

Observation of long-lived states of hydrogen-like atom consisting of π^+ and π^- mesons

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on behalf of the DIRAC collaboration

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DIRAC collaboration



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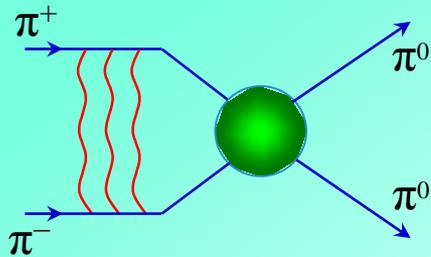
totally 68 physicists from 20 Institutes

Pionium lifetime

Pionium ($A_{2\pi}$) is a hydrogen-like atom consisting of π^+ and π^- mesons:

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

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



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

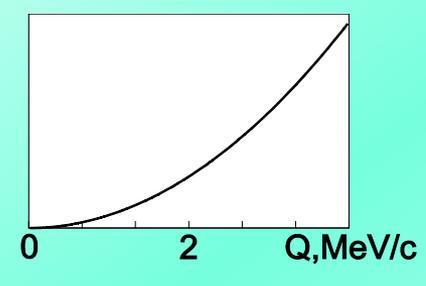
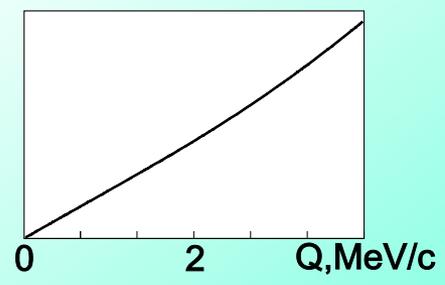
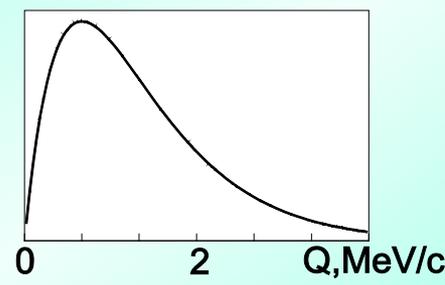
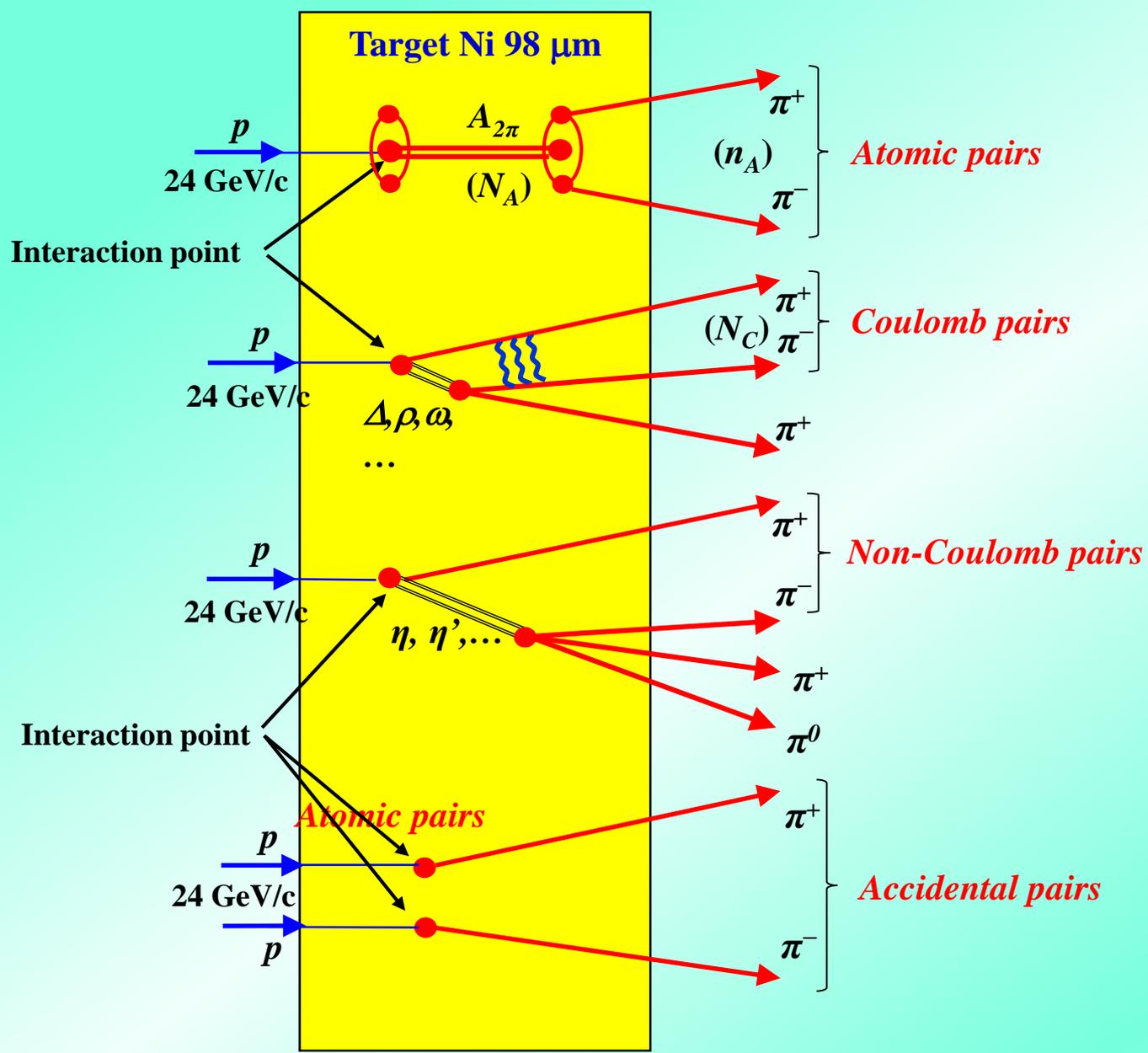
$$\Gamma_{1S,2\pi^0} = R |a_0 - a_2|^2 \quad \text{with} \quad \frac{\Delta R}{R} \approx 1.2\%$$

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

Gasser et al. – 2001

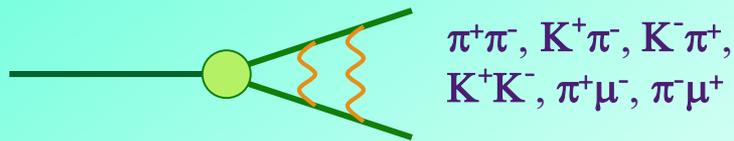
DIRAC data	$\tau_{1s} (10^{-15} \text{ s})$				$ a_0 - a_2 $				Reference
	value	stat	syst	<i>theo</i> * tot	value	stat	syst	<i>theo</i> * tot	
2001	2.91	+0.45 -0.38	+0.19 -0.49	[+0.49 -0.62]	0.264	+0.017 -0.020	+0.022 -0.009	[+0.033 -0.020]	PL B 619 (2005) 50
2001-03	3.15	+0.20 -0.19	+0.20 -0.18	[+0.28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

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

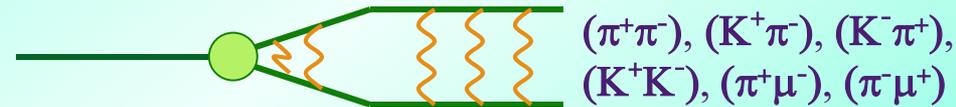


Coulomb pairs and atoms

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.



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:

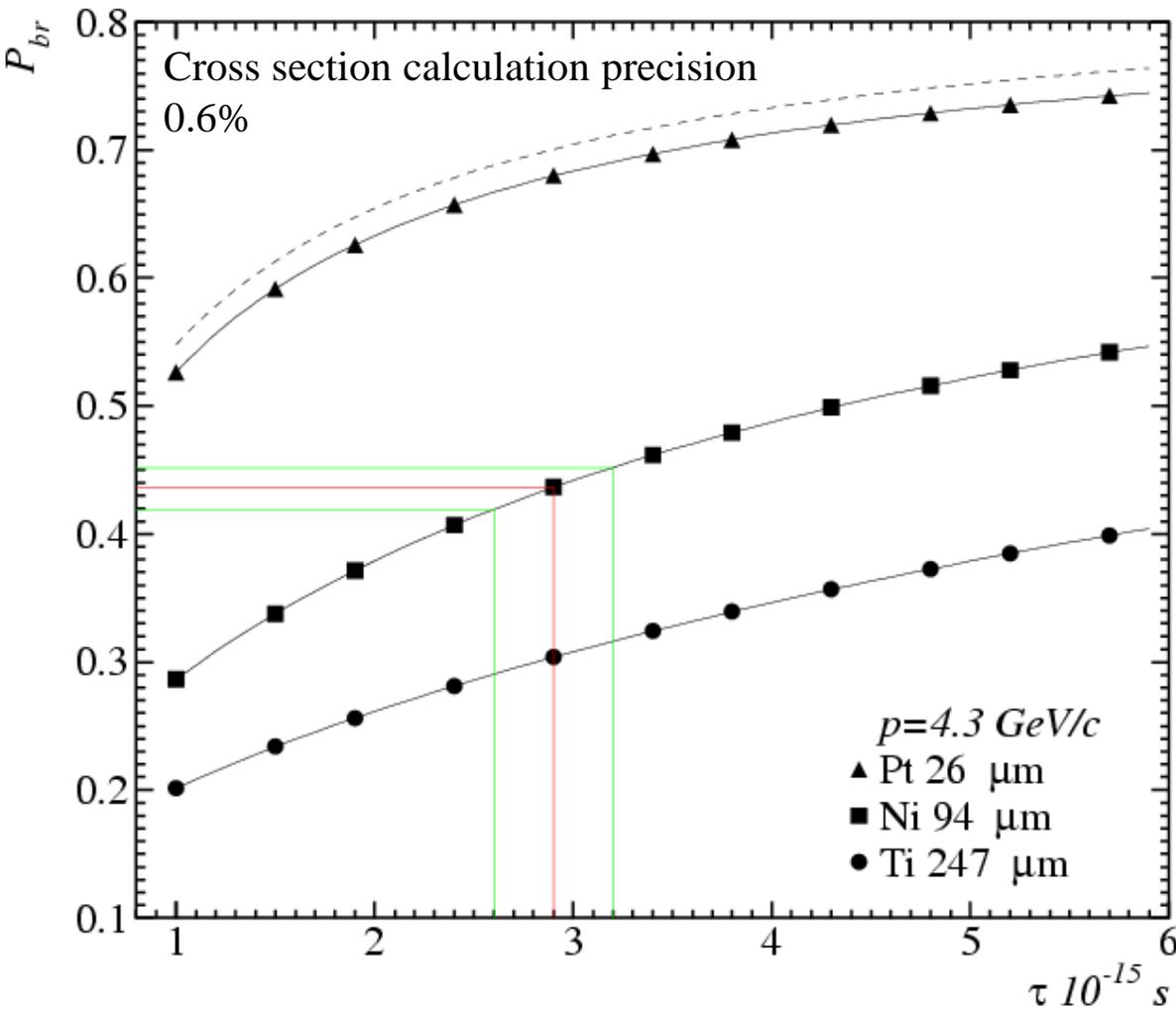
$$N_A = K(Q_0)N_C(Q \leq Q_0), \frac{\delta K(Q_0)}{K(Q_0)} \leq 10^{-2}$$

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

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

Accuracy of P_{br} is better than 1%



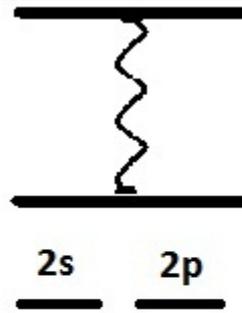
There is an optimal target material for a given lifetime

Energy splitting measurement

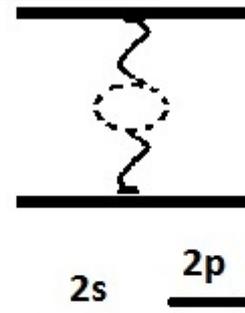
$A_{2\pi}$ Energy Levels

J. Schweizer [PL B (2004)]

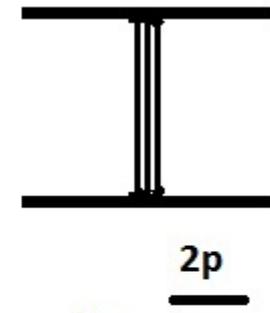
For Coulomb potential E depends only on n



Coulomb potential



Vacuum polarisation



Strong potential

Notation:

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

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

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

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

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

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

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

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

CONCLUSION: one parameter ($2a_0+a_2$) allow to calculate all Δ_{ns-np} values

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

The long-lived states are the states with non-zero orbital momenta, for which the strong interaction is suppressed. As result the lifetime and mean path of such states are a few order higher compared to the ground state.

n	$\tau_{2\pi}$ (10^{-11} sec)		Decay length $A_{2\pi}$ in L.S. (cm) for $\gamma=16$	
			$(\lambda_{ns}=c \cdot \gamma \cdot \tau_{nl})$	
	s ($l=0$)	p ($l=1$)	s ($l=0$)	p ($l=1$)
	$\tau_{ns}=\tau_{1s} \cdot n^3$			
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

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

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

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

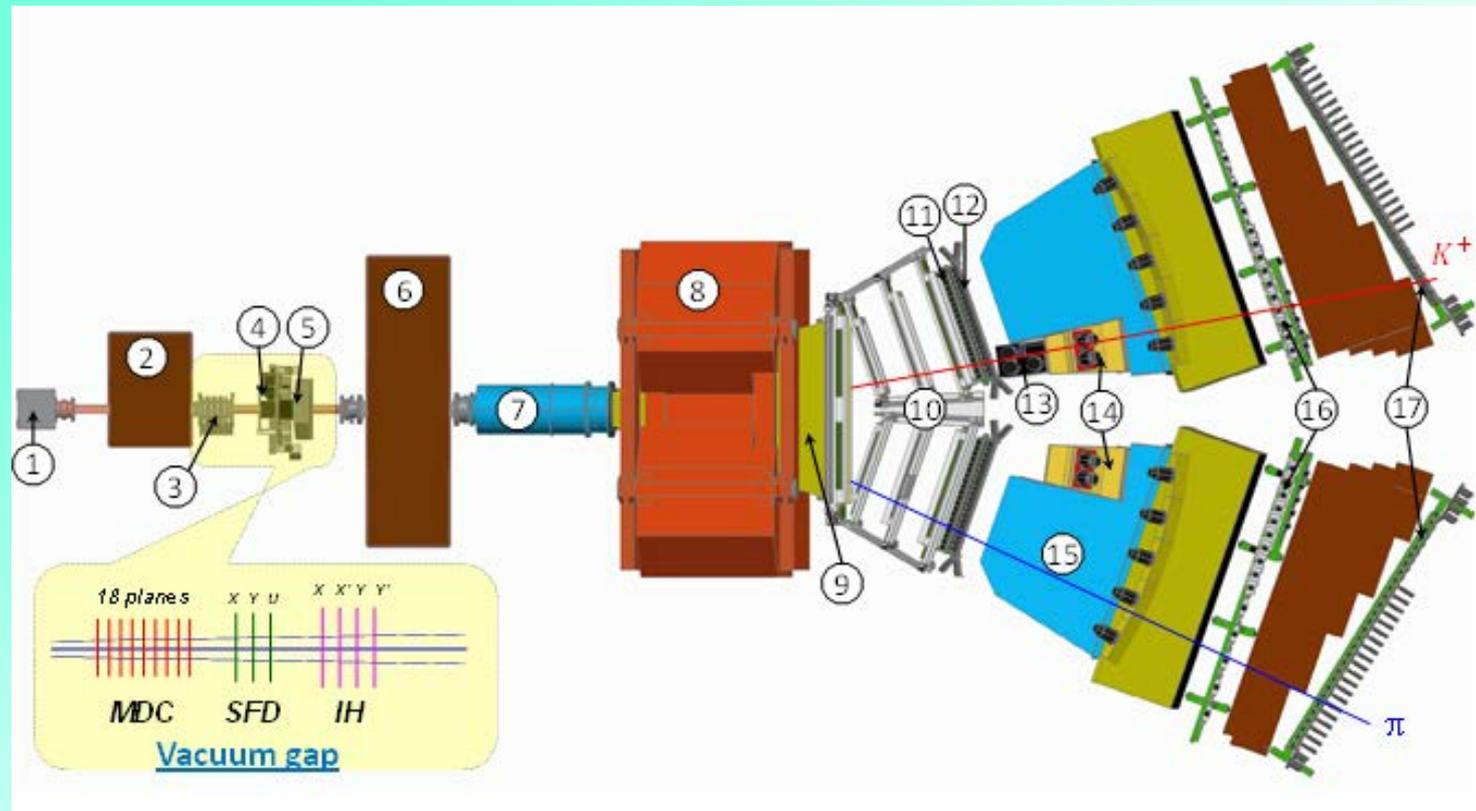
$$\tau_{eff} = \frac{\tau_{2p}}{1 + \frac{|\xi|^2}{4} \frac{\tau_{2p}}{\tau_{2s}}} = \frac{\tau_{2p}}{1 + 120 |\xi|^2}$$

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

$B_{Lab} = 2$ Tesla

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

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

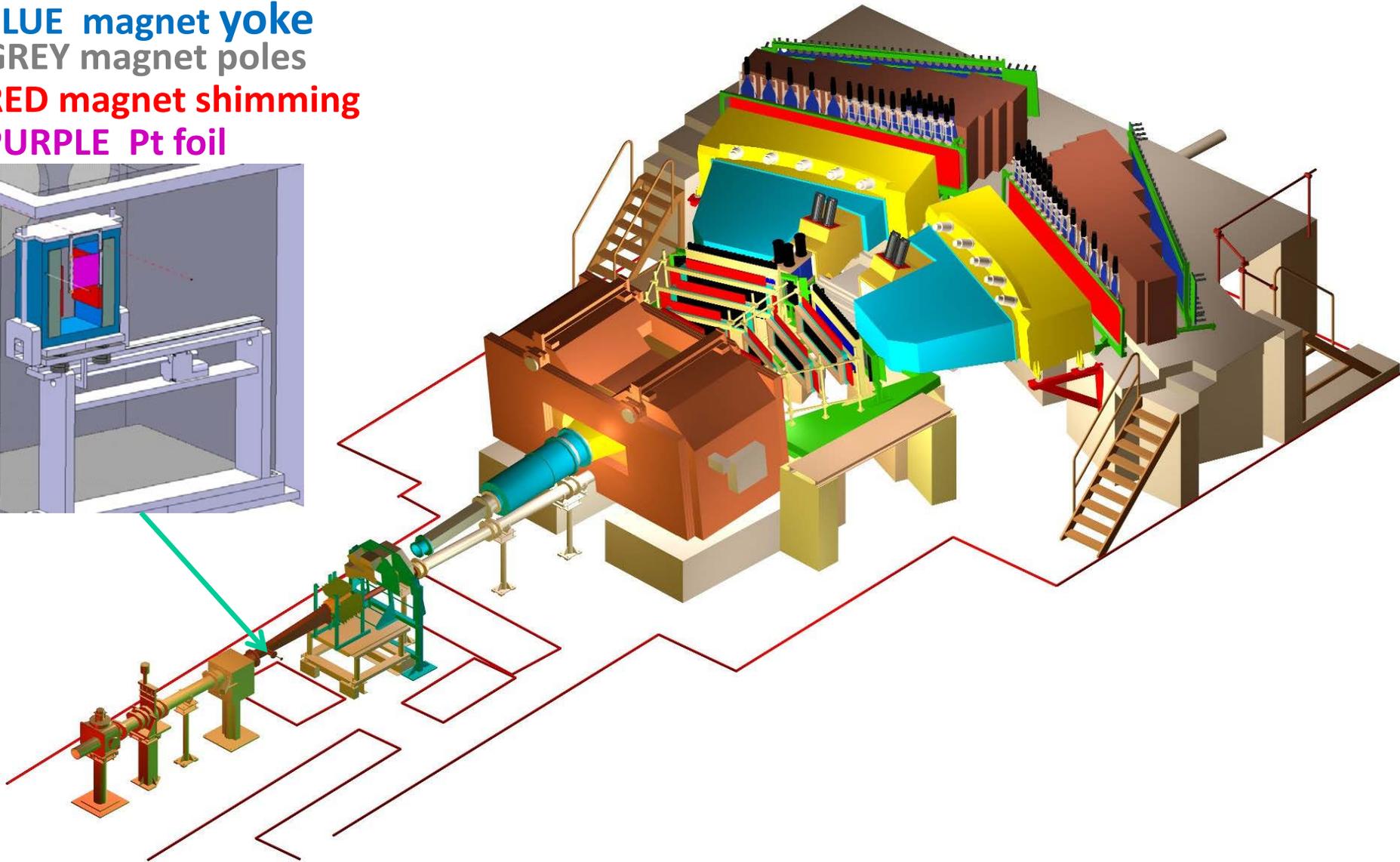
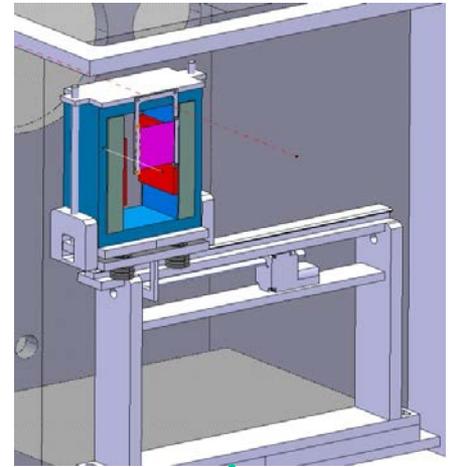
DIRAC upgraded Experimental setup

BLUE magnet yoke

GREY magnet poles

RED magnet shimming

PURPLE Pt foil



Experimental conditions

SFD

Coordinate precision	$\sigma_X = 60 \mu\text{m}$	$\sigma_Y = 60 \mu\text{m}$	$\sigma_W = 120 \mu\text{m}$
Time precision	$\sigma_X^t = 380 \text{ ps}$	$\sigma_Y^t = 512 \text{ ps}$	$\sigma_W^t = 522 \text{ ps}$

DC

Coordinate precision	$\sigma = 85 \mu\text{m}$
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VH

Time precision	$\sigma = 100 \text{ ps}$
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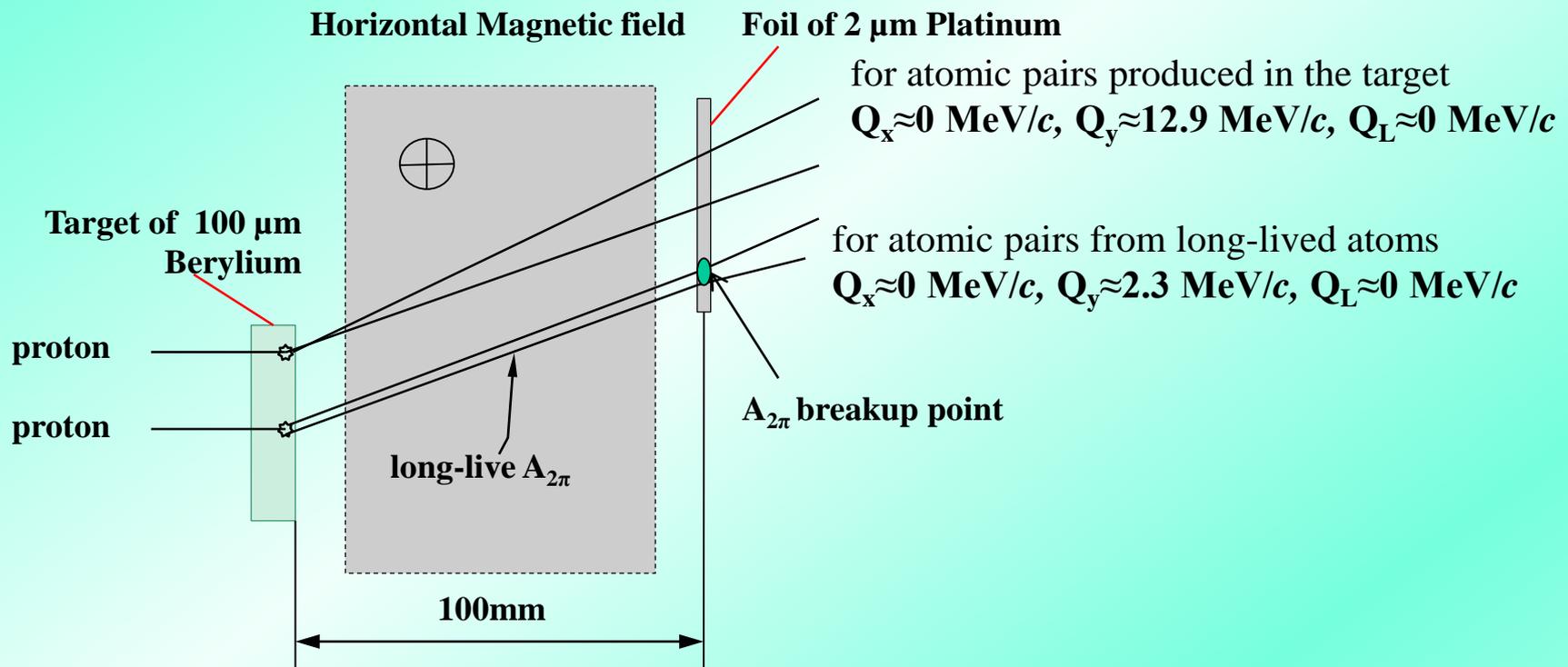
Spectrometer

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

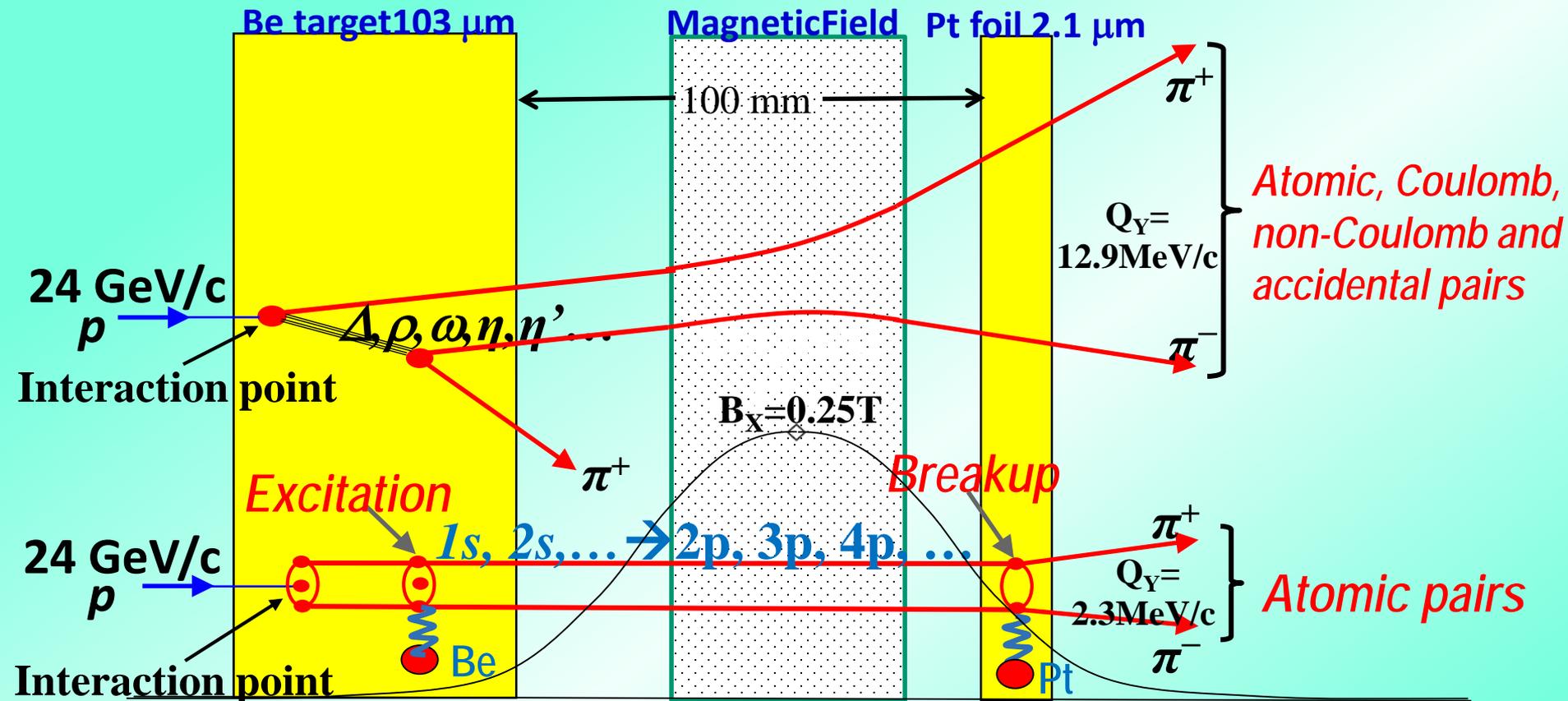
Trigger efficiency 98 %	for pairs with	$Q_L < 28 \text{ MeV}/c$ $Q_X < 6 \text{ MeV}/c$ $Q_Y < 4 \text{ MeV}/c$
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Search for long-lived states of $\pi^+\pi^-$ atoms

During 2011-2012 the data were collected for observation of the long-lived states of $\pi^+\pi^-$ atom. This observation opens the future possibility to measure the energy difference between ns and np states $\Delta E(ns-np)$ and the value of $\pi\pi$ scattering length combination $|2a_0+a_2|$.



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

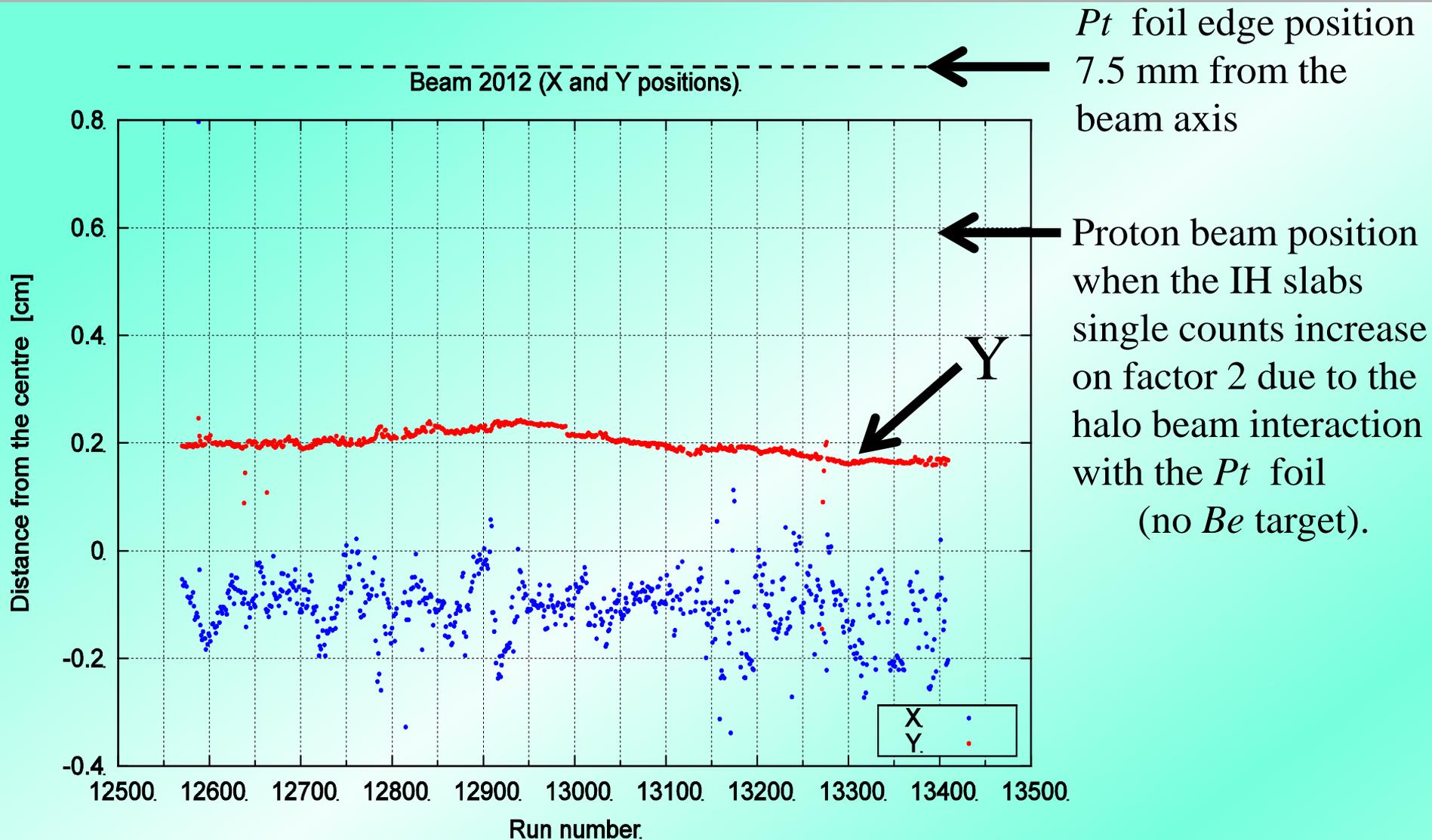


for $\gamma = 16$

$l(2p) = 5.6 \text{ cm}, l(3p) = 19 \text{ cm}, l(4p) = 43 \text{ cm}, l(5p) = 84 \text{ cm}$
 $l(2s) = 0.11 \text{ mm}, l(3s) = 0.38 \text{ mm}, l(4s) = 0.89 \text{ mm}, l(5s) = 1.74 \text{ mm}$

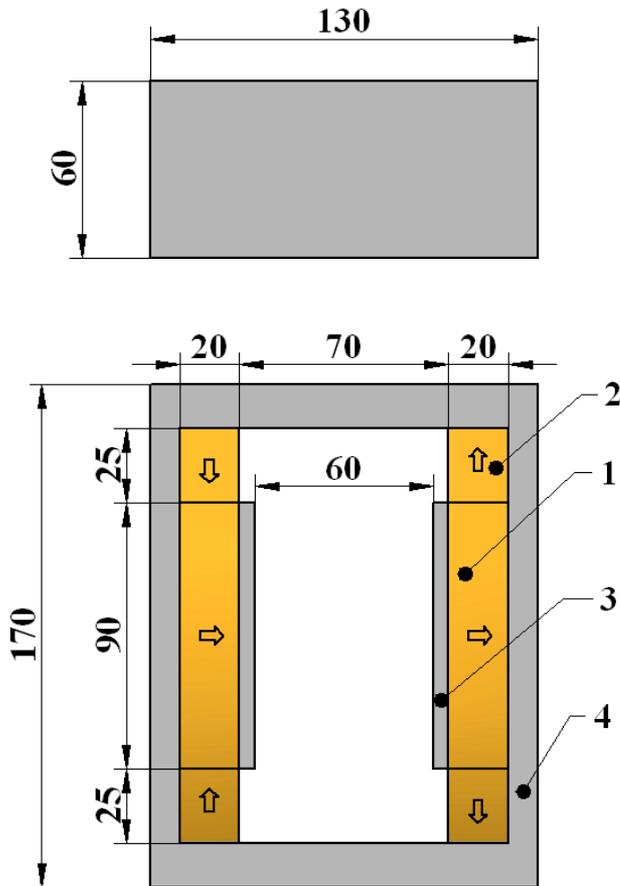
n	2	3	4	5	>2
$\epsilon_n(\text{Be}) \times 10^2$	$2.48 \pm 0(10^{-3})$	1.54 ± 0.01	0.86 ± 0.03	0.56 ± 0.06	7.1 ± 0.8
$\epsilon_n(\text{Pt}) \times 10^2$	$0.52 \pm 0(10^{-4})$	$1.10 \pm 0(10^{-3})$	0.78 ± 0.03	0.54 ± 0.06	4.6 ± 0.8

y-beam position (run 2012)



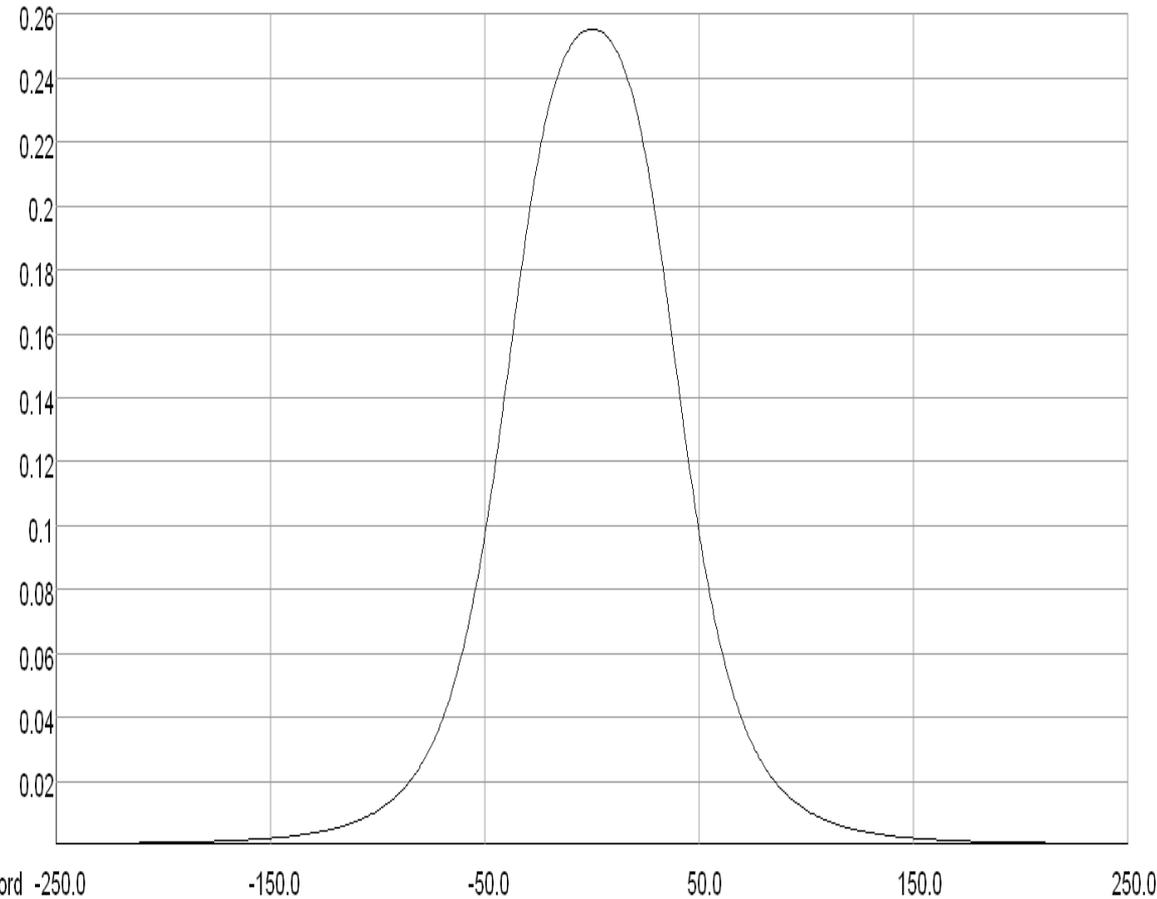
Study of long-lived states as a method for energy shift measurement

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



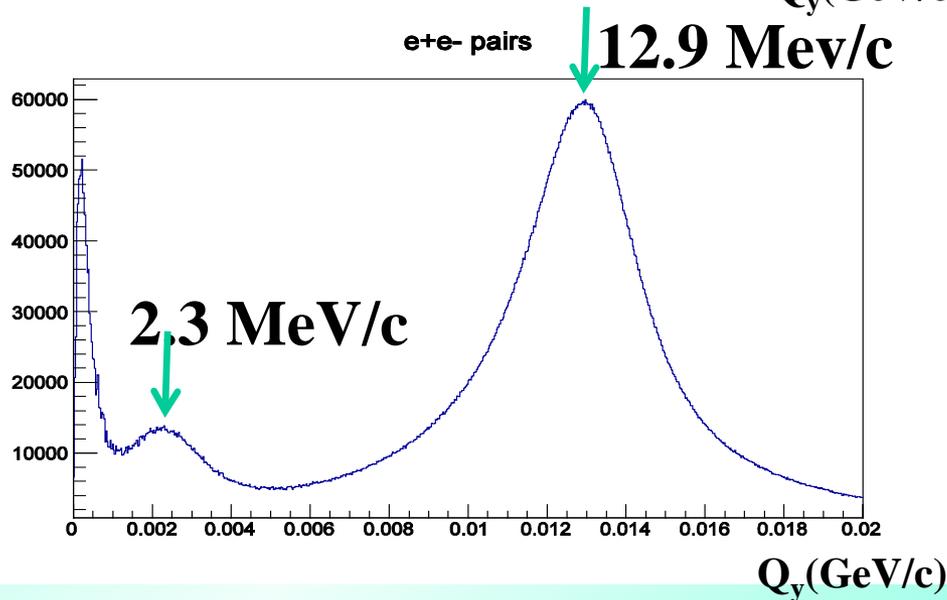
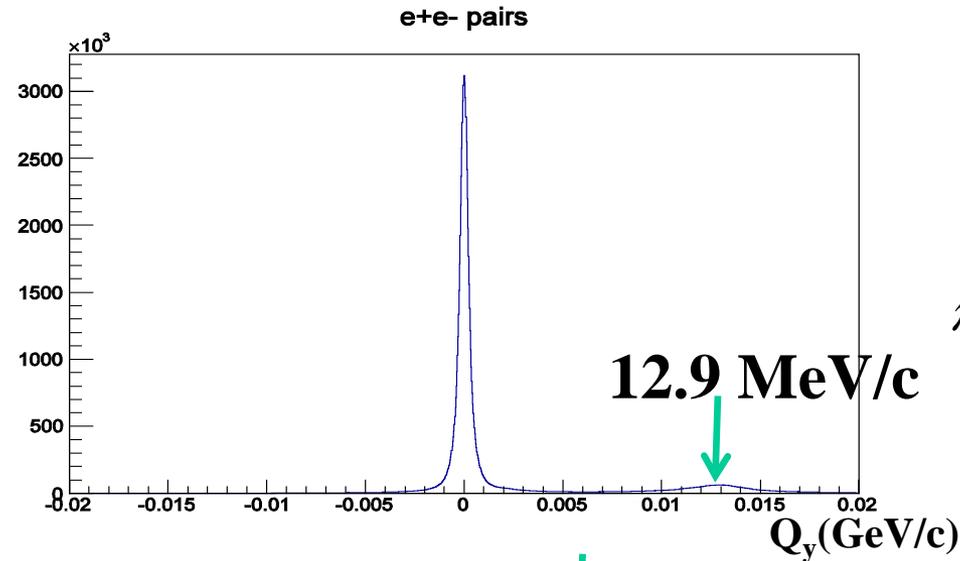
- 1- PM block Sm₂Co₁₇
- 2- PM block Sm₂Co₁₇

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

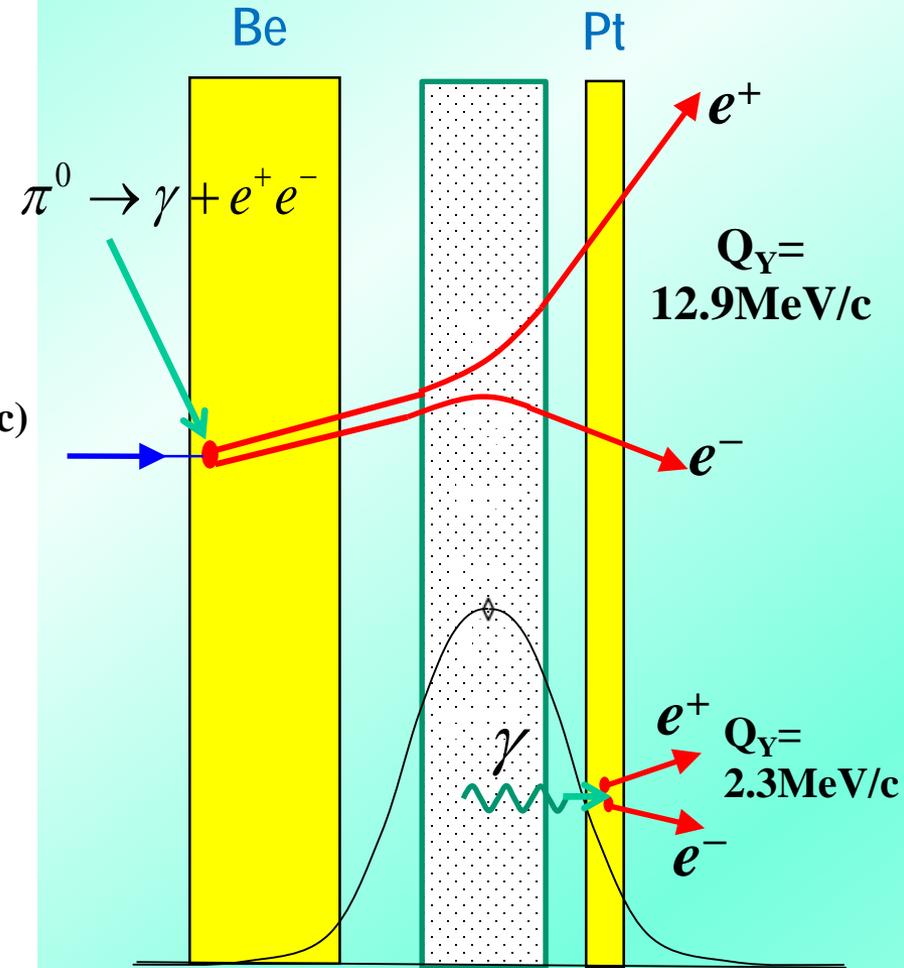


-Component: B_x [T], Integral = 24.6426 [mTm]

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

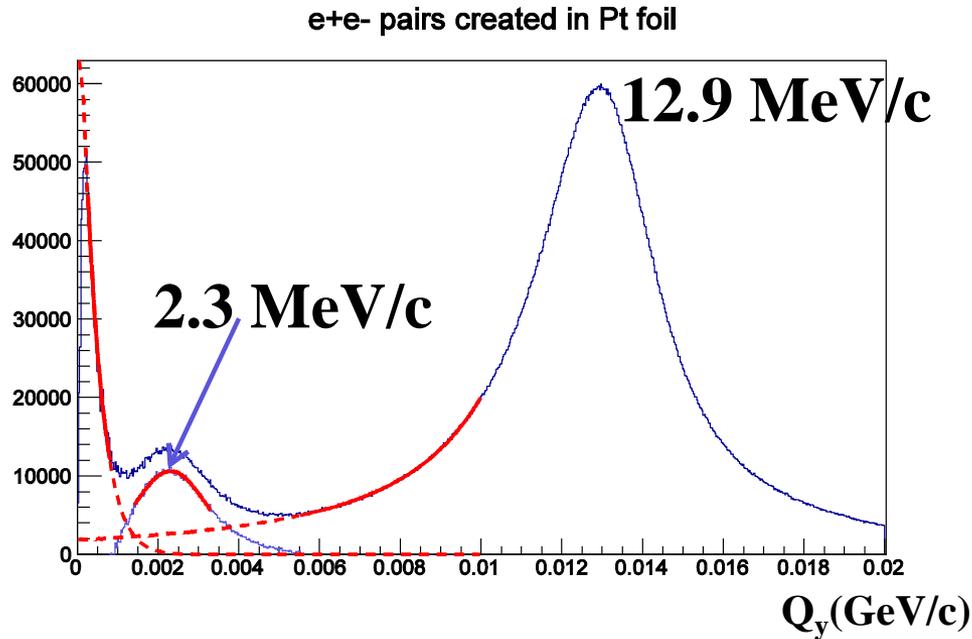


Real data

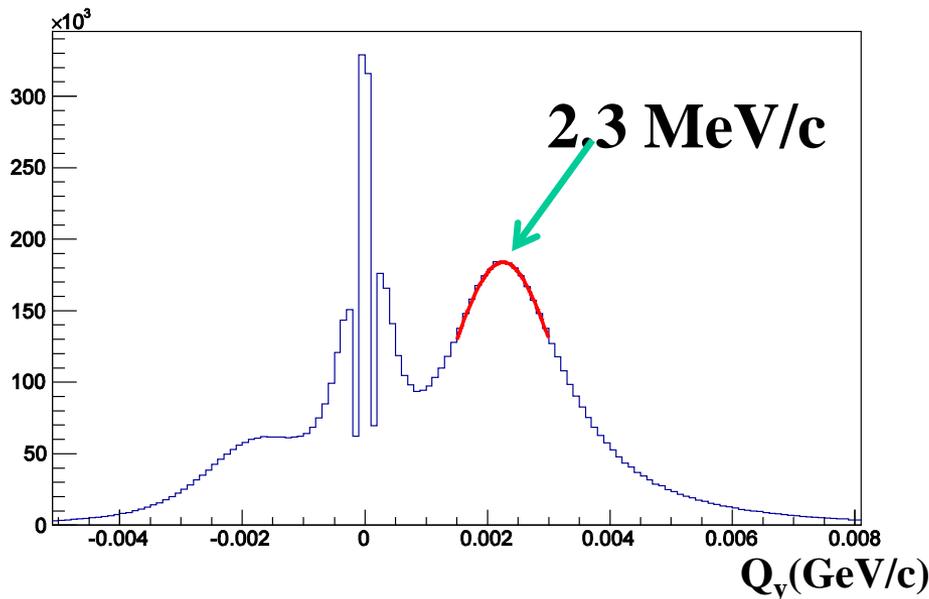


Peak at $Q_y = 2.3 \text{ MeV}/c$ evaluated after subtraction of the mirrored left side part.

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



Real Data

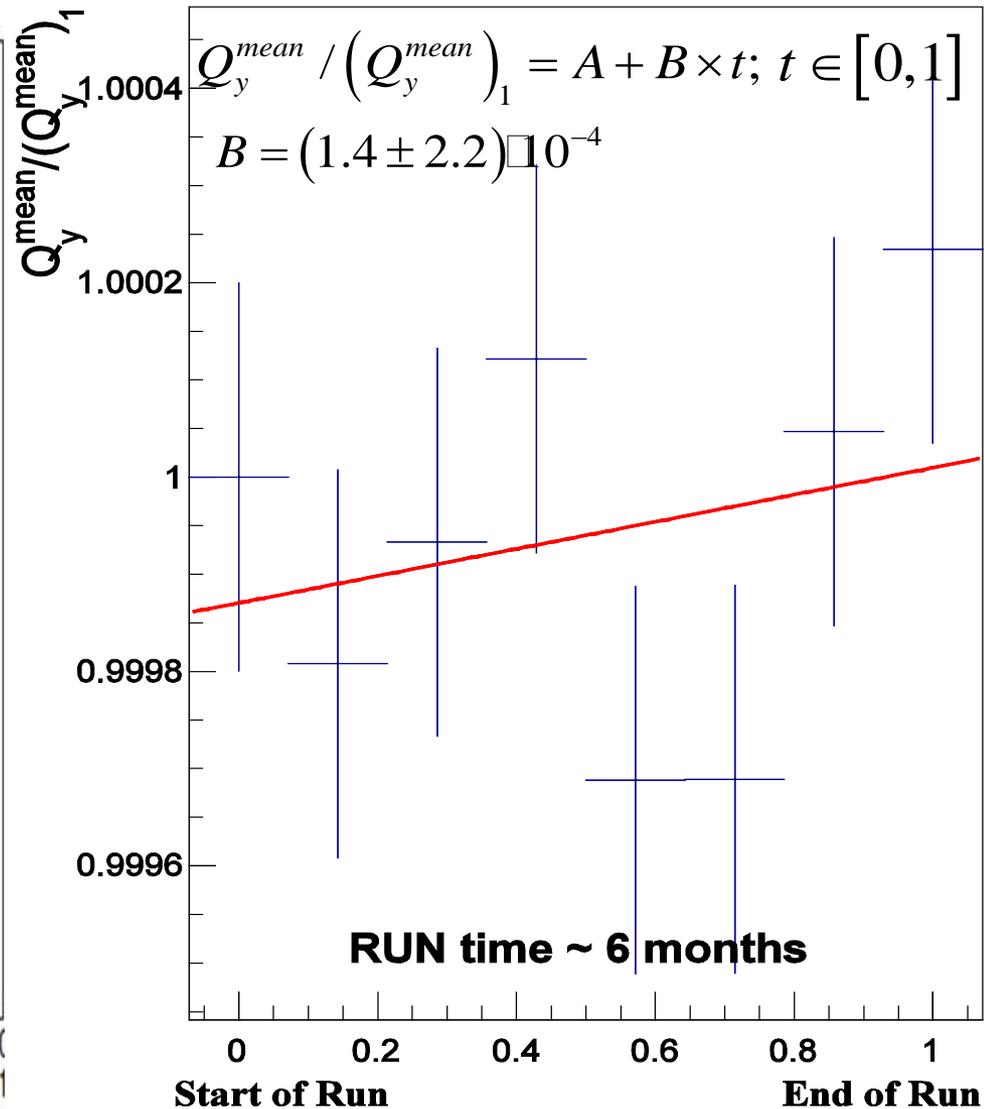
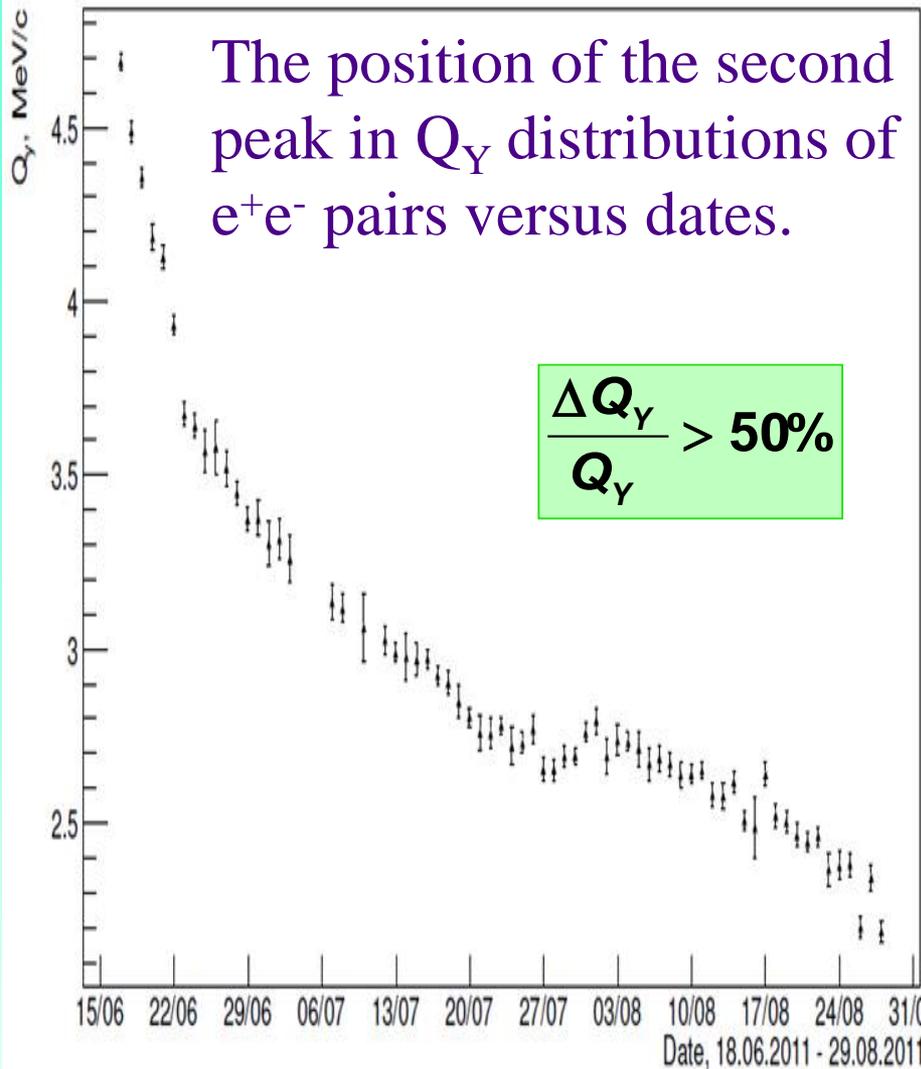


Simulation

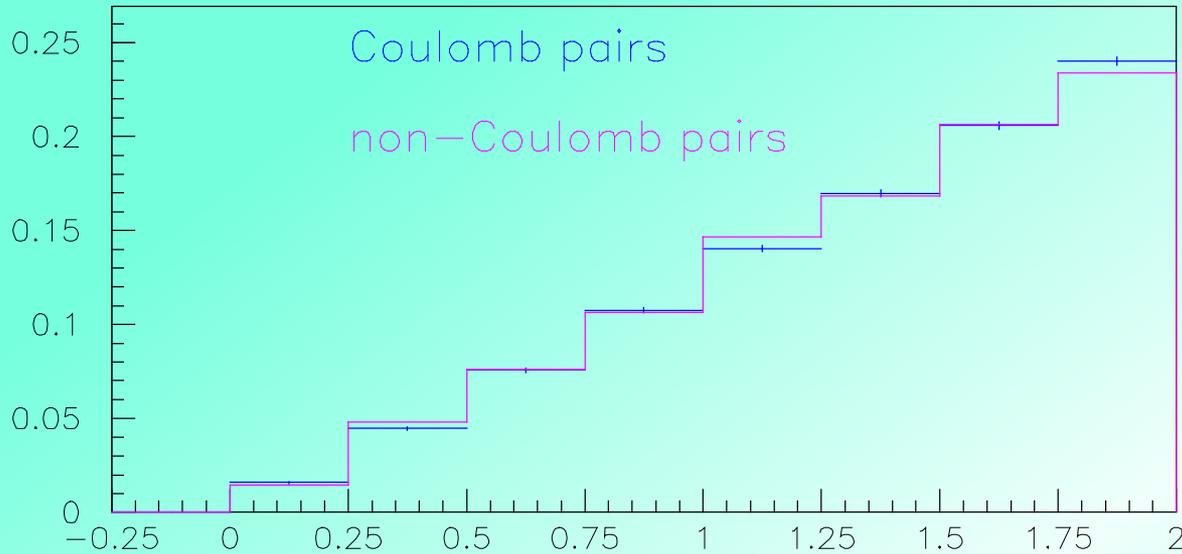
Degradation of the old magnet and the new one behavior

Old magnet (Nd-Fe-B), 2011

New magnet (Sm-Co), 2012

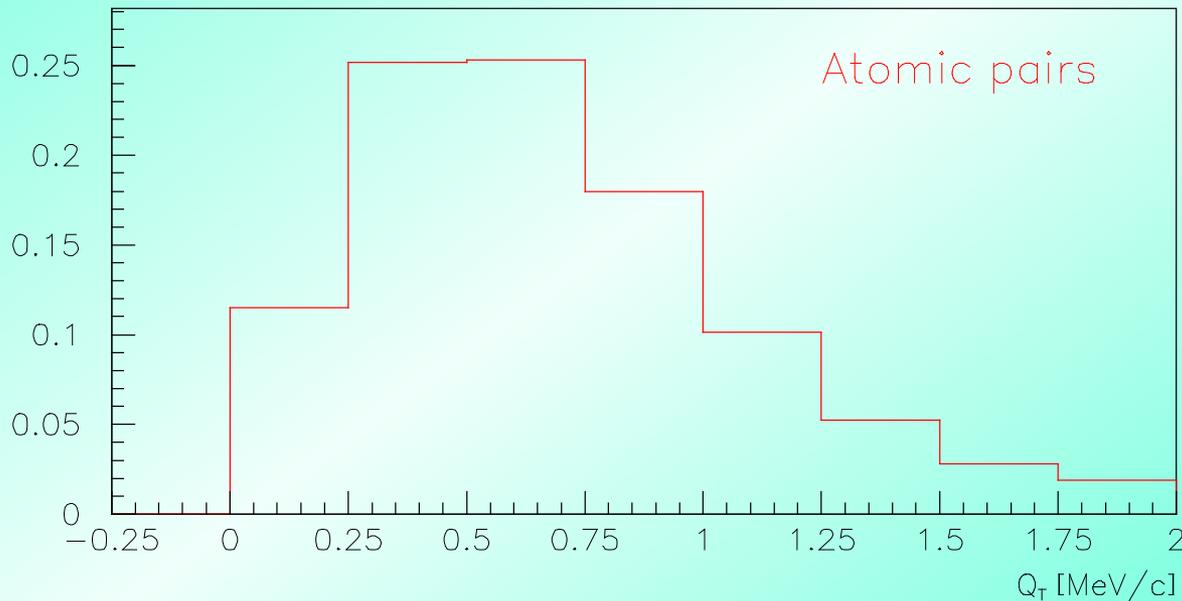


Long-lived $\pi^+\pi^-$ atom simulation



Simulated distributions of "Coulomb", "non-Coulomb" and atomic pairs over Q_T

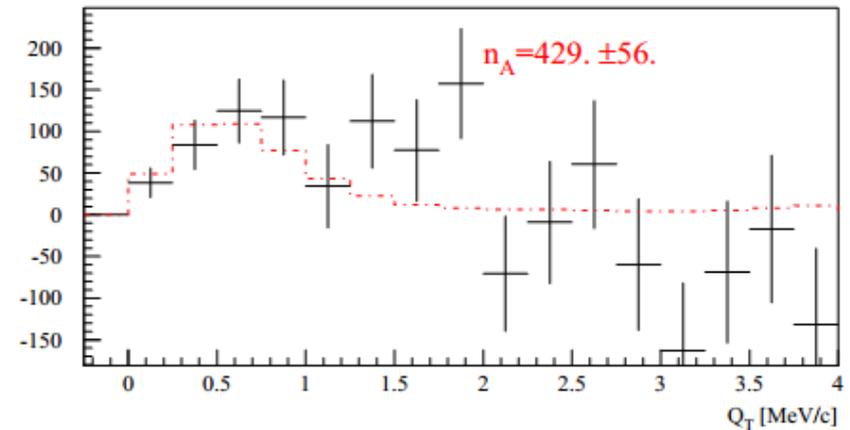
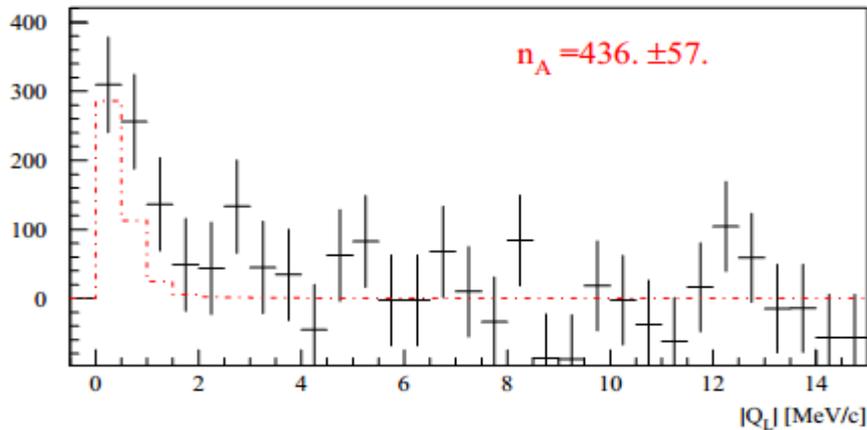
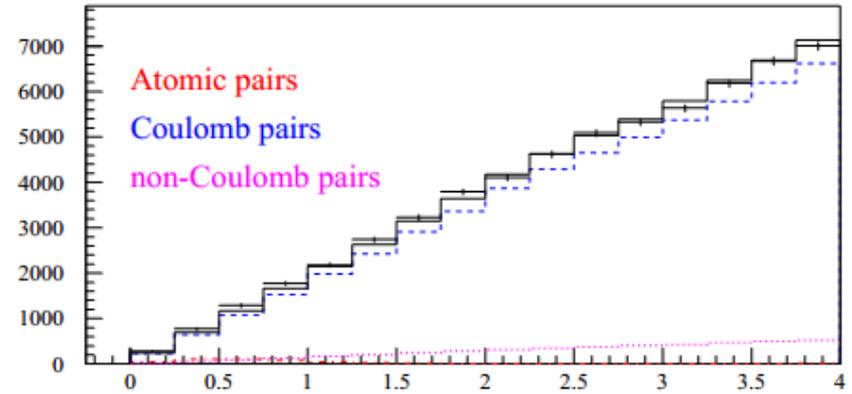
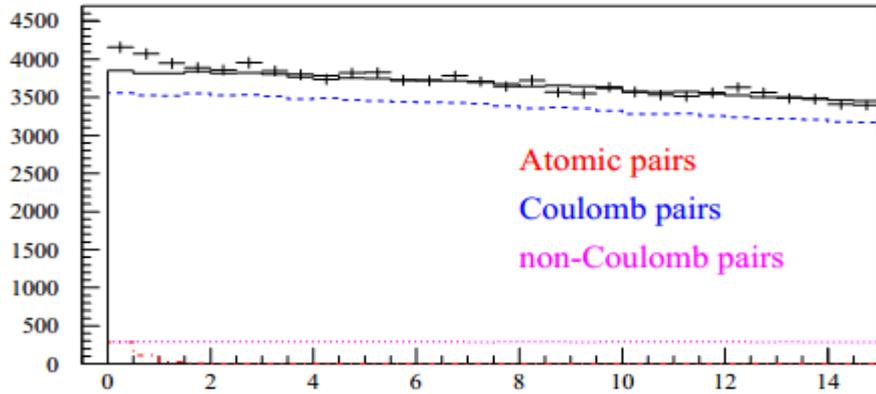
for $|Q_L| < 2 \text{ MeV}/c$



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

Observation of long-lived $\pi^+\pi^-$ atoms

Two-dimensional distribution over $|Q_L|$ Q_T , have been fitted with $\chi^2/\text{ndf} = 138/140$. Projections to $|Q_L|$ and Q_T are presented.



$|Q_L|$ for $Q_T < 2.0$ MeV/c

Q_T for $|Q_L| < 2.0$ MeV/c

Observation of long-lived $\pi^+\pi^-$ atoms

Q_T cut	n_A	n_A^{tot}	Background	χ^2/ndf
$Q_T < 2.0 \text{ MeV}/c$	436 ± 57 ($\sim 7.6\sigma$)	488 ± 64	16719	138/140
1-dimensional fit over Q_L				
$Q_T < 0.5 \text{ MeV}/c$	152 ± 29 ($\sim 5.2\sigma$)	467 ± 88	971	29/27
$Q_T < 1.0 \text{ MeV}/c$	349 ± 53 ($\sim 6.6\sigma$)	489 ± 75	3692	19/27
$Q_T < 1.5 \text{ MeV}/c$	386 ± 78 ($\sim 4.9\sigma$)	454 ± 91	9302	22/27
$Q_T < 2.0 \text{ MeV}/c$	442 ± 105 ($\sim 4.2\sigma$)	495 ± 117	16774	22/27

Observation of long-lived $\pi^+\pi^-$ atoms

Systematic errors of number of long-lived “atomic pairs”

Sources of systematic errors	σ^{syst}
Uncertainty in correction on Λ -width	4.4
Uncertainty of Platinum foil thickness	22
Total	23

$$n_A^L = 436 \pm 57(\text{stat}) \pm 23(\text{syst}) = 436 \pm 61(\text{tot})$$

Expected number $\rightarrow 653 \pm 110$ (453 \div 845)

Experiment DIRAC at SPS CERN

In 2013 DIRAC setup has been dismantled from the experimental hall of PS CERN. All detectors are stored for using in the future experiment.

*DIRAC collaboration is planning to continue investigation of π^-K^+ , π^+K^- and $\pi^+\pi^-$ atoms at SPS accelerator at CERN. The correspondent gains in production rates of these atoms at SPS relative to PS (450 GeV vs. 24 GeV) are **18, 24 and 12**. This allows to increase significantly the collected data and to check the precise prediction of Low-Energy QCD at a higher accuracy. Now the collaboration is planning to submit the Letter of Intend for study πK and $\pi^+\pi^-$ atoms at SPS to SPSC CERN.*

**Thank you
for your attention!**