Results and scientific plans of the DIRAC experiment at CERN

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DIRAC collaboration

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KEK
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Kyoto Sangyou University
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Tokyo Metropolitan University
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IFIN-HH
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Dubna, **Russia**

SINP of Moscow State University
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Santiago de Compostela University
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DIRAC scientific plan 2011

1. Request for data taking in 2011 to observe the $A_{2\pi}$ long-lived states. These will permit to measure the Lamb shift and the new combination $2a_0 + a_2$ of the $\pi^+\pi^-$ scattering lengths.

2. Data processing of the 2008 – 2010 runs to observe $K^+\pi^-$ atoms, to measure their lifetime and $|a_{1/2}-a_{3/2}|$ combination of the scattering lengths.

3. The 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.

4. The evaluation of the K^+K^- and $\pi\mu$ atom production cross section based on the 2008-2010(2011) experimental data.

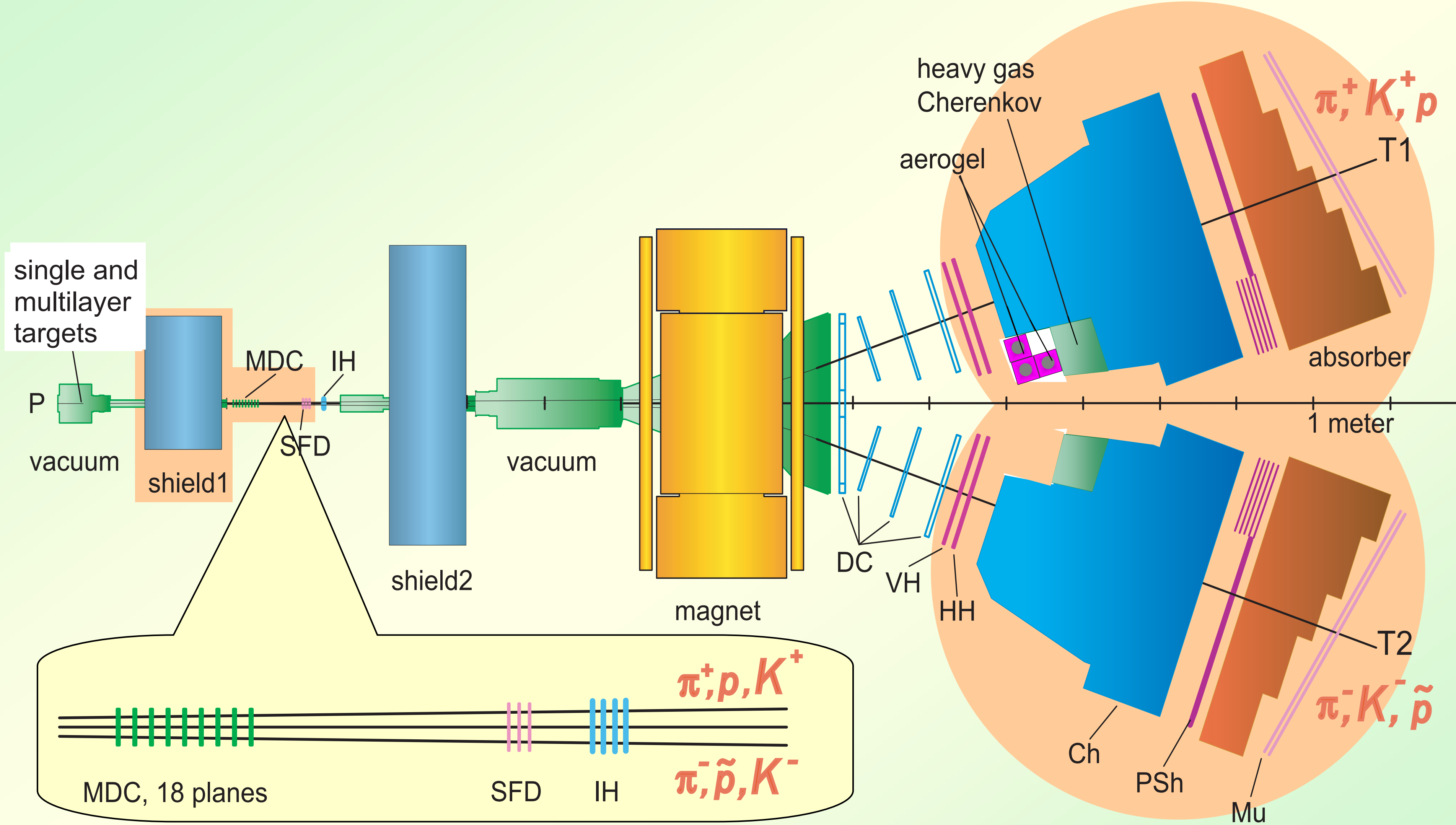
DIRAC plan beyond 2011

1. **The preparation of the DIRAC Collaboration for the new experiment at SPS**

2. **Presentation in 2013 of a Letter of Intent:**

   "Investigations of the $\pi\pi$, πK and other exotic atoms at the SPS proton beam to check the precise low energy *QCD* predictions"

Upgraded DIRAC experimental setup



1. Request for data taking in 2011 to observe the $A_{2\pi}$ long-lived states. These will permit to measure the Lamb shift and the new combination $2a_0 + a_2$ of the $\pi^+\pi^-$ scattering lengths.

1.1 Energy splitting between np - ns states in $\pi^+\pi^-$ atom

$$\Delta E_n \equiv E_{ns} - E_{np}$$

$$\Delta E_n \approx \Delta E_n^{vac} + \Delta E_n^{s} \qquad \Delta E_n^s \sim 2a_0 + a_2$$

For $n = 2$

$\Delta E_2^{vac} = -0.107\ eV$ *from QED calculations*

$\Delta E_2^{s} \approx -0.45\ eV$ *numerical estimated value from ChPT*

$$a_0 = 0.220 \pm 0.005$$
$$a_2 = -0.0444 \pm 0.0010$$

(2001) *G. Colangelo, J. Gasser and H. Leutwyler*

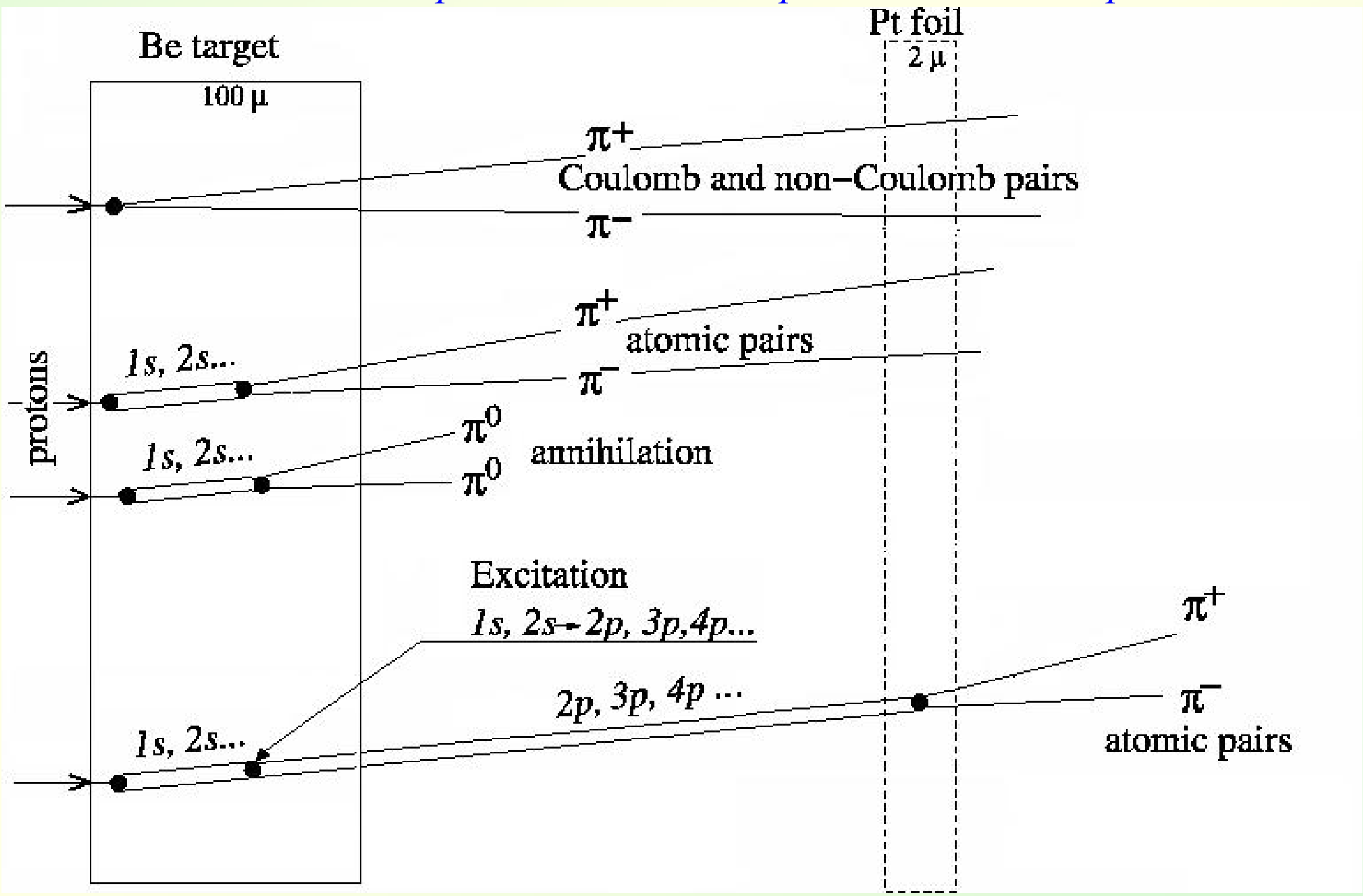
$\Rightarrow$ $\Delta E_2 \approx -0.56$ eV

(1979) A. Karimkhodzhaev and R. Faustov
(1983) G. Austen and J. de Swart
(1986) G. Efimov *et al.*
(1999) A. Gashi *et al.*
(2000) D. Eiras and J. Soto
(2004) J. Schweizer, EPJ C36 483
A. Rusetsky, *priv. comm.*

1.2 Metastable Atoms

For $p_A = 4.5$ GeV/c and $\gamma = 16.1$

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



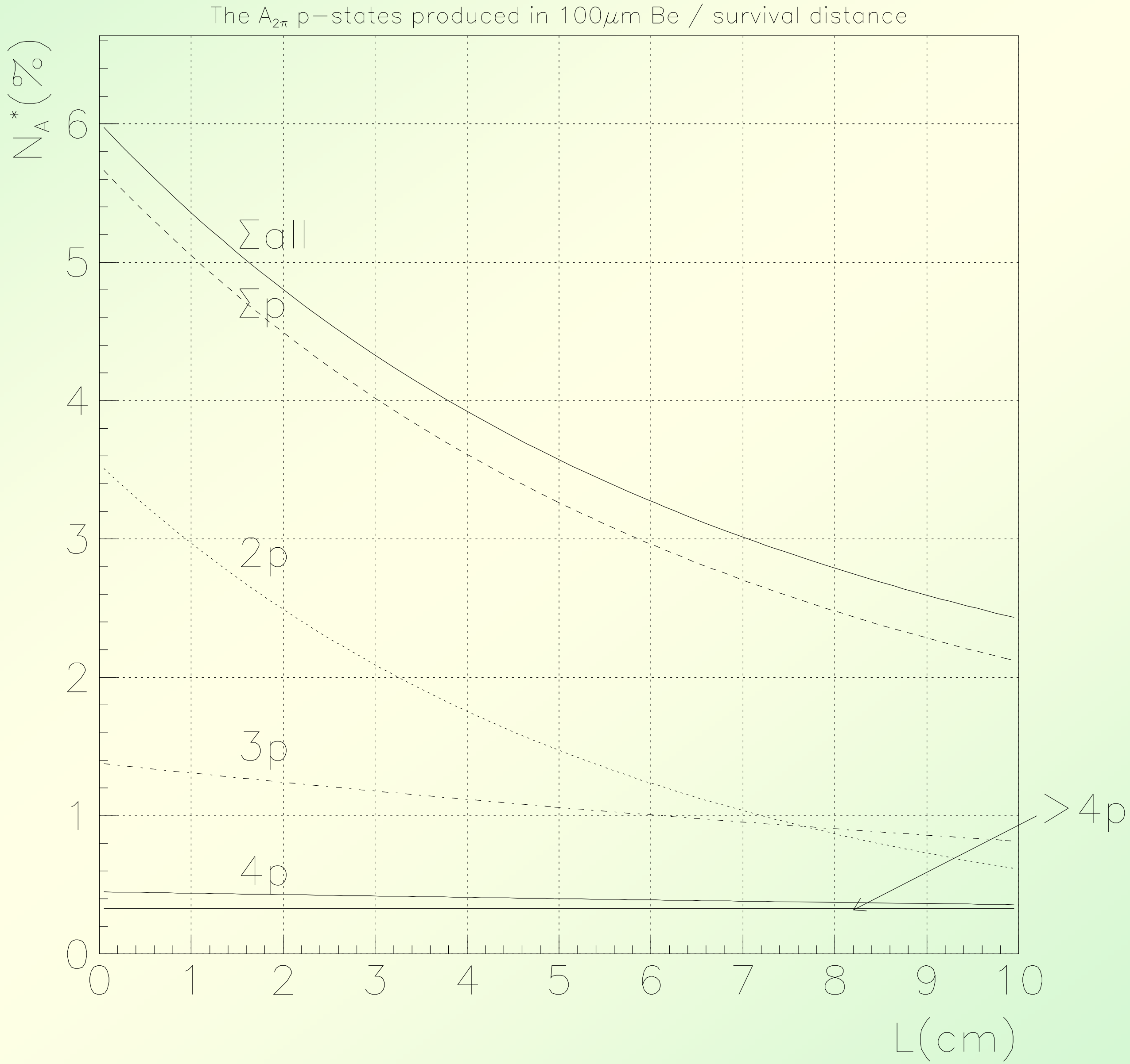
Observation of the $A_{2\pi}$ long-lived states using the breaking-up foil.

1.3 Metastable Atoms

Probabilities of the $A_{2\pi}$ breakup (Br),
Total production yield of the long-lived states: **$\Sigma(l \geq 1)$** and
Production yields of the long-lived p_0 states by different targets

Target Z	Thickness μm	Br	Σ $(l \geq 1)$	$2p_0$	$3p_0$	$4p_0$	Σ $(l = 1, m = 0)$
Be 04	100	4.45%	6.01%	1.18%	0.46%	0.15%	1.90%
C 06	50	5.00%	6.92%	1.46%	0.51%	0.16%	2.52%
Al 13	20	5.28%	7.84%	1.75%	0.57%	0.18%	2.63%
Ni 28	5	9.42%	9.69%	2.40%	0.58%	0.18%	3.29%
Pt 78	2	18.8%	10.5%	2.70%	0.54%	0.16%	3.53%

1.3 Metastable Atoms

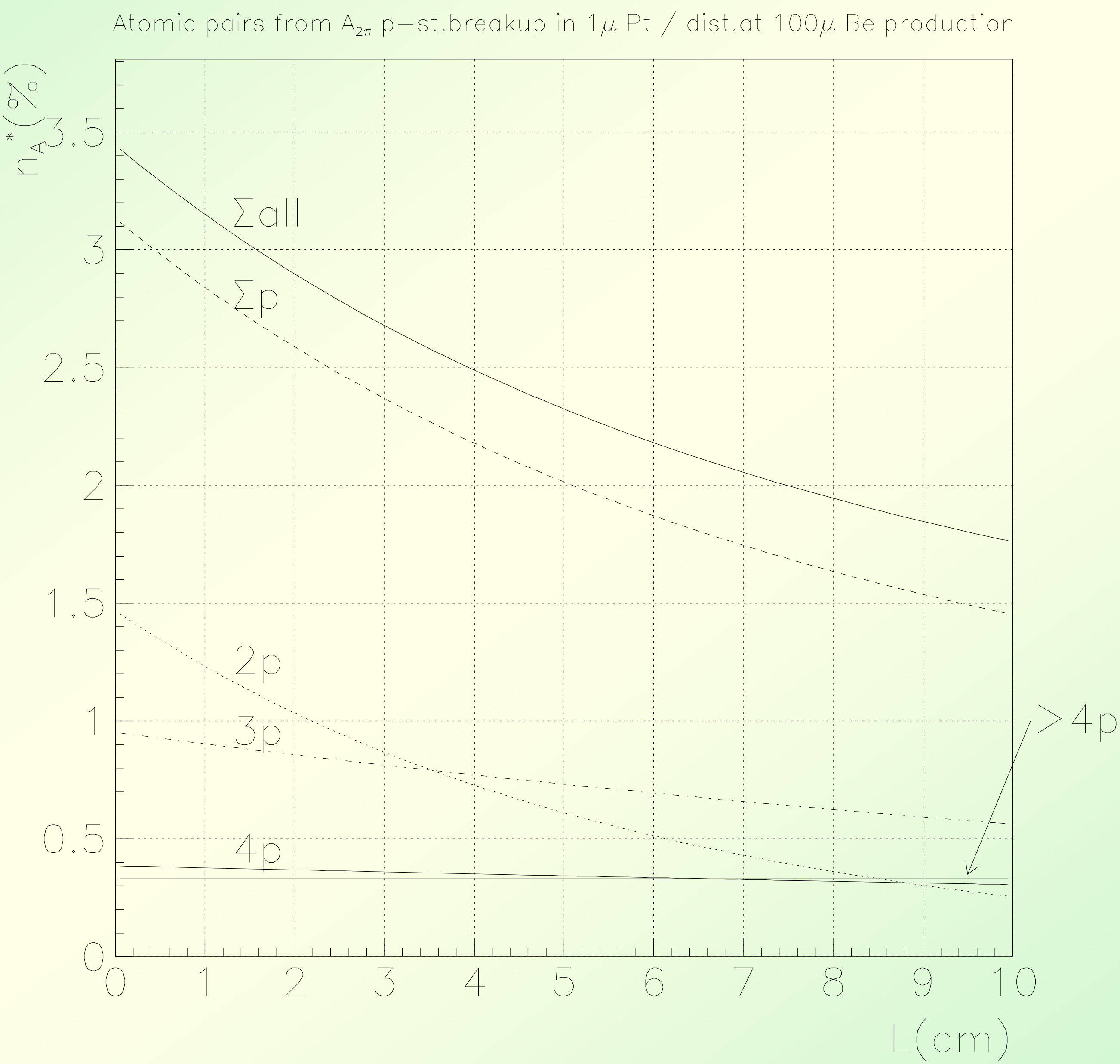


1.4 Metastable Atoms

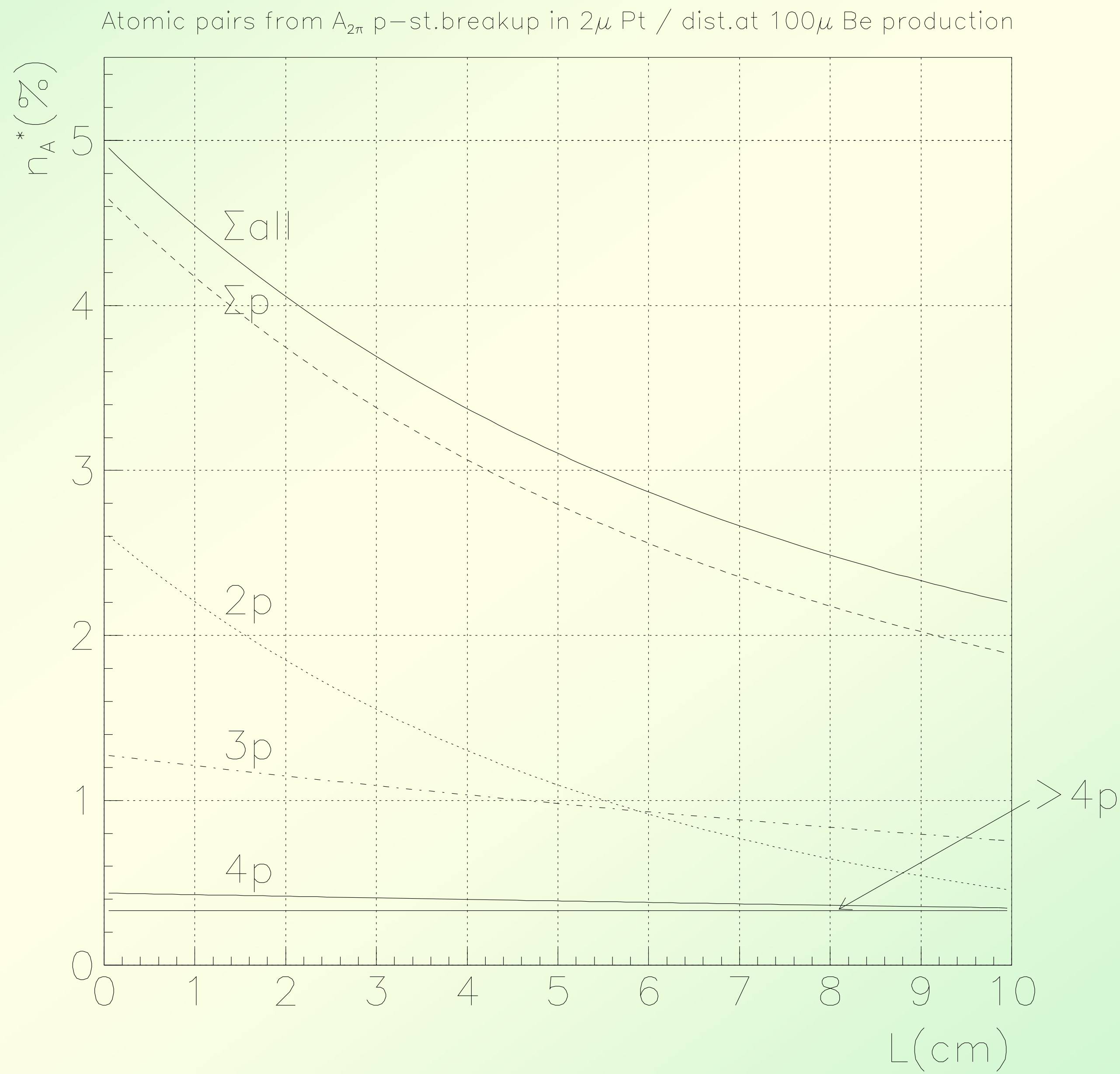
Breakup probability for *np* states and for different thickness of the Pt foils.
($A_{2\pi}$ momentum P_A=4.5 GeV/c and $A_{2\pi}$ lifetime $\tau=3\times10^{-15}$s)

Thickness (μm)	2p	3p	4p	5p	6p	7p
0.1	0.0251	0.0520	0.0858	0.1327	0.2035	0.3219
0.2	0.0559	0.1175	0.1978	0.3001	0.4185	0.5392
0.5	0.1784	0.3595	0.5537	0.7176	0.8323	0.9043
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
3.0	0.8844	0.9739	0.9918	0.9967	0.9985	0.9992
4.0	0.9415	0.9882	0.9964	0.9986	0.9993	0.9997
5.0	0.9651	0.9934	0.9980	0.9992	0.9996	0.9998
10.0	0.9862	0.9975	0.9993	0.9997	0.9999	0.9999

1.5 Metastable Atoms



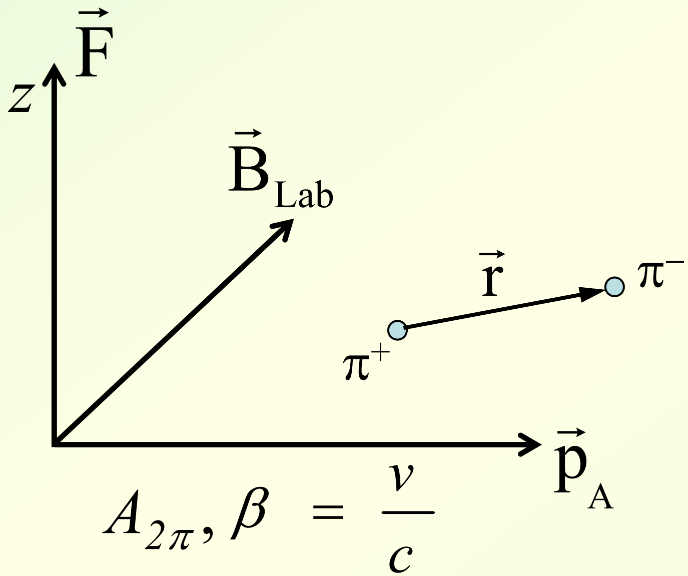
1.6 Metastable Atoms



1.7 Measurements of the Lamb shift using external magnetic and electric fields

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

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



$\vec{r} \equiv$ 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

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

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

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

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

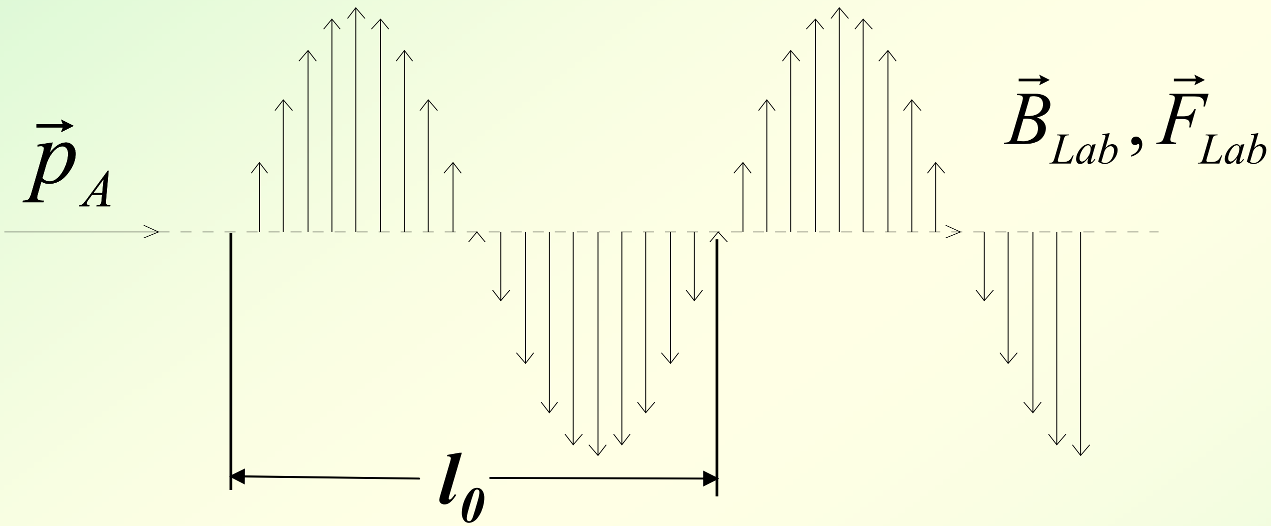
where: $|\xi|^2 \approx \dfrac{F^2}{\left(E_{2p}-E_{2s}\right)^2}$

$B_{Lab} = 2$ Tesla

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

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

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

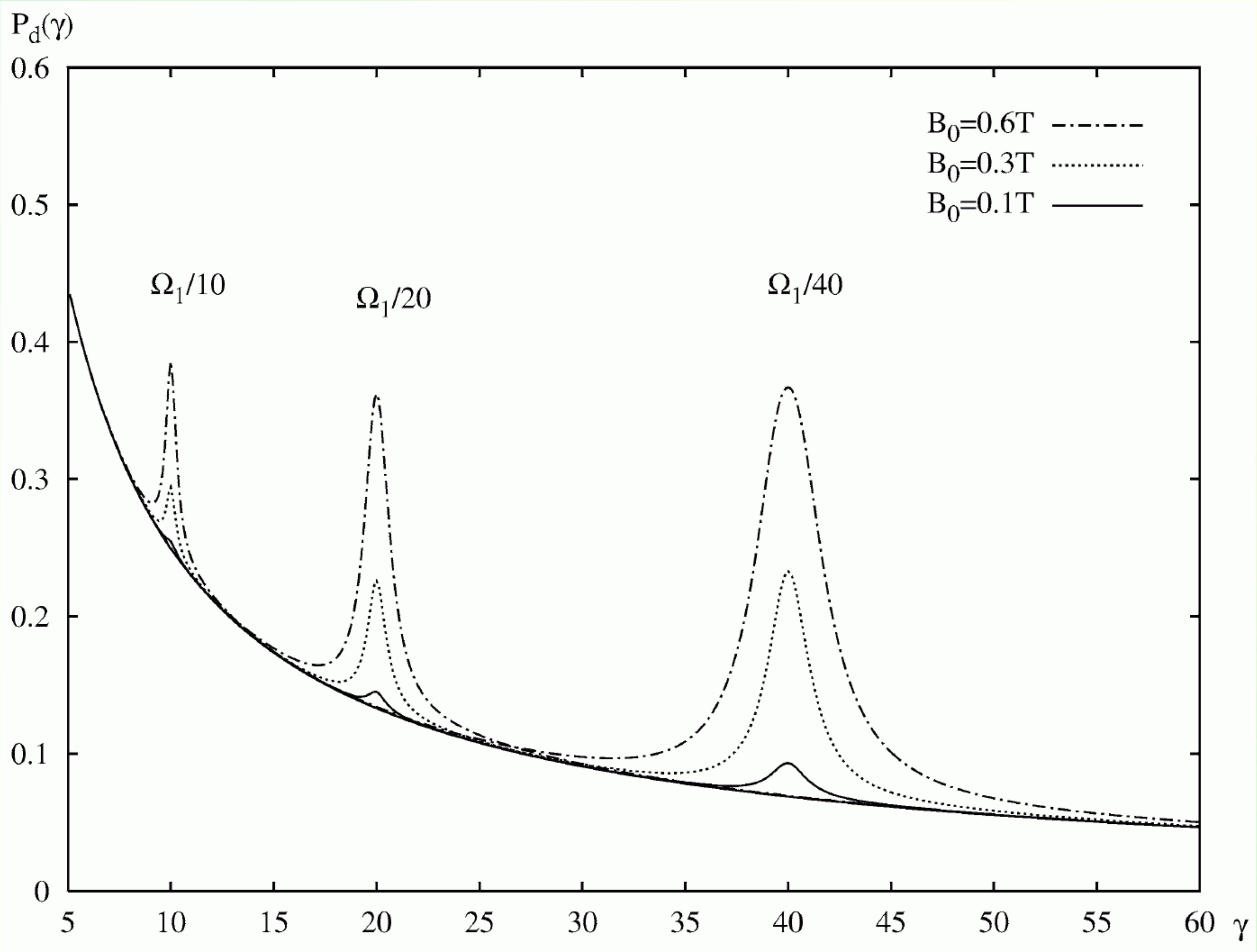


In Lab. System: $T_{Lab} = \frac{l_0}{\beta c}, \qquad \omega_{Lab} = \frac{2\pi}{T_{Lab}}$

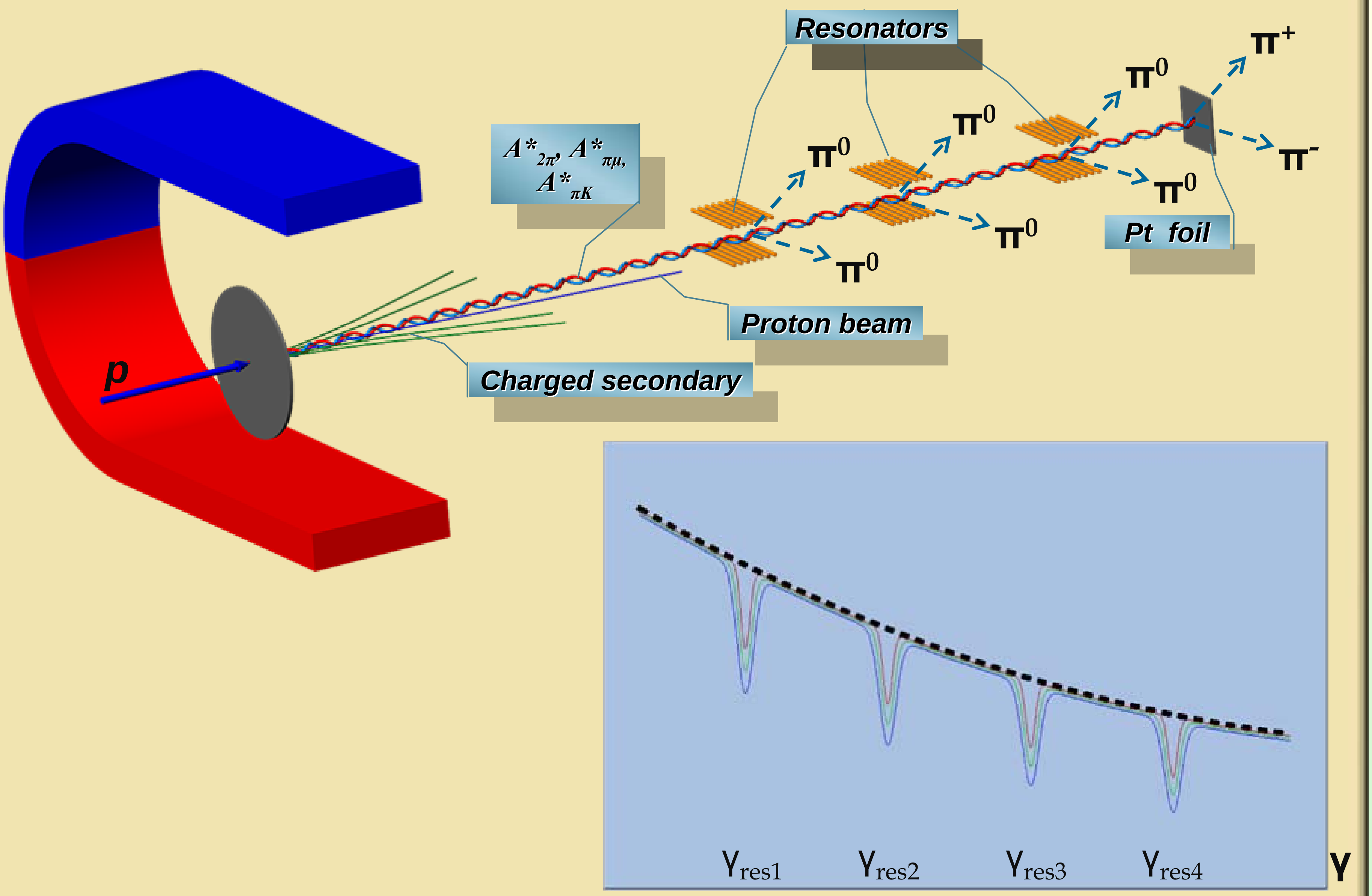
In CM System: $\tilde{\omega} = \gamma \omega_{Lab}, \qquad \tilde{\vec{F}} = \gamma \vec{F}_{Lab} \cdot \cos \tilde{\omega} t, \qquad \tilde{\Omega} = \frac{E_{2p} - E_{2s}}{\hbar}$

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

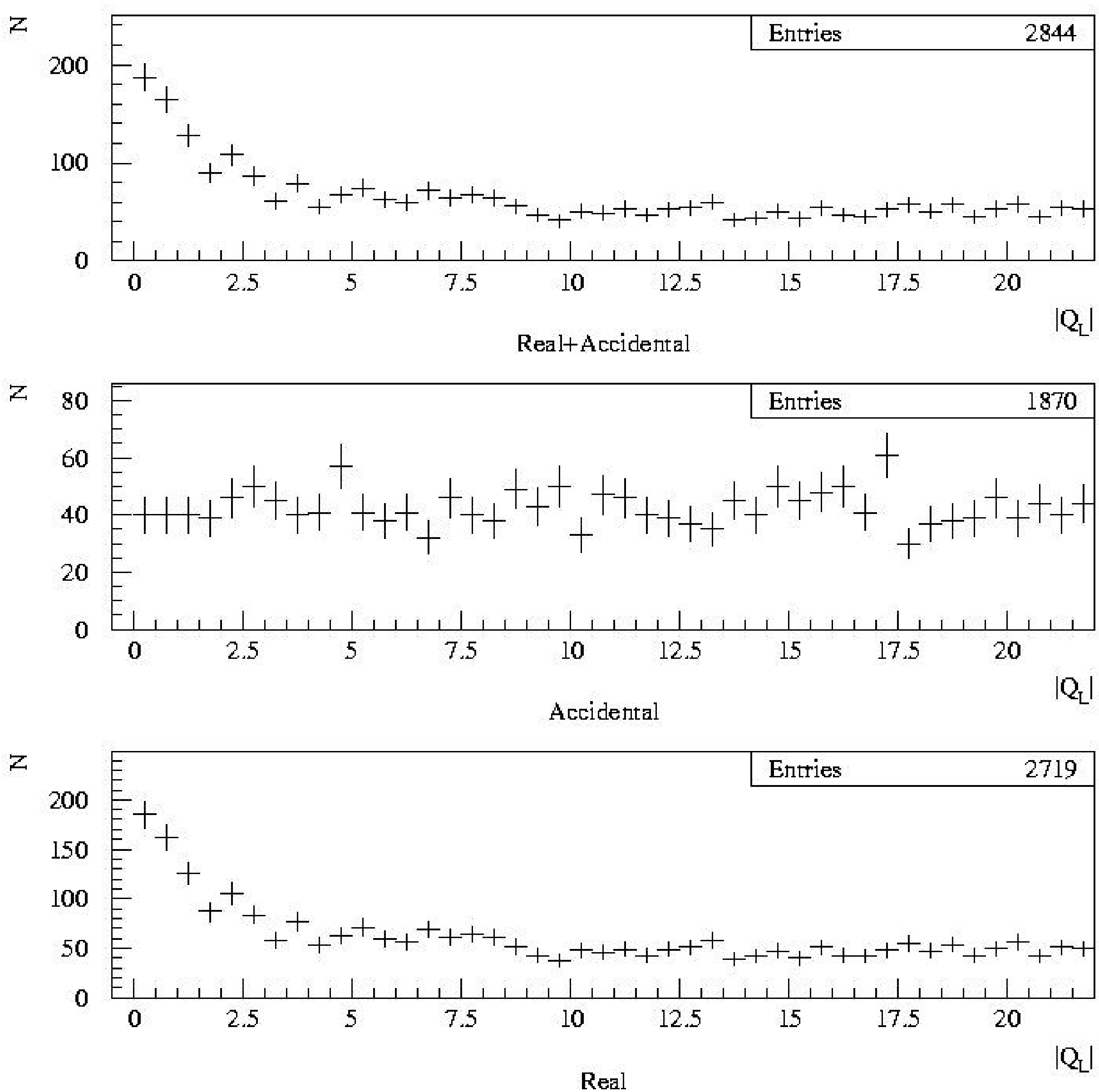
1.10 Resonant enhancement



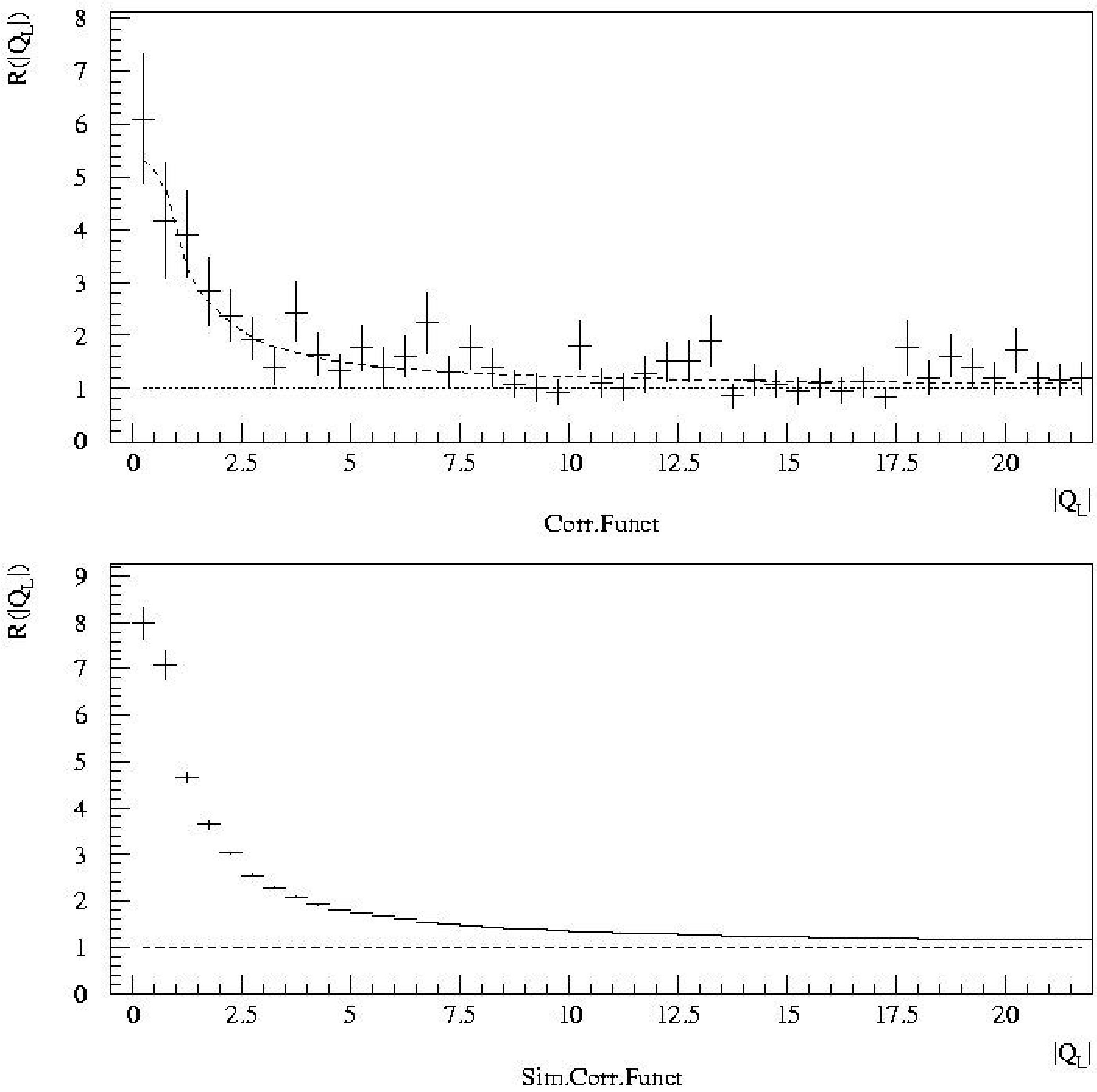
1.11 Resonant method



1.12 Be 2010 $Q_T<1$ MeV/c



1.13 Be 2010 Q_T<1 MeV/c



1.14 The background events in $A_{2\pi}$ measurements with different targets

N_A – Number of produced atoms, $\mathbf{N_{bckg}}$ – Number of background events in the region F<2.5 (~85% of atomic pairs) are presented. $\mathbf{Q_L}$ **x** $\mathbf{Q_X}$ **x** $\mathbf{Q_Y}$ – semi-axes of the ellipsoid for F<2.5

Data set	N_A ($A_{2\pi}$ atoms)	N_{bckg} (Coulomb and non-Coulomb pairs)	**Ellipsoid extension** Q_L x Q_X x Q_Y **(MeV/c)**	**Ratio** N_A/N_{bckg}
Ni 2001 (94 μm)	10000±400	18240	1.625 x 2.5 x 2.5	0.55
Ni 2009 (108 μm)	16000±250	27350	1.625 x 2.5 x 2.5	0.59
Be 2010 (100 μm)	736±75	266	1.5 x 0.9 x 0.9	2.8
Be 2010 (100 μm) + *Pt* (2 μm)	736±75	510	1.5 x 1.35 x 1.35	1.4

The 736 ±75 $A_{2\pi}$ atoms has been detected during 7.5 days of data taking

2. Data processing of the 2008 – 2010 runs to observe $K^+\pi^-$ atoms, to measure their lifetime and the $|a_{1/2}-a_{3/2}|$ combination of the scattering lengths.

2.1 πK scattering

What new will be known if πK scattering length will be measured?

The measurement of the s-wave πK scattering lengths would test our understanding of the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (u, d and s quarks), while the measurement of $\pi\pi$ scattering lengths checks only the $SU(2)_L \times SU(2)_R$ symmetry breaking (u, d quarks).

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

Experimental data on the πK low-energy scattering are absent

2.2 πK scattering lengths

I. ChPT predicts s-wave scattering lengths:

$$a_0^{1/2} = 0.19 \pm 0.2 \qquad a_0^{3/2} = -0.05 \pm 0.02$$

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

$\mathcal{L}^{(2)}, \mathcal{L}^{(4)}$ *and* $1-loop$

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

A. Rossel. – 1999

$$a_0^{1/2} - a_0^{3/2} = (0.220 - (-0.047)) = 0.267$$

J. Bijnens, P. P. Donthe P. Talavera. – 2004

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

$$\frac{\delta\left(a_0^{1/2} - a_0^{3/2}\right)}{a_0^{1/2} - a_0^{3/2}} < 10\%$$

II. Roy-Steiner equations:

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

P.Büttiker et al. – 2004

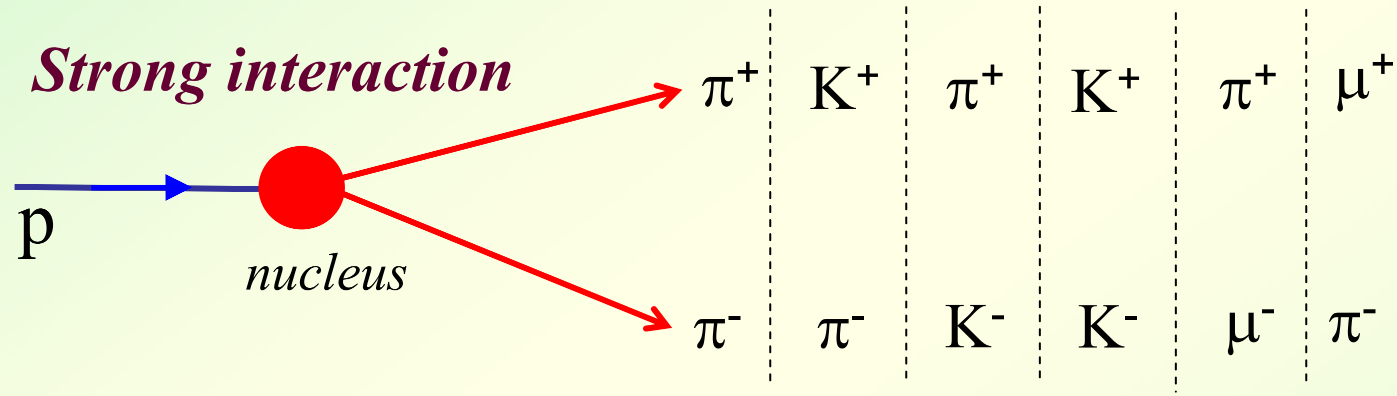
2.3 Accuracy of $|a_{1/2}-a_{3/2}|$ measurement

Accuracy of the measurement	5σ (20%)	6σ (17%)	6.5σ (15%)
τ (s)	$(3.7 \begin{smallmatrix} +60\% \\ -43\% \end{smallmatrix})\cdot 10^{-15}$	$(3.7 \begin{smallmatrix} +51\% \\ -38\% \end{smallmatrix})\cdot 10^{-15}$	$(3.7 \begin{smallmatrix} +46\% \\ -32\% \end{smallmatrix})\cdot 10^{-15}$
$\delta_{avreage}\lvert a_{1/2} - a_{3/2}\rvert$	26 %	23 %	20 %

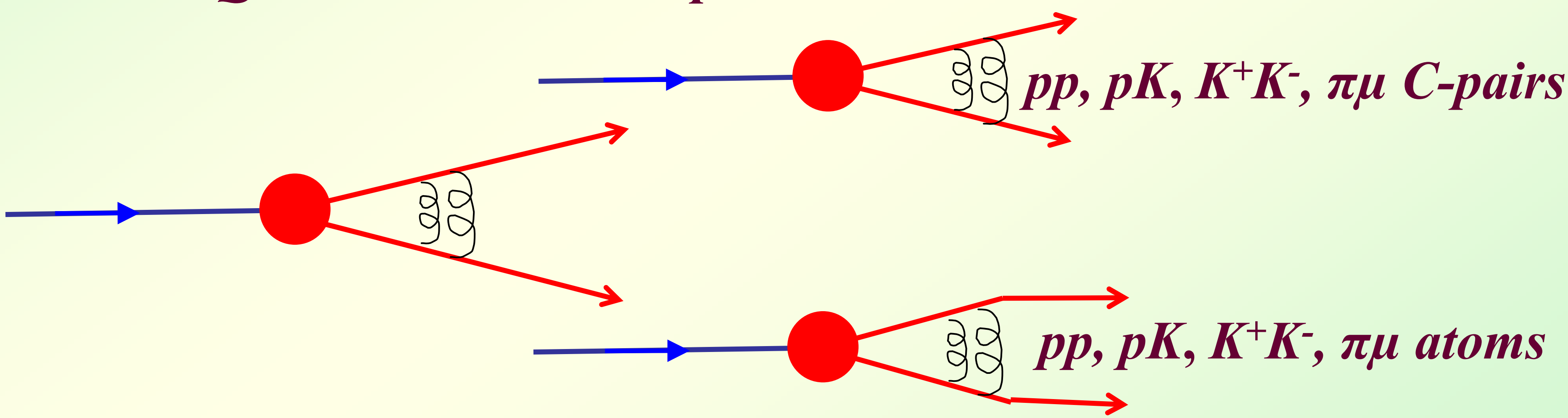
3. The multiple scattering measurement in *Be*, *Al*, *Ti*, *Ni* and *Pt* with better than 1% accuracy. The data will permit to obtain the $A_{2\pi}$ lifetime with better than 6% and $|a_0 - a_2|$ with better than 3% precisions.

4. The evaluation of the K^+K^- and $\pi\mu$ atom production cross section based on the 2008-2010(2011) experimental data.

4.1 Coulomb pairs and atoms



For small Q there are Coulomb pairs :



The production yield strongly increases for smaller Q

DIRAC plan beyond 2011

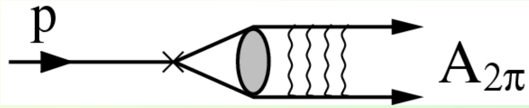
5. The preparation of the DIRAC Collaboration extension and the setup upgrade.

5.1 $A_{2\pi}$ and $A_{\pi K}$ production

$$\frac{d\sigma_{nlm}^{A}}{d\vec{P}} = (2\pi)^3 \frac{E}{M} \left|\psi_{nlm}^{(C)}(0)\right|^2 \frac{d\sigma_s^0}{dp_1 dp_2} \propto \frac{d\sigma}{dp_1} \cdot \frac{d\sigma}{dp_2}$$

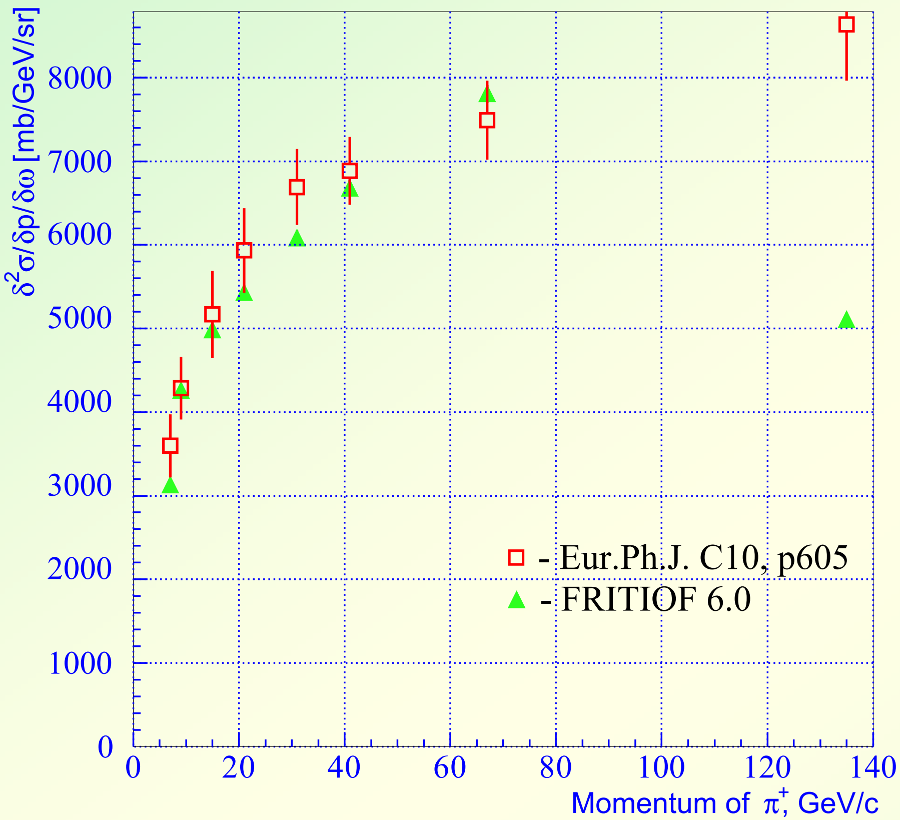
for atoms $\vec{v}_1 = \vec{v}_2$ *where* $\vec{v}_1, \vec{v}_2$ *– velocities of particles in the L.S. for all types of atoms*

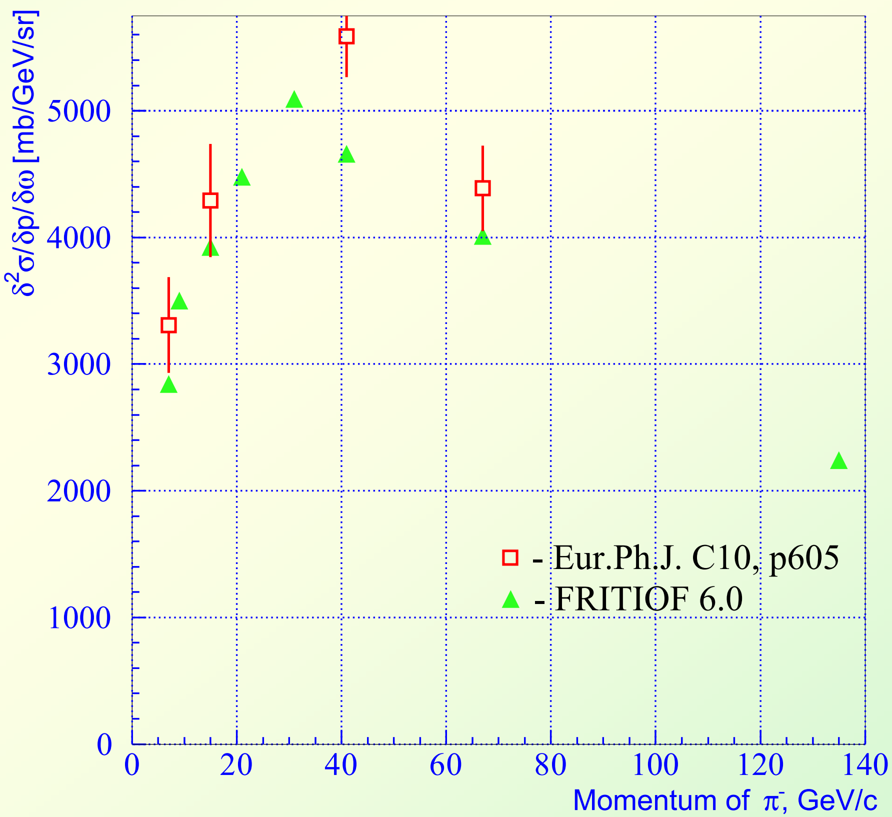
for $A_{2\pi}$ *production* $\vec{p}_1 = \vec{p}_2$



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

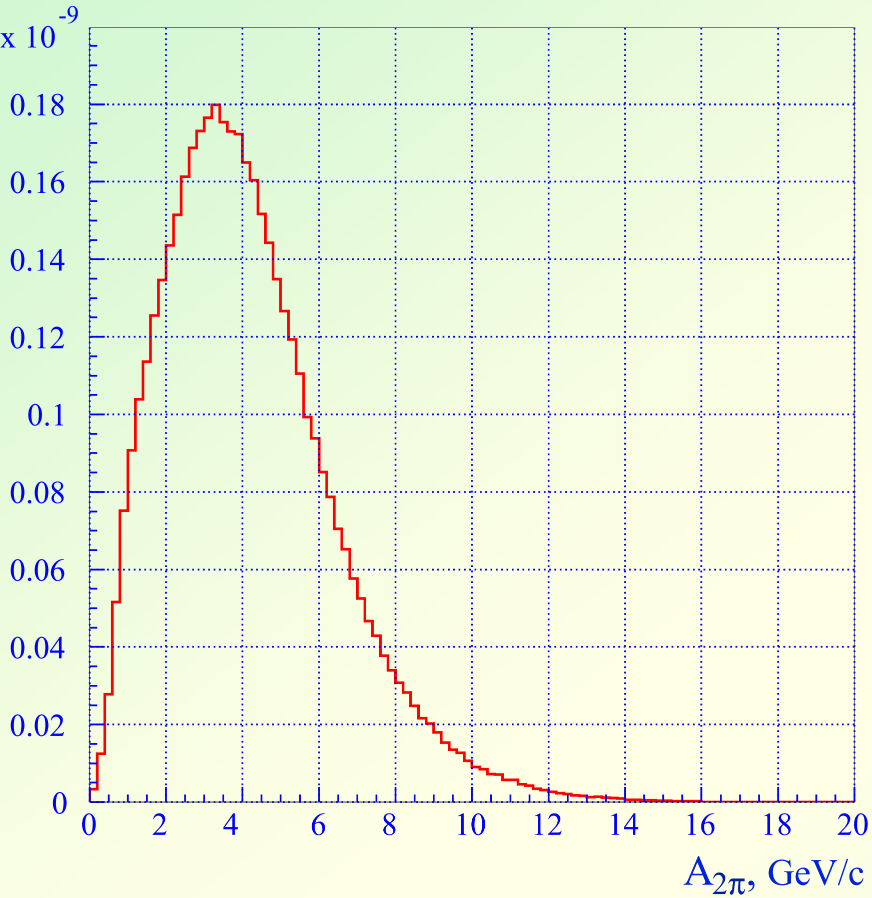
5.2 Inclusive cross-sections for π+, π− - mesons generation



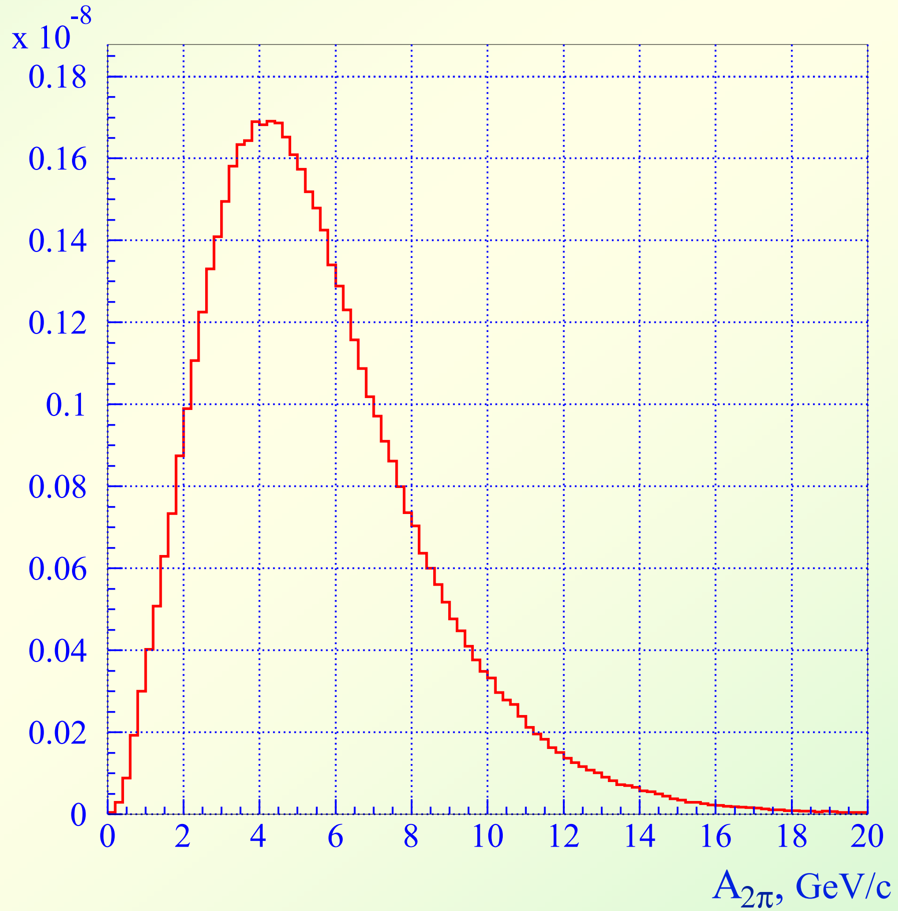


$$E_p = 450 GeV \qquad \theta_L = 0^\circ$$

5.3 $A_{2\pi}$ momentum distributions (5.7°)

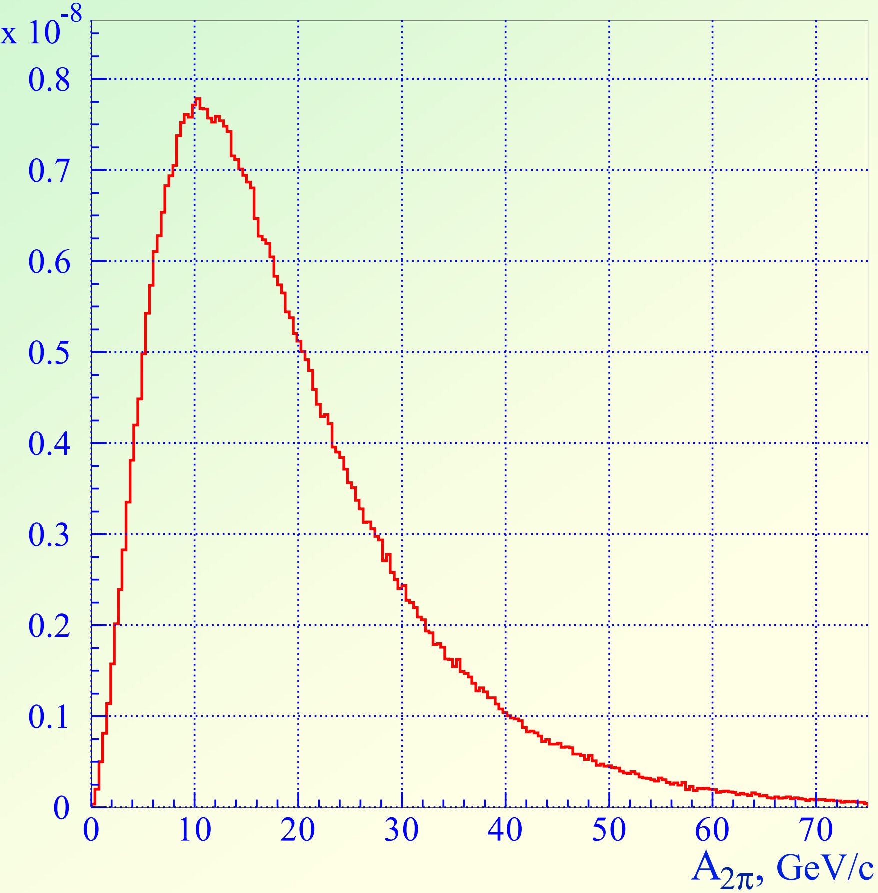


$$\theta_L = 5.7° \pm 1.3° \;\; E_p = 24 GeV$$

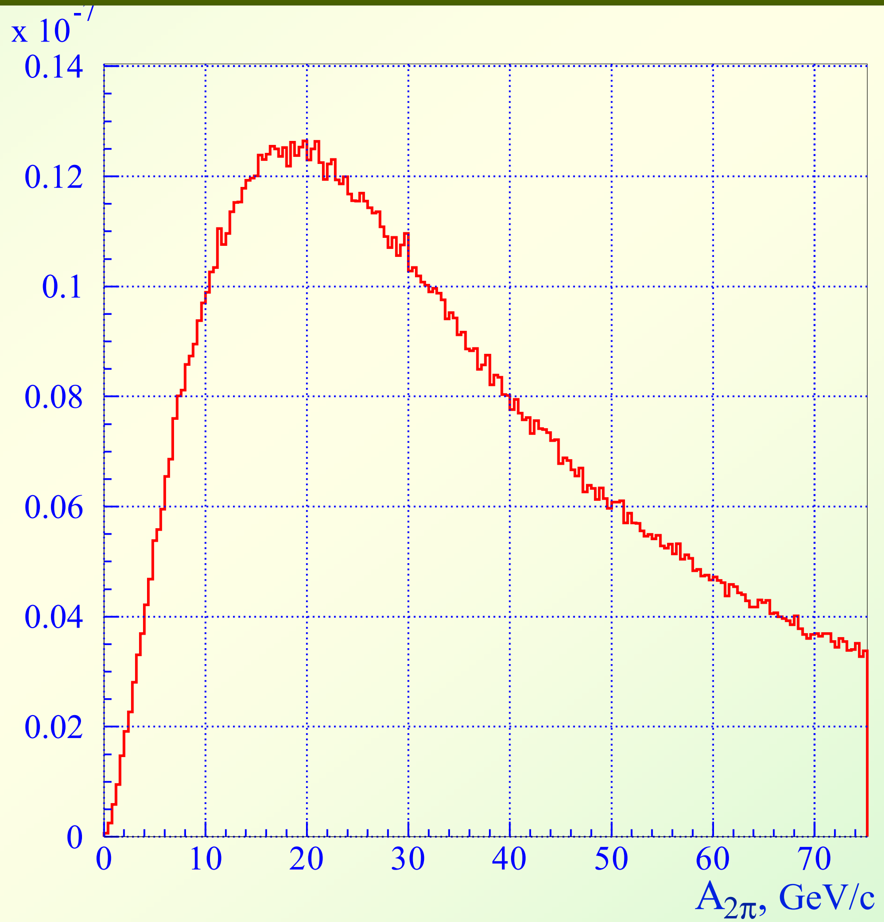


$$\theta_L = 5.7° \pm 1.3° \;\; E_p = 450 GeV$$

5.4 $A_{2\pi}$ momentum distributions (0-2°)

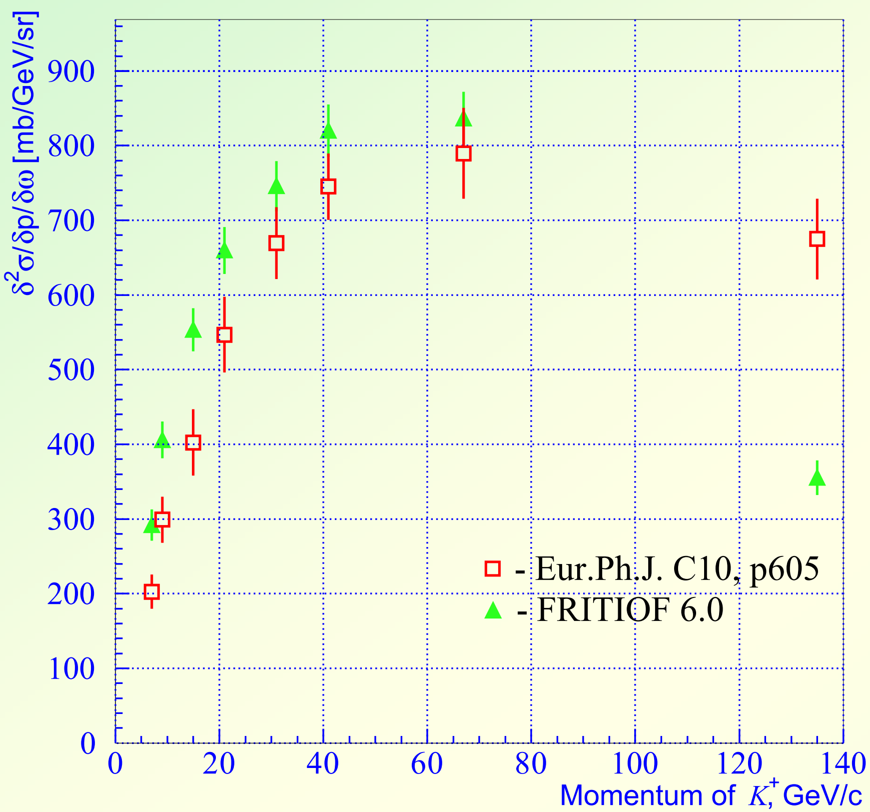


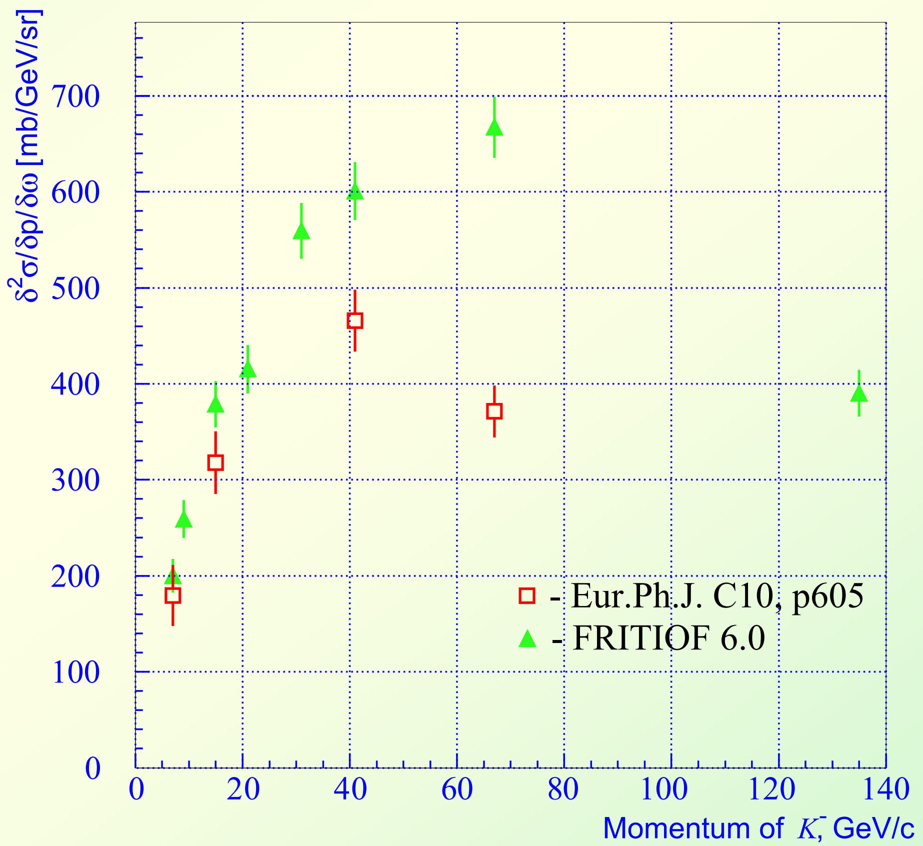
$$\theta_L = 2° \pm 1.3° \quad E_p = 450GeV$$



$$\theta_L = 0° \pm 1.3° \quad E_p = 450GeV$$

5.5 Inclusive cross-sections for K^+, K^- - mesons generation





$$E_p = 450GeV \quad \theta_L = 0^\circ$$

Yields of atoms at PS and SPS

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.**

5.7 DIRAC prospects at SPS CERN

Present low-energy QCD theoretical predictions for ππ 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 πμ atoms based on 2008-2010(2011) data				
τ(A2π) 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

5.8 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)	

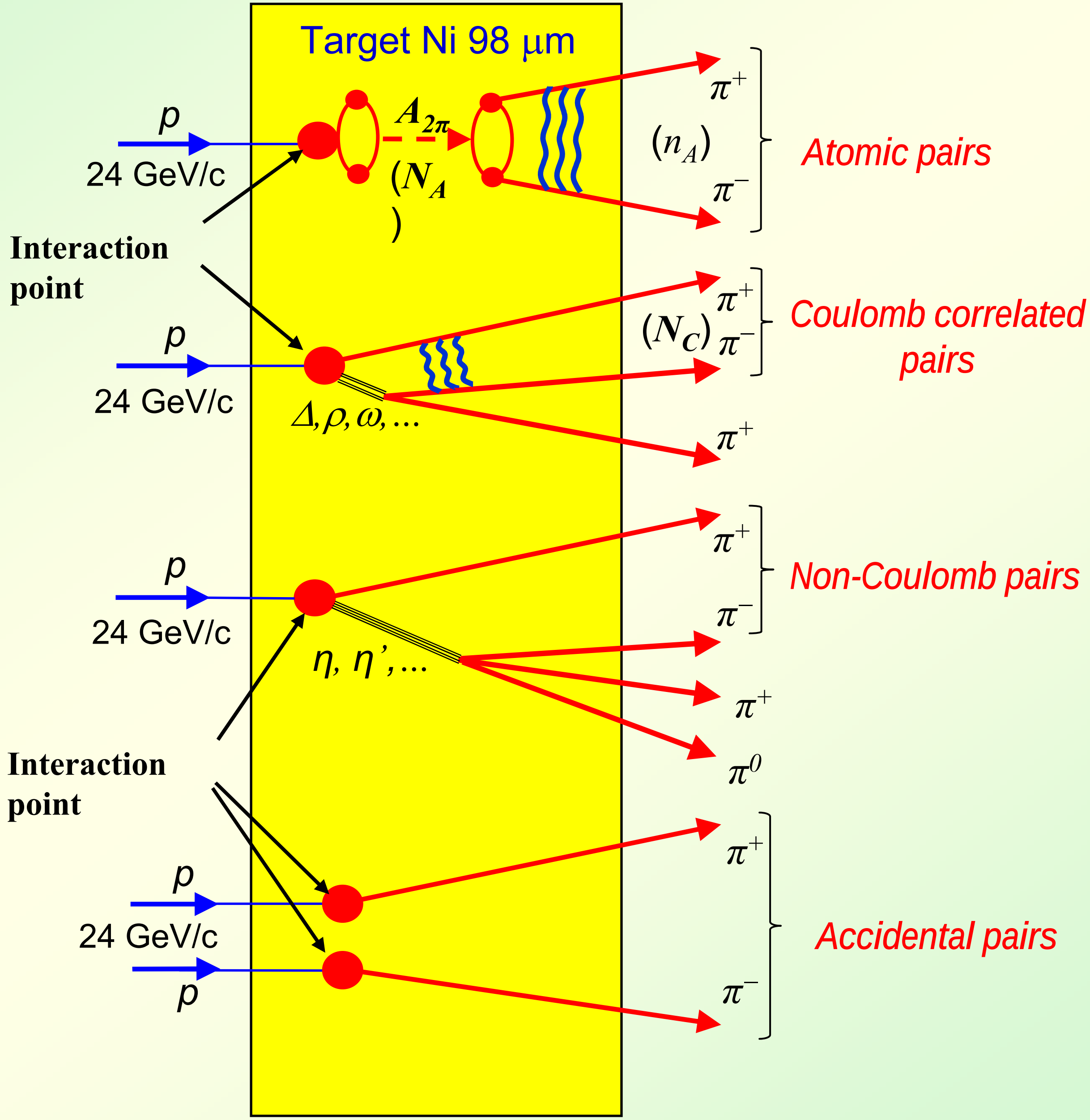
		$\delta(2a_{1/2}+a_{3/2})$ (%)	
$(E_{np}-E-_{ns})_{\pi K}$ SPS beyond 2013			

6. Presentation in 2013 of a Letter of Intent:

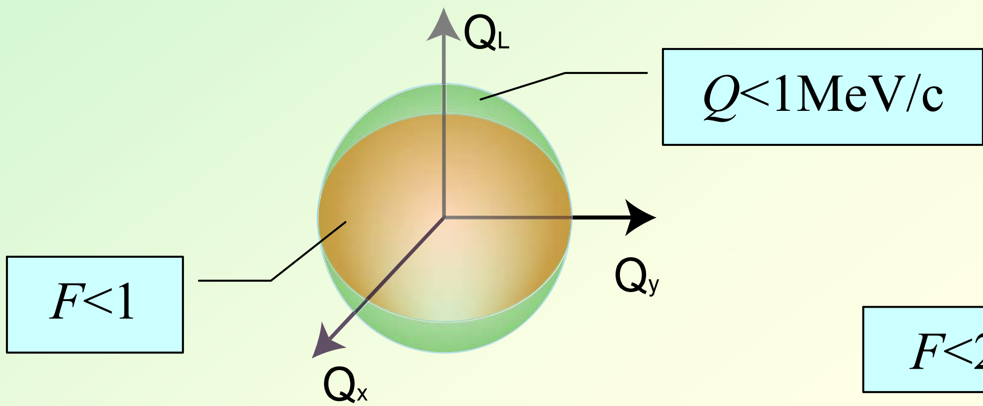
"Investigations of the $\pi\pi$, πK and other exotic atoms at the SPS proton beam to check the precise low energy *QCD* predictions"

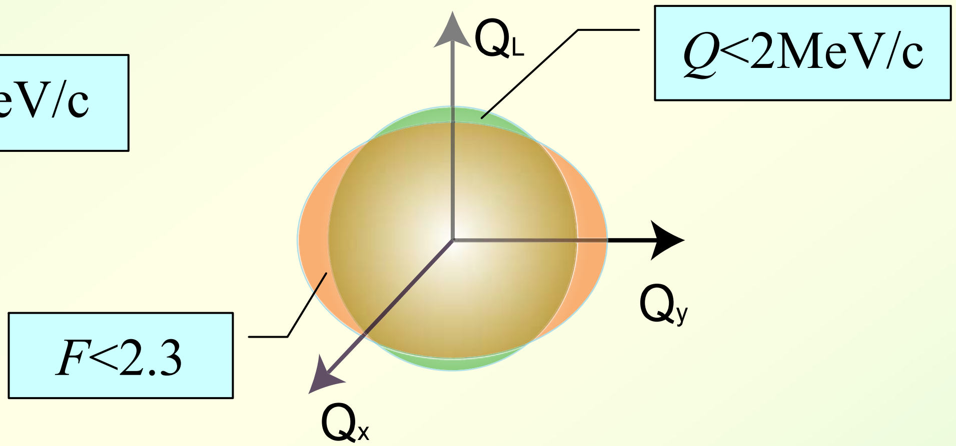
Thank you for your attention

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



Q and F





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

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

$$\sigma_{Q_X} = \sigma_{Q_Y} = 1 Mev / c$$

$$\sigma_{Q_L} = 0.65 Mev / c$$

$$N_a(F < 2.3) > N_a(Q < 2.0 MeV/c)$$

$$N_b(F < 2.3) \approx N_b(Q < 2.0 Mev/c)$$

Comparition with other experimental results

$K \to 3\pi$

2009 **NA48/2** (EPJ C64, 589)

$$\Rightarrow a_0 - a_2 = 0.2571 \pm 0.0048_{stat} \pm 0.0029_{syst}$$

...without constraint between a_0 and a_2:
and ±0.0088 theory uncertainty

Ke4:

2010 **NA48/2** (CERN-PH-EP-2010-036)
Submitted for publication in EPJ C

...without constraint between a_0 and a_2:

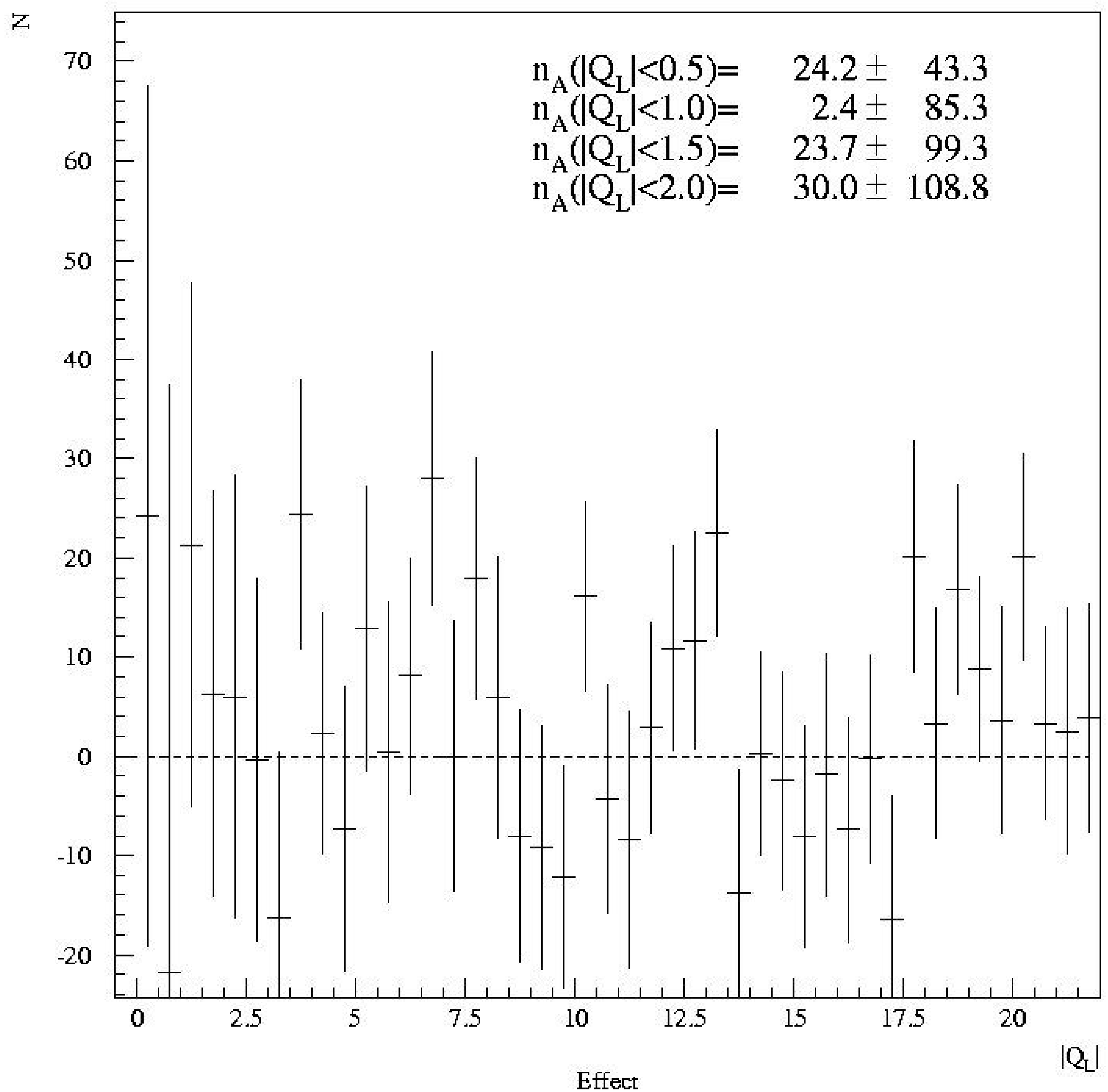
$$\Rightarrow a_0 = 0.2220 \pm 5.8\%\big|_{stat} \pm 2.3\%\big|_{syst} \pm 1.7\%\big|_{theo} = \ldots \pm 6.4\%$$

$$\Rightarrow a_2 = -0.0432 \pm 20\%\big|_{stat} \pm 7.9\%\big|_{syst} \pm 6.5\%\big|_{theo} = \ldots \pm 22\%$$

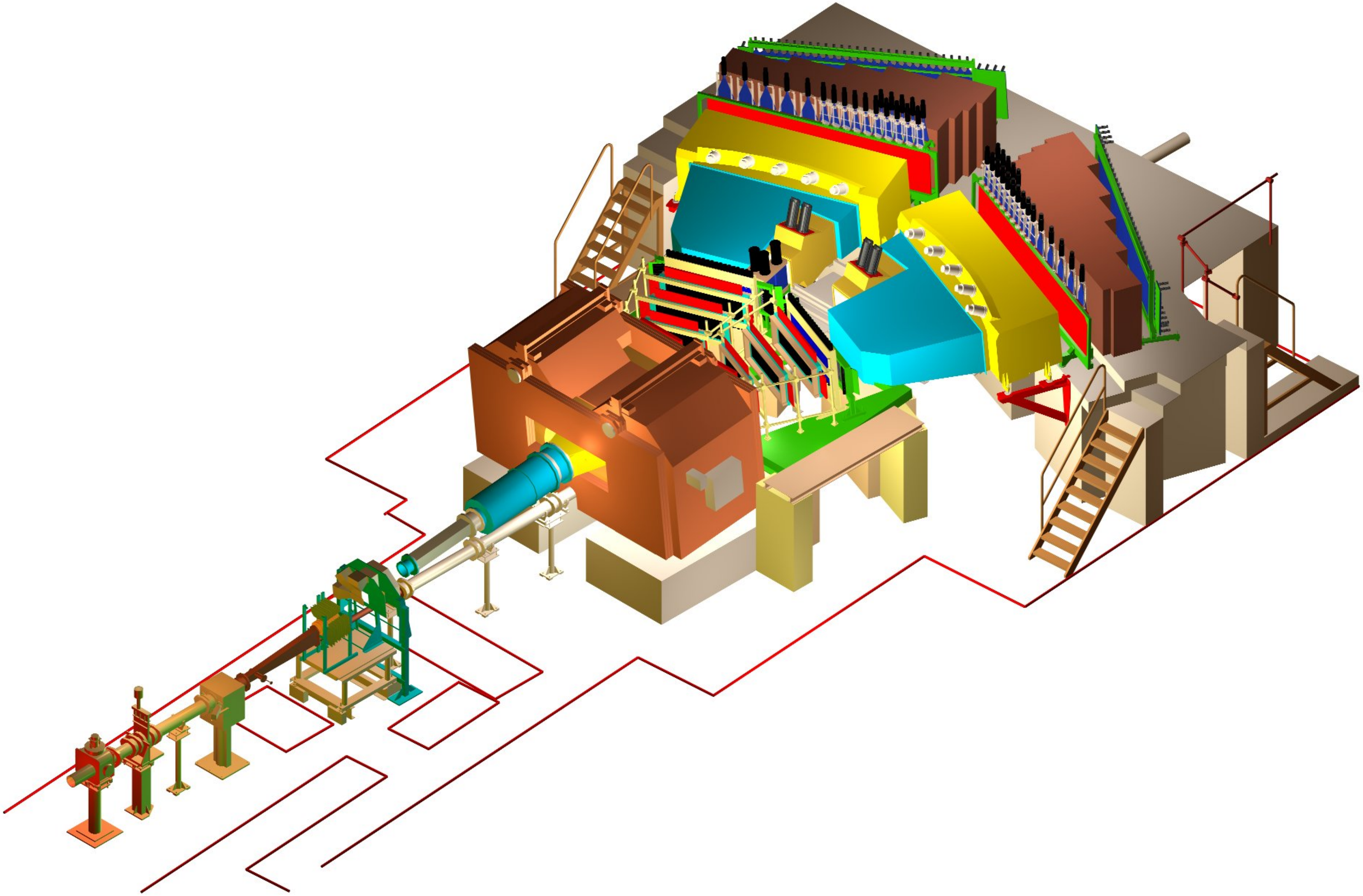
...with ChPT constraint between a_0 and a_2:

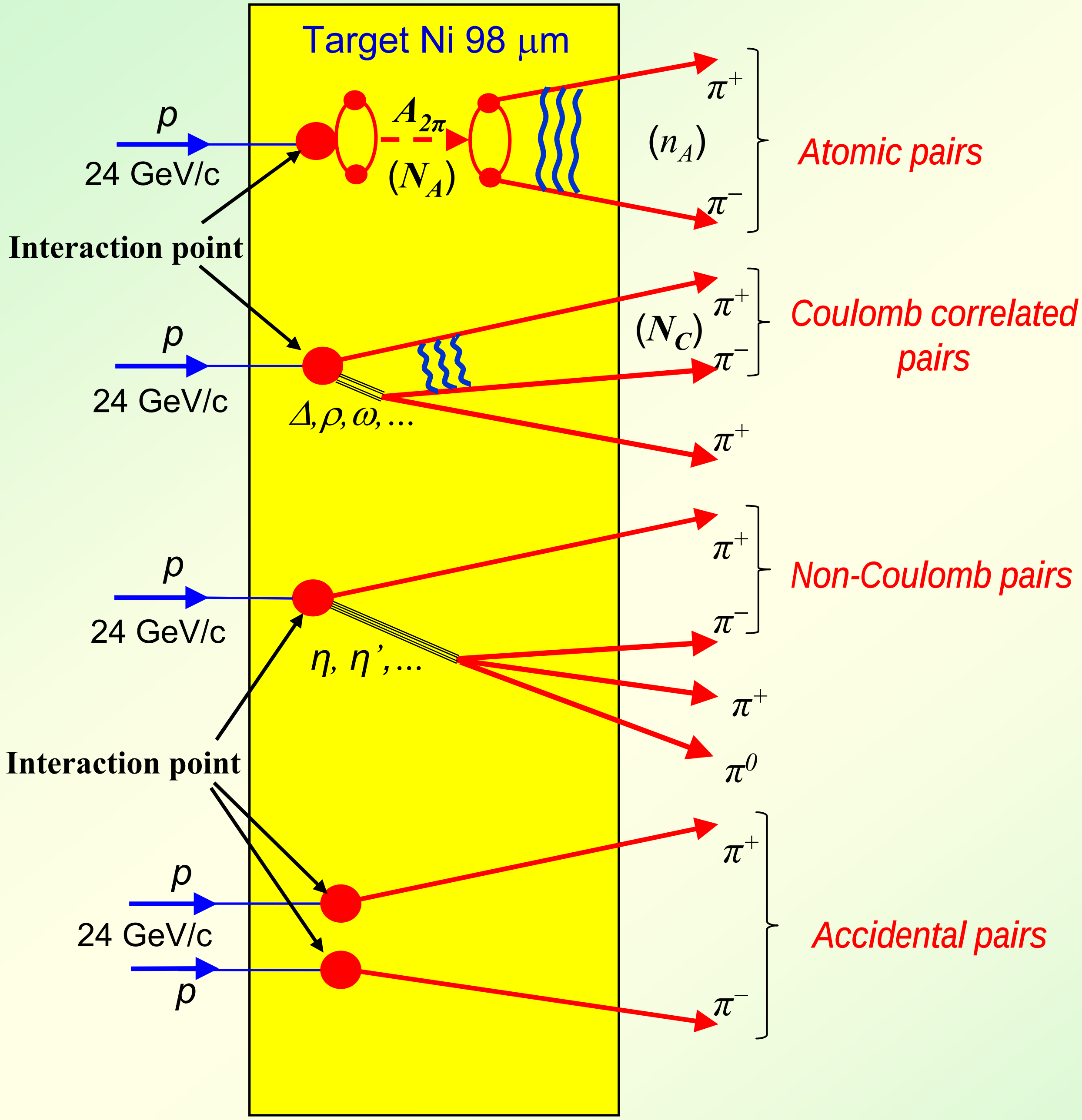
$$\Rightarrow a_0 = 0.2206 \pm 2.2\%\big|_{stat} \pm 0.8\%\big|_{syst} \pm 2.9\%\big|_{theo} = \ldots \pm 3.7\%$$

Be 2010 Q_T<1 MeV/c

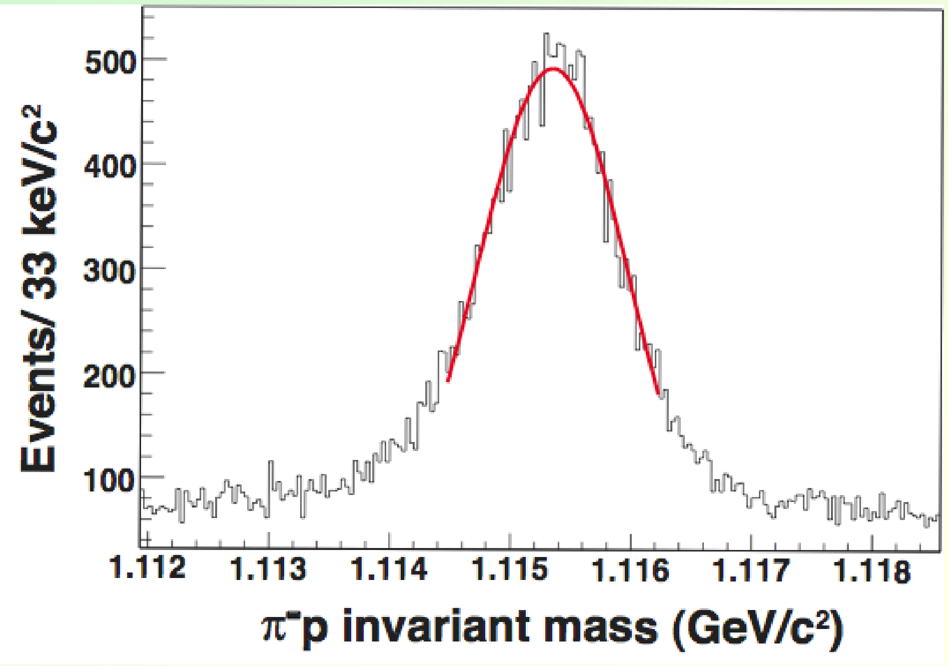


Upgraded DIRAC experimental setup



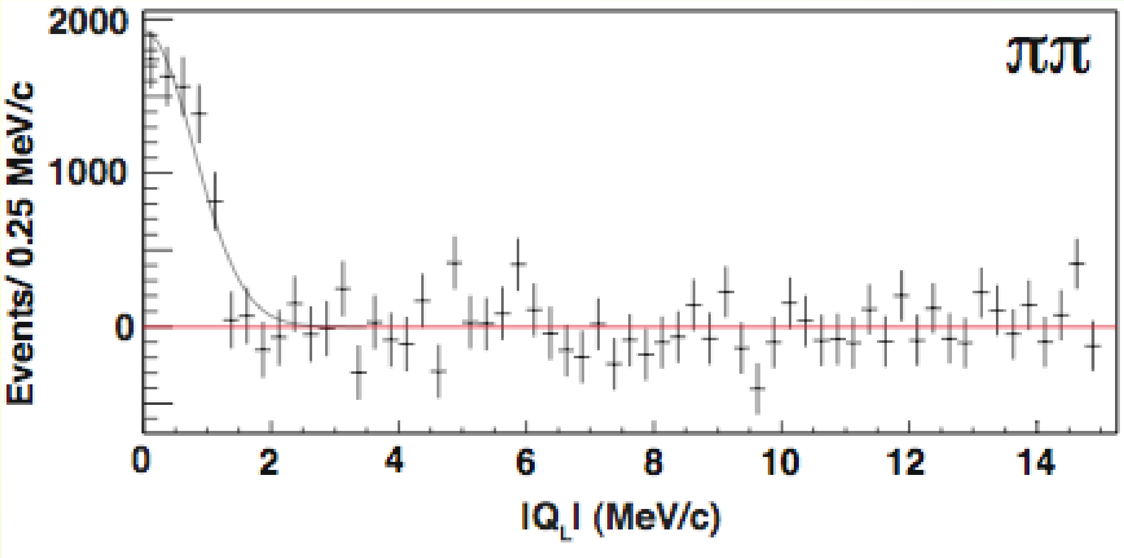

Target Ni 98 μm
p
24 GeV/c
$A_{2\pi}$
(N_A)
π^+
(n_A)
π^-
Atomic pairs
Interaction point
p
24 GeV/c
(N_C)
π^+
π^-
Coulomb correlated pairs
$\Delta, \rho, \omega, \ldots$
π^+
p
24 GeV/c
π^+
π^-
Non-Coulomb pairs
$\eta, \eta', \ldots$
π^+
π^0
Interaction point
p
24 GeV/c
p
π^+
π^-
Accidental pairs

$\pi-p$ mass & $\pi^+\pi^-$ signal in 2007



Setup calibration with Λ decays

Observation of $\pi^+\pi^-$ atoms with the Platinum target



1.7 DIRAC prospects at SPS CERN

Present low-energy ***QCD*** predictions for ***ππ*** and ***πK*** scattering lengths

$\pi\pi \quad \delta a_0 = 2.3\% \quad \delta a_2 = 2.3\% \quad \delta(a_0 - a_2) = 1.5\%$ …will be improved by *Lattice* calculations

$\pi K \quad \underbrace{\delta a_{1/2} = 11\% \quad \delta a_{3/2} = 40\%}_{ChPT} \quad \underbrace{\delta a_{1/2} = 10\% \quad \delta a_{3/2} = 17\%}_{Roy\text{-}Steiner}$ …will be significantly improved by *ChPT*

Expected results of DIRAC ADDENDUM at PS CERN after 2008-2010

$$\tau(A_{2\pi}) \to \delta(a_0 - a_2) = \pm 2\%(stat) \pm 1\%\ (syst) \pm 1\%\ (theor)$$

$$\tau(A_{\pi K}) \to \delta(a_{1/2} - a_{3/2}) = \pm 10\%(stat) \pm .... \pm 1.5\%\ (theor)$$

2011 Observation of metastable $\pi^+\pi^-$ atoms and study of a possibility to measure its Lamb shift.

Study of the possibility to observe K^+K^- and $\pi^\pm\mu^\mp$ atoms using 2008-2010 data.

DIRAC at SPS CERN beyond 2011

$$\tau(A_{2\pi}) \to \delta(a_0 - a_2) = \pm 0.5\%(stat) \qquad \tau(A_{\pi K}) \to \delta(a_{1/2} - a_{3/2}) = \pm 2.5\%(stat)$$

$$(E_{np} - E_{ns})_{\pi\pi} \to \delta(2a_0 + a_2) \qquad (E_{np} - E_{ns})_{\pi K} \to \delta(2a_{1/2} + a_{3/2})$$