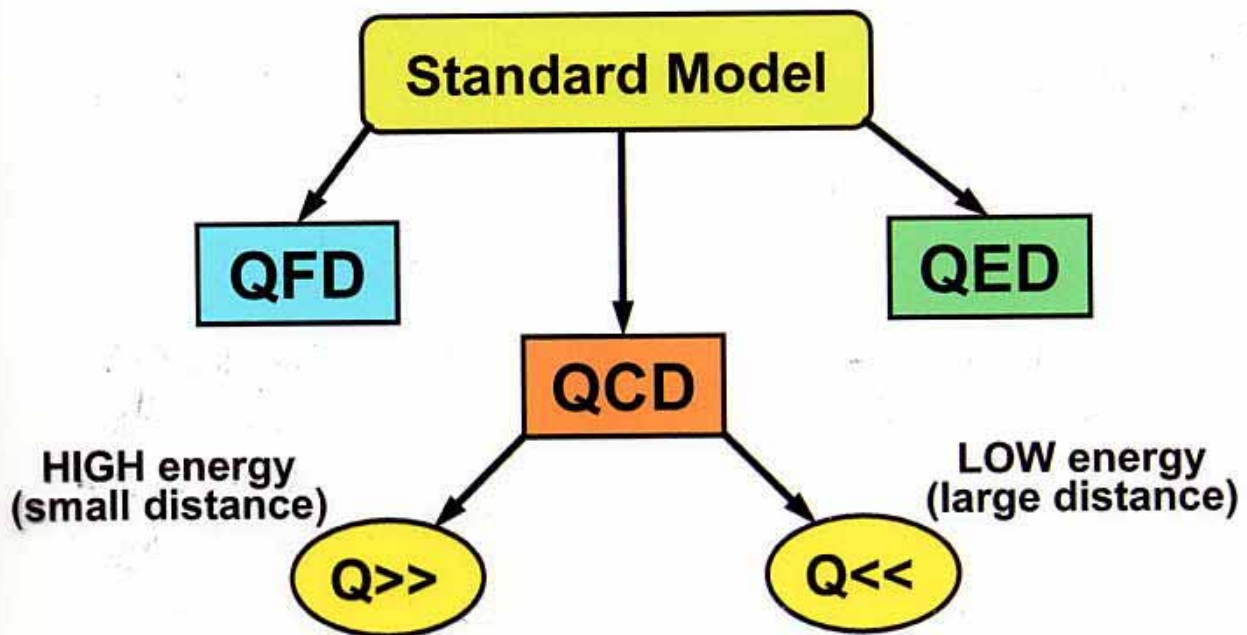


Theoretical motivation



perturbative QCD:
 $L_{QCD}(q,g)$

interaction \rightarrow „weak“
 (asympt. freedom):
 expansion in coupling

Check only L_{sym}

chiral sym. & break:
 $L_{eff}(GB: \pi, K, \eta)$

interaction \rightarrow „strong“
 (confinement) - **but**:
 expansion in energy

Check L_{sym} as well as

$L_{break-sym} \rightarrow$ **q-condensate**



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$\pi\pi$ scattering

ChPT predicts s-wave scattering lengths:

$$a_0 = 0.220 \pm 0.005 (2.3\%)$$

$$a_2 = -0.0444 \pm 0.0010 (2.3\%)$$

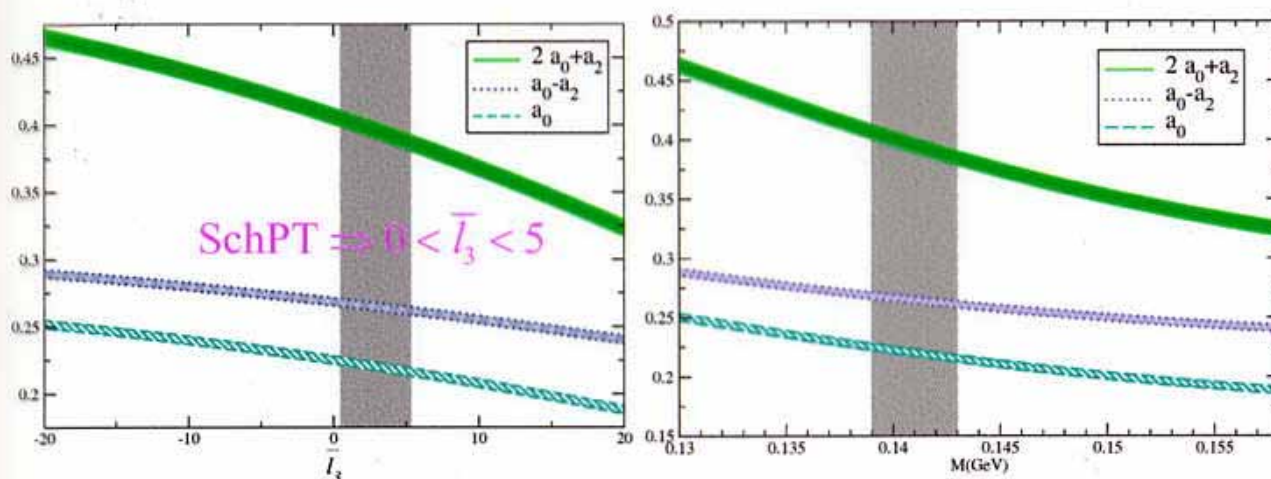
$$a_0 - a_2 = 0.265 \pm 0.004 (1.5\%)$$

Chiral expansion of the π mass:

$$M_\pi^2 = (m_u + m_d)B - [(m_u + m_d)B]^2 \frac{\bar{l}_3}{32\pi^2 F^2} + O((m_u + m_d)^3) \quad (1)$$

where $BF_\pi^2 = |\langle 0 | \bar{u}u | 0 \rangle|$ is the *quark condensate*, reflecting a property of the *QCD vacuum*.

Measurement of $\bar{l}_3^{(1)} \Rightarrow$ estimate of $(m_u + m_d) |\langle 0 | \bar{u}u | 0 \rangle|$:



e.g.: $a_0 - a_2 = 0.260 \pm 3\% \Rightarrow 1 < \bar{l}_3 < 11$ or $1.00 < M / M_\pi < 1.06$

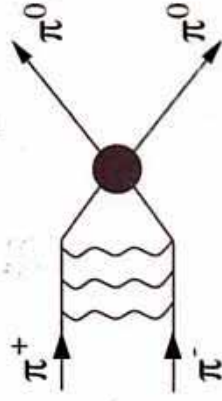
E865: $a_0 = 0.216 \pm 6\% \Rightarrow -4 < \bar{l}_3 < 12$ or $0.98 < M / M_\pi < 1.06$
(BNL)



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$$1/\tau_n = \Gamma_n^{2\pi^0} + \Gamma_n^{2\gamma} \quad (0.36\%) \implies \Gamma_n^{2\pi^0} = C\Delta^2 |\psi_n|^2, \quad \Delta \doteq (a_0 - a_2) :$$

- J. Uretsky and J. Palfrey, PR **121** (1961) 1798.
- S. Bilenky et al., Sov. JNP **10** (1970) 469.

$$\delta\tau/\tau = 10\% \implies \delta\Delta/\Delta = 5\%$$

$$\Gamma_n = \Gamma_{l.o.}(1 + \delta\Gamma) :$$

- H. Jallouli and H. Szadjian, PR D58 (1998) 014011.
- M. Ivanov, V. Lyubovitskij, E. Lipartia, A. Rusetsky, PR D58 (1998) 094024.
- A. Gall, J. Gasser, V. Lyubovitskij, A. Rusetsky, PR D64 (2001) 016008:

$$\delta\Gamma = (5.8 \pm 1.2)\% \implies \tau = (2.9 \pm 0.1) \cdot 10^{-15} \text{ s}$$

DIRAC

©Energy Splitting between np - ns states in $(\pi^+ - \pi^-)$ atom

$$\Delta E_n \equiv E_{ns} - E_{np}$$

$$\Delta E_n \approx \Delta E_n^{\text{vac}} + \Delta E_n^s$$

$$\Delta E_n^s \sim 2a_0 + a_2$$

For $n=2$

$$\Delta E_2^{\text{vac}} = -0.107 \text{ eV} \quad \text{from QED calculations}$$

$$\Delta E_2^s \approx -0.45 \text{ eV}$$

numerical estimated value from ChPT

$$a_0 = 0.220 \pm 0.005$$

$$a_2 = -0.0444 \pm 0.0010$$

(2001) G. Colangelo, J. Gasser and H. Leutwyler

\Rightarrow

$$\Delta E_2 \approx -0.56 \text{ eV}$$

(1979) A. Karimkhodzhaev and R. Faustov

(1983) G. Austen and J. de Swart

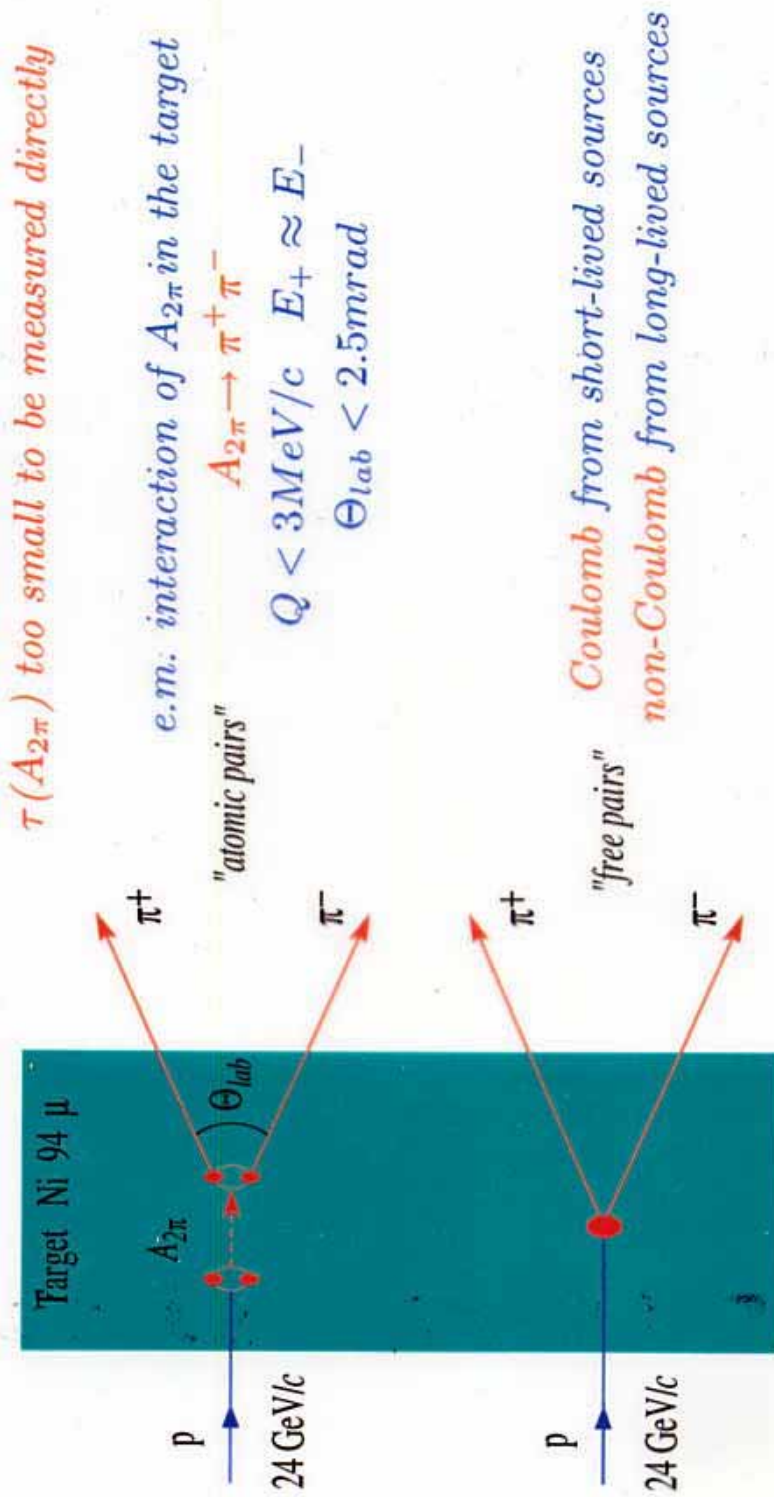
(1986) G. Efimov *et al.*

(1999) A. Gashi *et al.*

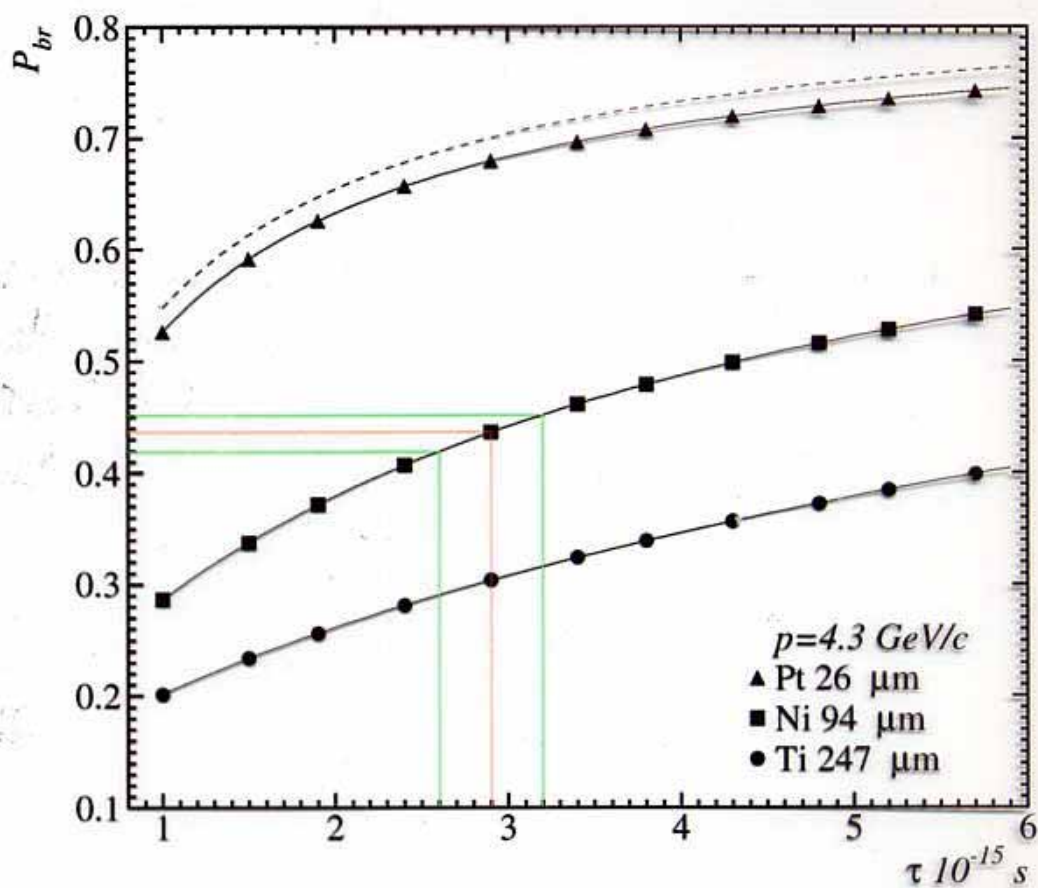
(2000) D. Eiras and J. Soto

A. Rusetsky, *priv. comm.*

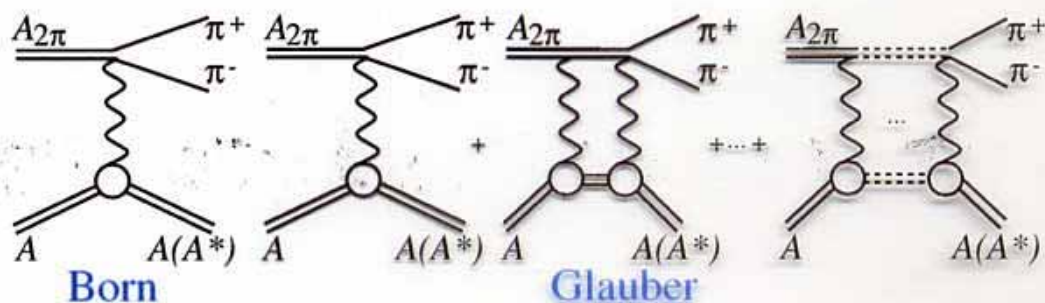
Method of $A_{2\pi}$ Observation



Probability of $A_{2\pi}$ breakup in targets



$\delta\tau = 10\%$ corresponds to $\delta P_{br} \approx 4\%$



DIRAC

LIFETIME MEASUREMENT OF $\pi^+ \pi^-$ AND $\pi^+ K^+$ ATOMS TO TEST LOW ENERGY QCD

Addendum to the DIRAC Proposal

	CERN	Geneva,	Switzerland
	Czech Technical University	Prague,	Czech Republic
	Institute of Physics ASCR	Prague,	Czech Republic
	Ioannina University,		Greece
	INFN - Laboratori Nazionali di Frascati	Frascati,	Italy
	Trieste University and INFN-Trieste		Italy
	KEK	Tsukuba,	Japan
	Kyoto Sangyou University		Japan
	UOEH-Kyushu		Japan
	Tokyo Metropolitan University		Japan
	National Institute for Physics and Nuclear Engineering IFIN-HH	Bucharest,	Romania
	JINR	Dubna,	Russia
	Skobeltsyn Institute for Nuclear Physics of Moscow State University	Moscow,	Russia
	IHEP	Protvino,	Russia
	Santiago de Compostela University		Spain
	Basel University		Switzerland
	Bern University		Switzerland

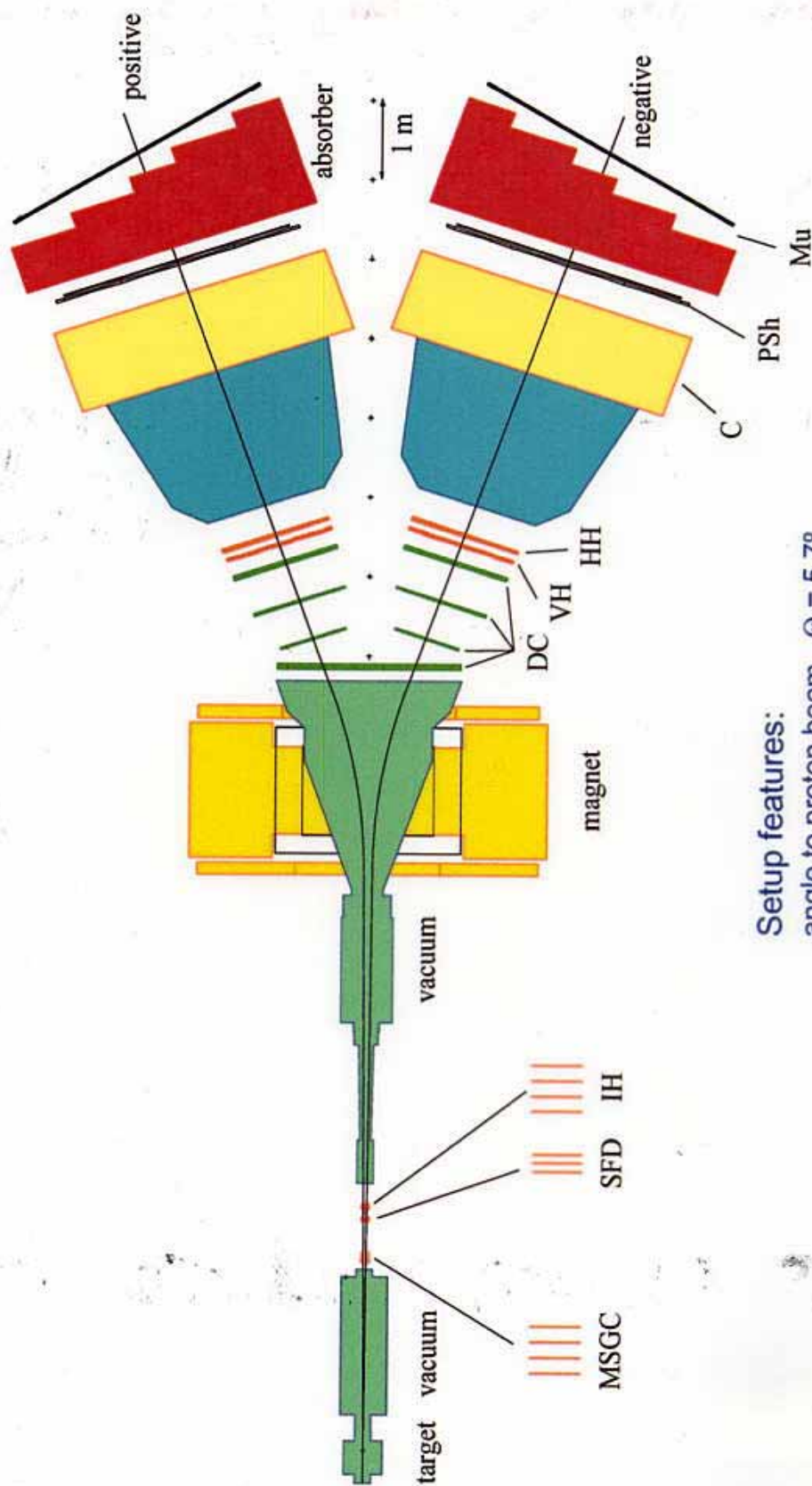
75 Physicists from 17 Institutes



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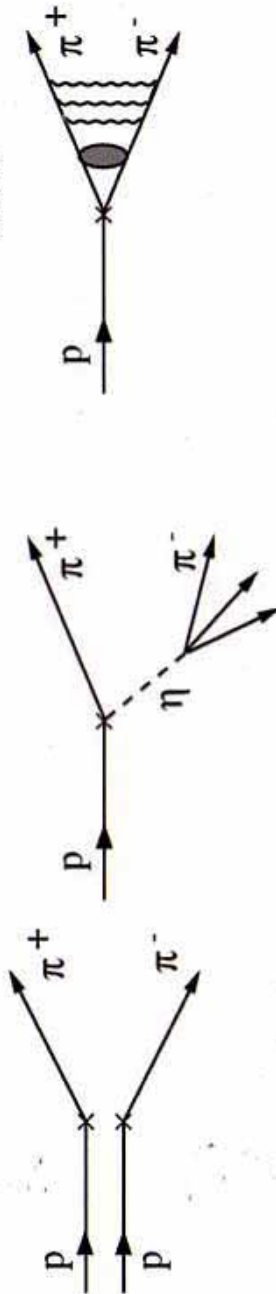
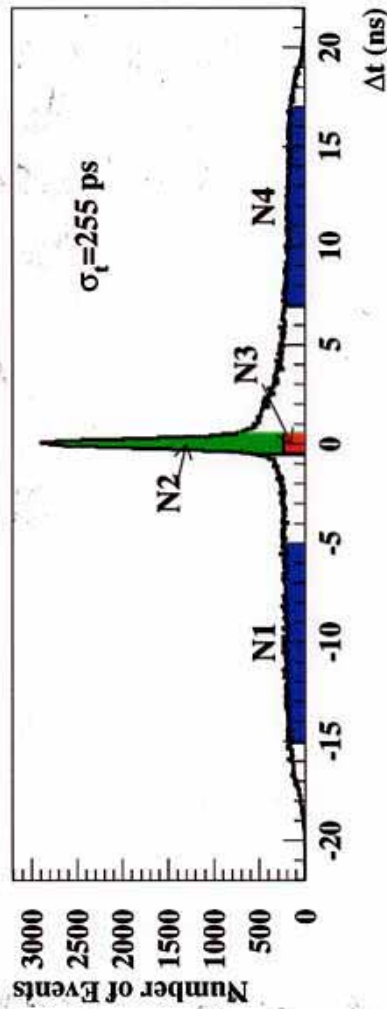
Setup features:

angle to proton beam $\Theta = 5.7^\circ$
channel aperture $\Omega = 1.2 \cdot 10^{-3} \text{sr}$
momentum range $1.2 \leq p_\pi \leq 7 \text{ GeV}/c$
momentum resolution $\Delta p/p = 0.3\%$

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 ($Q_L<1.5\text{ MeV}/c$ $Q_T<4\text{ MeV}/c$)	282 ± 96	1353 ± 385	935 ± 273	1476 ± 330	5733 ± 577	1925 ± 390	2555 ± 525	1410 ± 264	15387 ± 1078
Without upstream detectors ($Q_L<1.5\text{ MeV}/c$ $Q_T<6\text{ MeV}/c$)	219 ± 137	3839 ± 579	1767 ± 414	3314 ± 539	9050 ± 822	3040* ± 480	4030* ± 550	2230* ± 410	27270* ± 1470

* - estimation



Accidentals

non-Coulomb pairs

Coulomb pairs

$$\frac{dN_{\text{acc}}}{dQ} \propto \Phi(Q)$$

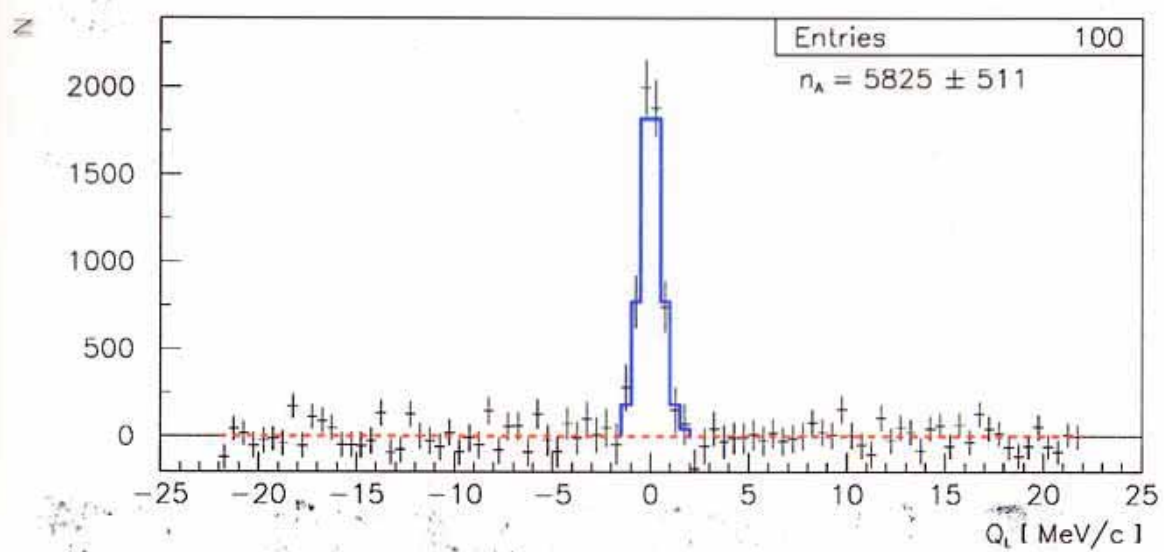
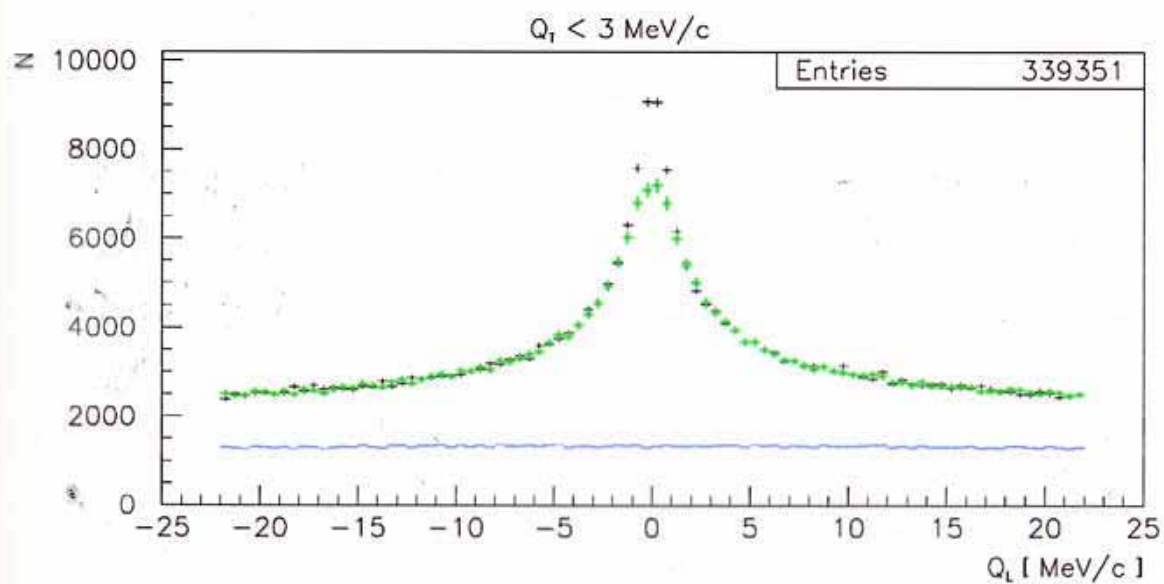
$$\frac{dN_{\text{corr}}^{\text{long}}}{dQ} \propto \Phi(Q)$$

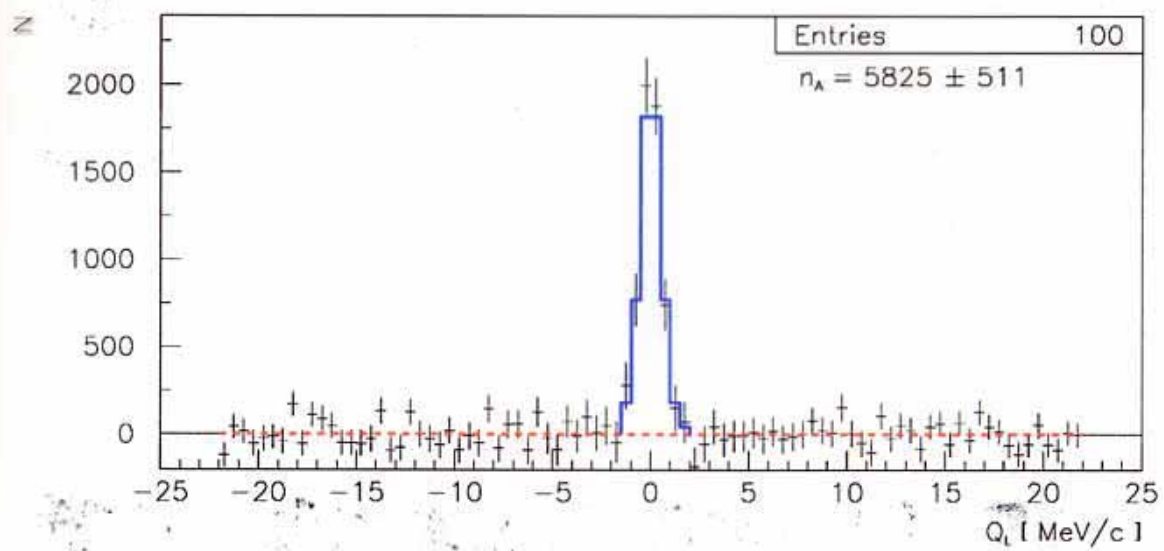
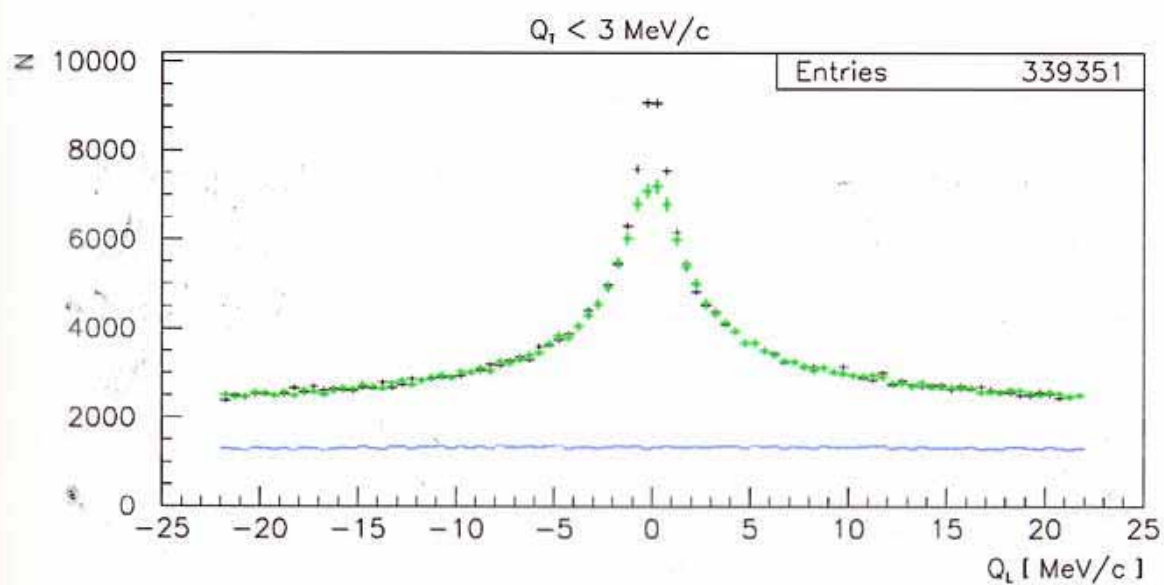
$$\frac{dN_{\text{corr}}^{\text{short}}}{dQ} \propto \Phi(Q)(1 + kQ)A_C(Q)$$

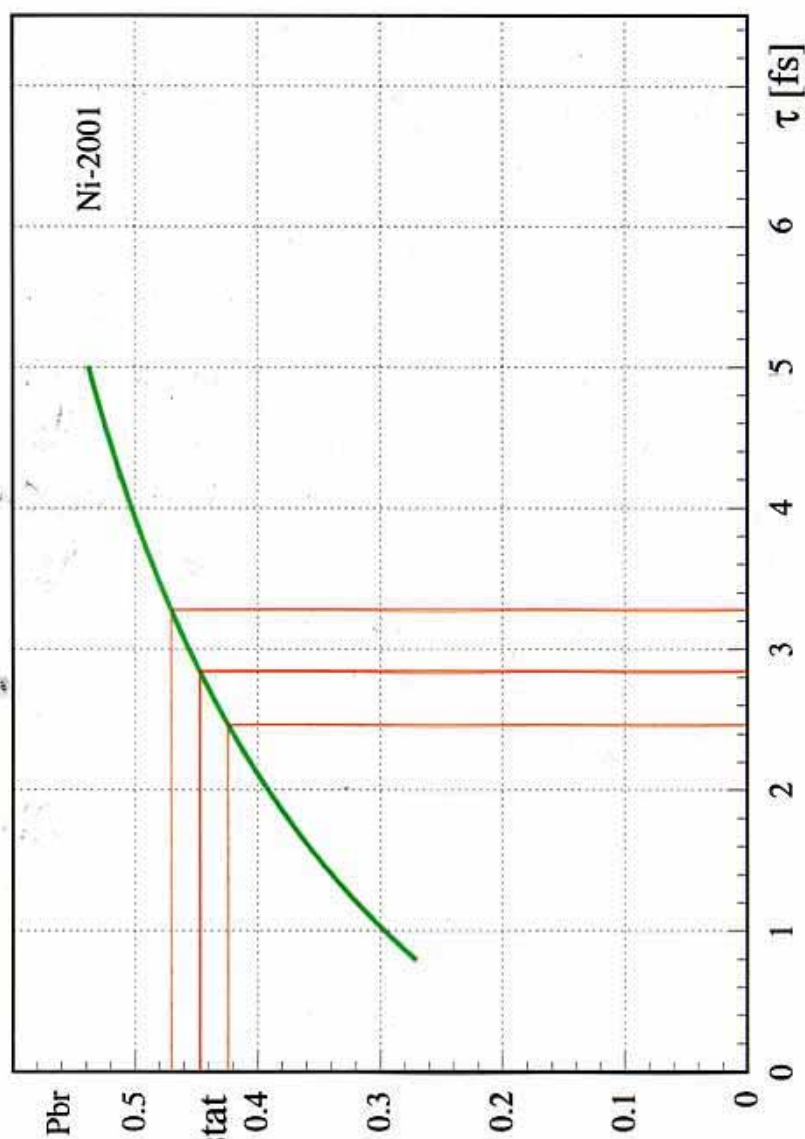
$$\frac{dN_{\text{corr}}}{dQ} = \frac{dN_{\text{corr}}^{\text{long}}}{dQ} + \frac{dN_{\text{corr}}^{\text{short}}}{dQ} = N\Phi(Q)[(1 + kQ)A_C(Q) + f]$$

N, k, f — free parameters

DIRAC







$$P_{Br} = 0.447 \pm 0.023_{stat}$$

$$\tau = 2.85 \begin{matrix} + 0.44_{stat} \\ - 0.38_{stat} \end{matrix} [fs]$$

LIFETIME MEASUREMENT

DIRAC Ni2001 Statistics

Monte-Carlo

$$B_{Br} = 0.447 \pm 0.023 (\text{stat}) \pm 0.009 (\text{syst})$$

$$\tau_{A_{2\pi}} = [2.85^{+0.44}_{-0.38}{}_{\text{stat}} (\pm 15\%) \pm 6\% (\text{syst})] \cdot 10^{-15} \text{ s}$$

Accidentals

$$B_{Br} = 0.455 \pm 0.034 (\text{stat})$$

$$\tau_{A_{2\pi}} = [3.1^{+0.7}_{-0.6}{}_{\text{stat}} (\pm 21\%)] \cdot 10^{-15} \text{ s}$$

DIRAC All Statistics

$$\Delta\tau_{A_{2\pi}} = \pm 10\% (\text{stat}) \pm 6\% (\text{syst})$$

Theory

$$\tau_{A_{2\pi}} = [2.9 \pm 0.1] \cdot 10^{-15} \text{ s}$$

DIRAC Addendum

$$\Delta\tau_{A_{2\pi}} = \pm 4\% (\text{stat}) \pm 2\% (\text{syst}) \pm 2\% (\text{theor})$$

$$\Delta\tau_{A_{\pi K}} = \pm 20\% (\text{stat})$$

Goals

To check the precise low energy QCD predictions for s -wave pion-pion $|a_0 - a_2|$, and pion-kaon $|a_{1/2} - a_{3/2}|$ scattering lengths with isospin 0, 2 and 1/2, 3/2 respectively,

1. measurement of the $A_{2\pi}$ lifetime with precision better than 6% which gives precision for $|a_0 - a_2|$ better than 3%.
2. observation of π^+K^- and π^-K^+ atoms and measurement of their lifetimes which gives precision for $|a_{1/2} - a_{3/2}|$ about 10%.
3. observation of long-lived (metastable) states of $A_{2\pi}$.

This opens up a possibility to measure the Lamb-shift in $A_{2\pi}$, and the value $2a_0 + a_2$.

πK scattering, experimental results

In the 60's and 70's set of experiments were performed to measure πK scattering amplitudes. Most of them were done studying the scattering of kaons on protons or neutrons, and later also on deuterons. The kaon beams used in these experiments had energies ranging from 2 to 13 GeV.

The main idea of those experiments was to determine the contribution of the One Pion Exchange (OPE) mechanism. This allows to obtain the πK scattering amplitude.

Analysis of experiments gave the phases of πK -scattering in the region of $0.7 \leq m(\pi K) \leq 2.5$ GeV. The most reliable data on the phases belong to the region $1 \leq m(\pi K) \leq 2.5$ GeV.

What new will be know if πK scattering length will be measured?

The measurement of *s-wave* πK scattering length would test our understanding of chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (*u, d and s*), while the measurement of $\pi\pi$ scattering length checks only $SU(2)_L \times SU(2)_R$ symmetry breaking (*u, d*).

This is the main difference between $\pi\pi$ and πK scattering!



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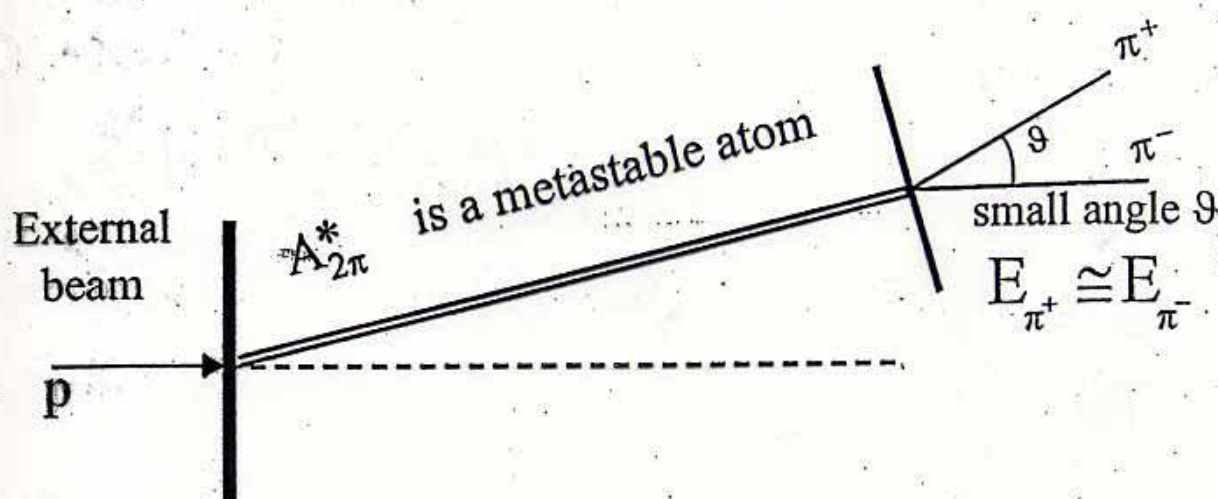
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Metastable atoms

For $p_A = 5.6 \text{ GeV}/c$ and $\gamma = 20$

$$\left\{ \begin{array}{ll} \tau_{1s} = 2.9 \times 10^{-15} \text{ s}, & \lambda_{1s} = 1.7 \times 10^{-3} \text{ cm} \\ \tau_{2s} = 2.3 \times 10^{-14} \text{ s}, & \lambda_{2s} = 1.4 \times 10^{-2} \text{ cm} \\ \tau_{2p} = 1.17 \times 10^{-11} \text{ s}, & \lambda_{2p} = 7 \text{ cm} \\ & \lambda_{3p} \approx 23 \text{ cm} \\ & \lambda_{4p} \approx 54 \text{ cm} \end{array} \right.$$



Probabilities of the $A_{2\pi}$ breakup (Br) and yields of the long-lived states for different targets provided the maximum yield of summed population of the long-lived states: $\Sigma(l \geq 1)$

Target Z	Thickness Mm	Br	Σ ($l \geq 1$)	$2p_0$	$3p_0$	$4p_0$	Σ ($l=1, m=0$)
04	100	4.45%	5.86%	1.05%	0.46%	0.15%	1.90%
06	50	5.00%	6.92%	1.46%	0.51%	0.16%	2.52%
13	20	5.28%	7.84%	1.75%	0.57%	0.18%	2.63%
28	5	9.42%	9.69%	2.40%	0.58%	0.18%	3.29%
78	2	18.8%	10.5%	2.70%	0.54%	0.16%	3.53%

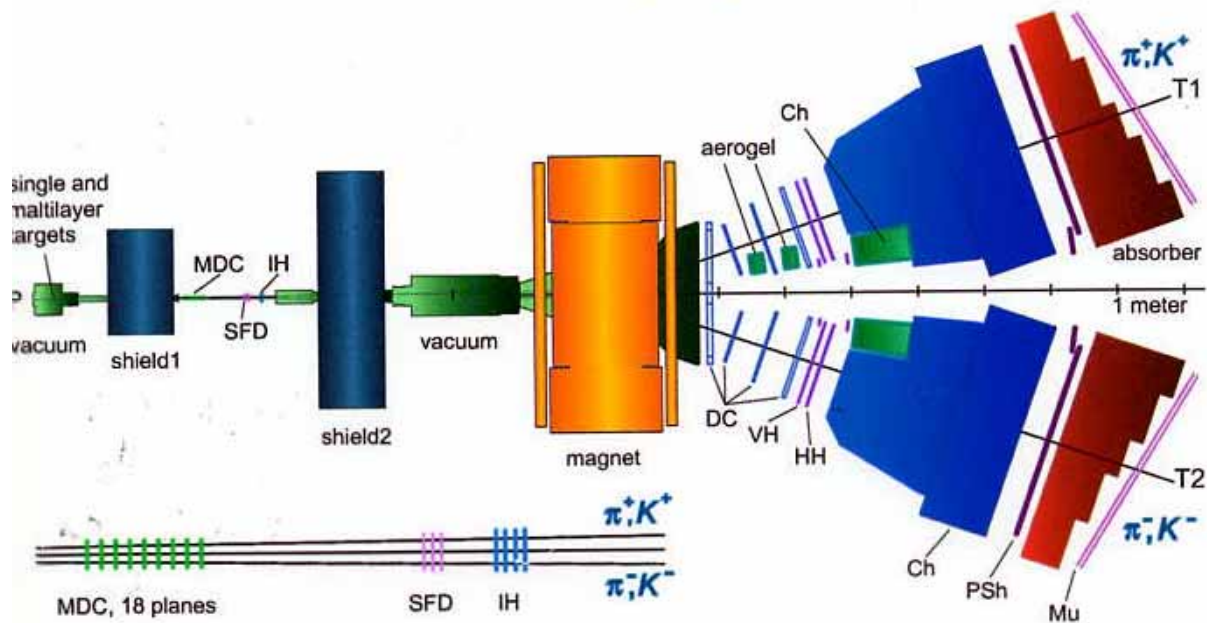


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Efficiency gain



1. Single-multilayer targets decrease the systematic errors.
2. Identification of e^\pm , π^\pm , K^\pm and p
3. Increasing of statistics and efficiency of the setup
 - Shielding $K \approx 1.9$
 - Formation of time structure of the spill with the trigger of setup
 - Microdrift chambers
 - New electronics for SFD
 - Increase in the aperture on VH hodoscope and PSH
 - Total $K \approx 4$



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Comparison of DIRAC and DIRAC-J-PARK

	DIRAC		DIRAC-J-PARC
I	Accelerator	PS	J-PARC
	beam time during 1 hour K_1	2.5 spill/16.8s 214 s 1	737 s 3.4

Yields of pion pairs and atoms as a function of the proton beam momentum relative to the 24 GeV proton beam

P GeV/c	$\pi^+\pi^-$	$A_{2\pi}$	$A_{2\pi}/\pi^+\pi^-$	$A_{\pi K} + A_{K\pi}$	$(A_{\pi K} + A_{K\pi})/\pi^+\pi^-$
24	1	1	1	1	1
30	1.2	1.4	1.14	1.5	1.26
40	1.4	1.8	1.27	2.2	1.56
50	1.6	2.2	1.43	2.8	1.74
60	1.8	2.6	1.52	3.5	1.91
90	2.0	3.4	1.72	4.6	2.30

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14 June 2004