SEARCH FOR LONG-LIVED STATES OF $\pi^+\pi^-$ ATOMS

Addendum to the DIRAC Proposal

GENEVA
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1. Physics motivation

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

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

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

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

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

1. Physics motivation

Numerical values for the energy shift contributions

[J. Schweizer, *Eur. Phys. J. C36 (2004) 483*]

	$\Delta E_{nl}^{em}(eV)$	$\Delta E_{nl}^{vac}(eV)$	$\Delta E_{nl}^{str}(eV)$
$n=1,l=0$	-0.065	-0.942	-3.80±0.1
$n=2,l=0$	-0.012	-0.111	-0.47±0.01
$n=2,l=1$	-0.004	-0.004	≈-1 x 10^{-6}

1. Physics motivation

Theoretical predictions for *s*-wave ππ scattering lengths

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

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

NA48/2 from K_{e4} decay
[NA48-10]

$$\begin{cases} a_0 = 0.2220 \pm 0.0128_{stat} \pm 0.0050_{syst} \pm 0.0037_{theo} \\ a_2 = -0.0432 \pm 0.0086_{stat} \pm 0.0034_{syst} \pm 0.0028_{theo} \end{cases}$$

NA48/2 from $K^{\pm} \rightarrow \pi^{\pm} \pi^0 \pi^0$ decay
[NA48-09]

$$\begin{cases} a_0 - a_2 = 0.2571 \pm 0.0048_{stat} \pm 0.0025_{syst} \pm 0.0014_{ext} \\ a_2 = -0.024 \pm 0.013_{stat} \pm 0.009_{syst} \pm 0.002_{ext} \end{cases}$$

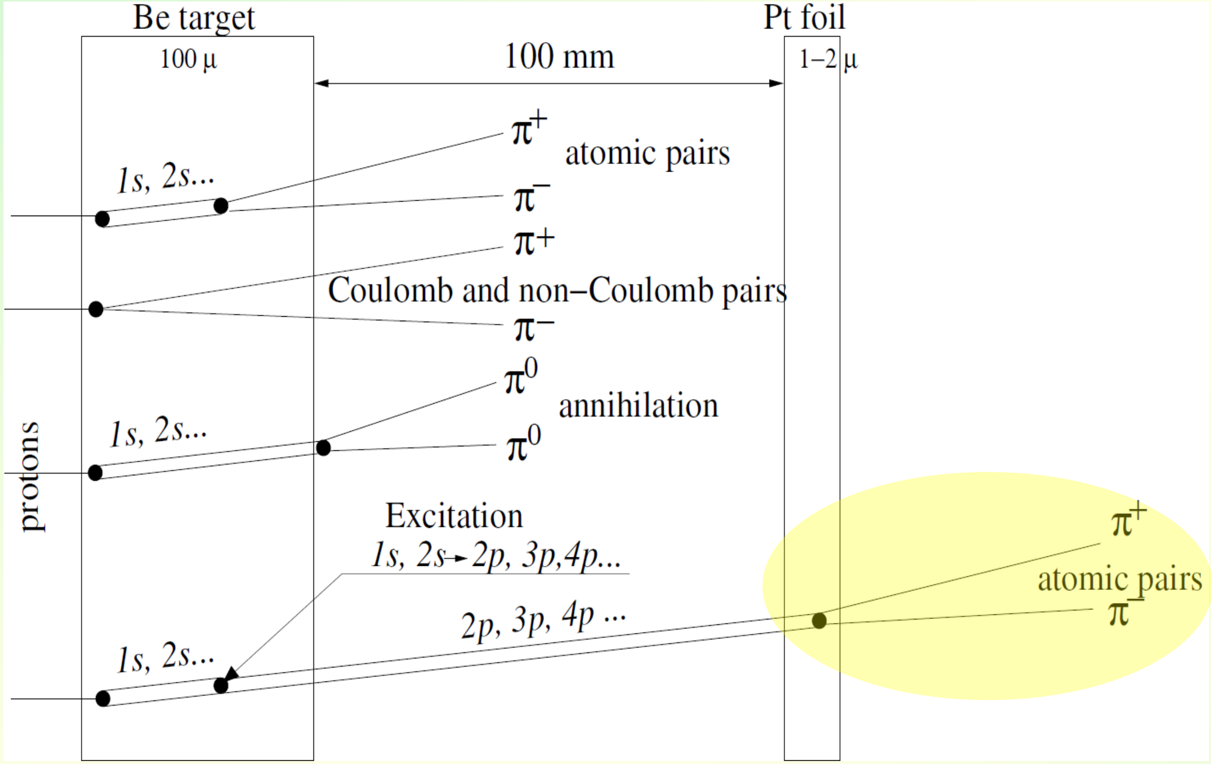
…… additional theoretical uncertainties: 0.0088 for a_0-a_2 and of 0.015 for a_2.

DIRAC based on 21000 observed $\pi^+\pi^-$ atomic pairs
[ADEVA11]

$$|a_0 - a_2| = 0.2533^{+0.0080}_{-0.0078}(stat)^{+0.0077}_{-0.0072}(sys) = 0.2533 \pm 4.3\%$$

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

The $A_{2\pi}$ decay in the *p*-state is forbidden by angular momentum conservation. So the lifetime of the $A_{2\pi}$ atom in the 2*p* state (τ_{2p}=1.17 $\cdot 10^{-11}$ s) is determined by the 2*p*–1*s* radiative transition with a subsequent annihilation in 1*s* state (τ_{1s}=3 $\cdot 10^{-15}$ s): $\pi^+ + \pi^- \rightarrow \pi^0 + \pi^0$



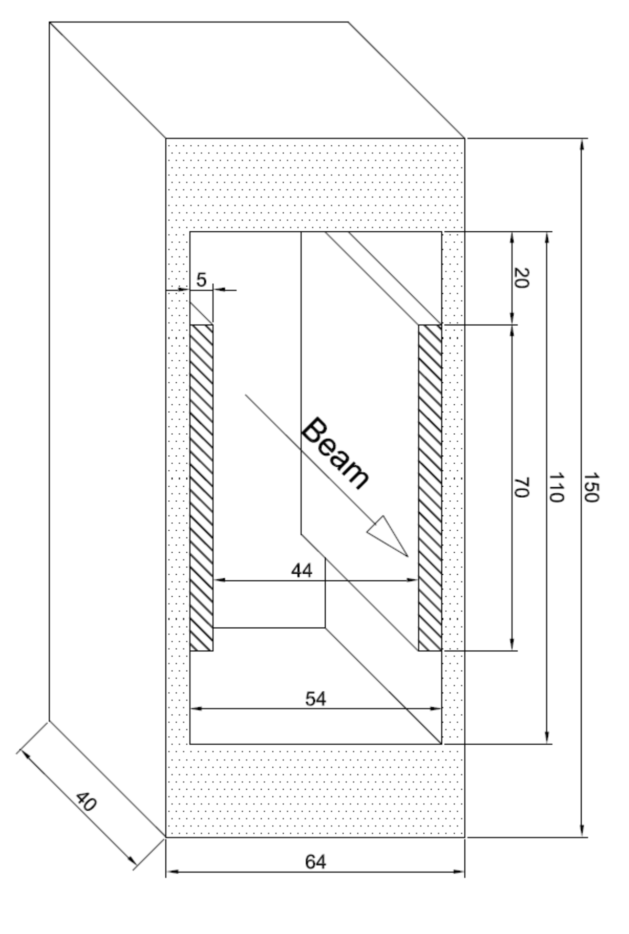
The lifetime of the *np*-states is about 10^3 larger than the *ns*-states, so it is possible to measure the **energy difference of these levels** by exerting an **electric field** (Stark effect) on the atom and tracking the field dependence of the decay probability.

The influence of an **magnetic field** on the $A_{2\pi}$ atom lifetime opens the possibility to measure the **splitting between 2*s* and 2*p* levels.**

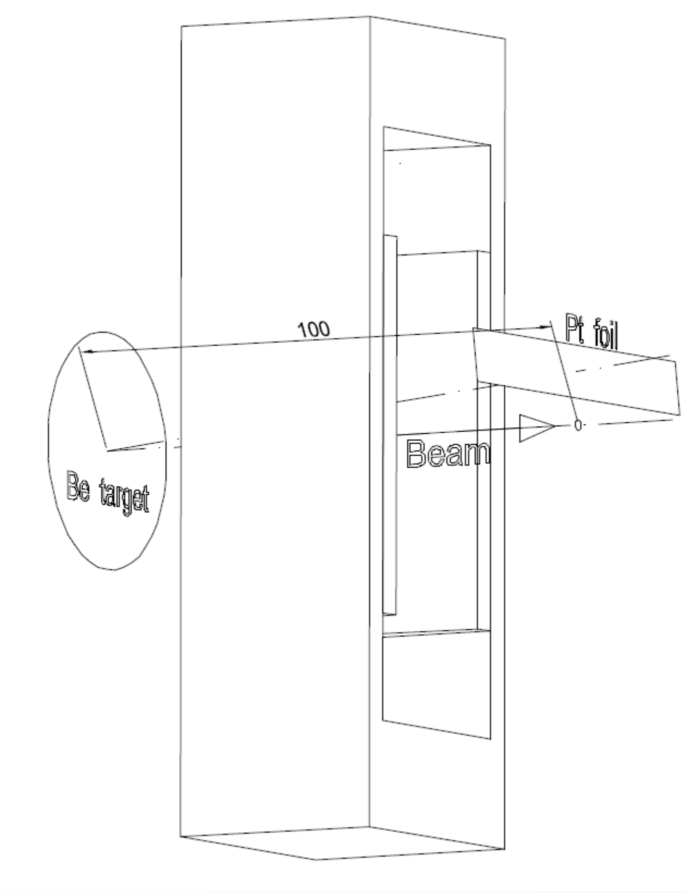
For p_A = 4.5 GeV/c (γ = 16.1)

$$\begin{cases} \tau_{1s} = 2.9 \times 10^{-15}\ \text{s}, & \lambda_{1s} = 1.4 \times 10^{-3}\ \text{cm} \\ \tau_{2s} = 2.3 \times 10^{-14}\ \text{s}, & \lambda_{2s} = 1.1 \times 10^{-2}\ \text{cm} \\ \tau_{2p} = 1.17 \times 10^{-11}\ \text{s}, & \lambda_{2p} = 5.7\ \text{cm},\ \lambda_{3p} \approx 19\ \text{cm}, \\ & \lambda_{4p} \approx 43\ \text{cm} \end{cases}$$

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

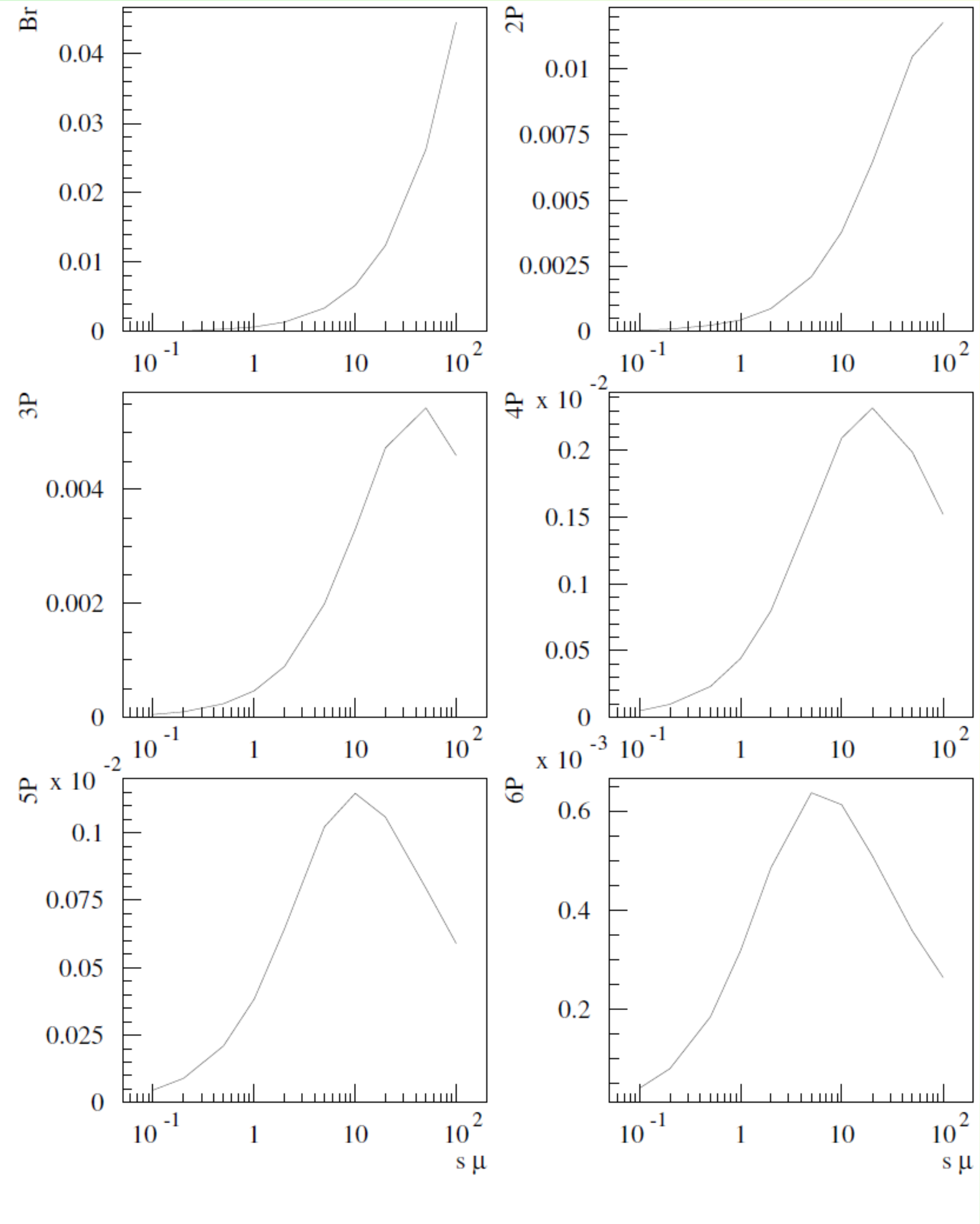


Permanent magnet dimensions



Arrangement of the Beryllium target, permanent magnet and Platinum foil.

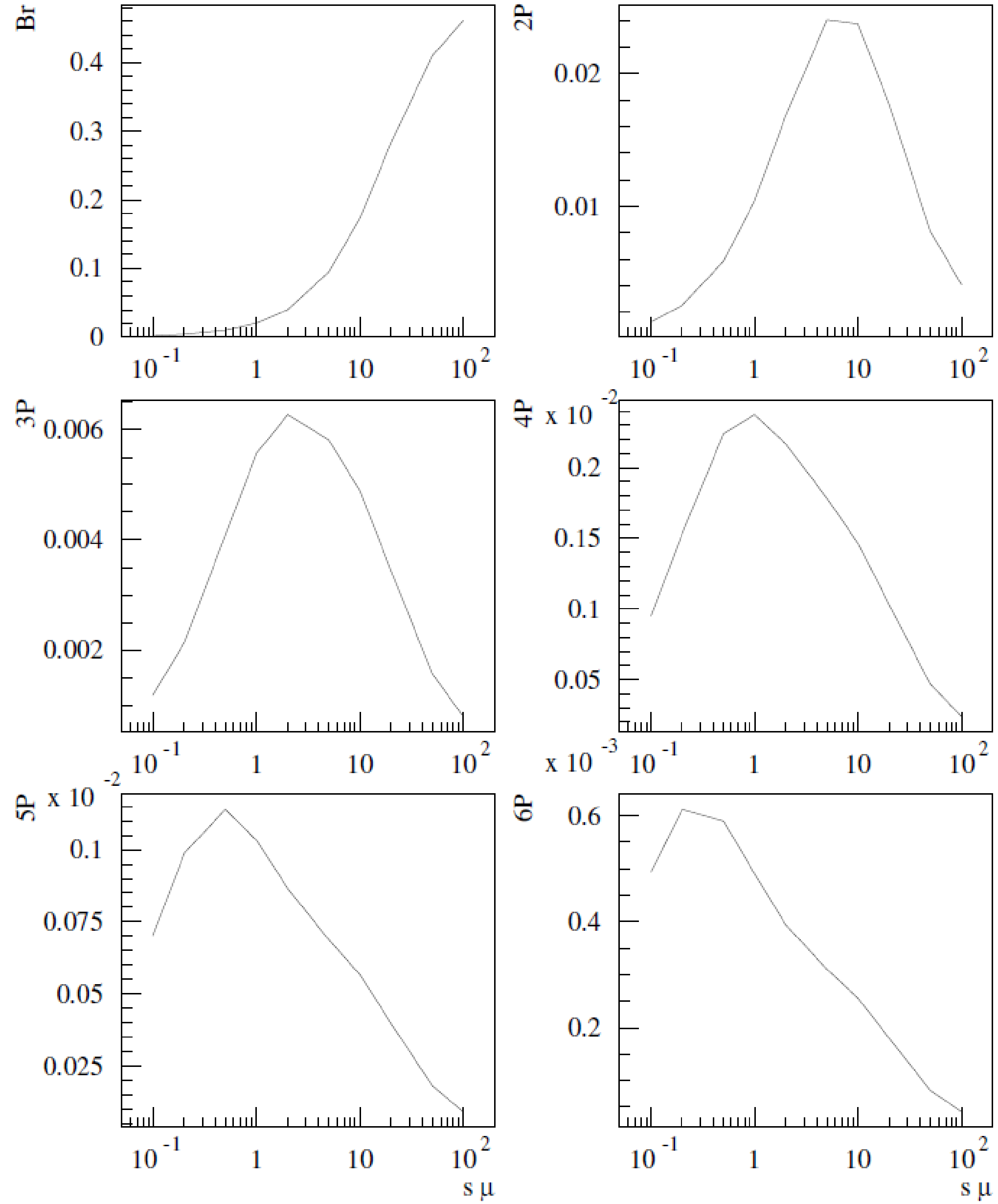
3. Production yields of $A_{2\pi}$ long-lived states



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.

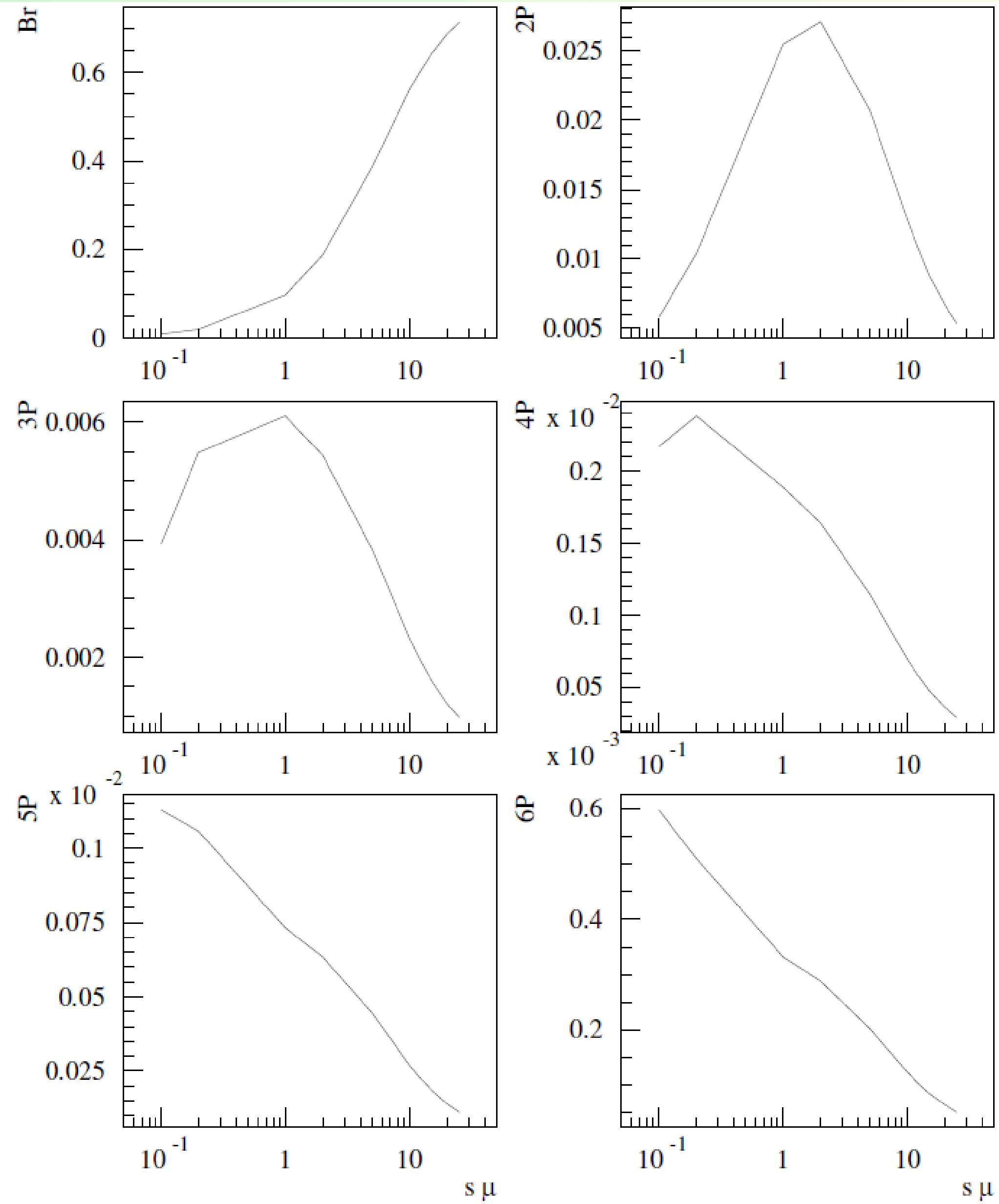
3. Production yields of $A_{2\pi}$ long-lived states



Probability of $A_{2\pi}$ breakup (Br) and production yields of the long-lived states 2p, 3p, 4p, 5*p, 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.

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



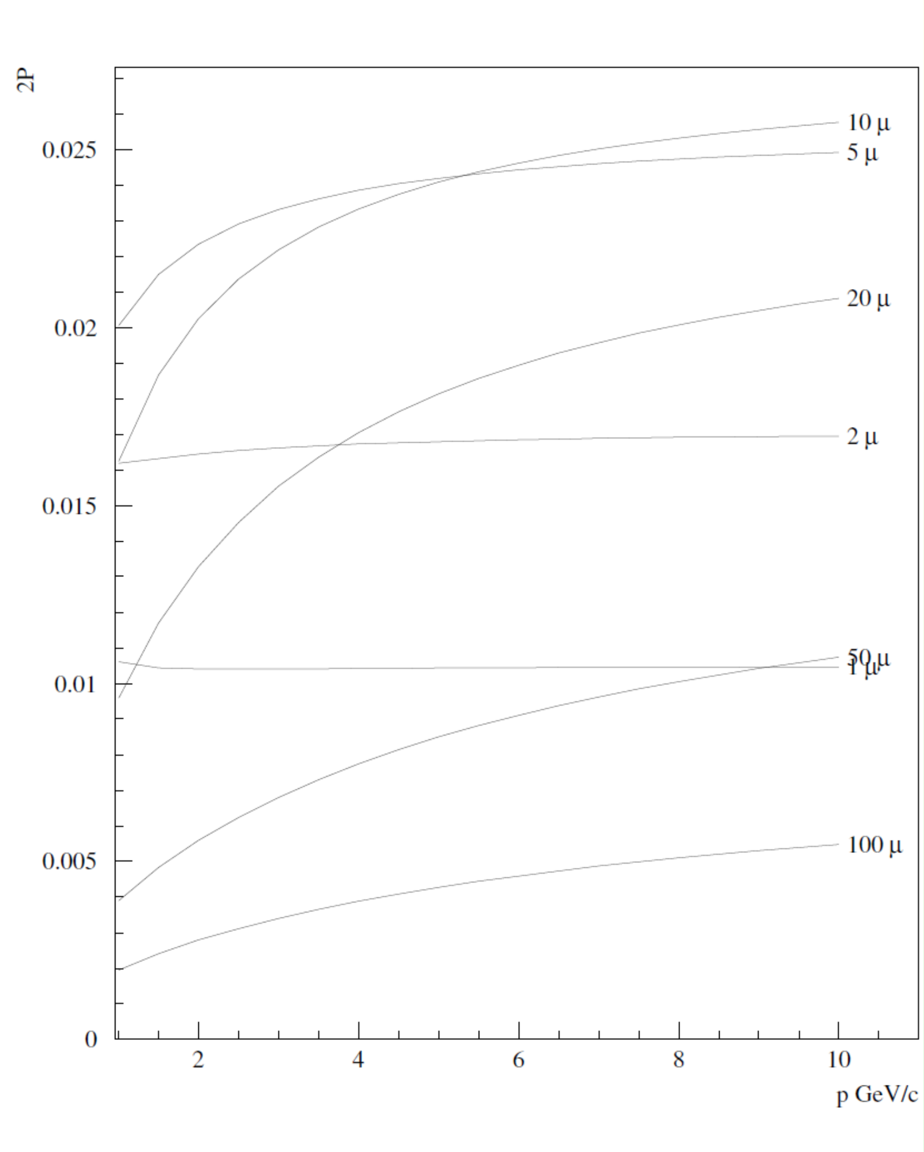
Probability of $A_{2\pi}$ breakup (Br) and production yields of the long-lived states 2p, 3p, 4p, 5*p, 6p (m=0) as a function of the target thickness, for* **Platinum** (Z=78) target.

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.

3. 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.



3. 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*

- **Σ ($l \geq 1$):** *total yield of long-lived states including states with $n \leq 7$*

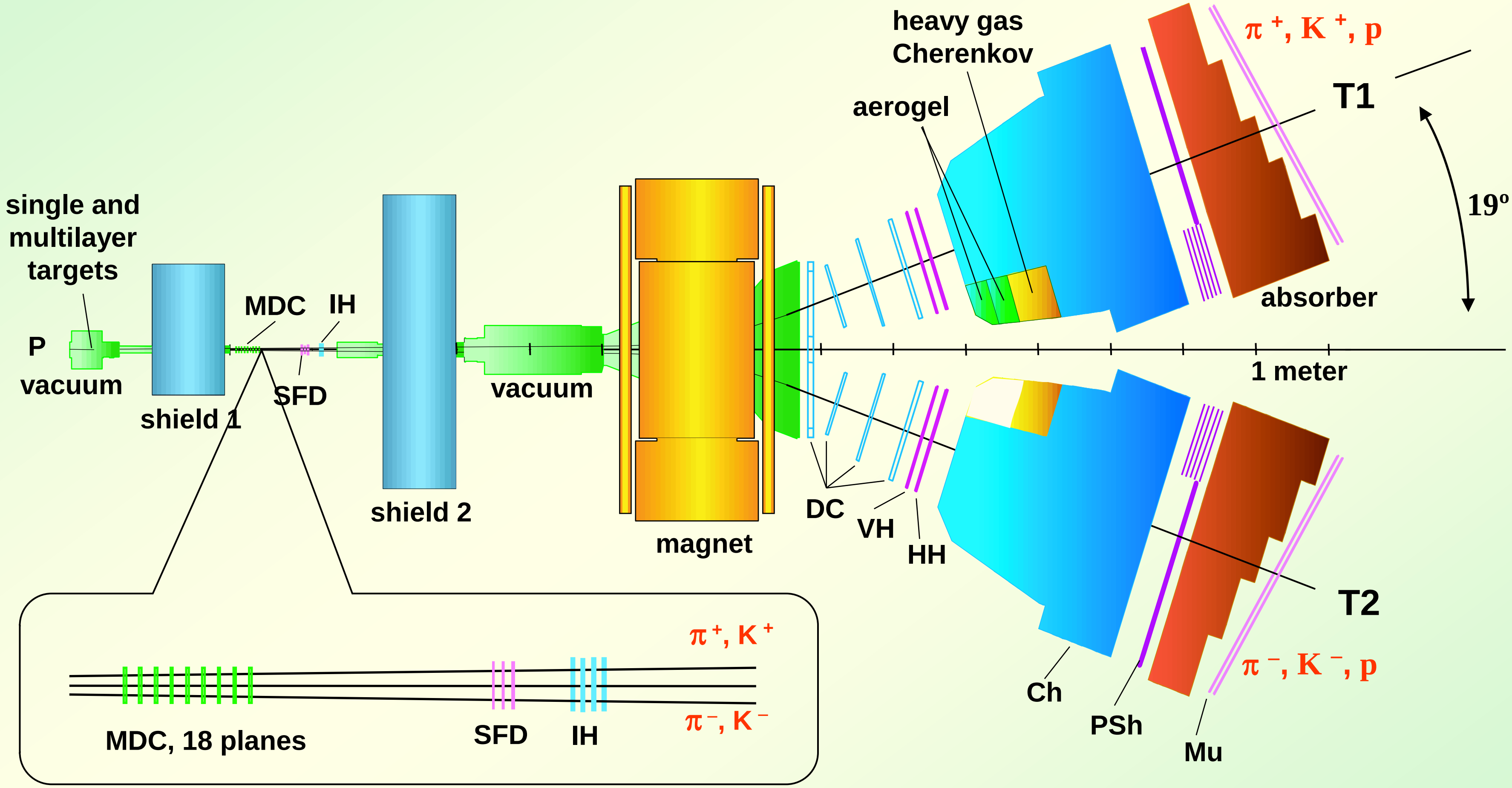
- **$2p_0$, $3p_0$, $4p_0$**, *production yield of p-states with magnetic quantum number $m = 0$*

- **Σ ($l = 1$, $m = 0$):** *sum of the p-states up to $n = 7$*

Target Z		Thickness μm	Breakup	$\sum(l \geq 1)$	$2p_0$	$3p_0$	$4p_0$	$\sum(l=1, m=0)$
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%

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

Upgraded DIRAC setup



MDC - microdrift gas chambers, SFD - scintillating fiber detector, IH – ionization hodoscope. DC - drift chambers , VH – vertical hodoscopes, HH – horizontal hodoscopes, Ch – nitrogen Cherenkov , PSh - preshower detectors , Mu - muon detectors

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

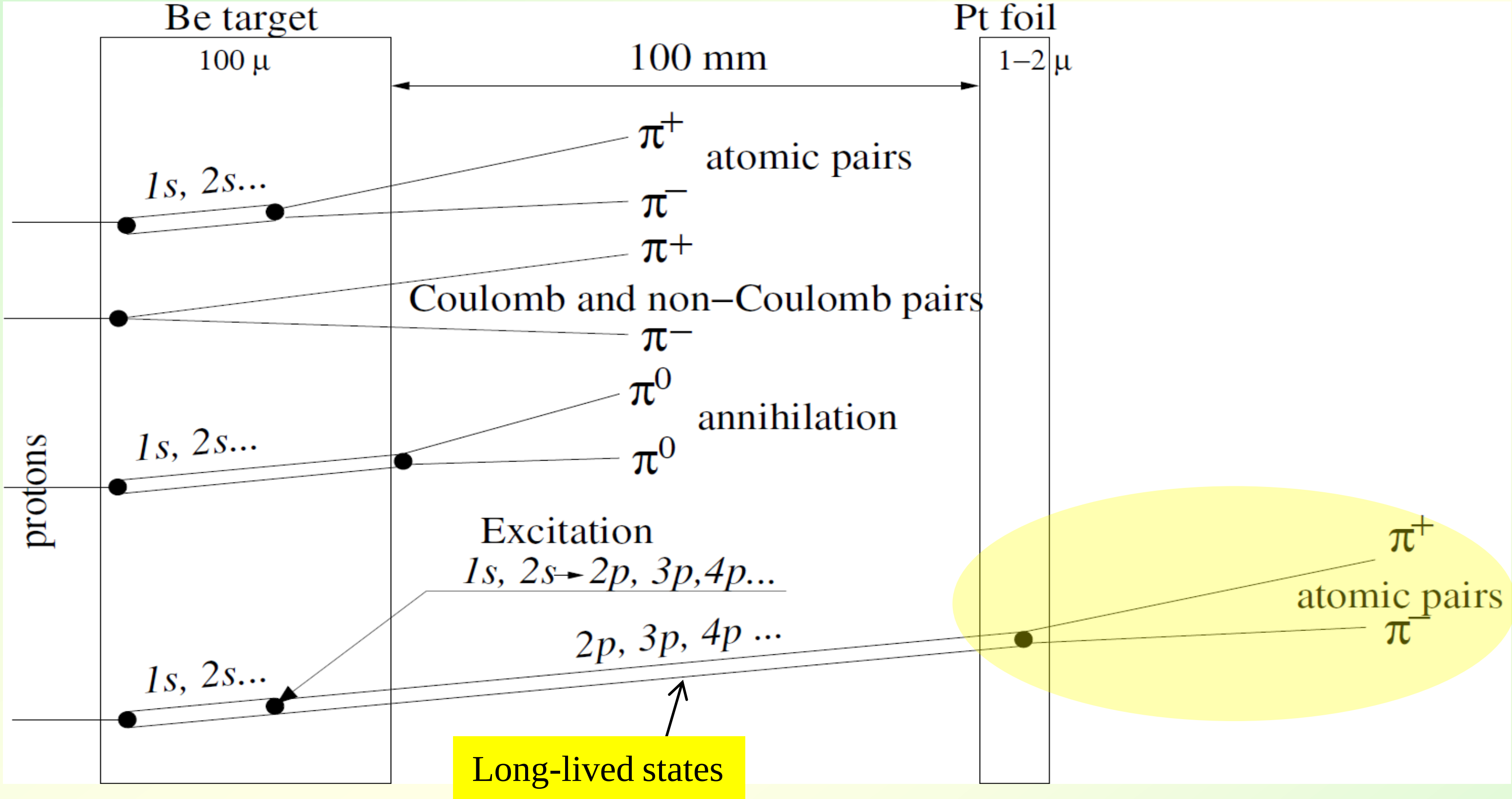
	Be	Al	Ni	Pt
$L(\mu m)$	100	20	5	2
$\frac{X}{X_0} \times 10^4$	2.84	2.24	3.53	6.57
$\varepsilon_{nucl} \times 10^4$	2.45	0.48	0.34	0.23

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%, W_{2s}= 10.4%, W_{3s} =3.1%, $W_{>3s}$ =3.5%

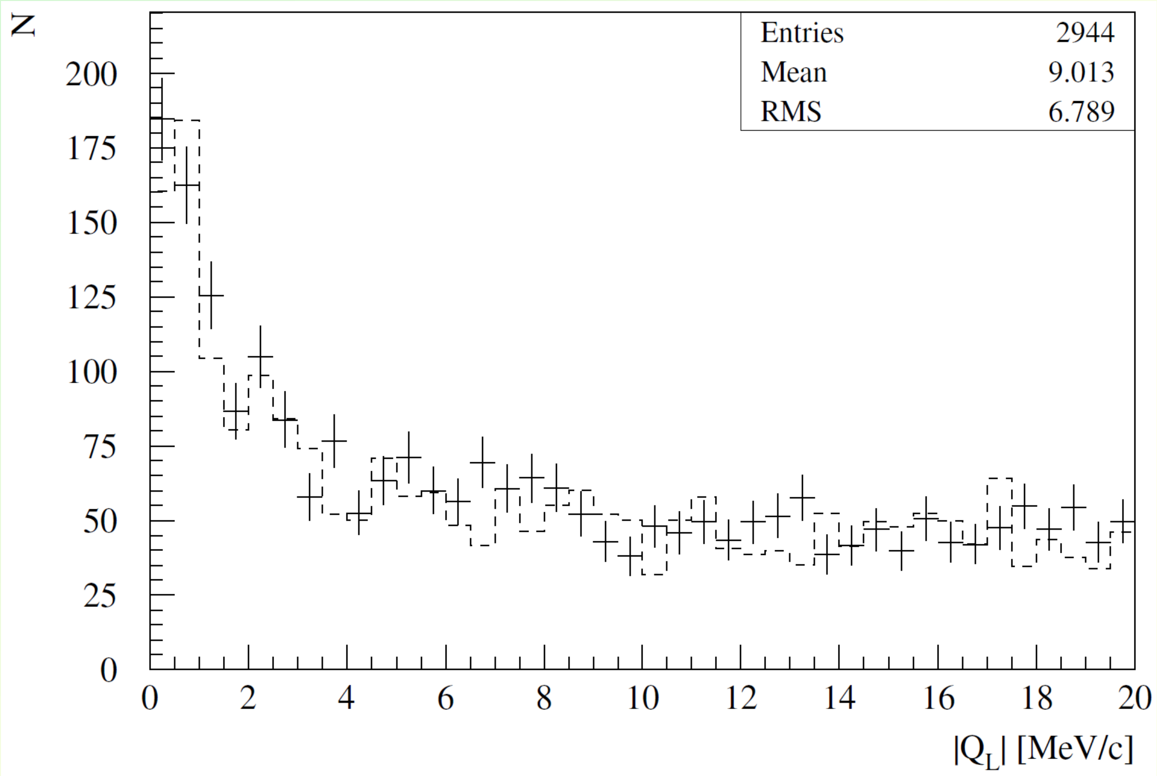
5. Detecting $A_{2\pi}$ in long-lived states with a thin Platinum foil



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

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

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



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

Using the cross section ratio between $A_{2\pi}$ & "Coulomb pairs" and the measured number of Coulomb pairs, the number of generated atoms can be estimated :

$$N_A = 736 \pm 75$$

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

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

at **Be** target exit							
l \ *n*	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

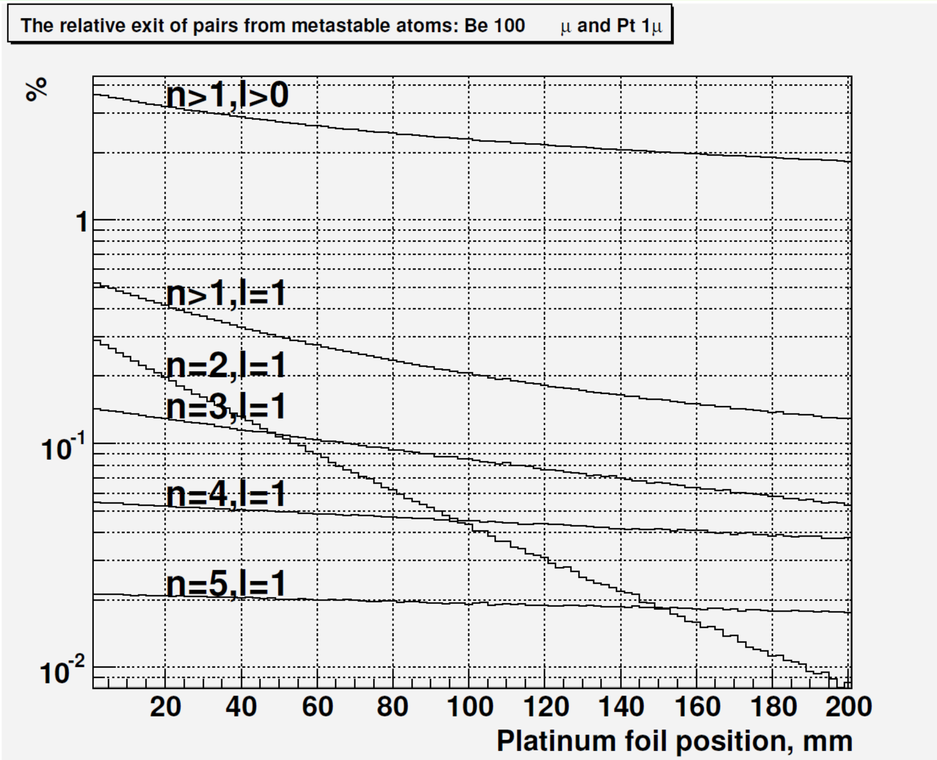
at **Pt** foil entry							
l \ *n*	2	3	4	5	6	7	8
1	0.32	0.43	0.20	0.09	0.04	0.02	0.01
2	0.00	0.50	0.24	0.11	0.05	0.02	0.01
3	0.00	0.00	0.24	0.12	0.05	0.03	0.01
4	0.00	0.00	0.00	0.11	0.06	0.03	0.01
5	0.00	0.00	0.00	0.00	0.06	0.03	0.01
6	0.00	0.00	0.00	0.00	0.00	0.03	0.01
7	0.00	0.00	0.00	0.00	0.00	0.00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

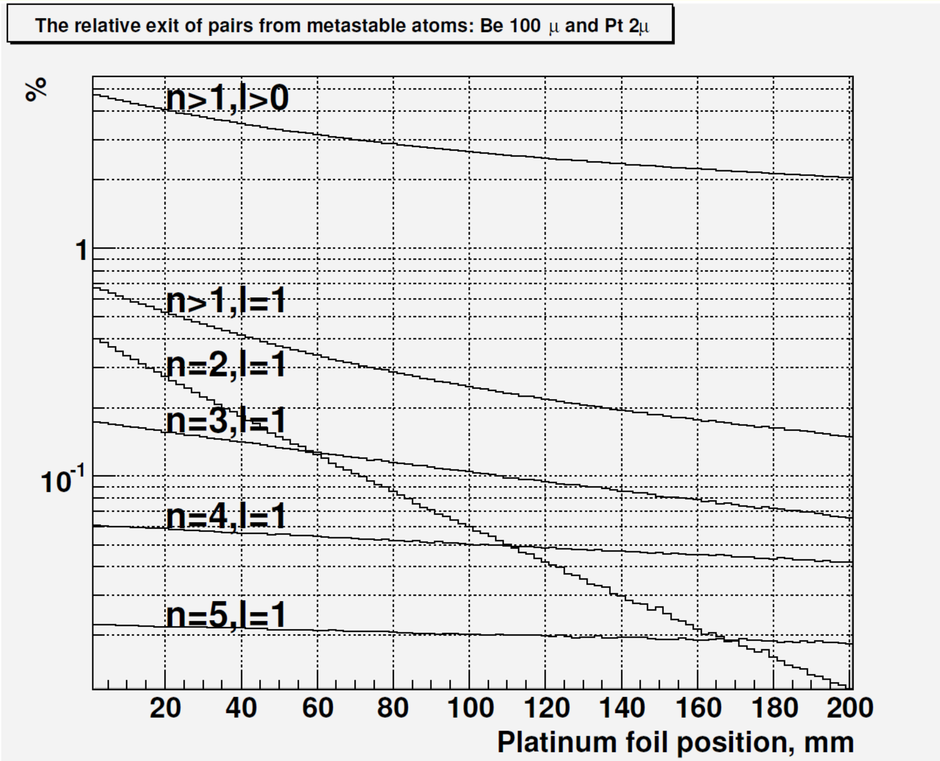
7. Simulation of all $\pi^+\pi^-$ pairs at experimental conditions

Number of atomic pairs produced by breakup in the 1μm ***Pt*** foil from states with specific *n* and *l*.
(percentage from total number of produced atoms)

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

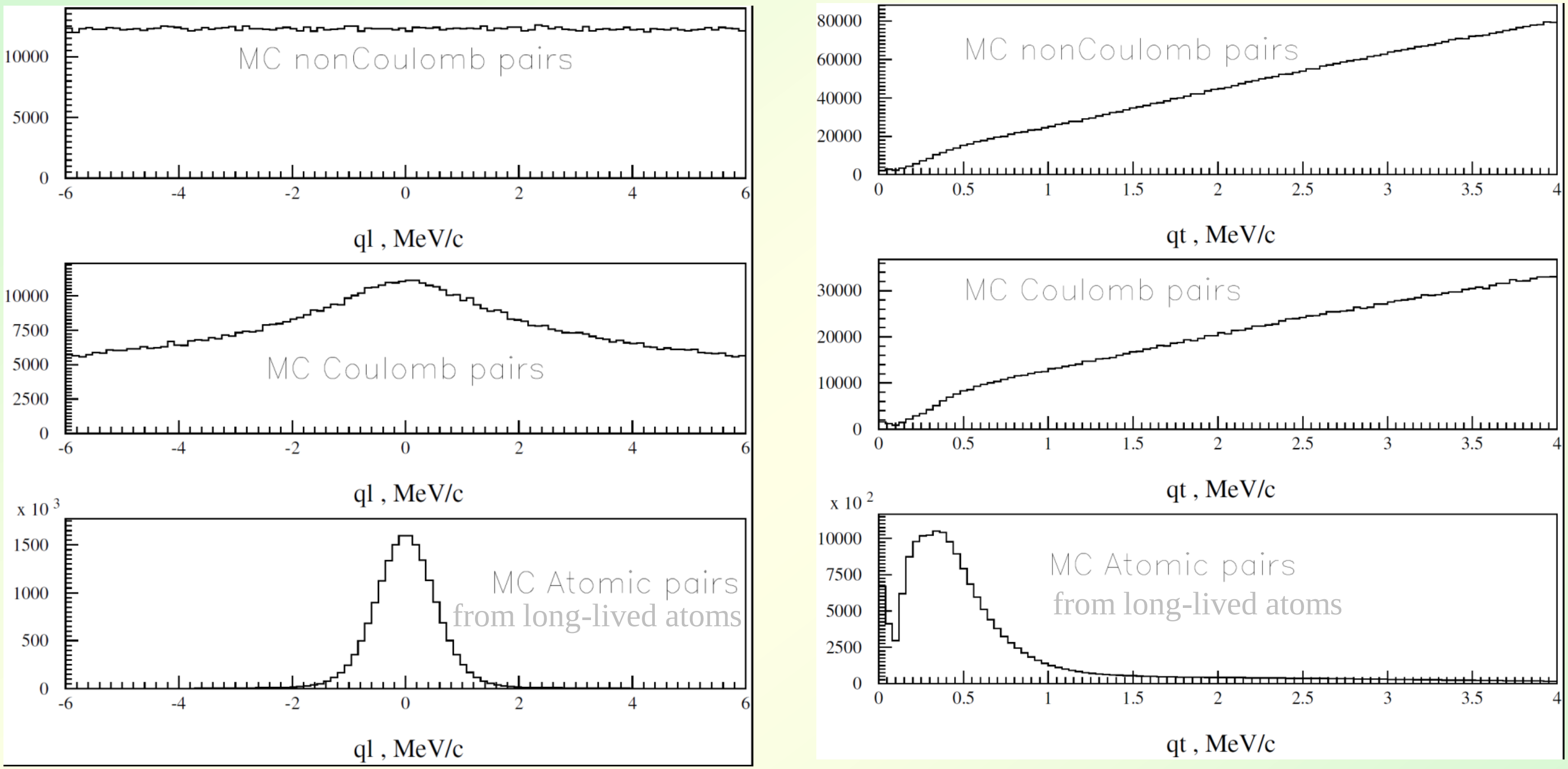
7. Simulation of all $\pi^+\pi^-$ pairs at experimental conditions





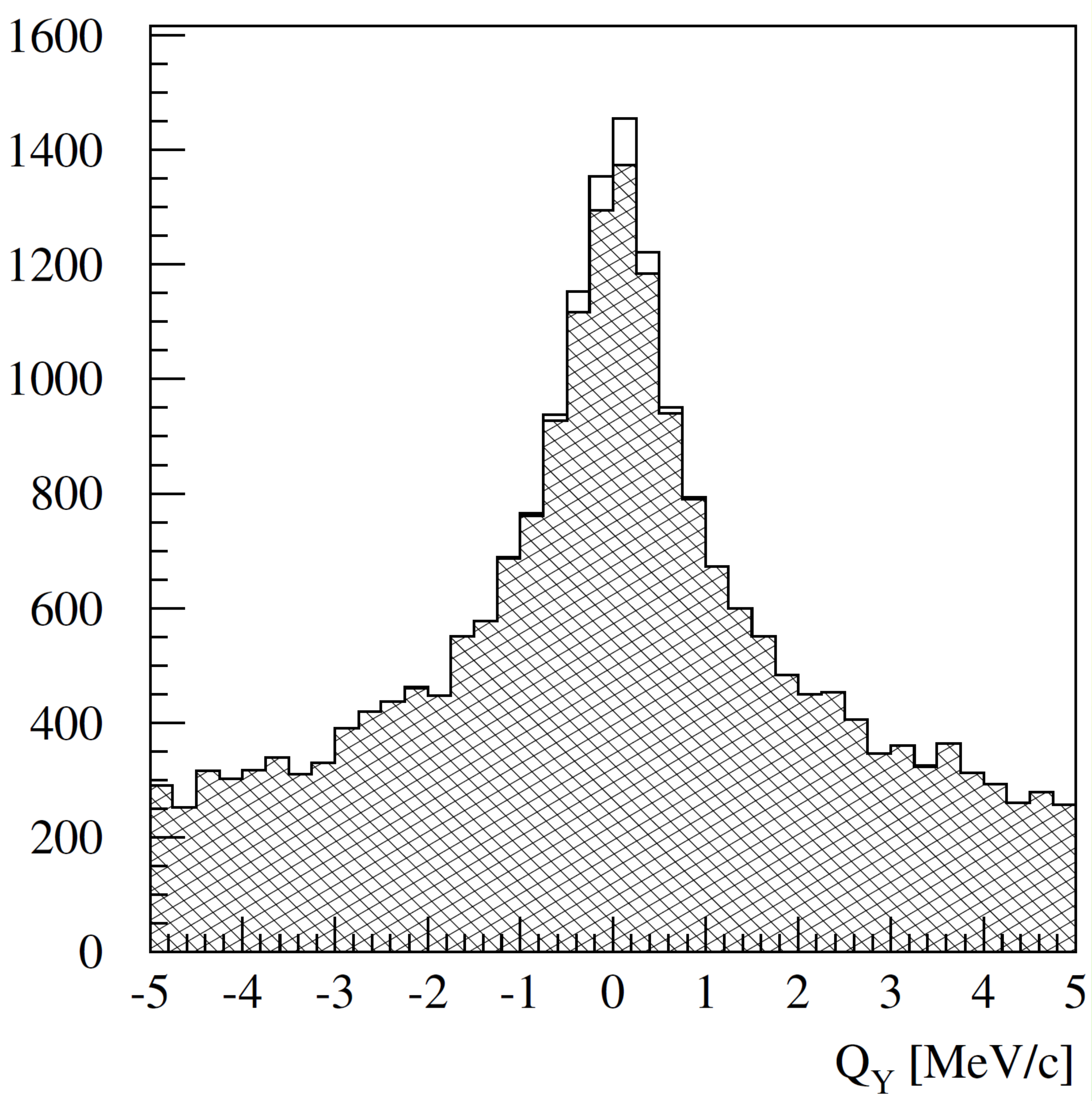
Part of the atoms, which were created in the Be target and then broken up in the *Pt* foil, as a function of the distance between *Be* target and *Pt* foil for all metastable states ($n>1$, $l>0$) and for some individual states with $l=1$. The foil thickness is 1μ and 2μ.

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



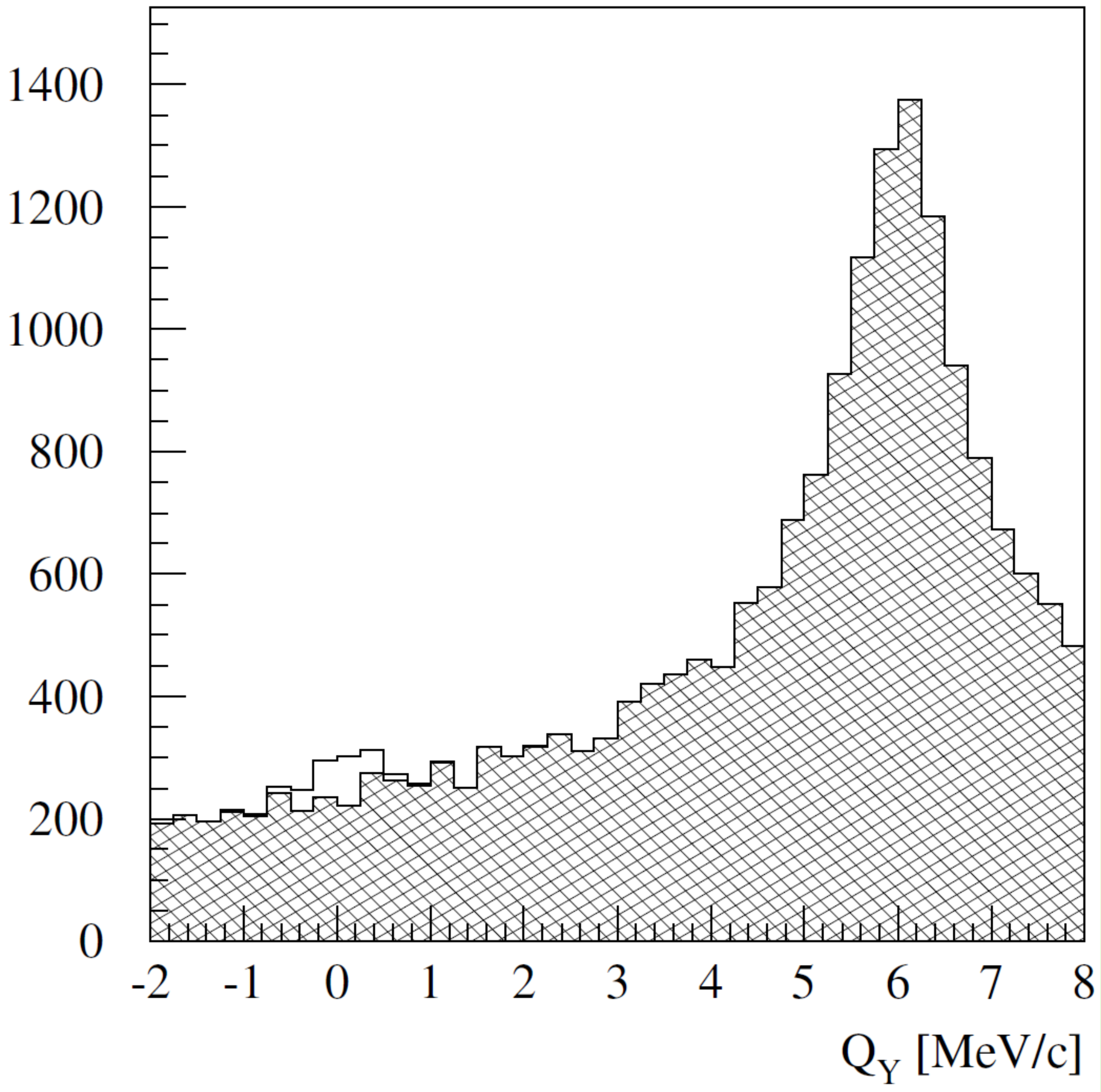
Distributions of reconstructed values of q_l and q_t for non-Coulomb pairs, Coulomb pairs and pairs from long-lived atoms.

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



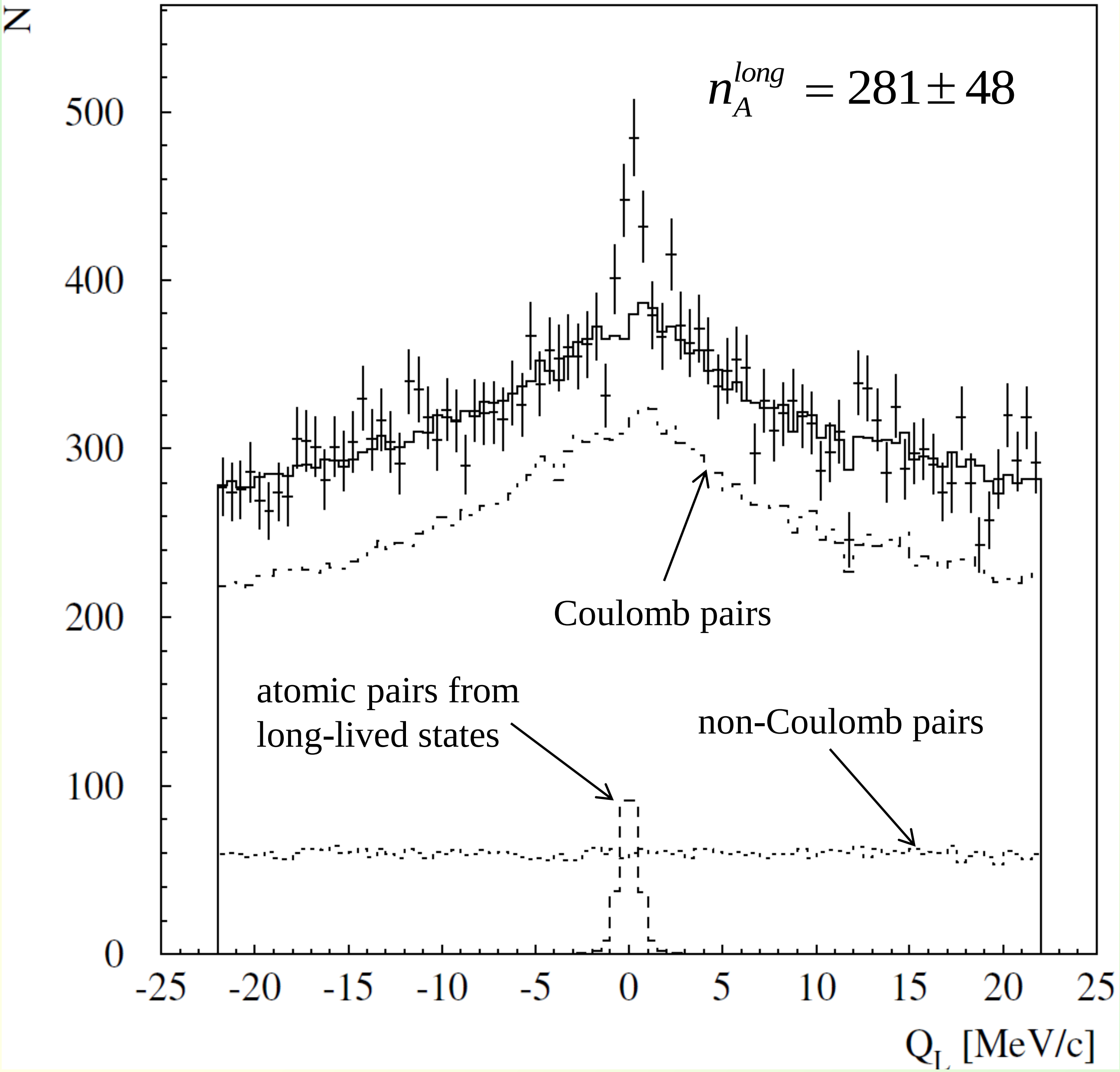
Simulated distribution of $\pi^+\pi^-$ pairs over Q_Y with criteria: $Q_X < 1$ MeV/c, $Q_L < 1$ MeV/c. "Atomic pairs" from long-lived atoms (light area) above the background produced in Beryllium target (hatched area).

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



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

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

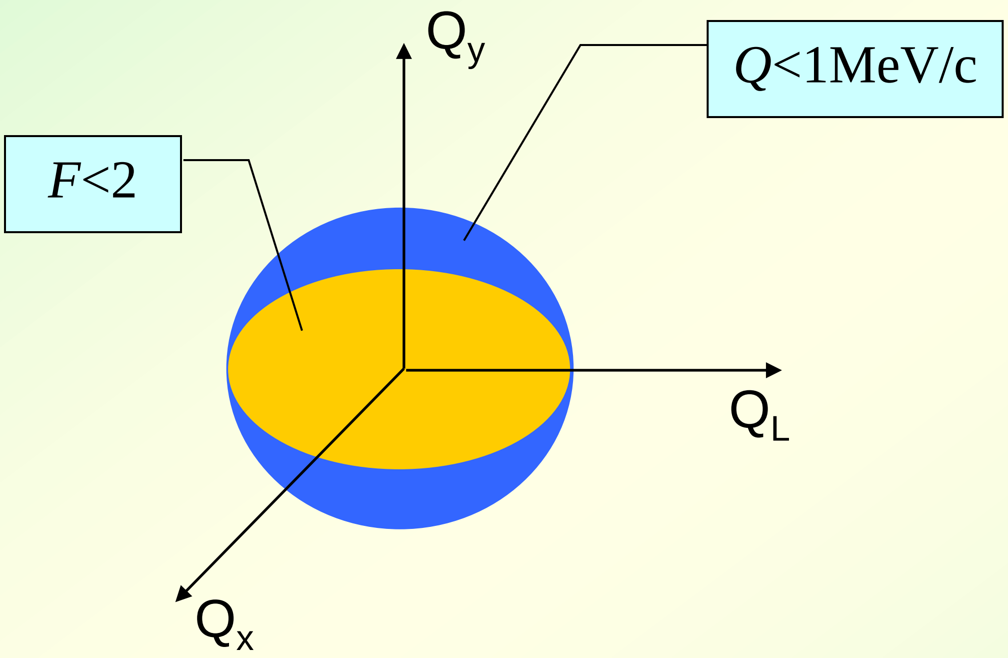


Simulated distribution of $\pi^+\pi^-$ pairs over Q_L, with criterium $Q_T < 1$ MeV/c. "Experimental" data (points with error bars) are fitted by a sum of "atomic pairs" from long-lived states, "Coulomb pairs" and "non-Coulomb pairs".
The background sum is shown by the solid line.

The number of atomic pairs are found to be

$$n_A^{long} = 281 \pm 48$$

Q and F variables for Be target

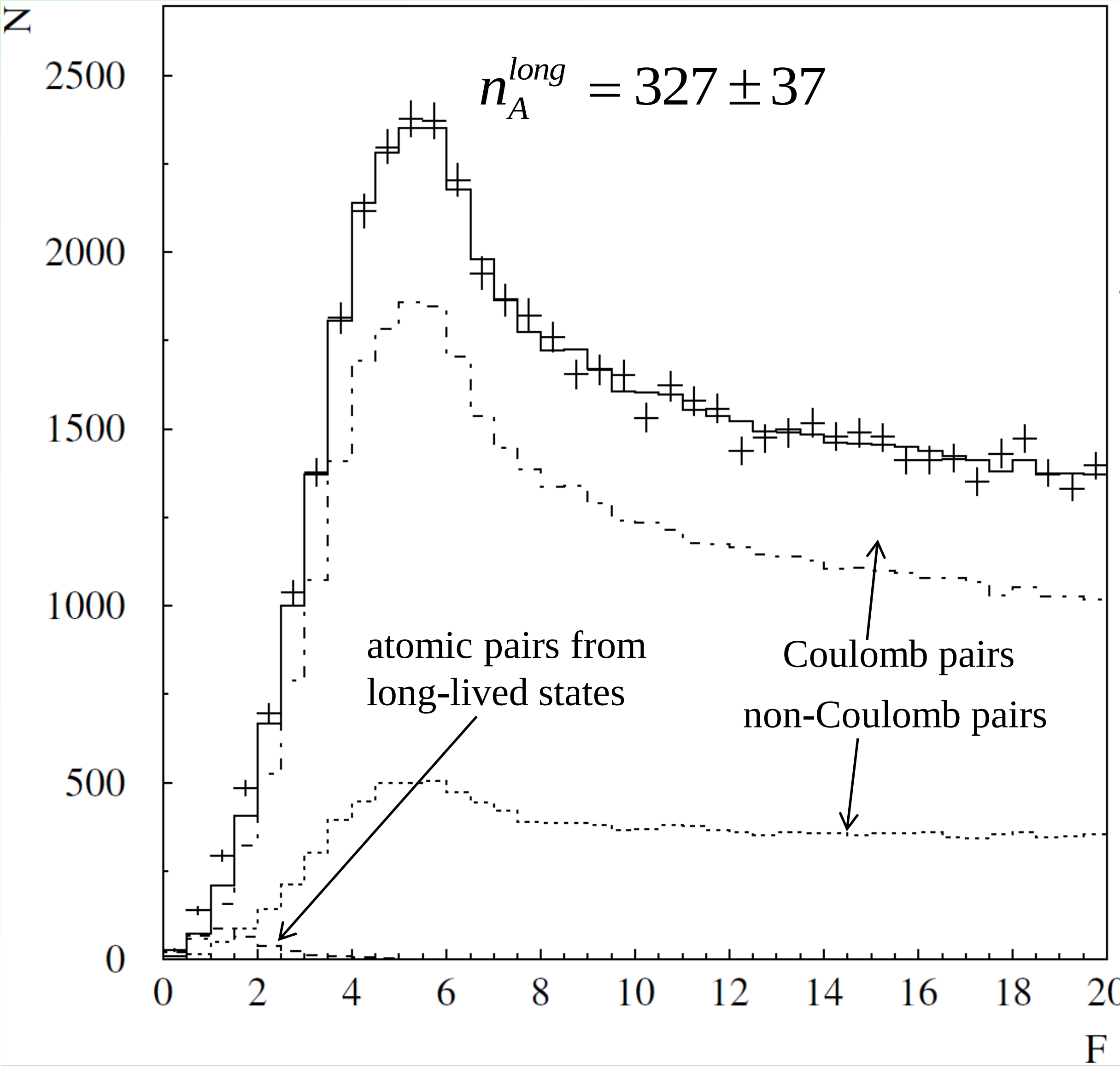


$$Q = \sqrt{Q_X^2 + Q_Y^2 + Q_L^2}$$

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

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

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



Simulated distribution of $\pi^+\pi^-$ pairs over F, with criterion $Q_T < 2MeV/c$. "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.

$$F = \sqrt{\left(\frac{Q_X}{0.50}\right)^2 + \left(\frac{Q_Y}{0.32}\right)^2 + \left(\frac{Q_L}{0.56}\right)^2}$$

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,

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

9. Measurement of multiple scattering for different materials

80% of our current systematic error is due to multiple scattering in the Ni target.

To reduce the systematic error in the final result, at the level of statistical one at least, we will do multiple scattering measurement in *Be, Al, Ti, Ni* and *Pt* with better than 1% accuracy.

The data will permit to obtain the $A_{2\pi}$ lifetime with better than 6% and $|a_0 - a_2|$ with better than 3% precisions.

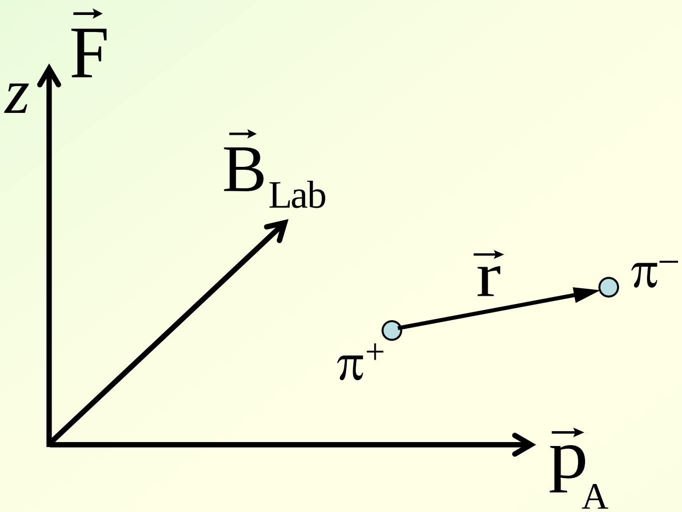
10.Conclusion

- **The long-lived $\pi^+ \pi^-$ atoms will be observed at the accuracy level better than 8σ.**
- **These observations open the possibility to measure the atom "Lamb shift" and the new combination ($2a_0 + a_2$) of $\pi\ \pi$ scattering lengths.**
- **Measurements of the multiple scattering in different materials with accuracy better than 1%, will be performed in parallel with atom observations. These measurements will improve the systematical accuracy in the $A_{2\pi}$ lifetime for the data already collected in 2008 – 2010.**
- **For the long-lived $A_{2\pi}$ observation we request in 2011 the proton beam (T8) during 6 months, with $2.6 \cdot 10^{11}$ protons/spill. The total proton flux through the target must be $2.9 \cdot 10^{17}$, which corresponds to $\sim 1.1 \cdot 10^{6}$ spills.**

Thank you for your attention

L.Nemenov, V.Ovsiannikov, Phys.Lett. B514 (2001)

Atom beams are influenced by external magnetic field and the relativistic Lorentz factor γ



$$A_{2\pi}\,,\ \beta = \frac{v}{c}$$

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

$\vec{B}_{Lab} \equiv$ laboratory magnetic field

$\vec{F} \equiv$ electric field in the CM system of an $A_{2\pi}$ atom

$$F = \beta\gamma B_{Lab} \approx \gamma B_{Lab}$$

The dependence of $A_{2\pi}$ life time τ_{eff} for *2p*-states of the electric field F strength

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

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

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

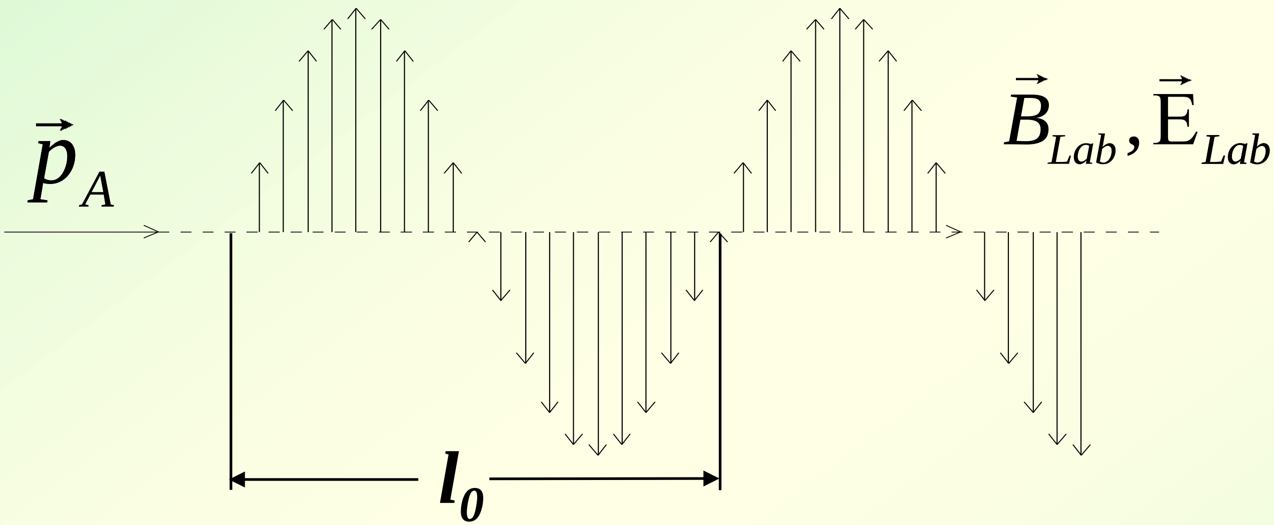
where: $|\xi|^2 \approx \frac{F^2}{\left(E_{2p} - E_{2s}\right)^2}$

B_{Lab} = 2 Tesla

$$\begin{cases} \gamma = 20\ , & |\xi| = 0.025 \quad \Rightarrow \quad \tau_{eff} = \frac{\tau_{2p}}{1.3} \\ \gamma = 40\ , & |\xi| = 0.05 \quad \Rightarrow \quad \tau_{eff} = \frac{\tau_{2p}}{2.25} \end{cases}$$

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

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

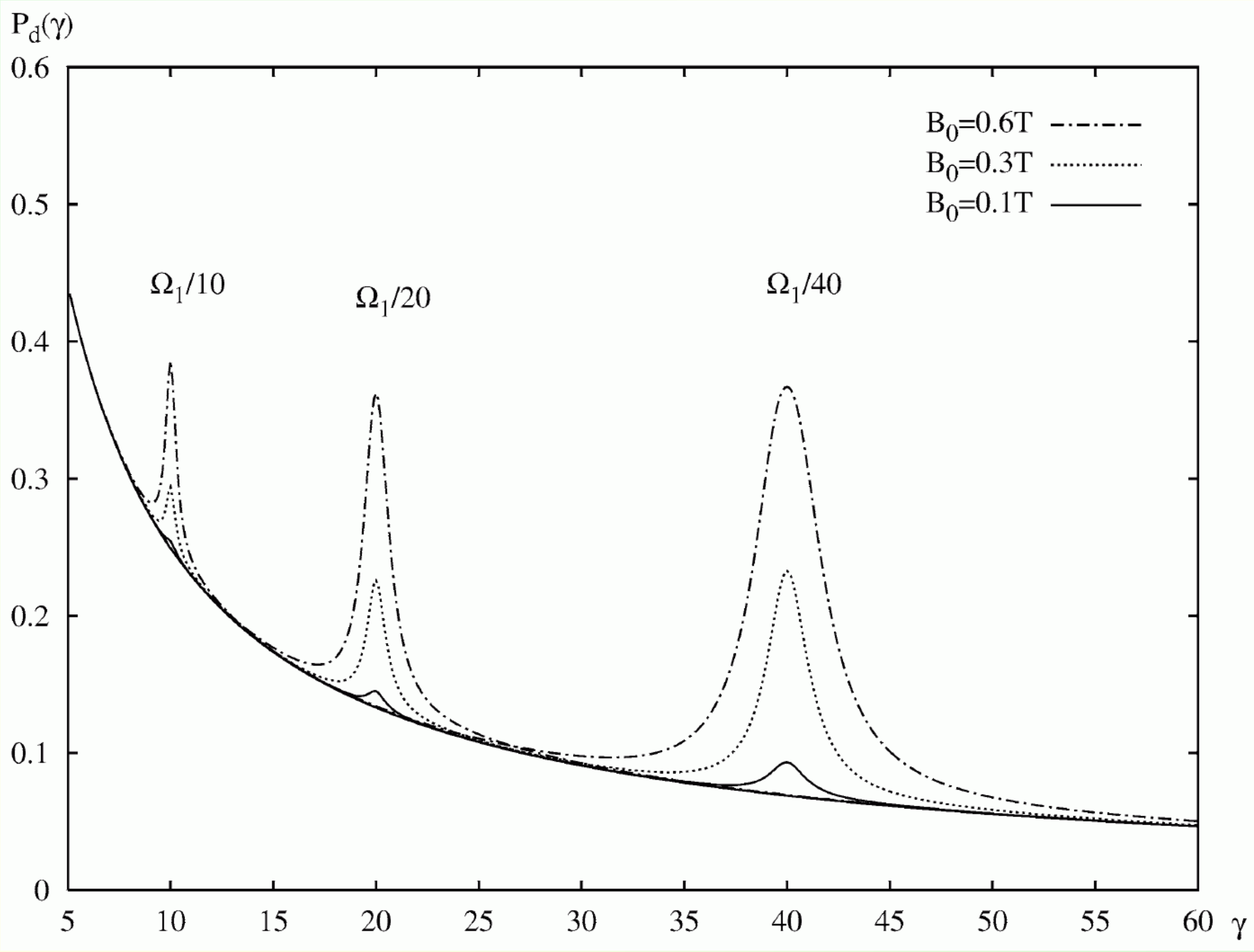


In Lab. System: $T_{Lab} = \dfrac{l_0}{\beta c}, \qquad \omega_{Lab} = \dfrac{2\pi}{T_{Lab}}$

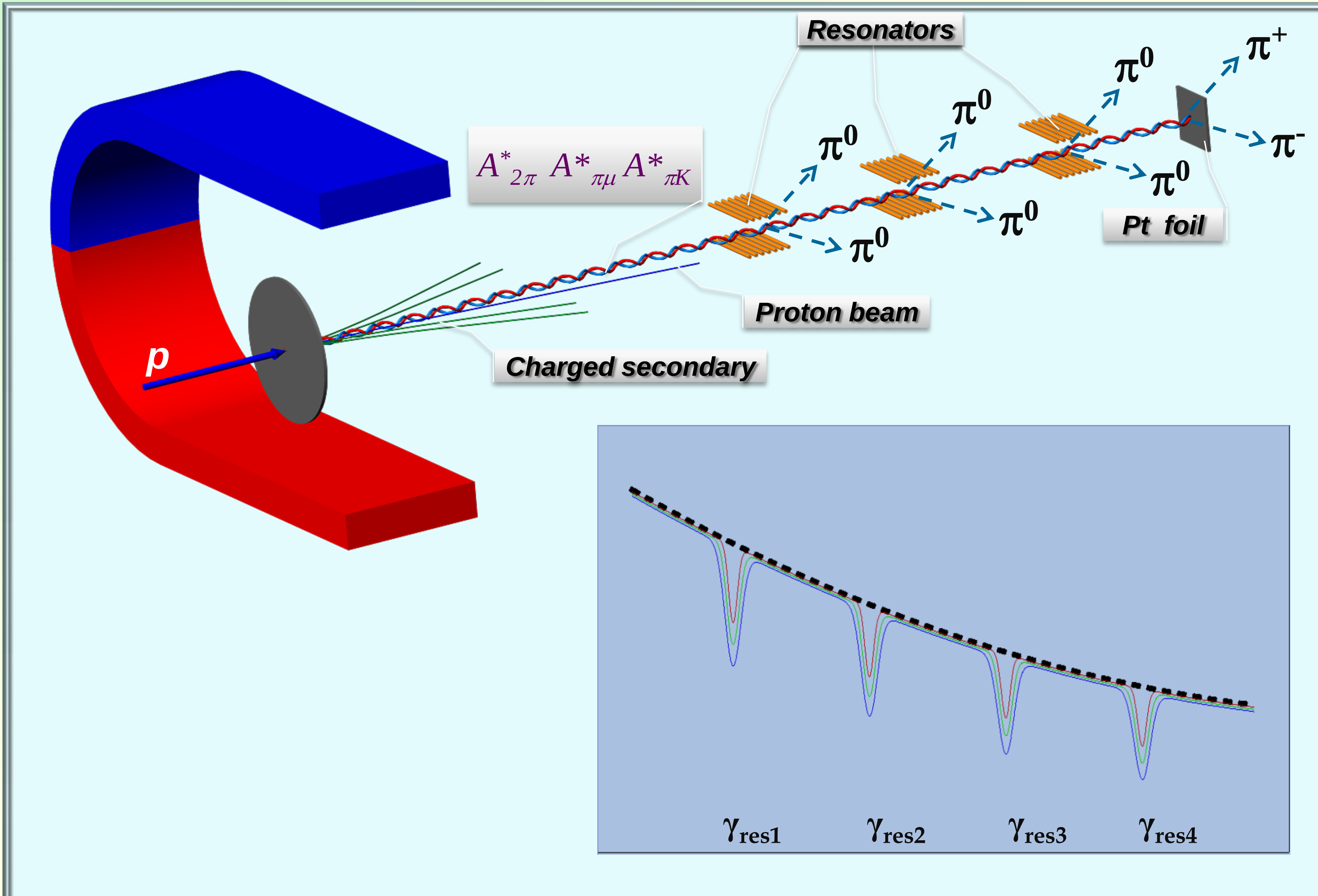
In CM System: $\tilde{\omega} = \gamma \cdot \omega_{Lab}, \qquad \tilde{\vec{E}} = \gamma \cdot \vec{E}_{Lab} \cdot \cos \tilde{\omega} t, \qquad \tilde{\Omega} = \dfrac{E_{2p} - E_{2s}}{\hbar}$

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

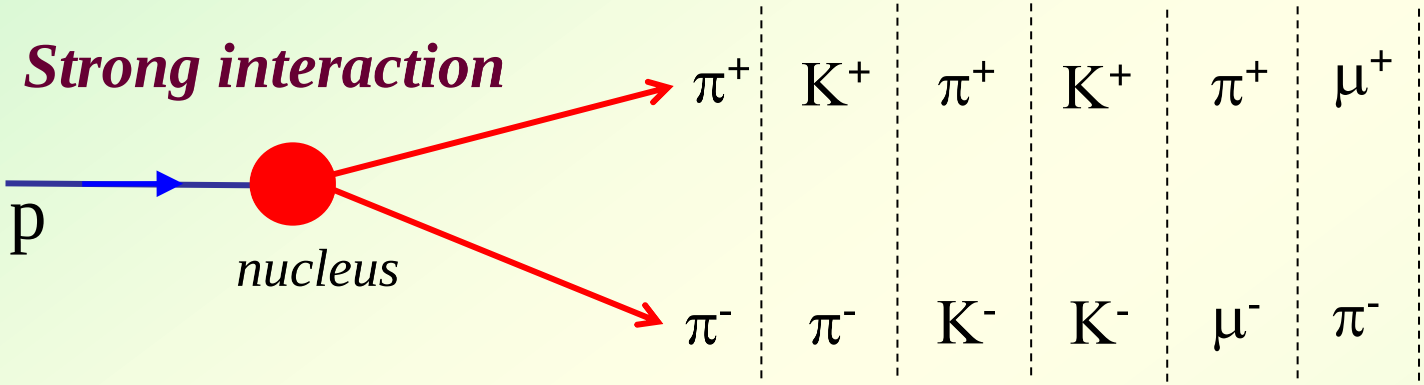
Resonant enhancement



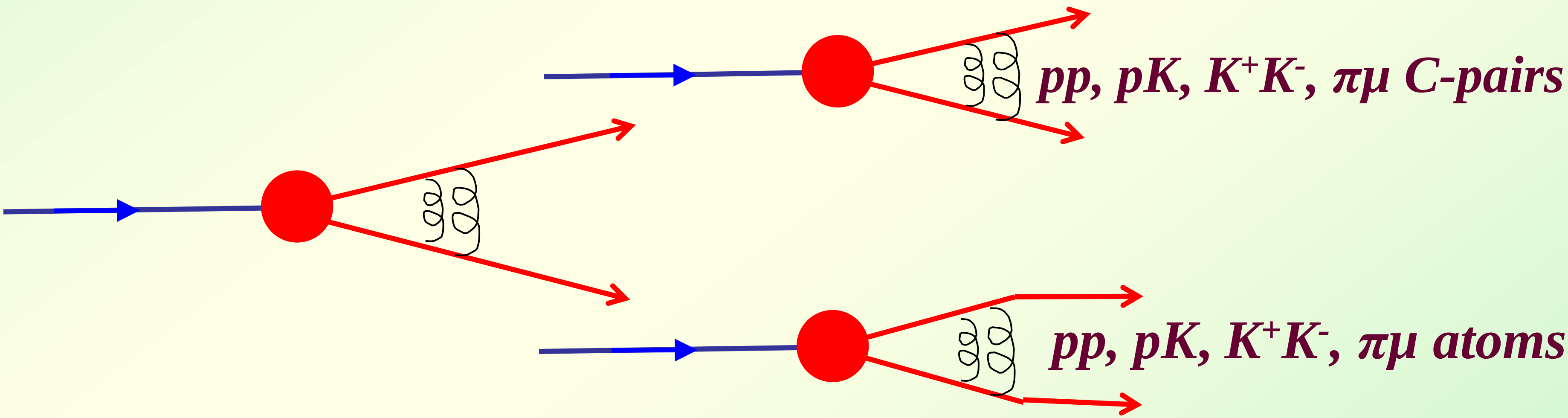
Resonant method



Coulomb pairs and atoms



For small Q there are Coulomb pairs :



The production yield strongly increases for smaller Q

DIRAC prospects at SPS CERN

Yield of dimeson atoms per one proton-Ni interaction, detectable by DIRAC upgrade setup at Θ_L=5.7º						
	24 GeV			450 GeV		
E_p	$A_{2\pi}$	$A_{K^+\pi^-}$	$A_{\pi^+K^-}$	$A_{2\pi}$	$A_{K^+\pi^-}$	$A_{\pi^+K^-}$
W_A	$1.1\cdot10^{-9}$	$0.52\cdot10^{-10}$	$0.29\cdot10^{-10}$	$0.13\cdot10^{-7}$	$0.10\cdot10^{-8}$	$0.71\cdot10^{-9}$
W_A^N	1.	1.	1.	12.	19.	24.
W_A / W_π	$3.4\cdot10^{-8}$	$16.\cdot10^{-10}$	$9.\cdot10^{-10}$	$1.3\cdot10^{-7}$	$1.\cdot10^{-8}$	$7.1\cdot10^{-9}$
W_A^N / W_π^N	1.	1.	1.	3.8	6.2	8.
				A multiplier due to different spill duration ~4		
Total gain	**1.**	**1.**	**1.**	**15.**	**25.**	**32.**

DIRAC prospects at SPS CERN

Present low-energy QCD theoretical predictions for ππ scattering lengths

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

DIRAC Expected results

	δa_0 (%)	δa_2 (%)	$\delta(a_0\text{-}a_2)$ (%)	
$\tau(A_{2\pi})$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	

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

DIRAC prospects at SPS CERN

Present theoretical predictions for πK scattering lengths

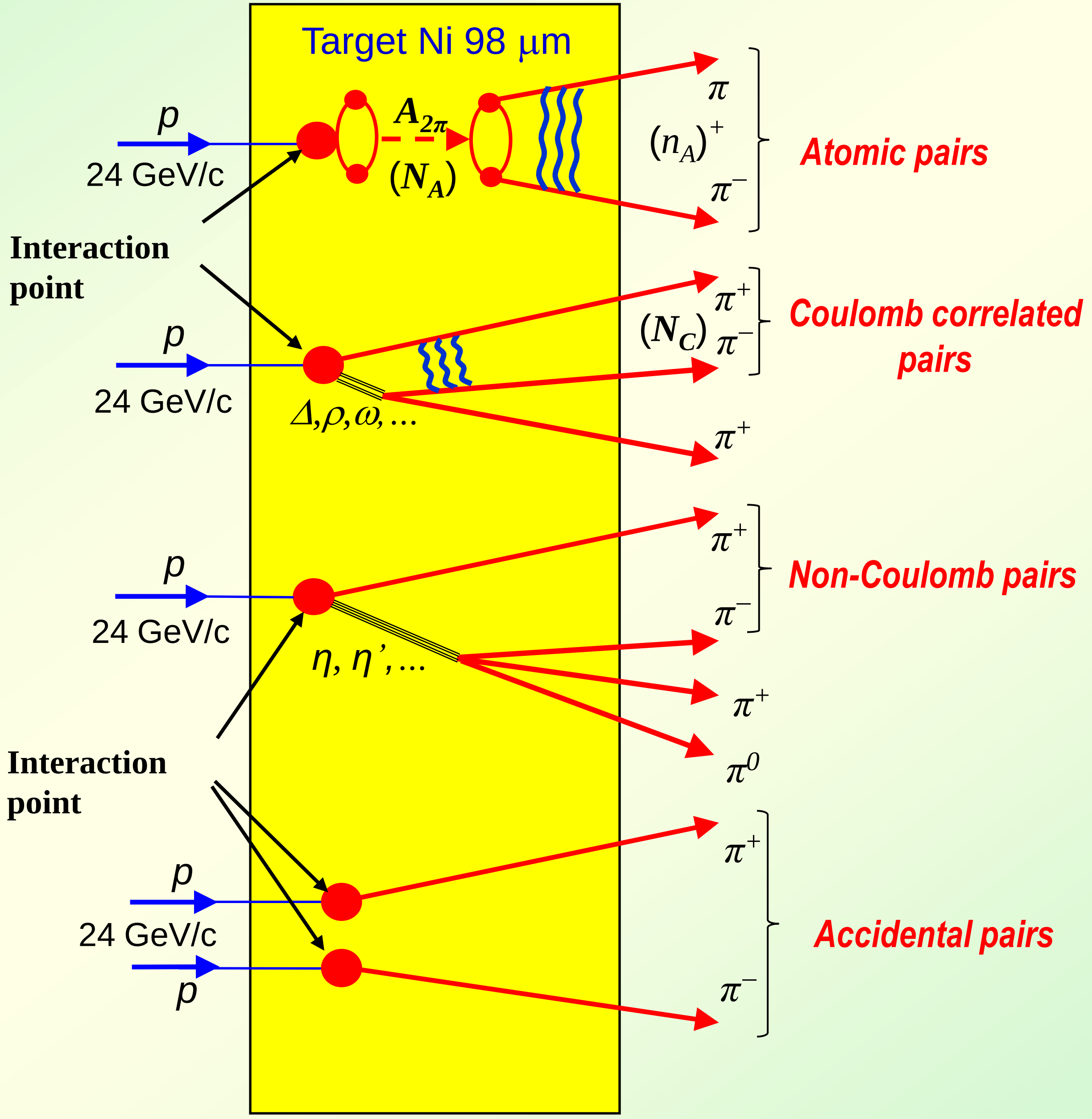
	$\delta a_{1/2}$ (%)	$\delta a_{3/2}$ (%)	$\delta(a_{1/2}-a_{3/2})$ (%)	
ChPT	11	40	10	Will be significantly improved by ChPT
Roy-Steiner	10	17		

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 2013			5 (stat)	

		$\delta(2a_{1/2}+a_{3/2})$ (%)	
$(E_{np}\text{-}E\text{-}_{ns})_{\pi K}$ SPS beyond 2013			

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



Upgraded DIRAC experimental setup