DIRAC

(DImeson Relativistic Atomic Complex)

- Theoretical bases (motivation, implications,...)
- Experimental method and setup
- Preliminary results

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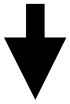
DIRAC aim

To measure the lifetime $\pi^+\pi^-$ exotic atoms

τ (10 % precision)



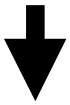
to determine the difference between $\pi\pi$

S-wave scattering lengths to 5%

ChPT has predicted this values with the same accurancy

but it has not been achieved experimetally

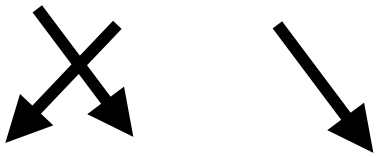
Comparing experimental measurement from DIRAC with the ChPT predictions



Important test of our understanding of the Chiral symmetry breaking

Theoretical motivation

Low energy processes in QCD



Perturbative QCD
(α_s increases if E decreases)

ChPT:

effective lagragians

exploits QCD symmetries

$\pi\pi$ scattering is an appropiate frame for testing ChPT:

theretical predictions are up to the moment more precisse than the experimental ones

Theoretical knowledge

$\pi\,\pi$ scattering

↓

$\pi\,\pi$ scattering lengths

$$\Delta = a_0^0 - a_0^2$$

In QCD :

Δ = f (invariant quark mass, scale of QCD)

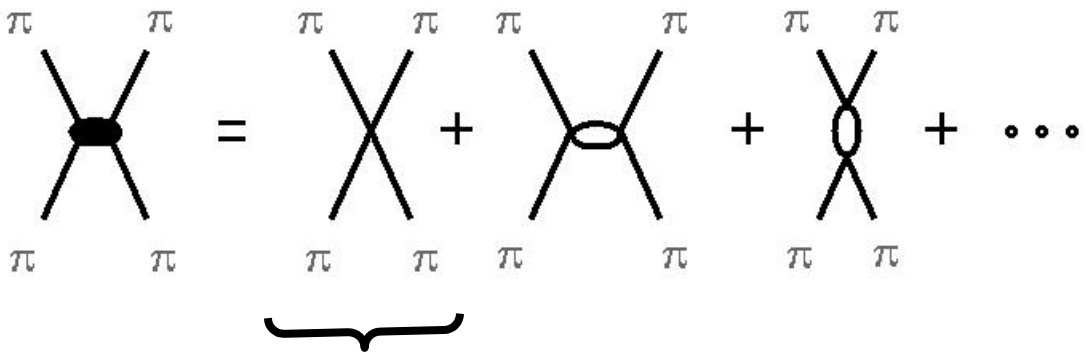
In ChPT :

$$\Delta = \Delta_0 \left(1 + \Delta_2 m_\pi^2 + \Delta_4 m_\pi^4 + \ldots \right)$$

$\Delta_0, \Delta_2, \Delta_4, \ldots$:

$$L^{\text{eff}} = L_{\pi\pi}^{(2)} + L_{\pi\pi}^{(4)} + L_{\pi\pi}^{(6)} + \ldots$$

π π scattering amplitude:



Weinberg (1966)

$$\ddot{A}_0 = 0.20\ (L^{(2)}_{\pi\pi})$$

Gasser - Leutwyler (1984):

$$\ddot{A} = 0.25 \pm 0.01 \quad (L^{(4)}_{\pi\pi})$$

$$a^0_0 = 0.20 \pm 0.01$$

$$a^2_0 = -0.042 \pm 0.002$$

Gasser et al.
Stern et al.
Rasche et al. *(1997-98):* $\ddot{A} = 0.258 \pm < 5\% \quad (L^{(6)}_{\pi\pi})$
Trautmann et al.
Tarasov et al.

Present experimental knowledge

- $K^+ \to \pi^+\pi^-e^+\nu_e$ (model independent)

$$a_0^0 = 0.31 \pm 0.11$$ *(Rosselet 1977)*

+ Roy dispersion constraints

$$a_0^0 = 0.26 \pm 0.05$$ *(Froggat-Petersen 1977)*

- $\pi N \to \pi\pi N$ Near threshold (OPE dominance?)

$$a_0^0 = 0.23 \pm 0.08$$ *(Ochs 1991)*

Threshold expansion $a_0^0 = 0.204 \pm 0.022$

Roy equations $a_0^0 = 0.223 \pm 0.025$

} *(Kermani 1998)*

(model dependent: estimation of the role of the one pion exchange and interpretation of the one pion diagram)

- **both were insensitive to the value of a_0^2**

Direct implications

$$m_\pi^2 = 2mB + O(m_q^2 \ln m_q)$$

$$m = 1/2(m_u + m_d)$$

- Standard ChPT assumes that term linear in m_q dominates

$$m_\pi^2 = (m_u + m_d)\,B$$

$$B = |\langle 0 \,|\, q\,\bar{q} \,|\, 0 \rangle| / f_\pi^2$$

(value given by the Gell-Mann, Oakes, Renner relation)

- **Large quark condensate** ⇒ $\left|\langle 0|q\bar{q}|0\rangle\right| \cong -(250\ \mathrm{MeV})^3$

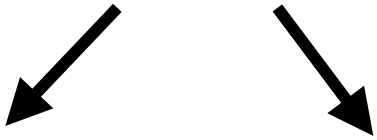
- $\dfrac{m_s}{m_u + m_d} \approx 25$ (fix) **Supported by lattice calculations**

⇒ $a_0^0 = 0.20 \pm 0.01$

Chiral symmetry spontaneously broken in the QCD vacuum

$|< 0 | q \bar{q} | 0 >|$ parameter of order

Symmetry broken with



large value of the order parameter (ChPT)

small value of the order parameter (GChPT)

Comparison with a spin system

Magnetization ($\vec{M}$) parameter of order

Spin symmetry broken below the Curie temperature

Paramagnetic materials: M large

Ferromagnetic materials: M ~ 0

- GChPT (Knecht,Stern,...)

$$m_\pi^2 = (m_u + m_d)\, B + (m_u + m_d)^2\, A$$

- **Small quark condensate** ⇨

$$\left|\langle 0|q\bar{q}|0\rangle\right| = O(m_q) \approx -(90\ MeV)^3$$

- $\dfrac{m_s}{m_u + m_d} \leq 10$ (free)

↳ $a_0^0 \geq 0.27$!!

Finding $(a_0 - a_2)^{exp}$ with 5% precission ⇨

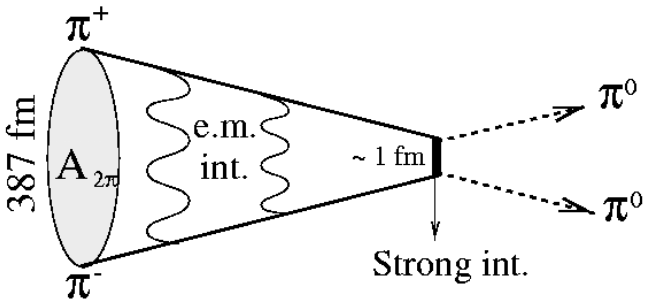
discerning between SChPT or GChPT

Affecting our understanding of the QCD vacuum structure

DIMESON ATOMS ($A_{2\delta}$)

$E_b \approx -1.86$ KeV

$p_B \approx$ 1 MeV



$$\Gamma_{2\pi 0} = 2/9\ \alpha^3\ p^*\ A^2\ (\ 1+ K) \quad \text{(Gasser et al. 1998)}$$

$$p^* = (M_{\pi+}^2 - M_{\pi 0}^2 - 1/4\ M_{\pi+}^2\ \alpha^2)^{1\backslash 2}$$

Measurement of $\hat{o} \longrightarrow A$ (no Ch expansion)

From CHPT,

$$A = a_0 - a_2 + \varepsilon$$

$$\varepsilon = (0.58 \pm 0.16) \times 10^{-2} \qquad K = 1.07 \times 10^{-2}$$

$$A \longrightarrow a_0 - a_2$$

$$\text{Predict } \hat{o} \sim 3.25 \times 10^{-15}\ \text{s}$$

$$(\Gamma_{2\pi 0} - \Gamma_{2\pi 0}^{LO})/\Gamma_{2\pi 0}^{LO} = 0.058$$

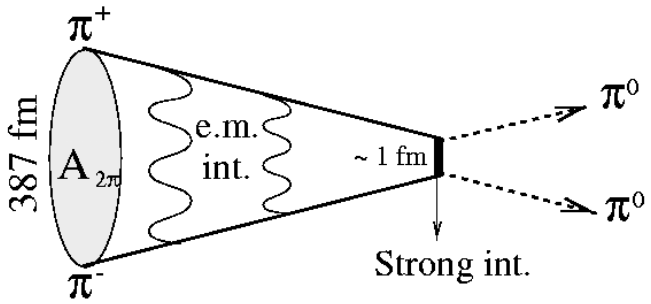
DIMESON ATOMS ($A_{2\delta}$)

Measurement of τ_A: model independent method for determining a_0-a_2

analysis of the $A_{2\pi}$ properties

$E_b \approx -1.86$ KeV

$p_B \approx$ 1 MeV



In QCD (including photons) using effective field theories , (Gasser et al. 1998)

$$\Gamma_{2\pi 0} = 2/9\ \alpha^3\ p^*\ A^2\ (\ 1+ K)$$

$$p^* = (M_{\pi+}^2 - M_{\pi 0}^2 - 1/4\ M_{\pi+}^2\ \alpha^2)^{1\backslash 2}$$

valid at leading and next to leading order in isospin breaking effects (e.m. interaction and m_u-m_d)

Measurement of $\hat{\mathbf{o}} \longrightarrow \mathbf{A}$ (no Ch expansion)

From CHPT,

$$A = a_0 - a_2 + \varepsilon$$

$$\varepsilon = (0.58 \pm 0.16) \times 10^{-2} \qquad K = 1.07 \times 10^{-2}$$

$$A \longrightarrow a_0 - a_2$$

Theoretical prediction for τ,

$$\hat{o} \sim 3.25 \times 10^{-15}\ s$$

Comparison with previous formula,

$$(\Gamma_{2\pi 0} - \Gamma_{2\pi 0}^{LO})/\Gamma_{2\pi 0}^{LO} = 0.058$$

Change in Δ: 3%

$\Gamma_{2\pi 0}^{LO}$ valid at leading order in isospin breaking effects (Uresky 1961)

Formation of $A_{2\delta}$

$A_{2\delta}$ originate from short-lived sources and broad resonances decays (ρ, K*, ω, …, r = 1– 3 fm)

$$\frac{d\sigma_n^A}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} |\Psi_n(0)|^2 \underbrace{\left. \frac{d\sigma_S^0}{d\vec{p}_1 d\vec{p}_2} \right|_{\vec{p}_1=\vec{p}_2=\vec{p}_{A/2}}}$$

From short-lived sources

$\pi^+\pi^-$ pairs coming from long-lived sources (η, η', K_S^0, …, r > 1000 fm) are not able to produce a bound state.

$$\frac{d\sigma_S^0}{d\vec{p}_1 d\vec{p}_2} \quad \alpha \quad \frac{d\sigma^0}{d\vec{p}_1 d\vec{p}_2}$$

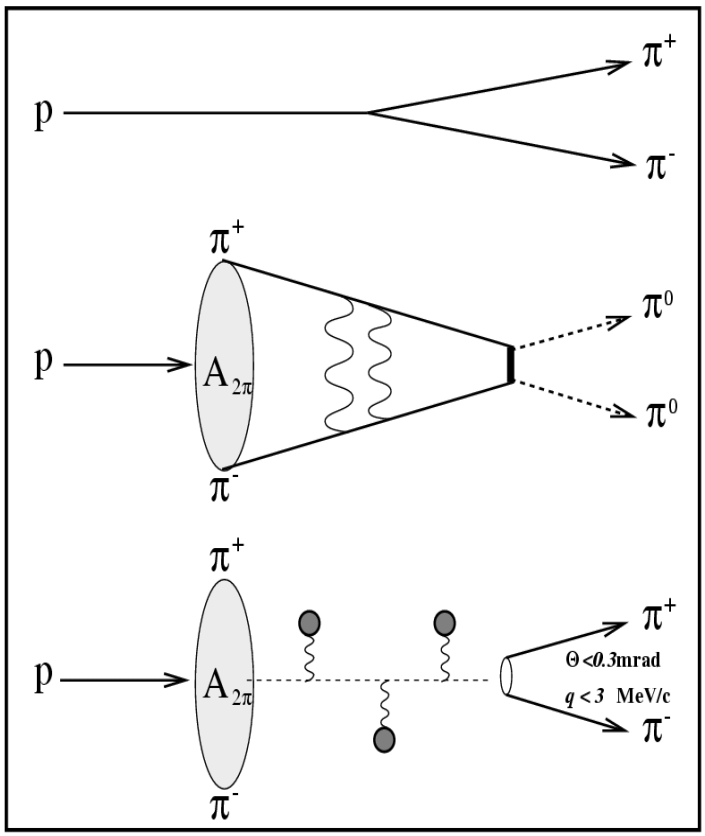
``Free'' pions

Useful in the DIRAC analysis, taking into account:

1) Corrections for short-range em+strong FSI of pions from short-lived sources.

2) MC calculation of relative proportion of pions originating from long- and short-lived sources.

METHOD OF A $_{2\pi}$ DETECTION



Enhance A $_{2\pi}$ ionization (A $_{2\pi} \longrightarrow \pi^+\pi^-$)
with respect to annihilation (A $_{2\pi} \longrightarrow \pi^0\pi^0$)

- Use dense target

$$\lambda_{int} \sim \lambda_{dec}$$

Ti 250 μm Ni 100 μm

	P_{ion}	P_{ann}
Ti	0.34	0.57
Ni	0.47	0.38

Minimize multiple scattering $\longrightarrow$ a few tens of microns

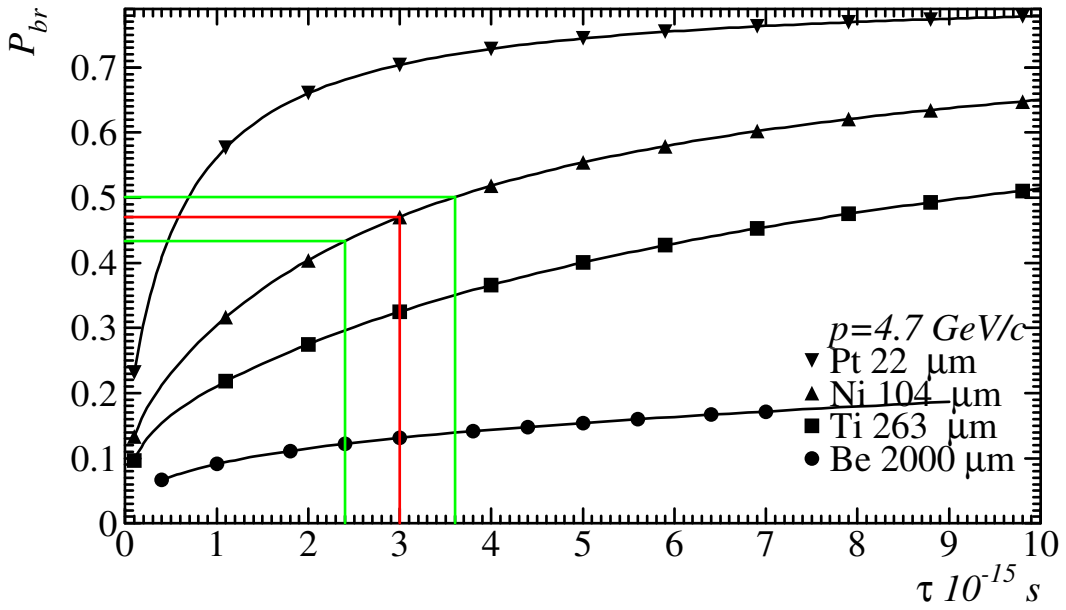
METHOD OF τ MEASUREMENT

$$P_{ion} = \frac{n_A}{N_A} = f(L_T, Z, P_{A\,2\pi}, \tau_{A\,2\pi})$$

n_A # of ionized $A_{2\pi}$

N_A # of produced $A_{2\pi}$

P^{exp}_{ion} (with 4% precision) compare to P^{th}_{ion} ⇨ τ



$$P^{th}_{ion} = 1 - (P_{dsc} + P_{ann})$$ (<1% error)

$\tau_{A\,2\pi}$ (~ 10 %) ⟶ $|a_0^0 - a_0^2|$ (~ 5 %)

P^{exp}_{ion} ⇨ N_A (calculated) and n_A (measured)

Determination of n_A with the "extrapolation" method

$q > 3$ MeV/c

$$\frac{dN^{free}}{dq} = \frac{dN^{NC}}{dq} + \frac{dN^{C}}{dq} = \xrightarrow[\text{no FSI}]{} \Phi(q)$$ distribution from acc.pairs

$$\frac{dN^{NC}}{dq} \sim \Phi(q)\, w_1$$

$$\frac{dN^{C}}{dq} \sim \Phi(q)\,(1 - w_1)\,\underbrace{A_C(\beta)}_{\text{e.m.}}\,\underbrace{(1 + aq)}_{\text{strong}}$$

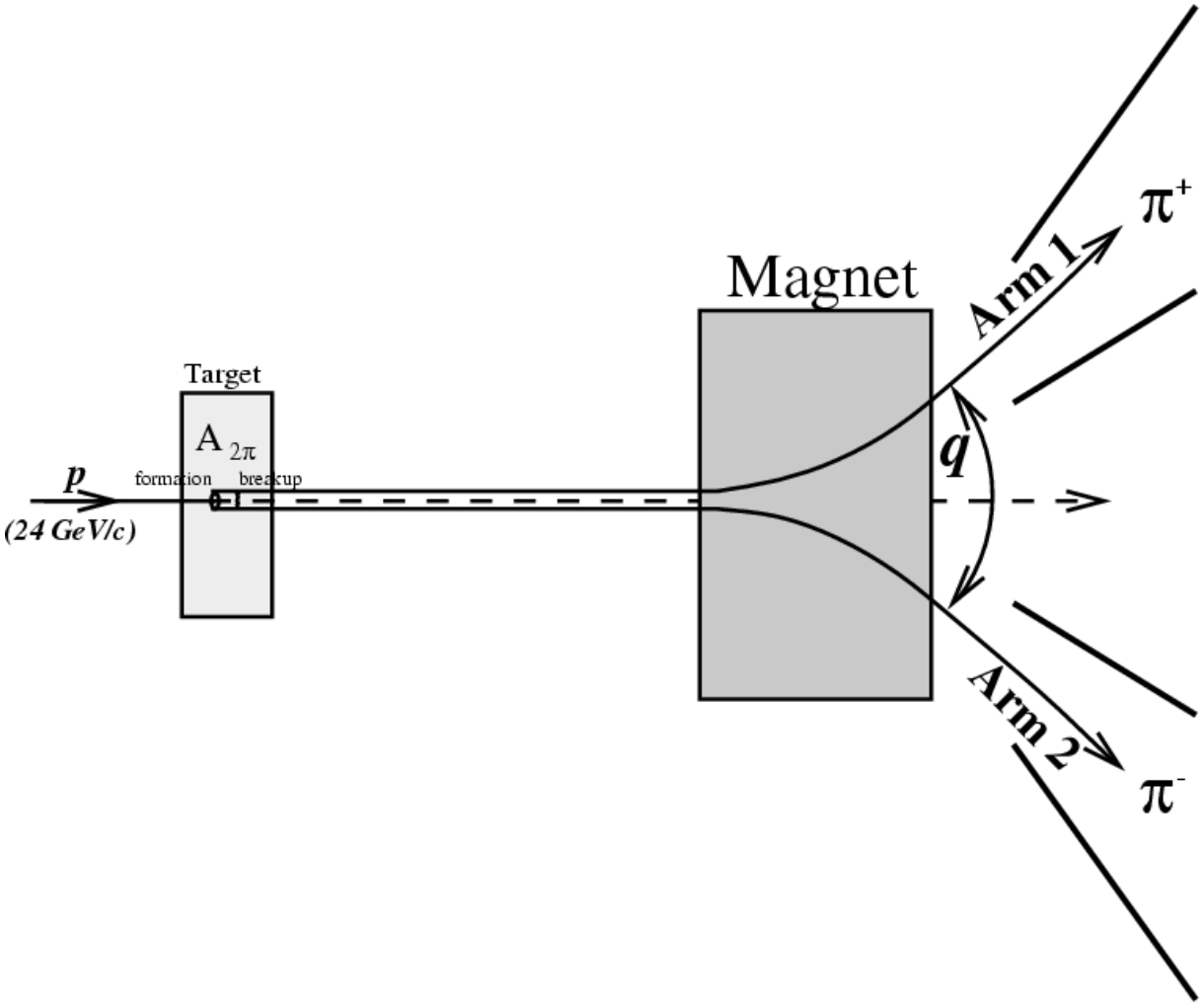
$$\frac{dN^{free}}{dq} = N\,\Phi(q)\,[\, f w_1 + (1 - w_1)\, A_C(\beta)\,(1 + aq)\,]$$

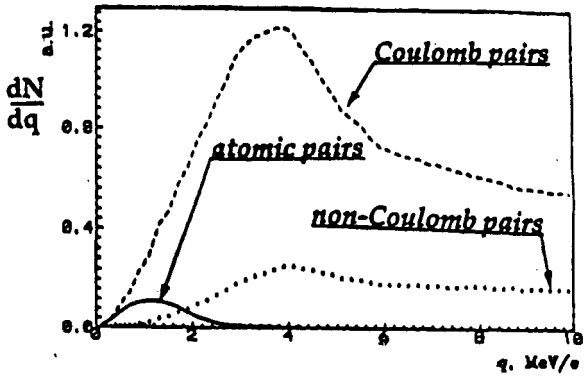
N, f, a free parameters

extrapolate into $q < 2$ MeV/c

$$\rightarrow\ n_A = \frac{dN^{exp}}{dq} - \frac{dN^{free}}{dq}$$

EXPERIMENTAL METHOD



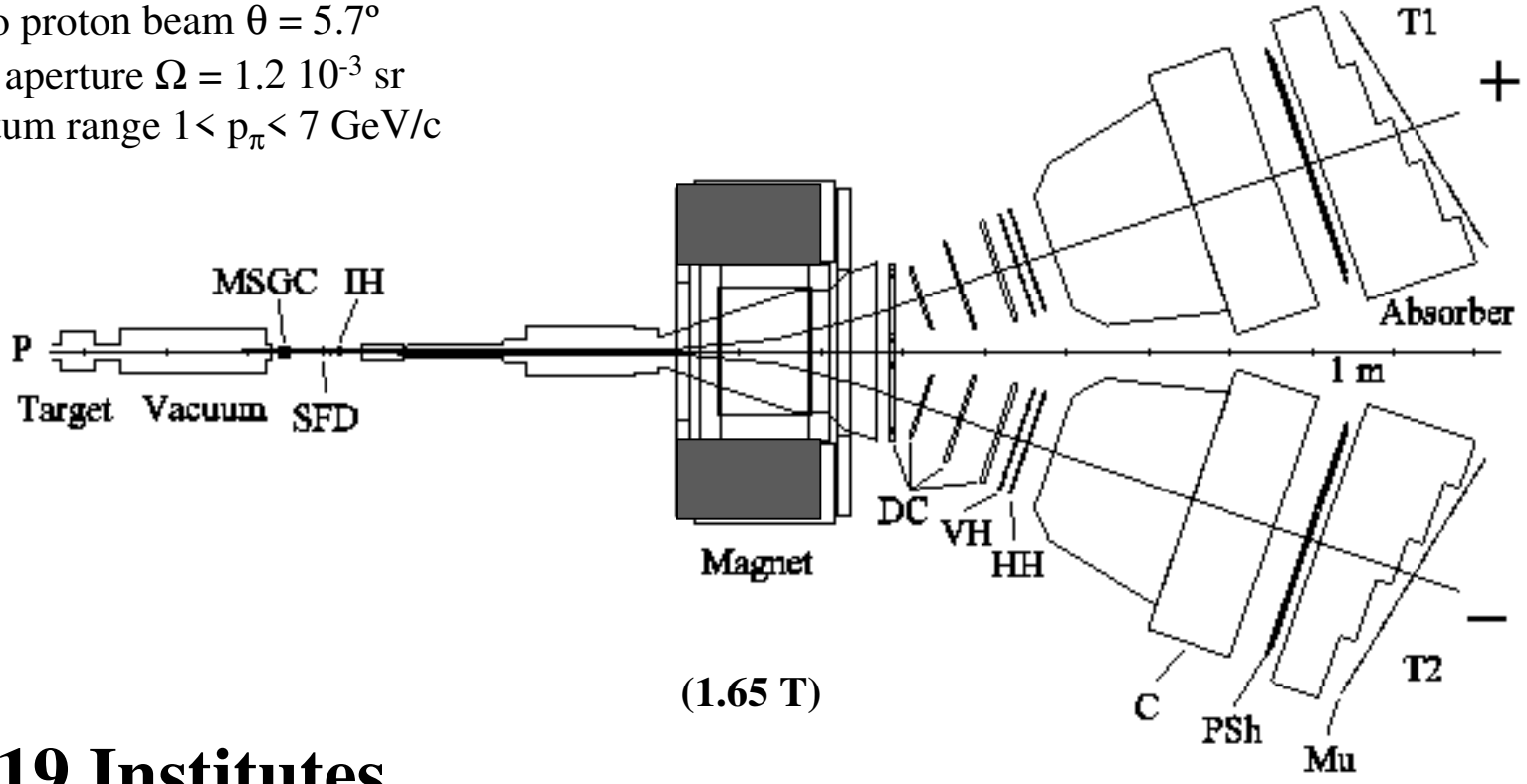


SETUP REQUIREMENTS

- resolution on relative momentum q = 1 MeV/c
- suppresion of free $\pi^+\pi^-$ pairs with q >30 MeV/c

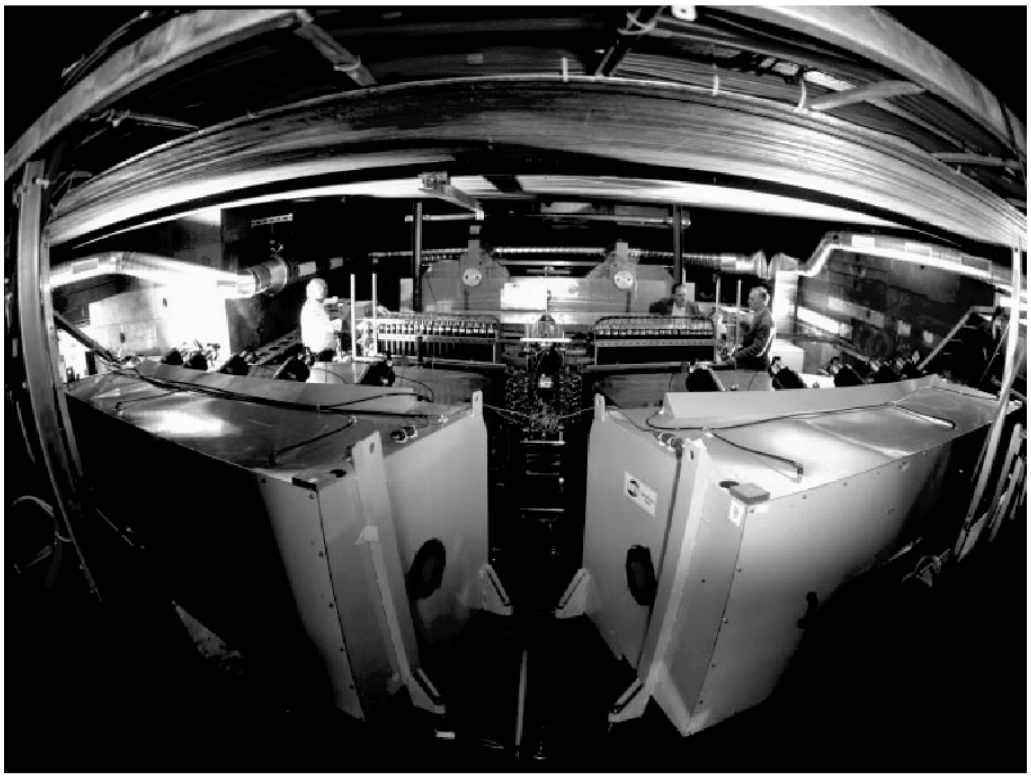
SETUP FEATURES

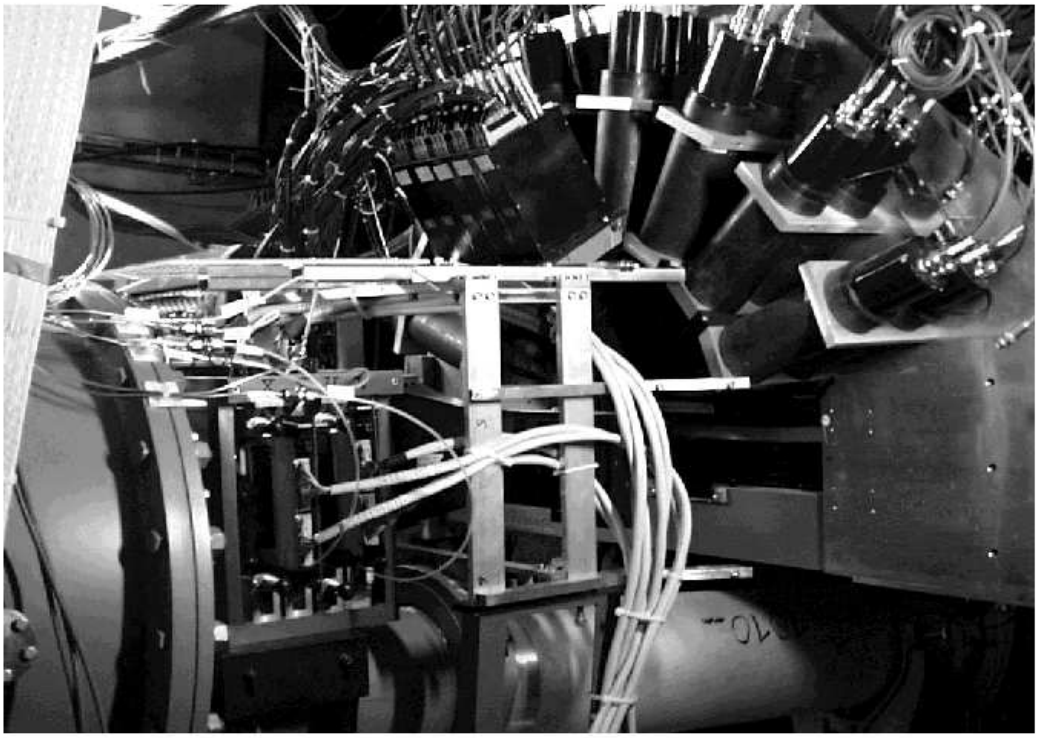
- angle to proton beam $\theta = 5.7°$
- channel aperture $\Omega = 1.2\ 10^{-3}$ sr
- momentum range $1 < p_\pi < 7$ GeV/c



19 Institutes

80 Participants

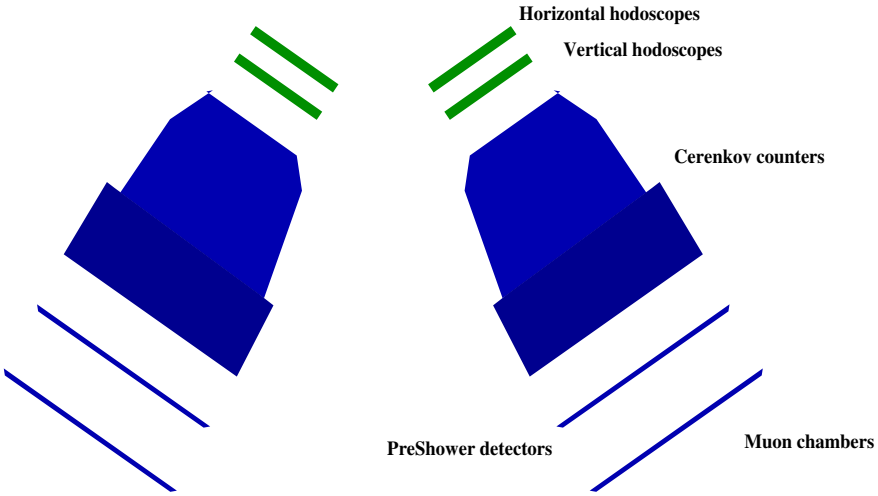




DIRAC Trigger

→ 1st level trigger (T1)

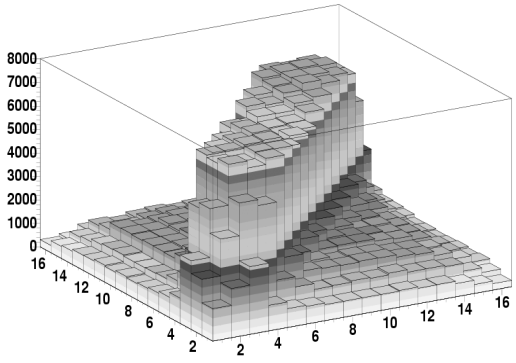
$$(VH * HH * \overline{CH} * \overline{PS} * \overline{\mu})_1 * (\ldots\ldots)_2 \qquad \tau_c = 40 \text{ ns}$$

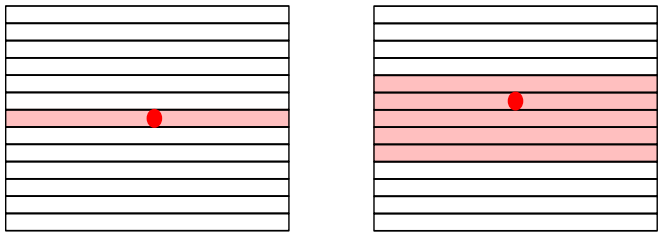


+ copl. (Δ slab$_{|\,HH1\,-\,HH\,2\,|} \leq 2$)

HH left vs HH right

07/11/99 18:50 Run 1406





H_1 H_2

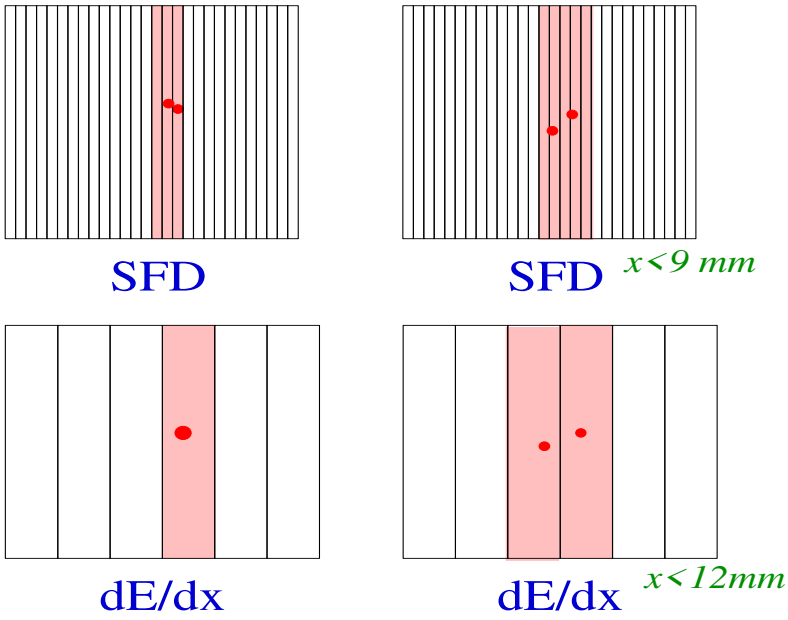
→ 2nd level trigger (T2)

Scintillation Fiber Detector * Ionitation hodoscope

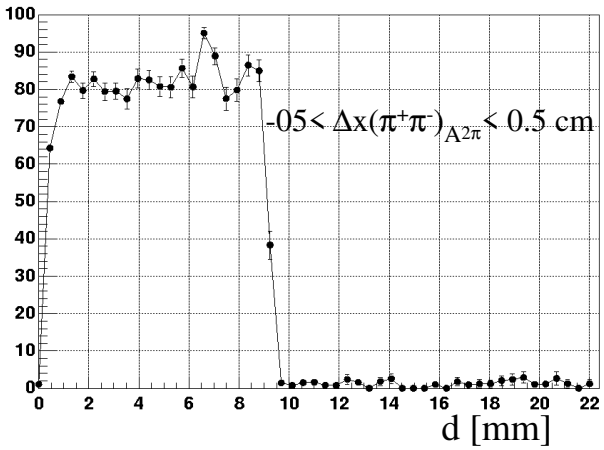
Selection of pairs less than 9 mm far before the magnet:

SFD → cut in 9 mm

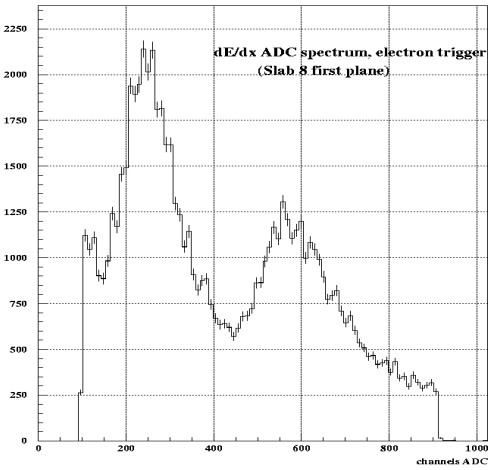
IH → cut in double ionization in 1 or 2 adjacent strips



Distance in the SFD plane

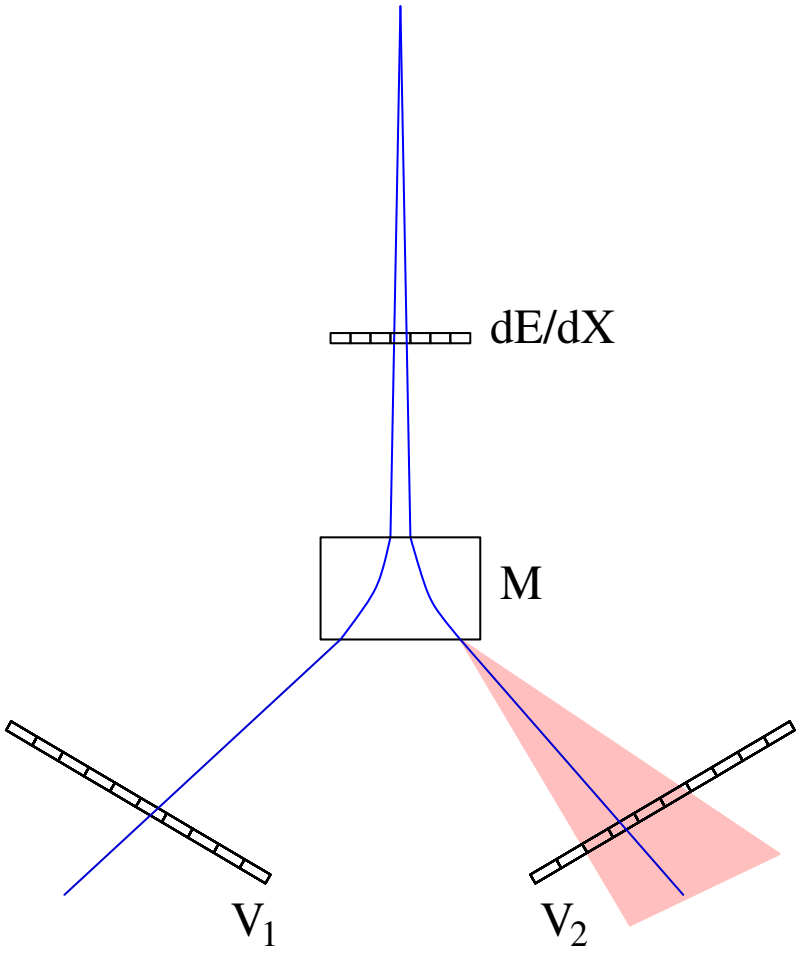


Signal amplitude in the dE/dx detector



Ip ~ 3.5 10^{10} p/spill T1 * T2 = 0.5 10^{3} trig/spill

→ **3rd level trigger (T3)** VH * IH ($\pi^+\pi^-$ with low q)



Correlations between right and left VH elements for a given IH hit

→ **4th level trigger (T4)** DC (Q_L < 30 MeV Q_X < 3 MeV)

Estimation of π momentum and emision angle based on the DC hit wires

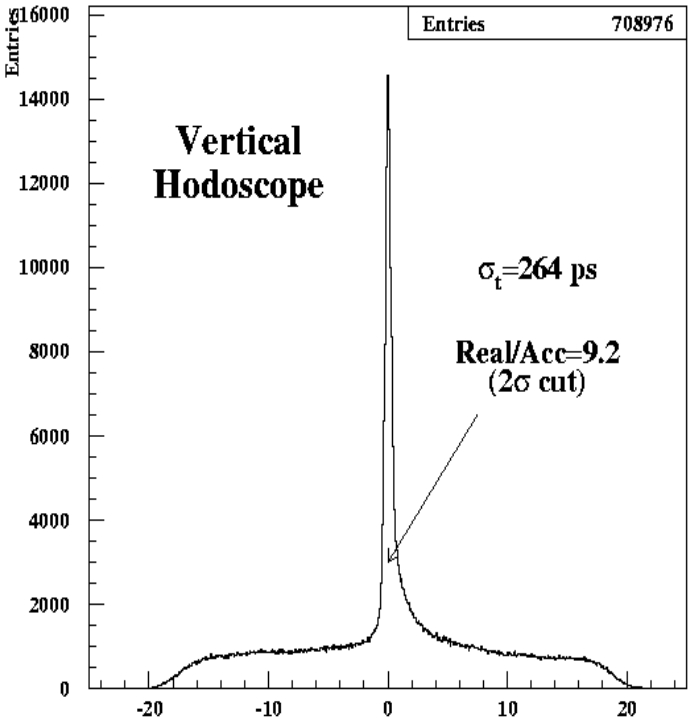
Time scale

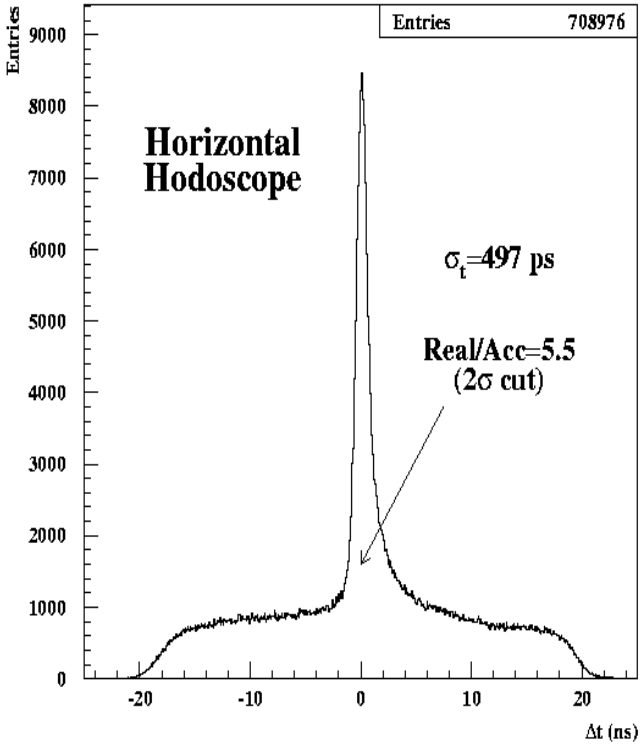
- Approved : 8 February 1996
- Preparation : 1996-1998
- Installation and commisioning : Oct-Nov ´98
- Data taking : Jun-Aug ´99 (6 weeks)
  (observation of Ni target
  $A_{2\pi}$ atoms) Ip ~ $4 \cdot 10^{10}$ p/spill

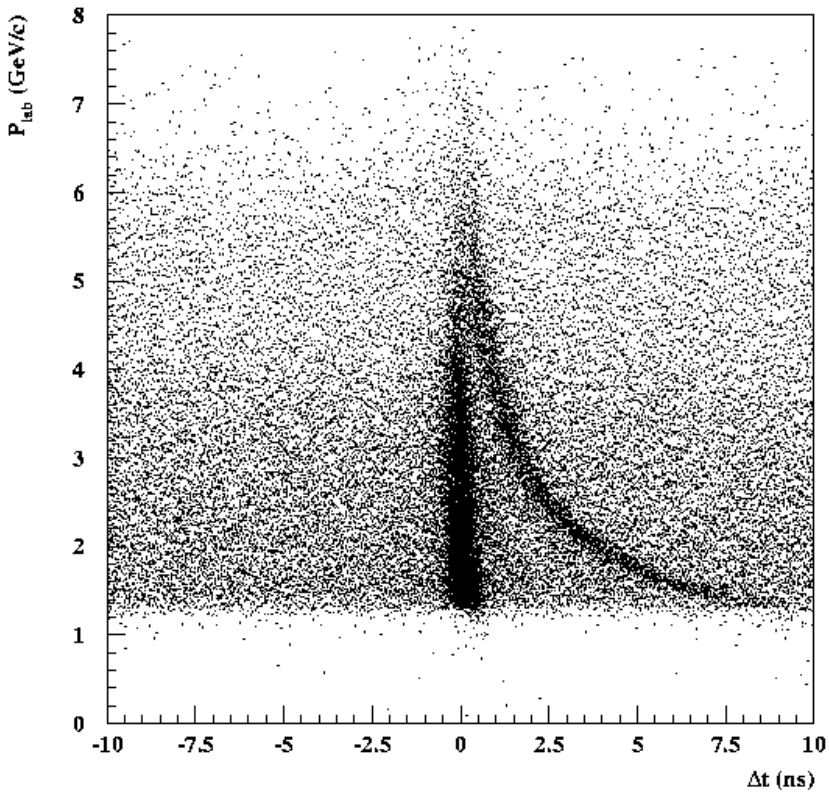
  Sep-Nov ´99 (10 weeks)
  Ni and Pt targets
  Up to Ip ~ $2 \cdot 10^{11}$ p/spill
- Processing data collected in 1999 : Jan-Jun ´00

Preliminary results

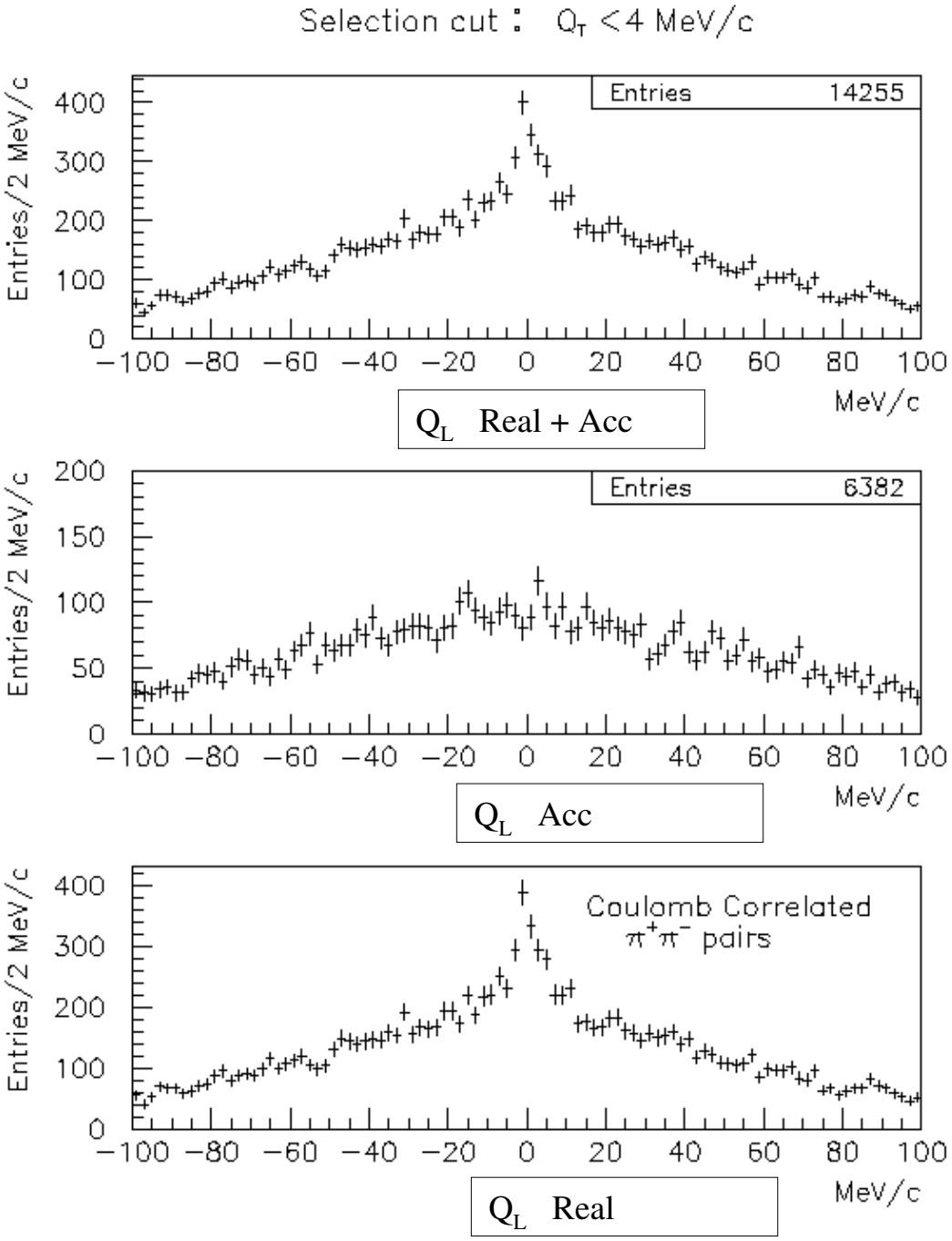
Time resolution







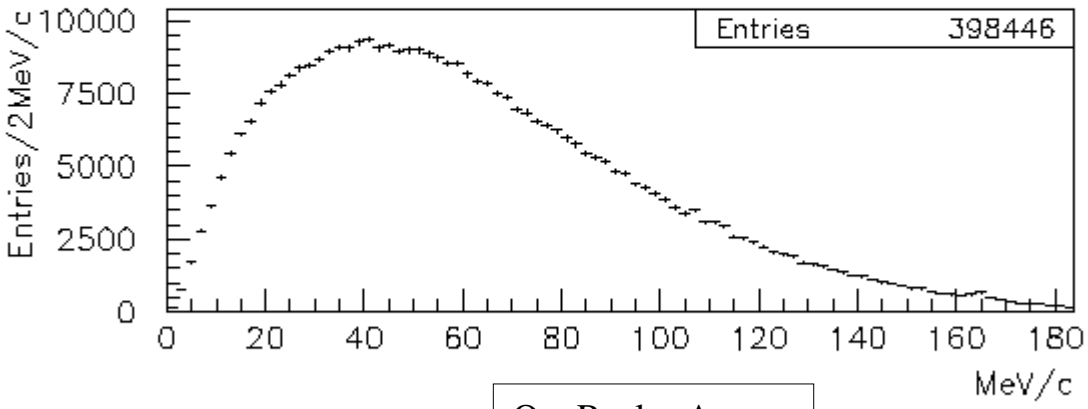
Evidence of $\pi^+ \pi^-$ Coulomb correlated pairs



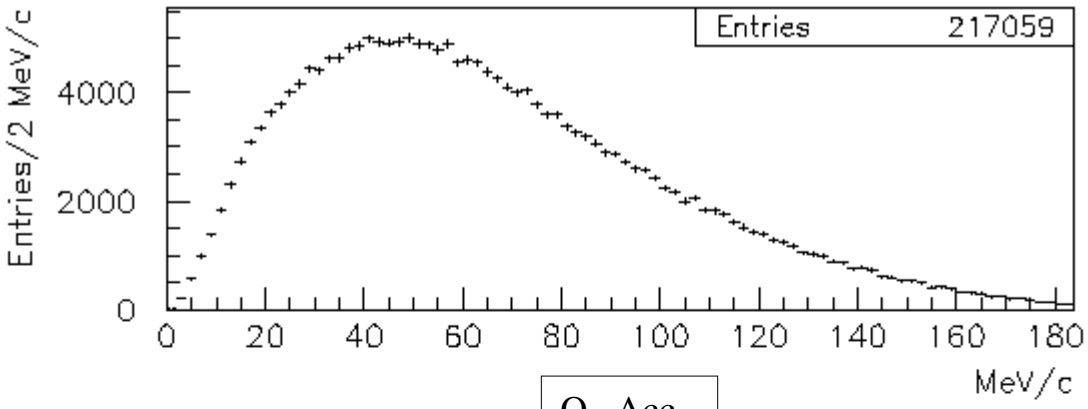
Real: $\pi^+\pi^-$ from free pairs (Coulomb + Non Coulomb)

+ $\pi^+\pi^-$ from $A_{2\pi}$

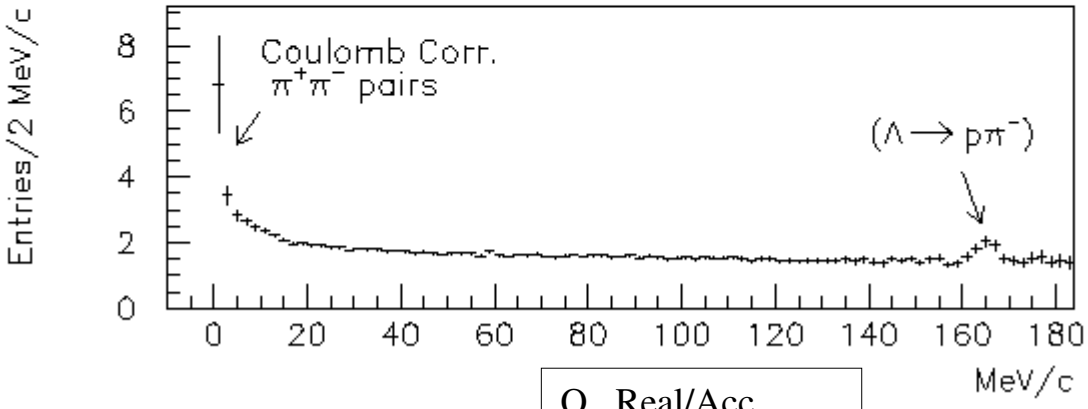
Acc: $\pi^+\pi^-$ from free pairs without FSI



Q Real + Acc



Q Acc



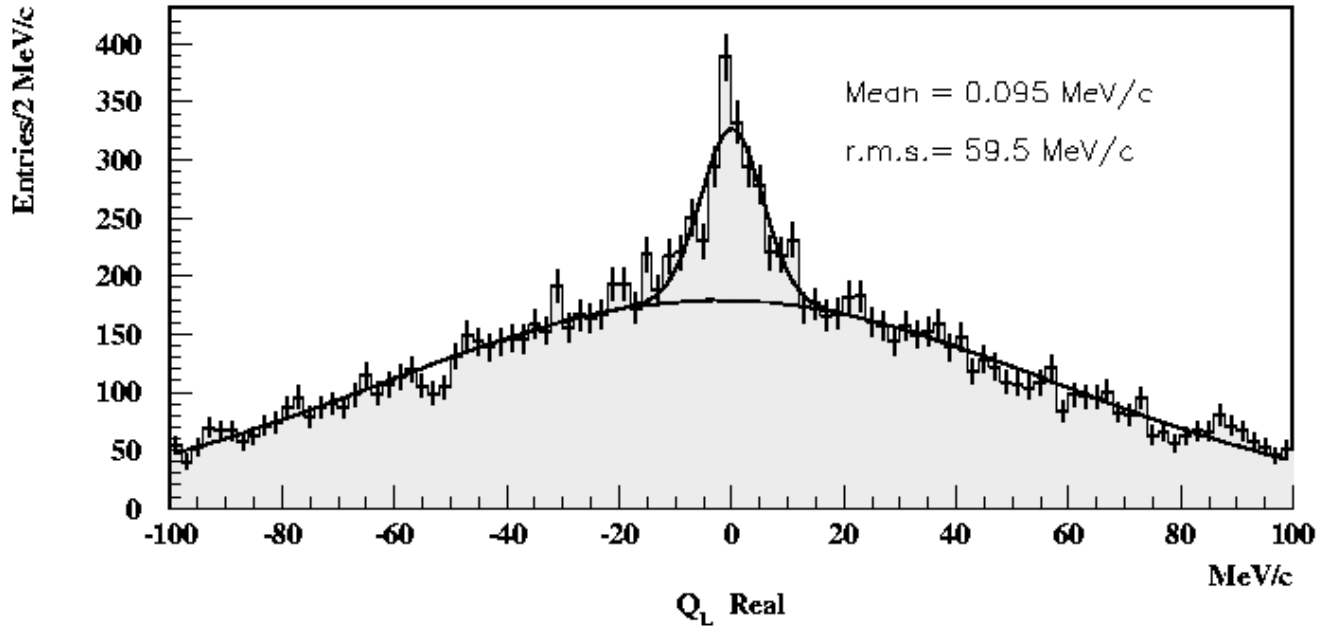
Q Real/Acc

Calibration with Coulomb peak

Misalignement of DC in each arm (asymmetrical errors) affect precision of reconstructed momenta and of opening angle of particles in the pair.

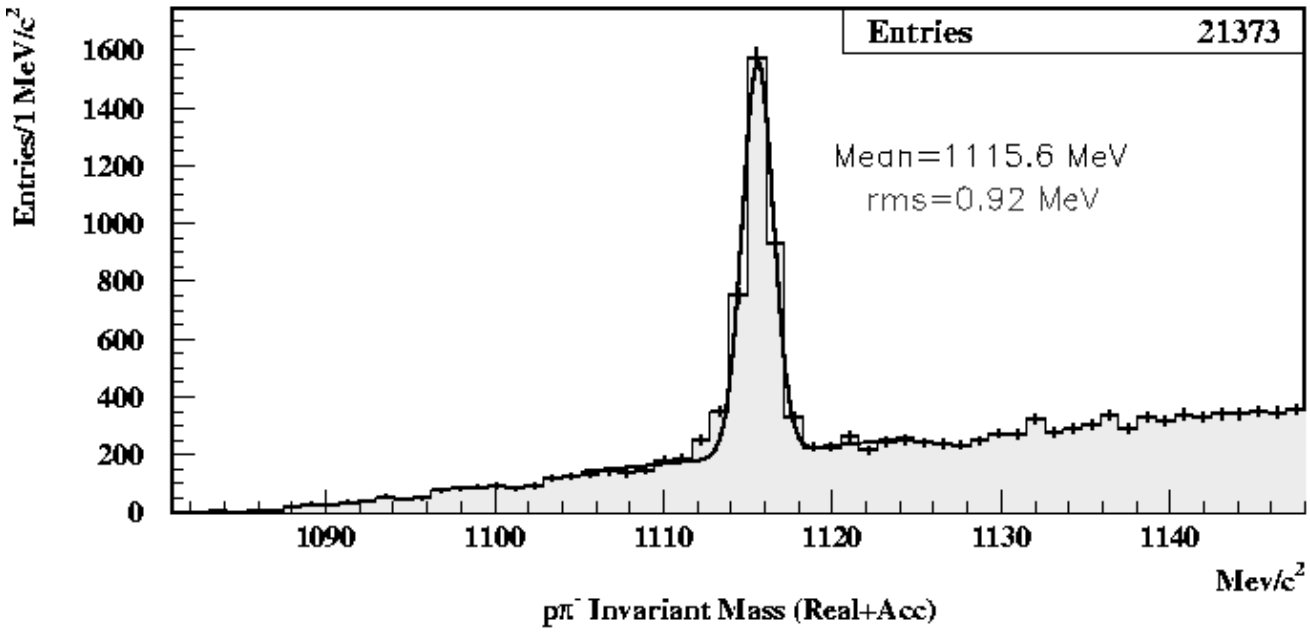
Reconstruction of Coulomb correlated ππ pairs

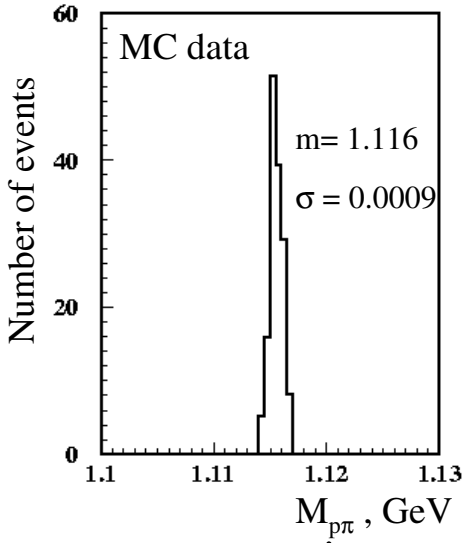
$(\vec{p}_1 \cong \vec{p}_2)$ is sensitive to precision of setup alignement.

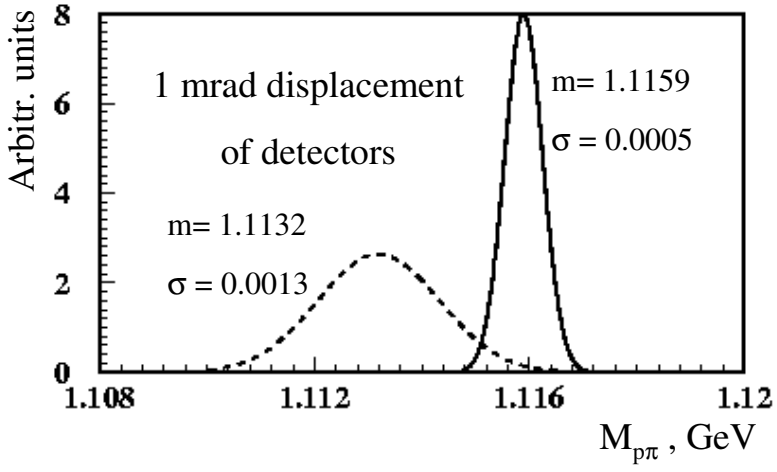


Calibration with particle decay

Detected Λ (4 ÷ 5 GeV/c): { $p\pi^-$ back-to-back in Λ cms; $p\pi^-$ with small p_T







- accuracy in mass resolution ~ 1MeV → $\frac{\ddot{A}p}{p} \leq 0.5\%$
- correct calibration of energy scale
- absence of symmetrical errors in telescope alignement

Summary and Conclusions

- Preliminary analysis of data collected has shown:

  • good detector performances (time resolution, energy resolution, energy calibration)

  • control of systematic errors

  • first signature of low energy $\pi^+\pi^-$ interaction, namely: evidence for Coulomb correlated $\pi^+\pi^-$ pairs

- Expect to collect ~ 500 $A_{2\pi}$ / week in current runs

- Future plans:

  need ~ 20.000 reconstructed $A_{2\pi}$ to measure Δ ~5%

  year 2000 Δ ~ 10% (2 targets)

  year $\geq$ 2001 Δ ~ 5% (> 2 targets)