The Preshower Detector for DIRAC Experiment

Workshop

Bucharest, 23 June 2008

CERN

IFIN-HH

Contents

Short history

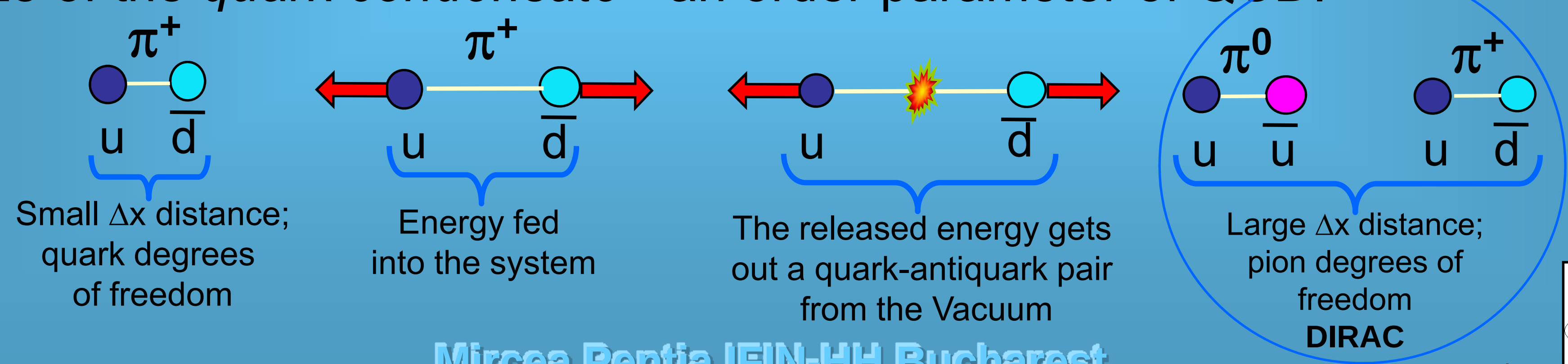
- **In 1995** the Bucharest IFIN-HH group, lead by Prof. Valeriu Zoran, joined to the Prof. Leonid Nemenov's initiative to have a proposal for an experiment at CERN, aiming to measure the lifetime of pionium (exotic atom formed by coupling a positive π^+ meson and a negative π^- meson). This proposal has been presented to CERN SPS Committee CERN/SPSLC 95-1, SPSLC/P284(1995) which recommended (CERN/SPSLC 96-11) the DIRAC experiment for approval to the Research Board (RB).
- **In 1996** RB approved the DIRAC Experiment.
- **In 1997** a MEMORANDUM OF UNDERSTANDING has been signed with IFIN-HH, aiming to design and construct a ***Preshower Detector***. The main goal of this detector is to separate pion and electron signals as to have a better chance to identify pion pairs from pionium breakup.
- **In 1998** the ***Preshower Detector*** was realized and installed in East Hall, T8 beam line. It has been used for $\pi^+\pi^-$ hadronic atom study along with DIRAC setup.
- **In 2004** has been presented to CERN SPS Committee (CERN/SPSLC 2004-020) a new proposal to extend the study of hadronic atoms to the πK atom.
- **In 2005** the CERN Research Board (CERN/DG/ Research Board 2004-363) approved continuation of the DIRAC Experiment.
- **In 2006** the ***New Preshower Detector*** was realized and installed at CERN.
  Now it is ready for data taking for new hadronic atom studies.

DIRAC main goal

Quantum Chromodynamics (QCD) is the general accepted *strong interaction* theory. It has successfully been tested only in the perturbative region of *high momentum transfer* (Q>2 GeV) or equally, at *short relative distance* $\Delta x \sim h/Q$ (Δx<0.1fm). But it has not appropriate answers for *non-perturbative processes.*

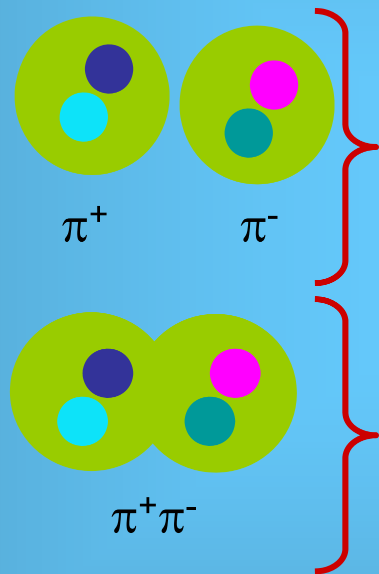
Chiral Perturbation Theory (ChPT), the non-perturbative candidate of QCD, is replacing the QCD quark degrees of freedom by the pion ones.

By measuring *Pionium lifetime*, DIRAC will determine in a model-independent way the difference $|a_0-a_2|$ between the S-wave $\pi\pi$ *scattering lengths* a_0 and a_2. ChPT predicts the *scattering lengths* with high accuracy ~2%. Therefore such a measurement will be a sensitive check in understanding Chiral symmetry breaking of QCD, giving an indication about the size of the *quark condensate* - an order parameter of QCD.



Quark Structure of Pions and Pionium

- up quark (charge +2/3)
- down quark (charge -1/3)
- anti-up quark (charge -2/3)
- anti-down quark (charge +1/3)



pions

Pionium
(dimeson atomic complex)

High energies gave us a picture about structure of the matter, and so they answered to the question WHAT IS THERE ?
DIRAC tries to answer to another question: HOW IT WORKS ?

DIRAC method

- In the absence of *strong interaction* between π^+ *and* π^- there exist the Coulomb bound states

momentum: $k_n = i\kappa_n = i/(na_B)$

energy: $E_n = -\kappa_n^2/(2m_r) = -m_r\alpha^2/(2n^2)$

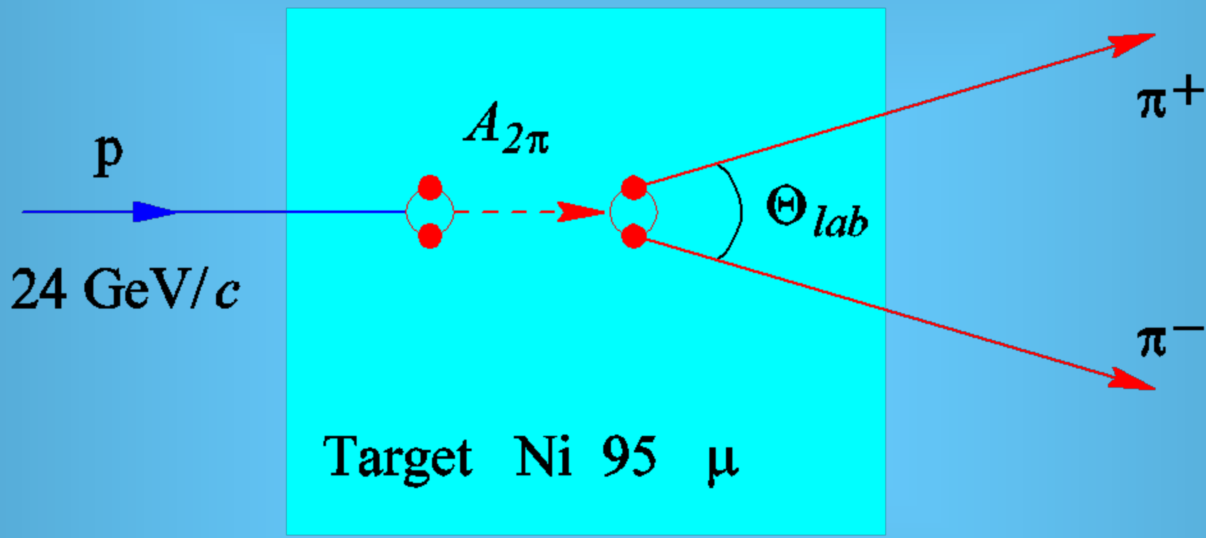
- In the presence of *strong interactions*, the energies will be shifted.

The real part of the energy shift ΔE_n: $\mathrm{Re}(\Delta E_n) \rightarrow$ level shift

The imaginary part of the energy shift: $-2\,\mathrm{Im}(\Delta E_n) = \Gamma_n \rightarrow$ decay width

$$\Gamma_0(\pi^+\pi^-) = \underbrace{\frac{16\pi}{9}\sqrt{\frac{2\Delta m_\pi}{m_\pi}}}_{\Delta m_\pi \text{ isospin symmetry breaking}} \underbrace{\left(a_0^0 - a_0^2\right)^2}_{\text{strong decay}} \underbrace{\left|\psi_c(0)\right|^2}_{\text{electromagnetic binding}}$$

$\pi^+\pi^-$ Atom Production and Break up



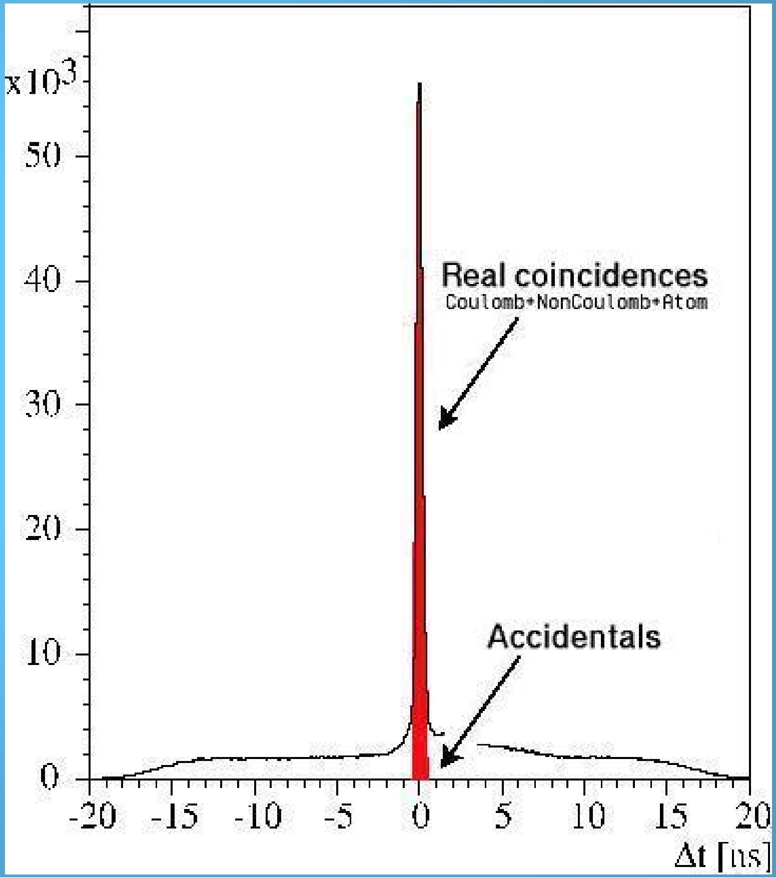
DIRAC setup must to detect oppositely charged pion pairs of low relative C.M. momenta (Q), with high resolution ($\sigma_Q \approx 0.50$ MeV/c), in the momentum range 1.2- 8 GeV/c, using a magnetic double arm spectrometer.

DIRAC Experimental method

Pionium atoms, produced in the target, may either annihilate, or breakup after interaction with target atoms into $\pi^+\pi^-$ pairs (atomic pairs). These pairs are experimentally observable by their characteristic low relative momentum ($Q \leq 4$ MeV/c).

By measuring the particle coincidences (see Figure) in the region $|\Delta t| \leq$ **0.5 ns** we find our atomic pairs along with a large background.

All $\pi^+\pi^-$ pairs produced in single proton-nucleus interaction and detected in the "Real coincidences" peak, can be separated by their particular Q distribution.

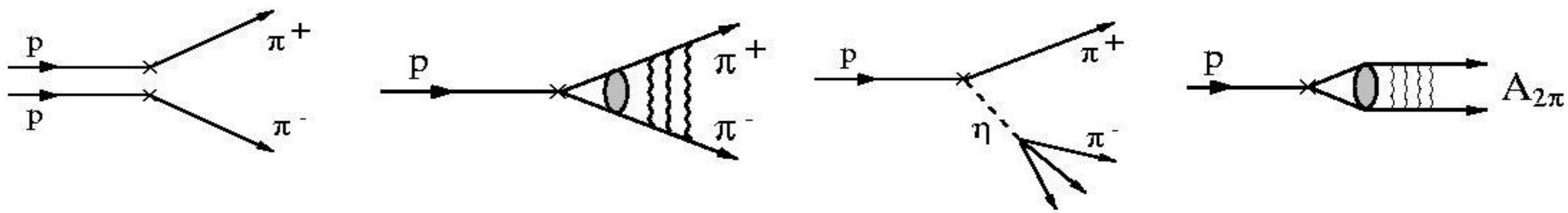


They are:

- N_C Coulomb correlated pairs
- N_{nC} Non-Coulomb correlated pairs
- n_A Atomic pairs
- N_{acc} Accidentals

Pionium signal and background events

The Q distributions of $\pi^+\pi^-$ pairs detected in the "Real coincidences" peak, are expressed by the free $\pi^+\pi^-$ pairs distribution $\Phi(Q)$, assumed the same as accidental one $dN_{acc}/dQ = \Phi(Q)$, and Coulomb correlation function $A_C(Q)$:



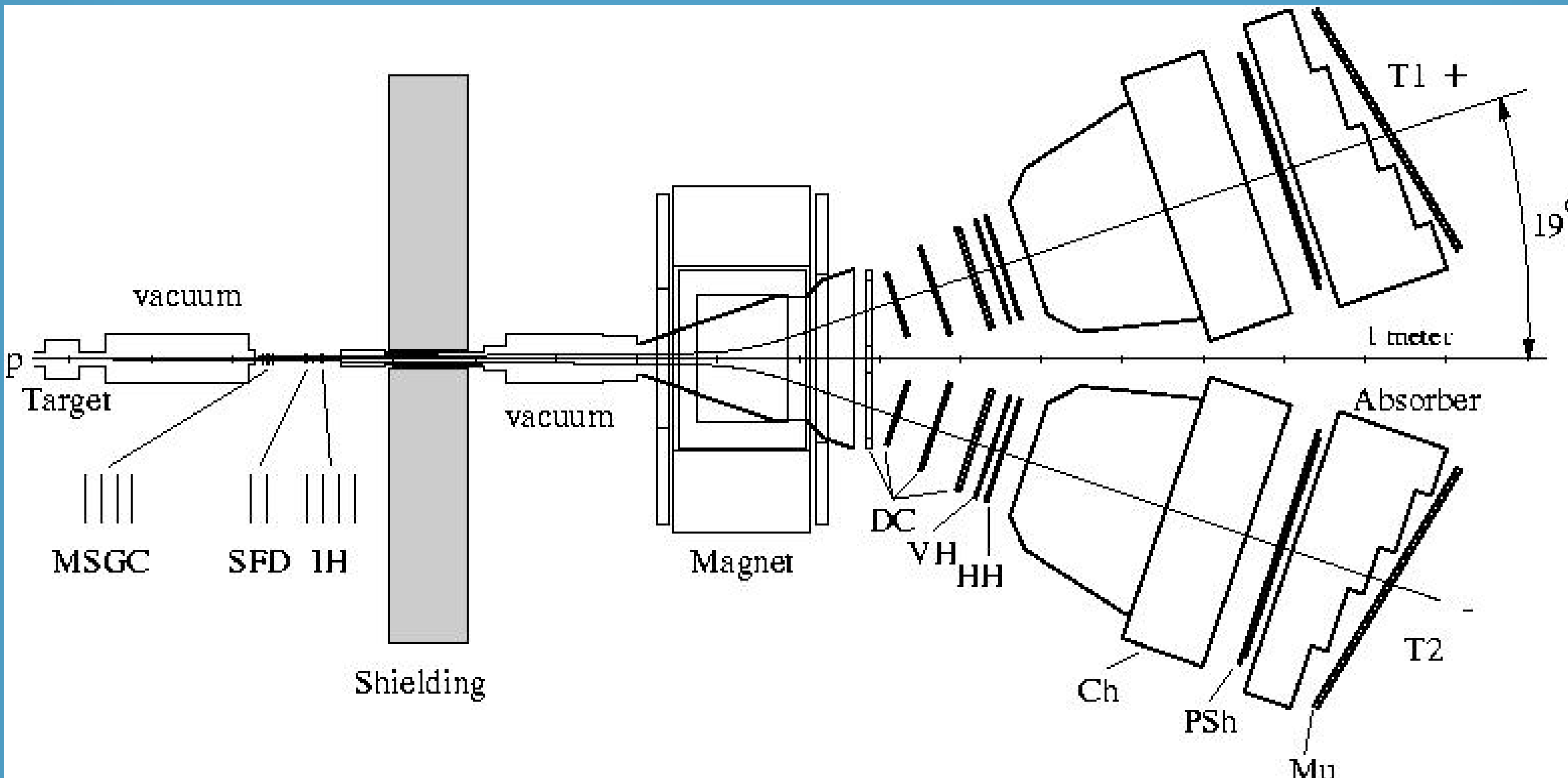
$$\frac{dN_{acc}}{dQ} \equiv \Phi(Q) \qquad \frac{dN_C}{dQ} = a \cdot \Phi(Q) A_c(Q) \qquad \frac{dN_{nC}}{dQ} = b \cdot \Phi(Q) \qquad \frac{dn_A}{dQ} \sim \Phi(Q)\, |\psi(0)|^2$$

Experimental correlation function R(Q) is defined as the ratio of real and accidental coincidences. In the background region, without Pionium signals ($Q > 4$ MeV/c), it is:

$$R(Q)|_{Q>4MeV/c} = \frac{dN/dQ}{dN_{acc}/dQ} = \frac{dN_C/dQ + dN_{nC}/dQ}{dN_{acc}/dQ} = \frac{a \cdot \Phi(Q) A_c(Q) + b \cdot \Phi(Q)}{\Phi(Q)} = N\,(A_c(Q) + f)$$

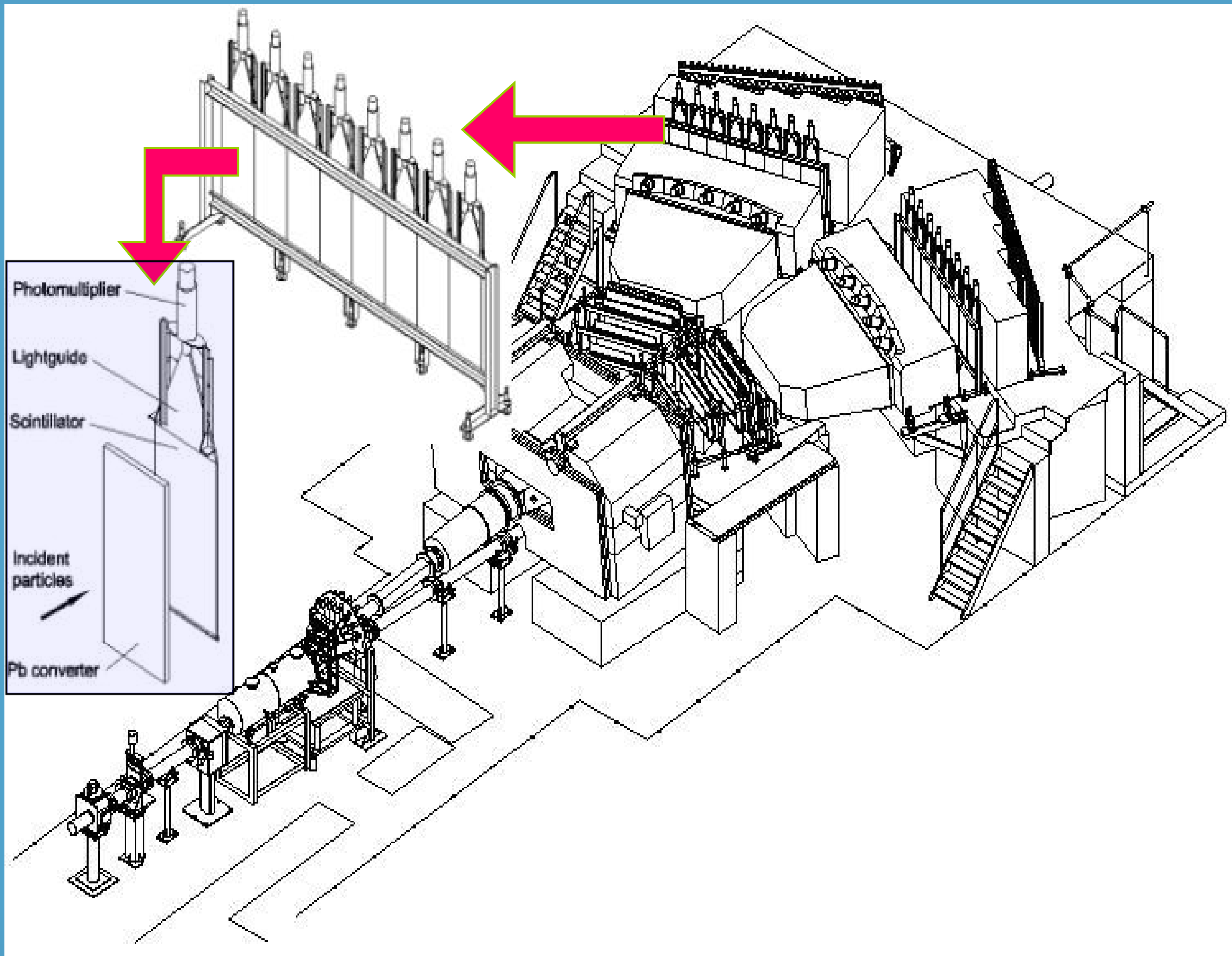
By fitting this function R(Q) on the region $Q > 4$ MeV/c, we can find *N* and *f* and so, the background contribution even for Pionium region $Q < 4$MeV.

DIRAC setup

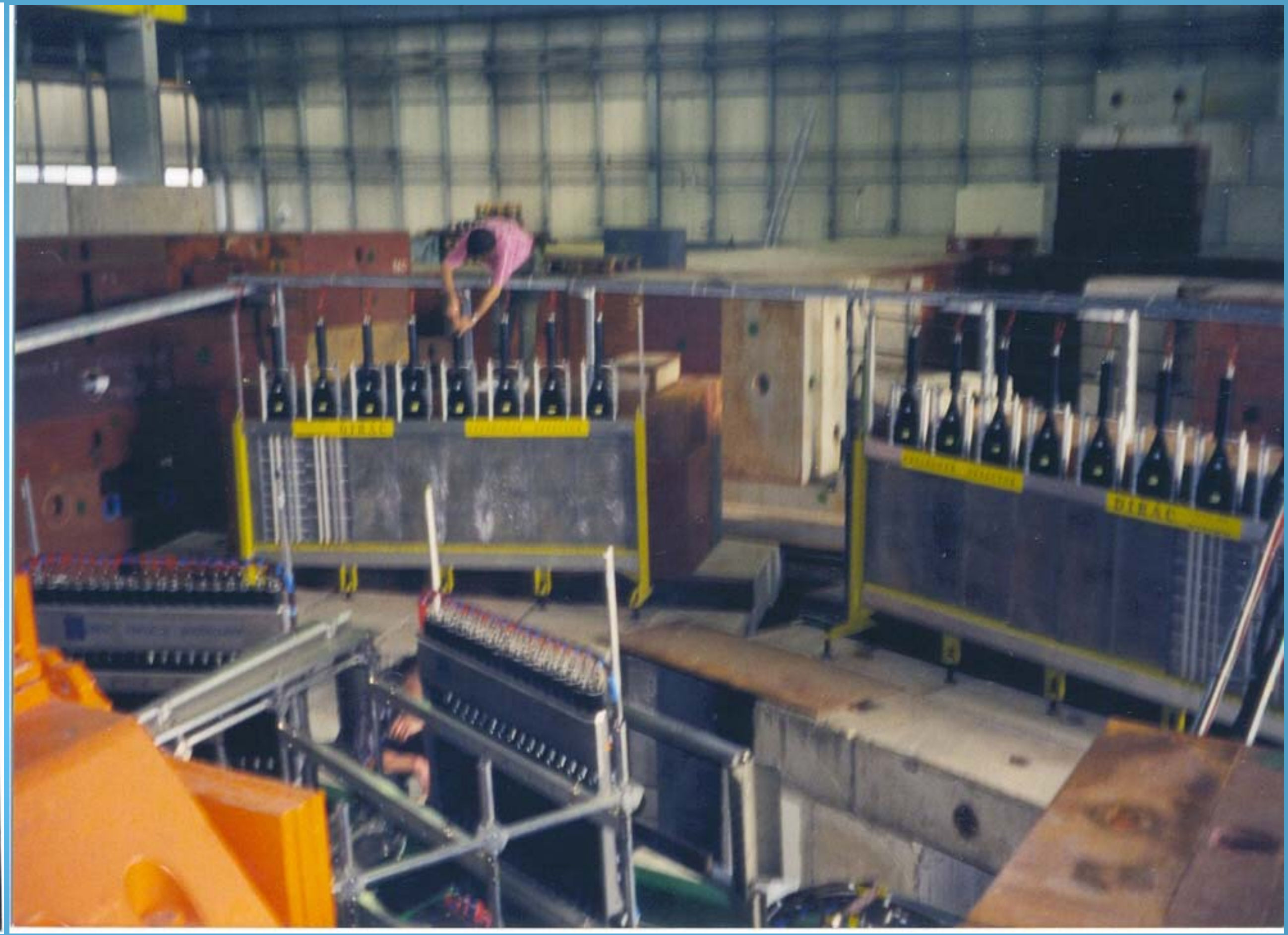


The Schematic top view of the DIRAC spectrometer. Upstream of the magnet are: target, microstrip gas chambers (MSGC), scintillating fiber detectors (SFD), ionization hodoscopes (IH), and iron shildieng. Downstream of the magnet are: drift chambers (DC), vertical and horizontal hodoscopes (VH, HH), gas Cherenkov counter (Ch), preshower detectors (PSh) and, behind the iron absorber, muon detectors (Mu).

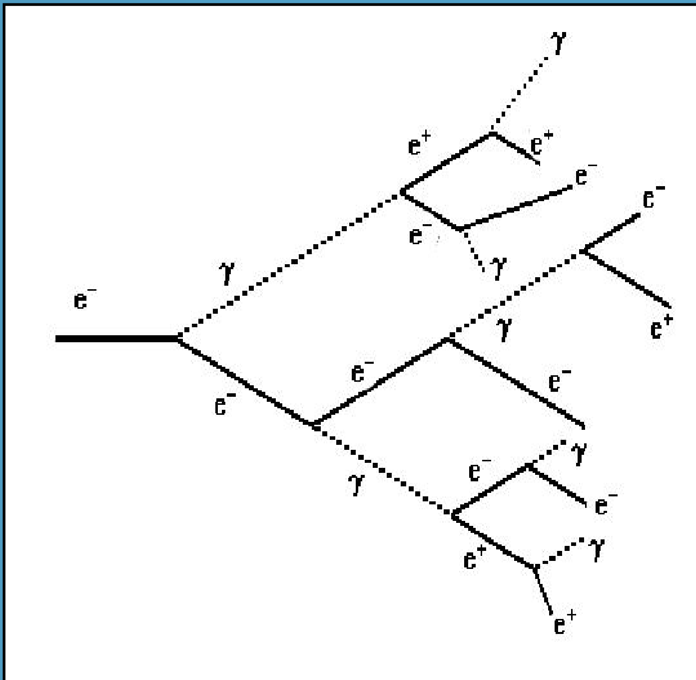
Preshower Detector for DIRAC Experiment

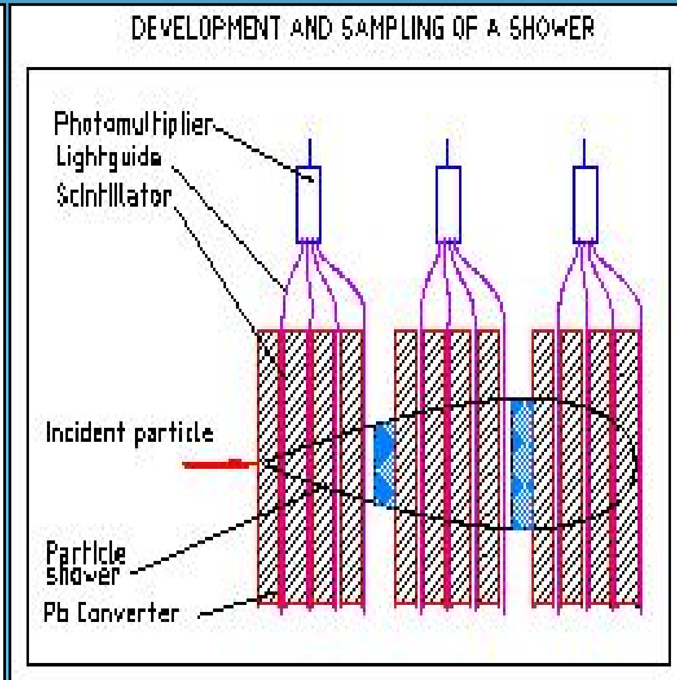


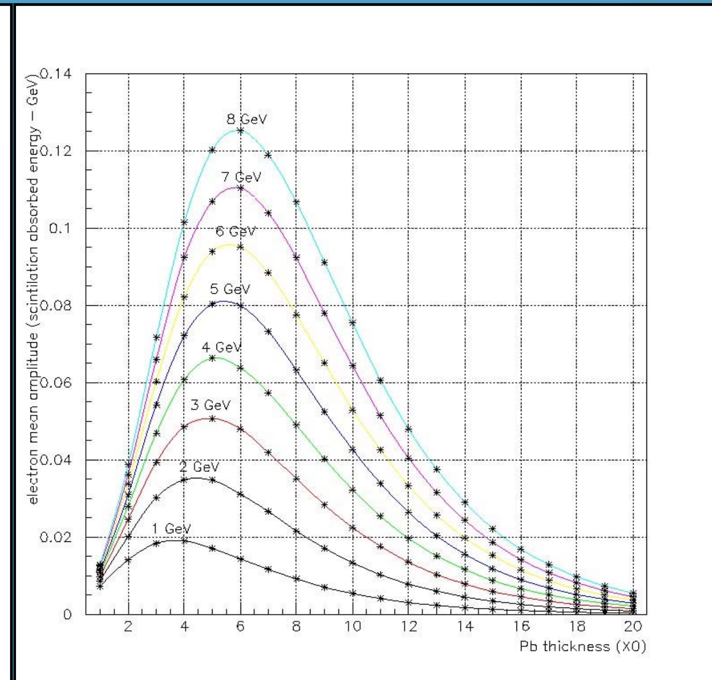
Mounting Preshower Detector at CERN - East Hall



How Preshower Detector works ?





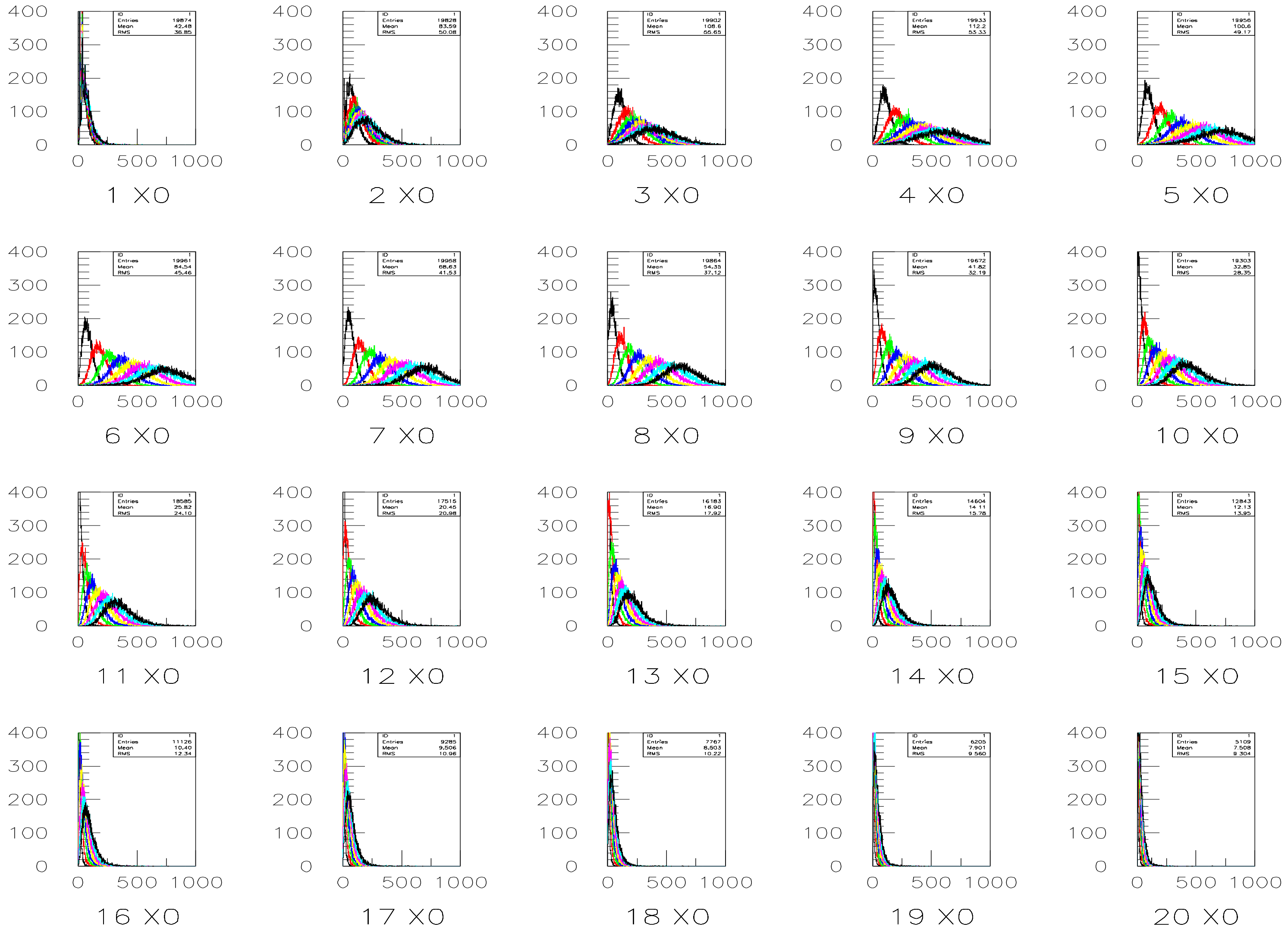


A high energy (above 100 MeV) electron, loses energy almost through bremsstrahlung. The emitted photons carry off a large fraction of the electron's initial energy. For photons with energy greater than 100 MeV the major interaction is pair production, which gives energetic electrons and positrons.

Thus a single electron or photon is the starting point of an avalanche of electrons, positrons and further photons. This avalanche is known as an electromagnetic shower. The figure shows the shower development and extinction in the converter material.

The histogram presents the 1 – 8 GeV/c electron shower sampled at different depths, as the mean amplitude signal (mean energy deposition) in a scintillation detector 10 mm thick, placed at different positions in the Pb converter. The distance is measured in radiation lengths units (X_0=0.56 cm for Pb).

Preshower Electron Spectra

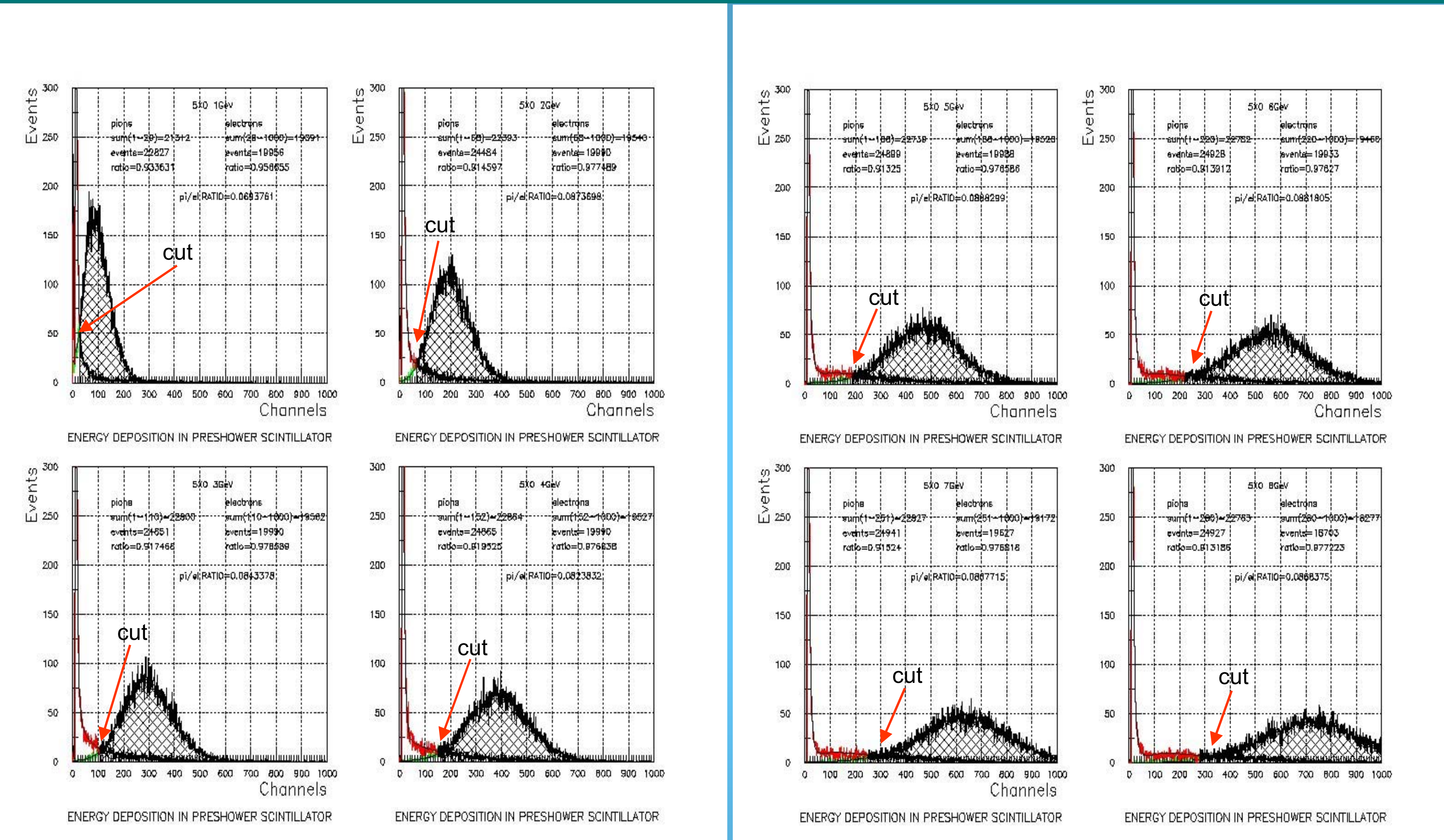


Preshower electron signal amplitude (ADC) distributions for 1– 8 GeV/c (with different colours).

The shower development in Pb converter is measured at different depths ($1X_0$, …,$20X_0$; for Pb X_0=0.56 cm).

It is seen that the maximum shower development is at 4 – 8 X_0depth in Pb.

Preshower Studies



Preshower amplitude distribution for e and π 1–8*GeV* produced by shower development at $5X_0$ depth in Pb (X_0=0.56 cm).

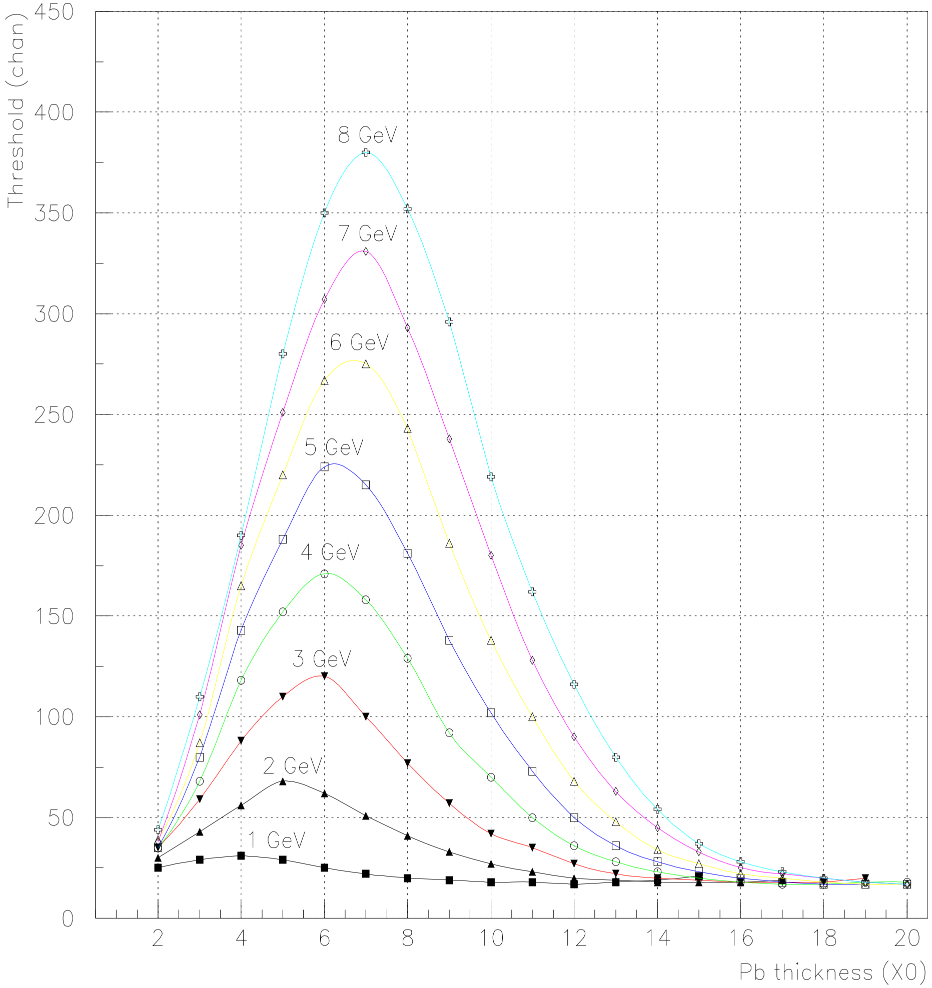
The $e-\pi$ separation cut at the intersection of the two distributions.

The cut level defines:

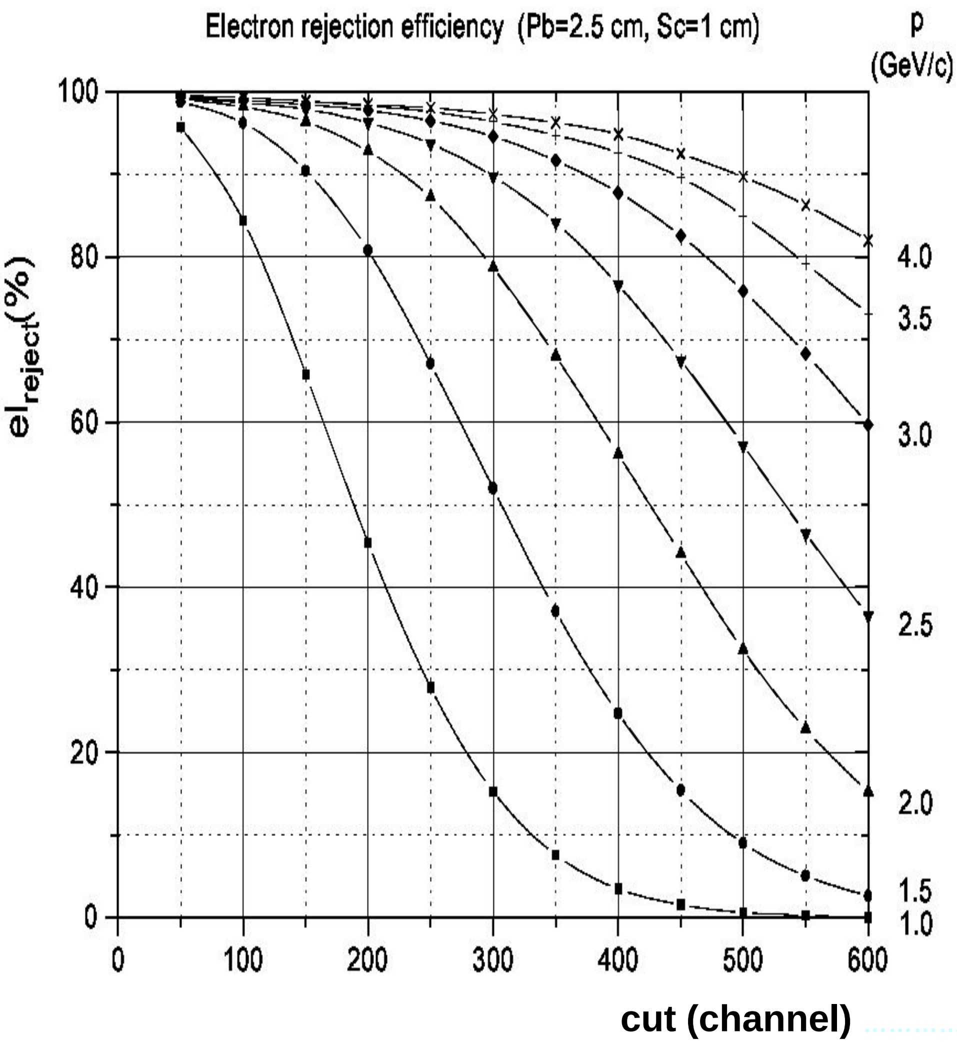
- ***electron rejection*** (e_{rej}) - ratio of the cut right side events and the total number of events in the electron spectrum
- ***electron escape*** (e_{esc}) – ratio of the cut left side events and the total number of events in the electron spectrum.
- ***pion efficiency*** (π_{eff}) - ratio of the cut left side events and the total number of events in the pion spectrum.

Preshower Electron-Pion Separation

Electron – pion cut position (threshold)



One-layer electron rejection efficiency



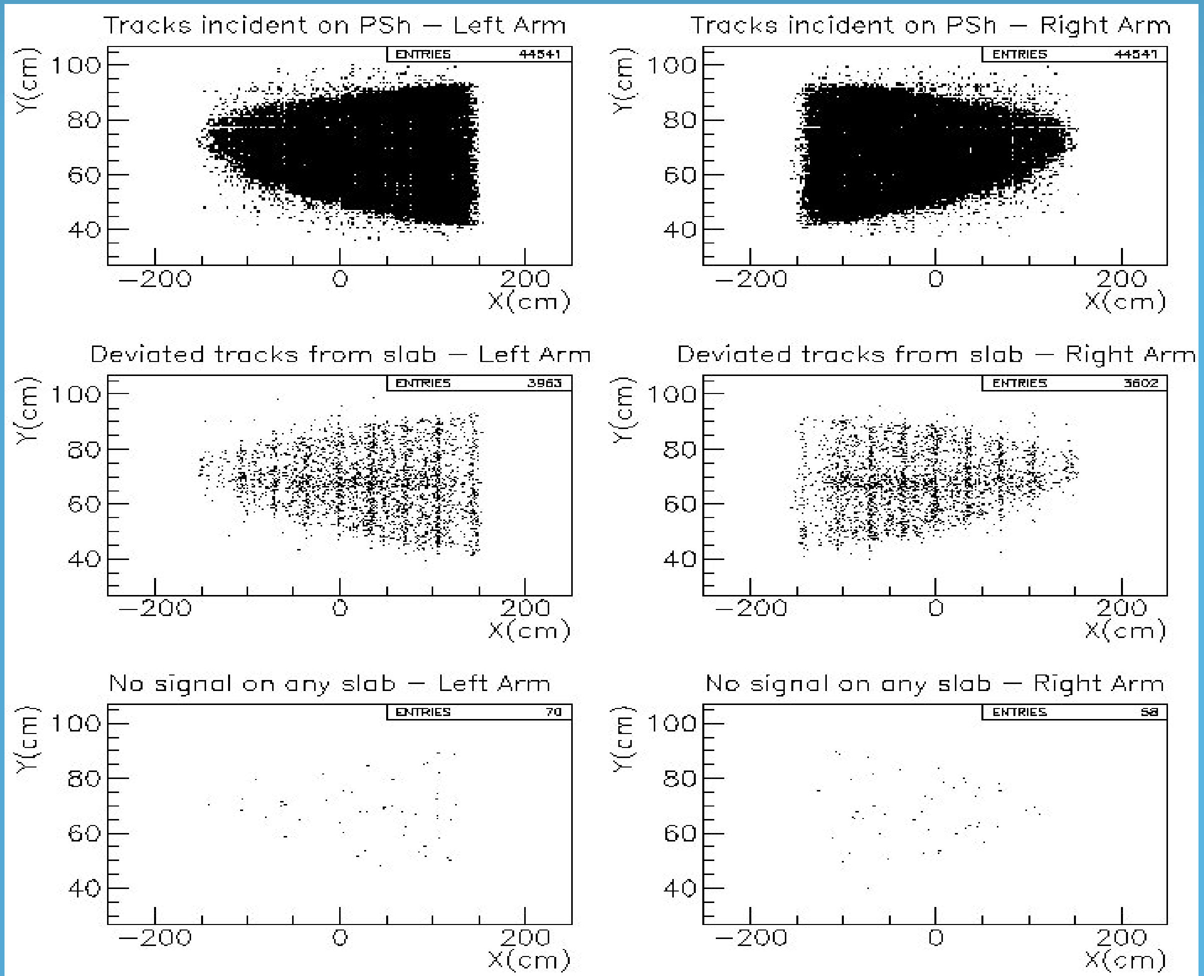
Preshower performances

electron rejection (cut right side events over total number of events in the electron spectrum)
pion loss (cut right side events over total number of events in the pion spectrum).

- $\left(V_1 \cdot H_1 \cdot Ch_1\right) \times \left(V_2 \cdot H_2 \cdot Ch_2\right)$ for $e^+ e^-$ pairs
- $\left(V_1 \cdot H_1 \cdot \overline{Ch_1}\right) \times \left(V_2 \cdot H_2 \cdot \overline{Ch_2}\right)$ for $\pi^+ \pi^-$ pairs

p (MeV/c)	cut (channel)	$N_\pi - n_\pi / N_\pi$ (π loss) (%)	$N_e - n_e / N_e$ (*e* rejec) (%)
1000	100	4.81	84.4
1500	100	7.04	96.2
2000	150	6.84	96.4
2500	150	8.44	97.9
3000	150	9.76	98.5
3500	150	10.7	98.9
4000	150	11.7	98.9

Track reconstruction on PSh detector



Arm	Tracks to PSh	Tracks on PSh	Signals on tracked slab	No signal on tracked slab (3-4)	No signal on tracked slab but on other one	ε_{arm} (%) (3/2)	ε_{slab} (%) (4/2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
left	44541	44296	42810	1486	1416	99.45	96.11
right	44541	44397	42991	1406	1348	99.68	96.52

FIRST MEASUREMENT OF THE $\pi^+\pi^-$ ATOM LIFETIME

B.Adeva, …, G.Caragheorgheopol, S.Constantinescu, M.Iliescu, M.Pentia, C.Petrascu, T.Ponta, D.Pop, et al.

Published in **Phys.Lett.B619:50-60,2005**

$$\tau = \frac{1}{\Gamma_0} = \left[2.91^{+0.49}_{-0.62} \right] \times 10^{-15}\, s$$

$$\left| a_0^0 - a_0^2 \right| = 0.264^{+0.033}_{-0.020}\, m_\pi^{-1}$$

Confirmation of the ChPT predictions (G.Colangelo, J.Gasser, H.Leutwyler, *Nucl. Phys.* B603 (2001) 125)

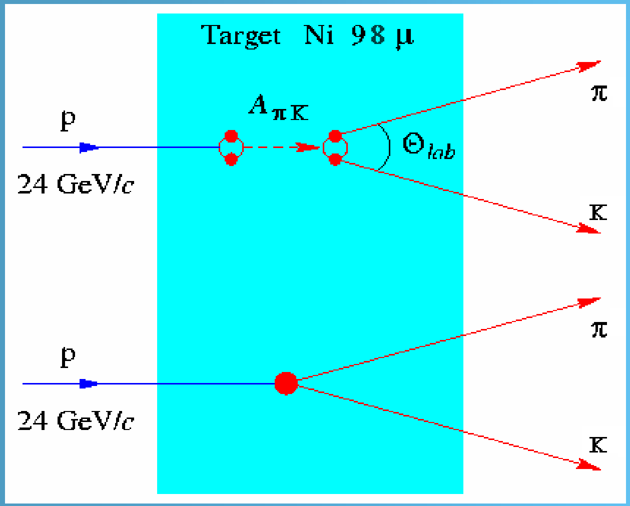
$$a_0^0 - a_0^2 = 0.265 \pm 0.004$$

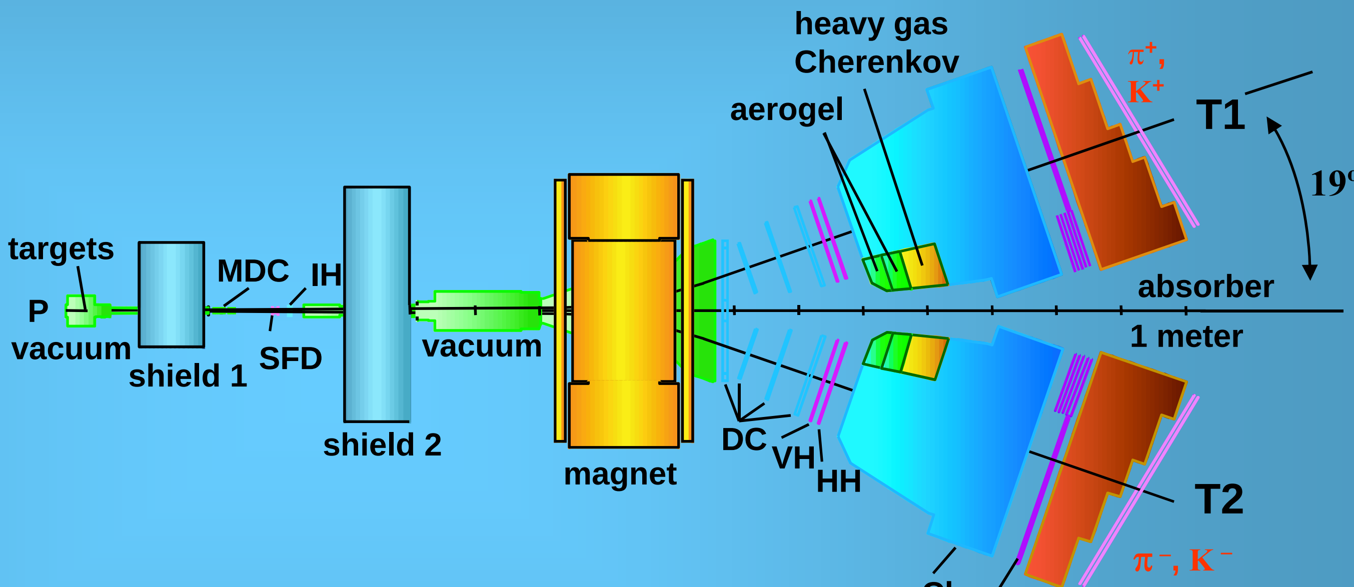
The New DIRAC project

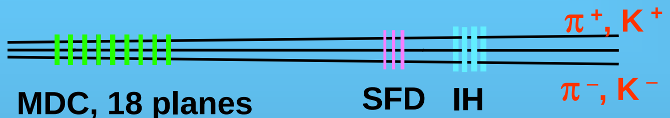
New tasks for DIRAC

πK hadronic atom

(asymmetric system)







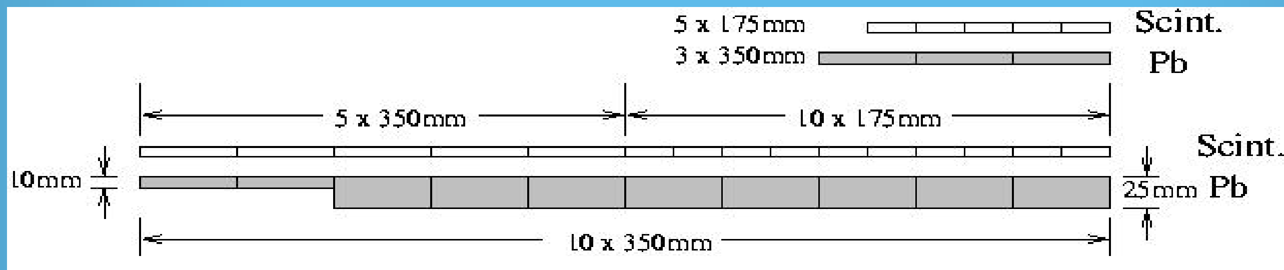
- Kaon detection
- Phase space modification
- *e – π separation*
- *π – K separation*
- *K – p separation*

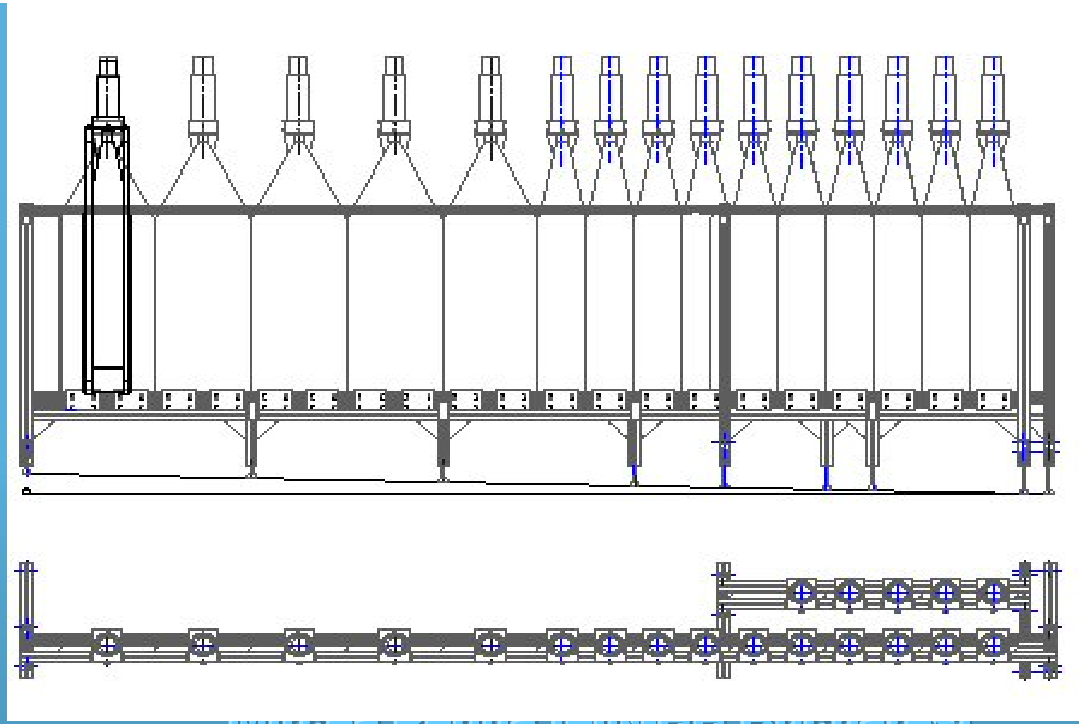
Preshower detector upgrade works

1. Monte – Carlo simulation study for the new detector design
2. The new detector preparation, mounting and commissioning at CERN – proton synchrotron (East Hall)
3. The new Preshower Detector test with the 24 GeV proton beam
4. The amplitude and time signal alignment for all 40 detector elements:
   - Pedestal level
   - Signal amplification
   - Signal attenuation
   - Signal delay
5. The new PSh characteristics:
   - larger aperture: 2 x 3500 mm x 750 mm
   - two layer configuration in the kaon region
   - increased electron rejection efficiency: > 99.6%
   - higher counting rate in the kaon region: by 2 times
   - larger granularity: 40 signal channels
6. PSh detector has been prepared, installed and tested within DIRAC setup

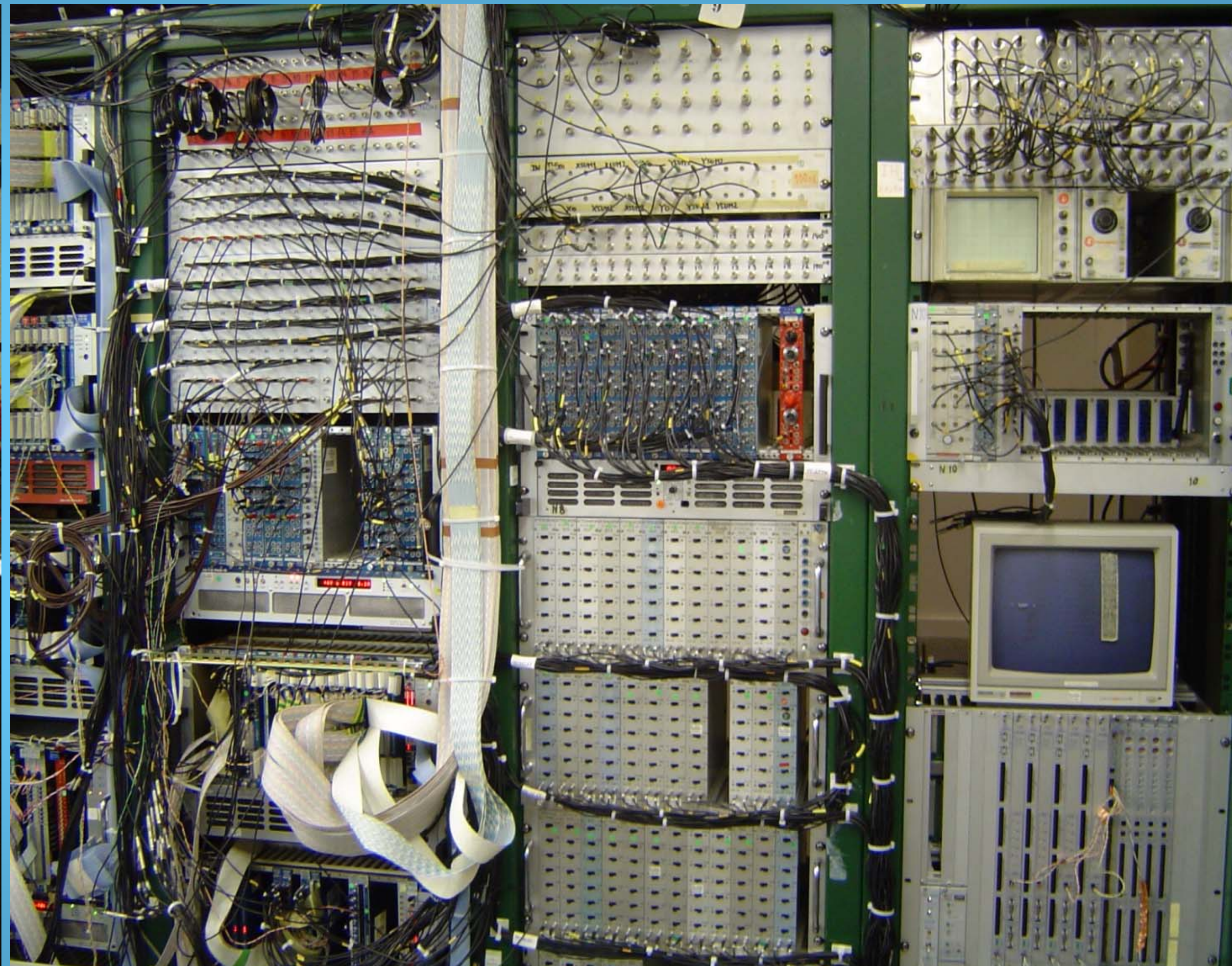
Technical Solution

Layer	Dimensions	Pb Convertor	Scintillators (BC-408)
I	width thickness	10 x 350 mm 2 x 10 mm + 8 x 25 mm	5 x 350 mm + 10 x 175 mm
II	width thickness	3 x 350 mm 3 x 10 mm	5 x 175 mm

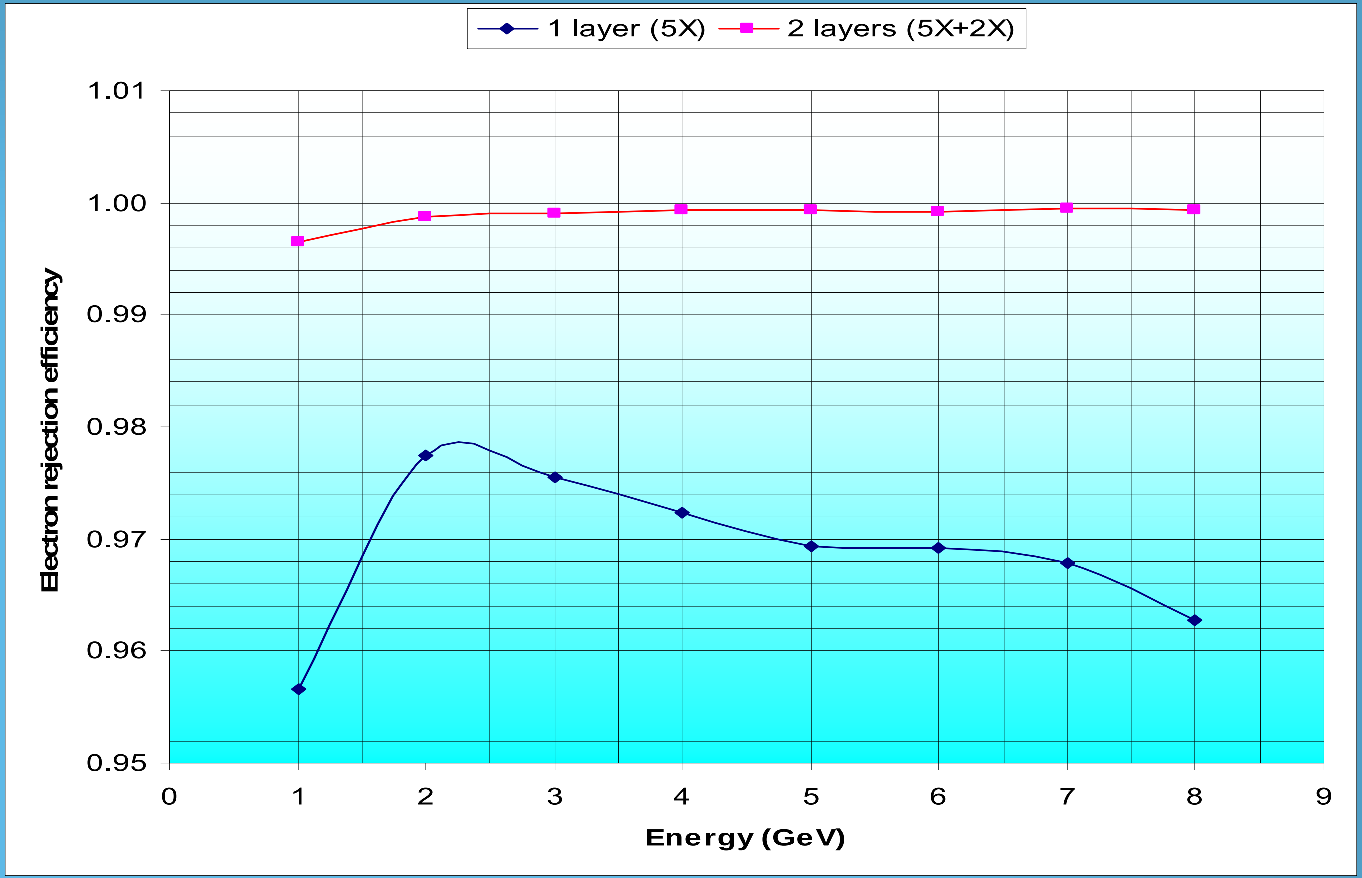




The New Preshower Detector at work



PSh Electron Rejection Efficiency



Two-layers electron rejection efficiency:

$$e_{rej}=e_{rej1}+ e_{esc1}{}^{*} e_{rej2}$$

Energy (GeV)	1	2	3	4	5	6	7	8
e_{rej1} $(5X_0)$	0.956655	0.977489	0.975488	0.972286	0.969282	0.969147	0.967901	0.962680
$e_{esc1}{}^{*}e_{rej2}$ $(2X_0)$	0.039814	0.021306	0.023616	0.026992	0.030044	0.030125	0.031540	0.036707
e_{rej} $(5X_0 + 2X_0)$	0.996469	0.998795	0.999104	0.999278	0.999326	0.999272	0.999441	0.999387

DIRAC measurements today and tomorrow

- Data taking in 2008 and 2009 will allow us to measure the lifetime of πK atom and to obtain the first evaluation of the scattering length combination $|a_{1/2} - a_{3/2}|$.
- The measurement of the *s*-wave $\pi\pi$ scattering lengths checks the $SU(2)_L \times SU(2)_R$ symmetry breaking of QCD (*u*, *d* quarks).
- The measurement of the *s*-wave πK scattering lengths would test the chiral $SU(3)_L \times SU(3)_R$ symmetry breaking of QCD (*u*, *d* and *s* quarks).
- In 2009 we are planning to present an Addendum to the DIRAC experiment with the aim to observe the $\pi^+\pi^-$ atom long-lived states in 2010.
- Further data taking in 2011 will allow us to obtain experimentally the Lamb shift ΔE_{2s-2p} in this atom.
- The measurement of ΔE_{2s-2p} allows determining in a model-independent way the combination of $\pi^+\pi^-$ scattering lengths $2a_0+a_2$.
- Together with the $\pi^+\pi^-$ atom lifetime measurement, a_0 and a_2 will then be determined separately.
- The method of the Lamb shift measurement use only the theory of the Stark effect and does not have the systematic errors known from the lifetime measurement.
- This experiment can be performed with the existing setup without change neither of detectors nor electronics.

DIRAC today and tomorrow

Present low-energy *QCD* predictions for *ππ* and *πK* scattering lengths

$\pi\pi \quad \delta a_0 = 2.3\% \quad \delta a_2 = 2.3\% \quad \delta(a_0 - a_2) = 1.5\%$ will be improved by Lattice calculations

$\pi K \quad \delta(a_{1/2} - a_{3/2}) = 10\%$ will be significantly improved by ChPT calculations

Expected results of DIRAC ADDENDUM at PS CERN after 2008-2009

$$\tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 2\% (stat) \pm 1\% \ (syst) \pm 1\% \ (theor)$$

$$\tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 10\% (stat) \pm .... \pm 1.5\% \, (theor)$$

2010-2011 Observation of metastable $\pi^+\pi^-$ atoms and estimation its Lamb shift

Study of the possibility to observe K^+K^- and $\pi^\pm\mu^\mp$ atoms using 2008-2009 data.

DIRAC at SPS CERN beyond 2011

The number of detected $\pi^+\pi^-$ atoms will be 15 times higher than the one at 24GeV,
The number of $K^+\pi^-$ atoms 25 times and the number of $K^-\pi^+$ atoms 32 times higher.

$$\tau(A_{2\pi}) \rightarrow \delta(a_0 - a_2) = \pm 0.5\% (stat) \qquad \tau(A_{\pi K}) \rightarrow \delta(a_{1/2} - a_{3/2}) = \pm 2.5\% (stat)$$

$$(E_{np} - E_{ns})_{\pi\pi} \rightarrow \delta(2a_0 + a_2) \approx \pm 2.5\% (stat) \qquad (E_{np} - E_{ns})_{\pi K} \rightarrow \delta(2a_{1/2} + a_{3/2})$$

Thank you !

Some PSh team members

IFIN-HH Bucharest Team

Dr. Mircea Pentia - Team leader
ing. Daniel Bartos
ing. Horia Bozdog
Dr. Constantin Ciortea
ing. Gheorghe Caragheorgheopol
ing. Serban Constantinescu
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Dr. Mihai Iliescu
ing. Constantin Nicolescu
Liviu Penescu
ing. Mirel Petcu
Dr. Catalina Petrascu
ing. Marian Petre
Dr. Titus Ponta
ing. Dan Pop
ing. Cristian Teodorescu
Dr. Valeriu Zoran

DIRAC

Additional slides

$\pi^+\pi^-$ Scattering Amplitude

$$f(\theta)=\sum_{l=0}^{\infty} f_l \cdot P_l(\cos\theta)=\sum_{l=0}^{\infty}(2l+1)\frac{1}{k\cot\delta_l - ik}P_l(\cos\theta)$$

Low energy – *S*-wave *scattering length* a_0

$$f_0=\frac{1}{k\cot\delta_0 - ik} \quad ; \quad a_0=\lim_{k\to 0} f_0=\lim_{k\to 0}\left(\frac{\sin\delta_0}{k}\right)$$

Effective range theory: $k\cot\delta_0=-\frac{1}{a_0}+\frac{1}{2}r_0k^2+\ldots$

Bound state if E<0 then k=iκ, where $\kappa=\sqrt{-2mE}$
specified by the presence of a pole along the positive imaginary axis, i.e. for $\kappa > 0$ under the analytic continuation $k\to i\kappa$

$$-\frac{1}{a_0}+\frac{1}{2}r_0k^2-ik\to-\frac{1}{a_0}-\frac{1}{2}r_0\kappa^2+\kappa=0$$

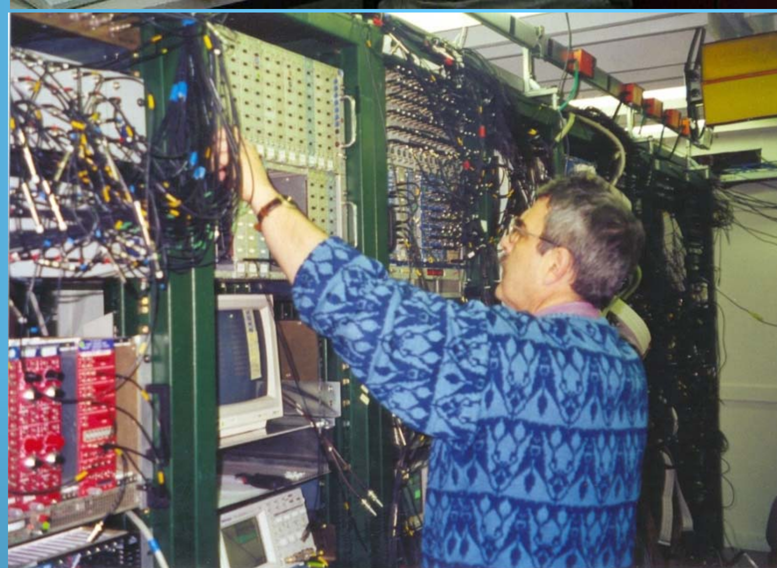
DIRAC method

The most precise predictions of ChPT (G.Colangelo, J.Gasser, H.Leutwyler, *Nucl. Phys.* B603 (2001) 125) have been achieved for the *s*-wave *scattering lengths* (in m_π^{-1} units):

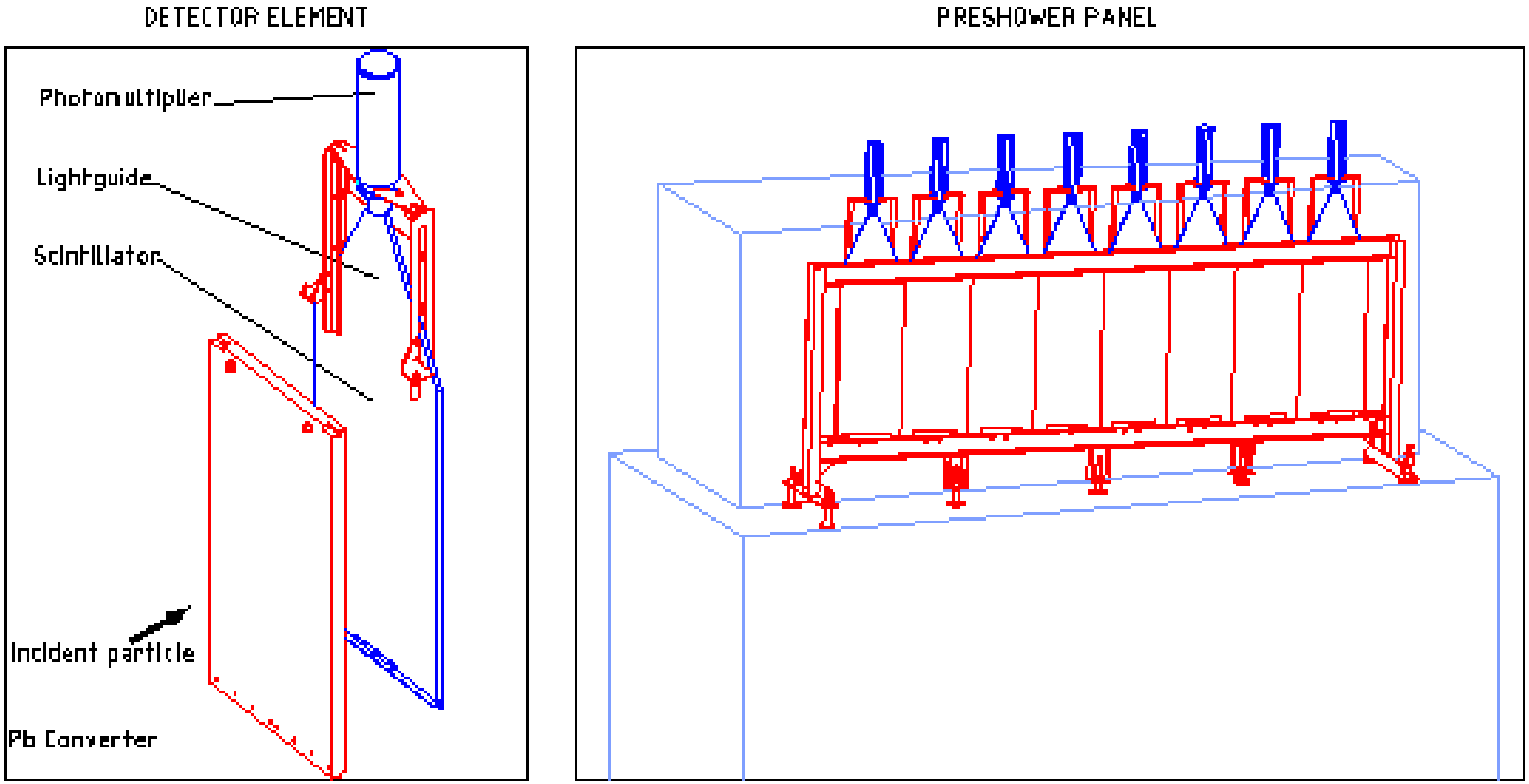
$$a_0 = 0.220 \pm 0.005,$$
$$a_2 = -0.0444 \pm 0.0010,$$
$$a_0 - a_2 = 0.265 \pm 0.004$$

These values will be compared with those determined in the decay of the pionium (atom $\pi^+\pi^-$).

Some Members of IFIN-HH Bucharest Team



Preshower Detector configuration

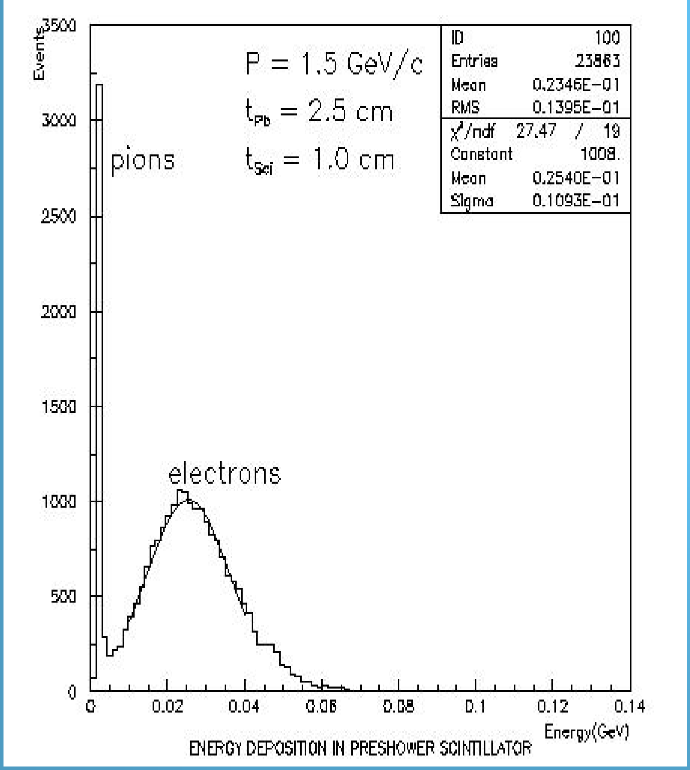


Preshower Amplitude Spectra

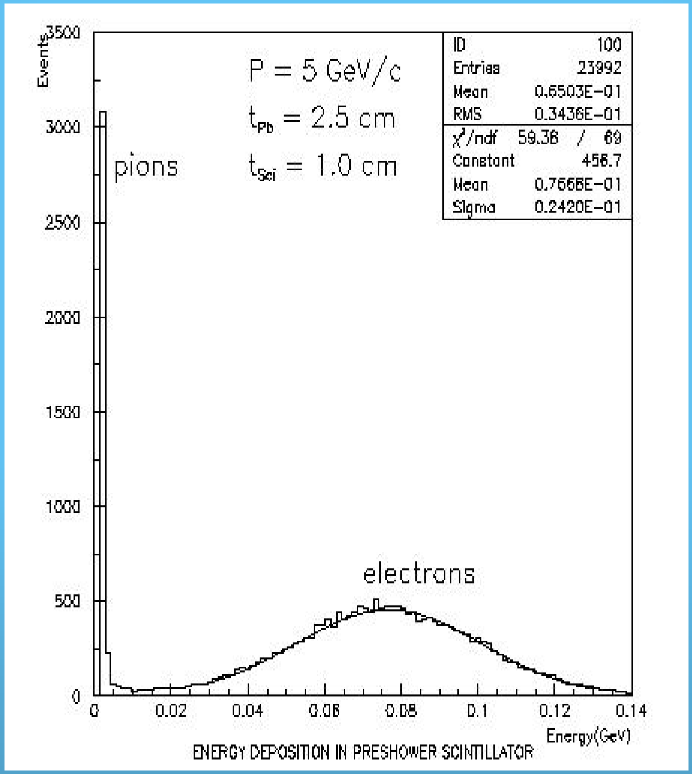
Our Preshower, consisting of a Pb converter (1 – 7X_0) followed by a scintillation detector, samples the early part of the electron shower, where it is in good shape. The pion (hadron) shower practically is not yet initiated, so pions interact as minimum ionizing particles (mip) and produce a small amplitude signal by direct interaction with the scintillation detector.

A simulation of the PSh amplitude spectra, produced by 1.5 GeV/c and 5 GeV/c electrons and pions in 2.5 cm Pb (~4.5 X0), can be seen in Figures (a) and (b). The PSh experimental spectra are presented in Figure (c).

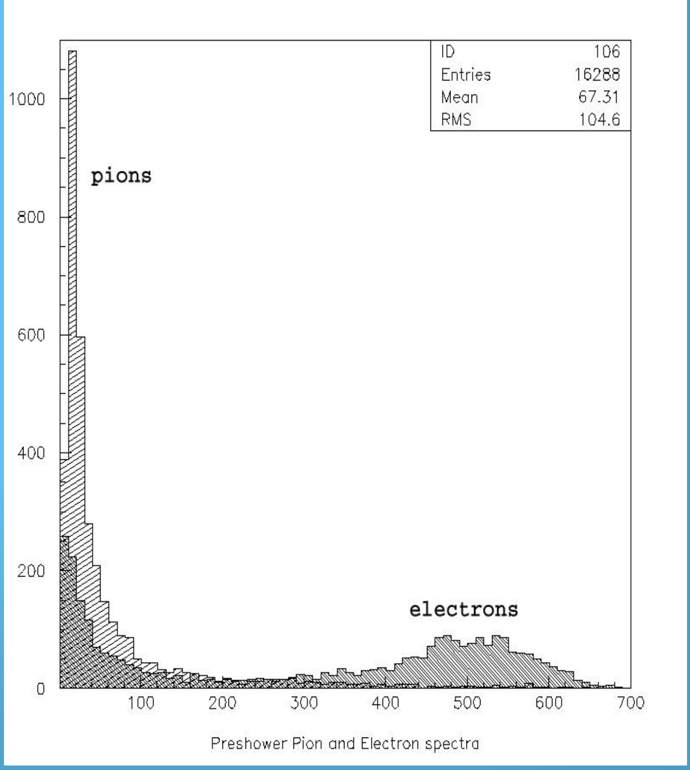
Therefore the PSh detector has a high amplitude spectrum for electrons and low amplitude one for pions. This provides the electron/pion separation capability.



(a)



(b)



(c)

Preshower Signals