Pionium Lifetime Measurement by DIRAC

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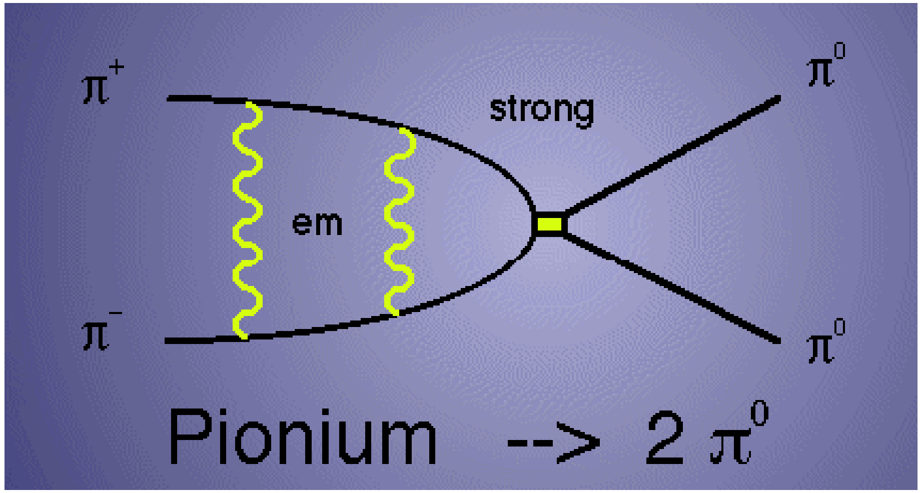
DIRAC

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.

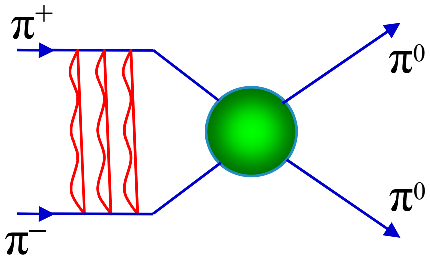
90 Physicists from 18 Institutes

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 is dominated by charge exchange process into $\pi^0\pi^0$:



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

at lowest order :

$$\Gamma_{2\pi_0} = \frac{2}{9}\alpha^3 p\,(a_0 - a_2)^2$$

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

Pionium lifetime in QCD

At next-to-leading order in α and $(m_d - m_u)^2$:

$$\Gamma_{1s} = \frac{1}{\tau_{1s}} = \frac{2}{9}\alpha^3 p\,|a_0 - a_2|^2\,(1+\delta)\,M_{\pi+}^2$$

$$p = \sqrt{M_{\pi+}^2 - M_{\pi 0}^2 - \frac{1}{4}\alpha^2 M_{\pi+}^2}$$

J. Gasser et al , Phys. Rev. D62 (2001) 016008

- $\delta = (5.8 \pm 1.2) \times 10^{-2}$ significant correction

Measurement of τ (10%) ↔ $|a_0 - a_2|$ (5%)

Pionium lifetime in QCD

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.

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

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

$$\tau_{1s} = 2.9 \pm 0.1\ fs$$

Experimental results

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

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

$a_0 = 0.216 \pm 0.013$ ± 0.003(syst) — New measurement at BNL (E865) S.Pislak et al., Phys.Rev. D 67 (2003) 072004

$a_2 = -0.0454 \pm 0.0031$ ± 0.0013(syst)

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

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

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

$K^+ \to \pi^+\pi^0\pi^0$ and $K_L \to 3\pi^0$ NA48/2

$|a_0 - a_2| = 0.261$

$\pm\, 0.006\,(stat.)$

$\pm 0.003\,(syst.)$

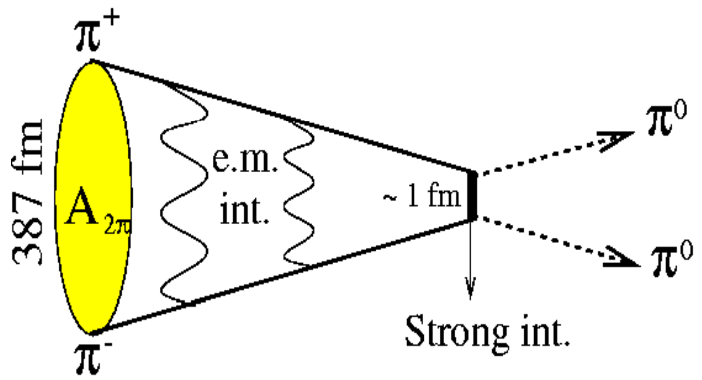
$\pm 0.0013\,(ext)$

$\pm 0.013\,(theor)$

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

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

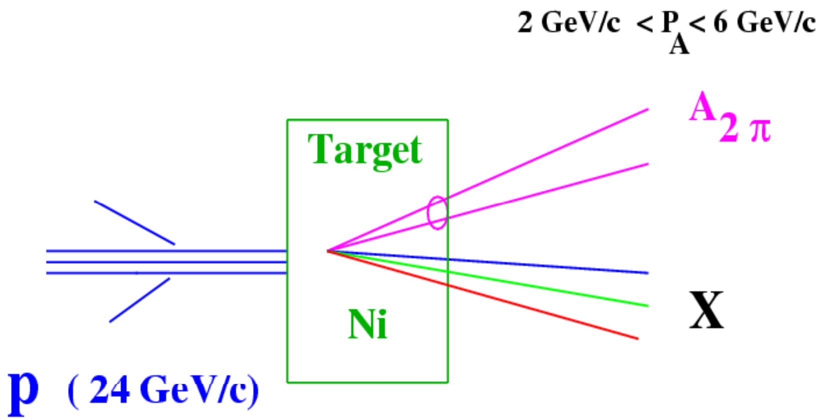
Production of pionium



The pionium is a Coulomb bound state:

$$E_B = -1.858 \quad \text{keV} \qquad J^{PC} = 0^{++}$$

$$R(A_{2\pi}) = 387 \quad \text{fm} \qquad P_B \approx 1 \text{ MeV}$$



CERN - PS

T8 - beam

Ip ~ 10^{11} p/spill

π^+ and π^- originating from short lived sources (ρ, K*, ω,...) and resonance decays may form a pionium atom. The differential cross section is:

$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} |\Psi_n(0)|^2 \left(\frac{d\sigma_s^0}{d\vec{p}d\vec{q}} \right)_{p=q=p_A/2}$$

Lorentz Center of Mass to Laboratory factor.

Wave function at origin (accounts for Coulomb interaction).

Pion pair production from short lived sources.

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: $A_{2\pi} \rightarrow \pi^0 \pi^0$

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

Excitation: **transitions between atomic levels**

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

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

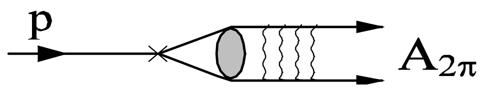
- **Q_{cms}<3MeV/c**
- **→ in laboratory system $E_+ \approx E_-$, small opening angle θ<3mrad**

Coulomb and atomic pairs are detected simultaneously:

$$P_{Br} = \frac{n_A}{N_A} = \frac{1}{K^{th}} \frac{n_A}{N_C}$$

Production of pionium

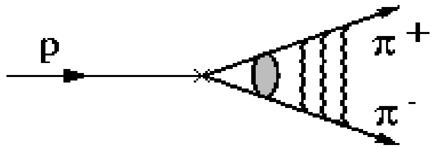
Atoms are Coulomb bound state of two pions produced in one proton-nucleus collision



$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} |\Psi_n(0)|^2 \left(\frac{d\sigma_s^0}{d\vec{p}d\vec{q}}\right)_{p=q=p_A/2}$$

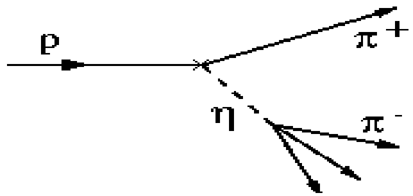
Background processes:

Coulomb pairs. They are produced in one proton nucleus collision from fragmentation or short lived resonances (ρ, K*, ω,...) and exhibit Coulomb interaction in the final state:

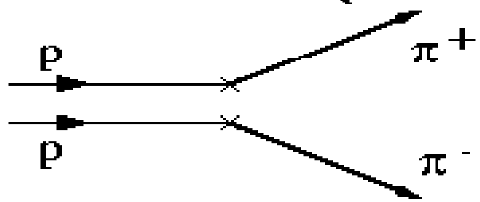


$$\frac{d^2\sigma_C}{dp_+dp_-} = A_C(q)\frac{d^2\sigma_S^0}{dp_+dp_-} \qquad A_C(q) = \frac{2\pi M_\pi \alpha/q}{1-\exp(-2\pi M_\pi \alpha/q)}$$

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



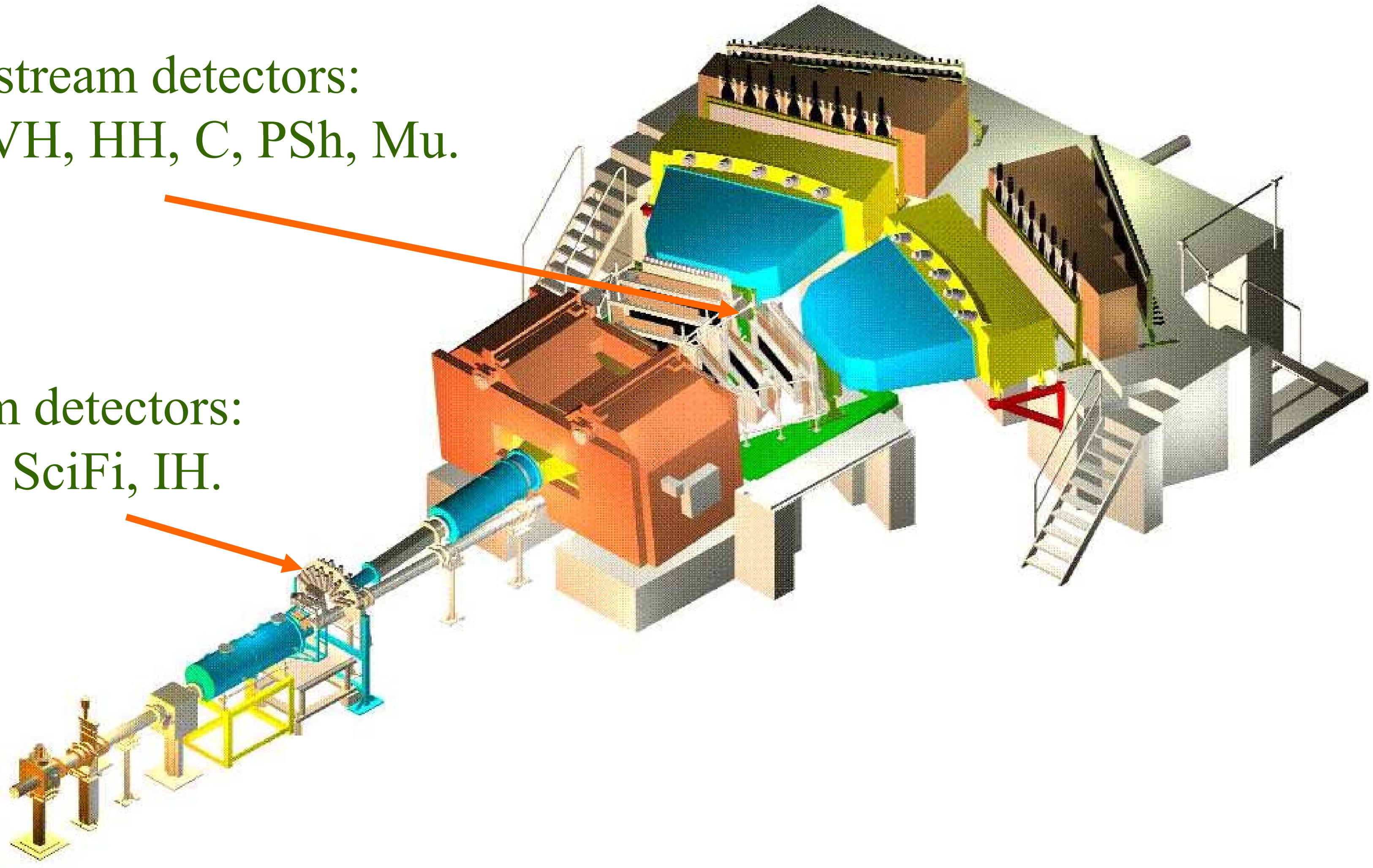
Accidental pairs. They are produced in two independent proton nucleus collision. They do not exhibit Coulomb interaction in the final state



DIRAC Spectrometer

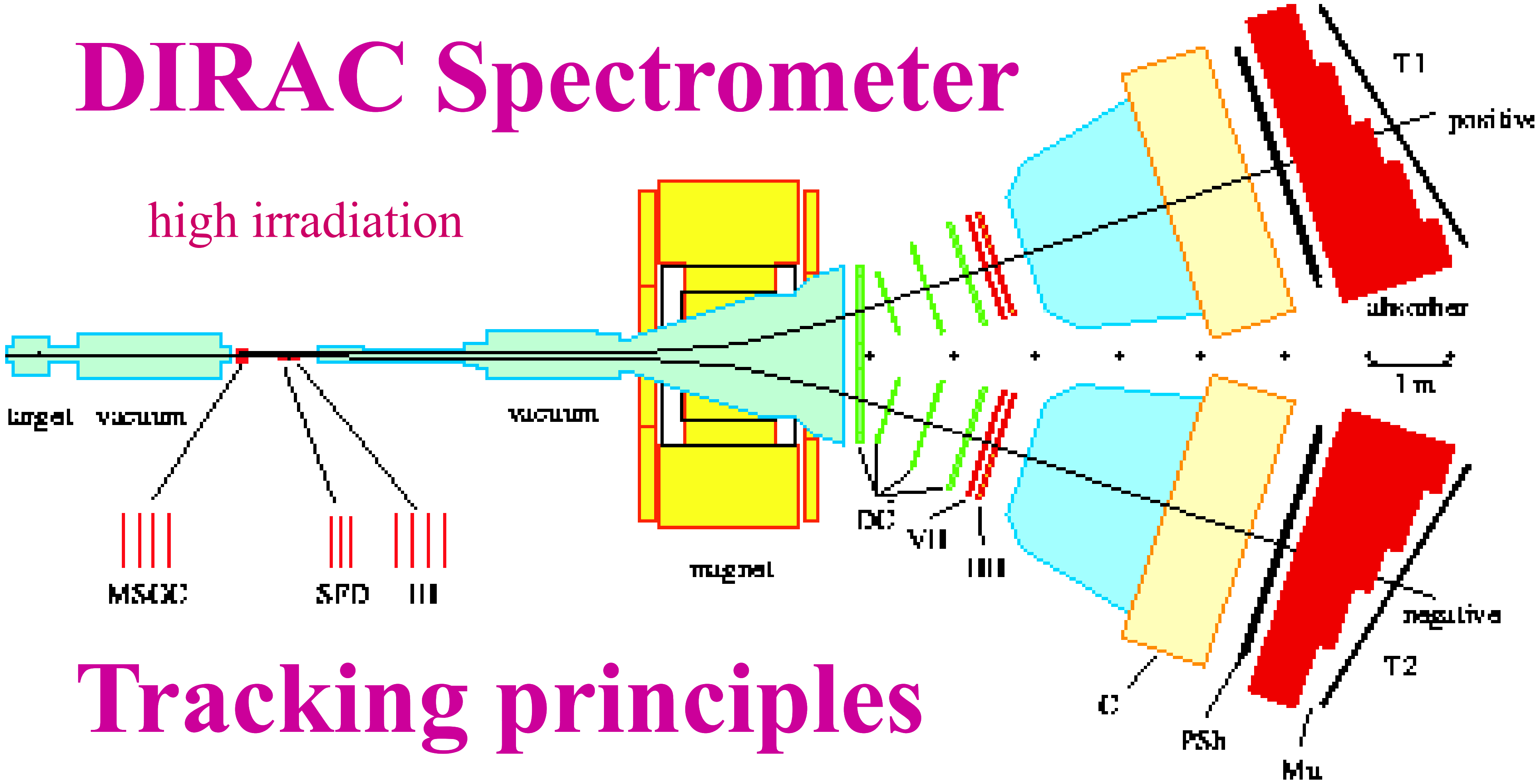
Downstream detectors:
DCs, VH, HH, C, PSh, Mu.

Upstream detectors:
MSGCs, SciFi, IH.



DIRAC Spectrometer

high irradiation



Tracking principles

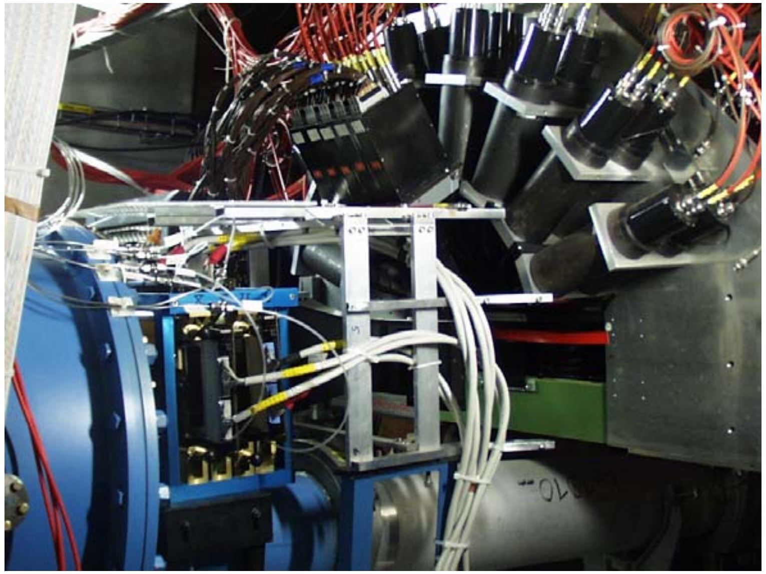
- Precison **time-of-flight** to reduce accidental and proton background
- Strong **e+e- rejection** by Čerenkov counters
- Unambiguous transverse momentum Q_T by **upstream tracking** (MSGC+SFD)
- Longitudinal momentum Q_L measured by **fast drift chambers** and upstream tracks

DIRAC Spectrometer

Nucl. Inst. Meth. A515 (2003) 467.

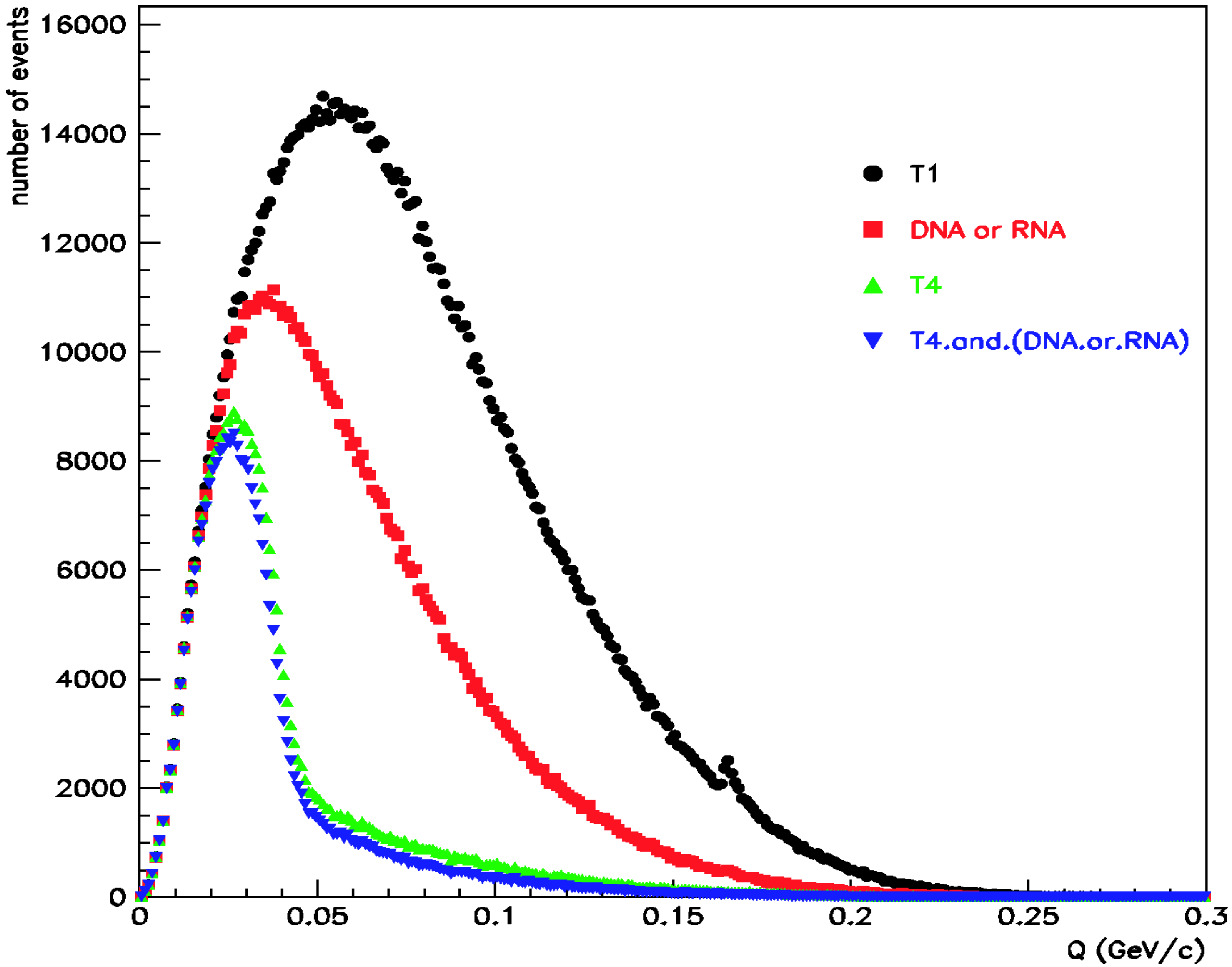
Downstream detectors:
Drift chambers
Cherenkov
Time-of-Flight

Pre-Shower and
Muon Counters unseen



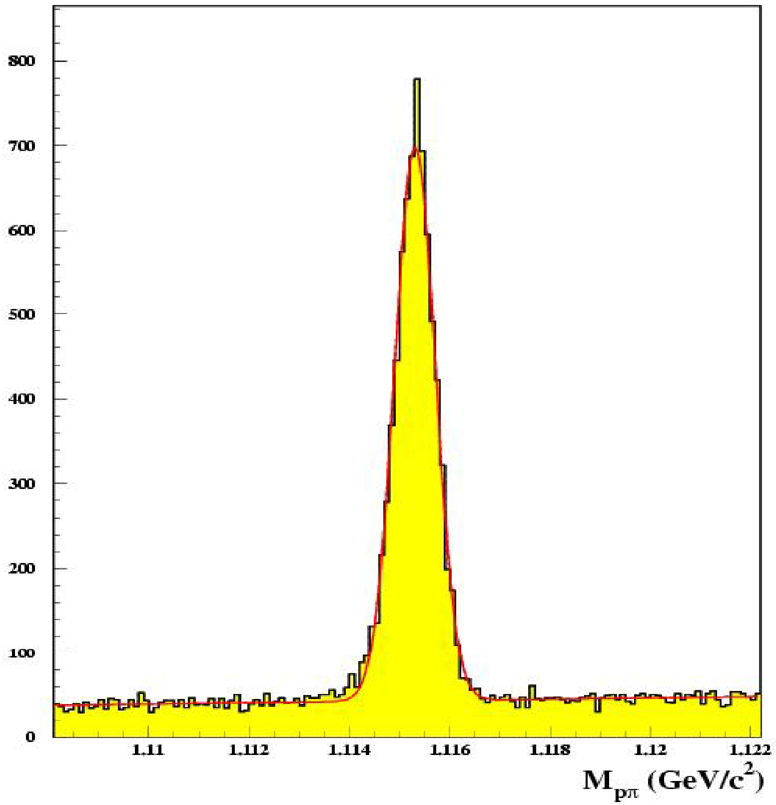
Upstream detectors:
MSGC/GEM
SFD
Ionisation Hodoscope

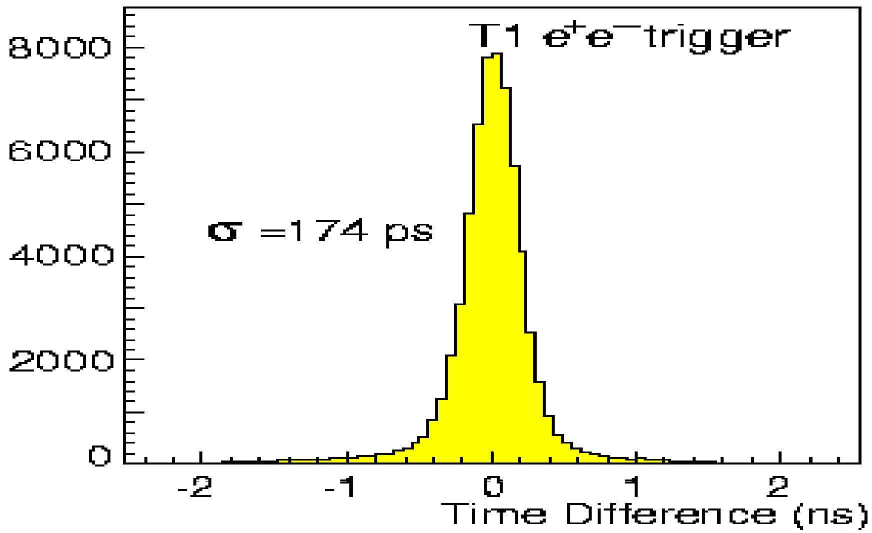
Trigger performance



Calibrations

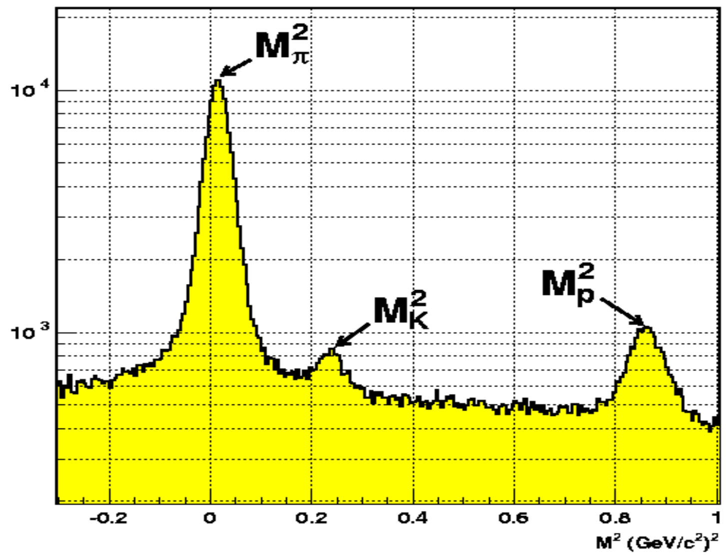
Mass distribution of $p\pi^-$ pairs from Λ decay. σ_Λ=0.39 MeV/c^2



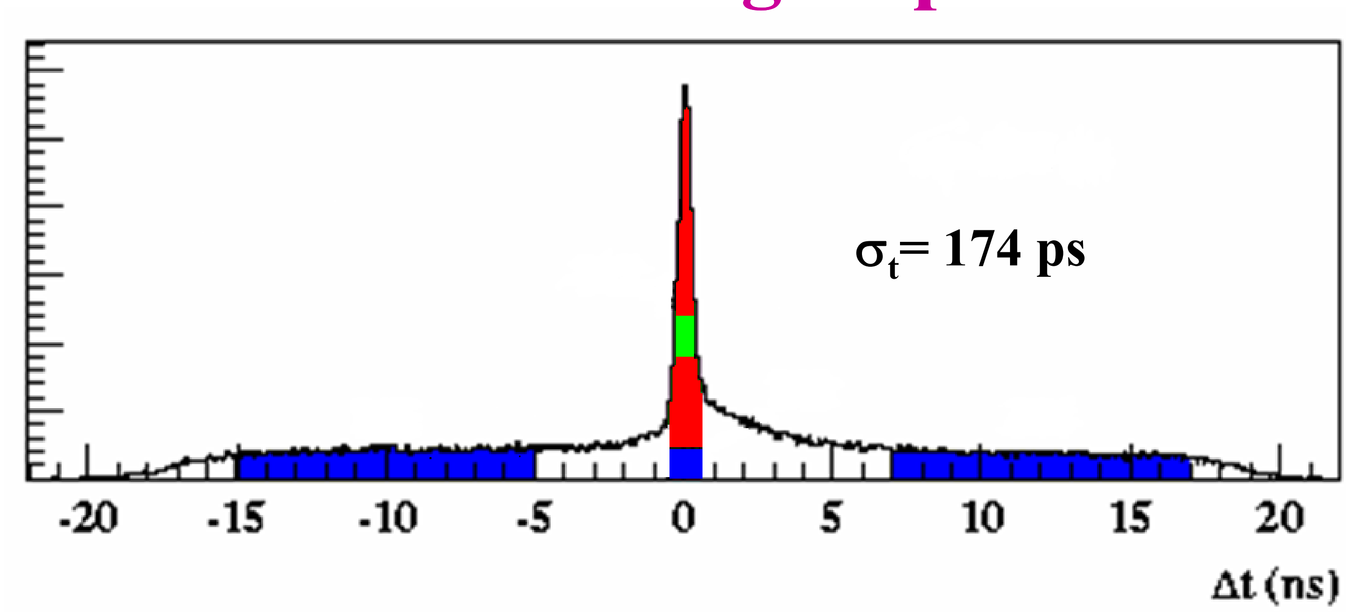


Time difference spectrum at VH with e^+e^- T1 trigger.

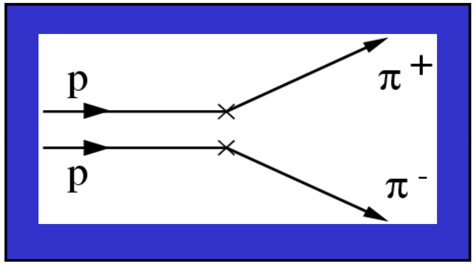
Positive arm mass spectrum, obtained by TOF difference, under π^- hypothesis in the negative arm.

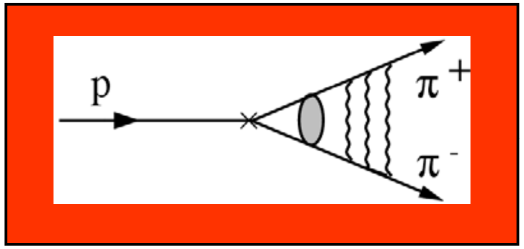


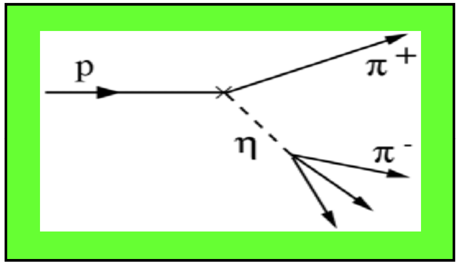
Time-of-Flight spectrum



π+π- pairs







Accidental pairs, different proton interactions in the target

Coulomb pairs. From short lived sources.
$r < 3$ fm, $< R(A_{2\pi})$

Non Coulomb pairs. From long lived sources.
$r \sim 1000$ fm.

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.

Monte Carlo simulation is restricted to detector response only, without relying on specific asumptions from proton-nucleus collision models

2D χ^2 FIT TO (Q_T, Q_L) SPECTRUM

$$\frac{dn_p}{d^2Q} = \alpha_1 \frac{dn_{CC}}{d^2Q} + \alpha_2 \frac{dn_{NC}}{d^2Q} + \alpha_3 \frac{dn_{AC}}{d^2Q} + \gamma \frac{dn_{AT}}{d^2Q}$$

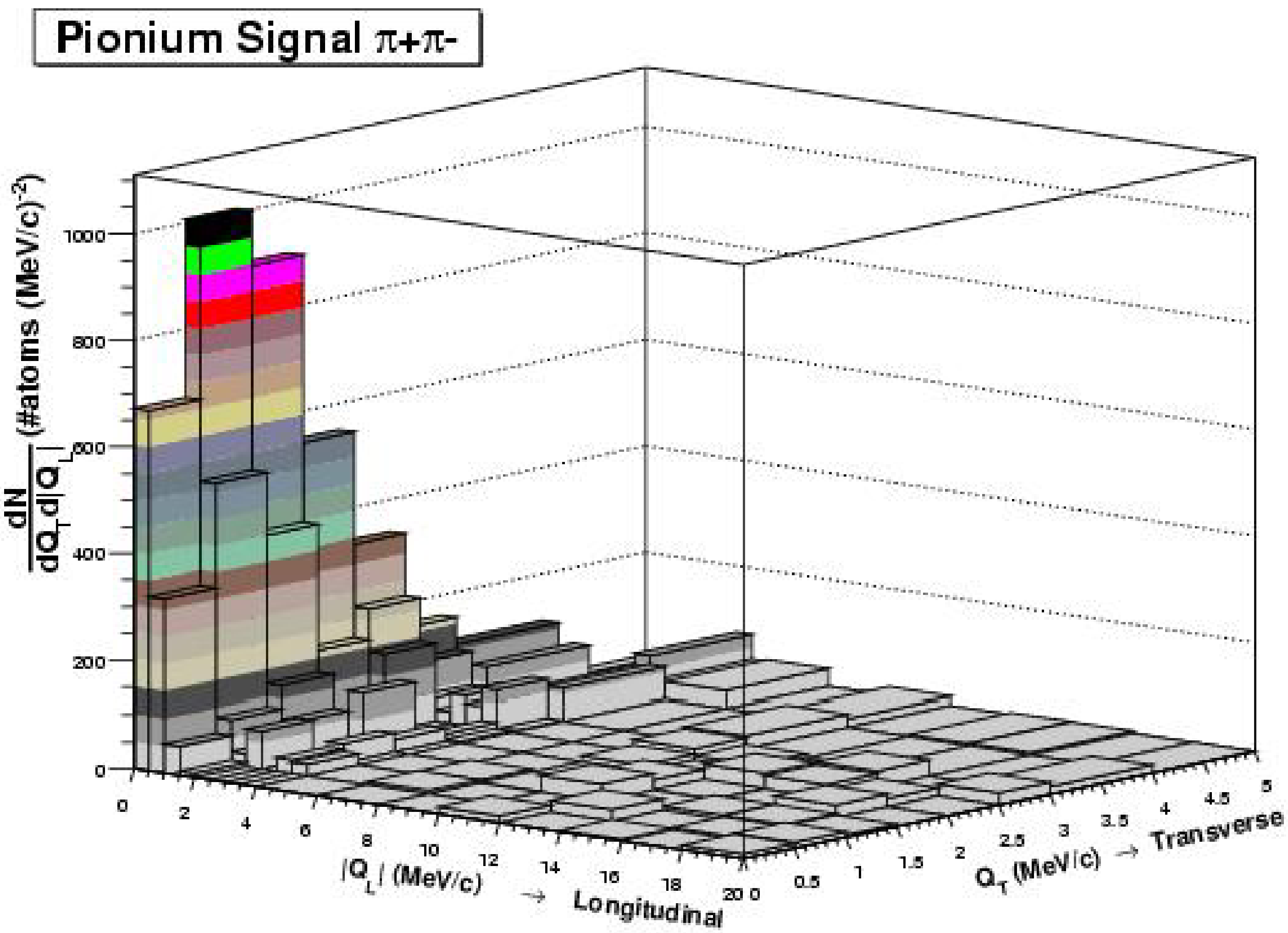
$$\frac{dn_i}{d^2Q} = \frac{1}{N_i} \frac{dn_i}{d^2Q} \qquad d^2Q = dQ_T dQ_L \qquad \alpha_1 + \alpha_2 + \alpha_3 + \gamma = 1$$

α_3 (accidentals fraction) measured from TOF

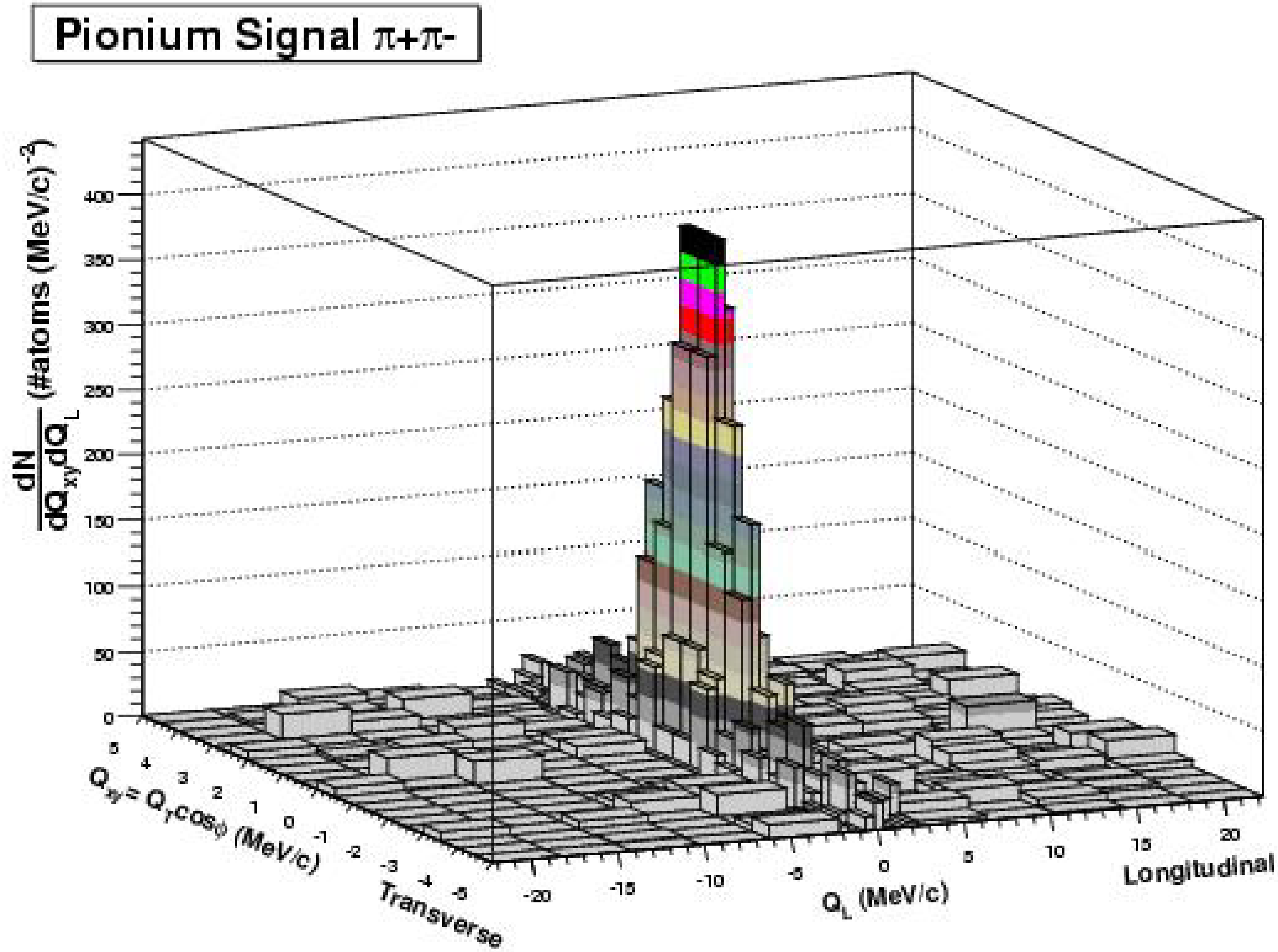
α_1 and γ free parameters in 10 independent 600 MeV/c $\pi+\pi-$ momentum bins

Atom signal defined as difference between prompt data and Monte Carlo with $\gamma = 0$

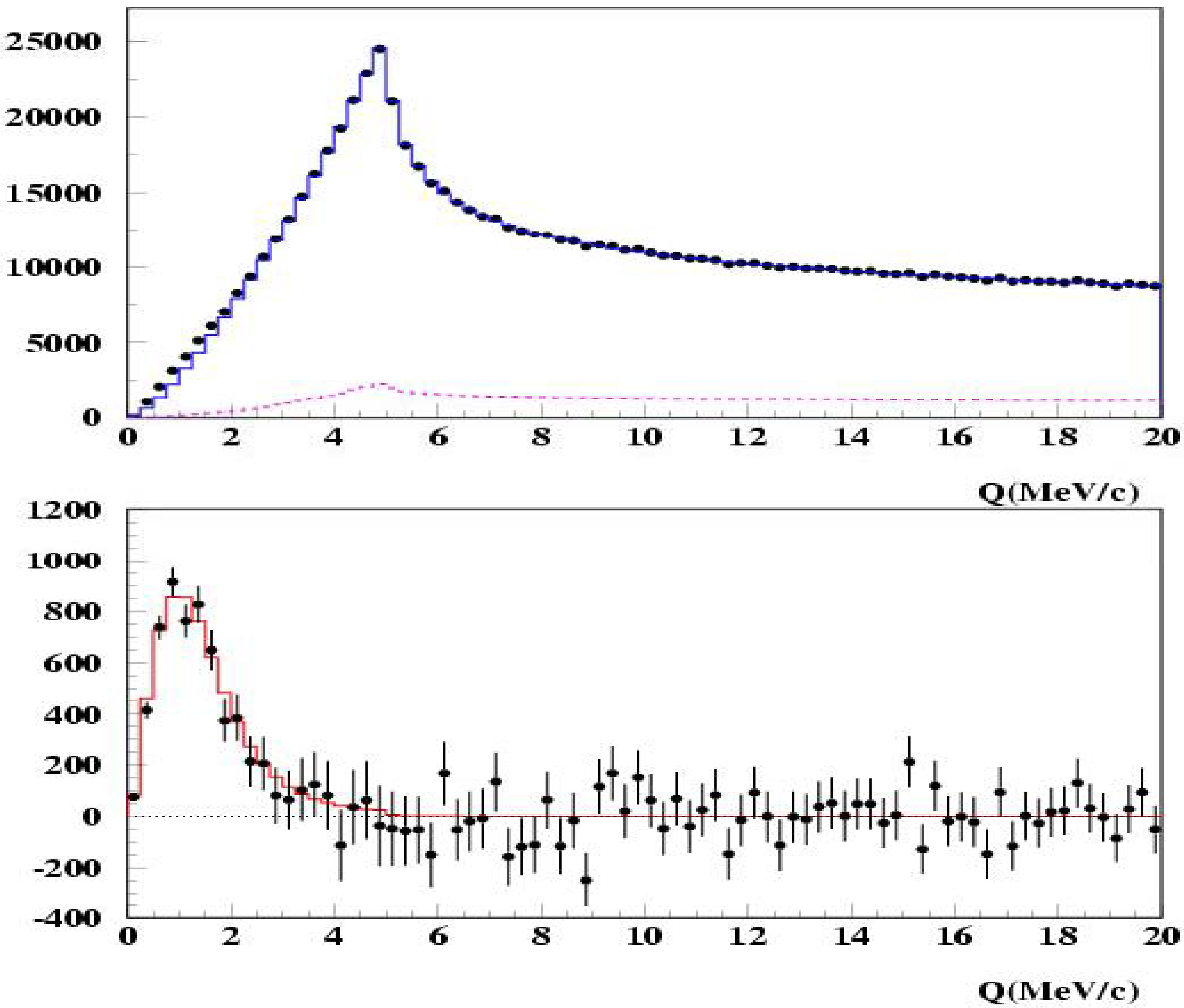
Pionium signal in Qt vs Ql



PIONIUM BREAK-UP SIGNAL IN $\pi^+\pi^-$ SPECTRUM



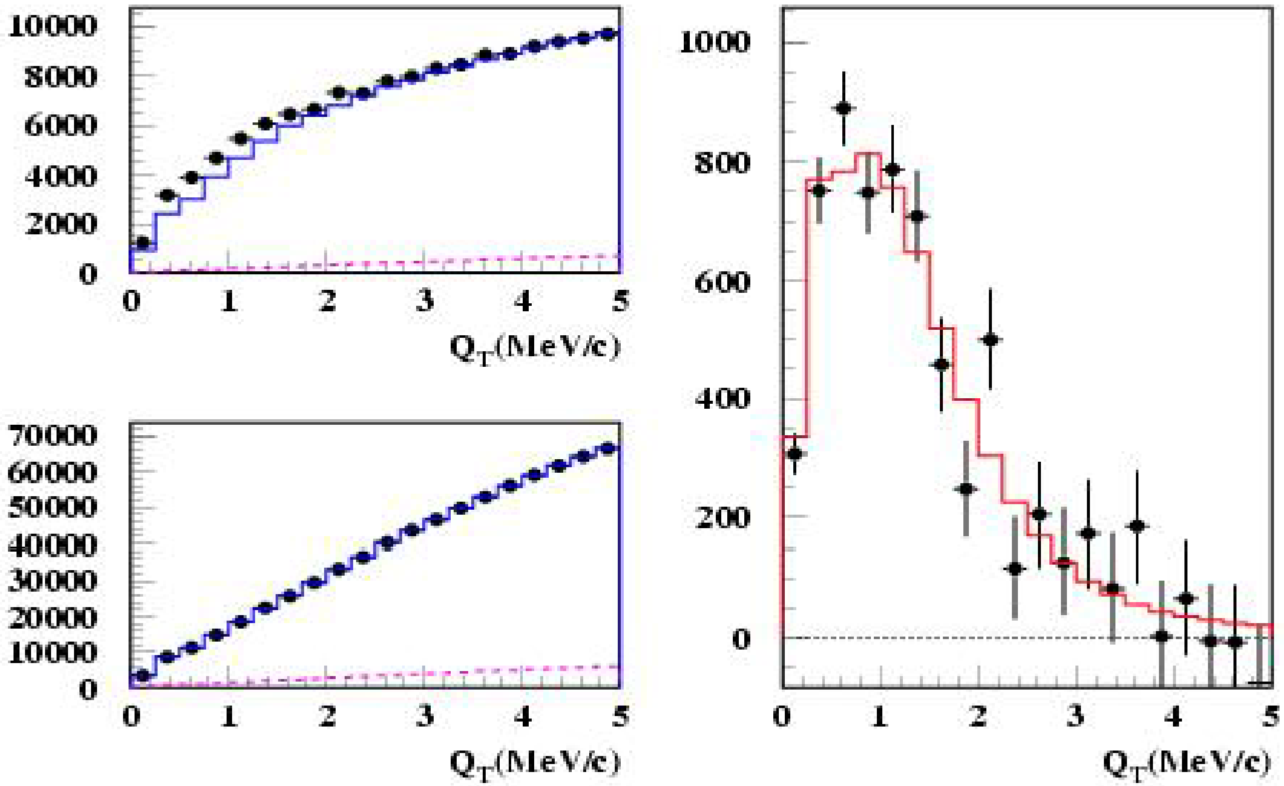
Pionium signal in $Q = \sqrt{Q_L^2 + Q_T^2}$



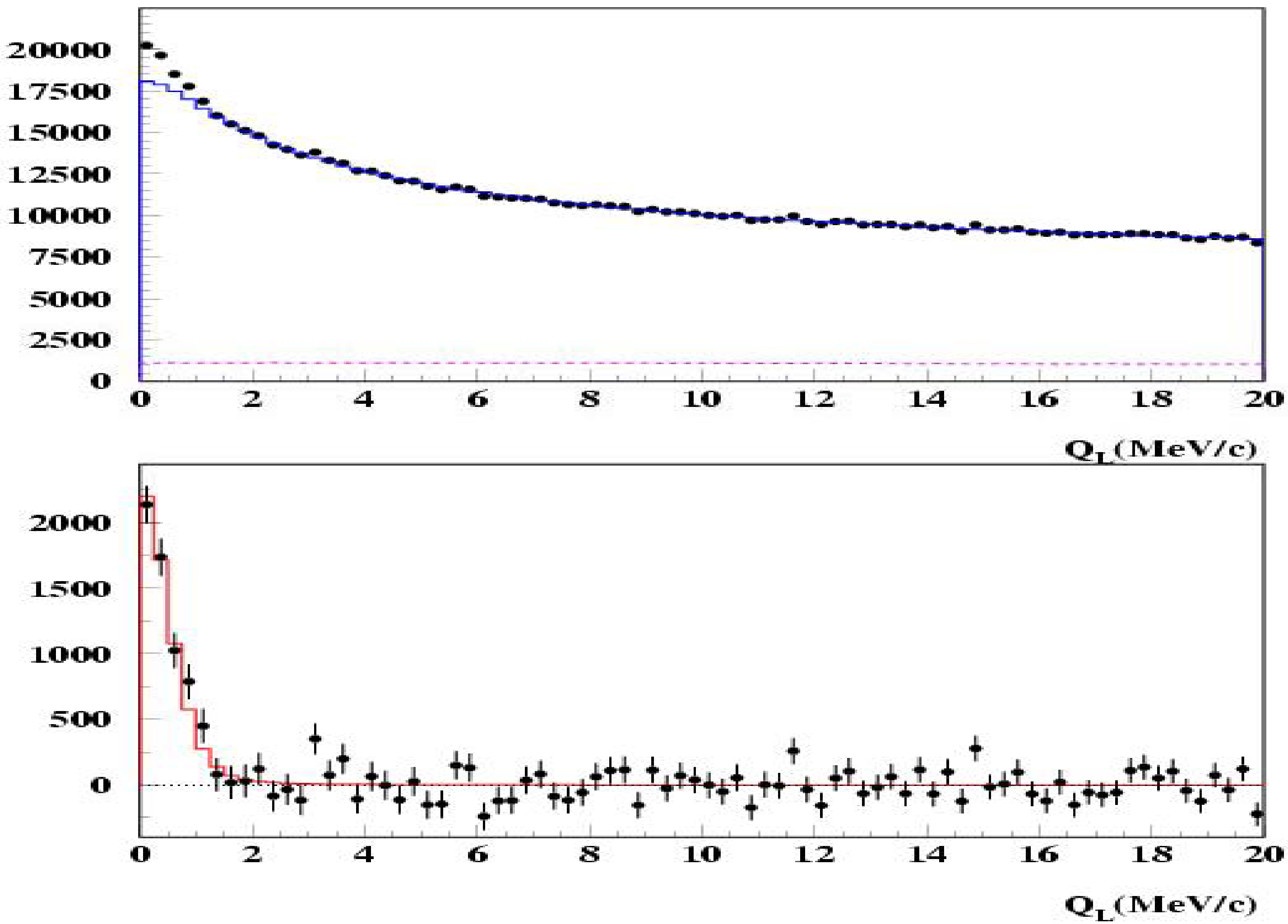
PIONIUM TRANSVERSE SIGNAL

$Q_L < 2$ MeV/c

$Q_L > 2$ MeV/c



Pionium Longitudinal Signal



DETERMINATION OF BREAK-UP PROBABILITY

Coulomb-pair background N_{CC} determined from fit α_1 parameter:

$$P_{Br} = \frac{n_A}{N_A} = \frac{1}{K^{th}} \frac{n_A}{N_C}$$

$$P_{Br} = \frac{N_{AT}(\Omega)}{N_{CC}(\Omega)} \frac{1}{K^{exp}(\Omega)}$$

$$K^{exp} = \frac{\varepsilon_{CC}(\Omega)}{\varepsilon_{AT}(\Omega)} K^{th}(\Omega)$$

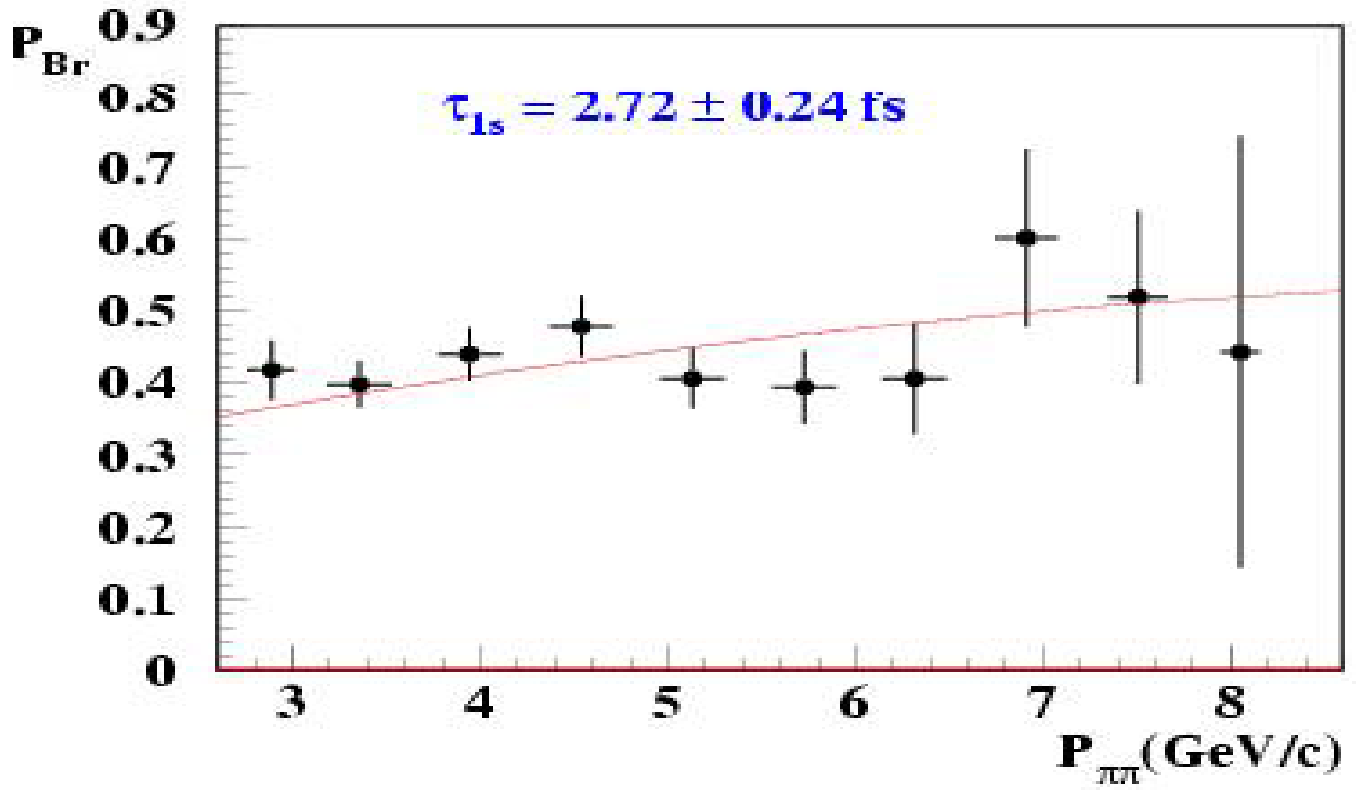
QM analytical factor: $$K^{th}(\Omega) = \frac{(2\pi\alpha M_\pi)^3}{\pi} \frac{\sum 1/n^3}{\int_\Omega A_C(Q)\, d^2Q}$$

Acceptance factors ε_i determined by Monte Carlo simulation

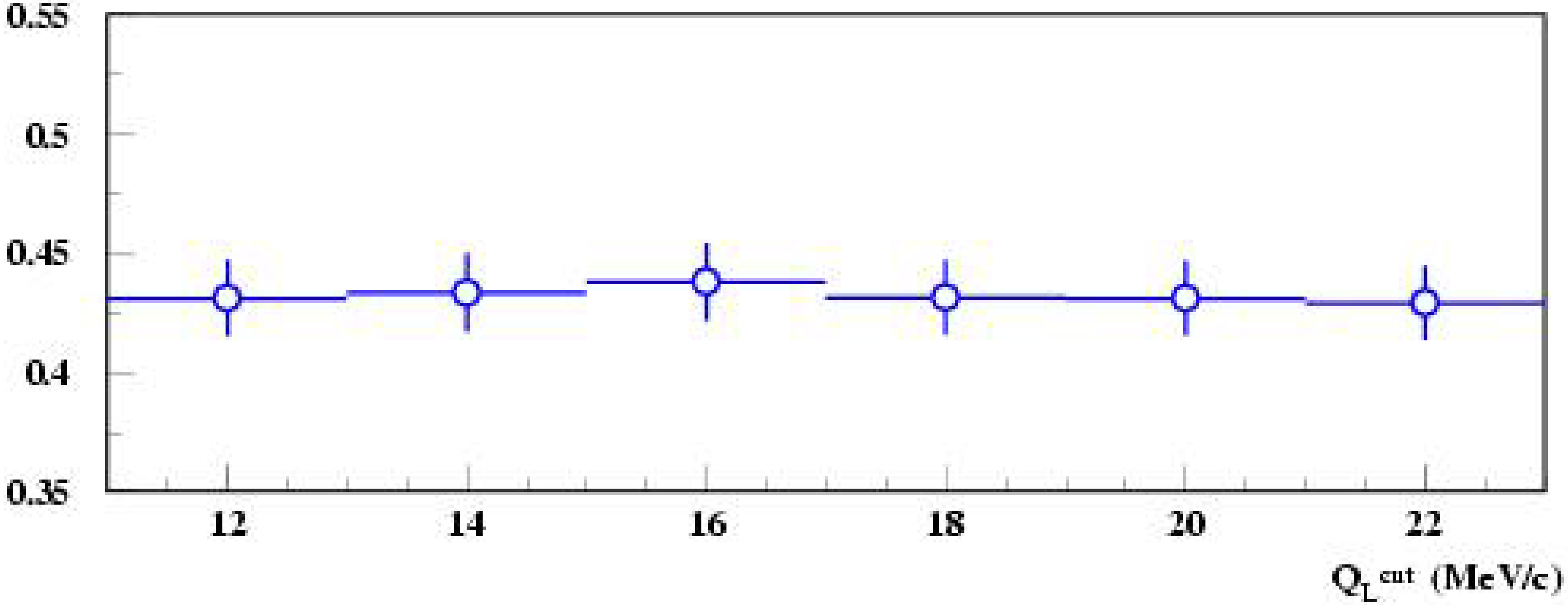
Different extrapolation domains: $\Omega = (0, Q_T^C) \times (0, Q_L^C)$

Standard choice is $Q_L{}^C = 2$ MeV/c and $Q_T{}^C = 5$ MeV/c

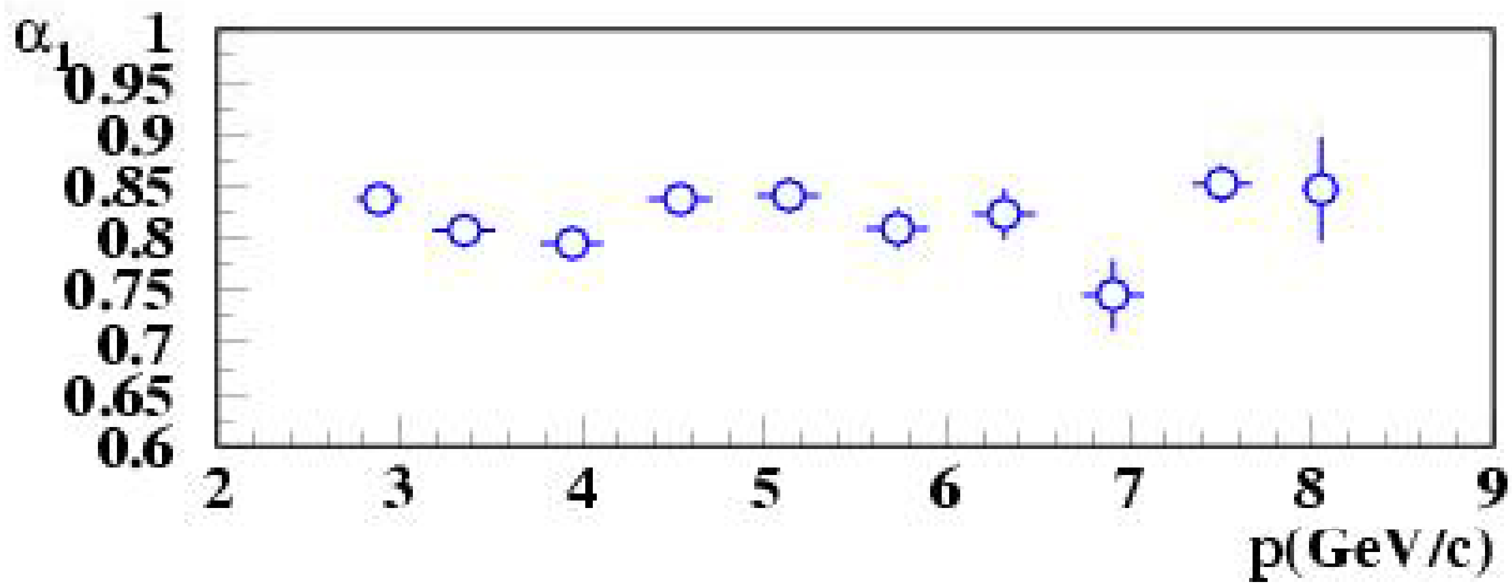
Break-up probability as function of pionium momentum

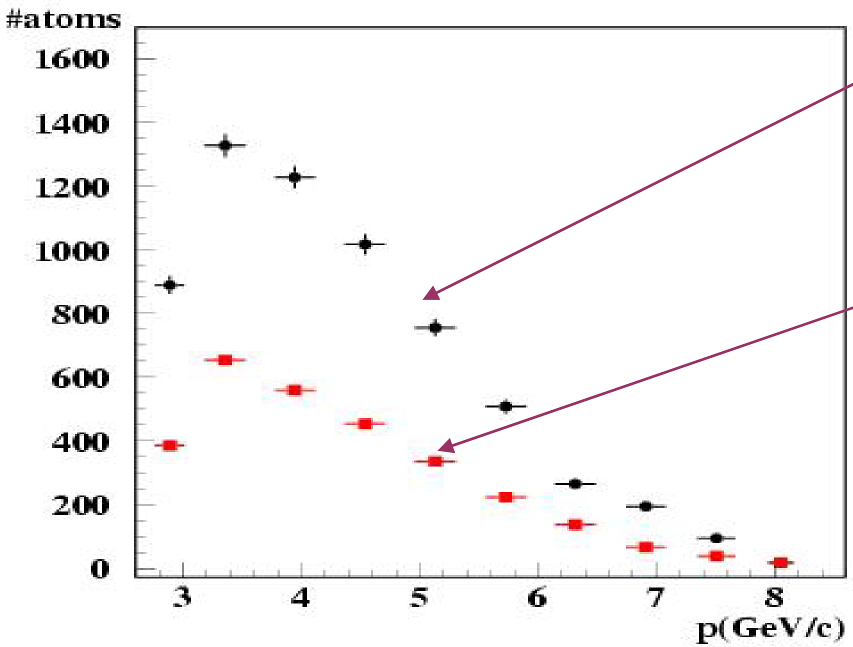


P_{Br} as function of Q_L upper cut



Fraction of Coulomb pairs as function of momentum

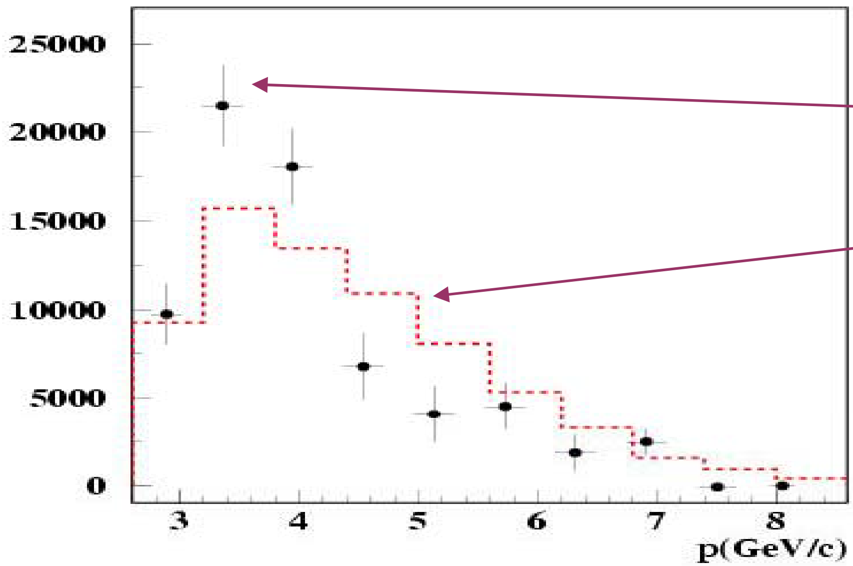




Atom Pairs

Coulomb Pairs x 1/40

Spectrum consistent with $\pi^+\pi^-$ bound state formation



Long-lived pairs (α_2)

Coulomb Pairs

Softer spectrum (η,ω ..) expected from Monte Carlo

Breakup probability

P_{Br}=0.435±0.016 (stat) ± 0.008 (syst) = 0.435 ± 0.018

Summary of systematic uncertainties:

Source	σ
Q_L trigger acceptance	± 0.004
MSGC+SFD background	± 0.006
Double Ionization cut	± 0.003
Double-track resolution	± 0.003
Target Impurity	± 0.003
KK contamination	± 0.003

Total ± 0.008

Results from DIRAC

- *DIRAC collaboration has built up a double arm spectrometer which provides a pair relative momentum (Q) resolution of 0.4 MeV/c for Q<30MeV/c*
- *More than 6000 of $\pi^+ \pi^-$ pairs from pionium break-up were observed*
- *The analysis of Ni 2001 data provides a lifetime measurement which translates into an S-wave amplitude measurement at rest :*

$$\tau_{1S} = 2.63^{+0.266}_{-0.255}(stat)^{+0.117}_{-0.111}(syst)\,fs$$

$$\tau_{1S} = 2.63^{+0.290}_{-0.278}\,fs$$

$$|a_2 - a_0| = 0.277^{+0.0153}_{-0.0146} M_\pi^{-1} = (0.277 \pm 0.015) M_\pi^{-1}$$

$$a_0 - a_2 = 0.265 \pm 0.004 \quad \text{(ChPT)}$$