# Measurement of $\pi^+\pi^-$ atom lifetime at DIRAC.

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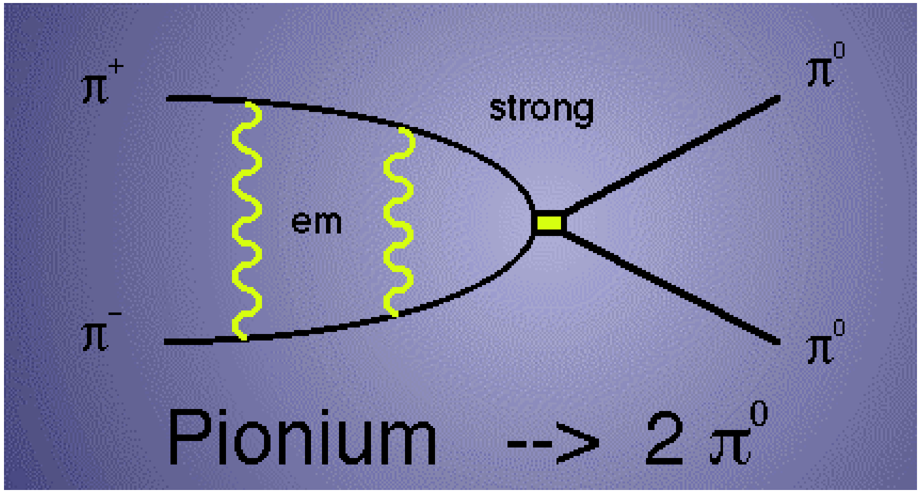
# DIRAC

## DImeson Relativistic Atomic Complexes

Lifetime Measurement of $\pi^+\pi^-$ atoms to test low energy QCD predictions.

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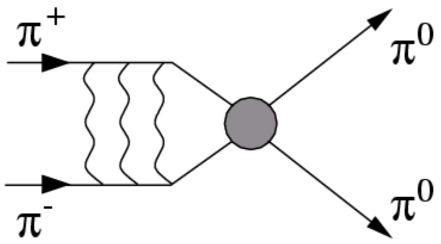
83 Physicists from 19 Institutes

# The Goal

The goal of the DIRAC Experiment is to measure the $\pi^+ \pi^-$ atom lifetime of order $3 \cdot 10^{-15}$ s with 10% precision. This measurement will provide in a model independent way the difference between S–wave $\pi\pi$ scattering lengths $|a_2 - a_0|$ with 5 % precision. Low energy QCD - chiral perturbation theory - predicts nowadays scattering lengths with very high accuracy ~ 2 % . Therefore, such a measurement will be a sensitive check of the understanding of chiral symmetry breaking of QCD by giving an indication about the value of the quark condensate, an order parameter of QCD.

# Theoretical Motivation

$\pi^+\pi^-$ atoms ($A_{2\pi}$) in the ground state decay by strong interaction mainly into $\pi^0\pi^0$.




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

Chiral Perturbation Theory (ChPt), which describes the strong interaction at low energies provides, at NLO in isospin symmetry breaking, a precise relation between $\Gamma_{2\pi}$ and the $\pi\pi$ scattering lengths:

(Deser et al) (Gall et al., Jalloli et al, Ivanov et al)

$$\Gamma^{LO}_{2\pi^0} = C\,|a_0 - a_2|^2 \qquad \Gamma^{NLO}_{2\pi^0} = \Gamma^{LO}_{2\pi^0}(1+\delta\Gamma)$$

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

$$\delta\Gamma = (5.8 \pm 1.2)\% \quad \Rightarrow \quad \tau = (2.9 \pm 0.1)\times 10^{-15}\,s$$

$$\sigma\tau/\tau = 10\% \quad \Rightarrow \quad \sigma(a_0 - a_2)/(a_0 - a_2) = 5\%$$

# Theoretical Status

In ChPT the effective Lagrangian which describes the ππ interaction is an expansion in (even) terms:

$$L_{eff} = L^{(2)} + L^{(4)} + L^{(4)} + \cdots$$

1966 Weinberg (tree): $L^{(2)}$ $a_0 - a_2 = 0.20$

1984 Gasser-Leutwyler (1-loop): $L^{(4)}$ $a_0 - a_2 = 0.25 \pm 0.01$

1995 Knecht et al. (2-loop): $L^{(6)}$ gChPT

1996 Bijnens et al. (2-loop): $L^{(6)}$ $a_0 - a_2 = 0.258 \pm (< 3\%)$

2001 Colangelo et al. (& Roy): $L^{(6)}$ $a_0 - a_2 = 0.265 \pm 0.004 (1.5\%)$

And the theoretical results for the scattering lengths up to 2-loops are:

| | Tree (Weinberg) | 1-loop (Gass.&Leut.) | 2-loop (Bijnens et al.) | 2loop+Roy (Colangelo et al.) |
|---|---|---|---|---|
| $a_0$ | 0.16 | 0.203 | 0.219 | 0.220 |
| $a_2$ | -0.045 | -0.043 | -0.042 | -0.044 |

# Experimental Status

Experimental data on ππ scattering lengths can be obtained via the following indirect processes:

Model independent, $K^+ \to \pi^+\pi^- e^+\nu_e \ (K_{e4})$

$a_0 = 0.28 \pm 0.05$ L. Rosselet et al., Phys. Rev. D 15 (1977) 574

$a_0 = 0.26 \pm 0.05$ M.Nagels et al., Nucl.Phys. B 147 (1979) 189
Combined analysis of $K_{e4}$, Roy equation and peripheral reaction $\pi N \to \pi\pi N$ data

$a_0 = 0.216 \pm 0.013 \pm 0.004(\text{syst}) \pm 0.005(\text{theor})$ New measurement at BNL (E865)
S.Pislak et al., Phys.Rev.Lett. 87 (2001) 221801

Model dependent: $\pi N \to \pi\pi N$ near threshold

$a_0 = 0.26 \pm 0.05 \ m_\pi^{-1}$ C.D. Froggatt, J.L. Petersen, Nucl. Phys. B 129 (1977) 89

…

$a_0 = 0.204 \pm 0.014 \pm 0.008(\text{syst})$ M. Kermani et al., Phys. Rev. C 58 (1998) 3431

# $A_{2\pi}$ production

- The pionic atoms are produced by the Coulomb interaction of a pion pair in proton-target collisions (Nemenov):

Wave function at origin (accounts for Coulomb interaction).

$$\frac{d\sigma_{nlm}^{A}}{d\vec{P}} = (2\pi)^3 \frac{E}{M} \left|\psi_{nlm}^{(C)}(0)\right|^2 \left.\frac{d\sigma_s^0}{d\vec{p}\,d\vec{q}}\right|_{\vec{p}=\vec{q}}$$

Lorentz Center of Mass to Laboratory factor.

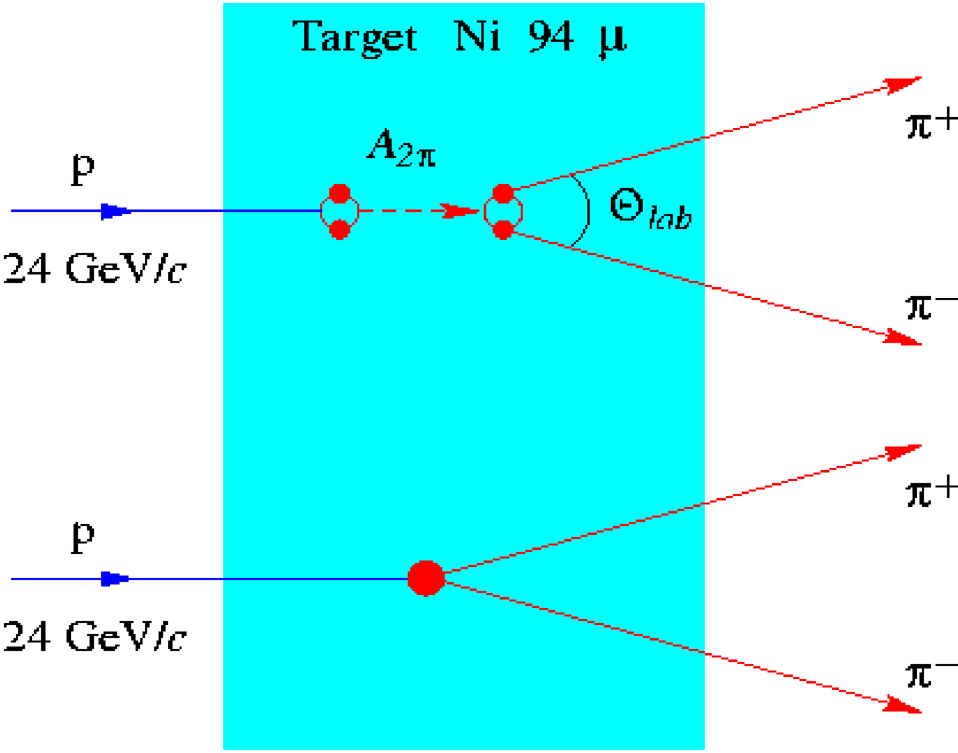
Pion pair production from short lived sources.

- Also free Coulomb pairs are created in the proton-target collisions.

- The atom production is proportional to the low relative momentum Coulomb pairs production ($N_A = K \times N_C$).

- The pionic atoms evolve in the target and some of them ($n_A$) are broken. The broken atomic pairs are emitted with small C.M.S. relative momentum ($Q$ < 3 MeV/$c$) and opening angle $\Theta$<0.3 *mrad*.

- DIRAC aims to detect and identify Coulomb and atomic pairs samples to calculate the break-up probability $P_{br} = n_A / N_A$.



# Lifetime and breakup probability

The $P_{br}$ value depends on the lifetime value, $\tau$. To obtain the precise $P_{br}(\tau)$ curve a large differential equation system must be solved:

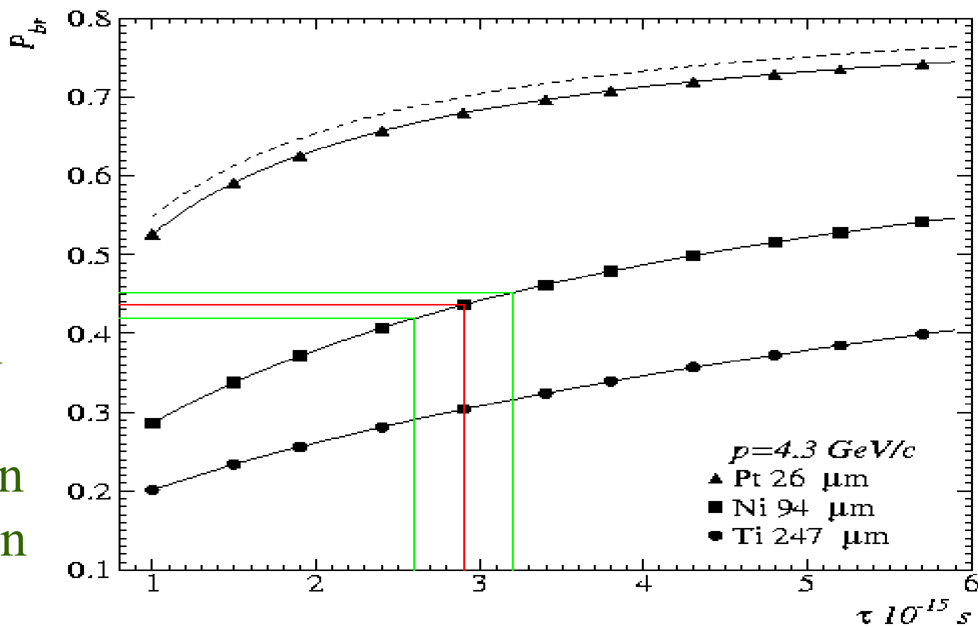
$$\frac{dp_{nlm}(s)}{ds} = \sum_{n'l'm'} a_{nlm}^{n'l'm'} p_{n'l'm'}(s)$$

where $s$ is the position in the target, $p_{nlm}$ is the population of a definite hydrogen-like state of pionium. The $a_{nlm}^{n'l'm'}$ coefficients are given by:

$$a_{nlm}^{n'l'm'} = \frac{\sigma_{nlm}^{n'l'm'} \rho N_0}{A}, \text{ if } nlm \neq n'l'm', \; a_{nlm}^{nlm} = -\frac{\sigma_{nlm}^{tot} \rho N_0}{A} - \begin{cases} 2M_\pi / Pc\tau_n & l=0. \\ 0 & l \neq 0. \end{cases}$$

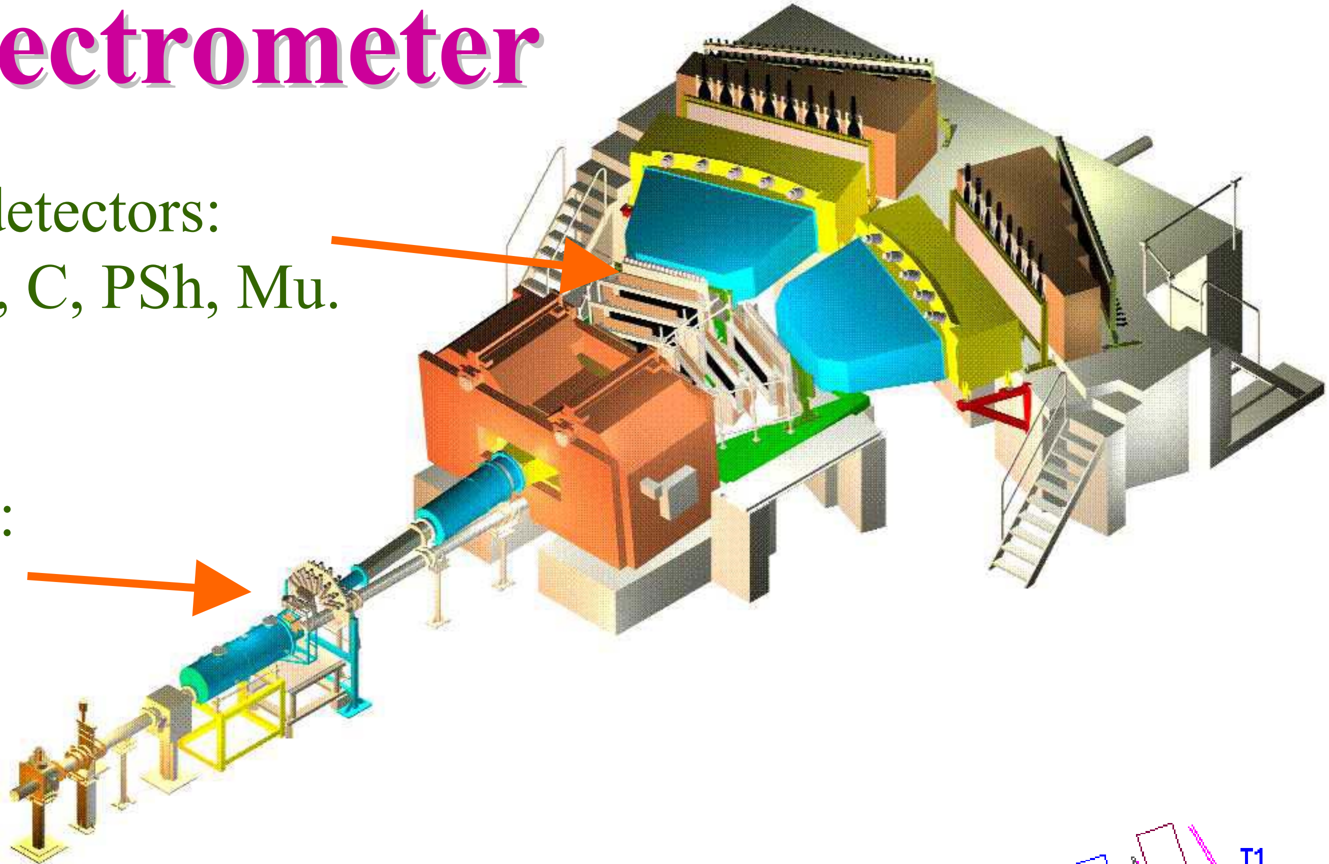
$\sigma_{nlm}^{n'l'm'}$ being the electro-magnetic pionium-target atom cross section, $N_0$ the Avogadro Number, $\rho$ the material density and $A$ its atomic weight.

The detailed knowledge of the cross sections (Afanasyev&Tarasov; Trautmann et al) (Born and Glauber approach) together with the accurate solution of the differential equation system permits us to know the curves within 1%.



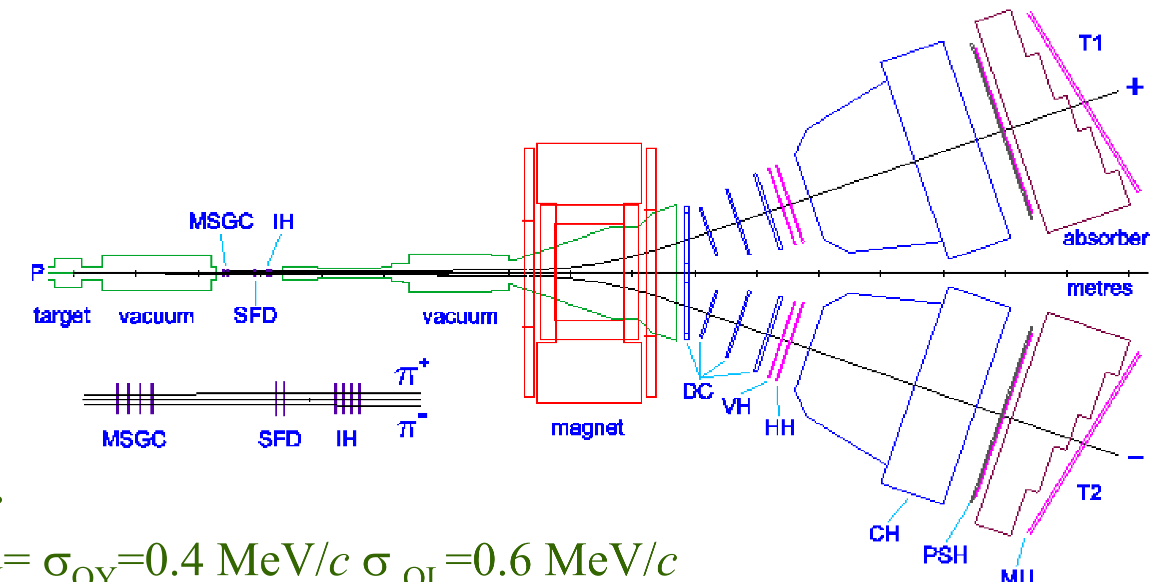

$\delta\tau$=10% → $\delta$Pbr =4%

# DIRAC Spectrometer



Downstream detectors:
DCs, VH, HH, C, PSh, Mu.

Upstream detectors:
MSGCs, SciFi, IH.




Setup features:

angel to proton beam $\Theta$=5.7°

channel aperture $\Omega=1.2\cdot 10^{-3}$ sr

magnet 1.85 T·m

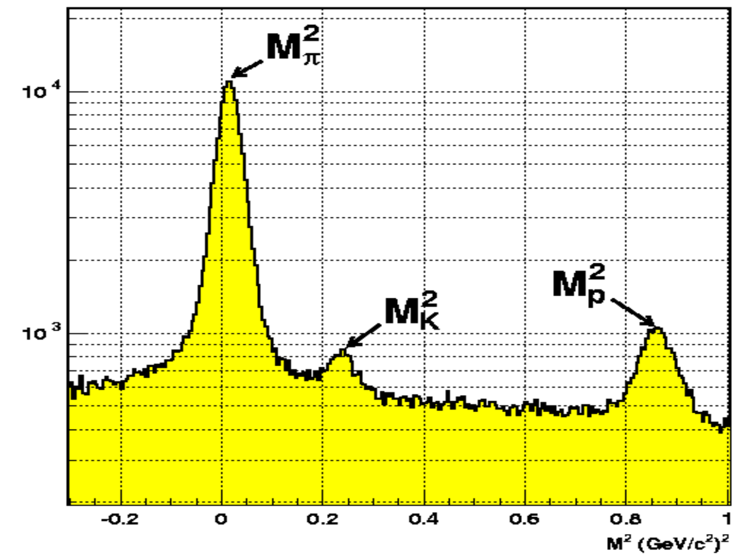
momentum range $1.2 \le p_\pi \le 7$ GeV/$c$

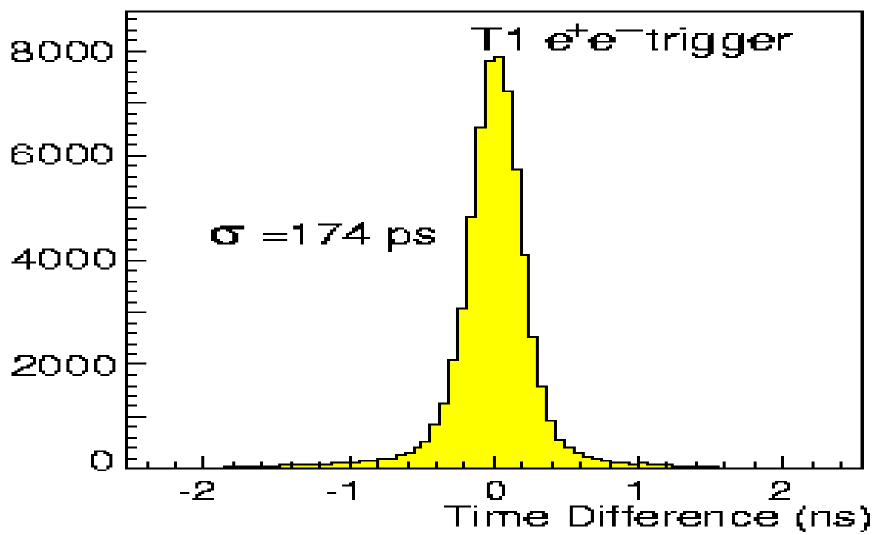
resolution on relative momentum $\sigma_{QX} = \sigma_{QY} = 0.4$ MeV/$c$ $\sigma_{QL} = 0.6$ MeV/$c$

# Calibration

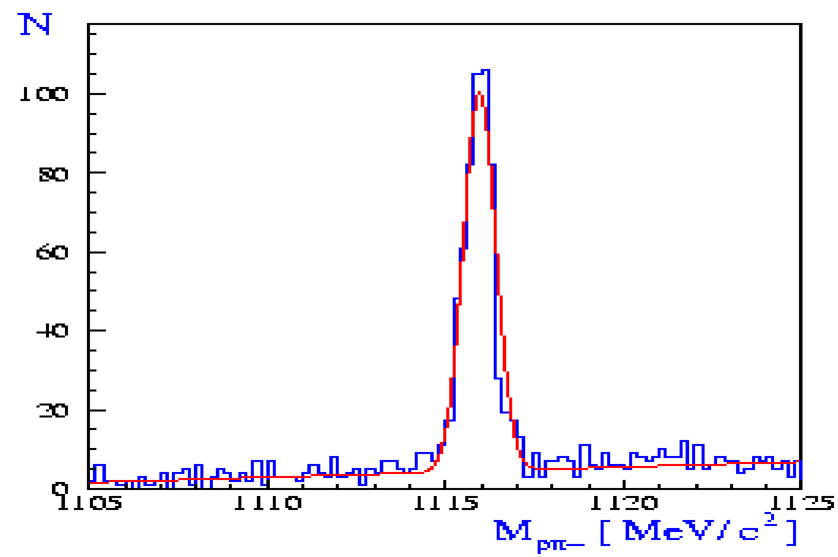
These results show that our set-up fulfils the needs in time and momentum resolution.

Positive arm mass spectrum, obtained by time difference at VHs, under $\pi^-$ hypothesis in the negative arm.



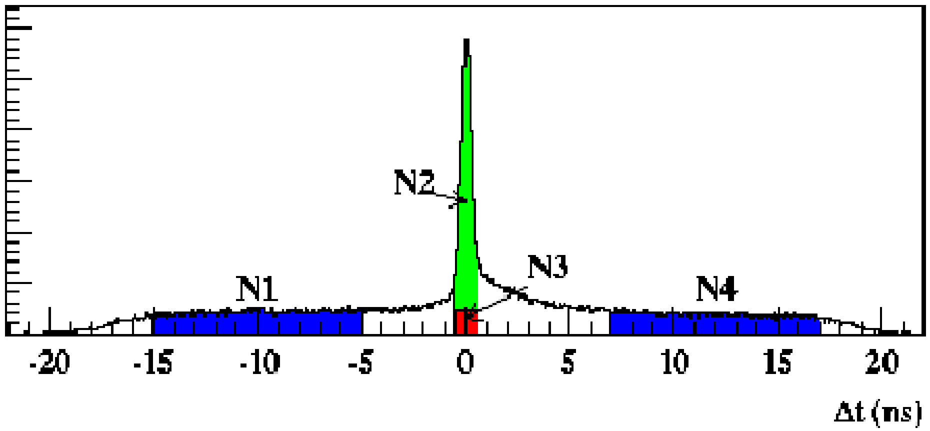

Time difference spectrum at VH with $e^+e^-$ T1 trigger.

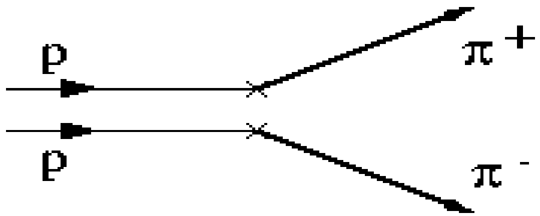



Mass distribution of $p\pi^-$ pairs from $\Lambda$ decay. $\sigma_\Lambda$=0.43 MeV/$c^2$ <0.49 MeV/$c^2$ (Hartouni et al.).

# Atoms detection

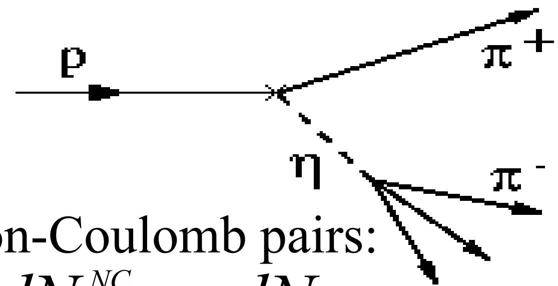
The time spectrum at VH provides us the criterion to select real (time correlated) and accidental (non correlated) pairs.



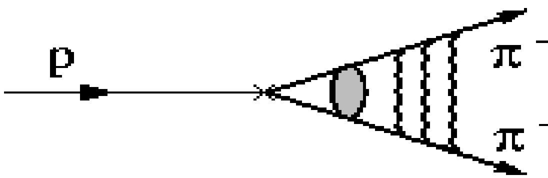

Accidentals:

$$\frac{dN_{acc}}{dQ}$$




Non-Coulomb pairs:

$$\frac{dN^{NC}_{corr}}{dQ} \propto \frac{dN_{acc}}{dQ}$$




Coulomb pairs:

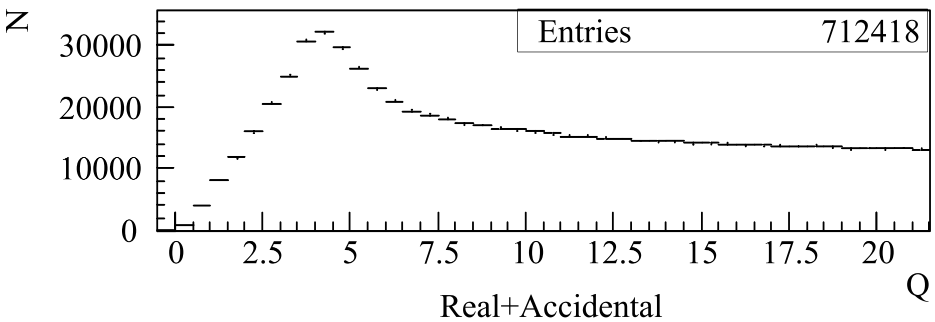
$$\frac{dN^{C}_{corr}}{dQ} \propto A_C(Q)\frac{dN_{acc}}{dQ}$$

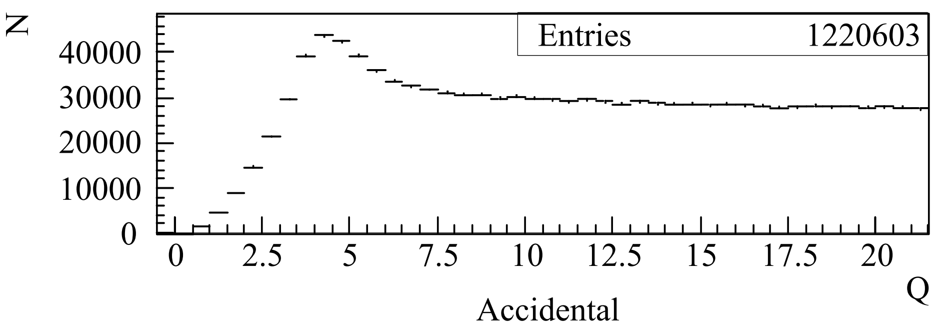
$$R(Q) = \frac{\frac{dN_{corr}}{dQ}}{\frac{dN_{acc}}{dQ}} = \frac{\frac{dN^{NC}_{corr}}{dQ} + \frac{dN^{C}_{corr}}{dQ}}{\frac{dN_{acc}}{dQ}} = N\left[A_C(Q) + f\right]$$

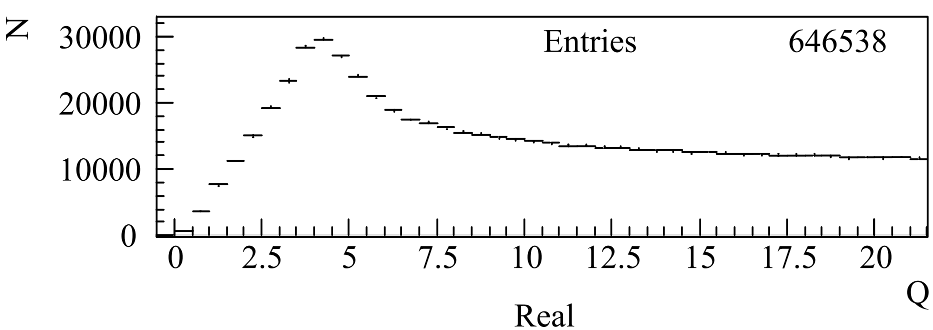
*N* and *f* are obtained from a fit to the pion pairs *Q* spectrum in the range without atomic pairs $Q > 3$ MeV/$c$

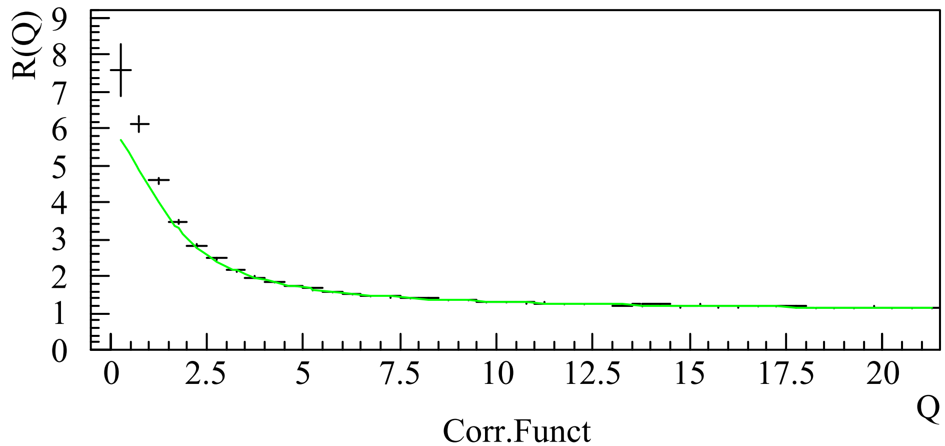
# Atoms detection

## Ni 2001 data

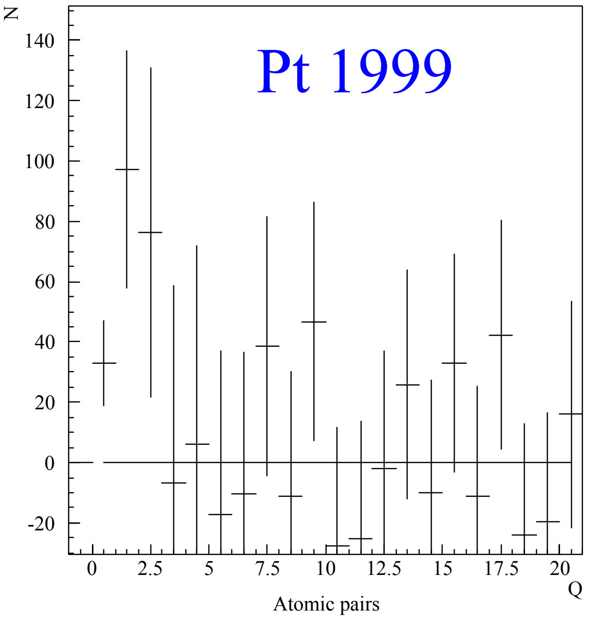


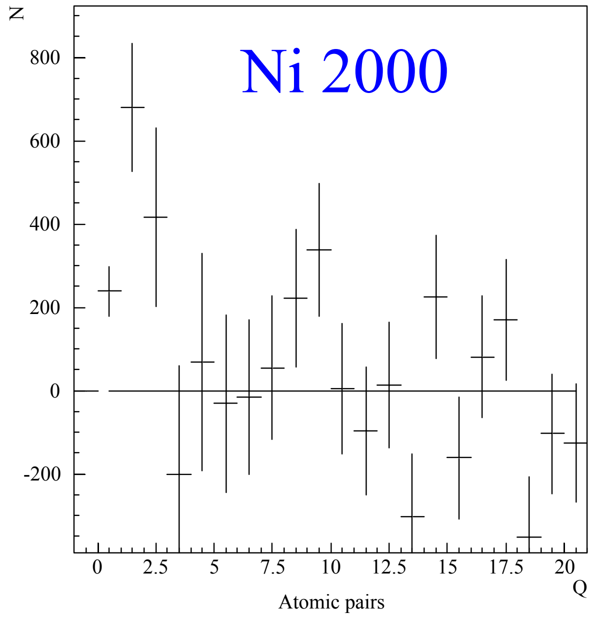



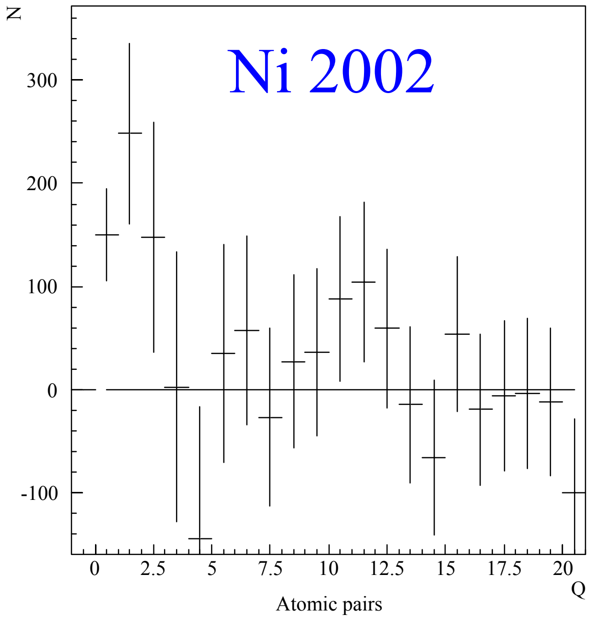



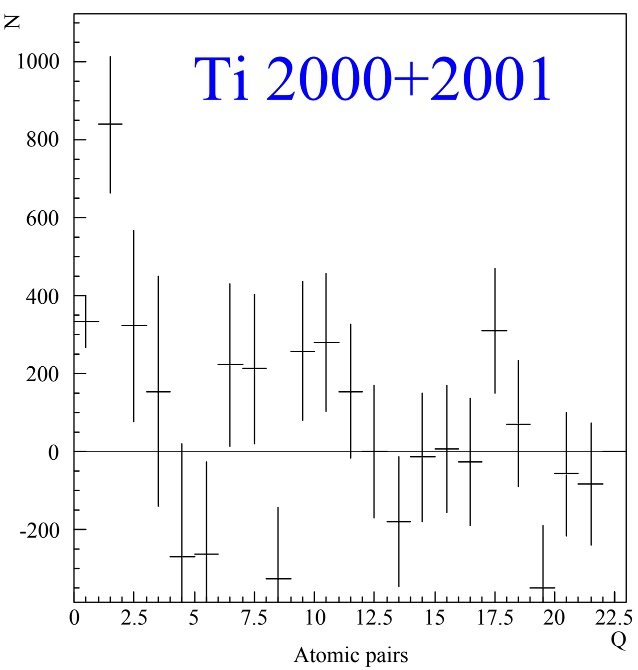



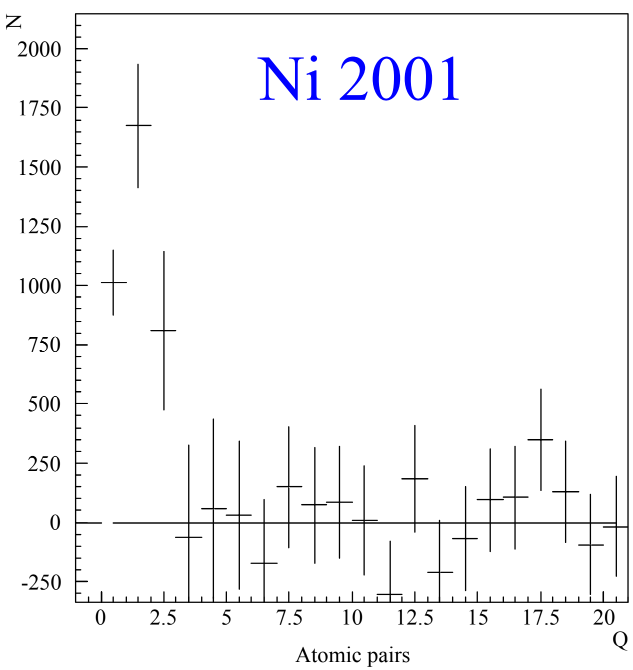
# Atomic Pairs



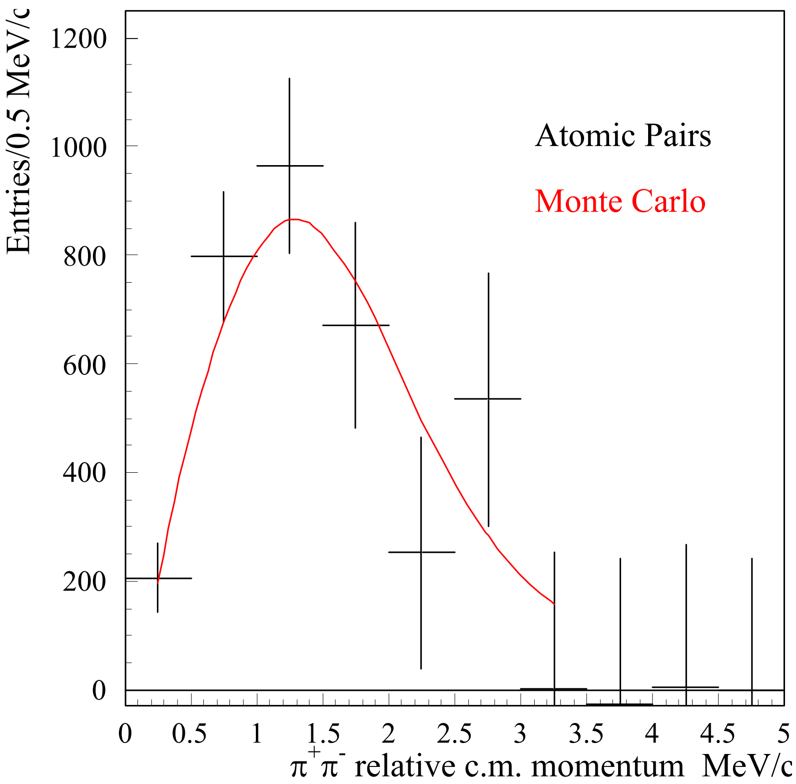




| Target | Z | Thick ($\mu m$) |
|---|---|---|
| Pt | 78 | 28 |
| Ni 2000<br>Ni 2001 | 28 | 94<br>98 |
| Ti | 22 | 251 |

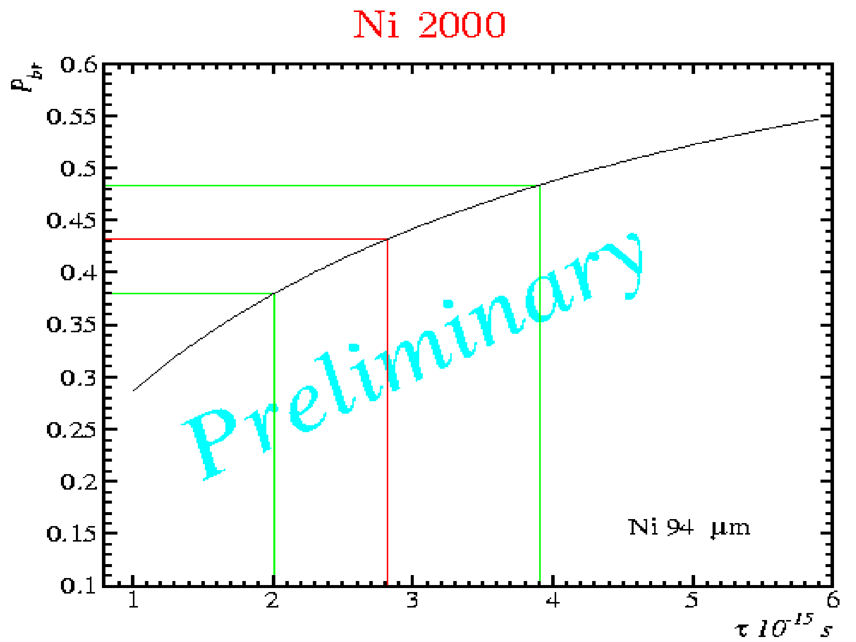
# Atomic pairs




| Sample | Triggers $10^6$ | $n_a$ at $Q<2$MeV/$c$ | $n_a$ at $Q<3$MeV/$c$ |
|---|---|---|---|
| Pt 1999 | 55.7 | 130±43 (3.σ) | 207±77 (2.7σ) |
| Ni 2000 | 896 | 920±170 (5.4σ) | 1335±300 (4σ) |
| Ti 2000+01 | 910 | 1170±190 (6.2σ) | 1495±340 (4.4σ) |
| Ni 2001 | 647 | 2686±310 (8.7σ) | 3500±510 (6.9σ) |
| Ni 2002 (*15 day*) | 77 | 400±100 (4σ) | 545±170 (3.2σ) |

# Conclusions and results

| Sample | Lifetime $10^{-15}$ s | Statistical error |
|---|---|---|
| Ni 2000 | $2.8^{+1.1}_{-0.8}$ | $\pm 34\%$ |
| Ti 2000/1 | $5.4^{+1.5}_{-1.3}$ | $\pm 26\%$ |
| Ni +Ti | $3.6^{+0.9}_{-0.7}$ | $\pm 22\%$ |




- *DIRAC collaboration has built up the double arm spectrometer which achieves 1 MeV/c resolution at low relative momentum (Q<30MeV/c) of particle pairs and has successfully demonstrated its capability to detect $\pi^+\pi^-$ atoms after 2 years of running time.*
- *Some preliminary lifetime results have been achieved with a 5000 atoms sample reaching an statistical accuracy of 22% in lifetime determination.*
- *The accurate determination of systematical errors requires a measurement of the background.*
- *A 10% accuracy on the atom lifetime value (goal of the experiment) will require running beyond 2002.*