

Search for long-lived States of $\pi^+\pi^-$ atoms

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on behalf of the DIRAC Collaboration

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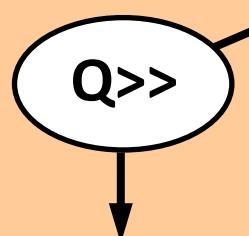
- 1. Low energy QCD and $\pi^+\pi^-$ atoms**
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Theoretical motivation



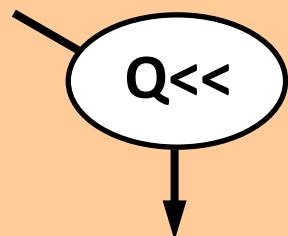
Strong interaction: $L_{QCD} = L_{sym} + L_{sym-break} (m_q \neq 0)$

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} ($m_q \ll 0$) !

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

Theoretical motivation

$\pi\pi$ scattering length

In ChPT the effective Lagrangian, which describes the $\pi\pi$ interaction, is an expansion in (even) 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) depend on the low-energy constants (LEC) \mathbf{l}_3 and \mathbf{l}_4 :
Lattice gauge calculations from 2006 provided values for these \mathbf{l}_3 and \mathbf{l}_4 .

Because \mathbf{l}_3 and \mathbf{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.

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 USA, 5 Europe, 2 Japan
- J. Gasser, H. Leutwyler: Model calculation (1985)
 $\bar{l}_3 = 2.6 \pm 2.5, \Delta \bar{l}_3 / \bar{l}_3 \approx 1$
- 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 $\pi\pi$ -scattering lengths and their combinations must be at the level (0.2-0.3)%

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 :

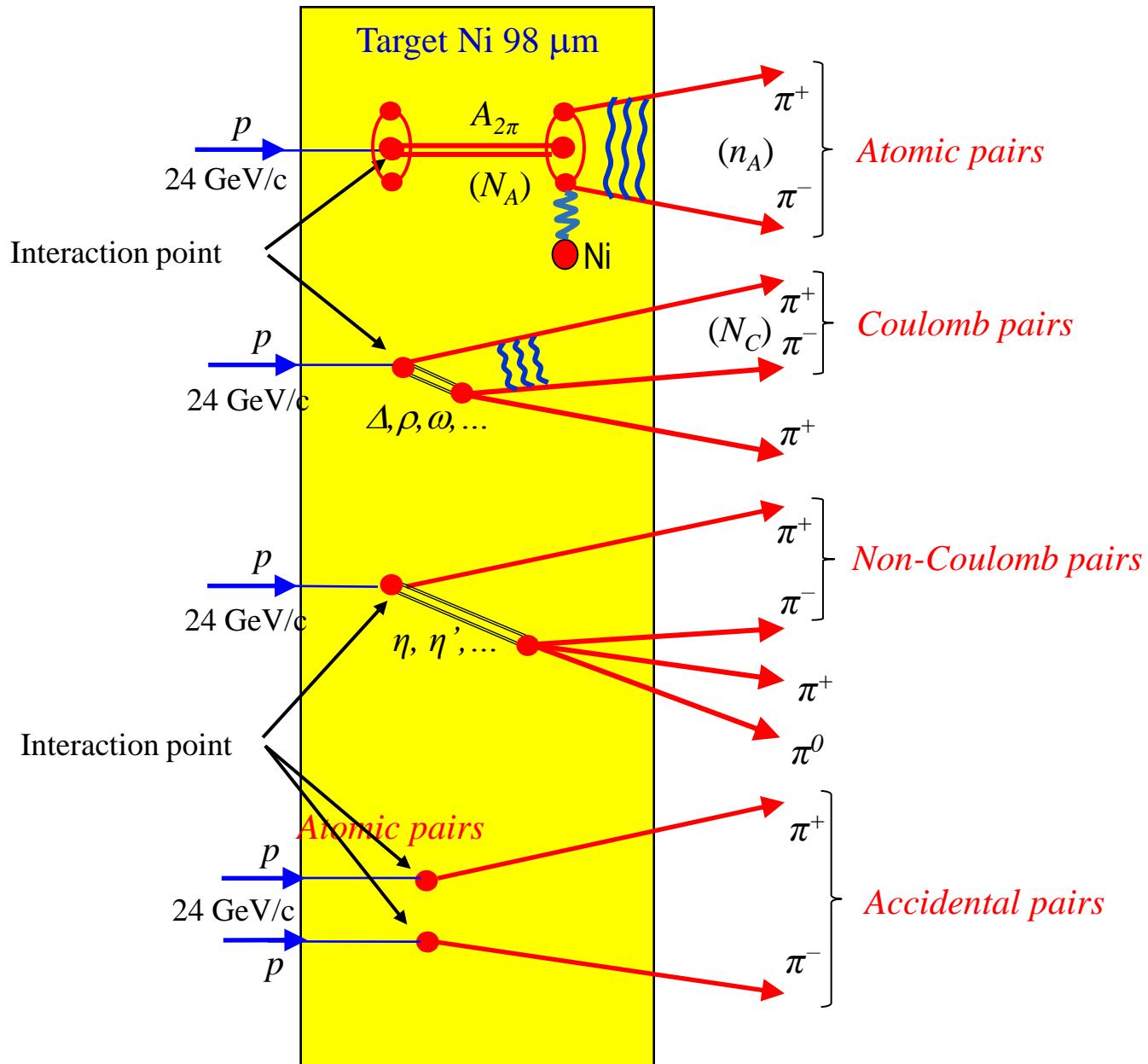
$$\Rightarrow a_0 = 0.2206 \pm 0.0049 \Big|_{stat} \pm 0.0018 \Big|_{syst} \pm 0.0064 \Big|_{theo} = \dots \pm 3.7\%$$

Ke4 & K→3π:

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

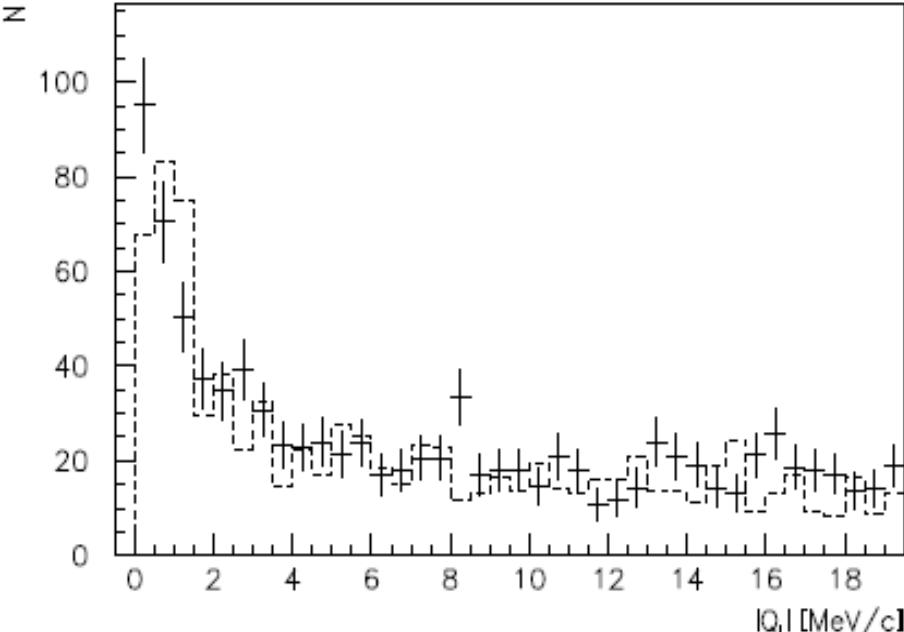
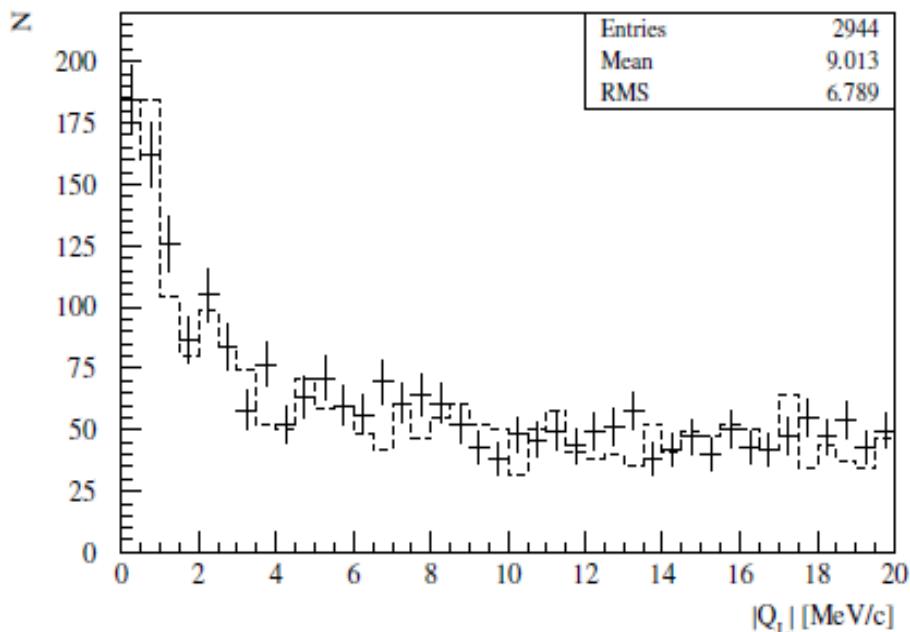
$$\Rightarrow a_0 - a_2 = 0.2639 \pm 0.0020 \Big|_{stat} \pm 0.0015 \Big|_{syst} = \dots \pm 0.9\%$$

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



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

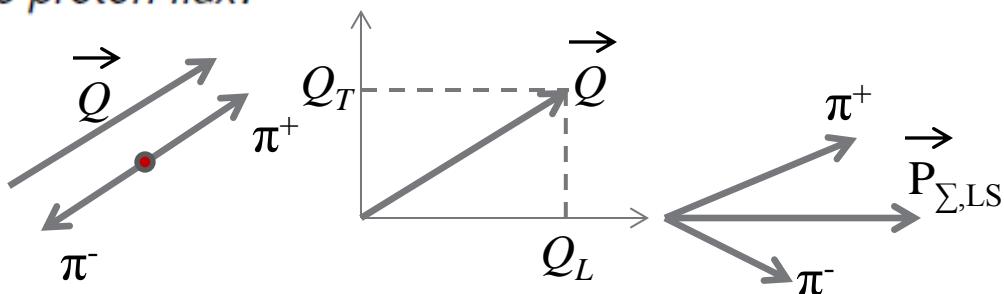
Distribution over $|Q_L|$ of $\pi^+\pi^-$ pairs collected in 2010 (left) and in 2011 (right) with Beryllium target with the cut $Q_T < 1$ MeV/c. Experimental data (points with error bars) have been fitted by a sum of the simulated distribution of “Coulomb” and “non-Coulomb” pairs (dashed line).



Produced atom numbers normalized on the proton flux:

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

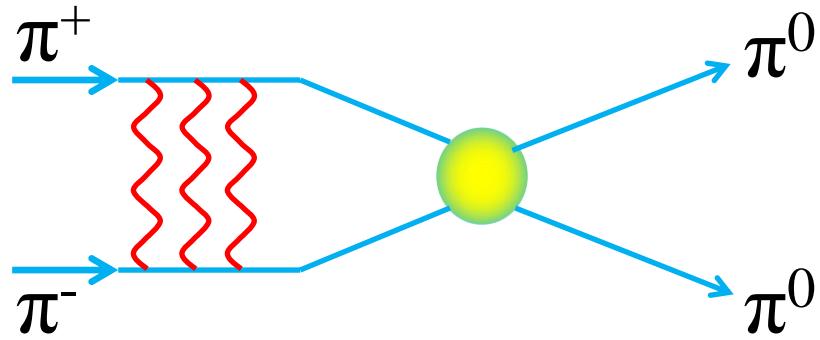
$$N_{A_{2\pi}}/p = (5.9 \pm 0.5) \times 10^{-14} \text{ (2011)}$$



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

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

$$\frac{\Gamma_{2\gamma}}{\Gamma_{2\pi^0}} \approx 4 \times 10^{-3}$$

$$\Gamma_{ns \rightarrow 2\pi^0} = R |\psi_{ns}(0)|^2 |a_0 - a_2|^2$$

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

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

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

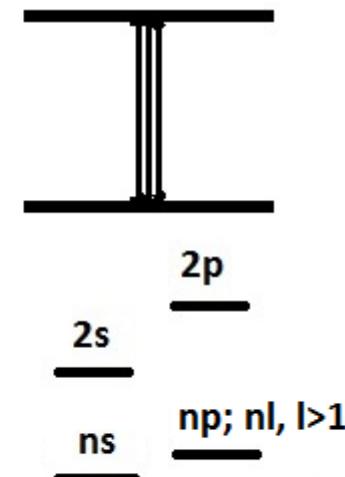
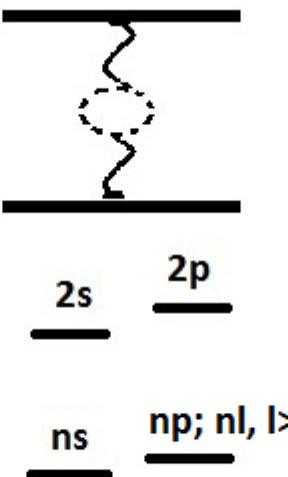
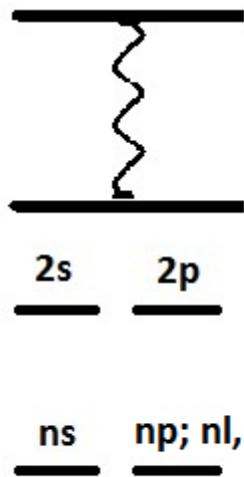
The lifetime of np states depends on transition $np \rightarrow 1s, 2s, \dots, (n-1)s$ probability
 This probability is about three orders less than $ns \rightarrow \pi^0 \pi^0$ decay into $\pi^0 \pi^0$

Energy splitting measurement

$A_{2\pi}$ Energy Levels

J. Schweizer [PL B (2004)]

For Coulomb potential E depends only on n



Notation:

Coulomb potential

Vacuum polarisation

Strong potential

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

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

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

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

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

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

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

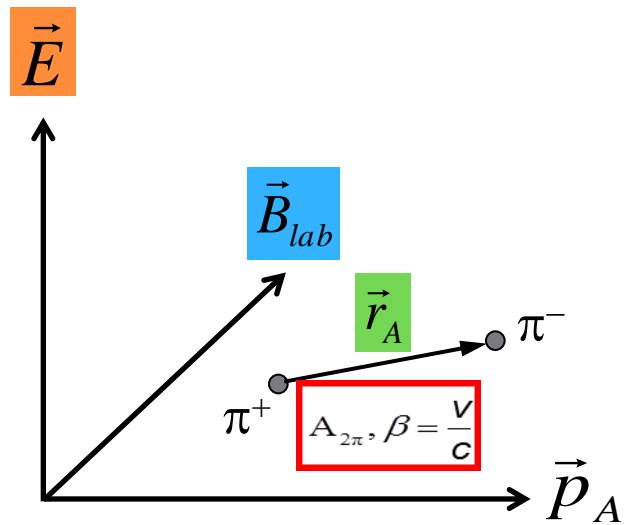
$$\Delta_{ns-np} = -\frac{\Delta_{2s-2p}}{n^3} \cdot 8$$

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

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

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

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

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

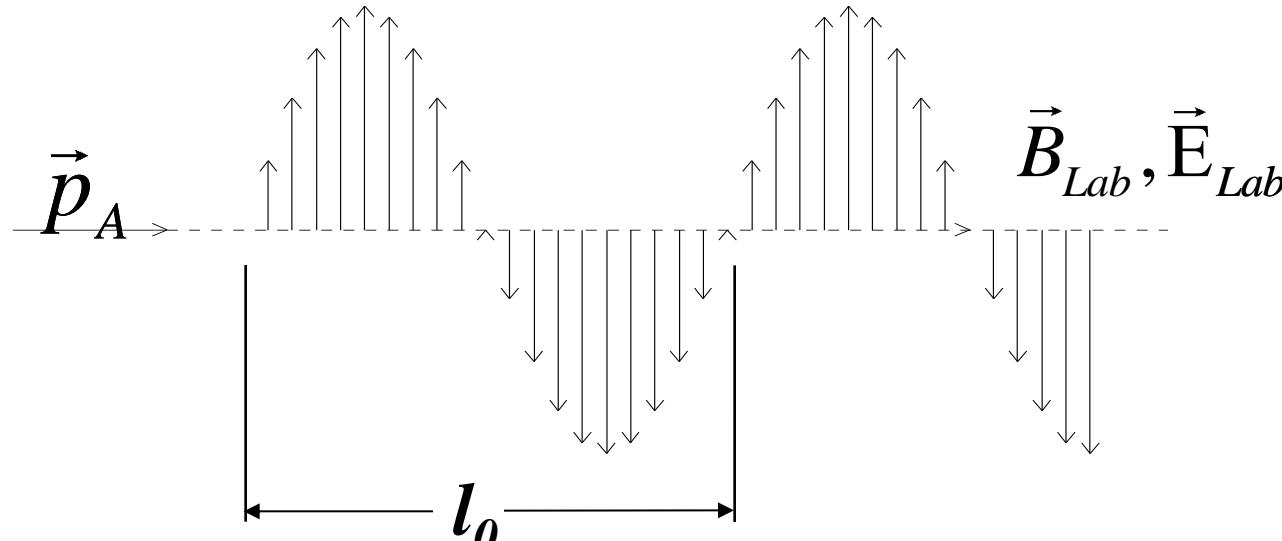
where: $|\xi|^2 \approx \frac{|\vec{E}|^2}{(E_{2p} - E_{2s})^2}$

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

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

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

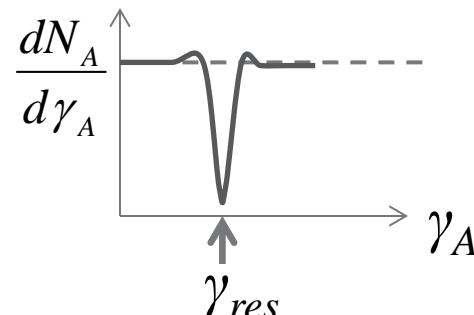
L.Nemenov, V.Ovsiannikov, E.Tchaplyguine, Nucl. Phys. (2002)



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

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

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



$\pi^+ \pi^-$ 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 ($l=0$)	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

Detecting $A_{2\pi}$ in long-lived states with a thin Platinum foil

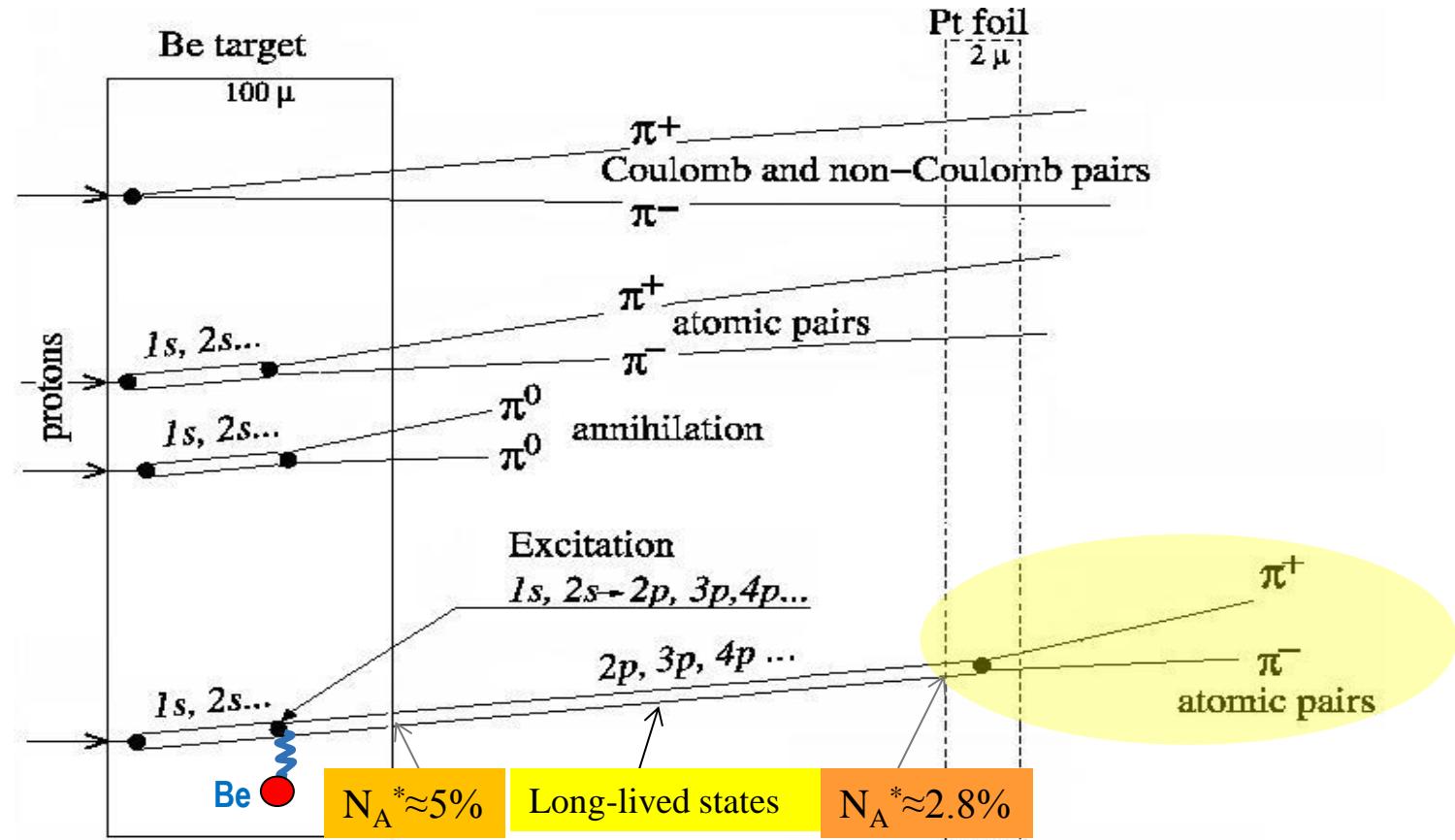
The probability of $A_{2\pi} ns$ states generation in proton-nucleus interaction:

$$W_{1s} = 83\%$$

$$W_{2s} = 10.4\%$$

$$W_{3s} = 3.1\%$$

$$W_{>3s} = 3.5\%$$



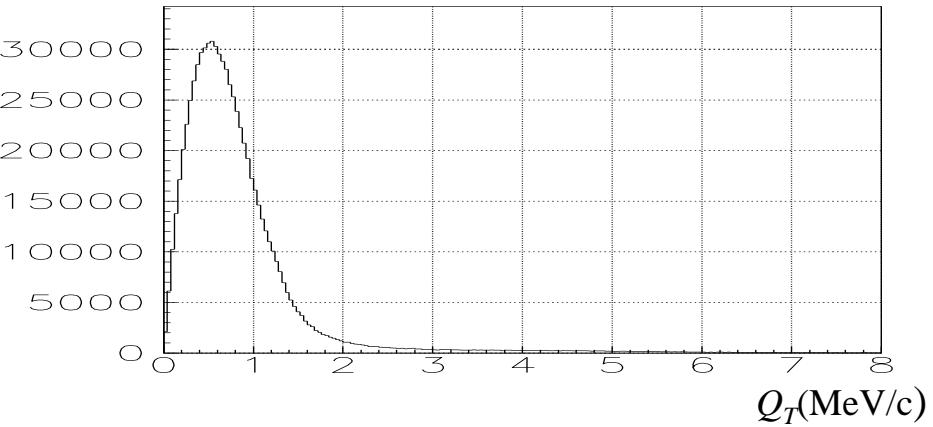
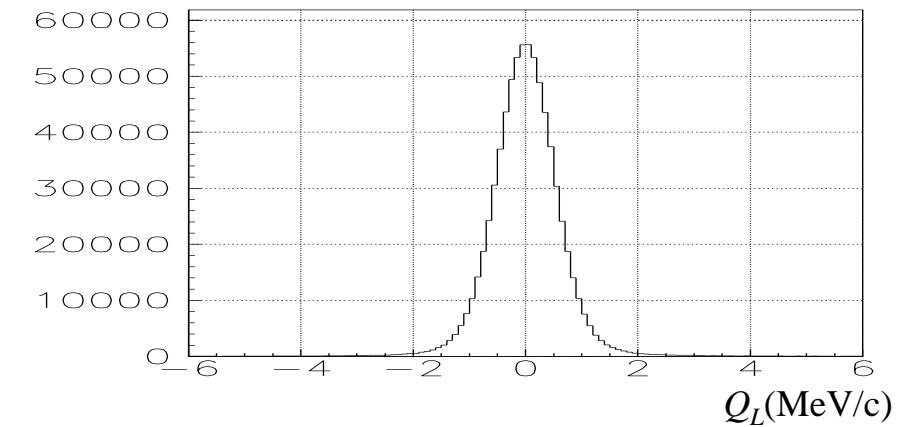
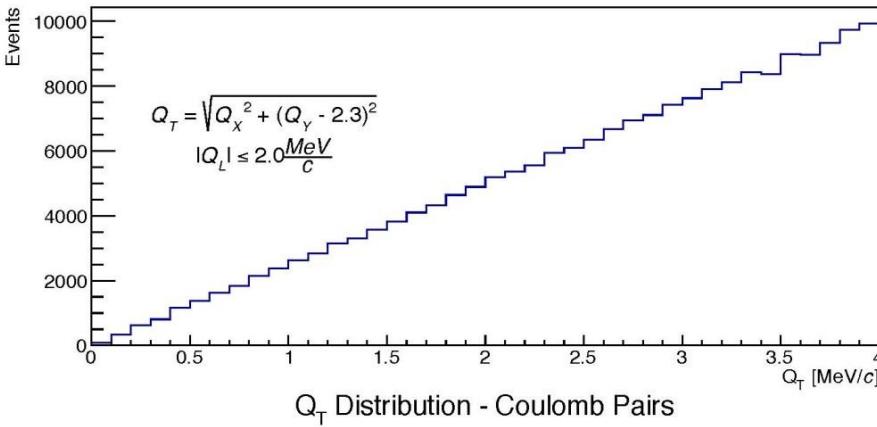
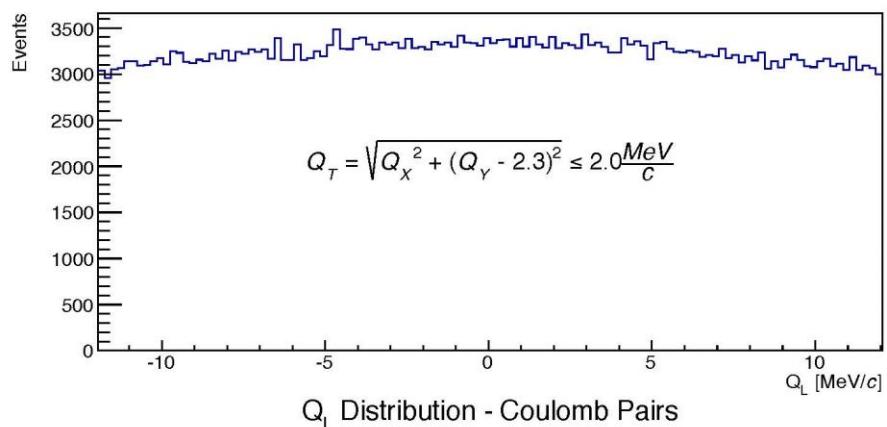
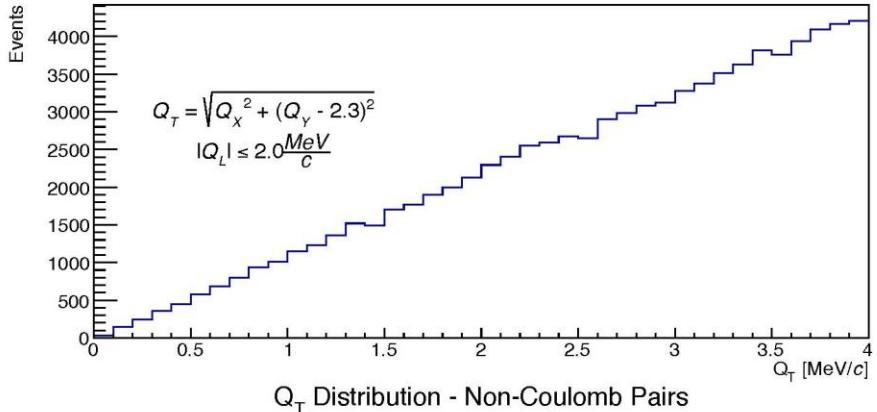
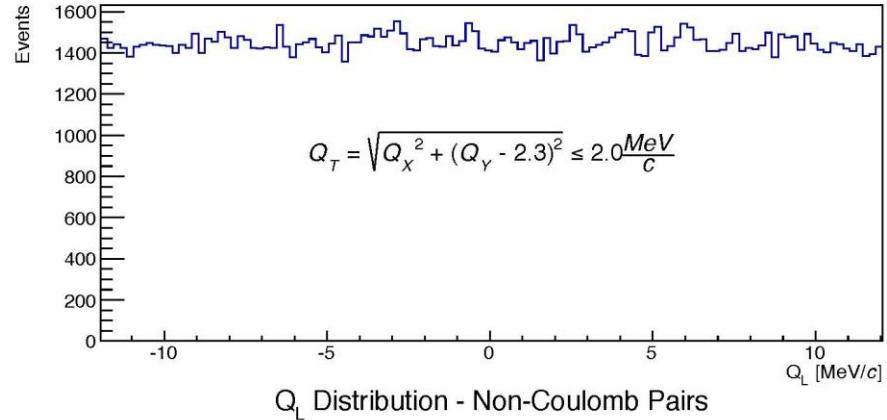
Breakup foil	Thick (μm)	2p	3p	4p	5p	6p	7p
Pt (Z=78)	1.0	0.4147	0.6895	0.8553	0.9324	0.9667	0.9828
	1.5	0.6084	0.8526	0.9446	0.9765	0.9889	0.9944
	2.0	0.7422	0.9244	0.9743	0.9895	0.9951	0.9975

12-Sep-14

Platinum foils:

The breakup probability for np states and different thicknesses ($A_{2\pi}$ momentum $P_A = 4.5 \text{ GeV}/c$ and $A_{2\pi}$ lifetime $\tau = 3.0 \cdot 10^{-15} \text{s}$)

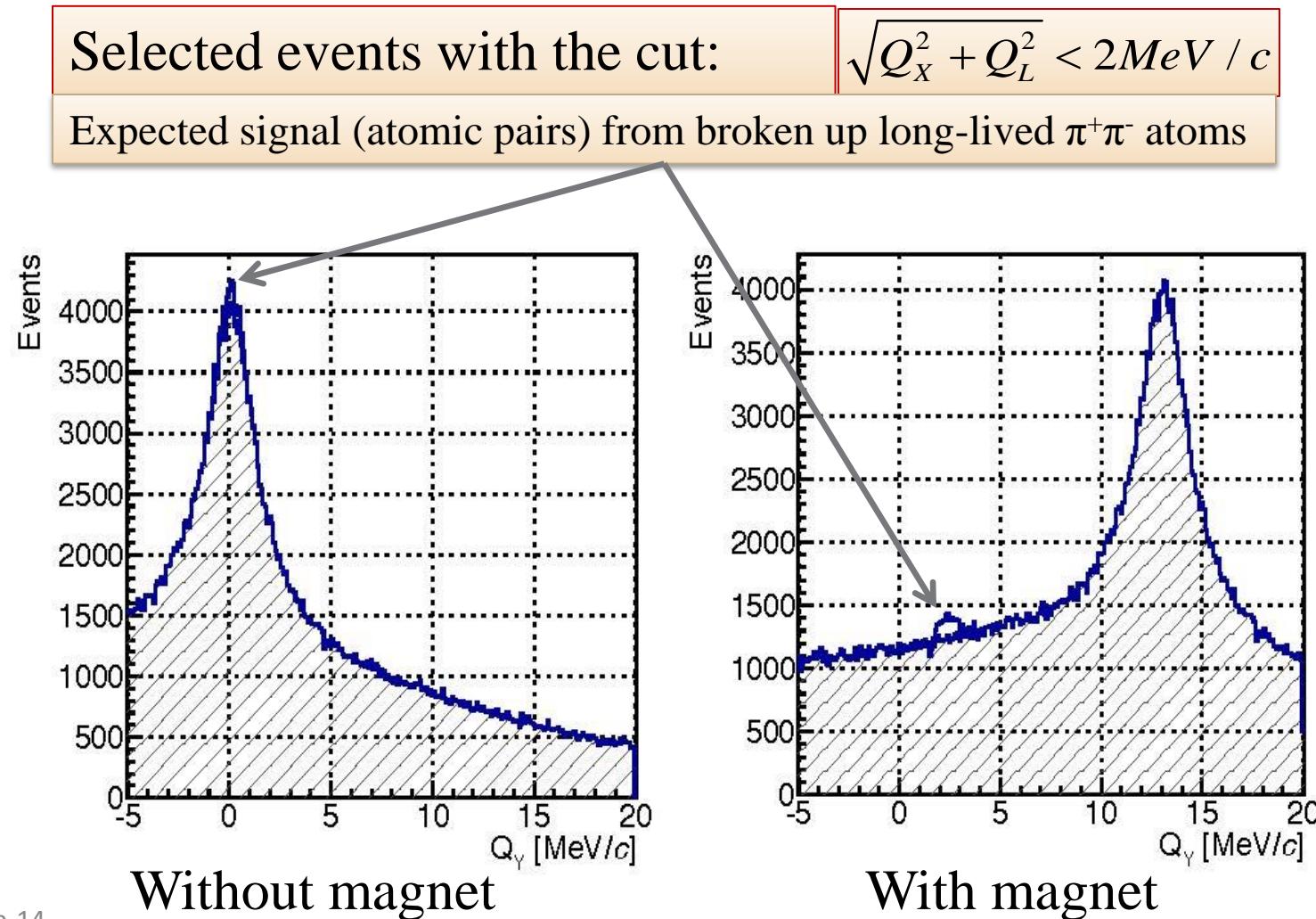
Simulation of $\pi^+\pi^-$ pairs for long-lived $A_{2\pi}$ observation



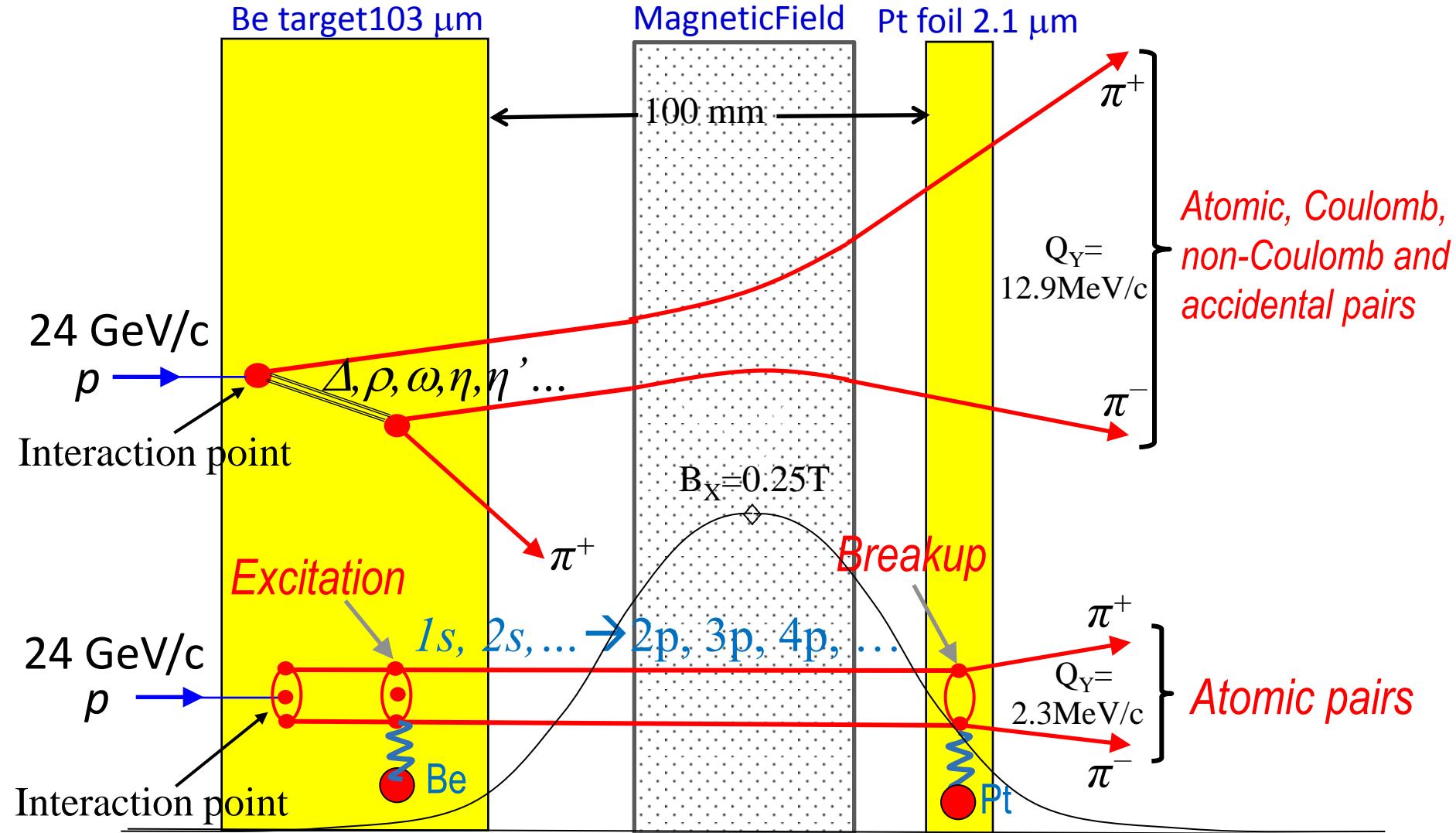
The background reduction with magnetic field for long-lived $A_{2\pi}$ observation

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.



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



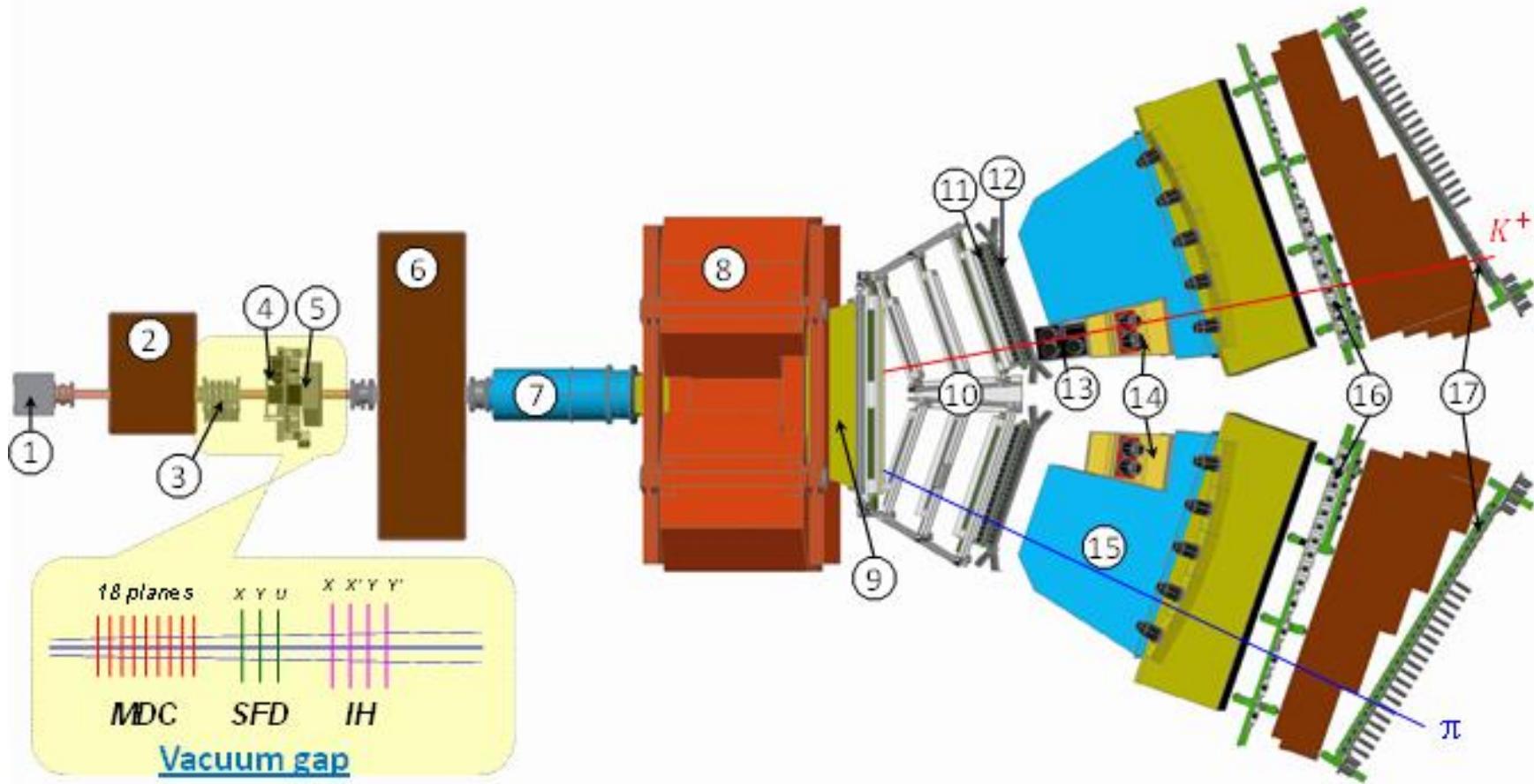
for

$\gamma = 16$
12-Sep-14

$$l(2p) = 5.6 \text{ cm}, l(3p) = 19 \text{ cm}, l(4p) = 43 \text{ cm}, l(5p) = 84 \text{ cm}$$

$$l(2s) = 0.11 \text{ mm}, l(3s) = 0.38 \text{ mm}, l(4s) = 0.89 \text{ mm}, l(5s) = 1.74 \text{ mm}$$

DIRAC upgraded 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 Detector²¹

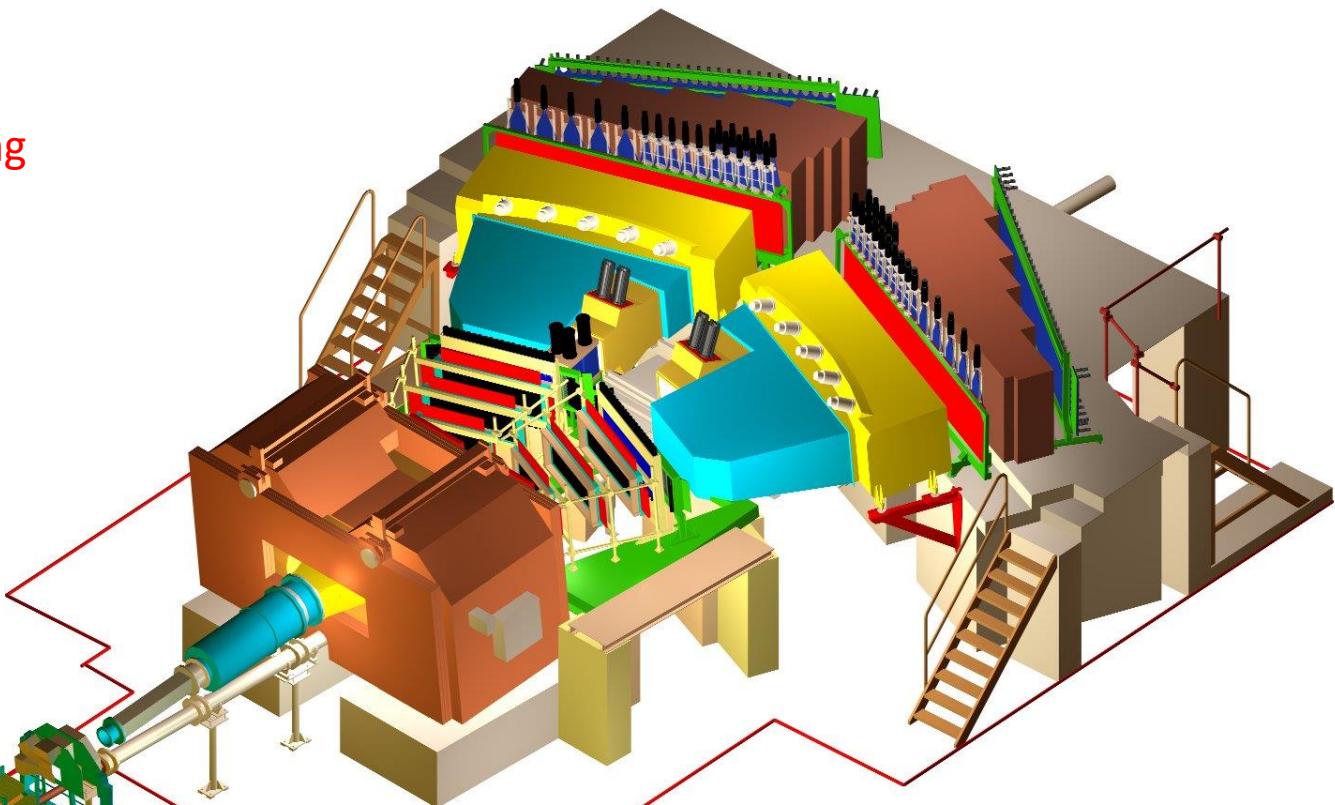
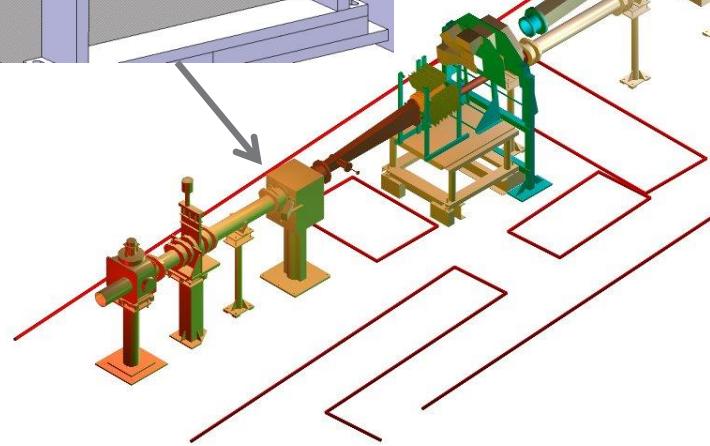
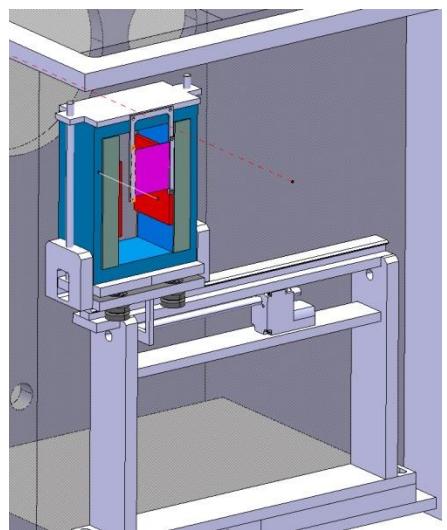
DIRAC upgraded Experimental setup

BLUE ... magnet yoke

GREY ... magnet poles

RED ... magnet shimming

PURPLE ... Pt foil



DIRAC setup characteristics and experimental conditions

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

Spectrometer

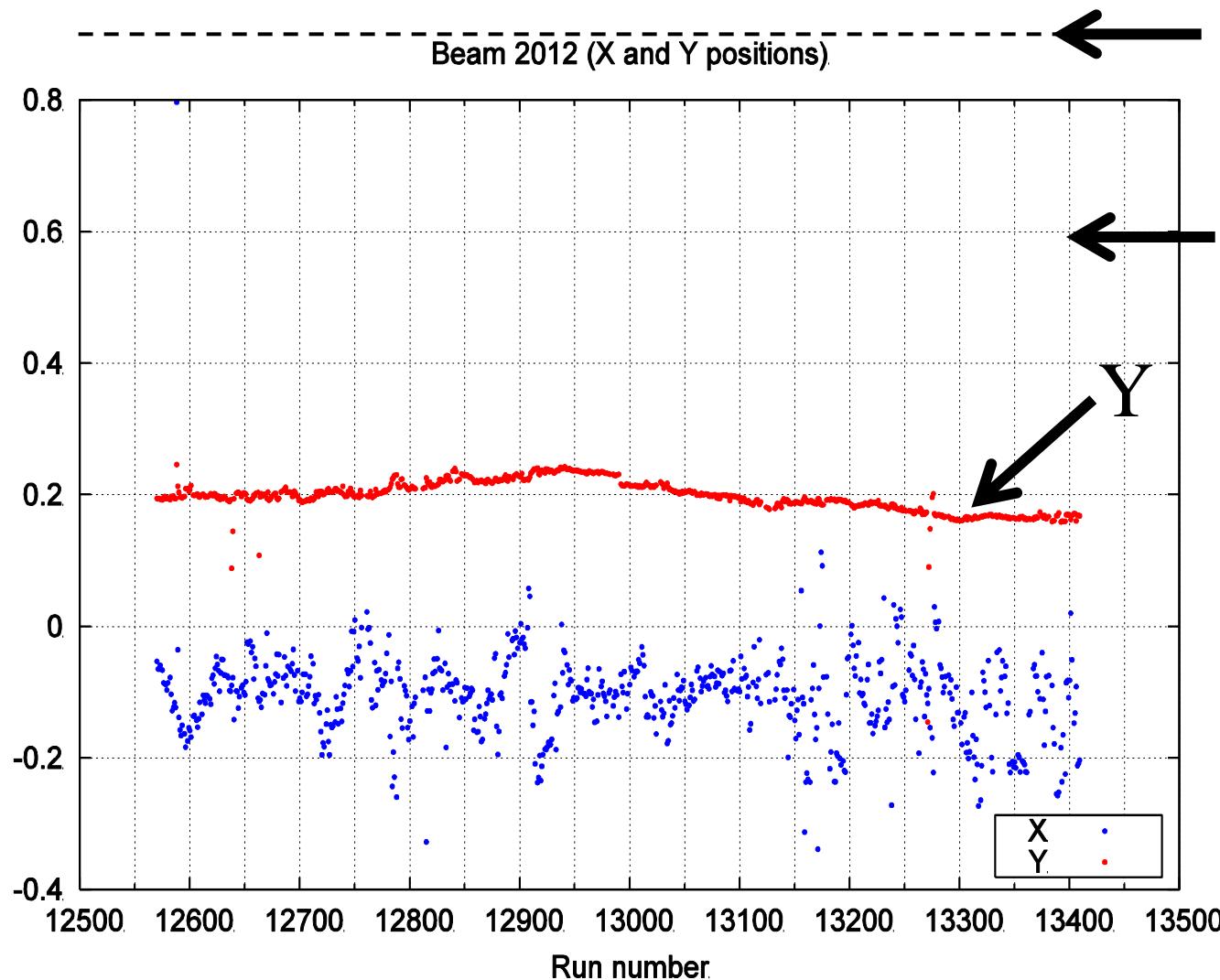
Relative resolution on the particle momentum in L.S.		$3 \cdot 10^{-3}$
Precision on Q-projections (experimental measurement)	$\sigma_{QX} = \sigma_{QY} = 0.5$ MeV/c	$\sigma_{QL} = 0.5$ MeV/c ($\pi\pi$) $\sigma_{QL} = 0.9$ MeV/c (πK)

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

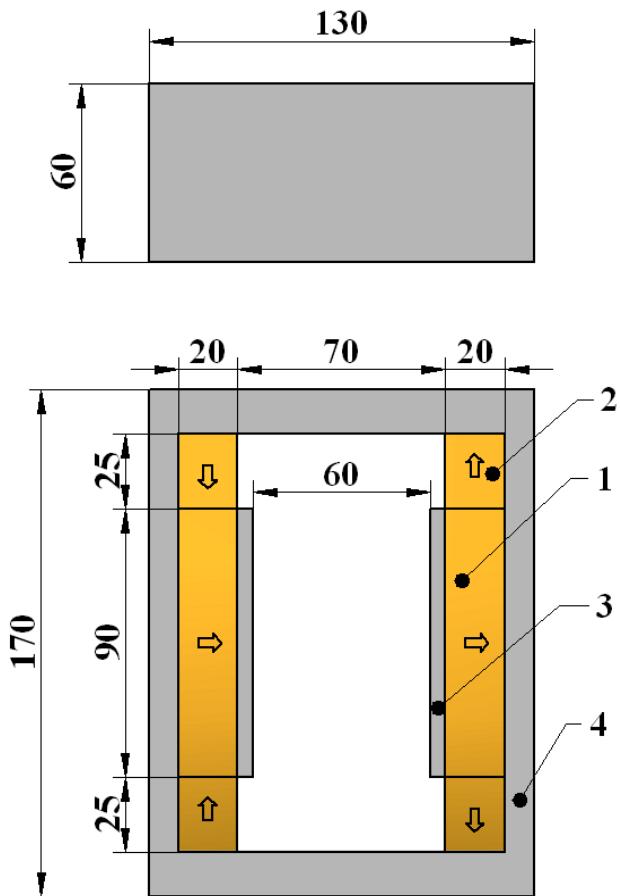
Be target	
Target thickness	103 μm
Radiation thickness	$2.93 \cdot 10^{-4} X_0$
Probability of inelastic proton interaction	$2.52 \cdot 10^{-4}$

y-beam position (run 2012)



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

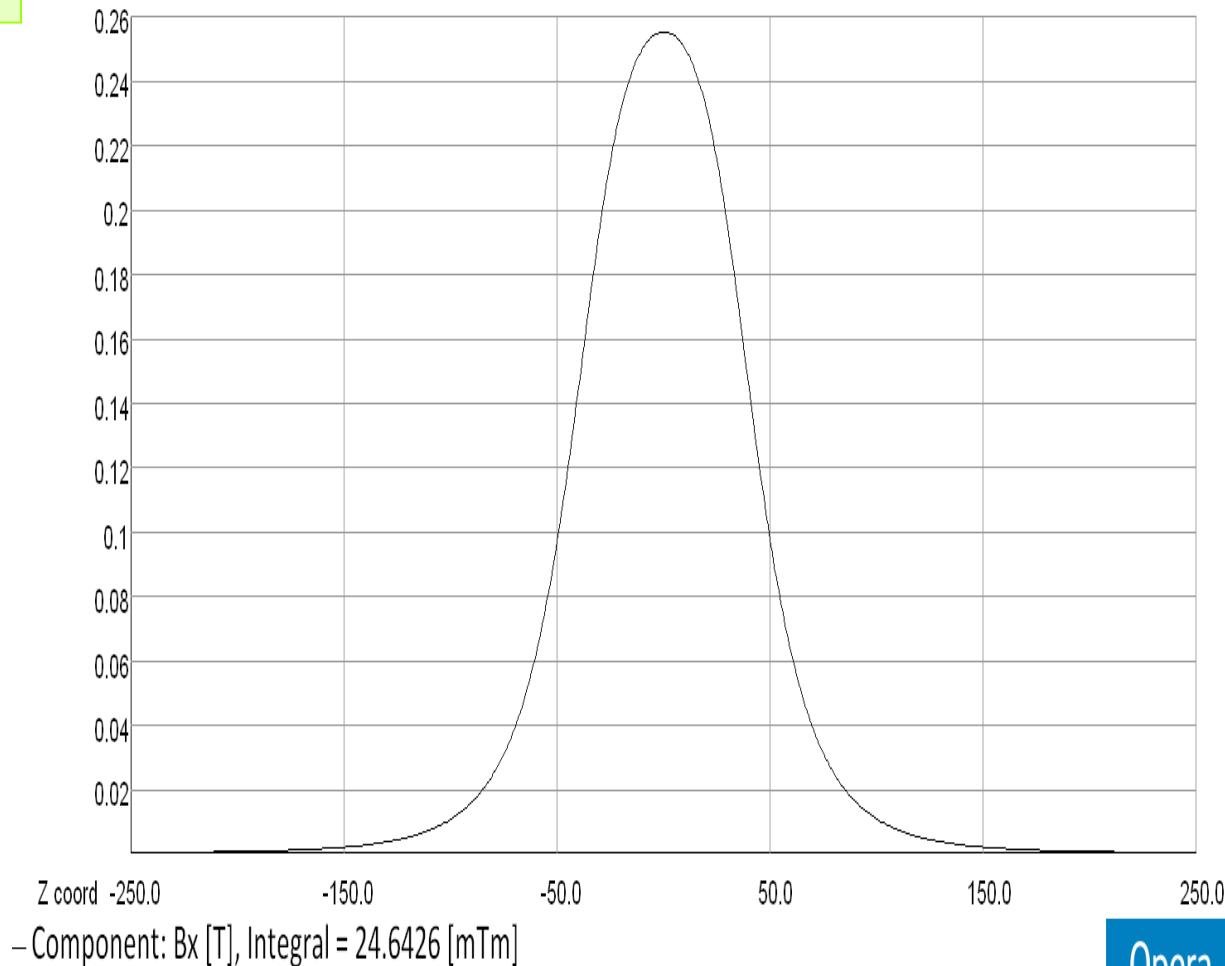
Layout of the dipole magnet
(arrows indicate the direction
of magnetization)



1- PM block Sm₂Co₁₇
2- PM block Sm₂Co₁₇

12-Sep-14

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

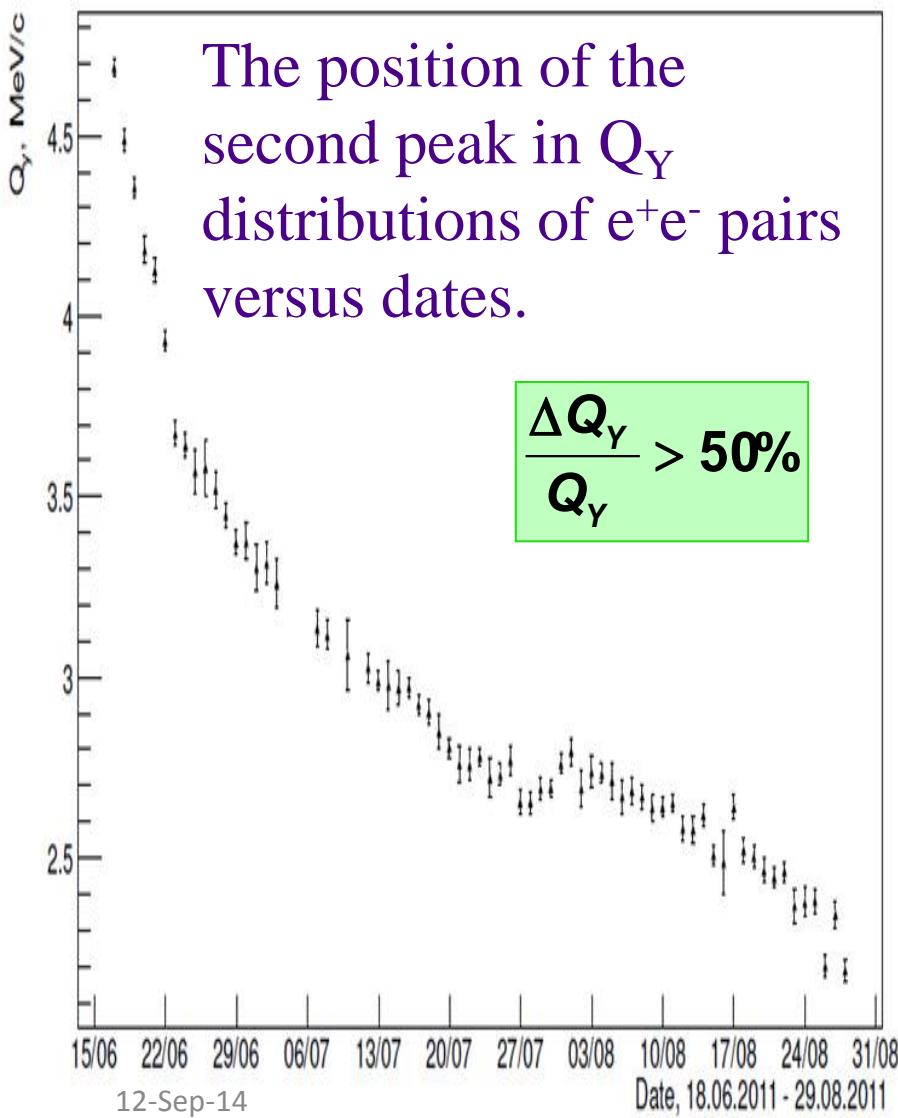


Opera

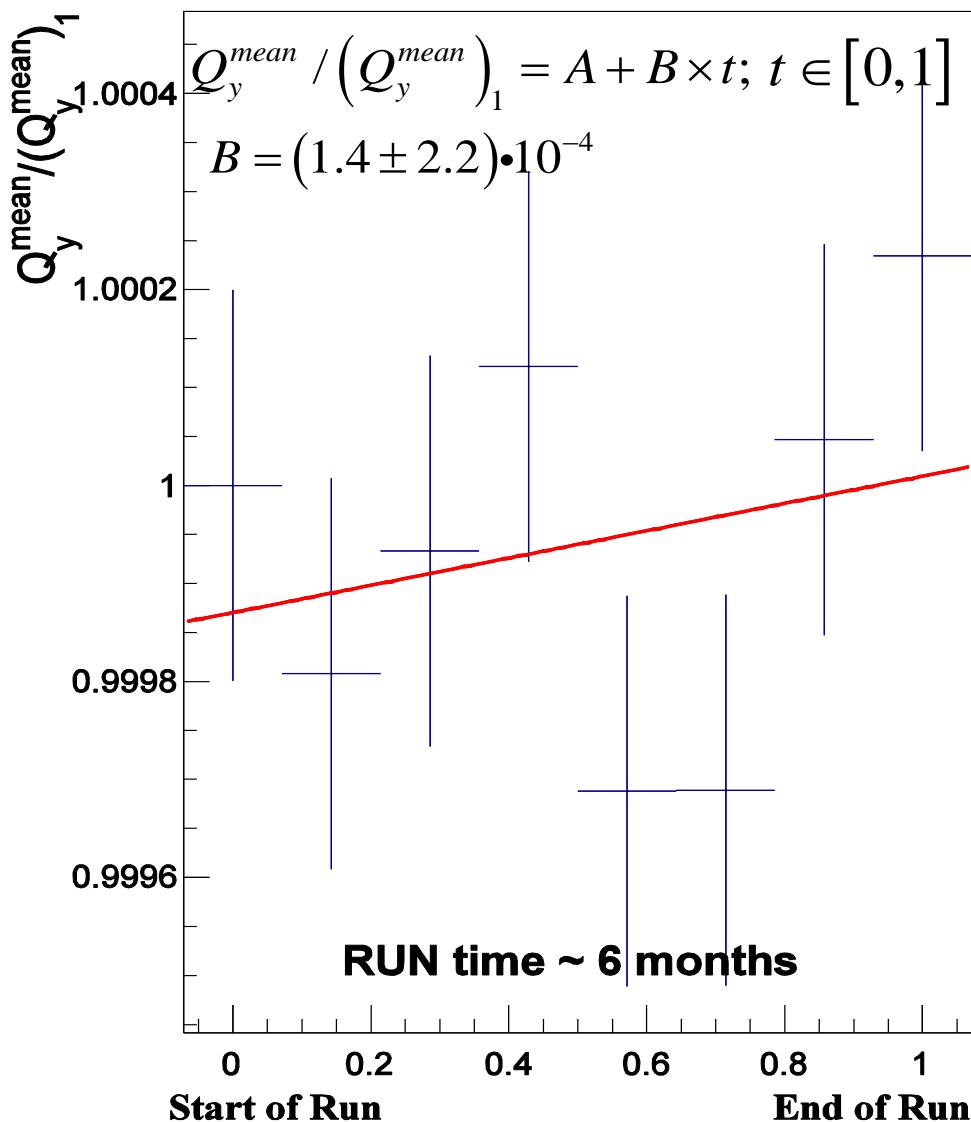
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Degradation of the old magnet and the new one behavior

Old magnet (Nd-Fe-B), 2011

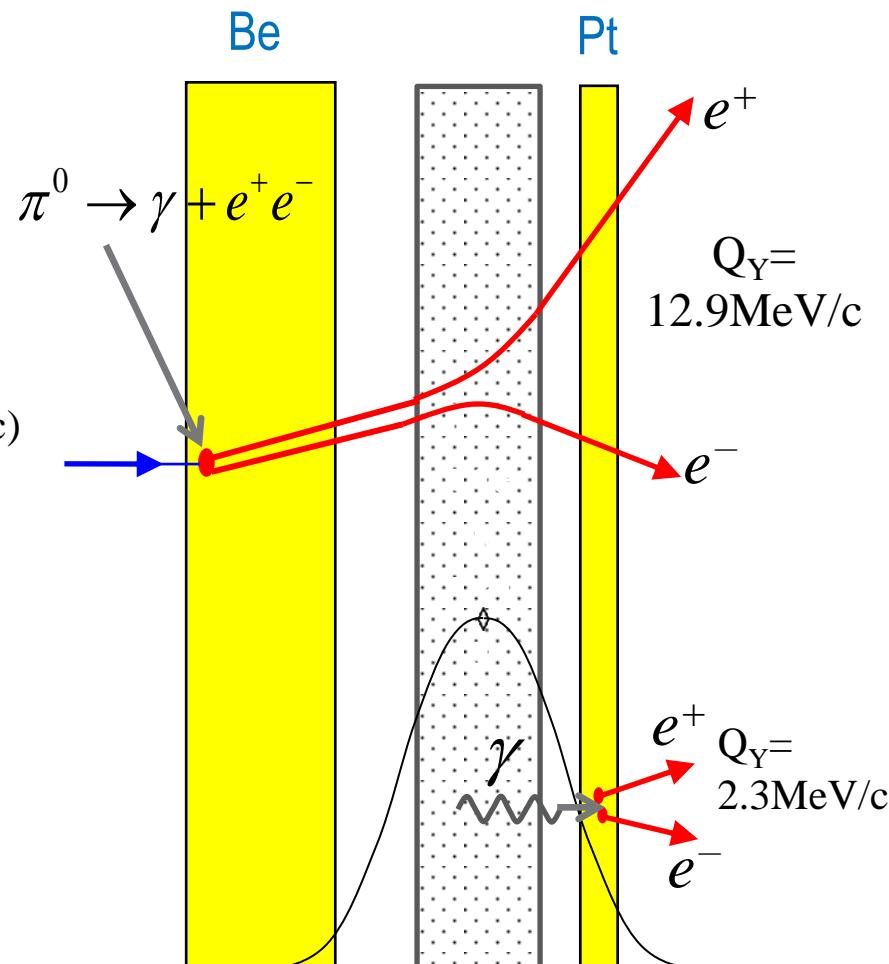
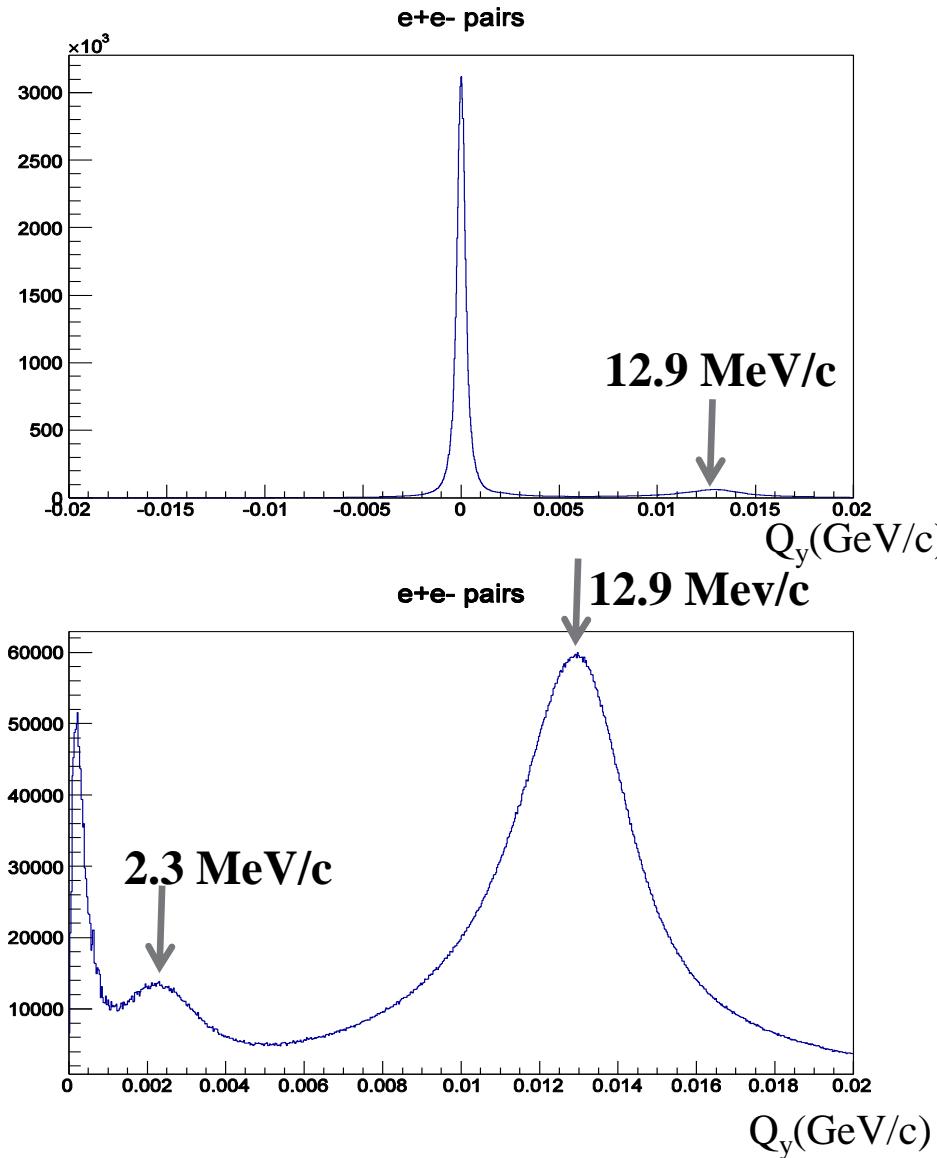


New magnet (Sm-Co), 2012



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

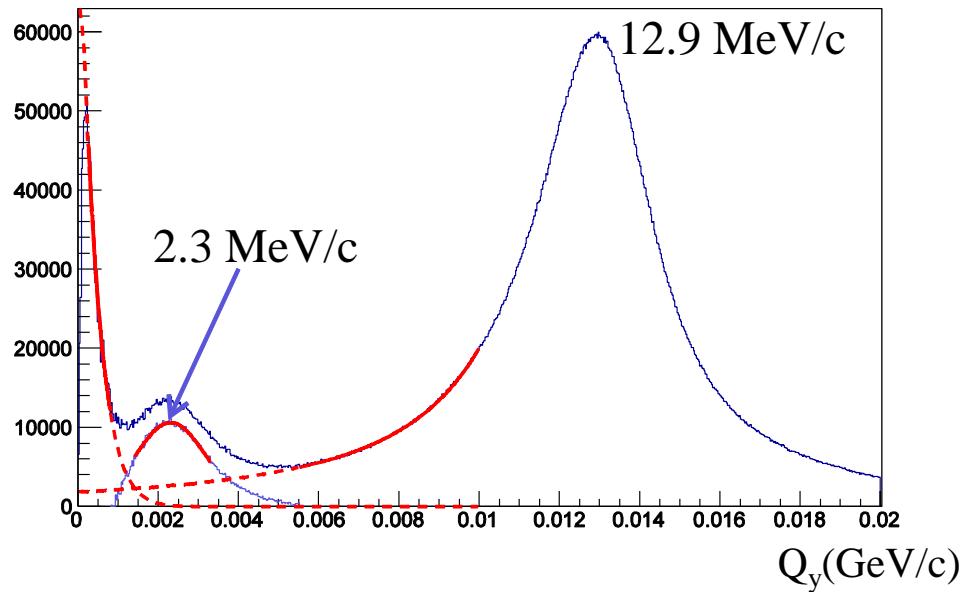
Real data



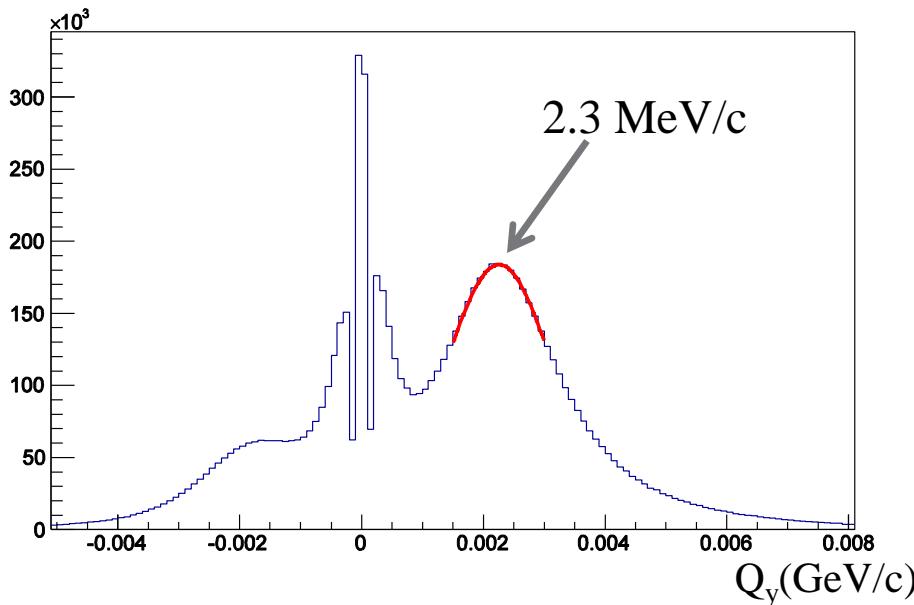
Peak at $Q_y=2.3\text{MeV}/c$ evaluated after subtraction of the mirrored left side part.

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

e^+e^- pairs created in Pt foil

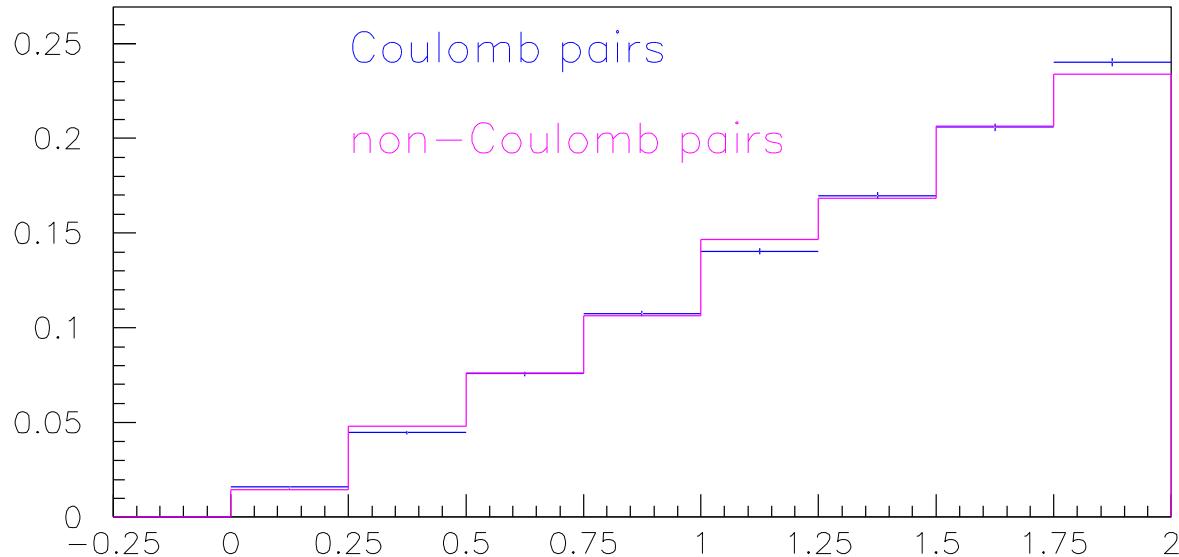


Real Data



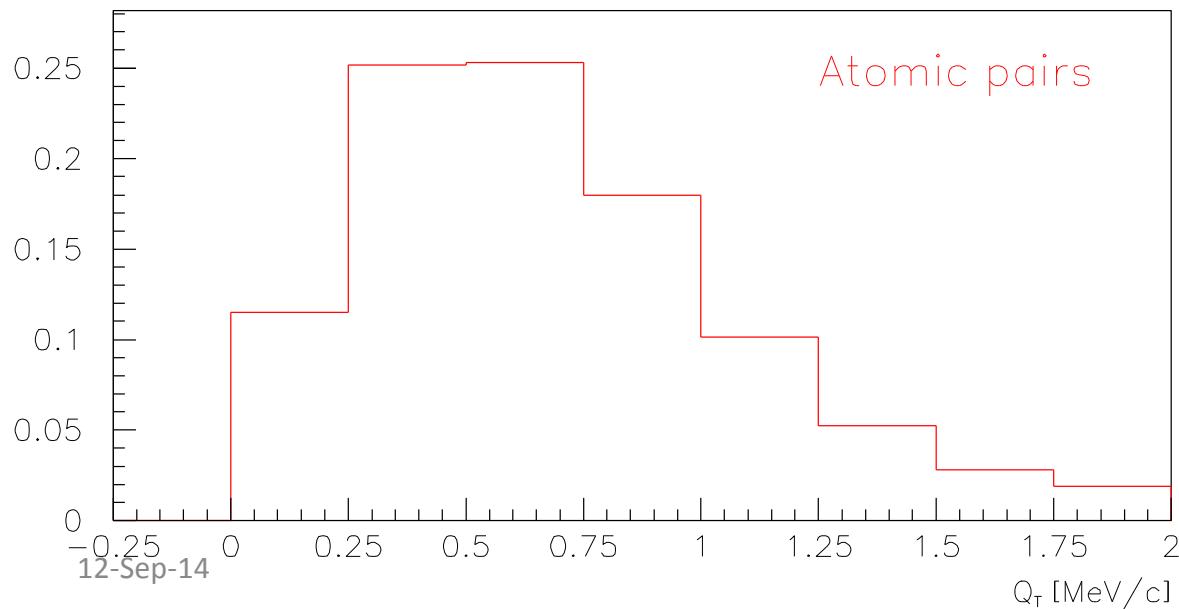
Simulation

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

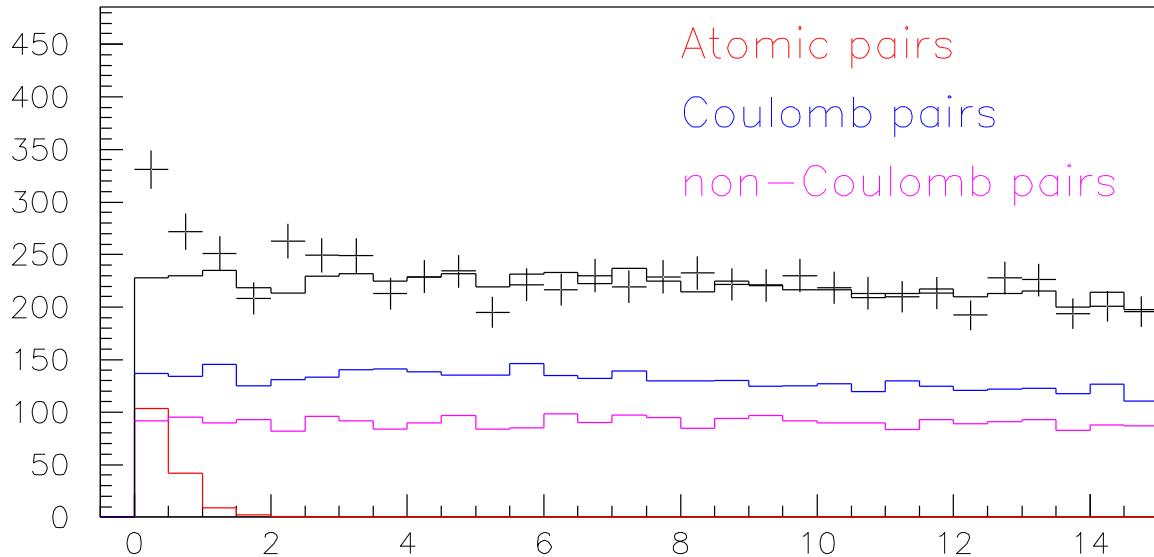


Simulated distributions
of "Coulomb", "non-
Coulomb" and atomic
pairs over Q_T
for $|Q_L| < 2$ MeV/c

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

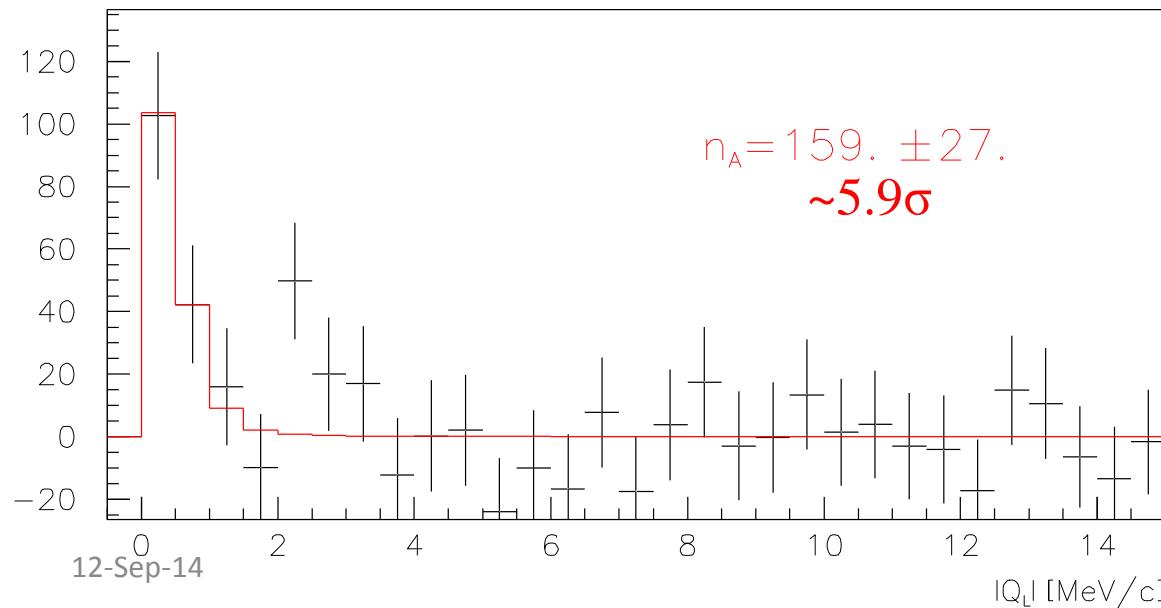


Long-lived $\pi^+\pi^-$ atoms



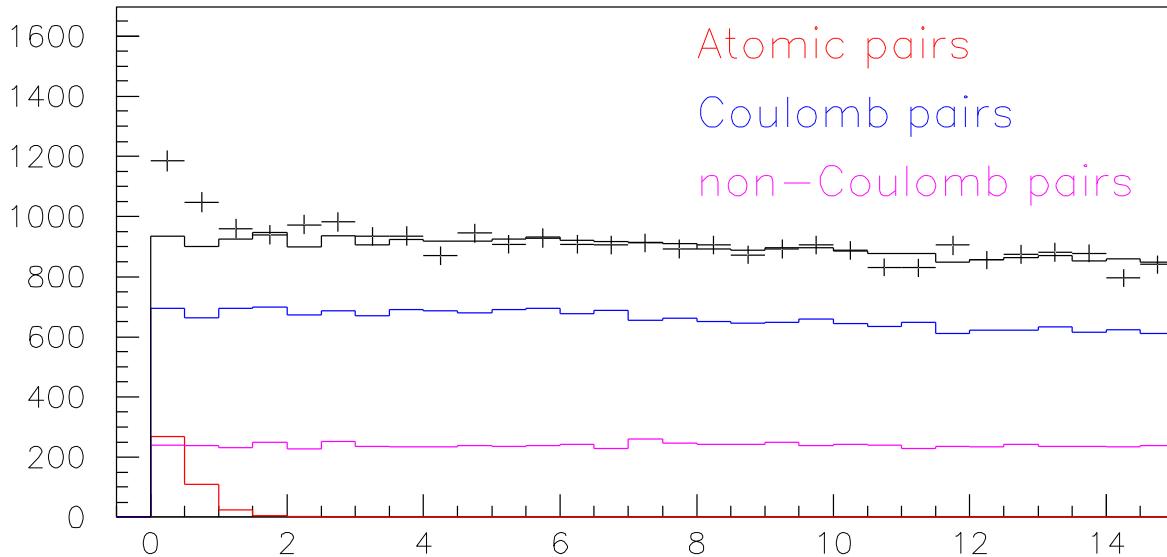
Experimental (real data) and simulated distributions over $|Q_L|$

for $Q_T < 0.5$ MeV/c



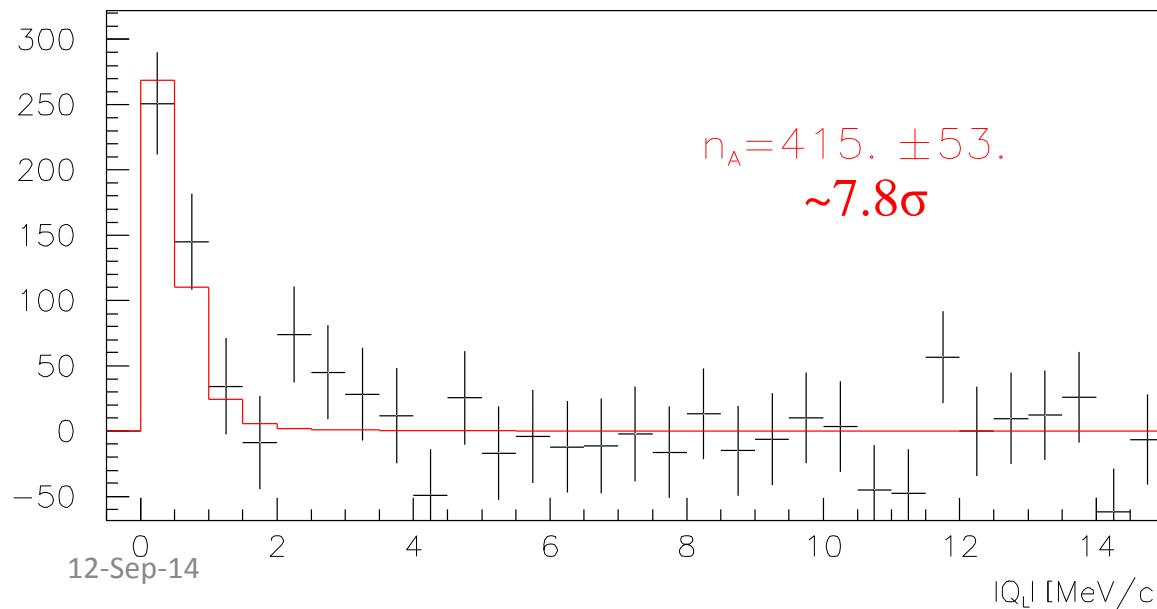
$$Q_T = \sqrt{Q_x^2 + (Q_y - 2.3 \text{ MeV}/c)^2}$$

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



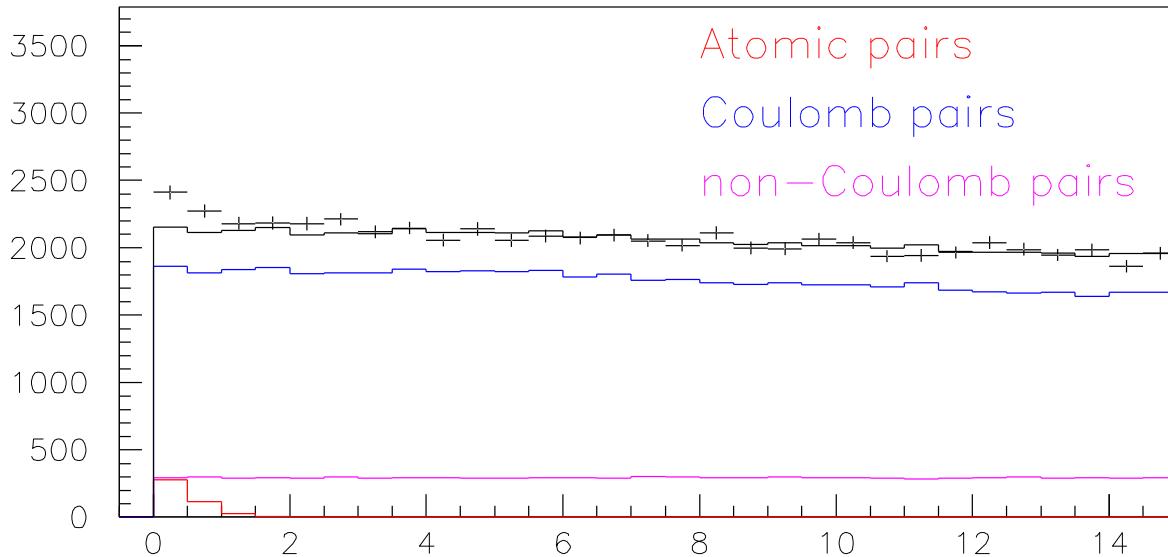
Experimental (real data) and simulated distributions over $|Q_L|$

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



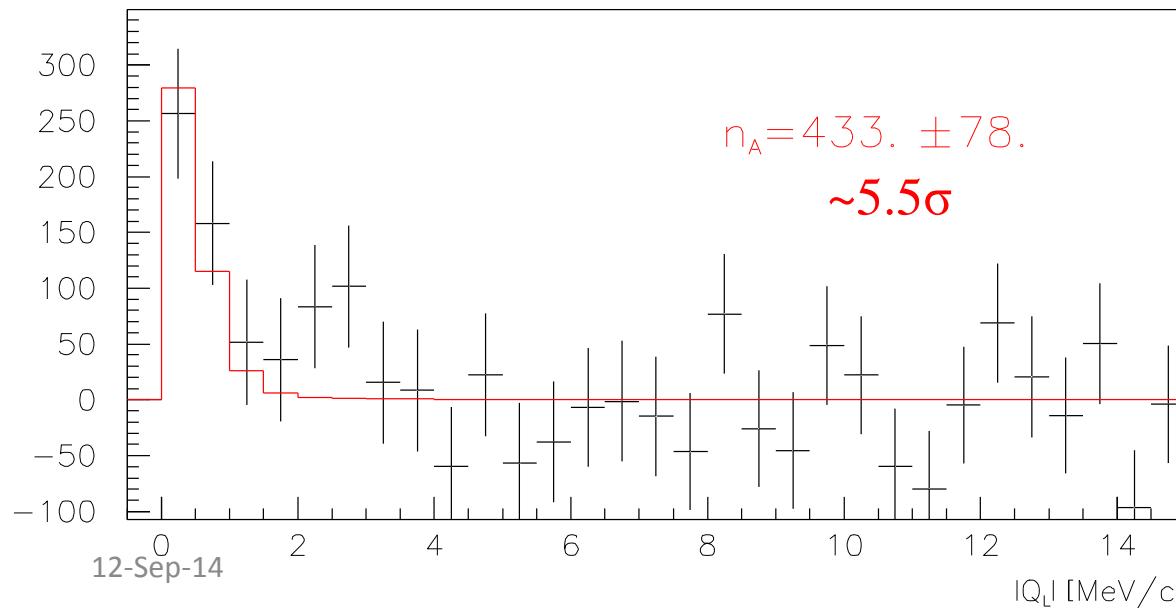
$$Q_T = \sqrt{Q_x^2 + (Q_y - 2.3 \text{ MeV}/c)^2}$$

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



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

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



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

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

Q_T cut	n _A	Selection efficiency	n _A ^{tot}	Background for $Q_L \leq 1.5$ MeV/c
$Q_T < 0.5$ MeV/c	159 ± 27 (~5.9 σ)	0.365	436 ± 74	690
$Q_T < 1.0$ MeV/c	415 ± 53 (~7.8 σ)	0.795	522 ± 67	2775
$Q_T < 1.5$ MeV/c	433 ± 78 (~5.5 σ)	0.945	458 ± 83	6360

$A_{\pi K}$ and $A_{2\pi}$ production on PS and SPS at CERN

	Yield ratio
π^+K^- atoms	35
$K^+\pi^-$ atoms	27
$\pi^+\pi^-$ atoms	17

The ratio of π^+K^- , $K^+\pi^-$ and $\pi^+\pi^-$ atom yields at the proton momentum 450 GeV/c and angle 4° to the yields at the proton momentum 24 GeV/c and angle 5.7° .

Thank you

Additional slides

$A_{2\pi}$ ($\pi^+\pi^-$ atom) characteristics

$A_{2\pi}$ decay dominated by the annihilation process: $\rightarrow \pi^+ + \pi^- \rightarrow \pi^0 + \pi^0$

$A_{2\pi}$ lifetime depends on the $\pi\pi$ scattering length difference $|a_0 - a_2|$ $\rightarrow \frac{1}{\tau} \approx W_{\pi^0\pi^0} = R |a_0 - a_2|^2$

Energy shift contributions $\rightarrow \Delta E_{nl} = \Delta E_{nl}^{em} + \Delta E_{nl}^{vac} + \Delta E_{nl}^{str}$

Strong interaction contribution $\rightarrow \Delta E_{n0}^{str} = A_n (2a_0 + a_2)$

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

Theoretical motivation

ChPT predicts s-wave $\pi\pi$ scattering length

[G. Colangelo, J. Gasser and H. Leutwyler, Nucl. Phys. B603 (2001) 125]

$$a_0 = 0.220 \pm 2.3\%, \quad a_2 = -0.0444 \pm 2.3\%, \quad a_0 - a_2 = 0.265 \pm 1.5\% \quad (\text{in } M_{\pi^+}^{-1} \text{ units})$$

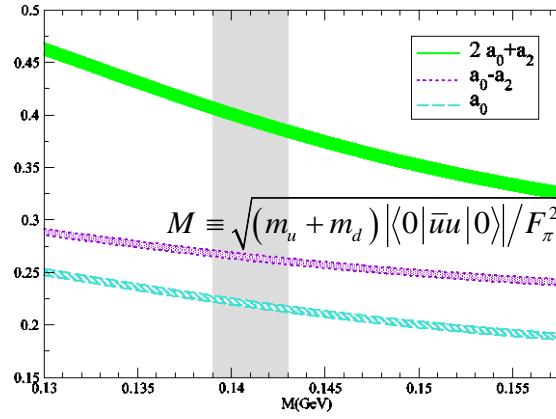
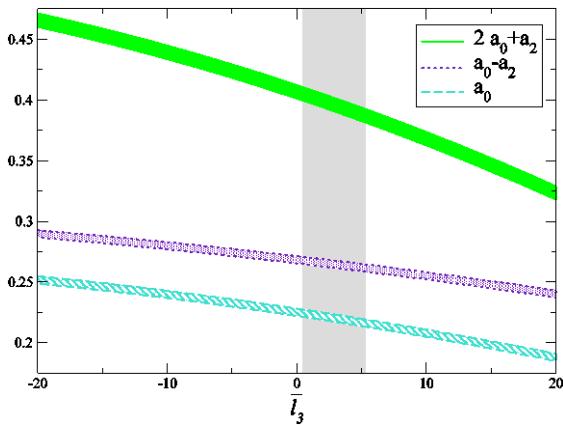
The expansion of M_π^2 in powers of the quark masses starts with the linear term:

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

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

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	$\sigma^t_X = 380 \text{ ps}$	$\sigma^t_Y = 512 \text{ ps}$	$\sigma^t_W = 522 \text{ ps}$
DC		VH	
Coordinate precision	$\sigma = 85 \mu\text{m}$	Time precision	$\sigma = 100 \text{ ps}$

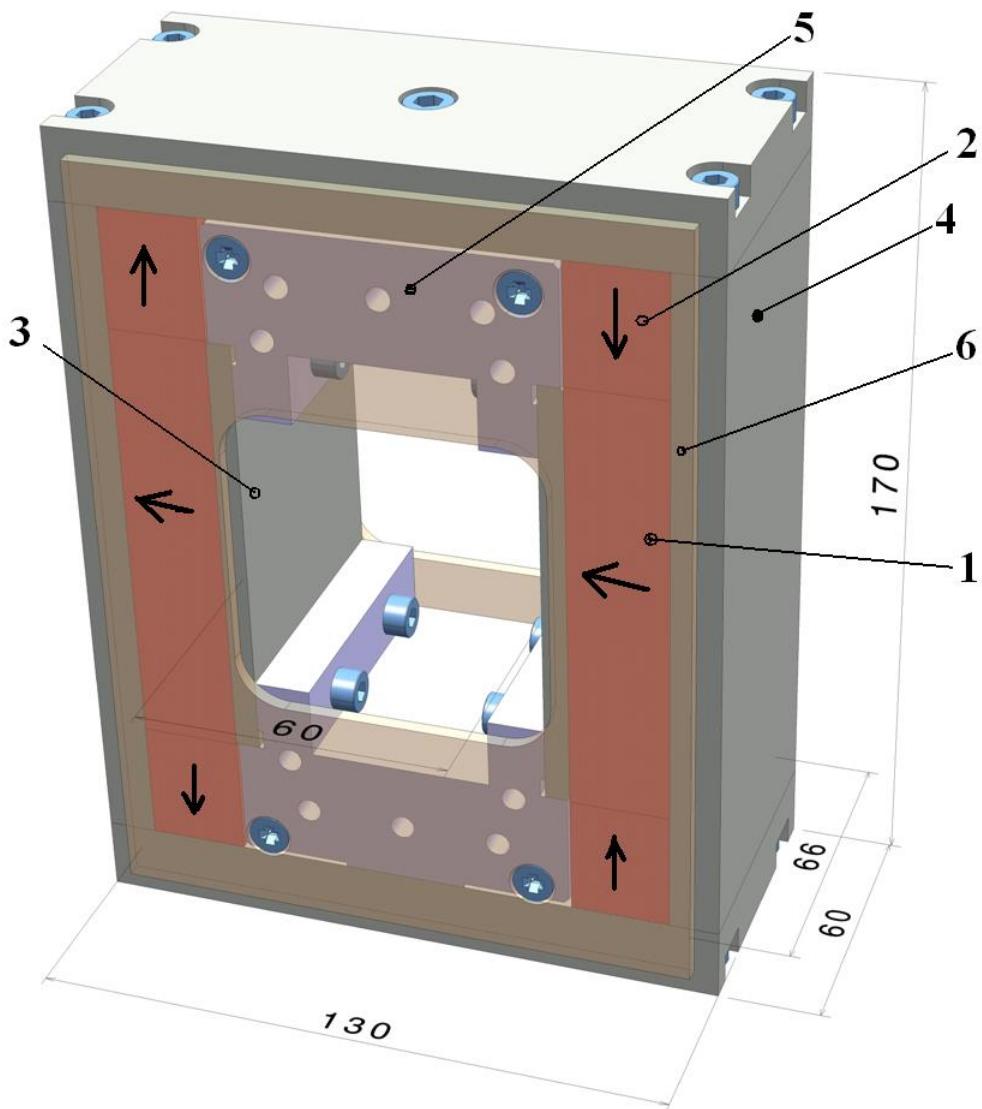
Spectrometer		
Relative resolution on the particle momentum in L.S.		$3 \cdot 10^{-3}$
Precision on Q-projections	$\sigma_{QX} = \sigma_{QY} = 0.5 \text{ MeV/c}$	$\sigma_{QL} = 0.5 \text{ MeV/c } (\pi\pi)$ $\sigma_{QL} = 0.9 \text{ MeV/c } (\pi K)$
Trigger efficiency 98 %	for pairs with	$Q_L < 28 \text{ MeV/c}$ $Q_X < 6 \text{ MeV/c}$ $Q_Y < 4 \text{ MeV/c}$

Experimental conditions

Secondary particles channel (relative to the proton beam)	5.7°
Angular divergence in vertical and horizontal planes	±1°
Solid angle	1.2·10 ⁻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

Magnet – mechanical structure



**1) Permanent block Type 1
(Sm₂Co₁₇)**

**2) Permanent block Type 2
(Sm₂Co₁₇)**

3) Pole (AISI 1010)

4) Return yoke (AISI 1010)

5) Central insert (stainless steel)

**6) Cover plates
(aluminum)**

Magnet - main parameters

Magnet Type	Permanent Magnet Dipole
Quantity	1+1(spare)
Magnet Height × Width × Length	170 mm × 130 mm × 66 mm
Magnet mass	8.6 kg
Full horizontal aperture	60 mm
Good Field Region(GFR) Horizontal × Vertical	20 mm × 30 mm
Magnetic field characteristics	
Nominal integrated horizontal field $\int B_{x(0,0,Z)} dz$	$24.6 \times 10^{-3} T \times m$
Horizontal field in magnet center $B_{x(0,0,0)}$	0.255 T
Magnetic length $\int B_{x(0,0,Z)} dz / B_{x(0,0,0)}$	96.5 mm
Integrated field homogeneity inside GFR $\Delta \int B_x dz / \int B_{x(0,0,Z)} dz$	< ±2%
Components	
Permanent magnet blocks	Sm2Co17, “Recoma 30S” or equivalent
Pole and Return Yoke	Low carbon steel: AISI 1010
Central inserts	Stainless steel: 316L+N
Cover plates	Aluminum: EN-AW-6082

Production yields of $A_{2\pi}$ long-lived states

Target material characteristics for production of long-lived atomic states

- *target thickness, chosen to provide maximum production yield of long-lived states*
- $A_{2\pi}$ **breakup probability**
- $\Sigma(l \geq 1)$: *total yield of long-lived states including states with $n \leq 7$*
- $2p_0, 3p_0, 4p_0$, *production yield of p-states with magnetic quantum number $m = 0$*
- $\Sigma(l=1, m=0)$: *sum of the p-states up to $n = 7$*

Target Z	Thickness μm	Breakup	$\Sigma(l \geq 1)$	$2p_0$	$3p_0$	$4p_0$	$\Sigma(l=1, m=0)$
Be 04	100	6.3%	5.5%	1.18%	0.46%	0.15%	1.90%
Ni 28	5	9.42%	9.69%	2.40%	0.58%	0.18%	3.29%
Pt 78	2	18.8%	10.5%	2.70%	0.55%	0.16%	3.53%

Simulation of all $\pi^+\pi^-$ pairs at experimental conditions

Population of $A_{2\pi}$ long-lived states at the ***Be*** target exit and at the ***Pt*** foil entry,
 (percentage from total number of produced atoms)

<i>at the Be target exit</i>							
<i>l \ n</i>	2	3	4	5	6	7	8
1	2.29	0.82	0.27	0.10	0.04	0.02	0.01
2	0.00	0.65	0.27	0.11	0.05	0.02	0.01
3	0.00	0.00	0.25	0.12	0.06	0.03	0.01
4	0.00	0.00	0.00	0.11	0.06	0.03	0.01
5	0.00	0.00	0.00	0.00	0.06	0.03	0.01
6	0.00	0.00	0.00	0.00	0.00	0.03	0.01
7	0.00	0.00	0.00	0.00	0.00	0.00	0.01

<i>at the Pt foil entry</i>							
<i>l \ n</i>	2	3	4	5	6	7	8
1	0.32	0.43	0.20	0.09	0.04	0.02	0.01
2	0.00	0.50	0.24	0.11	0.05	0.02	0.01
3	0.00	0.00	0.24	0.12	0.05	0.03	0.01
4	0.00	0.00	0.00	0.11	0.06	0.03	0.01
5	0.00	0.00	0.00	0.00	0.06	0.03	0.01
6	0.00	0.00	0.00	0.00	0.00	0.03	0.01
7	0.00	0.00	0.00	0.00	0.00	0.00	0.01

Simulation of all $\pi^+\pi^-$ pairs at experimental conditions

Number of atomic pairs produced by breakup in the $1\mu\text{m}$ **Pt** foil from states with specific n and l .
(percentage from total number of produced atoms)

		At the Pt foil exit						
l	n	2	3	4	5	6	7	8
1	1	0.05	0.07	0.04	0.02	0.01	0.01	0.00
2	2	0.00	0.08	0.06	0.04	0.02	0.01	0.01
3	3	0.00	0.00	0.06	0.04	0.03	0.02	0.01
4	4	0.00	0.00	0.00	0.05	0.03	0.02	0.01
5	5	0.00	0.00	0.00	0.00	0.03	0.02	0.01
6	6	0.00	0.00	0.00	0.00	0.00	0.02	0.01
7	7	0.00	0.00	0.00	0.00	0.00	0.00	0.01

Generating $A_{2\pi}$ in long-lived states on Beryllium target

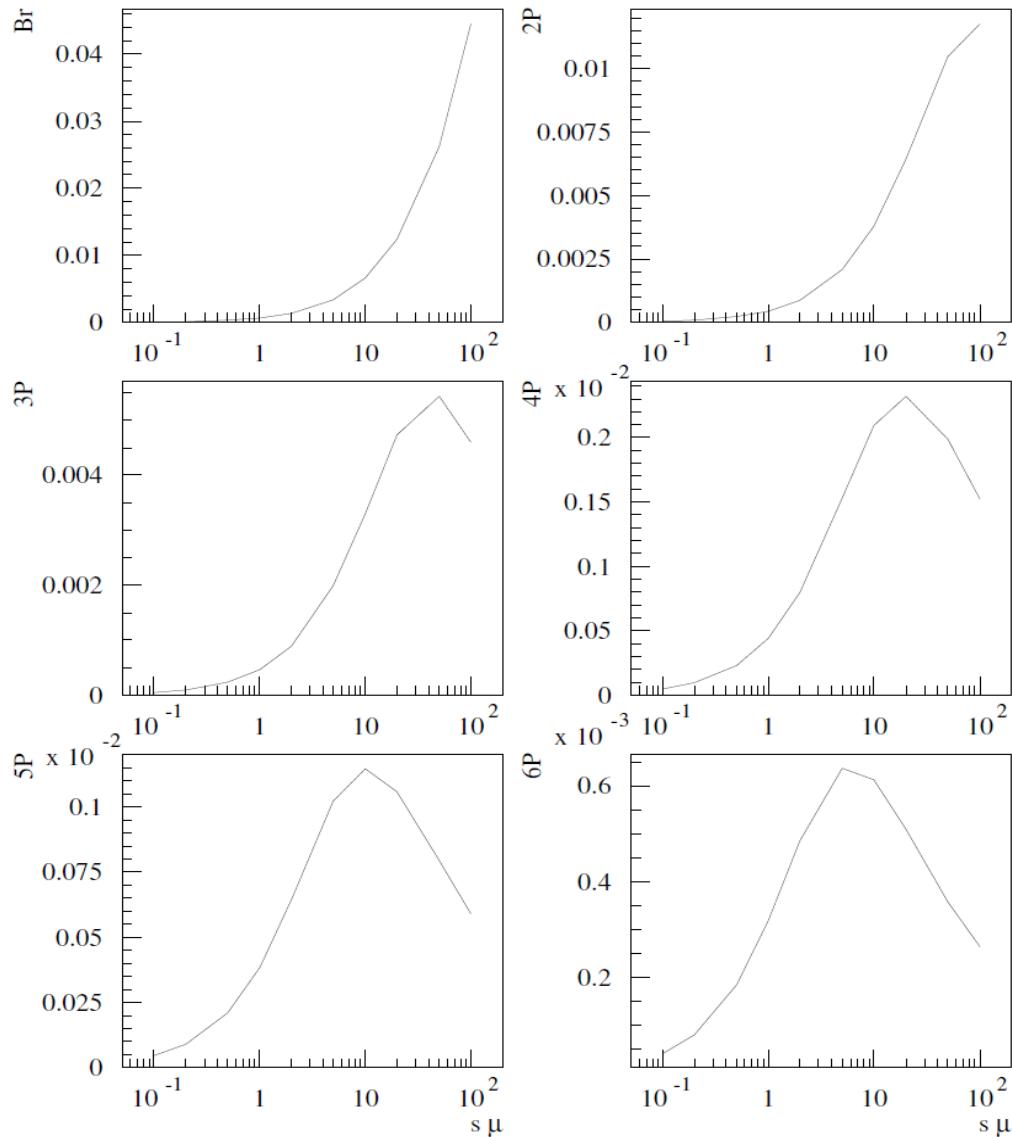
	Be	Al	Ni	Pt
$L(\mu\text{m})$	100	20	5	2
$\frac{X}{X_0} \times 10^4$	2.84	2.24	3.53	6.57
$\epsilon_{nucle} \times 10^4$	2.45	0.48	0.34	0.23

Target thickness L in microns, radiation length (X/X_0), and nuclear efficiency (probability for proton-nucleus interaction)

The proton-target beam interaction will generate $A_{2\pi}$ in ns states as follows:

$$W_{1s} = 83\%, \quad W_{2s} = 10.4\%, \quad W_{3s} = 3.1\%, \quad W_{>3s} = 3.5\%$$

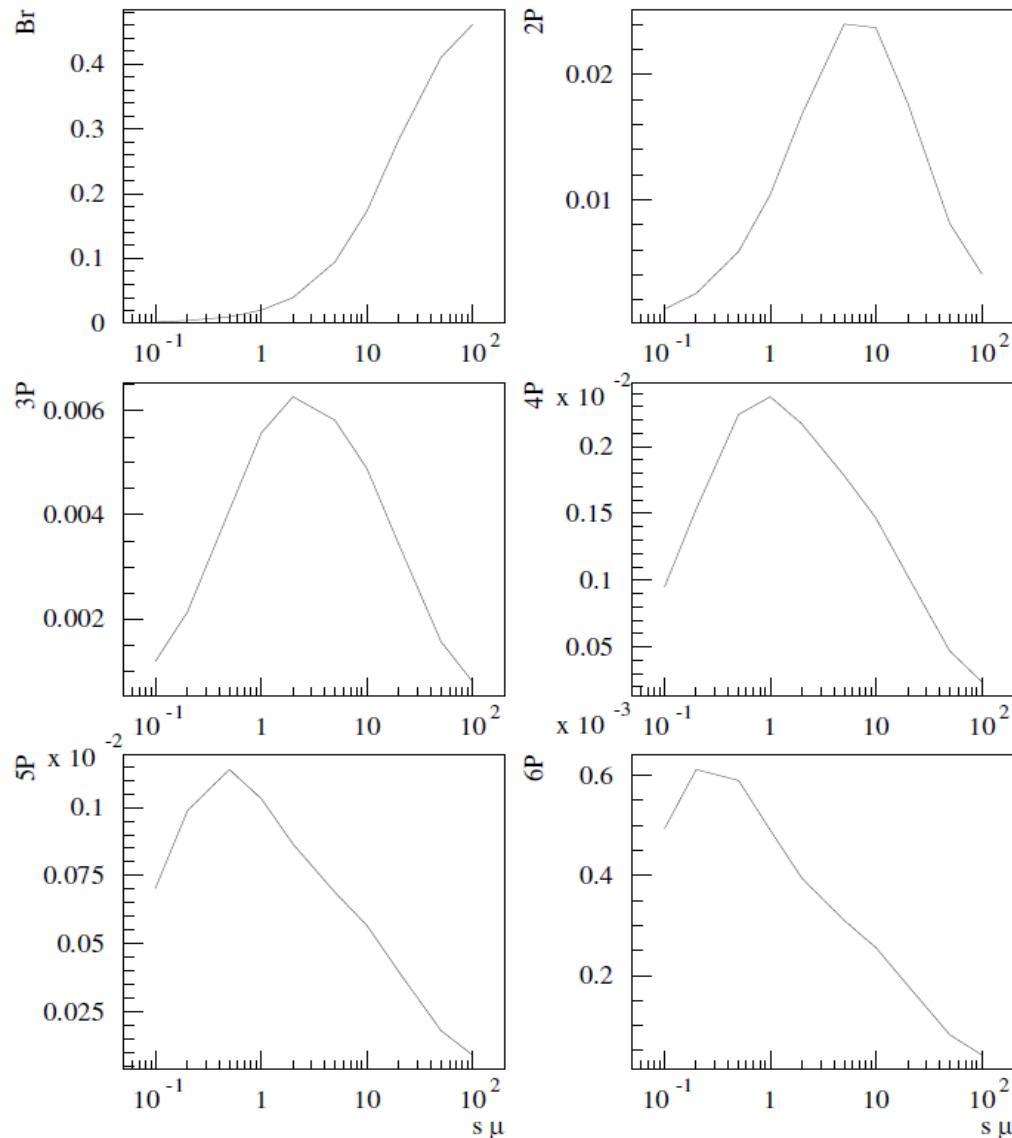
Production yields of $A_{2\pi}$ long-lived states



Probability of $A_{2\pi}$ breakup (Br) and production yields of the long-lived states $2p$, $3p$, $4p$, $5p$, $6p$ ($m=0$) as a function of the target thickness, for Beryllium ($Z=4$) target.

The $A_{2\pi}$ ground state lifetime is assumed to be $3.0 \cdot 10^{-15}$ s and the atom momentum 4.5 GeV/c.

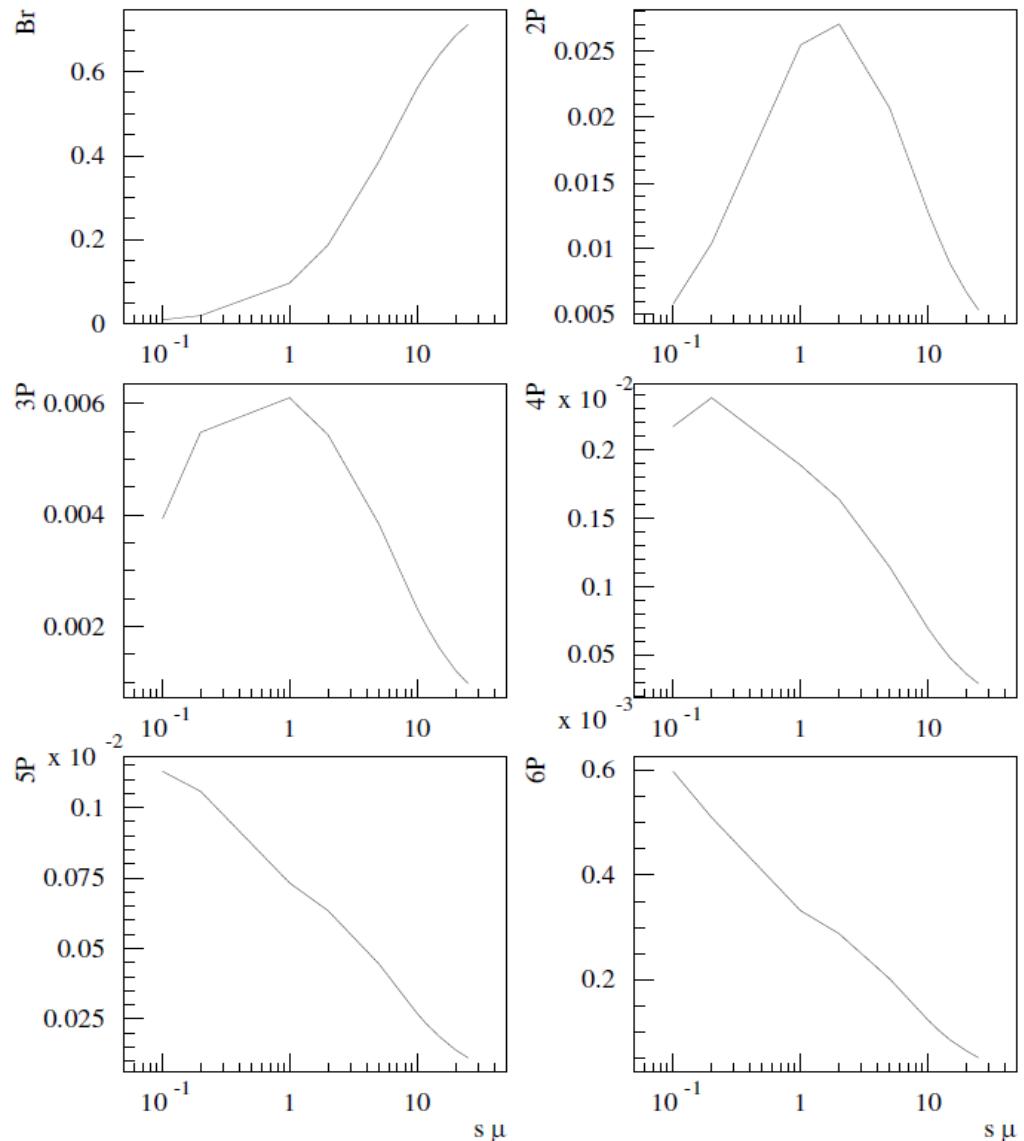
Production yields of $A_{2\pi}$ long-lived states



Probability of $A_{2\pi}$ breakup (Br) and production yields of the long-lived states 2p, 3p, 4p, 5p, 6p ($m=0$) as a function of the target thickness, for Nickel (Z=28) target.

The $A_{2\pi}$ ground state lifetime is assumed to be $3.0 \cdot 10^{-15}$ s and the atom momentum 4.5 GeV/c.

Production yields of $A_{2\pi}$ long-lived states



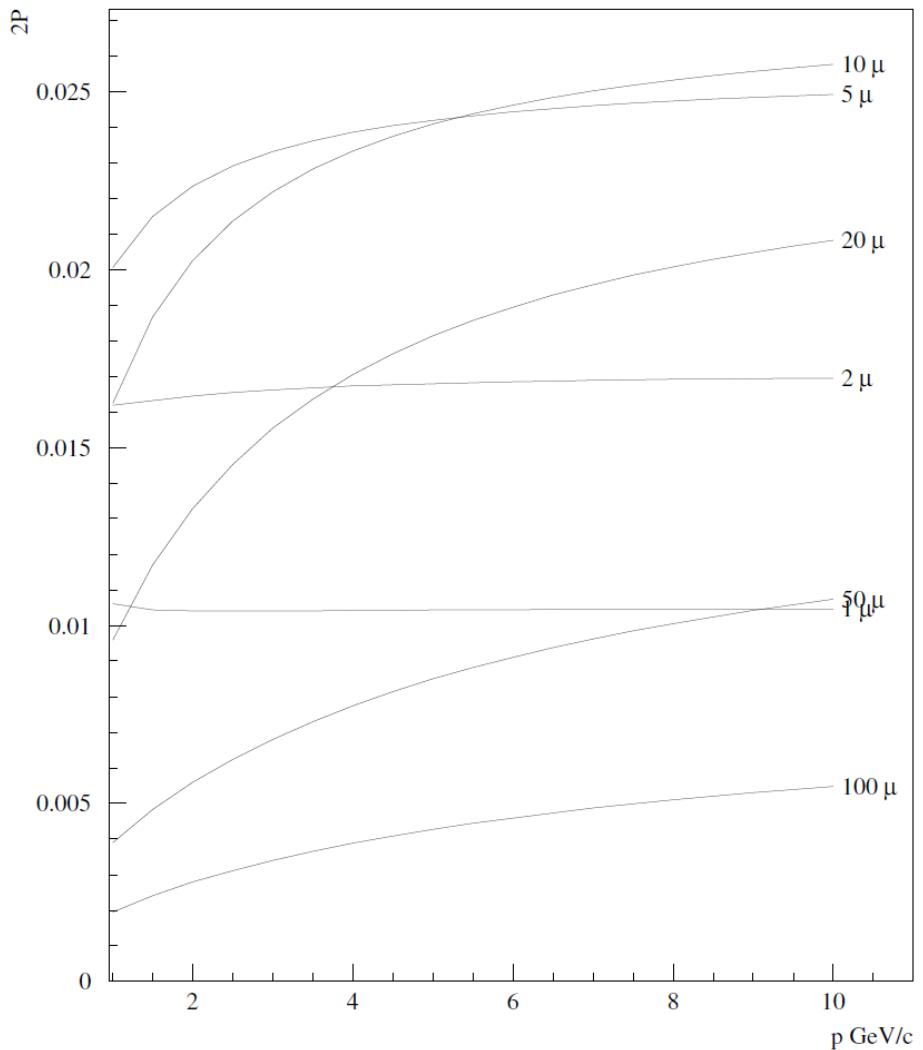
Probability of $A_{2\pi}$ breakup (Br) and production yields of the long-lived states $2p$, $3p$, $4p$, $5p$, $6p$ ($m=0$) as a function of the target thickness, for Platinum ($Z=78$) target.

The $A_{2\pi}$ ground state lifetime is assumed to be $3.0 \cdot 10^{-15}$ s and the atom momentum 4.5 GeV/c.

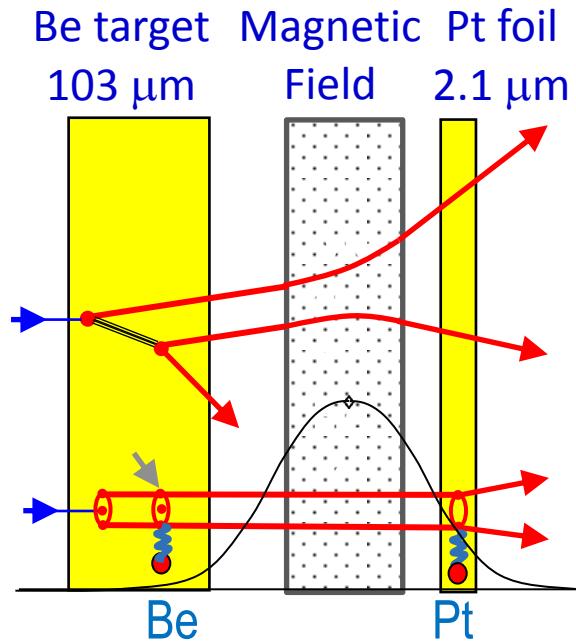
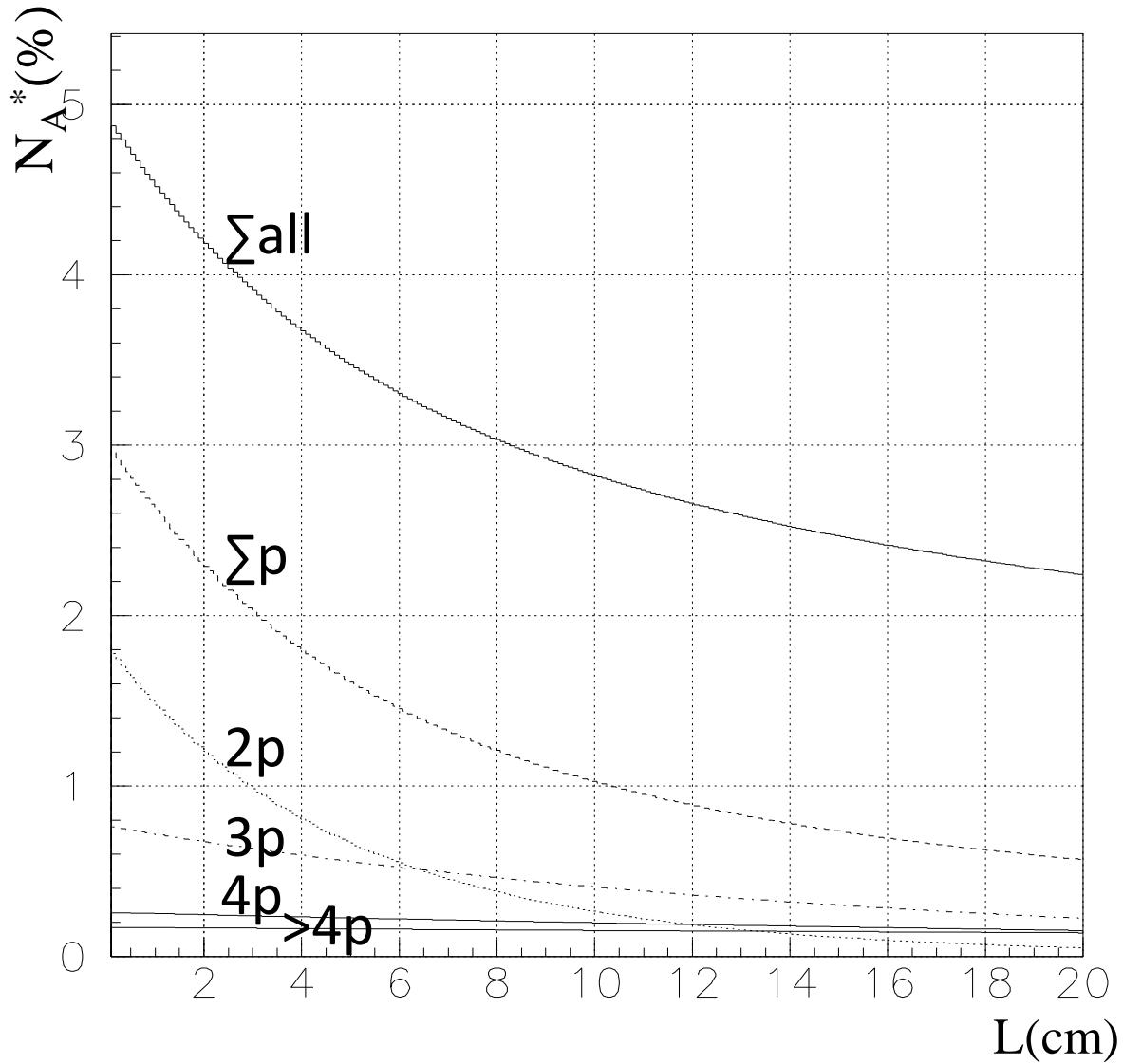
Production yields of $A_{2\pi}$ long-lived states

Production yield of the $A_{2\pi}$ long-lived state $2p$ ($m=0$) as a function of the atom momentum for the Nickel ($Z=28$) target.

Target thickness is given in microns on the right side. The $A_{2\pi}$ ground state lifetime was assumed to be $3.0 \cdot 10^{-15}$ s.



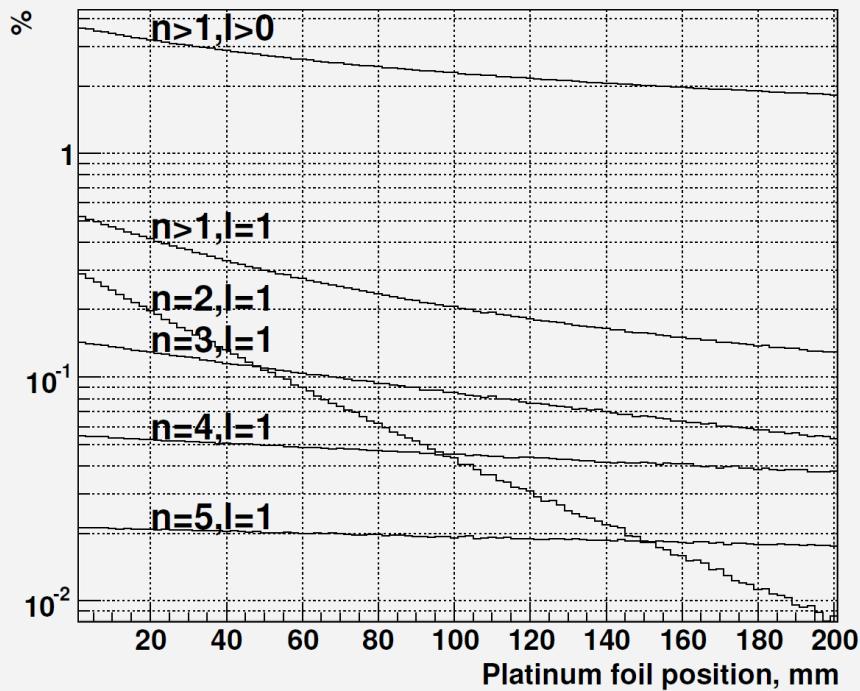
Simulation of all $\pi^+\pi^-$ pairs production from long-lived $A_{2\pi}$ states



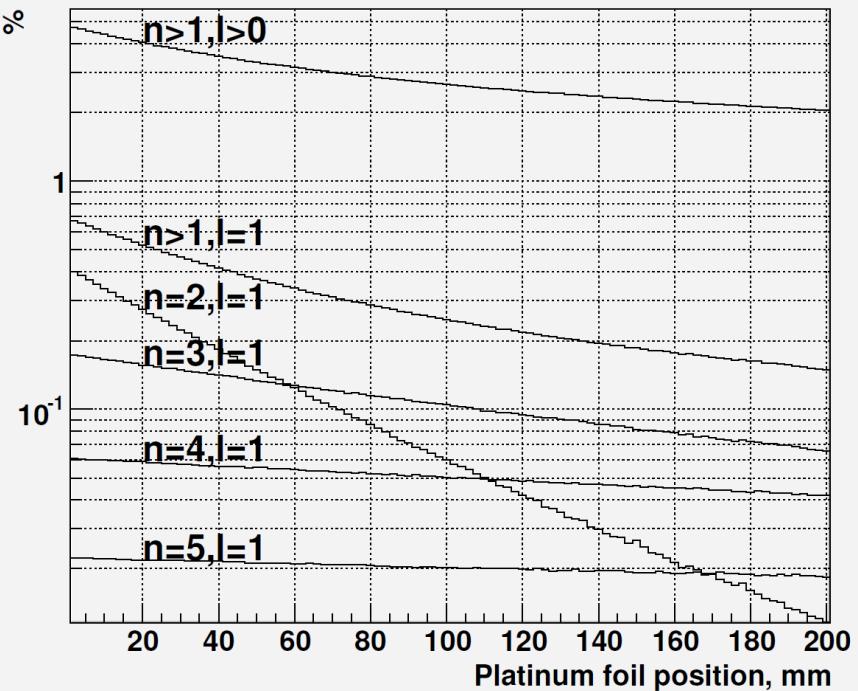
L – position of the Pt foil from Be target

Simulation of all $\pi^+\pi^-$ pairs at experimental conditions

The relative exit of pairs from metastable atoms: Be 100 μ and Pt 1 μ

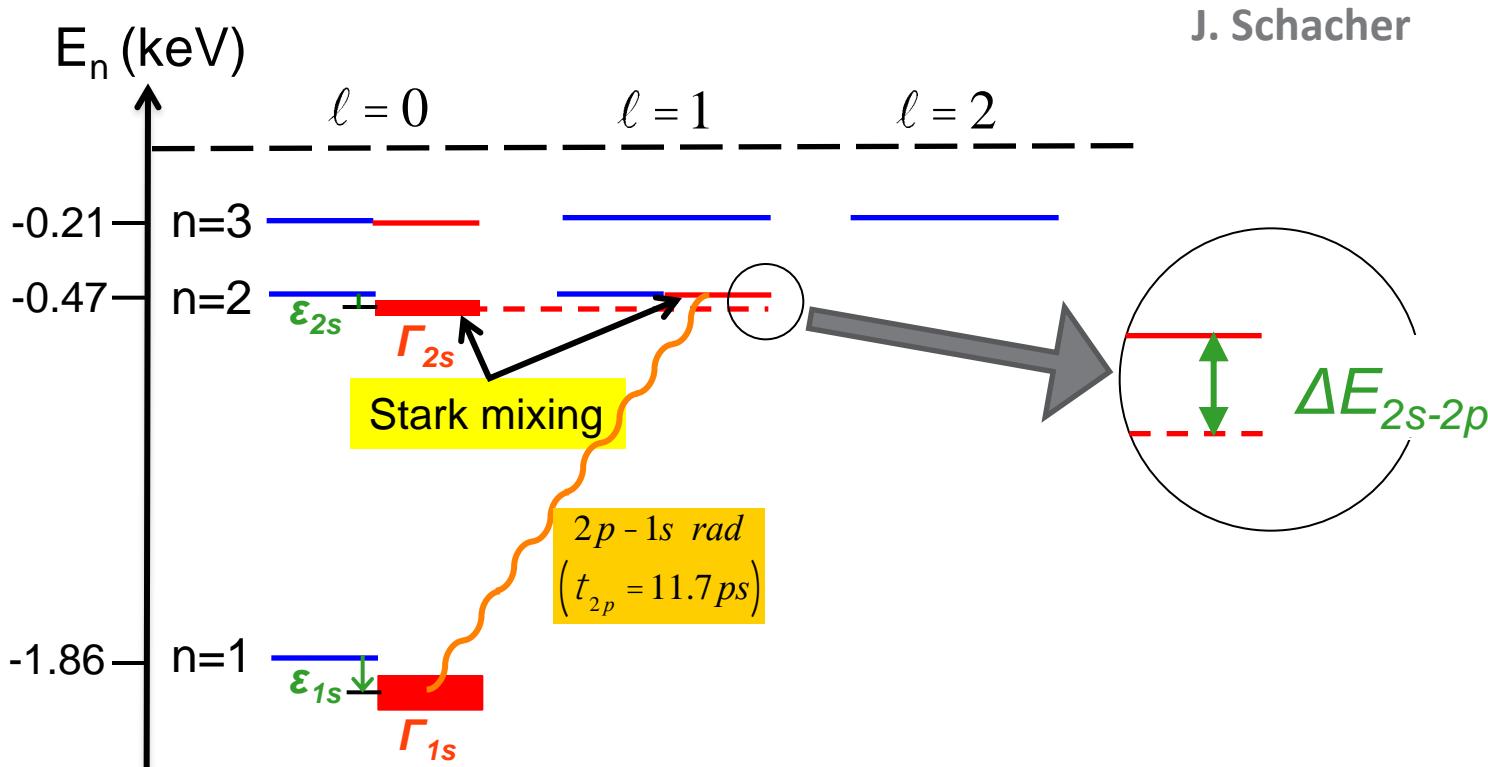


The relative exit of pairs from metastable atoms: Be 100 μ and Pt 2 μ



Part of the atoms, which were created in the Be target and then broken up in the Pt foil, as a function of the distance between Be target and Pt foil for all metastable states ($n > 1, l > 0$) and for some individual states with $l = 1$. The foil thickness is 1μ and 2μ .

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



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

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

$\begin{cases} \text{2s level shifted below 2p level} \\ \text{by } \approx 0.6 \text{ eV "Lamb" shift} \end{cases}$

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

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

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

J. Schacher

(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	$\approx 1 \cdot 10^{-6}$	$\approx 1.2 \cdot 10^4$

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

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

^{*)} $\Delta E_{n_0}^{str} \sim A_n (2a_0 + a_2)$

The lifetime of $\pi^+\pi^-$ atom in electric field

L. Nemenov, V. Ovsianikov (P. L. 2001)

$$M = \frac{3F\hbar^2}{\mu_l} \delta_{m,0}, \quad F - \text{strength of electric field in } A_{2\pi} \text{ c.m.s.}$$

$$F = \beta\gamma B_L, \quad B_L \text{ in lab. syst.}$$

→ m must be 0

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

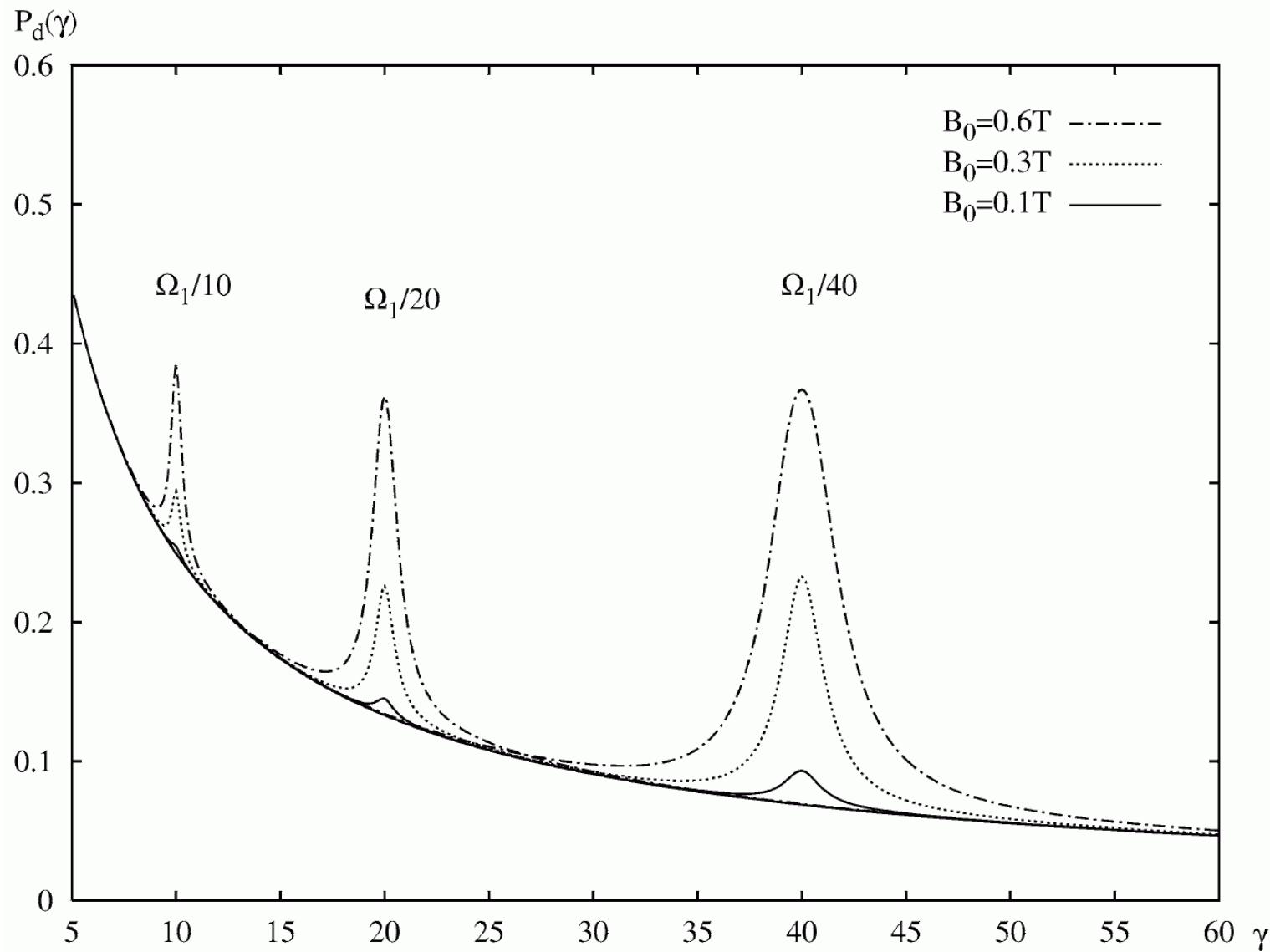
$$\xi(2s - 2p) = \xi_0 \gamma B_L \quad \xi_0 \sim \frac{1}{E_{2s} - E_{2p}} \quad \xi_n = \frac{\xi_0}{8} n^3 \gamma B_L$$

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

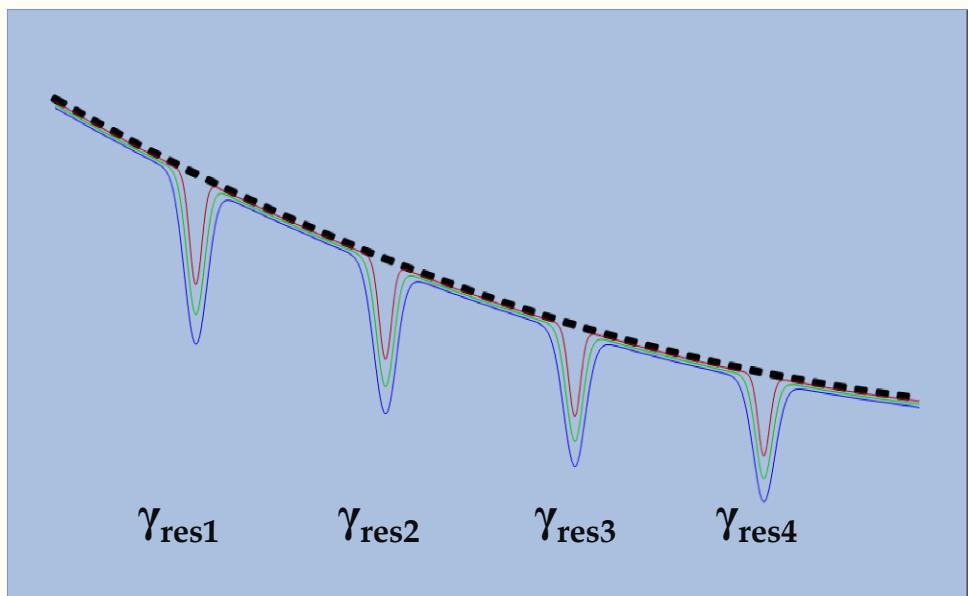
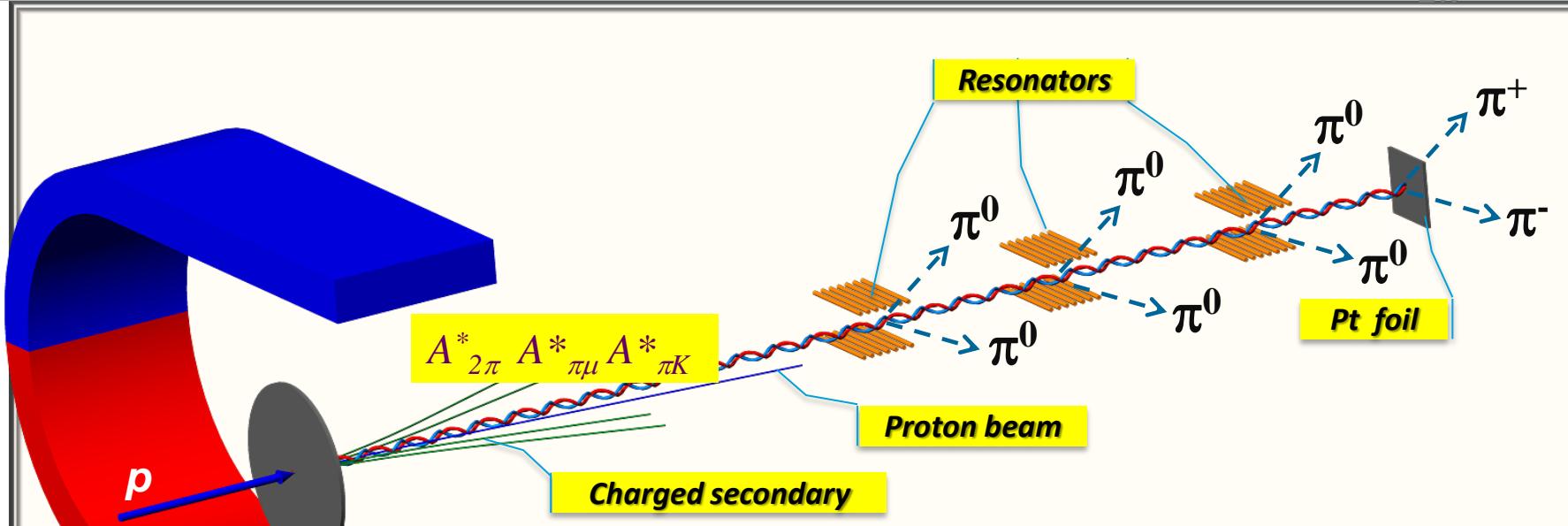
CONCLUSION: the lifetimes for long-lived states can be calculated using only one parameter → $E_{2s} - E_{2p}$.

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 $W(m=0) \approx 50\%$.

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



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



H=0.0 T $\xi=1$ $N_A=330 \pm 40$
H=0.1 T $\xi=1$ $N_A=330$ (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

Δ_{2s-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 $\xi = 40\%$ 317.273

	2p	3p	4p	5p	6p	7p	8p	Σ
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 $\xi = 100\%$ 276.147

	2p	3p	4p	5p	6p	7p	8p	Σ
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 $\xi = 160\%$ 240.908

	2p	3p	4p	5p	6p	7p	8p	Σ
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

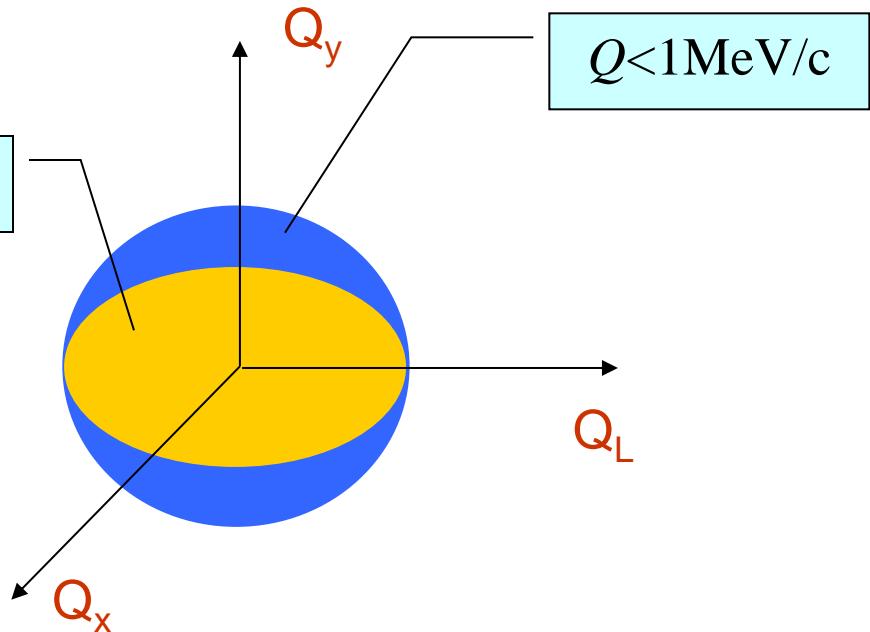
DIRAC prospects at SPS CERN

**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

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

Q and F for Be

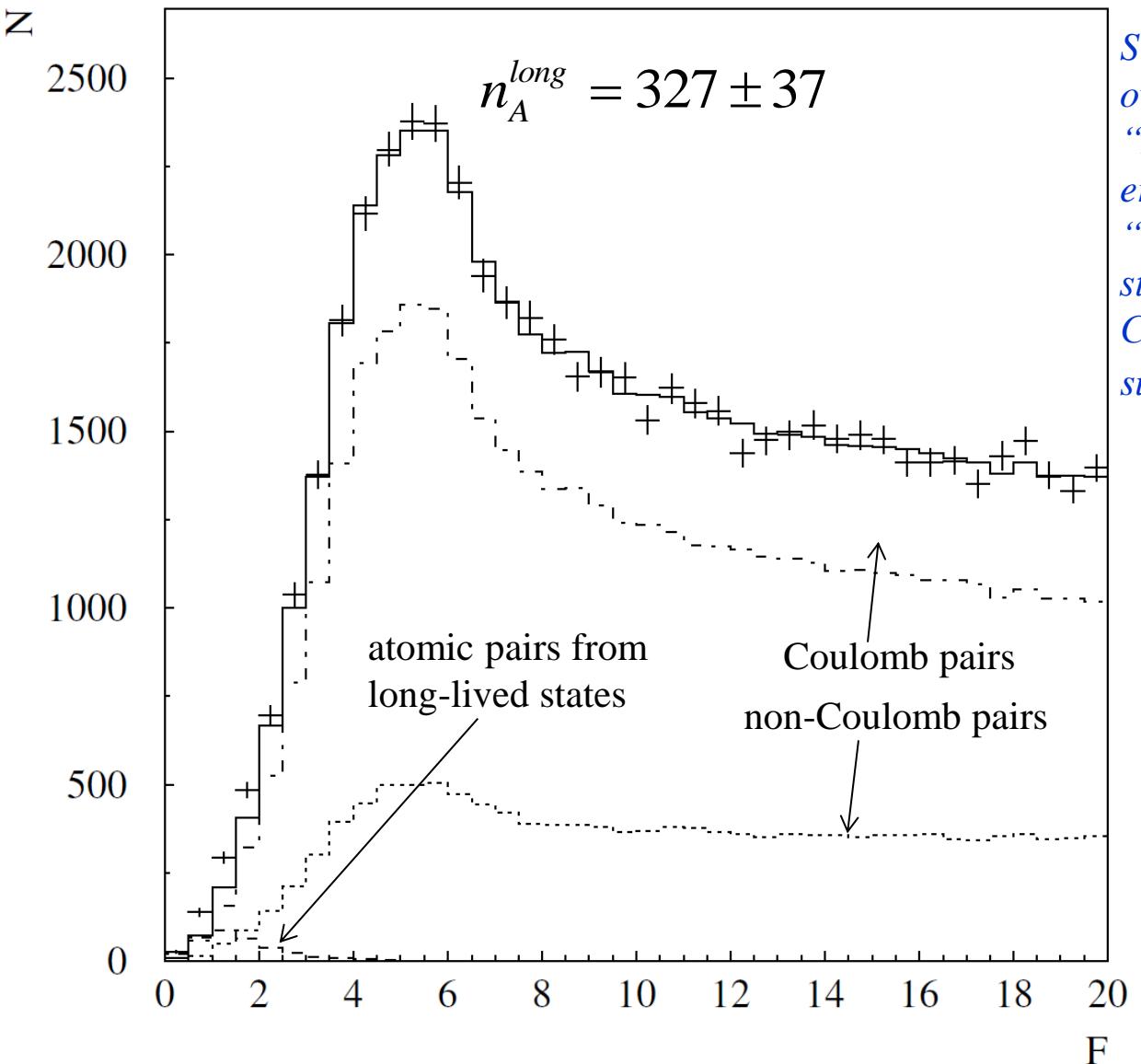


$$Q = \sqrt{Q_X^2 + Q_Y^2 + Q_L^2}$$

$$F = \sqrt{\frac{Q_X^2}{\sigma_{Q_X}^2} + \frac{Q_Y^2}{\sigma_{Q_Y}^2} + \frac{Q_L^2}{\sigma_{Q_L}^2}}$$

$$\begin{cases} \sigma_{Q_X} = 0.5 \text{ MeV} / c \\ \sigma_{Q_Y} = 0.32 \text{ MeV} / c \\ \sigma_{Q_L} = 0.56 \text{ MeV} / c \end{cases}$$

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



Simulated distribution of $\pi^+\pi^-$ pairs over F , with criterion $Q_T < 2\text{MeV}/c$. “Experimental” data (points with error bars) are fitted by a sum of “atomic pairs” from long-lived states, “Coulomb pairs”, “non-Coulomb pairs”. The background sum is shown by the solid line.

$$F = \sqrt{\left(\frac{Q_x}{0.50}\right)^2 + \left(\frac{Q_y}{0.32}\right)^2 + \left(\frac{Q_z}{0.56}\right)^2}$$

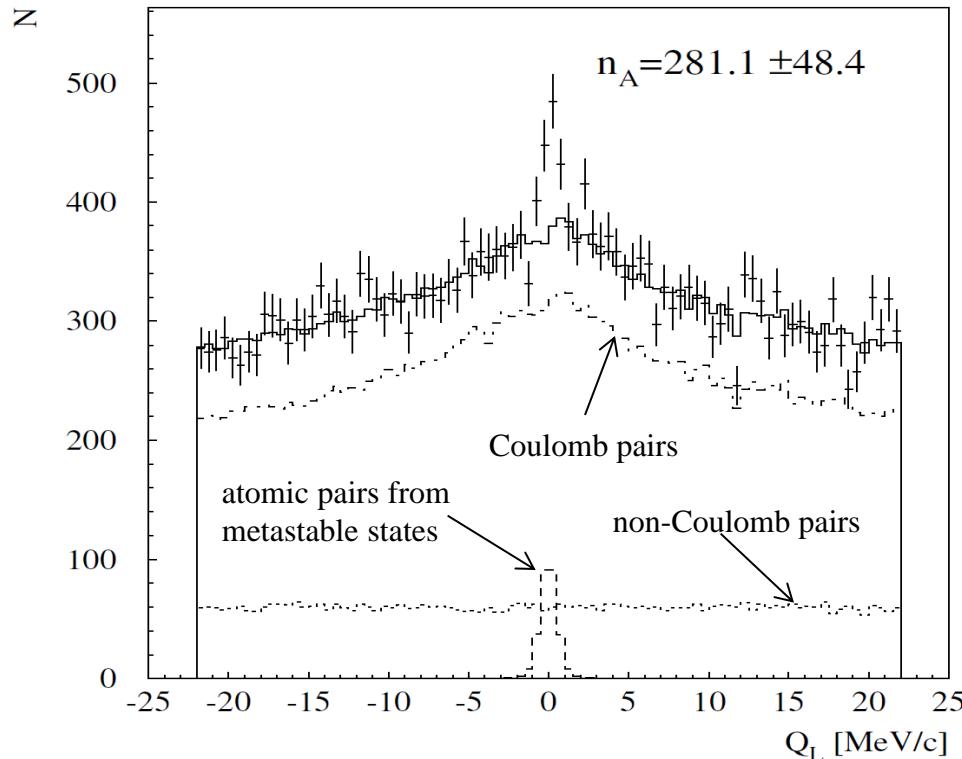
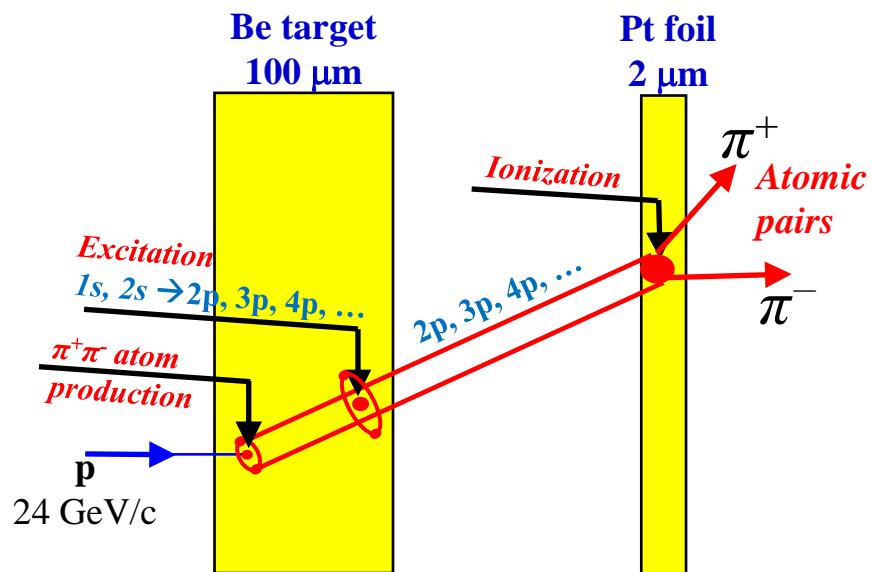
where 0.50, 0.32 and 0.56 Mev/c are RMS’s of the atomic pairs distribution over corresponding components of the relative momentum Q . Now,

$$n_A^{long} = 327 \pm 37 ; \frac{n_A}{\sigma_{n_A}} = 8.8$$

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

The observation of long-lived $\pi^+\pi^-$ atom states 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 lengths $|2a_0+a_2|$.

If a resonance method can be applied for the $\Delta E(ns-np)$ measurement, then the precision of $\pi^+\pi^-$ scattering length measurement can be improved by one order of magnitude relative to the precision of other methods.



Simulated distribution of $\pi^+\pi^-$ pairs over Q_L , with cut $Q_T < 1$ MeV/c. Experimental data (crosses) are fitted by a sum of “atomic pairs” from long-lived states (dash line), “Coulomb pairs” (dot-dash line) and “non-Coulomb pairs” (dot line). Total background shown by solid line.

DIRAC prospects at SPS CERN

Present low-energy QCD theoretical predictions for $\pi\pi$ scattering lengths

	δa_0 (%)	δa_2 (%)	$\delta(a_0-a_2)$ (%)	
ChPT	2.3	2.3	1.5	Will be improved by Lattice calculations

DIRAC Expected results

	δa_0 (%)	δa_2 (%)	$\delta(a_0-a_2)$ (%)	
$\tau(A_{2\pi})$ PS 2008-2010 (2011)			3.8 (3)	
2011: Observation of metastable $\pi^+\pi^-$ atoms and study the possibility to measure its Lamb shift Study the possibility to observe at SPS the K^+K^- and $\pi\mu$ atoms based on 2008-2010(2011) data				
$\tau(A_{2\pi})$ SPS beyond 2013			≤ 2	

	$\delta(2a_0+a_2)$ (%)
$(E_{np}-E_{ns})_{\pi\pi}$ SPS beyond 2013	Possible higher precision order relative to present methods

DIRAC prospects at SPS CERN

Present theoretical predictions for πK scattering lengths

	$\delta a_{1/2}$ (%)	$\delta a_{3/2}$ (%)	$\delta(a_{1/2}-a_{3/2})$ (%)	
ChPT	11	40	10	Will be significantly improved by ChPT
Roy-Steiner	10	17		

DIRAC expected results

			$\delta(a_{1/2}-a_{3/2})$ (%)	
$\tau(A_{\pi K})$ PS 2008-2010 (2011)			26	
$\tau(A_{\pi K})$ SPS beyond 2015			5 (stat)	

		$\delta(2a_{1/2}+a_{3/2})$ (%)	
$(E_{np}-E_{ns})_{\pi K}$ SPS beyond 2015			