How Rare Pion Decays Relate to Precision Neutron Decay Measurements

Dinko Počanić, University of Virginia

- Brief review of the basics
- Motivation for new measurements: the **PIBETA** experiment
- Recent results:
  - pion beta decay: $\pi^+ \to \pi^0 e^+ \nu$ (π_β)
  - radiative pion decay: $\pi^+ \to e^+ \nu \gamma$ ($\pi_{e2\gamma}$)
  - radiative muon decay: $\mu^+ \to e^+ \nu \bar{\nu} \gamma$ **[will not discuss today]**
- Current and future work:
  - The **PEN** experiment, $\pi^+ \to e^+ \nu$ (π_{e2})
  - Planned **Nab** and **abBA** experiments at the SNS
- Conclusions

INT, Seattle
4 June 2007

Known and Measured Pion and Muon Decays (PDG 2004)

Decay		BR		
$\pi^+ \longrightarrow$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(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})	

$\pi^0 \longrightarrow$	$\gamma\gamma$	$0.98798\,(32)$
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$
	e^+e^-	$6.2\,(5) \times 10^{-8}$

$\mu^+ \longrightarrow$	$e^+\nu\bar{\nu}$	~ 1.0
	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$

The PIBETA program of measurements

Perform precision checks of Standard Model and QCD predictions:

- $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ – main goal
  - 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 $V - A$ (?)
- $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$(or $e^+ e^-$)
  - departures from $V - A$ in $\mathcal{L}_{\mathbf{weak}}$

2nd phase:

- $\pi^+ \rightarrow e^+ \nu_e$ – The *PEN* experiment
  - e-μ universality
  - pseudoscalar coupling besides $V - A$
  - neutrino sector anomalies, Majoron searches, m_{h+}, PS l-q's, V l-q's, . . .

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)

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

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

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

- $|V_{ud}|$ from neutron β decay (many results; currently incompatible)

  $\sum |V_{ui}|^2 = \mathbf{0.9917\,(28)}$, or $1 - 3.0\sigma$. [PERKEO II (2002)]

- $|V_{ud}|$ from pion β decay PIBETA expt—discussed below.

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

The Pion Beta Decay:

$\pi^\pm \to \pi^0 e^\pm \nu$: $\mathbf{B} \simeq 1 \times 10^{-8}$, 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: $\frac{1}{\tau} = \frac{1}{\tau_0}(1+\delta)$, 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: $\boldsymbol{\delta = (3.230 \pm 0.002) \times 10^{-2}}$.

(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 $\mathbf{5 \times 10^{-4}}$ in extracting $|V_{ud}|$ from π_{e3}.

(3) Marciano and Sirlin recently 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 until recently: [McFarlane et al., PRD 32 (1985) 547.]

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

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

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

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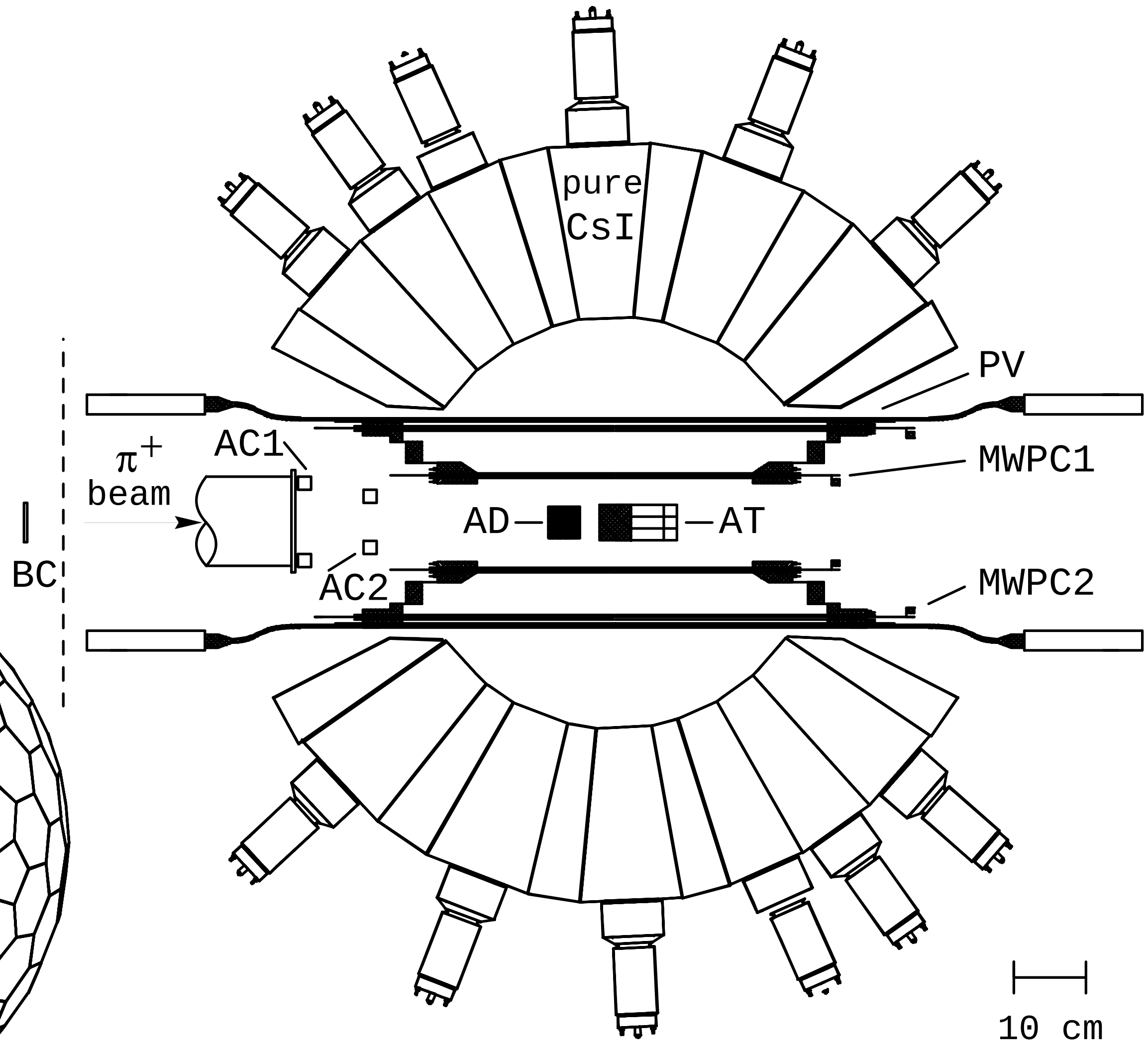
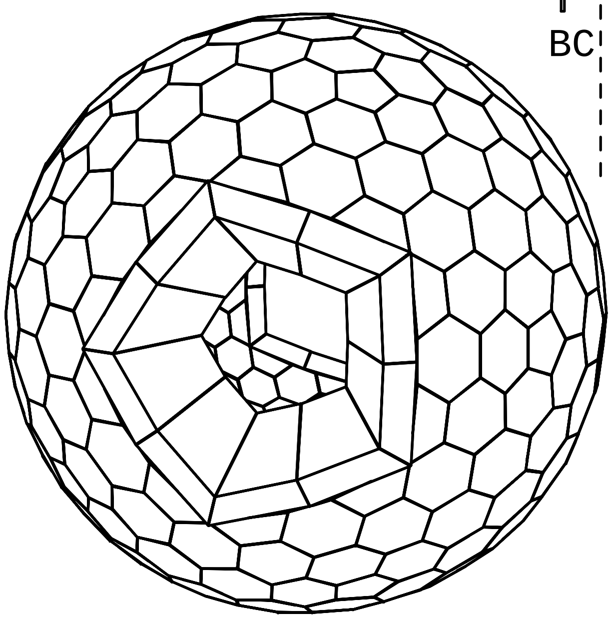
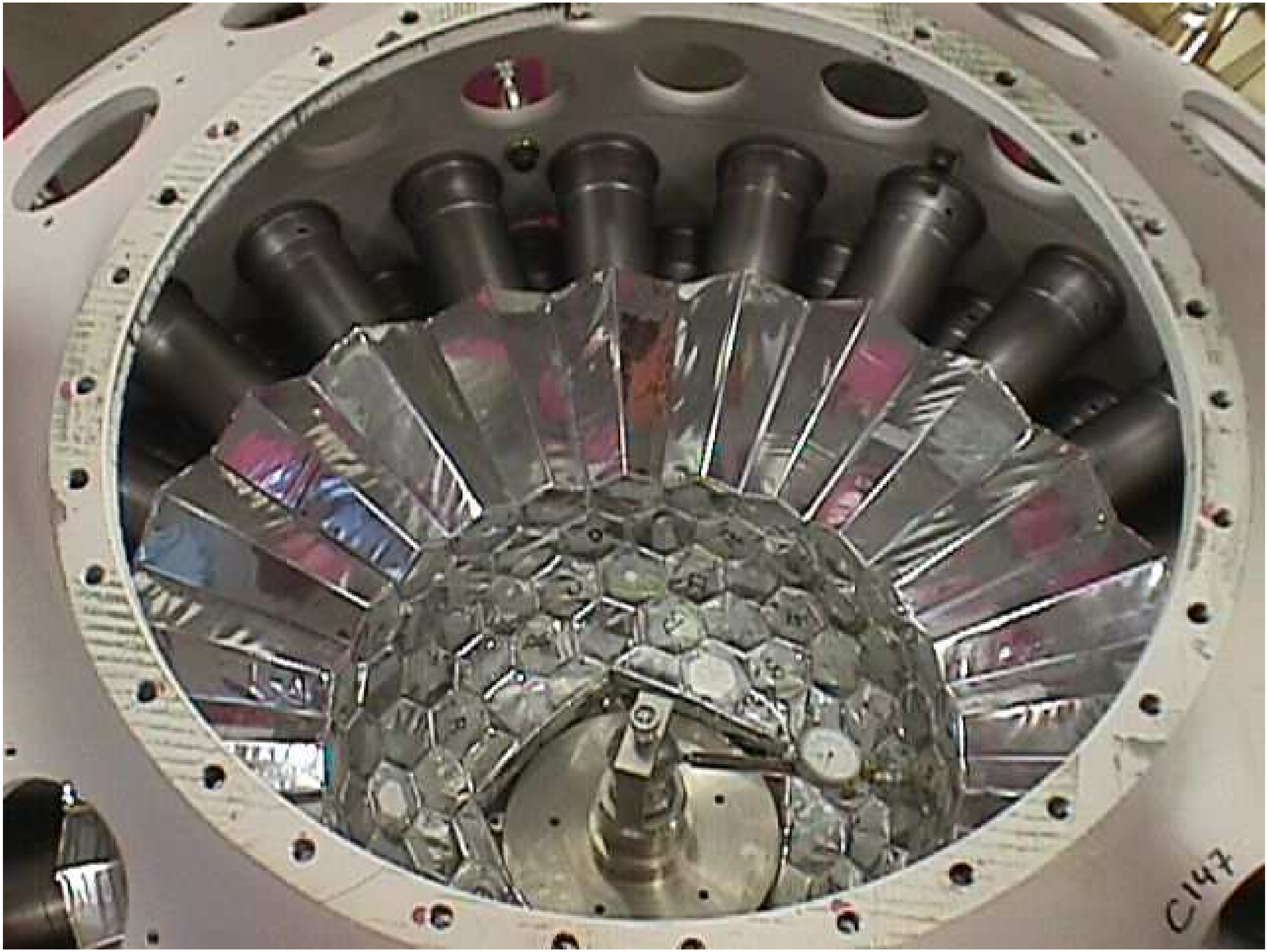
The PIBETA Experiment:

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

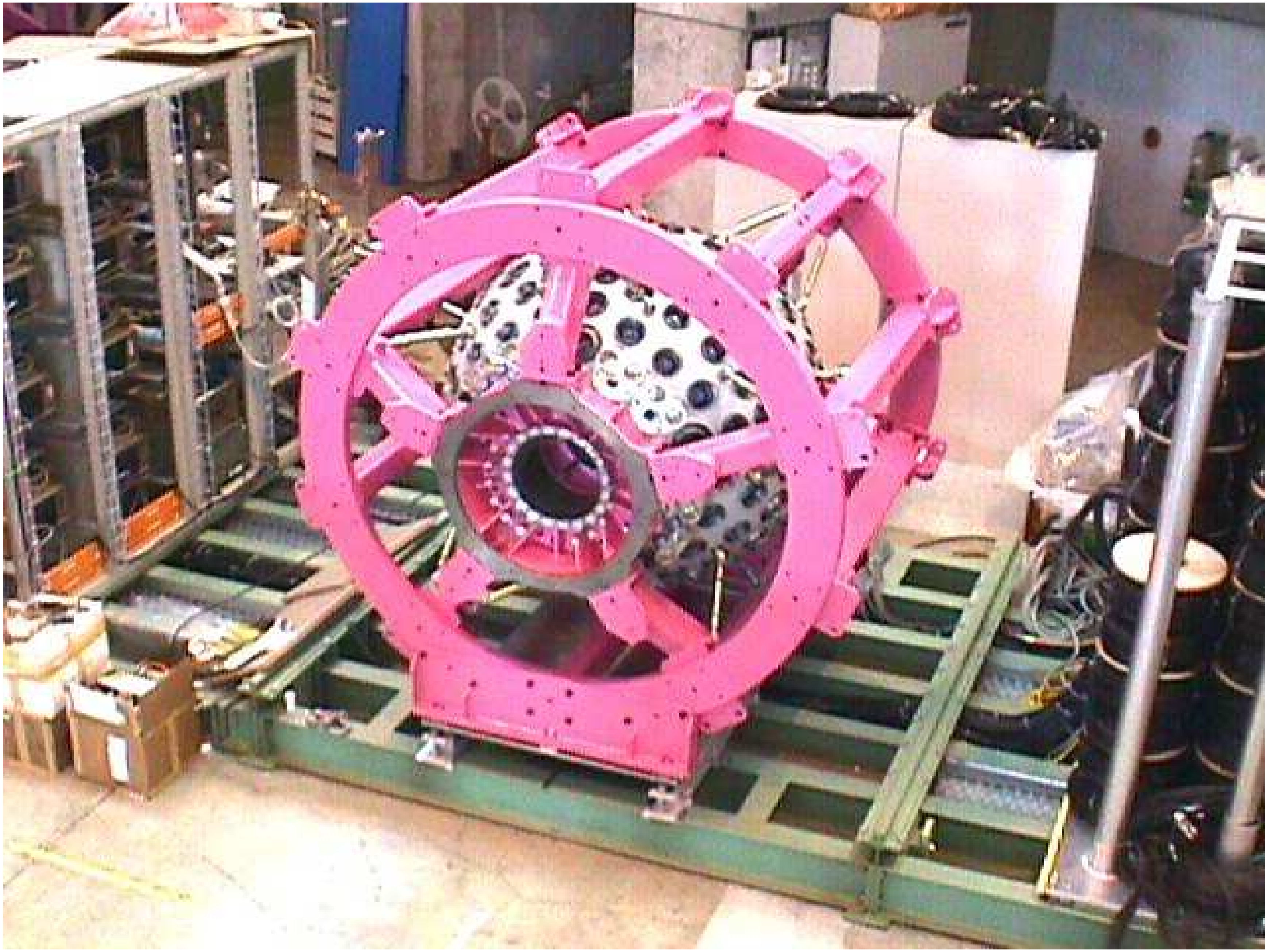




PIBETA Detector Assembly (1998)



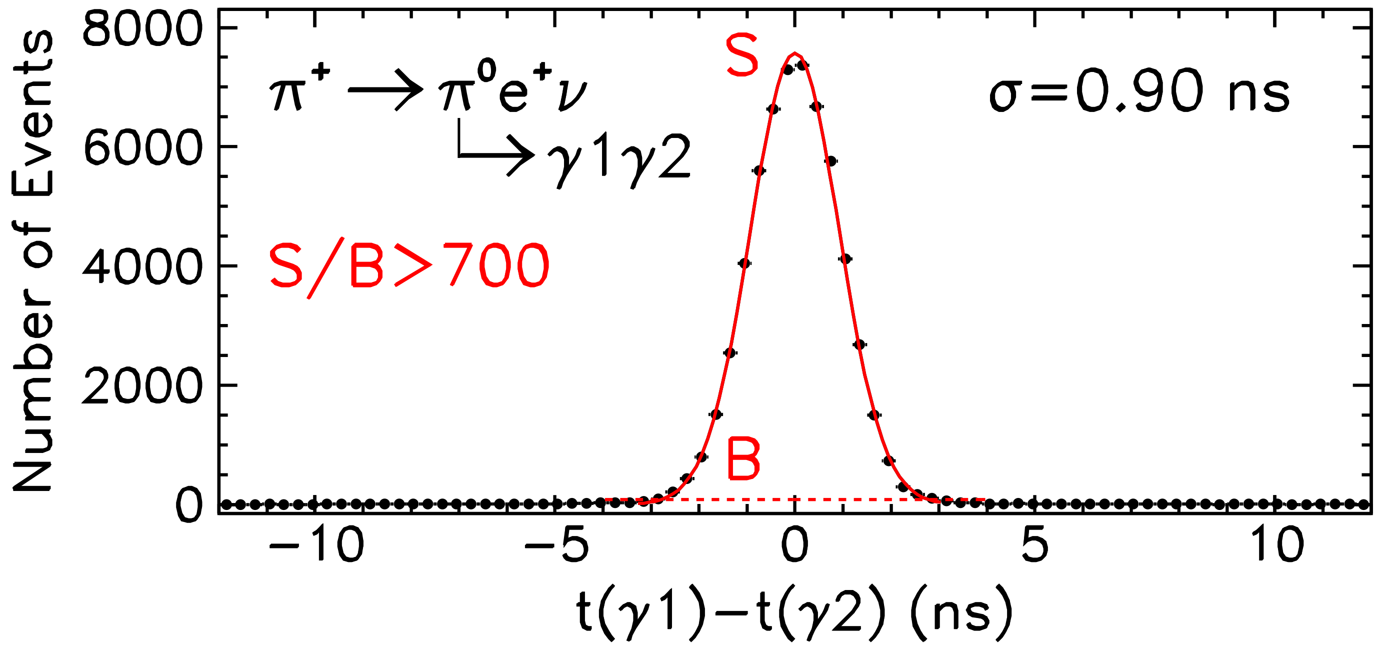
PIBETA Detector on Platform (1998)

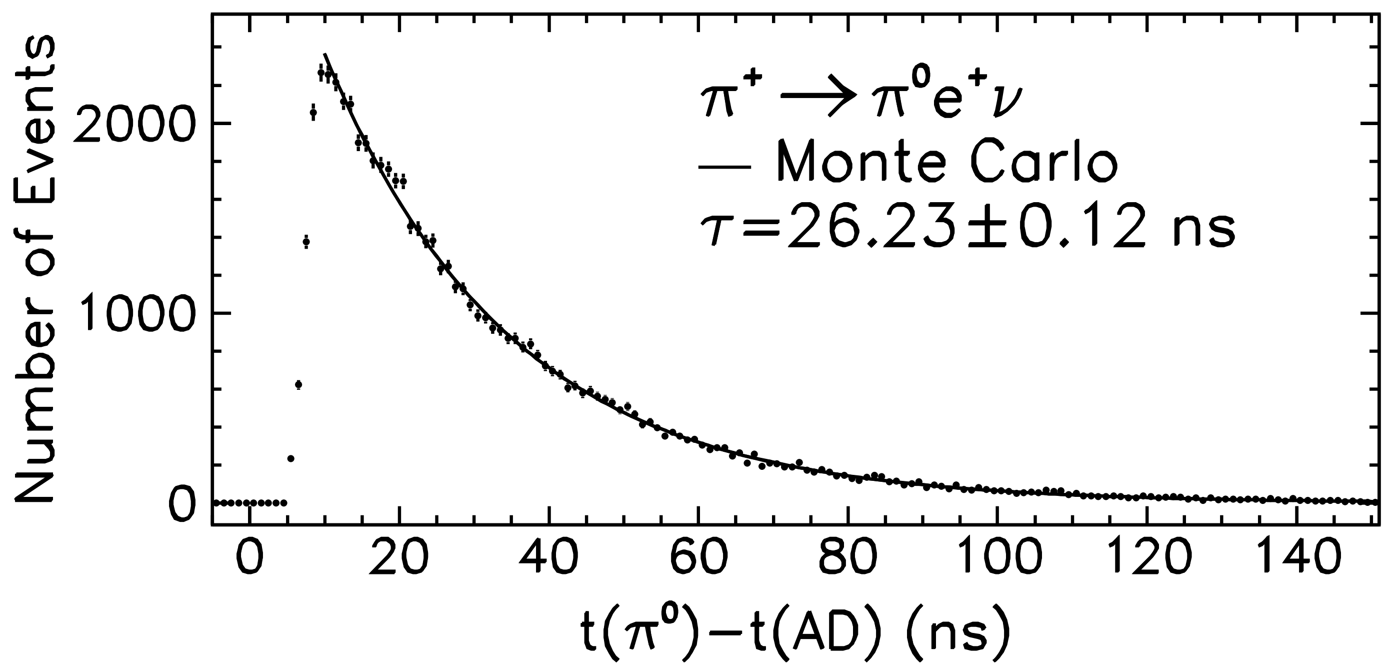


Pion beta decay: $\pi^+ \longrightarrow \pi^0 e^+ \nu$

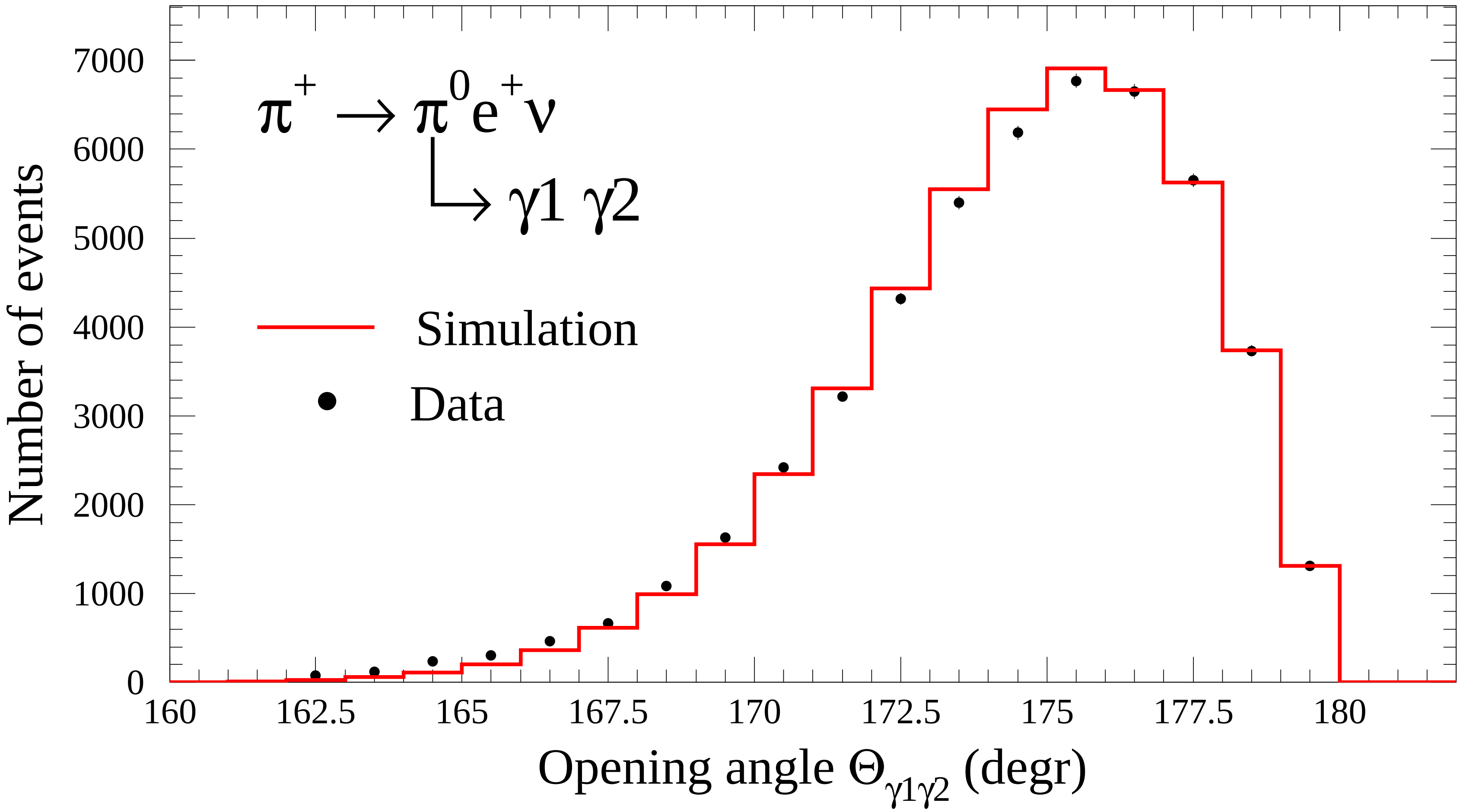
Results, runs 1999–2001

The $\boldsymbol{\pi^+ \to \pi^0 e^+ \nu}$ *decay*



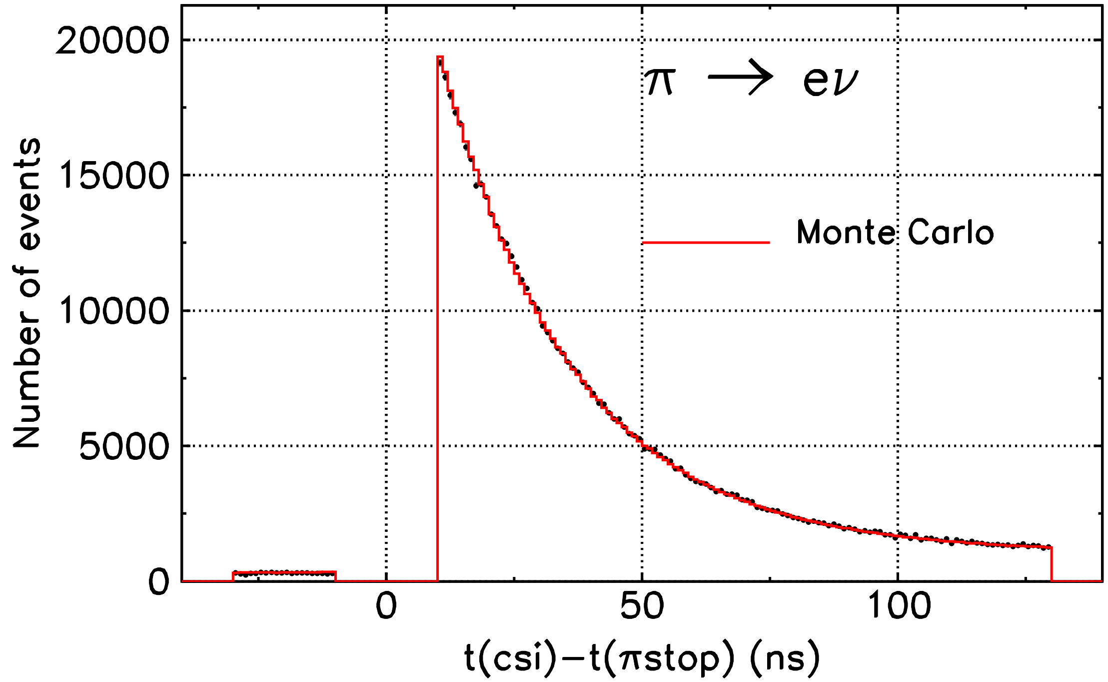


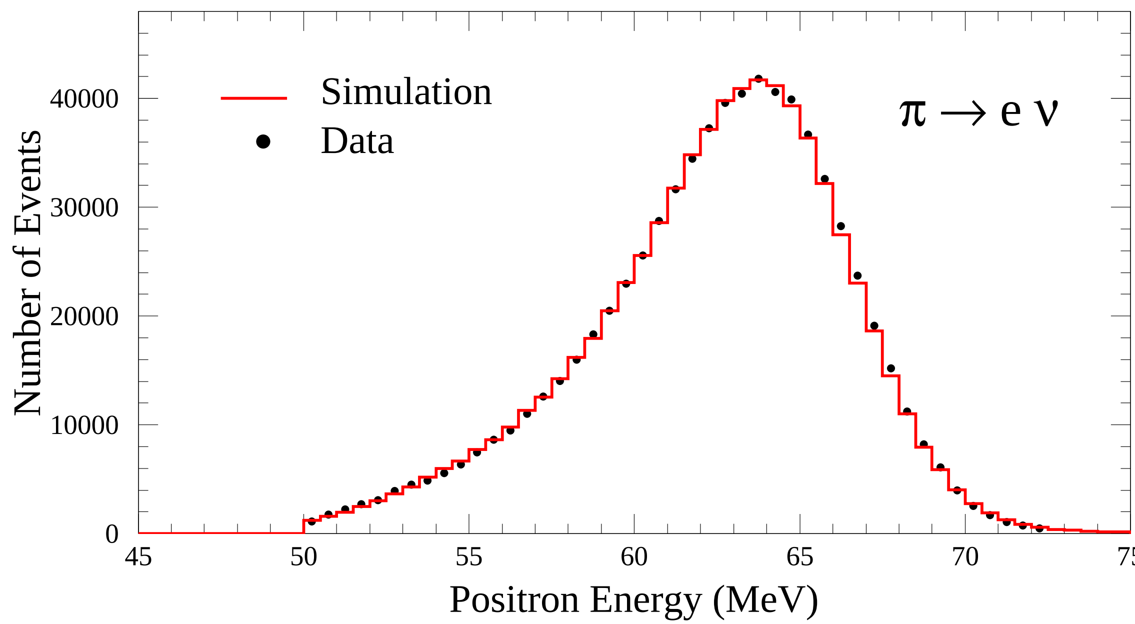
The $\pi^+ \rightarrow \pi^0 e^+ \nu$ *decay*



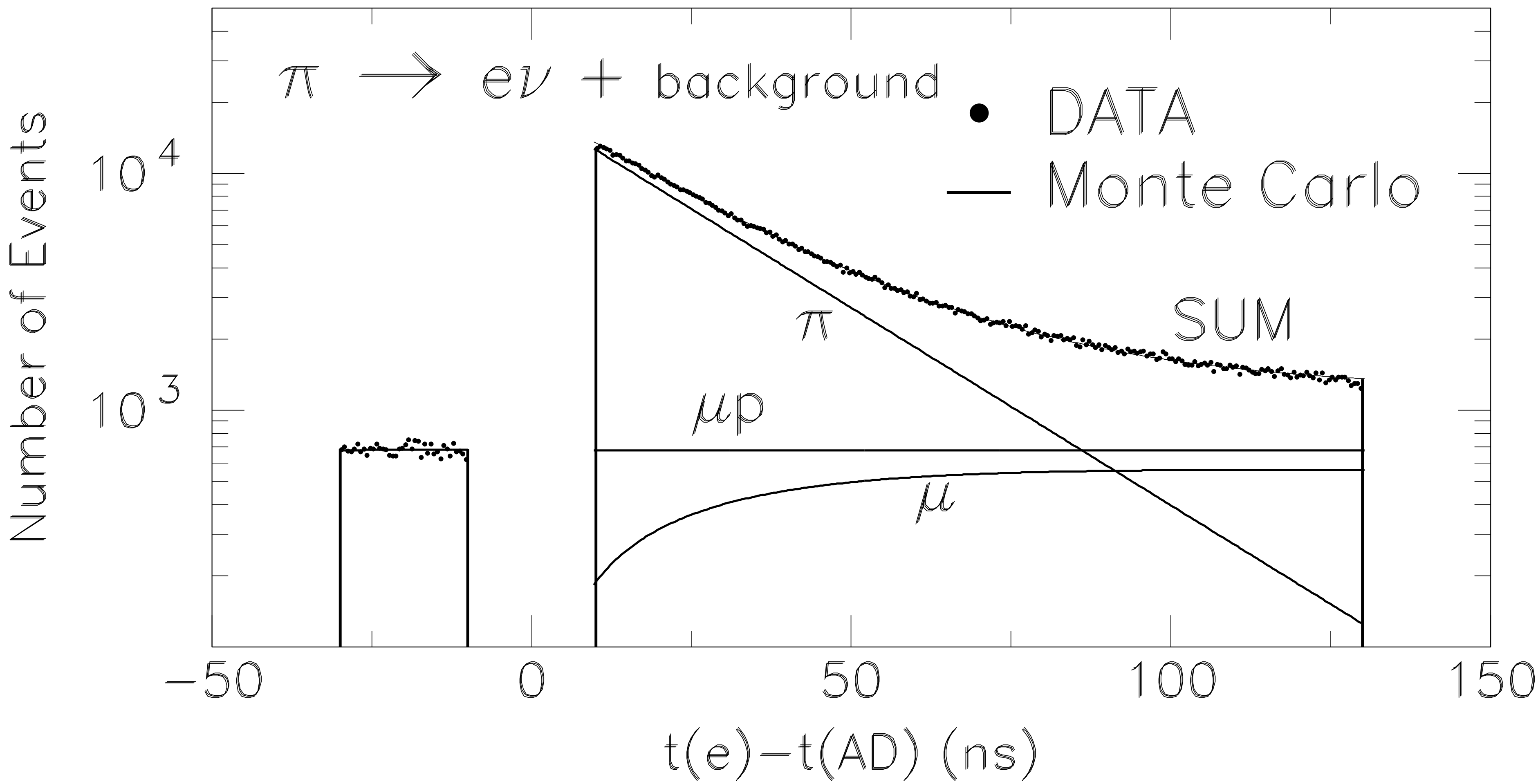
Normalizing decay:

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





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	
	$r_{\pi{\rm G}} = f^{\pi\beta}_{\pi{\rm G}}/f^{\pi e2}_{\pi{\rm G}}$	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

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

Marciano and Sirlin, [PRL **71** (1993) 3629]:

$$\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{\mathbf{calc}} = (1.2352 \pm 0.0005) \times 10^{-4}$$

Decker and Finkemeier, [NP B **438** (1995) 17]:

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

Experiment, world average (PDG 2004):

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

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

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

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

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

SM Prediction (PDG, 2006):

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

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

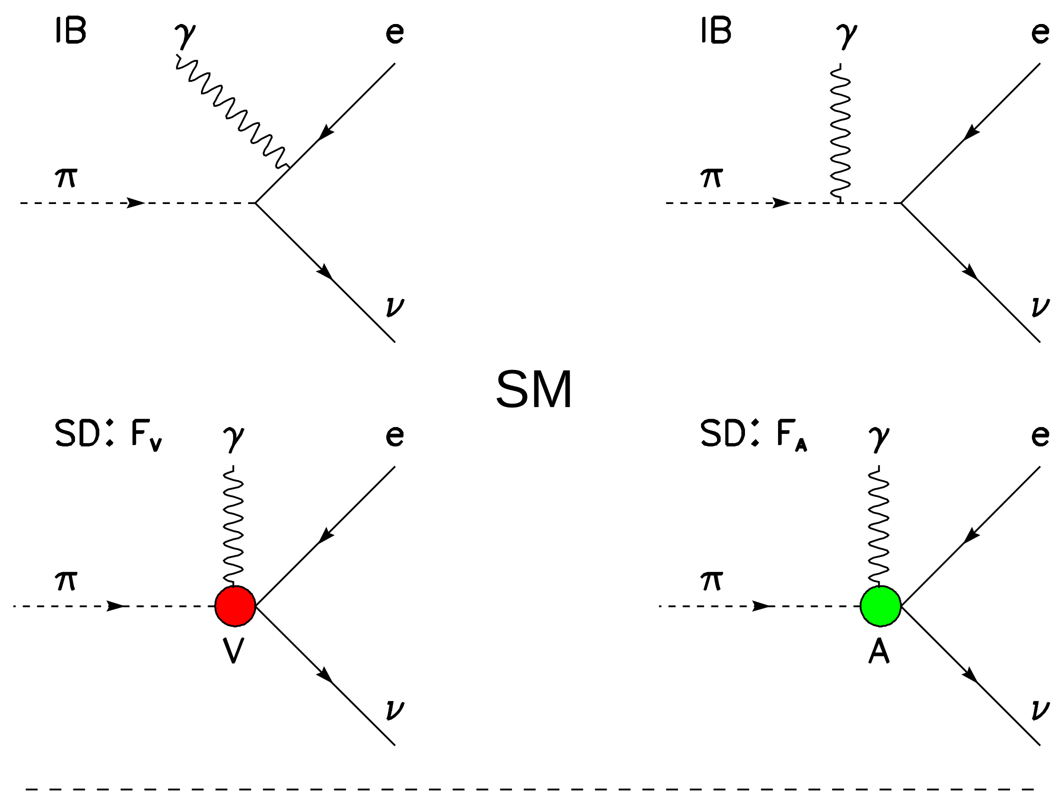
PDG 2006: $V_{ud} = 0.9738(3)$

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

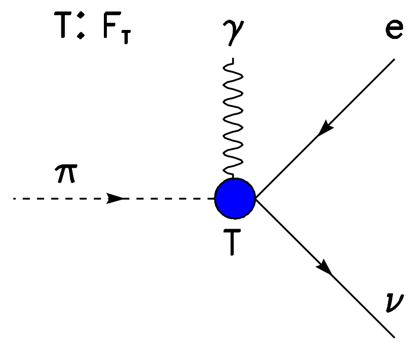
Radiative pion decay: $\pi \longrightarrow e\nu\gamma$

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

Standard $\boldsymbol{IB}$ *and*
$\boldsymbol{V - A}$ *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:

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

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

$$\frac{d\Gamma_{\pi e 2\gamma}}{dx\, dy} = \frac{\alpha}{2\pi} \Gamma_{\pi e2} \Big\{ IB\,(x,y) + \left(\frac{F_V m_\pi^2}{2 f_\pi m_e} \right)^2 \times \left[(1+\gamma)^2 SD^+ (x,y) + (1-\gamma)^2 SD^- (x,y) \right] + \left(\frac{F_V m_\pi}{f_\pi} \right) \Big[(1+\gamma) S_{\rm int}^+ (x,y) + (1-\gamma) S_{\rm int}^- (x,y) \Big] \Big\} \, .$$

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)	
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

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

$F_A \times 10^4$	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:

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

Region B:

$E_\gamma > 55.6$ MeV

$E_{e+} > 20$ MeV

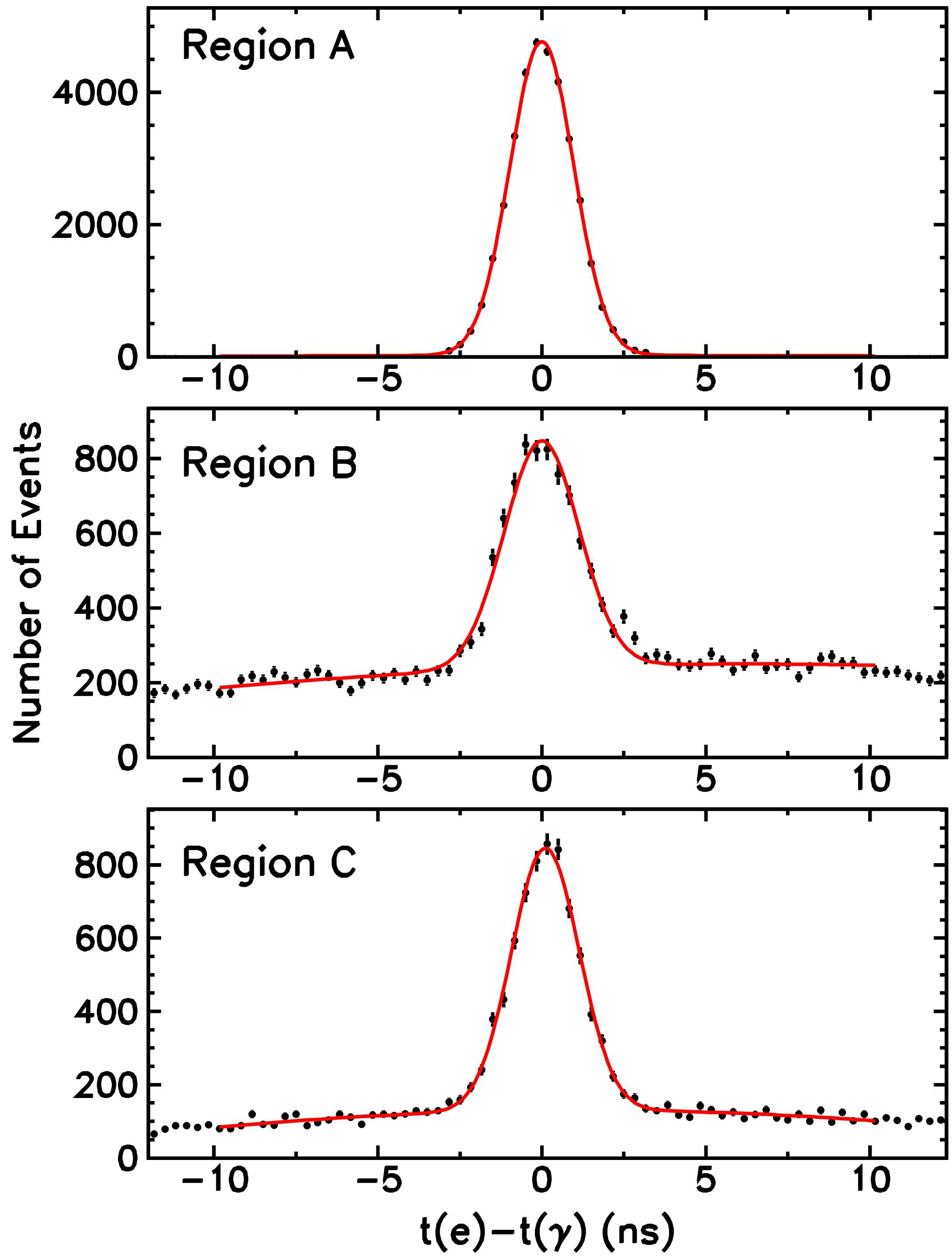
$\theta_{e\gamma} > 40°$

Region C:

$E_\gamma > 20$ MeV

$E_{e+} > 55.6$ MeV

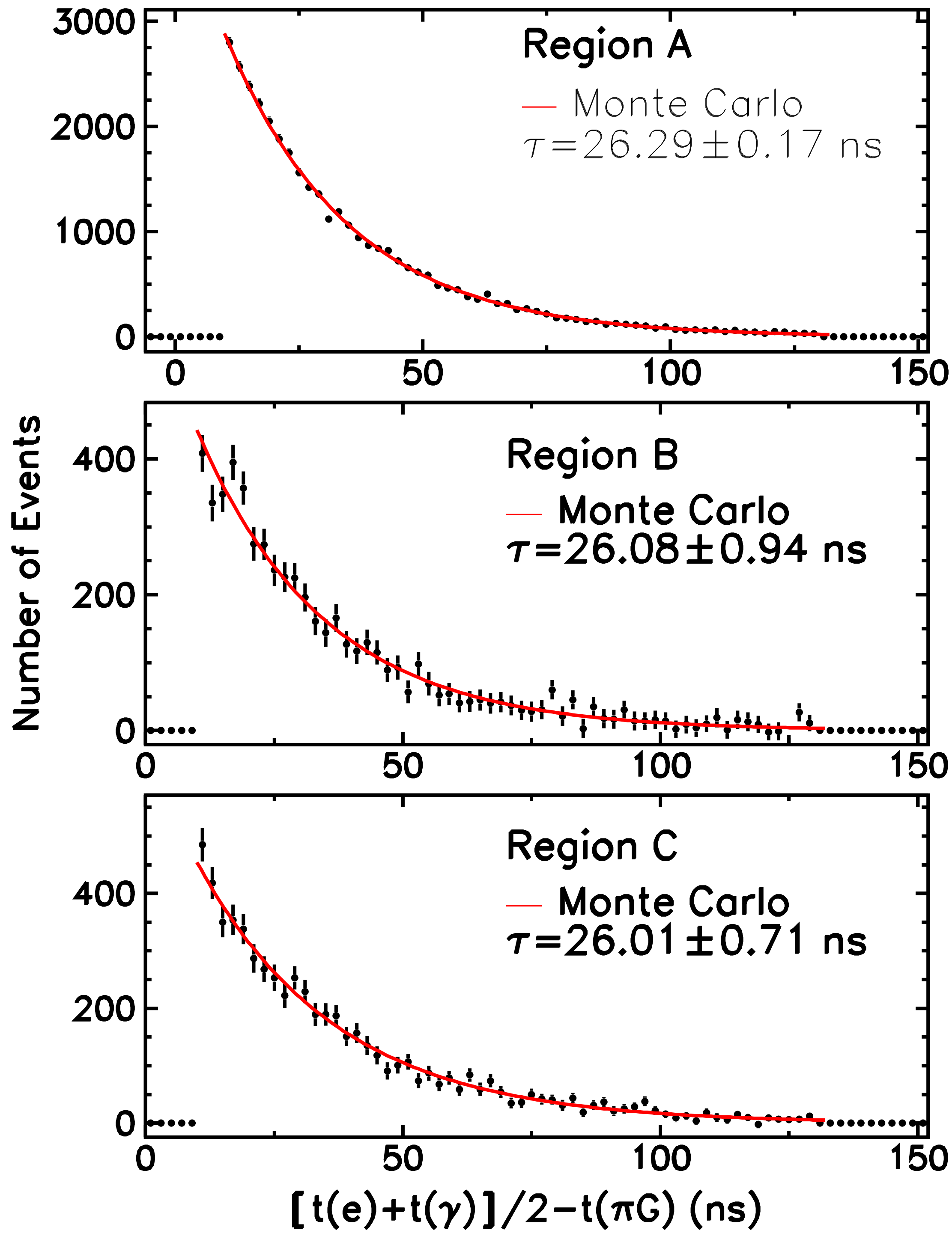
$\theta_{e\gamma} > 40°$



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

1999–2001 data set

(timing)



Results of the SM fit

[Phys. Rev. Lett. **93**, 181804 (2004)]

Best-fit $\pi \longrightarrow e\nu\gamma$ 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.

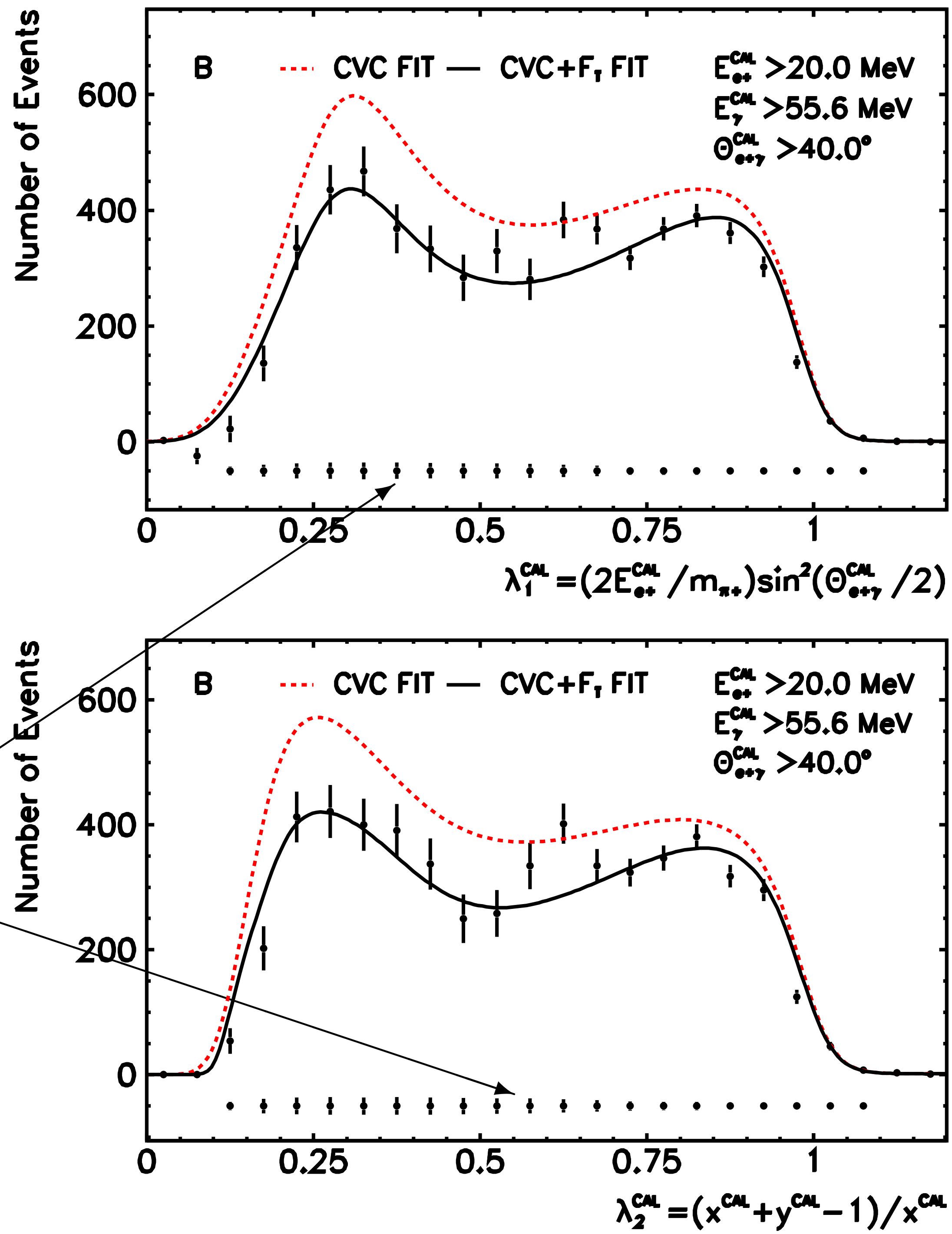
$E_{e^+}^{\text{min}}$ (MeV)	E_{γ}^{min} (MeV)	$\theta_{e\gamma}^{\text{min}}$	B_{exp} ($\times 10^{-8}$)	B_{the} ($\times 10^{-8}$)	no. of events
50	50	–	2.71(5)	2.583(1)	30.6 k
10	50	40°	11.6(3)	14.34(1)	5.2 k
50	10	40°	39.1(13)	37.83(1)	5.7 k

Region B:

global fits

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

projected
uncertainties
in 2004 run



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

Region A:

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

Region B:

$E_\gamma > 55.6\,\mathrm{MeV}$

$E_{e^+} > 20\,\mathrm{MeV}$

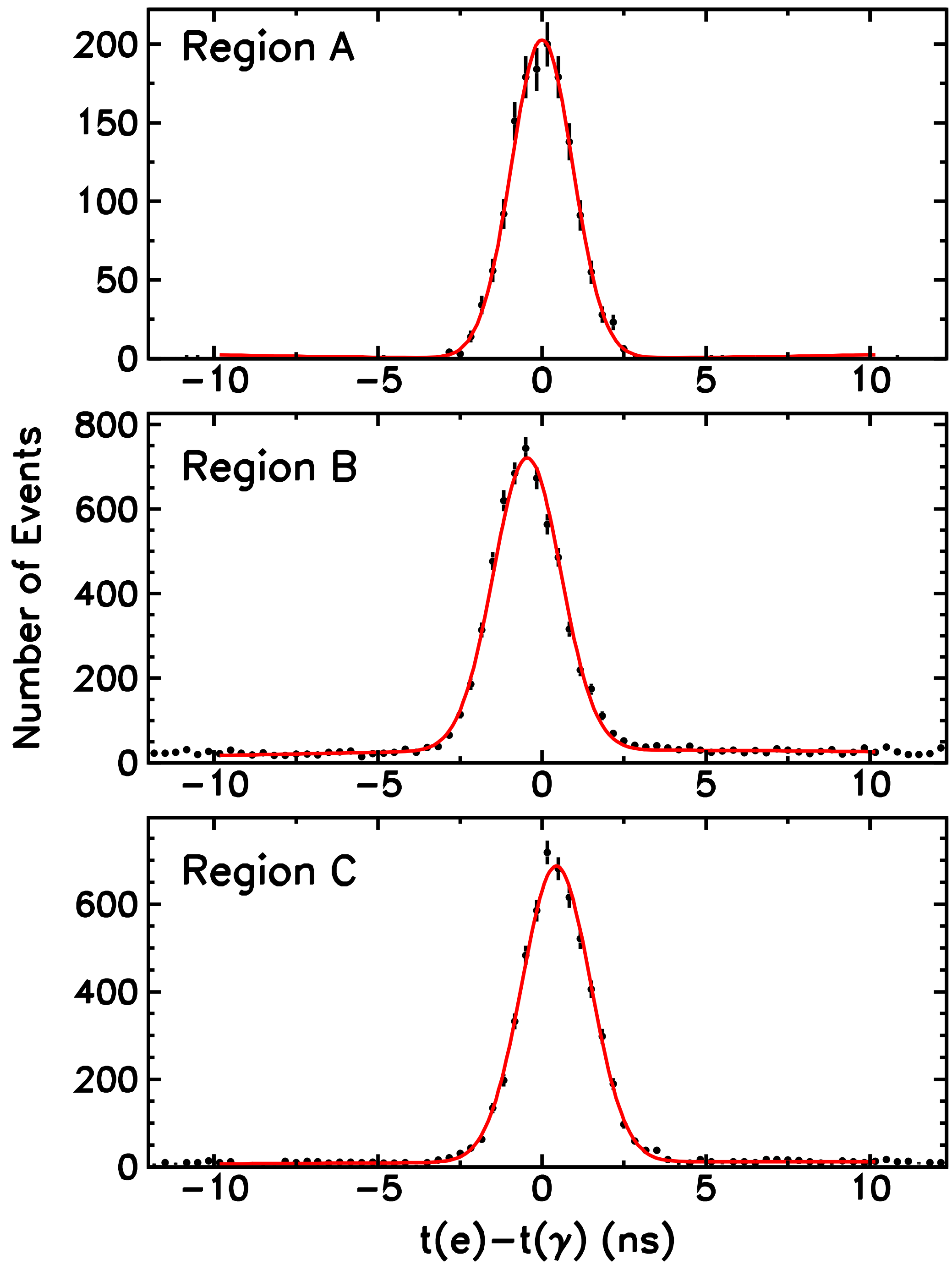
$\theta_{e\gamma} > 40^\circ$

Region C:

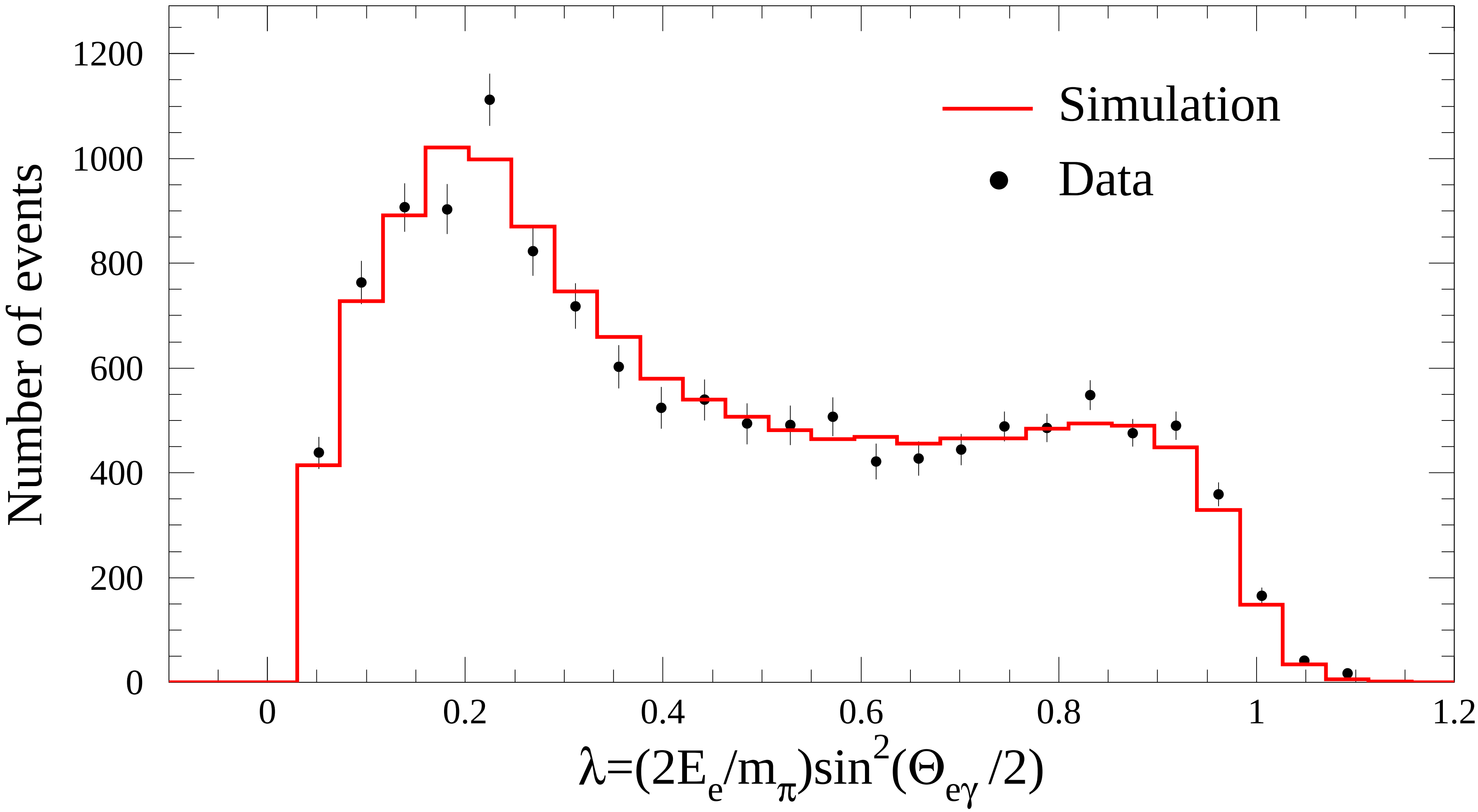
$E_\gamma > 20\,\mathrm{MeV}$

$E_{e^+} > 55.6\,\mathrm{MeV}$

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

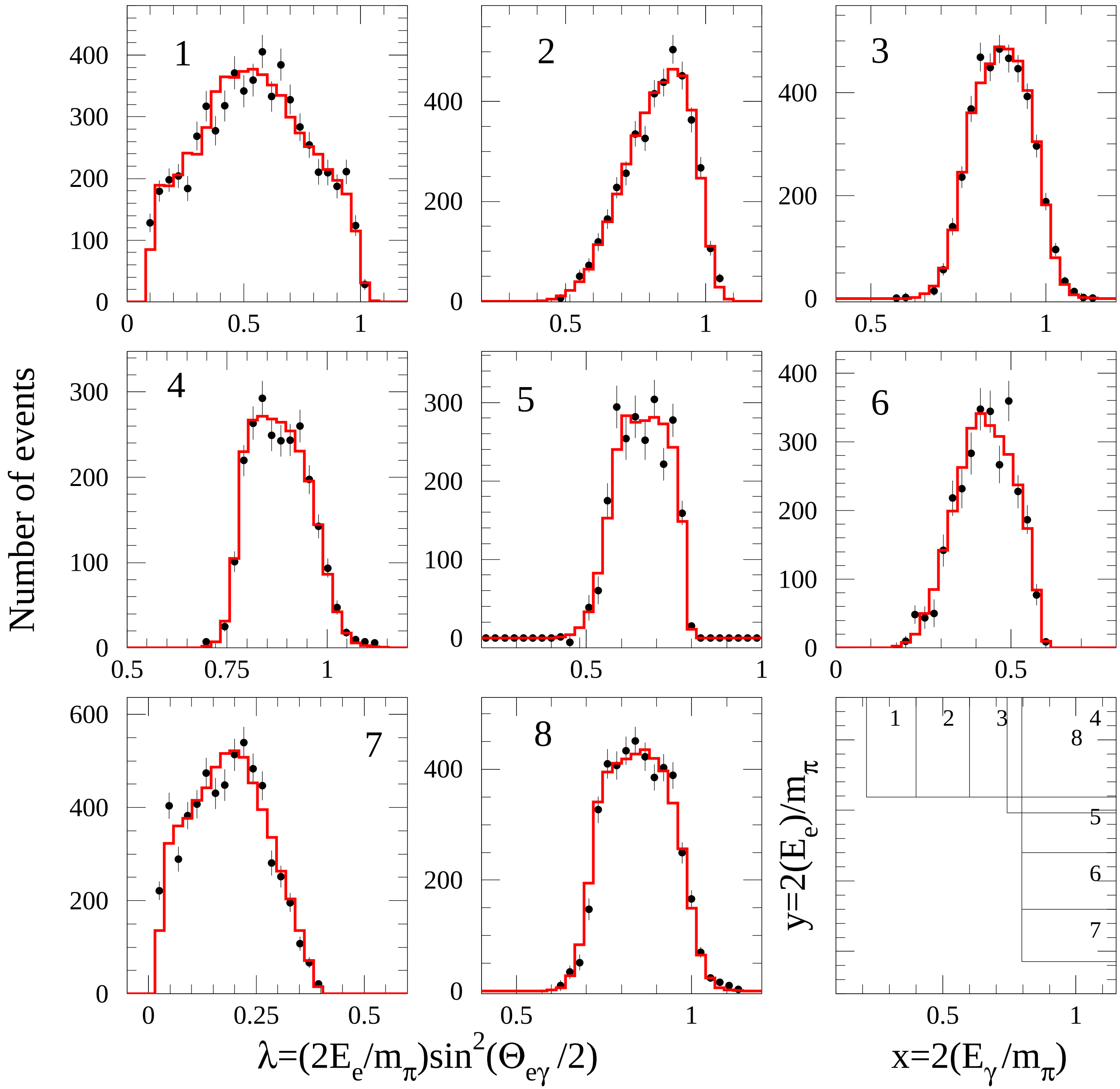


Analysis of 2004 data [M. Bychkov, PhD thesis, Aug 2005]



Standard Model fit — $(V - A)$ only.

Analysis of 2004 data, 8 regions [M. Bychkov, PhD thesis, Aug '05]



Combined analysis of the 99-01 and 2004 data sets

[M. Bychkov, April 2007]

$E_{e^+}^{\text{min}}$ (MeV)	E_{γ}^{min} (MeV)	$\theta_{e\gamma}^{\text{min}}$	B_{exp} $(\times 10^{-8})$	B_{the} $(\times 10^{-8})$	no. of events
50	50	–	2.614(21)	2.599	36 k
10	50	40°	14.46(22)	14.45	16 k
50	10	40°	37.69(46)	37.49	13 k

Obtained with best-values for F_A, F_V, and a (see below), where:

$$F_A(q^2) = F_A(0)\,, \qquad F_V(q^2) = F_V(0)(1 + a \cdot q^2) \quad \text{and}$$

$$q^2(e\nu) = 1 - 2E_\gamma/m_\pi$$ [Bijnens+Talavera ('97), Geng+Ho ('04)]

Alternatively, we evaluate the overall branching ratio for

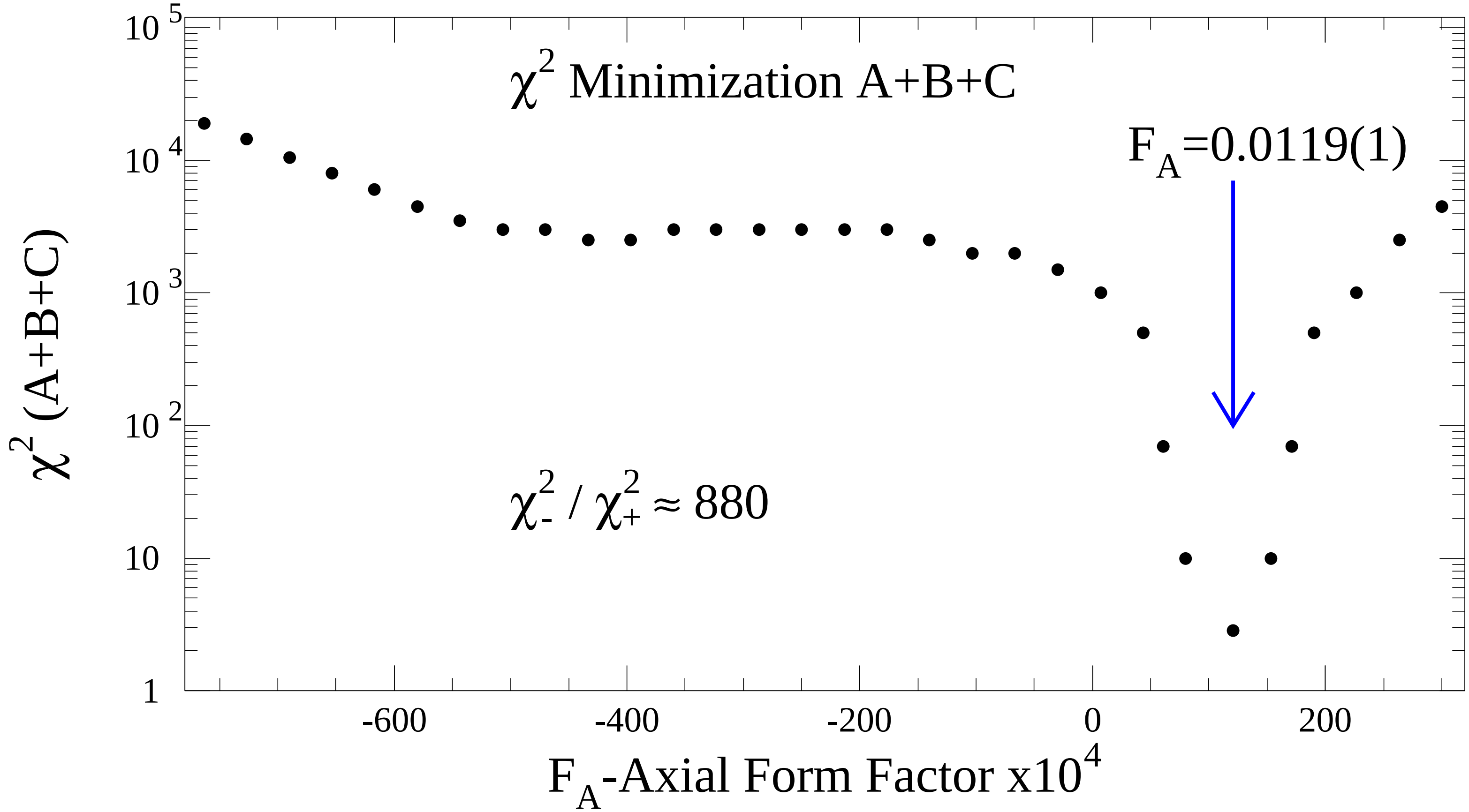
$$E_\gamma > 10\,\text{MeV}, \quad \theta_{e\gamma} > 40^\circ :$$

$$B^{\text{exp}} = 73.86(54) \times 10^{-8} \quad \text{and} \quad B^{\text{the}} = 74.11 \times 10^{-8}$$

Best values of Pion Form Factor Parameters

[M. Bychkov, Apr. '07]

Resolving the quadratic sign ambiguity:



Best values of Pion Form Factor Parameters

[M. Bychkov, Apr. '07]

Unconstrained fit results:

$$F_V = 0.0258(17)\,, \quad a = 0.095 \pm 0.058\,, \quad F_A = 0.0117(17)\,.$$

Excellent agreement with CVC and χPT:

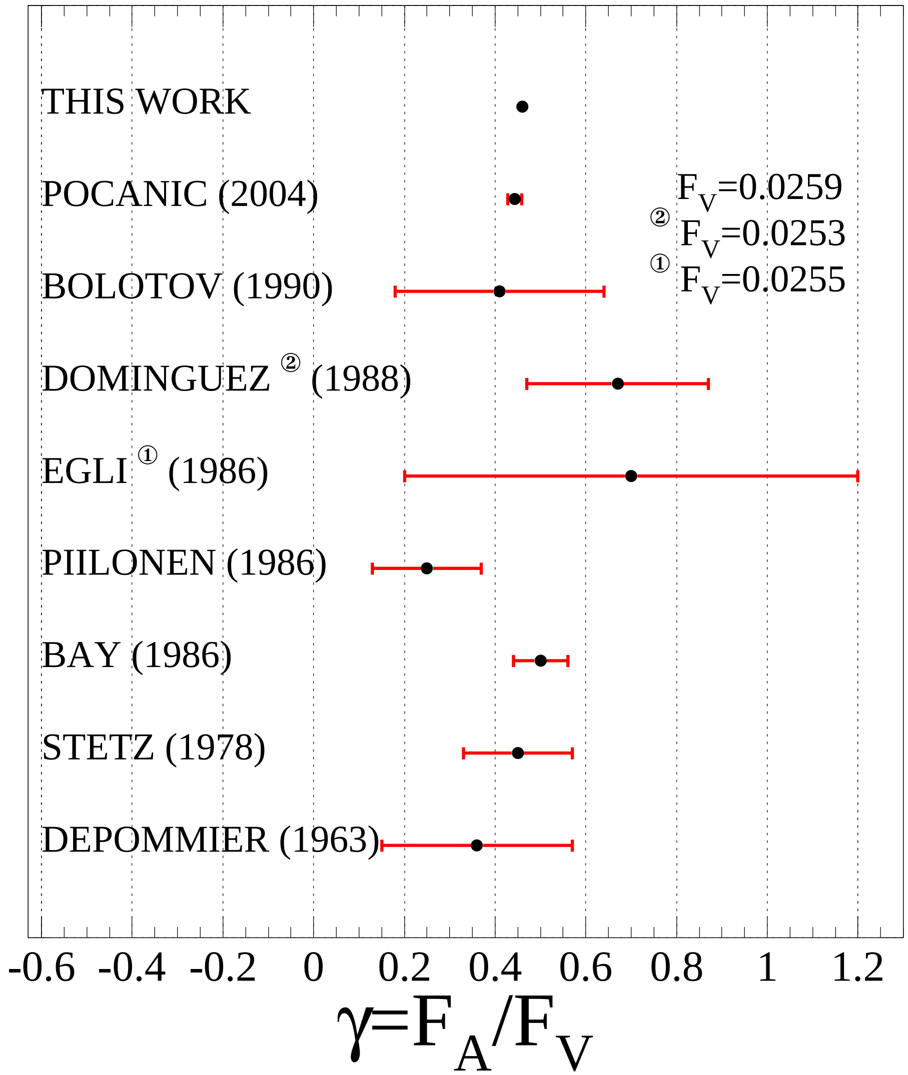
$$F_V^{\mathrm{CVC}} = 0.0259(9) \qquad \text{and} \qquad a^{\mathrm{CVC}+\chi\mathrm{PT}} = 0.041^{\dagger}\,.$$

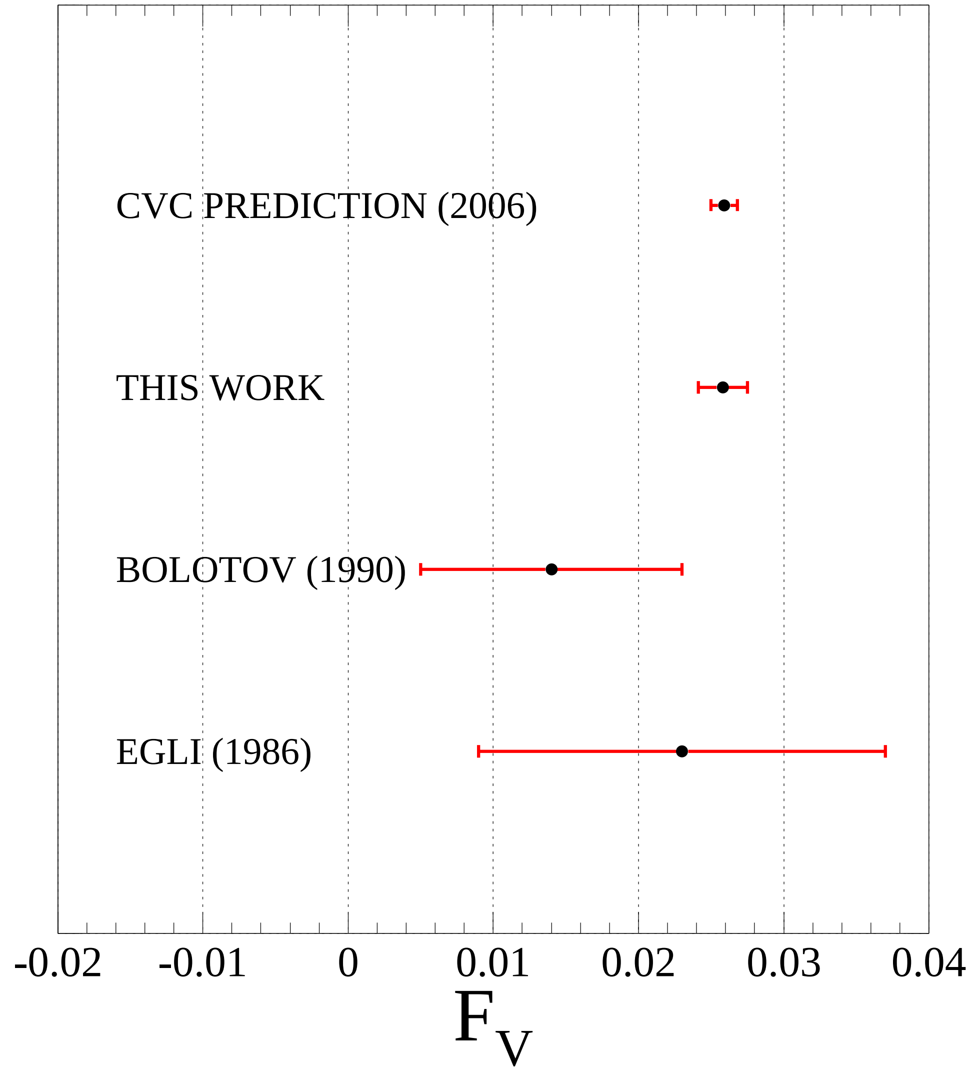
† J. Portoles and V. Mateu, priv. comm., (2007).

Constrained fit with $F_V = 0.0259$, and $a = 0.041$, yields:

$$F_A = 0.0119(1)_{\mathrm{F}_\mathrm{V}^{\mathrm{CVC}}} \qquad \text{or} \qquad \gamma = \frac{F_A}{F_V^{\mathrm{CVC}}} = 0.459(4)_{\mathrm{exp}}\,.$$

Experimental History of Pion F_A and F_V





$\pi \to e\nu\gamma$: Pion form factors and polarizability in χPT

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

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

so that

$$\alpha_E = \frac{\alpha}{8\pi^2 m_\pi F_\pi^2} \cdot \frac{F_A}{F_V} \simeq 6.058 \times 10^{-4}\,\mathrm{fm}^3 \cdot \frac{F_A}{F_V} .$$

with $F_\pi = 92.4$ MeV and $m_\pi = 137.28$ MeV.

Evaluating the pion polarizability

Using our new result for F_A/F_V, we obtain

$$\alpha_E = 2.783(23)_{\mathrm{exp}} \times 10^{-4}\,\mathrm{fm}^3\,.$$

[To resolve l_9 and l_{10}, one needs

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

world average accuracy is 1.1 %; most accurate data, NA7 1986.
We have now matched this precision!]

Is there a Tensor Term, after all?

Based on either free or constrained fit analyses (M. Bychkov, Apr. '07), stringent limits on F_T result. Keeping F_V, F_A and a fixed at their optimum values, we get:

$$F_T = (-0.6 \pm 2.8) \times 10^{-4}\,,$$

or

$$F_T < 3.0 \times 10^{-4} \quad \text{at } 90\,\%\ \text{C.L.}$$

Simultaneous variation of F_A and F_T gives essentially the same result.

This can be compared with the Poblaguev et al. original 1990 result:

$$F_T = (56 \pm 17) \times 10^{-4}$$

(their later analyses yielded F_T values twice as large).

Summary of Pion Form Factor Results

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

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

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

$$F_T < 3.0 \times 10^{-4} \qquad 90\,\%\ \text{C.L.}$$

Derived pion polarizability:

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

Also:

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

Summary of Pion Rare Decay Results

- We've improved the π_β and $\pi_{e2\gamma}$ branching ratio precision **sevenfold** and **fourteenfold**, respectively.
- We've improved the precision of pion form factors F_V and F_A, **fourteenfold** and **sixteenfold**, respectively.
- We have evaluated for the first time the momentum dependence of a pion FF from pion decay.
- Our radiative π, μ results provide critical input in controlling the systematics of the new $\pi \to e\nu$ (PEN) experiment, PSI R-05-01.
- The PEN experiment will double the R-04-01 data set on radiative π, μ decays, with yet lower backgrounds.
- A final analysis will also reduce both systematic and statistical uncertainties of the π_β BR.

The PEN Experiment:

$$\pi^+ \longrightarrow e^+\nu$$

A Study of e–μ Universality

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).

Processes (a)–(d) lead to PS currents. Most general 4-fermion π_{e2} amplitude:

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

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

The f^e_{PL} and Mass Bounds

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

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

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

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

Therefore

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

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

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

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

PEN Mass Bounds Cont'd.

(a) Charged Higgs, $m_{\mathsf{H+}}$

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

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

(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:

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

(c) Vector leptoquarks, M_G

Followig Shanker who assumes gauge coupling $g \simeq g_{\mathsf{SU(2)}}$, we have:

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

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:

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

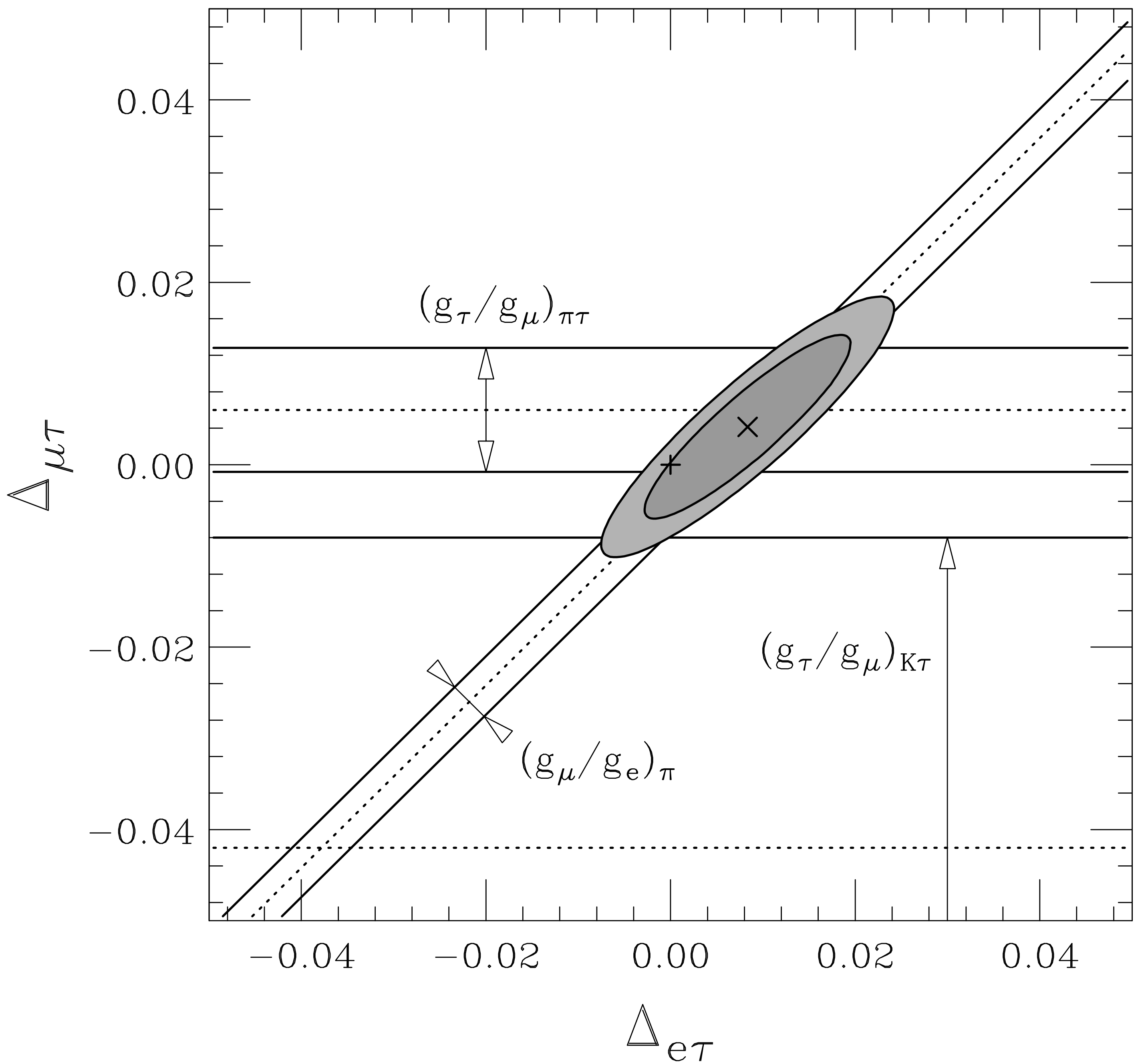
Two of the three are independent; experimental constraints are on:

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

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

Precision measurements of

neutron decay parameters:

Nab and **abBA** Experiments

Neutron Decay Parameters (SM)

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \simeq k_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + a \frac{\vec{k}_e \cdot \vec{k}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A \frac{\vec{k}_e}{E_e} + B \frac{\vec{k}_\nu}{E_\nu} + D \frac{\vec{k}_e \times \vec{k}_\nu}{E_e E_\nu} \right) \right]$$

with:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2 \frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

$$B = 2 \frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad D = 2 \frac{Im(\lambda)}{1 + 3|\lambda|^2}$$

$$\lambda = \frac{G_A}{G_V}$$

($D \neq 0 \Leftrightarrow T$ invariance violation.)

Goals of **Nab, abBA** (other experiments similar)

$$\frac{\delta a}{a} \lesssim 1 \times 10^{-3}$$

$$\frac{\delta b}{b} \lesssim 3 \times 10^{-3}$$

$$\frac{\delta A}{A} \lesssim 3 \times 10^{-3}$$

$$\frac{\delta B}{B} \lesssim 1 \times 10^{-3}$$

n-decay Correlation Parameters Beyond V_{ud}

- Beta decay parameters constrain L-R symmetric model extensions to the SM. [Review: Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (2001)]

- Measurement of the electron-energy dependence of a and A can separately confirm CVC and absence of SCC.
  [Gardner, Zhang, PRL **86**, 5666 (2001), Gardner, hep-ph/0312124]

- Fierz interference term, never measured for the neutron, offers a sensitive test of non-$(V - A)$ terms in the weak Lagrangian (S, T).

- A general connections exists between non-SM (e.g., S, T) terms in $d \longrightarrow ue\bar{\nu}$ and limits on ν masses. [Ito + Prézaeu, PRL **94** (2005)]

The Fierz interference term b

b can be estimated from nuclear beta decays:

$$b_F = \frac{C_S C_V}{|C_S|^2 + |C_V|^2} \qquad b_{GT} = \frac{C_T C_A}{|C_T|^2 + |C_A|^2}$$

These terms vanish for pure $\nu^{(R)}$ coupling.

$b \neq 0$ only for S, T coupling to $\nu^{(L)}$. (leptoquarks?)

From $0^+ \longrightarrow 0^+$ decays [Towner + Hardy '98]:

$$|b_F| \simeq \frac{|C_S|}{|C_V|} \leq 0.0077 \ (90\,\% \text{ c.l.})$$

From analysis of GT decays [Deutsch + Quin, '95]:

$$b_{GT} = -0.0056(51) \simeq \frac{C_T}{|C_A|}$$ (now bounded by F_T from $\pi_{e2\gamma}$)

$\Rightarrow$ a $\sim 10^{-3}$ measurement of b_n would be very interesting!

Correlation Parameters with Recoil Correction

[Gardner, Zhang, PRL **86**, 5666 (2001), Gardner, hep-ph/0312124]

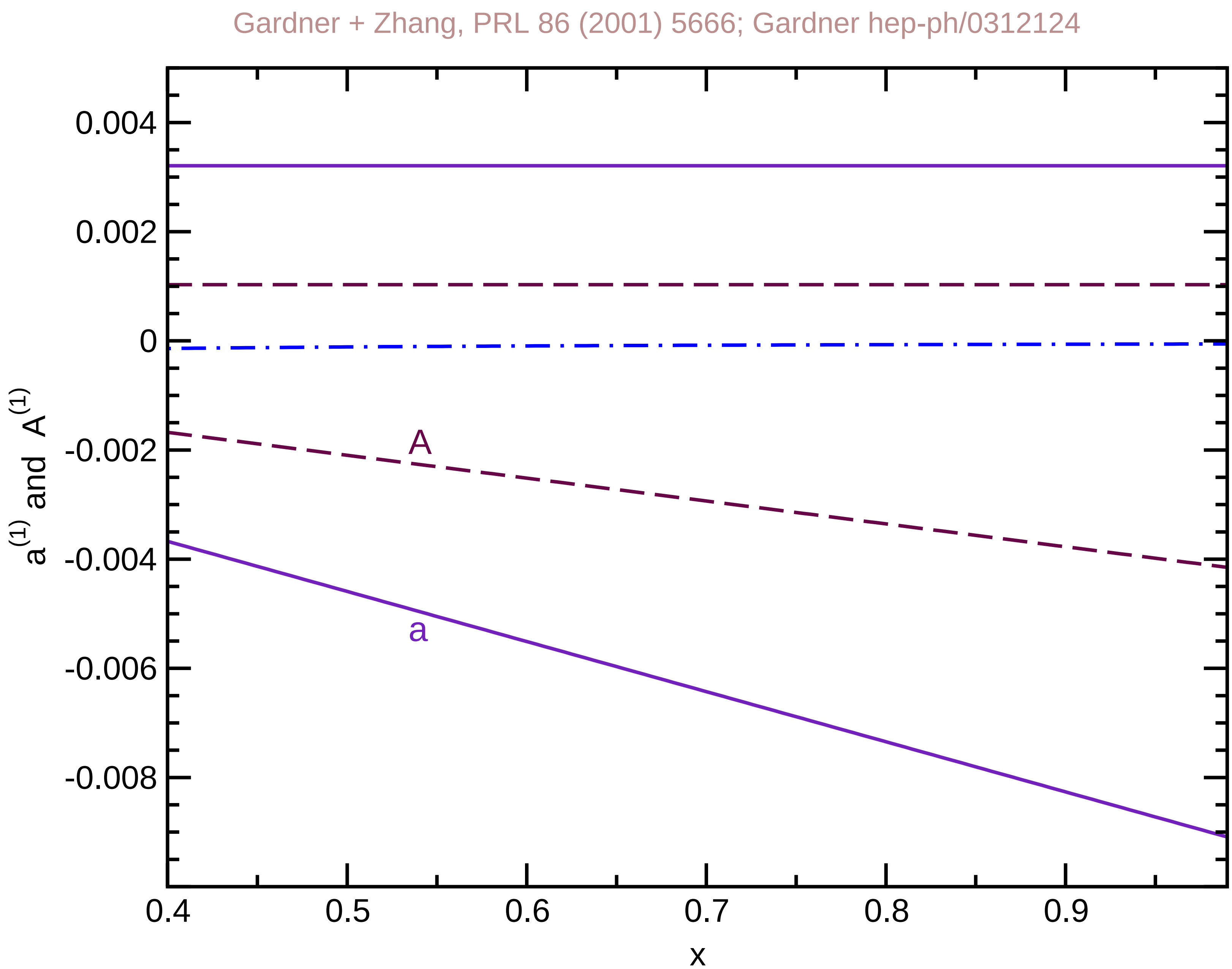
Most general form of hardonic weak current consistent with (V-A):

$$\langle p(p_p)|J^\mu|n(p_n,P)\rangle =$$
$$\bar{u}_p(p_p)\bigg(f_1(q^2)\gamma^\mu - i\frac{f_2(q^2)}{M_n}q^\mu + \frac{f_3(q^2)}{M_n}q^\mu + g_1(q^2)\gamma^\mu\gamma_5 - i\frac{g_2(q^2)}{M_n}\sigma^{\mu\nu}\gamma_5 q_\nu + \frac{g_3(q^2)}{M_n}\gamma_5 q^\mu\bigg)u_n(p_n,P)$$

$$a, A, B \Rightarrow \lambda = \frac{g_1}{f_1} \qquad \text{while} \quad \tau_n \propto (f_1)^2 + 3(g_1)^2$$

However, f_2 (weak magnetism) and SCC's (g_2, g_3), remain unresolved in beta decays (best tested in A=12 system). With recoil corrections, Gardner and Zhang find:

$$a(E_e) = \text{func}(f_2) \qquad \text{while} \qquad A(E_e) = \text{func}(f_2, g_2)$$


Gardner + Zhang, PRL 86 (2001) 5666; Gardner hep-ph/0312124
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
a(1) and A(1)
A
a
0.4
0.5
0.6
0.7
0.8
0.9
x

Final Comments

Low-energy precision experiments provide complementary crosschecks of the SM for a subset of potentially realizable physical processes.

These experiments won't directly detect particles like the Higgs, but do produce useful limits on fundamental physics.

Theoretical precision is unparalleled; experiments are catching up.

New facilities and experiments are being planned or are under way.

Excellent training ground for graduate students and postdocs.

The measurements are very cost-effective.