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

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XII INTERNATIONAL CONFERENCE ON HADRON SPECTROSCOPY

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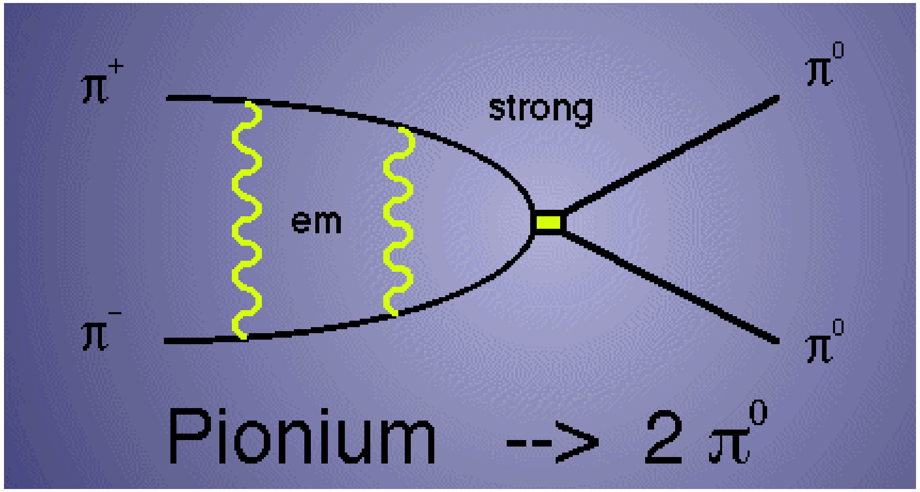
DIRAC

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.

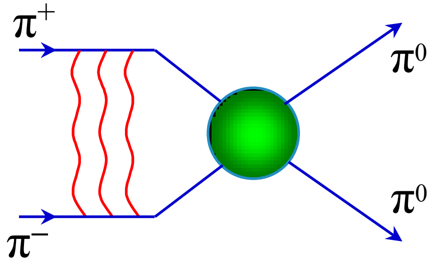
90 Physicists from 18 Institutes

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 $\pi^0\pi^0$:



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

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

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:

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

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

$K^+ \rightarrow \pi^+\pi^- e^+\nu_e$ (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 New measurement at BNL (E865)

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

a_2=-0.0454 0.0031

0.0013 (syst)

$\pi N \rightarrow \pi\pi N$ 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 M. Kermani et al., Phys. Rev. C 58 (1998) 3431

0.008(syst)

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

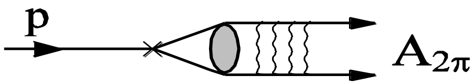
$$|a_0 - a_2| = 0.268 \pm 0.010(stat.) \pm 0.004\ (syst.) \pm 0.013(ext.)$$

NA48/2, Phys. Lett. B 633, 2006

Production of pionium

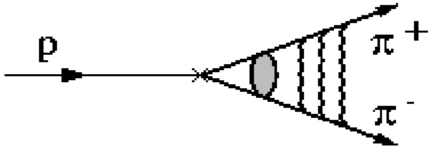
Atoms are Coulomb bound state of two pions produced in one proton-nucleus collision

$$\frac{d\sigma^{A}_{nlm}}{d\vec{P}} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi^{(C)}_{nlm}(0)\right|^2 \frac{d\sigma^0_s}{d\vec{p}_+ d\vec{p}_-}\bigg|_{\vec{p}_+=\vec{p}_-}$$



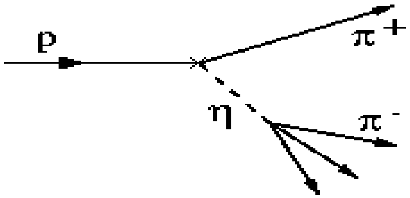
Background processes:

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

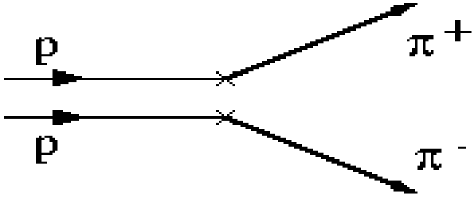


$$\frac{d^2\sigma_C}{d\vec{p}_+ d\vec{p}_-} = A_C(q)\frac{d\sigma^0_s}{d\vec{p}_+ d\vec{p}_-}, \qquad A_C(q) = \frac{2\pi m_\pi \alpha / q}{1-\exp(-2\pi m_\pi \alpha / q)}$$

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**

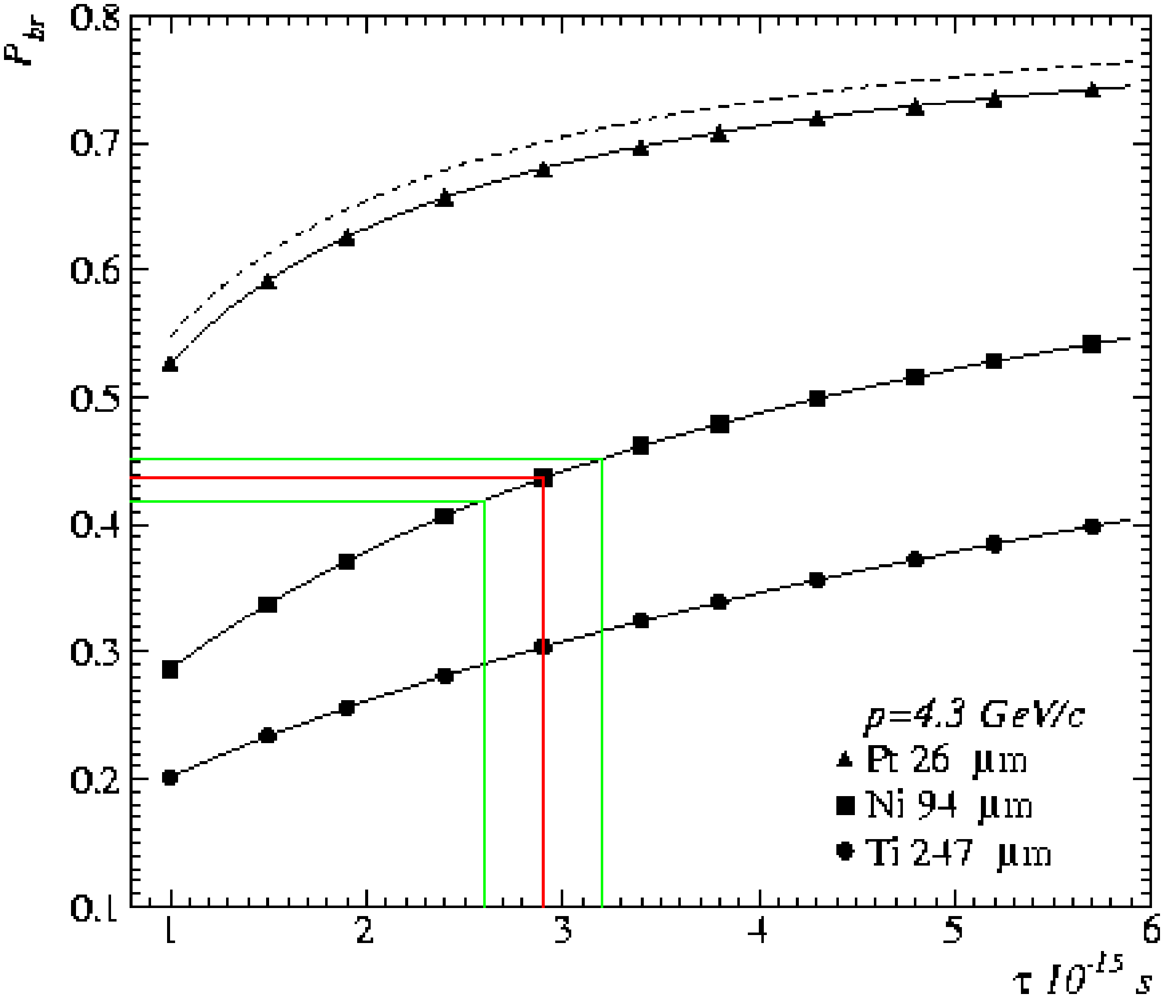
- $Q_{cms} < 3 MeV/c$
- → in laboratory system $E_+ \approx E_-$, small opening angle $\theta < 3$mrad

Coulomb and atomic pairs are detected simultaneously

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

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

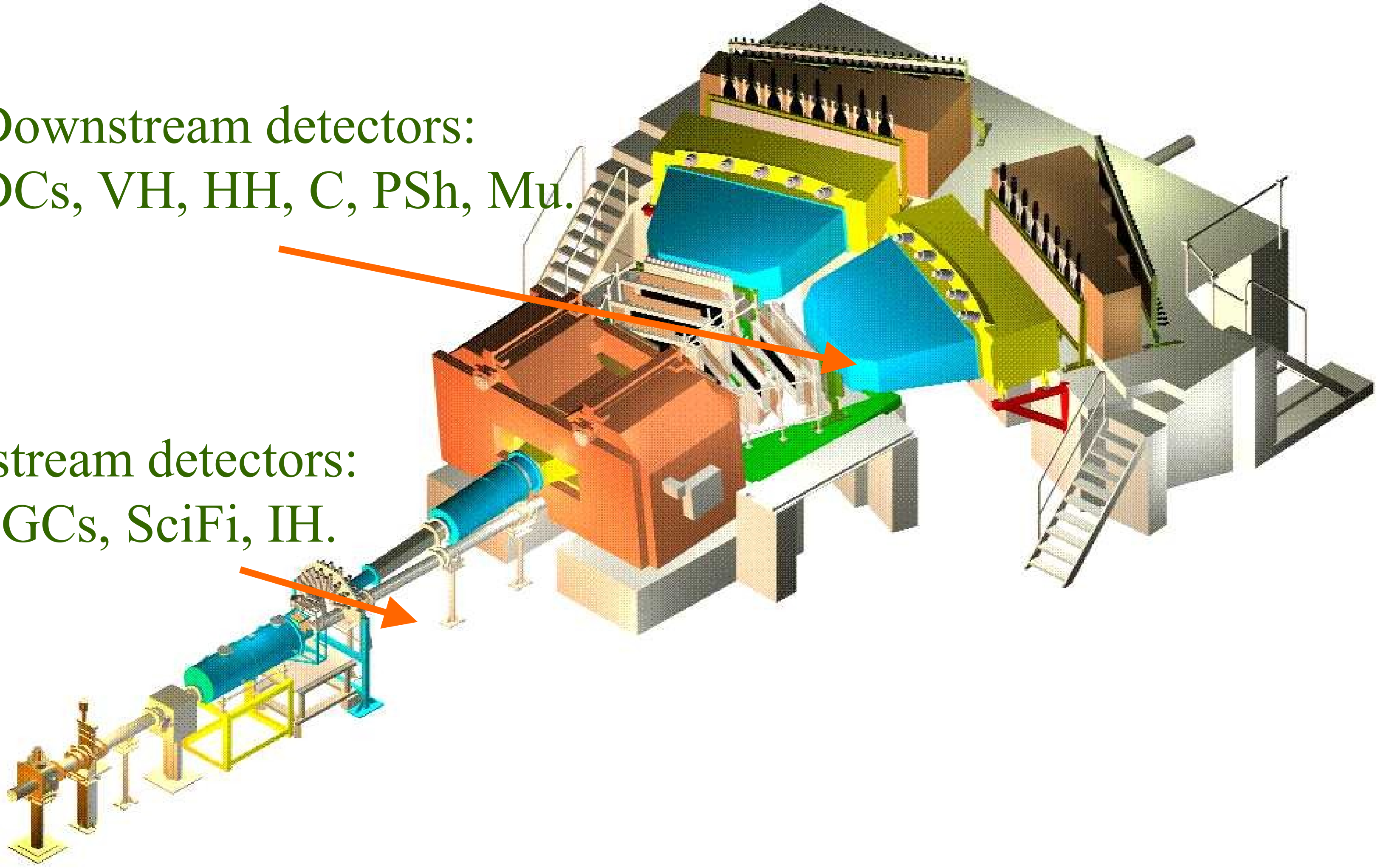


All targets have the same thickness in radiation lengths $6.7*10^{-3}$ X_0

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%.

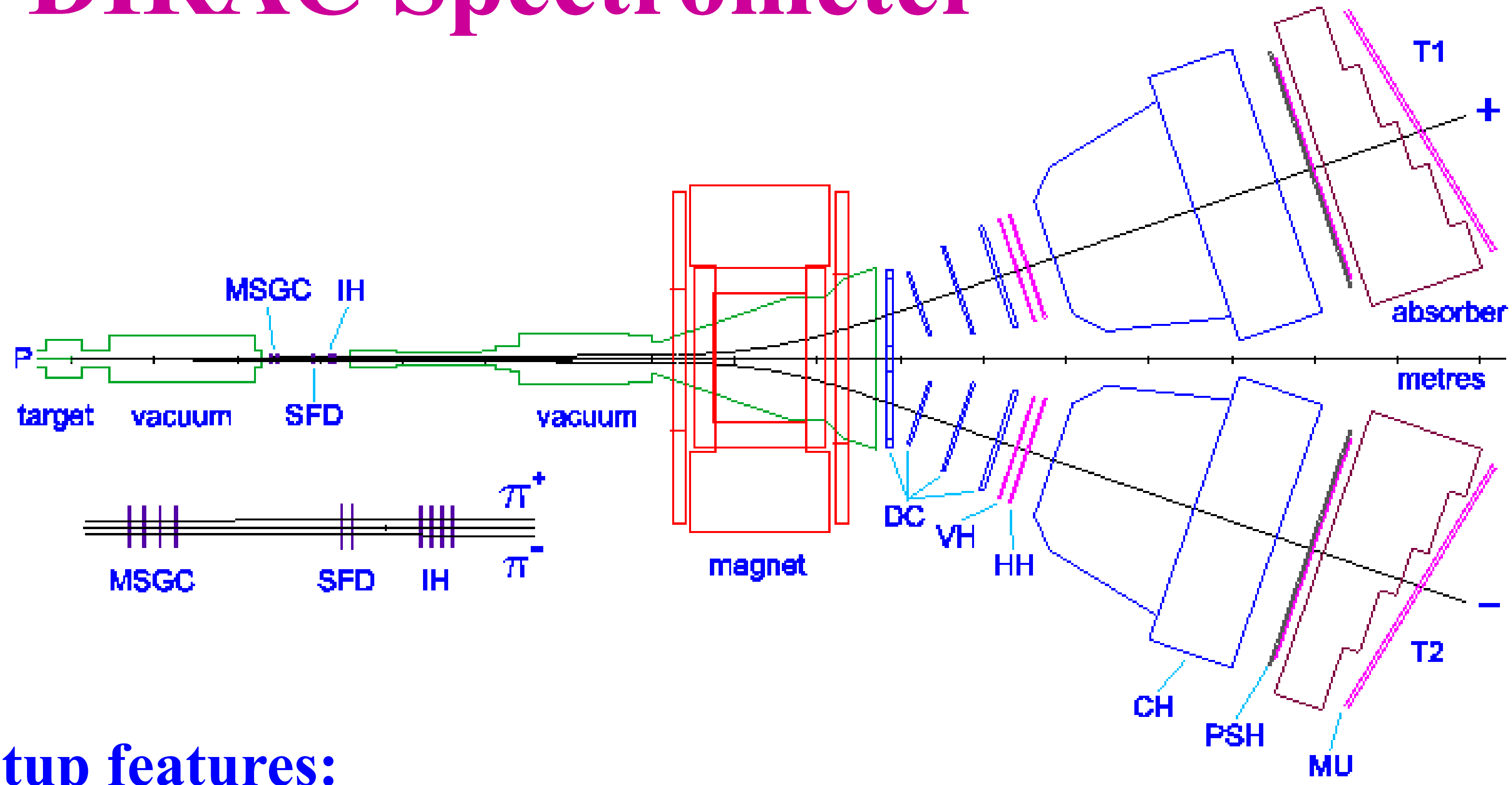
DIRAC Spectrometer



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

Upstream detectors:
MSGCs, SciFi, IH.

DIRAC Spectrometer



Setup features:

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

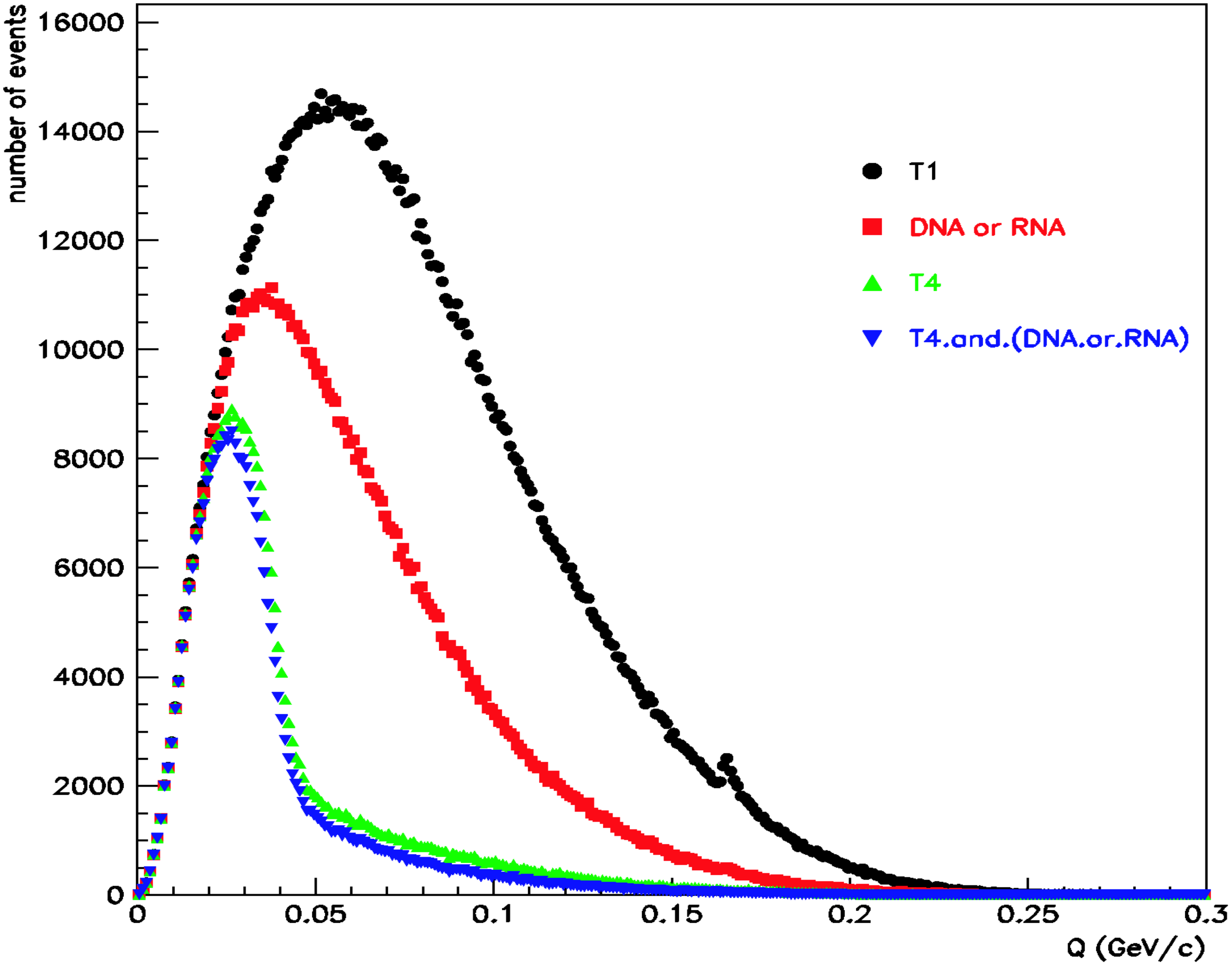
channel aperture $\Omega=1.2\cdot10^{-3}$ sr

magnet 2.3 T·m

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

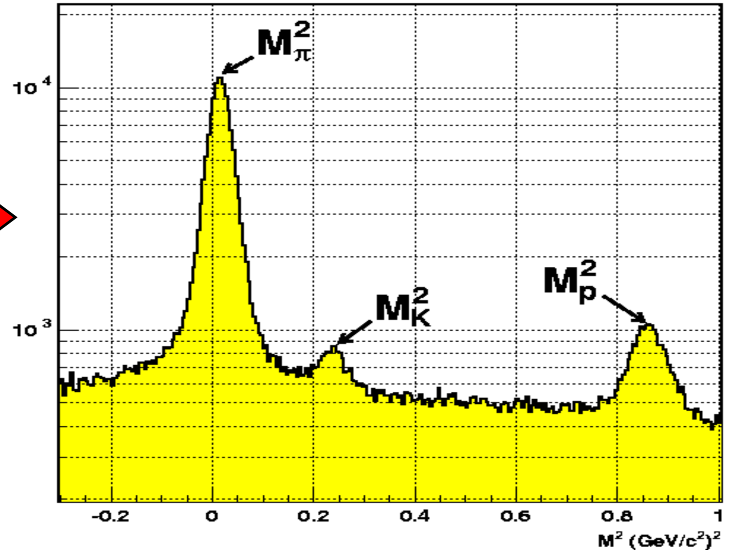
resolution on relative momentum $\sigma_{QX}\approx\sigma_{QY}\leq 0.5$ MeV/*c*, $\sigma_{QL}\approx 0.5$ MeV/*c*

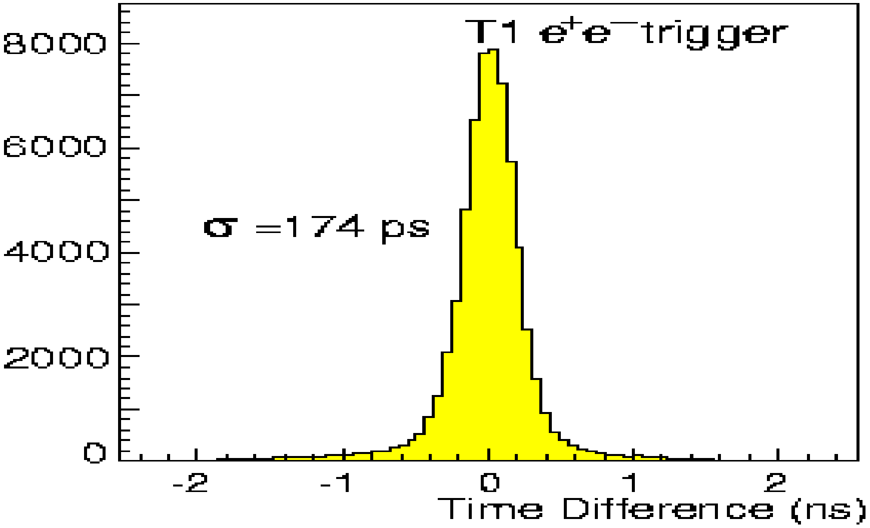
Trigger performance



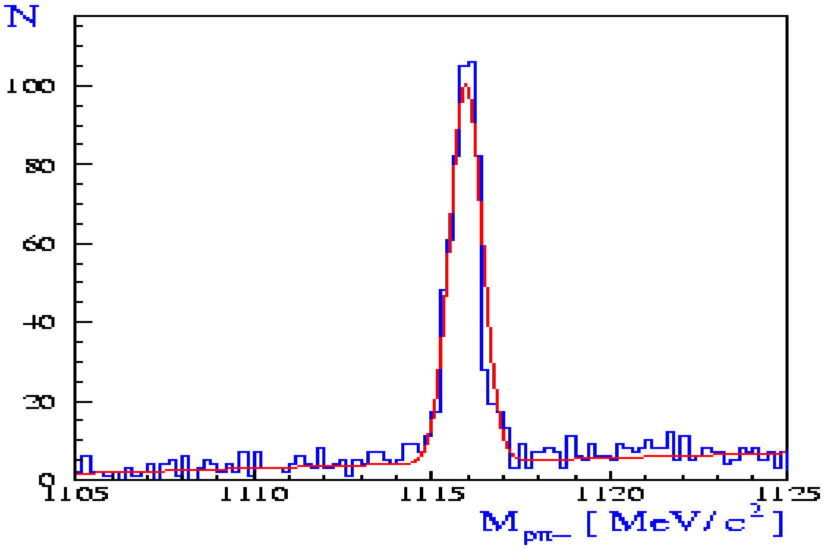
Calibrations

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

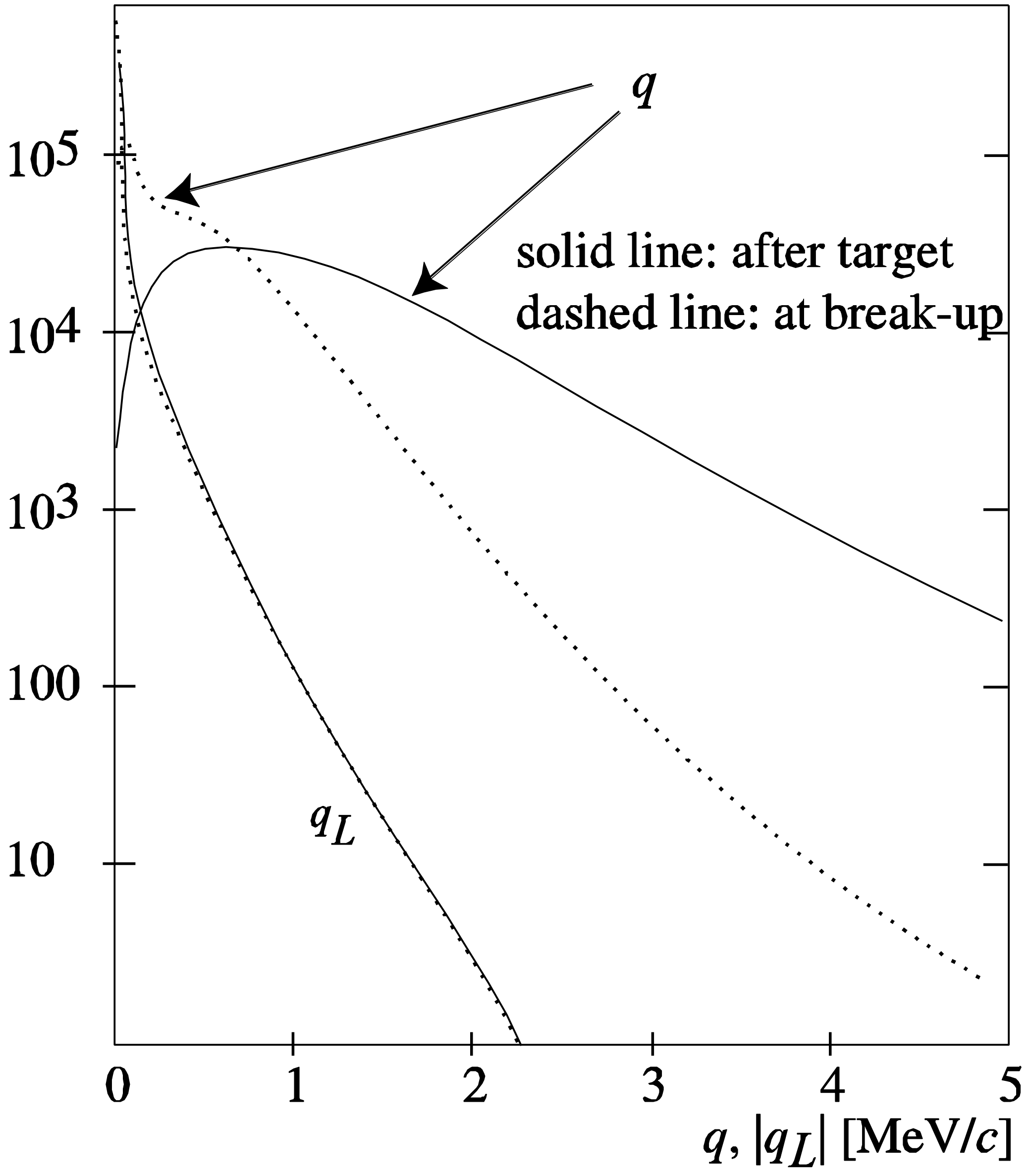
Atoms are generated in **nS states** using measured momentum distribution for **short-lived** sources. The atomic pairs are generated according to the evolution of the atom while propagating through the target

Background processes:

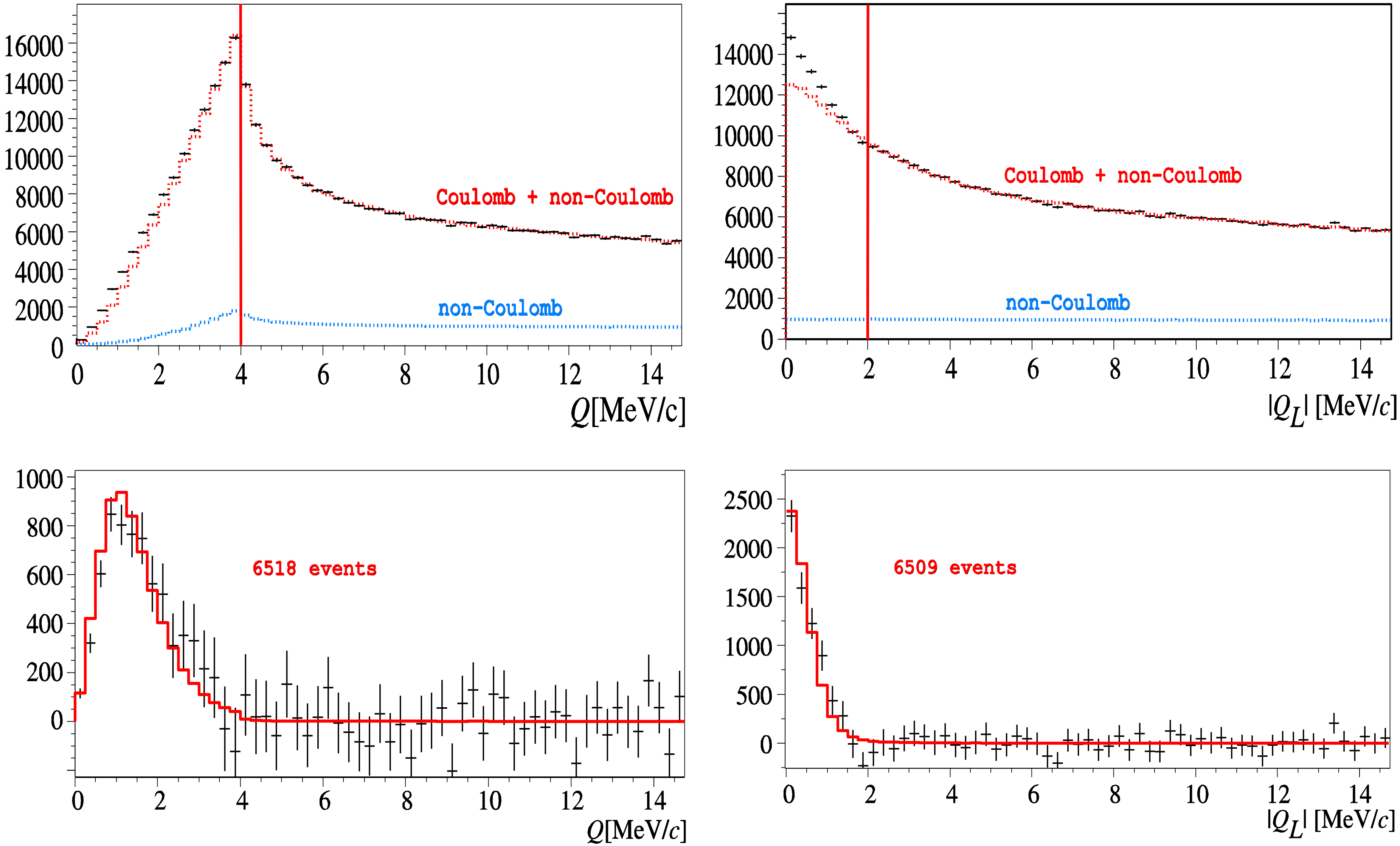
Coulomb pairs are generated according to $A_C(Q)Q^2$ using measured momentum distribution for **short-lived** sources.

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

Atomic pairs MC



Atomic pairs (2001)



Break-up probability

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

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

Lifetime

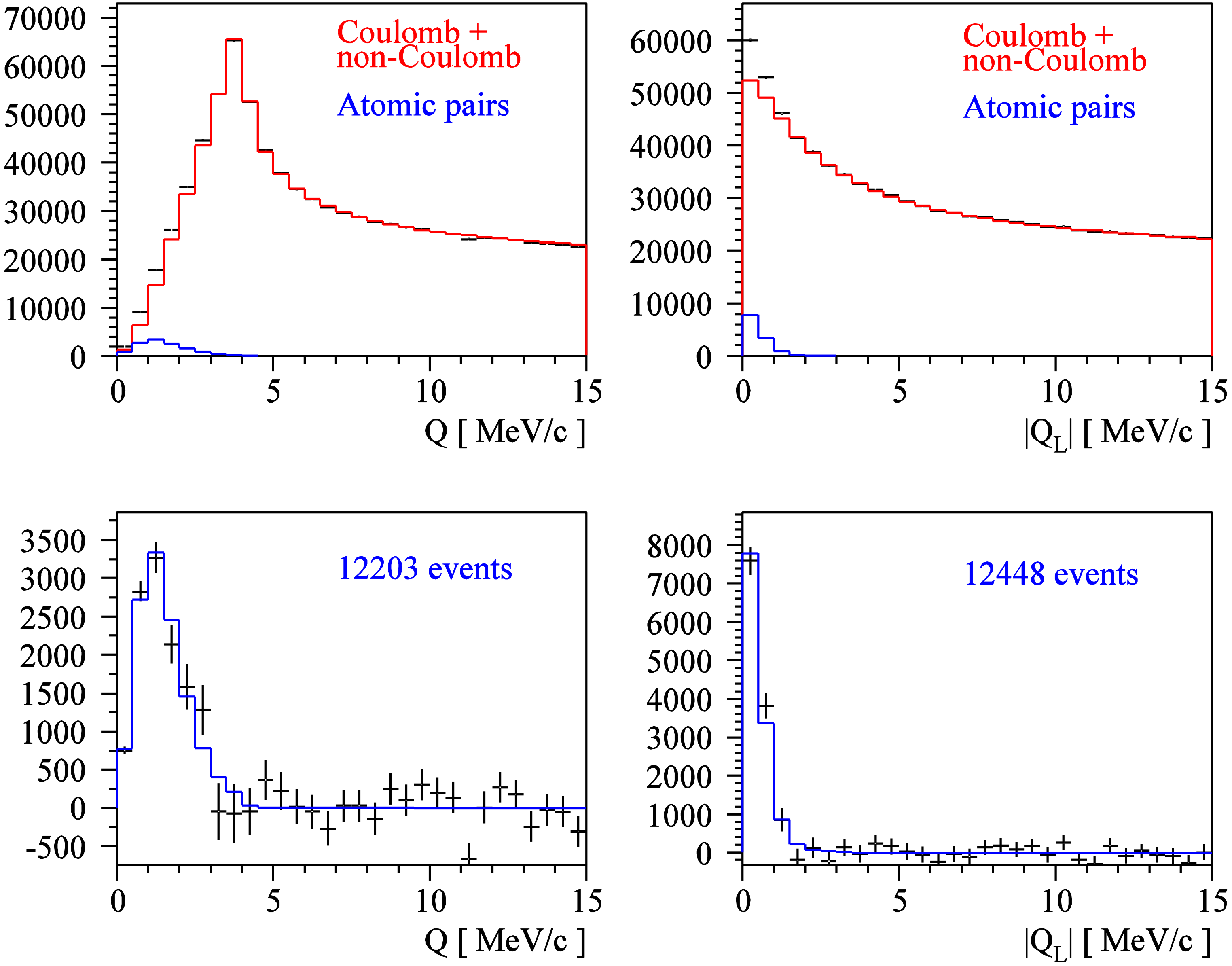
$$\tau = \left(2.91 \left.\begin{matrix} +0.45 \\ -0.38 \end{matrix}\right\}_{stat} \left.\begin{matrix} +0.19 \\ -0.49 \end{matrix}\right\}_{syst}\right) \mathrm{fs}$$

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

ChPT prediction:

$$\tau = \left(2.9 \pm 0.1\right) \mathrm{fs}$$

Atomic pairs (2001+2002+2003)



Estimation of relative errors for break-up probability measurement

	Q	Q_L	Q_L, Q_T
Statistical	0.031	0.044	0.031
Multiple scattering	0.018	0.008	0.014
Heavy particles admixture	0.001	0.008	0.001
Finit size effects	0./ -0.006	0./ -0.004	0./ -0.005/
Double track resolution	0.009	0.001	0.003
Background particles	0.002	0.003	0.002
Trigger simulation	0.002	0.002	0.003
All systematic	+0.021/ -0.022	0.012	+0.015/ -0.016

Estimation of relative errors for lifetime

Statistical	**0.087 - 0.122**
Systematic	0.033 - 0.060

Conclusions

1. Data collected in 2001, 2002 and 2003 are analyzed. These data allows to obtain statistical accuracy better than 10%.
2. Multiple scattering and admixture of K^+K^- and $p\bar{p}$ pairs is measured in order to decrease systematic errors.
3. Systematic errors due to detector response description are estimated.

Break-up probability

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

	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

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

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

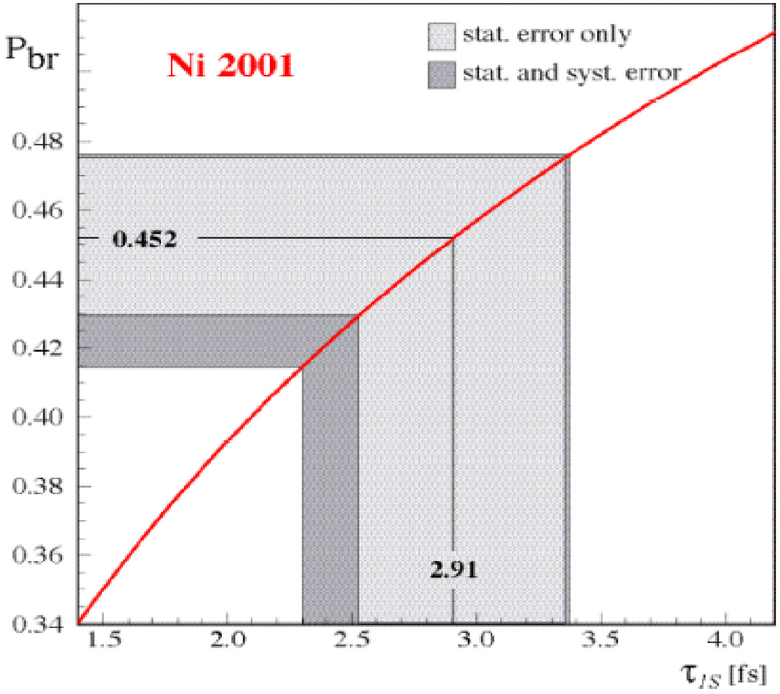
Breakup probability

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

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 $\bar{p}p$ 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:

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

ChPT prediction:

$$\tau = \left(2.9 \pm 0.1\right)\mathrm{fs}$$

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