RARE PION DECAYS

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- Experimental status and prospects of rare pion decays (a brief review).
- Main experiment during the last decade: PIBETA at PSI. Runs: 1999–2001; 2004 (May–August)

Proton Driver Workshop
FNAL, 6–9 October 2004

Known and Measured Pion Decays

	Decay	BR	
$\pi^+ \longrightarrow$	$\mu^+\nu$	~ 1.0	$(\pi_{\mu 2})$
	$\mu^+\nu\gamma$	$\sim 2.0 \times 10^{-4}$	
	$e^+\nu$	$\sim 1.2 \times 10^{-4}$	(π_{e2})
	$e^+\nu\gamma$	$\sim 5.6 \times 10^{-8}$	$(\pi_{e2\gamma})$
	$\pi^0 e^+\nu$	$\sim 1.0 \times 10^{-8}$	$(\pi_{e3},\ \pi_\beta)$
$\pi^0 \longrightarrow$	$\gamma\gamma$	~ 0.9880	
	$e^+e^-\gamma$	$\sim 1.2 \times 10^{-2}$	
	$e^+e^-e^+e^-$	$\sim 3.1 \times 10^{-5}$	
	e^+e^-	$\sim 6.2 \times 10^{-8}$	

PIBETA experiment: program of measurements

Preform precision tests of Standard Model and QCD predictions:

- $\pi^+ \to \pi^0 e^+ \nu_e$ – main goal
  - ∘ SM tests related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma (ee)$
  - ∘ F_A/F_V, π polarizability (χPT prediction)
  - ∘ tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma (ee)$
  - ∘ departures from $V - A$ in $\mathcal{L}_{\rm weak}$
- $\pi^+ \to e^+ \nu_e$ – 2nd phase
  - ∘ e-μ universality
  - ∘ pseudoscalar coupling besides $V - A$
  - ∘ massive neutrino, Majoron, ...

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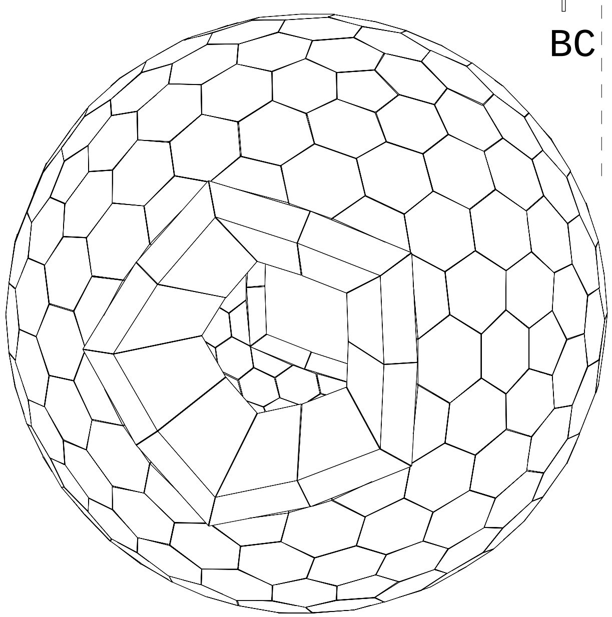
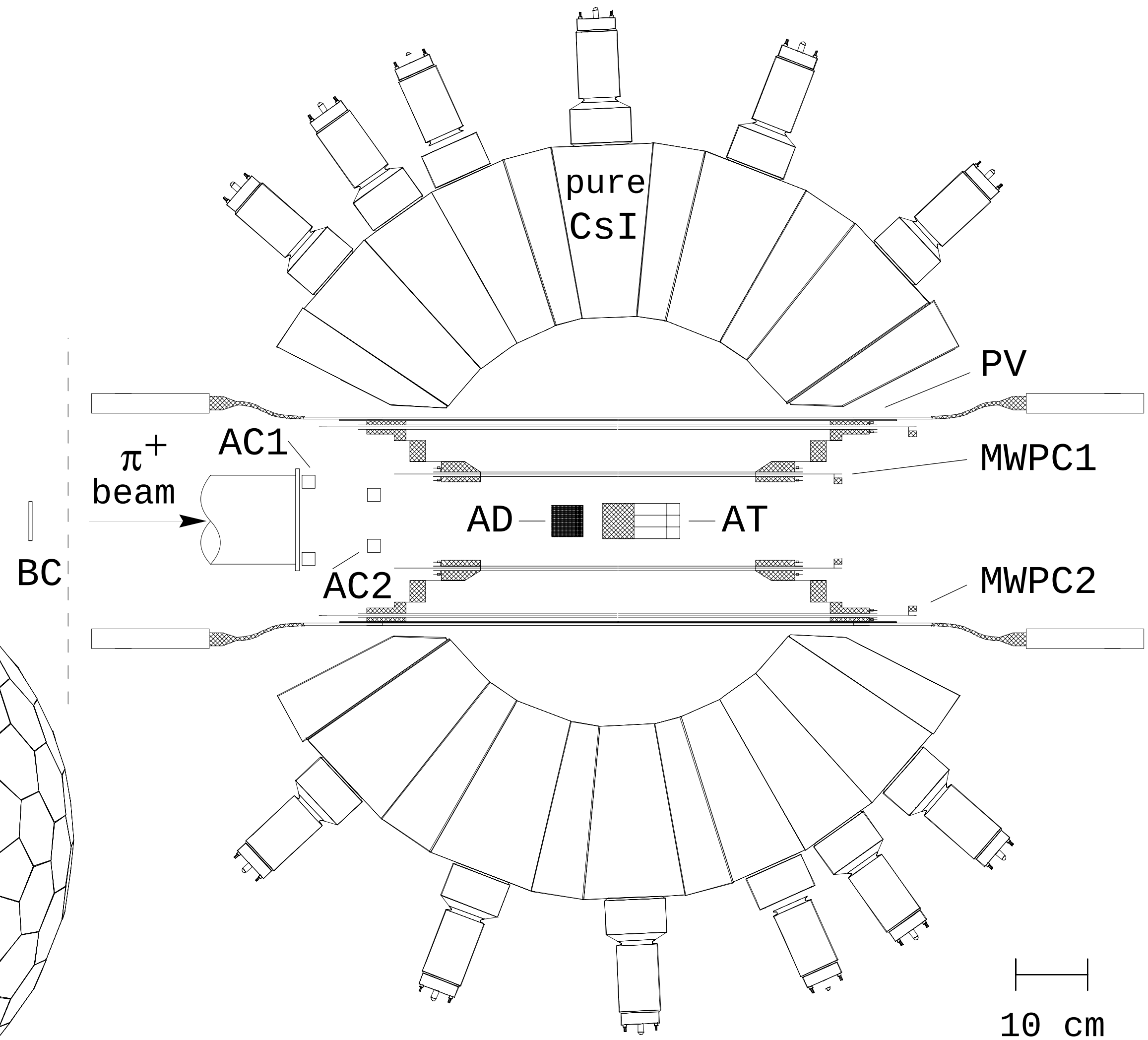
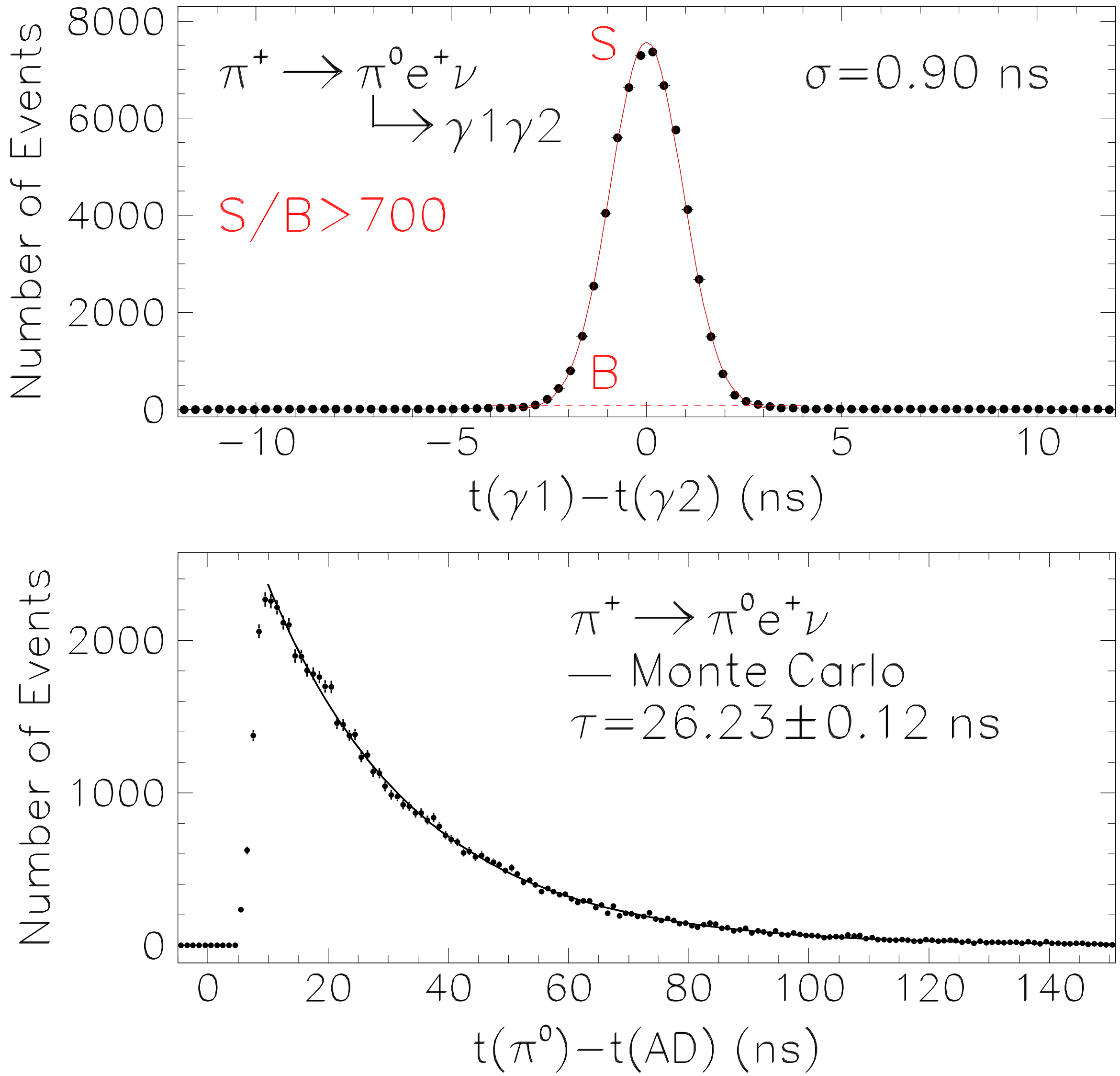
The PIBETA Experiment:

- ∘ stopped π^+ beam
- ∘ segmented active tgt.
- ∘ 240-det. CsI(p) calo.
- ∘ central tracking
- ∘ digitized PMT signals
- ∘ stable temp./humidity
- ∘ cosmic μ antihouse



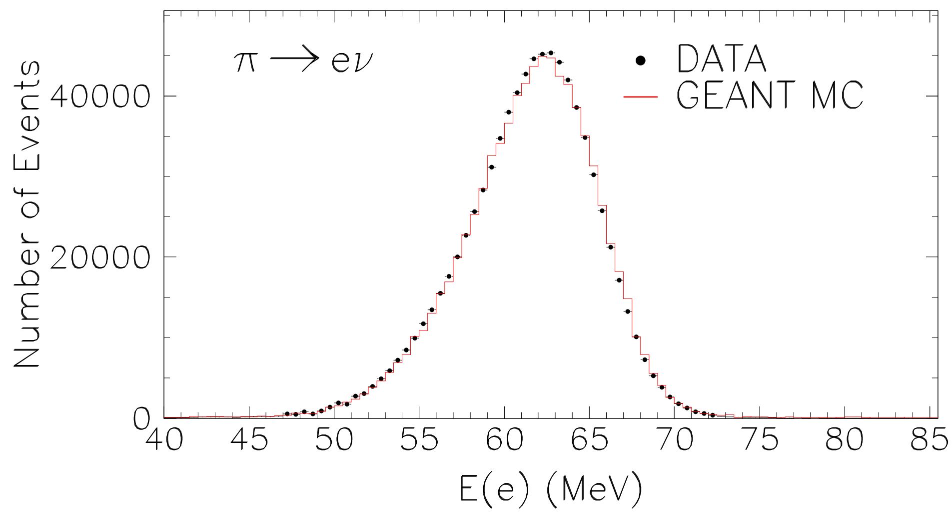


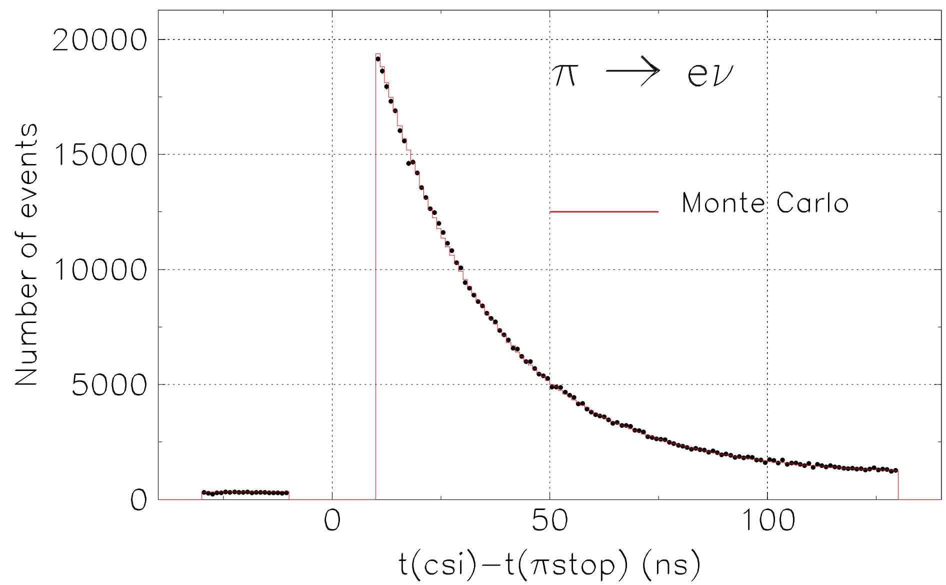
The $\pi^+ \rightarrow \pi^0 e^+ \nu$ *decay*



Normalizing decay:

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





Summary of the main $\pi\beta$ uncertainties

Type	Quantity	Value	Uncertainty (%)	
external:	$R^{\rm exp}_{\pi e2}$	1.230×10^{-4}	0.33	
	$R^{\rm exp}_{\pi^0\to\gamma\gamma}$	0.9880	0.03	
	π^+ lifetime	26.033 ns	0.02	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	
	$r_{\pi \rm G} = f^{\pi\beta}_{\pi \rm G}/f^{\pi e2}_{\pi \rm G}$	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

Recent calculations of pion beta decay radiative corrections

(1) In the light-front quark model

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

- total 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 BR$\left(\pi_{e3(\gamma)}\right)$.

Our Current Branching Ratio for $\pi\beta$ Decay

[arχiv: hep-ex/0312030]

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

McFarlane et al. (PRD 1985): $R \simeq 1.026 \pm 0.039 \times 10^{-8}$

SM Prediction (PDG, 2004):

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

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

PDG 2004: $V_{ud} = 0.9738(5)$

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

$\pi \to e\nu\gamma$: *Pion form factors and polarizability in* χ*PT*

To first order in χPT the pion weak form form factors fix:

$$\frac{F_A}{F_V} = 32\pi^2 \left(l_9^{\mathrm{r}} + l_{10}^{\mathrm{r}}\right) \ ,$$

while the pion polarizability is given by

$$\alpha_E = \frac{4\alpha}{m_\pi F_\pi^2} \left(l_9^{\mathrm{r}} + l_{10}^{\mathrm{r}}\right) \ ,$$

so that

$$\alpha_E = \frac{\alpha}{8\pi^2 m_\pi F_\pi^2} \cdot \frac{F_A}{F_V} \simeq 6.24 \times 10^{-4} \cdot \frac{F_A}{F_V} \ .$$

[To resolve l_9 and l_{10} one needs

$$\frac{1}{6}\langle r_\pi^2 \rangle = \frac{2}{F_\pi^2} l_9^{\mathrm{r}} - \frac{1}{96\pi^2 F_\pi^2} \left(\ln \frac{m_\pi^2}{\mu^2} + \frac{1}{2} \ln \frac{m_K^2}{\mu^2} + \frac{3}{2} \right) \ ,$$

w.a. 1.1 %; most accurate data, NA7 1986; last revisited at SELEX in 2001].

AVAILABLE DATA on Pion Form Factors

$$|F_V| \stackrel{\text{cvc}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi \tau_{\pi^0} m_{\pi^0}}} = 0.0259(5) \ .$$

$F_A \times 10^4$	reference
106 ± 60	Bolotov et al. (1990)
135 ± 16	Bay et al. (1986)
60 ± 30	Piilonen et al. (1986)
110 ± 30	Stetz et al. (1979)
116 ± 16	world average (PDG 2002)

Problems with pion form factors prior to 1999

A.A. Poblaguev found: [PL B238 (1990) 108, PL B286 (1992) 169]

(a) inconsistencies in data set (part. ISTRA data),

(b) need to include Tensor q-l coupling with:
$F_T \sim -0.0056 \pm 0.0017$. (updated recently in several papers)

P. Herczeg: [PRD 49 (1994) 247]

confirmed there is room (barely) for F_T of this order of magnitude from other weak decay data ($S = 0$ leptoquarks at tree level?).

M. Chizhov: [Mod. Phys. Lett. A8 (1993) 2753]

proposed a new intermediate chiral boson with anomalous T interaction with matter. (updated recently in several papers)

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

Region A:

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

Region B:

$E_\gamma > 55.6$ MeV

$E_{e^+} > 20$ MeV

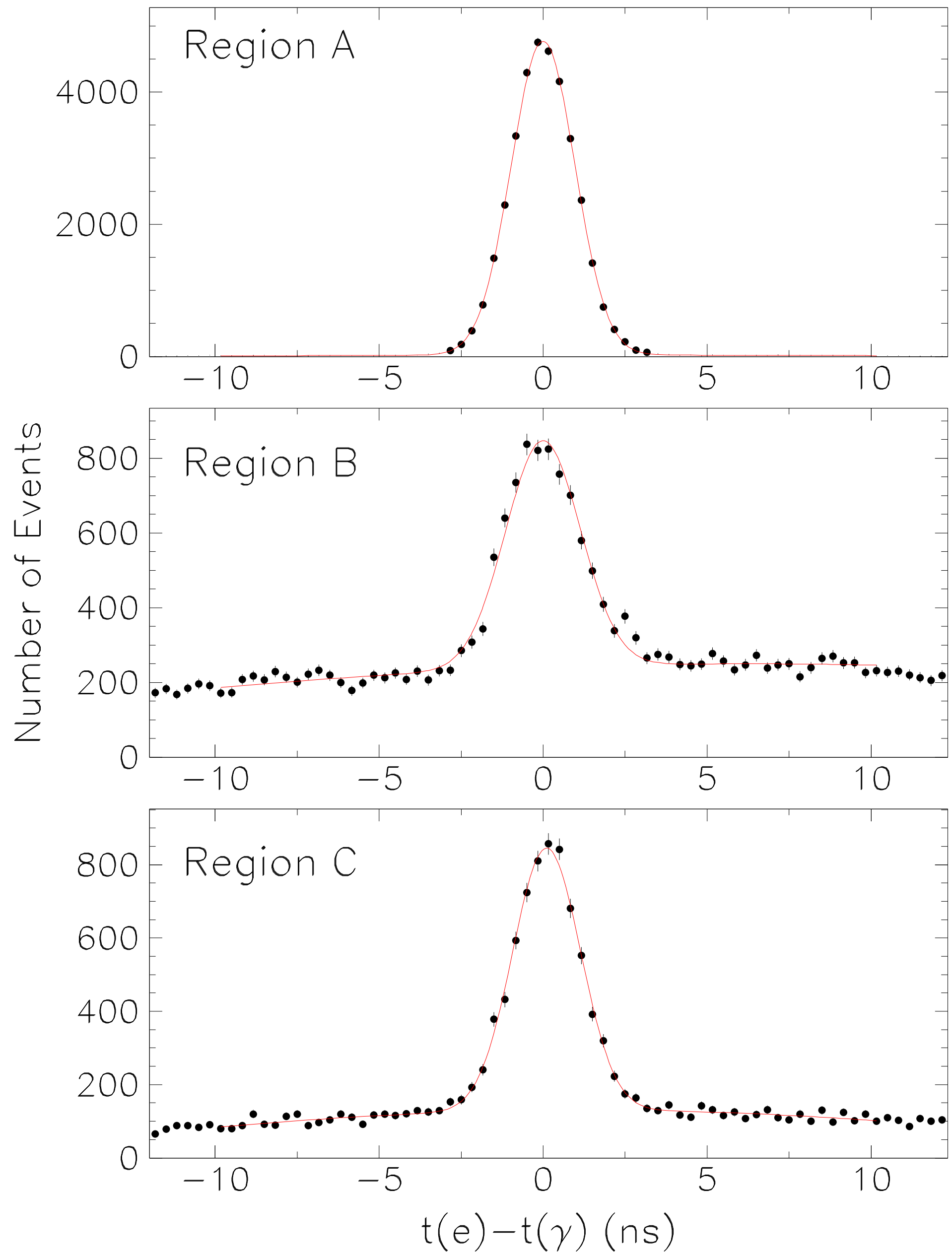
$\theta_{e\gamma} > 40^\circ$

Region C:

$E_\gamma > 20$ MeV

$E_{e^+} > 55.6$ MeV

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



Results of the SM fit

[arχiv: hep-ex/0312029]

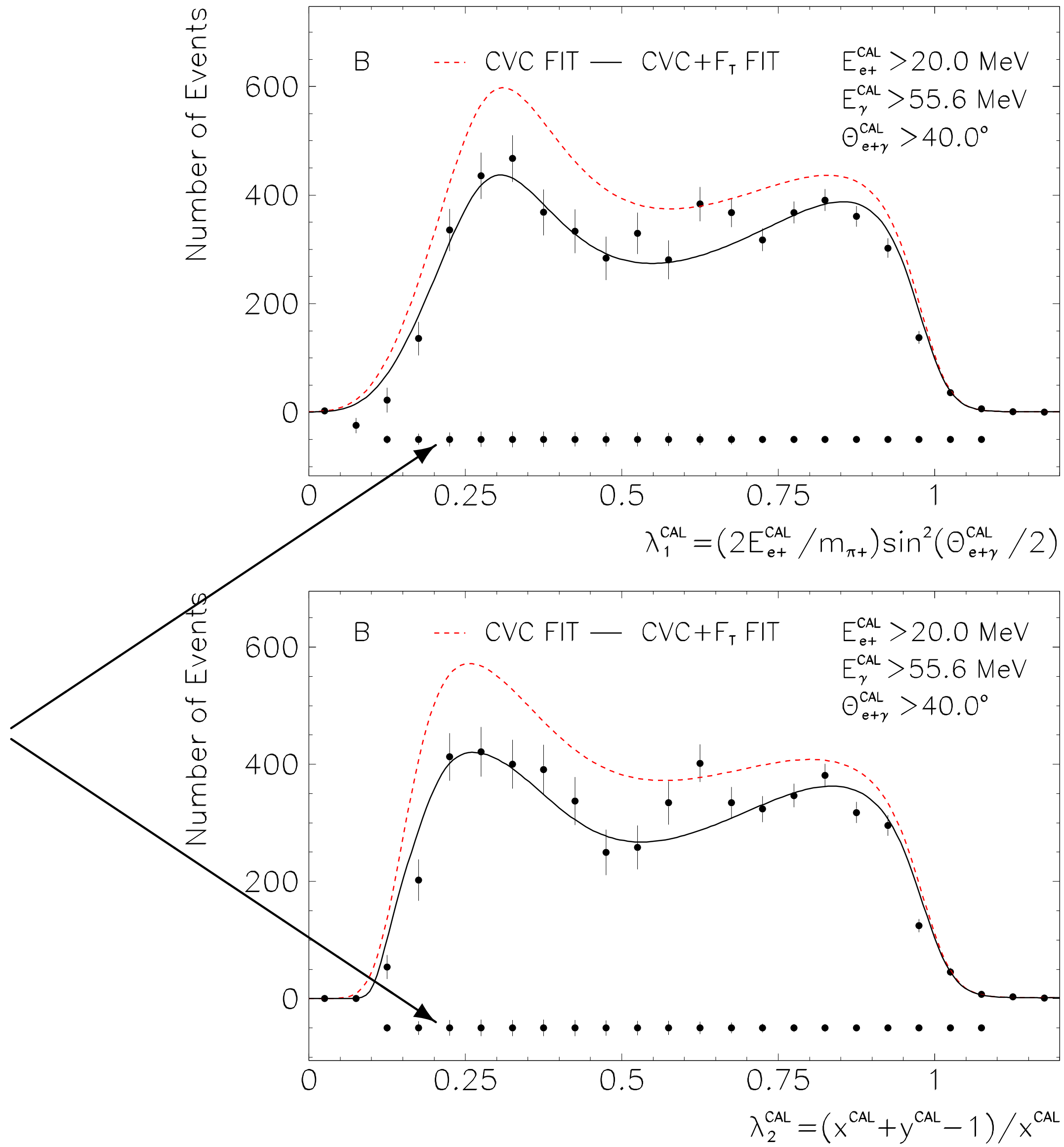
Best-fit $\pi \to e\nu\gamma$ branching ratios obtained with:
$F_V = 0.0259$ (fixed) and $F_A = 0.0115(4)$ (fit)
χ^2/d.o.f. $= 25.4$.
Radiative corrections are included in the calculations.

$E_{e^+}^{\text{min}}$ (MeV)	E_{γ}^{min} (MeV)	$\theta_{e\gamma}^{\text{min}}$	R_{exp} $(\times 10^{-8})$	R_{the} $(\times 10^{-8})$
50	50	–	$2.71(5)$	$2.583(1)$
10	50	40°	$11.6(3)$	$14.34(1)$
50	10	40°	$39.1(13)$	$37.83(1)$

Region B:

global fits

projected uncertainties in 2004 run



Remaining opportunities in pion decay

1. Improve the $\pi \to e\nu$ decay precision

   – highly motivated !

2. Improve the π_β decay precision

   – not as urgent $(+$ very hard).

3. A new search for the $\pi^0 \to \gamma\gamma\gamma$ decay?

   – sets the best limit on C-violation

4. Search for the allowed $\pi^0 \to 4\gamma$ decay?

   – QED γ splitting $R \simeq (2.6 \pm 0.1) \times 10^{-11}$

   Bratkovskaya et al, PL B359 (95) 217

$\pi^0 \to 3\gamma$ *decay: theoretical predictions*

- D. Dicus, Phys. Rev. D **12** (1975) 2133,
  SM estimate (single quark loop + parity violation):

$$BR(\pi^0 \to 3\gamma) \sim 10^{-31\pm6}$$

- Grosse and Liao, Phys. Lett. **B520** (2001) 63,
  Non-commutative QED estimate (anomalous $\pi^0\gamma$ interaction):

$$BR(\pi^0 \to 3\gamma) \approx 6 \cdot 10^{-21}$$

- Current PDG Limit: $< 3.1 \cdot 10^{-8}$ (90 % CL) [XTAL box, LAMPF 1988]
  could be experimentally reduced down to $\sim 10^{-10}$.

- $\pi^0 \to 3\gamma$ will continue to provide the best test of C-violation!

$\pi \longrightarrow e\nu$ *decay: SM predictions and measurements*

Marciano and Sirlin, Phys. Rev. Lett. **71** (1993) 3629:

$$\left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\text{calc}} = (1.2342 \pm 0.0005) \times 10^{-4}$$

Decker and Finkemeier, Nucl. Phys. B **438** (1995) 17:

$$\left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\text{calc}} = (1.2356 \pm 0.0001) \times 10^{-4}$$

Experiment, world average (PDG 2004):

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

Lepton universality

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

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

A $\pi \to e\nu$ measurement at FNAL

- In-flight decay (all previous measurements at rest) — direct measurement of decay rate ($\tau_{\pi^\pm}$ enters into BR).
- Requirements:
  1. intense tagged pion beam,
  2. large decay volume,
  3. large-acceptance high-resolution detector.
- Advantage: one can measure both π^+ and π^- decays !!!
- Challenges (all at the sub–10^{-3} level !):
  1. accurate beam normalization,
  2. measuring acceptance/proper time in decay volume,
  3. suppression of background events (false signals).