Determination of Pion Scattering Lengths from $\pi^+\pi^-$ Atom with the DIRAC Experiment

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DIRAC Collaboration

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Total number of institutions: 19
Total number of collaborators: 83

Motivation

- Measurement of the difference of $I = 0$ and 2, S-wave scattering lengths will provide a crucial **test of the theoretical predictions**, such as the Chiral Perturbation theory.
- DIRAC will **find** $|\mathbf{a_0} - \mathbf{a_2}|$ **by measuring the lifetime** of the $\pi^+\pi^-$ ($A_{2\pi}$) bound state ($1/\tau \propto |a_0 - a_2|^2$).
- Our method is **model-independent**.

Introduction

- DIRAC uses a 24 GeV proton beam striking a thin target.
- Coherent π^+'s and π^-'s resulting from proton-target collisions may form a $\pi^+\pi^-$ bound state.
- As it travels through the target, the pionium atom may:
  1. Annihilate via $\pi^+\pi^- \longrightarrow \pi^0\pi^0$ $(BR = 99.6\%)$.
  2. Break up by colliding with target atoms.

$A_{2\pi}$ Lifetime and Scattering Lengths

- Lifetime measurement yields the difference between the a_0 and a_2 scattering lengths ($I = 0, 2$) through:

$$\Gamma_{\pi^0\pi^0} = \frac{2}{9}\alpha^3 p^* \cdot |a_0 - a_2|^2 (1 + \delta_\Gamma)$$

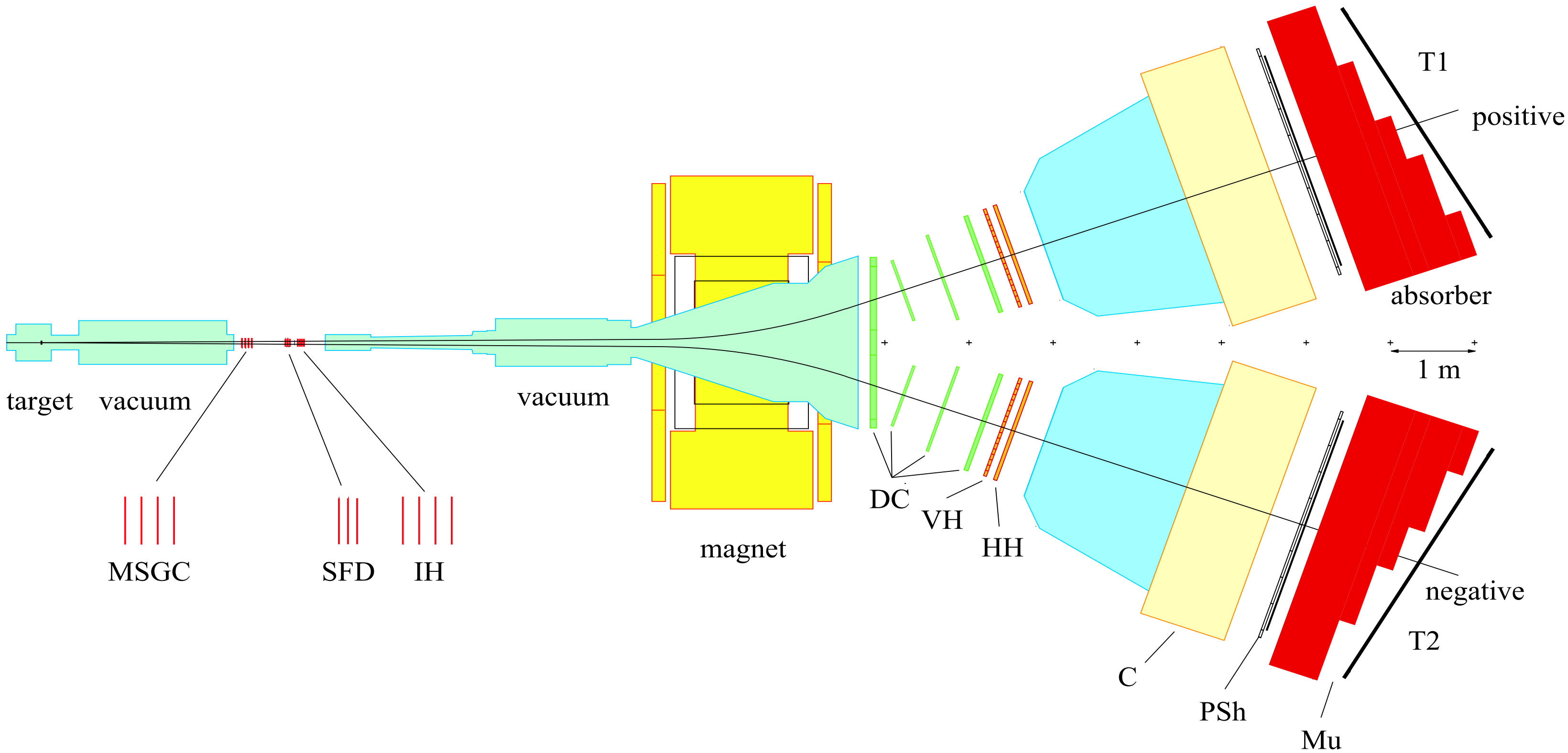
- Chiral Perturbation theory predicts (e.g., *Colangelo et al., 2001*):

$$\Delta = |a_0 - a_2| = 0.265 [m_\pi^{-1}] \quad \tau = 2.9\, fs$$

- DIRAC's goal: **Measure lifetime (thereby finding $|\mathbf{a_0} - \mathbf{a_2}|$) with precision of**:

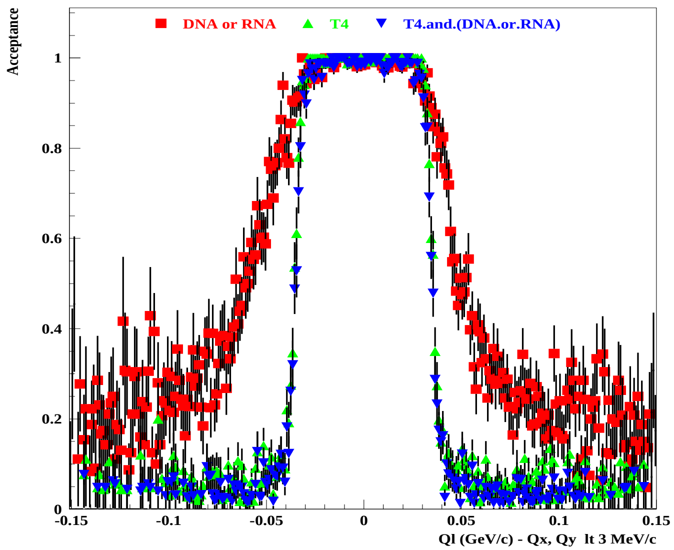
$$\sigma_\tau = 0.2 - 0.3\, fs$$

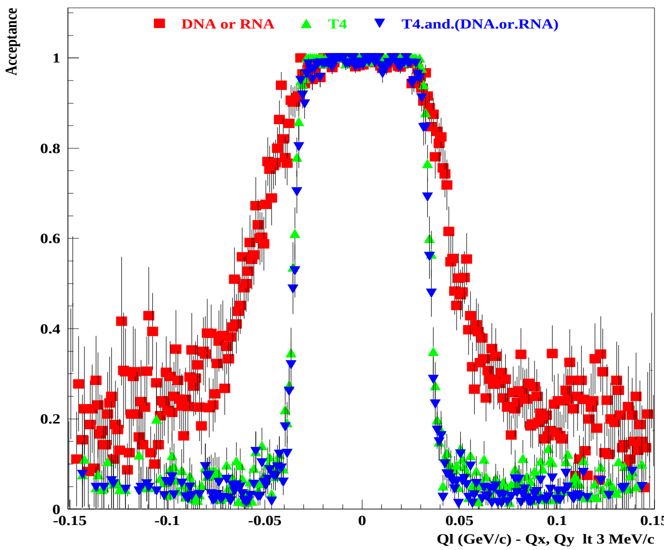
Experimental Setup



Trigger

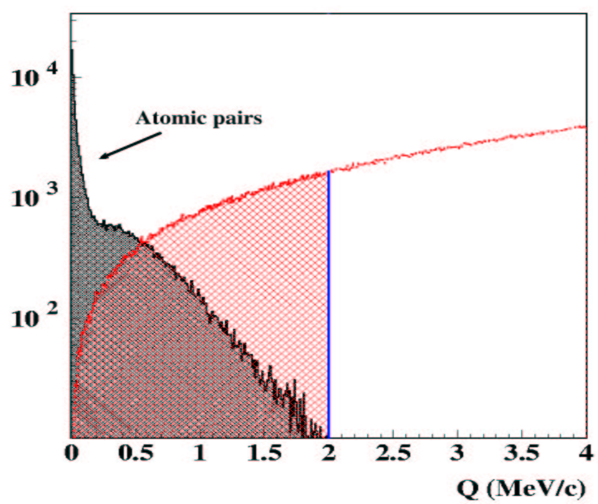
- **Current full trigger:** $T1 \cdot (DNA + RNA) \cdot T4$. Overall reduction factor: 1000. Overall efficiency: 95%.
  - **T1**: Selects events with one track per arm.
  - **DNA+RNA**: Neural network triggers selecting events with relative momenta: $Q_x < 3$ MeV, $Q_x < 10$ MeV, $Q_l < 30$ MeV.
  - **T4**: Selects events satisfying $Q_x < 3$ MeV and $Q_l < 30$ MeV.





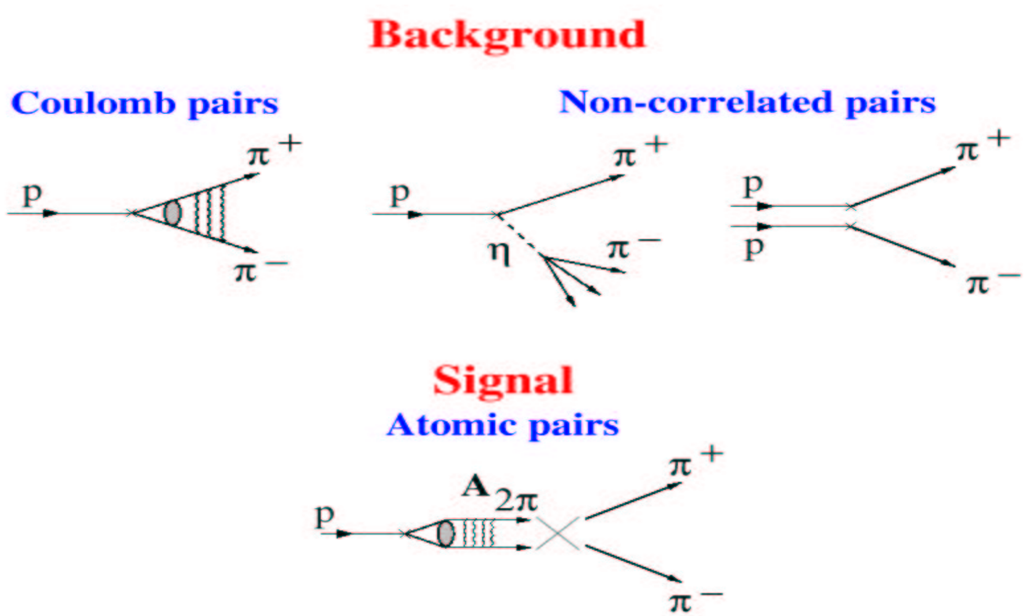
Offline Tracking

- Track reconstruction:
  1. Downstream tracks reconstructed in DC's.
  2. Upstream part of the tracks adjusted with the Kalman filter procedure.
- Track reconstruction challenging since looking for very low *relative* momenta at high *lab* momenta.
- Need to have a high relative momentum resolution. In fact: $\sigma_{Q_x} < 0.4\,MeV/c$, $\sigma_{Q_y} < 0.4\,MeV/c$, $\sigma_{Q_l} < 0.6\,MeV/c$.

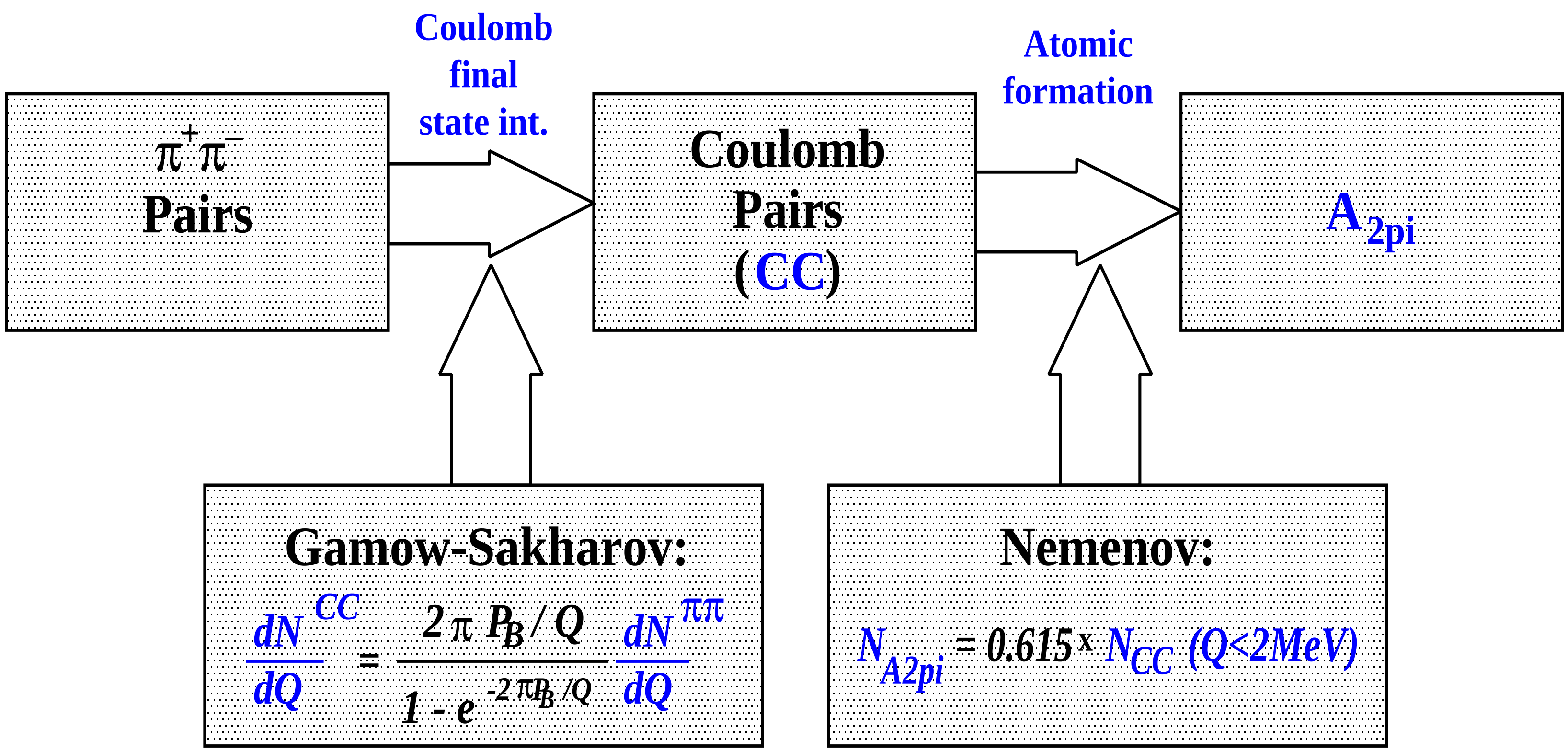


Signal and Background

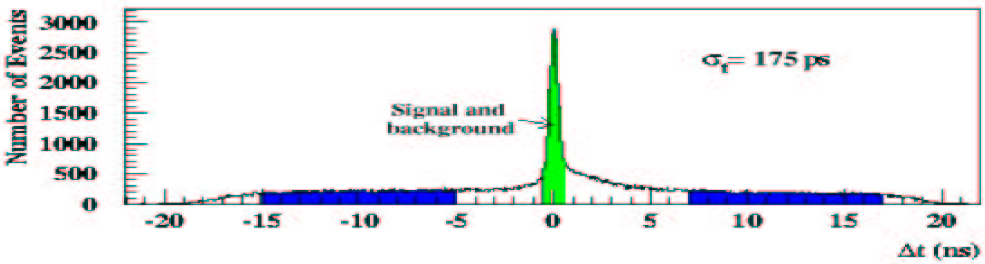
- Background:
  - **Coulomb-correlated** pairs: formed by **coherent** π^+ and π^- having a Coulomb final state interaction.
  - **Non-correlated** pairs: formed by **incoherent** $\pi^+\pi^-$ pairs.
- Signal: detected pion pairs, called **atomic pairs**, coming from $A_{2\pi}$ breakups. ($A_{2\pi}$ atoms are essentially Coulomb pairs that formed a bound state.)



Signal and Background Are Interrelated



Signal Layer Target Signal Extraction (Cuts)



- Prompt events: $\Delta t_{VH} \in [-0.5\,ns, 0.5\,ns]$.
- Reject electrons with the Cherenkov detector.
- Reject muons with the muon counter.
- Eliminate fast protons with the $P_+ < 4GeV/c$ cut.
- Pion pair relative momenta cuts:

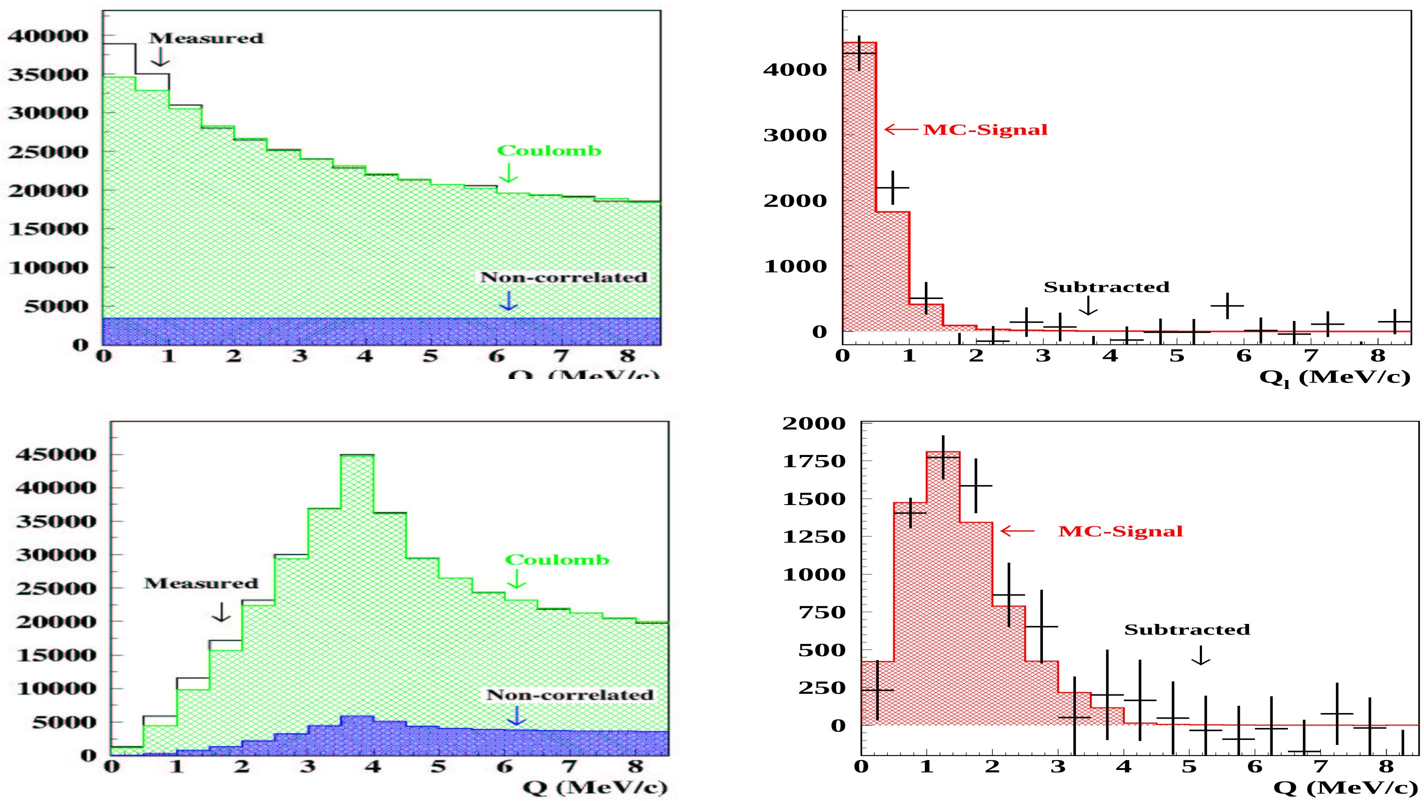
$$Q_{trans} = \sqrt{Q_x^2 + Q_y^2} < 4\,MeV/c, \qquad |Q_l| < 22\,MeV/c$$

Signal Layer Target Signal Extraction (Cuts)

- Generate **Coulomb-correlated** and **non-correlated** background inside target. Non-correlated background produced according to: $dN_{nc}/dQ_{tot} \propto Q_{tot}^2$. Coulomb background: $dN_{cc}/dQ \propto A_c(Q)Q^2$.
- **Reconstruct** tracks offline.
- **Fit** MC-produced Q_l and Q_{tot} background to the signal-free regions of the measured data: $Q_l > 2\,MeV$ and $Q_{tot} > 4\,MeV$.
- **Subtract** thus obtained background from measured data in the **entire** Q_l **and** Q_{tot} **range**.

Single Layer Target Signal Extraction (1)

2001 Run



$$n_A = 6800 \pm 400(stat\ err)$$

Single Layer Target Signal Extraction (2)

- Breakup probability:

$$P_{br} \equiv n_A/N_A$$

with

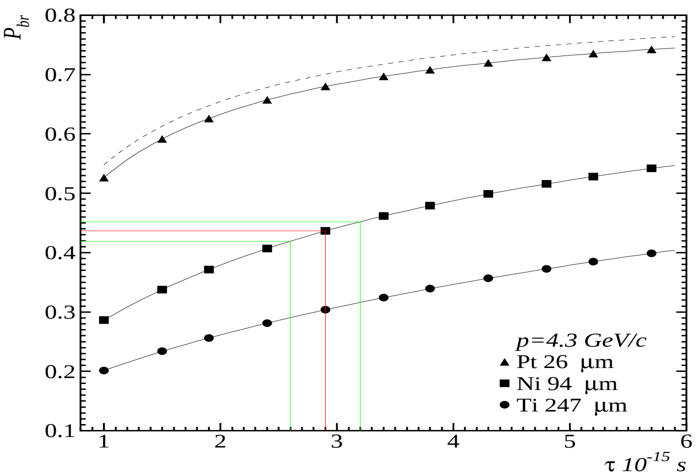
$n_A = number\ of\ dissociated\ atoms$

$N_A = number\ of\ initially\ produced\ atoms.$

- Since $N_A = 0.615 \cdot N_{cc}(Q < 2\,MeV/c)$, then

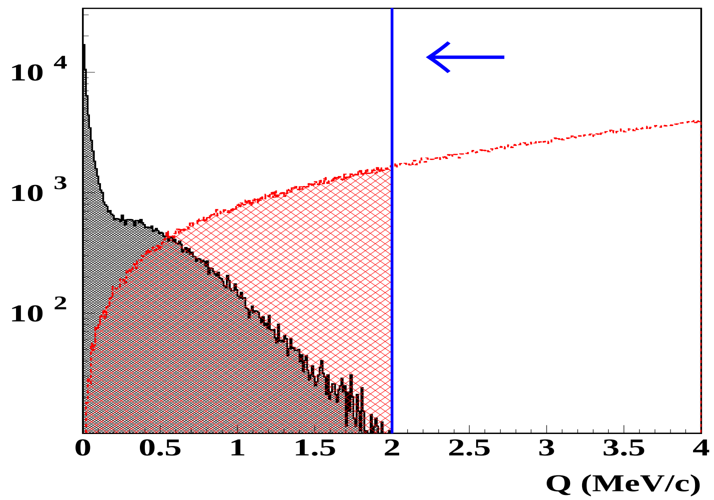
$$P_{br} = n_A/(0.615 \cdot N_{cc}(Q < 2\,MeV/c))$$

- And get the lifetime (*L. Afanasyev, L. Tarasov, D. Trautmann*).
- BUT the formula above is an idealization due to...



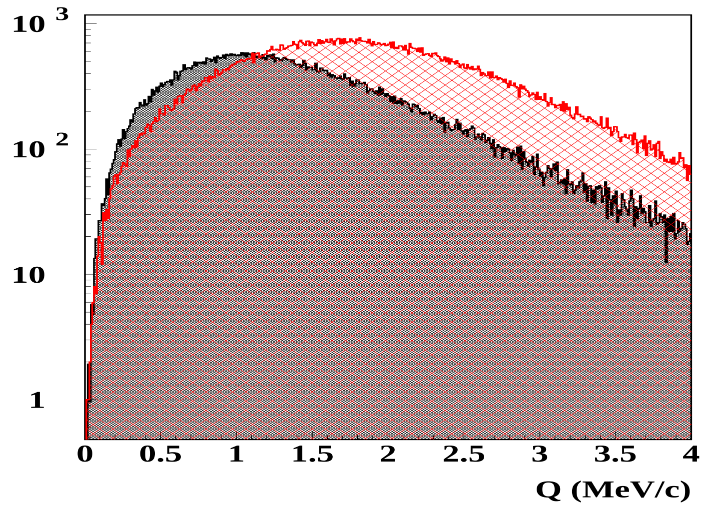
Multiple Scattering Effects

At production:



$$\frac{N_A}{N_{cc}}(Q < 2MeV) = 0.615$$

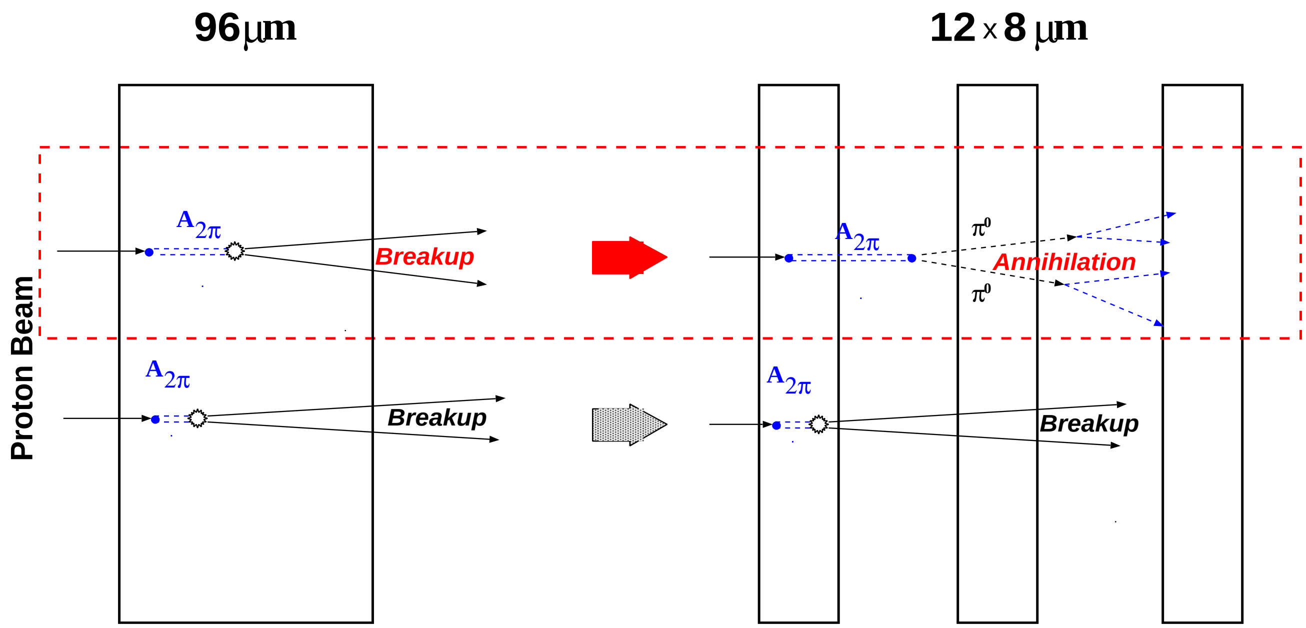
After Target:



$$\frac{N_A}{N_{cc}}(Q < 2MeV) = ??$$

- Atomic pair signal (very low relative momenta) is washed out by multiple scattering.
- In fact, $N_A = K_{eff} \cdot N_{cc}(Q < 2\,MeV/c)$ with $K_{eff} \neq 0.615$. Need to find K_{eff} by measuring MS very accurately.

Single/Multilayer Target Measurement

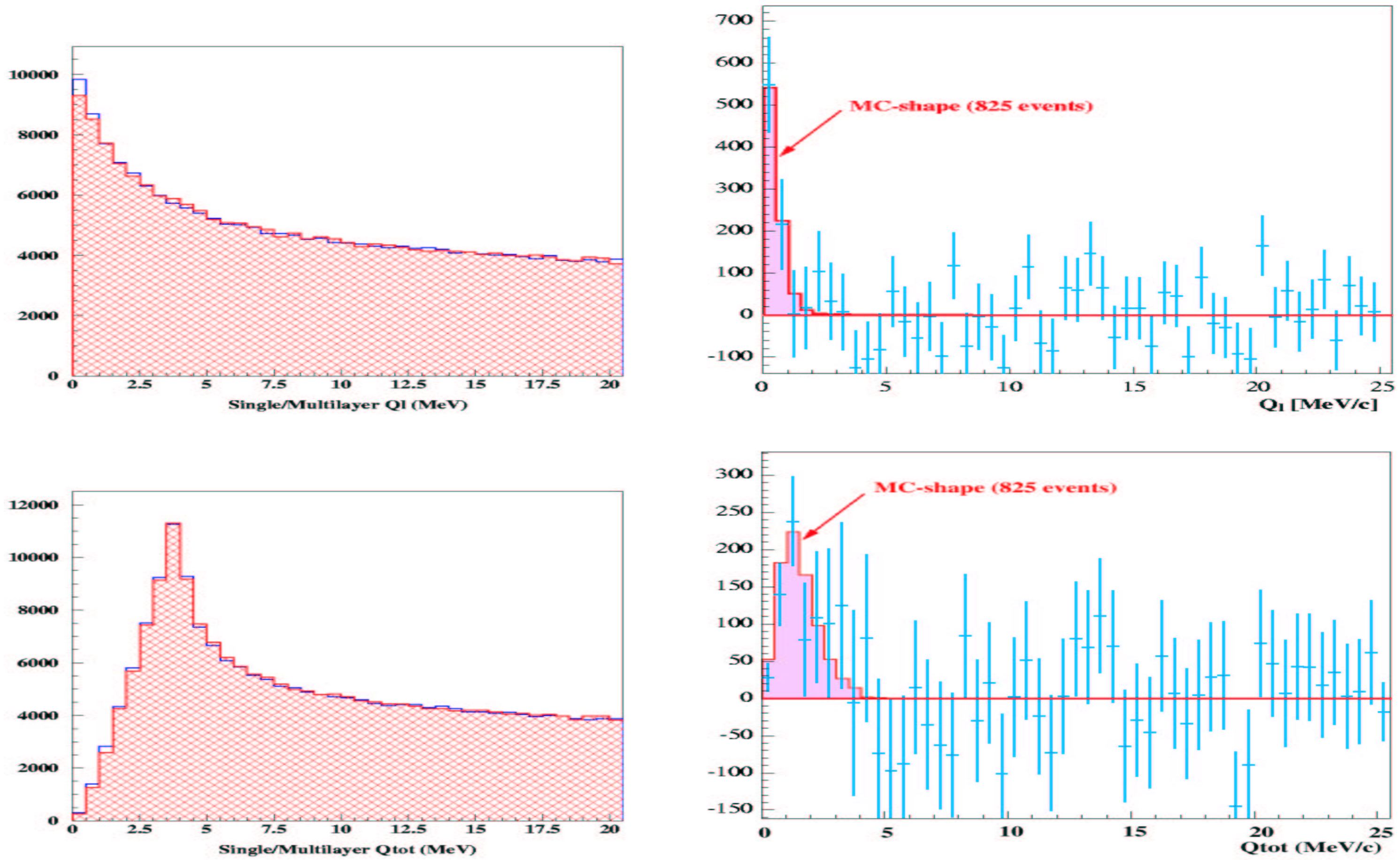


- Comparison of the single and multilayer targets:
  - Same amount of multiple scattering.
  - Same Coulomb and non-correlated pair (background) yield.
  - Same number of produced $A_{2\pi}$, but **lower number of dissociated pairs**.

Signals from Single and Multilayer Targets (1)

- **Subtract** experimental single layer Q_l and Q_{tot} distributions from multilayer ones. Result: Atomic pair signal difference between the two targets.

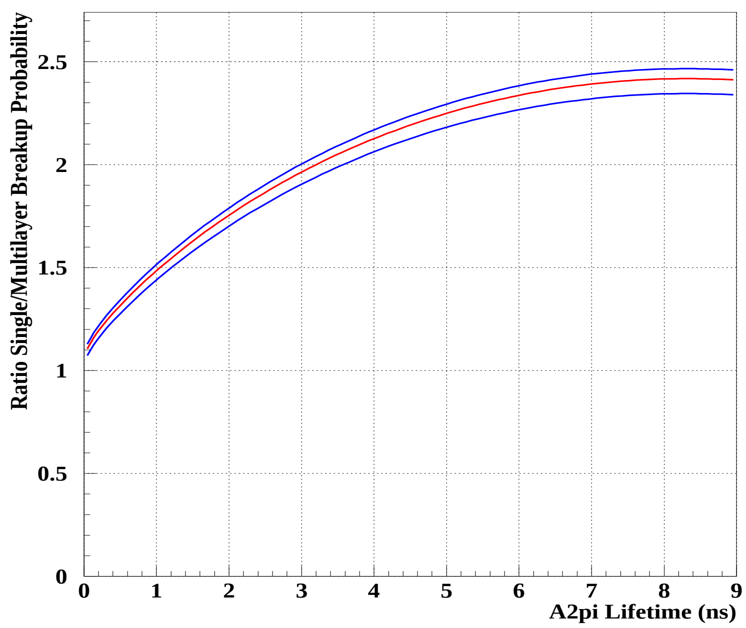
2002 Run



Signals from Single and Multilayer Targets (2)

- Individual atomic pair signals from the single and multilayer targets can be found in a standard way using MC.
- From the ratio of single/multilayer target signals get $A_{2\pi}$ lifetime:

$$\epsilon = \frac{N^A_{single}}{N^A_{multi}} = \frac{P^{br}_{single}}{P^{br}_{multi}}$$



Signals from Single and Multilayer Targets (2)

- Purely experimental determination of the signal shape with the subtraction method.
- Allows us to determine lifetime without $N_{cc} \longrightarrow N_A$ $(N_A = K_{eff} \cdot N_{cc}(Q < 2\,MeV/c))$ procedure.
- Can obtain "pure" background distribution to use as a cross-check of the MC-generated background:

$$N_{bknd} = \epsilon \cdot N^{exp}_{multi} - N^{exp}_{single}$$

Summary and Outlook

- **Good spectrometer resolution** allows us to accurately measure very low relative momenta at high energies.
- MC simulation of the **background is consistent** with normalization in Q and Q_l.
- **Extracted signal** is in good agreement with the one from simulated atomic pairs.
- In 2003 we **will collect more single and multilayer data** to obtain $A_{2\pi}$ lifetime, signal shape and background.
- **Need to get a good handle on multiple scattering**, now known with 3% precision. Dedicated measurement is planned to determine it to within 1% accuracy.