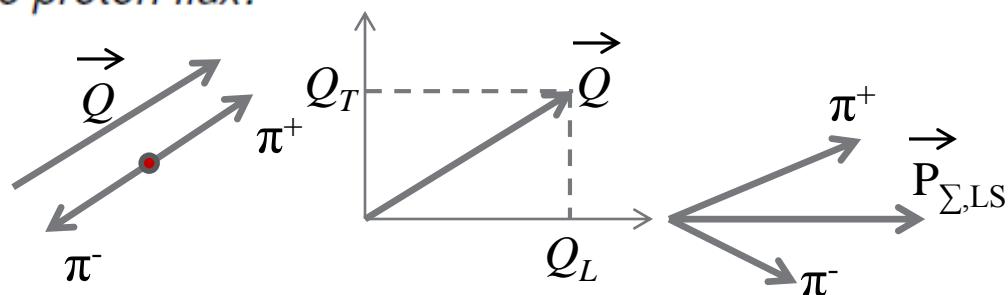
Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of “Coulomb” and “non-Coulomb” pairs (dashed line).



Produced atom numbers normalized on the proton flux:

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

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



DIRAC setup characteristics and experimental conditions

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

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