A Study of Rare Decays of Pions and Muons with PIBETA detector

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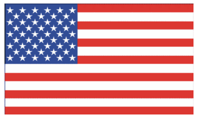
- About Us and Our Physics Goals
- Theoretical Description and Motivation
- Apparatus and Method
- Results And More Results

Seminar at INR Moscow
22 Nov 2005

The PIBETA Collaboration:



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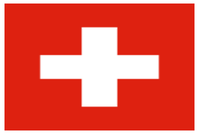

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Location

Paul Scherrer Institute in Switzerland

Physics Goals

We study rare decays of pions and muons:

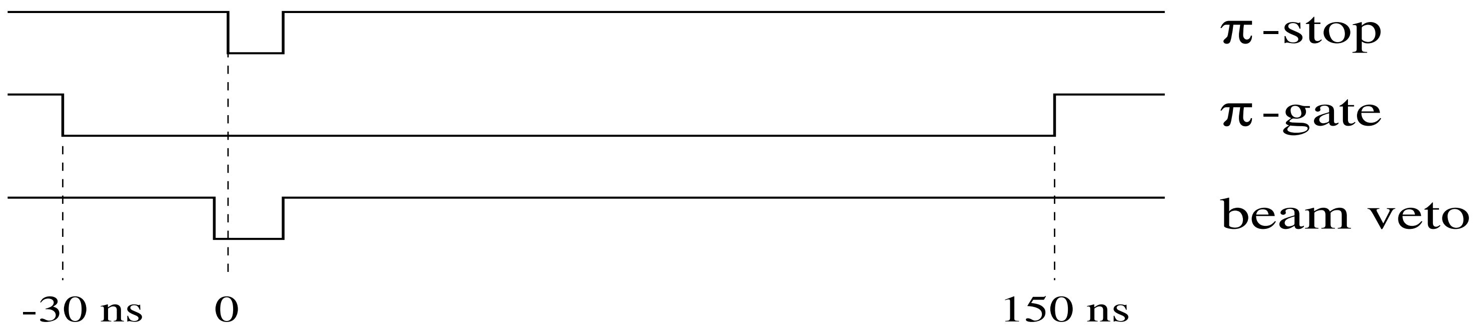
Mode	Fraction(Γ_j/Γ)%	Subsequently
$\pi^+ \to \mu^+\nu_\mu$	(99.98770 ± 0.00004)	$\mu^+ \to \mathrm{e}^+\overline{\nu}_\mathrm{e}\nu_\mu$ $(\approx 100\%)$
		$\mu^+ \to \mathrm{e}^+\overline{\nu}_\mathrm{e}\nu_\mu\gamma$ $(kin.)$
$\pi^+ \to \mu^+\nu_\mu\gamma$	$\sim 10^{-4}$ $(kin.)$	
$\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}$	$(1.230 \pm 0.004) \times 10^{-4}$	
$\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}\gamma$	$\sim 10^{-7}$ $(kin.)$	
$\pi^+ \to \pi^0\mathrm{e}^+\nu_\mathrm{e}$	$(1.036 \pm 0.006) \times 10^{-8}$	$\pi^0 \to 2\gamma$ (98.8%)
		$\pi^0 \to \mathrm{e}^+\mathrm{e}^-\gamma$ (1.2%)
$\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}\mathrm{e}^+\mathrm{e}^-$	$(3.2 \pm 0.5) \times 10^{-9}$	

Physics Goals

- Study β decay of the pion $\pi^+ \to \pi^0 e^+ \nu_e$
  - Precise measurment of V_{ud} element of the CKM matrix
- Study pion radiative decay $\pi^+ \to e^+ \nu_e \gamma$
  - Structure of the pion, check of the CVC hypothesis, deviations from $V - A$ form of $\mathcal{L}_{\mathrm{weak}}$
- Study muon radiative decay $\mu^+ \to e^+ \nu \overline{\nu} \gamma$
  - Precise test of the weak interaction, deviations from $V - A$ form of $\mathcal{L}_{\mathrm{weak}}$
- Study nonradiative decay $\pi^+ \to e^+ \nu_e$
  - electron-muon universality

Experimental Method

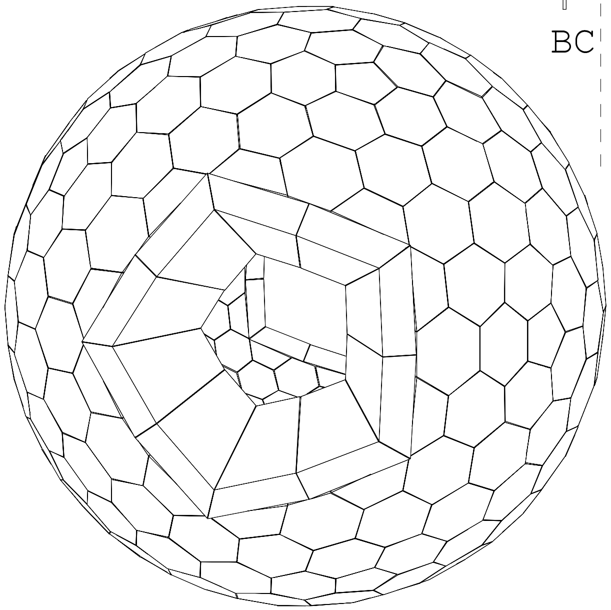
- π^+s are stopped in the active target and subsequently decay <u>at rest</u> in the lab.
- The beam veto suppresses events resulting from strong interactions in the degrader. It lasts 10 ns and is initiated by a π-stop signal.
- π-stop signal opens a 180 ns wide π-gate during which all events are collected.

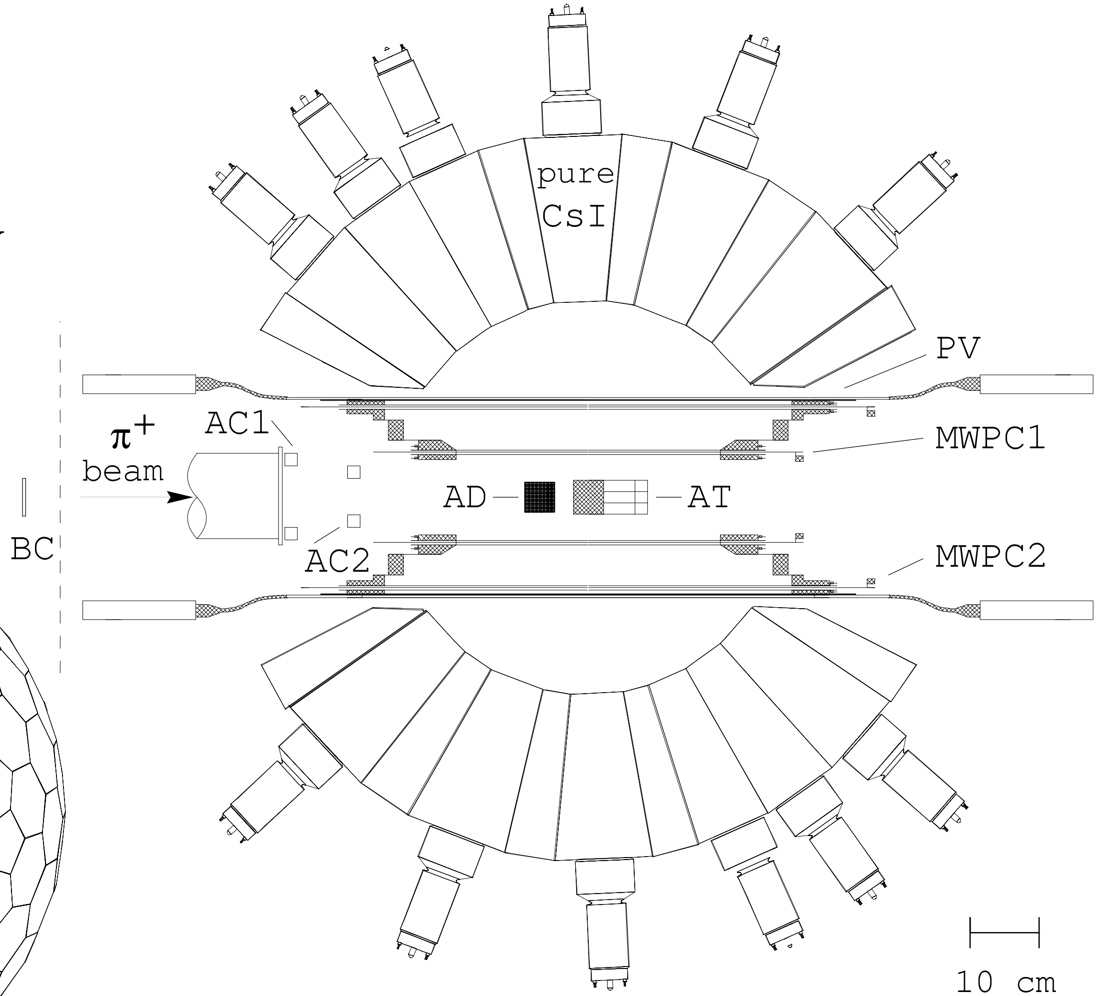


- All pion decays normalized to $\pi^+ \to e^+\nu_e$ decays and muon decays to $\mu^+ \to e^+\nu\overline{\nu}$.

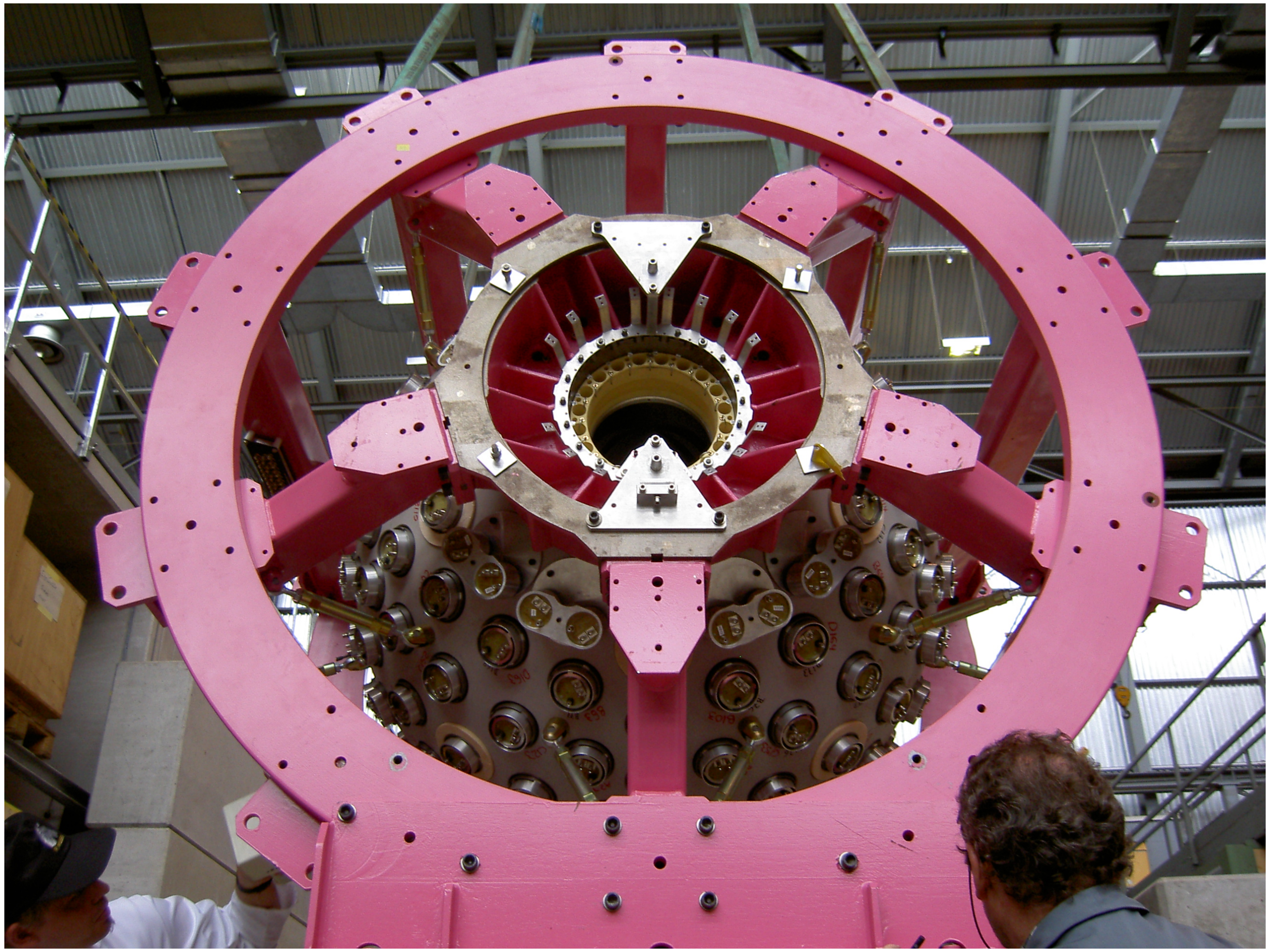
The PIBETA Apparatus:

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





Apparatus



Data Analysis: Method

In order to reduce the systematic uncertainties we use $\pi^+ \to e^+\nu_e$ (π_{e2}) decay for normalization:

$$\Gamma^{\mathrm{exp}}_{\mathrm{decay}} = \Gamma_{\pi_{e2}} \cdot \frac{A_{\pi_{e2}} \cdot N_{\mathrm{decay}}}{N_{\pi_{e2}} \cdot A_{\mathrm{decay}}}$$

$\Gamma_{\pi_{e2}}$ is branching ratio of $\pi^+ \to e^+\nu_e$ decay

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

A_{decay} is the acceptance for the same decay

Pion Decay: $\pi^+ \rightarrow e^+ \nu_e \quad (\pi_{e2})$

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

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

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

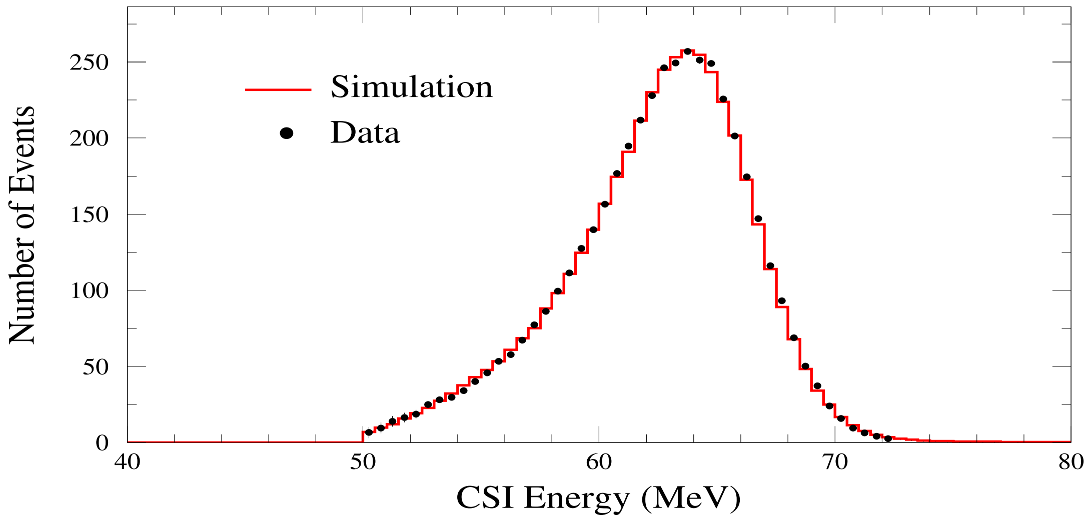
Decker and Finkemeier, [NP B **438** (1995) 17]:

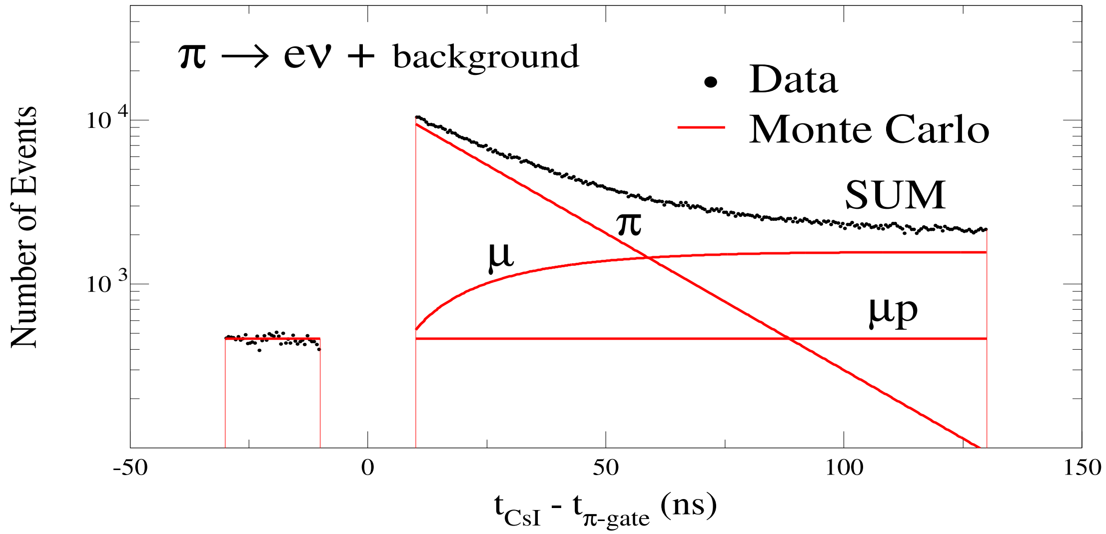
$$\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{\text{calc}} = (1.2356 \pm 0.0001) \times 10^{-4}$$

Experiment, world average (PDG 2004):

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

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





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

$$N_{\pi_{e2}} = 23\,838\,114 \pm 34063 \quad (0.1\%)$$

$$A_{\pi_{e2}} = 0.6606 \pm 0.0015 \quad (0.2\%)$$

An independent check is $\Gamma_{\pi_{e2}}$ normalized to $N_{\pi\text{-stop}}$

$$\Gamma_{\pi_{e2}} = (1.241 \pm 0.010) \times 10^{-4} \quad (0.8\%)$$

The Pion Beta Decay: $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ (π_β)

Quark-Lepton (Cabibbo) Universality

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

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

persists in hadronic weak decays

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

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 Cabibbo-Kobayashi-Maskawa matrix (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)

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

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

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

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

Theoretical Description: The Pion Beta Decay

$\pi^\pm \to \pi^0 e^\pm \nu$: BR $\simeq 1 \times 10^{-8}$, 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:

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

Experimental State of Things

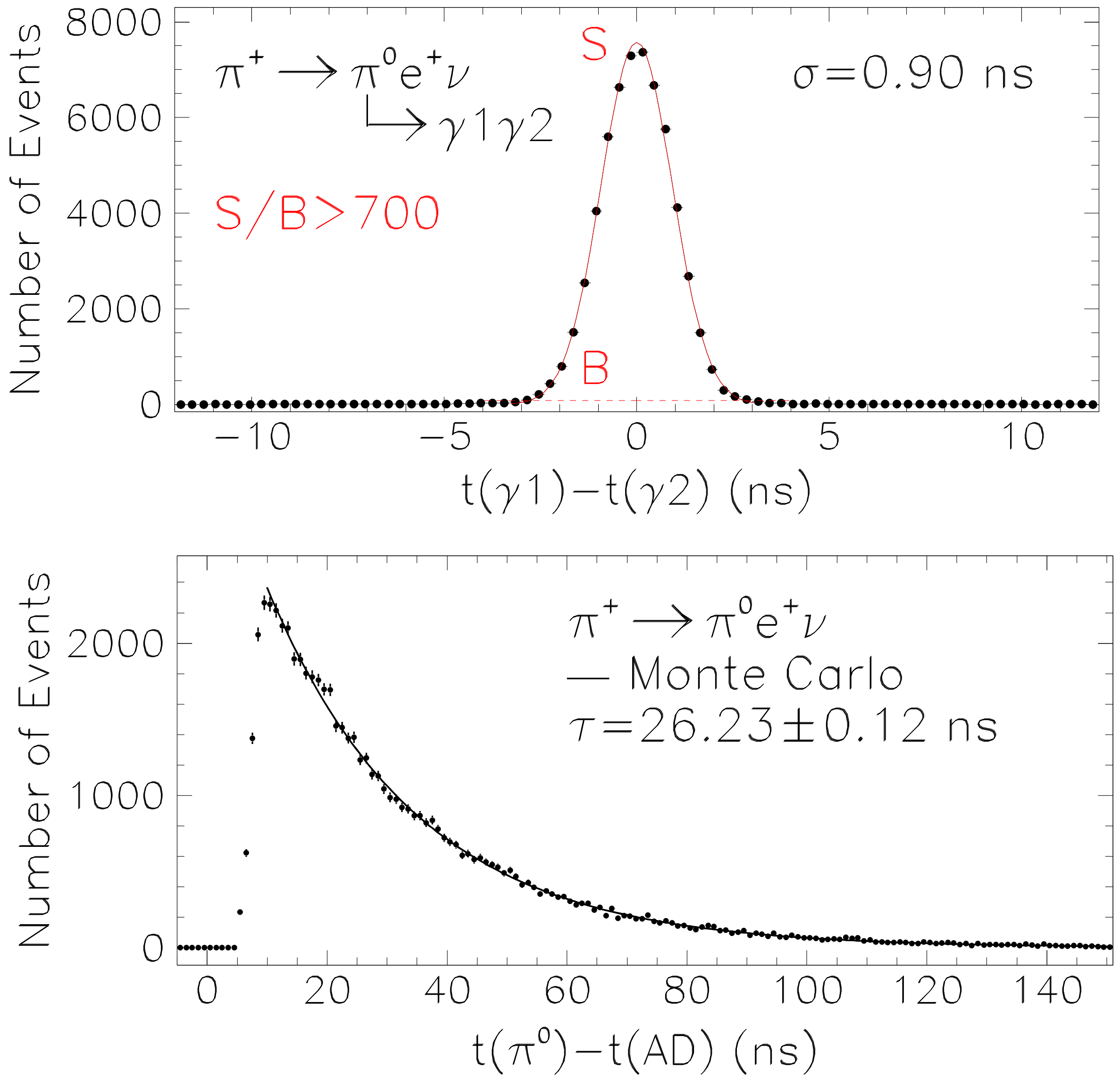
Best result until recently: [McFarlane et al., PRD 32 (1985) 547.]

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

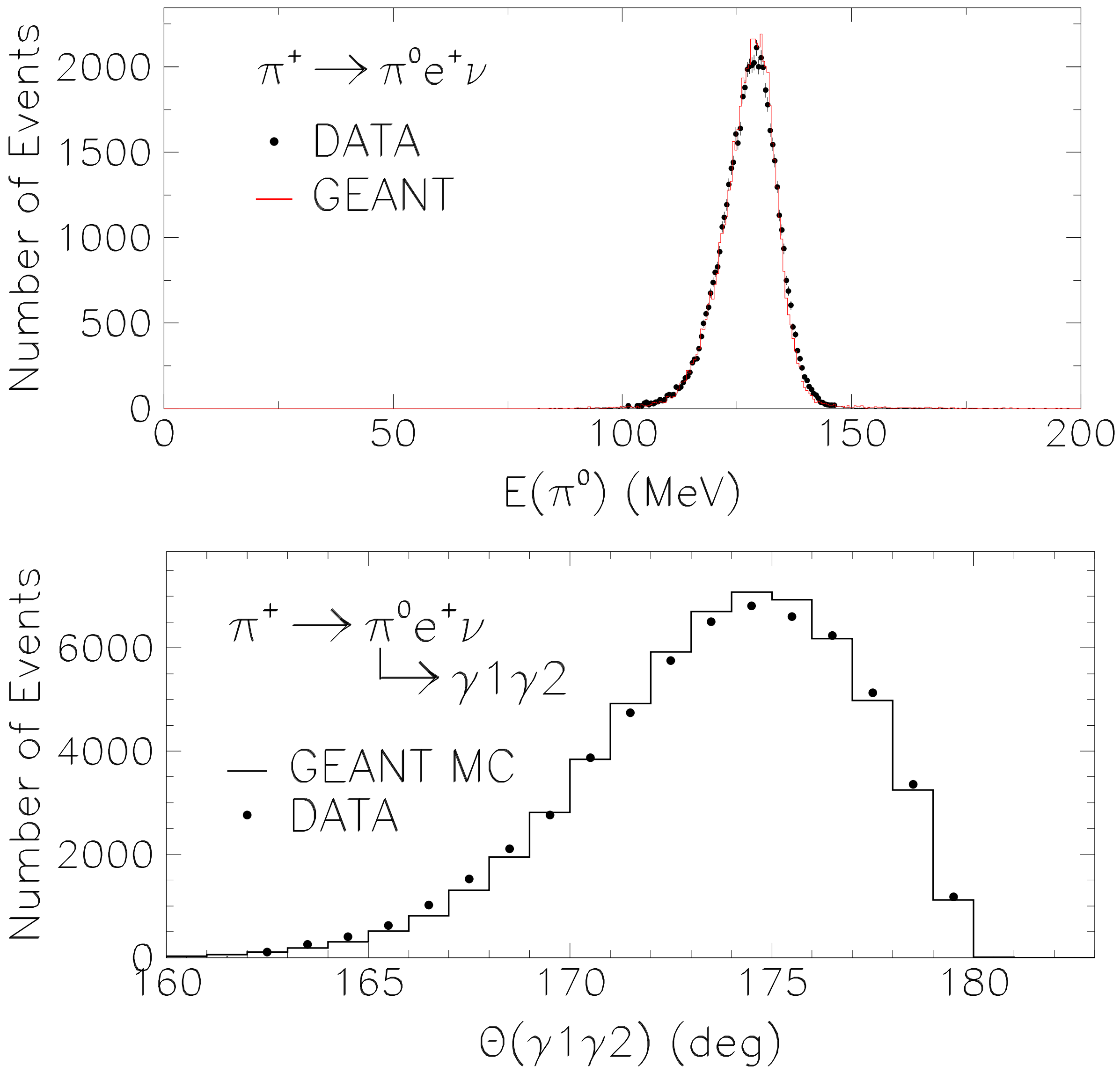
Accuracy: $\leq 1\,\%$	check CVC and rad. corrections
$\sim 0.5\,\%$	add to SAF & n_β input to V_{ud}
$< 0.3\,\%$	check for failure of CKM unitarity:

Extracting $|V_{ud}|$ from pion β decay is very lucrative.

The $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ decay



The $\pi^+ \to \pi^0 e^+ \nu_e$ decay



PIBETA Current Result for $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ Decay [PRL **93**, 181803 (2004)]

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

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

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

SM Prediction (PDG, 2004):

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

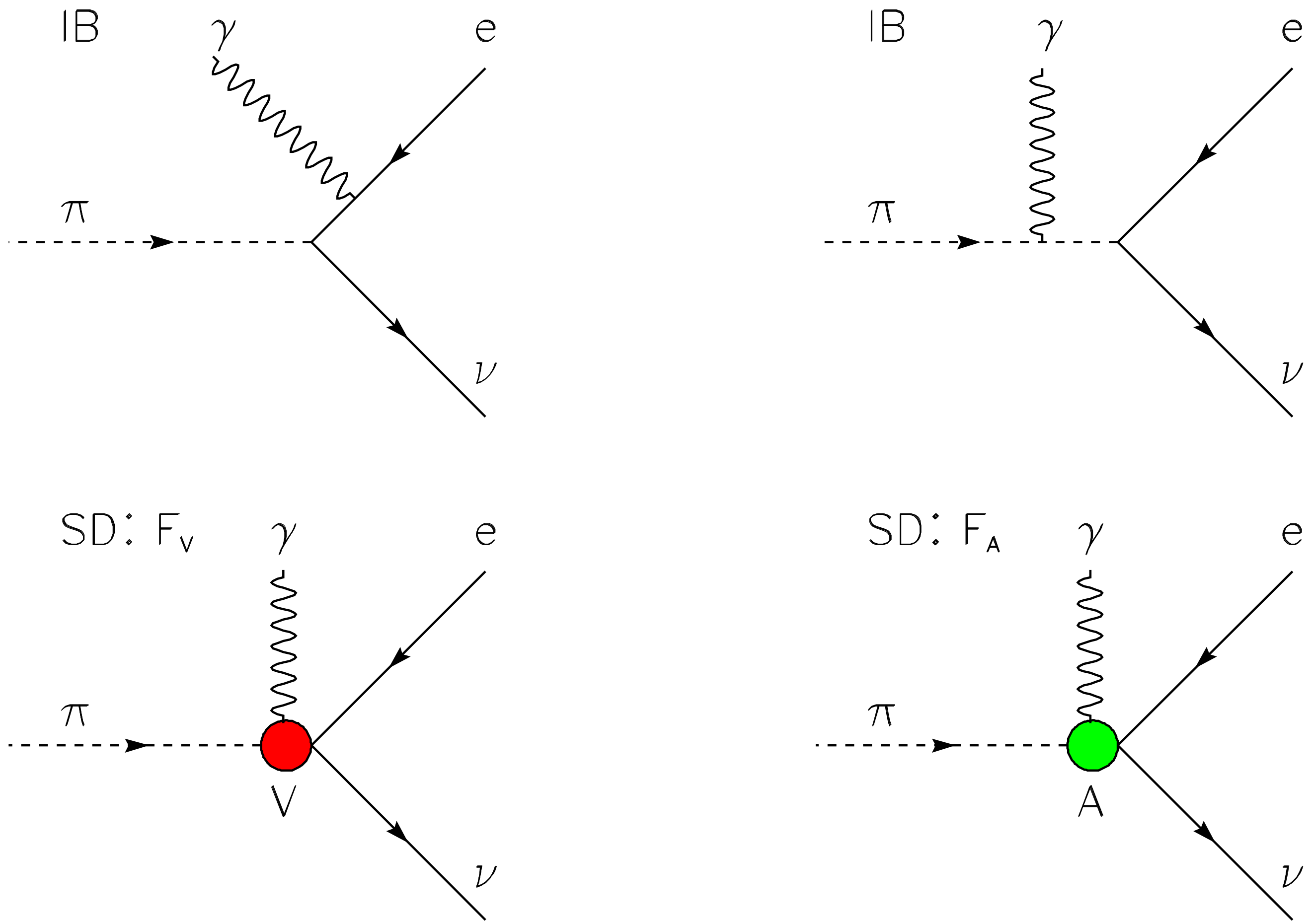
$$(1.005 - 1.007 \times 10^{-8} \qquad \text{excl. rad. corr.})$$

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

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

Radiative Pion Decay: $\pi^+ \longrightarrow e^+\nu_e\gamma$ $(\pi_{e2\gamma})$

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



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

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

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

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

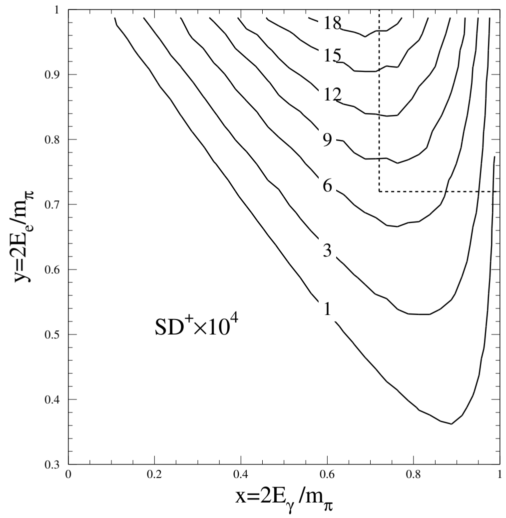
where IB, $SD^\pm$, $SD^\pm_{\text{int}}$ are analytical functions of
$x \equiv 2E_\gamma/m_{\pi^+}$ and $y \equiv 2E_e/m_{\pi^+}$

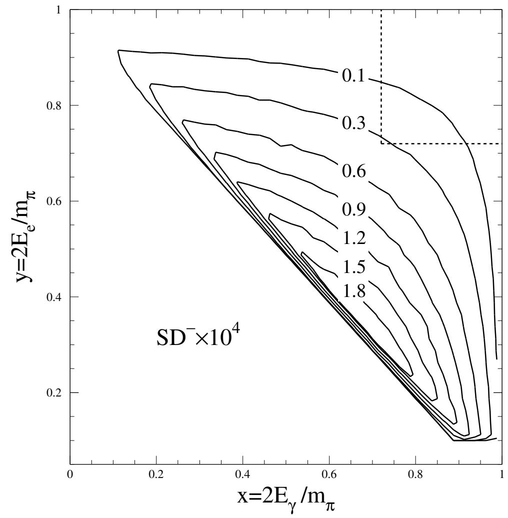
$F_A(a) = F_A(0)(1 + a\cdot(1-x)^2)$ is the axial-vector form factor

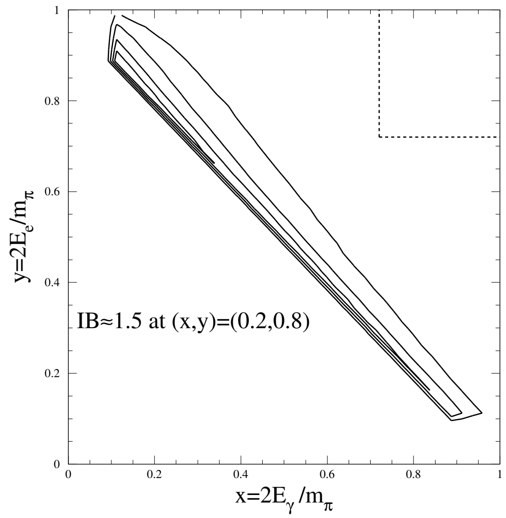
$F_V(a) = F_V(0)(1 + a\cdot(1-x)^2)$ is the vector form factor

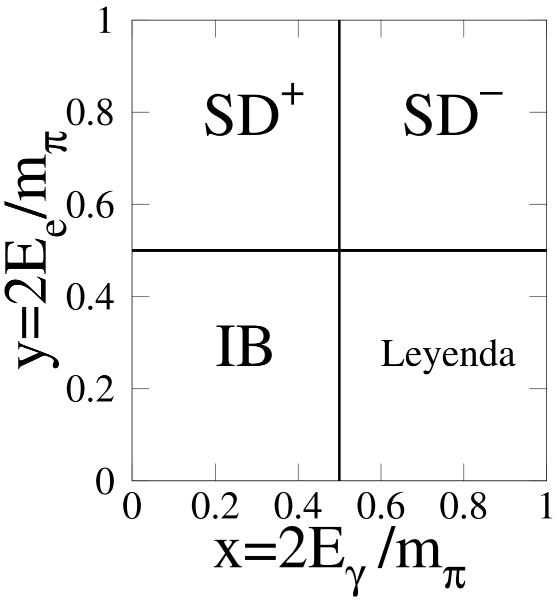
$$\gamma = F_A/F_V$$

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









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

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

[To resolve l_9 and l_{10} one needs

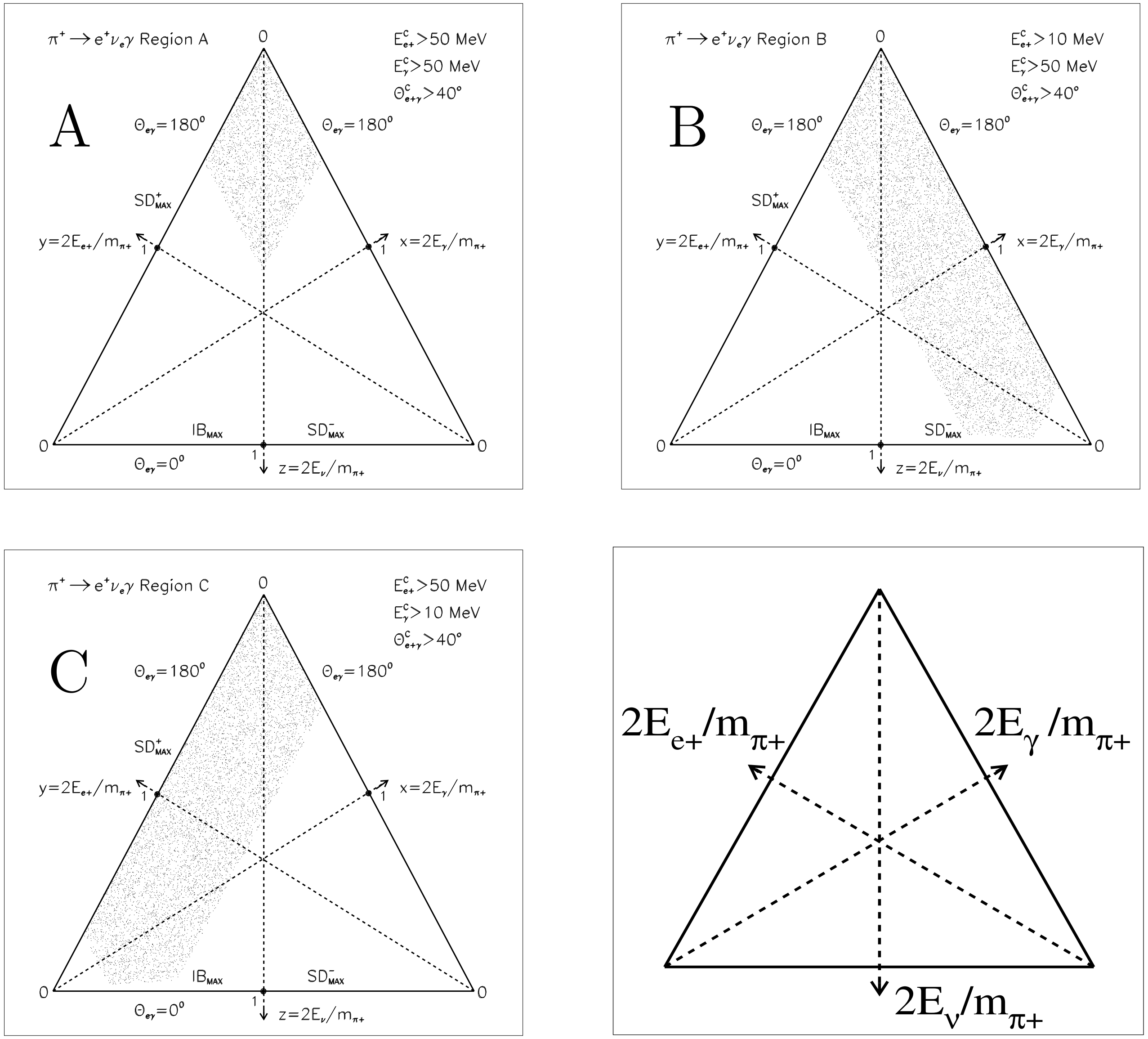
$$\frac{1}{6}\langle r_\pi^2 \rangle = \frac{2}{F_\pi^2} l_9^{\mathrm{r}} - \frac{1}{96\pi^2 F_\pi^2} \left(\ln \frac{m_\pi^2}{\mu^2} + \frac{1}{2} \ln \frac{m_K^2}{\mu^2} + \frac{3}{2} \right) \ ,$$

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

Available Data on Pion Form Factors

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

$F_A \times 10^4$	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)	



$\pi^+ \to e^+\nu_e\gamma$ Region A
A
$E^c_{e+}>50$ MeV
$E^c_\gamma>50$ MeV
$\Theta^c_{e+\gamma}>40^\circ$
$\Theta_{e\gamma}=180^\circ$
$\Theta_{e\gamma}=180^\circ$
SD^+_{MAX}
$y=2E_{e+}/m_{\pi+}$
$x=2E_\gamma/m_{\pi+}$
IB_{MAX}
SD^-_{MAX}
$\Theta_{e\gamma}=0^\circ$
$z=2E_\nu/m_{\pi+}$
$\pi^+ \to e^+\nu_e\gamma$ Region B
B
$E^c_{e+}>10$ MeV
$E^c_\gamma>50$ MeV
$\Theta^c_{e+\gamma}>40^\circ$
$\pi^+ \to e^+\nu_e\gamma$ Region C
C
$E^c_{e+}>50$ MeV
$E^c_\gamma>10$ MeV
$\Theta^c_{e+\gamma}>40^\circ$
$2E_{e+}/m_{\pi+}$
$2E_\gamma/m_{\pi+}$
$2E_\nu/m_{\pi+}$

$\pi^+ \rightarrow e^+\nu_e\gamma$: Data analyses 1999-2001

Results of the SM fit

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

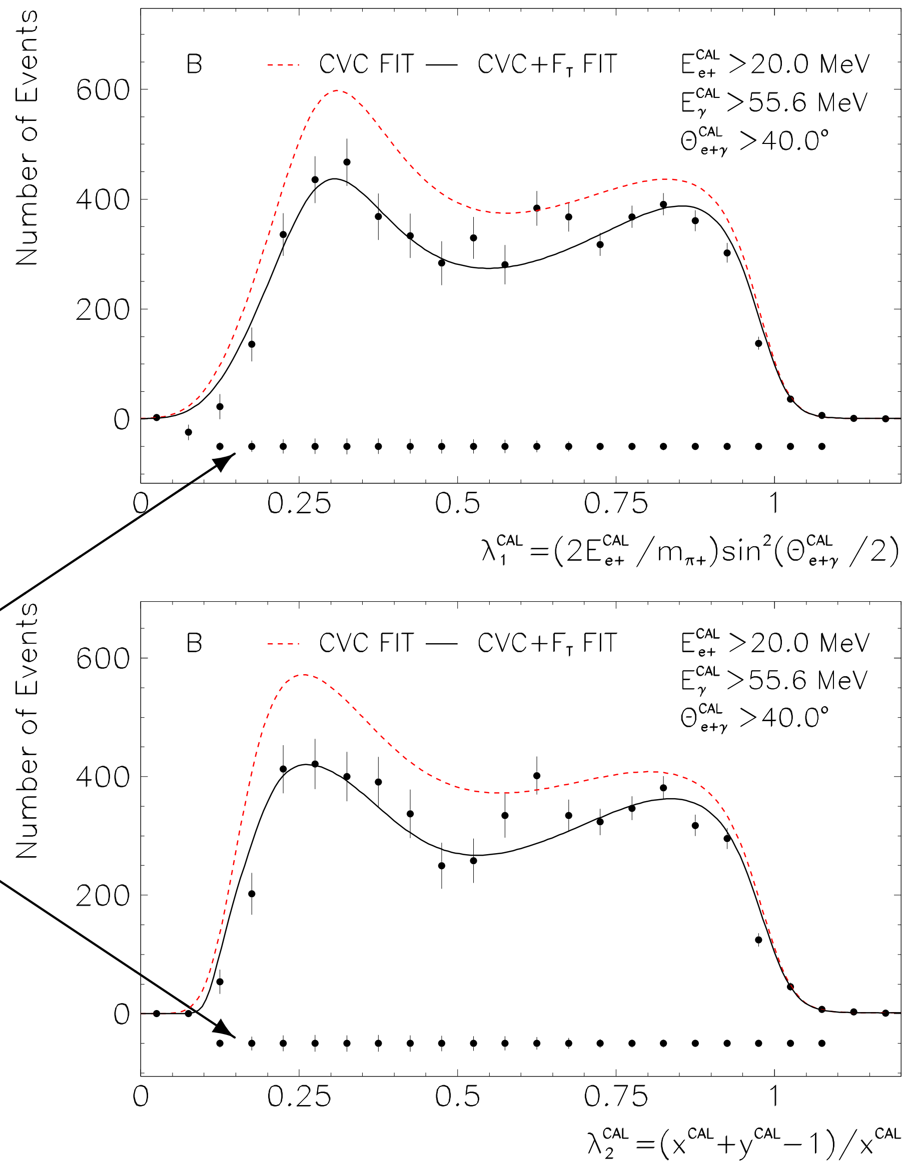
Best-fit $\pi \to e\nu\gamma$ branching ratios obtained with:
$F_V = 0.0259$ (fixed) and $F_A = 0.0115(4)$ (fit)
$\chi^2/\mathrm{d.o.f.} = 25.4$.
Radiative corrections are included in the calculations.

$E_{e^+}^{\min}$ (MeV)	$E_\gamma^{\min}$ (MeV)	$\theta_{e\gamma}^{\min}$	B_{exp} $(\times 10^{-8})$	B_{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)

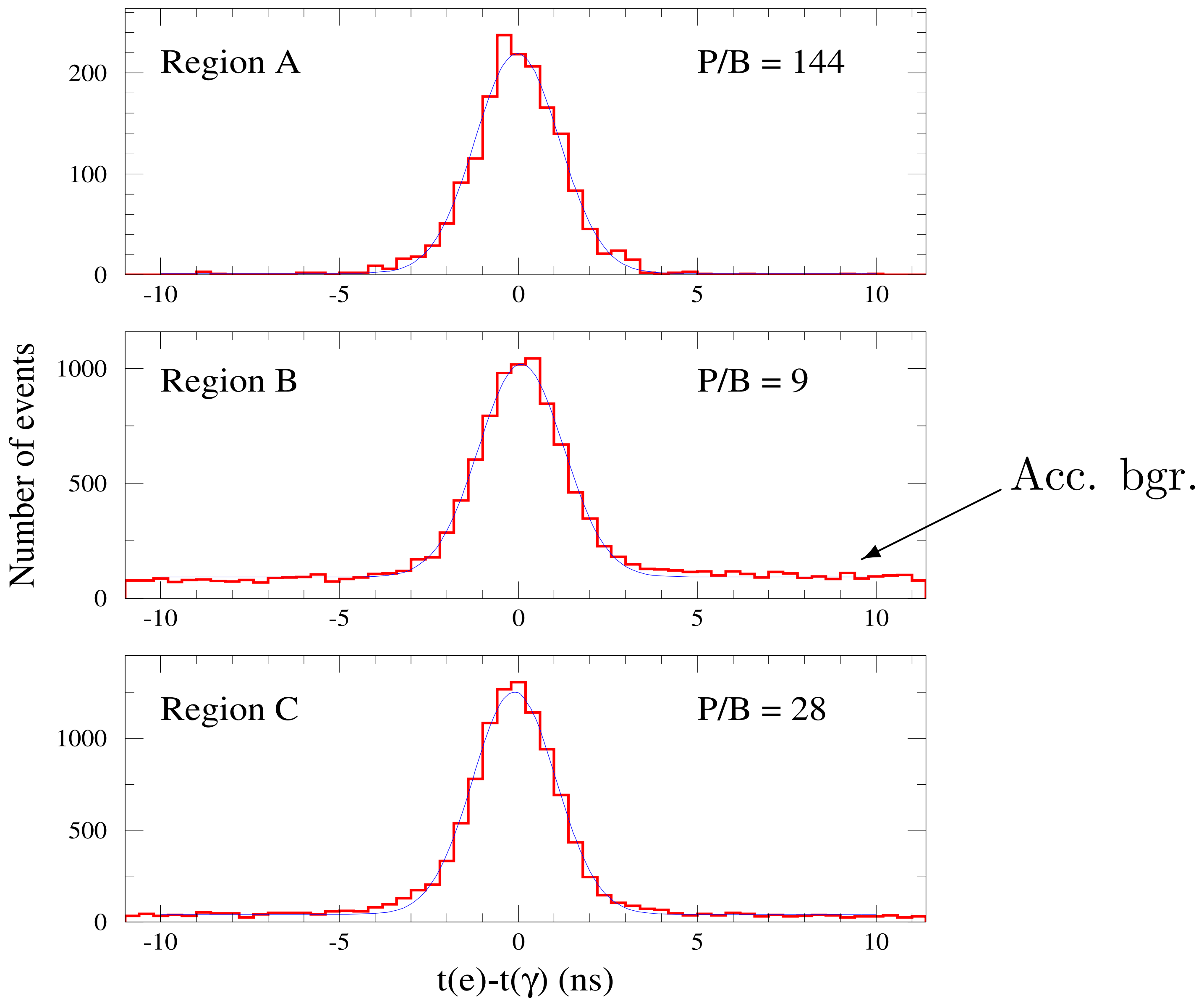
Region B:

global fits

projected uncertainties in 2004 run



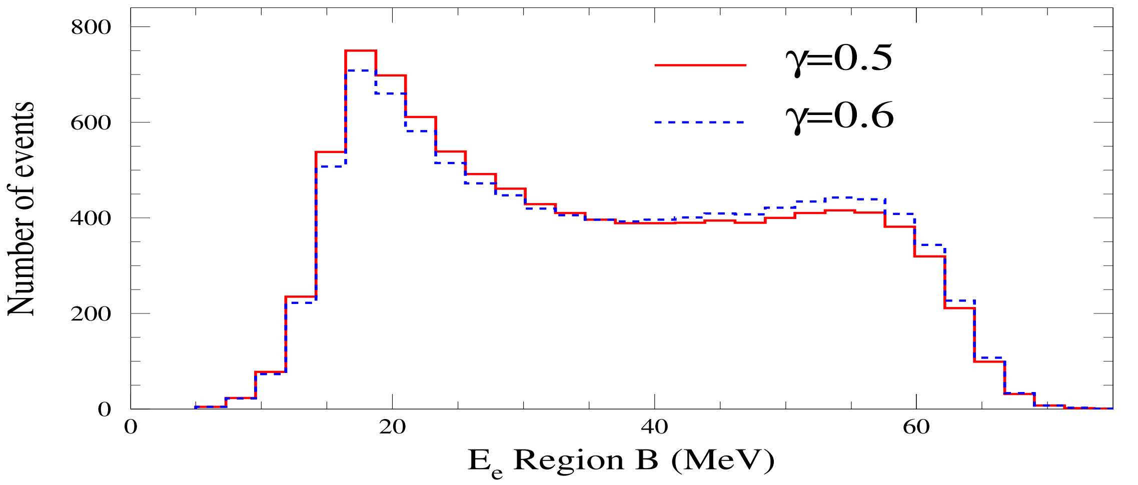
$\pi^+ \rightarrow e^+\nu_e\gamma$: **Data analyses 2004**

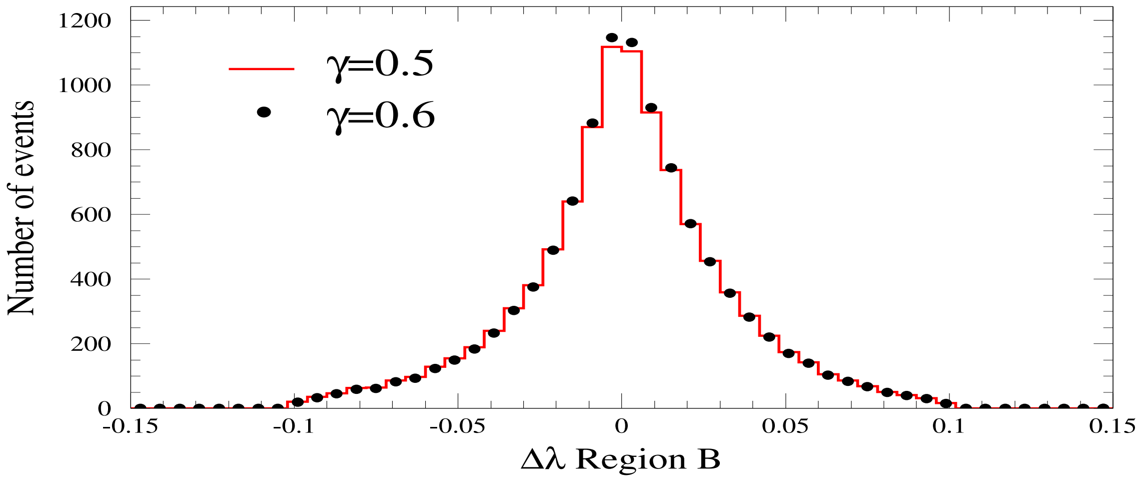


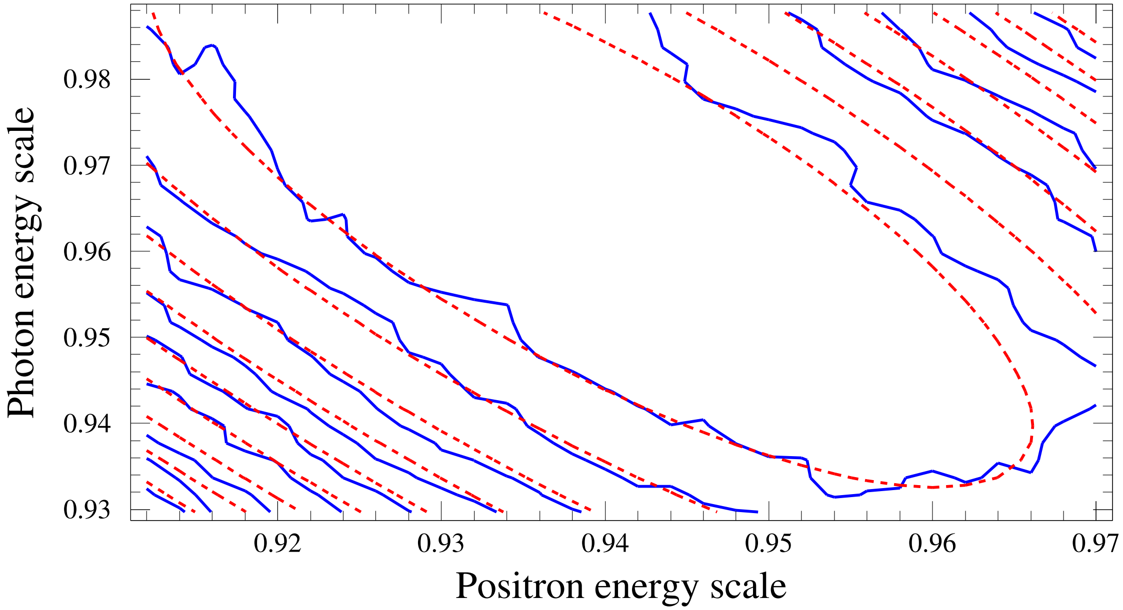
Region A
P/B = 144
Region B
P/B = 9
Region C
P/B = 28
Number of events
t(e)-t(γ) (ns)
Acc. bgr.

Adjusting Energy Scales

$$\Delta\lambda = y \cdot \sin^2(\theta_{e\gamma}/2) - (x + y - 1)/x$$



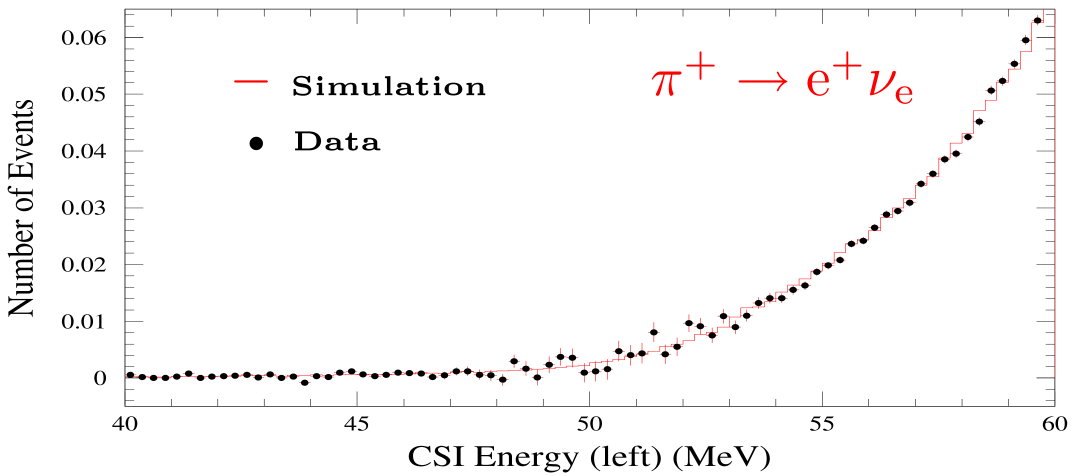


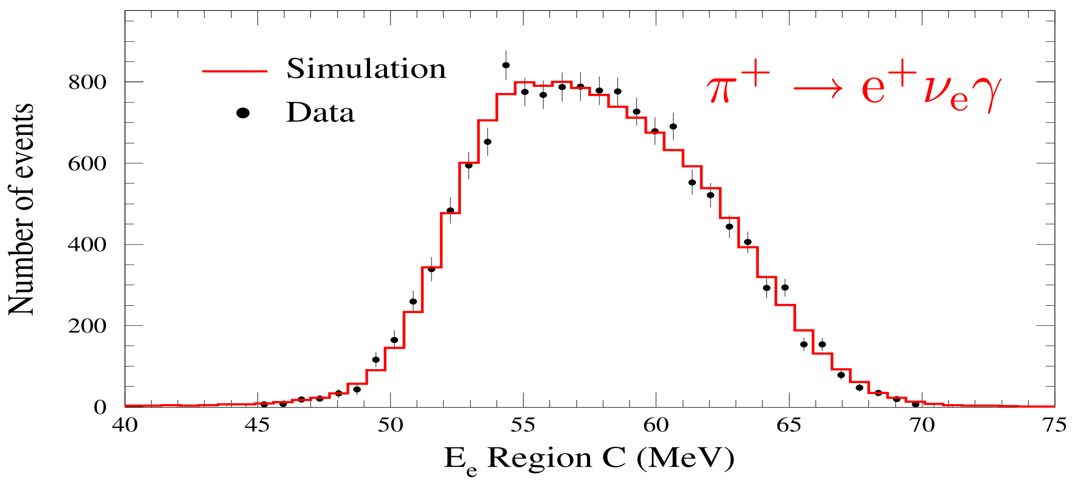


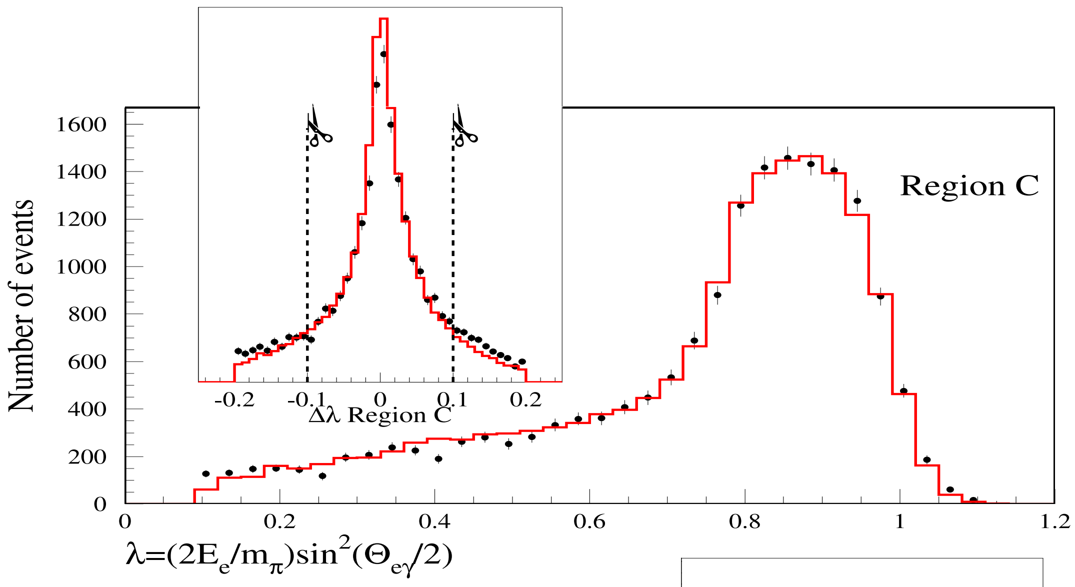
Summary of the Energy Scales and Cross-checks

Variable	π_{e2}	π_{β}	$\Delta\lambda$
e Energy Scale	0.941 ± 0.002	n/a	0.941 ± 0.002
γ Energy Scale	n/a	0.958 ± 0.010	0.965 ± 0.001

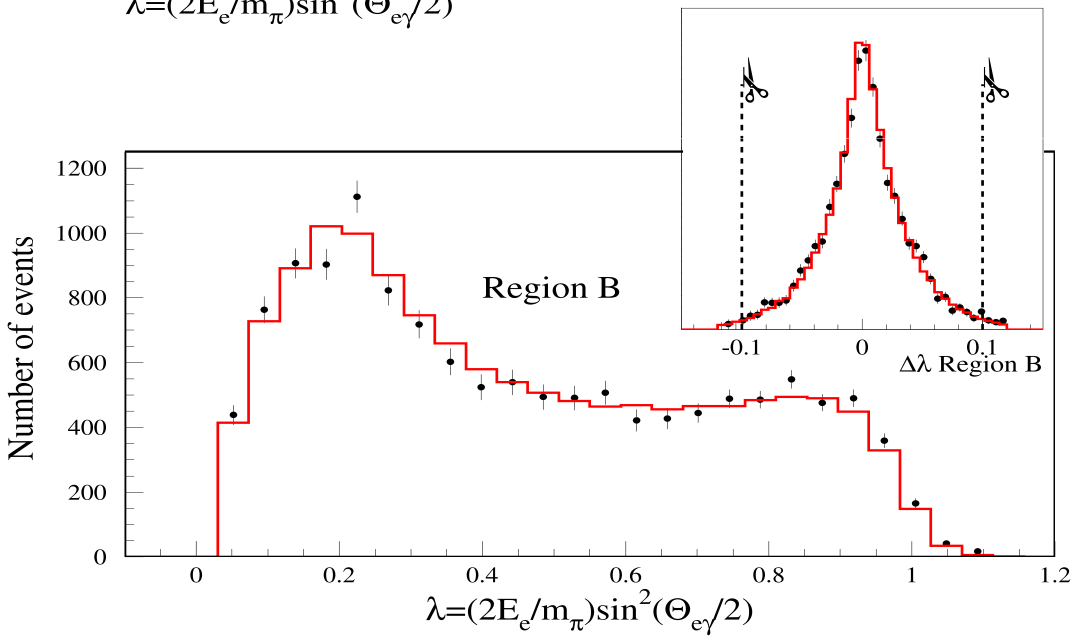
Simulating Trigger Threshold







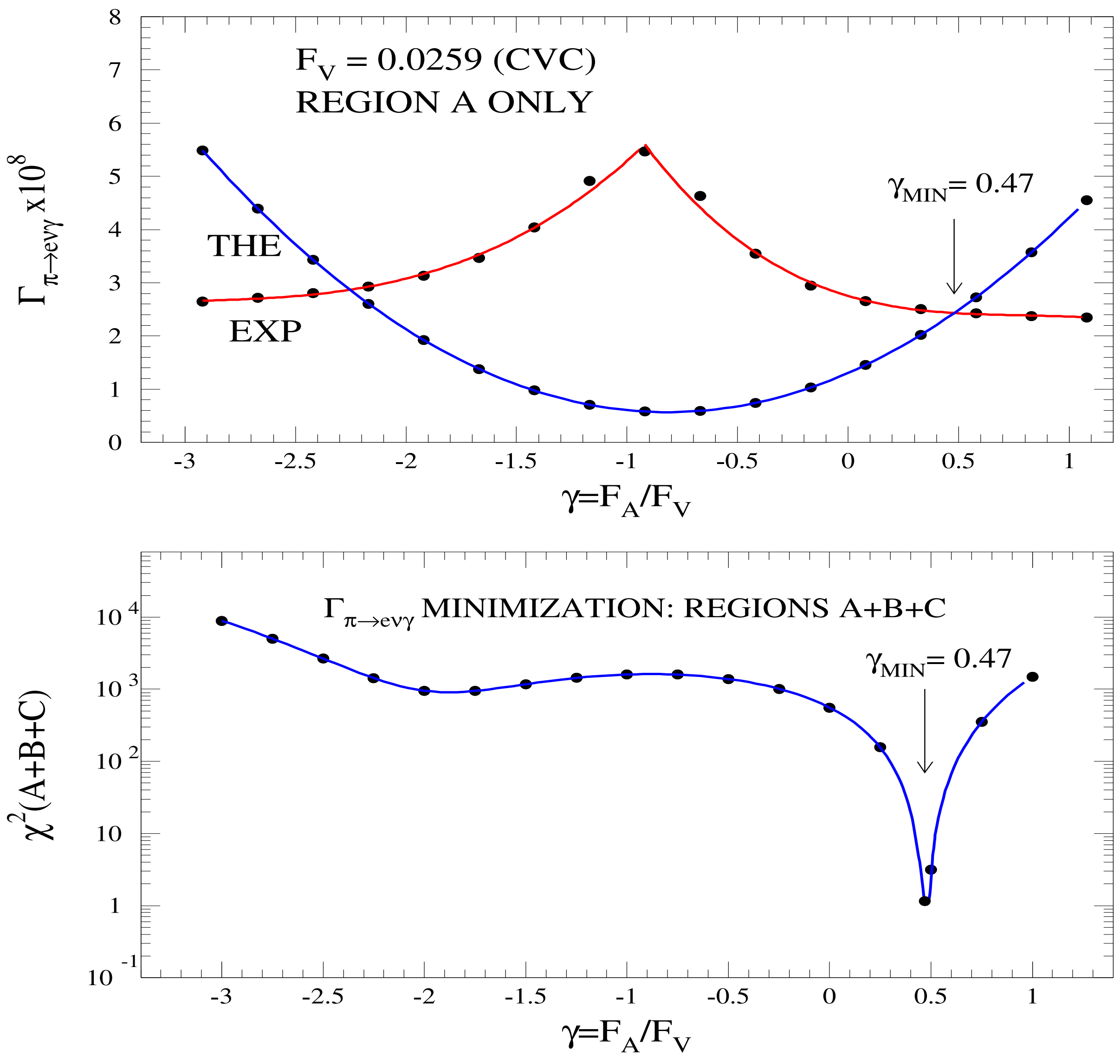
Number of events
Region C
Δλ Region C
λ=(2E_e/m_π)sin²(Θ_eγ/2)



Number of events
Region B
Δλ Region B
λ=(2E_e/m_π)sin²(Θ_eγ/2)

Main Systematic Uncertainties

Name	Region	Value (%)
Threshold	A	0.6
	B	0.2
	C	1.9
E-Scale	A	0.6
	B	0.4
	C	0.7
$\pi\beta$	A	0.2
	B	0.1
	C	0.1
Zero−Time	A	0.03
	B	0.05
	C	0.07


$F_V = 0.0259$ (CVC)
REGION A ONLY
THE
EXP
$\gamma_{MIN} = 0.47$
$\Gamma_{\pi\to e\nu\gamma} \times 10^8$
$\gamma = F_A/F_V$
$\Gamma_{\pi\to e\nu\gamma}$ MINIMIZATION: REGIONS A+B+C
$\gamma_{MIN} = 0.47$
χ^2(A+B+C)
$\gamma = F_A/F_V$

Results of 2004 Data Analyses

$$F_A = 0.0118 \pm 0.0003$$

$$F_V = 0.0262 \pm 0.0015$$

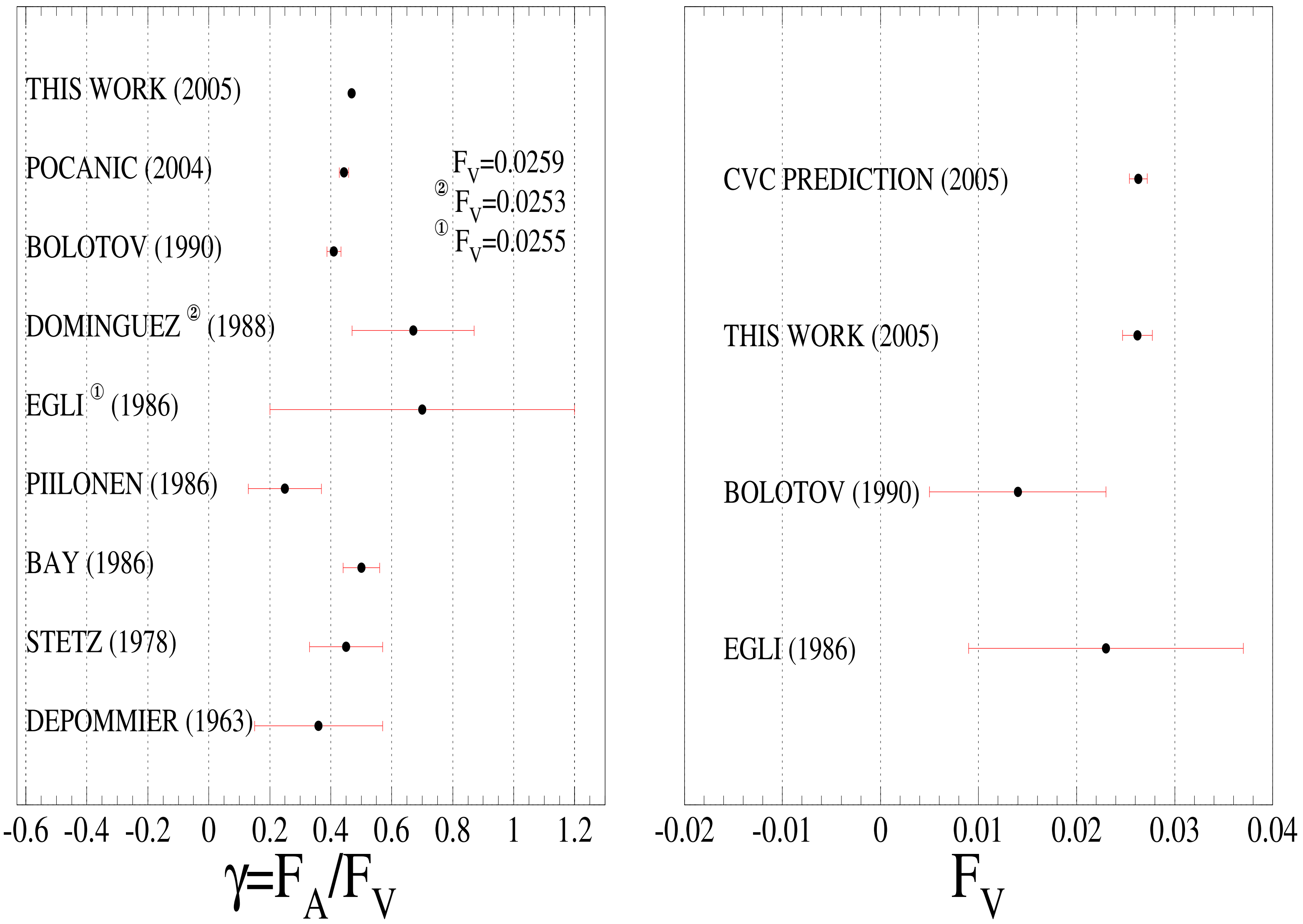
$$a = 0.241 \pm 0.093$$

$$|F_T| < 5.1 \cdot 10^{-4} \quad 90\% \text{ CL}$$

$$\alpha_E = 2.81 \pm 0.07$$

Region	Theoretical $BR(\times 10^8)$	Experimental $BR(\times 10^8)$	Events
A	2.641 ± 0.001	2.655 ± 0.058	2 970
B	14.49 ± 0.01	14.59 ± 0.26	8 895
C	37.90 ± 0.03	37.95 ± 0.60	11 352

Results and Comparison



The Radiative Muon Decay: $\mu^+ \longrightarrow e^+\nu\overline{\nu}\gamma$

Theoretical Description: $\mu^+ \rightarrow e^+\nu\overline{\nu}\gamma$ Decay

Muon decay is **THE** test of the weak interaction of the form

$$M = 4\frac{G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} \sum_{\alpha,\beta=R,L} g^{\gamma}_{\alpha\beta} \left\langle \overline{e}_\alpha | \hat{O}^\gamma | (\nu_e)_n \right\rangle \left\langle \overline{\nu_\mu}_m | \hat{O}_\gamma | \mu_\beta \right\rangle ,$$

where $g^{\gamma}_{\alpha\beta}$ proportional to the relative probability that a β-handed muon will decay into an α-handed electron via the interaction $\hat{O}^\gamma$

SM postulates

$$g^V_{LL} = 1$$

and all other coupling constants vanish.

Theoretical Description: $\mu^+ \to e^+\nu\overline{\nu}\gamma$ Decay

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

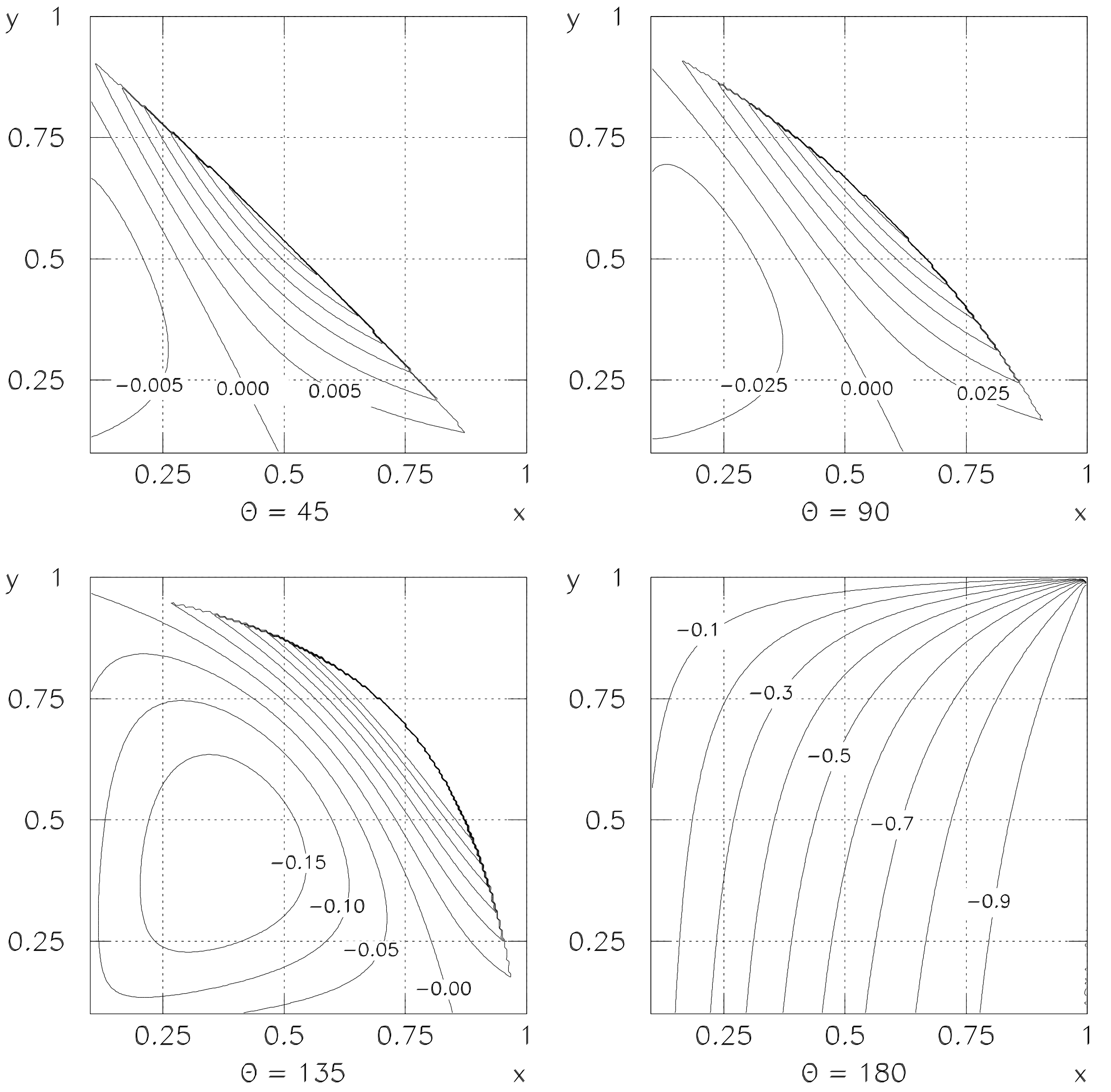
where f_is are polynomials in

$x = 2E_{e^+}/m_\mu$, $y = 2E_\gamma/m_\mu$, $cos\theta = \hat{p}_{e^+} \cdot \hat{p}_\gamma$ and $\Delta = 1 - \beta cos\theta$ and

$$\rho = \frac{3}{4} - \frac{3}{4}\left[|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + \mathrm{Re}(g^S_{RL} g^{T*}_{RL} + g^S_{LR} g^{T*}_{LR})\right]$$

$$\overline{\eta} = \left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + \frac{1}{8}\left(|g^S_{LR} + 2g^T_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2\right) + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right).$$

$\mu^+ \to e^+\nu\bar{\nu}\gamma$: f_2/f_1 for various values of θ



Available Data on Michel parameters

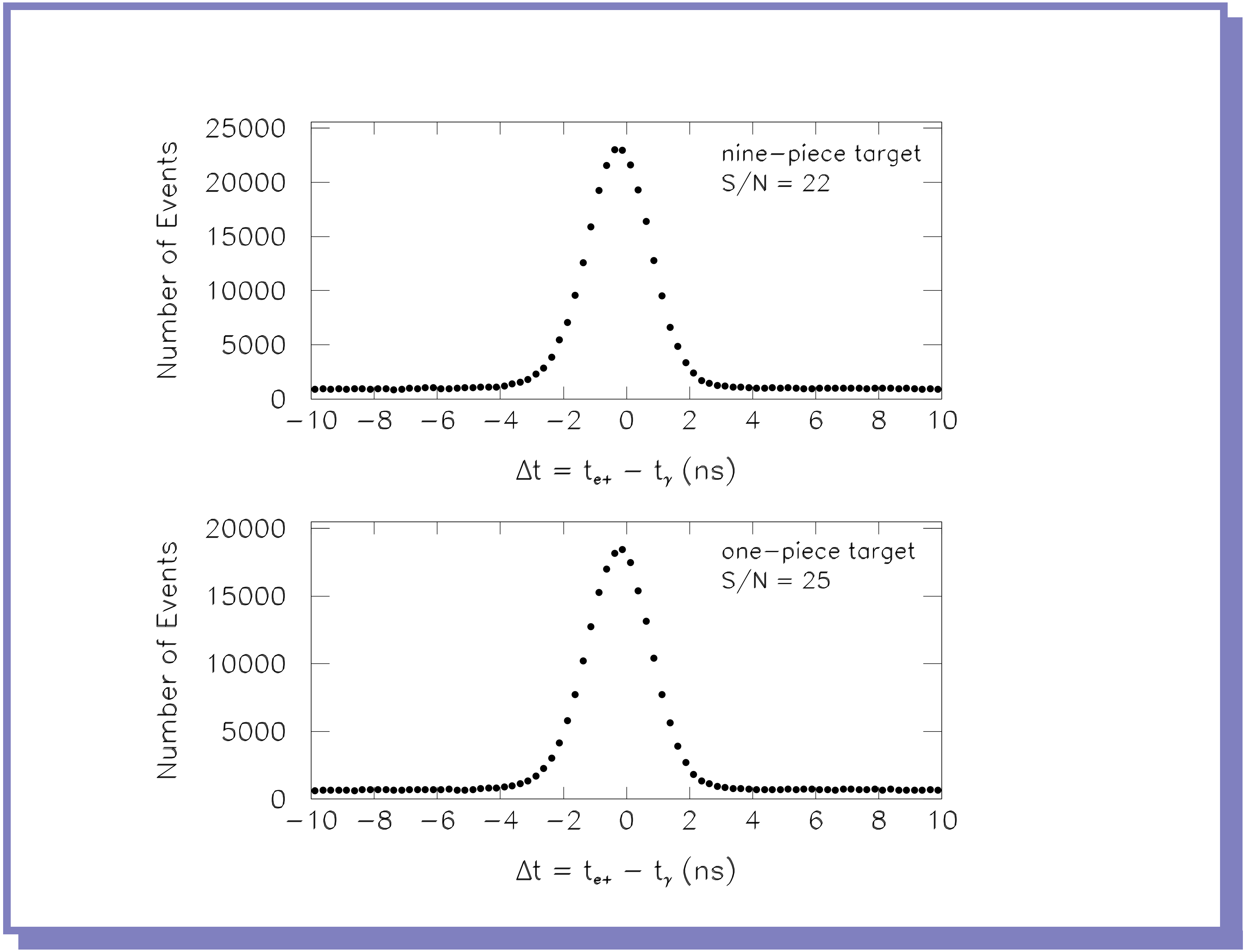
$$\rho \stackrel{\mathrm{SM}}{=} 3/4 \ , \ \overline{\eta} \stackrel{\mathrm{SM}}{=} 0.$$

ρ	reference
0.7508 ± 0.0011	Musser et al. (2005) (N/I)
0.7518 ± 0.0026	Derenzo et al. (1969)
0.7518 ± 0.0026	world average (PDG 2005)

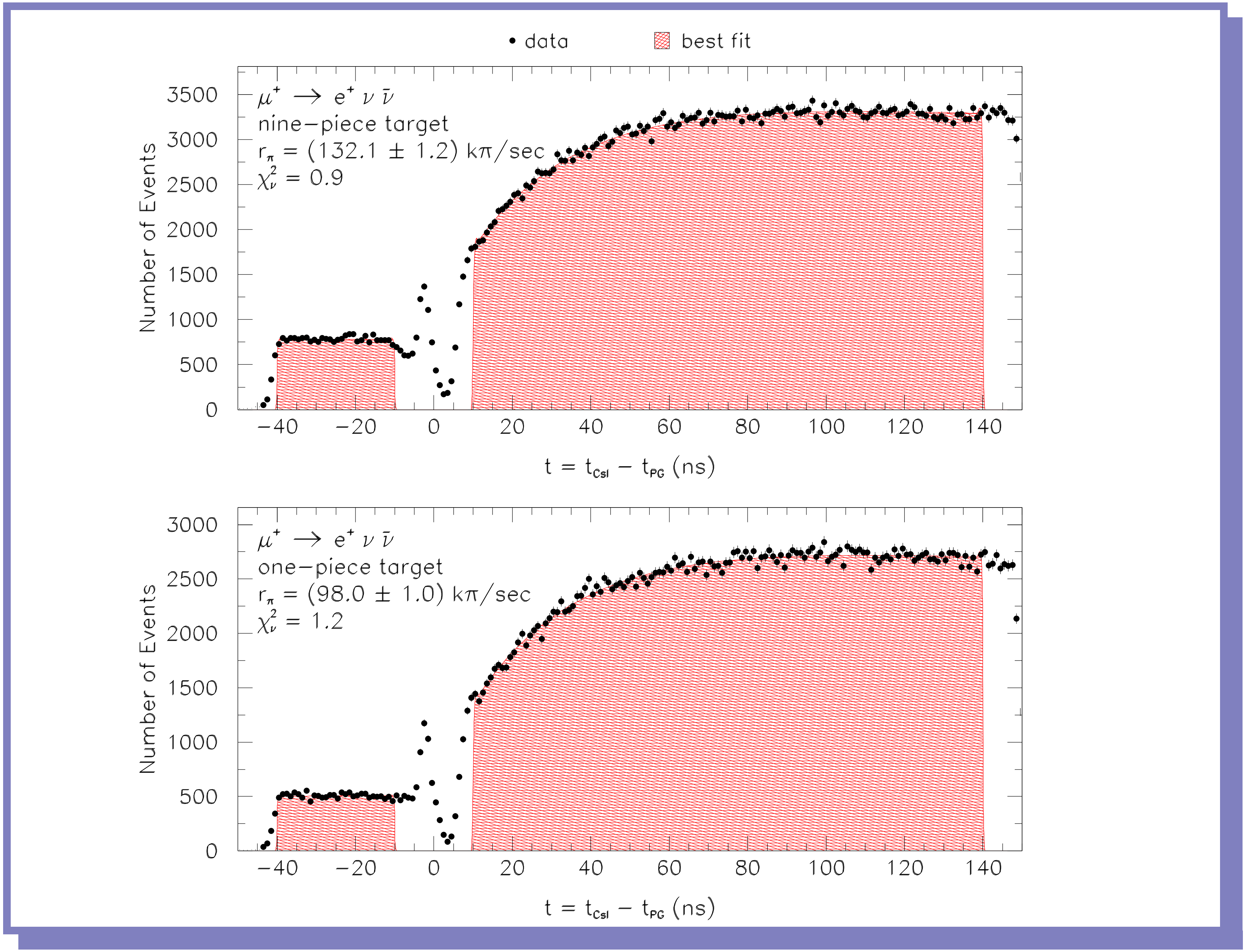
$\overline{\eta}$	reference
-0.014 ± 0.090	Eichenberger et al. (1984)
0.09 ± 0.14	Bogart et. al. (1967)
0.02 ± 0.08	world average (PDG 2005)

Preliminary Data Analysis: $\boldsymbol{\mu^+ \rightarrow \mathrm{e}^+ \nu \bar{\nu} \gamma}$

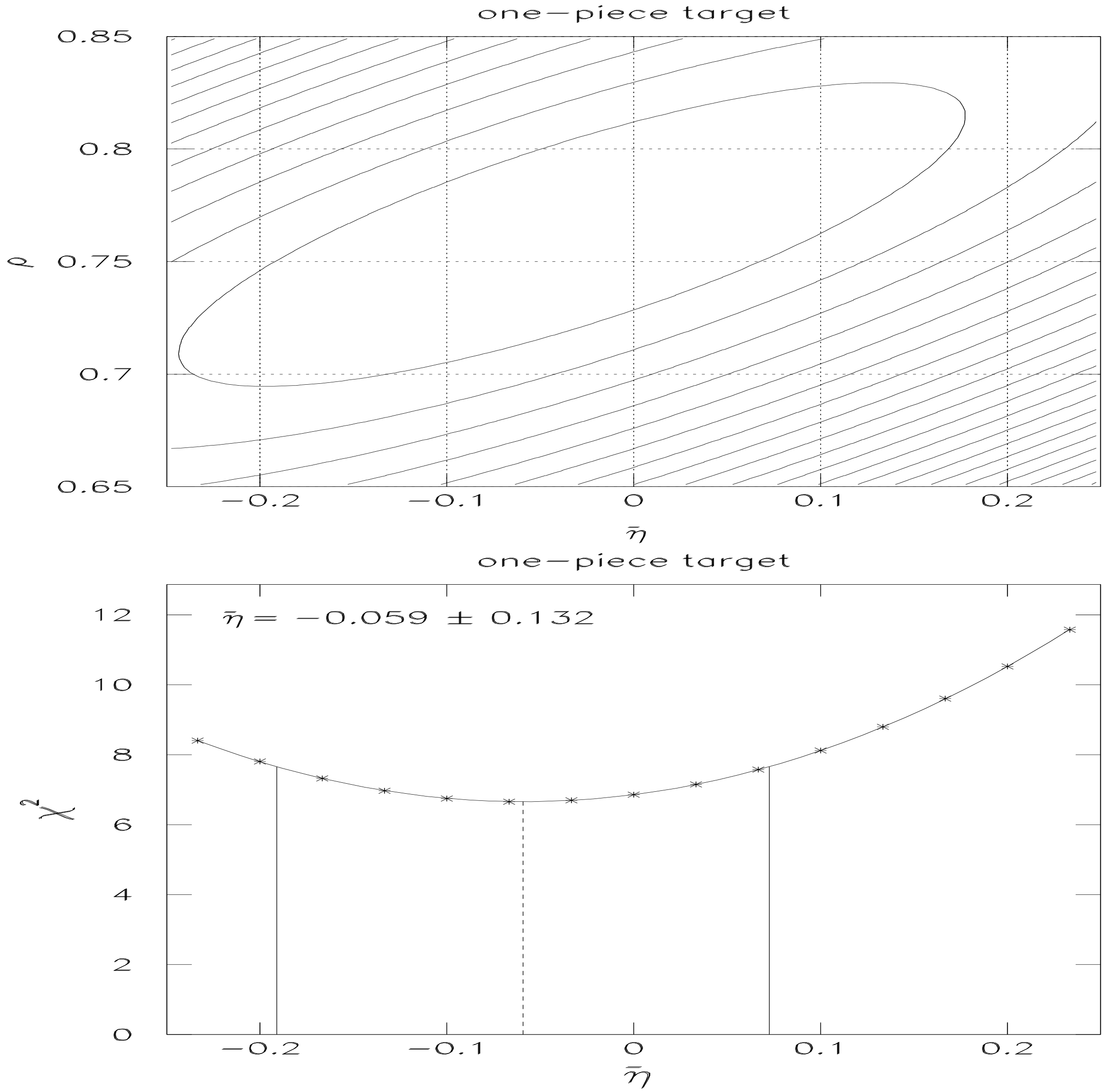
[B. VanDevender]



nine−piece target
S/N = 22
Number of Events
25000
20000
15000
10000
5000
0
−10 −8 −6 −4 −2 0 2 4 6 8 10
Δt = t_e+ − t_γ (ns)
one−piece target
S/N = 25
Number of Events
20000
15000
10000
5000
0
−10 −8 −6 −4 −2 0 2 4 6 8 10
Δt = t_e+ − t_γ (ns)



• data
best fit
$\mu^+ \rightarrow e^+ \nu \bar{\nu}$
nine−piece target
r_π = (132.1 ± 1.2) kπ/sec
χ^2_ν = 0.9
Number of Events
t = t_{CsI} − t_{PG} (ns)
$\mu^+ \rightarrow e^+ \nu \bar{\nu}$
one−piece target
r_π = (98.0 ± 1.0) kπ/sec
χ^2_ν = 1.2
Number of Events
t = t_{CsI} − t_{PG} (ns)


one−piece target
0.85
0.8
0.75
0.7
0.65
ρ
−0.2
−0.1
0
0.1
0.2
$\bar{\eta}$
one−piece target
$\bar{\eta} = -0.059 \pm 0.132$
12
10
8
6
4
2
0
χ^2
−0.2
−0.1
0
0.1
0.2
$\bar{\eta}$

Results of 2004 Data Analyses

$$\rho = 0.758 \pm 0.005$$

$$\overline{\eta} = 0.015 \pm 0.088$$

$$\overline{\eta} \; < \; 0.096 \quad 68\% \text{ CL}$$

Region	Theor. $BR(\times 10^3)$	Exper. $BR(\times 10^3)$	Events
$E_\gamma^{\rm th} > 10$ MeV $\theta_{\rm e\gamma}^{\rm th} > 30^{\rm o}$	4.30 ± 0.01	4.40 ± 0.09	$424\,162 \pm 704$

Conclusions

1. In recent years the PIBETA collaboration has:
   - increased the world data set on π_β, $\pi_{e2\gamma}$, $\mu \to e\nu\bar{\nu}\gamma$ decays by ~ 2 orders of magnitude or more,
   - increased the precision of BR's of π_β, $\pi_{e2\gamma}$ decays $4-7\times$,
   - quantified and will soon resolve the $\pi_{e2\gamma}$ anomaly,
2. Other forthcoming developments:
   - new values of the μ decay parameters $\bar{\eta}$ and ρ from the $\mu \to e\nu\bar{\nu}\gamma$ data,
   - LoI for a π_{e2} expt: test run '05; aim for a full proposal in '06.
3. Interesting opportunities in pion rare decays remain open for a future high intensity machine (incl. Dalitz versions of above).

http://pibeta.phys.virginia.edu

http://pibeta.psi.ch