Rare Pion and Muon Decays: Summary of Results and Prospects

Dinko Počanić

University of Virginia

"Low Energy Precision Electroweak Physics in the LHC Era"

Institute for Nuclear Theory, University of Washington, Seattle

21 Nov 2008

Outline

The PIBETA–PEN program

Pion Beta Decay: $\pi^+ \to \pi^0 e^+ \nu$

- PIBETA Apparatus and Method
- Results

Radiative pion decay: $\pi \to e\nu\gamma$

Radiative muon decay: $\mu \to e\nu\bar{\nu}\gamma$

The PEN Experiment: $\pi \to e\nu$

- SM calculations; mass limits
- Lepton universality
- New detectors
- Brief look at 2007 and 2008 results

Summary

The PIBETA–PEN Program of Measurements

Perform precision checks of Standard Model and QCD predictions:

1st phase: The **PIBETA** experiment

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

2nd phase: The **PEN** experiment

- $\pi^+ \rightarrow e^+ \nu_e$
  - **e**-μ universality
  - pseudoscalar coupling besides $\mathbf{V} - \mathbf{A}$
  - ν sector anomalies, Majoron searches, $\mathbf{m_{h^+}}$, 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})	✓
	$e^+\nu\gamma$	$1.61\,(23) \times 10^{-7}$	$(\pi_{e2\gamma})$	✓
	$\pi^0 e^+\nu$	$1.025\,(34) \times 10^{-8}$	$(\pi_{e3},\ \pi_\beta)$	✓
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(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		
	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$ ✓		
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

Pion Beta Decay:

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

Quark-Lepton (Cabibbo) Universality

The basic weak-interaction **V-A** form (e.g., μ decay):

$$\mathcal{M} \propto \langle e | l^\alpha | \nu_e \rangle \rightarrow \bar{u}_e \gamma^\alpha (1 - \gamma_5) u_\nu$$

persists in hadronic weak decays

$$\mathcal{M} \propto \langle p | h^\alpha | n \rangle \rightarrow \bar{u}_p \gamma^\alpha (G_V - G_A \gamma_5) u_n \qquad \text{with} \qquad G_{V,A} \simeq 1 \ .$$

Departure from $G_V = 1$ (plain CVC) comes from weak quark mixing (Cabibbo 1963): $G_V = G_\mu \cos\theta_C (= G_\mu V_{ud})$ $\quad \cos\theta_C \simeq 0.97$

3 **q** generations lead to the CKM matrix (Kobayashi, Maskawa 1973):

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM unitarity cond.: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1$, can test the SM.

Status of CKM unitarity (PDG 2002 + before)

- $|\mathbf{V_{us}}| = \mathbf{0.2196\,(26)}$ from $\mathbf{K_{e3}}$ decays.
- $|\mathbf{V_{ub}}| = \mathbf{0.0036\,(7)}$ from **B** decays.
- $|\mathbf{V_{ud}}|$ from superallowed Fermi nuclear β decays

1990 Hardy reconciled Ormand & Brown's and Towner's **ft** values:

$$|\mathbf{V_{ud}}|^2 + |\mathbf{V_{us}}|^2 + |\mathbf{V_{ub}}|^2 = \mathbf{0.9962\,(16)}, \qquad \text{or } \mathbf{1 - 2.4\sigma}.$$

- $|\mathbf{V_{ud}}|$ from neutron β decay (many results; currently incompatible)
  $\sum |\mathbf{V_{ui}}|^2 = \mathbf{0.9917\,(28)}$, or $\mathbf{1 - 3.0\sigma}$. [PERKEO II (2002)]
- $|\mathbf{V_{ud}}|$ from pion β decay PIBETA expt—discussed below.

2004: $\mathbf{V_{us}}$ revised upward; CKM unitarity discrepancy removed!

The Pion Beta Decay

$\pi^{\pm} \to \pi^{0} e^{\pm} \nu$: $\mathrm{B} \simeq 1 \times 10^{-8}$, pure vector trans.: $0^{-} \to 0^{-}$.
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: $\dfrac{1}{\tau} = \dfrac{1}{\tau_0}(1+\delta)$, so that the branching ratio becomes:

$$B(\pi\beta) = \frac{\tau_+}{\tau_0}(1+\delta) = 1.0593\,(6) \times 10^{-8}(1+\delta)|V_{ud}|^2 \,.$$

Recent calculations of pion beta decay radiative corrections

(1) In the light-front quark model

W. Jaus, Phys. Rev. D **63** (2001) 053009.

- full RC for pion beta decay: $\delta = (3.230 \pm 0.002) \times 10^{-2}$.

(2) In chiral perturbation theory

Cirigliano, Knecht, Neufeld and Pichl, Eur. Phys. J. C **27** (2003) 255.

- χPT with e-m terms up to $\mathcal{O}(e^2 p^2)$
- theoretical uncertainty of 5×10^{-4} in extracting $|V_{ud}|$ from π_{e3}.

(3) Marciano and Sirlin further reduced theoretical uncert's in all beta decays [hep-ph/0519099, PRL **96**,032002 (2006)].

Experimental accuracy of the pion beta decay rate

Best result prior to PIBETA: [McFarlane et al., PRD 32 (1985) 547.]

$$\mathbf{B(\pi^+ \to \pi^0 e^+ \nu) = (1.026 \pm 0.039) \times 10^{-8}}, \text{ (i.e., } \sim \mathbf{4}\,\%)$$

Accuracy: $\leq \mathbf{1\,\%}$	check CVC and rad. corrections
$\sim \mathbf{0.5\,\%}$	add to SAF & $\mathbf{n}_\beta$ input to $\mathbf{V_{ud}}$
$< \mathbf{0.3\,\%}$	check for failure of CKM unitarity: ◦ $4^{\mathbf{th}}$ generation coupling ◦ $\mathbf{m_{Z'}}$ ◦ $\mathbf{\Lambda}$ of compositeness ◦ SUSY viol. of **q-l** universality ◦ signal of a smaller $\mathbf{G_F}$ (ν osc.)

Experiment R-04-01 (PIBETA) collaboration members:

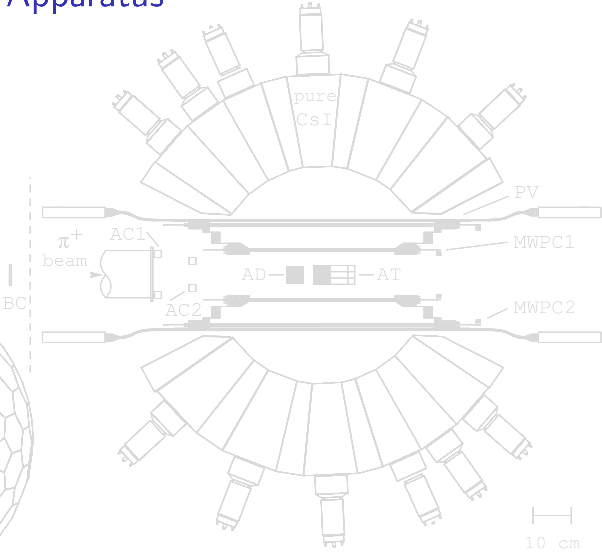
V. A. Baranov,[c] W. Bertl,[b] M. Bychkov,[a] Yu.M. Bystritsky,[c] E. Frlež,[a] N.V. Khomutov,[c] A.S. Korenchenko,[c] S.M. Korenchenko,[c] M. Korolija,[f] T. Kozlowski,[d] N.P. Kravchuk,[c] N.A. Kuchinsky,[c] D. Mzhavia,[c,e] D. Počanić,[a] P. Robmann,[g] O.A. Rondon-Aramayo,[a] A.M. Rozhdestvensky,[c] T. Sakhelashvili,[b] S. Scheu,[g] V.V. Sidorkin,[c] U. Straumann,[g] I. Supek,[f] Z. Tsamalaidze,[e] A. van der Schaaf,[g] B. A. VanDevender,[a] E.P. Velicheva,[c] V.V. Volnykh,[c] and Y. Wang[a]

[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*

Web page: `http://pibeta.phys.virginia.edu`

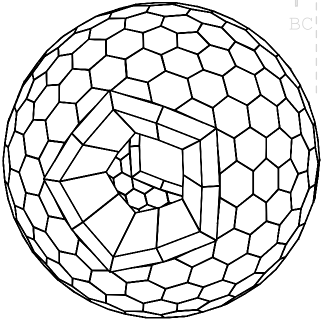
The PIBETA/PEN Apparatus

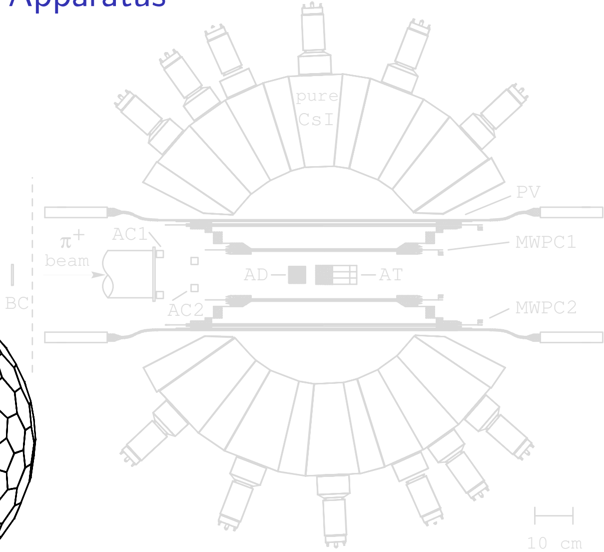
- stopped π^+ beam
- active target counter
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity



The PIBETA/PEN Apparatus

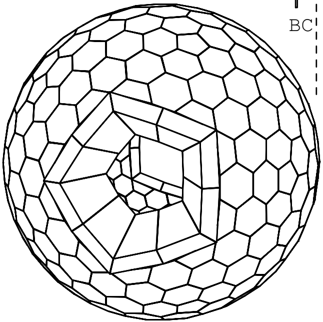
- stopped π^+ beam
- active target counter
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity

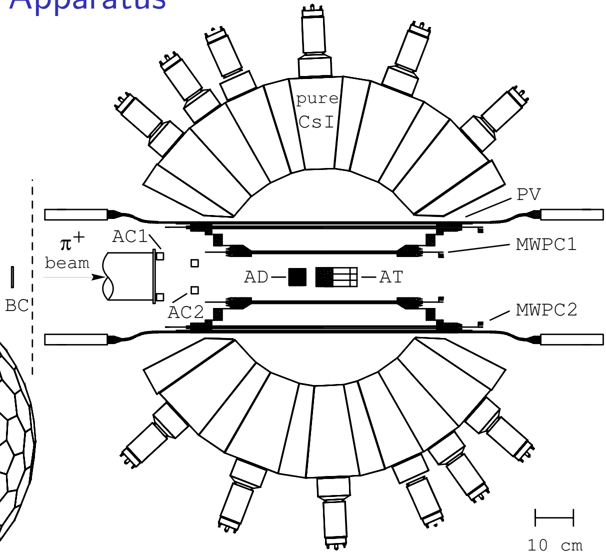




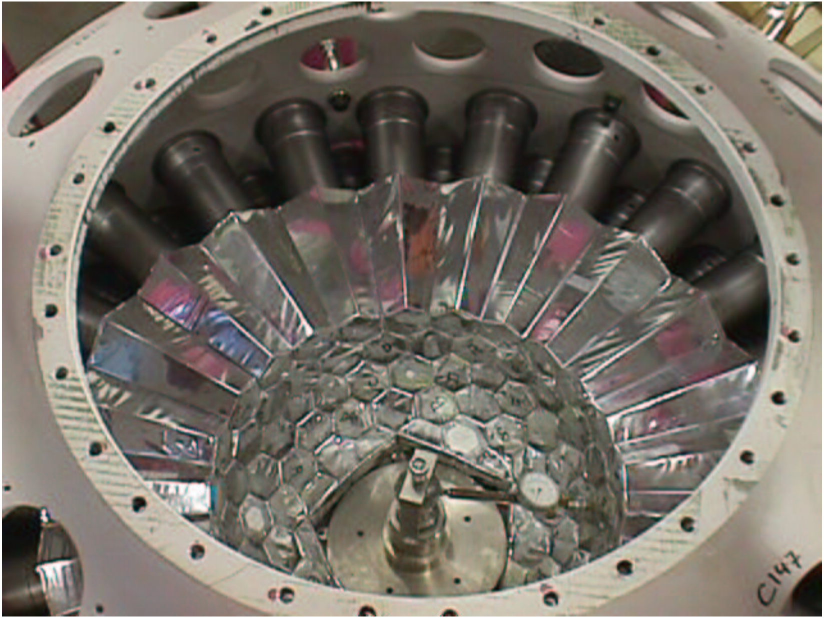
The PIBETA/PEN Apparatus

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

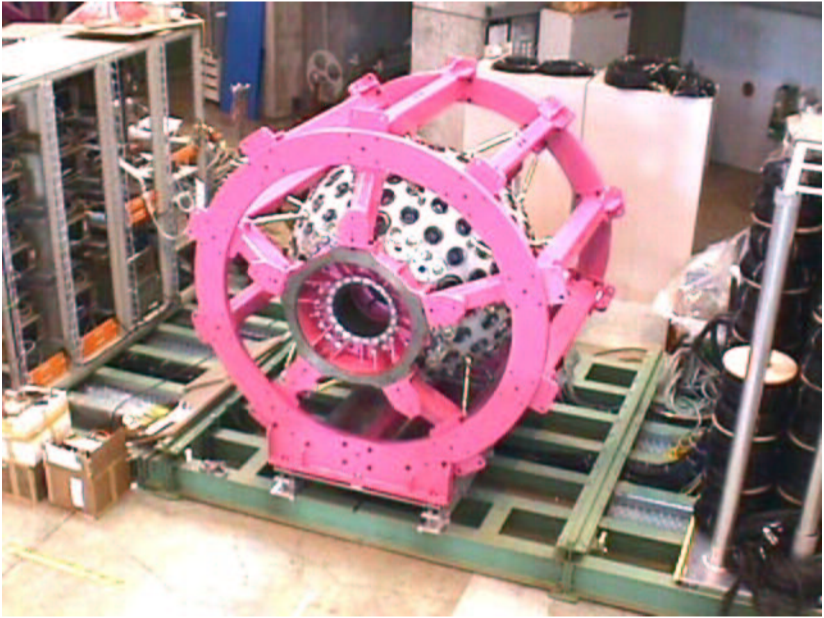


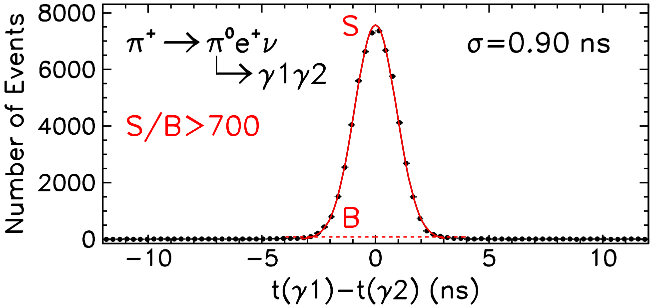


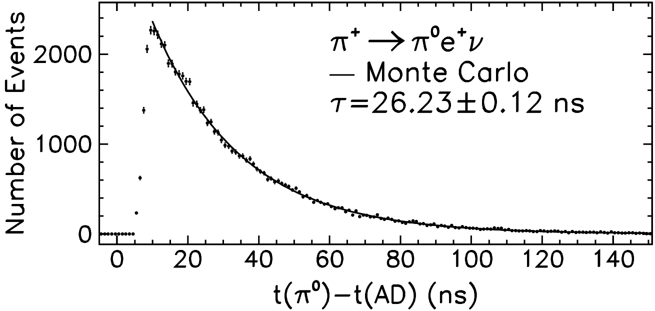
PIBETA Detector Assembly (1998)

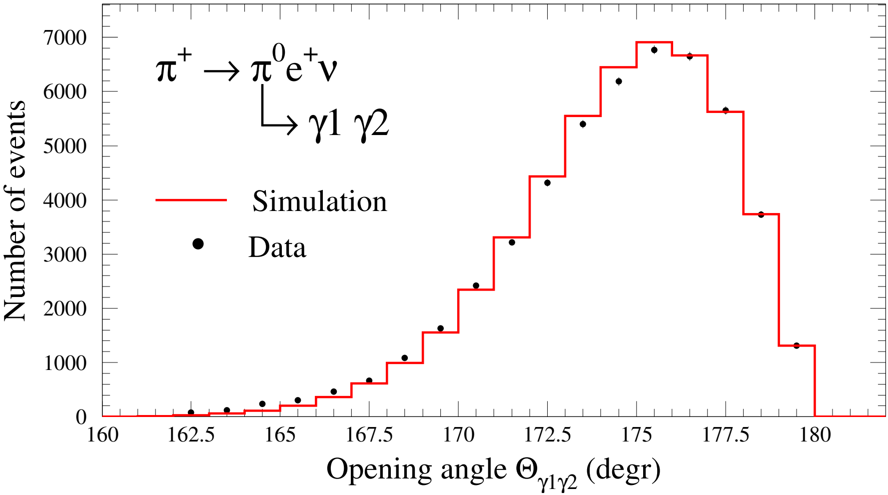


PIBETA Detector on Platform (1998)



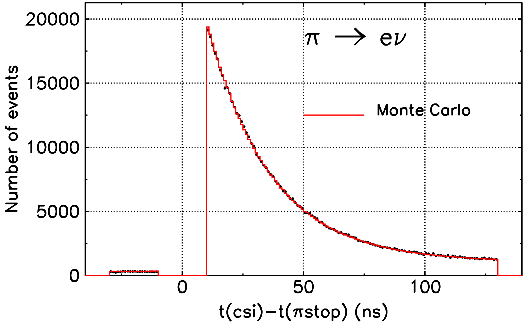

Number of Events
8000
6000
4000
2000
0
−10
−5
0
5
10
t(γ1)−t(γ2) (ns)
π⁺ → π⁰e⁺ν
→ γ1γ2
S
B
S/B>700
σ=0.90 ns

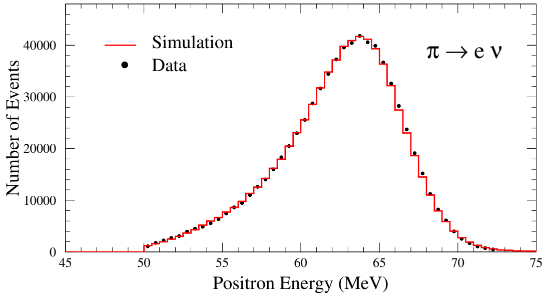

Number of Events
2000
1000
0
0
20
40
60
80
100
120
140
t(π⁰)−t(AD) (ns)
π⁺ → π⁰e⁺ν
— Monte Carlo
τ=26.23±0.12 ns



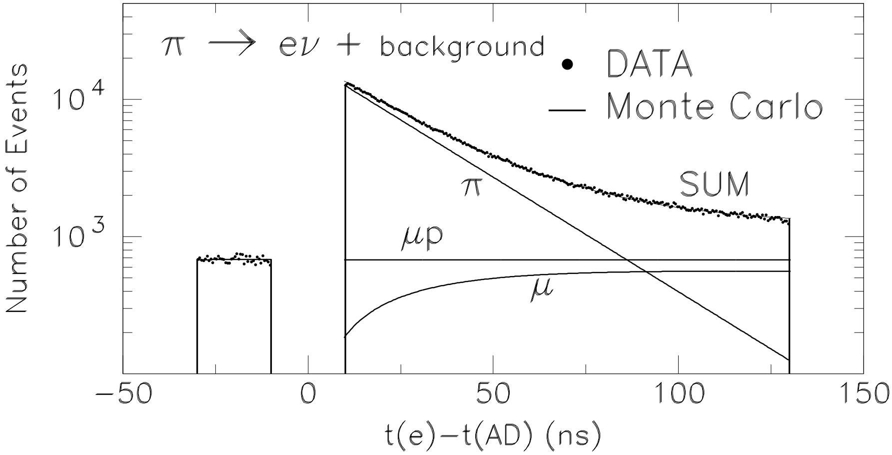
$\pi^+ \rightarrow \pi^0 e^+ \nu$
$\rightarrow \gamma 1\ \gamma 2$
Simulation
Data
Number of events
0
1000
2000
3000
4000
5000
6000
7000
160
162.5
165
167.5
170
172.5
175
177.5
180
Opening angle $\Theta_{\gamma 1 \gamma 2}$ (degr)

Normalizing decay:
$\pi^+ \to e^+\nu$





Extracting the $\pi \to e\nu$ Signal



Summary of the main $\pi\beta$ uncertainties

Type	Quantity	Value	Uncertainty (%)	
external:	π^+ lifetime	26.033 ns	0.02	
	$R^{\rm exp}_{\pi^0\to\gamma\gamma}$	0.9880	0.03	
	$R^{\rm exp}_{\pi e2}$	1.230×10^{-4}	0.33	0.33
internal:	$N^{\rm tot}_{\pi e2}$ (syst.)	6.779×10^{8}	0.19	
	$A^{\rm HT}_{\pi\beta}/A^{\rm HT}_{\pi e2}$	0.9432	0.12	
	$r_{\pi G} = f^{\pi\beta}_{\pi G}/f^{\pi e2}_{\pi G}$	1.130	0.26	
	π_β accid. bgd.	0.00	< 0.1	
	$f_{\rm CPP}$ correction	0.9951	0.10	
	$f_{\rm ph}$ correction	0.9980	0.10	0.38
statistical:	$N_{\pi\beta}$	64 047		0.395

$\pi \longrightarrow e\nu$ decay: SM predictions; measurements

Modern theoretical calculations:

$$B_{\text{calc}} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{calc} =$$

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

Experiment, world average [current PDG]:

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

$\pi \longrightarrow e\nu$ decay: SM predictions; measurements

Modern theoretical calculations:

$$B_{\text{calc}} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{calc} =$$

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

Experiment, world average [current PDG]:

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

PIBETA Result for π_β Decay [PRL **93**, 181803 (2004)]

$$B^{\text{exp}}_{\pi\beta} = [1.040 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst})] \times 10^{-8}\,,$$

$$B^{\text{exp}}_{\pi\beta} = [1.036 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.003\,(\pi_{e2})] \times 10^{-8}\,,$$

McFarlane et al. [PRD 1985]: $B = (1.026 \pm 0.039) \times 10^{-8}$

SM Prediction (PDG, 2006):

$B = \quad 1.038 - 1.041 \times 10^{-8} \quad$ (90% C.L.)

$(1.005 - 1.007 \times 10^{-8} \quad$ excl. rad. corr.)

PDG 2008: $V_{ud} = 0.9742(3)$

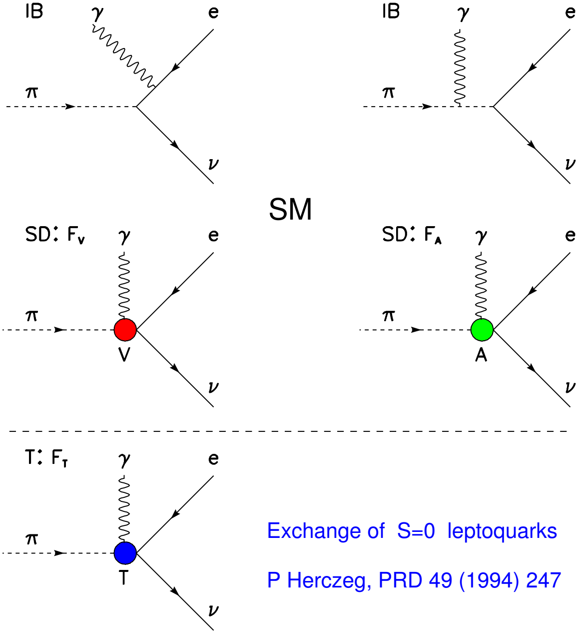
PIBETA current: $V_{ud} = 0.9748(25)$ or $V_{ud} = 0.9728(30)$.

Radiative pion decay:

$$\pi \to e\nu\gamma$$

$\pi^+ \to e^+ \nu \gamma$:

Standard **IB** *and* **V − A** *terms*



A tensor interaction, too?

Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

The $\pi \to e\nu\gamma$ amplitude and FF's

The IB amplitude (QED):

$$M_{IB} = -i\frac{eG_F V_{ud}}{\sqrt{2}} f_\pi m_e \epsilon^{\mu *} \bar{e}\left(\frac{k_\mu}{kq} - \frac{p_\mu}{pq} + \frac{\sigma_{\mu\nu} q^\nu}{2kq}\right) \times (1-\gamma_5)\,\nu\,.$$

The structure-dependent amplitude:

$$M_{SD} = \frac{eG_F V_{ud}}{m_\pi\sqrt{2}} \epsilon^{\nu *} \bar{e}\gamma^\mu (1-\gamma_5)\nu \times \left[F_V \epsilon_{\mu\nu\sigma\tau} p^\sigma q^\tau + i F_A (g_{\mu\nu} pq - p_\nu q_\mu)\right]\,.$$

The SM branching ratio ($\gamma \equiv F_A/F_V$; $x = 2E_\gamma/m_\pi$; $y = 2E_e/m_\pi$,)

$$\begin{aligned}\frac{d\Gamma_{\pi e2\gamma}}{dx\,dy} =& \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Bigg\{ IB\,(x,y) + \left(\frac{F_V m_\pi^2}{2 f_\pi m_e}\right)^2 \\ & \times \left[(1+\gamma)^2\, SD^+\,(x,y) + (1-\gamma)^2\, SD^-\,(x,y) \right] \\ & + \left(\frac{F_V m_\pi}{f_\pi}\right) \left[(1+\gamma)\, S^+_{\rm int}\,(x,y) + (1-\gamma)\, S^-_{\rm int}\,(x,y)\right] \Bigg\}\,.\end{aligned}$$

Available data on Pion Form Factors

$$|F_V| \stackrel{\text{cvc}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0} m_\pi}} = 0.0259(9) \,.$$

$F_A \times 10^4$	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)	

Available data on Pion Form Factors

$$|F_V| \overset{\text{cvc}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0}m_\pi}} = 0.0259(9)\ .$$

$F_A \times 10^4$	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)	

Available data on Pion Form Factors

$$|F_V| \overset{\text{cvc}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0} m_\pi}} = 0.0259(9) \;.$$

$F_A \times 10^4$	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)	

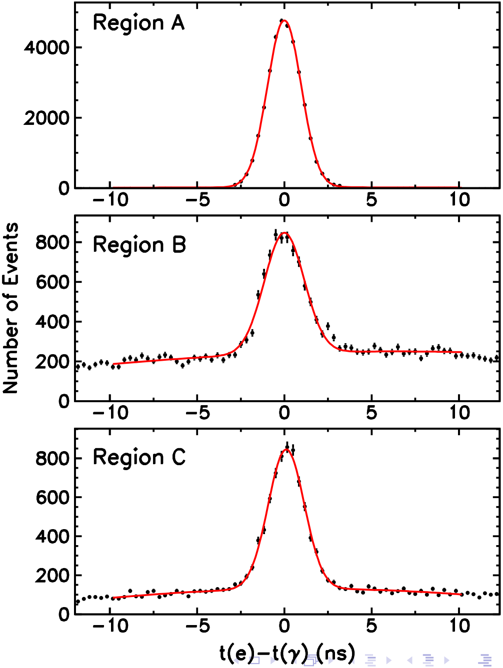
$\pi^+ \to e^+\nu\gamma$ (S/B)

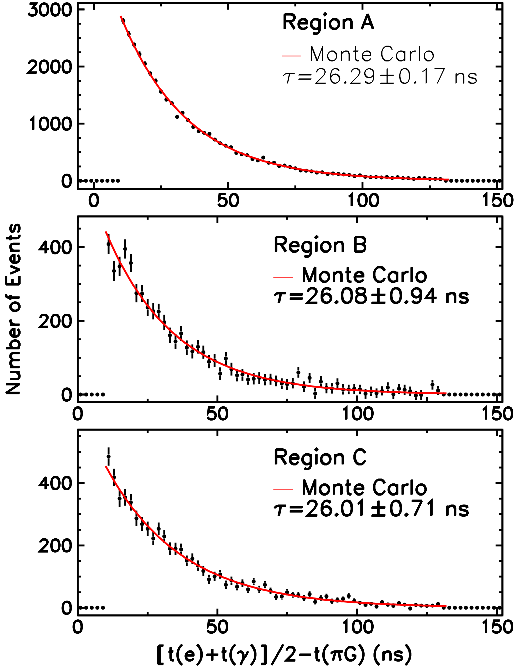
1999–2001 data set

Region A:
$E_\gamma, E_{e^+} > 51.7\,\text{MeV}$

Region B:
$E_\gamma > 55.6\,\text{MeV}$
$E_{e^+} > 20\,\text{MeV}$
$\theta_{e\gamma} > 40^\circ$

Region C:
$E_\gamma > 20\,\text{MeV}$
$E_{e^+} > 55.6\,\text{MeV}$
$\theta_{e\gamma} > 40^\circ$





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

1999–2001 data set

(timing)

Results of the SM fit [Phys. Rev. Lett. **93**, 181804 (2004)]

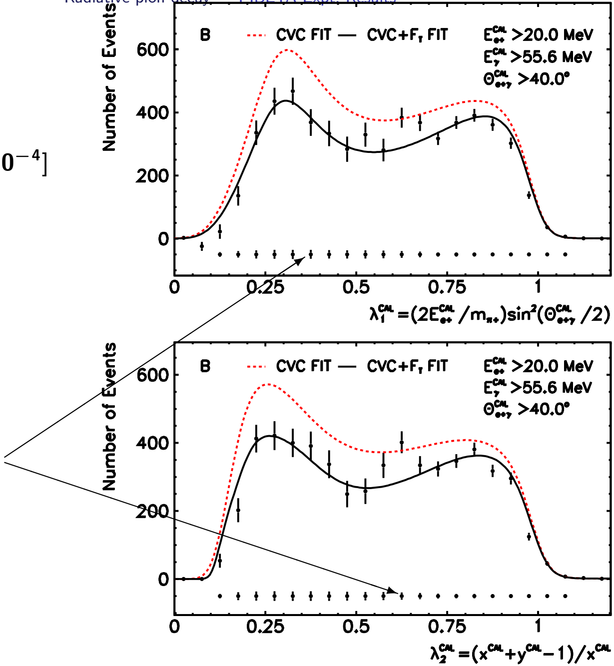
Best-fit $\pi \to e\nu\gamma$ branching ratios obtained with:
$F_V = 0.0259$ (fixed) and $F_A = 0.0115(4)$ (fit)
χ^2/d.o.f. = **25.4**.
Radiative corrections are included in the calculations.

$E_{e^+}^{min}$ (MeV)	E_{γ}^{min} (MeV)	$\theta_{e\gamma}^{min}$	B_{exp} ($\times 10^{-8}$)	B_{the} ($\times 10^{-8}$)	no. of events
50	**50**	–	**2.71(5)**	**2.583(1)**	**30.6 k**
10	**50**	**40°**	**11.6(3)**	**14.34(1)**	**5.2 k**
50	**10**	**40°**	**39.1(13)**	**37.83(1)**	**5.7 k**

Region B:

global fits

$[\mathbf{F_T} = (-16 \pm 2) \times 10^{-4}]$



projected uncertainties in 2004 run

$\pi^+ \to e^+\nu\gamma$ (S/B) 2004

Region A:

$E_\gamma, E_{e^+} > 51.7$ MeV

Region B:

$E_\gamma > 55.6$ MeV

$E_{e^+} > 20$ MeV

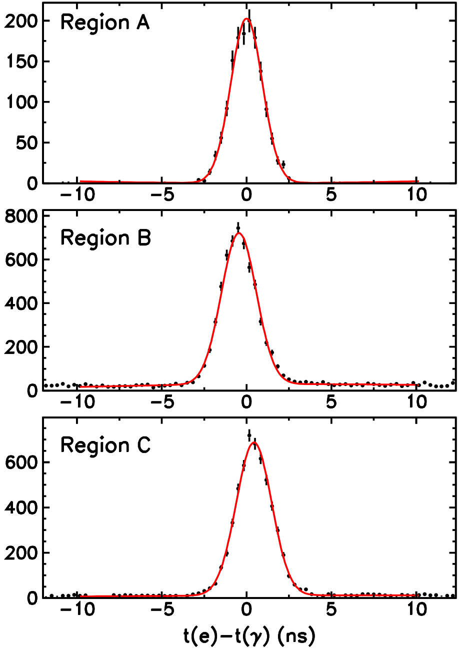
$\theta_{e\gamma} > 40^\circ$

Region C:

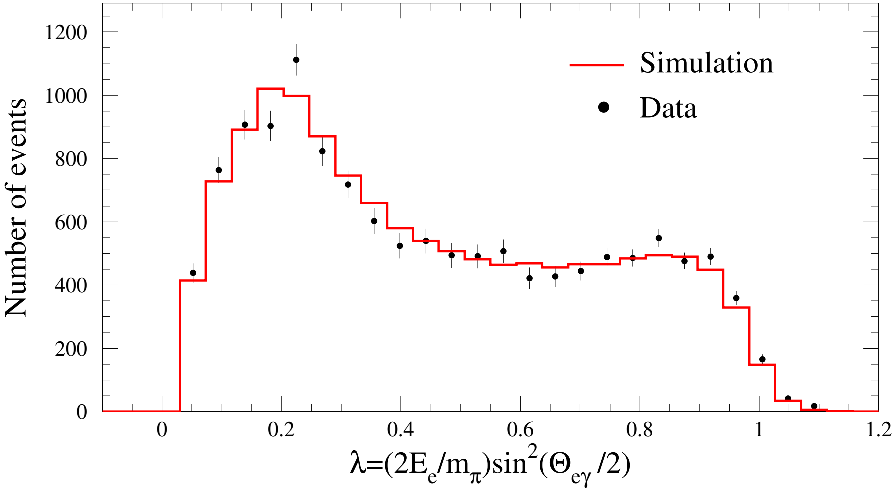
$E_\gamma > 20$ MeV

$E_{e^+} > 55.6$ MeV

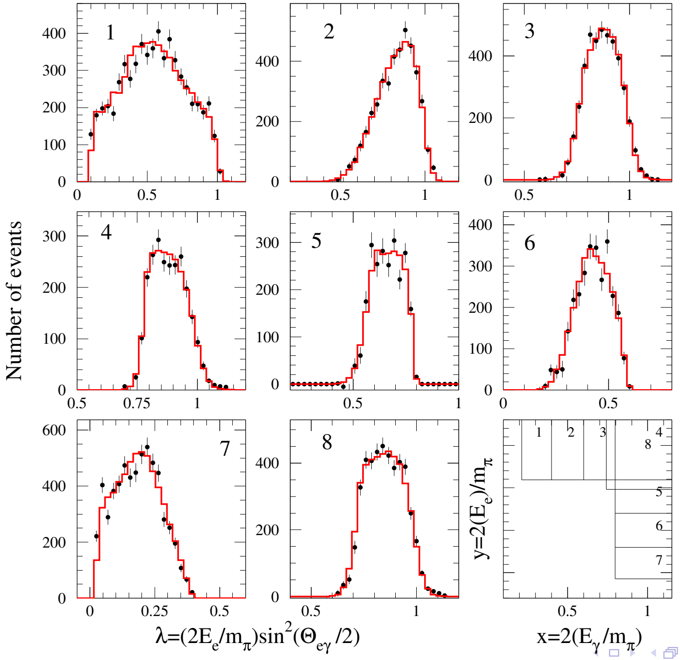
$\theta_{e\gamma} > 40^\circ$



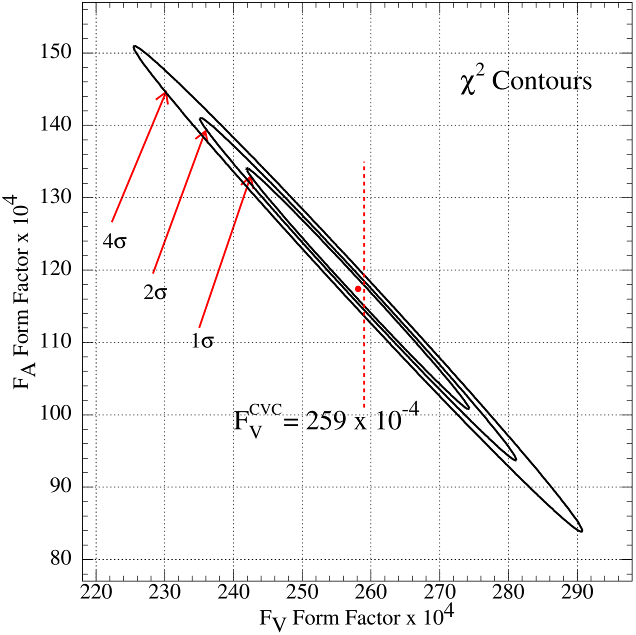
Analysis of 2004 data [M. Bychkov, PhD thesis, 2005]



Standard Model fit — $(V - A)$ only.



8 region analysis
[M. Bychkov, PhD thesis, 2005]

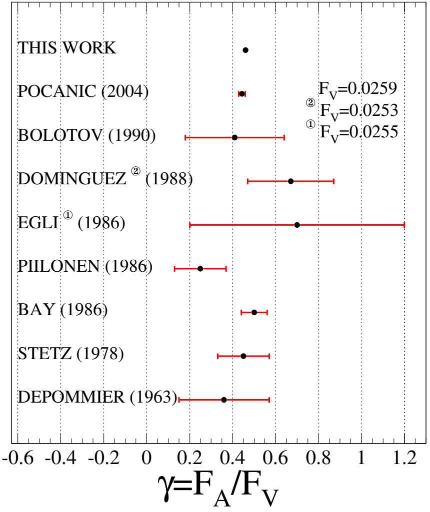


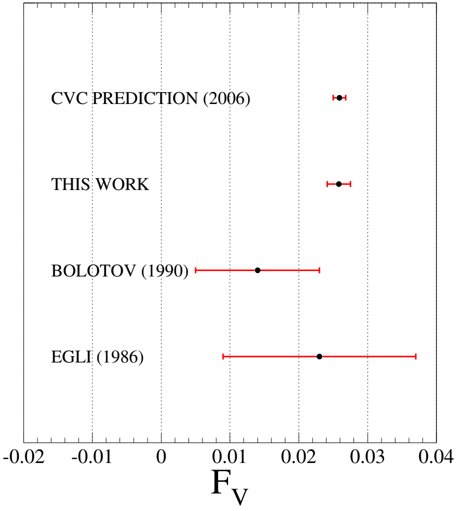
Best values of pion Form Factor Parameters:

Combined analysis of 1999-2001 and 2004 data sets

[M. Bychkov, 2007]

Experimental History of Pion F_A and F_V





Summary of Pion Form Factor Results

$$F_V = 0.0258 \pm 0.0017 \qquad (14\times)$$

$$F_A = 0.0119 \pm 0.0001^{\text{exp}}_{(F_V^{\text{CVC}})} \qquad (16\times)$$

$$a = 0.095 \pm 0.058 \qquad (\infty)$$

$$-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4} \qquad 90\,\%\ \text{C.L.}$$

Derived pion polarizability and π^0 lifetime:

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

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\text{s} \qquad \text{PDG: } 8.4(6)$$

Also:

$$B_{\pi_{e2\gamma}}(E_\gamma > 10\,\text{MeV}, \theta_{e\gamma} > 40^\circ) = 73.86(54) \times 10^{-8} \qquad (17\times)$$

Radiative muon decay:

$$\mu \to \mathrm{e}\nu\bar{\nu}\gamma$$

Michel Parameters of Muon Decay: $\mu \rightarrow e\nu\bar{\nu}$

$$\frac{d^2\Gamma}{dx\; d(\cos\theta)} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \times$$
$$\times \left[\mathbf{F_{IS}}(x) + P_{\mu^+} \cos\theta\, \mathbf{F_{AS}}(x)\right] \left[1 + \vec{P}_{e^+}(x,\theta) \cdot \hat{\zeta}\right]$$

Isotropic part:

$$\mathbf{F_{IS}}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta\, x_0(1-x)$$

Anisotropic part:

$$\mathbf{F_{AS}}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left(1 - x + \frac{2}{3}\delta\left[4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right]\right)$$

Michel Parameters of Radiative Muon Decay: $\mu \longrightarrow e\nu\bar{\nu}\gamma$

$$\frac{d^3B(x,y,\theta)}{dx\,dy\,2\pi\,d(\cos\theta)} = f_1(x,y,\theta) + \bar{\eta} f_2(x,y,\theta) + (1 - \frac{4}{3}\rho) f_3(x,y,\theta)$$

$$\rho = \frac{3}{4} - \frac{3}{4}\Big[|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + \Re(g^S_{RL} g^{T*}_{RL} + g^S_{LR} g^{T*}_{LR})\Big] \overset{\text{SM}}{\equiv} \frac{3}{4}\,,$$

$$\bar{\eta} = \left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + \frac{1}{8}\left(|g^S_{LR} + 2g^T_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2 + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right)\right) \overset{\text{SM}}{\equiv} 0\,.$$

Experimental Limits (90 % C.L.) on $\mathbf{g}^{\gamma}_{\alpha\beta}$

$\lvert g^{\gamma}_{\alpha\beta}\rvert$	S	V	T
LL	0.550	>0.960	$\equiv 0$
LR	0.125	0.060	0.036
RL	0.424	0.110	0.122
RR	0.066	0.033	$\equiv 0$
max. values:	$\lvert g^{S}_{\alpha\beta}\rvert \leq 2$	$\lvert g^{V}_{\alpha\beta}\rvert \leq 1$	$\lvert g^{T}_{\alpha\beta}\rvert \leq \frac{1}{\sqrt{3}} \approx 0.58$

[For more details cf. reviews and publications by W. Fetscher et al.]

Experimental Limits (90 % C.L.) on $\mathbf{g}^{\gamma}_{\alpha\beta}$

$\lvert g^{\gamma}_{\alpha\beta}\rvert$	S	V	T
LL	0.550	>0.960	$\equiv 0$
LR	0.125	0.060	0.036
RL	0.424	0.110	0.122
RR	0.066	0.033	$\equiv 0$
max. values:	$\lvert g^{S}_{\alpha\beta}\rvert \le 2$	$\lvert g^{V}_{\alpha\beta}\rvert \le 1$	$\lvert g^{T}_{\alpha\beta}\rvert \le \frac{1}{\sqrt{3}} \approx 0.58$

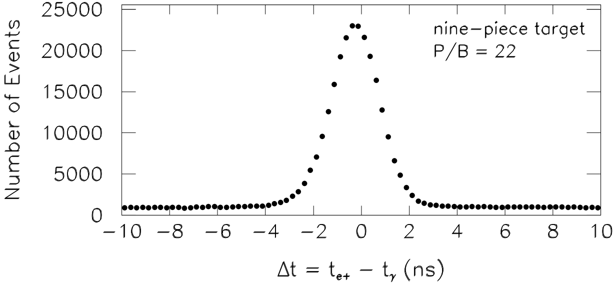
[For more details cf. reviews and publications by W. Fetscher et al.]

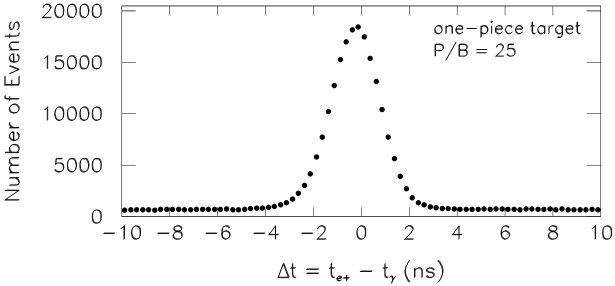
Experimental Limits (90 % C.L.) on $\mathbf{g}^{\gamma}_{\alpha\beta}$

$\lvert g^{\gamma}_{\alpha\beta}\rvert$	S	V	T
LL	0.550	$>$0.960	$\equiv 0$
LR	0.125	0.060	0.036
RL	0.424	0.110	0.122
RR	0.066	0.033	$\equiv 0$
max. values:	$\lvert g^{S}_{\alpha\beta}\rvert \le 2$	$\lvert g^{V}_{\alpha\beta}\rvert \le 1$	$\lvert g^{T}_{\alpha\beta}\rvert \le \frac{1}{\sqrt{3}} \approx 0.58$

[For more details cf. reviews and publications by W. Fetscher et al.]

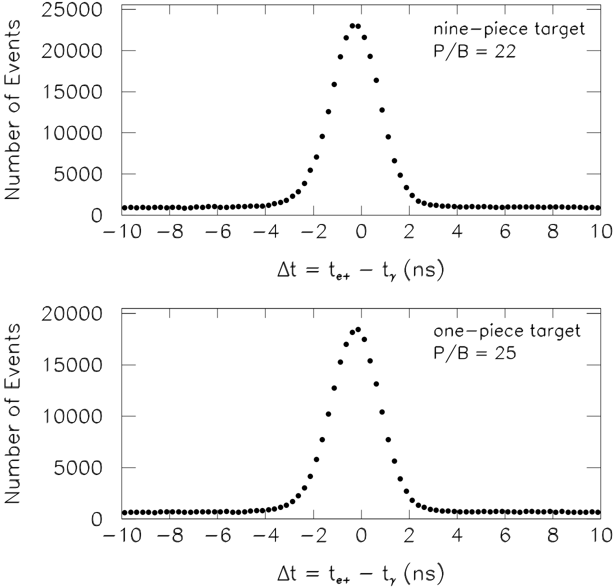
RMD analysis (2004 data)   [B. VanDevender's thesis]





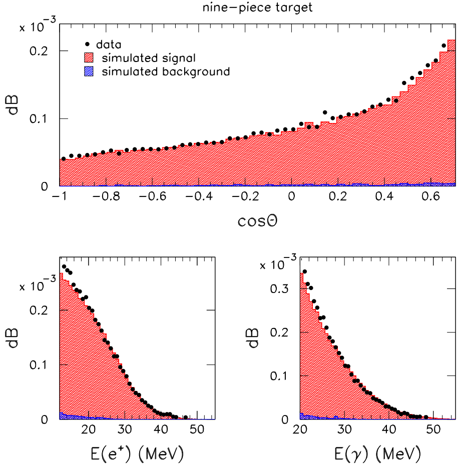
PEN Expt:
(2008 data)
P/B = 36;
$\sigma_t \simeq 1$ ns

RMD analysis (2004 data) [B. VanDevender's thesis]



PEN Expt:
(2008 data)
$P/B = 36$;
$\sigma_t \simeq 1\,\mathrm{ns}$

Differential Branching Ratio [B. VanDevender]



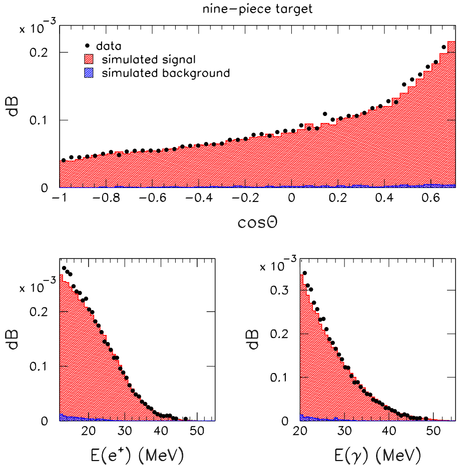
due to small-angle bremsstrahlung uncertainties in GEANT

$$B^{\rm exp} = [4.40 \pm 0.02\;(\rm stat.) \pm 0.09\;(\rm syst.)] \times 10^{-3}$$

14×!

$$B^{\rm theo} = 4.30 \times 10^{-3} \qquad (E_\gamma > 10\,\rm MeV,\;\; \theta > 30^\circ)$$

Differential Branching Ratio [B. VanDevender]



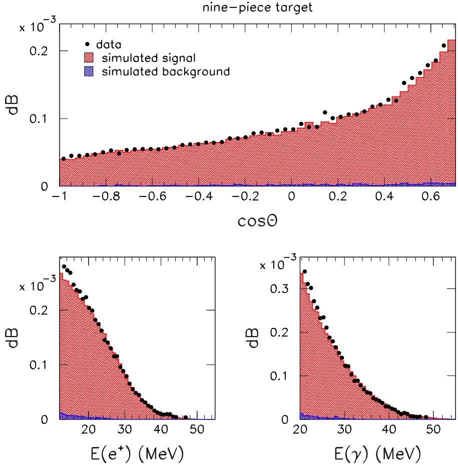
due to small-angle bremsstrahlung uncertainties in GEANT

$$B^{\rm exp} = [4.40 \pm 0.02\ ({\rm stat.}) \pm 0.09\ ({\rm syst.})] \times 10^{-3}$$

14×!

$$B^{\rm theo} = 4.30 \times 10^{-3} \qquad (E_\gamma > 10\,{\rm MeV},\ \theta > 30^\circ)$$

Differential Branching Ratio [B. VanDevender]



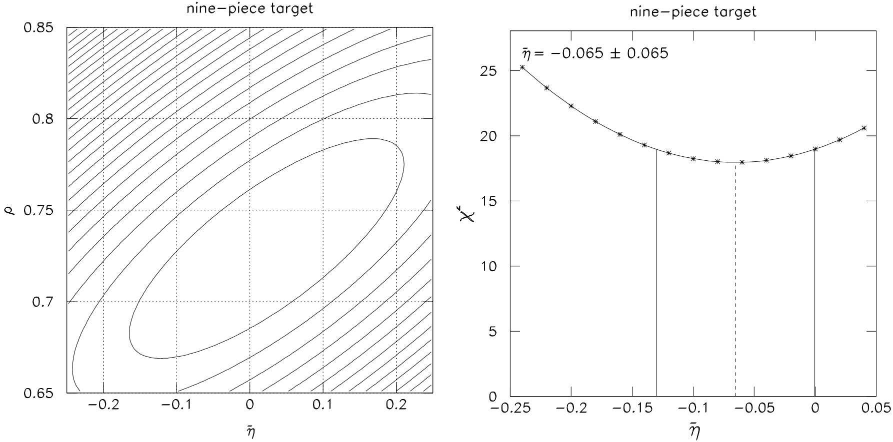
due to small-angle bremsstrahlung uncertainties in GEANT

$$B^{\mathrm{exp}} = [4.40 \pm 0.02\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{syst.})] \times 10^{-3}$$

14×!

$$B^{\mathrm{theo}} = 4.30 \times 10^{-3} \qquad (E_\gamma > 10\,\mathrm{MeV},\ \theta > 30^\circ)$$

RMD analysis: $\bar{\eta}$ and ρ [B. VanDevender's thesis]



χ^2 contours for fits of Michel parameters $\bar{\eta}$ and ρ for relevant RMD kinematics.

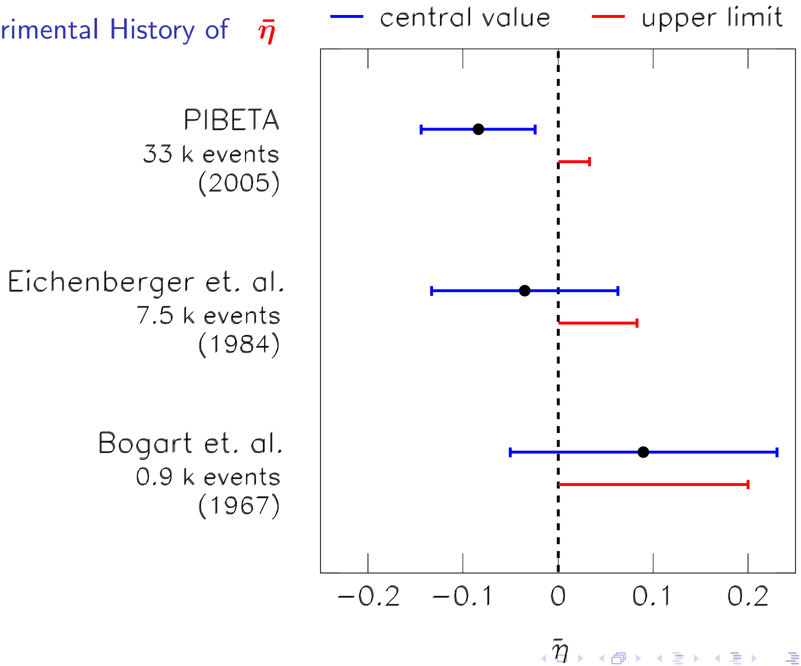
RMD analysis: Final $\bar{\eta}$ and ρ [B. VanDevender's thesis]

data set	$\bar{\eta}$	ρ
nine-piece target	-0.066 ± 0.070	0.750 ± 0.010
	-0.065 ± 0.065	0.75 (fixed)
one-piece target	-0.115 ± 0.085	0.751 ± 0.011
	-0.111 ± 0.077	0.75 (fixed)

Combined: $\bar{\eta} = \mathbf{-0.084 \pm 0.050(stat.) \pm 0.034(syst.)}$

$$\Rightarrow \bar{\eta} \leq \mathbf{0.033}\ (68\,\%\ \text{c.l.})\ \text{or}\ \bar{\eta} \leq \mathbf{0.060}\ (90\,\%\ \text{c.l.})$$

Experimental History of $\bar{\eta}$



Summary of RMD results

- First precise measurement of $B(\mu \to e\nu\bar{\nu}\gamma)$ over a large phase space
  - 313 events (bubble chamber) $\to 4.2 \times 10^5$ events
  - 30 % uncertainty $\to$ 2 % uncertainty
  - $B^{\mathrm{exp}} = (4.40 \pm 0.09) \times 10^{-3}$, ($B^{\mathrm{theo}} = 4.30 \times 10^{-3}$)
- New measurement of Michel parameter $\bar{\eta}$
  - $\bar{\eta} \leq 0.087 \to \bar{\eta} \leq 0.033$ (68 % c.l.)
  - new world average: $\bar{\eta} \leq 0.028$ (68 % c.l.)
    reduced by a factor of 2.5.
- Above results based on our 2004 run data set; the PEN experiment will double this data set with lower backgrounds.

The PEN Experiment:

$\pi \longrightarrow e\nu$

$\pi \longrightarrow e\nu$ decay: status revisited

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

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

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

$\pi \longrightarrow e\nu$ decay: status revisited

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

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

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

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) ⇒ PS currents. Most general 4-fermion π_{e2} amplitude:

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

In the SM: $f^l_{\text{AL}} = 1$, while $f^l_{\text{xR}} = f^l_{\text{Px}} = 0$, with $l = e, \mu$.

The f_{PL}^{e} and Mass Bounds

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

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

where 2nd term in denominator is negligible because $f_{\mathrm{PL}}^{e} \simeq f_{\mathrm{PL}}^{\mu}$, while

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

Therefore

$$\left(B_{\pi e2}^{\mathrm{obs}} - B_{\pi e2}^{\mathrm{SM}}\right) / B_{\pi e2}^{\mathrm{SM}} = \frac{\Delta B}{B^{\mathrm{SM}}} \simeq \frac{2m_\pi a_{\mathrm{P}}}{m_e a_{\mathrm{A}}} f_{\mathrm{PL}}^{e} \simeq 7700 f_{\mathrm{PL}}^{e} \ !$$

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

$$\delta f_{\mathrm{PL}}^{e} \simeq 6.5 \times 10^{-8} .$$

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."]

Departures from lepton universality

Various models beyond the SM predict flavor non-universal suppressions of the lepton coupling constants in $W\ell\nu$:

$$g_\ell \to g'_\ell = g_\ell(1 - \frac{\epsilon_\ell}{2}) \qquad \text{where} \qquad \ell = e, \mu, \tau$$

Linear combinations constrained by W, τ, π, K decays are:

$$\frac{g_\mu}{g_e} = 1 + \frac{\epsilon_e - \epsilon_\mu}{2}, \qquad \frac{g_\tau}{g_\mu} = 1 + \frac{\epsilon_\mu - \epsilon_\tau}{2}, \qquad \frac{g_\tau}{g_e} = 1 + \frac{\epsilon_e - \epsilon_\tau}{2},$$

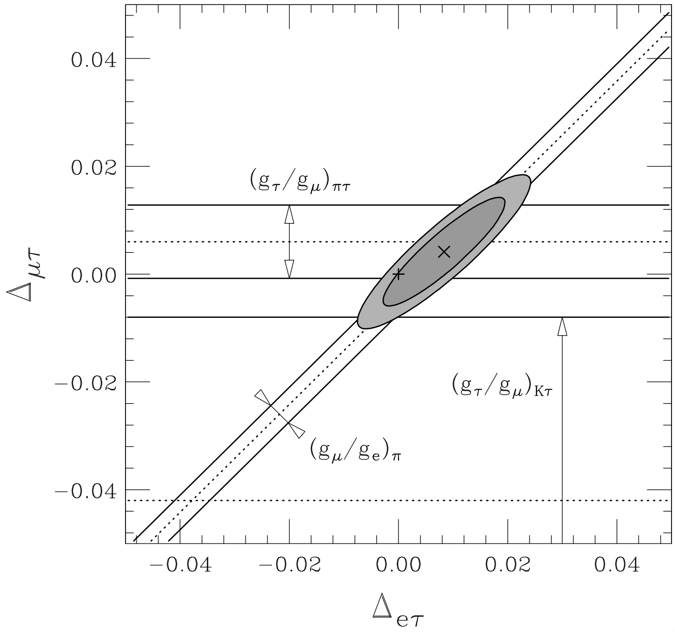
Two of the three are independent; experimental constraints are on:

$$\Delta_{e\mu} \equiv \epsilon_e - \epsilon_\mu, \qquad \Delta_{\mu\tau} \equiv \epsilon_\mu - \epsilon_\tau, \qquad \Delta_{e\tau} \equiv \epsilon_e - \epsilon_\tau.$$

Recent comprehensive reviews:

A. Pich, Nucl. Phys. Proc. Suppl. **123** (2003) 1; (hep-ph/0210445)

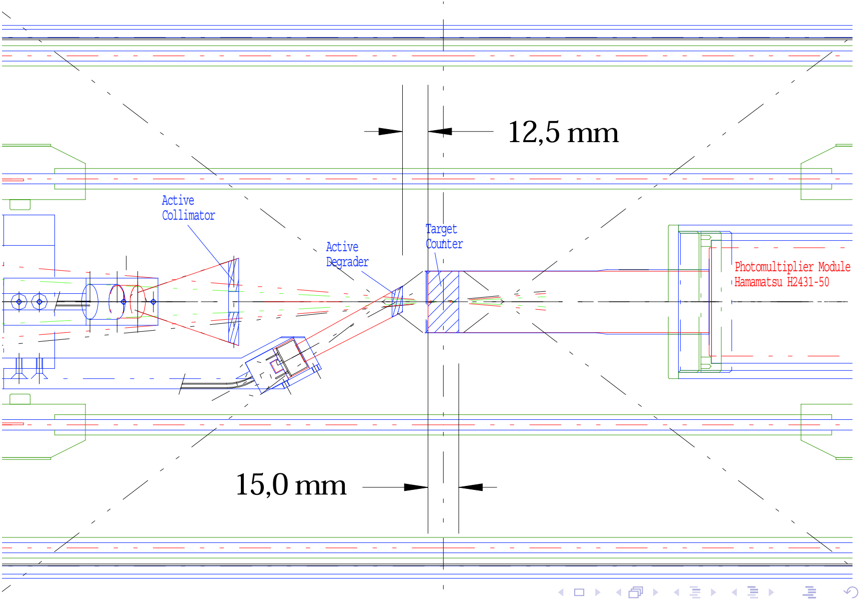
W. Loinaz et al., PRD **70** (2004) 113004; (hep-ph/0403306).



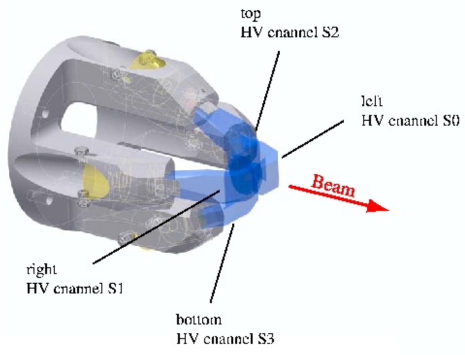
From
Loinaz et al.,
PRD **70** (2004)
113004

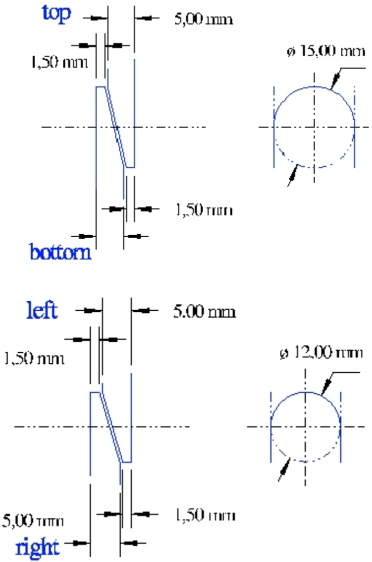
$$\Delta_{\ell\ell'} = 2\frac{g_\ell}{g_{\ell'}}$$

Central Detectors: 2007 Engineering Run

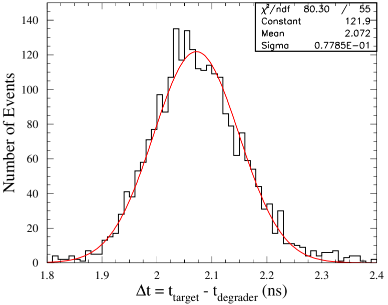


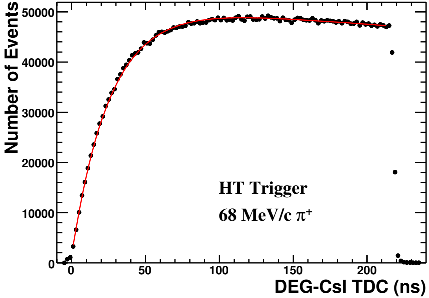
Wedged Degrader: 2008 Run

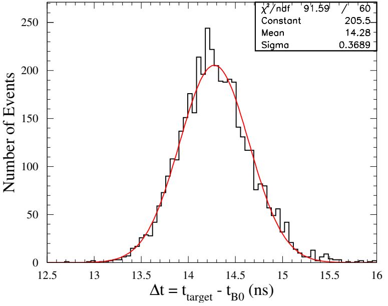


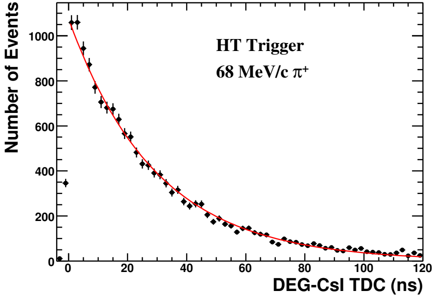


Timing in the central beam detectors



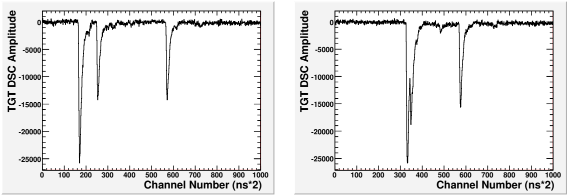




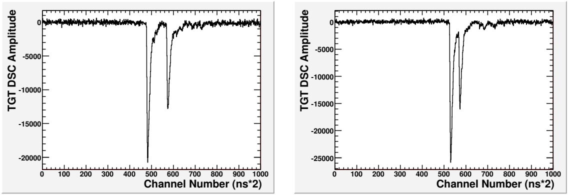


Sample waveforms 2007:

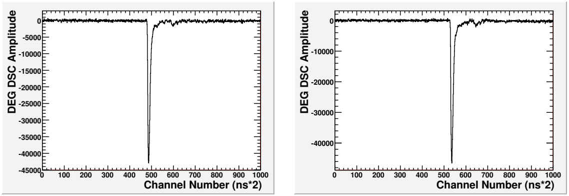
$\pi \rightarrow \mu \rightarrow e$
(in TGT)



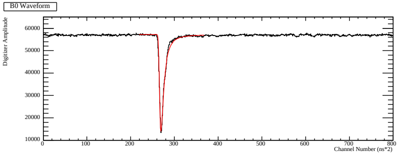
$\pi \rightarrow e$
(in TGT)



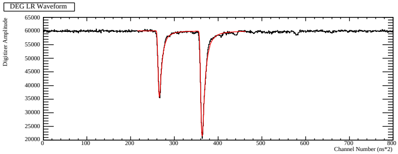
Beam π^+
(in DEG)



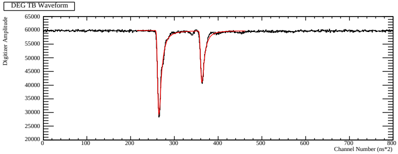
Waveforms 2008:



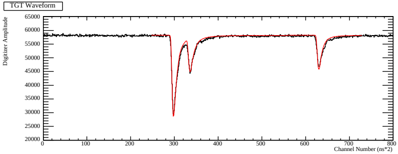
B0



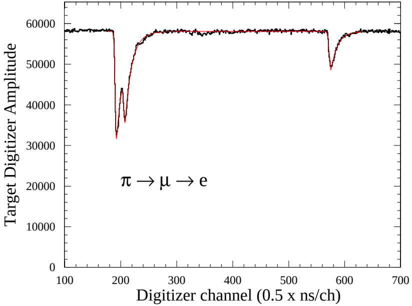
DEG–horiz

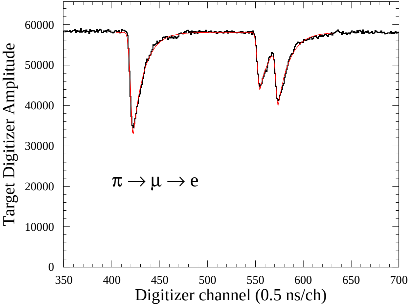


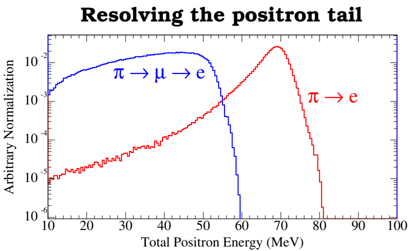
DEG–vert

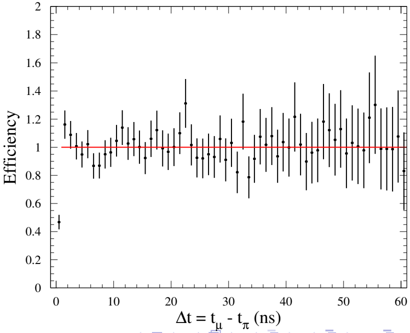


TGT


Target Digitizer Amplitude
Digitizer channel (0.5 x ns/ch)
π → μ → e
0
10000
20000
30000
40000
50000
60000
100
200
300
400
500
600
700


Target Digitizer Amplitude
Digitizer channel (0.5 ns/ch)
π → μ → e
0
10000
20000
30000
40000
50000
60000
350
400
450
500
550
600
650
700


Resolving the positron tail
Arbitrary Normalization
Total Positron Energy (MeV)
π → μ → e
π → e
10^-2
10^-3
10^-4
10^-5
10^-6
10
20
30
40
50
60
70
80
90
100


Efficiency
Δt = t_μ - t_π (ns)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
10
20
30
40
50
60

PEN Experiment: Present Status and Plans

- 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.

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* Web page:

http://pen.phys.virginia.edu