Investigation of atoms consisting of $\pi^+\pi^-$, $K^+\pi^-$ and $K^-\pi^+$ at DIRAC experiment in order to check low energy QCD predictions

Valeriy Yazkov [Skobeltsyn Institute of Nuclear Physics,
Lomonosov Moscow State University]

on behalf of the DIRAC collaboration

The XXI International Workshop
High Energy Physics and Quantum Field Theory
June 23 --- June 30, 2013
Saint Petersburg Area, Russia

DIRAC collaboration

CERN
Geneva, Switzerland

Czech Technical University
Prague, Czech Republic

Institute of Physics ASCR
Prague, Czech Republic

Nuclear Physics Institute ASCR
Rez, Czech Republic

INFN-Laboratori Nazionali di Frascati
Frascati, Italy

University of Messina
Messina, Italy

KEK
Tsukuba, Japan

Kyoto University
Kyoto, Japan

Kyoto Sangyo University
Kyoto, Japan

Tokyo Metropolitan University
Tokyo, Japan

IFIN-HH
Bucharest, Romania

JINR
Dubna, Russia

SINP of Moscow State University
Moscow, Russia

IHEP
Protvino, Russia

Santiago de Compostela University
Santiago de Compostela, Spain

Bern University
Bern, Switzerland

Zurich University
Zurich, Switzerland

Contents

1. Low-energy QCD precise predictions.
2. Method of $\pi\pi$ and $K\pi$ atom investigation.
3. DIRAC setup.
4. Status of $\pi^+\pi^-$ atom investigation.
5. Status of $K^+\pi^-$, $K^-\pi^+$ atom investigation.
6. Generation of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms in p-nuclear interaction at proton beam momentum 24 GeV/c and 450 GeV/c.

1. Low energy QCD predictions

ππ scattering lengths

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

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

Colangelo et al. in 2001, using ChPT (2-loop) & Roy equations:

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

These results (precision) depend on the low-energy constants (LEC) l_3 and l_4:
Lattice gauge calculations from **2006** provided values for these l_3 and l_4.

Because l_3 and l_4 are sensitive to the quark condensate, precision measurements of a_0, a_2 are a way to study the **structure** of the QCD vacuum.

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

- 2006: l_3, l_4 First lattice calculations
- 2012: 10 collaborations: 3 USA, 5 Europe, 2 Japan
- J. Gasser, H. Leutwyler: Model calculation (1985)
  $\bar{l}_3$=2.6±2.5, $\Delta\bar{l}_3/\bar{l}_3 \approx 1$
- Lattice calculations in near future will obtain
  $\Delta\bar{l}_3/\bar{l}_3 \approx 0.1$ or $\Delta\bar{l}_3 \approx 0.2\text{-}0.3$
- To check the predicted values of $\bar{l}_3$ the experimental relative errors of ππ-scattering lengths and their combinations must be at the level (0.2-0.3)%

ππ scattering

ChPT predicts s-wave scattering lengths:

$$a_0 = 0.2220 \pm 0.005 (2.3\%),\ a_2 = -0.0444 \pm 0.0010 (2.3\%),\ a_0 - a_2 = 0.265 \pm 0.004 (1.5\%)$$

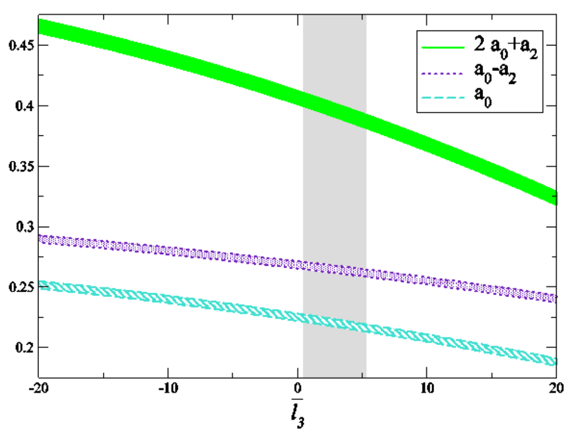
The expansion of M_π^2 in powers of the quark masses starts with the linear term:

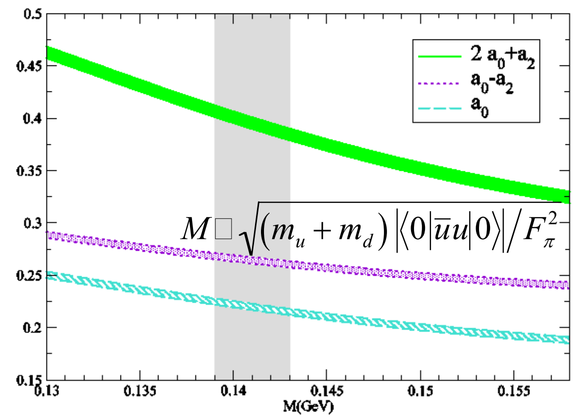
$$M_\pi^2 = (m_u + m_d)B - [(m_u + m_d)B]^2 \frac{\bar{l}_3}{32\pi^2 F^2} + O((m_u + m_d)^3)$$

where $B = \frac{1}{F_\pi^2} |\langle 0|\bar{q}q|0\rangle|$ is the quark condensate, reflecting the property of QCD vacuum.

The estimates indicate values in the range $0 < \bar{l}_3 < 5$

Measurement of $\bar{l}_3 \Rightarrow$ improved the value of $(m_u + m_d)|\langle 0|\bar{u}u|0\rangle|$





e.g.: $a_0 - a_2 = 0.260 \pm 3\% \Rightarrow \quad 1 < \bar{l}_3 < 11$ or $1.00 < M / M_\pi < 1.06$

E865 (BNL): $a_0 = 0.216 \pm 6\% \Rightarrow -4 < \bar{l}_3 < 12$ or $0.98 < M / M_\pi < 1.06$

πK scattering lengths

I. ChPT predicts s-wave scattering lengths:

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

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

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

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

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

A. Roessl. – 1999

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

$$a_{1/2} - a_{3/2} = 0.267$$

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

II. Roy-Steiner equations:

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

P.Büttiker et al. – 2004

πK scattering

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).

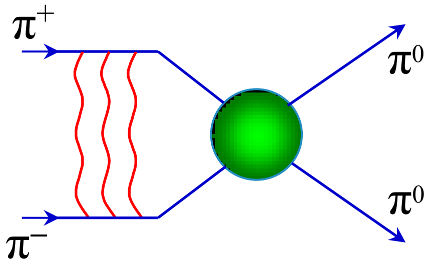
This is the principal difference between $\pi\pi$ and πK scattering!

Experimental data on the πK low-energy phases are absent

Pionium lifetime

Pionium ($A_{2\pi}$) 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



The lifetime of $\pi^+\pi^-$ atoms is dominated by the annihilation process into $\pi^0\,\pi^0$:

$$\Gamma = \frac{1}{\tau} = \Gamma_{2\pi_0} + \Gamma_{2\gamma} \quad \text{with} \quad \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi_0}} \approx 4 \times 10^{-3}$$

$$\Gamma_{1S,2\pi^0} = R\,|a_0 - a_2|^2 \quad \text{with} \quad \frac{\Delta R}{R} \approx 1.2\%$$

$$\tau = (2.9 \pm 0.1) \times 10^{-15}\,s$$

Gasser et al. – 2001

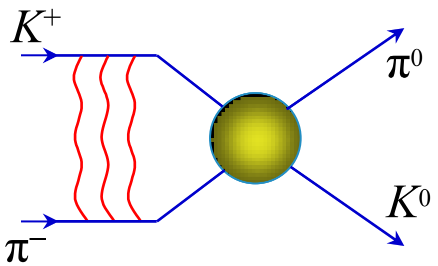
a_0 and a_2 are the ππ S-wave scattering lengths for isospin I=0 and I=2.

If $$\frac{\Delta\tau}{\tau} = 4\% \quad \Rightarrow \quad \frac{\Delta|a_0 - a_2|}{|a_0 - a_2|} = 2\%$$

$K^+\pi^-$ and $K^-\pi^+$ atoms lifetime

Kπ-atom ($A_{K\pi}$) is a hydrogen-like atom consisting of K^+ and π^- mesons:

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



The *Kπ*-atom lifetime (ground state 1S), τ=1/Γ is dominated by the annihilation process into $K^0\pi^0$:

$$A_{K^+\pi^-} \to \pi^0 K^0 \qquad A_{\pi^+K^-} \to \pi^0 \overline{K}^0$$

$$\Gamma_{1S,K^0\pi^0} = R_K \left|a_{1/2} - a_{3/2}\right|^2 \quad \text{with} \quad \frac{\Delta R_K}{R_K} \approx 2\%^{**}$$

(**) J. Schweizer (2004)

From Roy-Steiner equations: $a_0^{1/2} - a_0^{3/2} = 0.269 \pm 0.015$

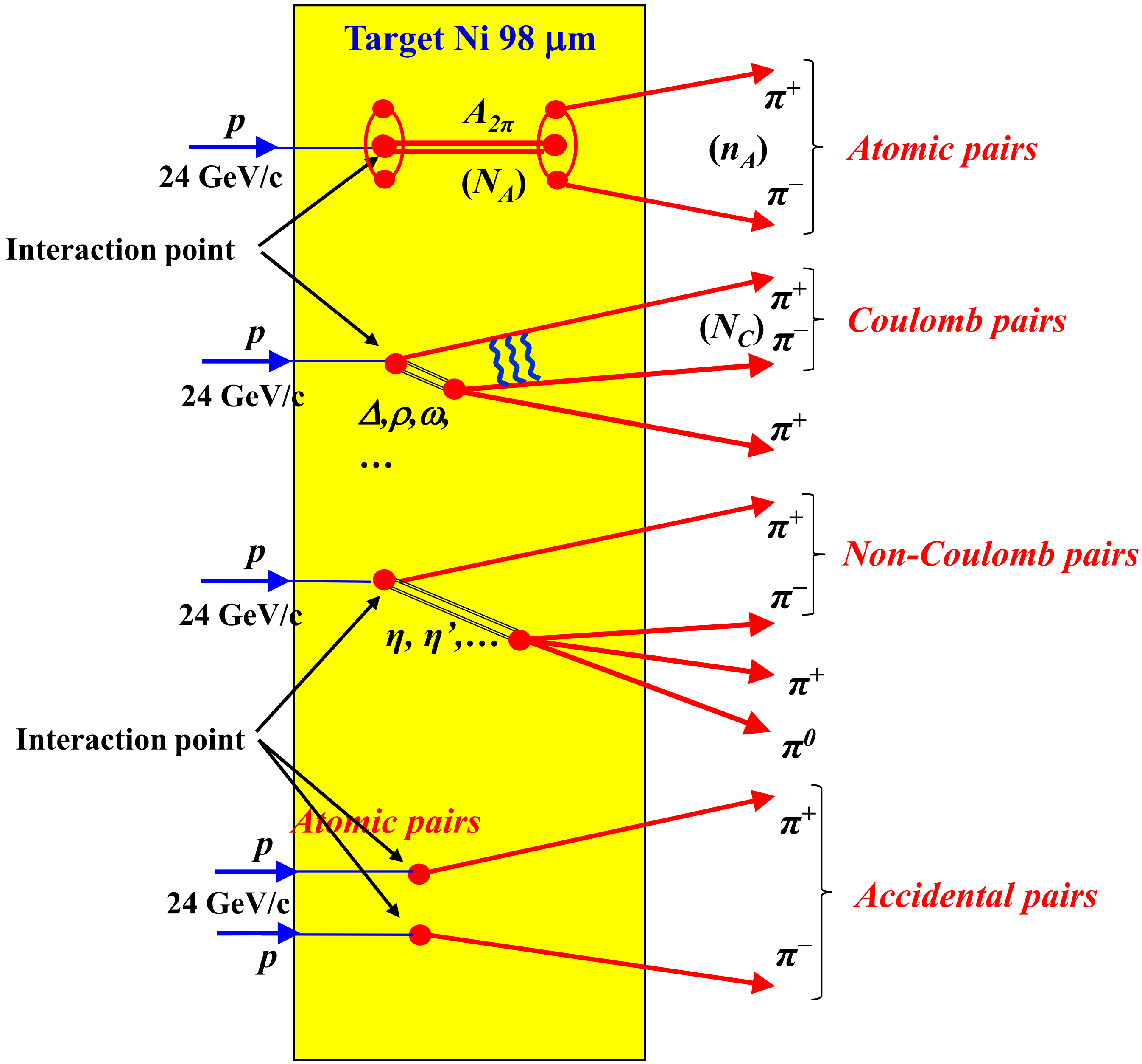
$$\downarrow$$

$$\tau = (3.7 \pm 0.4) \cdot 10^{-15}\ s$$

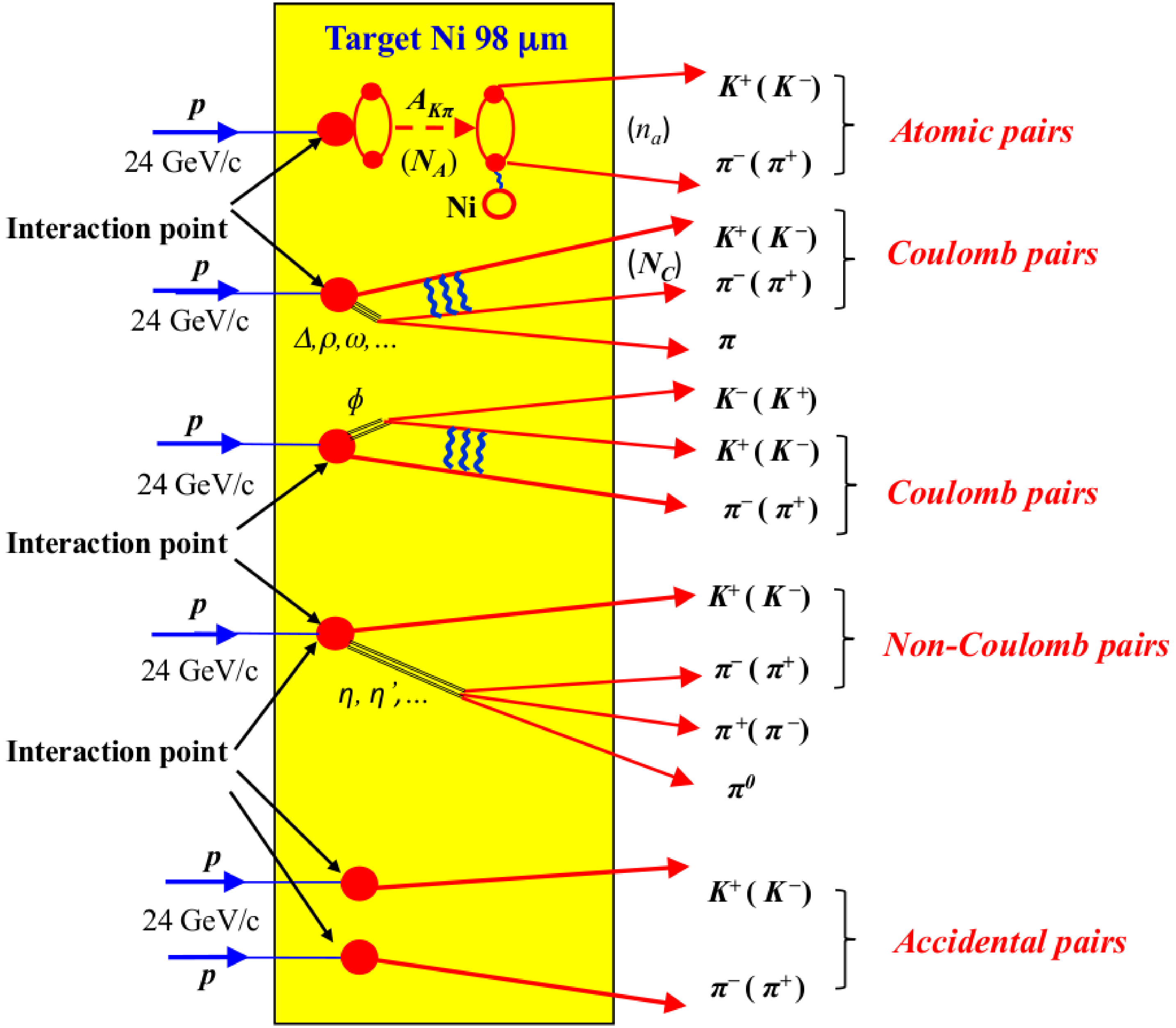
If $\dfrac{\Delta\Gamma}{\Gamma} = 20\% \Rightarrow \dfrac{\Delta\left|a_{1/2} - a_{3/2}\right|}{\left|a_{1/2} - a_{3/2}\right|} = 10\%$

2. Method of $\pi^+\pi^-$ and $K\pi$ atom observation and investigation

Method of $\pi^+\pi^-$ atom observation and investigation

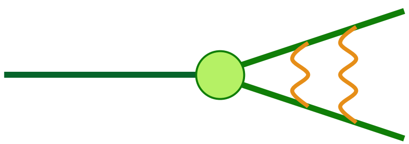


Method of Kπ atom observation and investigation



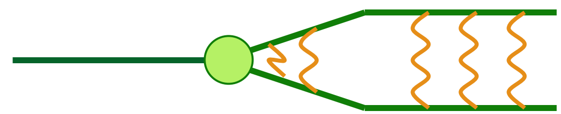
Coulomb pairs and atoms

For the charged pairs from the short-lived sources and small relative momentum Q there is strong Coulomb interaction in the final state. 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 pairs



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

Atoms

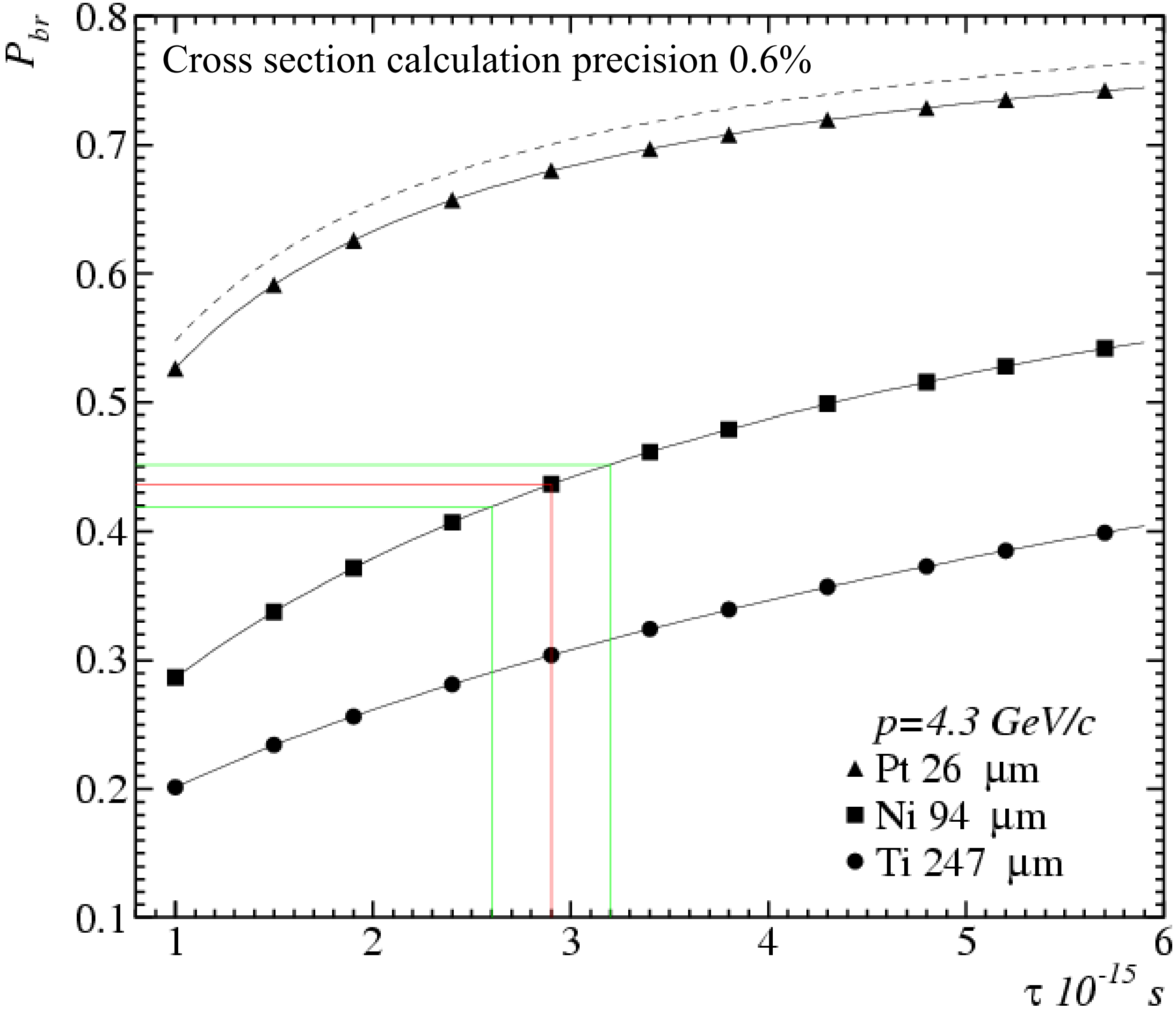
There is precise ratio between the number of produced Coulomb pairs (N_C) with small Q and the number of atoms (N_A) produced simultaneously with these Coulomb pairs:

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

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

Break-up probability

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ

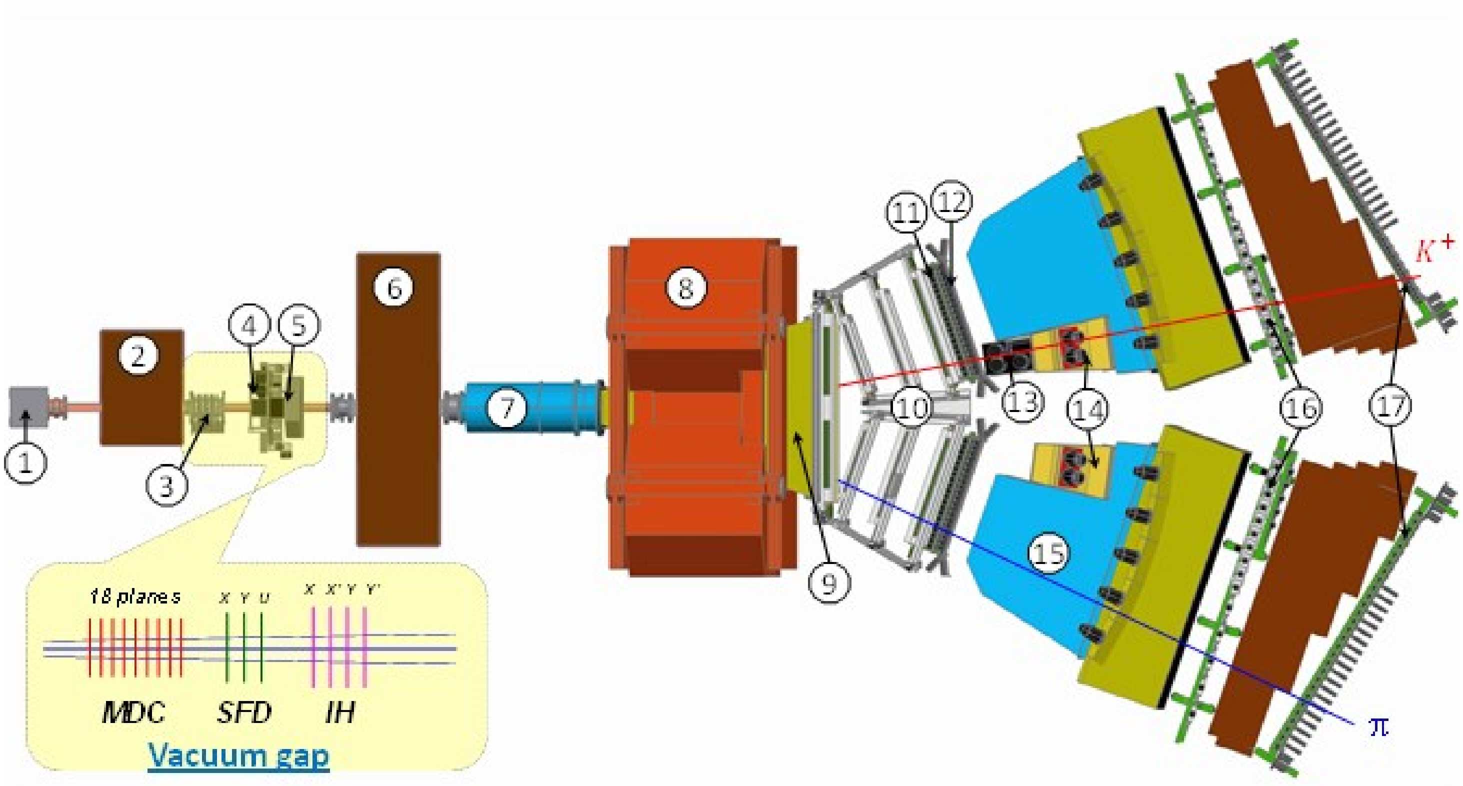


All targets have the same thickness in radiation lengths $6.7 {*} 10^{-3}\ X_0$

There is an optimal target material for a given lifetime

3. DIRAC setup

Experimental setup



1 Target station with Ni foil; 2 First shielding; 3 Micro Drift Chambers; 4 Scintillating Fiber Detector; 5 Ionization Hodoscope; 6 Second Shielding; 7 Vacuum Tube; 8 Spectrometer Magnet; 9 Vacuum Chamber; 10 Drift Chambers; 11 Vertical Hodoscope; 12 Horizontal Hodoscope; 13 Aerogel Čerenkov; 14 Heavy Gas Čerenkov; 15 Nitrogen Čerenkov; 16 Preshower; 17 Muon Detector

Experimental conditions

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

DC	
Coordinate	$\sigma = 85$

VH	
Time precision	$\sigma = 100$ ps

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

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

Published results on $\pi^+\pi^-$ atom lifetime and scattering length

DIRAC data	τ_{1s} (10^{-15} s) value	stat	syst	*theo**	tot	$\lvert a_0-a_2 \rvert$ value	stat	syst	*theo**	tot	Reference
2001	**2.91**	$+0.45$ -0.38	$+0.19$ -0.49		$\left[\begin{matrix}+0.49\\-0.62\end{matrix}\right]$	**0.264**	$+0.017$ -0.020	$+0.022$ -0.009		$\left[\begin{matrix}+0.033\\-0.020\end{matrix}\right]$	PL B 619 (2005) 50
2001-03	**3.15**	$+0.20$ -0.19	$+0.20$ -0.18		$\left[\begin{matrix}+0.28\\-0.26\end{matrix}\right]$	**0.2533**	$+0.0078$ -0.0080	$+0.0072$ -0.0077		$\left[\begin{matrix}+0.0106\\-0.0111\end{matrix}\right]$	PL B 704 (2011) 24

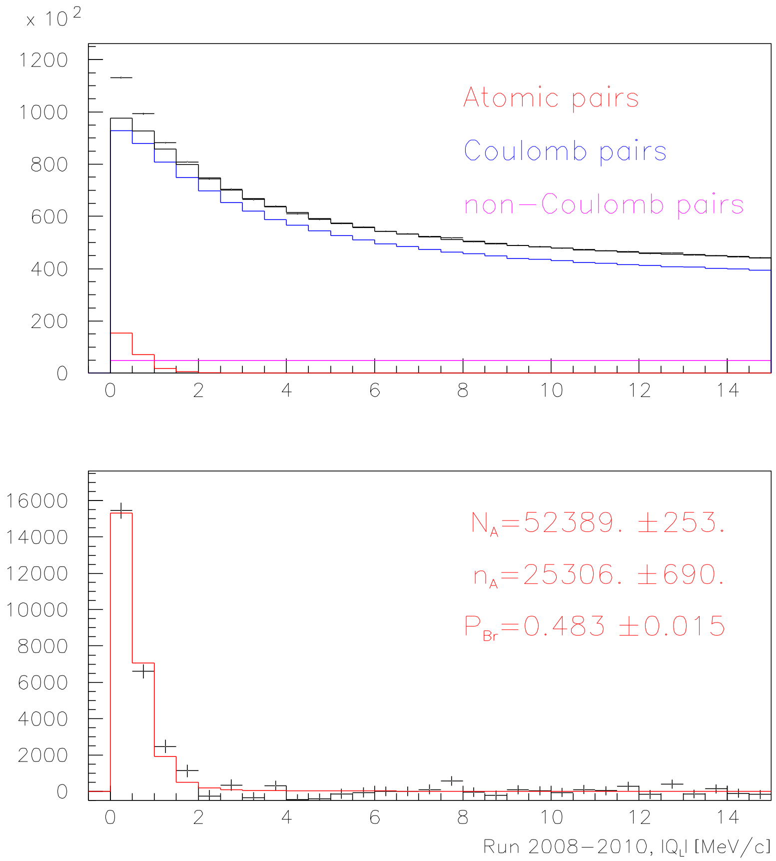
* theoretical uncertainty included in systematic error

NA48	K-decay	a_0-a_2 value stat syst theo tot	Reference
2009	$K_{3\pi}$	$0.2571 \pm 0.0048 \pm 0.0029 \pm 0.0088$	EPJ C64 (2009) 589
2010	K_{e4} & $K_{3\pi}$	$0.2639 \pm 0.0020 \pm 0.0015$	EPJ C70 (2010) 635

4. Status of $\pi^+\pi^-$ atom investigation

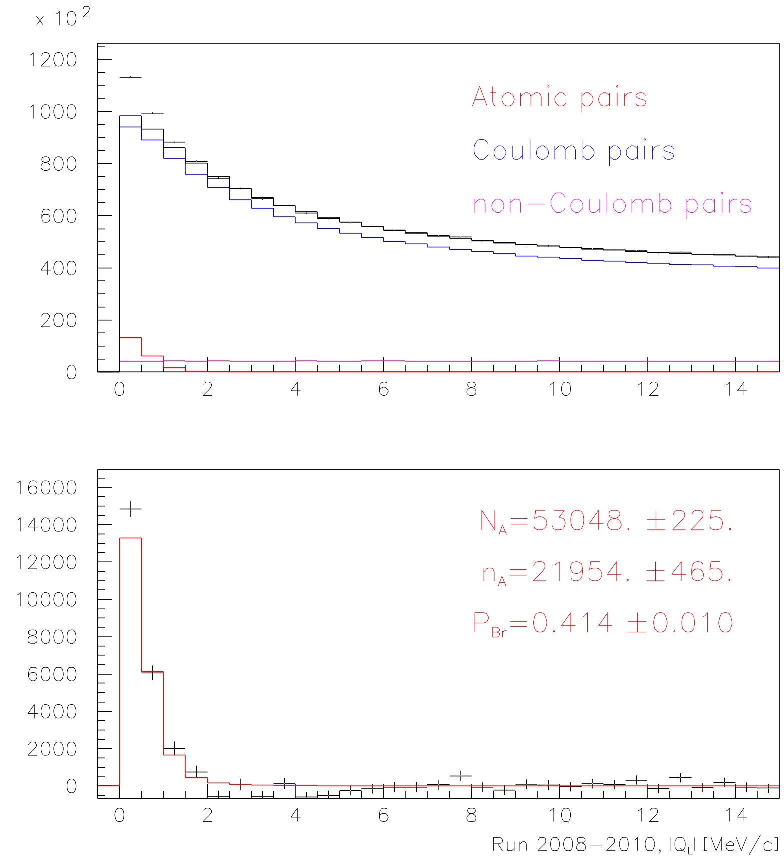
$\pi^+\pi^-$ atoms – run 2008-2010

Run 2008-2010, statistics with low and medium background (2/3 of all statistics).
Pointlike production of all particles, the K^+K^-, $p\bar{p}$ admixture has not been take into account



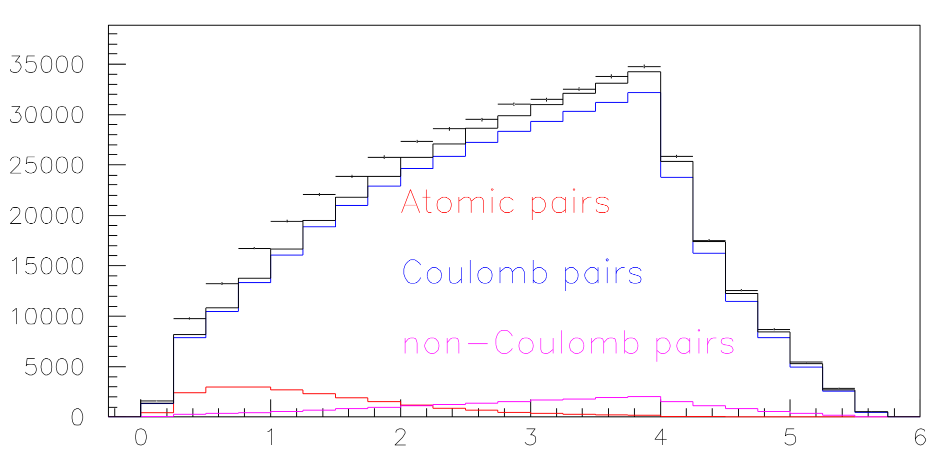
$|Q_L|$ distribution
analysis on $|Q_L|$ for $Q_T < 4$ MeV/c

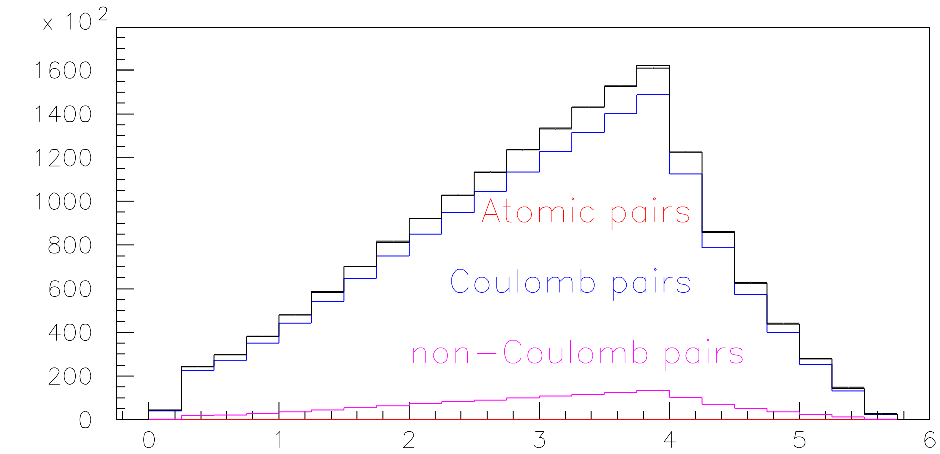
P_{br} (2001-2003) = 0.446±0.0093

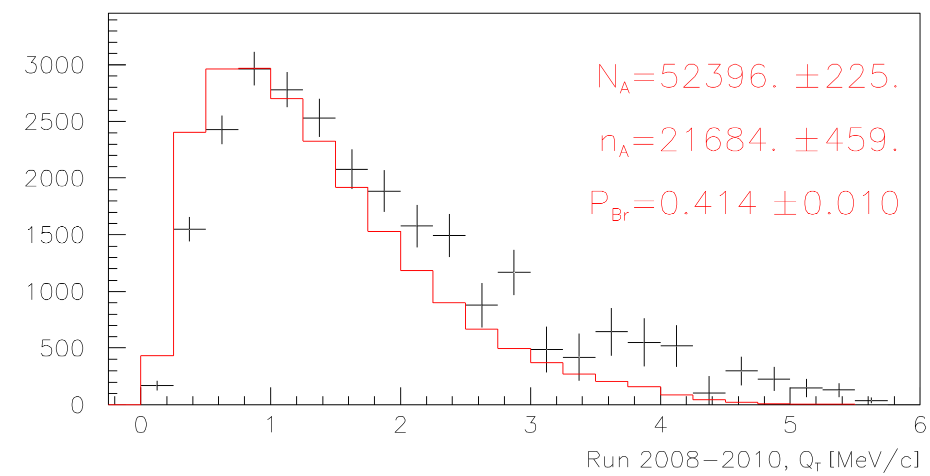


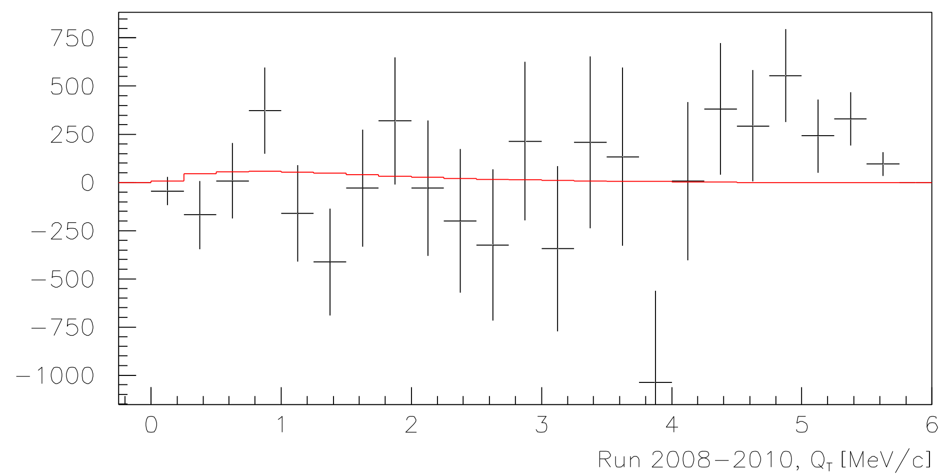
$|Q_L|$ distribution
analysis on $|Q_L|$ and Q_T for $Q_T < 4$ MeV/c

$\pi^+\pi^-$ atoms – run 2008-2010









Q_T distribution
analysis on $|Q_L|$, Q_T for $|Q_L| < 2$ MeV/c

Q_T distribution
analysis on $|Q_L|$, Q_T for $|Q_L| > 2$ MeV/c

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

	2008	2009	2010	2008-2010
$N_A(Q_L)$	13141±129	19774±153	19474±155	52389±253
$N_A(Q_L\text{-}Q_T)$	13245±114	20072±137	19732±138	53048±225
$n_A(Q_L)$	6140±352	9769±419	9397±420	25306±690
$n_A(Q_L\text{-}Q_T)$	5537±233	8384±284	8033±284	21954±465
$P_{br}(Q_L)$	0.467±0.030	0.494±0.024	0.483±0.024	0.483±0.0148
$P_{br}(Q_L\text{-}Q_T)$	0.418±0.020	0.418±0.016	0.407±0.016	0.414±0.010
P_{br}(2001-2003)=0.446±0.0093				

$\pi^+\pi^-$ data

Statistics for measurement of $|a_0-a_2|$ scattering length difference and expected precision

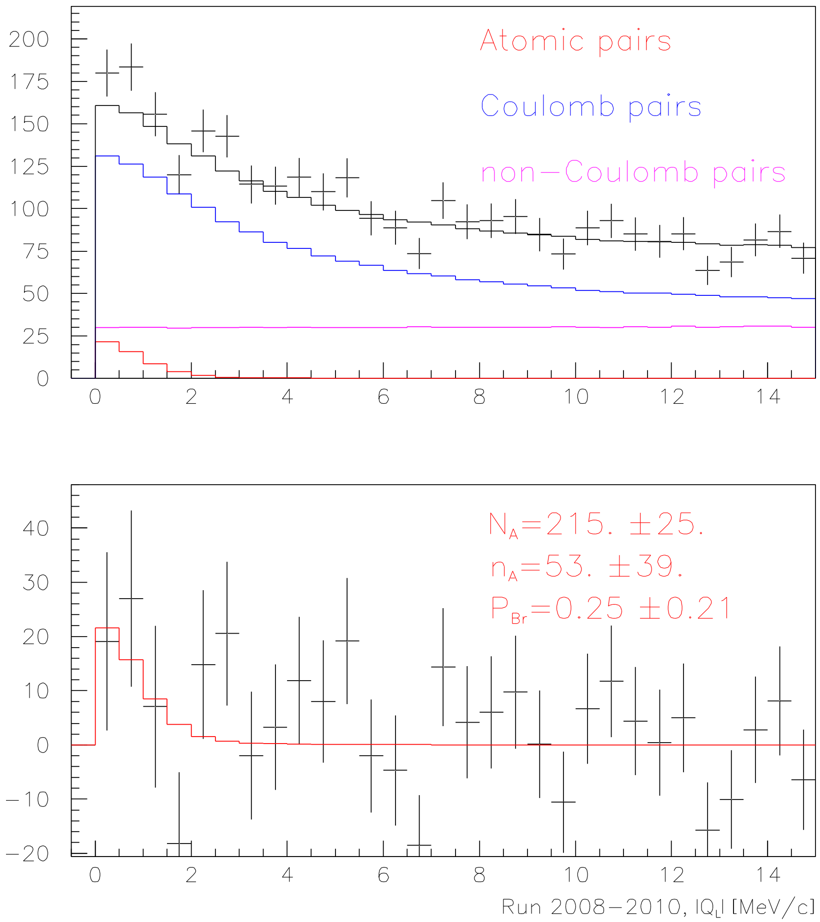
Year	n_A	$\delta_{stat}(\%)$	$\Delta_{syst}(\%)$	$\delta_{syst}(\%)$MS	$\delta_{tot}(\%)$
2001-2003	21000	3.1	3.0	2.5	4.3
2008-2010*	25000	3.1	3.0	2.5	4.3
2001-2003 2008-2010	46000	2.2	3.0 2.1	2.5 1.25	3.7 3.0

* There is 1/3 of the data with a higher background whose implication will be investigated.

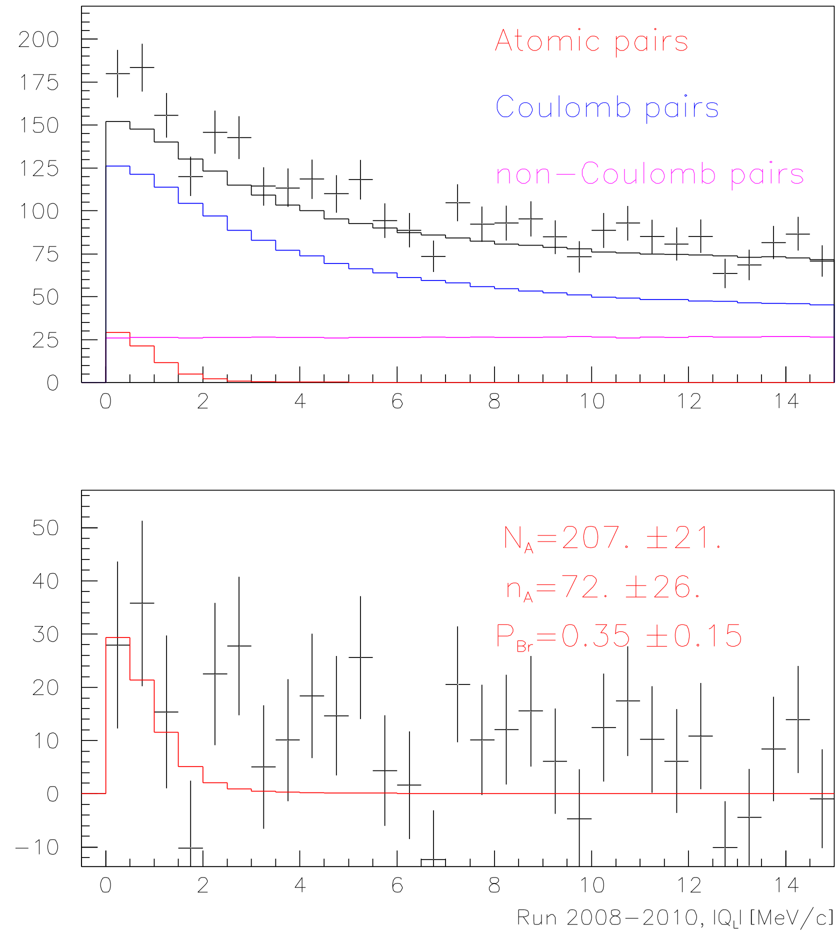
5.a. Status of $K^-\pi^+$ atom investigation

$K^-\pi^+$ atoms – run 2008-2010

Run 2008-2010, statistics with low and medium background (2/3 of all statistics). Point-like production for all particles.



$|Q_L|$ 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

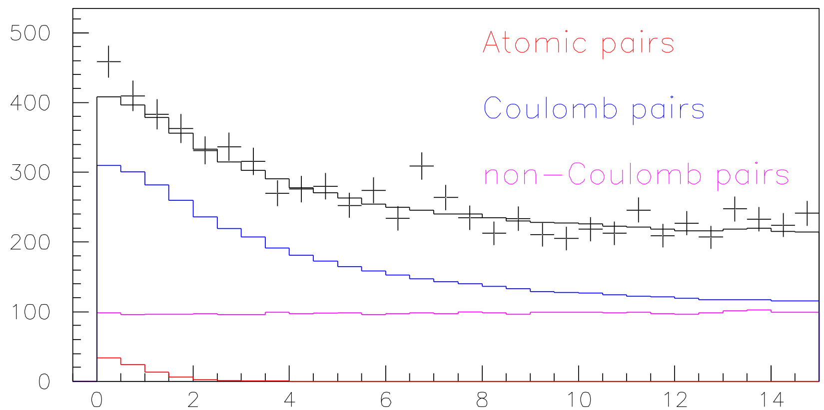
$K^-\pi^+$ pair analysis

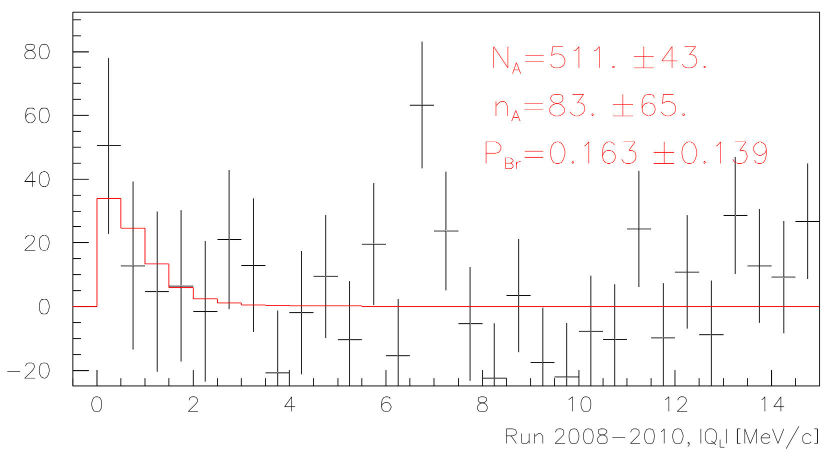
	2008	2009	2010	2008-2010
$N_A(Q_L)$	48±13	82±15	86±15	215±25
$N_A(Q_L\text{-}Q_T)$	59±11	82±13	65±12	207±21
$n_A(Q_L)$	34±21	24±24	-5±22	53±39
$n_A(Q_L\text{-}Q_T)$	16±13	24±16	32±16	72±26
$P_{br}(Q_L)$	0.71±0.59	0.30±0.34	-0.06±0.25	0.25±0.21
$P_{br}(Q_L\text{-}Q_T)$	0.27±0.26	0.29±0.22	0.49±0.31	0.35±0.15

5.b. Status of $K^+\pi^-$ atom investigation

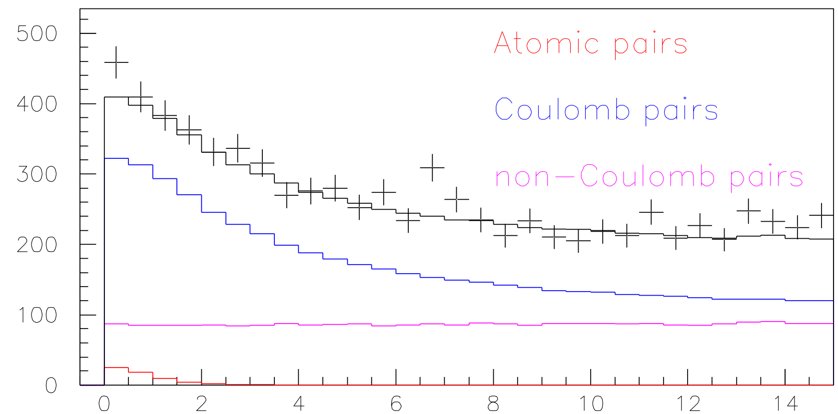
$K^+\pi^-$ atoms – run 2008-2010

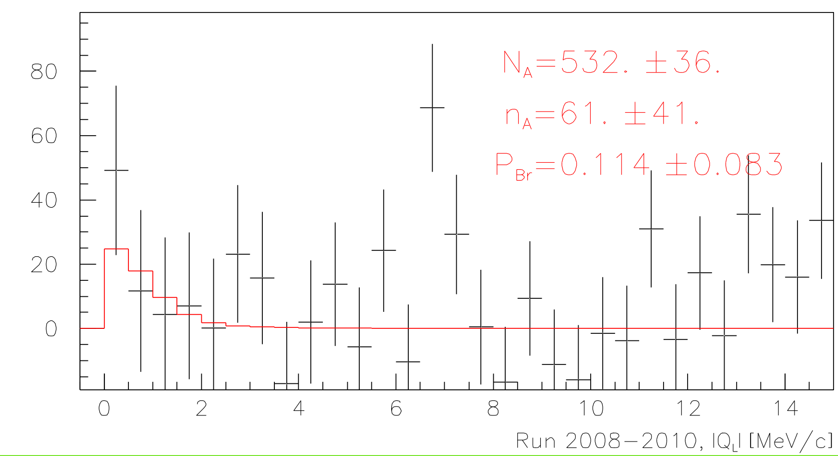
Run 2008-2010, statistics with low and medium background (2/3 of all statistics).
Point-like production for all particles.





$|Q_L|$ 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

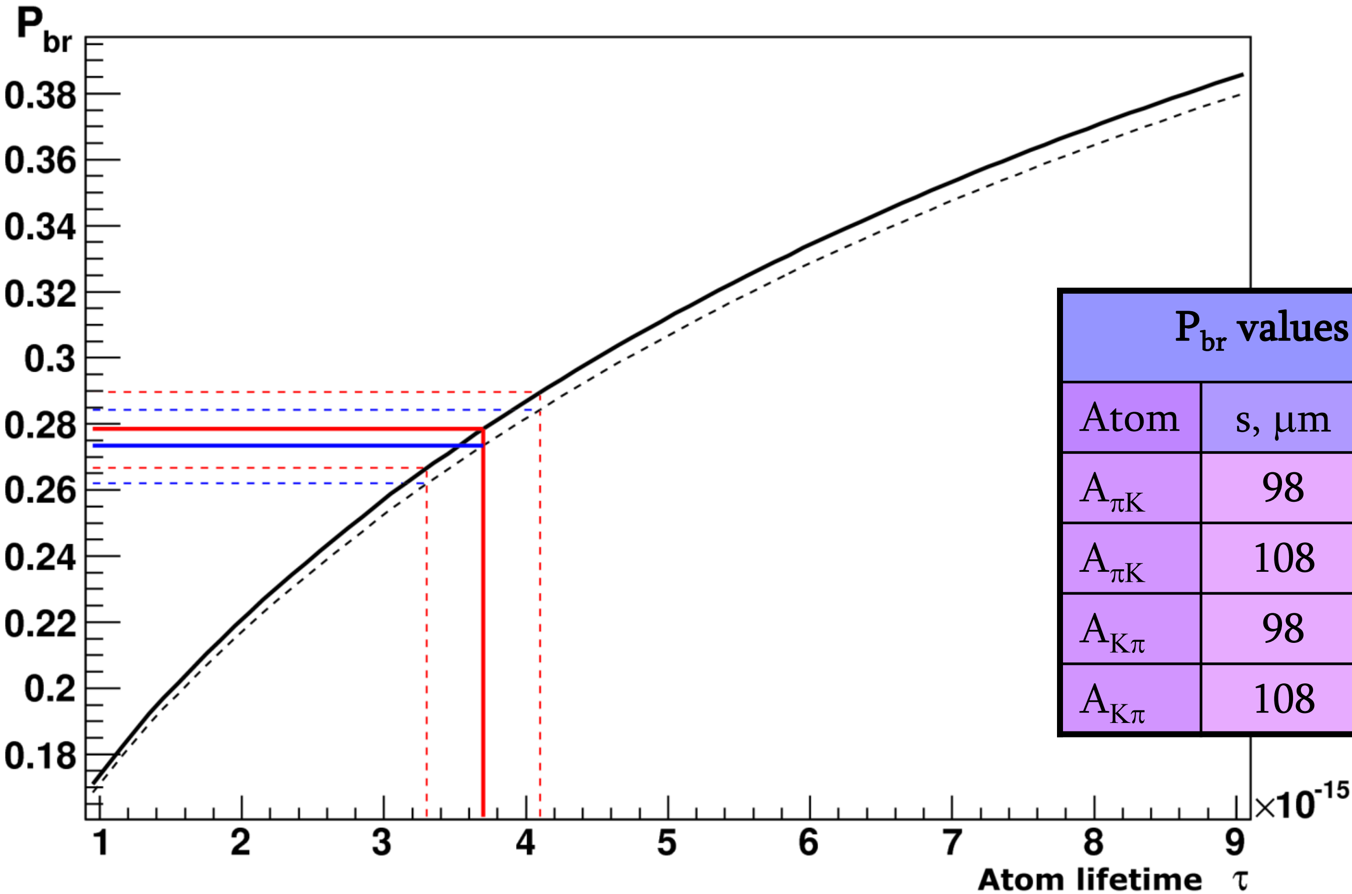
$K^+\pi^-$ pair analysis

	2008	2009	2010	2008-2010
$N_A(Q_L)$	139±19	184±28	188±27	511±43
$N_A(Q_L\text{-}Q_T)$	143±16	197±23	192±23	532±36
$n_A(Q_L)$	16±29	30±41	37±41	83±65
$n_A(Q_L\text{-}Q_T)$	8±18	18±26	34±26	61±41
$P_{br}(Q_L)$	0.11±0.22	0.17±0.24	0.20±0.24	0.16±0.14
$P_{br}(Q_L\text{-}Q_T)$	0.06±0.13	0.09±0.14	0.18±0.15	0.11±0.08

$K^-\pi^+$ and $K^+\pi^-$ pairs analysis

	$K^-\pi^+$ pairs 2008-2010	$K^+\pi^-$ pairs 2008-2010	$K^-\pi^+$ and $K^+\pi^-$ pairs sum 2008-2010
$N_A(Q_L)$	215±25	511±43	726±49
$N_A(Q_L\text{-}Q_T)$	207±21	532±36	739±42
$n_A(Q_L)$	53±39	83±65	136±76
$n_A(Q_L\text{-}Q_T)$	72±26	61±41	133±49
$P_{br}(Q_L)$	0.25±0.21	0.16±0.14	0.19±0.12
$P_{br}(Q_L\text{-}Q_T)$	0.35±0.15	0.114±0.083	0.180±0.073
P_{br}^{theor}			$0.278 \pm^{0.012}_{0.011}$

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

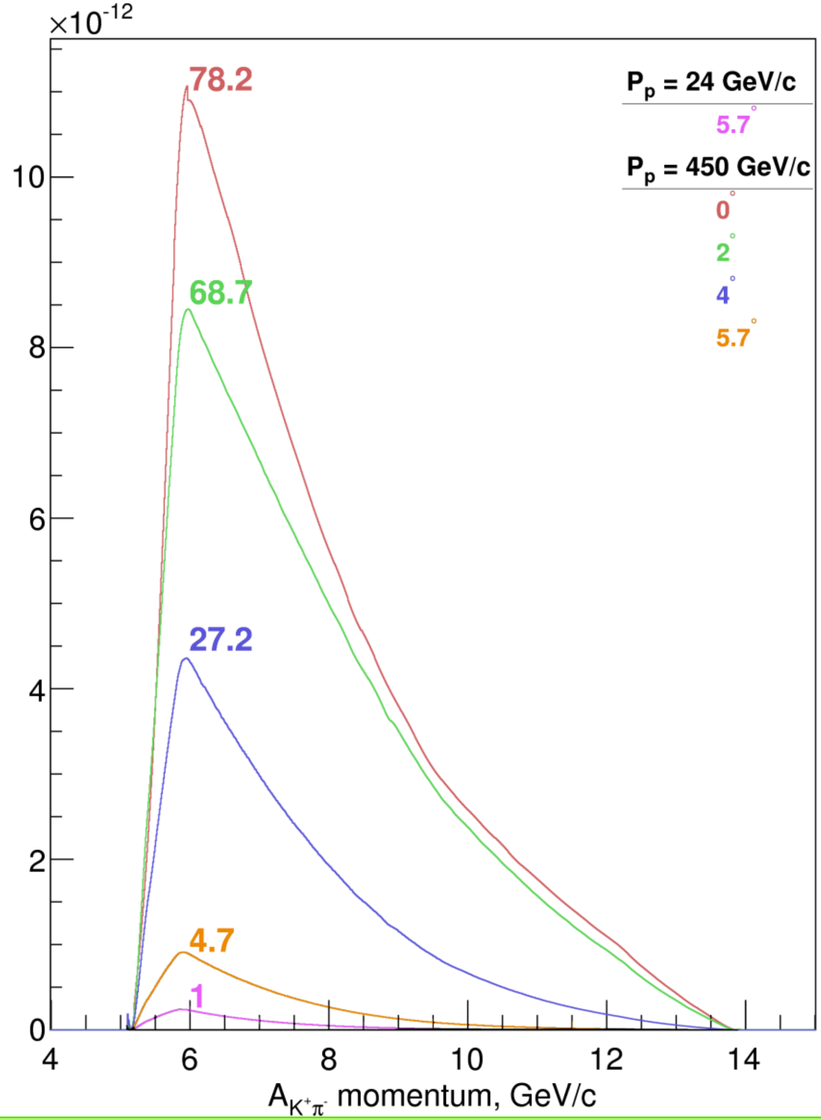


P_{br} values corresponding to τ_{1S}^{th}				
Atom	s, μm	P_{br}	$P_{br}-\sigma$	$P_{br}+\sigma$
$A_{\pi K}$	98	0.274	0.263	0.285
$A_{\pi K}$	108	0.278	0.267	0.290
$A_{K\pi}$	98	0.269	0.258	0.280
$A_{K\pi}$	108	0.273	0.262	0.284

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

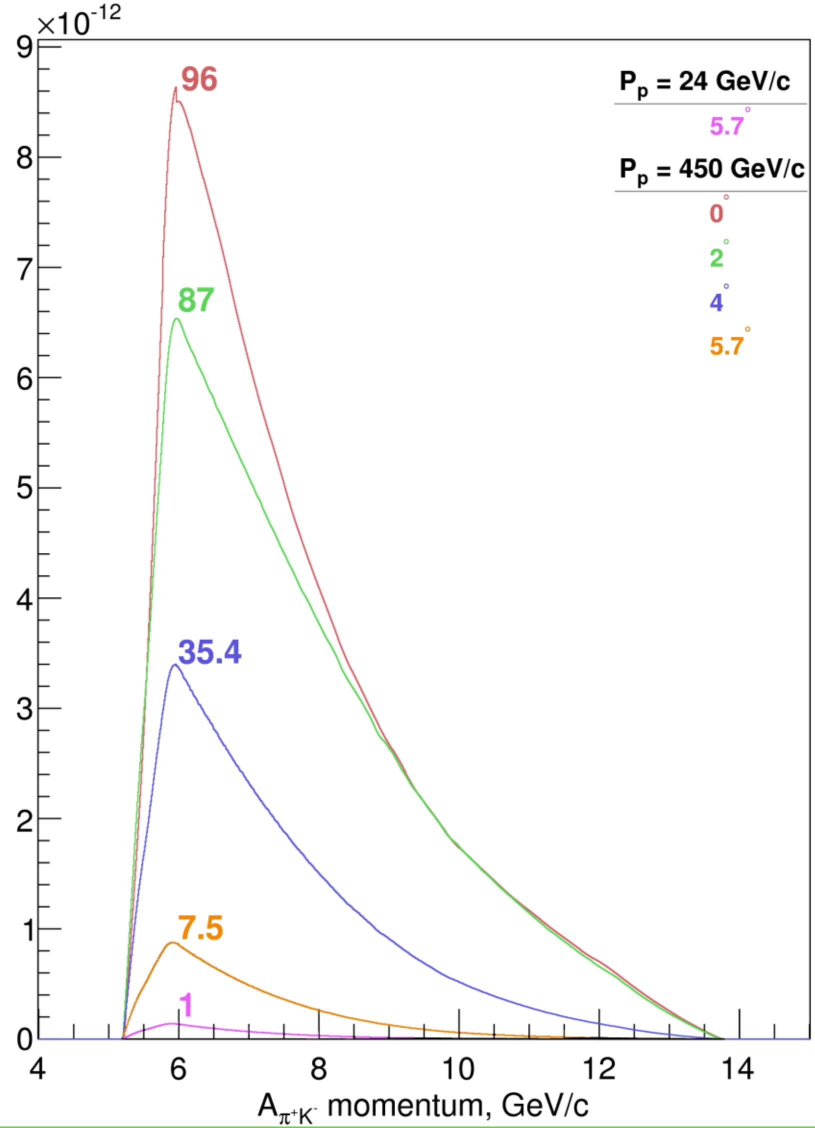
6. Generation of $K^+\pi^-$, $K^-\pi^+$ and $\pi^+\pi^-$ atoms in p-nuclear interaction at proton beam momentum 24 GeV/c and 450 GeV/c.

Yield of $A_{K\pi}$ per one p-Ni interaction



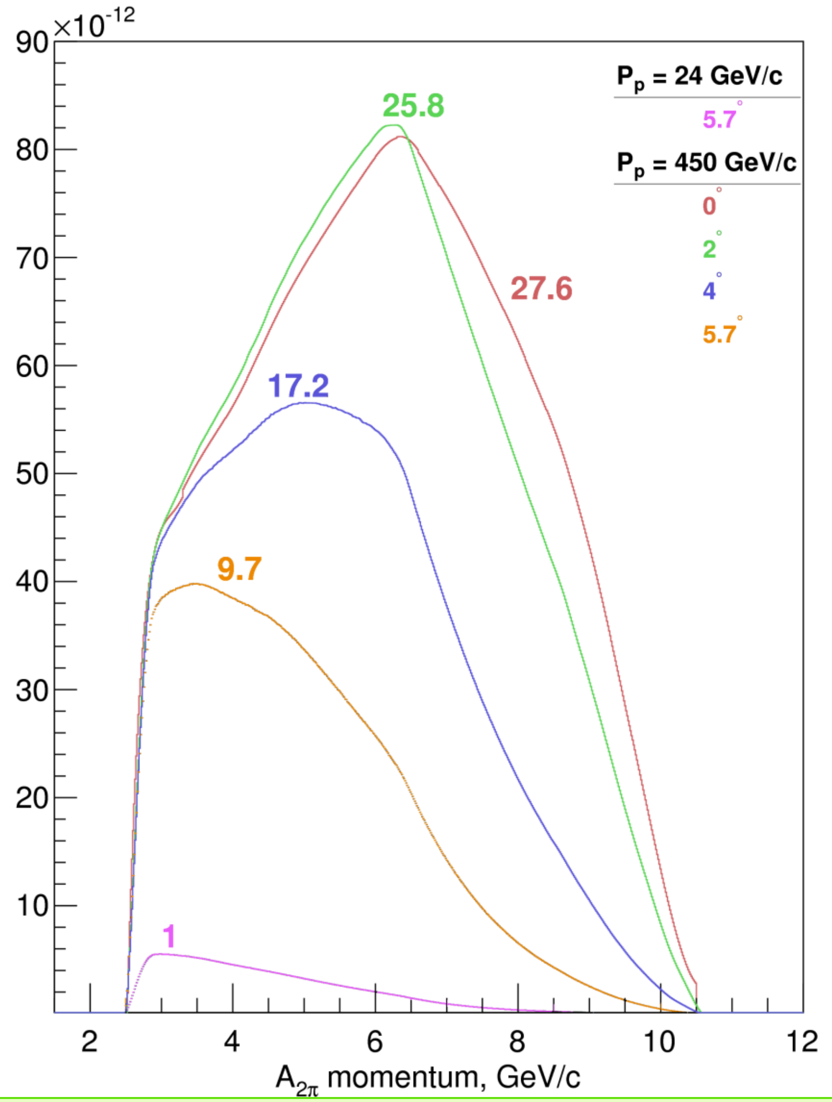
Yield of $A_{K\pi}$ dependence as a function of the atoms angle production and momentum in L. S. Bin = 9.6 MeV/c.

Yield of $A_{\pi K}$ per one p-Ni interaction



Yield of $A_{\pi K}$ dependence as a function of the atoms angle production and momentum in L. S. Bin = 9.6 MeV/c.

Yield of $A_{2\pi}$ per one p-Ni interaction



Yield of $A_{2\pi}$ dependence as a function of the atoms angle production and momentum in L. S. Bin = 15 MeV/c.

DIRAC prospects at SPS CERN

Yield of dimeson atoms per one *p-Ni* interaction, detectable by DIRAC upgrade setup

E_p	PS - 24 GeV			SPS - 450 GeV								
Θ_{lab}	5.7^0			5.7^0			4^0			2^0		
Atoms	$\pi^+\pi^-$	$K^-\pi^+$	$K^+\pi^-$	$\pi^+\pi^-$	$K^-\pi^+$	$K^+\pi^-$	$\pi^+\pi^-$	$K^-\pi^+$	$K^+\pi^-$	$\pi^+\pi^-$	$K^-\pi^+$	$K^+\pi^-$
W_A	1.1E-9	2.6E-11	4.4E-11	1.0E-8	2.0E-10	2.1E-10	1.8E-8	9.3E-10	1.2E-9	2.7E-8	2.3E-9	3.0E-9
W_A^N	1	1	1	9.7	7.5	4.7	17.2	35.4	27.2	25.8	86.9	68.7
W_A/W_π	7.0E-8	1.7E-9	2.9E-9	2.3E-7	4.4E-9	4.7E-9	2.0E-7	1.0E-8	1.3E-8	8.3E-8	7.0E-9	9.2E-9
W_A^N/W_π^N	1	1	1	3.3	2.6	1.6	2.9	6.0	4.6	1.2	4.0	3.2
				A multiplier factor due to spill duration: ~ 4								
Total gain				13	10	6	12	24	18	5	16	13

Thank you
for your attention!

Supplementary slides

Experimental conditions (run 2008-2010)

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

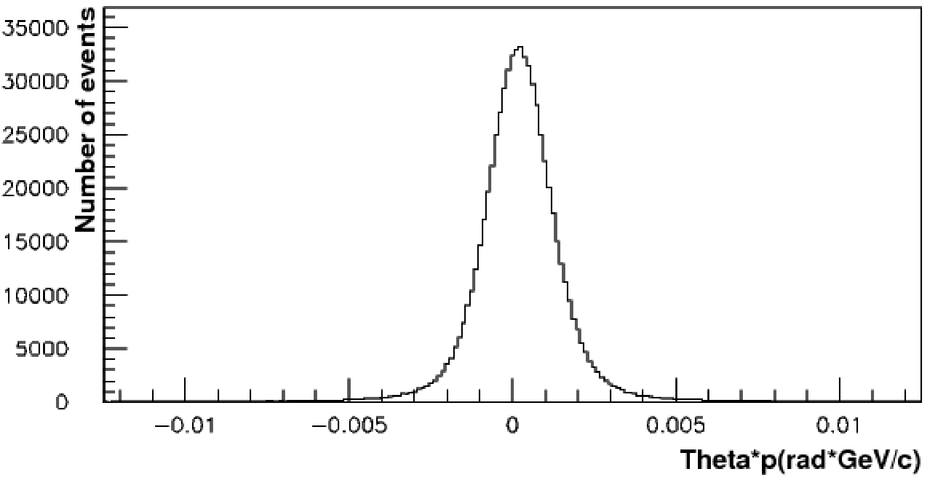
Ni target		
Purity	99.98%	
Target thickness (year)	98±1 μm (2008)	108 ±1 μm (2009-2010)
Radiation thickness	$6.7 \cdot 10^{-3} X_0$	$7.4 \cdot 10^{-3} X_0$
Probability of inelastic proton interaction	$6.4 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$

Experimental conditions

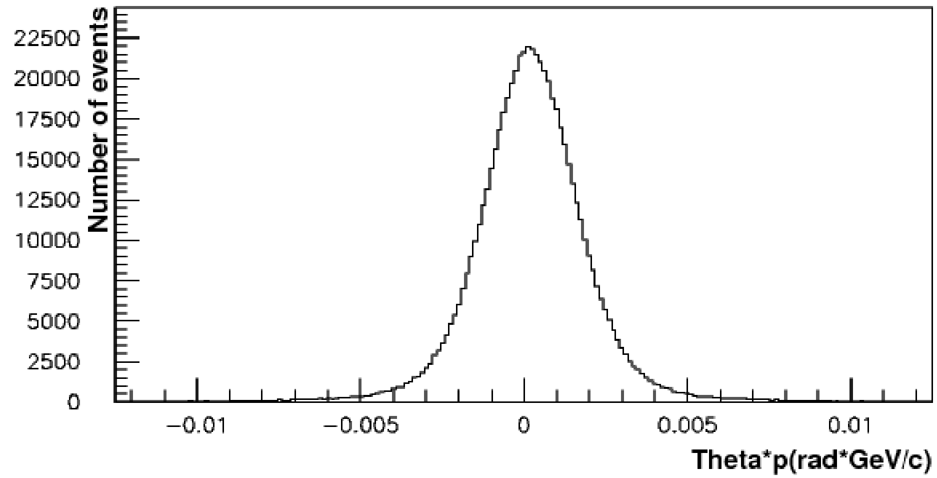
Secondary particles channel (relative to the proton beam)	5.7°
Angular divergence in vertical and horizontal planes	±1°
Solid angle	$1.2 \cdot 10^{-3}$ sr
Dipole magnet	B_{max} = 1.65 T, BL = 2.2 Tm

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

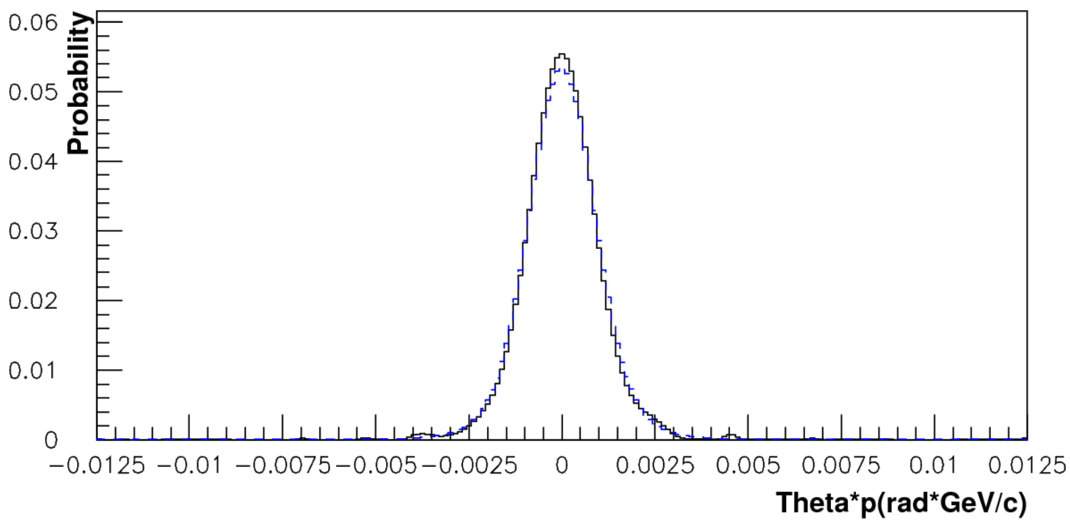
Analysis of multiple scattering in Ni (100 μm)



DC system resolution without scatter



DC system resolution with scatter



Reconstructed and simulated (blue) MS distributions

$$\frac{\delta\theta}{\theta} \approx 0.7\%$$

will be less than 0.5%

Run 2011. Analysis of multiple scattering in Ni (100 μm). Only events with one track in each projection were analyzed. $\delta\theta/\theta \sim 0.7$ %. After including in the analysis of all available events the statistics will be doubled and the expected value will be less than 0.5 %.

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

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

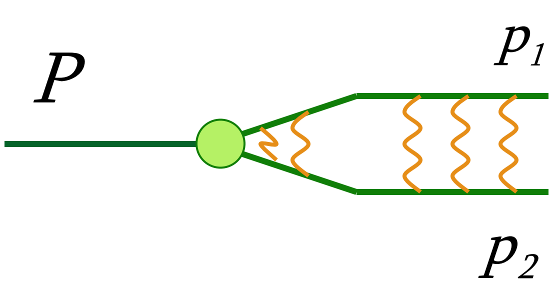
$$\vec{P}_A = \vec{p}_1 + \vec{p}_2$$

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

for all types of atoms

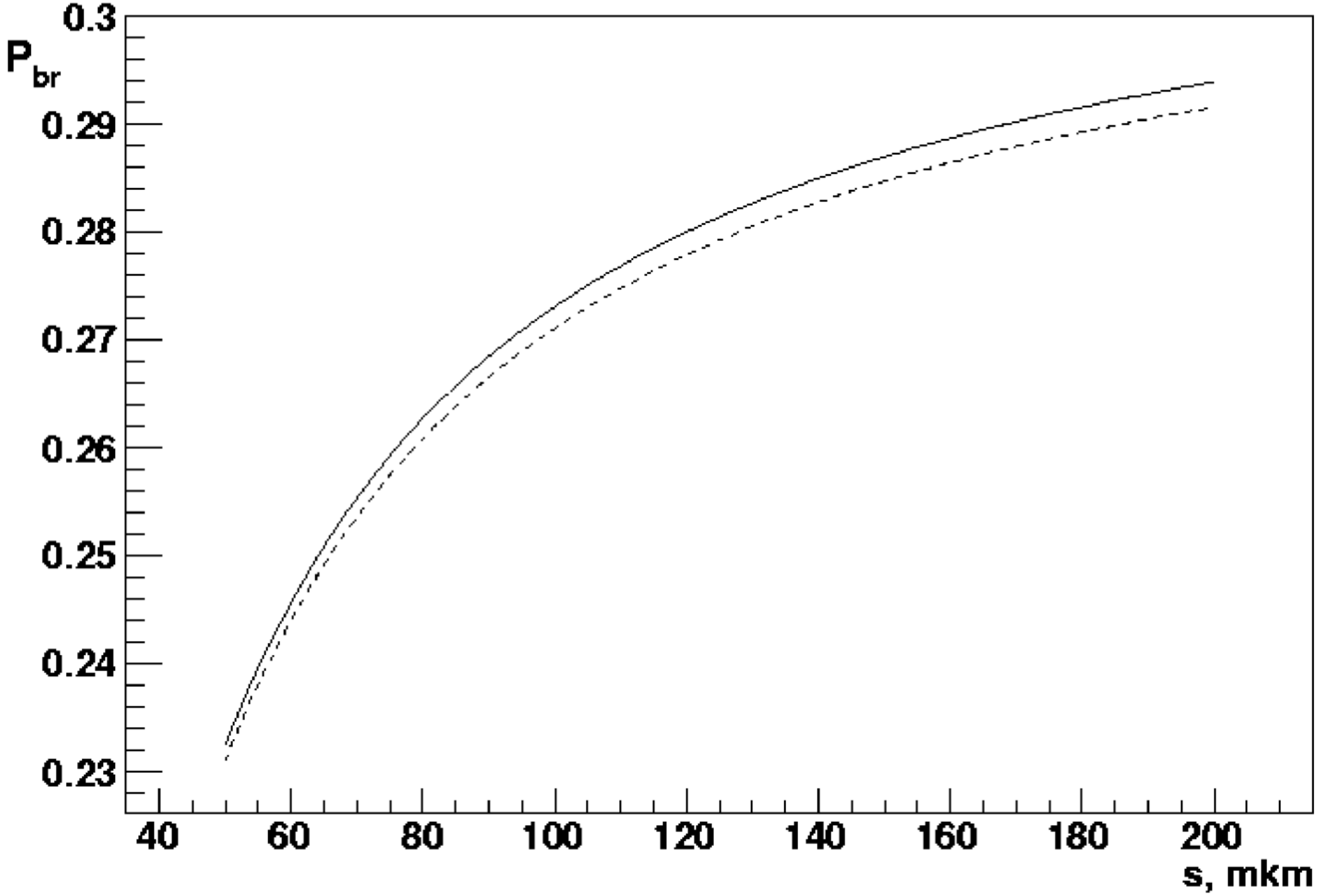
for $A_{2\pi}$ *production* $\vec{p}_1 = \vec{p}_2$

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



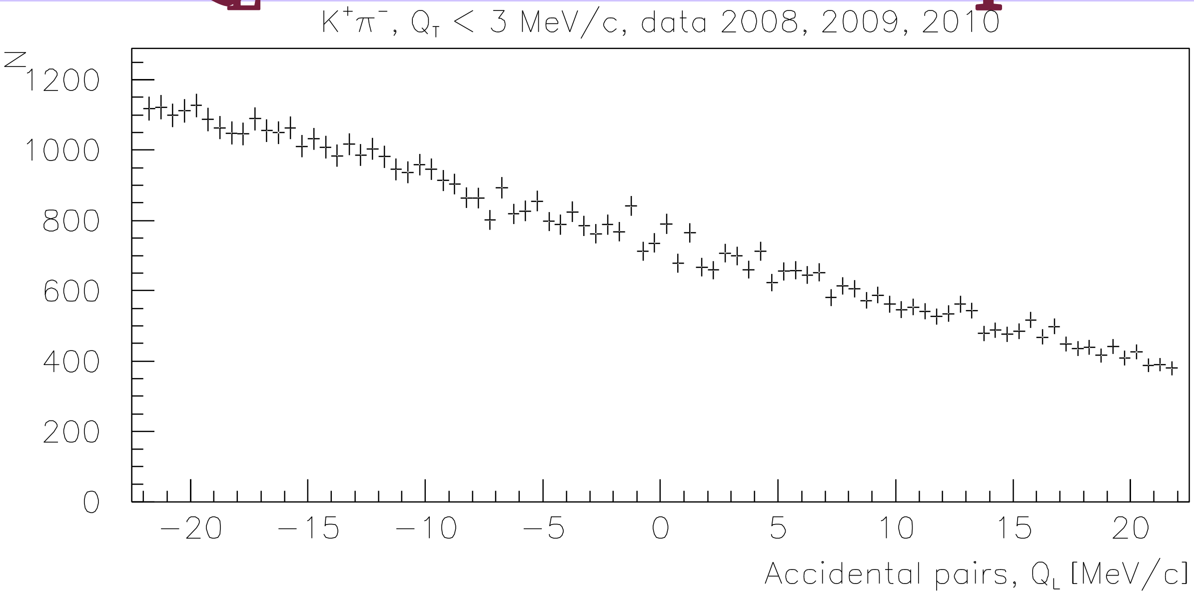
$R(\vec{p}_1, \vec{p}_2; s)$ *- correlation function*

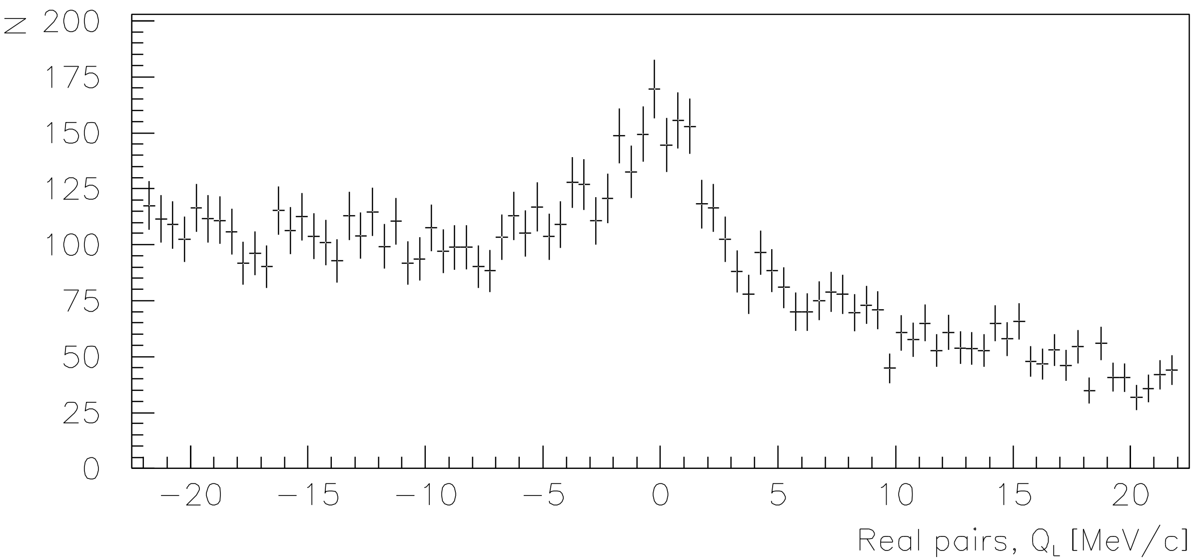
Break-up dependencies P_{br} from the target thickness for $K^+\pi^-$ atom ($A_{K\pi}$) and $K^-\pi^+$ atom ($A_{\pi K}$)



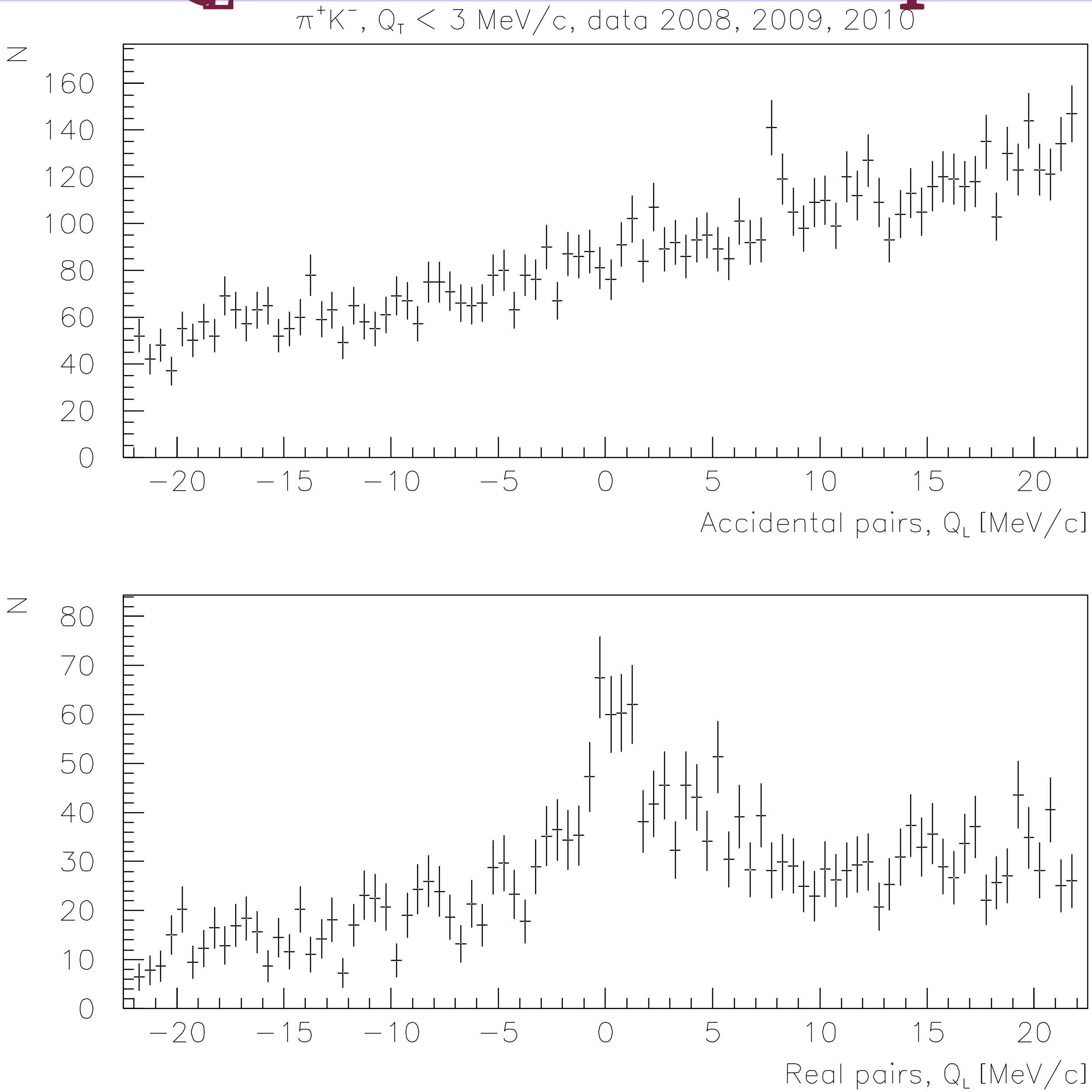
Probability of break-up as a function of Ni target thickness for $A_{\pi K}$ (solid line) and $A_{K\pi}$ atoms (dashed line), $\tau_{1S} = 3.7 \cdot 10^{-15}$ s.
Average momentum of $A_{K\pi}$ and $A_{\pi K}$ are 6.4 GeV/c and 6.5 GeV/c accordingly.

Q_L distribution $K^+\pi^-$ pairs



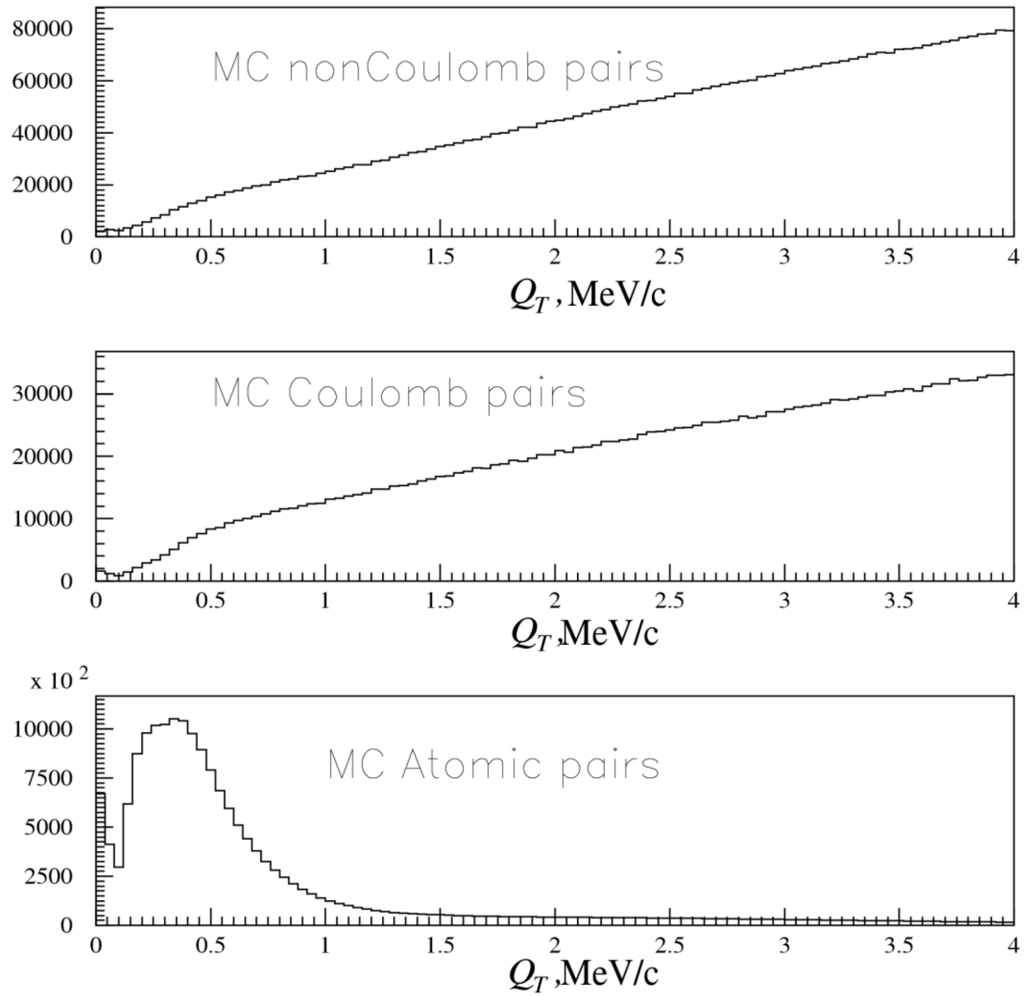


Q_L distribution π^+K^- pairs



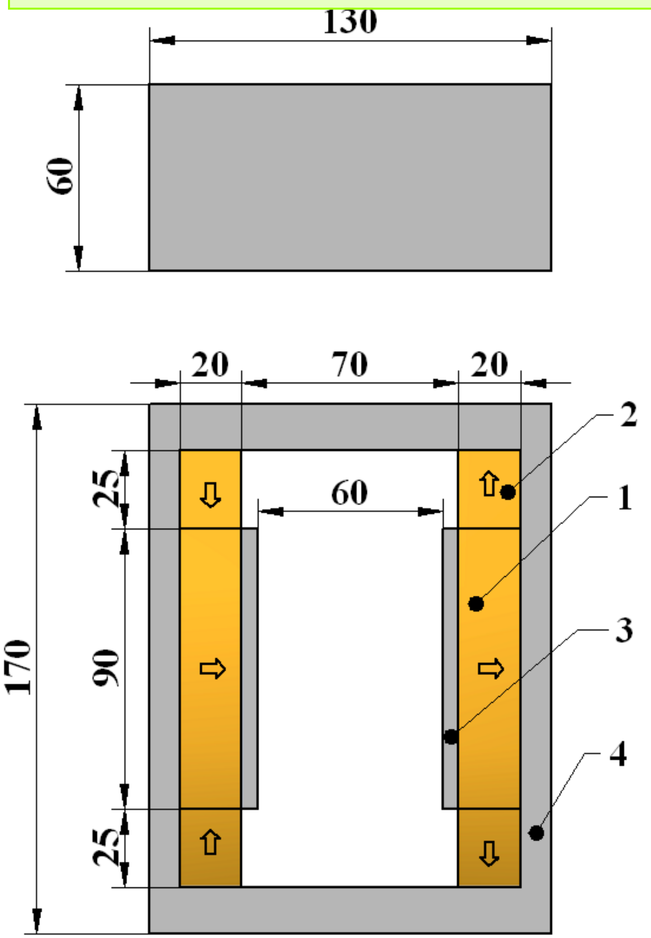
Simulation of $\pi^+\pi^-$ pairs from Beryllium target and "atomic pairs" from Platinum foil

Distributions of reconstructed values of Q_T for non-Coulomb, Coulomb pairs and pairs from metastable atom



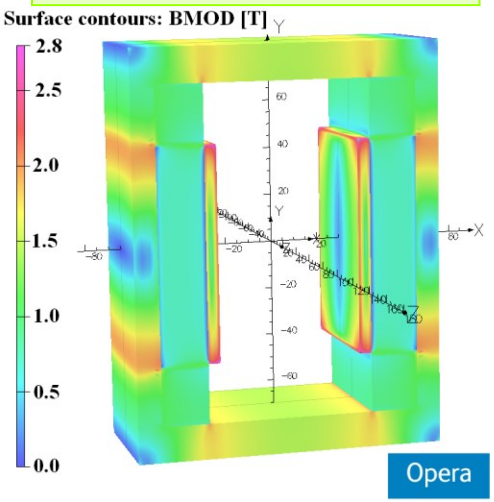
Magnet was designed and constructed in CERN (TE/MCS/MNC)

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

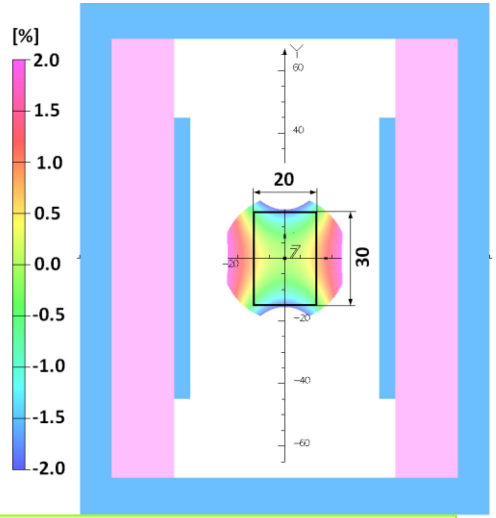


1- PM block Sm2Co17
2- PM block Sm2Co17
3- Pole AISI 1010
4- Return yoke AISI 1010

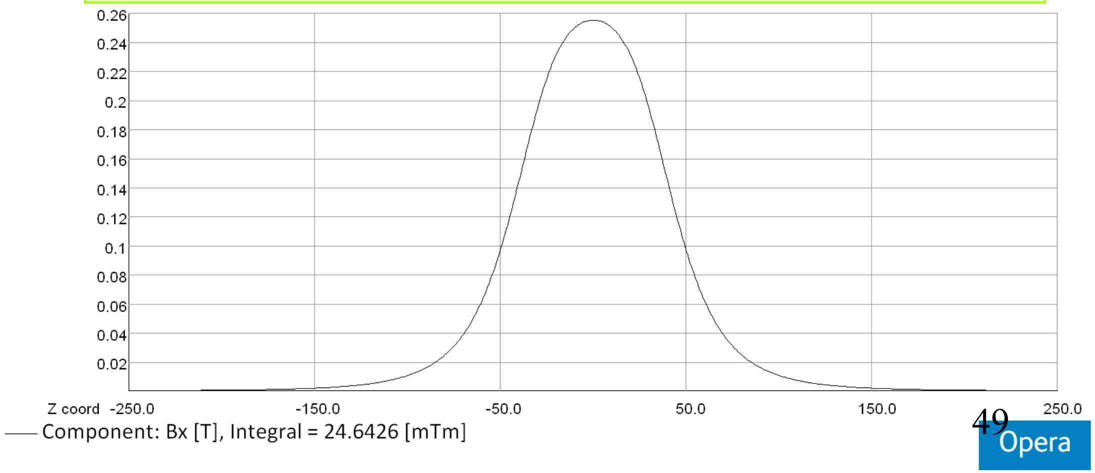
Opera 3D model with surface field distribution



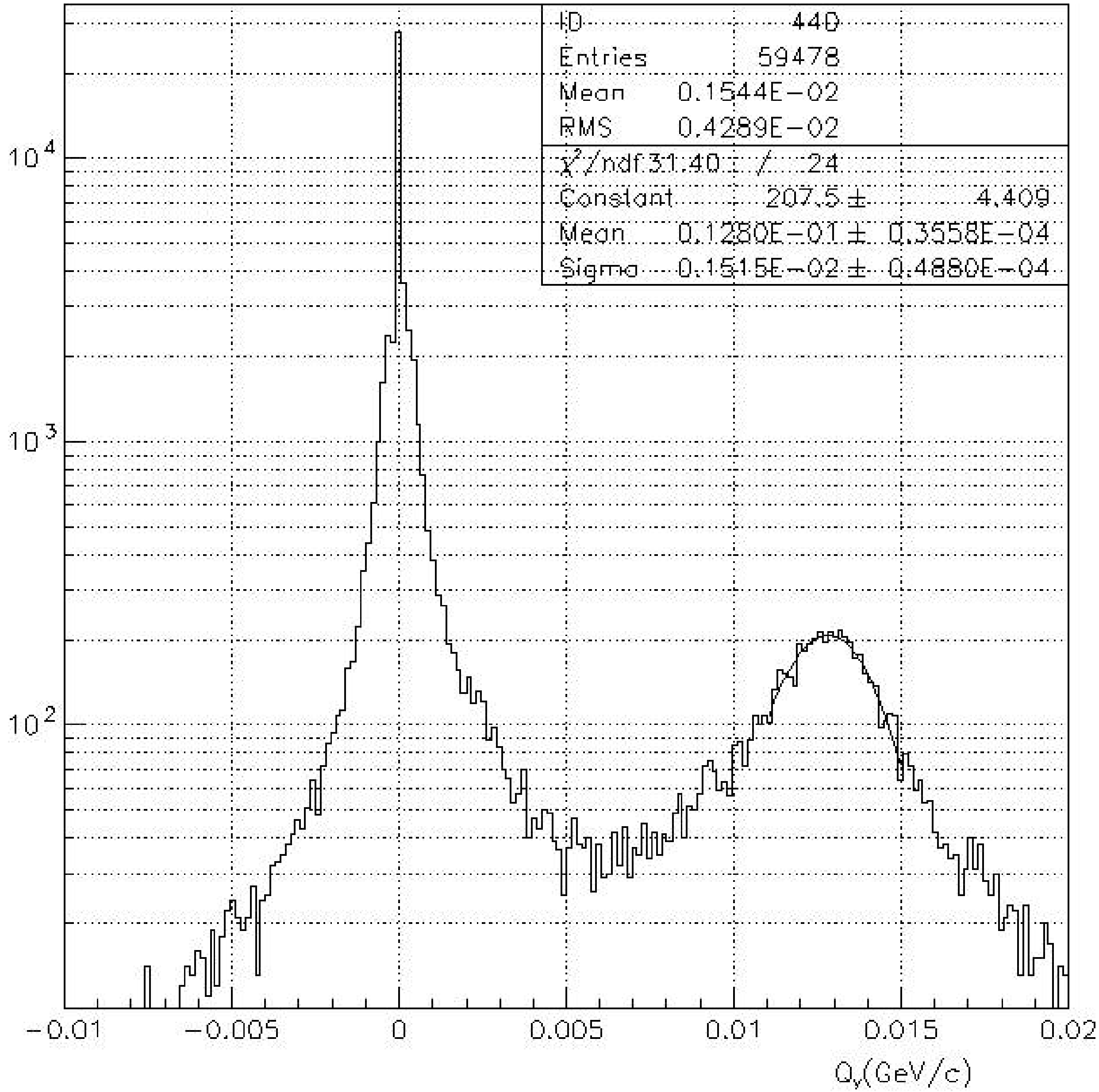
Integrated horizontal field homogeneity inside the GFR X x Y = 20 mm x 30 mm:
$\Delta\int Bxdz / \int Bx(0,0,z)dz$ [%]



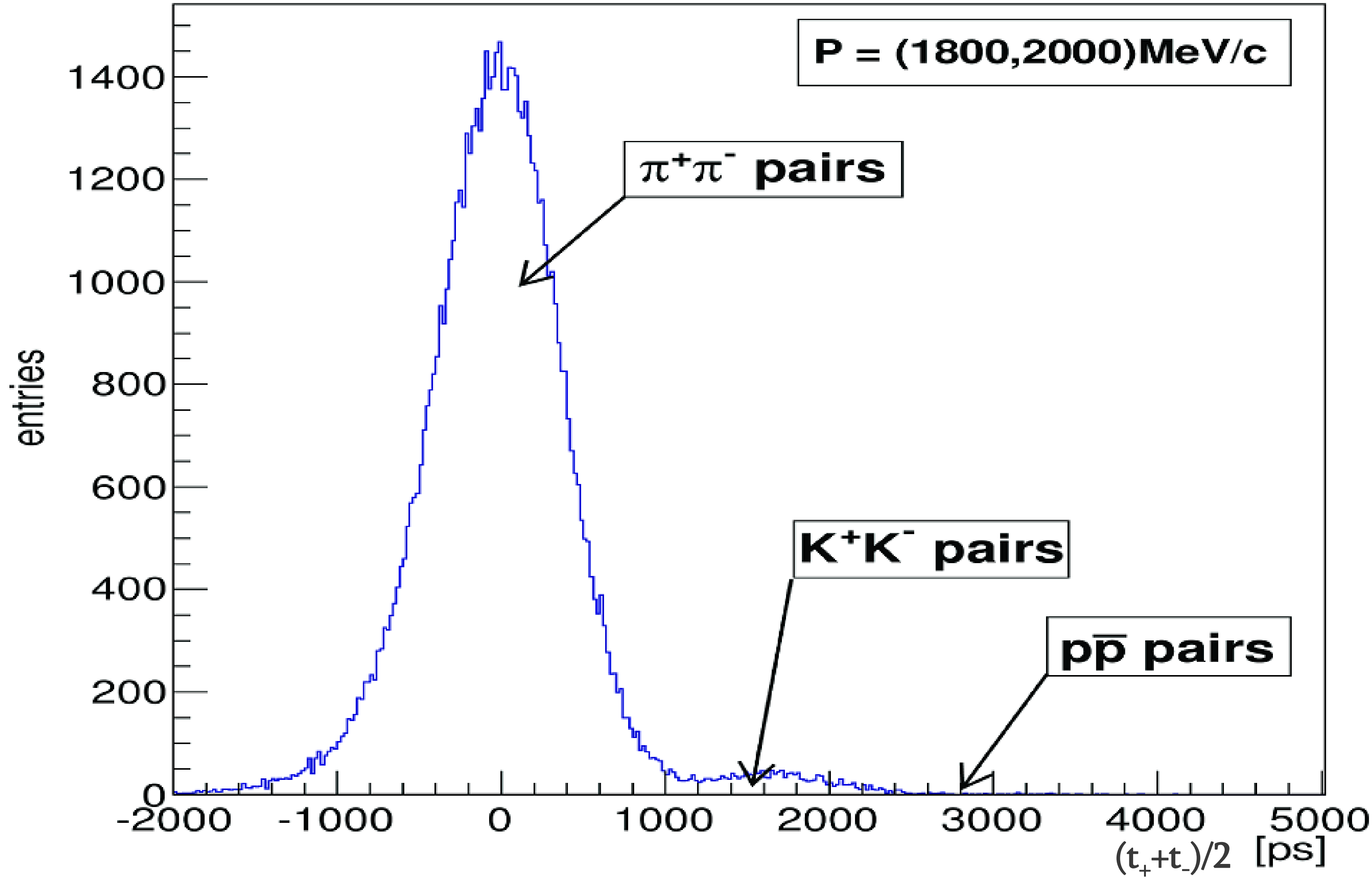
Horizontal field distribution along z-axis at X=Y=0 mm
$\int Bx(0,0,z)dz = 24.6\times10^{-3}$ [Txm]



Q_Y distribution for e^+e^- pair



2010 data: distribution of pairs on $(t_+ + t_-)/2$ for P=(1800, 2000) MeV/c



2010 data: results for kaons and K^+K^- pairs in low momenta

Mom. inter. [MeV/c]	K^+	sse(K^+)	K^-	sse(K^-)	K^+K^-	sse(K^+K^-)
1000-1200	75	±9	40	±6	-	-
1200-1400	2032	±64	1308	±51	522	±23
1400-1600	4546	±95	3628	±85	1884	±61
1600-1800	6314	±112	5450	±104	2101	±65
1800-2000	-	-	-	-	2068	±64

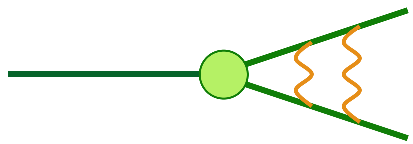
sse(K^+), sse(K^-), sse(K^+K^-) – standard statistic error for K^+, K^-, K^+K^- pairs accordingly.

Total number of K^+K^- pairs in low momenta 1200-2000 MeV/c is 6600.

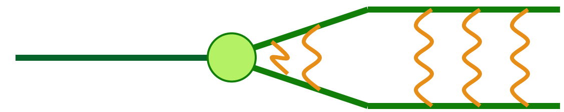
Total number of K^+K^- pairs in high momenta 3000-3800 MeV/c is 3200.
The sum of low and high energy kaon pairs is 9800.

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

For the charged pairs from the short-lived sources and small relative momentum Q there is strong Coulomb interaction in the final state.



Coulomb pairs



Atoms

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

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

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

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

K^+K^- atom and its lifetime

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

K^+K^- interaction complexity ↓

$\tau\ (A_{2K} \rightarrow \pi\pi, \pi\eta)$	K^+K^- interaction
1.2×10^{-16} s [1]	Coulomb-bound
8.5×10^{-18} s [3]	momentum dependent potential
3.2×10^{-18} s [2]	+ one-boson exchange (OBE)
1.1×10^{-18} s [2]	+ f_0' (I=0) + $\pi\eta$-channel (I=1)
2.2×10^{-18} s [4]	ChPT

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

2010 data: results for K^+K^- and $p\bar{p}$ pairs in high momenta

Mom. intervals [MeV/c]	$p\bar{p}$	$\text{error}_{p\bar{p}}$	ratio [%]	$\text{error}_{\text{ratio}}$	K^+K^- pairs	$\text{error}_{K^+K^-}$
3000-3200	85	±14	0.33	±0.18	1366	±105
3200-3400	116	±17	0.56	±0.16	830	±86
3400-3600	96	±17	0.73	±0.19	709	±69
3600-3800	88	±15	0.99	±0.18	326	±52

ratio...ratio between $p\bar{p}$ and $\pi^+\pi^-$ pairs

$\text{error}_{p\bar{p}}$...error of fit for $p\bar{p}$ pairs

$\text{error}_{\text{ratio}}$...error for the $p\bar{p}$ and $\pi^+\pi^-$ pair ratio

$\text{error}_{K^+K^-}$...error of fit for K^+K^- pairs

Total number of K^+K^- pairs in high momenta is 3231.
The sum of low and high energy kaon pairs is 9806.

K^+K^- atom and its lifetime

Interests in $K\bar{K}$ physics?

•General:
non-understood $K\bar{K}$ interplay with the **scalar mesons** $f_0[0^+(0^{++})]$ and $a_0[1^-(0^{++})]$ &
kaonium, the only double-mesonic atom with hidden strangeness, is decaying via
strangeness annihilation

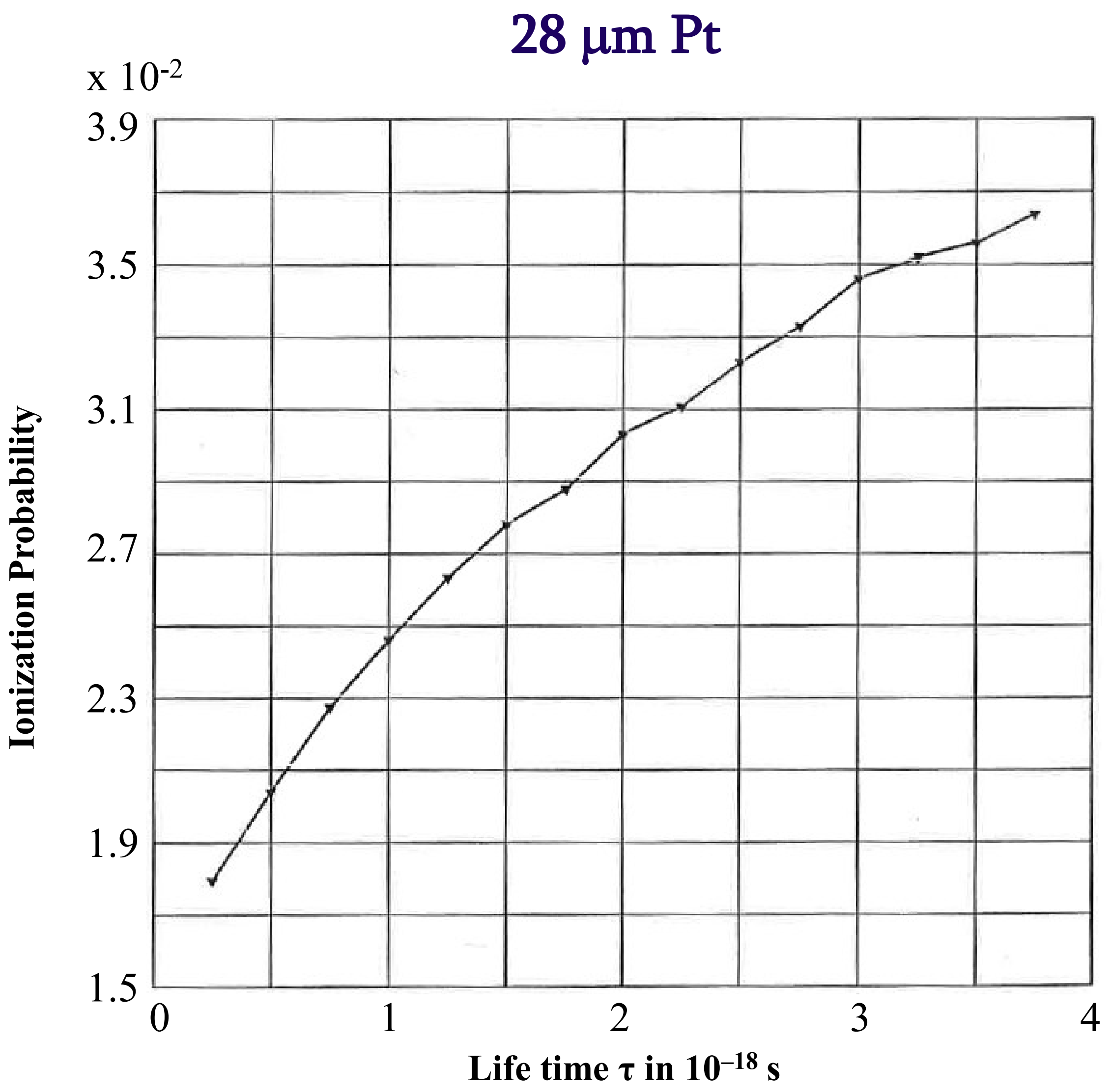
•DIRAC experiment:
study of low-energy K^+K^- scattering $\rightarrow$ estimate **number of produced atoms A_{2K}**

Kaonium decay width or lifetime "expected":

•Decay width $\Gamma(A_{2K}) = [\tau(A_{2K})]^{-1} = -\alpha^3 m_K^2 \, \mathrm{Im}(a_{KK})$ … A_{2K} structure dependent:
strong effects enter through the complex scattering length a_{KK} .

•DIRAC experiment:
search for "atomic pairs" K^+K^- from A_{2K} ionization
$\rightarrow$ upper limit on $\tau(A_{2K})$ $\rightarrow$ info about scattering length $\mathbf{a_{KK}}$!

K^+K^- atoms ionization probability

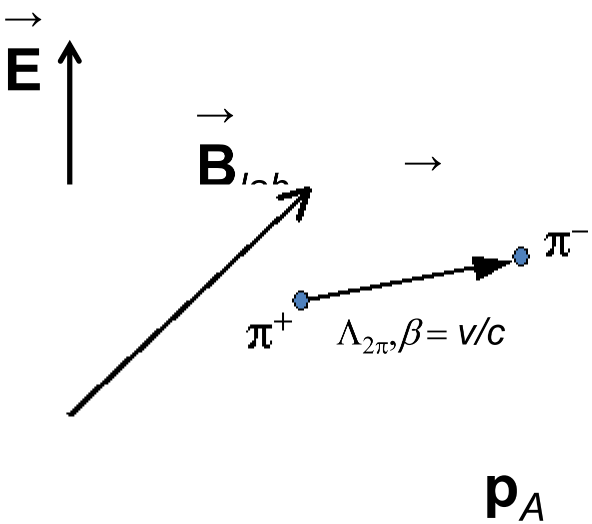


K^+K^- atoms Lorentz factor is $\gamma = 18$

Lamb shift measurement with external magnetic field

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

Impact on atomic beam by external magnetic field $\boldsymbol{B}_{lab}$ and Lorentz factor γ



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

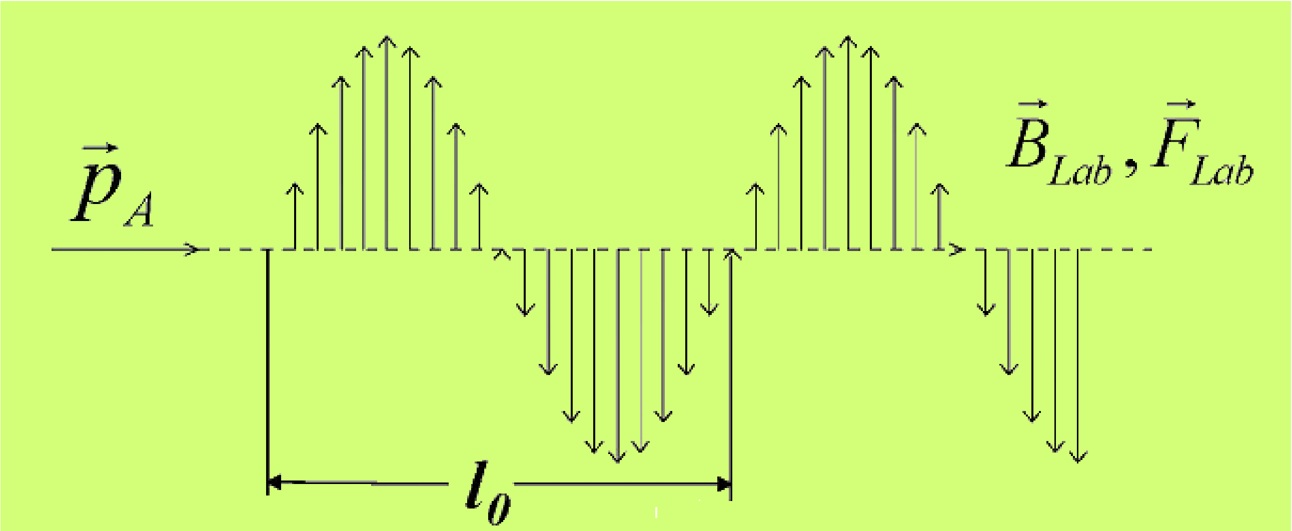
$\vec{B}_{lab}$ …. laboratory magnetic field

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

$$|\vec{E}| = \beta\gamma \mathbf{B}_{lab} \approx \gamma \mathbf{B}_{lab}$$

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

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

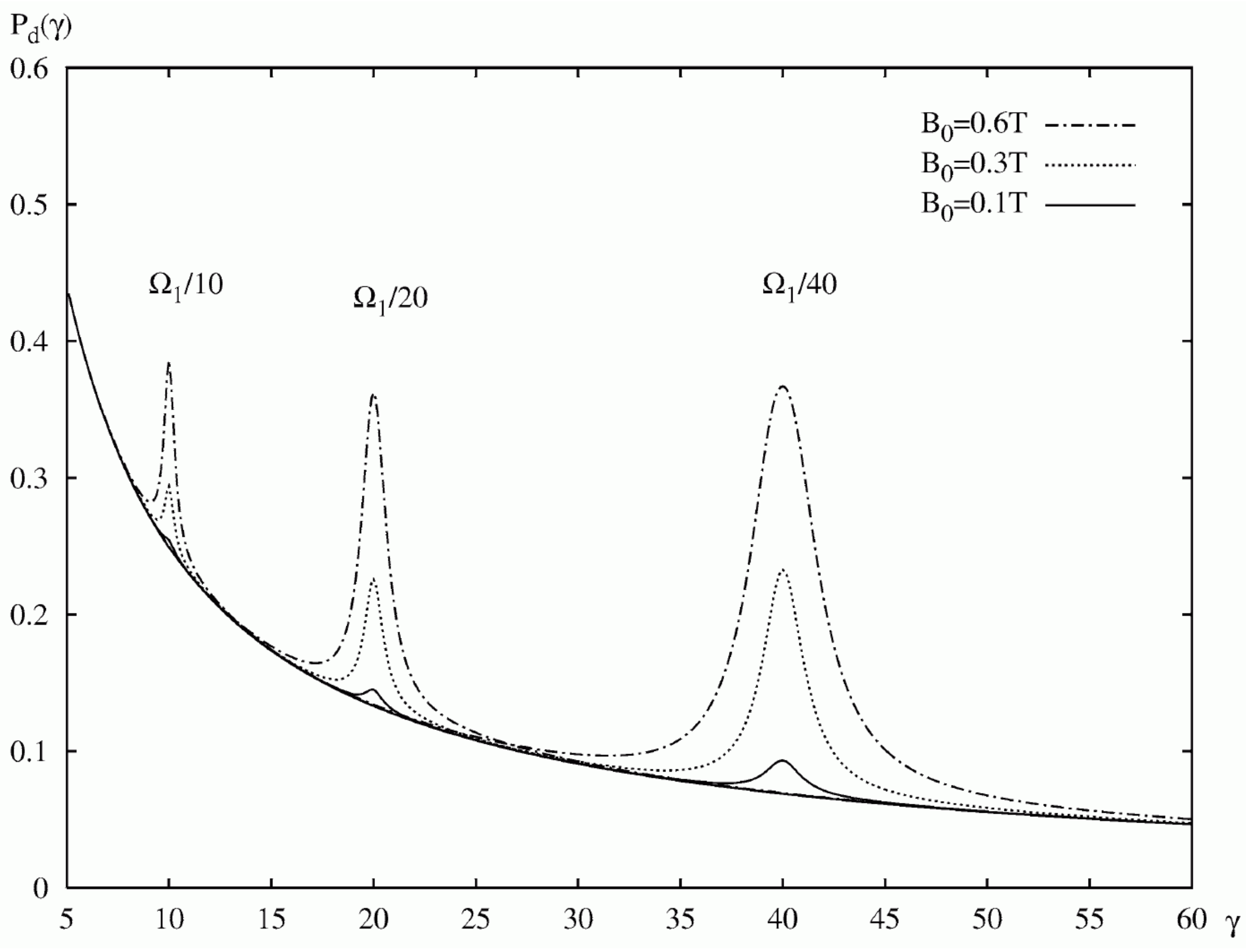


In Lab. System: $T_{Lab} = \dfrac{l_0}{\beta c}$, $\omega_{Lab} = \dfrac{2\pi}{T_{Lab}}$

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

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

Resonant enhancement



Resonant method