An Independent test of the CVC hypothesis in the charged pion

via the radiative pion decay $\pi^+ \to e^+\nu_e\gamma$

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- Brief review of rare pion decay modes
- Radiative pion decay: $\pi^+ \to e^+\nu_e\gamma$ ($\pi_{e2\gamma}$) in more detail
- CVC connection to the neutral pion
- Results, predictions and conclusions

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Known and Measured Pion and Muon Decays (PDG 2006)

Decay		B		
$\pi^+ \to$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(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^-	$6.2\,(5) \times 10^{-8}$

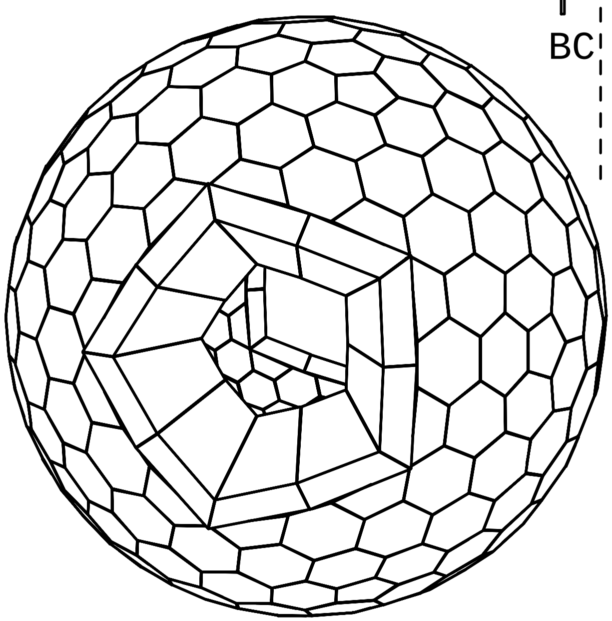
$\mu^+ \to$	$e^+\nu\overline{\nu}$	~ 1.0
	$e^+\nu\overline{\nu}\gamma$	$0.014\,(4)$
	$e^+\nu\overline{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$

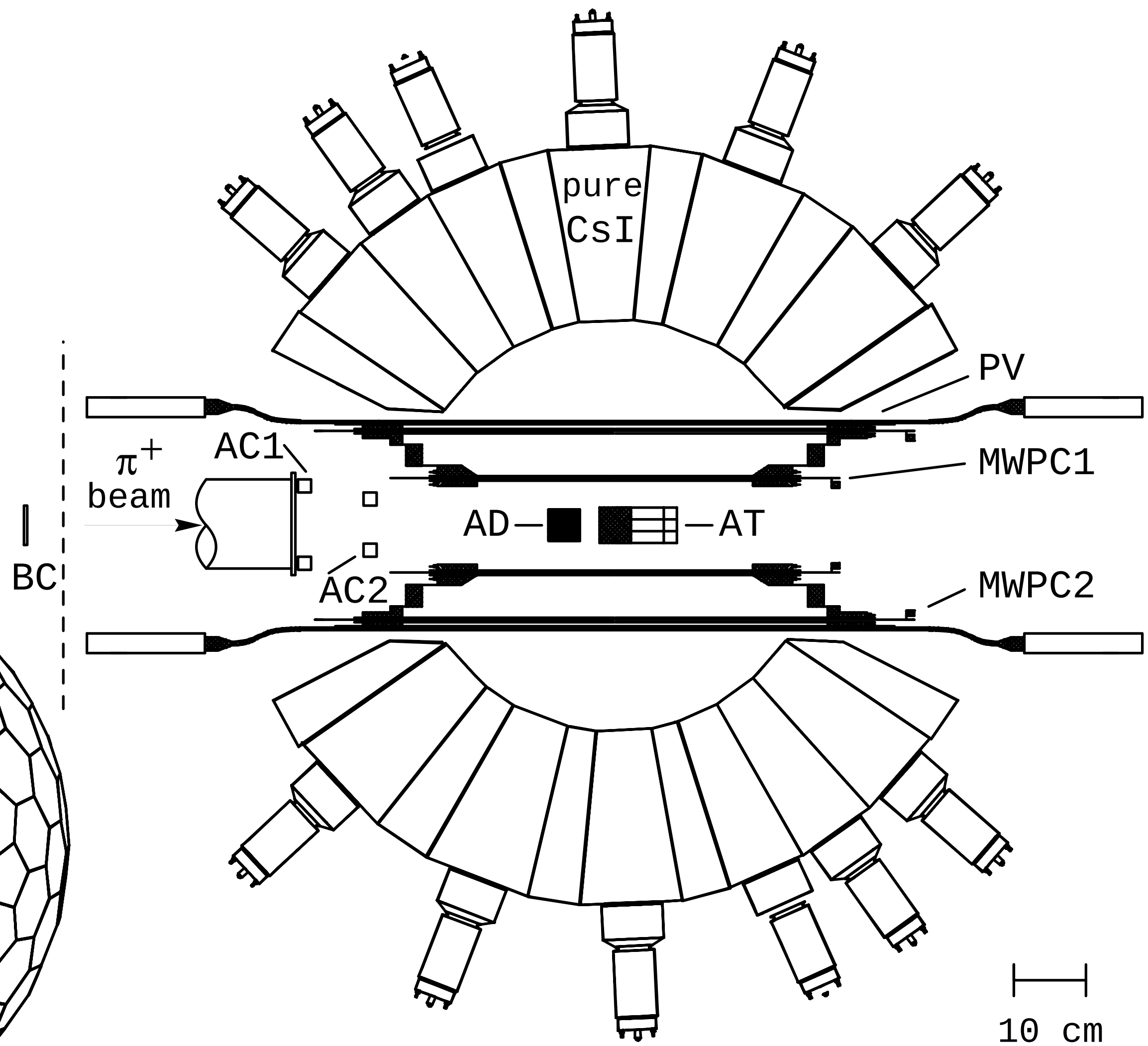
Physics Goals in Radiative Pion Decay

- Structure of the pion by measuring pion form factors. Independent measurement of pion polarizibility α_E with real photon
- Deviations from $V - A$ form of $\mathcal{L}_{\mathrm{weak}}$ by measuring absolute branching ratio
- Check of the CVC hypothesis by precise determination of the vector form factor F_V and its momentum transfer dependence
- Comprehensive input to the $\chi\mathrm{PT}$ expansion coefficients

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





Data Analysis: Method

In order to reduce the systematic uncertainties we use $\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}$ ($\pi_{\mathrm{e}2}$) decay for normalization:

$$B^{\mathrm{exp}}_{\mathrm{decay}} = B_{\pi_{\mathrm{e}2}} \cdot \frac{A_{\pi_{\mathrm{e}2}} \cdot N_{\mathrm{decay}}}{N_{\pi_{\mathrm{e}2}} \cdot A_{\mathrm{decay}}}$$

$B(A)_{\pi_{\mathrm{e}2}}$ is branching ratio (acceptance) of $\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}$ decay

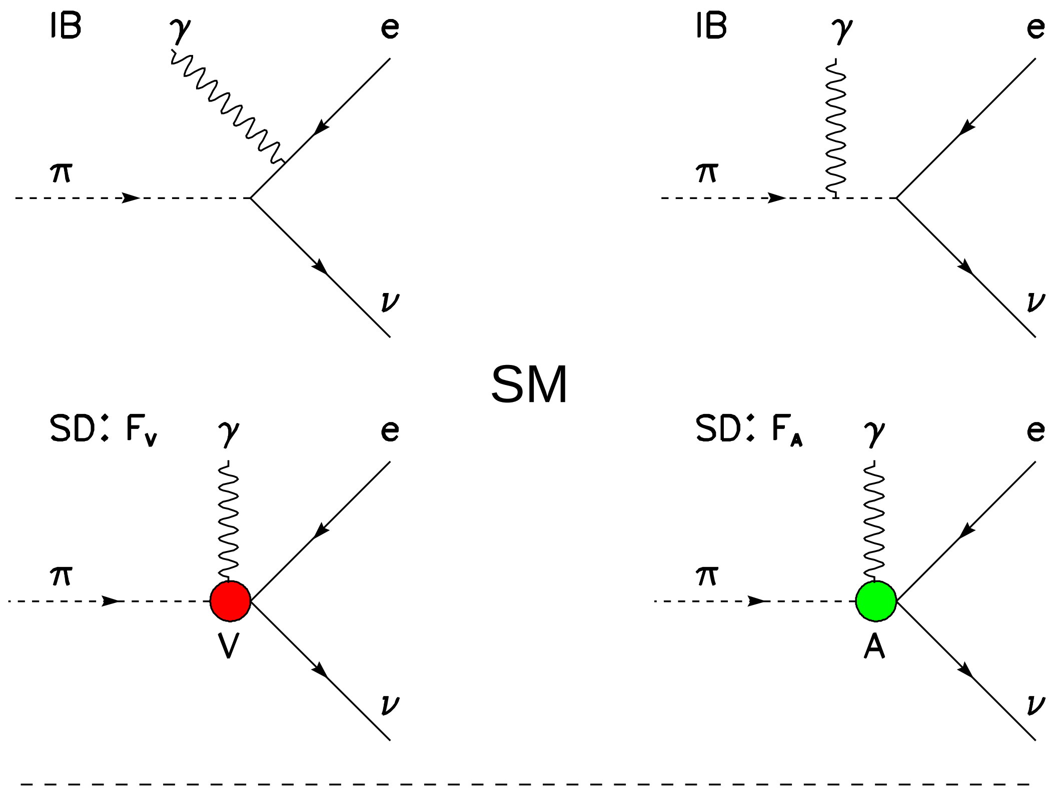
N_{decay} is the number of events detected for a given decay in question

A_{decay} is the acceptance for the same decay in question

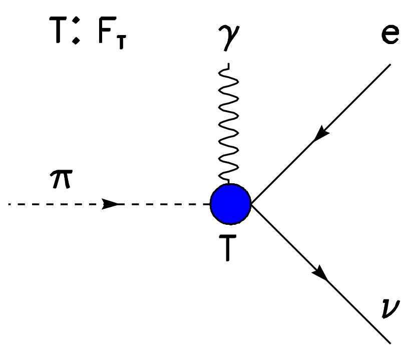
$\pi \to e\nu\gamma$:

Standard $\boldsymbol{IB}$ and

$\boldsymbol{V - A}$ terms



A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

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

$$\frac{d^2B^{\mathrm{theor}}}{dxdy} = \frac{d^2B_{IB}}{dxdy} + \frac{d^2B_{SD}}{dxdy} + \frac{d^2B_{\mathrm{int}}}{dxdy} = \frac{\alpha}{2\pi}\boxed{B_{\pi\to e\nu}}\Bigg\{ IB(x,y) +$$

$$\frac{m_\pi^2}{4\boxed{m_e^2}}\left(\frac{F_V}{f_\pi}\right)^2 \left[(1+\gamma)^2 SD^+(x,y) + (1-\gamma)^2 SD^-(x,y)\right] +$$

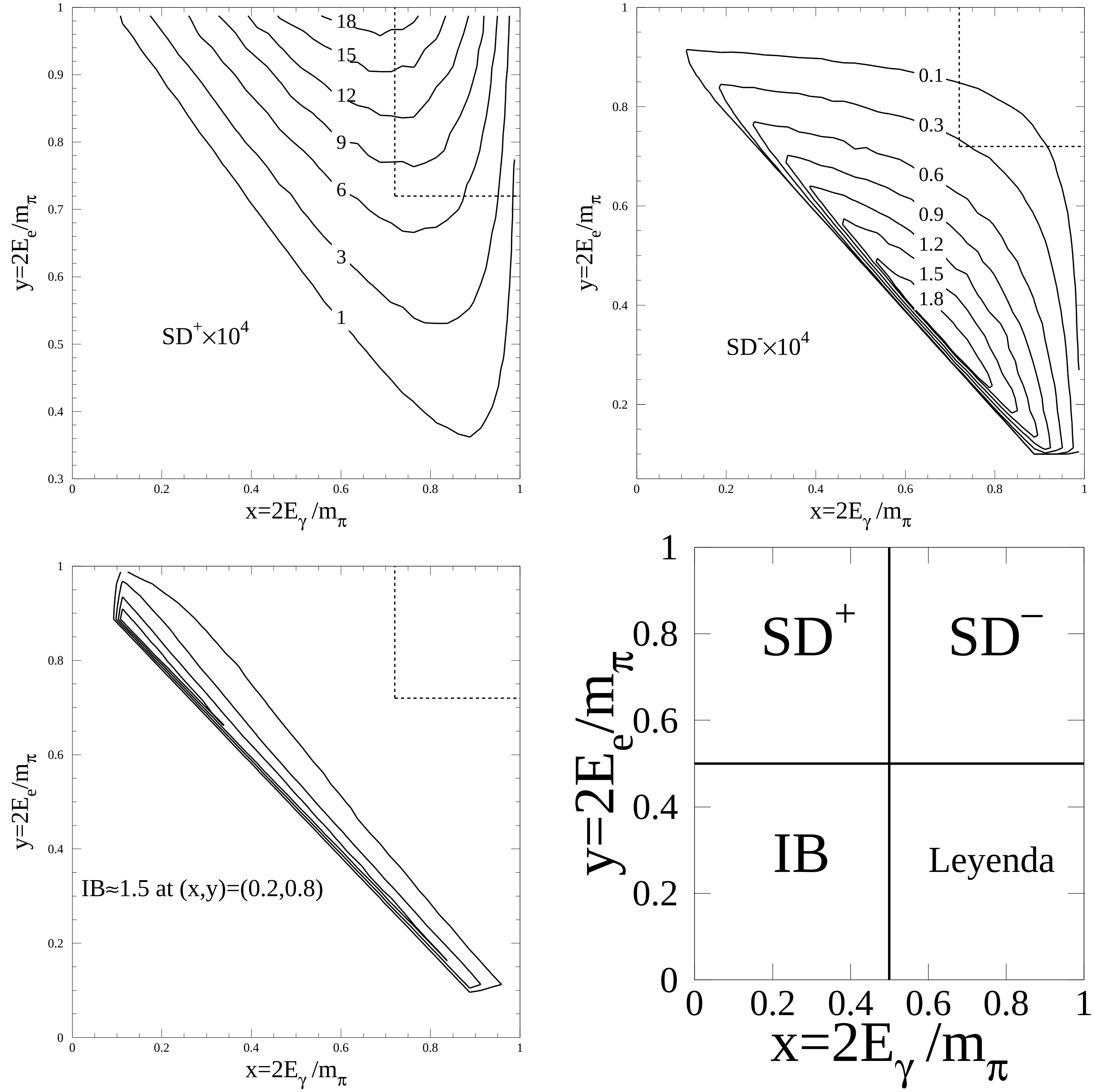
$$\frac{F_V}{f_\pi}\left[(1+\gamma)SD^+_{\mathrm{int}}(x,y) + (1-\gamma)SD^-_{\mathrm{int}}(x,y)\right]\Bigg\} ,$$

where IB, $SD^{\pm}$, $SD^{\pm}_{\mathrm{int}}$ are analytical functions of
$x \equiv 2E_\gamma/m_{\pi^+} \equiv 1 - q^2$ and $y \equiv 2E_e/m_{\pi^+}$ and $\gamma = F_A/F_V$

$F_A(q^2) = F_A(0)$ is the axial-vector form factor

$F_V(q^2) = F_V(0)(1 + a \cdot (1-x))$ is the vector form factor

Theoretical Description: $\pi^+ \rightarrow e^+\nu_e\gamma$ *Decay*



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)	

In $SU(3)$ limit CVC also predicts slope a is the same as for $\pi^0 \to \gamma\gamma^*$

$a = 0.032 \pm 0.004$ (PDG 2006)

$\pi \to e\nu\gamma$: *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

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

so that

$$\alpha_E = \frac{\alpha}{8\pi^2 m_\pi F_\pi^2} \cdot \frac{F_A}{F_V} \simeq 6.24 \times 10^{-4}\,\mathrm{fm}^3 \cdot \frac{F_A}{F_V}.$$

[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 Results: $\boldsymbol{\pi^+ \rightarrow e^+\nu_e}$ *Decay*

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

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

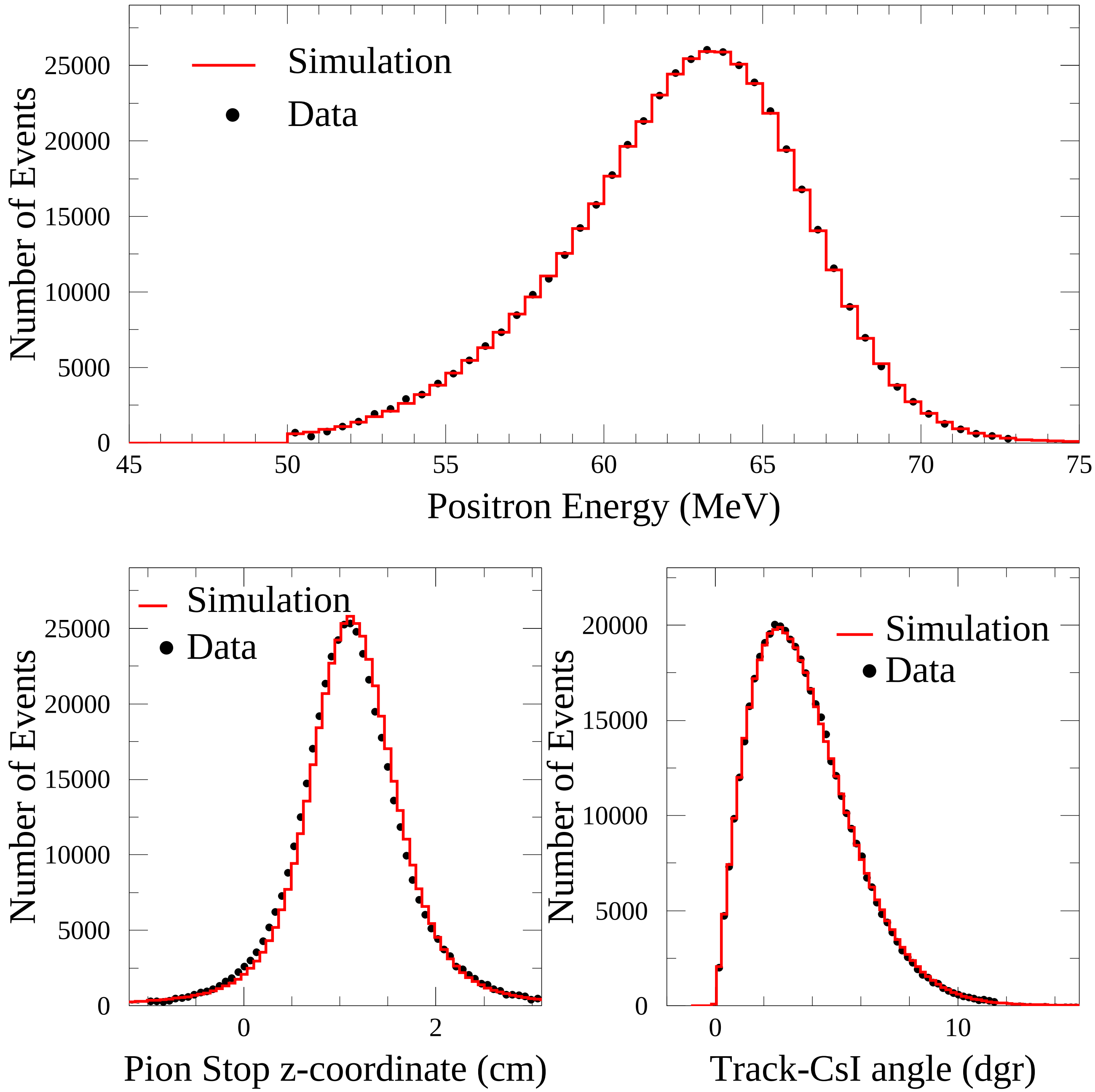
Decker and Finkemeier, [NP B **438** (1995) 17]:

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

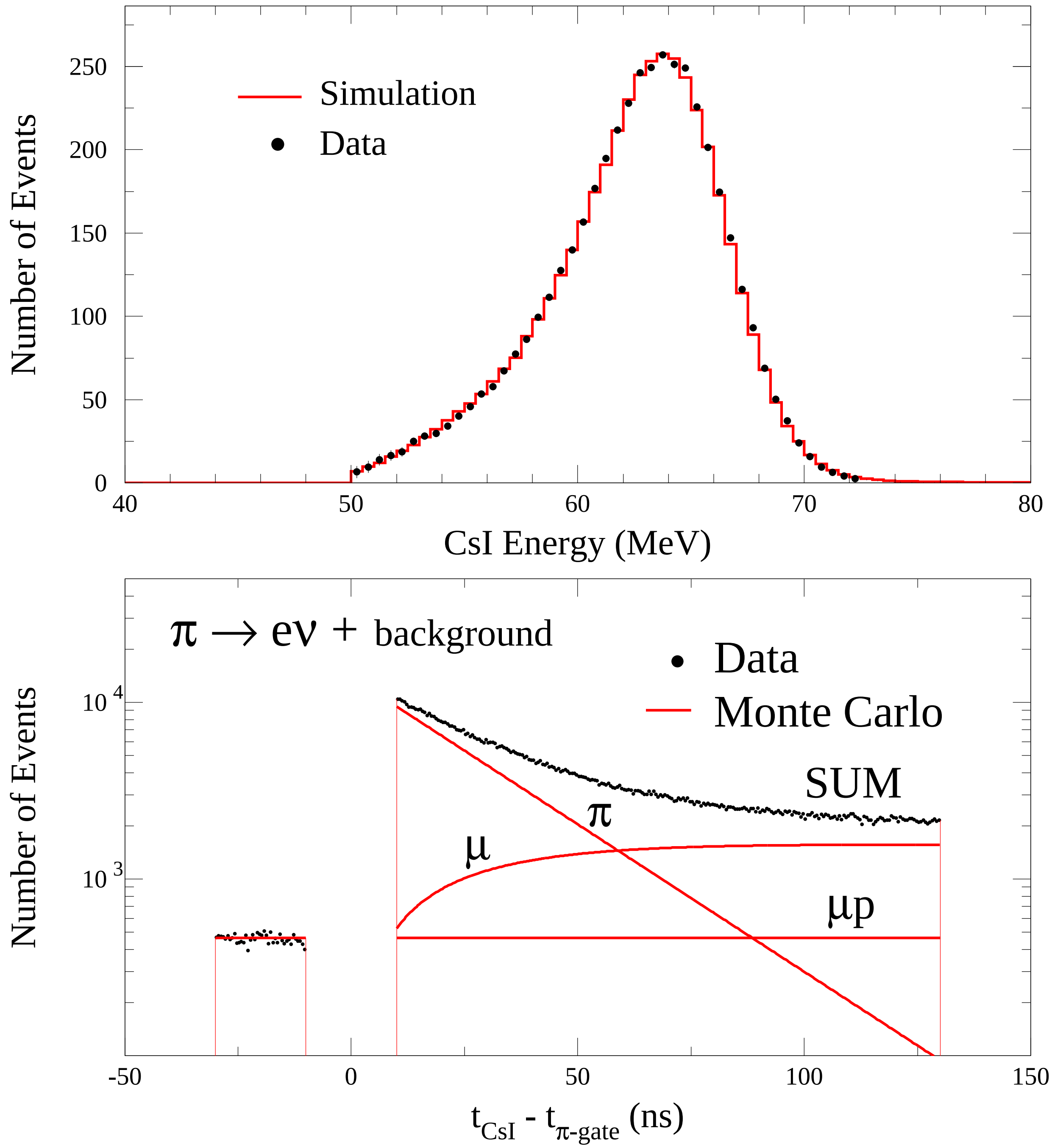
Experiment, world average (PDG 2006):

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

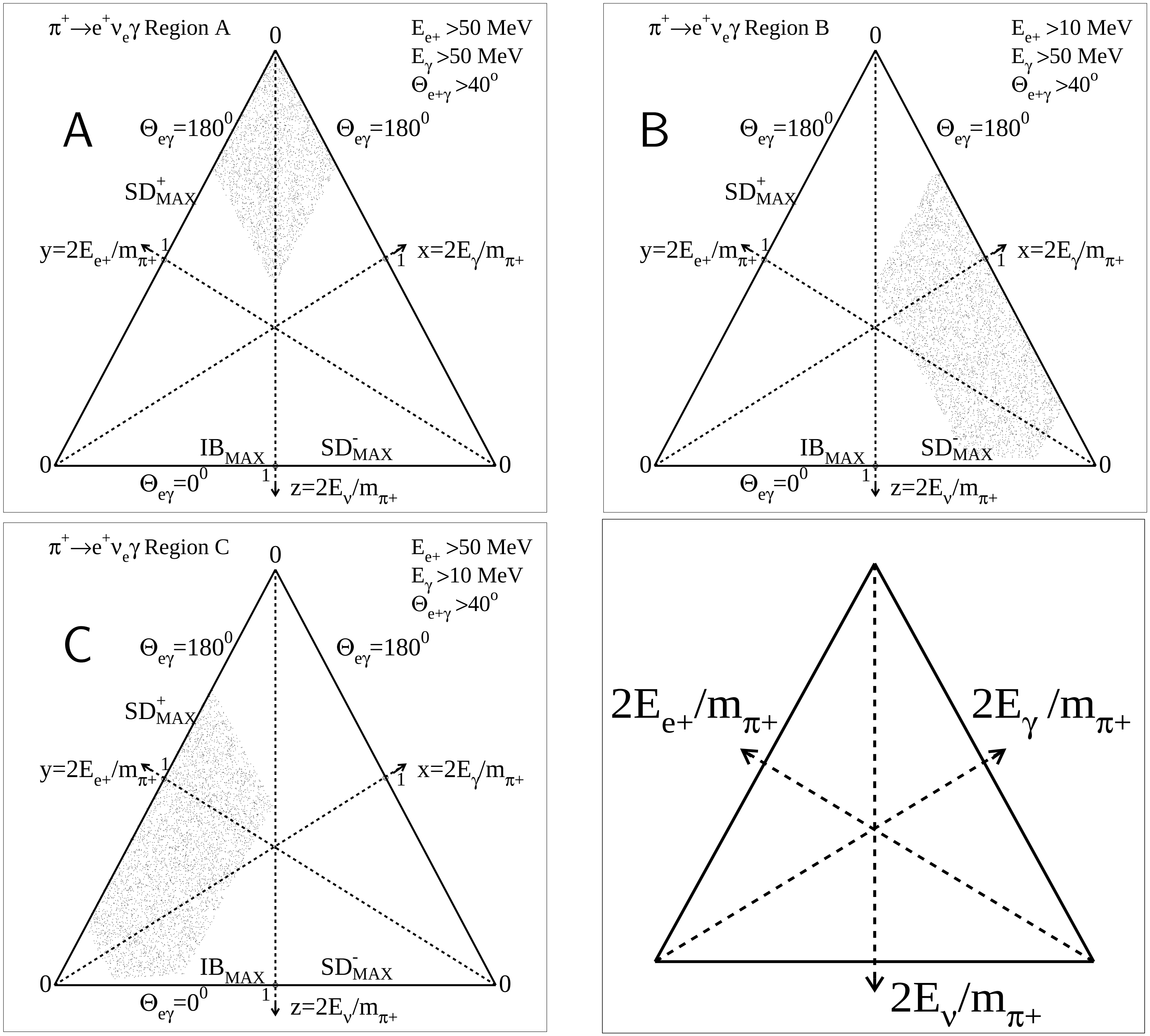
Data Analysis 99-01: $\pi^+ \rightarrow e^+\nu_e$



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



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

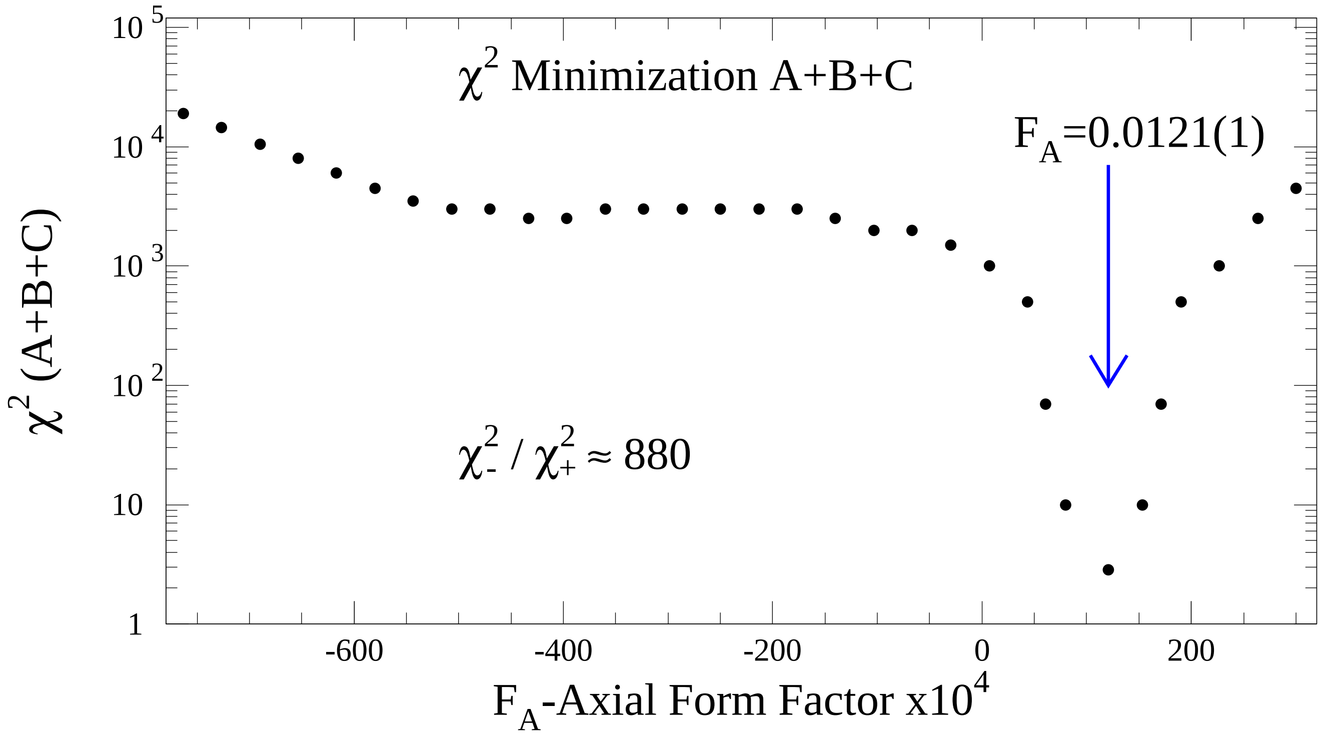


Data Analysis Method: $\pi^+ \to e^+\nu_e\gamma$

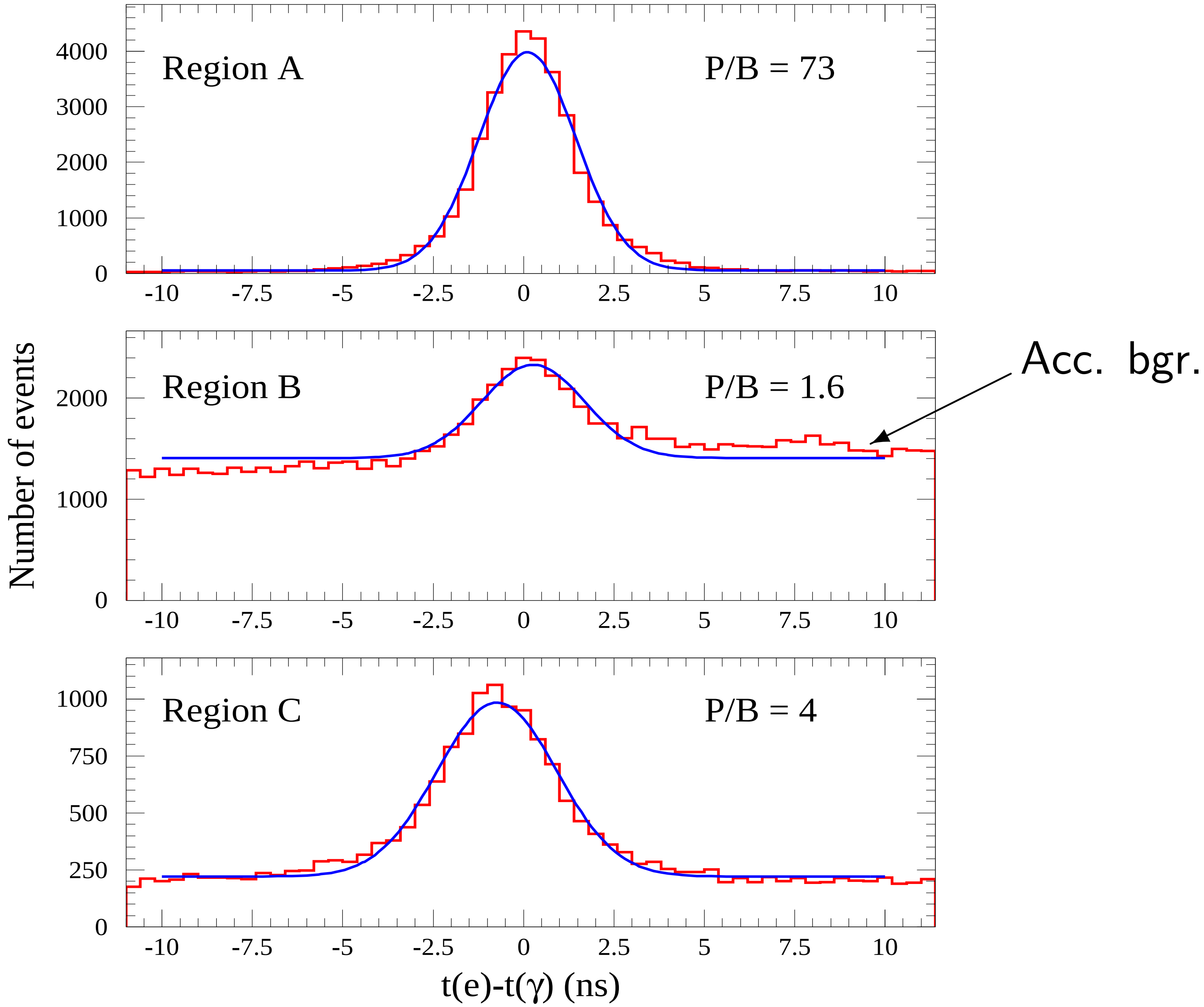
To extract the values of the FF's we minimize:

$$\chi^2 = \sum_{i=A,B,C} \frac{(B_i^{\mathrm{exp}}(F_A, F_V, a) - B_i^{\mathrm{the}}(F_A, F_V, a))^2}{\sigma_i^2(F_A, F_V, a)}$$

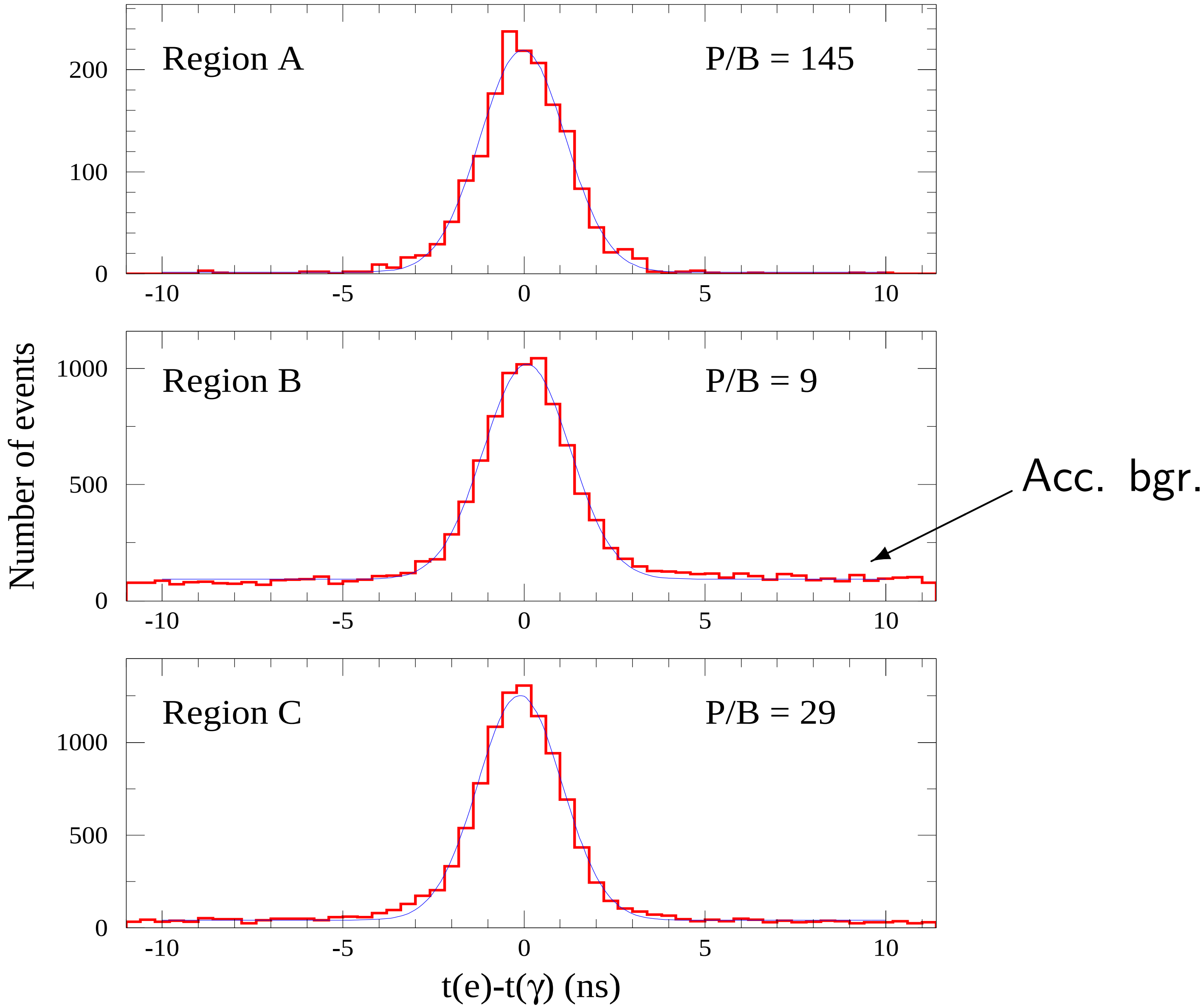
Both experimental and theoretical Bs depend on F_A, F_V, a.



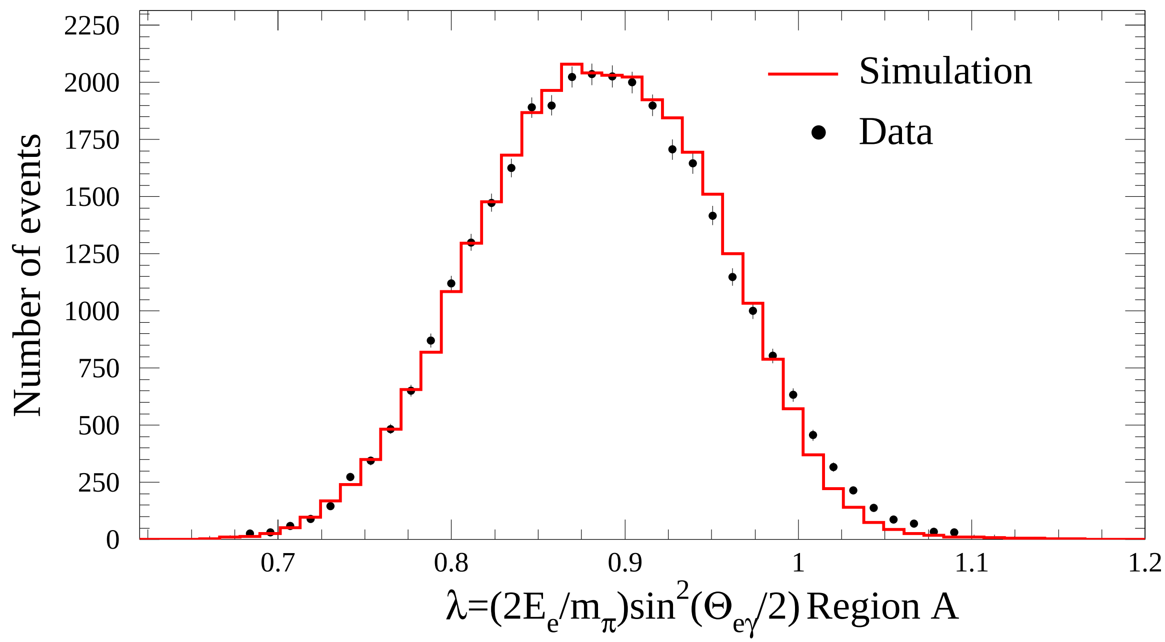
Data Analysis 99-01: $\pi^+ \to e^+\nu_e\gamma$

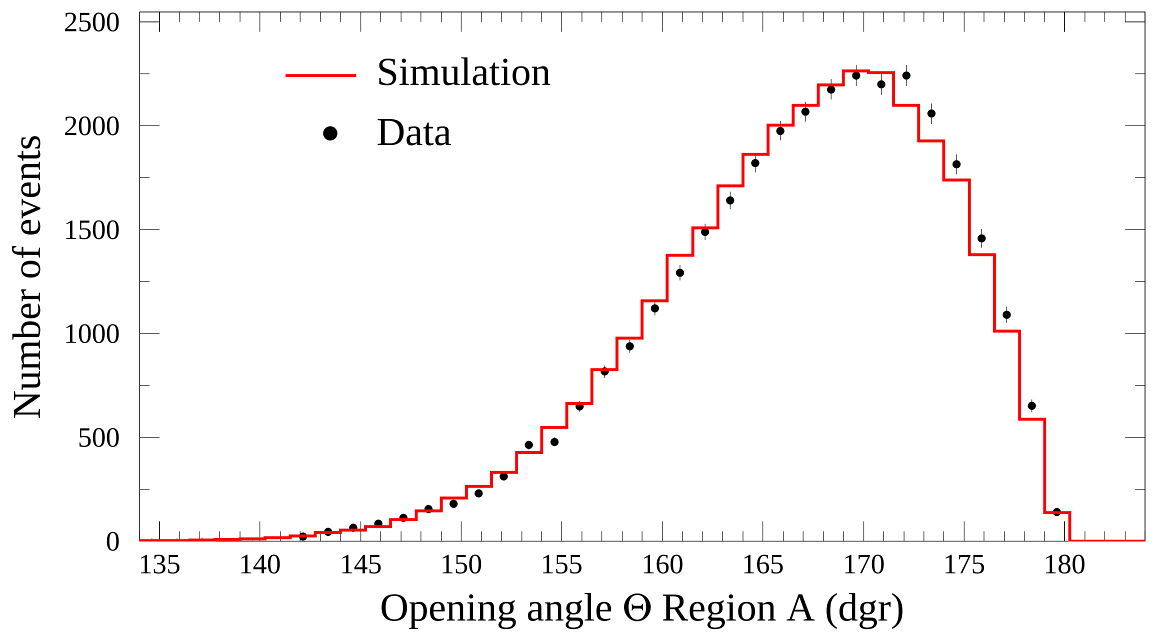


Data Analysis 04: $\pi^+ \rightarrow e^+\nu_e\gamma$

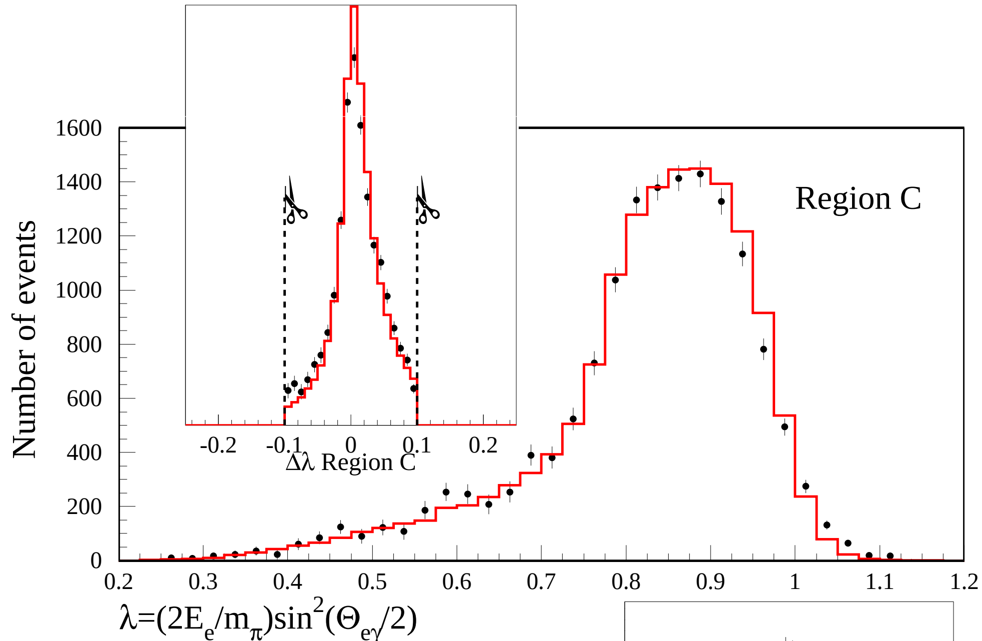


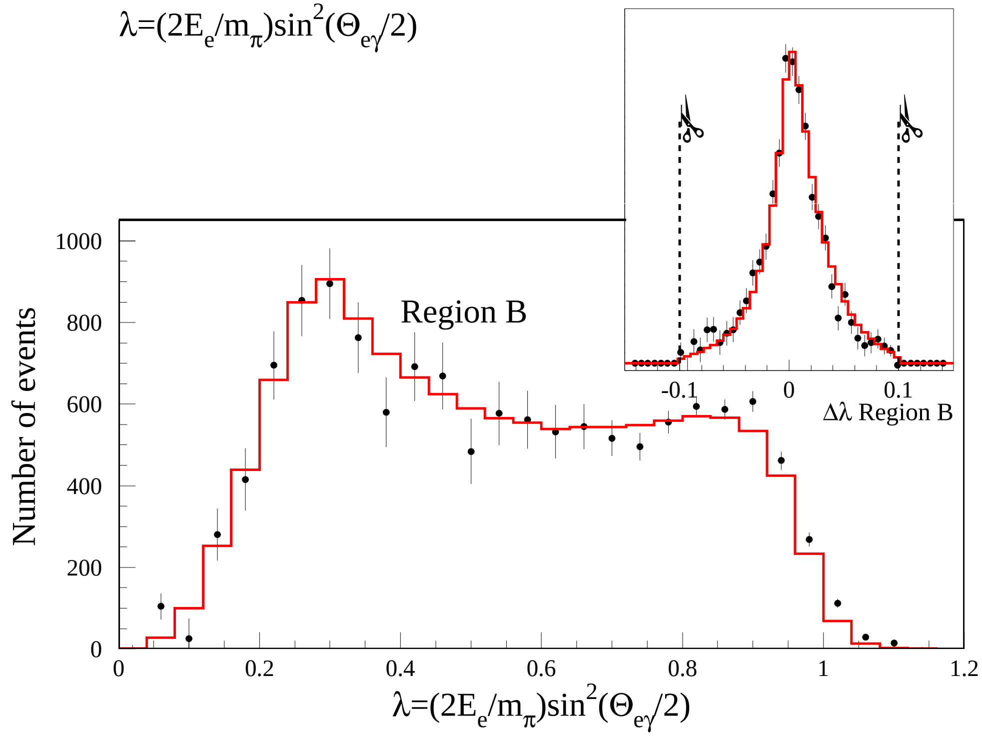
Data Analysis 99-01: $\pi^+ \to e^+ \nu_e \gamma$



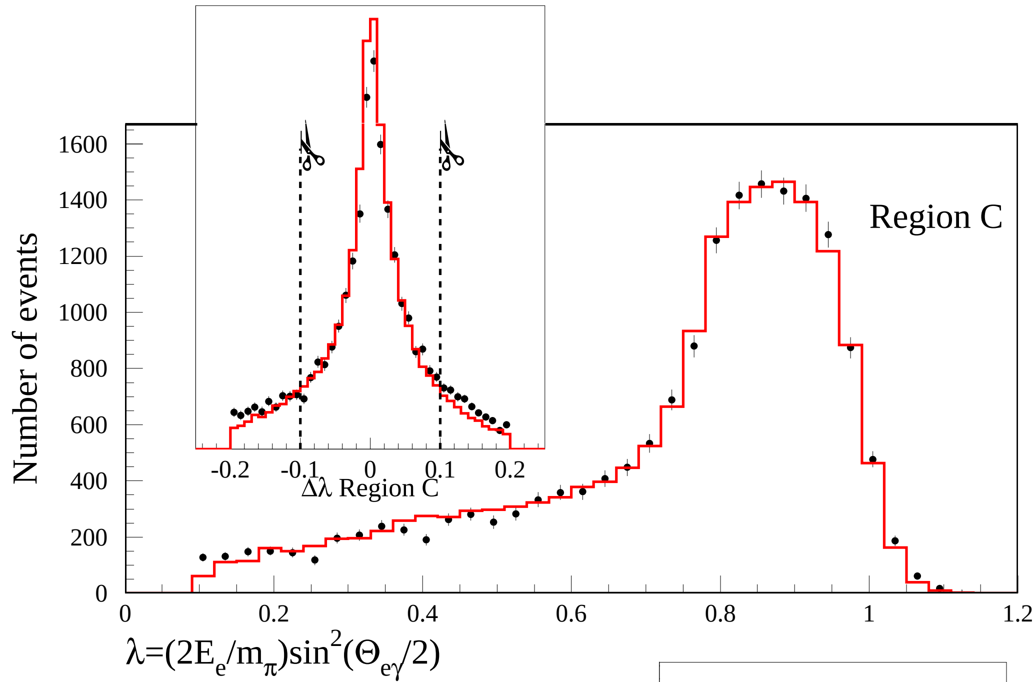


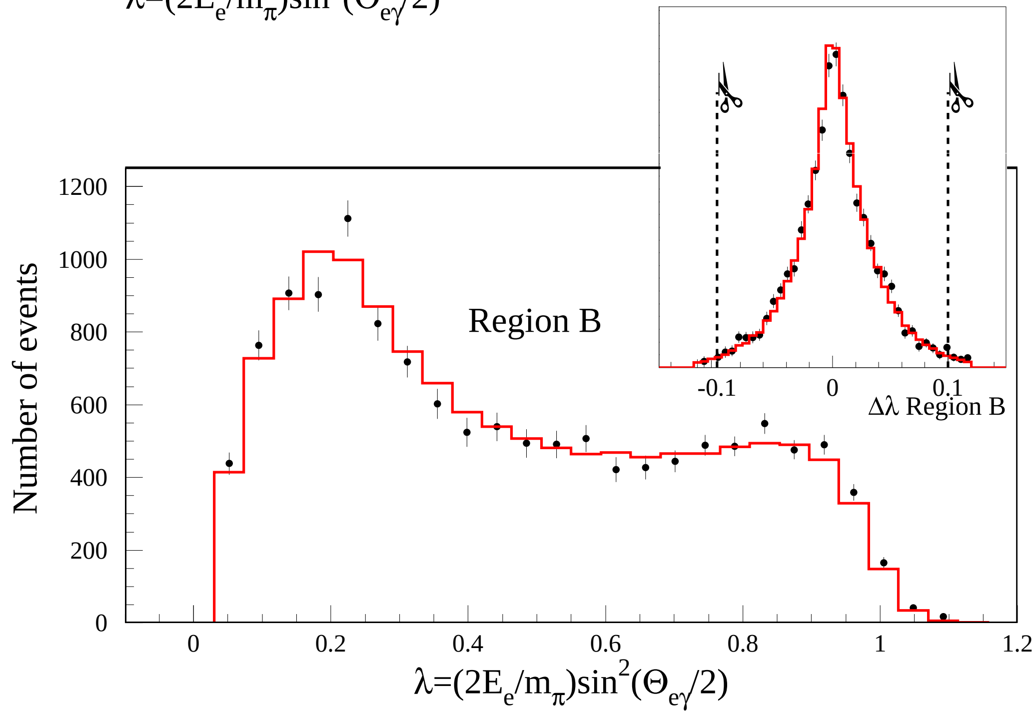
Data Analysis 99-01: $\pi^+ \rightarrow e^+\nu_e\gamma$





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





Results of the combo (99-01+04) analysis

a new exp. value of	$F_V = 0.0258 \pm 0.0018$
the value of	$F_A = 0.0121 \pm 0.0018$
first meas't of q^2 dep.:	$a = 0.070 \pm 0.058$
improved limit on $\lvert F_T \rvert$:	$\lvert F_T \rvert \leq 3.1 \times 10^{-4}$ 90% CL

ALTERNATIVELY

for fixed CVC value of	$F_V = 0.0259$
and fixed q^2 dep.	$a = 0.032$
improved value of	$F_A = 0.0121 \pm 0.0001$

Results of the combo (99-01+04) analysis

Using fixed F_V=0.0259 and a=0.032 we obtain

$E_{e^+}^{\text{min}}$ (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	–	2.612(20)	2.612	35.9 k
10	50	40°	14.45(22)	14.46	16.2 k
50	10	40°	37.85(46)	37.51	17.3 k

$$\alpha_E = (2.91 \pm 0.10) \cdot 10^{-4}\,\text{fm}^3$$

Results of the combo (99-01+04) analysis

a new exp. value of	$F_V = (258 \pm 17) \cdot 10^{-4}$
the value of	$F_A = (117 \pm 17) \cdot 10^{-4}$
first meas't of q^2 dep.:	$a = 0.095 \pm 0.058$
improved limit on F_T:	$F_T \leq 3.0 \cdot 10^{-4}$ 90% CL

ALTERNATIVELY

for fixed CVC value of	$F_V = 259 \cdot 10^{-4}$
and fixed q^2 dep.	$a = 0.041$
improved value of	$F_A = (119 \pm 1) \cdot 10^{-4}$
numerical value of	$F_T = (-0.60 \pm 2.78) \cdot 10^{-4}$

Results of the combo (99-01+04) analysis

Using fixed F_V=0.0259 and a=0.041 we obtain

$E_{e^+}^{\text{min}}$ (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	$35.9\,k$
10	50	40°	14.46(22)	14.45	$16.2\,k$
50	10	40°	37.69(46)	37.49	$13.3\,k$
$\frac{m_e}{2}$	10	40°	73.86(54)	74.11	$65.4\,k$

$$\alpha_E = (2.87 \pm 0.10) \cdot 10^{-4}\ \text{fm}^3$$

Summary of Radiative Pion Decay Results

- We improved the precision of pion form factors F_A, F_V and absolute B^{exp} **sixteen-**,**five-** and **tenfold** respectively. Confirmed the sign of the ratio F_A/F_V.
- We have determined for the first time the momentum dependence of the charged pion FF's.
- We set a new stringent upper limit on the tensor interaction;excellent agreement with SM.
- We provided a sub percent precision input data for the $\chi\mathbf{PT}$.
- Our radiative π results provide critical input in controlling the systematics of the approved $\pi \to e\nu$ (PEN) experiment, R-05-01.
- The PEN experiment will double the R-04-01 data set on radiative π decays, with yet lower backgrounds.
- Possibility of observing the Dalitz version $\pi^+ \to e^+\nu e^+e^-$.