DIRAC status

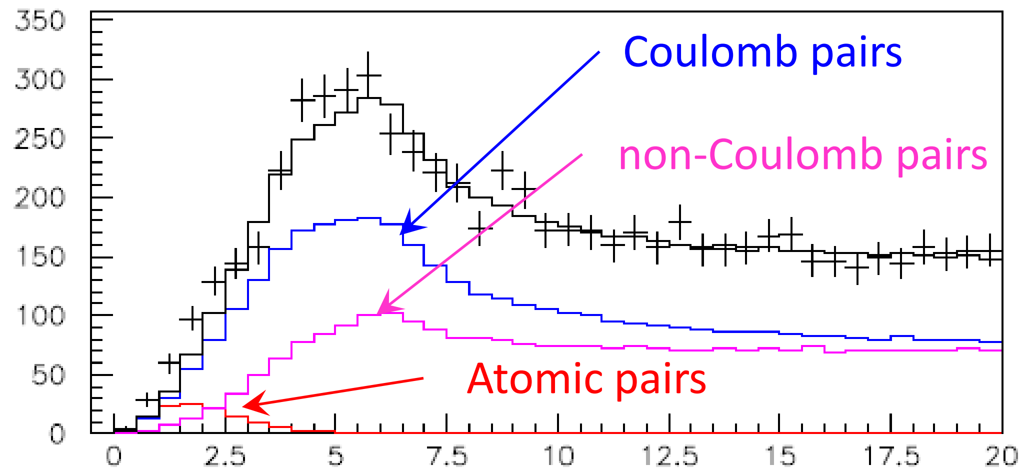
21. October 2011

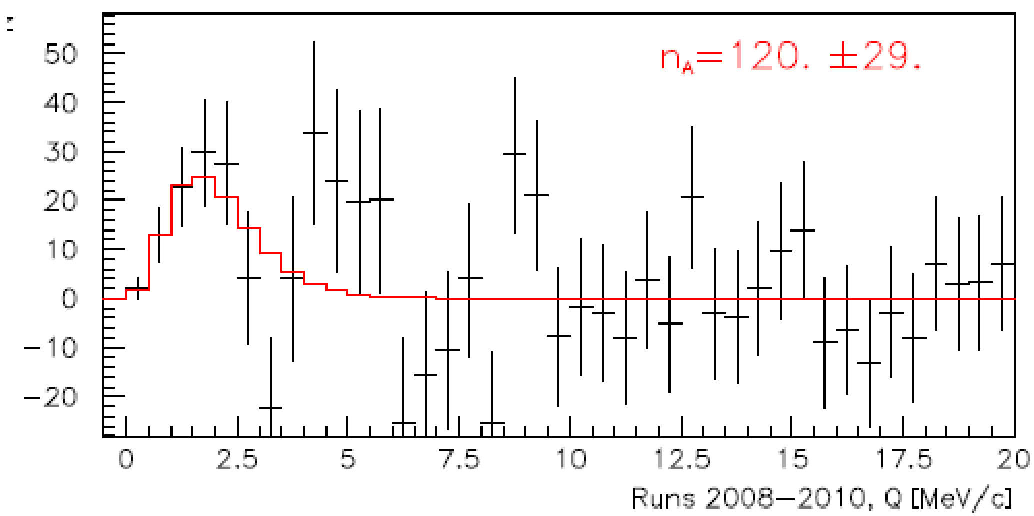
Leonid Nemenov

- **π^+K^-- and π^-K^+-atoms**
- **$\pi^+\pi^-$-atoms ($A_{2\pi}$)**
- **Run 2011**
- **Future magnet**
- **$A_{2\pi}$ level scheme, Stark effect and energy splitting measurement**

I Status of π^+K^--atoms

A. Benelli, V. Yazkov



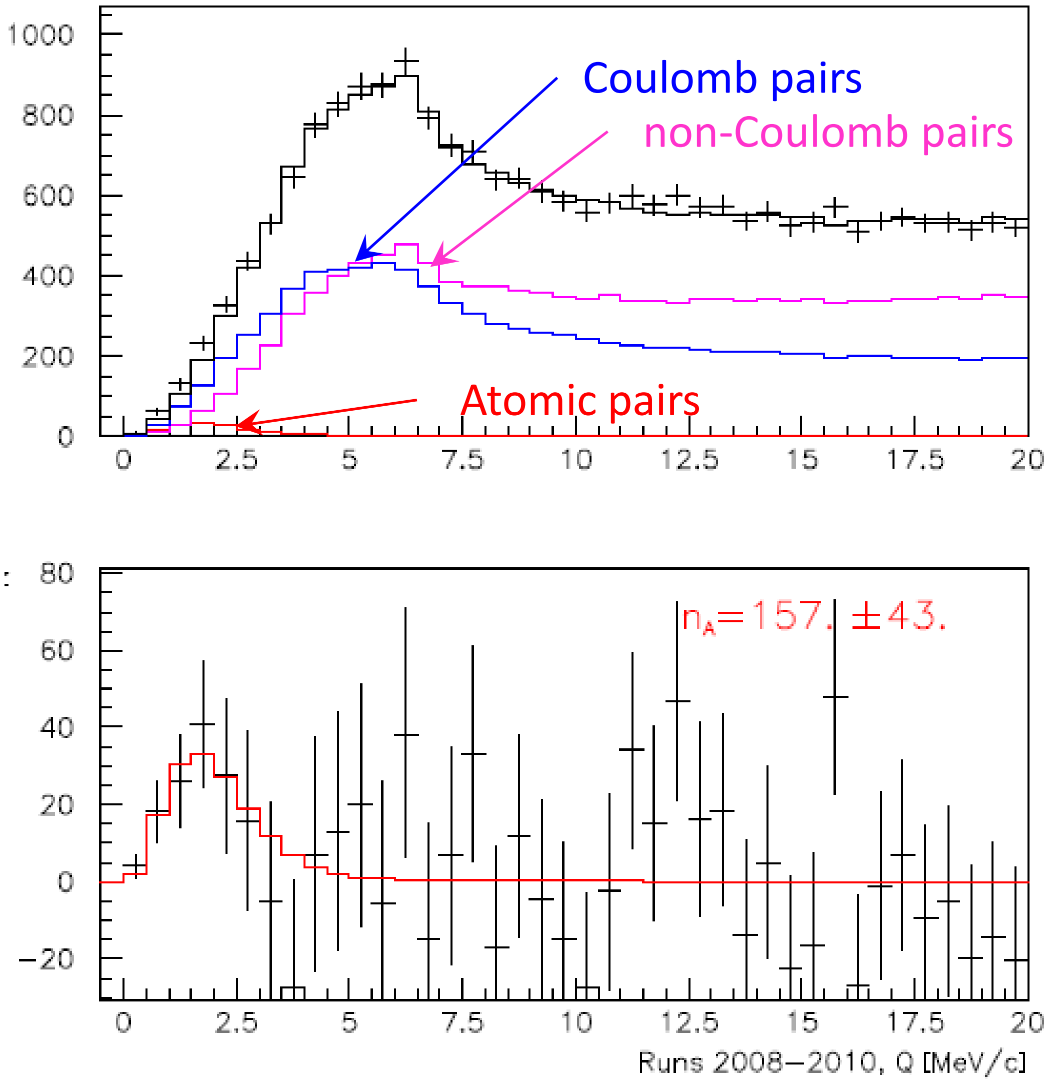


Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

Q – relative momentum in the πK c.m.s.

II Status of $\pi^- K^+$ -atoms

A. Benelli, V. Yazkov

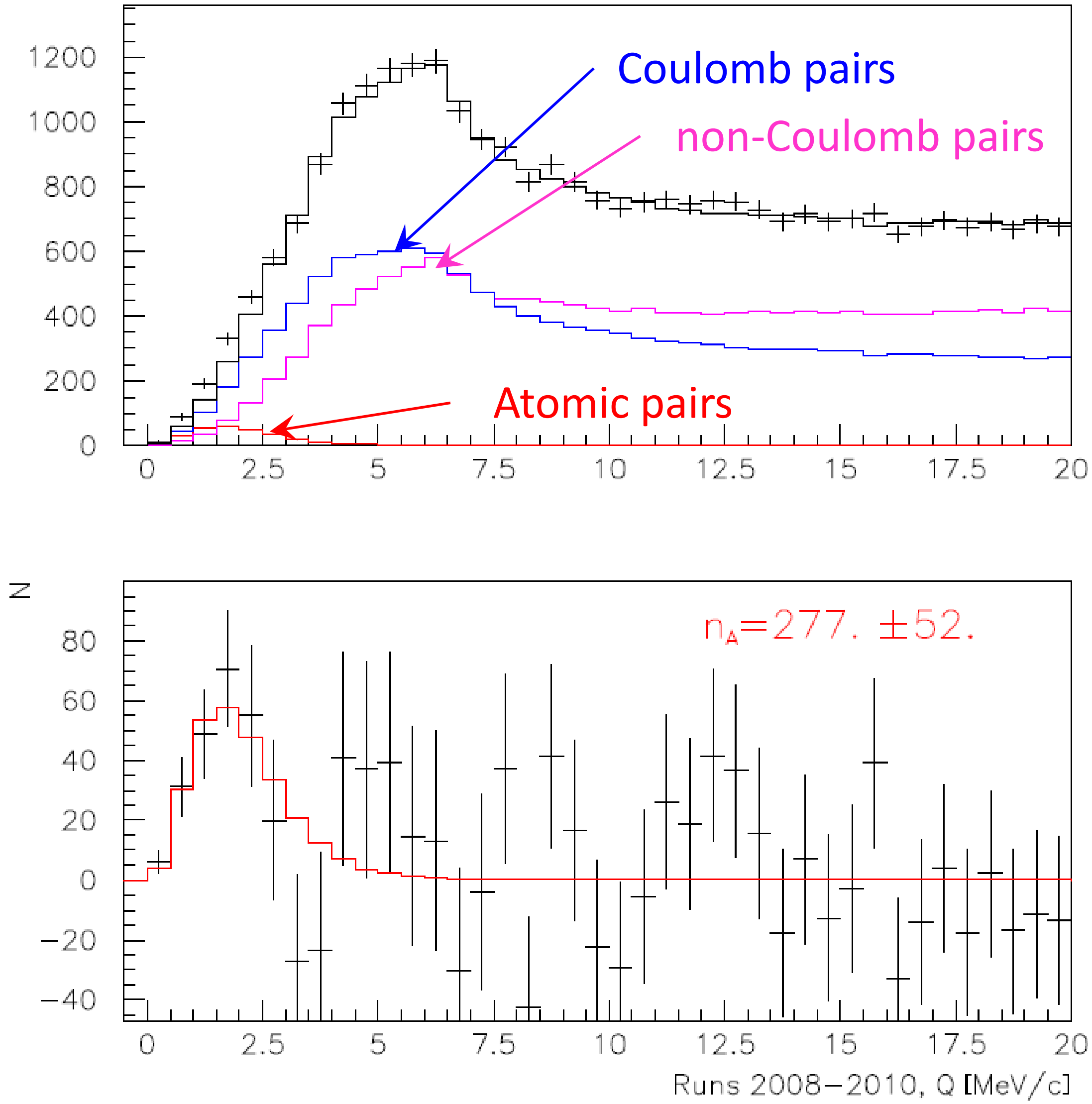


Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

Q – relative momentum in the πK c.m.s.

III. The status of π^-K^+ and π^+K^- atoms

A. Benelli, V. Yazkov

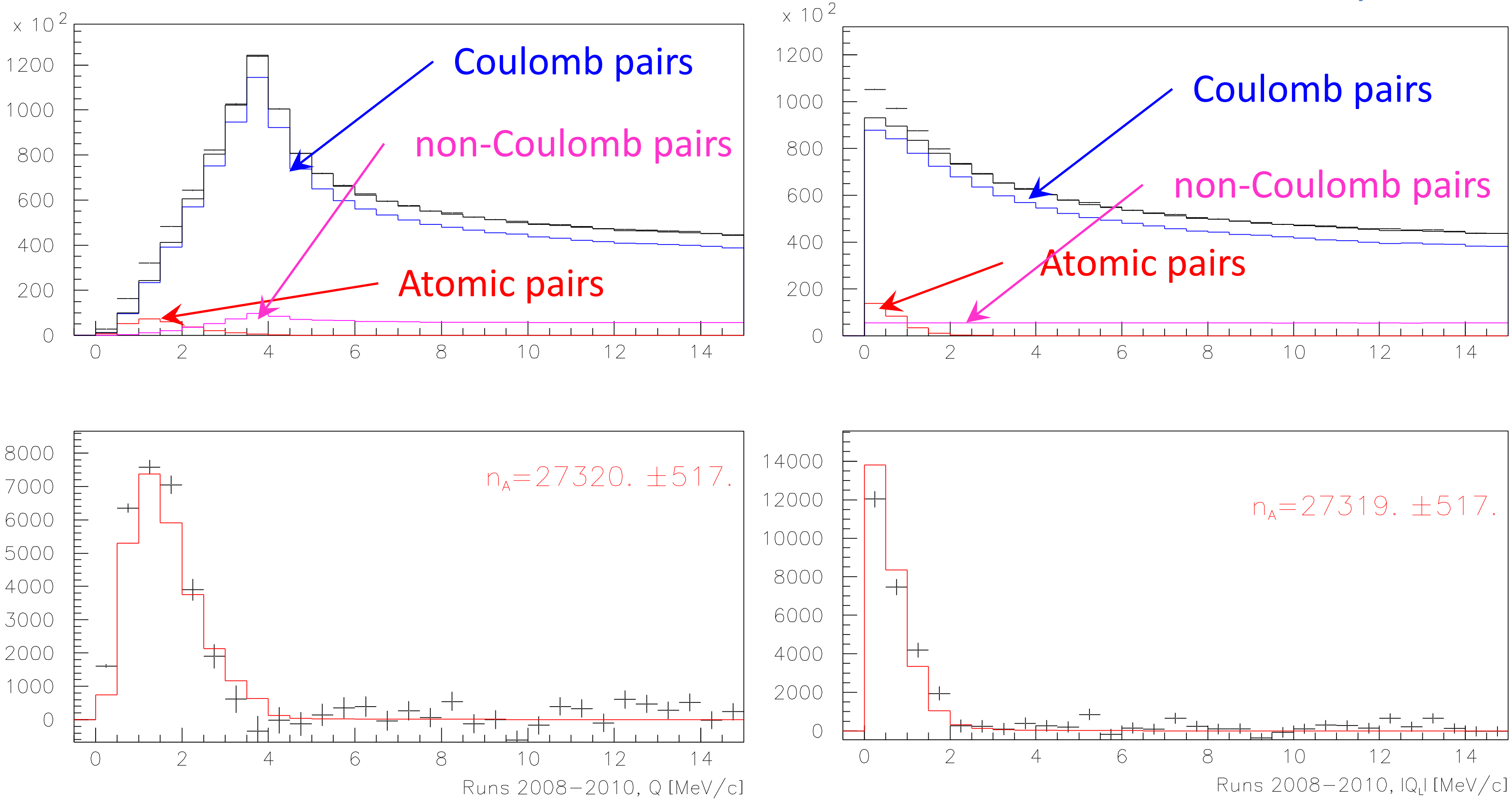


Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

Q – relative momentum in the πK c.m.s.

IV Status $\pi^+\pi^-$-atoms

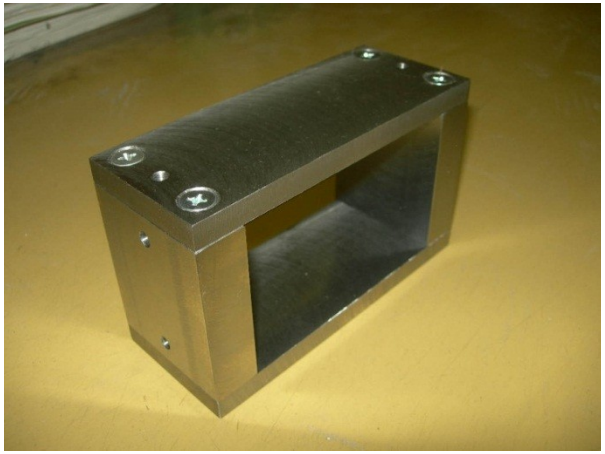
A. Benelli, V. Yazkov

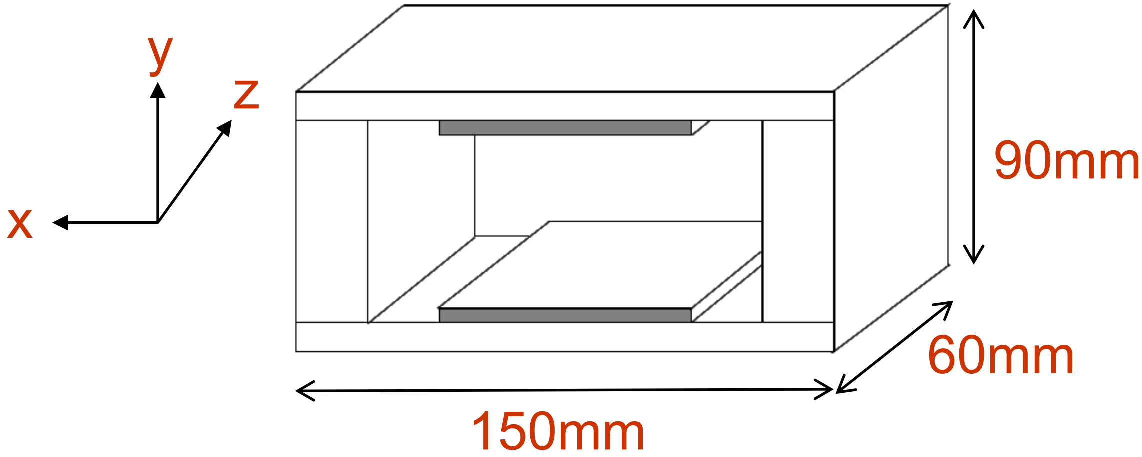


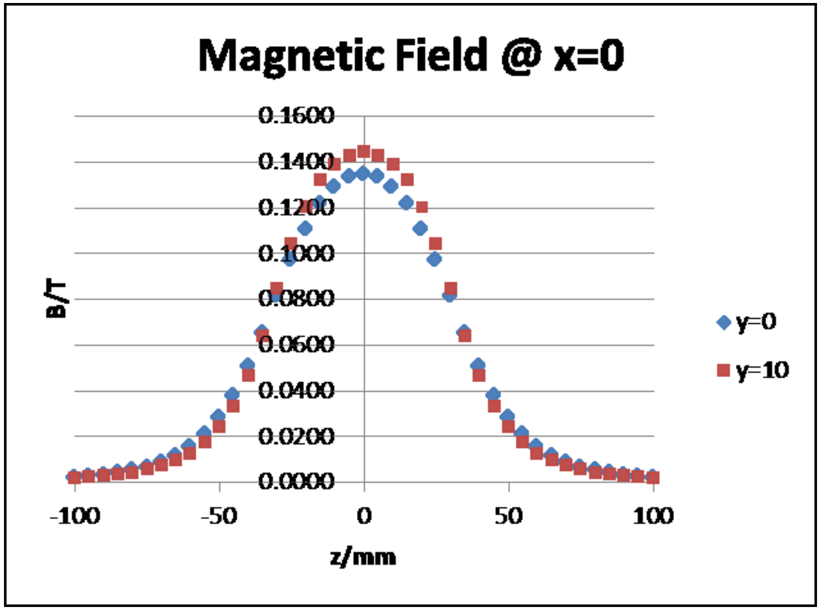
Run 2008-2010, statistics with low and medium background (⅔ of all statistics). Point-like production of all particles. The e^+e^- background was not subtracted.

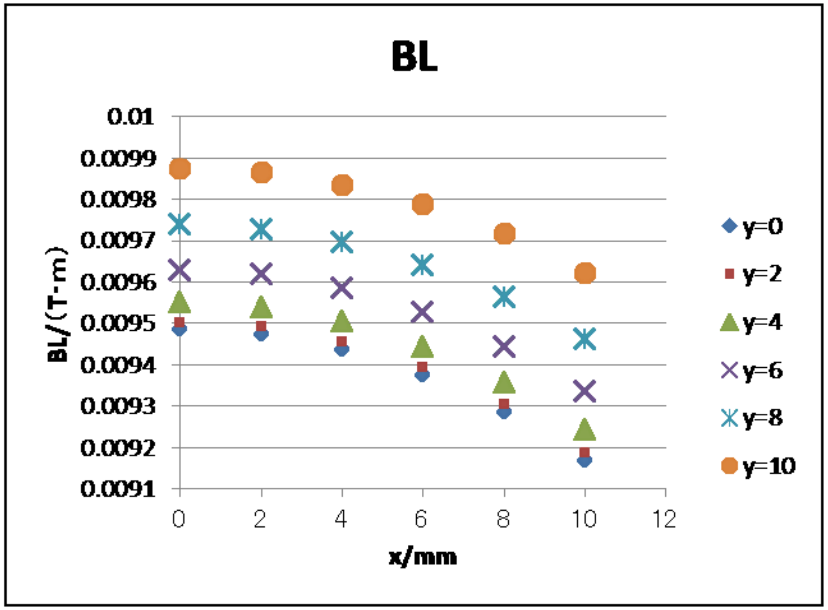
V Status of 2011 run

Tokyo Metropolitan University & Kyoto University





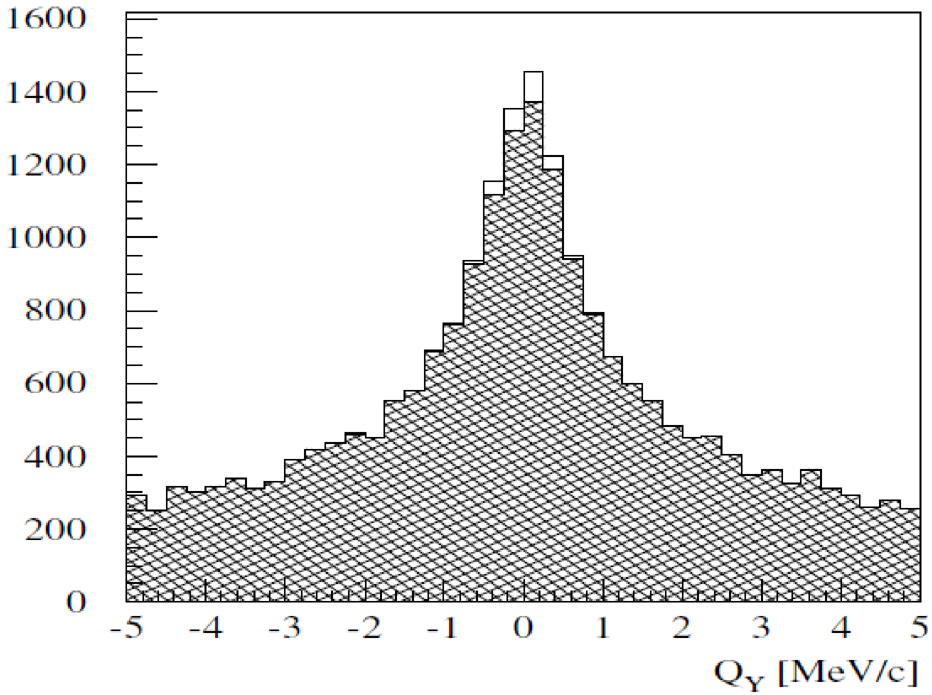




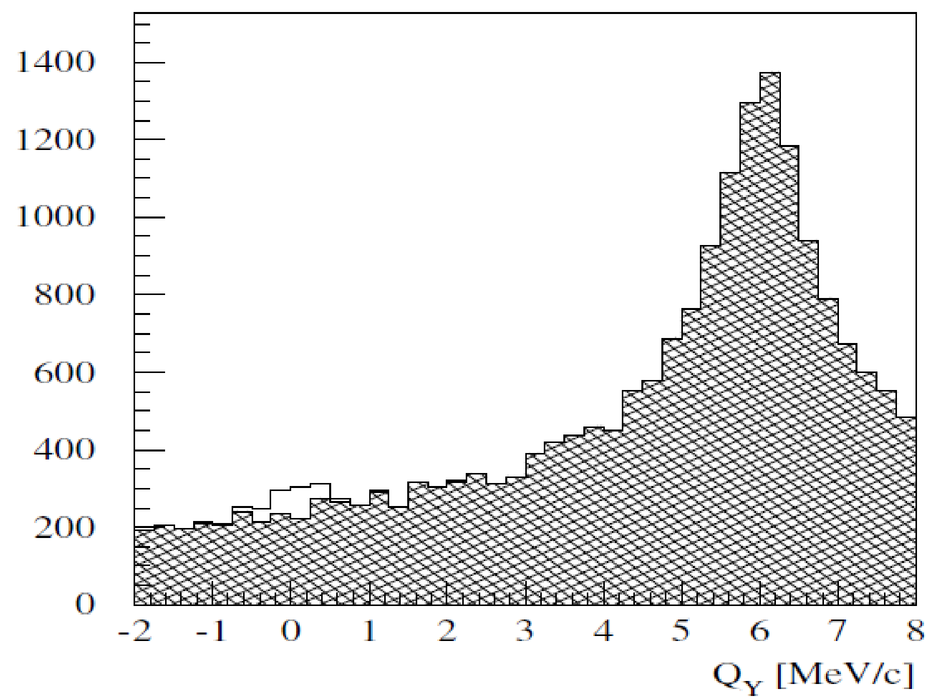
Neodymium magnetic piece=70x60x5mm^3: Gap=60mm; BL=0.01Tm
Time of delivery to CERN: before 4 May 2011

Simulation of long-lived $A_{2\pi}$ observation

V. Yazkov



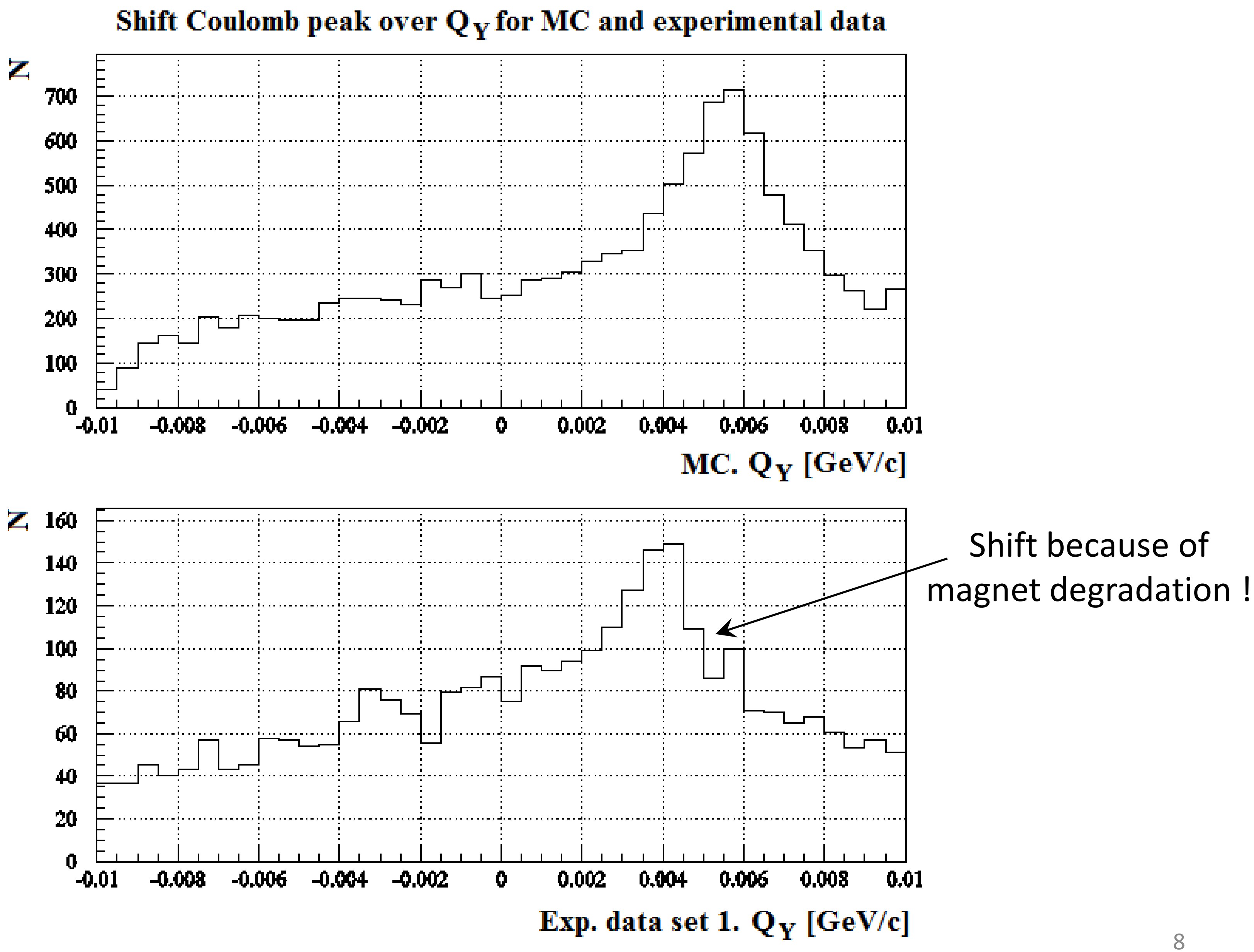
Without magnet



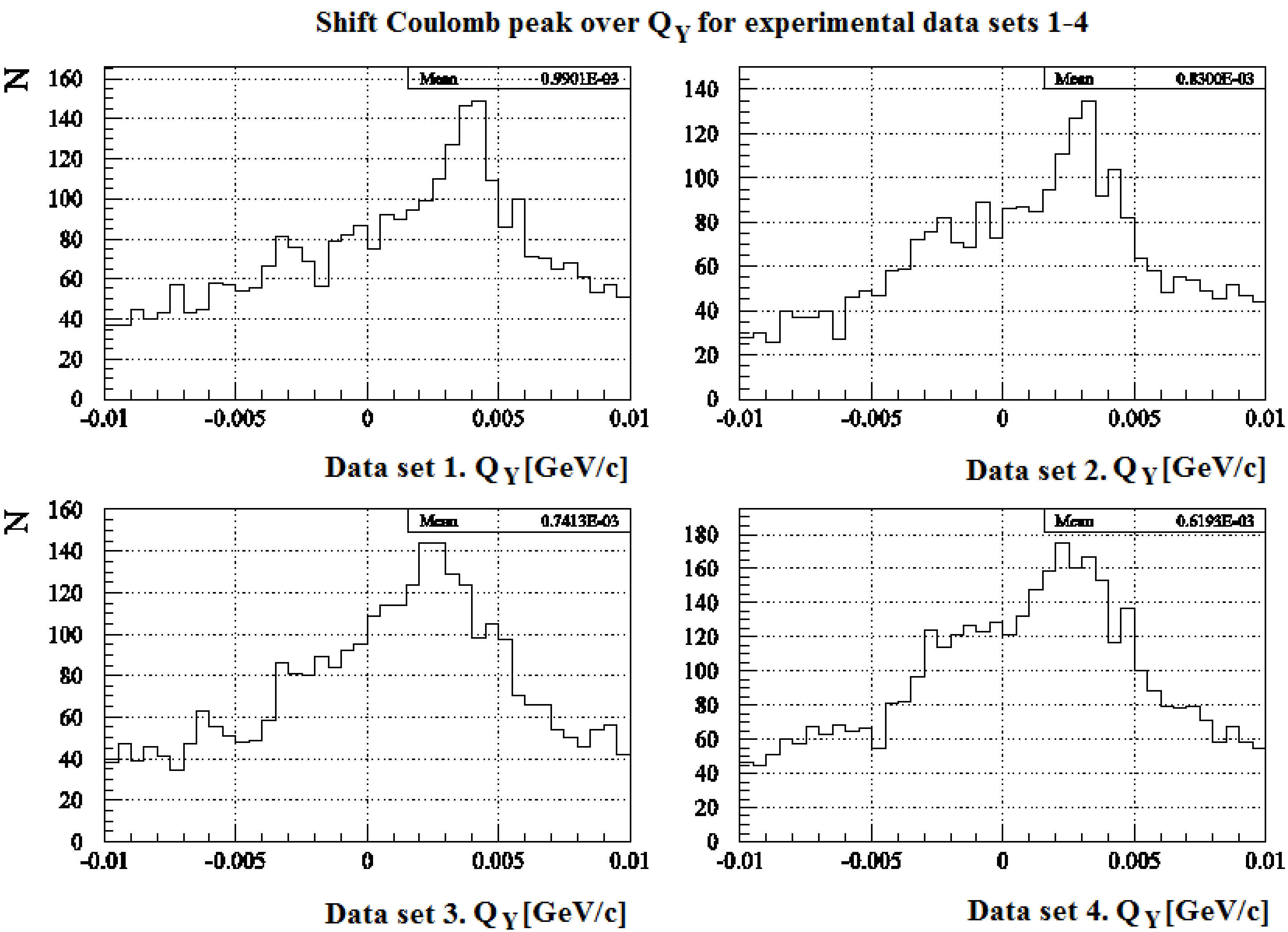
With magnet after Be target

Simulated distribution of $\pi^+\pi^-$ pairs over Q_Y with criteria: $|Q_X| < 1$ MeV/c, $|Q_L| < 1$ MeV/c. "Atomic pairs" from long-lived atoms (light area) above background (hatched area) produced in Beryllium target.

Coulomb peak of $\pi^+\pi^-$

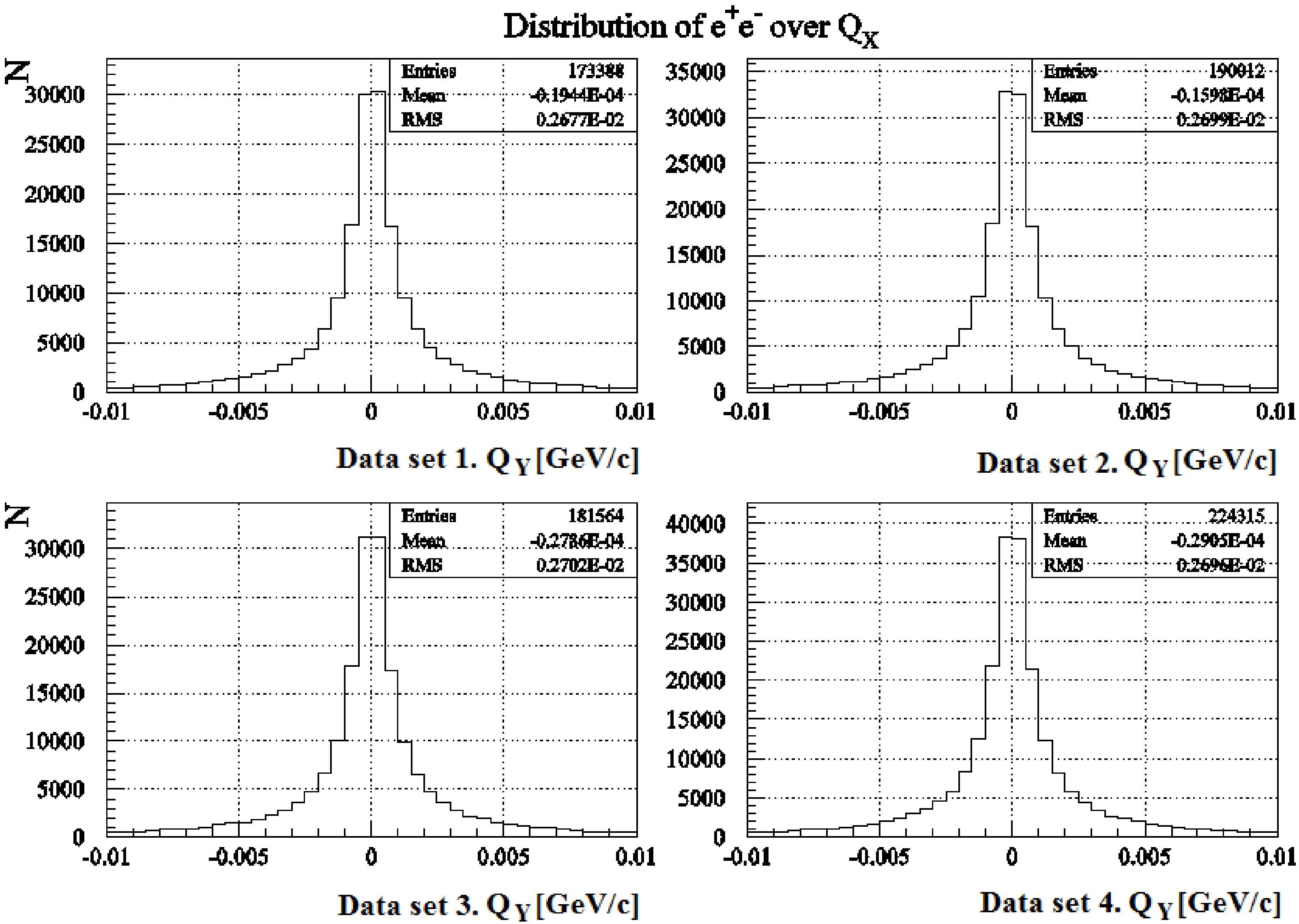


Shift of Q_y (June-August) $\pi^+\pi^-$ data



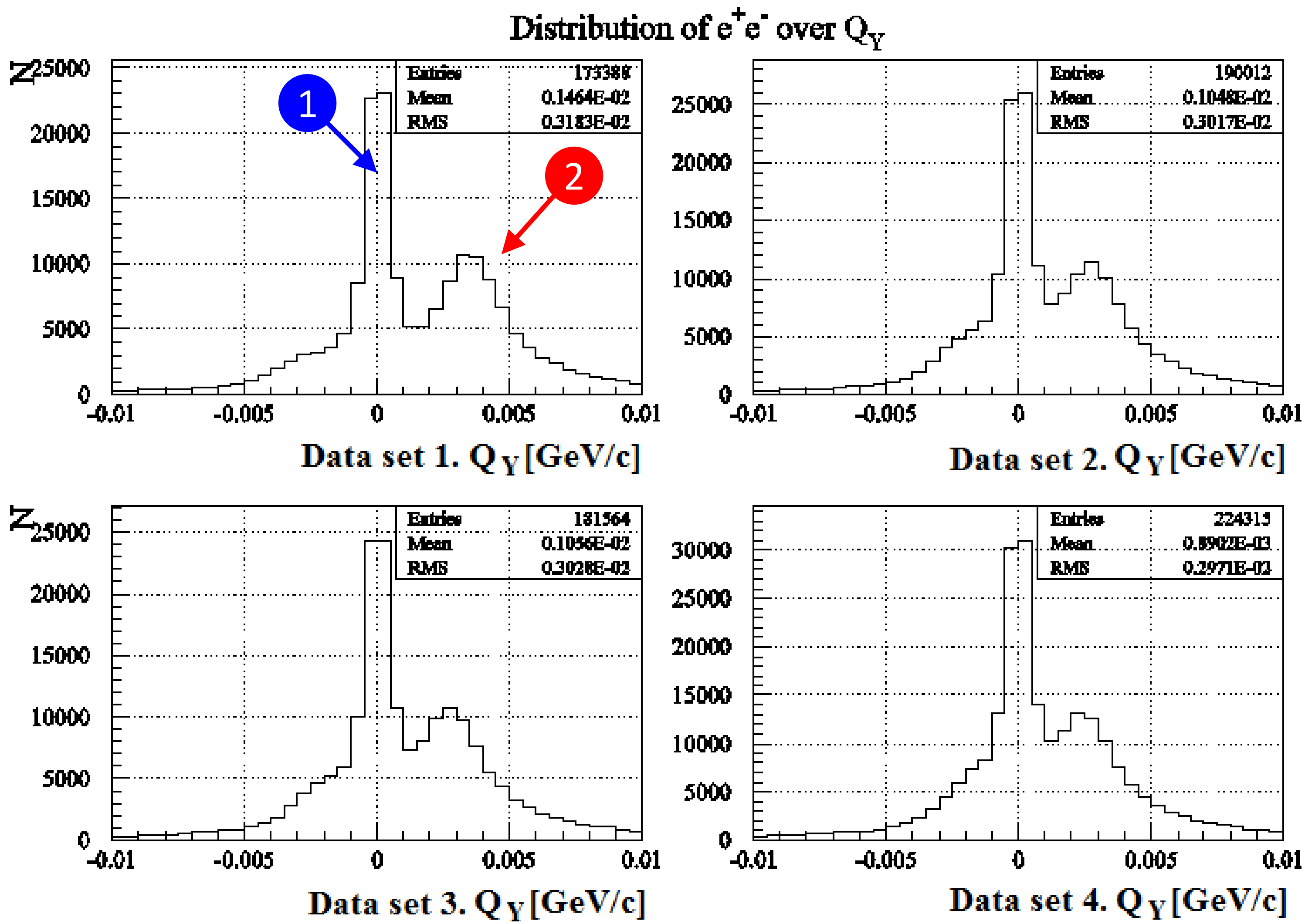
Q_x distribution (B_x=0)

F. Takeutchi, V. Yazkov



Shift of Q_y (June-August) e^+e^- data

F. Takeutchi, V. Yazkov

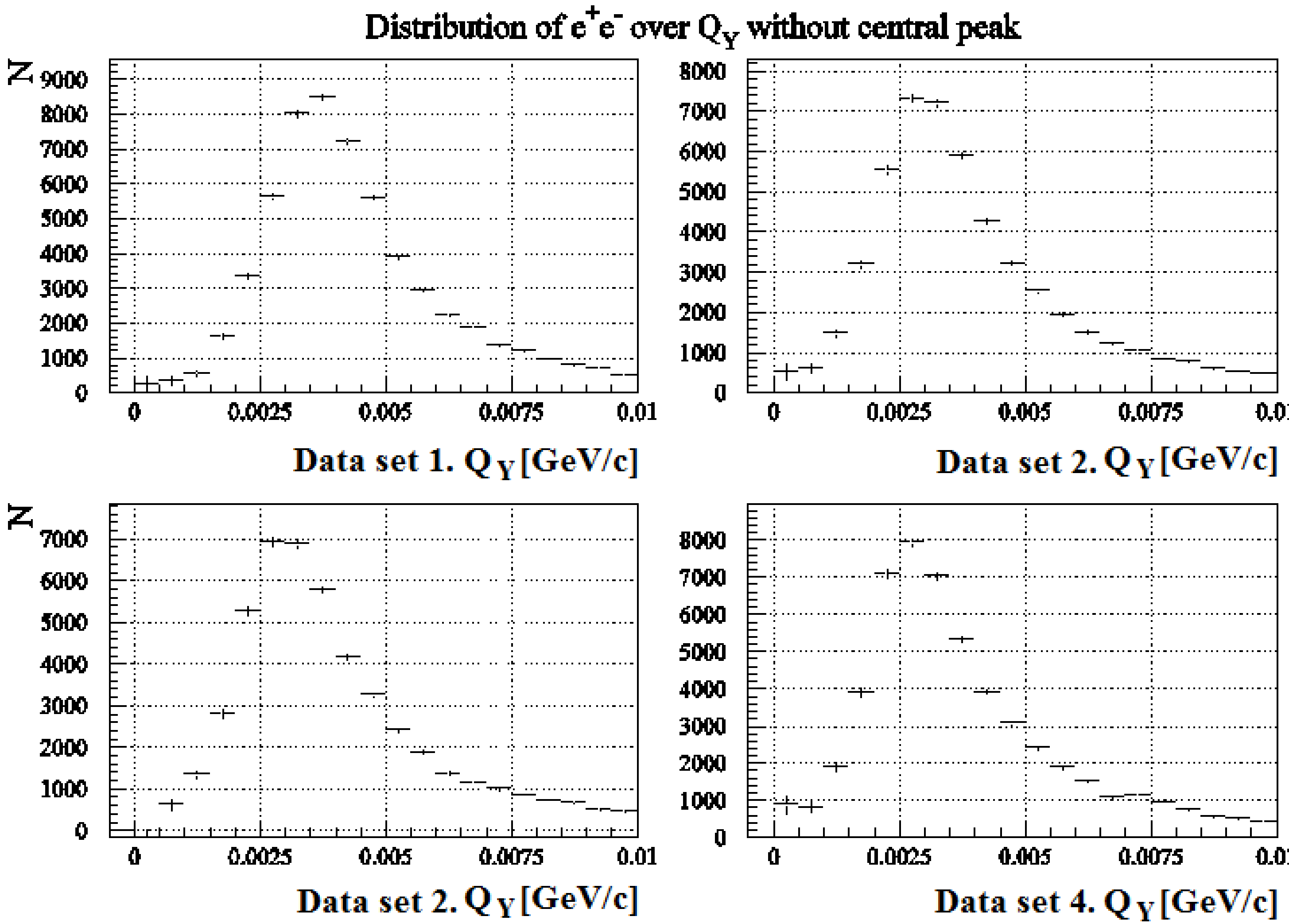


1 Pairs generated after magnet

2 Pairs generated on Be target before magnet

Shift of Q_y (June-August) e^+e^- data without central peak

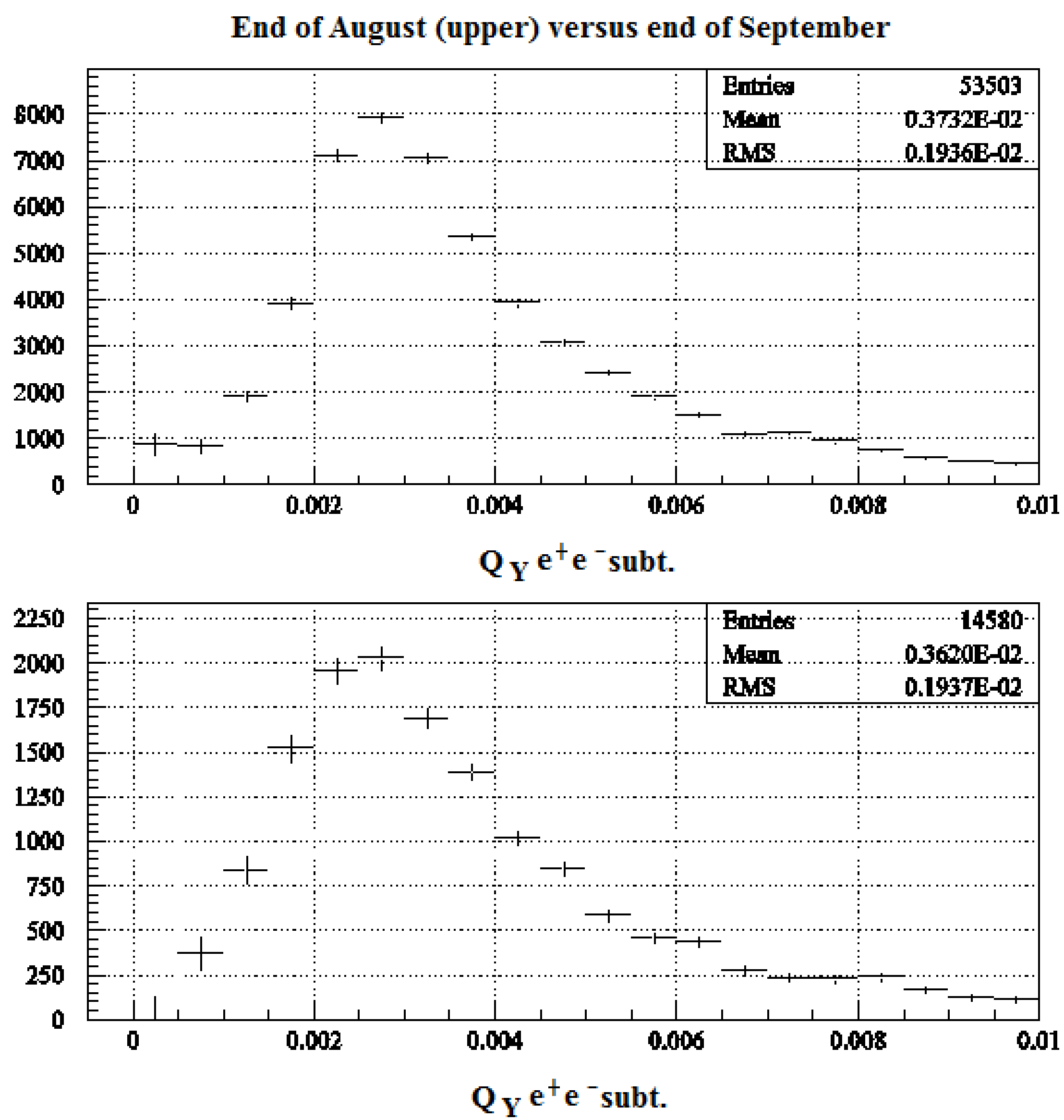
F. Takeutchi, V. Yazkov



e^+e^- generated on Be target before magnet

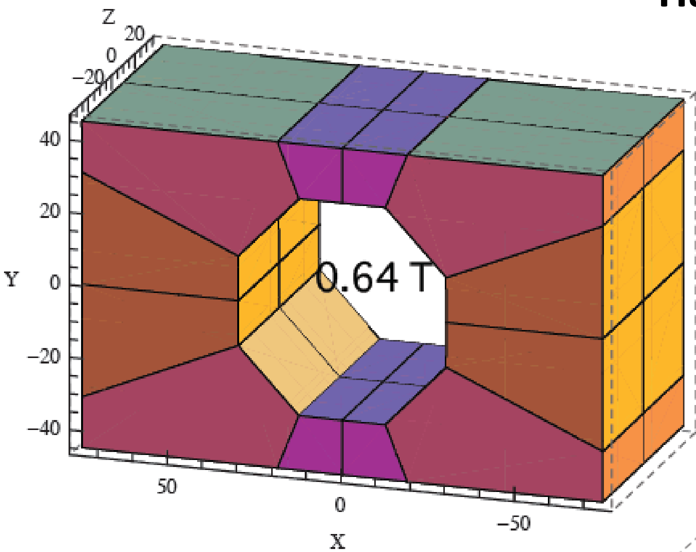
Shift of Q_y (August-September) e^+e^- data without central peak

F. Takeutchi, V. Yazkov



VI STATUS OF THE FUTURE MAGNET

Y. Iwashita



150x90x70; ~7.4 Kg.

Halbach configuration

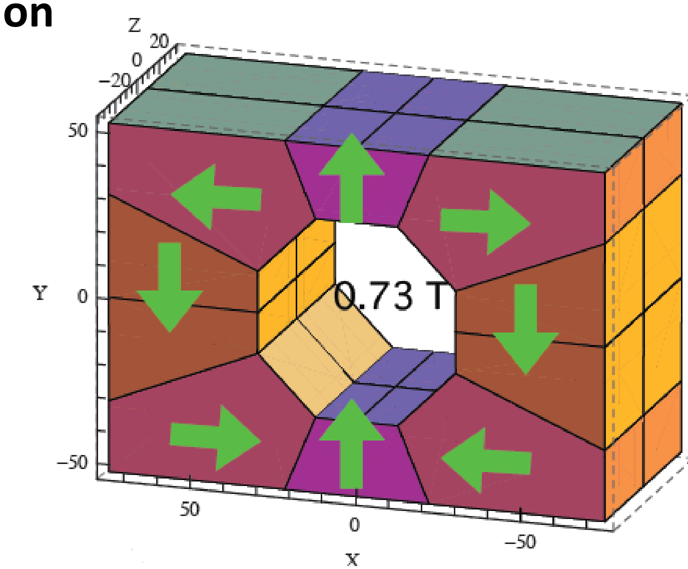
NdBFe

or

SmCo

60 x 60 bore

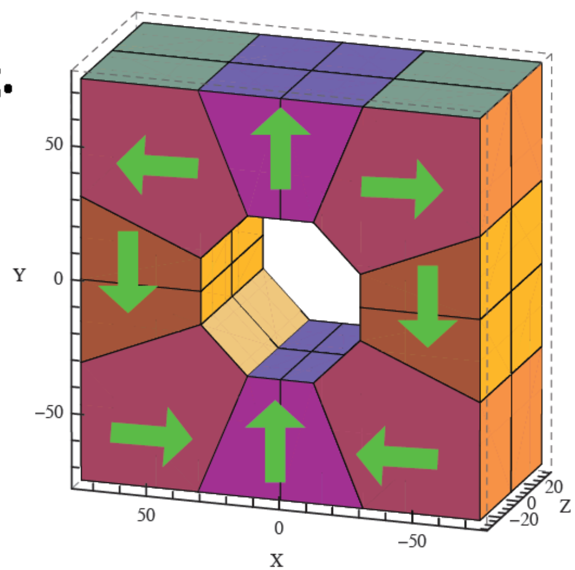
flat

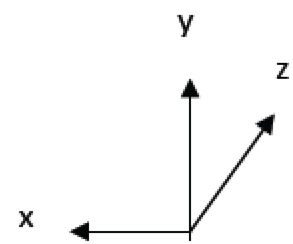


150x105x70; ~8.7 Kg.

B = 0.89 T

ρ ~ 7.7 g/cm³



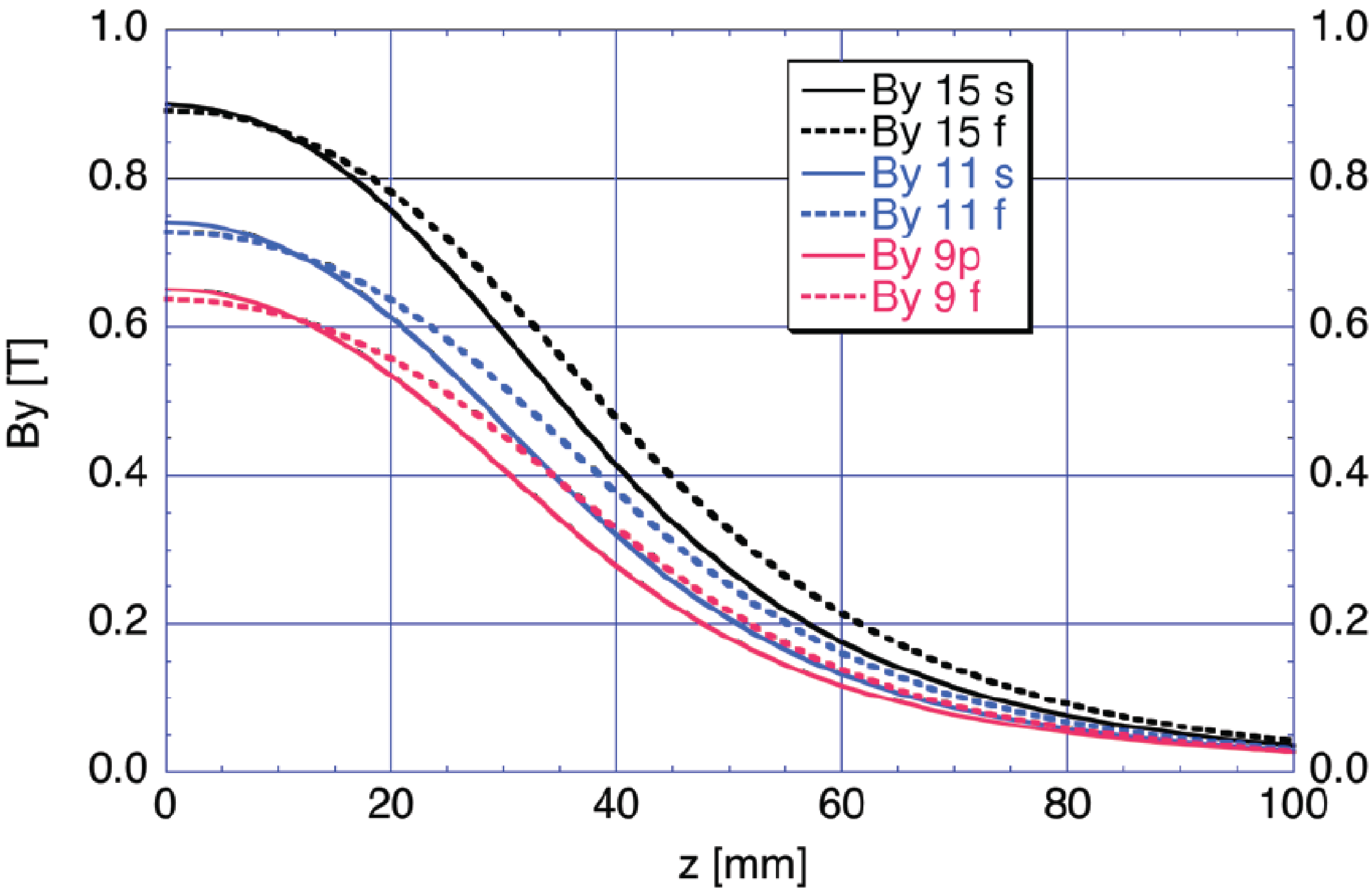


150x150x70; ~13.0 Kg.

The magnets cost about 17000 $. The fabrication time is about 65 days.

By along z-axis

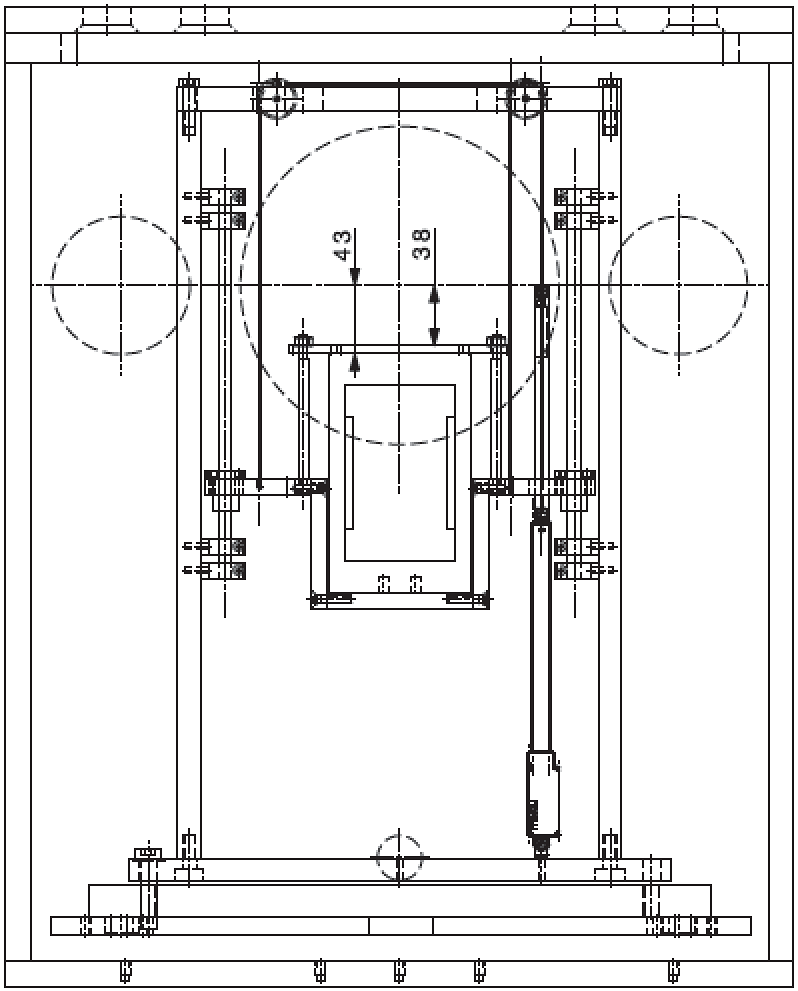
Y. Iwashita



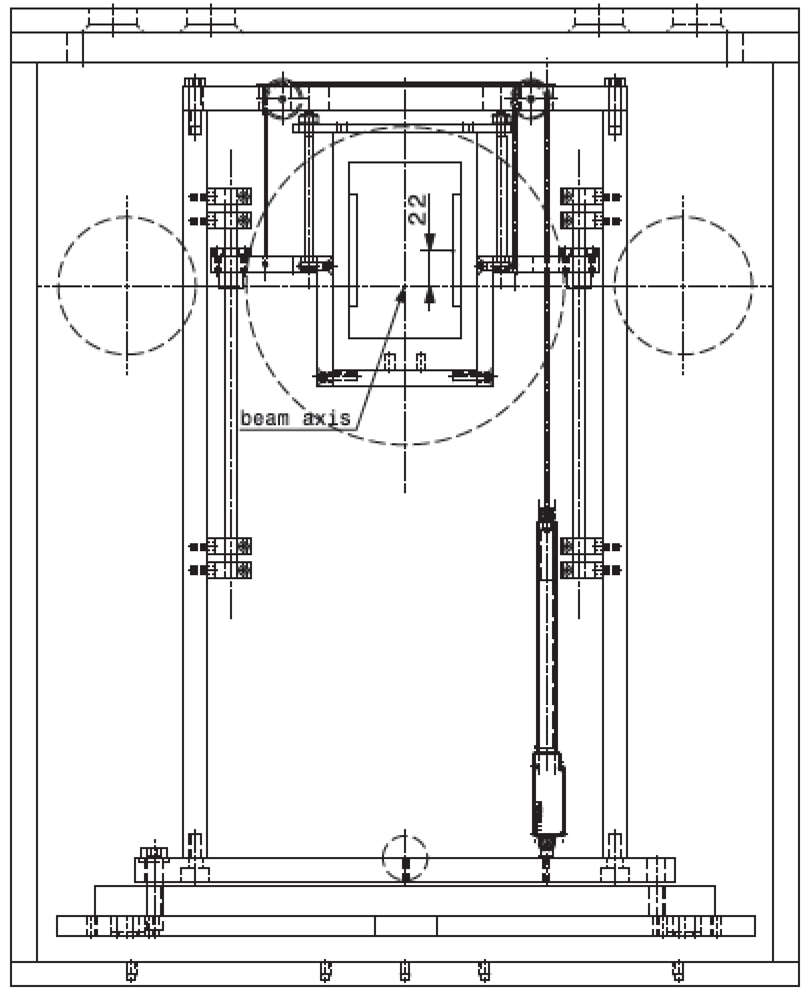
Current Magnet Holder

V. Brekhovskikh

lower position



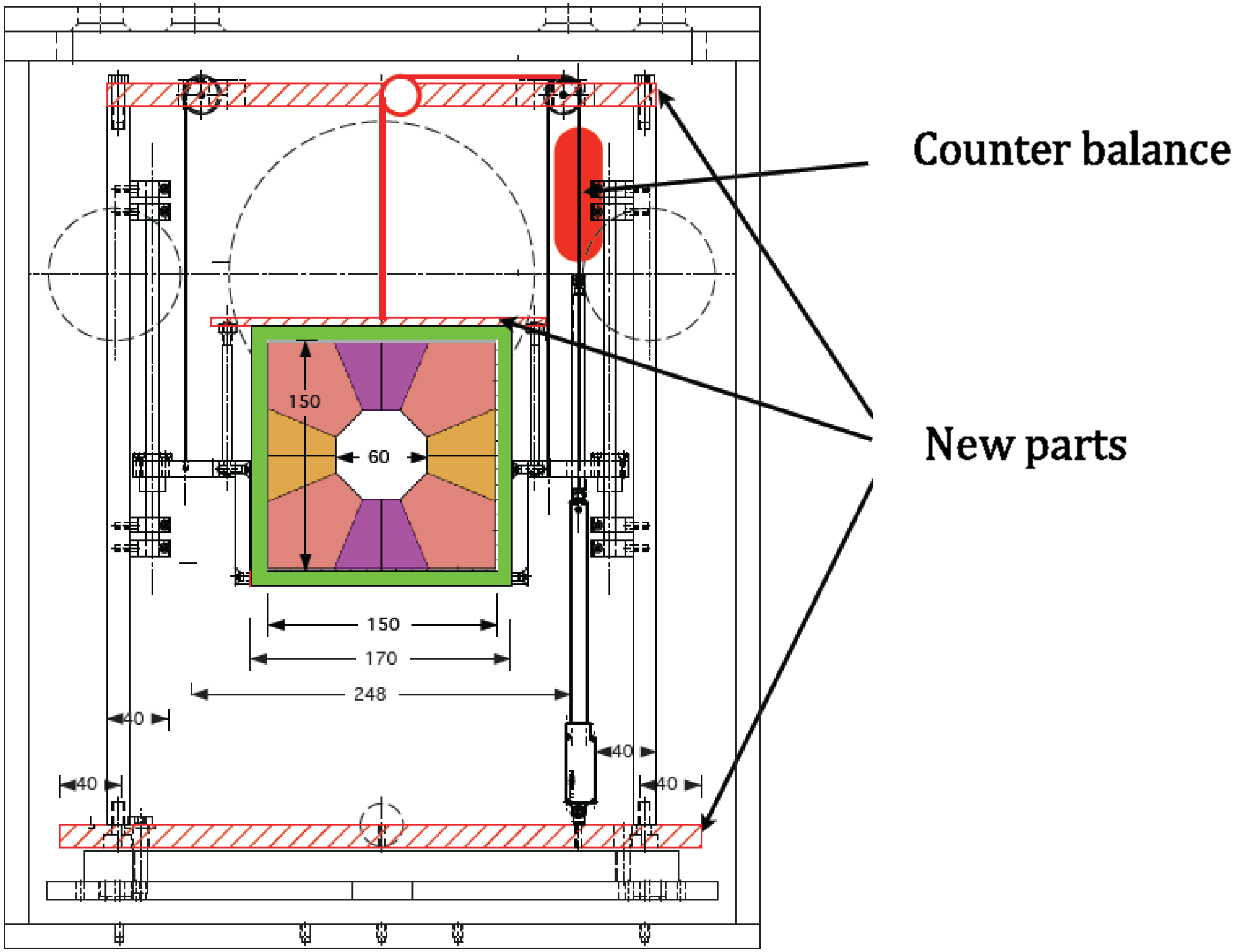
operating position



The New Magnet Holder

Y. Iwashita

lower position

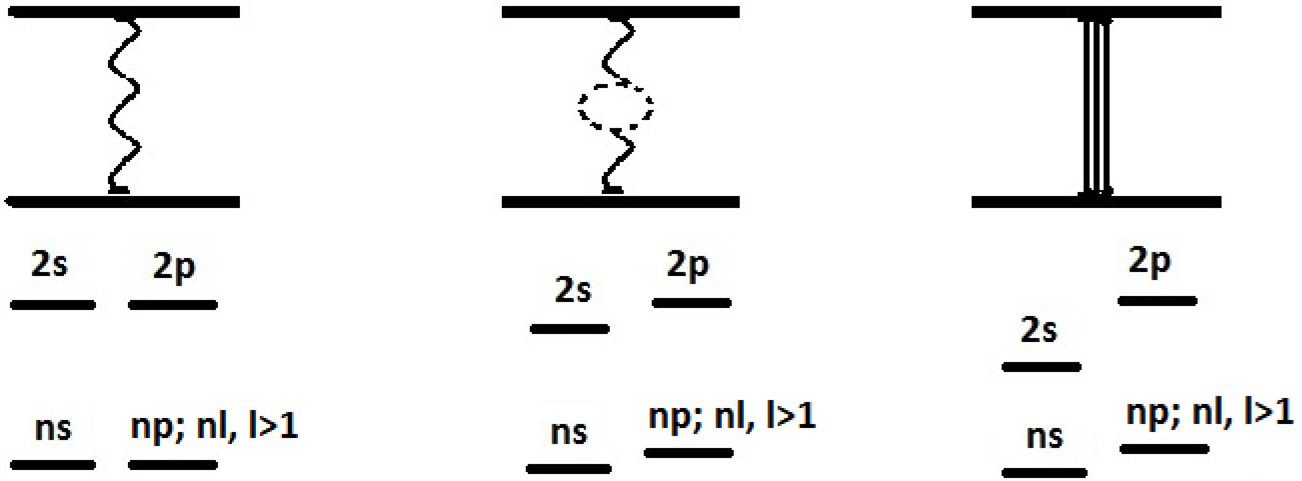


VII ENERGY SPLITTING MEASUREMENT

$A_{2\pi}$ Energy Levels

J. Schweizer (P. L. 2oo4)

For Coulomb potential E depends on n only.



Coulomb potential   Vacuum polarisation   Strong potential

$$E_{2s} - E_{2p} = \Delta_{2s-2p} \qquad \Delta^{vac}_{2s-2p} = -0.107\ \mathrm{eV} \qquad \Delta^{str}_{2s-2p} = -0.47\ \mathrm{eV}$$

$$\Delta^{vac+str}_{2s-2p} = -0.58\ \mathrm{eV} \qquad \Delta^{tot}_{2s-2p} = -0.59 \pm 0.01\ \mathrm{eV}$$

$$\Delta^{str}_{2s-2p} = -\frac{\alpha^3 m_\pi}{8}\frac{1}{6}(2a_0 + a_2) + \cdots \qquad \Delta_{ns-np} = -\frac{\Delta_{2s-2p}}{n^3}\cdot 8$$

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

Coulomb bound state and strong & electromagnetic perturbation

*DGBT *) formula & numerical values:*

A) Energy shift contributions:

em shift | vacuum polarization | strong shift

$$\Delta E_{nl} = \Delta E^{em}_{nl} + \Delta E^{vac}_{nl} + \Delta E^{str}_{n} + \ldots$$

with

$$\Delta E^{str}_{n} = -\frac{\alpha^3 M_\pi}{6n^3}(2a_0 + a_2)(1+\delta'_n) + \ldots$$

B) Decay width:

$$\Gamma_n = \frac{2}{9n^3}\alpha^3 p^*_n (a_0 - a_2)^2 (1+\delta_n) + \ldots$$

Remark

S-wave scattering lengths are amplitudes at threshold:

$$T\left(\pi^+\pi^- \to \pi^+\pi^-\right) \propto (2a_0 + a_2)$$

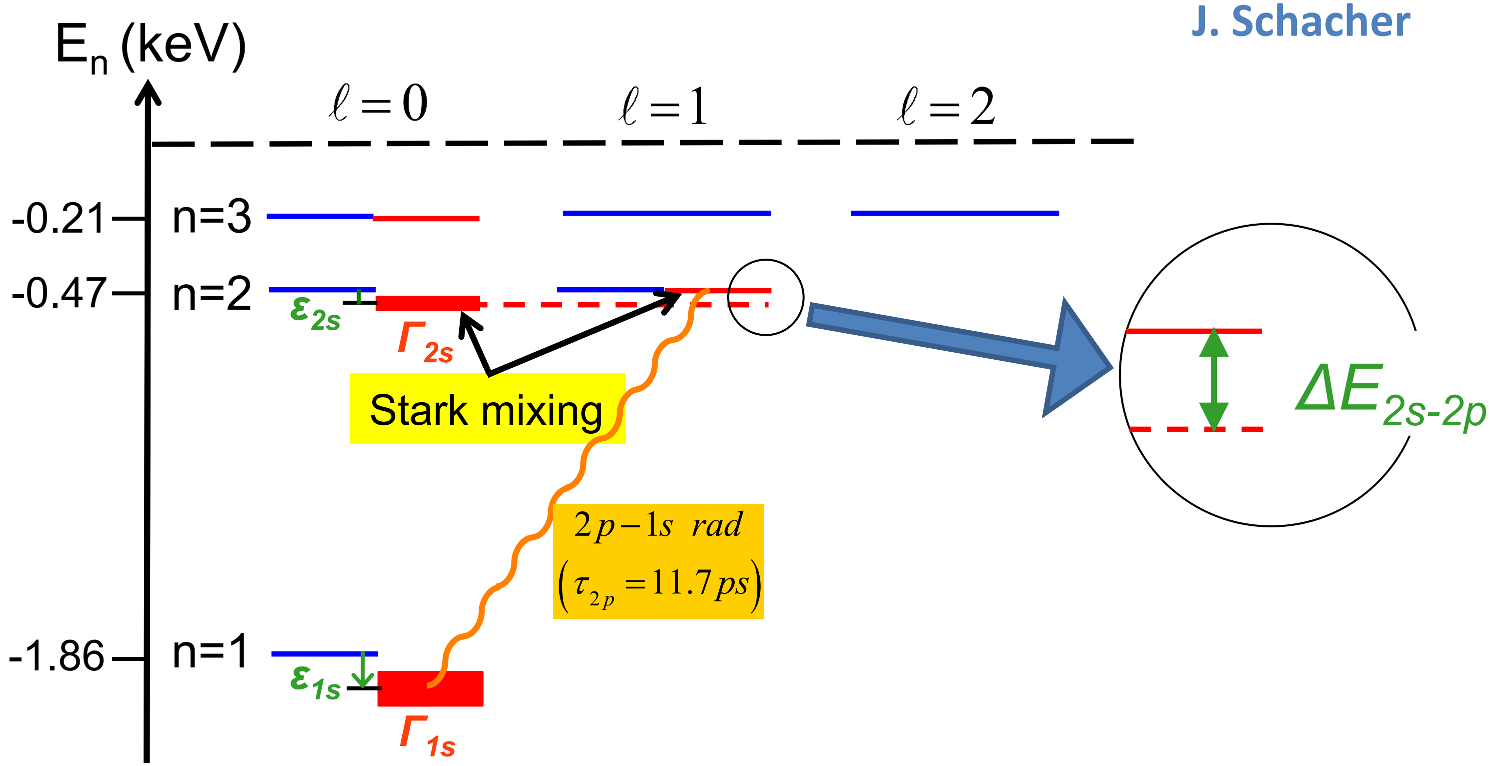
and

$$T\left(\pi^+\pi^- \to \pi^0\pi^0\right) \propto (a_0 - a_2)$$

*) Deser, Goldberger, Baumann, Thirring, PR 96 (1954) 774.

$A_{2\pi}$ level scheme and 2s – 2p energy splitting

J. Schacher



$$\rightarrow \varepsilon_{nl} \equiv \Delta E_{nl} = \sum_i \Delta E^i_{nl} : \varepsilon_{1s} = -4.807eV;\ \varepsilon_{2s} = -0.593eV;\ \varepsilon_{2p} = -0.008eV$$

$$\Rightarrow \Delta E_{2s-2p} = \varepsilon_{2s} - \varepsilon_{2p} = -0.585eV$$

2s level shifted below 2p level
by ≈ 0.6eV ..... "Lamb" shift

$$\rightarrow \Gamma_n \equiv \Gamma_n(\pi^0\pi^0) = \tau_n^{-1} : \tau_{1s} = 2.9\,fs\,;\ \tau_{2s} = 8\cdot\tau_{1s} = 23.2\,fs$$

Values for energy shifts and lifetimes of $\pi^+\pi^-$ atom

J. Schacher

[J. Schweizer, PL B587 (2004) 33]

(n,ℓ)	$\Delta E_{nl}^{em}\,[eV]$	$\Delta E_{nl}^{vac}\,[eV]$	$\Delta E_{nl}^{str}\,[eV]^{*)}$	$\tau_{nl}\,[10^{-15}s]$
$(1,0)$	-0.065	-0.942	-3.8 ± 0.1	2.9 ± 0.1
$(2,0)$	-0.012	-0.111	-0.47 ± 0.01	23.3 ± 0.7
$(2,1)$	-0.004	-0.004	□-1□10^{-6}	□1.2□10^{4}

$$\Delta E_{2s-2p} = \Delta E_{20}^{str} + \Delta E_{20}^{em} - \Delta E_{21}^{em} + \Delta E_{20}^{vac} - \Delta E_{21}^{vac} = -0.59 \pm 0.01 eV$$

$$\begin{cases} \langle nlm | V_{op} | n'l'm' \rangle \neq 0 \quad \Rightarrow \quad \text{Stark mixing} \\ \rightarrow \text{selection rules}: \quad \Delta n = 0,\ \Delta l = \pm 1,\ \Delta m = 0 \end{cases}$$

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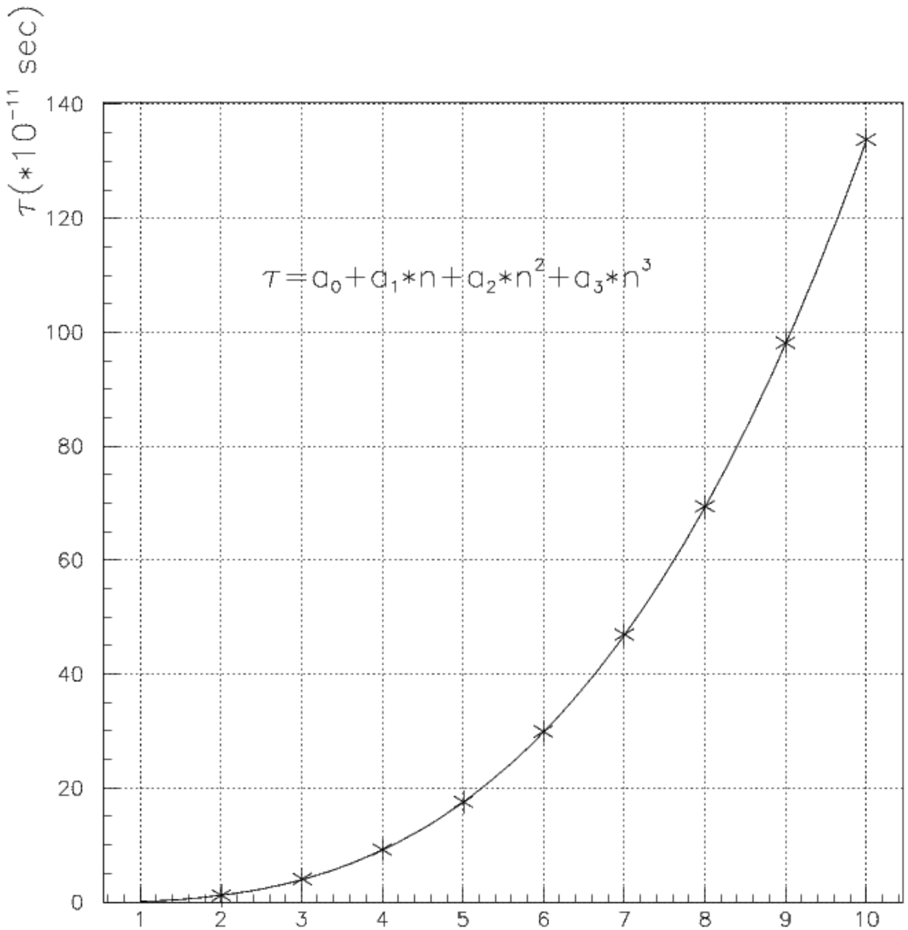
*) $\Delta E_{n0}^{str} \sim A_n (2a_0 + a_2)$

$A_{2\pi}$ lifetime, τ, in np states

M. Pentia

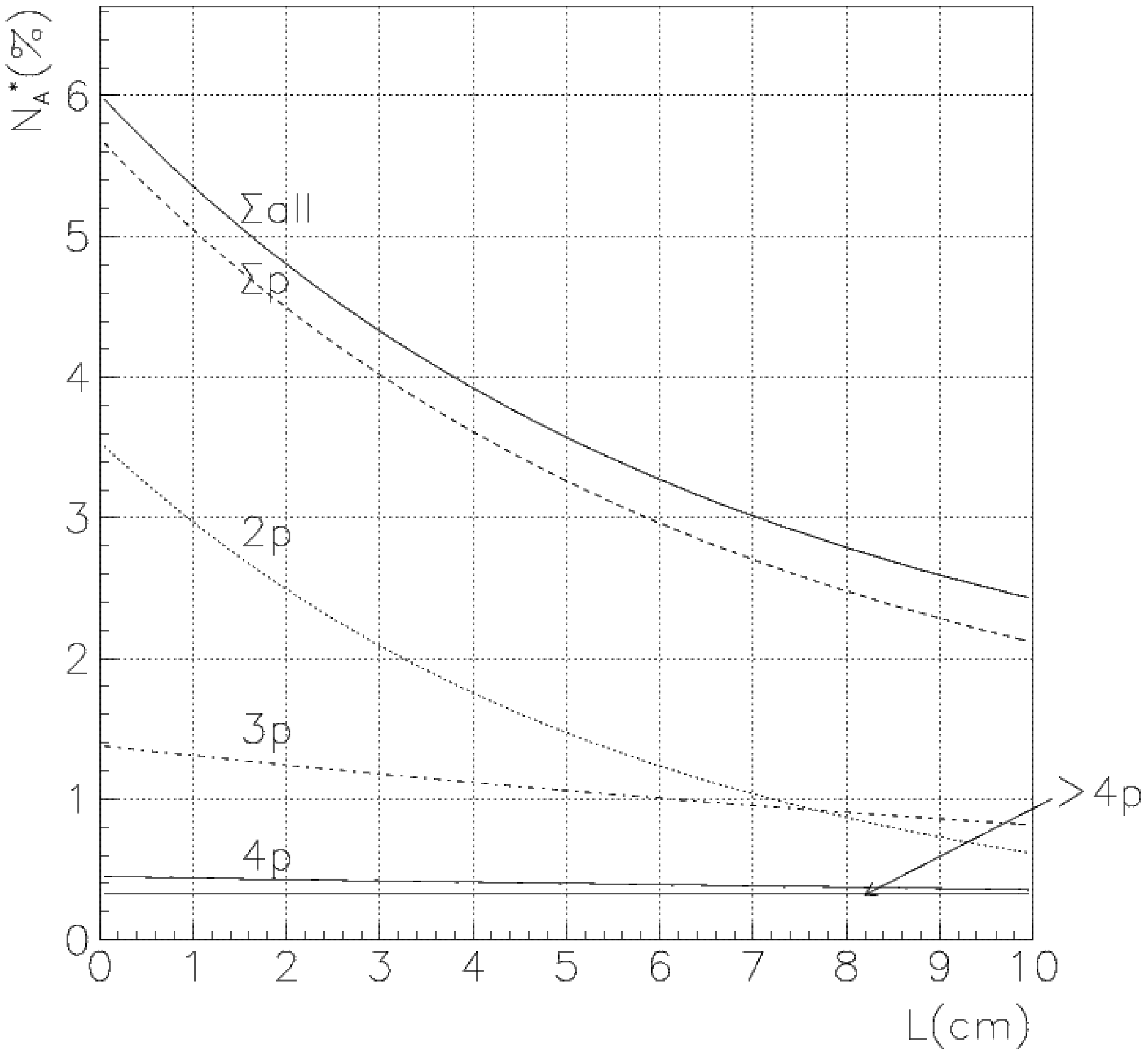


n_H	$\tau_H \bullet 10^8$ s	$\tau_{2\pi} \bullet 10^{11}$ s	Decay length $A_{2\pi}$ in L.S. cm for γ=16.1
2p	0.16	1.17	5.7
3p	0.54	3.94	19
4p	1.24	9.05	44
5p	2.40	17.5	84.5
6p	4.1	29.9	144
7p		46.8*	226
8p		69.3*	335

*** - extrapolated values**

Long-lived $A_{2\pi}$ yield and quantum numbers

L. Afanasev; O. Gorchakov (DIPGEN)

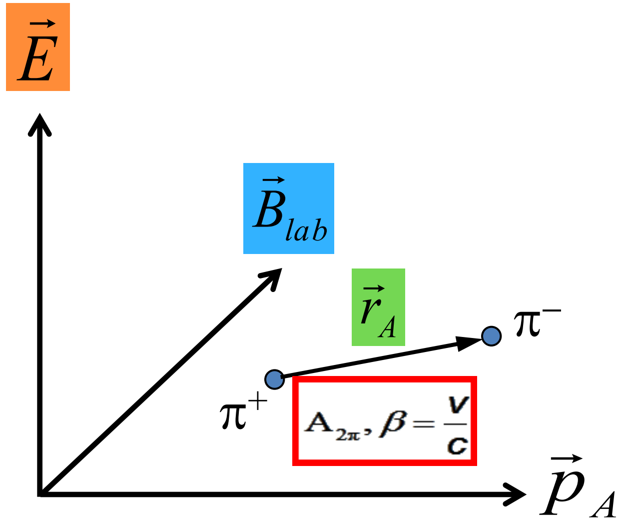


Atomic pairs from $A_{2\pi}$ long-lived states breakup in 2μm Pt.

Lamb shift measurement with external magnetic field

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

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



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

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

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

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

The lifetime of $A_{2\pi}$ in electric field

L. Nemenov, V. Ovsiannikov [PL B514 (2oo1) 247]

$$M = \frac{3\kappa\hbar^2}{e\mu} F\, \delta_{m,0}, \quad \kappa = 4\pi\varepsilon_0,$$ F ... strength of electric field in $A_{2\pi}$ c.m.s.

$$\mathbf{F} = \beta\gamma \mathbf{B_L},$$ $B_L \equiv B_{lab}$ in lab system

→ m must be 0

$$\xi = \frac{2\,M}{\Omega_1}, \qquad \Omega_1(n=2) = \frac{E_{2s} - E_{2p}}{\hbar}$$

$$\xi(2s - 2p) = \xi_0 \gamma B_L \qquad \xi_0 \sim \frac{1}{E_{2s} - E_{2p}} \qquad \xi_n = \frac{\xi_0}{8} n^3 \gamma B_L$$

$$\tau_n^{eff} = \frac{\tau_n}{1 + 120\xi_n^2}$$

CONCLUSION: the lifetimes for long-lived states can be calculated using only one parameter → E_{2s}-E_{2p}.

The probability W(m=0) of $A_{2\pi}$ to have m=0 on $\vec{F}$ will be calculated by L. Afanasev. The preliminary value is W (m=0) ≈ 50%.

$A_{2\pi}$* (2p-state) lifetime versus electric field

J. Schacher

Atom-field interaction:

$$M(\vec{E}) \equiv \langle 2pm | V_{op} | 2s \rangle = -d_e^{n=2} |\vec{E}| = -3 \frac{\kappa \hbar^2}{e \mu_r} |\vec{E}| \delta_{m0}$$

with $V_{op} = e|\vec{E}|\, z,\ d_e^{n=2} = 3\, e\, a_{Bohr}$ ... electric dipole (n = 2), μ_r ... reduced mass, $\kappa = 4\pi\varepsilon_0$

$|\vec{E}| = \beta\gamma\, B_{lab}$ ... electric field in $A_{2\pi}$ − system ‖ z − axis

$\vec{B}_{lab} = 0:\quad \Psi_{2pm}(\vec{r},t) = a_{2pm}\phi_{2pm}(\vec{r})\, e^{-iE_{2p}t/\hbar} \quad \Rightarrow \quad P_{B=0}(t) = \exp(-t/\tau_{2p})$

$\vec{B}_{lab} \neq 0:\quad \Psi_{2p0}(\vec{r},t) = \tilde{a}_{2p0}(\boldsymbol{t})\, \phi_{2p0}(\vec{r})\, e^{-iE_{2p}t/\hbar}$ ...will change => $P(t)|_{m=0} \approx \exp(-t/\tau_{2p}^{eff})$:

↑

[weak-field limit]

$$\tau_{2p}^{eff} = \tau_{2p}\left[1 + 0.25\left|\xi\left(|\vec{E}|, \Delta E_{2s-2p}\right)\right|^2 \left(\frac{\tau_{2p}}{\tau_{2s}} - 1\right)\right]^{-1} \quad \text{and} \quad |\xi(...)|^2 \propto \frac{|\vec{E}|^2}{(\Delta E_{2s-2p})^2}$$

Using $\vec{B}_{lab} \to \vec{E}$, measure $\tau_{2p}^{eff} \Rightarrow |\xi(...)|^2 \Rightarrow \Delta E_{2s-2p} \Rightarrow \underline{2a_0 + a_2}$

H=0.0 T ξ=1 N_A=330 ± 40
H=0.1 T ξ=1 N_A=330 (1-0.7%)

V. Brekhovskikh

ξ	0.4	1	1.6
H=0.4 T	328	317	302
	11	15	13
H=0.6 T	325	304	279
	21	25	23
H=0.8 T	322	290	258
	32	32	32
H=1.0 T	317	276	241
	41	35	38
H=1.2 T	312	263	227
	49	36	46
H=1.4 T	307	251	215
	56	36	46
H=1.6 T	302	241	206
	61	35	48

$\Delta_{2s\text{-}2p}$ can be measured at H = 1.4 ÷ 1.6 T with 60% precision using low level background events and with 50% precision using low level and medium level background events.

Magnetic Field - 1.0 T

V. Brekhovskikh

Magnetic Field 1.0 T ξ = 40% 317.273

	2p	3p	4p	5p	6p	7p	8p	∑
n,%	0.42	0.27	0.15	0.079	0.046	0.025	0.012	1.002
$\tau \cdot 10^{-11}$,s	1.17	3.94	9.05	17.5	29.9	46.8	69.3	177.66
L,cm	5.64	19.02	43.68	84.47	144.32	225.89	334.49	857.50
ξ_n	0.0075	0.0254	0.0603	0.1177	0.2034	0.3231	0.4822	1.2197
$\tau_{eff} \cdot 10^{-11}$,s	1.162	3.656	6.302	6.571	5.011	3.461	2.397	28.561
L_{eff},cm	5.609	17.647	30.418	31.715	24.188	16.703	11.572	137.85
N_a	0.0714	0.1595	0.1193	0.0701	0.0429	0.0239	0.0116	0.499
N_a^{eff}	0.0710	0.1557	0.1124	0.0624	0.0349	0.0171	0.0070	0.4605

Magnetic Field 1.0 T ξ = 100% 276.147

	2p	3p	4p	5p	6p	7p	8p	∑
n,%	0.42	0.27	0.15	0.079	0.046	0.025	0.012	1.002
$\tau \cdot 10^{-11}$,s	1.17	3.94	9.05	17.5	29.9	46.8	69.3	177.66
L,cm	5.64	19.02	43.68	84.47	144.32	225.89	334.49	857.50
ξ_n	0.0188	0.0636	0.1507	0.2943	0.5086	0.8076	1.2056	3.0492
$\tau_{eff} \cdot 10^{-11}$,s	1.122	2.653	2.429	1.535	0.933	0.590	0.395	9.659
L_{eff},cm	5.416	12.806	11.726	7.412	4.504	2.849	1.907	46.622
N_a	0.0714	0.1595	0.1193	0.0701	0.0429	0.0239	0.0116	0.499
N_a^{eff}	0.0683	0.1369	0.0821	0.0335	0.0118	0.0030	0.0005	0.3362

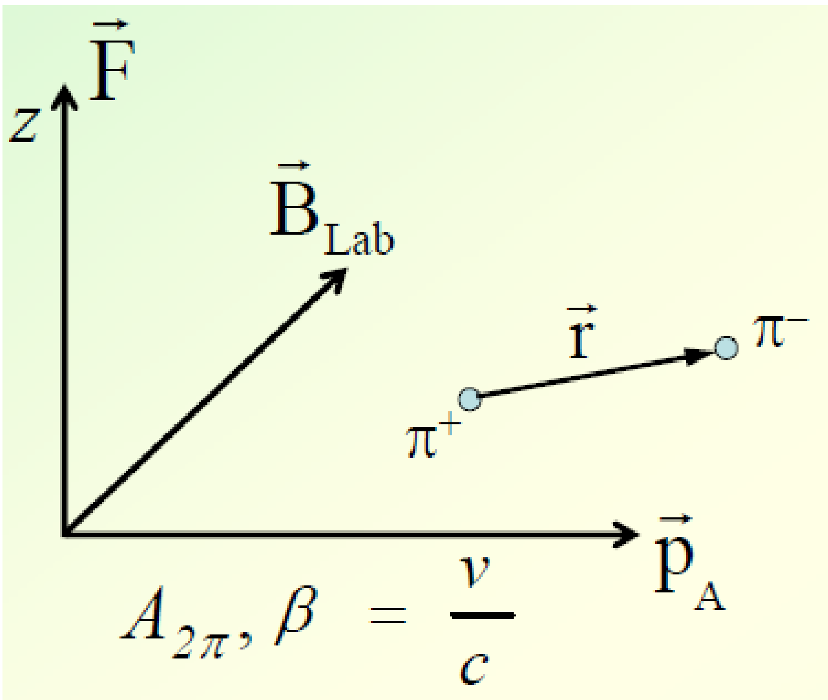
Magnetic Field 1.0 T ξ = 160% 240.908

	2p	3p	4p	5p	6p	7p	8p	∑
n,%	0.42	0.27	0.15	0.079	0.046	0.025	0.012	1.002
$\tau \cdot 10^{-11}$,s	1.17	3.94	9.05	17.5	29.9	46.8	69.3	177.66
L,cm	5.64	19.02	43.68	84.47	144.32	225.89	334.49	857.50
ξ_n	0.0301	0.1017	0.2411	0.4709	0.8137	1.2922	1.9289	4.8788
$\tau_{eff} \cdot 10^{-11}$,s	1.055	1.757	1.135	0.634	0.372	0.233	0.155	5.339
L_{eff},cm	5.092	8.483	5.476	3.059	1.793	1.122	0.747	25.774
N_a	0.0714	0.1595	0.1193	0.0701	0.0429	0.0239	0.0116	0.499
N_a^{eff}	0.0637	0.1079	0.0458	0.0106	0.0016	0.0001	$3.87 \cdot 10^{-6}$	0.2296

Reserve:

External magnetic and electric fields

Atoms in a beam are influenced by external magnetic field and the relativistic Lorentz factor.



$\vec{r}$ – **relative distance between π^+ and π^- in $A_{2\pi}$ atom**

$\vec{B}$ – **laboratory magnetic field**

$\vec{F}$ – **electric field in the c. m. s. of $A_{2\pi}$ atom**

$$\mathbf{F} = \beta\gamma \mathbf{B}_L \approx \gamma \mathbf{B}_L$$

The lifetime of $A_{2\pi}$ in electric field

L. Nemenov, V. Ovsiannikov (P. L. 2oo1)

$$M = \frac{3F\hbar^2}{\mu_1}\delta_{m,0},$$

F – strength of electric field in $A_{2\pi}$ c.m.s.

$$F = \beta\gamma B_L,$$ B_L in lab. syst.

→ m must be 0

$$\xi = \frac{2M}{\Omega_1},$$

$$\Omega_1(n=2) = \frac{E_{2s} - E_{2p}}{\hbar}$$

$$\xi(2s-2p) = \xi_0 \gamma B_L \qquad \xi_0 \sim \frac{1}{E_{2s} - E_{2p}} \qquad \xi_n = \frac{\xi_0}{8} n^3 \gamma B_L$$

$$\tau_n^{eff} = \frac{\tau_n}{1 + 120\xi_n^2}$$

CONCLUSION: the lifetimes for long-lived states can be calculated using only one parameter → E_{2s}-E_{2p}.

The probability W(m=0) of $A_{2\pi}$ to have m=0 on $\vec{F}$ will be calculated by L. Afanasev. The preliminary value is W (m=0) ≈ 50%.