PIBETA: A new precise measurement of rare pion and muon decays

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- motivation
- about the experimental method
- our working results
  - pion beta decay: $\pi^+ \to \pi^0 e^+ \nu$
  - radiative pion decay: $\pi^+ \to e^+ \nu \gamma$
- further plans

JLAB, 2 May 2003

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PIBETA Experiment: MOTIVATION

Provide precision tests of Standard Model and QCD predictions:

- $\pi^+ \to \pi^0 e^+ \nu_e$ – main goal
  - SM tests from 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, Majoran, ...

VECTOR CURRENT CONSERVATION

(a) Leptonic current (as in μ decay):

$$l^\alpha(x) = \bar{e}(x)\gamma^\alpha(1-\gamma_5)\nu_e(x)$$

$$\langle e|l^\alpha|\nu_e\rangle \to \bar{u}_e\gamma^\alpha(1-\gamma_5)u_\nu \qquad (V-A \text{ form})$$

(b) Hadronic current (as in $n \to pe\bar{\nu}$):

$$\langle p|h^\alpha|n\rangle \to \bar{u}_p\gamma^\alpha(G_V - G_A\gamma_5)u_\nu$$

with $G_V \simeq 1$ and $G_A \simeq 1$. Puzzling!!
Large strong correction expected!

1956 Gerstein + Zeldovich	formulated the
1958 Feynman + Gell-Mann	CVC hypothesis

Analogy with electric charge: $Q(p) \equiv Q(e)$, i.e.,

$$Q(\text{bare } p) \equiv Q(\text{screened } p)$$

due to exact conservation of electric charge.

Cabibbo Universality

Cabibbo (1963):

$$G_V = G_\mu \cos\theta_{\rm C} (= G_\mu V_{ud}) \quad \cos\theta_{\rm C} \simeq 0.97$$

weak quark mixing: d' $= \cos\theta_{\rm C}$ d $+ \sin\theta_{\rm C}$ s.

With 3 generations, Cabibbo–Kobayashi–Masakawa matrix (1973):

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \longrightarrow \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1 \ .$$

Experimental limits on V_{ud} have come from:

(a) superallowed Fermi nuclear β decays,

(b) neutron β decay.

These have disagreed in the past.

Pure vector weak (Fermi β) decays

$$A(J^\pi) \rightarrow B(J^\pi) + e + \bar{\nu}$$

with $J(e + \bar{\nu}) = 0$, i.e., $\vec{S}(e) = -\vec{S}(\nu)$.

Guaranteed when $J^\pi(A) = J^\pi(B) = 0^+$ or 0^-.
In nuclei $0^+ \rightarrow 0^+$ are called superallowed β transitions.

No direct axial vector contribution, only from "loop corrections".

Neutron decay: $n(\frac{1}{2}^+) \rightarrow p(\frac{1}{2}^+) + e^- + \bar{\nu}_e$

has both V and A transition amplitudes.

Status of CKM Unitarity

$|V_{us}| \simeq 0.2196 \pm 0.0026$ from K_{e3} decays.
$|V_{ub}| \simeq 0.0036 \pm 0.0007$ from B decays.

(a) Superallowed Fermi nuclear β decays

Longstanding discrepancies between Ormand & Brown and Towner & Hardy ft values "reconciled" in 1990:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9962 \pm 0.0016,$$

or $1 - 2.4\sigma$.

(b) Neutron β decay has varied considerably:

$$\sum_{i=1}^{3} |V_{ui}|^2 = 1.0096 \pm 0.0044, \text{ or } 1 + 2.3\sigma,$$

[after Erozolimskiĭ et al. (1990); since retracted]

$$\sum_{i=1}^{3} |V_{ui}|^2 = 0.9917 \pm 0.0028, \text{ or } 1 - 3.0\sigma.$$

[Abele et al (2002); at odds w/world data set]

(c) Pion β decay – this work

Pion Beta Decay:

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

Pure vector transition: $0^- \to 0^-$

Theoretical decay rate at tree level:

$$\begin{aligned} \frac{1}{\tau_0} &= \frac{G_F^2 |V_{ud}|^2}{30\pi^3} \left(1 - \frac{\Delta}{2M_+}\right)^3 \Delta^5 f(\epsilon, \Delta) \\ &= 0.40692\,(22) |V_{ud}|^2\,(\mathrm{s}^{-1}) \ . \end{aligned}$$

With radiative and loop corrections we get:

$$\frac{1}{\tau} = \frac{1}{\tau_0}(1+\delta) \ ,$$

so that the branching ratio is

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

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

V. Cirigliano, M. Knecht, H. Neufeld and H. Pichl, hep-ph/0209226

- χPT with e-m terms up to $\mathcal{O}(e^2p^2)$
- theoretical uncertainty of 5×10^{-4} in extracting $|V_{ud}|$ from BR$\left(\pi_{e3(\gamma)}\right)$.

Experimental accuracy of the pion beta decay rate

Best result published to date:

$$BR(\pi^+ \to \pi^0 e^+ \nu) = (1.026 \pm 0.039) \times 10^{-8} \ ,$$

i.e., about 4 % [McFarlane et al. (1985)].

Accuracy	Constraints or cross-checks on
$\leq 1\,\%$	CVC and radiative corrections
$\sim 0.5\,\%$	Add to SAF & $n\beta$ input to V_{ud}
$< 0.3\,\%$	Failure of CKM unitarity (?):
	◦ $4^{\rm th}$ generation coupling
	◦ $m_{Z'}$
	◦ Λ of compositeness
	◦ SUSY viol. of q-l universality
	◦ signal of a smaller G_F (ν osc.)

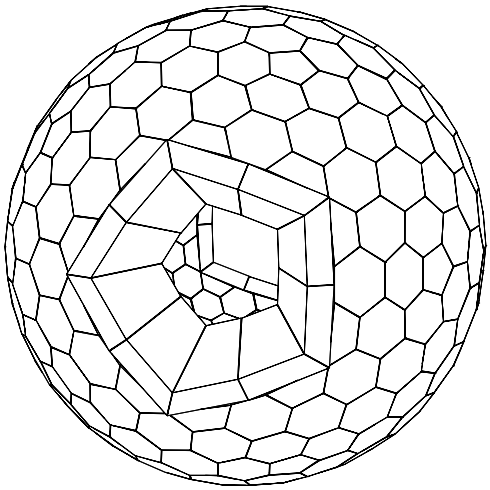
Design of the Experiment

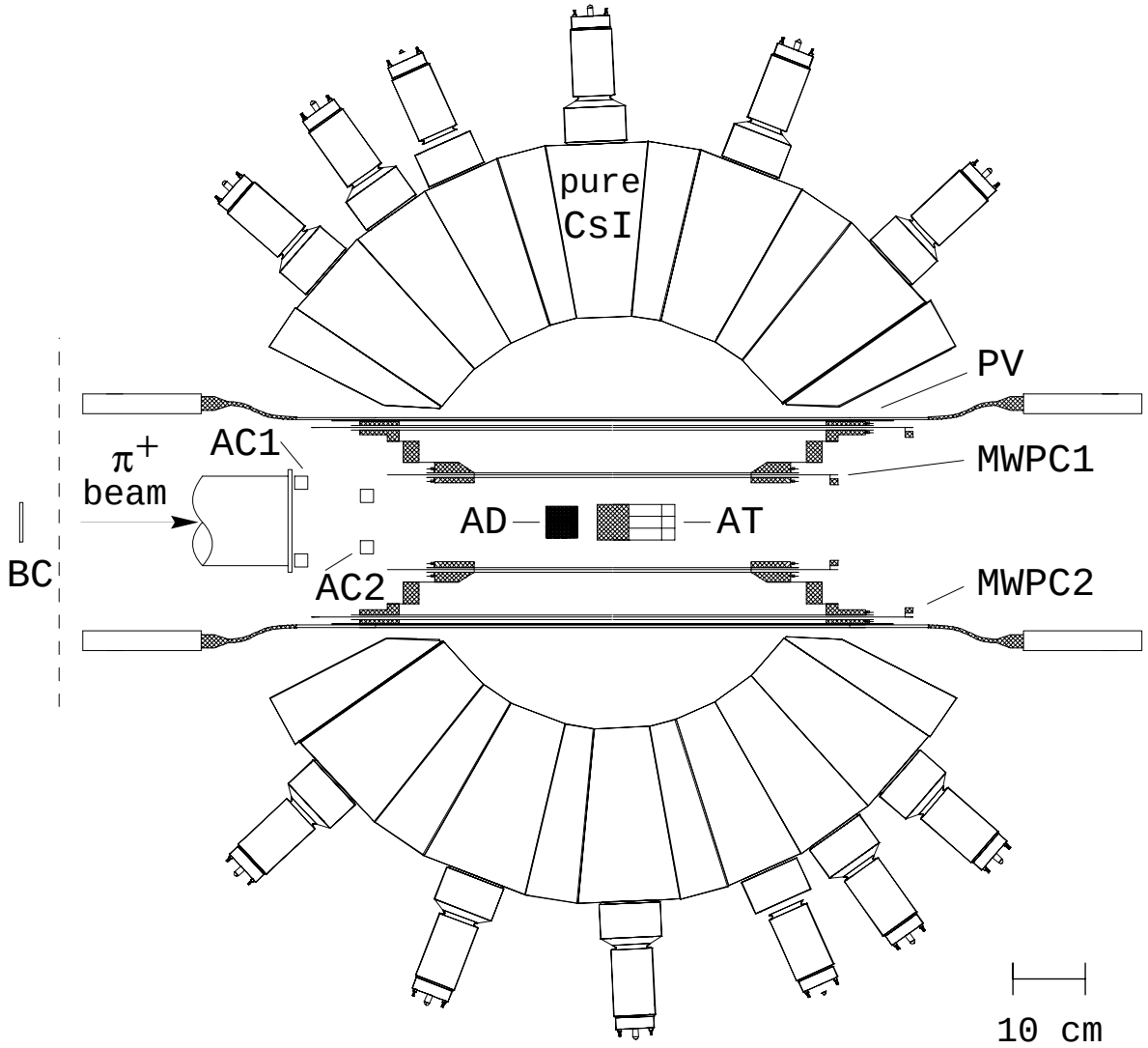
Pion and Muon Decays in the PIBETA Experiment

$\pi^+ \to$	$\mu^+\nu$	(1.0),	
	$\mu^+\nu\gamma$	$(\sim 2.0 \times 10^{-4})$	
	$\mathrm{e}^+\nu$	$(\sim 1.2 \times 10^{-4})$	normalize to
	$\mathrm{e}^+\nu\gamma$	$(\sim 5.6 \times 10^{-8})$	measure
	$\pi^0\mathrm{e}^+\nu$	$(\sim 1.0 \times 10^{-8})$	measure
$\pi^0 \to$	$\gamma\gamma$	(~ 0.9880)	measure
	$\mathrm{e}^+\mathrm{e}^-\gamma$	$(\sim 1.2 \times 10^{-2})$	measure
	$\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$	$(\sim 3.1 \times 10^{-5})$	
	$\mathrm{e}^+\mathrm{e}^-$	$(\sim 6.2 \times 10^{-8})$	
$\mu^+ \to$	$\mathrm{e}^+\nu\bar{\nu}$	(1.0)	normalize to
	$\mathrm{e}^+\nu\bar{\nu}\gamma$	(~ 0.014)	measure
	$\mathrm{e}^+\nu\bar{\nu}\mathrm{e}^+\mathrm{e}^-$	$(\sim 3 \times 10^{-5})$	measure

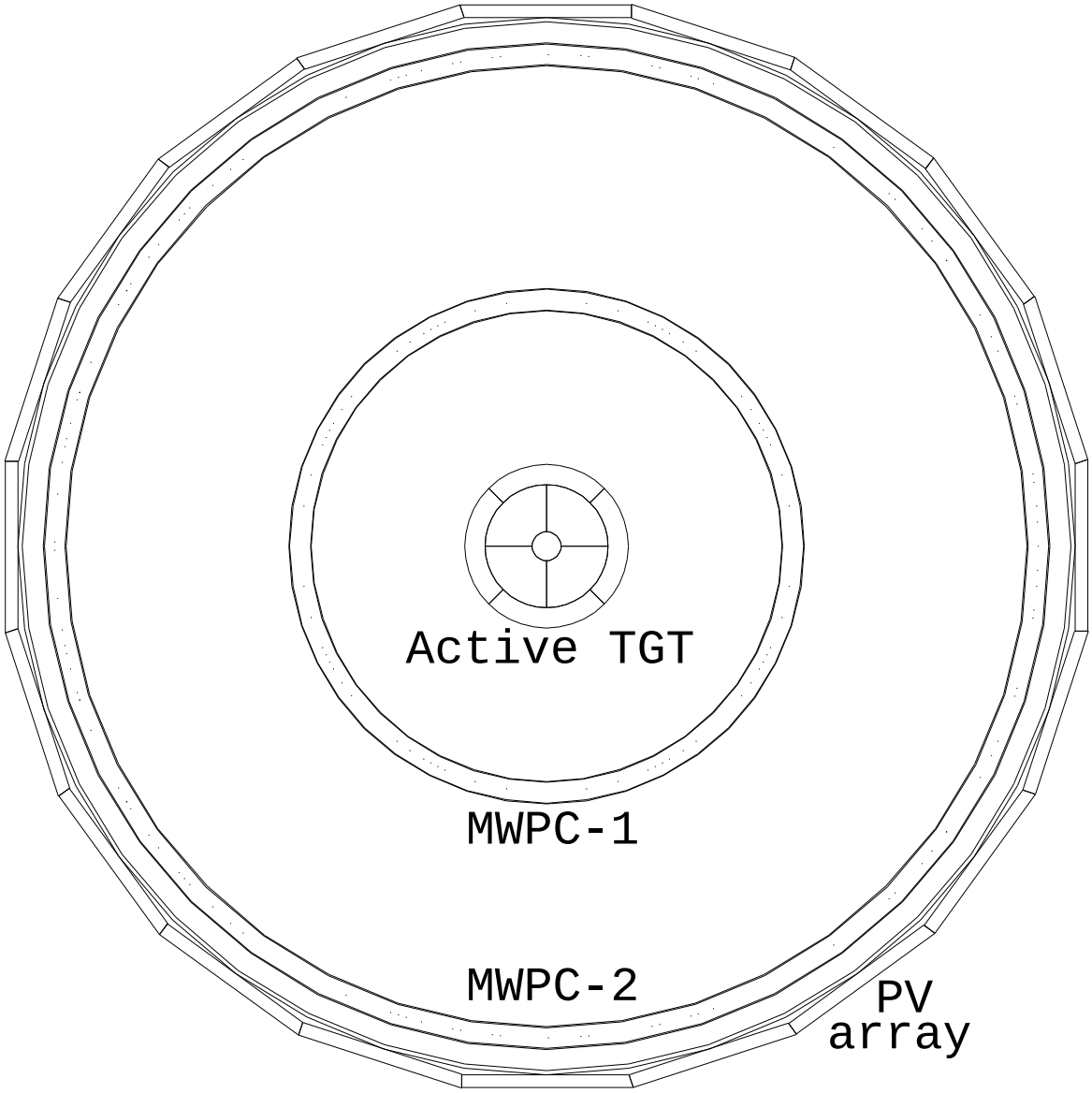
PIBETA Experiment:

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





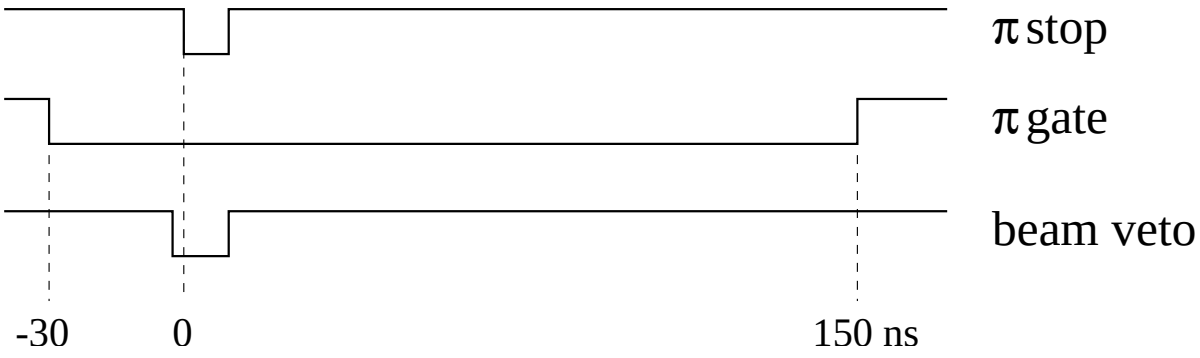
CENTRAL DETECTOR REGION



(beam is perpendicular at center)

Experimental Method: Summary

- Detect π^+ decays <u>at rest</u> (during a delayed 180 ns gate).



- Use prescaled $\pi^+ \to e^+\nu$ (π_{e2}) decays for normalization.
- Accept every $\pi\beta$ trigger – unbiased ($\gamma\gamma$ coincidences above Michel endpoint)

$$\frac{1}{\tau_{\pi\beta}} = \frac{1}{\tau_{\pi^+}} \cdot \frac{BR_{e\nu} f_{\rm presc}}{BR_{\pi^0 \to \gamma\gamma}} \cdot \frac{A_{e\nu}}{A_{\pi\beta}} \cdot \frac{N_{\pi\beta}}{N_{e\nu}}$$

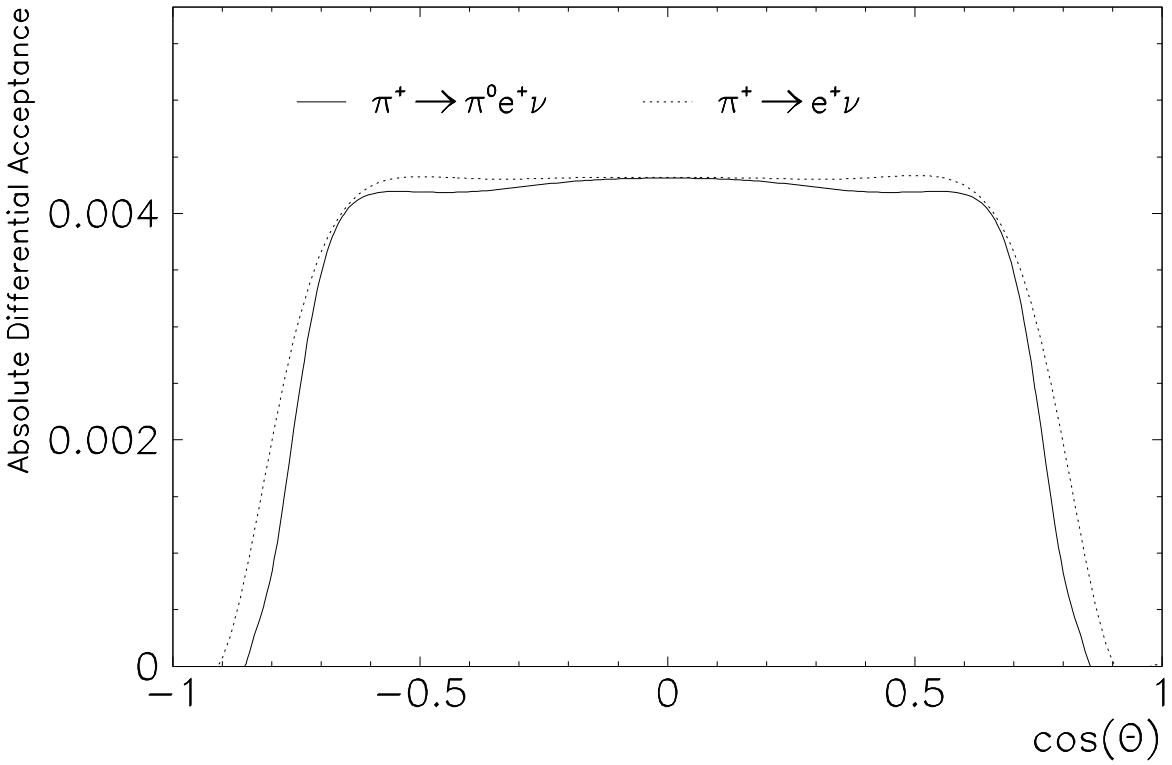
$A_{\pi\beta}$, $A_{e\nu}$ are acceptances for the $\pi\beta$ and π_{e2} decay modes, respectively.

Experimental method (cont'd.)

$A_{\pi\beta}$, $A_{e\nu}$ influenced by:

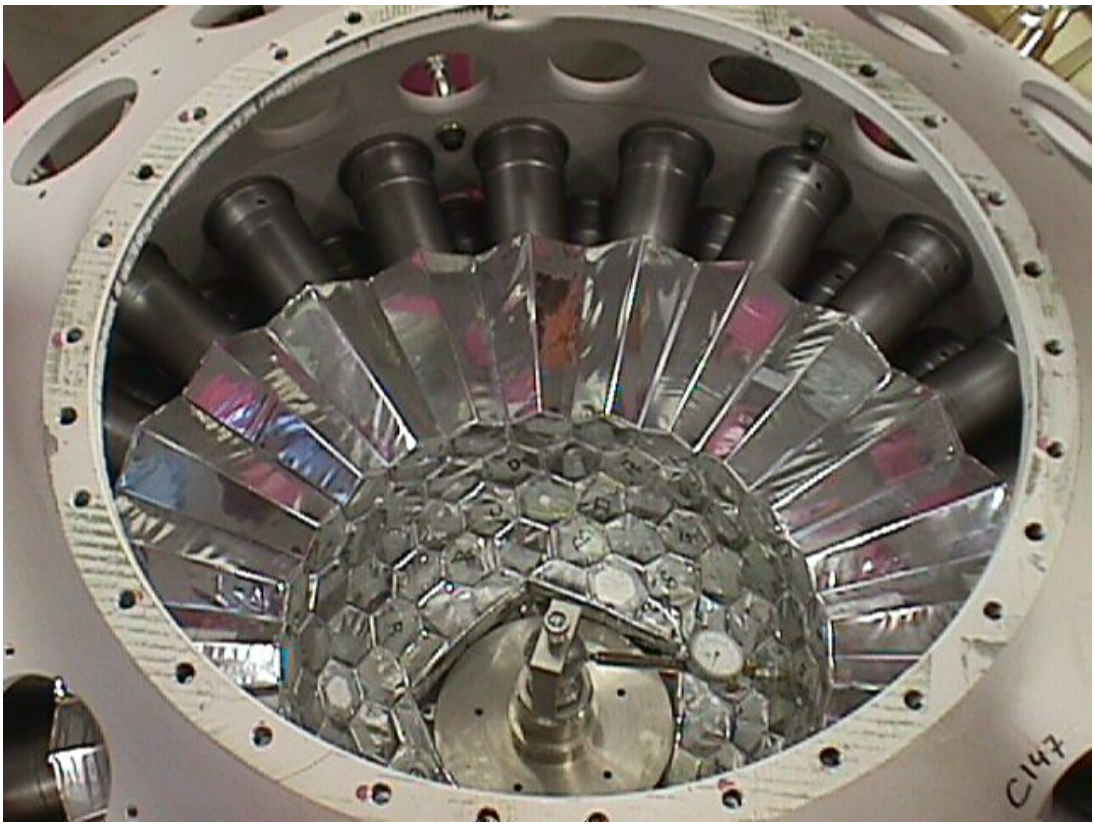
- geometry (including beam spot, alignment, cracks),
- e-m shower leak-through, backsplash, etc.,
- e-m interactions in TGT and tracking detectors,
- volume uniformity of CsI light response, photoelectron statistics,
- gain stability of CsI detector modules,
- photonuclear and e knockout react's in CsI.

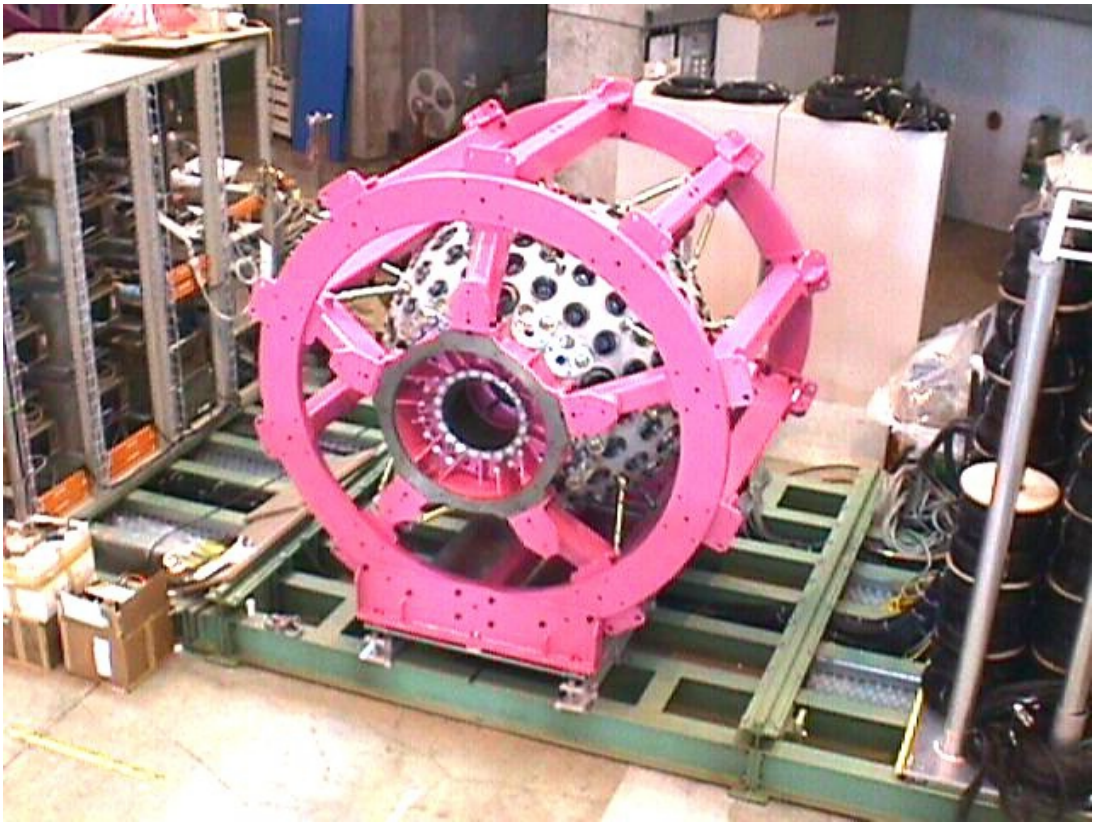
Key acceptances compared



GEANT calculated acceptances for the $\pi\beta$ and π_{e2} decays as a function of $\cos\theta$.

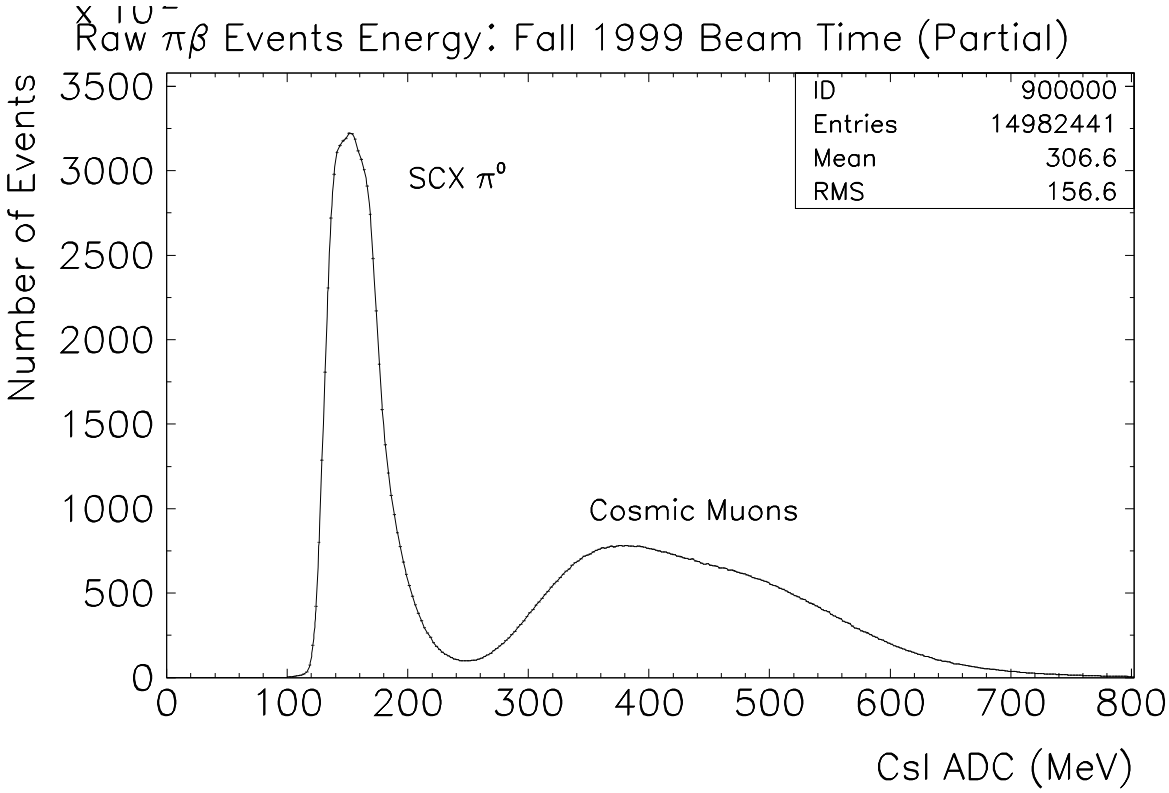
PIBETA Detector Assembly (1998)





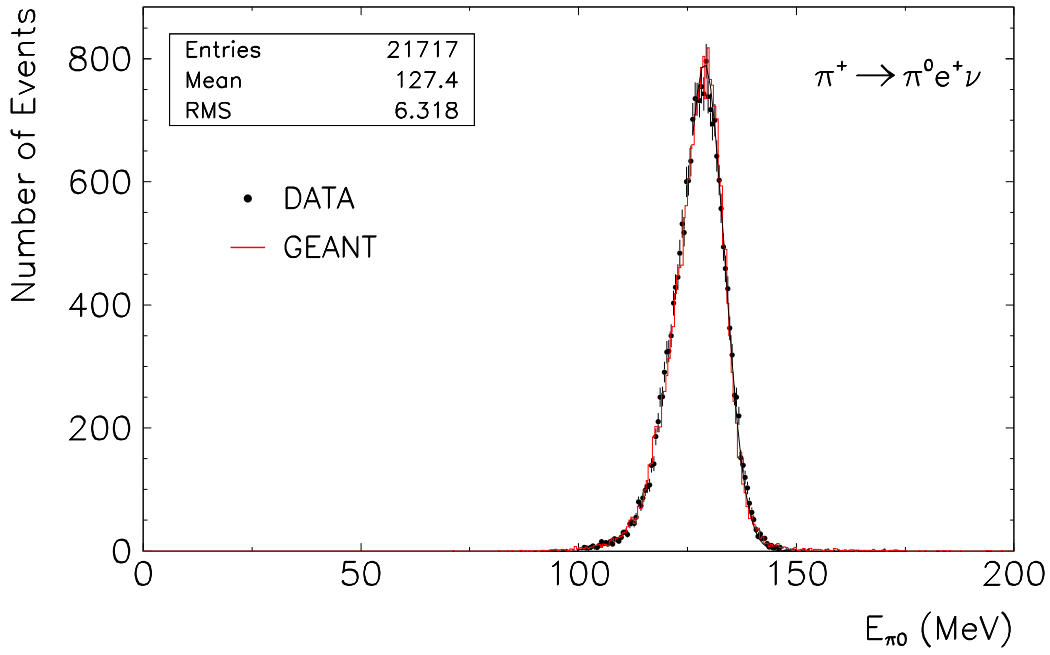
Detector Performance

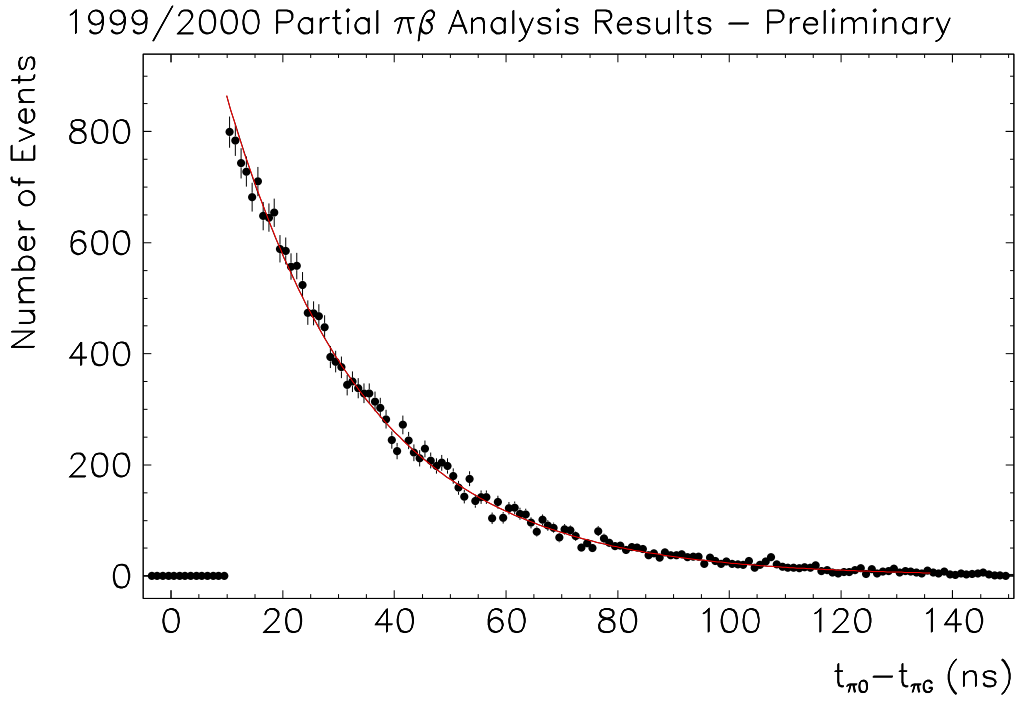
Online "$\pi\beta$" Energy Spectrum:



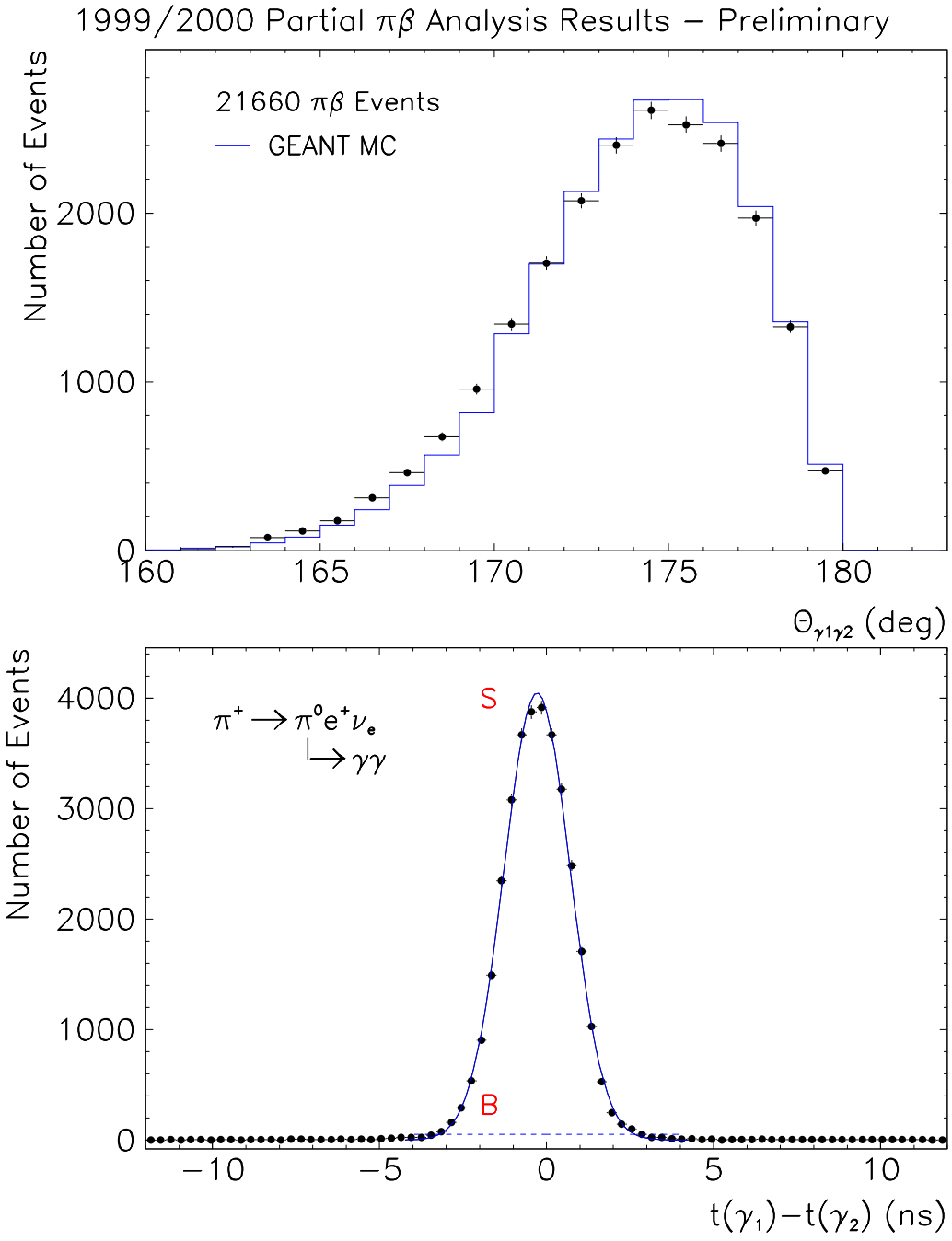
True $\pi\beta$ events buried deep under overwhelming background!

Preliminary Results: $\pi^+ \rightarrow \pi^0 e^+ \nu$

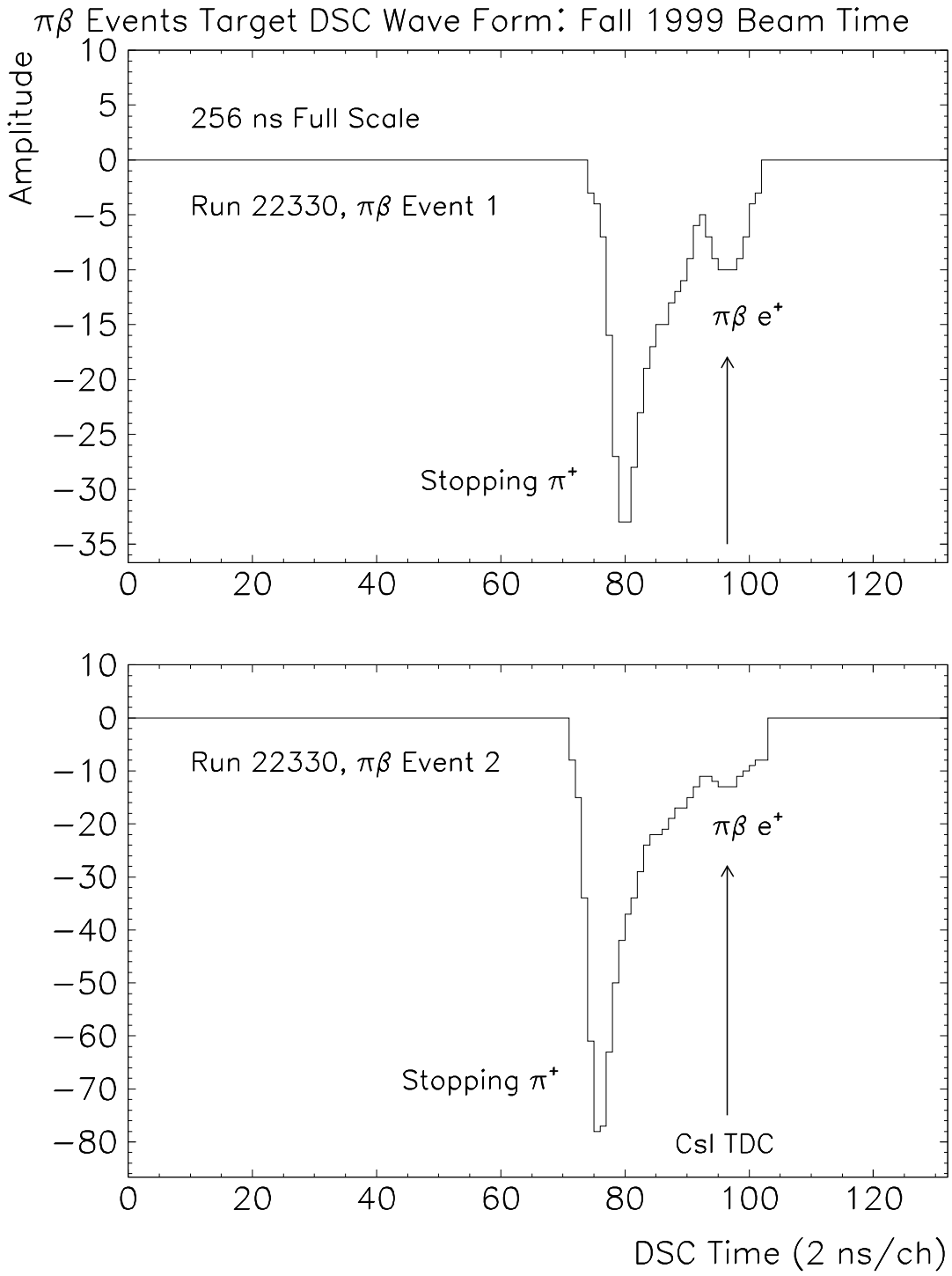




Preliminary Results: $\pi^+ \to \pi^0 e^+ \nu$

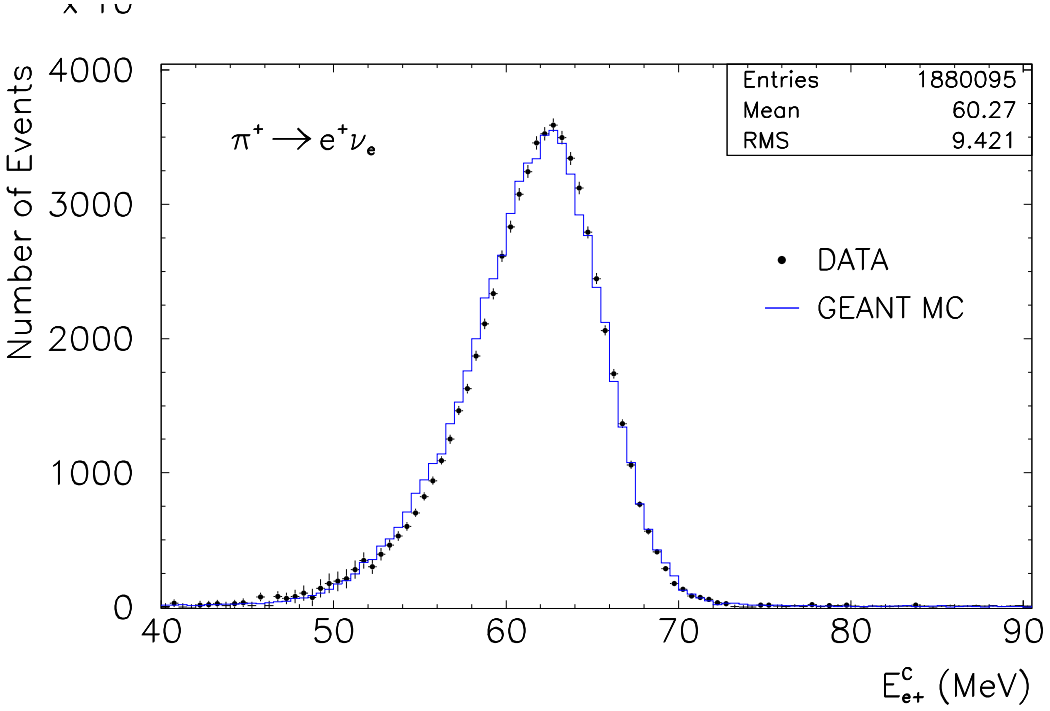


Domino Sampling Chip (DSC) Analysis

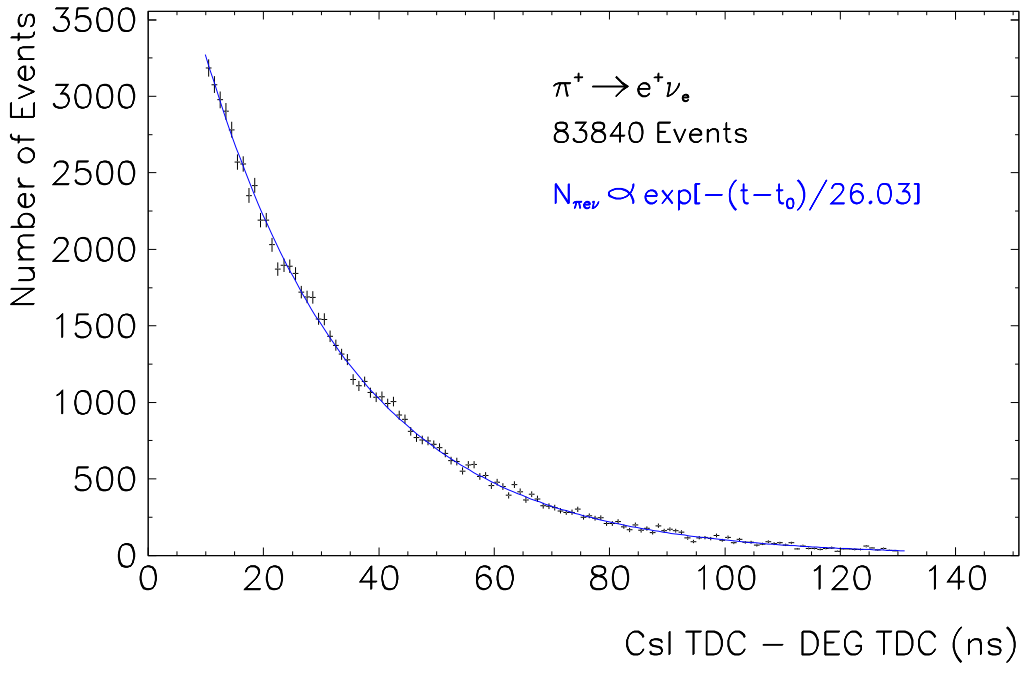


$$\pi^+ \rightarrow \pi^0 e^+ \nu$$

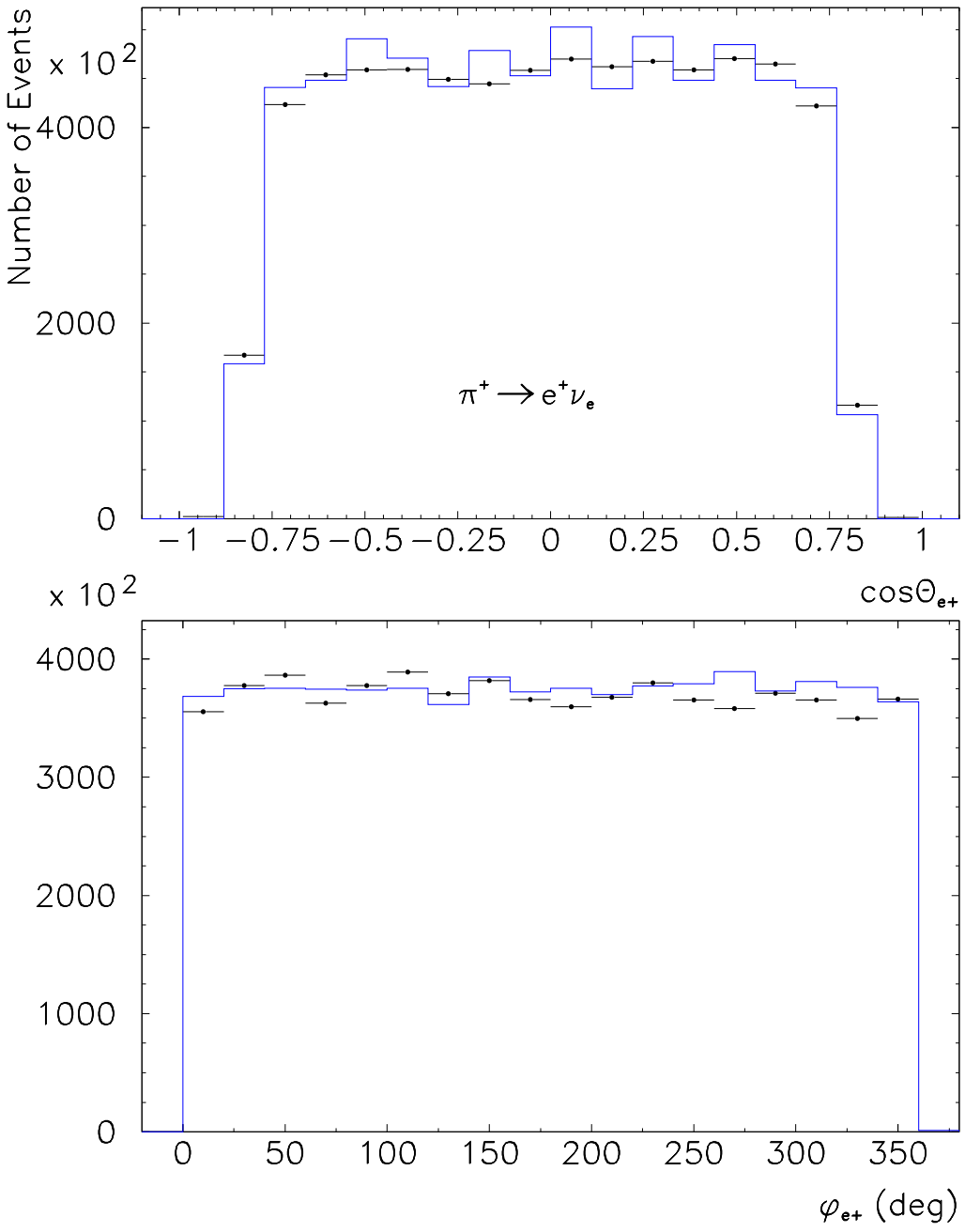
Preliminary Results: $\pi^+ \to e^+\nu$



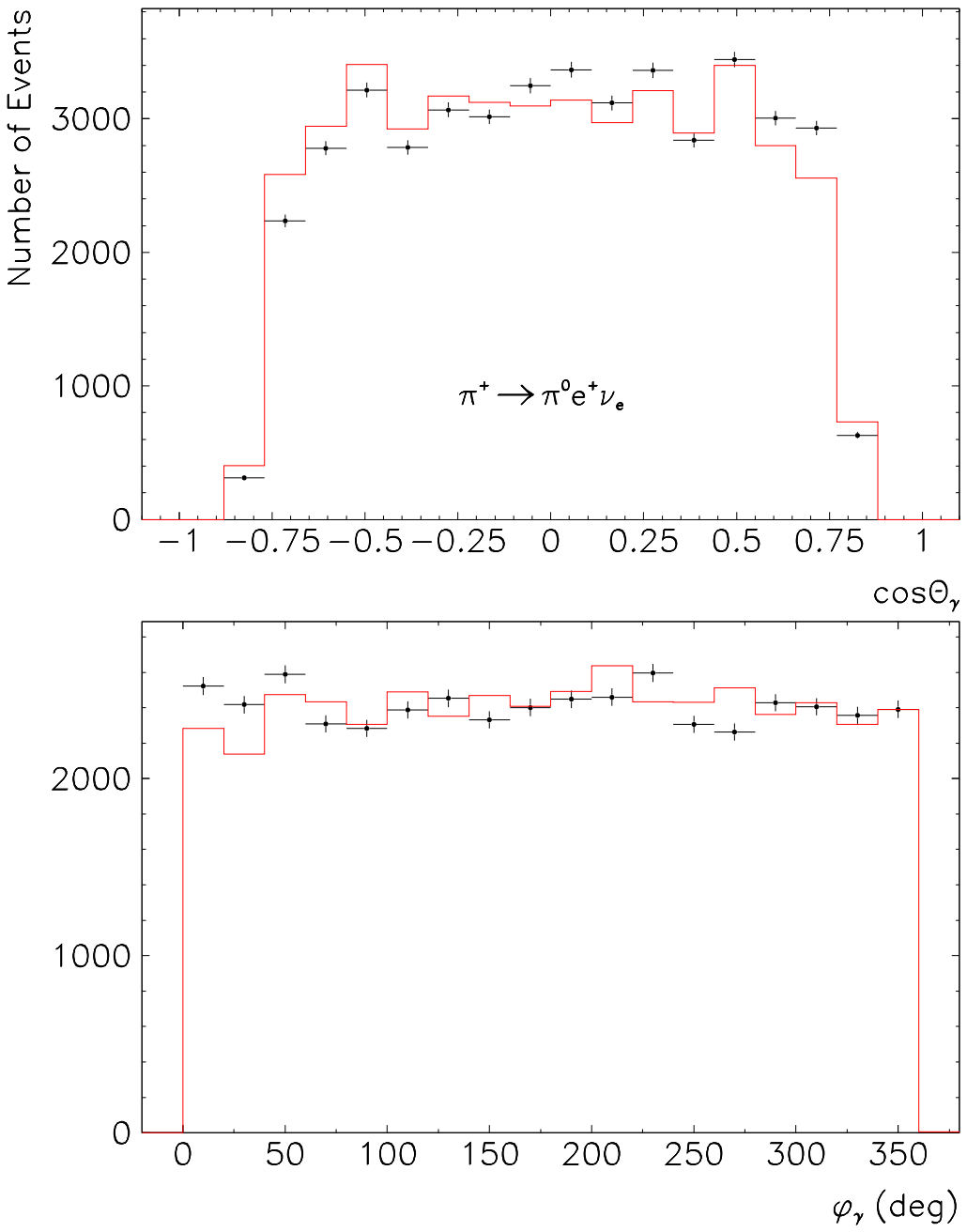
1999/2000 Partial Results – Preliminary



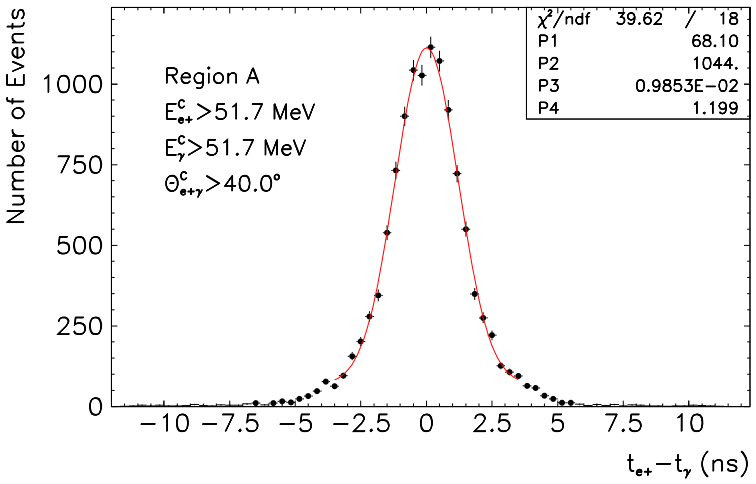
Angular acceptance: $\pi^+ \to e^+\nu$

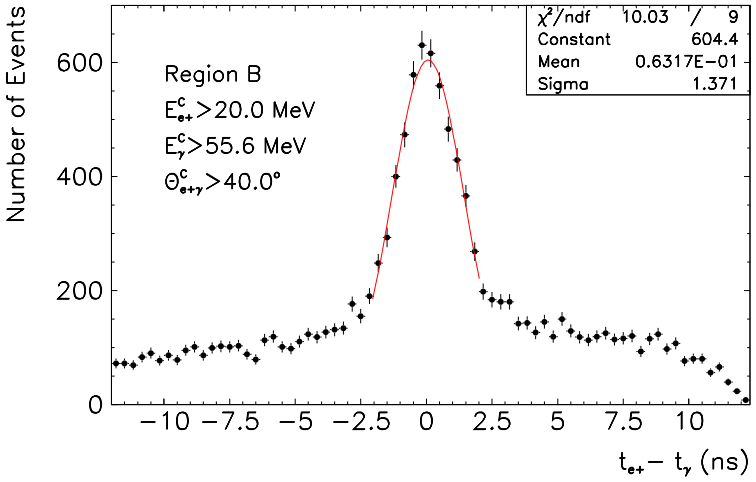


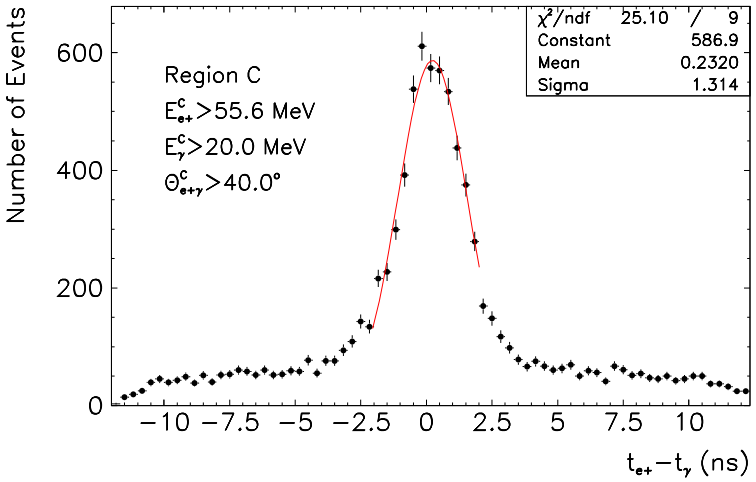
Angular acceptance: $\pi^+ \to \pi^0 e^+ \nu$



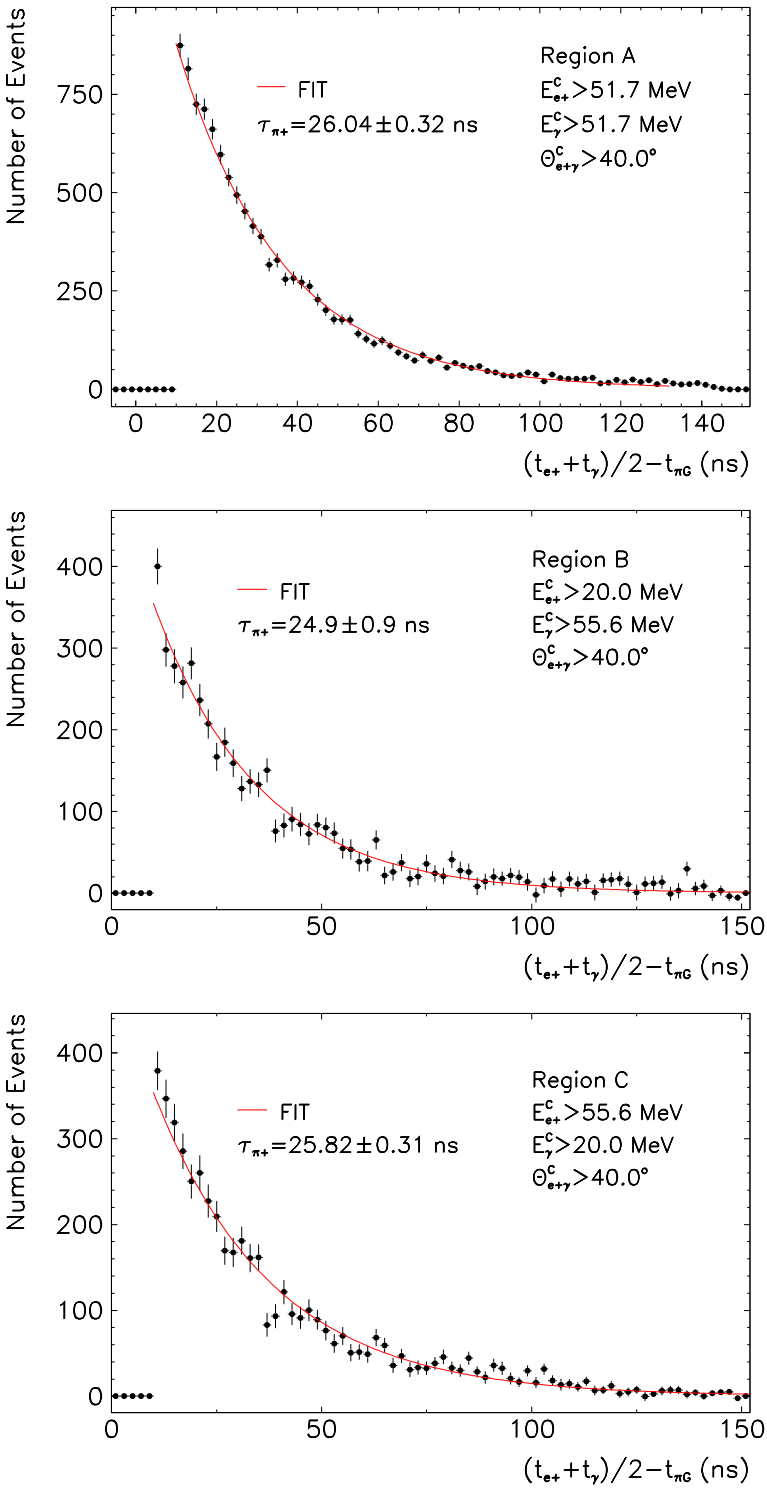
Preliminary Results: $\pi^+ \to e^+\nu\gamma$ *(S/B)*



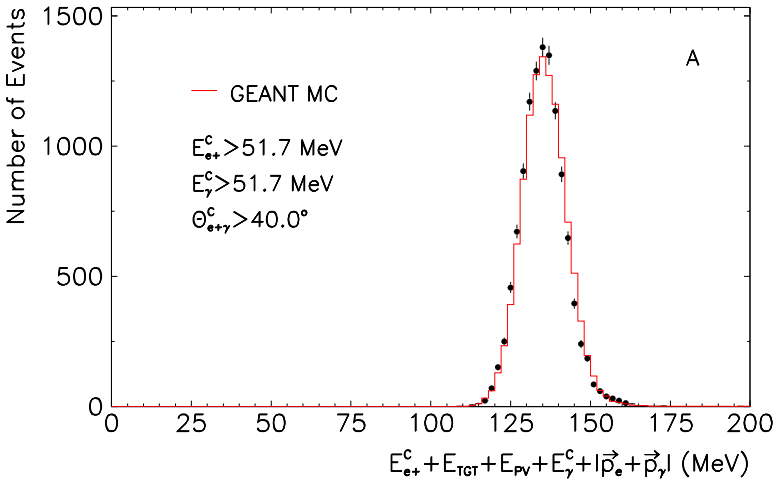


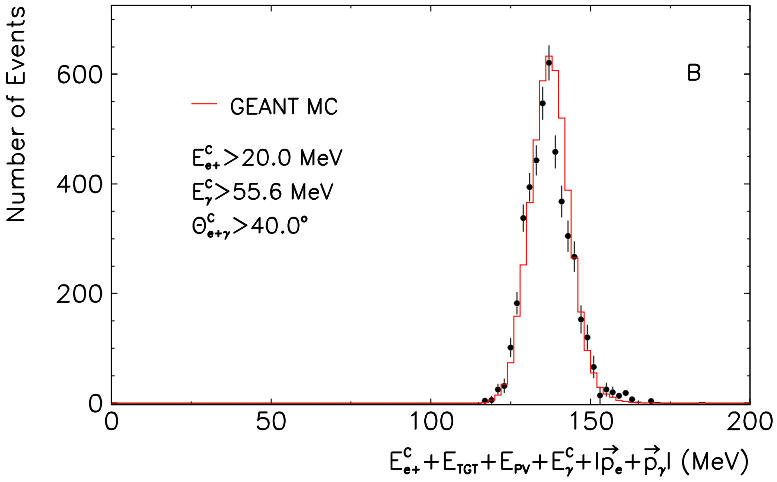


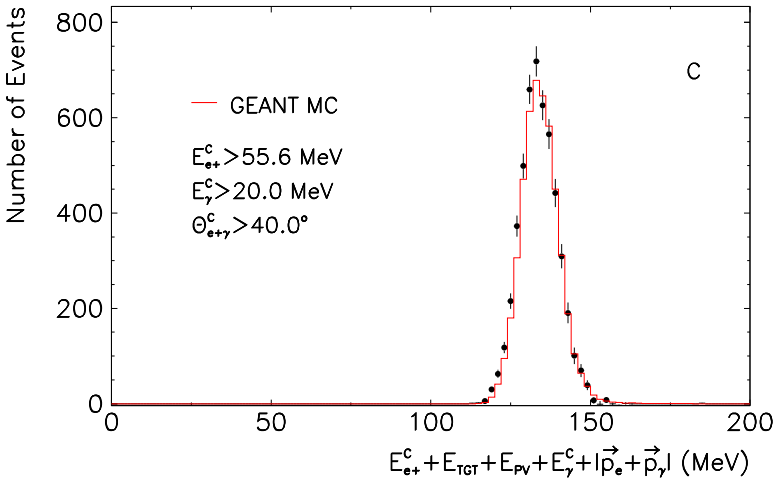
Preliminary Results: $\pi^+ \to e^+\nu\gamma$ *(t)*



Preliminary Results: $\pi^+ \to e^+\nu\gamma$ (m_π)





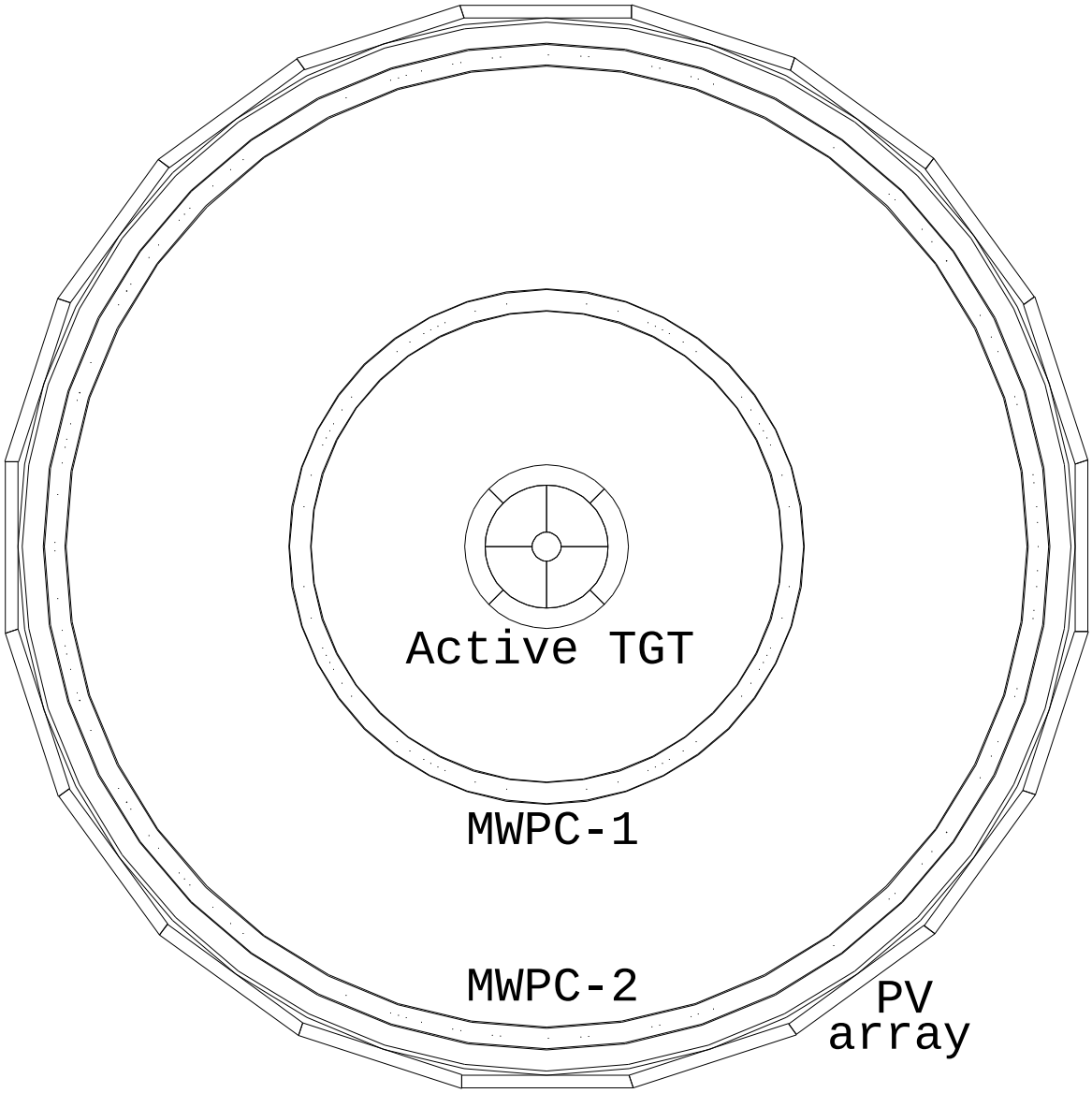


Experiment Systematics

Main sources of uncertainty:

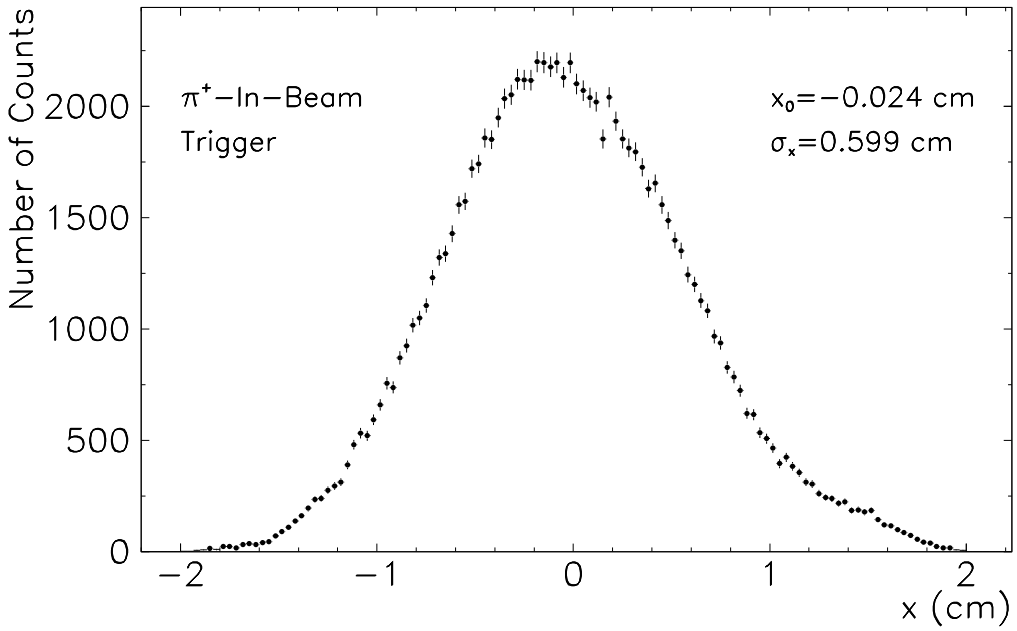
- Acceptance: beam geometry
- Timing: pion decay fraction
- External: BR($\pi \to e\nu$)

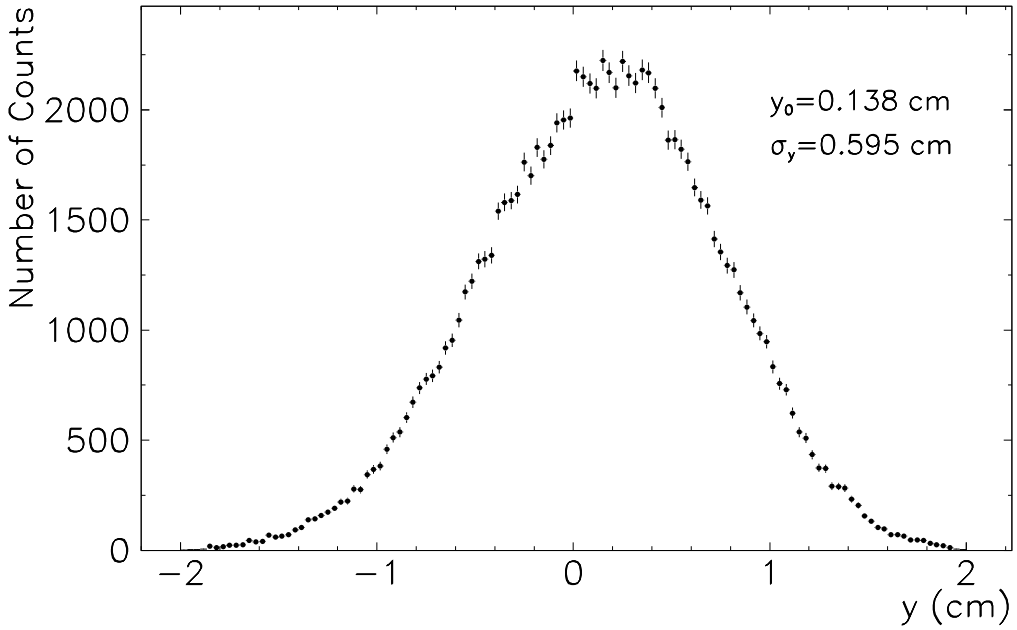
Central detector region revisited



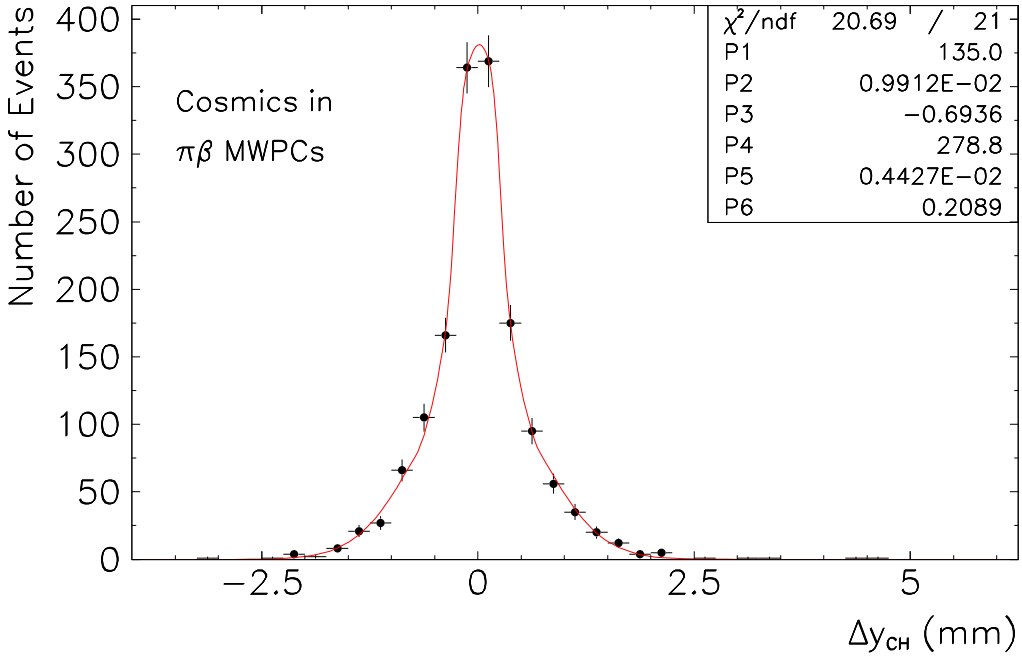
(beam is perpendicular at center)

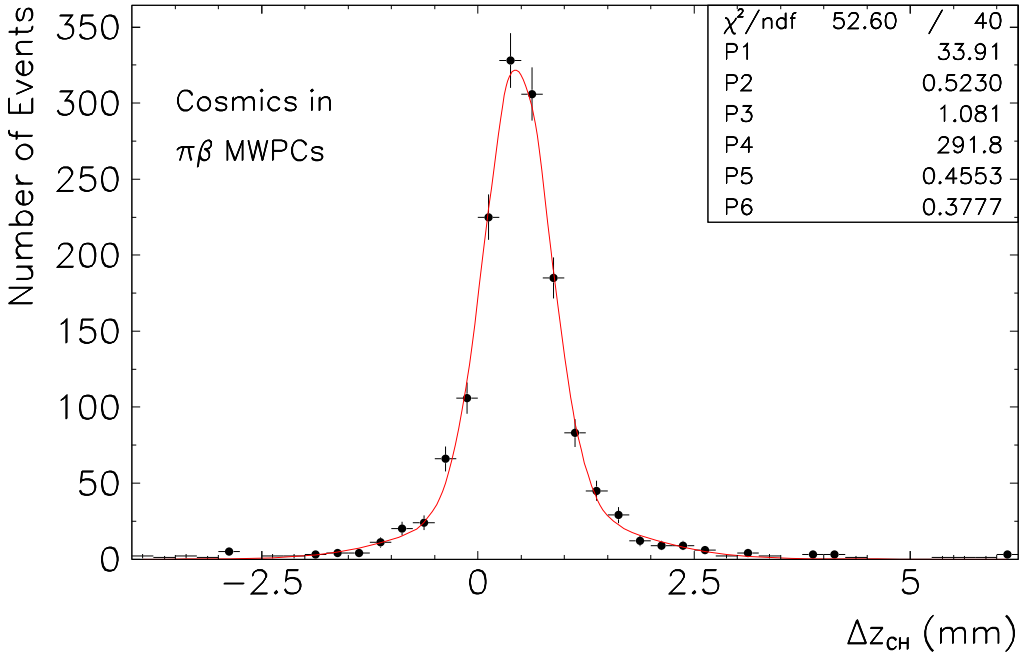
Beam geometry: TGT rate deconvolution



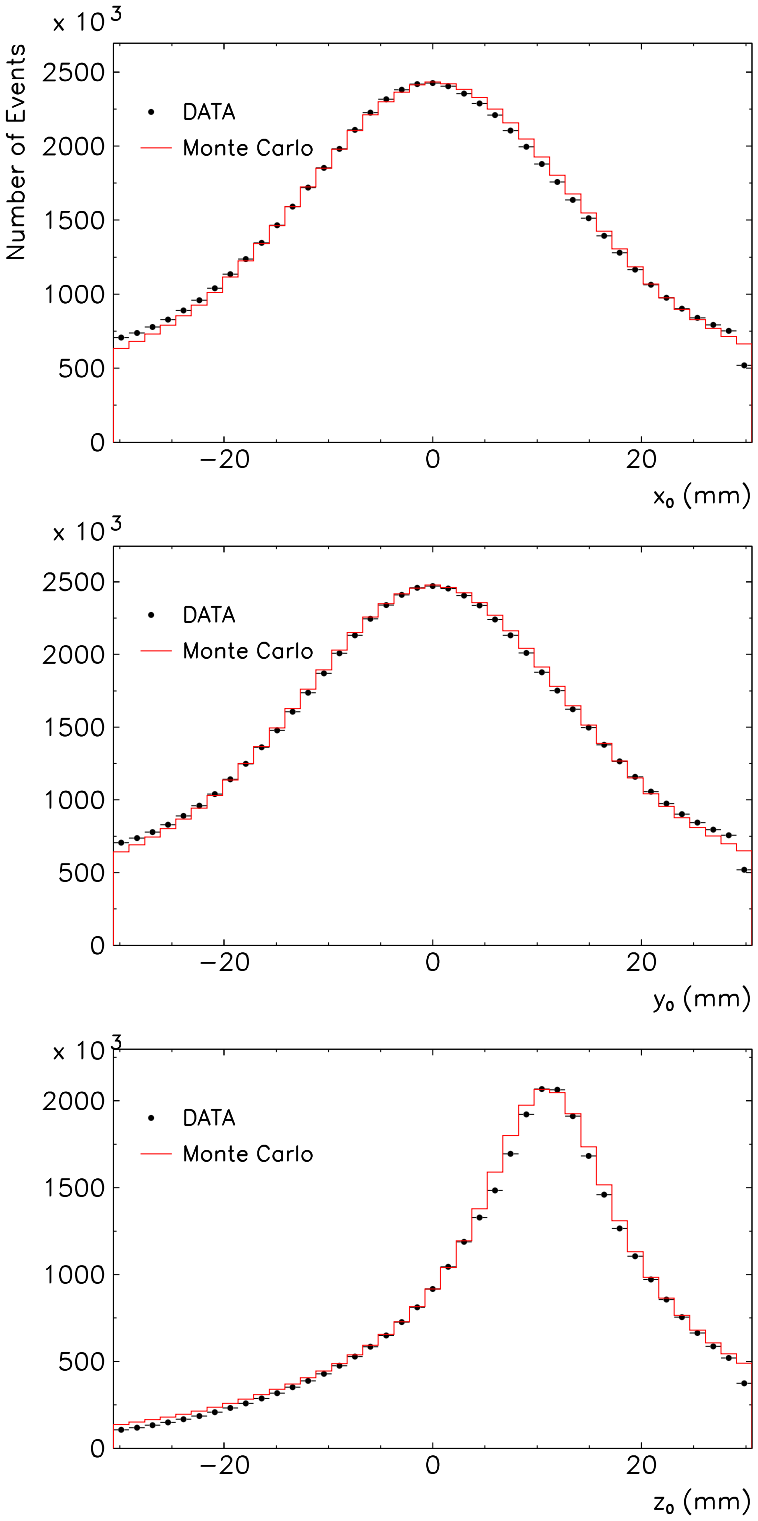


TGT tomography: MWPC resolution

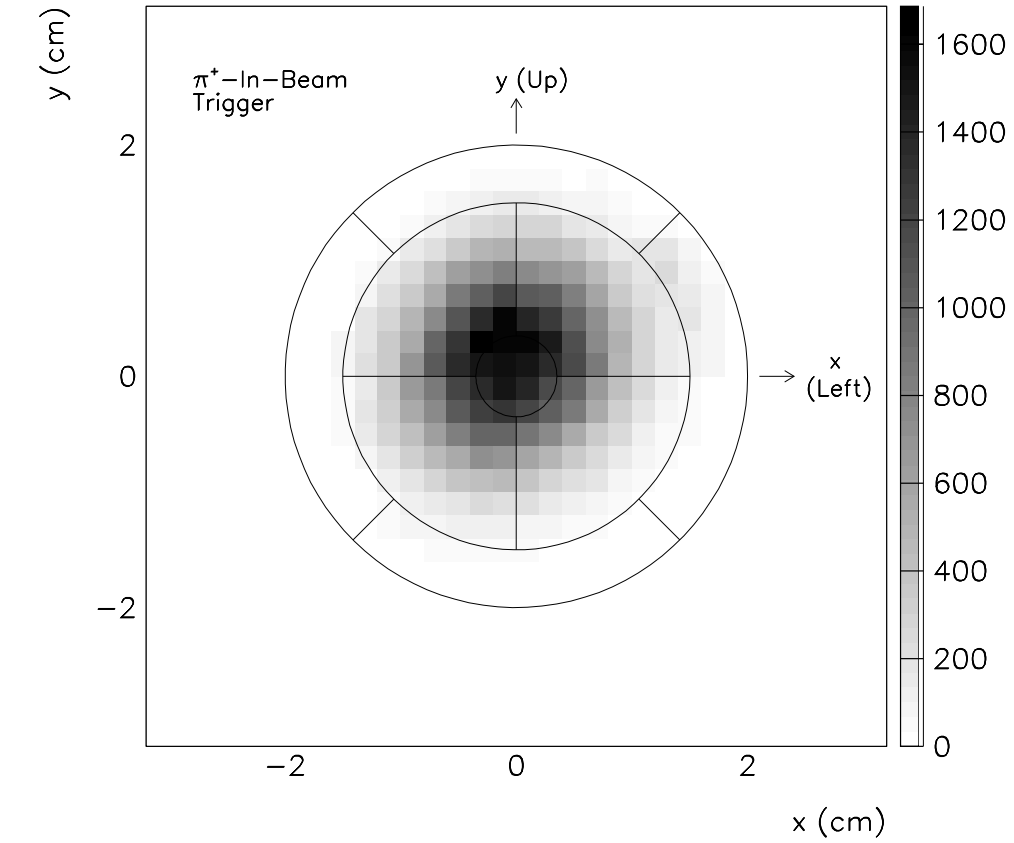


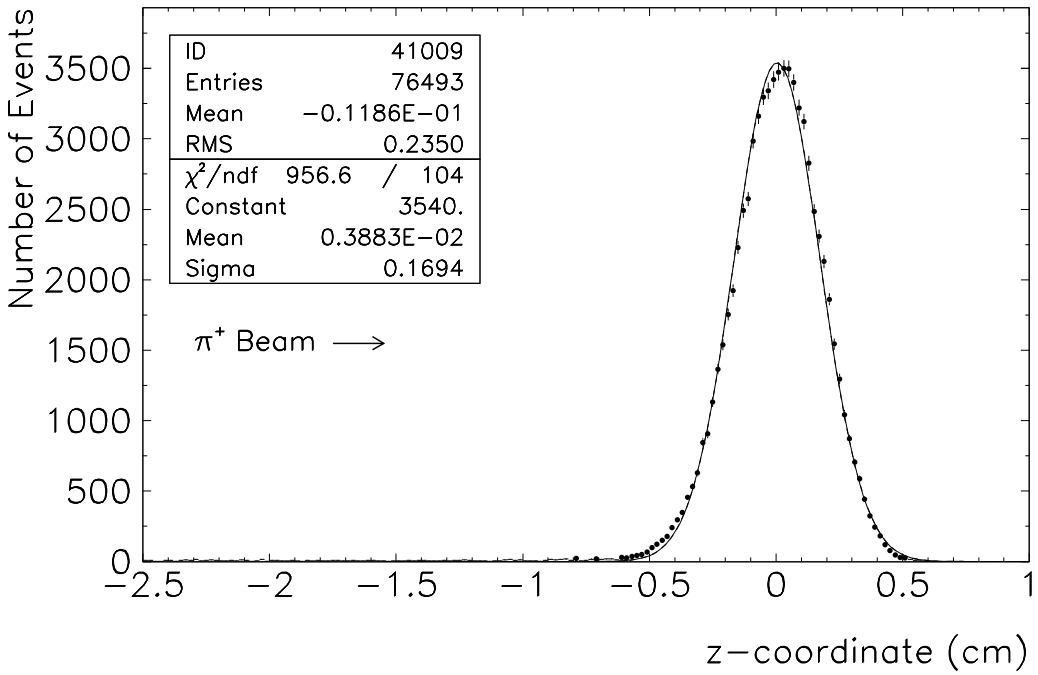


TGT tomography: track reconstruction

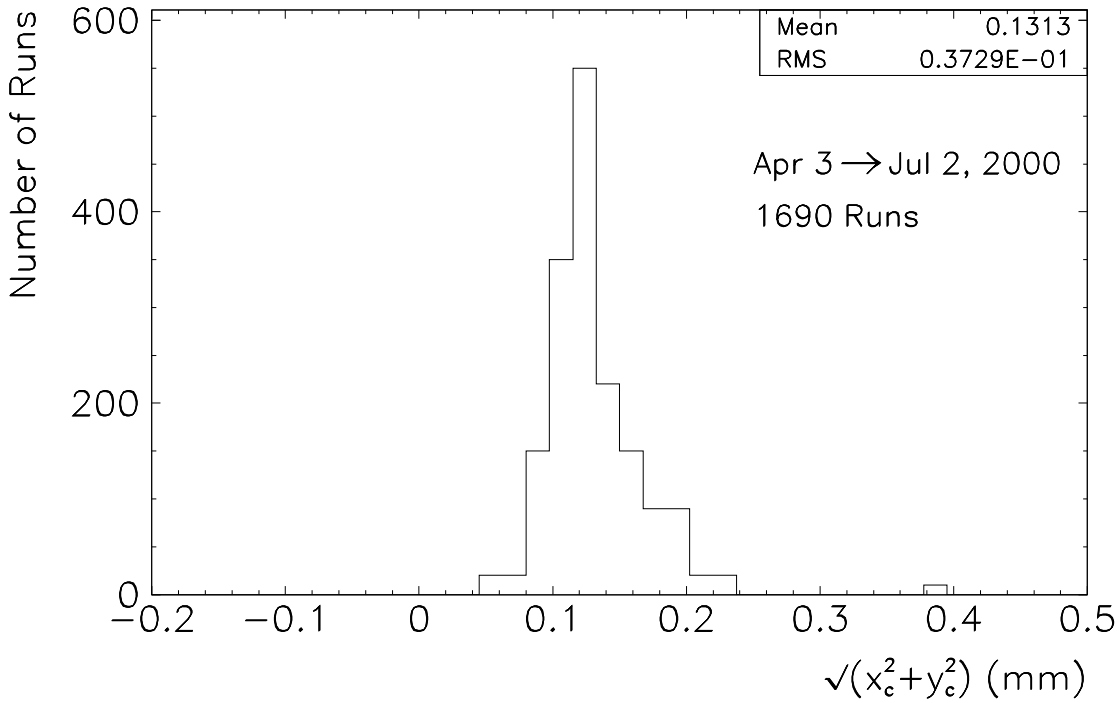


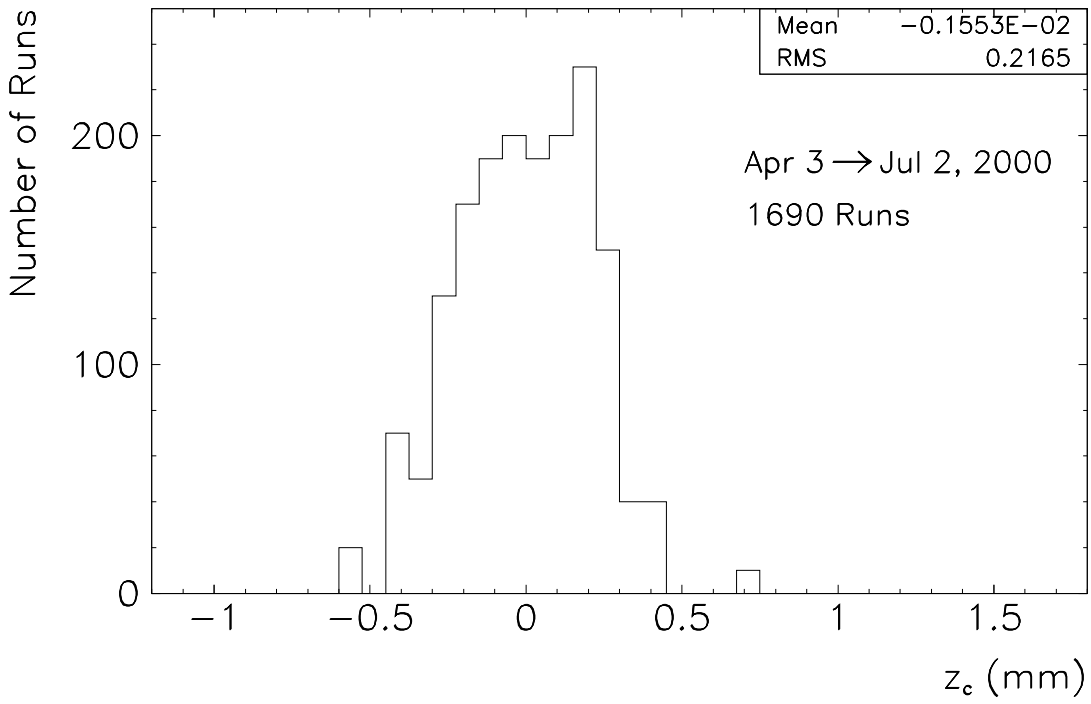
Beam geometry: π^+ stopping distribution



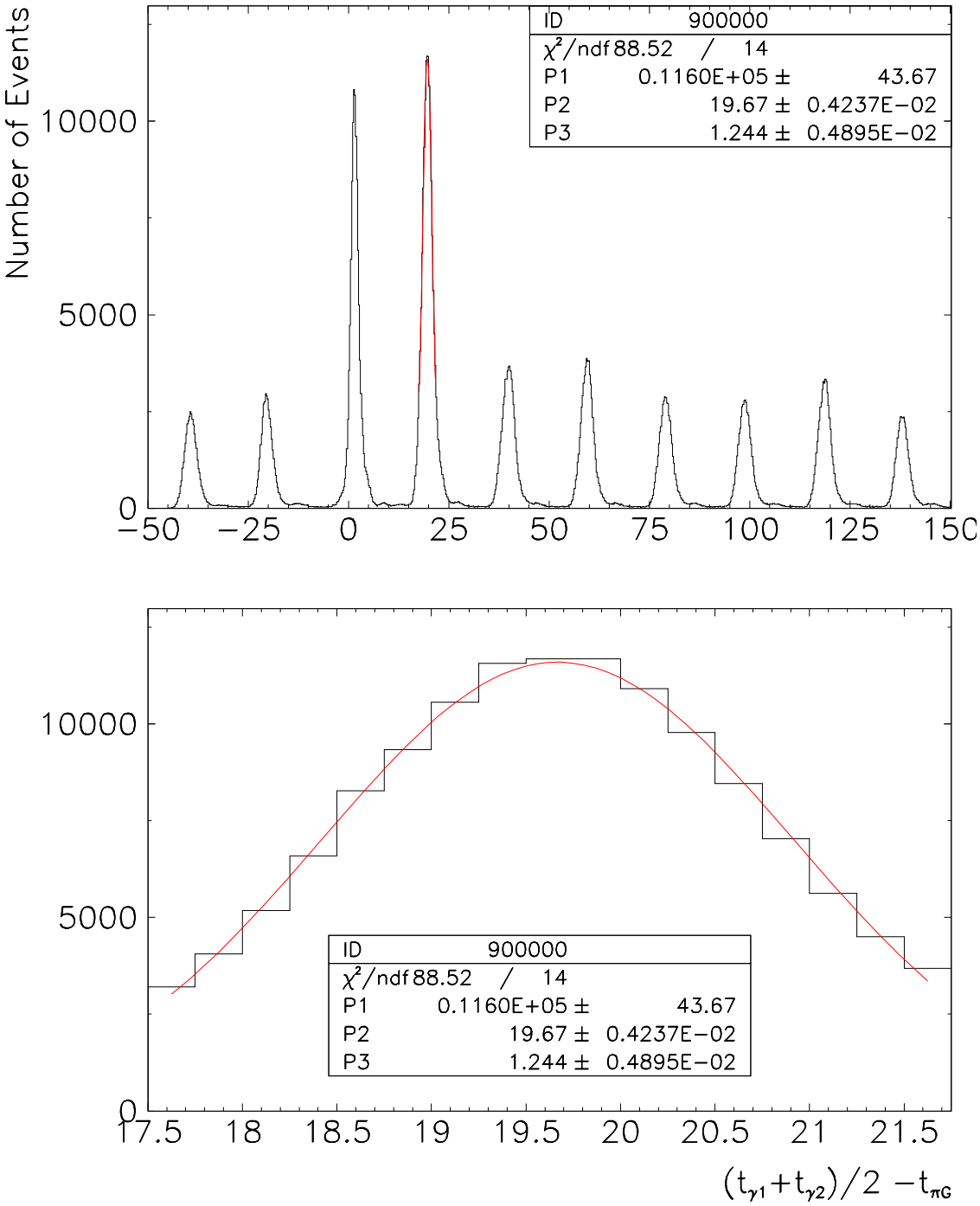


Beam stability





Pion stop timing



$\Delta t_{\text{peak}} \approx 4\,\text{ps}$

Preliminary Results

$\pi^+ \longrightarrow \pi^0 e^+ \nu$

Branching Ratio for $\pi\beta$ Decay

Our Preliminary Interim Result:

$$\text{BR} \simeq \quad 1.044 \pm 0.007 \quad \pm 0.009 \quad \times 10^{-8}$$

(stat.) (syst.)

McFarlane et al. (Phys. Rev. D 1985):

$$\text{BR} \simeq 1.026 \pm 0.039 \times 10^{-8}$$

SM Prediction (PDG, 2002):

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

$$(1.005 - 1.008 \times 10^{-8} \quad \text{excl. rad. corr.})$$

PDG 2002: $V_{ud} = 0.9734(8)$

PIBETA prelim: $V_{ud} = 0.9765(56).$

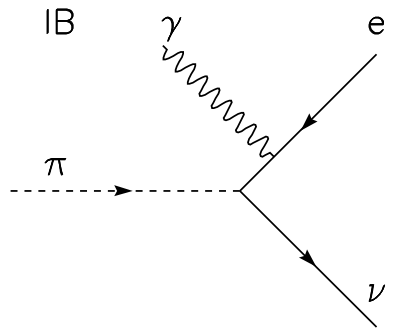
Summary of $\pi\beta$ Uncertainties

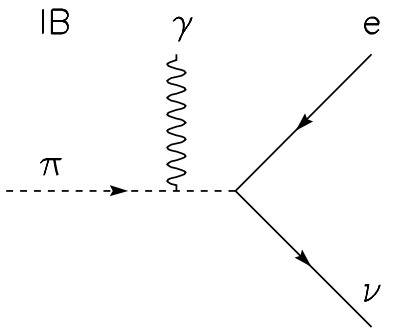
at end of analysis phase:		current (%)	final (%)
external			
	pion lifetime	0.019	0.019
	$BR(\pi \to e\nu)$	0.33	~ 0.1?
	$BR(\pi^0 \to \gamma\gamma)$	0.032	0.032
internal			
	$A(\pi\beta)/A(e\nu)$	0.5	< 0.3
	$\Delta t(\gamma - e)$	0.03	0.03
	E threshold	< 0.1	< 0.1
statistical:		0.7	~ 0.4
total:		~ 0.9	$\lesssim 0.5$

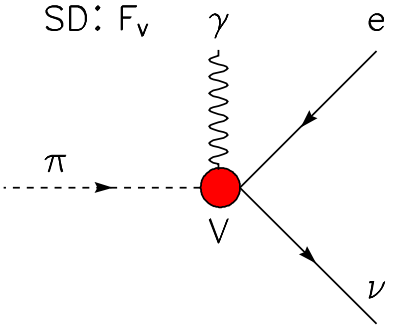
Radiative Pion Decay

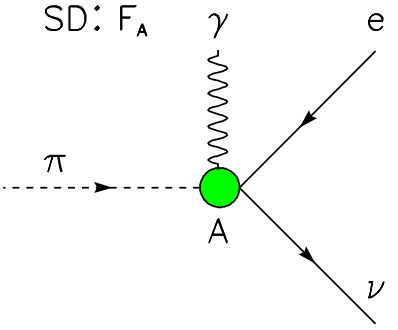
$$\pi^+ \longrightarrow e^+ \nu \gamma$$

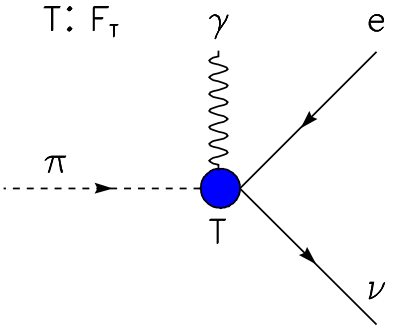
Anything beside $V-A$ in RPD?











Exchange of Spin−Zero Leptoquarks

P. Herczeg, Phys. Rev. 49 (1994) 247

AVAILABLE DATA on Pion Form Factors

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

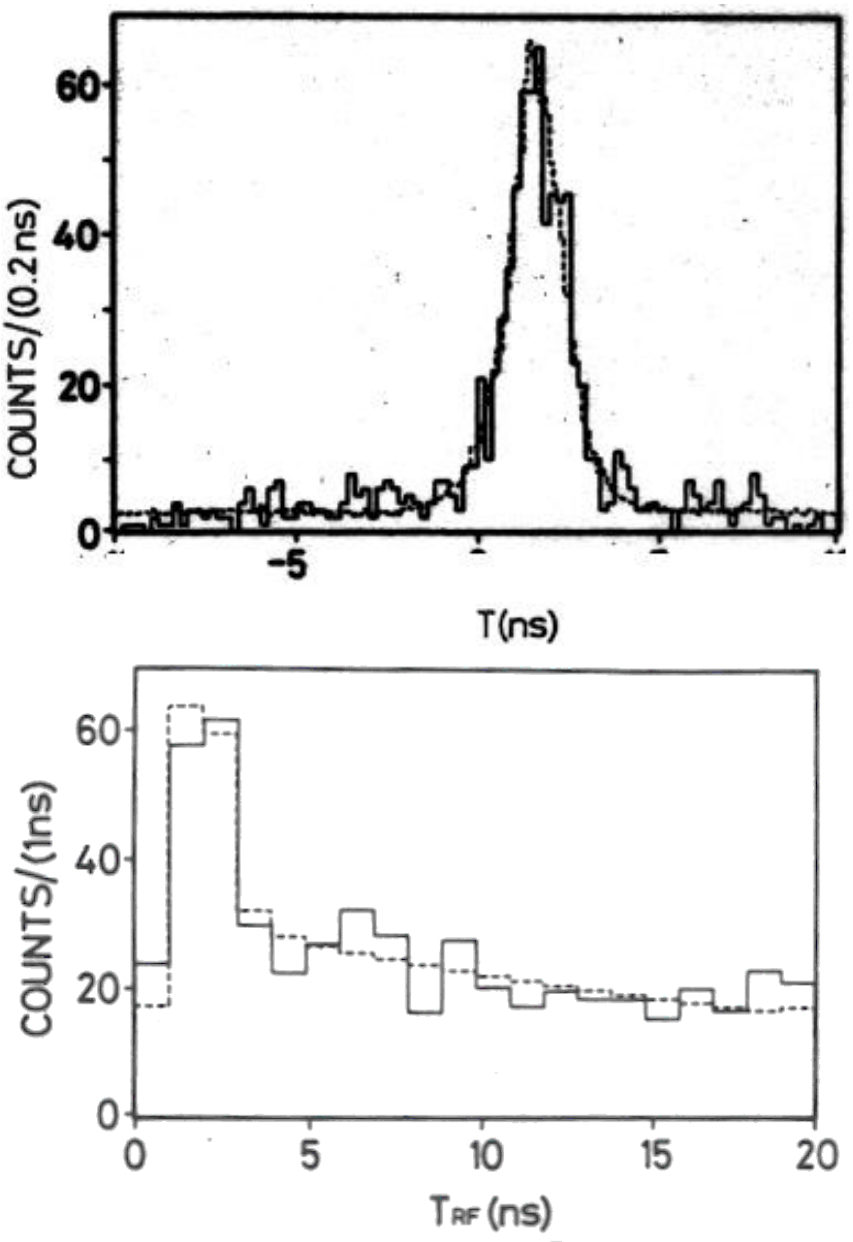
$F_A \times 10^4$	reference
106 ± 60	Bolotov et al. (1990)
135 ± 16	Bay et al. (1986)
60 ± 30	Piilonen et al. (1986)
110 ± 30	Stetz et al. (1979)
116 ± 16	world average (PDG 2002)

Poblaguev (1990, '92) found:
(a) inconsistencies in data set (part. ISTRA data),
(b) need to include T q-l coupling:

$$F_T \sim -0.0056 \pm 0.0017 \ .$$

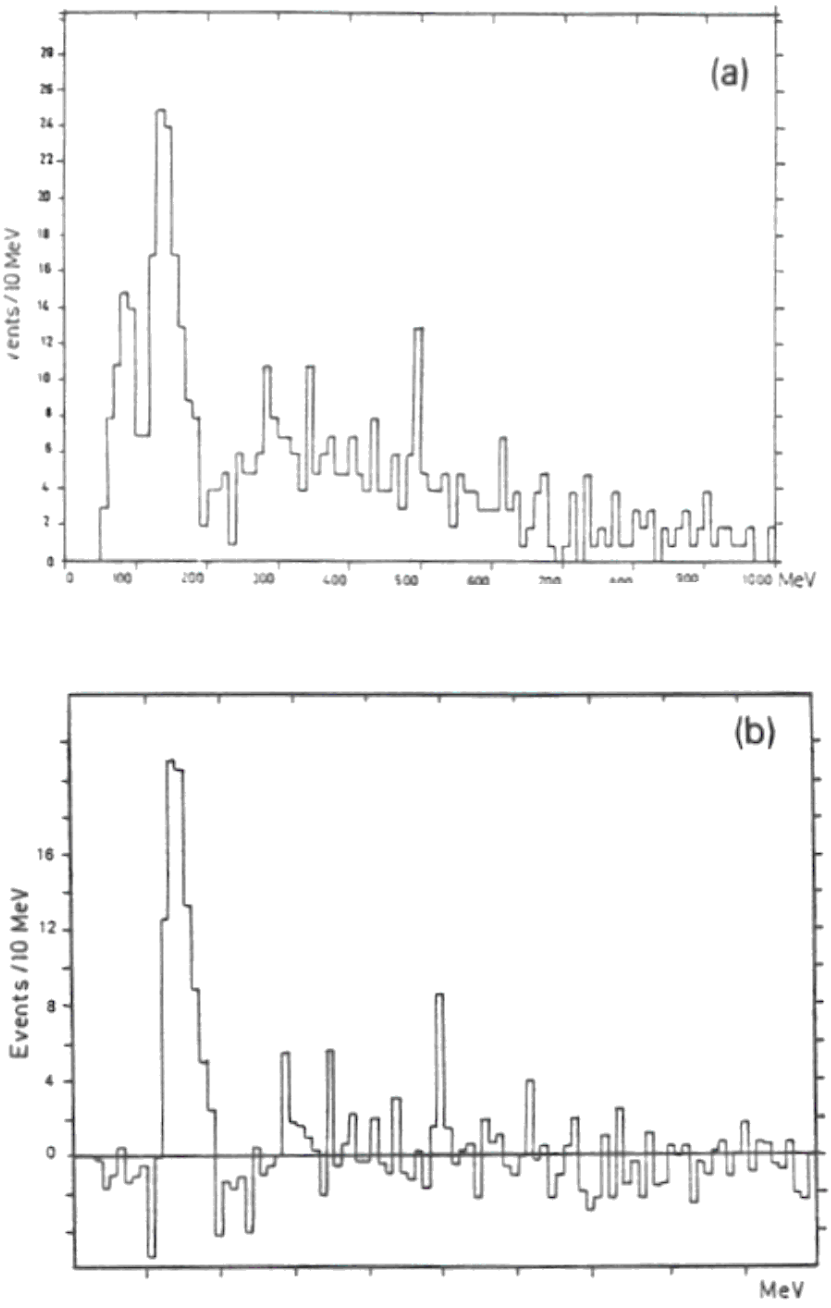
Herczeg (1994) confirmed there is room (barely) for F_T of the above order of magnitude. Only plausible explanation—leptoquarks at tree level.

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



Bay et al., PSI 1986

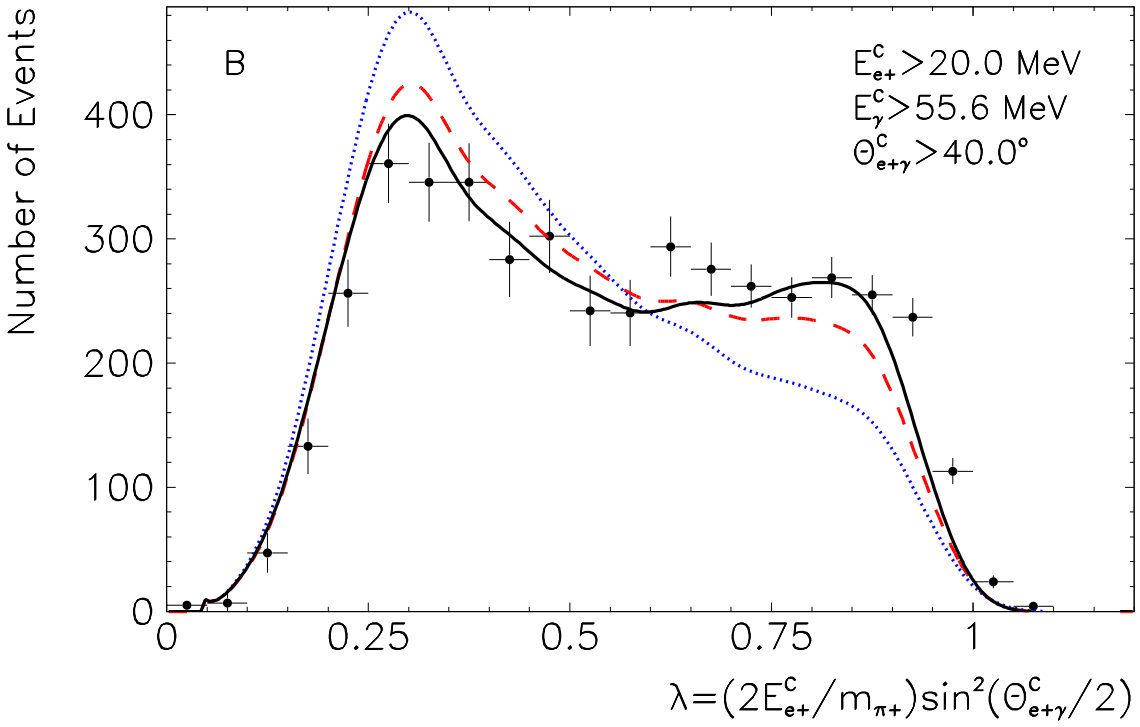
Previous $\pi \to e^+\nu\gamma$ experiments



(reconstructed π mass)

Bolotov et al., IHEP, Protvino, 1990

PRELIMINARY RESULTS: $\pi^+ \to e^+\nu\gamma$



	Fixed	Free
....	$F_V^{\rm CVC}$, $F_T = 0$	F_A
- - - -	$F_T = 0$	F_A, F_V
———	$F_V^{\rm CVC}$	F_A, F_T

A Glimpse at Pion Form Factors

- based on analysis of regions A and B only,
- 2-dim fits exclude border regions in acceptance

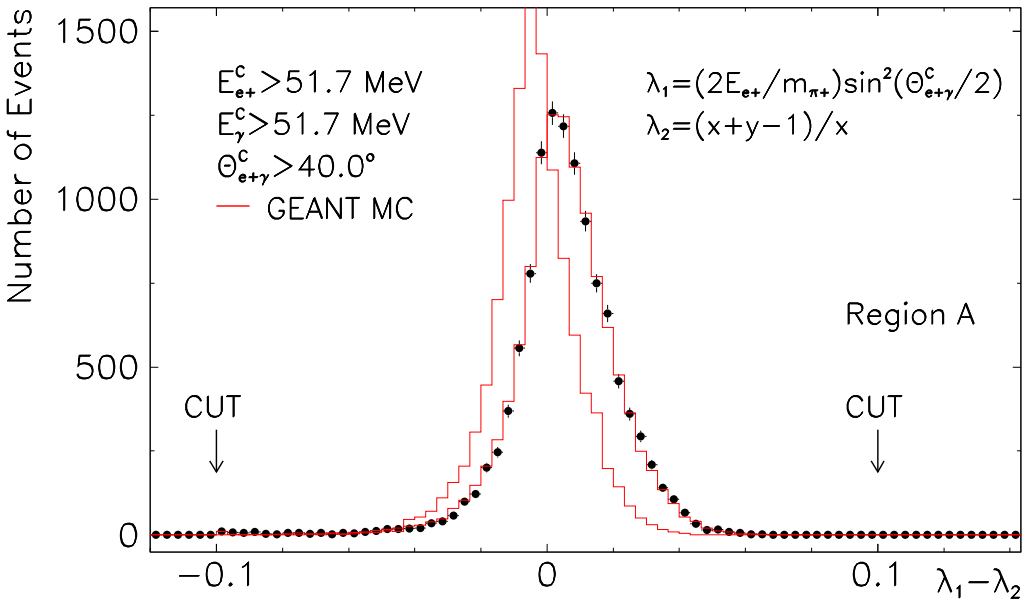
Fit	Fixed parameters	Fit parameters	χ^2
'PDG'	F_V: 0.0170(80) F_A: 0.0116(16) F_T: 0	none	9.2
'SM'	F_V: 0.0259(5) F_T: 0	F_A: $-0.0028(1)$	5.6
all free no T	F_T: 0	F_V: 0.0136(13) F_A: 0.0136(13)	2.3
CVC +T	F_V: 0.0259(5)	F_A: 0.0067(6) F_T: $-0.0017(1)$	1.1

In the meantime we:

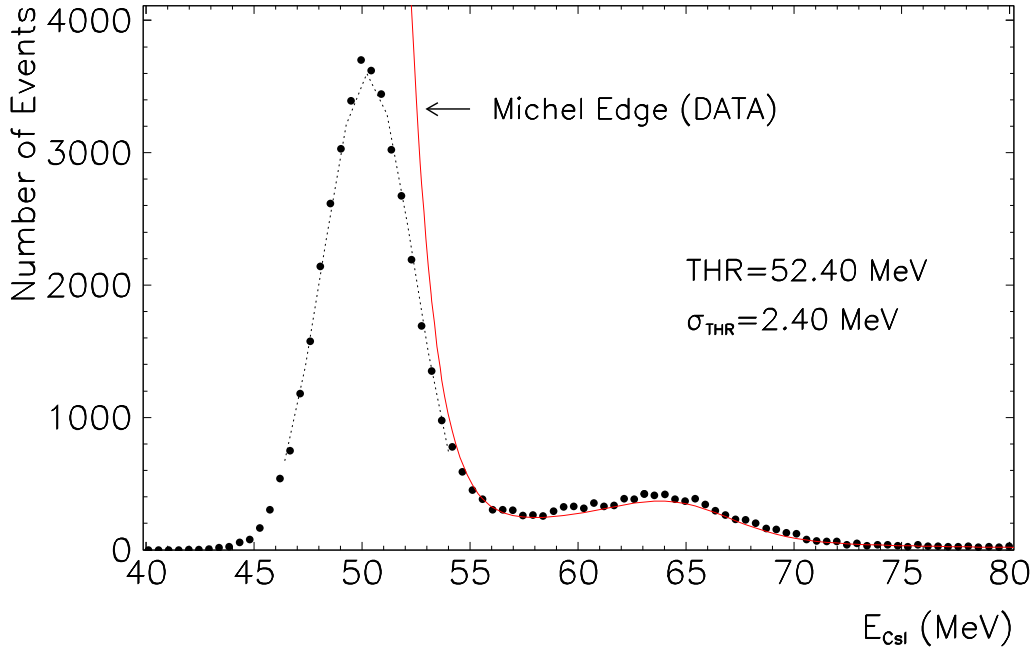
- have reduced region C background,
- have refined aspects of MC simulation,
- are pursuing additional global fit strategies.

A Closer Look at Energy Calibration

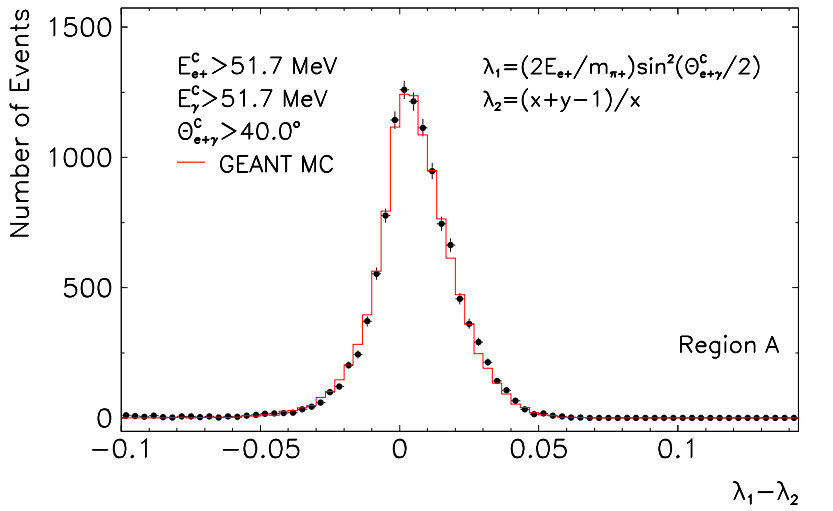
effect of a 1 % gain variation:

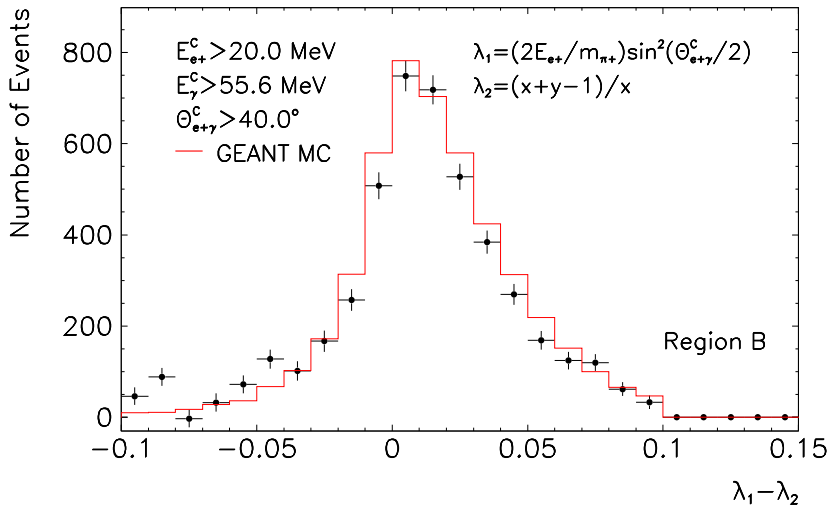


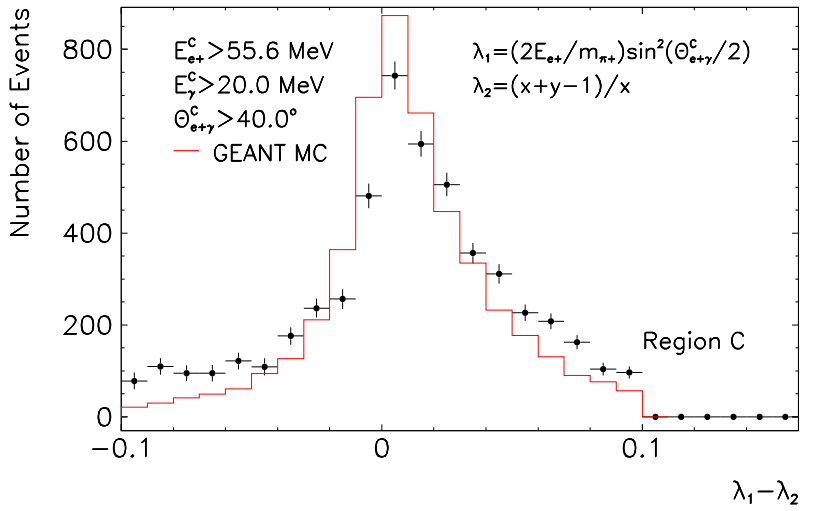
Michel edge and π_{e2} peak:



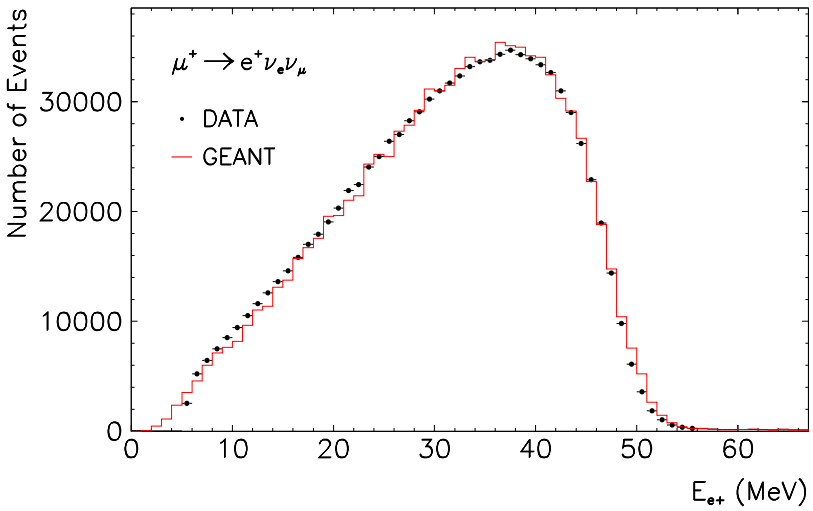
More on Energy Calibration

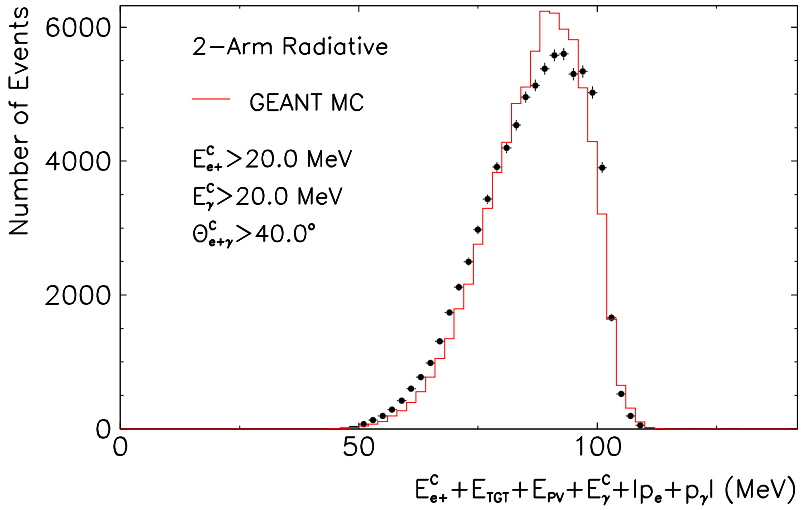


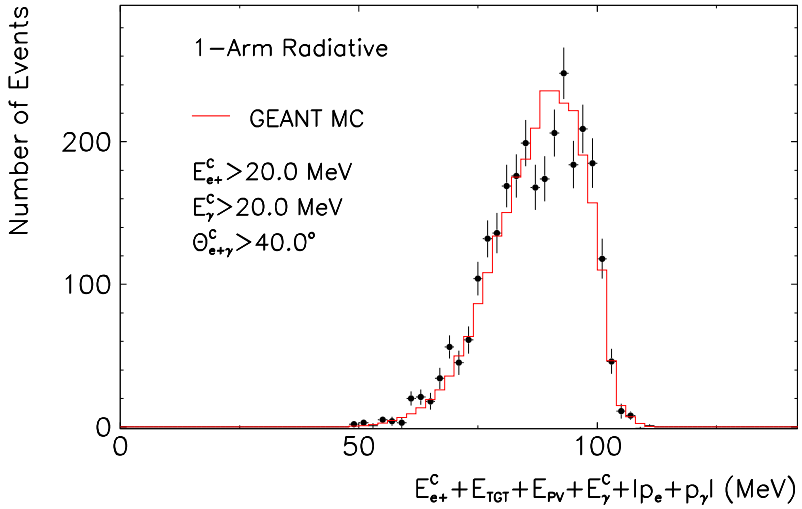




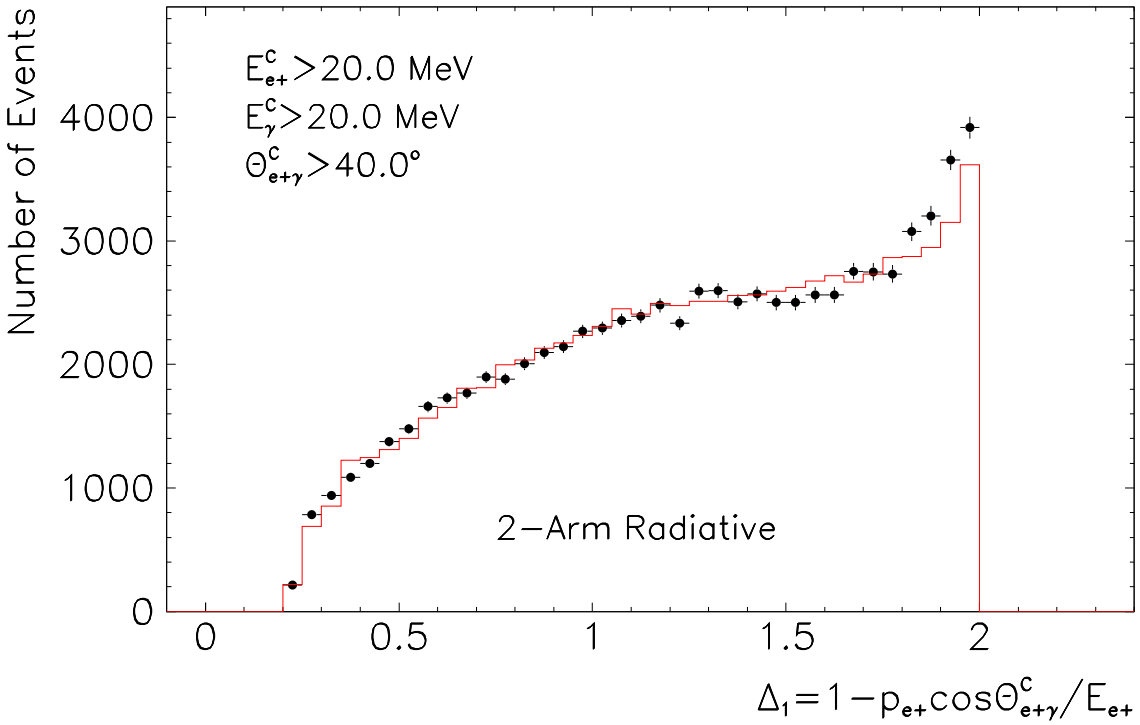
A Look at Muon Decays

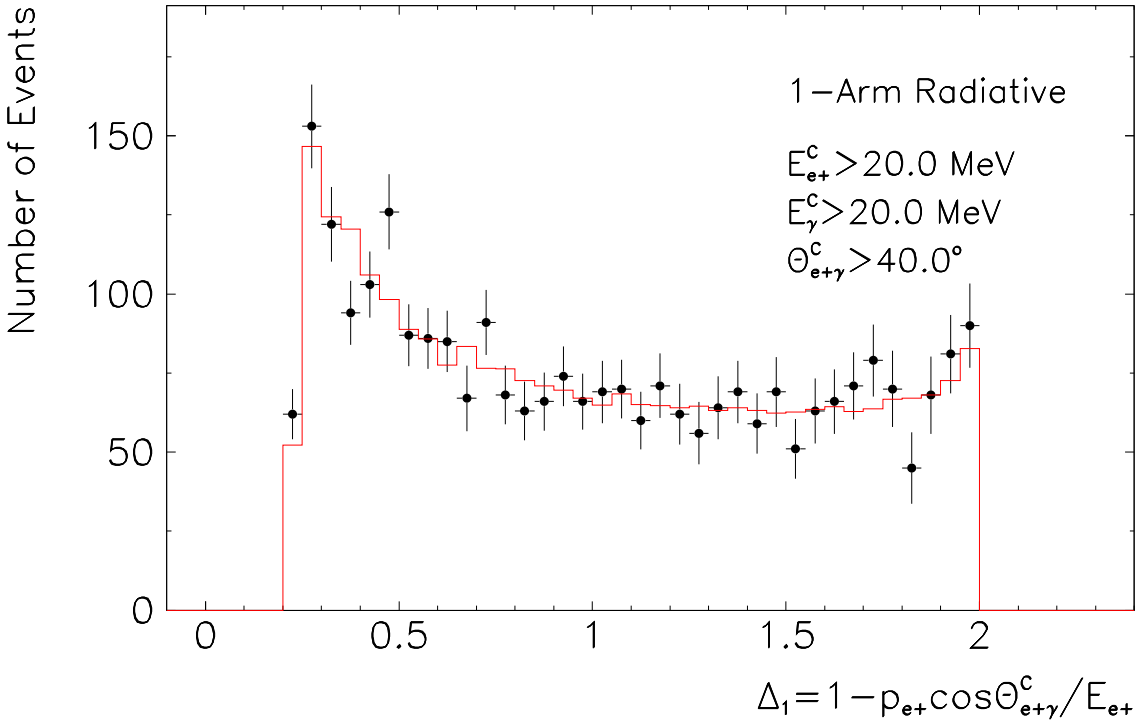






More on Radiative Muon Decays





What We've Learned

- Very high precision experiments are needed in order to study truly rare processes.
- There appear to be no surprises in the pion beta decay channel.
- The accepted description of the $\pi \to e\nu\gamma$ process is inadequate, and will require revision.

Plans for the Future

- Bring analysis up to the proposed level of uncertainty.
- Prepare new proposal and collaboration for a precise $\pi \to e\nu$ measurement.
- We are actively considering a new search for the $\pi^0 \to \gamma\gamma\gamma$ decay using the PIBETA apparatus.

http://pibeta.phys.virginia.edu/
http://pibeta.web.psi.ch/