DIRAC

First measurement of the $\pi^+\pi^-$ atom lifetime

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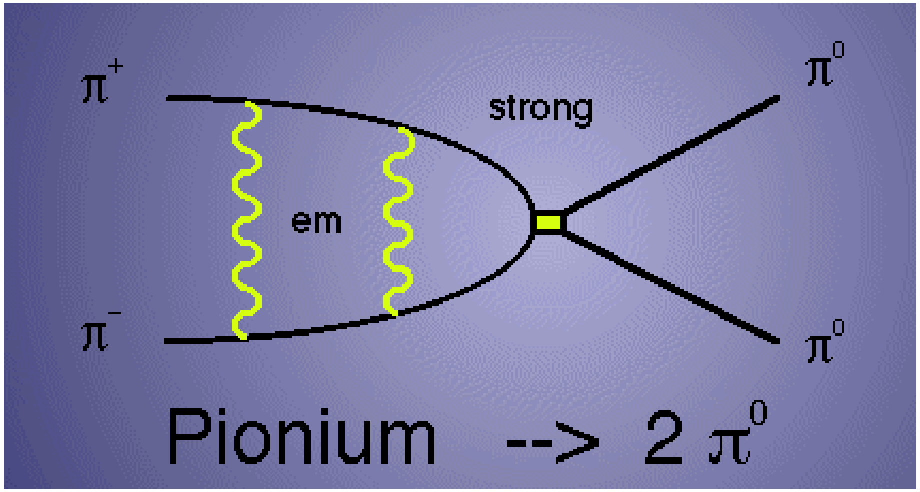
DIRAC

DImeson Relativistic Atomic Complexes

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

www.cern.ch/DIRAC



Basel Univ., Bern Univ., Bucharest IAP, CERN, Dubna JINR, Frascati LNF-INFN, Ioannina Univ., Kyoto-Sangyo Univ., Kyushu Univ. Fukuoka, Moscow NPI, Paris VI Univ., Prague TU, Prague FZU-IP ASCR, Protvino IHEP, Santiago de Compostela Univ., Tokyo Metropolitan Univ., Trieste Univ./INFN, Tsukuba KEK.

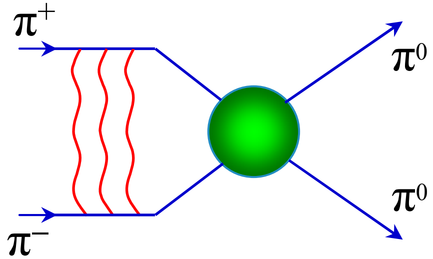
90 Physicists from 18 Institutes

Pionium lifetime

Pionium is a hydrogen-like atom consisting of π^+ and π^- mesons

E_B=-1.86 keV, r_B=387 fm, $p_B \approx 0.5$ MeV

The lifetime of $\pi^+\pi^-$ atoms ($A_{2\pi}$) is dominated by charge exchange process into $\pi^0\pi^0$:



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

$$\Gamma_{1S,2\pi^0} = \frac{1}{\tau_{1S}} \propto \left| a_0 - a_2 \right|^2$$

a_0 and a_2 are the ππ S-wave scattering lengths for isospin I=0 and I=2.

$$\frac{\Delta\tau}{\tau} = 10\% \quad \Rightarrow \quad \frac{\Delta(a_0 - a_2)}{a_0 - a_2} = 5\%$$

Pionium lifetime in QCD

J.Gasser et al., Phys.Rev. D64 (2001) 016008:

$$\Gamma_{2\pi^0} = \frac{1}{\tau} = \frac{2}{9}\alpha^3 p\left|a_0 - a_2\right|^2 (1+\delta_\Gamma), \qquad \delta_\Gamma = (5.8 \pm 1.2)\%$$

The ππ scattering lengths have been calculated in the framework of Chiral Perturbation Theory (ChPT):

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

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

$$a_0 - a_2 = 0.265 \pm 0.004$$

$$\tau = (2.9 \pm 0.1) \times 10^{-15}\, s$$

Experimental results

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

a_0=0.26±0.05 — L. Rosselet et al., Phys. Rev. D 15 (1977) 574

a_0=0.216±0.013 ±0.003(syst) — New measurement at BNL (E865)

S.Pislak et al., Phys.Rev. D 67 (2003) 072004

a_2=-0.0454±0.0031 ±0.0013(syst)

$\pi N \to \pi\pi N$ near threshold

a_0=0.26±0.05 — C.D. Froggatt, J.L. Petersen, Nucl. Phys. B 129 (1977) 89

a_0=0.204±0.014 ±0.008(syst) — M. Kermani et al., Phys. Rev. C 58 (1998) 3431

$K^+ \to \pi^+\pi^0\pi^0$ and $K_L \to 3\pi^0$ NA48

$|a_0 - a_2| = 0.281 \pm 0.007\ (stat.) \pm 0.014\ (syst.)$

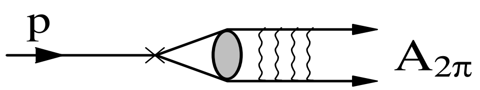
N.Cabibbo, Phys. Rev. Lett. 93, 121801 (2004)

N.Cabibbo, G.Isidori, hep-ph/0502130

Production of pionium

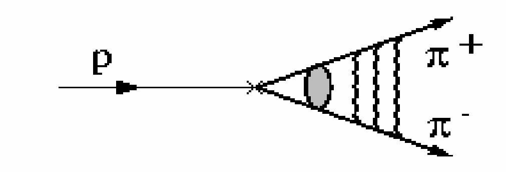
Atoms are Coulomb bound state of two pions produced in one proton-nucleus collision

$$\frac{d\sigma_{nlm}^{A}}{d\vec{P}} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi_{nlm}^{(C)}(0)\right|^2 \frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}\Bigg|_{\vec{p}_+=\vec{p}_-}$$



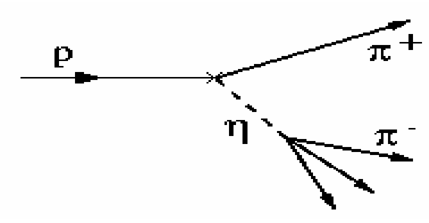
Background processes:

Coulomb pairs. They are produced in one proton nucleus collision from fragmentation or short lived resonances and exhibit Coulomb interaction in the final state

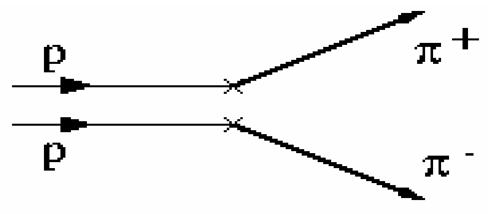


$$\frac{d^2\sigma_C}{d\vec{p}_+ d\vec{p}_-} = A_C(q)\frac{d\sigma_s^0}{d\vec{p}_+ d\vec{p}_-}, \qquad A_C(q) = \frac{2\pi m_\pi \alpha / q}{1-\exp(-2\pi m_\pi \alpha / q)}$$

Non-Coulomb pairs. They are produced in one proton nucleus collision. At least one pion originates from a long lived resonance. No Coulomb interaction in the final state



Accidental pairs. They are produced in two independent proton nucleus collision. They do not exhibit Coulomb interaction in the final state



Method of pionium detection

L.Nemenov, Sov.J.Nucl.Phys. 41 (1985) 629

Pionium is created in nS states then it interacts with target material:

Annihilation: $A_{2\pi} \to \pi^0 \pi^0$

$$\lambda_{\text{decay}} = \gamma c \tau \approx 15 \mu m \text{ for } \gamma \approx 17$$

Excitation: **transitions between atomic levels**

$$\lambda_{\text{int}}^{1S} \approx 20\ \mu m \text{ for Ni}$$

Break-up(ionisation): **characteristic "atomic" pairs n_A**

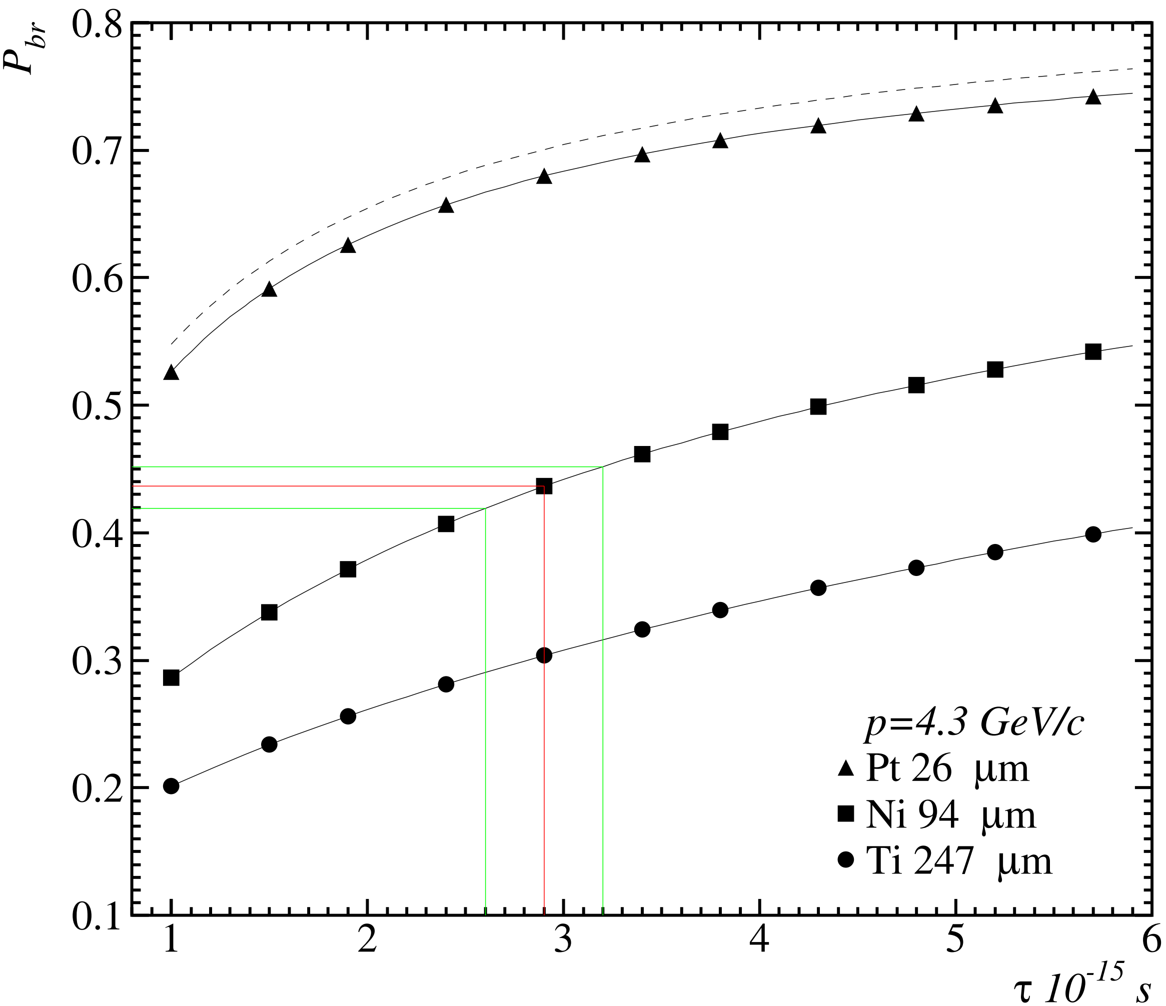
- Q_{cms}<3MeV/c
- → in laboratory system $E_+ \approx E_-$, small opening angle θ<3mrad

Coulomb and atomic pairs are detected simultaneously

$$P_{br} = \frac{n_A}{N_A} = \frac{n_A}{k\ N_C}$$

Break-up probability

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ



All targets have the same thickness in radiation lengths $6.7*10^{-3}$ X_0

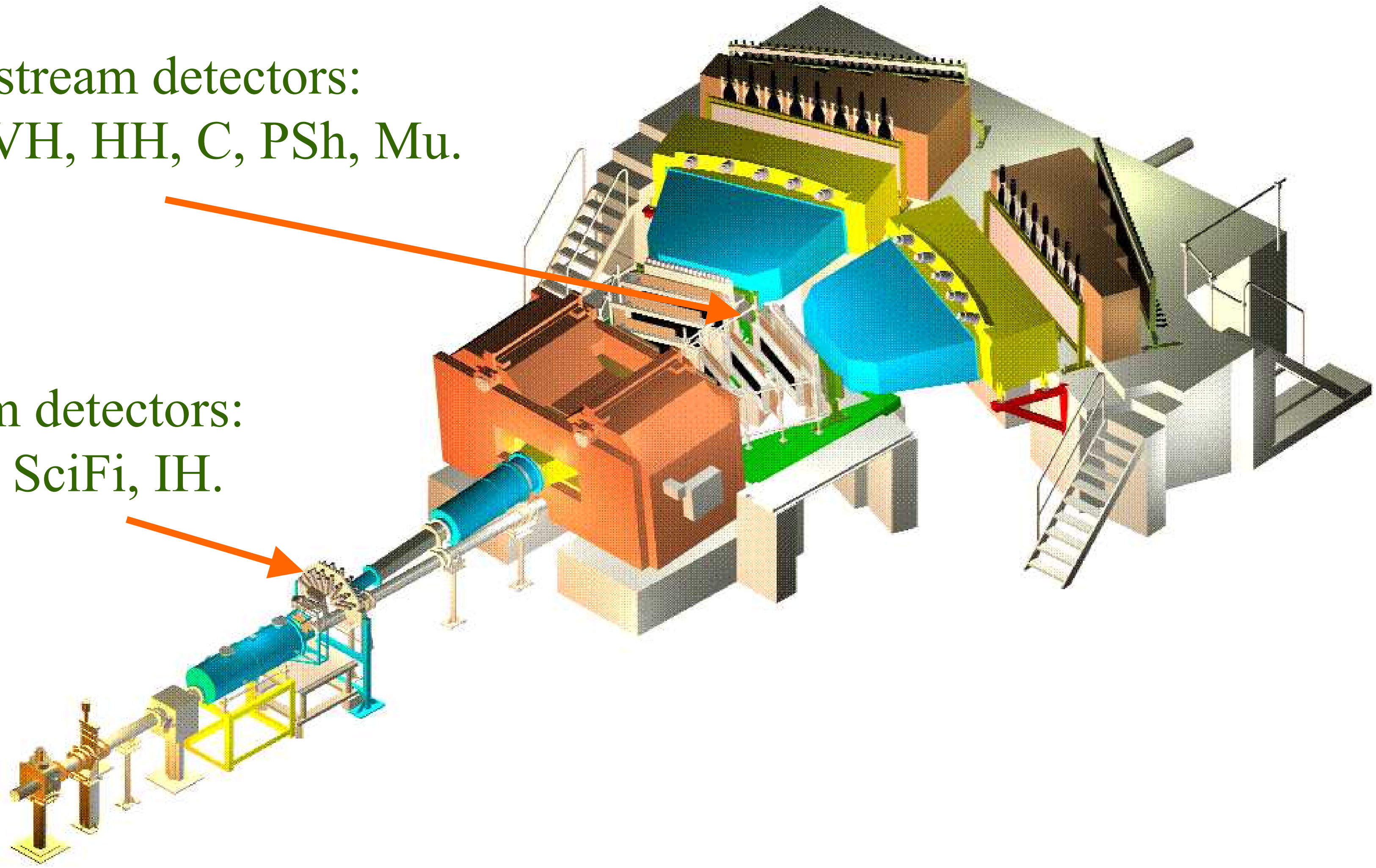
There is an optimal target material for a given lifetime

The detailed knowledge of the cross sections (Afanasyev&Tarasov; Trautmann et al) (Born and Glauber approach) together with the accurate description of atom interaction dynamics (including density matrix formalism) permits us to know the curves within 1%.

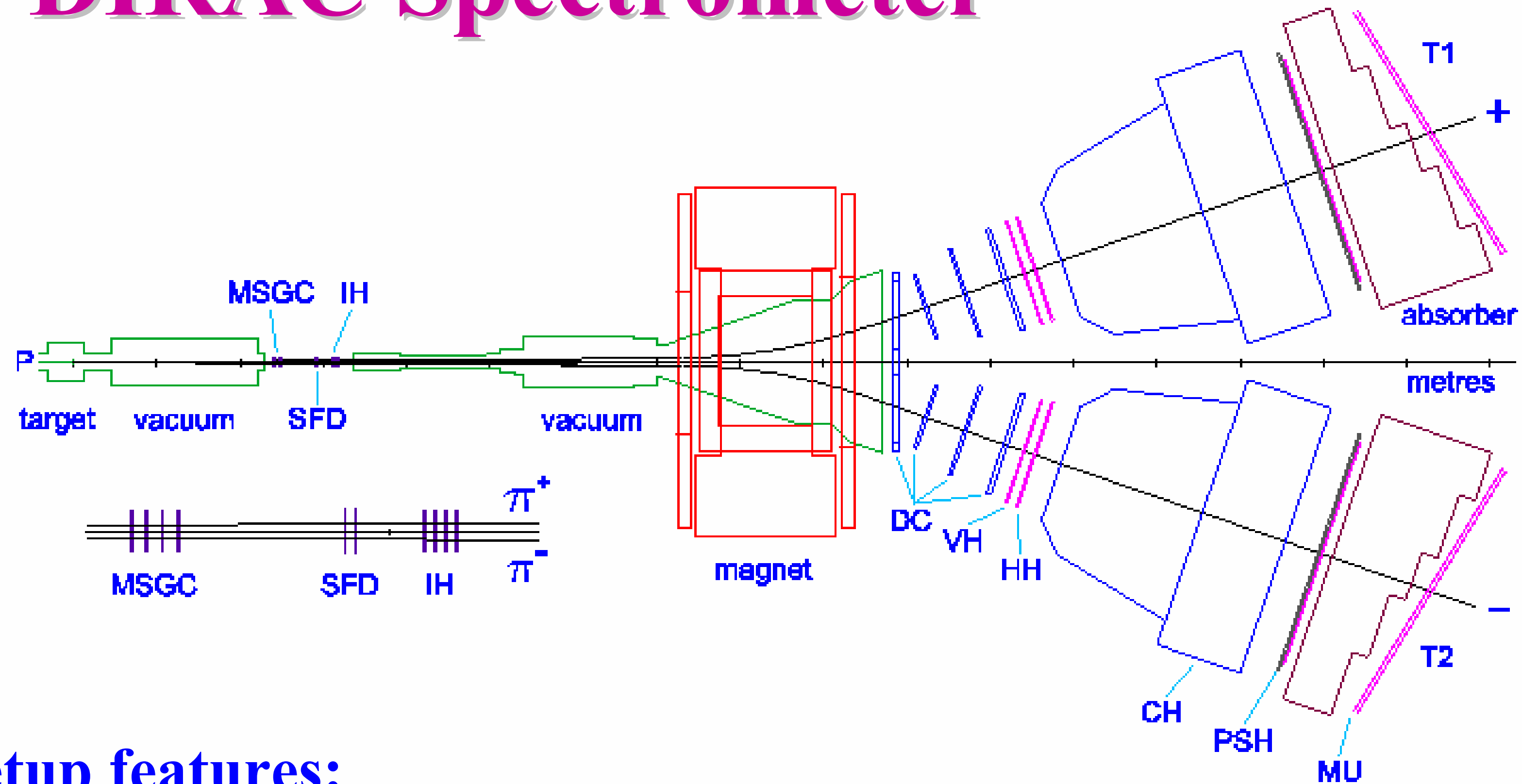
DIRAC Spectrometer

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

Upstream detectors:
MSGCs, SciFi, IH.



DIRAC Spectrometer



Setup features:

angle to proton beam $\Theta = 5.7^{\circ}$

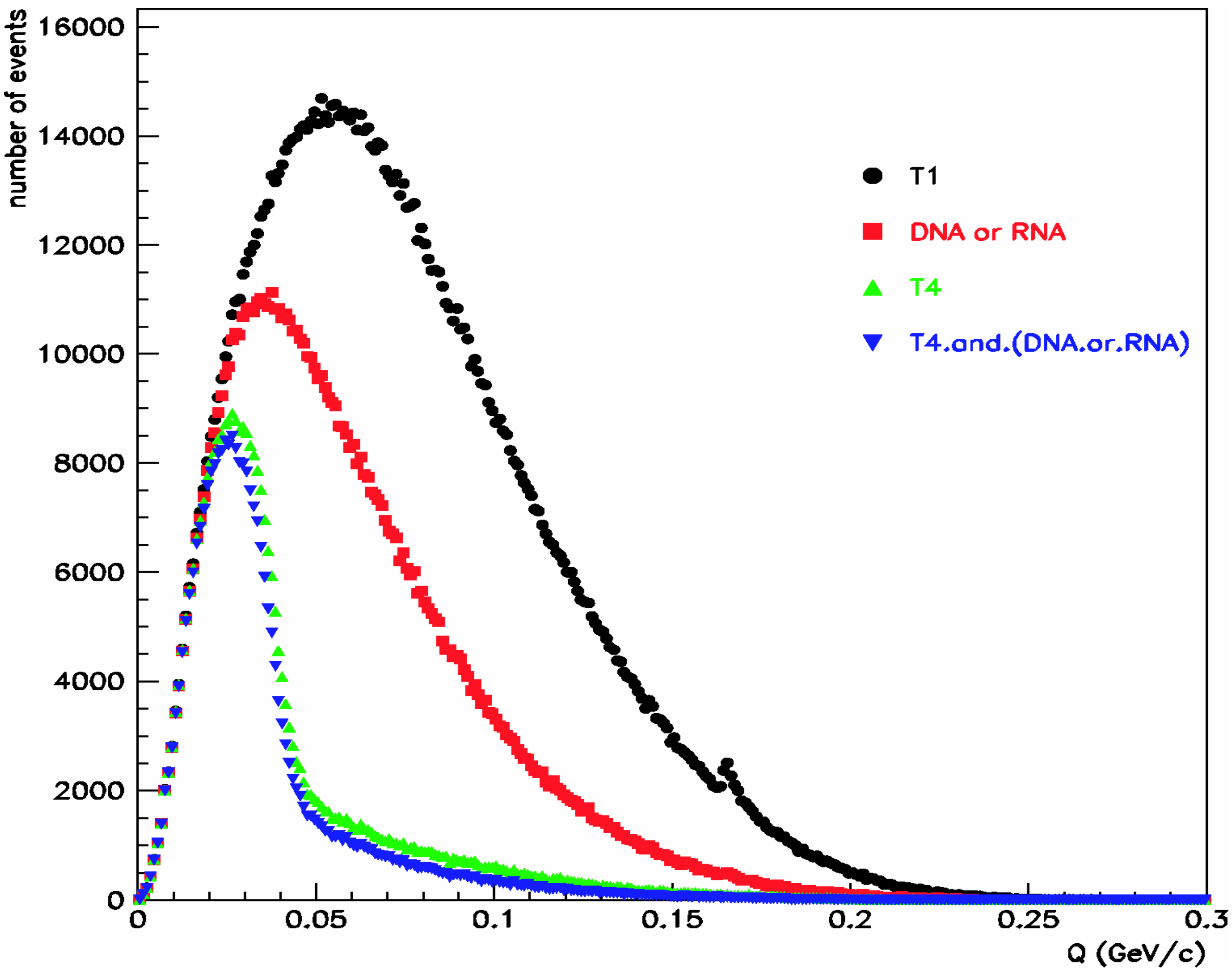
channel aperture $\Omega = 1.2 \cdot 10^{-3}$ sr

magnet 2.3 T·m

momentum range $1.2 \leq p_{\pi} \leq 7$ GeV/c

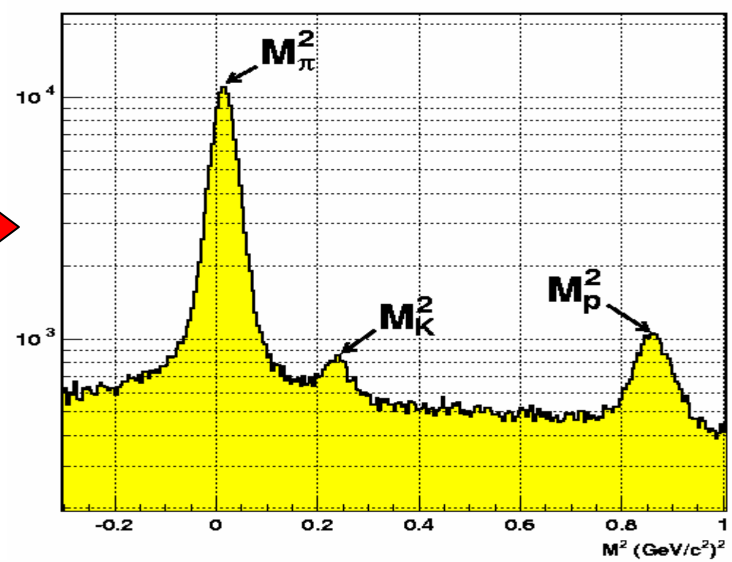
resolution on relative momentum $\sigma_{QX} \approx \sigma_{QY} \leq 0.5$ MeV/c, $\sigma_{QL} \approx 0.5$ MeV/c

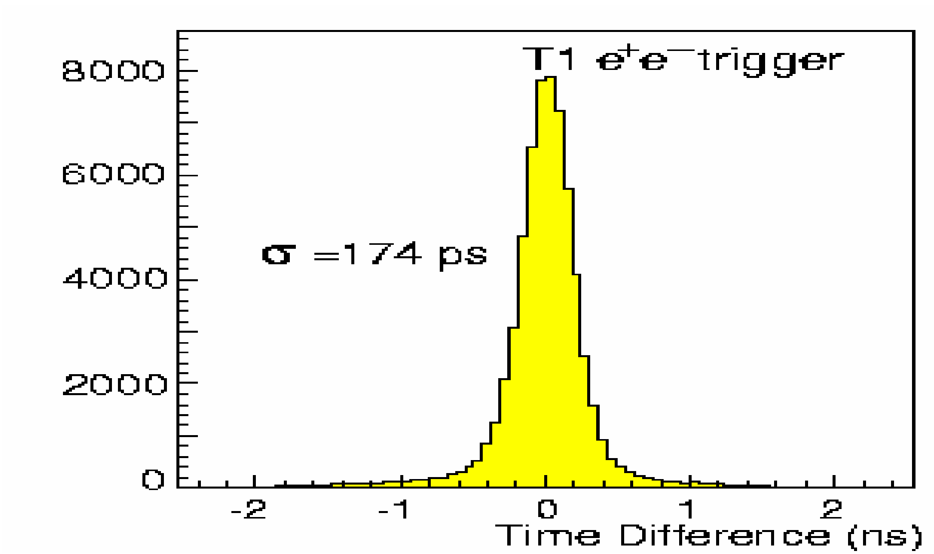
Trigger performance



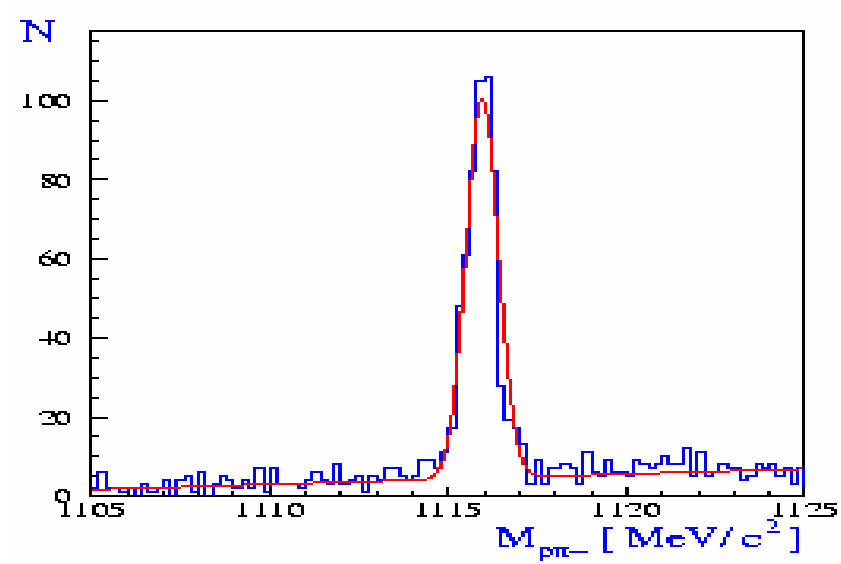
Calibrations

Positive arm mass spectrum, obtained by TOF difference, under π^- hypothesis in the negative arm.





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



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

Analysis based on MC

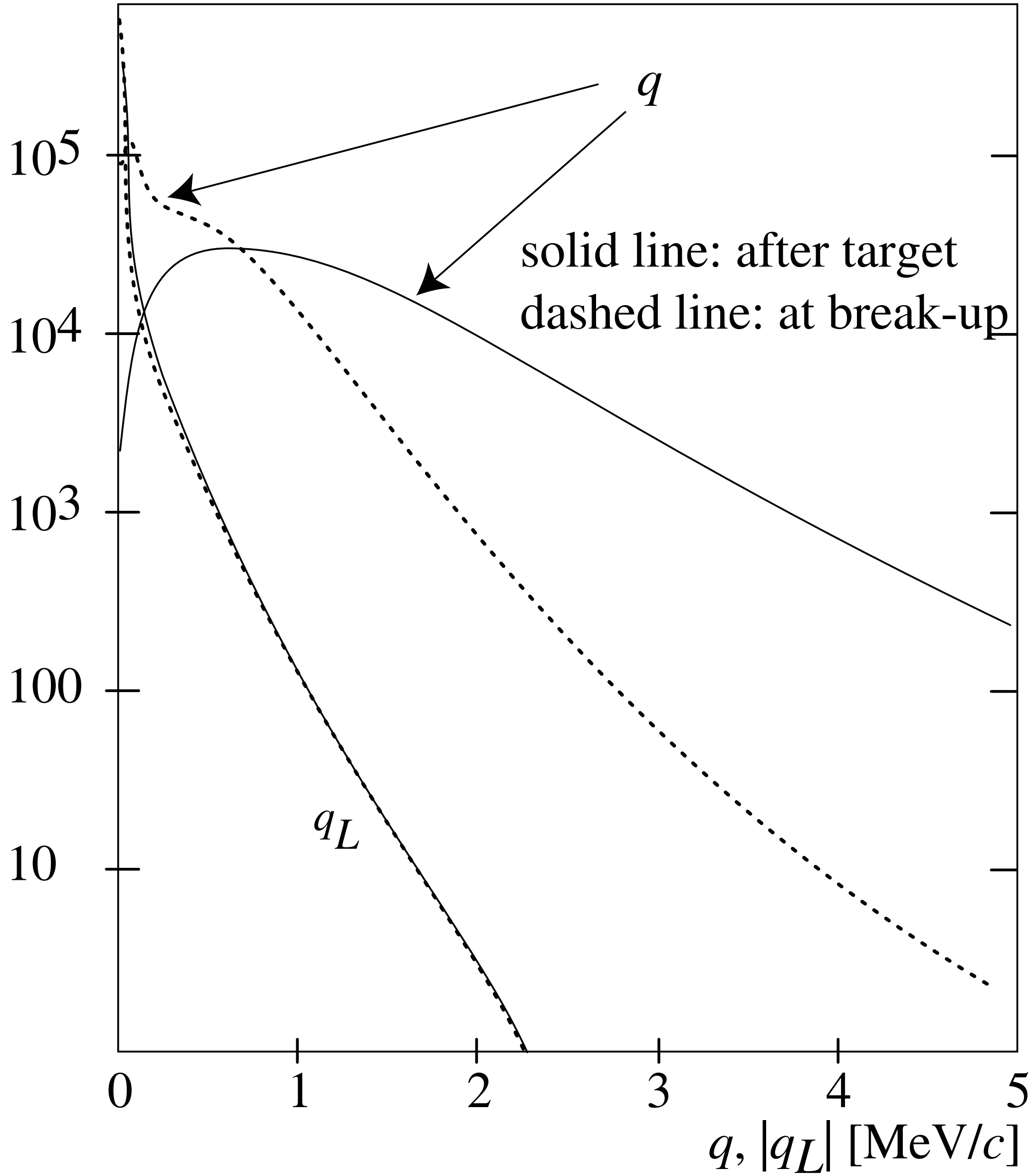
Atoms are generated in **nS states** using measured momentum distribution for **short-lived** sources. The atomic pairs are generated according to the evolution of the atom while propagating through the target

Background processes:

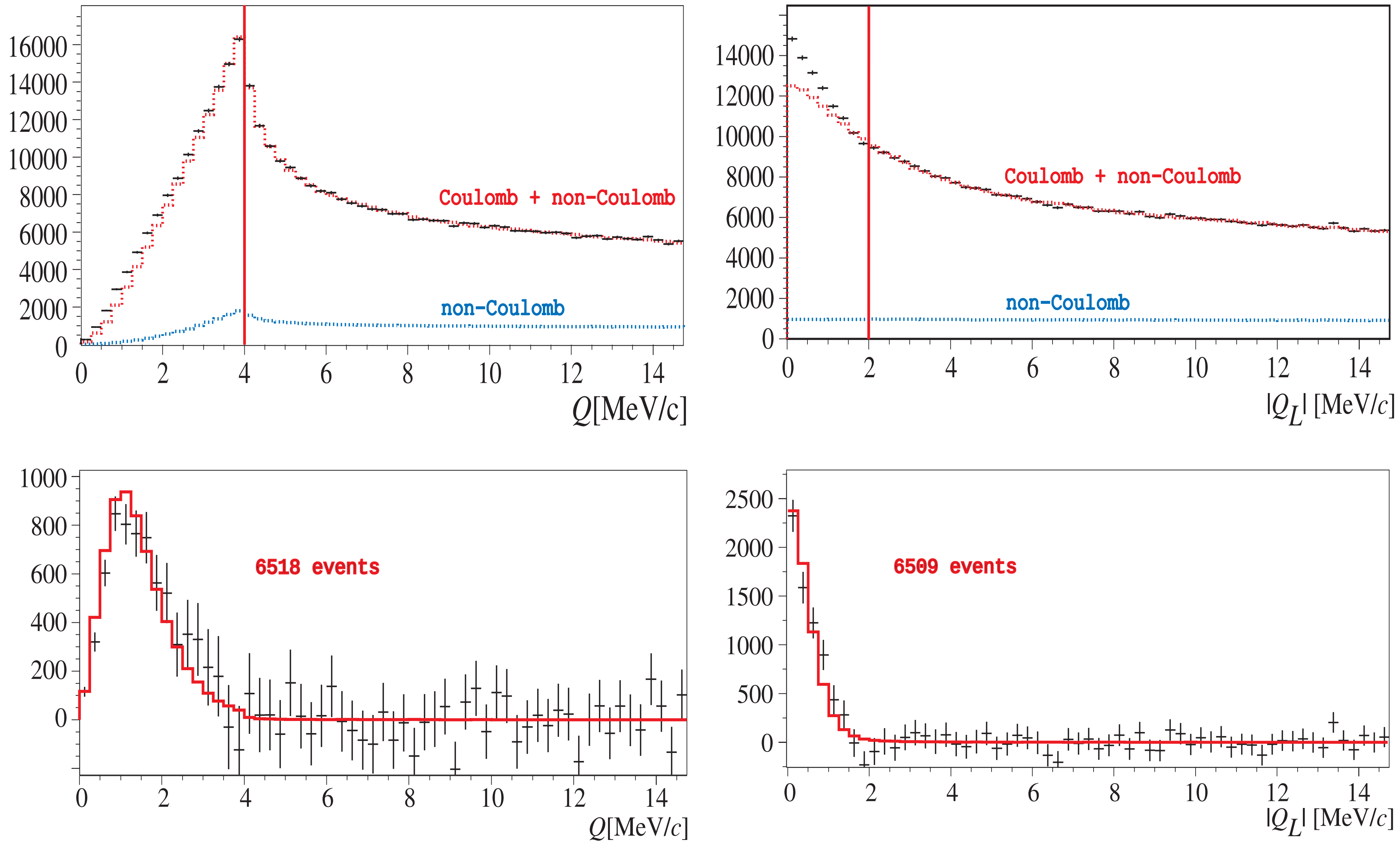
Coulomb pairs are generated according to $A_C(Q)Q^2$ using measured momentum distribution for **short-lived** sources.

Non-Coulomb pairs are generated according to Q^2 using measured momentum distribution for **long-lived** sources.

Atomic pairs MC



Atomic pairs



Break-up probability

$$P_{br} = \frac{n_A}{N_A} = \frac{n_A^{rec}\left(Q \le Q_{cut}\right)}{k\left(Q_{cut}\right) N_C^{rec}\left(Q \le Q_{cut}\right)}$$

	n_A	$N_C(Q_{cut})$	P_{br}
Q	6518±373	106500±1130	0.442±0.026
Q_L	6509±330	82289±873	0.445±0.023
$Q\&Q_L$	6530±294	106549±1004	0.447±0.023

$k(Q_{cut}$=4 MeV/c)=0.1384, $k(Q_{L,cut}$=2 MeV/c)=0.1774

Due to target impurities by atoms with Z<28 P_{br} has to be increased by 0.005

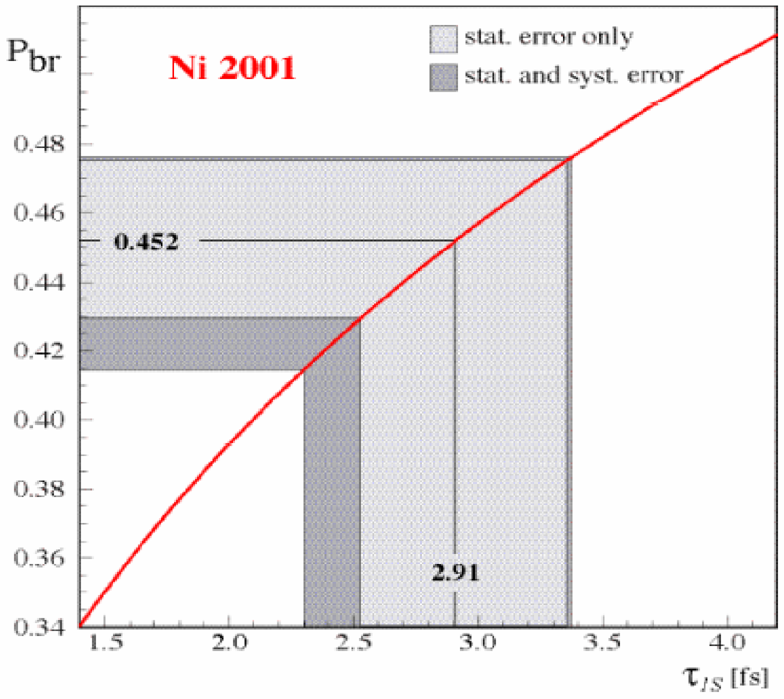
Breakup probability

$$P_{br} = 0.452 \pm 0.023_{stat} \left. \begin{matrix} +0.009 \\ -0.032 \end{matrix} \right\}_{syst} = 0.452^{+0.025}_{-0.039}$$

Summary of systematic uncertainties:

source	σ
CC-background	±0.007
signal shape	±0.002
multiple scattering angle $^{+5\%}_{-10\%}$	+0.006 -0.013
K^+K^- and $p\bar{p}$ pairs admixture	+0.000 -0.024
correlation function for non-point production	+0.000 -0.017
Total	**+0.009** **-0.032**

Lifetime of Pionium



Result from DIRAC:

$$\tau = \left(2.91^{+0.45}_{-0.38}\Big\}_{stat}\ {}^{+0.19}_{-0.49}\Big\}_{syst}\right)\ \text{fs}$$

ChPT prediction:

$$\tau = (2.9 \pm 0.1)\,\text{fs}$$

Phys. Lett. B 619 (2005) 50-60; hep-ex/0504044

Results from DIRAC

- *DIRAC collaboration has built up the double arm spectrometer which provides a pair relative momentum (Q) resolution of 1 MeV/c for Q<30MeV/c*
- *Observation of more than 15000 of $\pi^+\pi^-$ pairs from pionium break-up*
- *The analysis of Ni 2001 data provides a lifetime measurement:*

$$\tau = \left(2.91^{+0.49}_{-0.62}\right) \text{ fs}$$

$$|a_0 - a_2| = 0.264^{+0.033}_{-0.020} m_\pi^{-1}$$

- *Improvements to come:*
  1. *to improve on statistics: analyse full $\pi^+\pi^-$ data sample*
  2. *to improve on systematics:*
     - ✓ *different analysis procedures*
     - ✓ *study of correlation function*
     - ✓ *detailed study of multiple scattering*
     - ✓ *analysis of data taken with single-multi layer target*

Atomic pairs

Number of Atomic pairs									
	Pt1999 24 GeV	**Ni2000 24 GeV**	**Ti2000 24 GeV**	**Ti2001 24 GeV**	**Ni2001 24 GeV**	**Ni2002 20 GeV**	**Ni2002 24 GeV**	**Ni2003 20 GeV**	**Sum for Ni and Ti**
With upstream detectors ***(Q_L<1.5 MeV/c Q_T<4 MeV/c)***	282 ± 96	1353 ± 385	935 ± 273	1476 ± 330	5733 ± 577	1925 ± 390	2555 ± 525	1410 ± 264	**15387 ± 1078**
Without upstream detectors ***(Q_L<1.5 MeV/c Q_T<6 MeV/c)***	219 ± 137	3839 ± 579	1767 ± 414	3314 ± 539	9050 ± 822	3040* ± 480	4030* ± 550	2230* ± 410	**27270* ± 1470**

* - estimation

Goals of the experiment

- The proposed experiment is the further development of the current DIRAC experiment at CERN PS. It aims to measure simultaneously the lifetime of $\pi^+ \pi^-$ atoms ($A_{2\pi}$), to observe πK atoms ($A_{\pi K}$) and to measure their lifetime using 24 GeV proton beam PS CERN and the upgraded DIRAC setup.
- The precision of $A_{2\pi}$ lifetime measurement will be better than 6% and the difference $|a_0 - a_2|$ will be determined within 3% or better.
- The accuracy of $A_{\pi K}$ lifetime measurement will be at the level of 20% and the difference $|a_{1/2}-a_{3/2}|$ will be estimated at the level of 10%.
- The pion-pion and pion-kaon scattering lengths have never been verified by experimental data with the sufficient accuracy. For this reason the proposed measurements will be a crucial check of the low energy *QCD* predictions and our understanding of the nature of the *QCD* vacuum.
- The observation of the long-lived (metastable) $A_{2\pi}$ states is also considered with the same setup. This will allow us to measure the energy difference between *ns* and *np* states and to determine the value of $2a_0+a_2$ in a model-independent way.

DIRAC II Set-up