

An Independent test of the CVC hypothesis in the charged pion

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

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- Brief review of rare pion decay modes
- Radiative pion decay: $\pi^+ \rightarrow e^+ \nu_e \gamma$ ($\pi_{e2\gamma}$) 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)

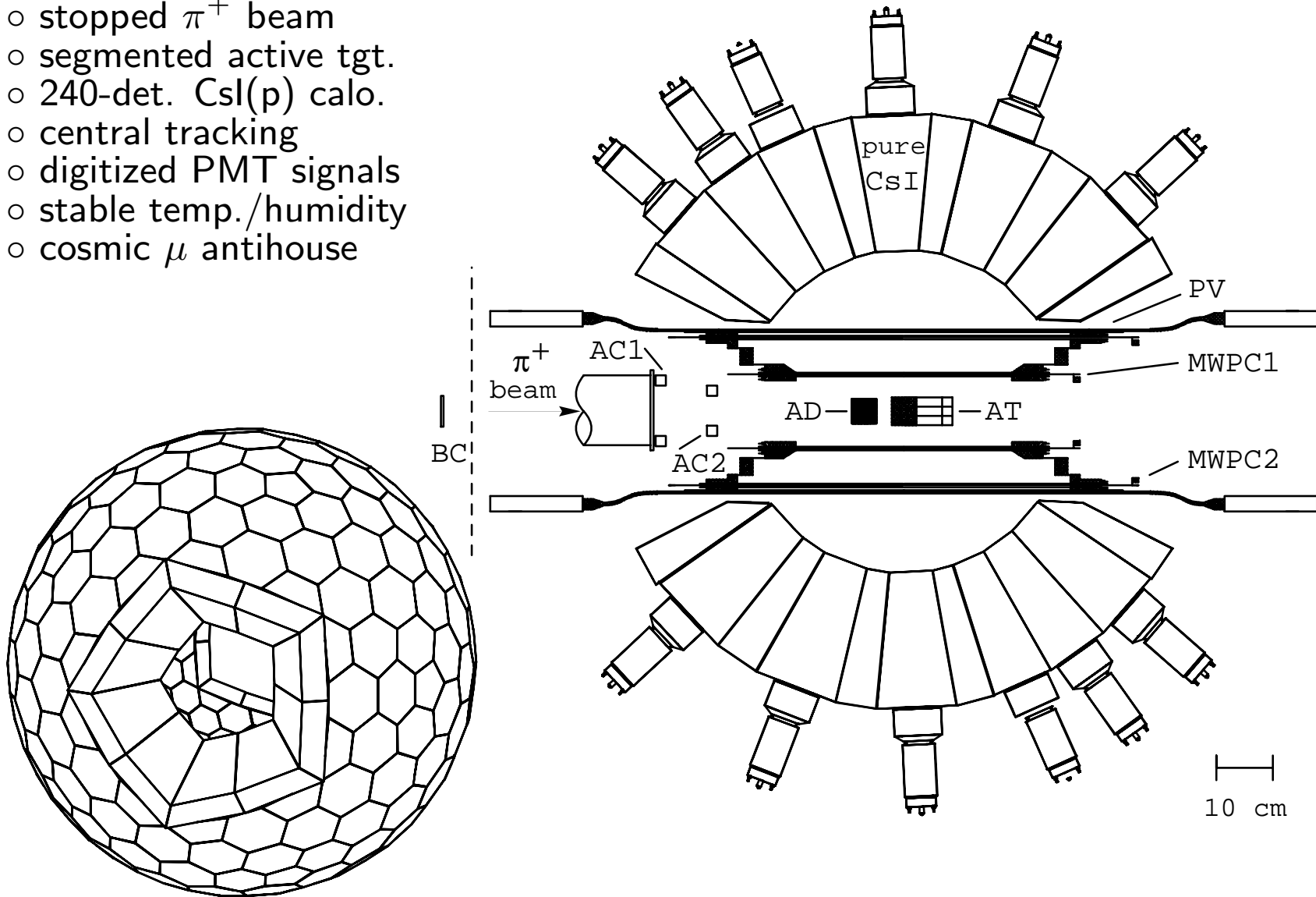
Decay	B	
$\pi^+ \rightarrow \mu^+ \nu$	0.9998770 (4)	$(\pi_{\mu 2})$
$\mu^+ \nu \gamma$	$2.00 (25) \times 10^{-4}$	$(\pi_{\mu 2 \gamma})$
$e^+ \nu$	$1.230 (4) \times 10^{-4}$	$(\pi_{e 2})$
$e^+ \nu \gamma$	$1.61 (23) \times 10^{-7}$	$(\pi_{e 2 \gamma}) \quad \checkmark$
$\pi^0 e^+ \nu$	$1.025 (34) \times 10^{-8}$	$(\pi_{e 3}, \pi_{\beta})$
$e^+ \nu e^+ e^-$	$3.2 (5) \times 10^{-9}$	$(\pi_{e 2 ee})$
$\pi^0 \rightarrow \gamma \gamma$	0.98798 (32)	$\mu^+ \rightarrow e^+ \nu \bar{\nu} \quad \sim 1.0$
$e^+ e^- \gamma$	$1.198 (32) \times 10^{-2}$	$e^+ \nu \bar{\nu} \gamma \quad 0.014 (4)$
$e^+ e^- e^+ e^-$	$3.14 (30) \times 10^{-5}$	$e^+ \nu \bar{\nu} e^+ e^- \quad 3.4 (4) \times 10^{-5}$
$e^+ e^-$	$6.2 (5) \times 10^{-8}$	

Physics Goals in Radiative Pion Decay

- Structure of the pion by measuring pion form factors. Independent measurement of pion polarizability α_E with real photon
- Deviations from $V - A$ form of $\mathcal{L}_{\text{weak}}$ 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 χ 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

$\pi^+ \rightarrow e^+ \nu_e$ (π_{e2}) decay for normalization:

$$B_{\text{decay}}^{\text{exp}} = B_{\pi_{e2}} \cdot \frac{A_{\pi_{e2}} \cdot N_{\text{decay}}}{N_{\pi_{e2}} \cdot A_{\text{decay}}}$$

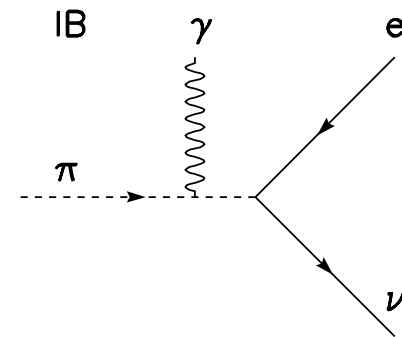
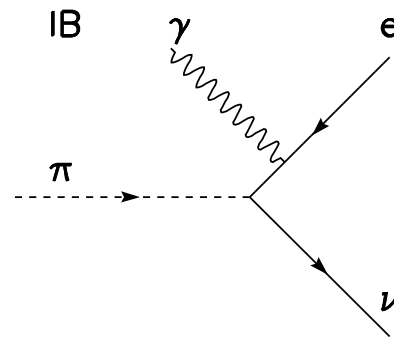
$B(A)_{\pi_{e2}}$ is branching ratio (acceptance) of $\pi^+ \rightarrow e^+ \nu_e$ decay

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

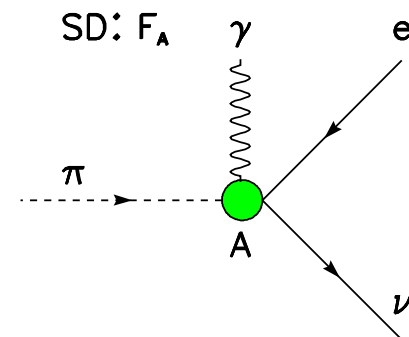
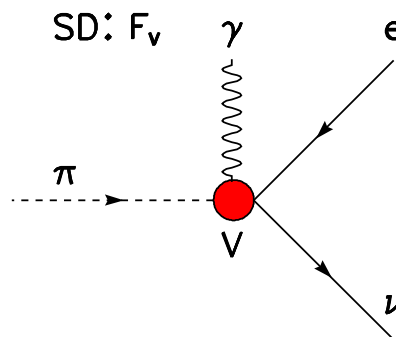
A_{decay} is the acceptance for the same decay in question

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

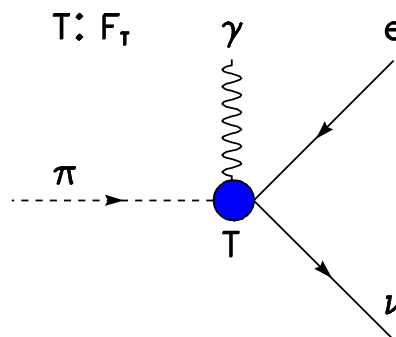
Standard *IB* and
V - A terms



SM



A tensor
interaction, too?



Exchange of $S=0$ leptoquarks

P Herczeg, PRD 49 (1994) 247

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

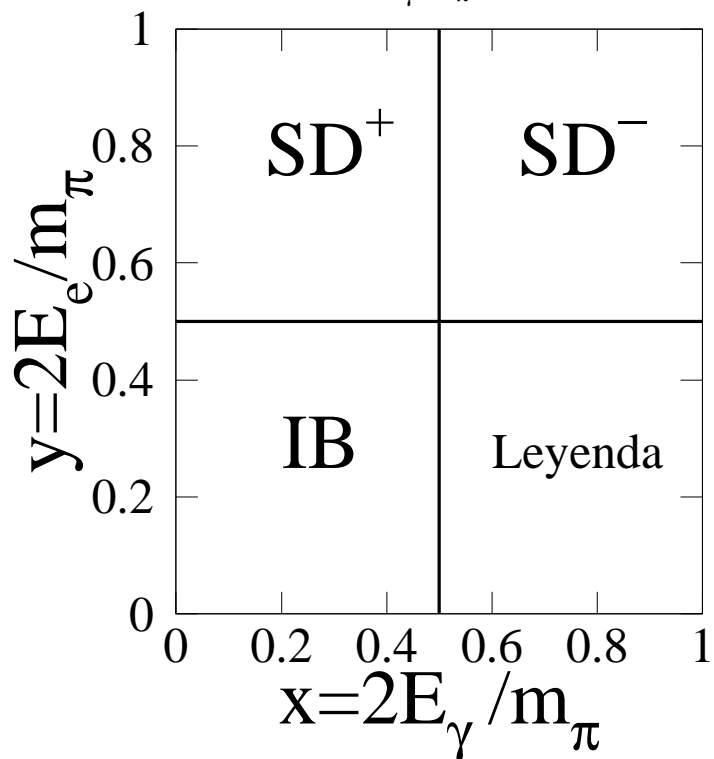
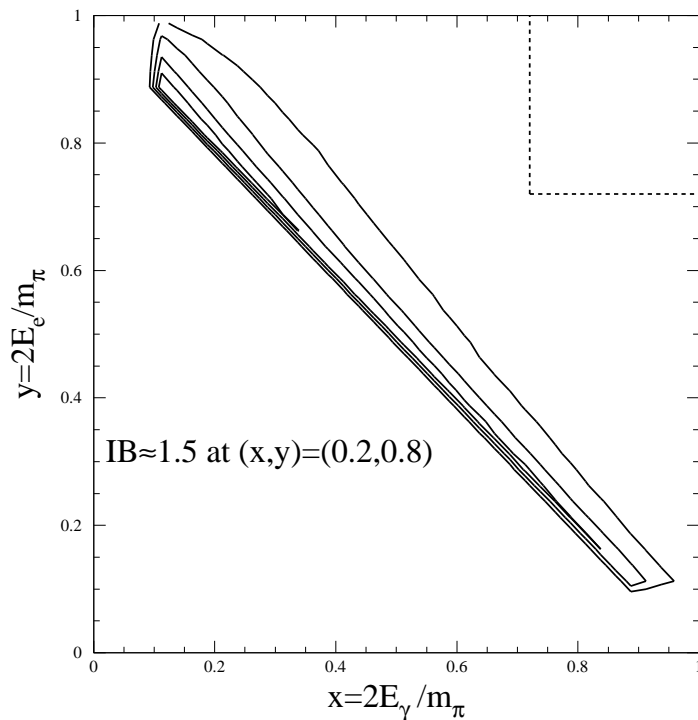
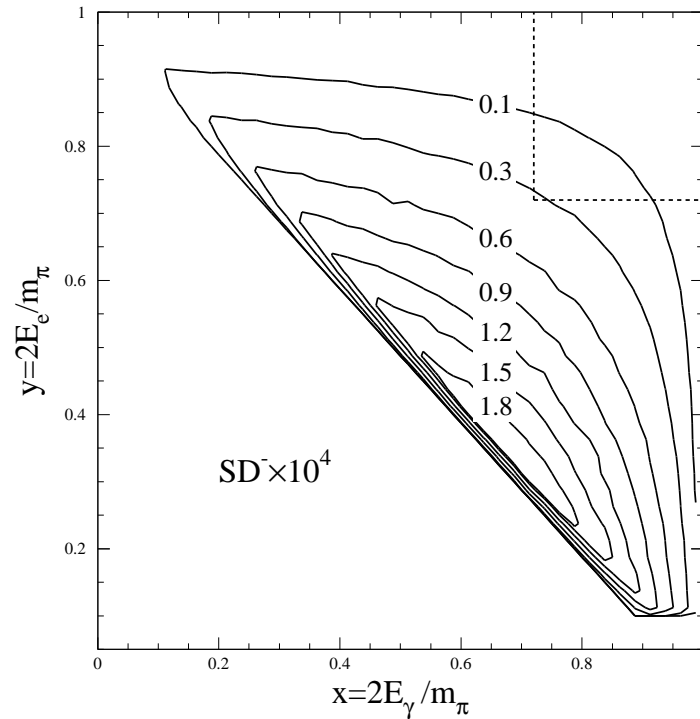
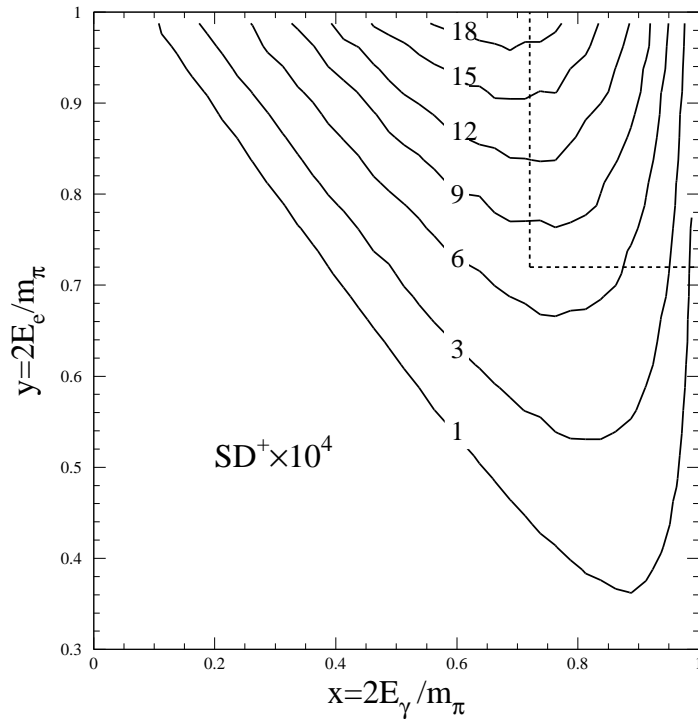
$$\frac{d^2 B^{\text{theor}}}{dxdy} = \frac{d^2 B_{IB}}{dxdy} + \frac{d^2 B_{SD}}{dxdy} + \frac{d^2 B_{\text{int}}}{dxdy} = \frac{\alpha}{2\pi} \boxed{B_{\pi \rightarrow e\nu}} \left\{ IB(x, y) + \frac{m_\pi^2}{4 \boxed{m_e^2}} \left(\frac{F_V}{f_\pi} \right)^2 [(1 + \gamma)^2 SD^+(x, y) + (1 - \gamma)^2 SD^-(x, y)] + \frac{F_V}{f_\pi} [(1 + \gamma) SD_{\text{int}}^+(x, y) + (1 - \gamma) SD_{\text{int}}^-(x, y)] \right\},$$

where IB , SD^\pm , SD_{int}^\pm 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

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

$F_A \times 10^4$	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)	

In $SU(3)$ limit CVC also predicts slope a is the same as for $\pi^0 \rightarrow \gamma\gamma^*$
 $a = 0.032 \pm 0.004$ (PDG 2006)

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

To first order in χ PT the pion weak form factors fix:

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

while the pion polarizability is given by

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

so that

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

[To resolve l_9 and l_{10} one needs

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

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

Available Results: $\pi^+ \rightarrow e^+ \nu_e$ Decay

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

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

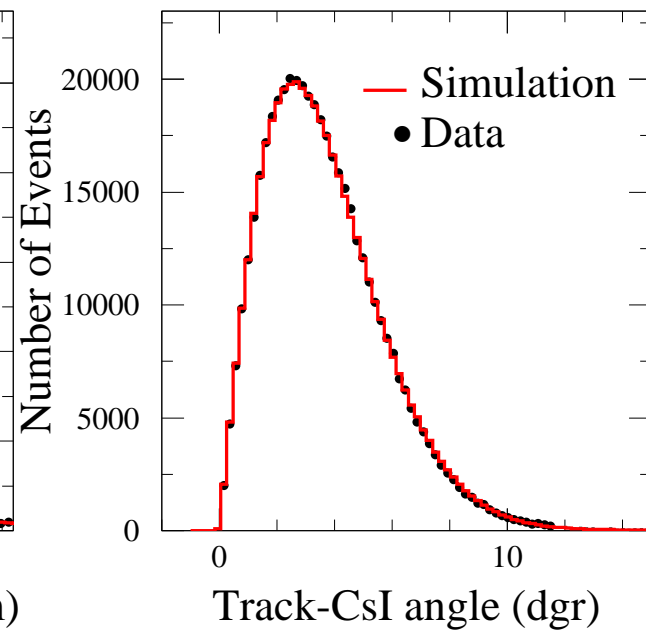
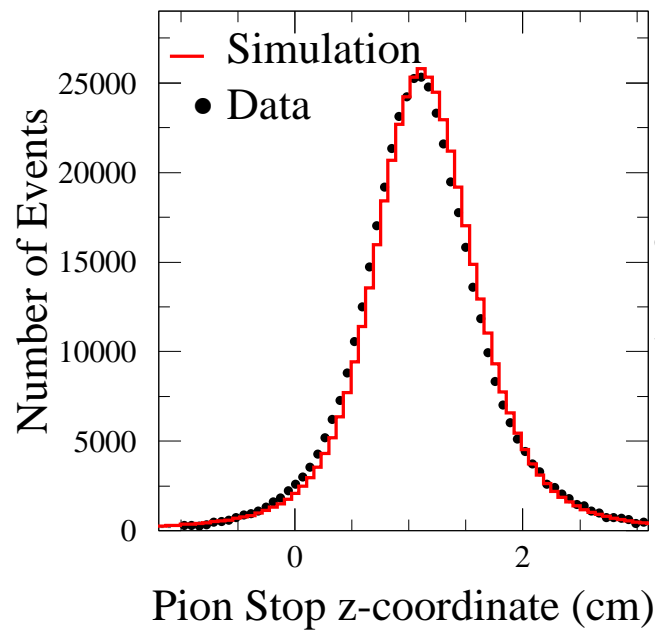
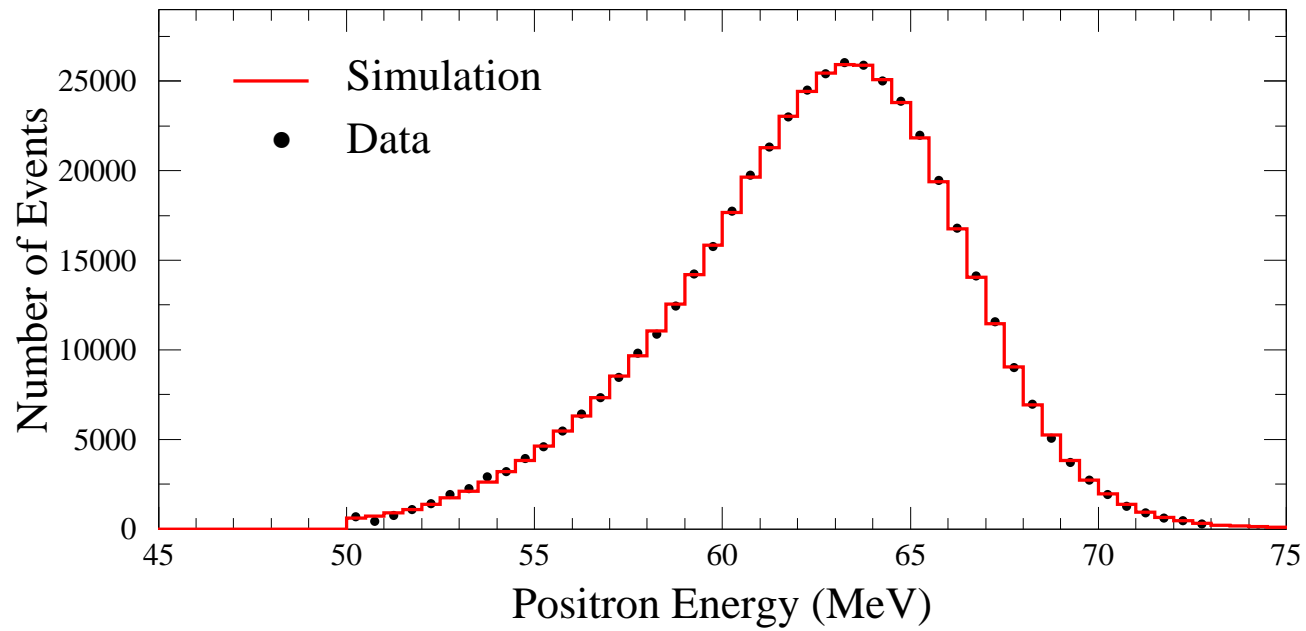
Decker and Finkemeier, [NP B **438** (1995) 17]:

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

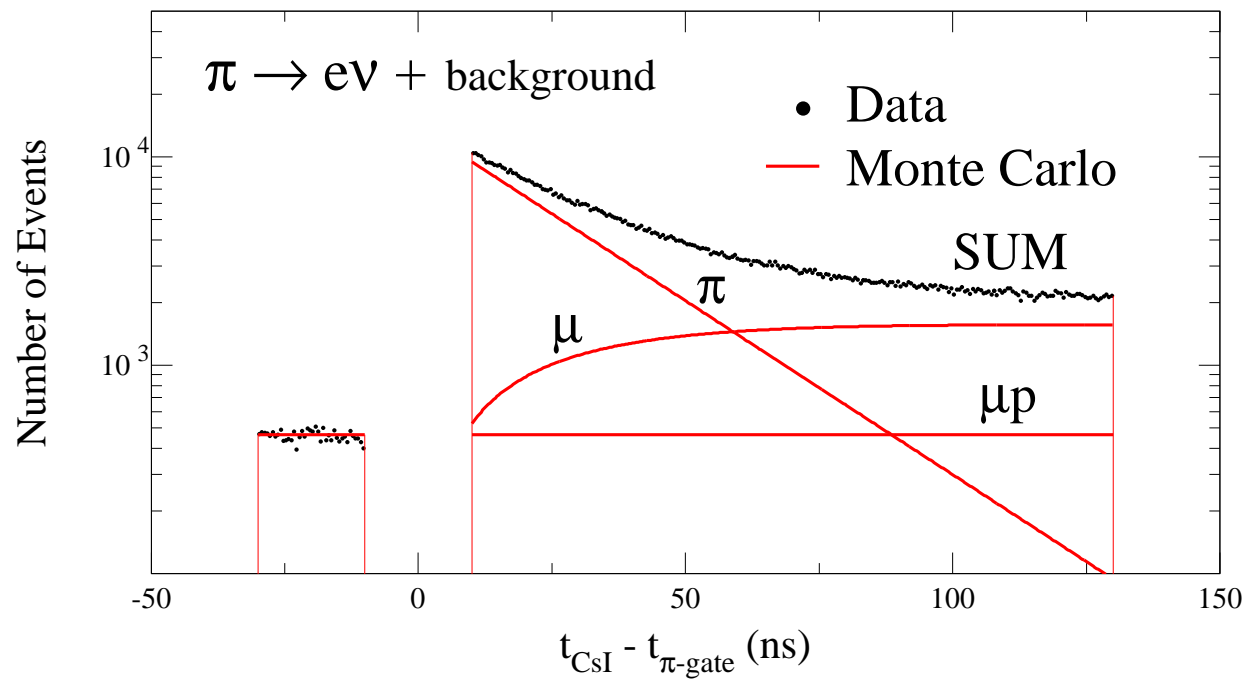
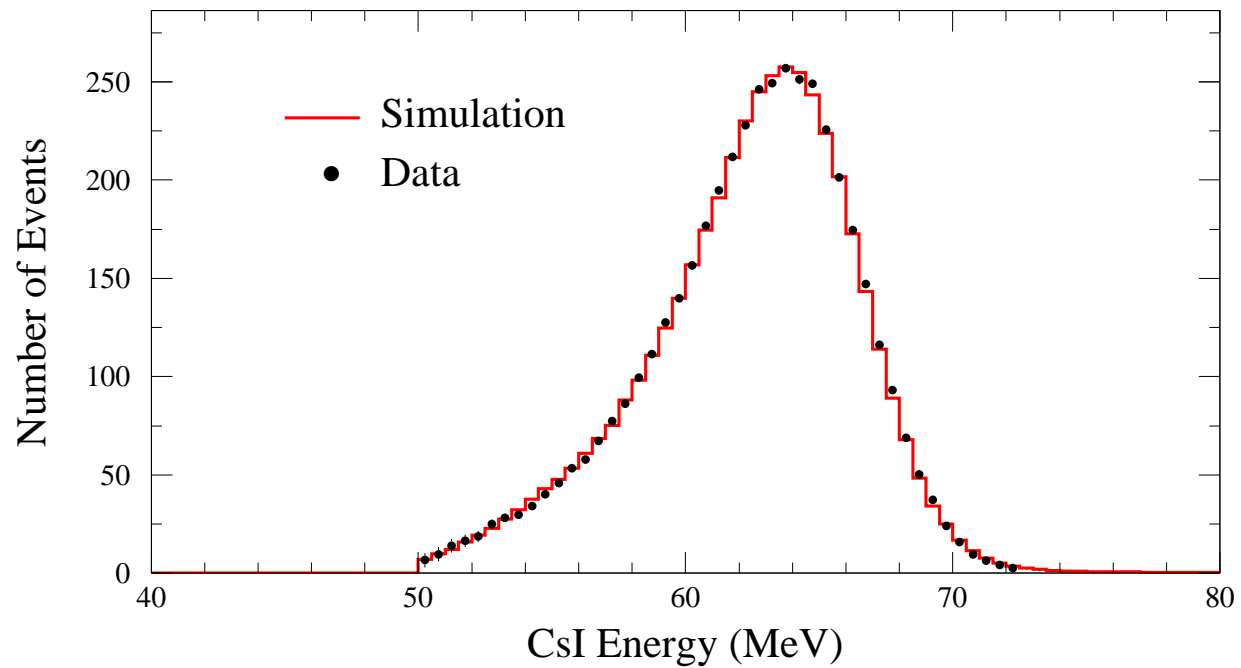
Experiment, world average (PDG 2006):

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

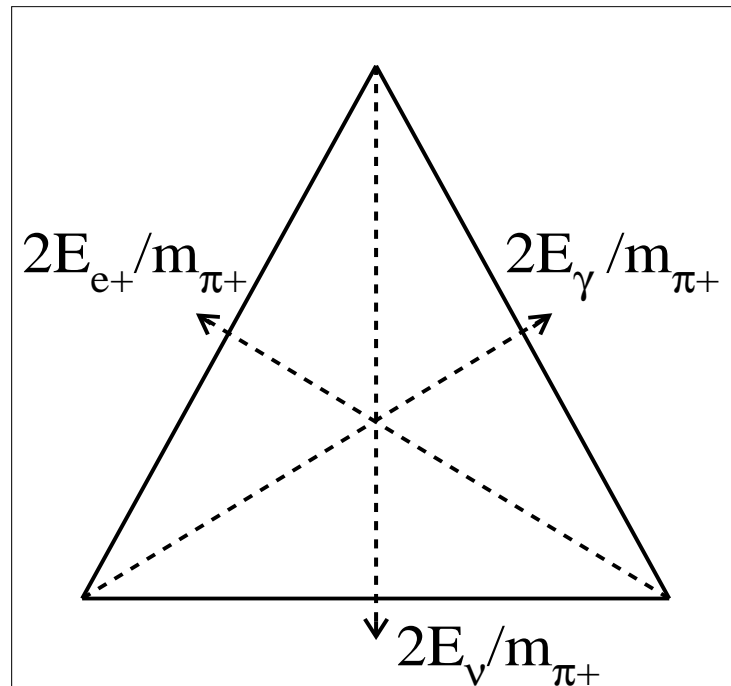
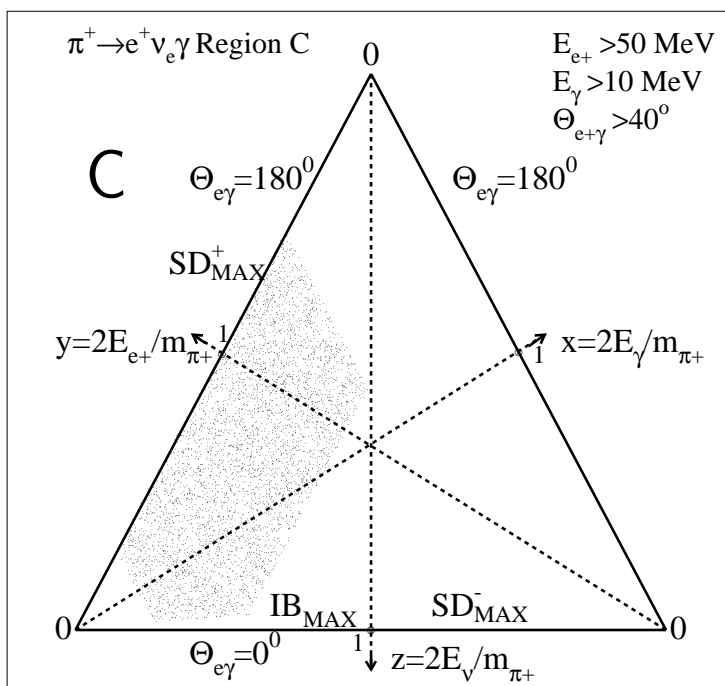
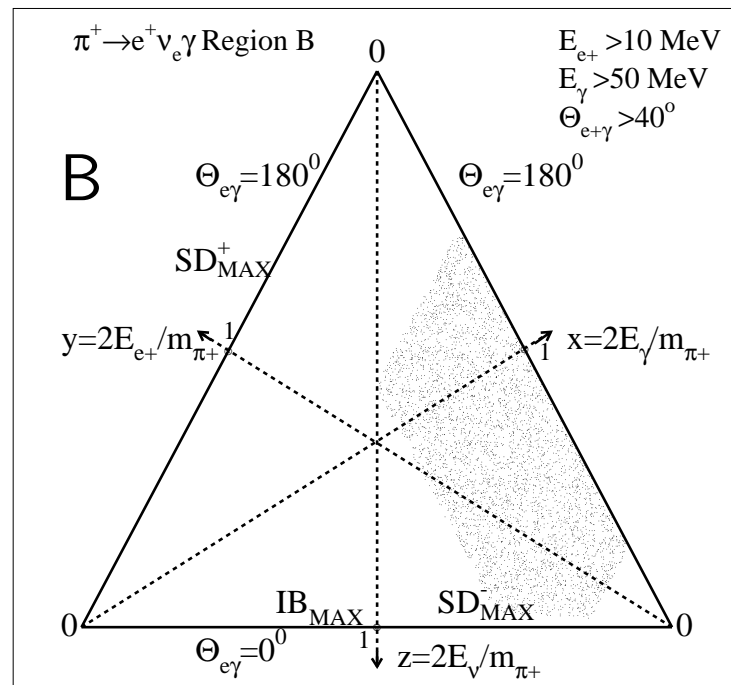
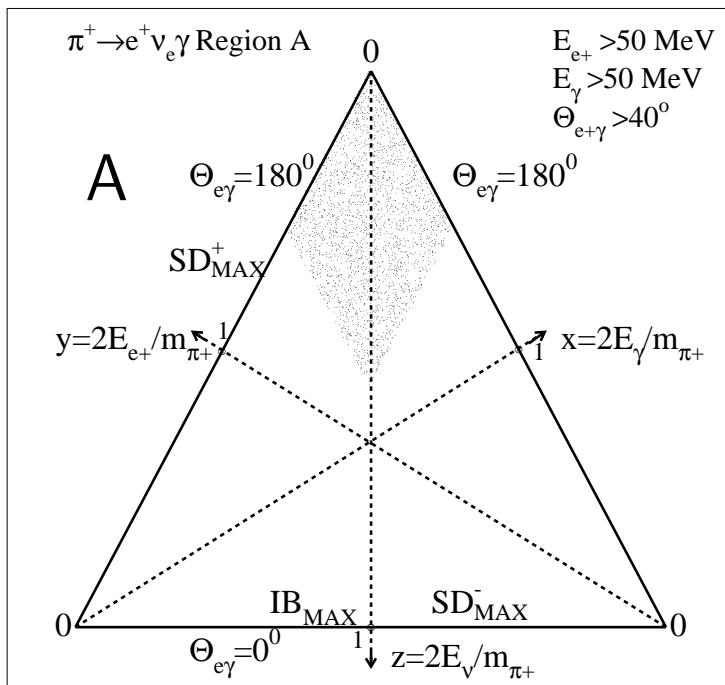
Data Analysis 99-01: $\pi^+ \rightarrow e^+ \nu_e$



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



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

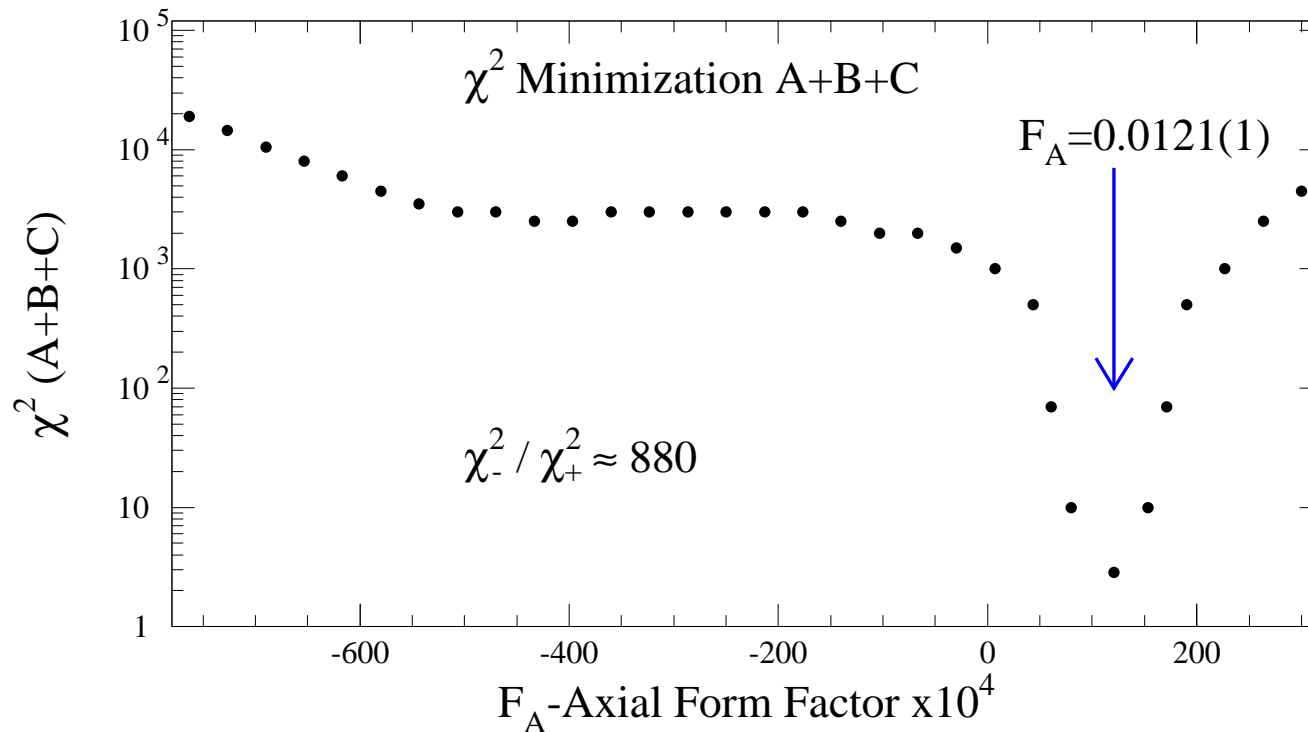


Data Analysis Method: $\pi^+ \rightarrow e^+ \nu_e \gamma$

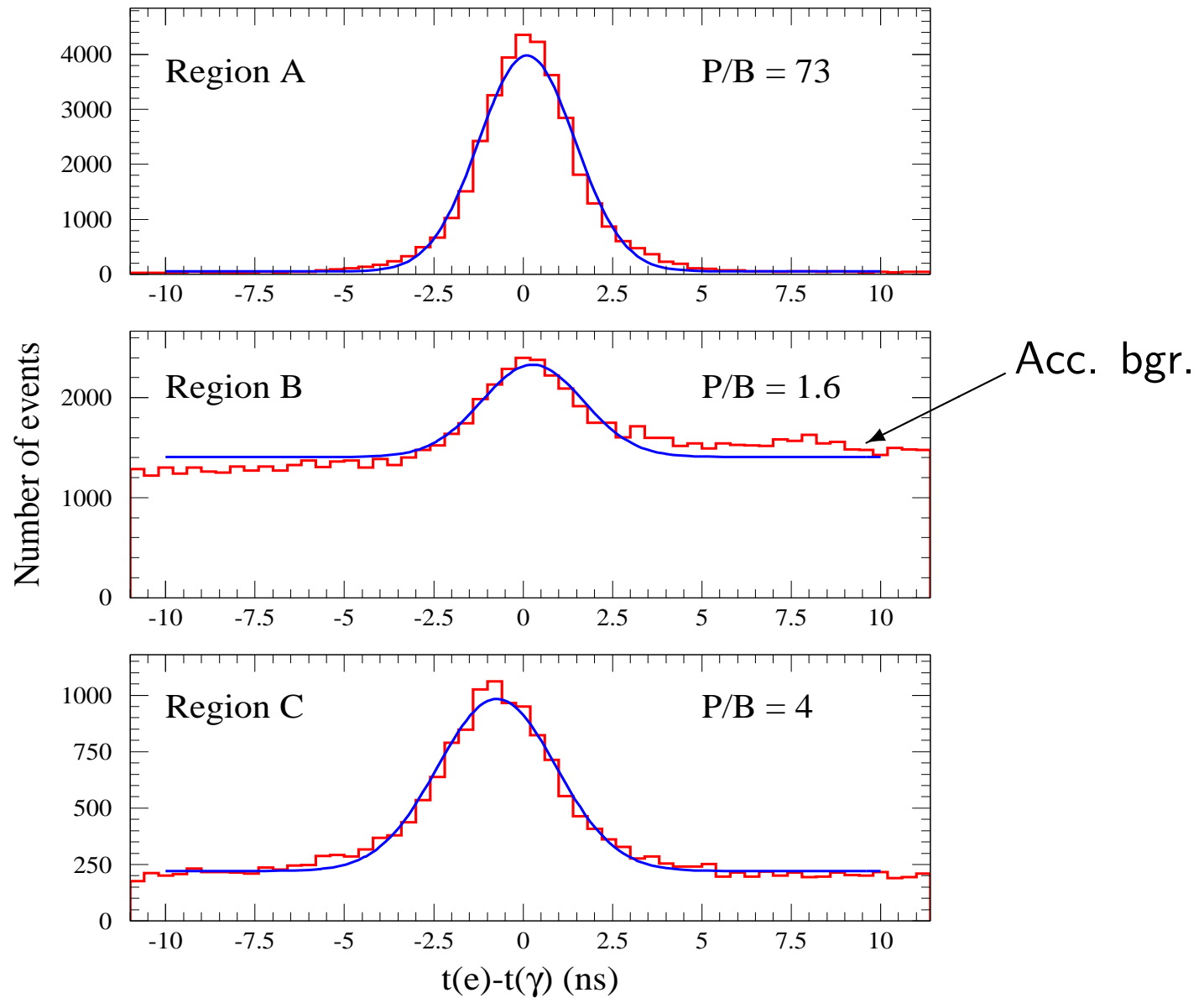
To extract the values of the FF's we minimize:

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

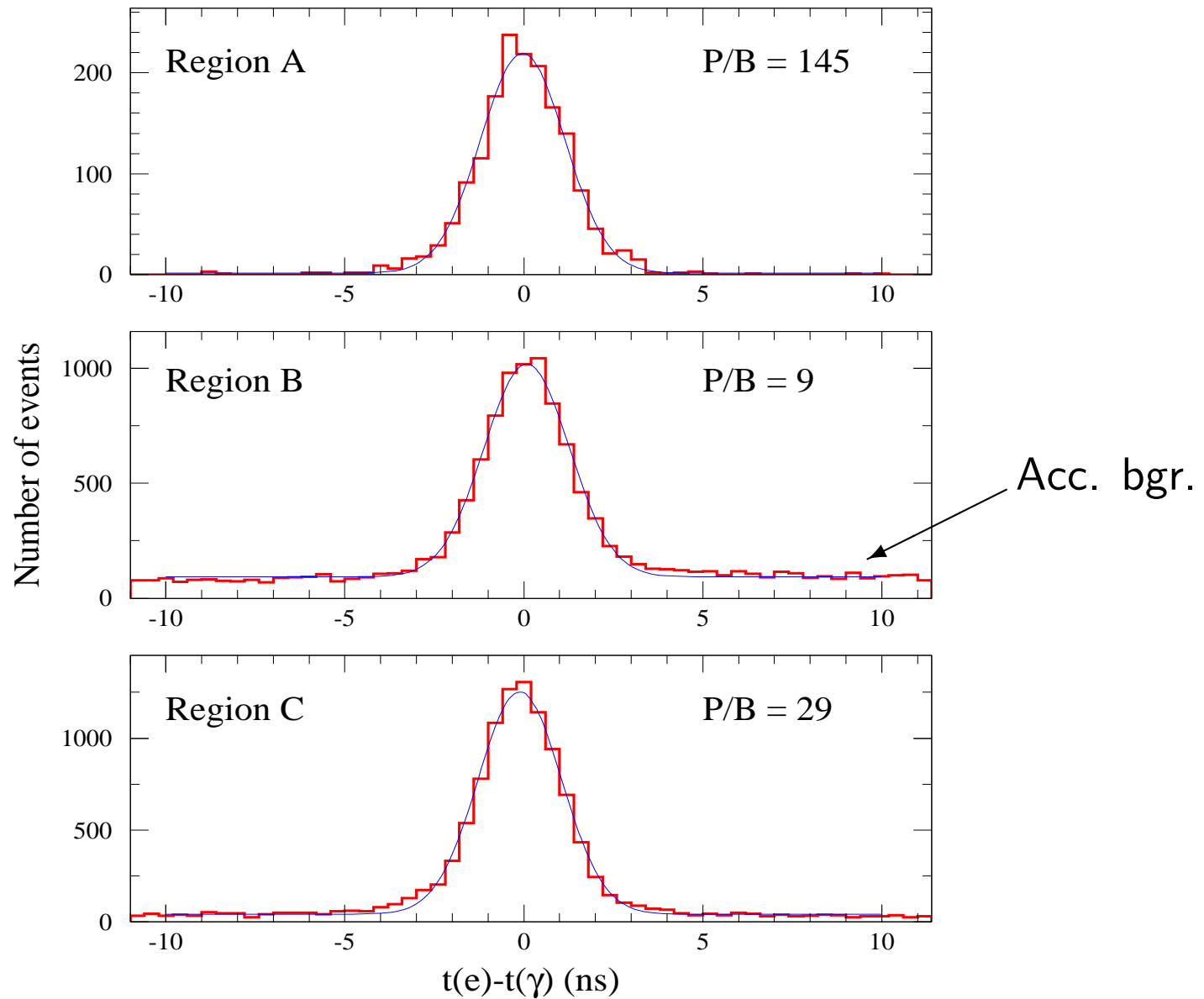
Both experimental and theoretical B s depend on F_A, F_V, a .



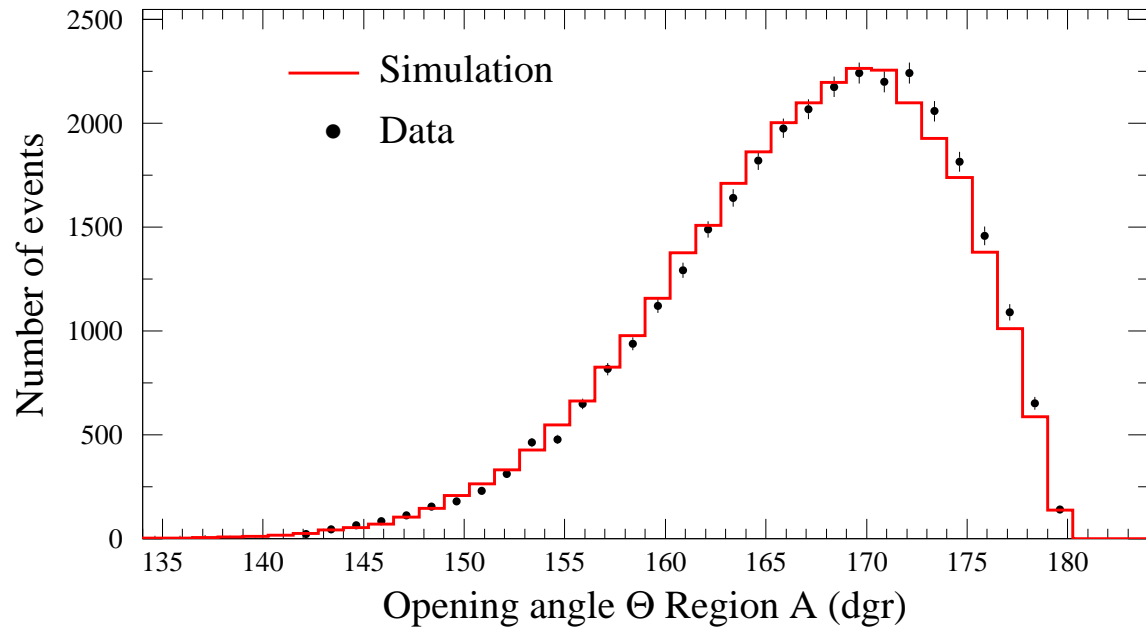
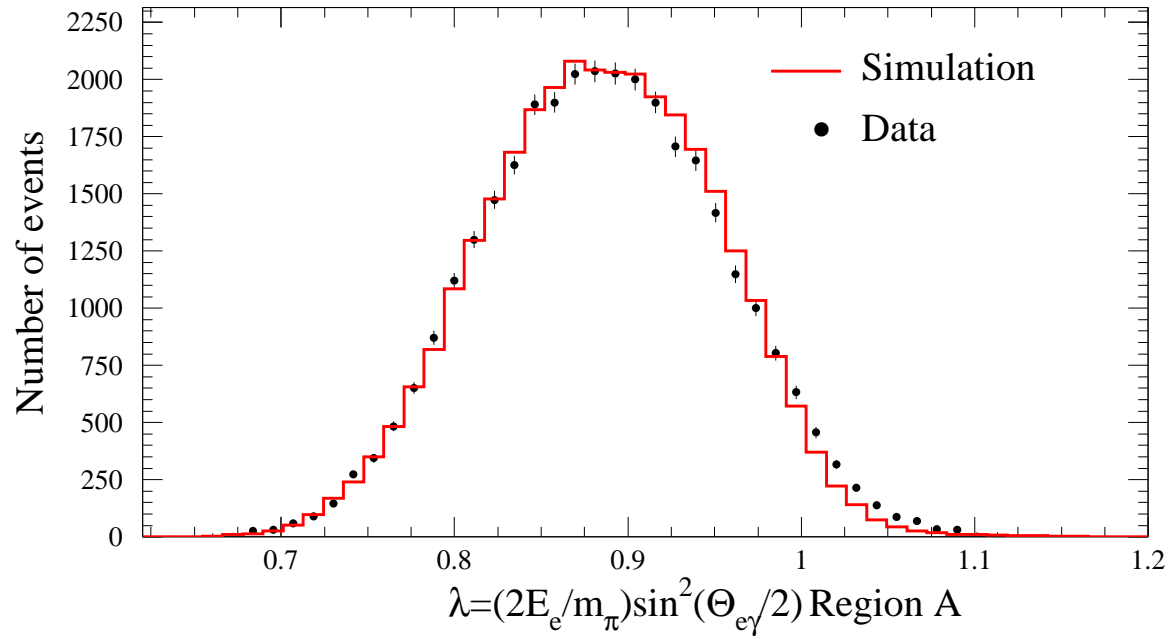
Data Analysis 99-01: $\pi^+ \rightarrow e^+ \nu_e \gamma$



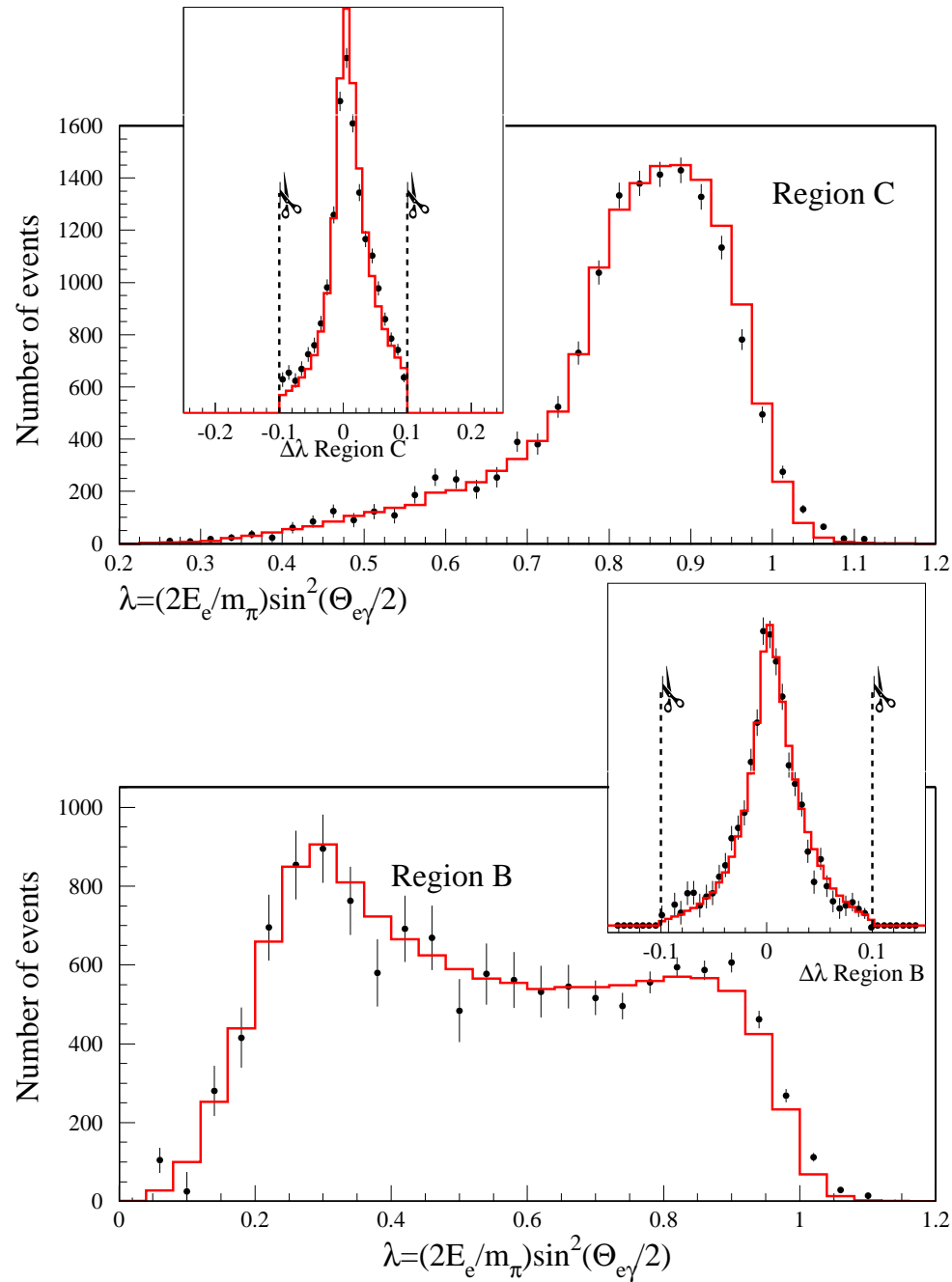
Data Analysis 04: $\pi^+ \rightarrow e^+ \nu_e \gamma$



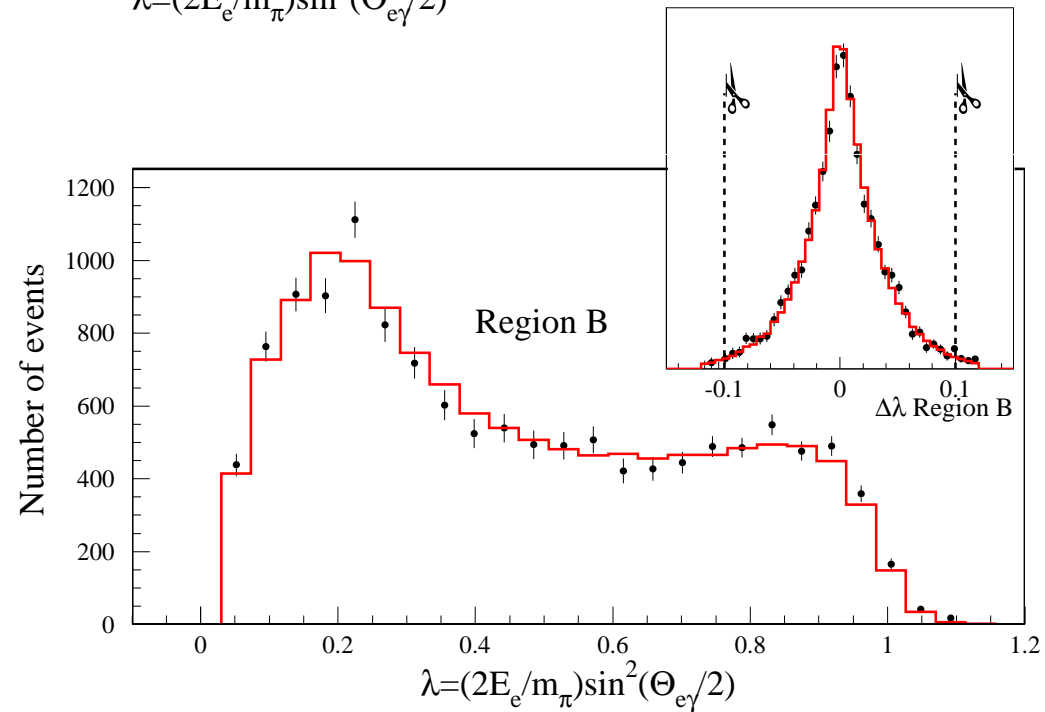
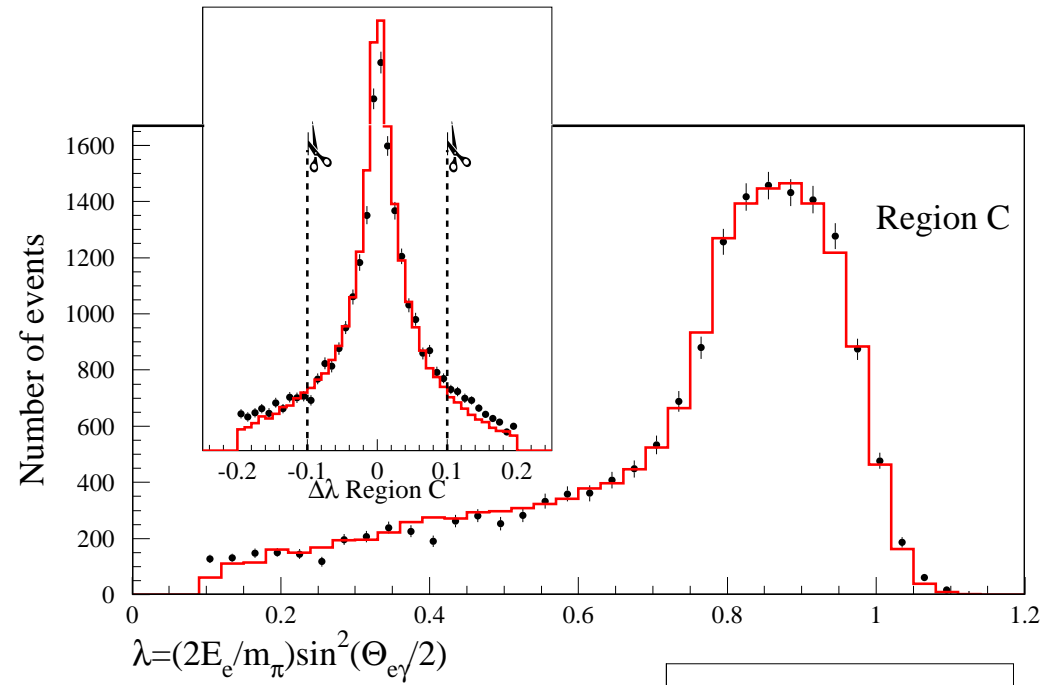
Data Analysis 99-01: $\pi^+ \rightarrow e^+ \nu_e \gamma$



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 $ F_T $:	$ F_T \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

$E_{e^+}^{\min}$ (MeV)	E_{γ}^{\min} (MeV)	$\theta_{e\gamma}^{\min}$	B_{exp} ($\times 10^{-8}$)	B_{the} ($\times 10^{-8}$)	no. of events
50	50	—	2.612(20)	2.612	35.9 <i>k</i>
10	50	40°	14.45(22)	14.46	16.2 <i>k</i>
50	10	40°	37.85(46)	37.51	17.3 <i>k</i>

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

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

$E_{e^+}^{\min}$ (MeV)	E_{γ}^{\min} (MeV)	$\theta_{e\gamma}^{\min}$	B_{exp} ($\times 10^{-8}$)	B_{the} ($\times 10^{-8}$)	no. of events
50	50	—	2.614(21)	2.599	35.9 <i>k</i>
10	50	40°	14.46(22)	14.45	16.2 <i>k</i>
50	10	40°	37.69(46)	37.49	13.3 <i>k</i>
$\frac{m_e}{2}$	10	40°	73.86(54)	74.11	65.4 <i>k</i>

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

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 χPT .
- Our radiative π results provide critical input in controlling the systematics of the approved $\pi \rightarrow e\nu$ (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 $\pi^+ \rightarrow e^+\nu e^+e^-$.