PEN Experiment: A Sensitive Search for Non-(V-A) Weak Processes

Dinko Počanić (for the PEN Collaboration)

University of Virginia

PANIC 2008, Eilat, Israel
9-14 Nov 2008

Outline

Motivation

The PIBETA–PEN program

SM calculations; mass limits

Lepton universality

Overview of the PEN Experiment

The apparatus and method

Brief look at 2007 and 2008 results

Sample waveforms and histograms

Summary: present status, plans

The PIBETA–PEN Program of Measurements

Perform precision checks of Standard Model and QCD predictions:

1st phase: The **PIBETA** experiment

- $\pi^+ \to \pi^0 e^+ \nu_e$
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-)
  - F_A/F_V, π polarizability (χPT prediction)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-)
  - departures from $V - A$ in $\mathcal{L}_{weak}$

2nd phase: The **PEN** experiment

- $\pi^+ \to e^+ \nu_e$
  - e-μ universality
  - pseudoscalar coupling besides $V - A$
  - ν sector anomalies, Majoron searches, m_{h^+}, PS **l-q**'s, V **l-q**'s, . . .

Known and Measured Pion and Muon Decays

Decay		BR		
$\pi^+ \to$	$\mu^+\nu$	0.9998770 (4)	($\pi_{\mu 2}$)	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	($\pi_{\mu 2\gamma}$)	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(π_{e2})	✓
	$e^+\nu\gamma$	$1.61\,(23) \times 10^{-7}$	($\pi_{e2\gamma}$)	✓
	$\pi^0 e^+\nu$	$1.025\,(34) \times 10^{-8}$	(π_{e3}, π_β)	✓
	$e^+\nu e^+ e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \to$	$\gamma\gamma$	0.98798 (32)		
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$		
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$		
	e^+e^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \to$	$e^+\nu\bar{\nu}$	~ 1.0		
	$e^+\nu\bar{\nu}\gamma$	0.014 (4) ✓		
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

$\pi \longrightarrow e\nu$ Decay: SM Calculations; Measurements

Modern theoretical calculations: $B_{\text{calc}} = \dfrac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{calc} =$

$$\begin{cases} 1.2352\,(5) \times 10^{-4} & \text{Marciano and Sirlin, [PRL 71 (1993) 3629]} \\ 1.2356\,(1) \times 10^{-4} & \text{Decker and Finkemeier, [NP B 438 (1995) 17]} \\ 1.2352\,(1) \times 10^{-4} & \text{Cirigliano and Rosell, [PRL 99, 231801 (2007)]} \end{cases}$$

Experiment, world average [current PDG]:

$$\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{exp} = (1.230 \pm 0.004) \times 10^{-4}$$

N.B.:

PEN goal: $\dfrac{\delta B}{B} \simeq 5 \times 10^{-4}$.

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π_{e2} Decay and the SM

$B(\pi \to e\nu) = \Gamma(\pi_{e2})/\Gamma(\pi_{\mu2})$ 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:

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

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

The $f^e_{\rm PL}$ and Mass Bounds

Allowing for pseudoscalar coupling [Shanker, NP B204 (82) 375]:

$$B_{\pi e2} = B_{\rm SM}\left(1 + \frac{2m_\pi a_{\rm P}}{m_e a_{\rm A}} f^e_{\rm PL}\right) \Big/ \left(1 + \frac{2m_\pi a_{\rm P}}{m_\mu a_{\rm A}} f^\mu_{\rm PL}\right) ,$$

where 2nd term in denominator is negligible because $f^e_{\rm PL} \simeq f^\mu_{\rm PL}$, while

$$\frac{a_{\rm P}}{a_{\rm A}} \simeq \frac{m_\pi}{m_u + m_d} \simeq 14 \,.$$

Therefore

$$\left(B^{\rm obs}_{\pi e2} - B^{\rm SM}_{\pi e2}\right) / B^{\rm SM}_{\pi e2} = \frac{\Delta B}{B^{\rm SM}} \simeq \frac{2m_\pi a_{\rm P}}{m_e a_{\rm A}} f^e_{\rm PL} \simeq 7700 f^e_{\rm PL} \ !$$

Tgt accuracy of the PEN experiment is $\Delta B/B \simeq 5\times 10^{-4}$, which gives a 1σ sensitivity of

$$\delta f^e_{\rm PL} \simeq 6.5 \times 10^{-8} \,.$$

We can use this sensitivity to get estimates of the mass reach of PEN.

Mass Bounds from PEN Goal Accuracy

(a) Charged Higgs, $m_{\mathrm{H}+}$ [Shanker, NP B204 (82) 375]

Given a mixing angle suppression $S \approx 10^{-2}$, we get

$$f^e_{\mathrm{PL}} \approx S \frac{m_t m_\tau}{m^2_{\mathrm{H}+}} \qquad \text{yielding} \qquad m_{\mathrm{H}+} > 6.9\,\mathrm{TeV}\,.$$

(b) Pseudoscalar leptoquarks, m_{P}

Given an estimated effective Yukawa coupling of $y \simeq 1/250$, we can find m_{P}, mass of the color-triplet PS l-q:

$$f^e_{\mathrm{PL}} \approx \frac{\sqrt{2}}{G_F} \frac{y^2}{2m^2_{\mathrm{P}}} \qquad \text{yielding} \qquad m_{\mathrm{P}} > 3.8\,\mathrm{TeV}\,.$$

(c) Vector leptoquarks, M_G

Following Shanker who assumes gauge coupling $g \simeq g_{\mathrm{SU(2)}}$, we get:

$$f^e_{\mathrm{PL}} \approx \frac{4M^2_W}{M^2_G} \qquad \text{yielding} \qquad M_G > 630\,\mathrm{TeV}\,.$$

Lepton Universality (and Neutrinos)

From

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2}\frac{m_e^2}{m_\mu^2}\frac{(1 - m_e^2/m_\mu^2)^2}{(1 - m_\mu^2/m_\pi^2)^2}\left(1 + \delta R_{e/\mu}\right)$$

$$R_{\tau/\pi} = \frac{\Gamma(\tau \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_\tau^2}{g_\mu^2}\frac{m_\tau^3}{2m_\mu^2 m_\pi}\frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2}\left(1 + \delta R_{\tau/\pi}\right)$$

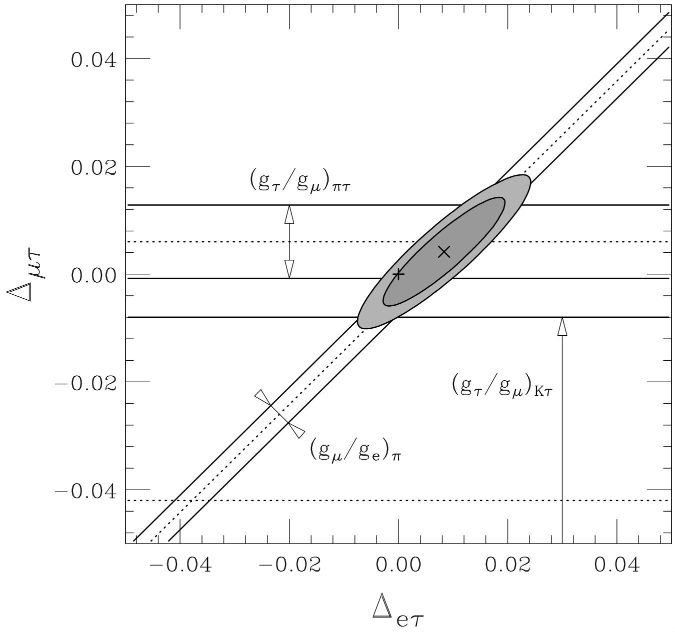
one can evaluate

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 1.0021 \pm 0.0016 \quad \text{and} \quad \left(\frac{g_\tau}{g_\mu}\right)_{\pi\tau} = 1.0030 \pm 0.0034\,.$$

For comparison

$$\left(\frac{g_e}{g_\mu}\right)_W = 0.999 \pm 0.011 \quad \text{and} \quad \left(\frac{g_\tau}{g_e}\right)_W = 1.029 \pm 0.014\,.$$

[Violation of LU at presently allowed level would account for "NuTeV anomaly."]

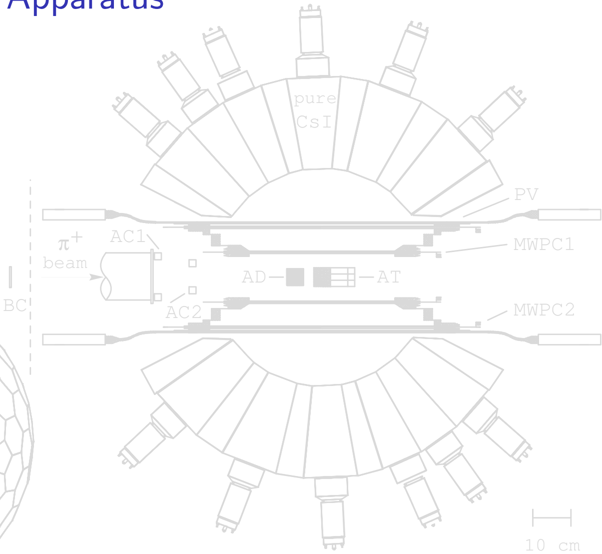


From
Loinaz et al.,
PRD **70** (2004)
113004

$$\Delta_{\ell\ell'} = 2\frac{g_\ell}{g_{\ell'}}$$

The PIBETA/PEN Apparatus

- stopped π^+ beam
- active target counter
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity



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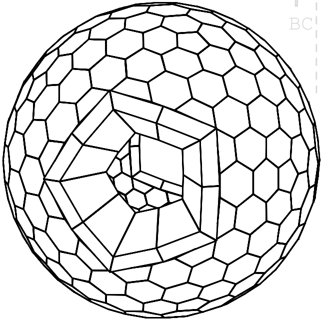

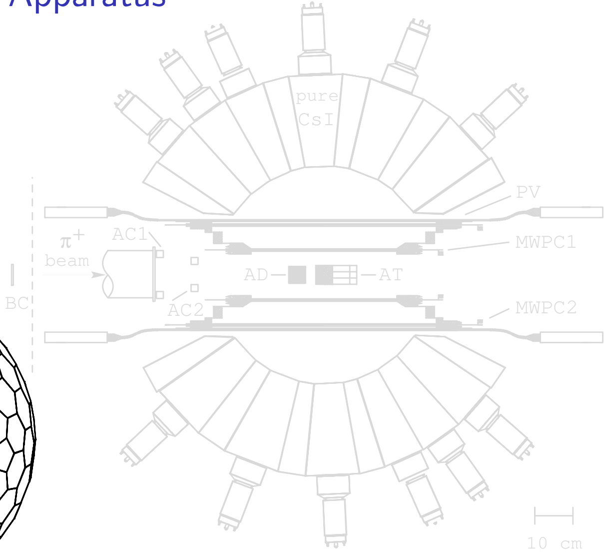

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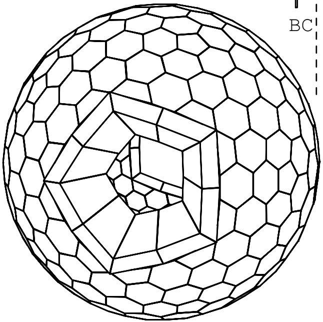
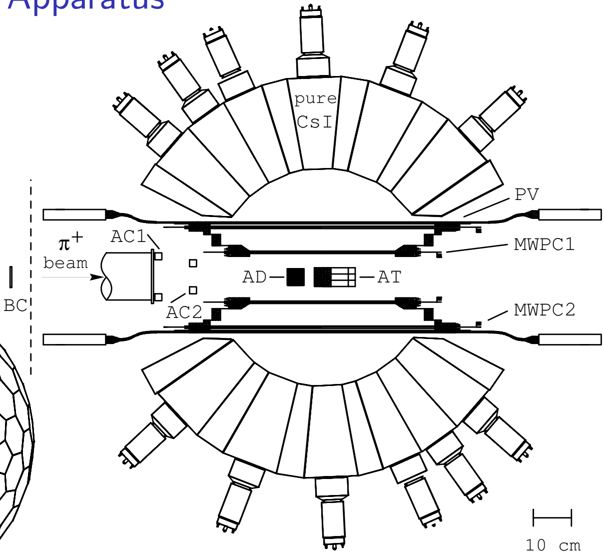
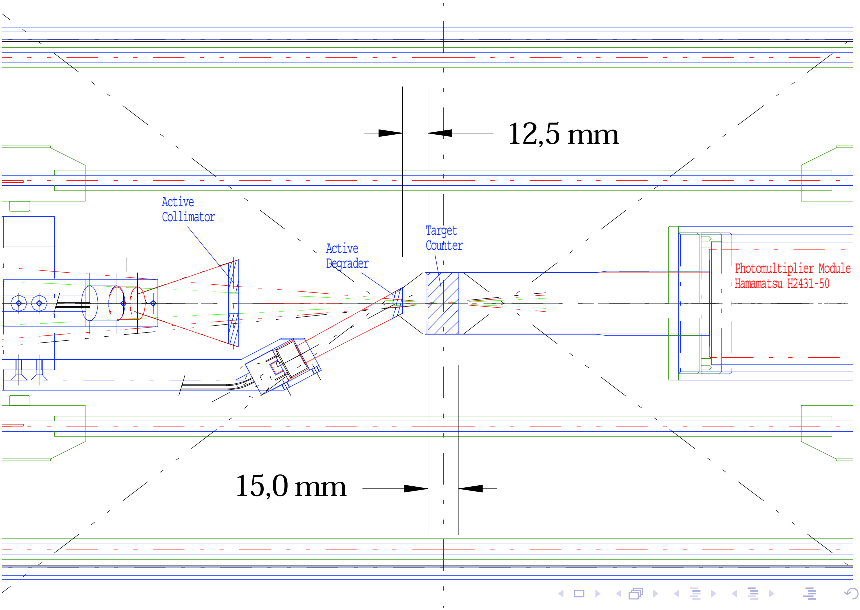
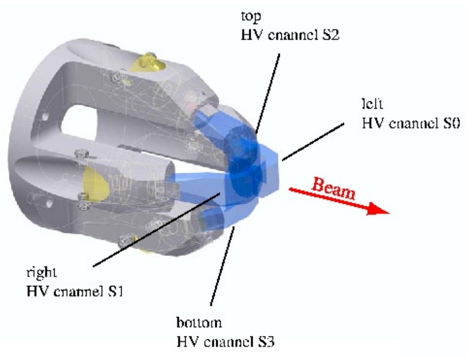


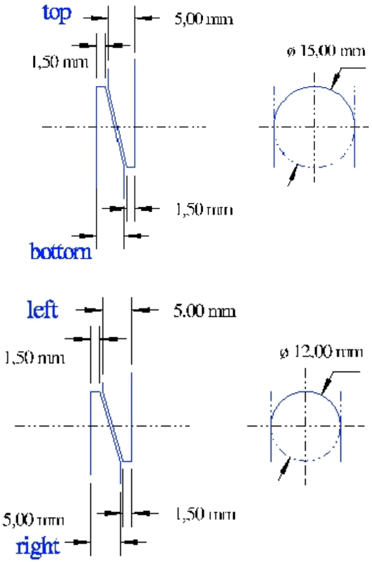


Central Detectors: 2007 Engineering Run

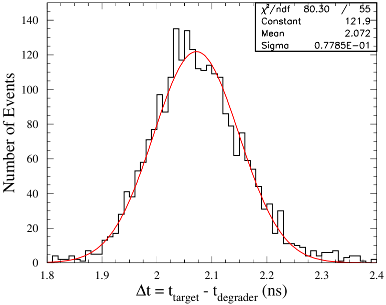


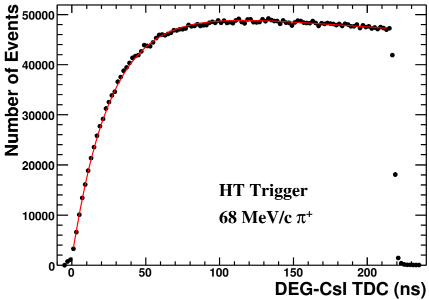
Wedged Degrader: 2008 Run

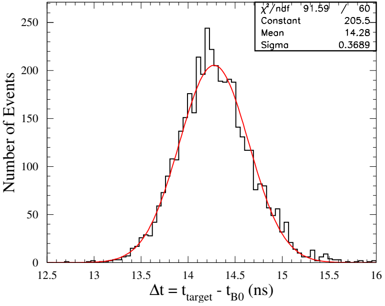


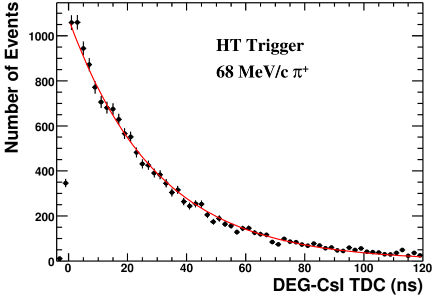


Timing in the central beam detectors







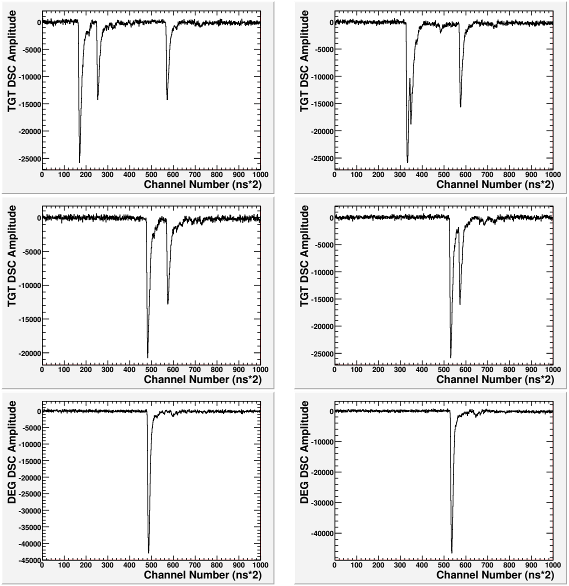


Sample waveforms 2007:

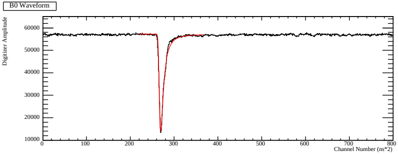
$\pi \to \mu \to e$
(in TGT)

$\pi \to e$
(in TGT)

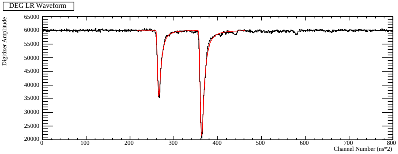
Beam π^+
(in DEG)



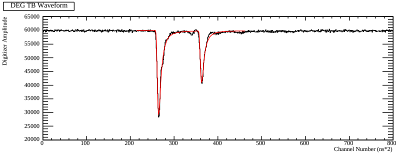
Waveforms 2008:



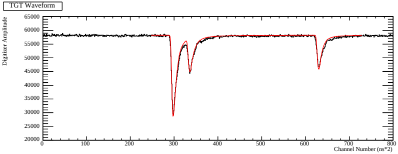
B0



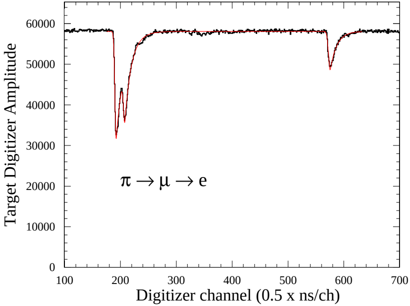
DEG–horiz

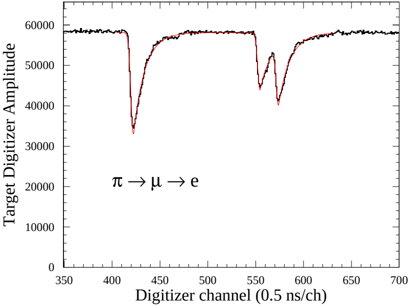


DEG–vert



TGT


Target Digitizer Amplitude
π → μ → e
Digitizer channel (0.5 x ns/ch)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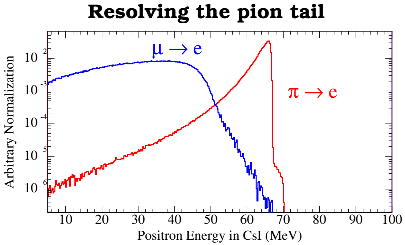
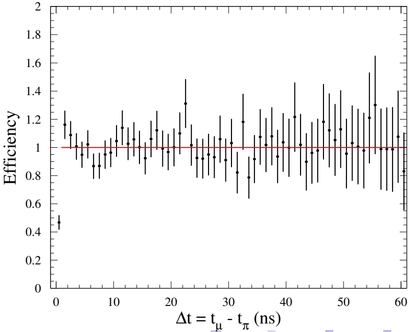

Resolving the pion tail
μ → e
π → e
Arbitrary Normalization
Positron Energy in CsI (MeV)


Efficiency
Δt = t_μ - t_π (ns)

PEN Experiment: Present Status

- Stopped beam at $\sim 15,000\,\pi^+$/sec.
- Pion decays detected in a 250 ns wide gate.
- Position sensitive two-piece wedged active degrader detector.
- Digitized signals of beam counters: forward (B0), active degrader (DEG), and active target (AT).
- Two development runs, in 2007 and 2008, ramping up beam stop and DAQ rates to design specifications.
- Total pions stopped in 2007 and 2008 runs: $> 8 \times 10^{10}$.
  To date $> 4.7 \times 10^{6}$ $\pi \to e\nu$ decays recorded, corresponding to $(\delta B/B)_{\text{stat}} < 5 \times 10^{-4}$.
- Detailed data analysis under way in preparation for a 2009 run, planned to complete the required event statistics. Improved beam tracking with a miniTPC under design.

  Web page: http://pen.phys.virginia.edu

Experiment R-05-01 (PEN) collaboration members:

L. P. Alonzi,[a] V. A. Baranov,[c] W. Bertl,[b] M. Bychkov,[a] Yu.M. Bystritsky,[c] E. Frlež,[a] 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] D. Mekterović,[f] D. Mzhavia,[c,e] A. Palladino,[a] D. Počanić,[a]* P. Robmann,[g] A.M. Rozhdestvensky,[c] V.V. Sidorkin,[c] U. Straumann,[g] I. Supek,[f] Z. Tsamalaidze,[e] A. van der Schaaf,[g]* E.P. Velicheva,[c] and V.V. Volnykh[c]

[a] *Dept of Physics, Univ 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*