А.М.Рождественский

Исследование редких распадов пионов с помощью установки PIBETA

(В связи с выборами на должность снс)

B. Pontecorvo

μ-e universality, 1947.

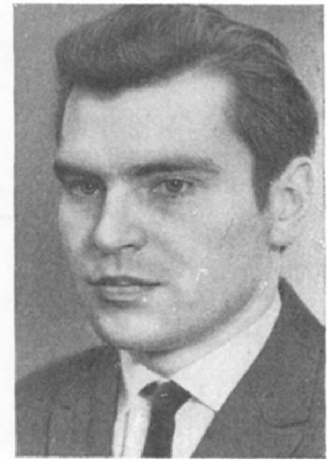
"We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β- processes and processes of emission or absorption of charged mesons" (muons)

Phys.Rev., v72(1947)246.

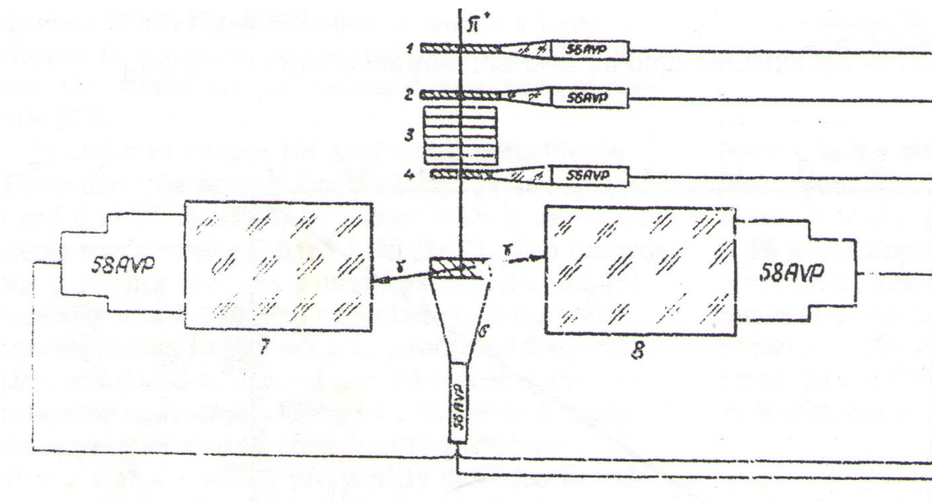
A.D.Dunaitsev

V.I.Petrukhin

Yu.D.Prokoshkin



V.I.Rykalin



$$\pi^+ \rightarrow \pi^0 e^+ \nu$$

1962 год

С середины 60-х по наст. время

Синхрофазотрон ЛЯП:

МMИС (Магнитный Многозазорный Искровой Спектрометр)
Поиск запрещенного распада $\mu^+ \to e^+ e^- e^+$

АРЕС (Анализатор РЕдких Событий)
Исследование редких распадов пионов и мюонов

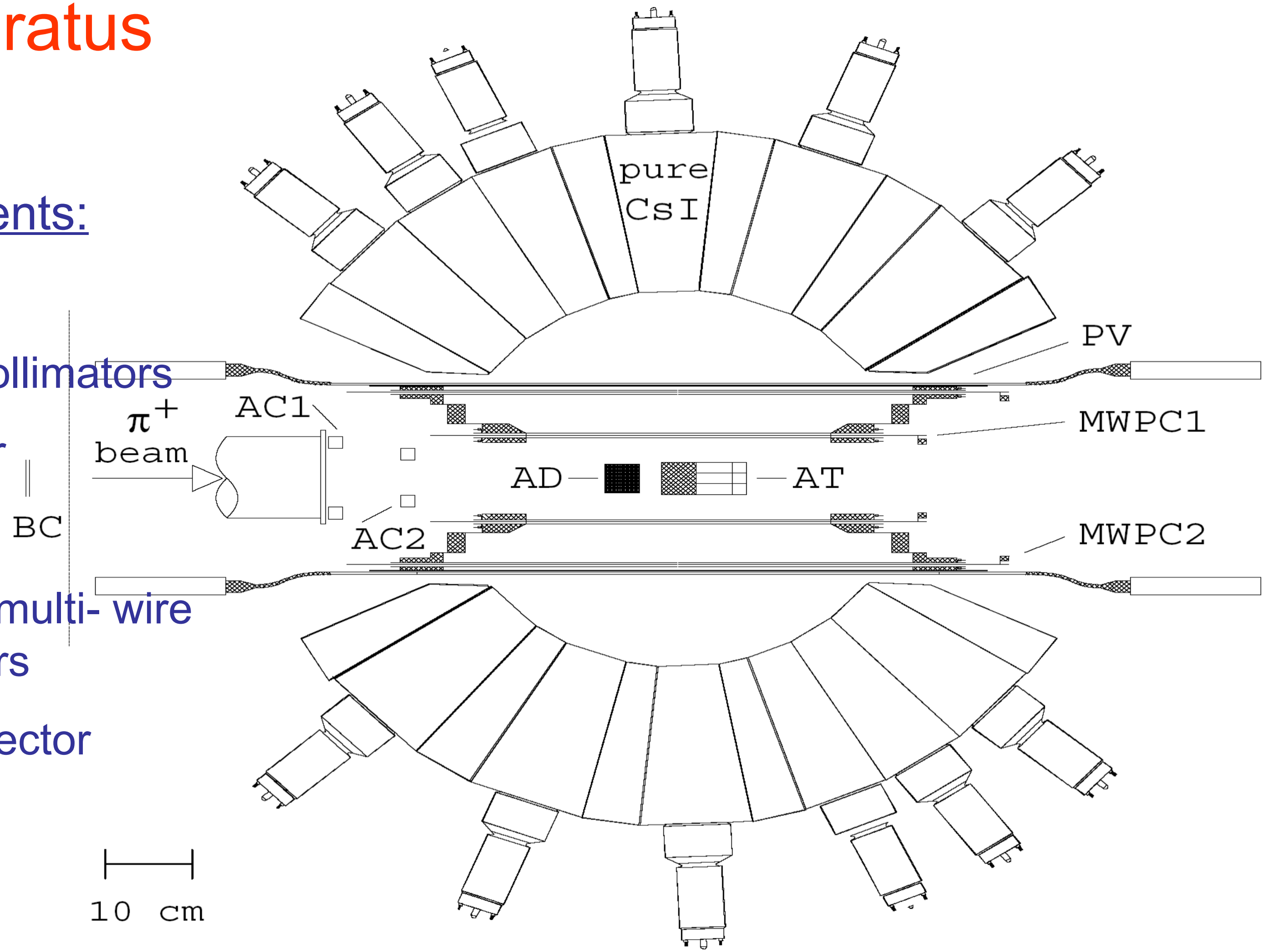
Мезонная фабрика в PSI:
PIBETA (PEN)
Изучение бета распада заряженного пиона,
радиационного распада пиона и мюона,
распада пиона на позитрон и нейтрино


SINQ

Physics goals for the PIBETA (PEN)

- Study β decay of the pion $\pi^+ \to \pi^0 e^+ \nu_e$
  - Precise measurment of V_{ud} element of the CKM matrix
- Study pion radiative decay $\pi^+ \to e^+ \nu_e \gamma$
  - Structure of the pion, check of the CVC hypothesis, deviations from $V - A$ form of $\mathcal{L}_{\text{weak}}$
- Study muon radiative decay $\mu^+ \to e^+ \nu \overline{\nu} \gamma$
  - Precise test of the weak interaction, deviations from $V - A$ form of $\mathcal{L}_{\text{weak}}$
- Study nonradiative decay $\pi^+ \to e^+ \nu_e$
  - electron-muon universality

Cross section of the PIBETA apparatus



The main components:

BC – beam counter

AC1, AC2 – active collimators

AD – active degrader

AT – active target

MWPC1, MWPC2 – multi- wire proportional chambers

PV – plastic veto detector

CsI (pure) crystals

CsI (pure) Calorimeter

The PEN calorimeter consists of 240 pure CsI crystals.
The inner radius of the calorimeter is 26 cm, and the module axial length is 22 cm; corresponding to 12 CsI radiation lengths (X_0 = 1.85cm)

Weight is 1.6 T.

Fast component decay time 7 ns

Slow component decay time 35 ns

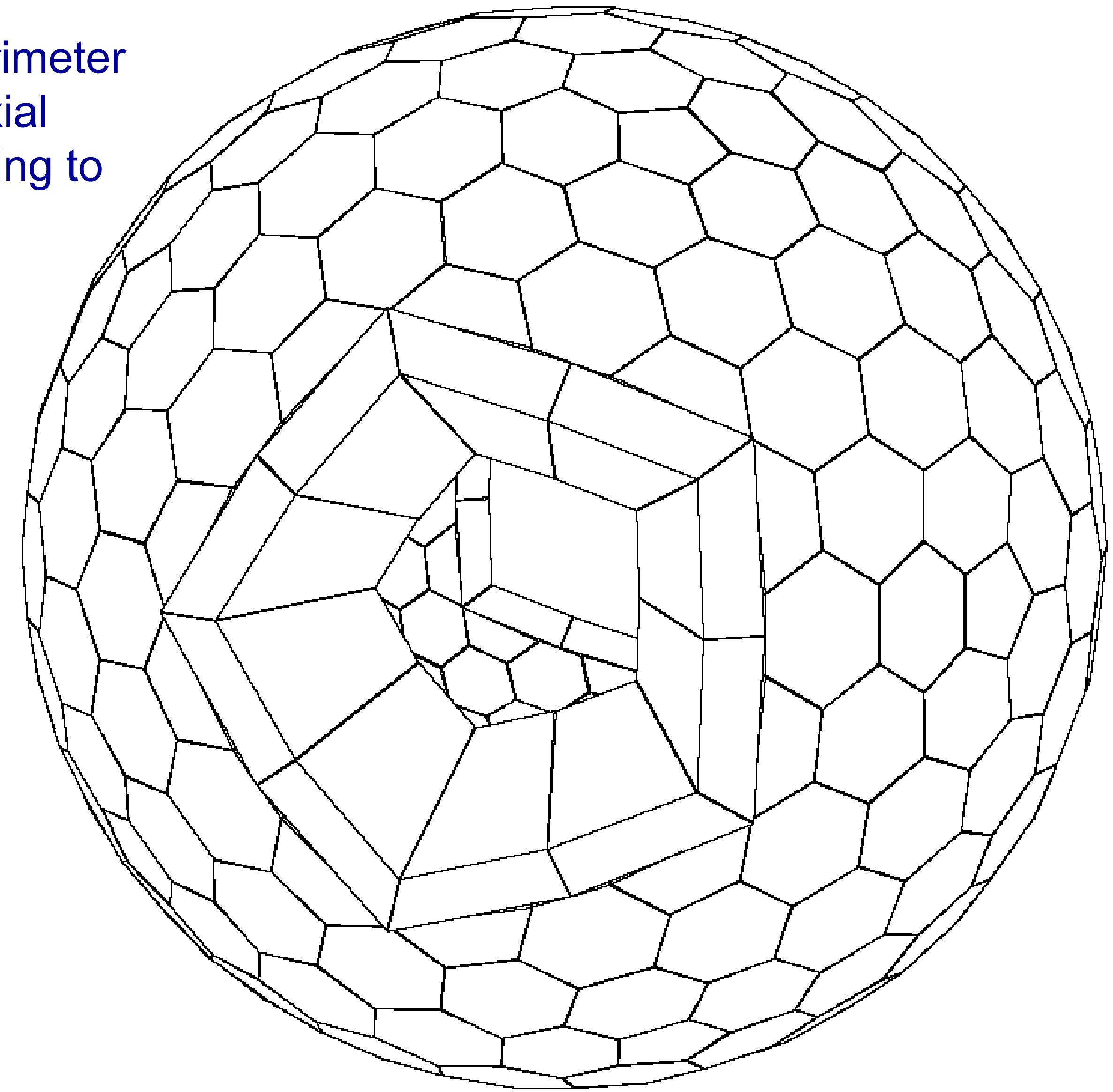
Fast/Total >0.76

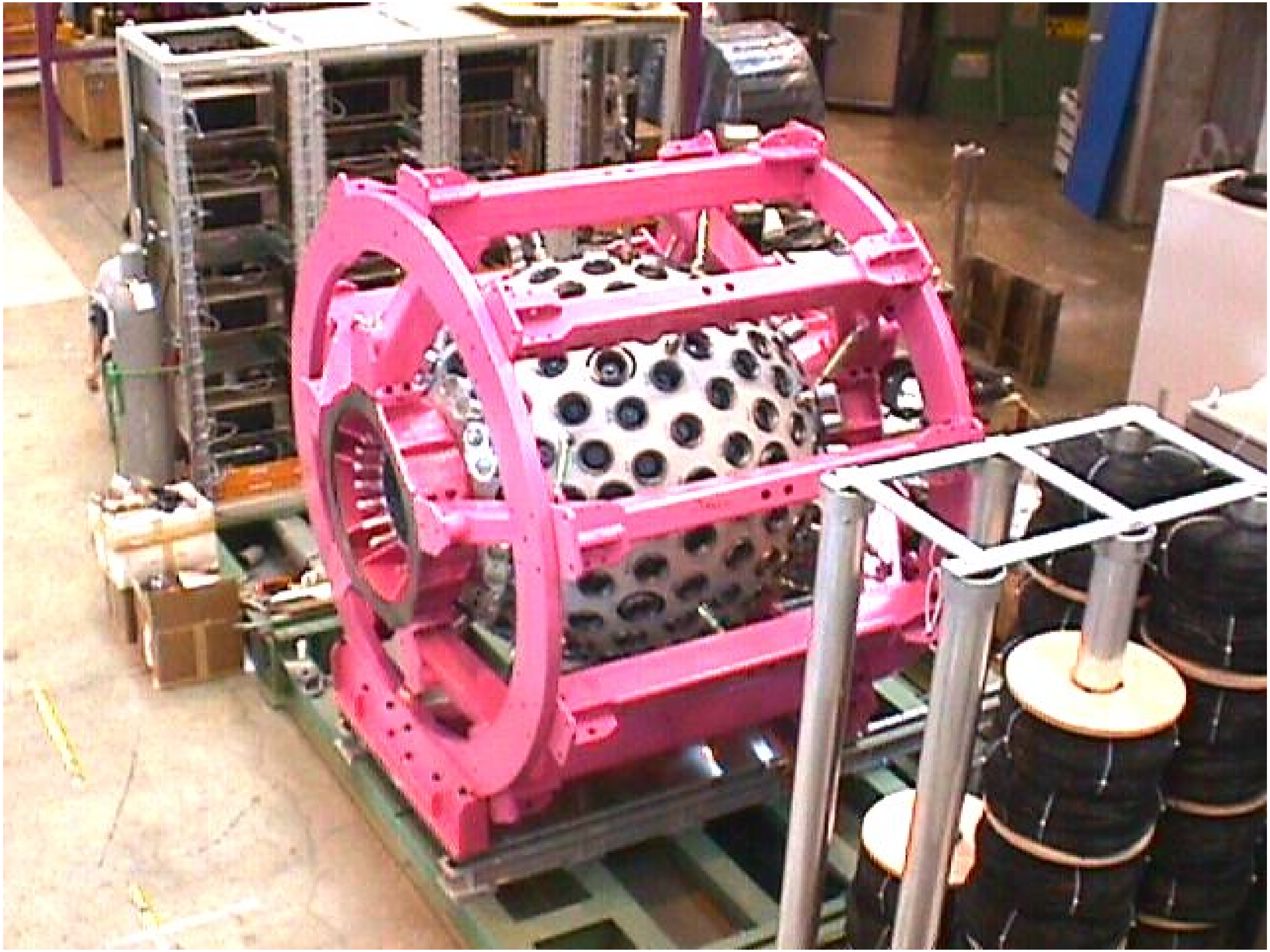
total solid angle ~0.77·4π

Angle resolution ~2°

ΔE/E ~ 4-5%

Time resolution ~ 0.68 ns





MWPC: трековый детектор должен обладать следующими свойствами

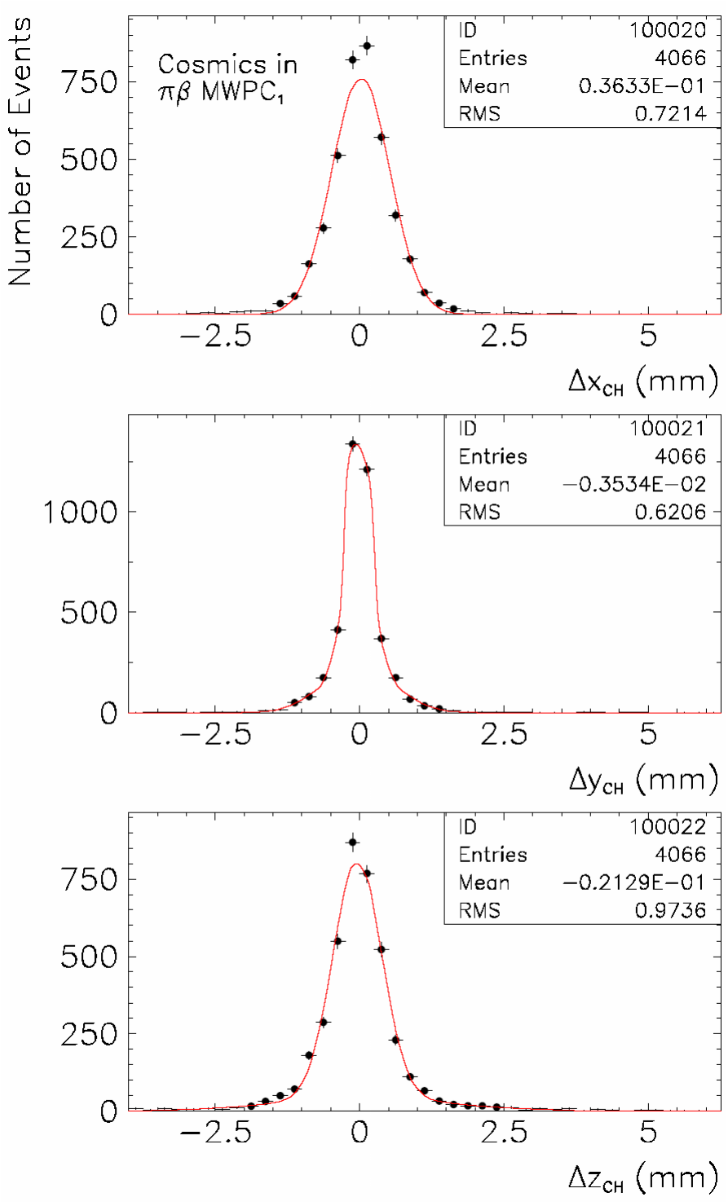
Высокой эффективностью регистрации заряженных частиц;

Возможностью работать при больших загрузках (10^7 $с^{-1}$);

Стабильностью в работе и радиационной стойкостью;

Цилиндрической геометрией;

Малым количеством вещества для уменьшения вероятности конверсии γ-квантов в e^+e^--пары;



Разрешение по X, Y и Z

полученное из экспериментальных данных

Угловое разрешение по $\varphi \approx 0.75^{O}$
Разрешение по z ~0.97мм
Разрешение по x,y ~0.6-0.7мм

Plastic Hodoscope

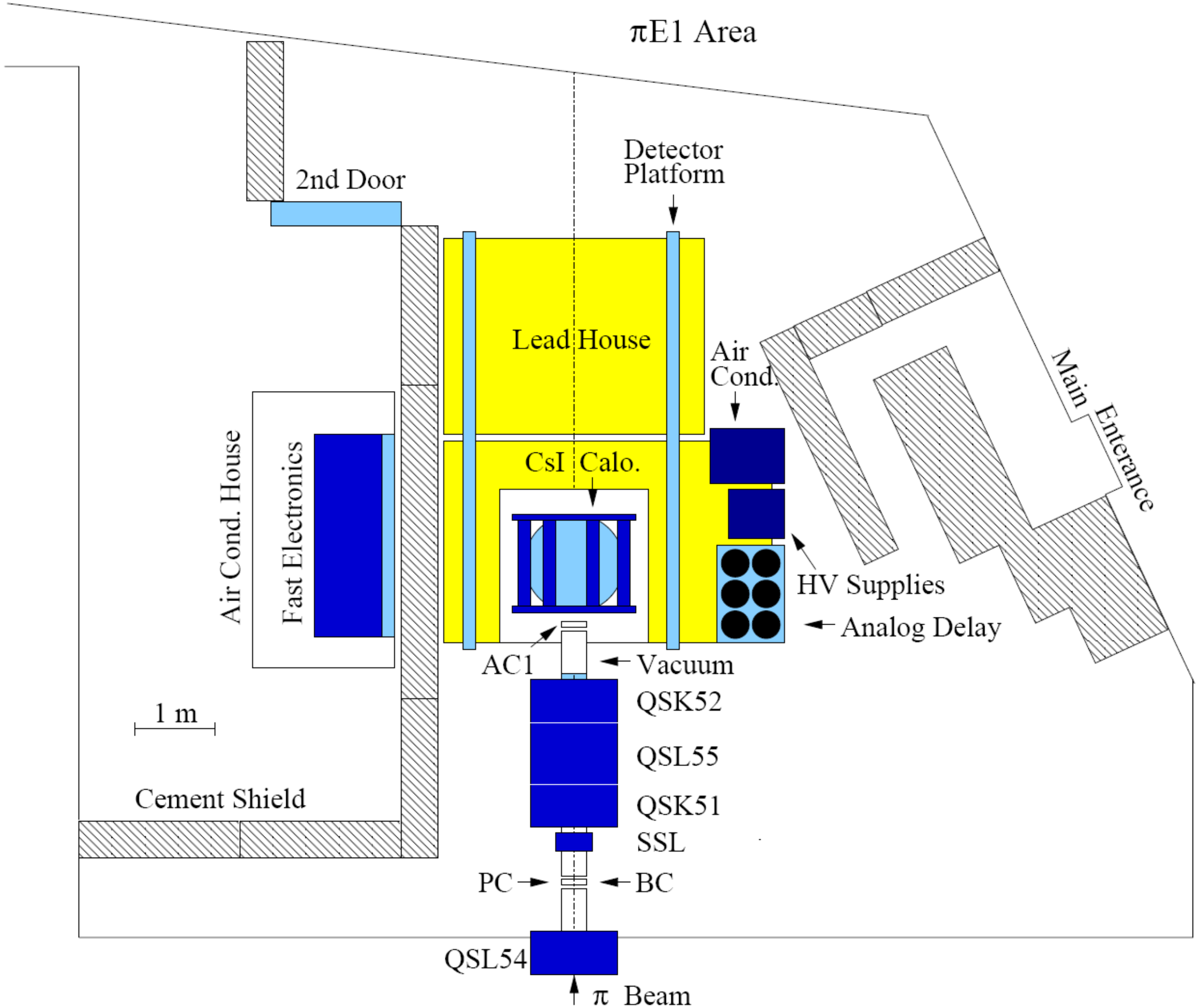
It supplements the MWPC tracking and CsI calorimetry by providing:

(1) efficient charged particle detection, particularly when combined with the MWPC data;

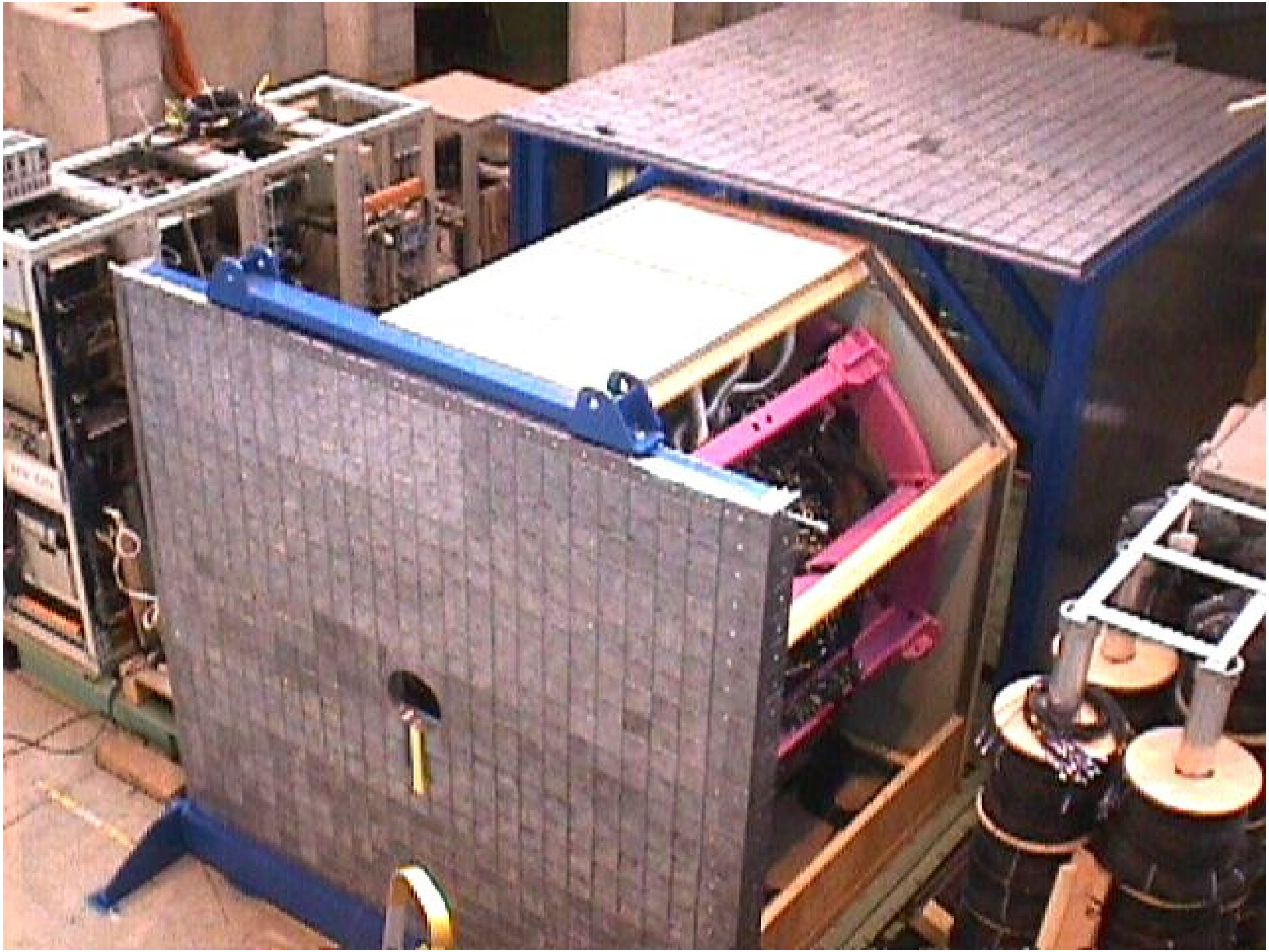
(2) reliable discrimination between minimum ionizing particles (cosmic muons, positrons/electrons) and protons;

(3) crude measurements of charged particle azimuthal angle 9 degree;

(4) precise charged particle timing information +-0.3 ns



Расположение установки на канале πE1 ускорителя PSI (вид сверху)



The PEN Collaboration

D.Počanić,[a] A. van der Schaaf,[g] L.P.Alonzi,[a] V.A.Baranov,[c] W.Bertl,[b] M.Bychkov,[a] Yu.M.Bystritsky,[c] E.Frlež,[a] C.J.Glaser,[a] V.A.Kalinnikov,[c] N.V.Khomutov,[c] A.S.Korenchenko,[c] S.M.Korenchenko,[c] M.Korolija,[f] T.Kozlowski,[d] N.P.Kravchuk,[c] N.A.Kuchinsky,[c] M.C.Leman,[a] D.Mekterović,[f] D.Mzhavia,[c,e] A.Palladino,[a] P.Robmann,[g] A.M.Rozhdestvensky,[c] S.N.Shkarovskiy,[c] U.Straumann,[g] I.Supek,[f] P.Truől,[g] Z.Tsamalaidze,[c,e] E.P.Velicheva,[c] M.G.Vitz,[a] V.P.Volnykh[c]

a)Department of Physics, University of Virginia, Charlottesville, VA 22904-4714, USA
b)Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
c)Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
d)Institute for Nuclear Studies, PL-05-400 Swierk, Poland
e)IHEP, Tbilisi, State University, GUS-380086 Tbilisi, Georgia
f)Rudjer Bošković Institute, HR-10000 Zagreb, Croatia
g)Physik-Institut der Universität Zürich, CH-8057 Zürich, Switzerland

$$\pi^+ \rightarrow \pi^0\ e^+\ \nu$$

Pion beta decay rates offers on of the most precise means of testing the concerved vector current hypothesis (CVC) and studing the weak u-d quark mixing.

The SM description of the πβ decay is theoretically unambigous with a 0.1% uncertainty, but a small ~10^{-8} branching ratio poses significant experimental challenges.

The Pion Beta Decay Branching Ratio

$\pi^\pm \rightarrow \pi^0 e^\pm \nu_e$ BR$_{\pi\beta} \sim 1 \times 10^{-8}$

Pure vector transition: $0^- \rightarrow 0^-$

Theoretical decay rate at tree level:

$$\frac{1}{\tau_0} = \frac{G_F^2 |V_{ud}|^2}{30\pi^3} \left(1 - \frac{\Delta}{2M_+}\right)^3 \Delta^5 f(\epsilon, \Delta)$$

$$= 0.40692(22)|V_{ud}|^2 (\mathrm{s}^{-1})$$

With radiative and loop corrections we get:

$$\frac{1}{\tau} = \frac{1}{\tau_0}(1+\delta),$$

so that the branching ratio is

$$BR_{\pi\beta} = \frac{\tau_\pm}{\tau_0}(1+\delta)$$

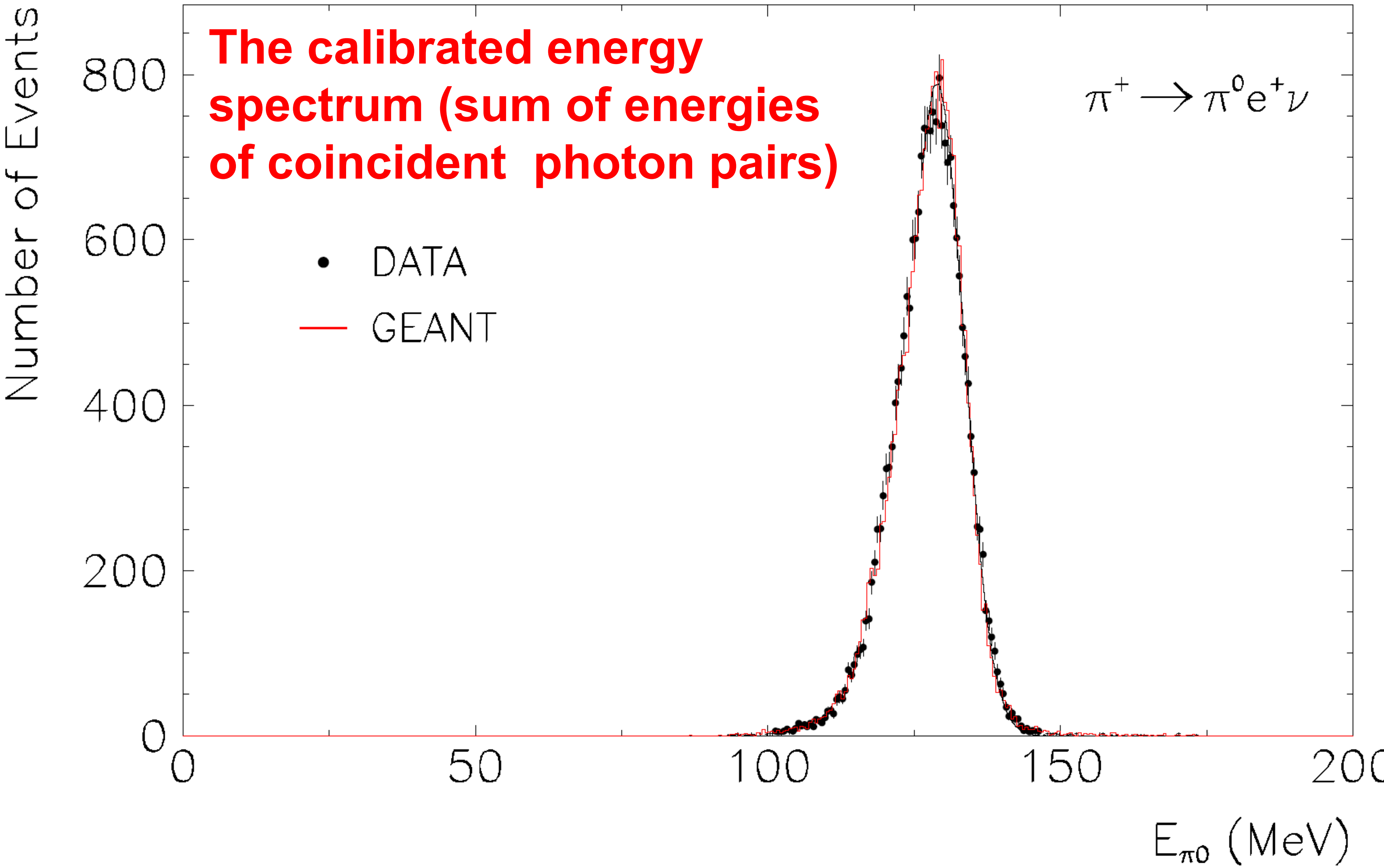
$$= 1.0593(6) \cdot 10^{-8} (1+\delta) |V_{ud}|^2.$$

The Pion Beta Decay Radiative Corrections

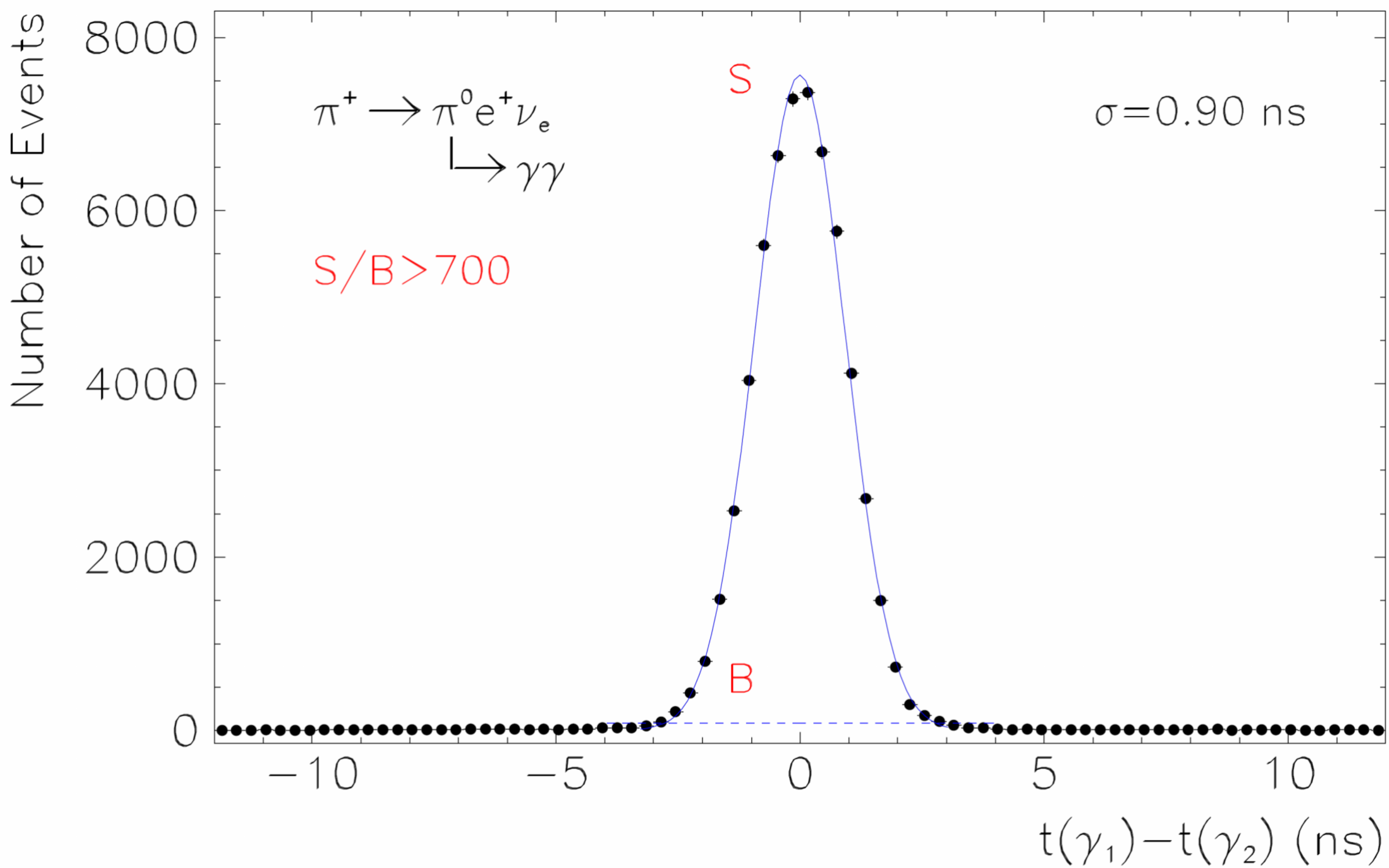
(1) In the light-front quark model
W. Jaus, Phys. Rev. D **63** (2001) 053009
• total RC for the pion beta decay:

$$\delta = (3.223 \pm 0.002) \times 10^{-2}.$$

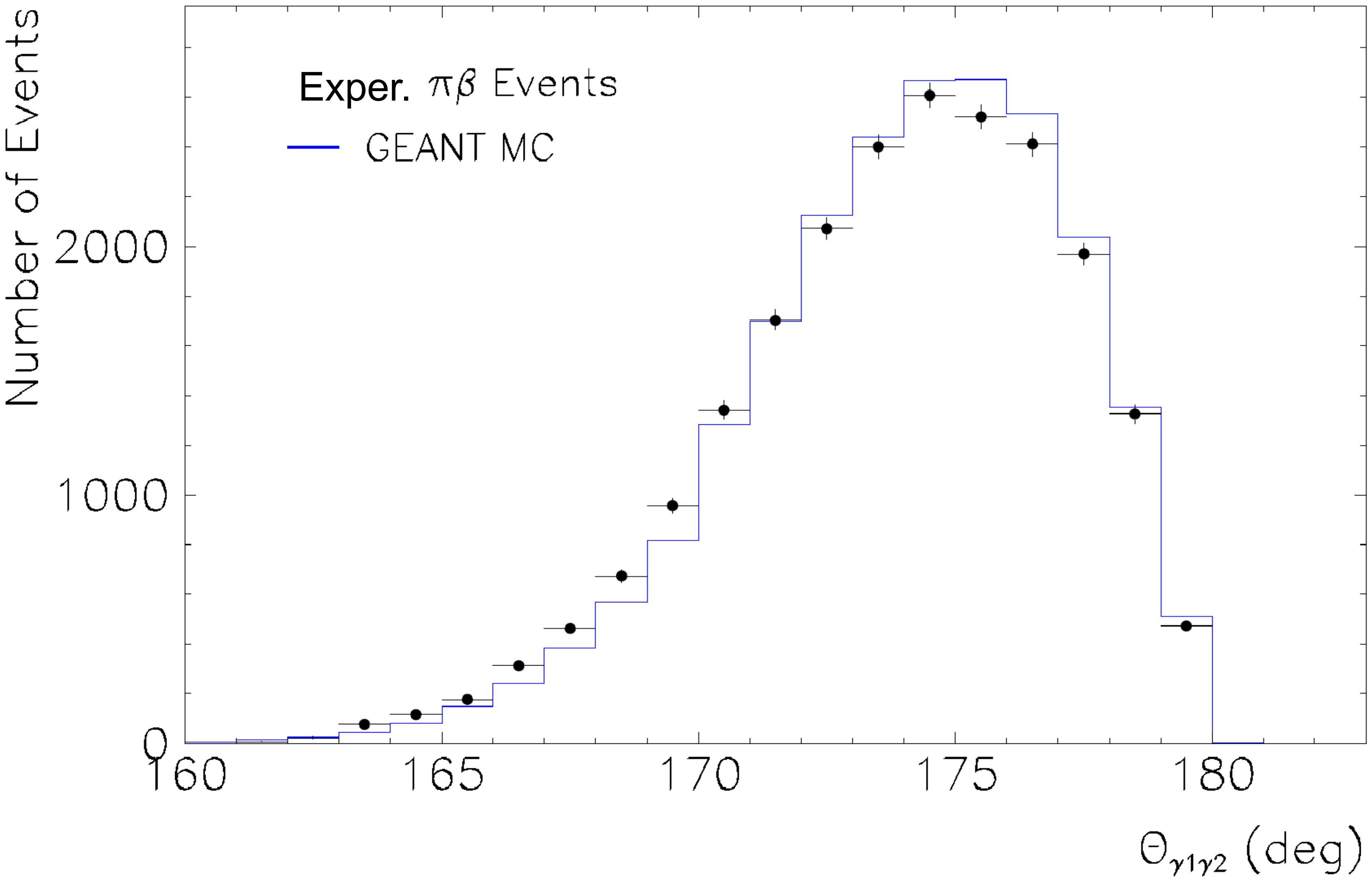
(2) in the chiral perturbation theory
V. Cirigliano, M. Knecht, H. Neufeld and H. Pichl,
Eur. Phys. J. C 27 (2003) 255-262
• χPT with e-m terms up to $O(e^2 p^2)$
• $\mathrm{BR}_{\pi\beta} \rightarrow |V_{ud}|$, theoretical uncertainty of $5 \cdot 10^{-4}$



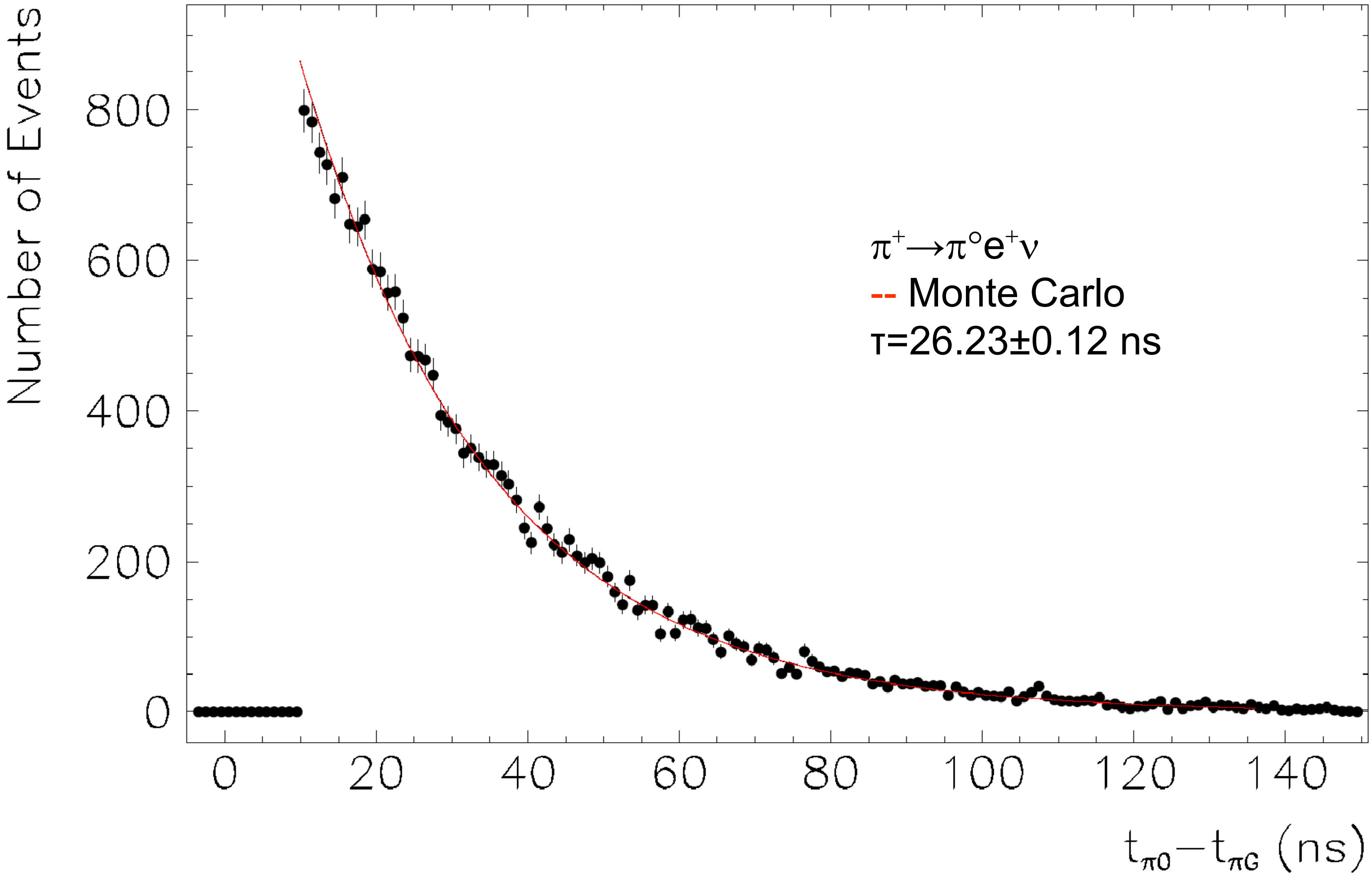
The calibrated energy spectrum (sum of energies of coincident photon pairs)
Number of Events
800
600
400
200
0
0
50
100
150
200
DATA
GEANT
$\pi^+ \rightarrow \pi^0 e^+ \nu$
$E_{\pi 0}$ (MeV)



Measured time difference between two coincident photons from π^0 produced via decay $\pi^+ \to \pi^\circ e^+ \nu$ in the active target.



Histogram of the γ–γ opening angle in the πβ decay.



Histogram of time difference between the beam pion stop and the $\pi^+ \rightarrow \pi^\circ e^+ \nu$ decay events (dots); curve: pion lifetime.

Pion Beta Decay Experiments

(B x 10^8)

1.037±0.002		Standard Model	
1.036±0.004±0.005	6×10^4	PIBETA	2004
1.026±0.039	1224	McFarlane	1985
1.00-0.10+0.08	332	Depommier	1968
1.07±0.21	38	Bacastow	1965
1.10±0.26		Bertram	1965
1.1±0.2	43	Dunaitsev	1965
0.97±0.20	36	Bartlet	1964
1.15±0.22	52	Depommier	1963

A.F. Dunaitsev, V. I. Petrukhin, Yu. D. Prokoshkin, V. I. Rykalin (Dubna, JINR)
Published in Zh.Eksp.Teor.Fiz. 42(1962)1423.

Status of CKM Unitarity $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

$|V_{ud}| = 0.9728 \pm 0.0030$ **PIBETA**

PDG (2016):

$|V_{ud}| = 0.97417 \pm 0.00021$
$|V_{us}| = 0.2248 \pm 0.0006$ **from K_{e3} decay**
$|V_{ub}| = 0.00409 \pm 0.00039$ **from B decays**

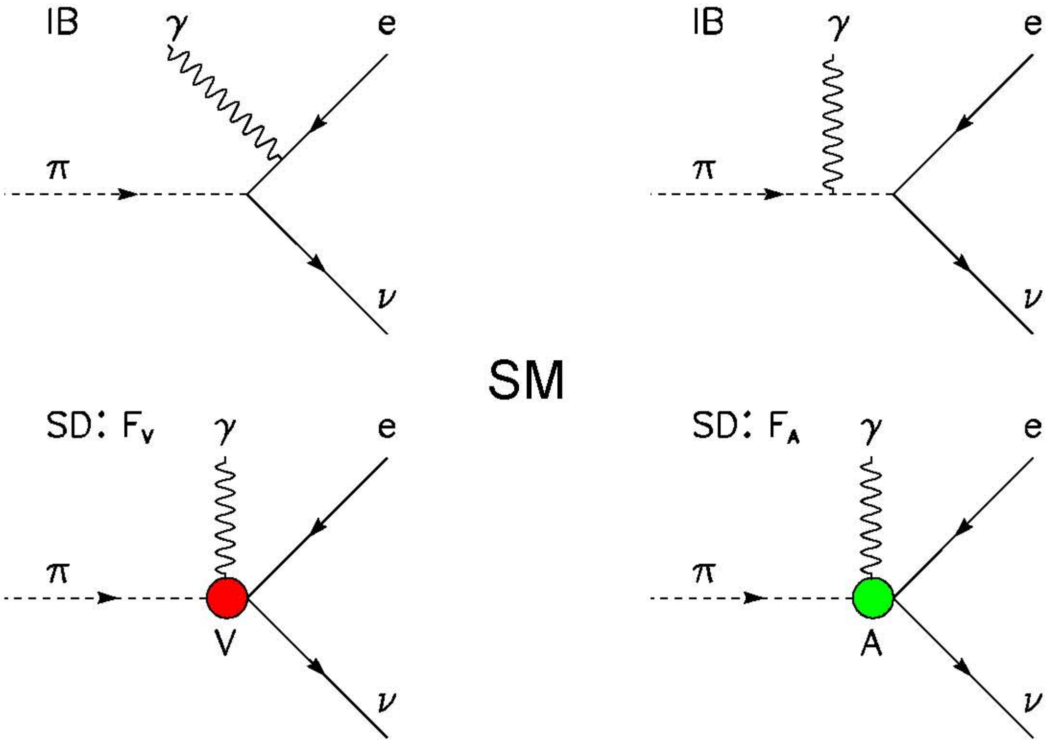
$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9996 \pm 0.0005$

Amplitude of Decay

$\pi \longrightarrow e\nu\gamma$:

Standard IB *and*

$V - A$ *terms*



$\pi \to e\nu\gamma$ Differential Branching Ratio

$$\frac{d\Gamma_{\pi\to e\nu\gamma}}{dxdy} = \frac{\alpha}{2\pi}\Gamma_{\pi\to e\nu}\left\{ IB(x,y) + \left(\frac{F_V m_\pi^2}{2f_\pi m_e}\right)^2 \left[(1+\gamma)^2 SD^+(x,y) + (1-\gamma)^2 SD^-(x,y)\right] + \right.$$

$$\left. + \frac{F_V m_\pi}{f_\pi}\left[(1+\gamma)S_{int}^+(x,y) + (1-\gamma)S_{int}^-(x,y)\right] \right\},$$

$$IB(x,y) = \frac{(1-y)\left(1+(1-y)\right)^2}{x^2(x+y-1)}$$

$$S_{int}^+(x,y = -\frac{1}{x}(1-x)(1-y)$$

$$SD^+(x,y) = (1-x)(x+y-1)^2$$

$$S_{int}^-(x,y) = \frac{1}{x}(1-y)\left(1-x+\frac{x^2}{x+y-1}\right)$$

$$SD^-(x,y) = (1-x)(1-y)^2$$

Weak form factors

$$x = \frac{2E_{\gamma}}{m_{\pi}}, \; y = \frac{2E_{e^+}}{m_{\pi}} \qquad \gamma = \frac{F_A}{F_V}$$

F_V calculated from the measured π^0 lifetime, using the conserved vector current (CVC)

$F_A \times 10^4$	reference	note
106 ± 60	Bolotov et al. (1990)	$(F_T = -56 \pm 17)$
135 ± 16	Bay et al. (1986)	
60 ± 30	Piilonen et al. (1986)	
110 ± 30	Stetz et al. (1979)	
116 ± 16	world average (PDG 2004)	

Data analysis

The RPD data were grouped into three kinematic regions:

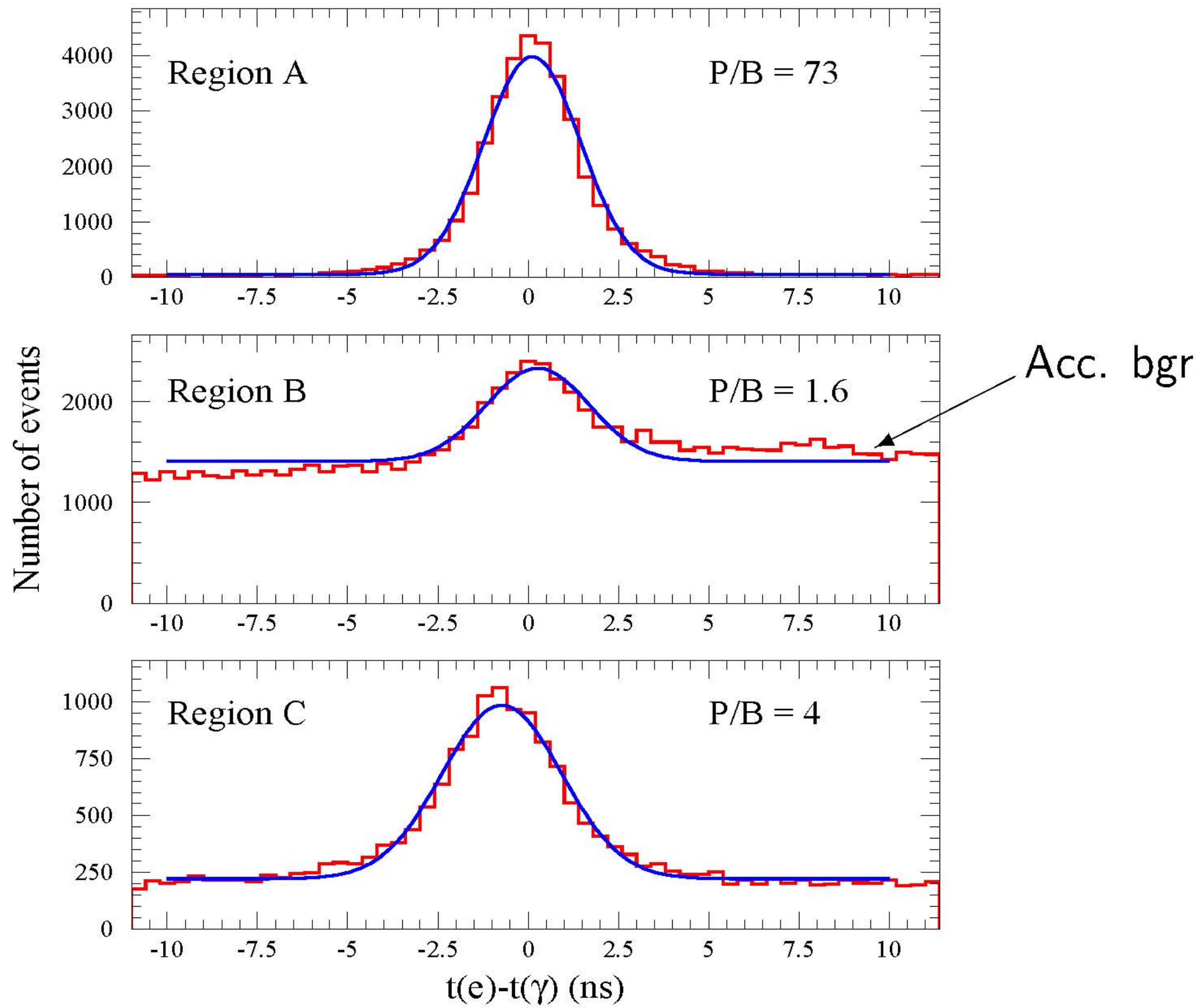
A: $E_e, E_\gamma \geq 51.7\,\mathrm{Me}$

B: $E_e \geq 20.0\,\mathrm{MeV}, E_\gamma \geq 55.6\,\mathrm{MeV}$

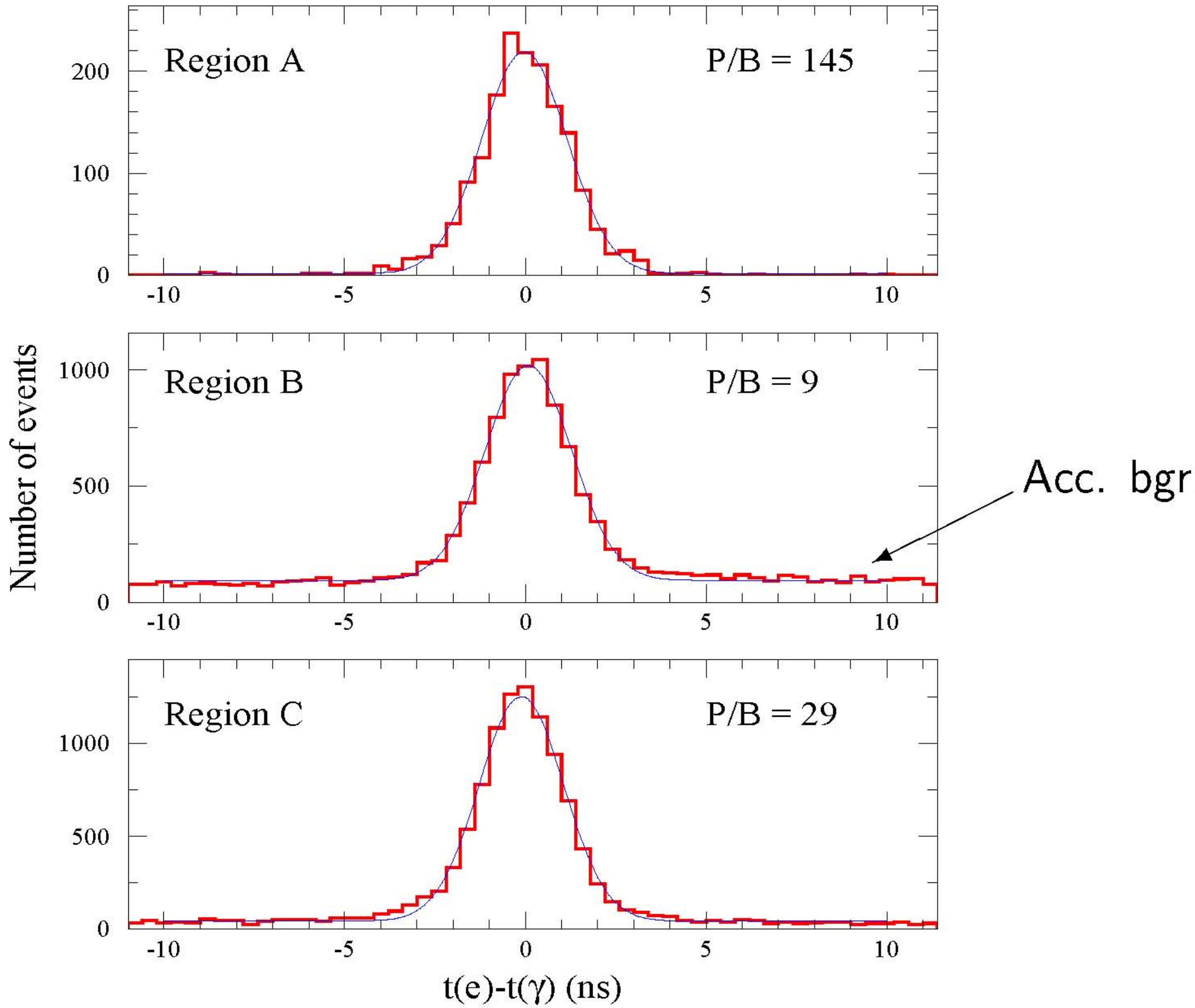
C: $E_e \geq 55.6\,\mathrm{MeV}, E_\gamma \geq 20.0\,\mathrm{MeV}$

The region A is the most sensitive to the structure parameters of the pion. The region C can be used to determine the dependence of the pion form factors on the momentum squared transferred to the lepton pair. For all regions opening angle $\theta_{e\gamma} > 40^o$.

Data Analysis 99-01: $\pi^+ \rightarrow e^+\nu_e\gamma$



Data Analysis 04: $\pi^+ \rightarrow e^+ \nu_e \gamma$



Theoretical Model

The theoretical model including tensor interaction and suggested by Chizhov **(Phys. Part. Nucl. Lett., 2, (2005), 7)**

$$\frac{d\Gamma_{\pi\to e\nu\gamma}}{dxdy} = \frac{\alpha}{2\pi}\Gamma_{\pi\to e\nu}\left\{ IB + \left[(f_V + f_A)^2 SD^+ + (f_V - f_A)^2 SD^- \right] + \right.$$

$$+ 2\sqrt{\beta}\left((f_V + f_A) SD^+_{int} + (f_V - f_A)^2 SD^-_{int} \right) +$$

$$+ 2\left(2f_T (f_T - f_{T'}) + f^2_{T'} \right) T_1 + 2\left(2(f_T - f_{T'}) + f_{T'} x \right) T_2$$

$$\left. + RC \right\}$$

$$\beta \equiv \left(\frac{m_e}{m_\pi} \right) = 1.34 \cdot 10^{-5}$$

$$T_1 = (1 - y)(x + y - 1)$$

$$T_2 = \frac{1 - y}{x}$$

$$f_{V,A,T,T'} = \frac{m^2_\pi}{2m_e f_\pi} F_{V,A,T,T'}$$

Radiative Corrections

E. Kuraev, Yu.Bystritsky, E.Velicheva

(Phys. Rev. D 69, (2004), 114004)

	A:	B:	C:
$(B_{RC})_{LO}$	-0.8×10^{-9}	-0.704×10^{-9}	-3.74×10^{-9}
$(B_{RC})_{NLO}$	0.008×10^{-9}	-0.11×10^{-9}	-0.037×10^{-9}
$\frac{(B_{RC})_{LO}}{B}$, %	-3.56	-1.56	-4.74
$\frac{(B_{RC})_{NLO}}{B}$, %	0.036	-0.24	-0.05

Value of the Form Factors:

Assuming CVC hypothesis the vector form factor $F_V(0)$ is directly related to the $\pi^0 \rightarrow \gamma\gamma$ amplitude and can be extracted from the experimental width of the decay

$$F_V(0) = \frac{1}{\alpha}\sqrt{\frac{2\Gamma(\pi^0 \rightarrow \gamma\gamma)}{\pi m_{\pi^0}}} = 0.0262(9) \text{ or } |F_V(0)| = \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0} m_\pi}} = 0.0259(9)$$

(V. G. Vaks& B. L. Ioffe, Nuovo Cimento 10, (1958), 342)

Momentum squared transferred to the lepton pair

$$q^2 = 1 - 2E_\gamma / m_\pi$$

$$F_V(q^2) = F_V(0)(1 + aq^2)$$

$$F_A(q^2) = F_A(0)$$

Scheme of Minimization

- 1) fixed (free) value of F_V and value of parameters a, F_A were free
- 2) fit

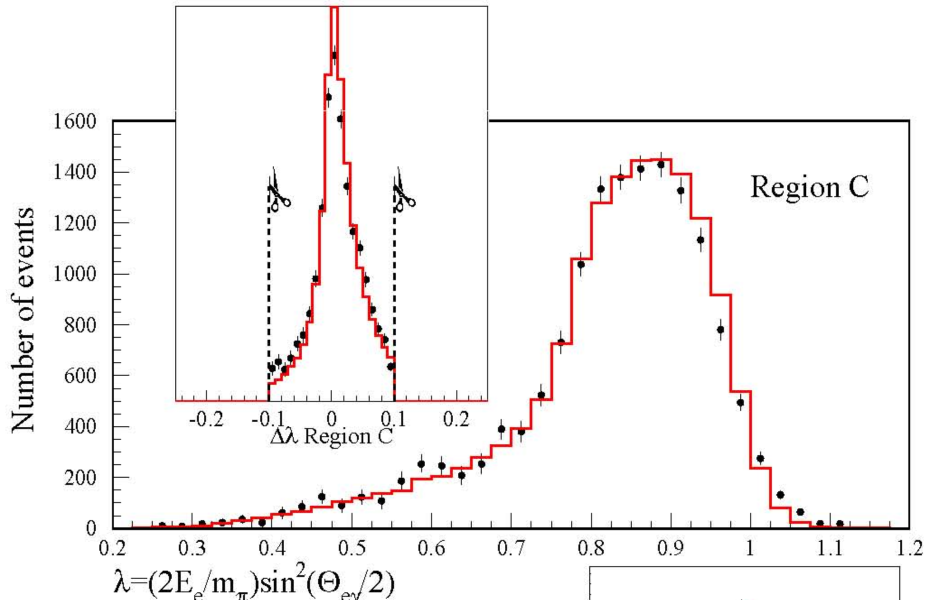
$$\chi^2 = \sum_i \frac{(\lambda_i^{theor} - \lambda_i^{exp})^2}{\sigma_i^2}$$

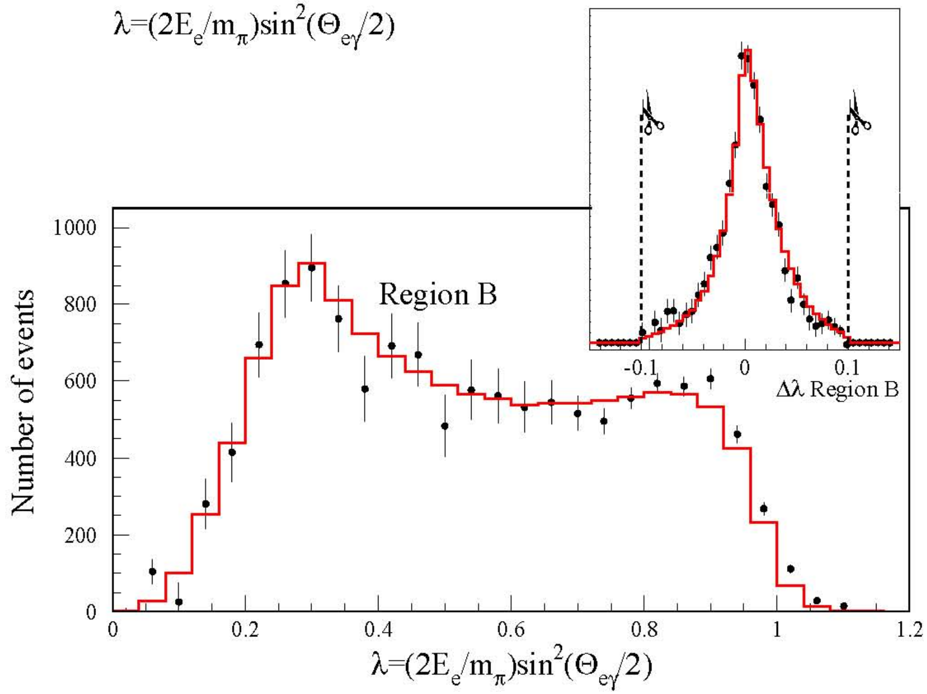
where or

$$\lambda = {}^{2E_e}/_{m_\pi} \cdot \sin^2\left({}^{\theta_{e\gamma}}/_2\right)$$

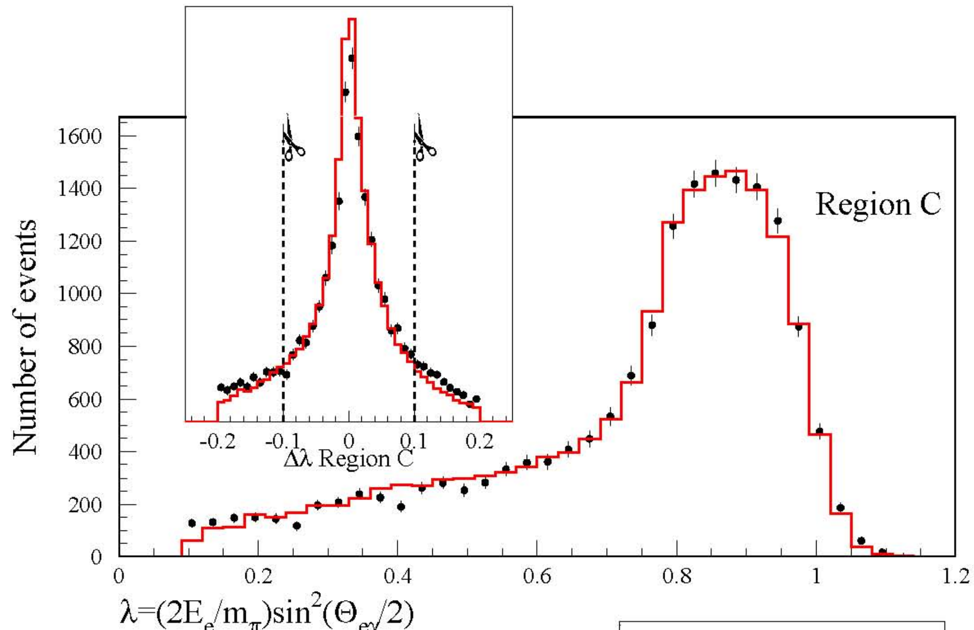
$$\lambda = \frac{x + y - 1}{x}$$

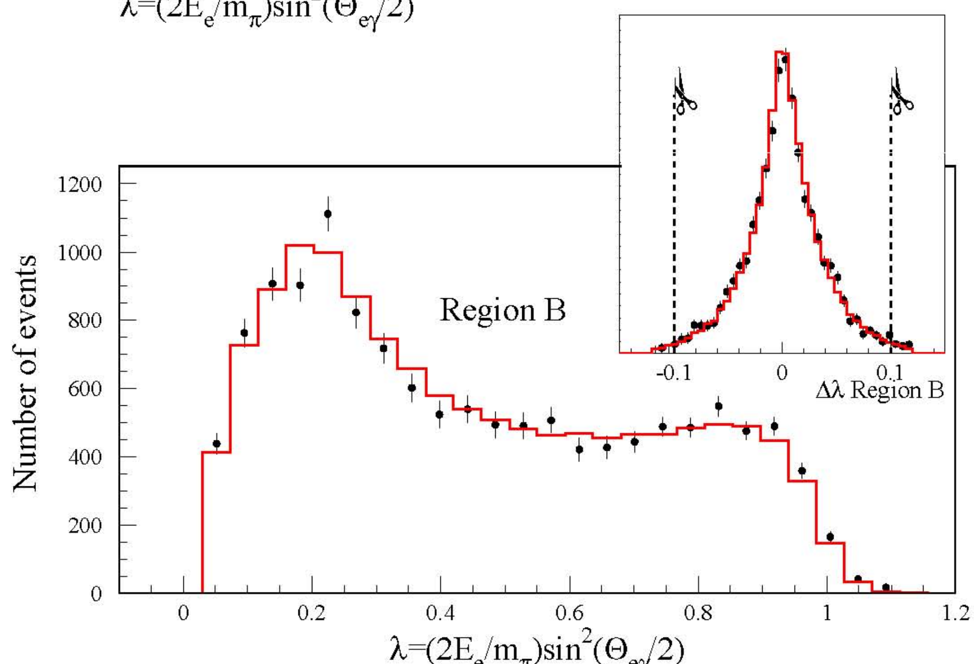
Data Analysis 99-01: $\pi^+ \rightarrow e^+ \nu_e \gamma$





Data Analysis 04: $\pi^+ \to e^+\nu_e\gamma$





$\pi^+ \to e^+ \nu_e \gamma$

$F_V = 0.0258 \pm 0.0017$ (8x)
$F_A = 0.0119 \pm 0.0001$ (16x)
$a = 0.10 \pm 0.06$

$B(\times 10^8) = 73.86$	± 0.54	(17x)	65k	PIBETA	2009
16.1	± 2.3			BOLOTOV	1990
5.6	± 0.7		226	STETZ	*1978*
3.0			143	DEPOMMIER	1963

Upper limit on tensor value

$-5.2 \times 10^{-4} < F_T < 4 \times 10^{-4}$ 90% CL

Pion polarizability (Terent`ev Pisma ZhETP 15, 1972, 299)

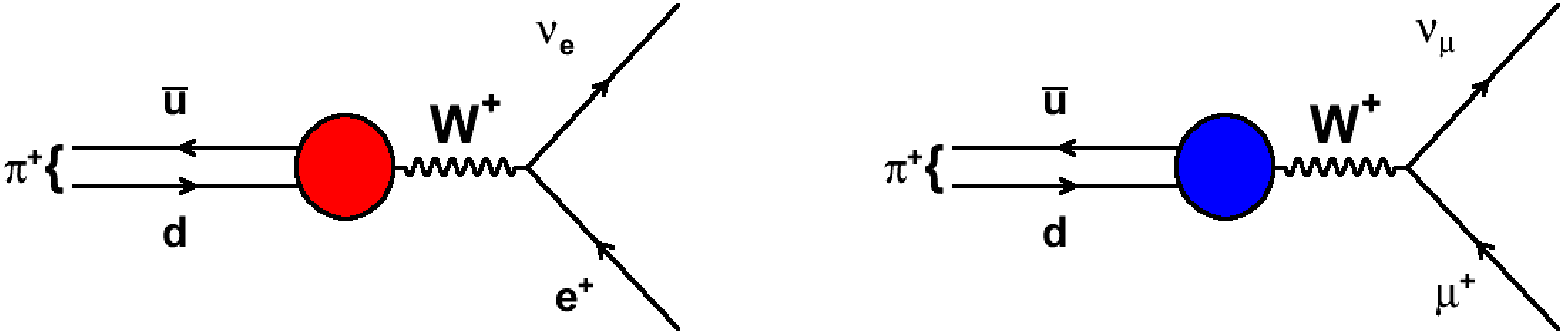
$$\alpha_E^{LO} = -\beta_M^{LO} = (2.783 \pm 0.023_{exp}) \times 10^{-4}\ \mathrm{fm}^3$$

Number of events of rare pion and muon decays, recorded on PIBETA facility and in all previous experiments

Decay	PIBETA statistics	Statistics worldwide
$\pi^+ \rightarrow \pi^0 + e^+ + \nu_e$	$> 5 \times 10^4$	$1,77 \times 10^3$
$\pi^+ \rightarrow e^+ + \nu_e$	$> 5,8 \times 10^8$	$0,35 \times 10^6$
$\pi^+ \rightarrow e^+ + \nu_e + \gamma$	$> 6 \times 10^4$	$1,35 \times 10^3$
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu + \gamma$	$> 5 \times 10^5$	$8,5 \times 10^3$

$\pi \rightarrow e\nu$

Pion decay, lepton universality



Physics Motivation / Theory

$$B_{e/\mu}^{Theor} = \frac{\Gamma(\pi \to e\nu_e + \pi \to e\nu_e\gamma)}{\Gamma(\pi \to \mu\nu_\mu + \pi \to \mu\nu_\mu\gamma)} = \left(\frac{g_e}{g_\mu}\right)^2 \left(\frac{m_e}{m_\mu}\right)^2 \frac{\left(1 - m_e^2 / m_\mu^2\right)^2}{\left(1 - m_\mu^2 / m_\pi^2\right)^2} (1 + \delta R)$$

Modern SM calculations:

$1.2352(5) \times 10^{-4}$ Marciano and Sirlin, Phys.Rev.Lett. **71** (1993)3629

$1.2354(2) \times 10^{-4}$ Decker and Finkemeier, Nucl.Phys. **B438** (1995)17

Chiral PerturbationTheory:

$1.2356(1) \times 10^{-4}$ Cirigliano and Rosell, Phys.Rev.Lett. **99** (2007) 231801

π_{e2} Decay and the SM

$B(\pi \to e\nu) = \Gamma(\pi_{e2})/\Gamma(\pi_{\mu 2})$ given in SM to 10^{-4} accuracy; dominated by helicity suppression ($V - A$). Deviations from this rate can be caused by:

(a) charged Higgs in theories with richer Higgs sector than SM,

(b) PS leptoquarks in theories with dynamical symmetry breaking,

(c) V leptoquarks in Pati-Salam type GUT's,

(d) loop diagrams involving certain SUSY partner particles,

(e) non-zero neutrino masses (and mixing).

Proc's. (a)–(d) $\Rightarrow$ PS currents. Most general 4-fermion π_{e2} amplitude:

$$\frac{G_F}{\sqrt{2}}\Big[(\bar{d}\gamma_\mu\gamma^5 u)\,(\bar{\nu}_e\gamma^\mu\gamma^5(1-\gamma^5)e)\, f^e_{\rm AL} + f^e_{\rm PL}\,(\bar{d}\gamma^5 u)\,(\bar{\nu}_e\gamma^5(1-\gamma^5)e)\Big] + \text{r.h. } \nu \text{ term}$$

In the SM: $f^\ell_{\rm AL} = 1$, while $f^\ell_{\rm xR} = f^\ell_{\rm Px} = 0$, with $\ell = e, \mu$.

Experiment

(1.2344±0.0023(stat)±0.0019(syst))x 10^{-4}

***TRIUMF**, Phys.Rev.Lett. 115 (2015) 071601*

(1.2265±0.0034(stat)±0.0044(syst))x 10^{-4}

***TRIUMF**, Phys.Rev D49 (1994) 28*

(1.2346±0.0035(stat)±0.0036(syst))x 10^{-4}

***PSI**, Phys.Rev.Lett. 70 (1993) 17*

New average (PDG 2016):

(1.2327±0.0023)x10^{-4}

$$\frac{\Delta B_{e/\mu}^{Theor}}{B_{e/\mu}^{Theor}} \approx 1x10^{-4}$$

$$\frac{\Delta B_{e/\mu}^{Exp}}{B_{e/\mu}^{Exp}} \approx 1.8x10^{-3}$$

PEN $\rightarrow \frac{\Delta B_{e/\mu}^{Exp}}{B_{e/\mu}^{Exp}} \leq 5x10^{-4}$

PEN Events

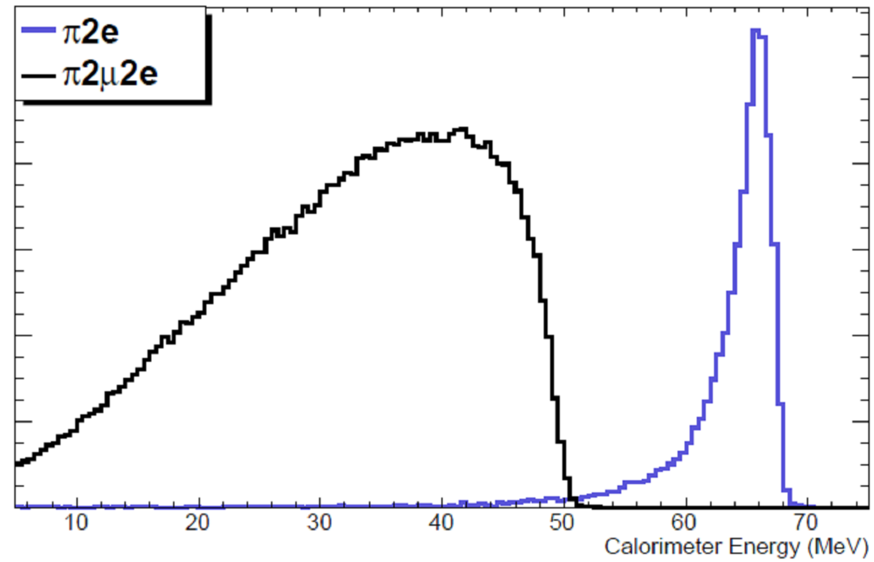
Process to Observe

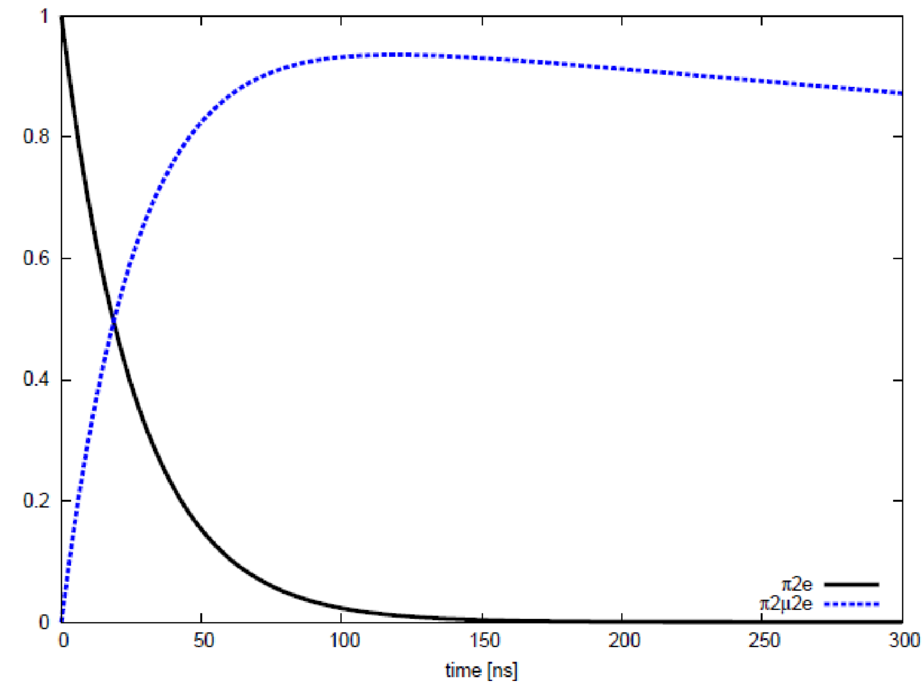
•75 MeV/c pion beam

•$\pi \rightarrow e\nu$ ($\pi 2e$), $E_e \approx 0.5 m_\pi = 69.79$MeV, $\tau_\pi \sim 26$ ns

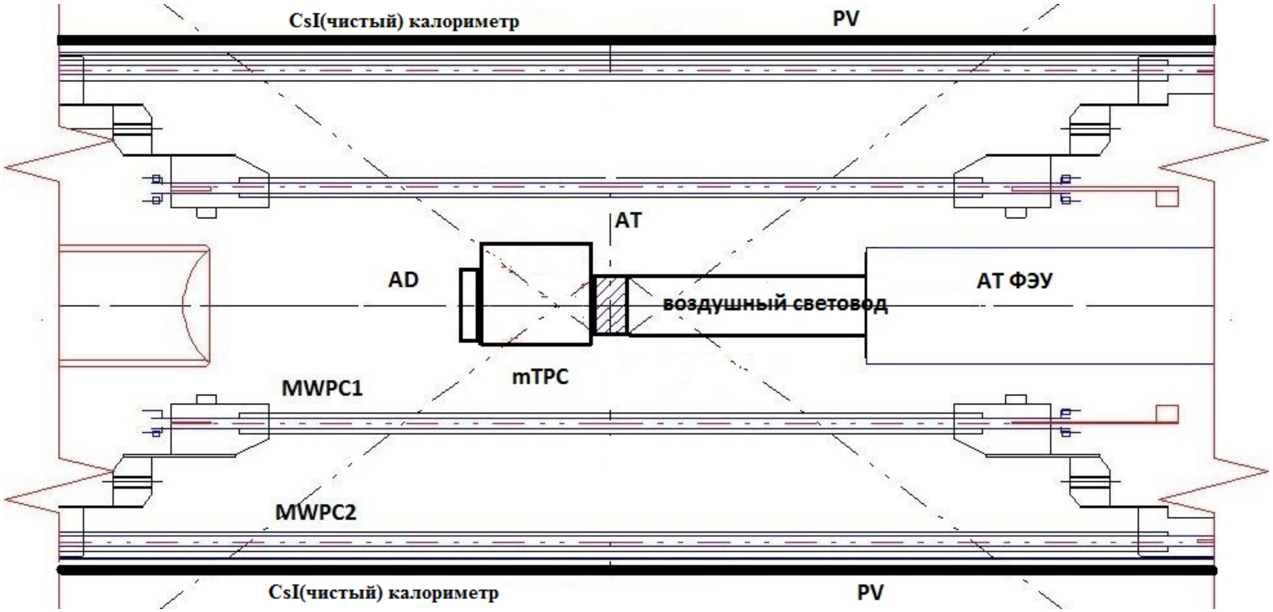
•$\pi \rightarrow \mu\nu$,

•$\mu \rightarrow e\nu\nu$, $E_{emax} \approx 0.5 m_\mu = 52.83$ MeV, $\tau_\mu \sim 2197$ ns





Модернизация установки для сеансов в 2008-2010г.



mTPC:

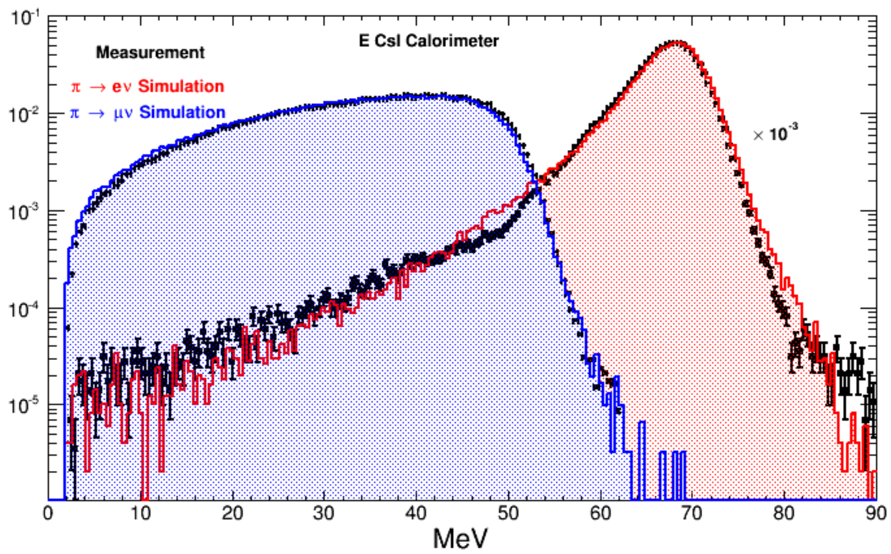
- мониторинг распределения остановок π^+ и μ^+ в мишени;

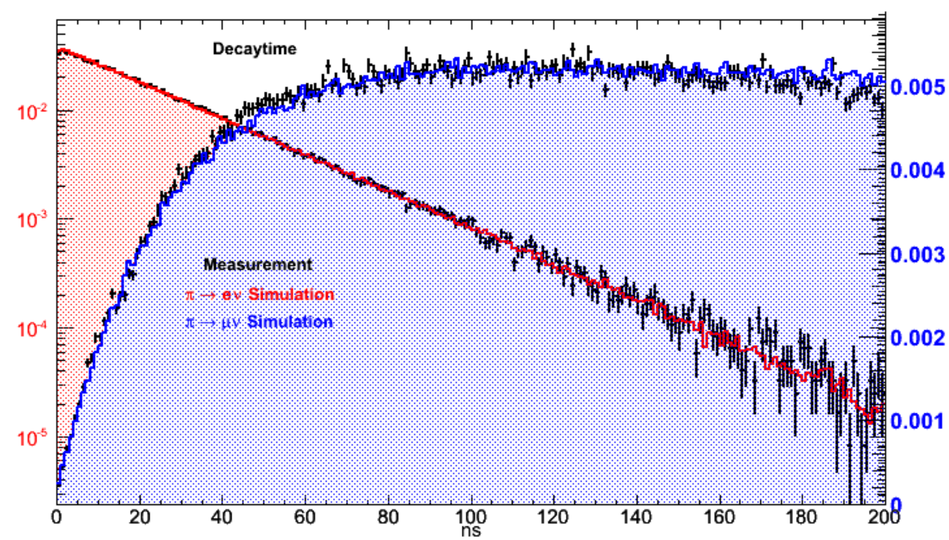
- восстанавление вершины распада пиона в активной мишени и коррекция потерь энергии π^+, μ^+ и e^+ с учетом неоднородности светосбора в активной мишени;

- определение длины треков e^+ в мишени для определения потерь энергии e+ для каждого отдельного события;

- исключение событий с π^+ и μ^+, распадающимися на лету.

Energy and timing





PEN Experiment Vital Statistics

	2008	2009	2010	Total
Calendar Days	111	98	68	277
π^+ Stops	$7.46 \cdot 10^{10}$	$1.31 \cdot 10^{11}$	$1.64 \cdot 10^{11}$	$3.70 \cdot 10^{11}$
Low Thresh. Trig.	$1.70 \cdot 10^{5}$	$8.61 \cdot 10^{7}$	$7.14 \cdot 10^{7}$	$1.58 \cdot 10^{8}$
High Thresh. Trig.	$4.38 \cdot 10^{6}$	$7.80 \cdot 10^{6}$	$1.01 \cdot 10^{7}$	$2.23 \cdot 10^{7}$
Tail Trig.	–	$5.47 \cdot 10^{7}$	$4.47 \cdot 10^{7}$	$9.97 \cdot 10^{7}$

PEN total/clean π_{e2}'s: $1.8 \cdot 10^7 / 1.2 \cdot 10^7$

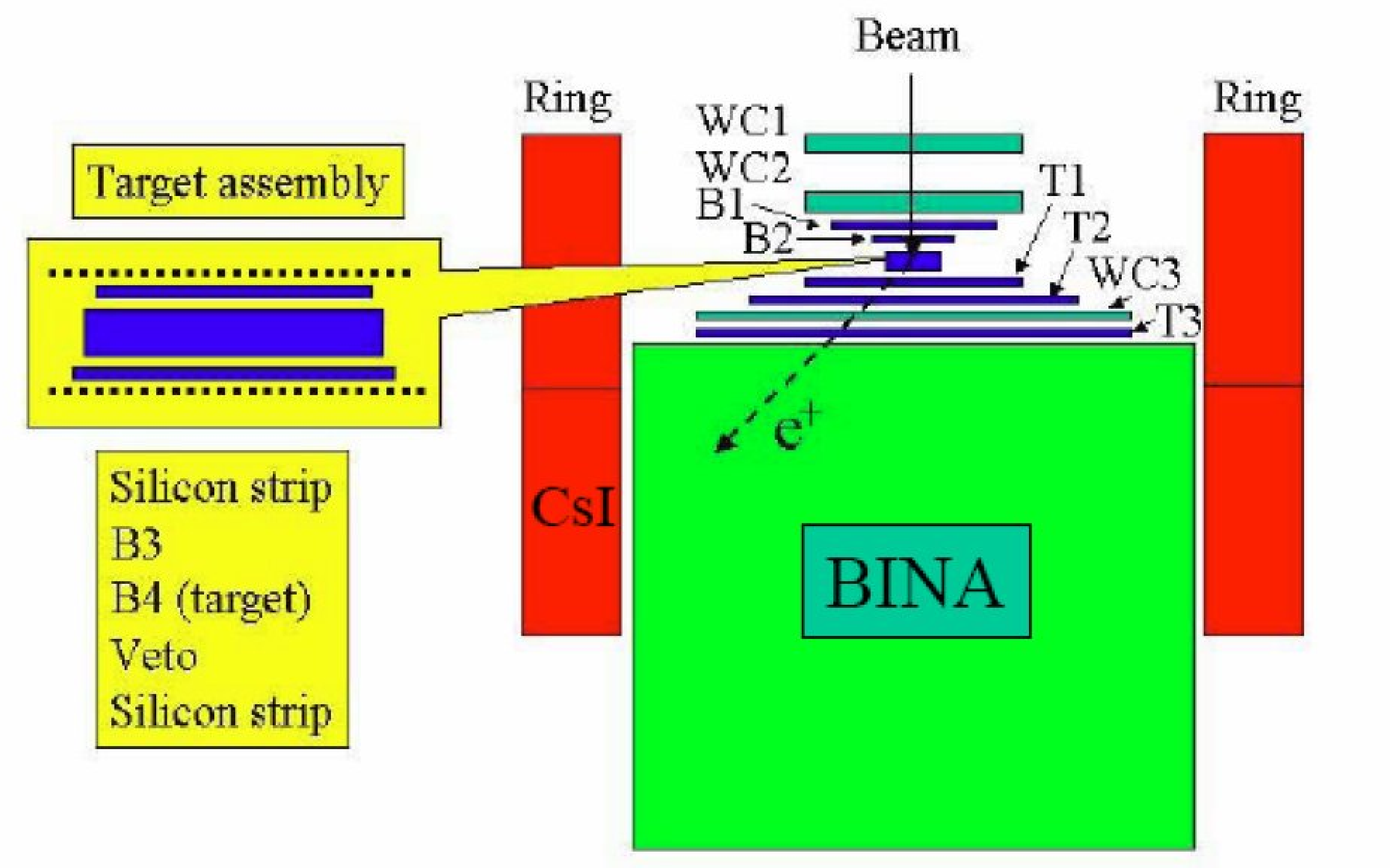
PEN total/clean $\pi \to \mu \to e$: $8.6 \cdot 10^7 / 5.7 \cdot 10^7$

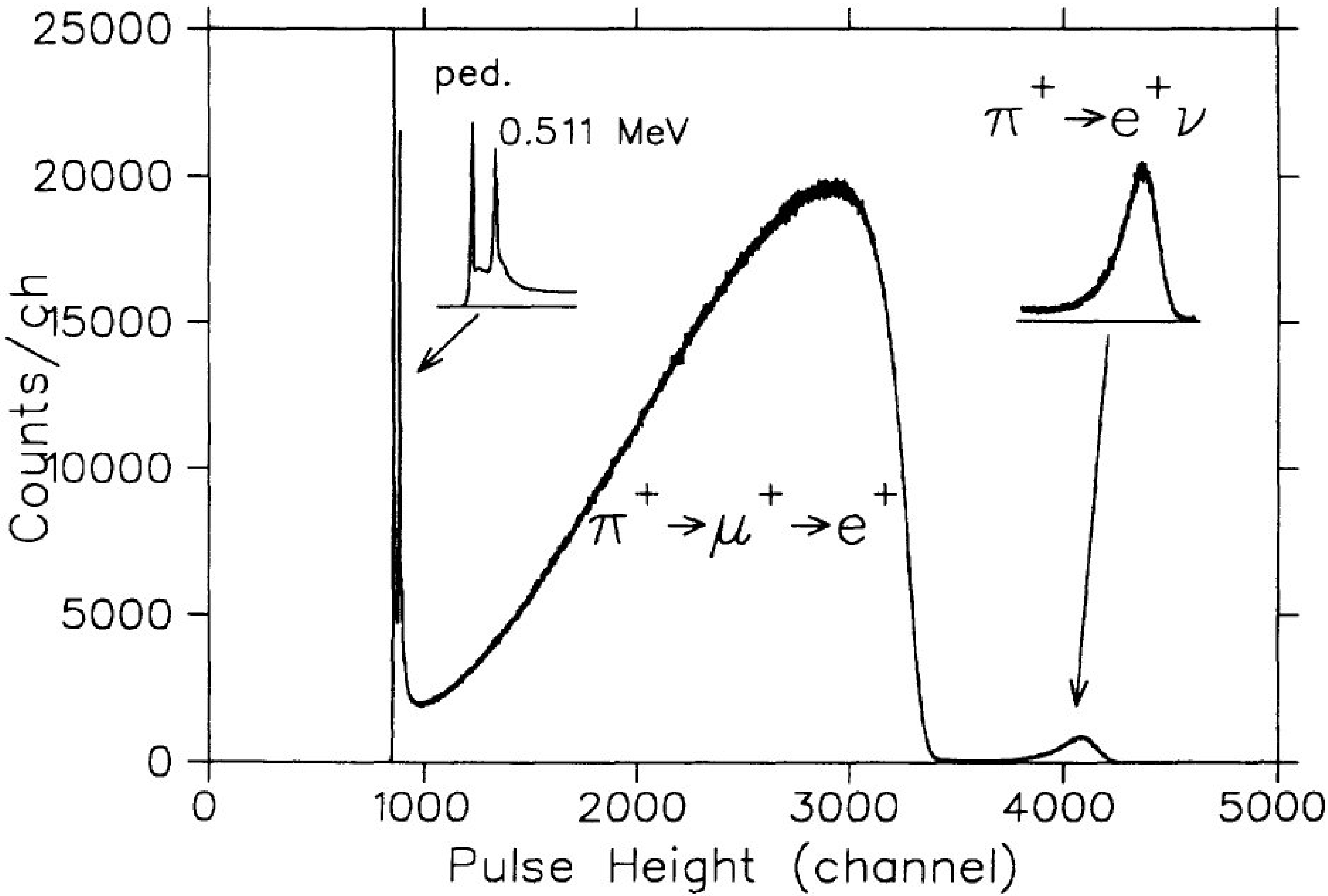
PEN total/clean π_{e2}'s tail trigger events: $1.9 \cdot 10^6 / 250,000$

Compare TRIUMF PIENU Exp. (Bryman *et al.*): $4 \cdot 10^6$ π_{e2} decays

Спасибо за внимание!

PIENU (TRIUMF)





25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
Counts/ch
Pulse Height (channel)
ped.
0.511 MeV
$\pi^+ \rightarrow e^+ \nu$
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$

RESULTS

Region	B_{th} ($\times 10^{-8}$)	B_{exp} ($\times 10^{-8}$)	Events ($\times 10^{3}$)
A	2.599(11)	2.614(21)	35.9
B	14.45(2)	14.46(22)	16.2
C	37.49(3)	37.69(46)	13.3
Tot.	74.11(3)	73.86(54)	65.4

Эксперимент PEN

Beam:

75-58 MeV/c

R(π-stop) ~ 20000 1/сек

Замена:

мишень, замедлитель, пучковый счетчик

электроника (digitizer) 2Ггц / 10 бит

Добавлена времяпроекционная камера mTPC (ЛЯП)

Регистрация событий

π^+ останавливается в мишени (≈15000 π^+/сек).

Распад пиона детектируется во временных воротах шириной 250нсек, начинающихся за 40нсек до остановки пиона.

Сигналы с пучкового счетчика, замедлителя и активной мишени оцифровываются (0.5нсек/канал):

$\pi \rightarrow e\upsilon$ (2 импульса в мишени: остановка π и сигнал от e)

$\pi \rightarrow \mu \rightarrow e$ (3 импульса в мишени от π, μ и e)