# Precise Measurement of the $\pi^+ \to e^+\nu$ Branching Ratio

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for the PEN Collaboration

1. motivation
2. the PIBETA apparatus, previous results
3. results of the October 2005 beam development run
4. proposed measurement method

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# Followup to the PIBETA Experiment

PIBETA program (precision checks of SM and QCD predictions):

- $\pi^+ \to \pi^0 e^+ \nu_e$—main goal
  - ∘ SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or $e^+e^-$)
  - ∘ $F_A/F_V$, $\pi$ polarizability ($\chi$PT prediction)
  - ∘ tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or $e^+e^-$)
  - ∘ departures from $V - A$ in $\mathcal{L}_{\rm weak}$

⇒ $\pi^+ \to e^+ \nu_e$ – 2nd phase

- ∘ $e$-$\mu$ universality
- ∘ pseudoscalar coupling besides $V - A$
- ∘ massive neutrino, Majoron, ...

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

Marciano and Sirlin, Phys. Rev. Lett. **71** (1993) 3629:

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

Decker and Finkemeier, Nucl. Phys. B **438** (1995) 17:

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

Experiment, world average (PDG 2004):

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

# $\pi \longrightarrow e\nu$ decay: most recent experiments

Branching ratios of $\pi_{e2(\gamma)}$ decay most recently measured at TRIUMF and PSI.

TRIUMF: [D.I. Britton et al., PRL **68**, 3000 (1992)]

$$B(\pi_{e2(\gamma)})_{\rm exp} = [1.2265 \pm 0.0034(\mathsf{stat}) \pm 0.0044(\mathsf{syst})] \times 10^{-4}\,,$$

PSI: [ G. Czapek et al., PRL **70**, 17 (1993)]

$$B(\pi_{e2(\gamma)})_{\rm exp} = [1.2346 \pm 0.0035(\mathsf{stat}) \pm 0.0036(\mathsf{syst})] \times 10^{-4}\,.$$

The $\pi_{e2(\gamma)}$ branching ratio world average presently provides the best test of $\mu$–$e$ universality.

# Lepton universality

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

$$\left(\frac{g_e}{g_\mu}\right)_W = 0.999 \pm 0.011 \quad \text{and} \quad \left(\frac{g_\tau}{g_e}\right)_W = 1.029 \pm 0.014\,.$$

## *Departures from lepton universality*

Various models beyond the SM predict flavor non-universal suppressions of the lepton coupling constants in $W\ell\nu$:

$$g_\ell \rightarrow g'_\ell = g_\ell(1 - \frac{\epsilon_\ell}{2}) \qquad \text{where} \qquad \ell = e, \mu, \tau$$

Linear combinations constrained by $W, \tau, \pi, K$ decays are:

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

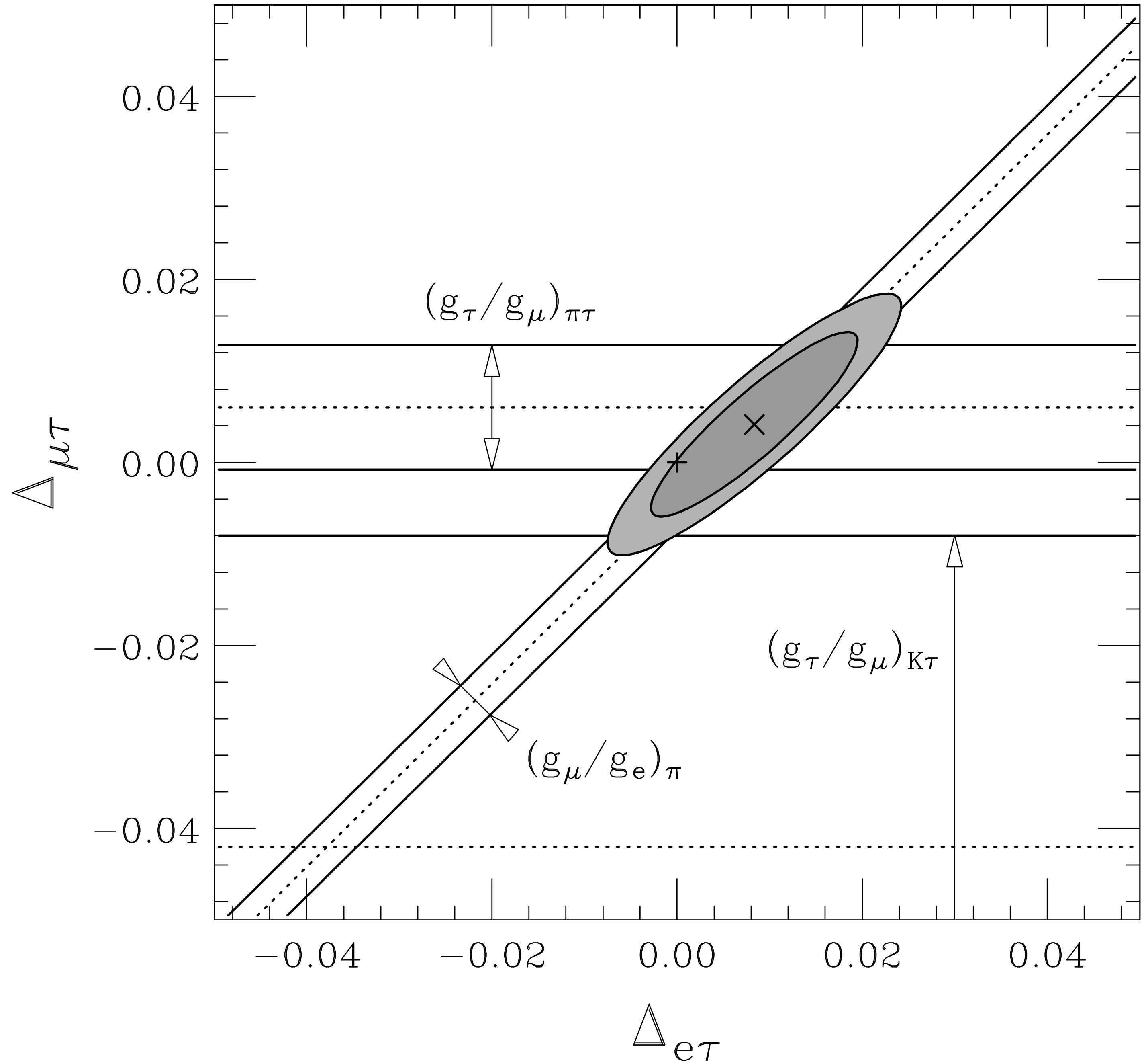
Two of the three are independent; experimental constraints are on:

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

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

# Constraints on Pseudoscalar and Scalar Couplings

P coupling destroys the V−A helicity suppression; in the extreme limit:

$$\Gamma_{\pi e2(\gamma)}/\Gamma_{\pi\mu2(\gamma)} \to 5.5\,.$$

Nonzero $C_P$ could be related to: extra Higgs ($m_{h+}$), P leptoquarks ($m_{pl}$), vector leptoquarks ($m_{pV}$), SUSY particles.

Current $2\sigma$ limits [following Bryman, Comm Nuc Part Phys **21** (93) 101]:

$$-7\times10^{-3} \le \frac{C_P}{f_\pi m_{\rm e}} \le 2.5\times10^{-3}\,,$$

$$m_{h^+} > 2\,{\rm TeV}\,,\quad m_{pl} > 1.3\,{\rm TeV}\,,\quad m_{pV} > 220\,{\rm TeV}\,.$$

Indirect constraints on scalar coupling [Campbell & Maybury, Nuc Ph B **709** (05) 419]

$$-1.2\times10^{-3} \le C_S \le 2.7\times10^{-4}\,.$$

# Goal of the Experiment

To measure the branching ratio $B(\pi^+ \to e^+\nu(\gamma)) = B_{e2}$ decay with

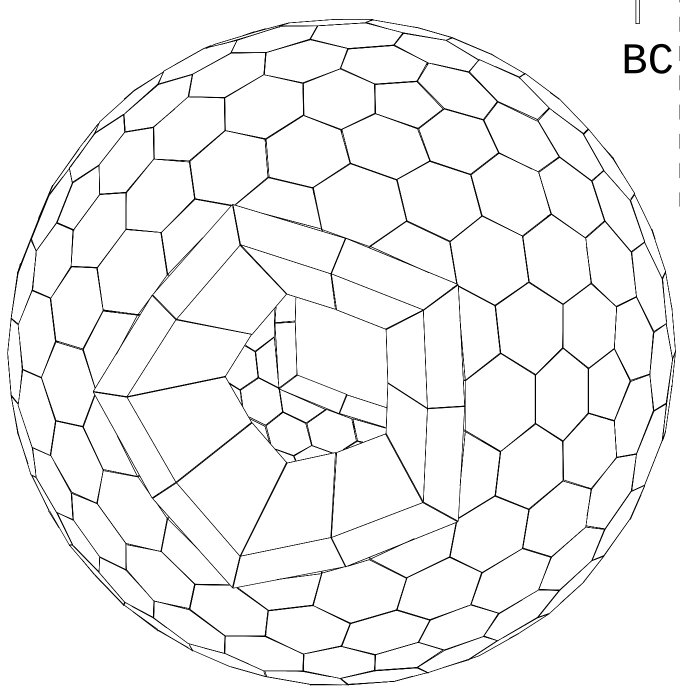
$$\frac{\Delta B_{e2}}{B_{e2}} \leq 5 \times 10^{-4}$$

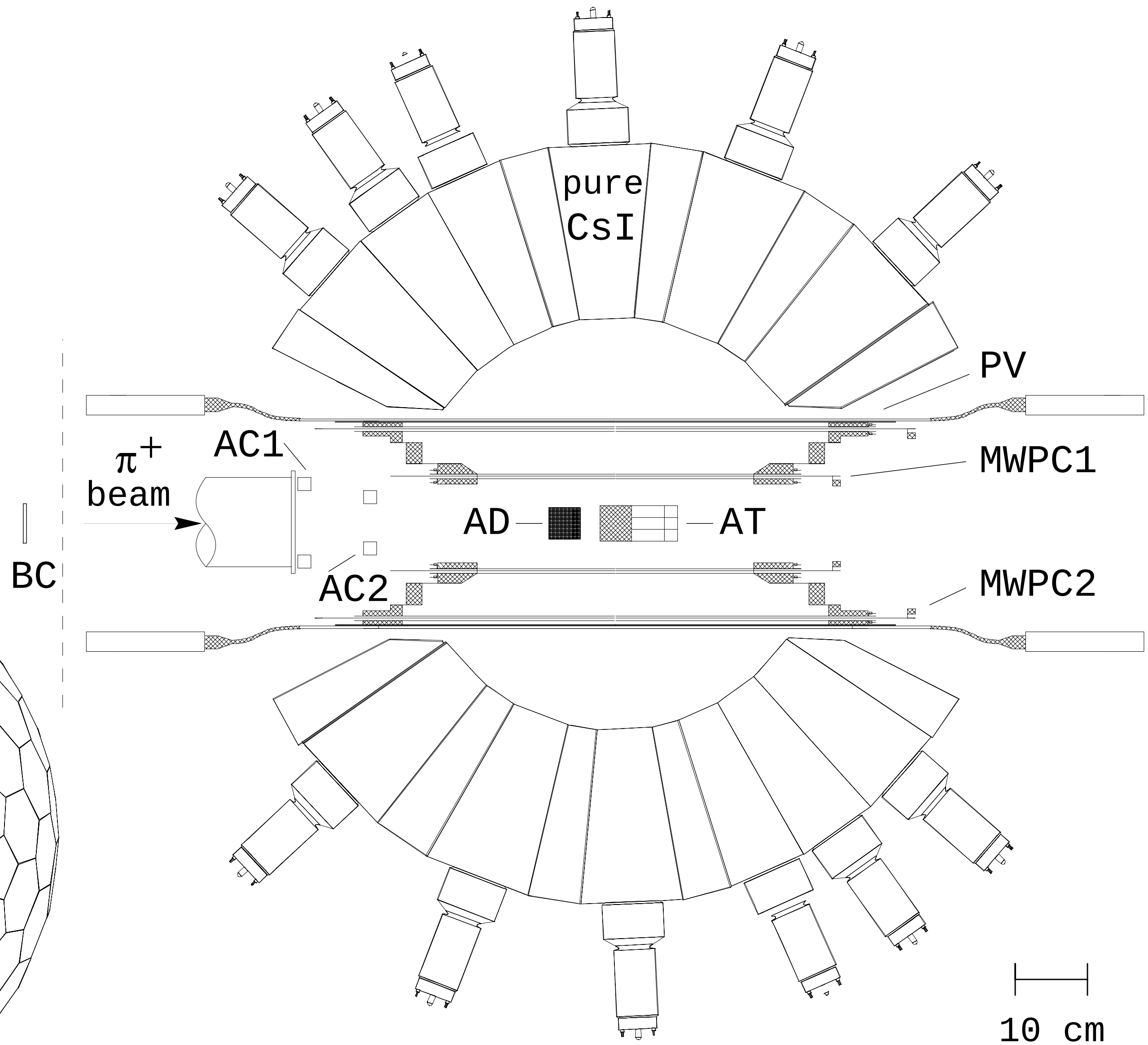
Challenges:

- Signal definition and suppression of backgrounds,
- Trigger rate that allows accumulation of a sample of $\sim 3 \times 10^7$ clean events in a reasonable time,
- Control sources of systematic uncertainty at a few parts in $10^4$.

*The PIBETA Apparatus:*

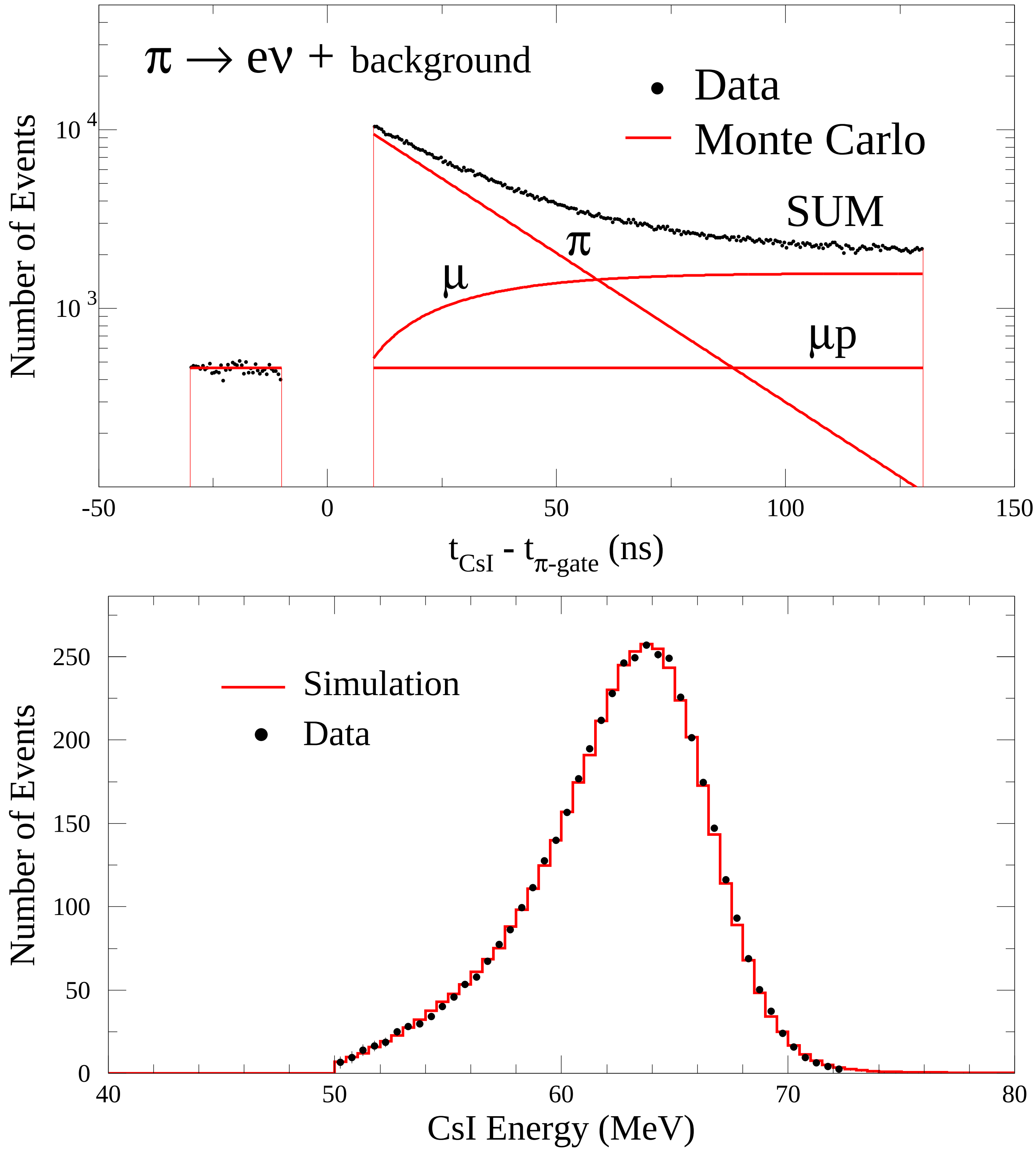
- ∘ stopped $\pi^+$ beam
- ∘ segmented active tgt.
- ∘ 240-det. CsI(p) calo.
- ∘ central tracking
- ∘ digitized PMT signals
- ∘ stable temp./humidity
- ∘ cosmic $\mu$ antihouse





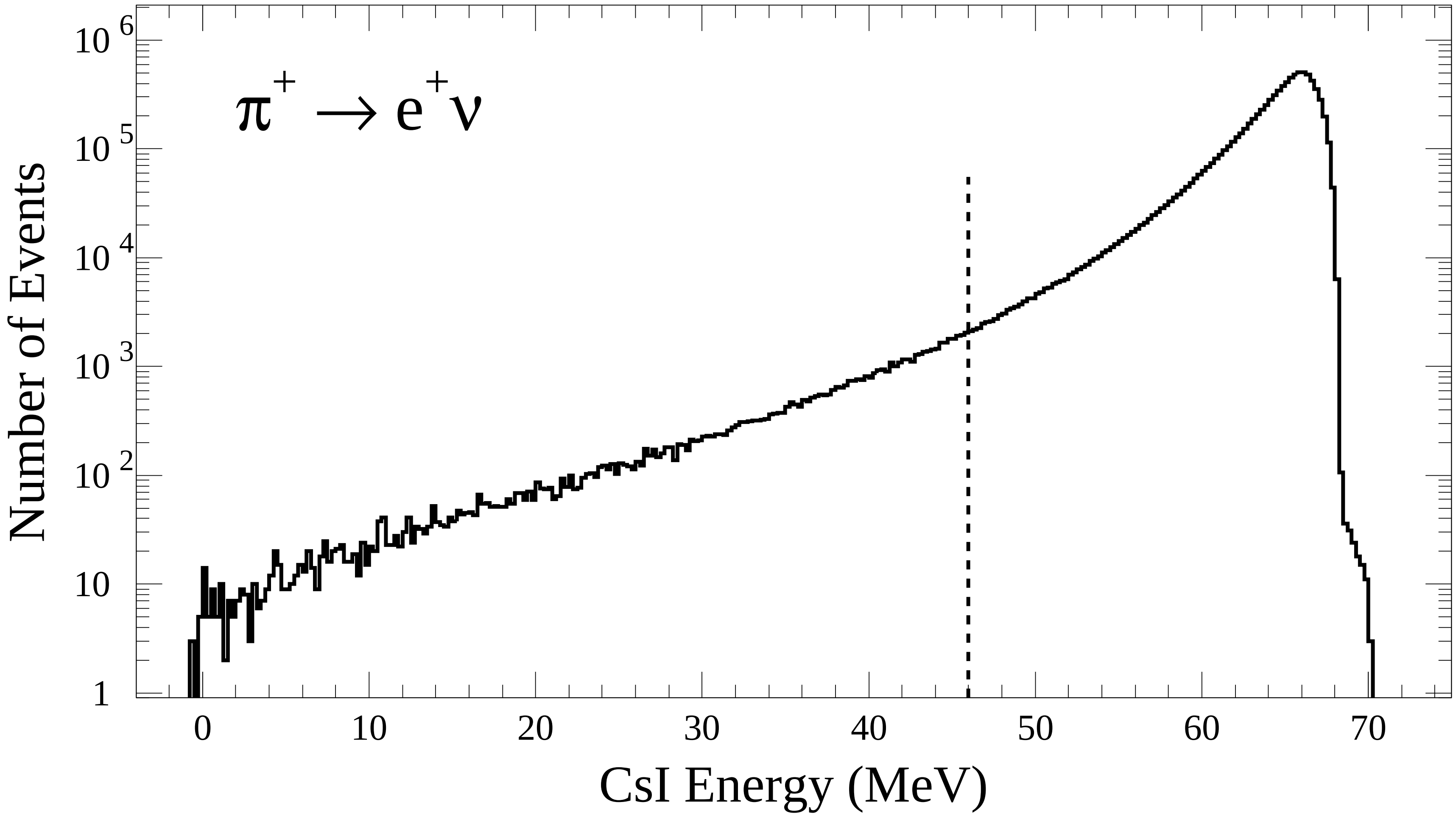
## Proposed Method – the Basics

- Use $\pi \to \mu \to e$ decays for normalization. $\Rightarrow$ Important systematics cancel.
- Use stopped pions of the lowest momentum feasible (Oct 2005 beam test)
- Use a $\sim$180 ns long Pion Gate which samples 30 ns before $t_{\pi\mathrm{stop}}$.
- Run with several unbiased triggers, most importantly, one-arm High- (HT1) and Low-threshold (LT1) triggers.
  Pre-scale the LT1 trigger by a factor ($f$).
- Measure "energy tail fraction" using prescaled LT1 trigger.
- Rely on energy and time resolution in the Target Counter to resolve $\pi \to e$ from $\pi \to \mu \to e$ event types. $\Rightarrow$ Use fast waveform digitization.



π → eν + background
Data
Monte Carlo
SUM
π
μ
μp
Number of Events
t_CsI - t_π-gate (ns)
-50
0
50
100
150
Simulation
Data
Number of Events
CsI Energy (MeV)
40
50
60
70
80
0
50
100
150
200
250

## $\pi \longrightarrow e\nu$ energy tail (GEANT4)




Tail fraction with a 46 MeV threshold is below $\boldsymbol{\epsilon = 0.02}$.

# Trigger Rates and Statistical Uncertainties

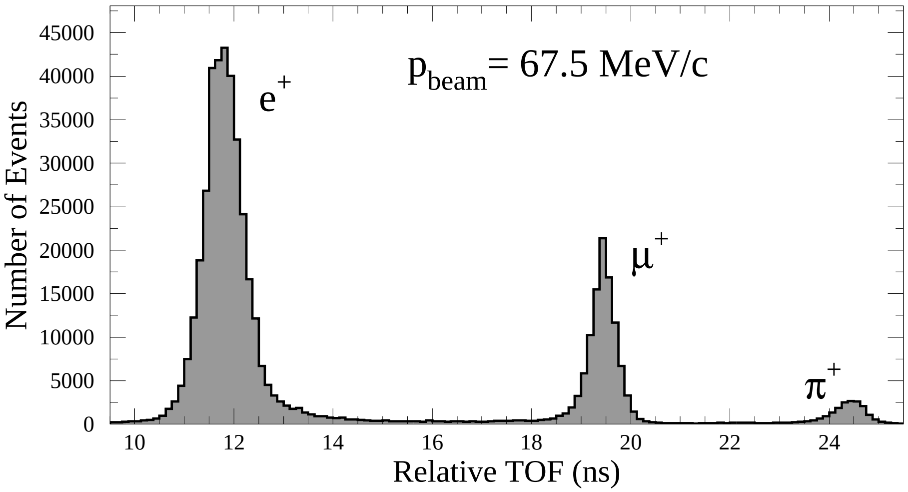
In our scheme, the relative statistical uncertainty is given by:

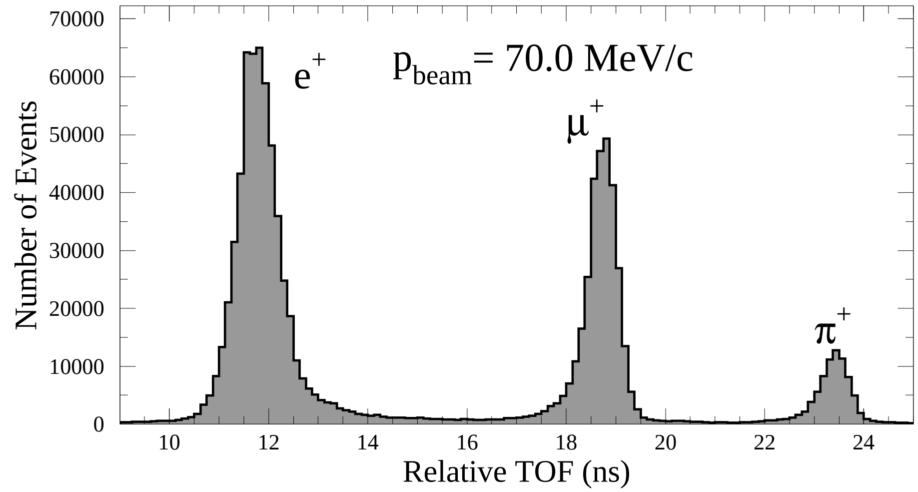
$$\frac{\Delta N_{e2}}{N_{e2}} = \left[\frac{1}{N_p} + \frac{\epsilon^2}{N_t'} + \frac{\epsilon^2}{N_p'}\right]^{1/2} = \left[\frac{f + \epsilon + \epsilon^2}{f N_p}\right]^{1/2} .$$

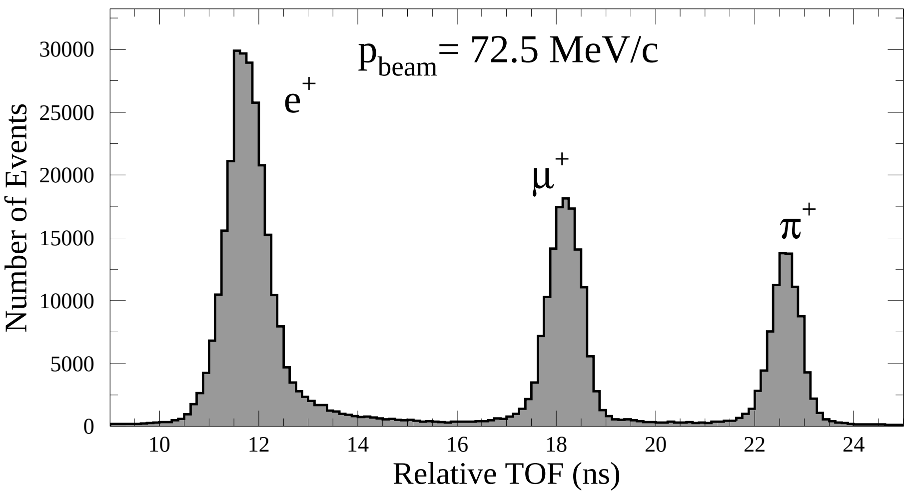
Requiring $\Delta N_{e2}/N_{e2} \leq 2 \times 10^{-4}$ and assuming $R_{\pi\mathrm{stop}} \simeq 2 \times 10^4/\mathrm{s}$:

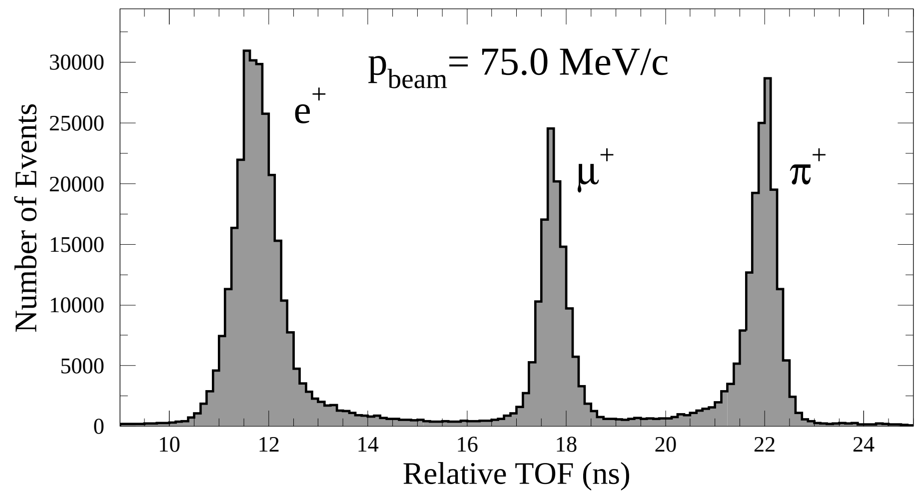
| $\boldsymbol{N_p}$ | $\boldsymbol{f}$ | $\boldsymbol{r_{\mathbf{trig}}}$ ($\mathrm{s}^{-1}$) |
|---|---|---|
| $\mathbf{2.7 \times 10^7}$ | $\mathbf{1/4}$ | $\sim \mathbf{280}$ |
| $\mathbf{2.9 \times 10^7}$ | $\mathbf{1/8}$ | $\sim \mathbf{145}$ |
| $\mathbf{3.4 \times 10^7}$ | $\mathbf{1/16}$ | $\sim \mathbf{75}$ |
| $\mathbf{4.4 \times 10^7}$ | $\mathbf{1/32}$ | $\sim \mathbf{45}$ |

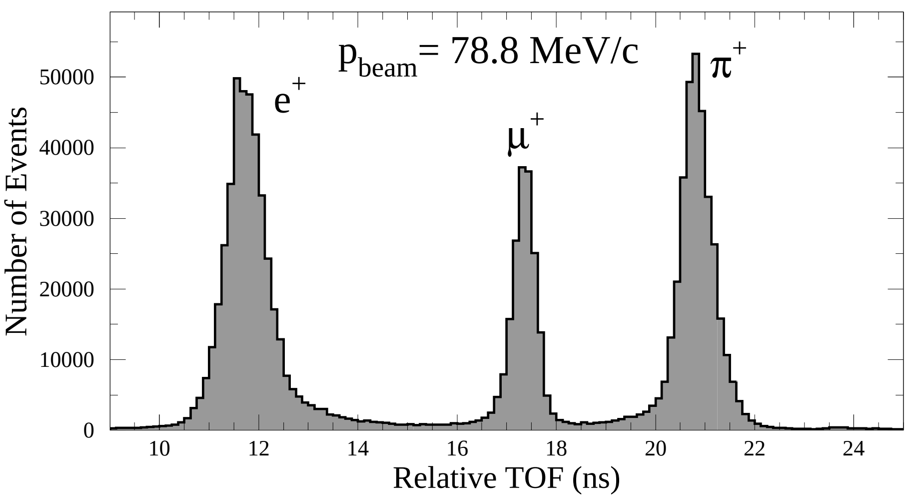
This requires ∼6 months of **net** "production" beam time to acquire the statistics. Ramp-up and overheads will increase this time.



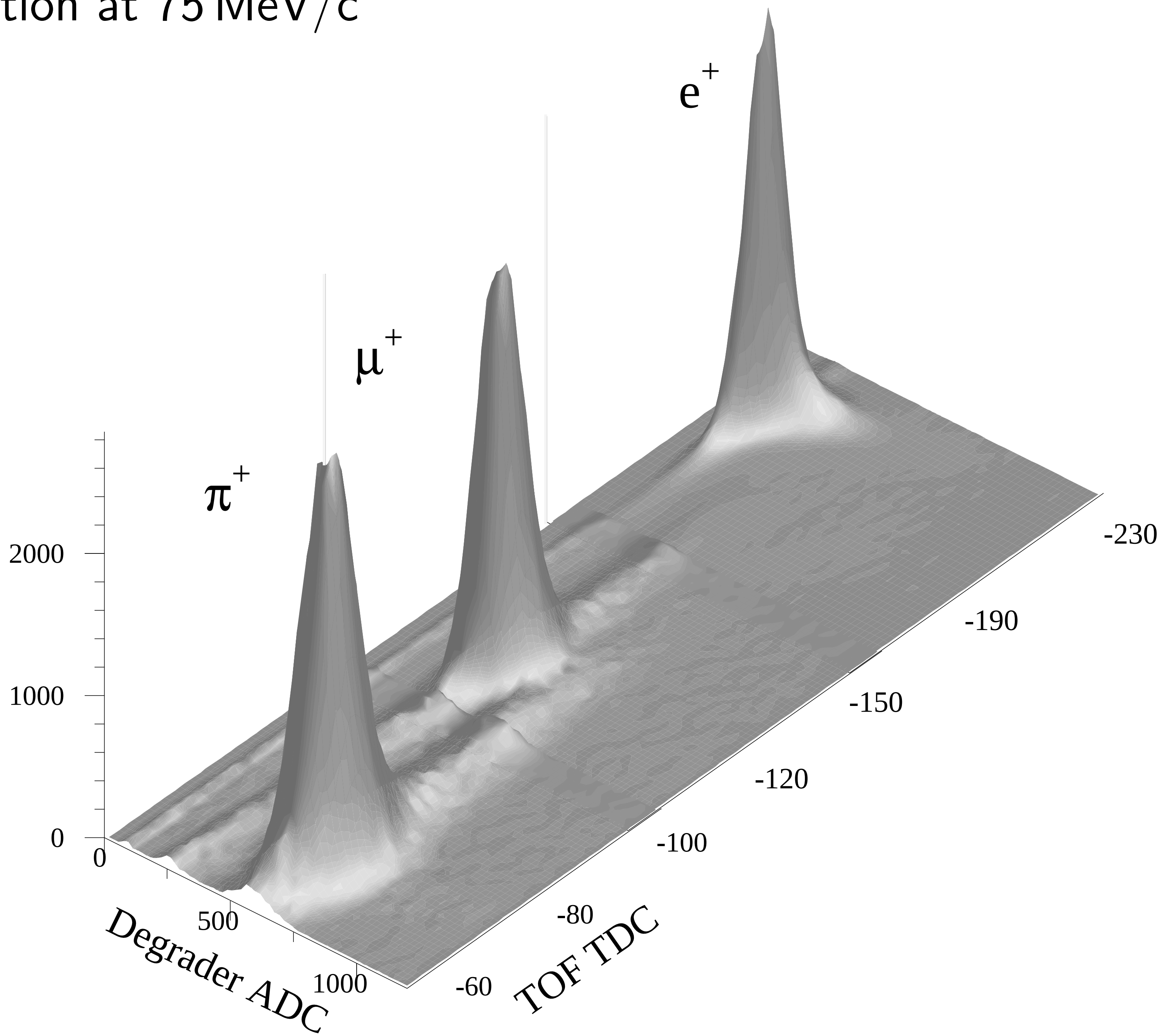




TOF between BC and TGT,

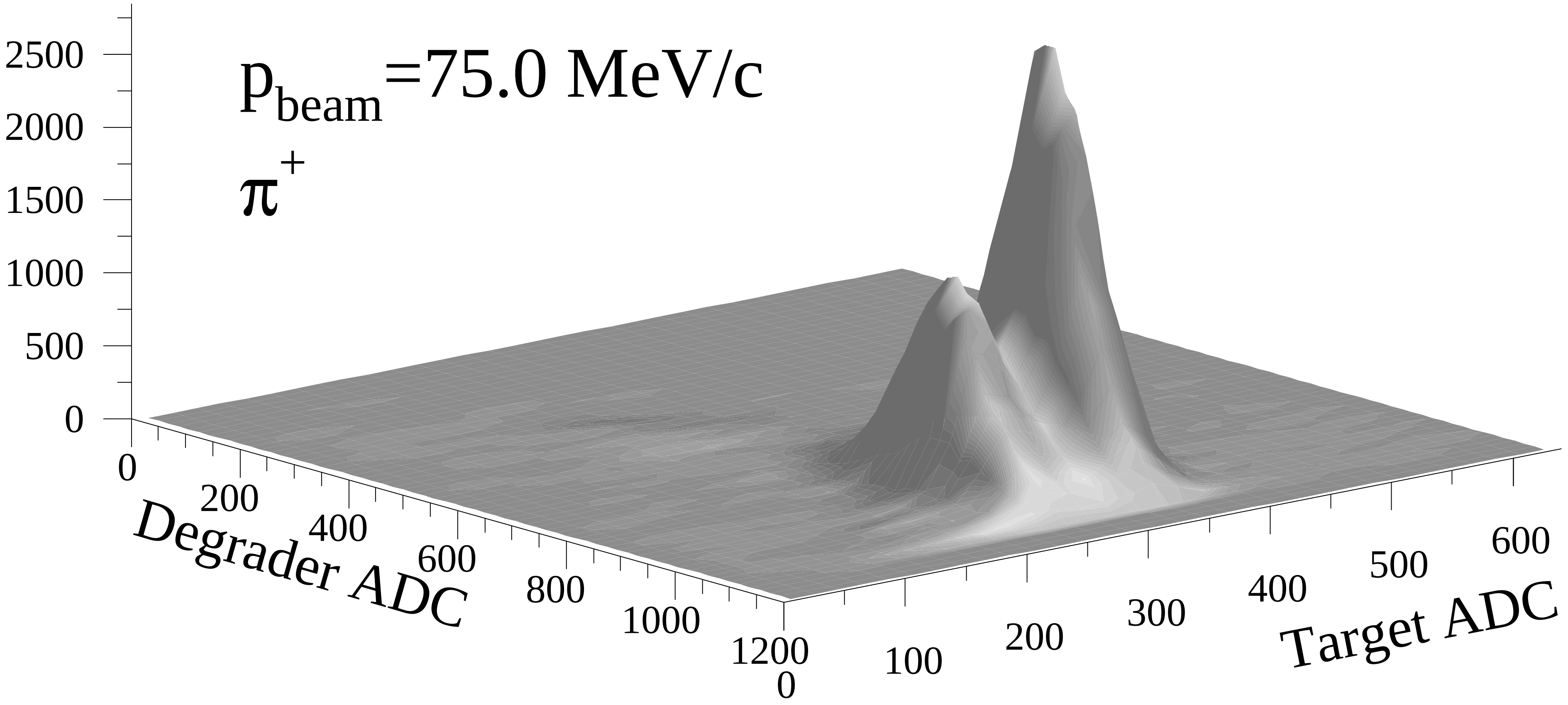
$\sim$3.5 m flightpath

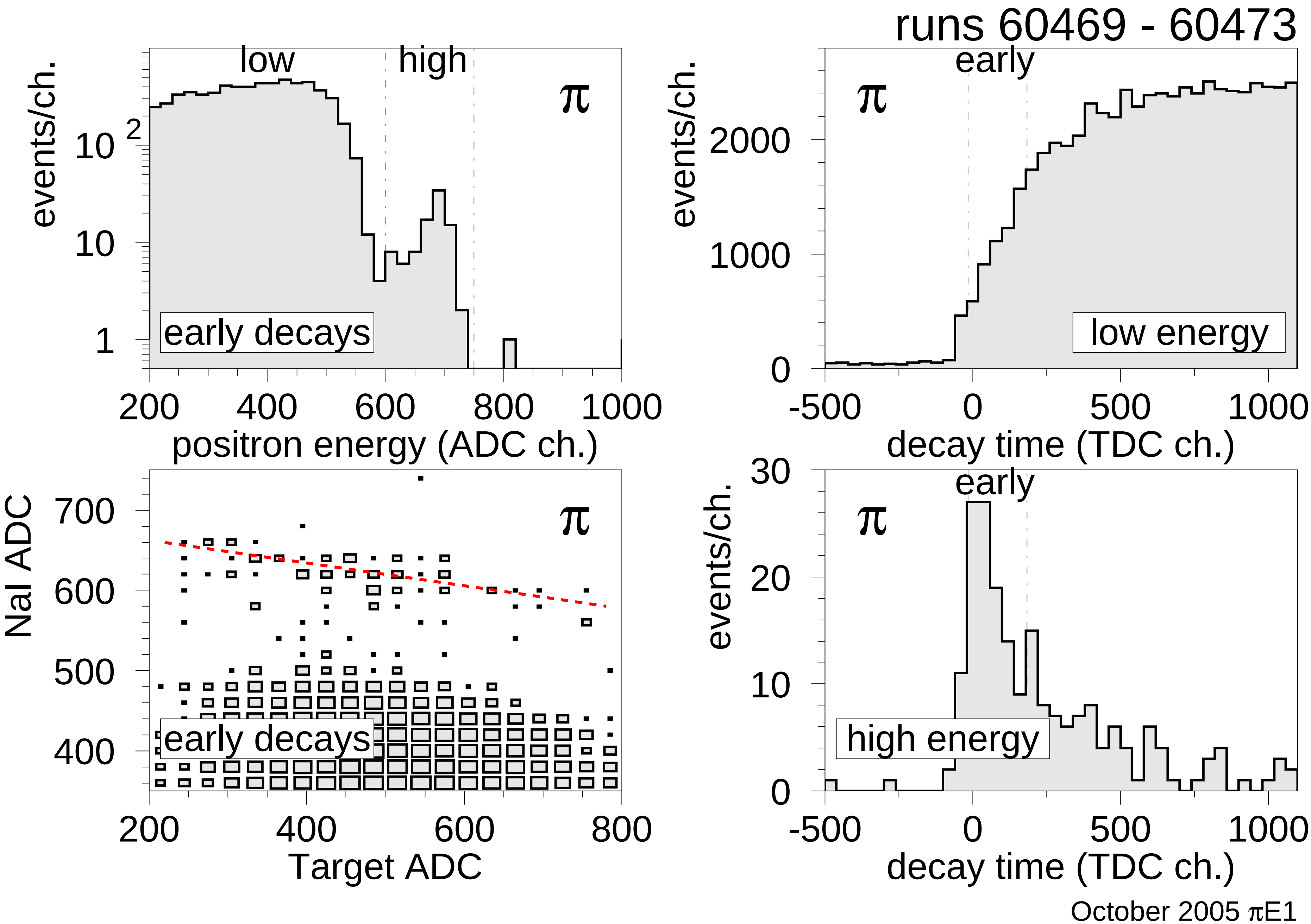
Oct 2005 test run

# $\pi$, $\mu$, e separation at 75 MeV/c



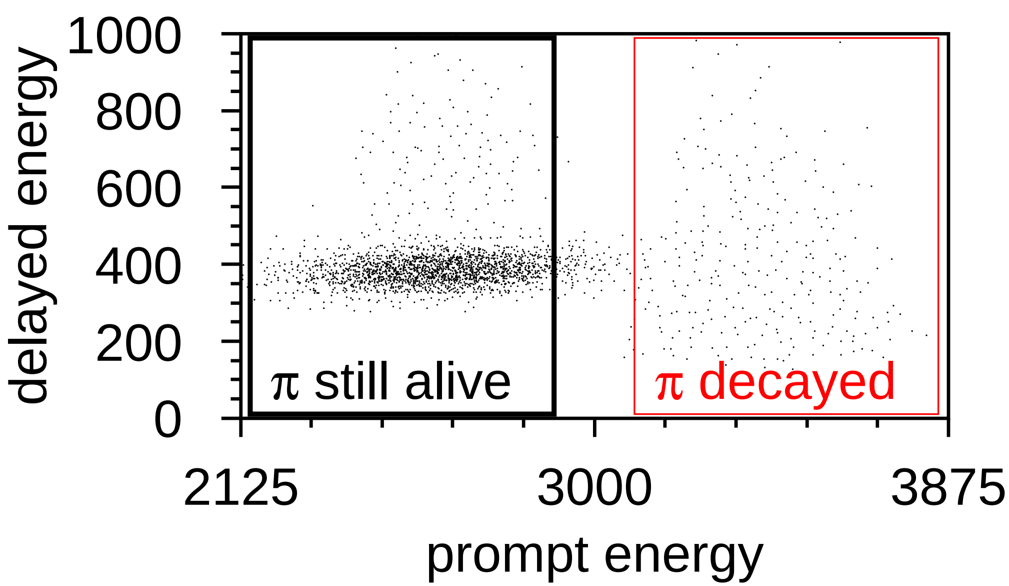
## Separation between $\pi$-stop and $\pi \longrightarrow \mu$ events in the Target

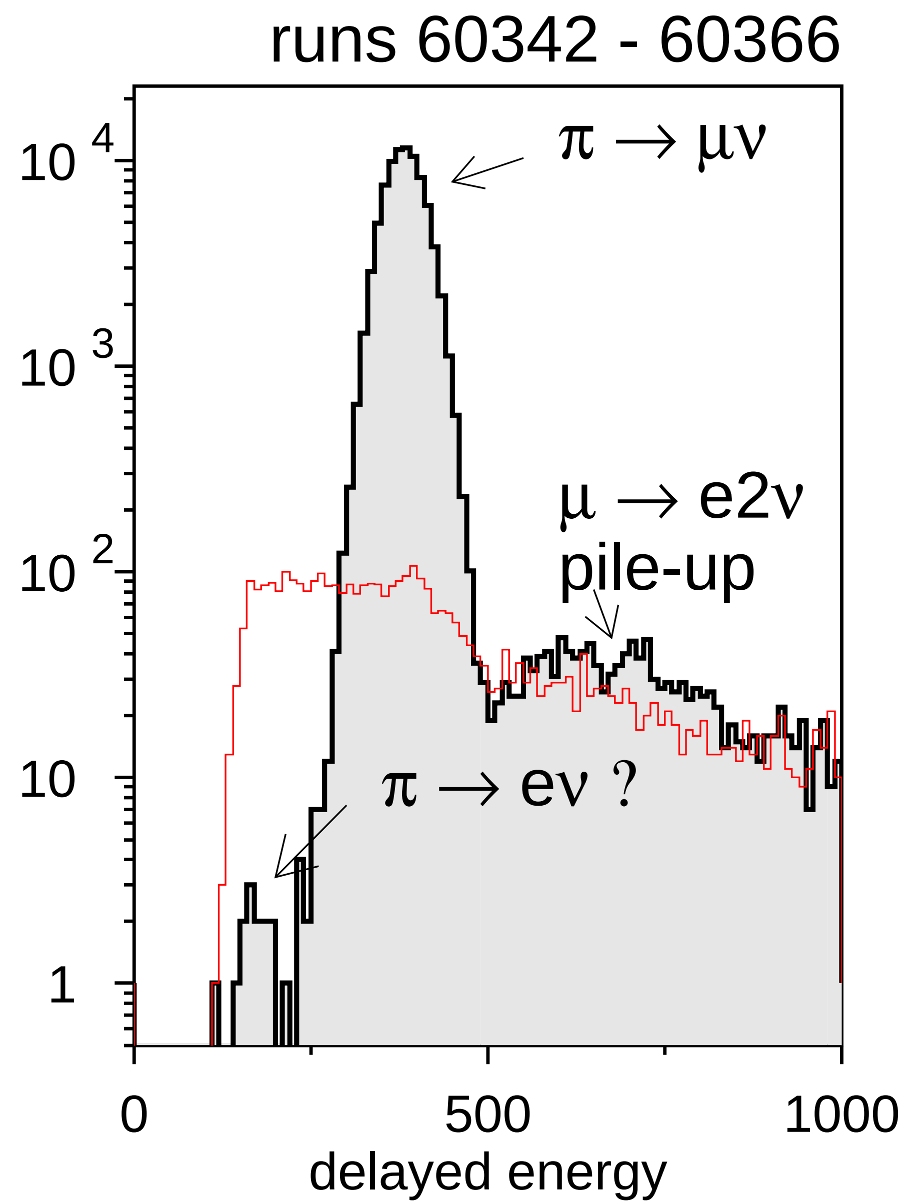


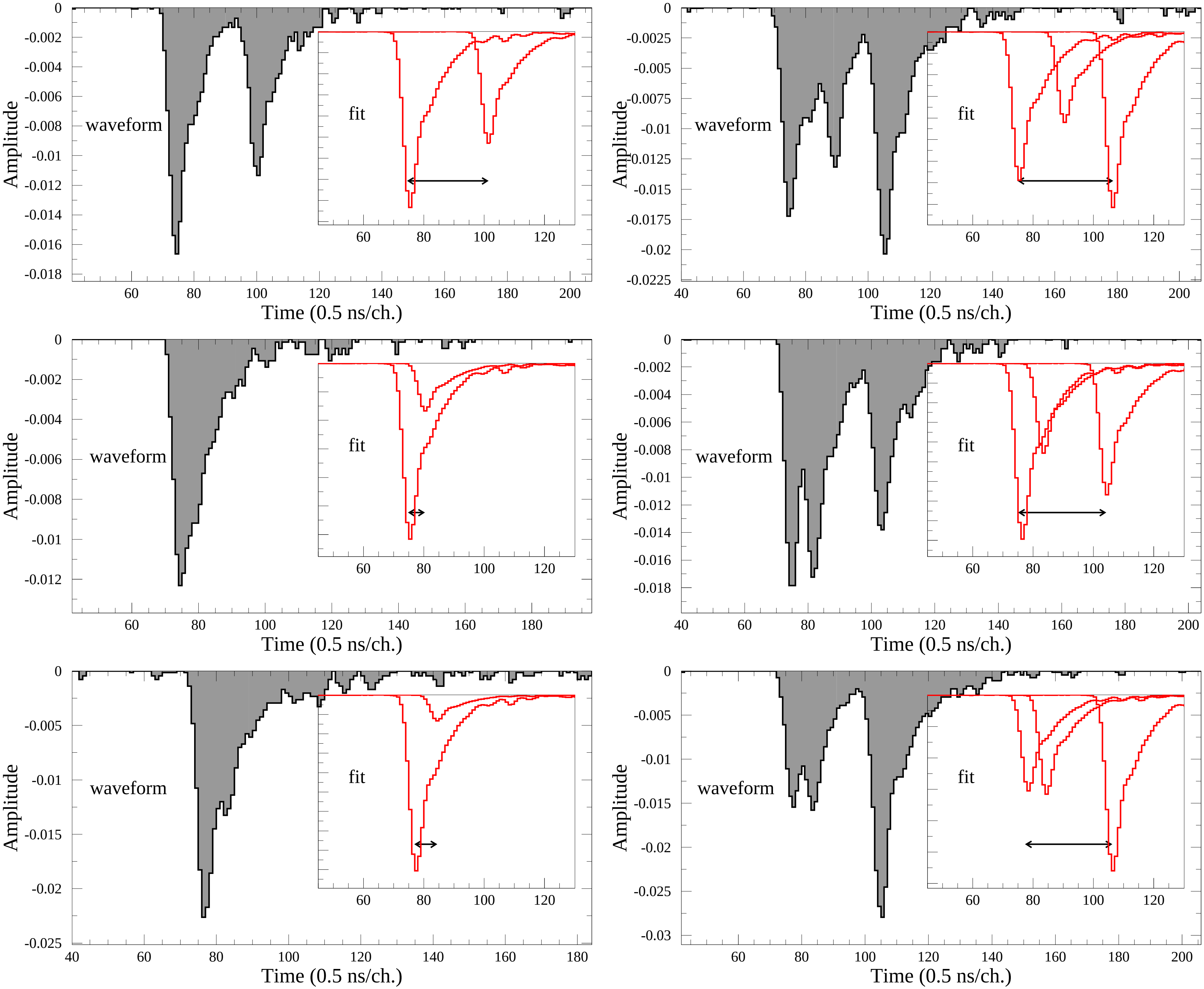



TGT + NaI energy sum histogram October 2005 test run

pion time of flight selected
events with a second target signal





waveform
fit
Amplitude
Time (0.5 ns/ch.)
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
-0.018
60
80
100
120
140
160
180
200
waveform
fit
Amplitude
Time (0.5 ns/ch.)
0
-0.0025
-0.005
-0.0075
-0.01
-0.0125
-0.015
-0.0175
-0.02
-0.0225
40
60
80
100
120
140
160
180
200
waveform
fit
Amplitude
Time (0.5 ns/ch.)
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
60
80
100
120
140
160
180
waveform
fit
Amplitude
Time (0.5 ns/ch.)
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
-0.018
40
60
80
100
120
140
160
180
200
waveform
fit
Amplitude
Time (0.5 ns/ch.)
0
-0.005
-0.01
-0.015
-0.02
-0.025
40
60
80
100
120
140
160
180
waveform
fit
Amplitude
Time (0.5 ns/ch.)
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
60
80
100
120
140
160
180
200

# SYSTEMATICS

- Pion and muon decay event discrimination. Required:
  - $\sigma_E \leq 700\,\mathrm{keV}$, or L.O. $\geq 40\,\mathrm{pe/MeV}$, and
  - excellent timing (2-peak) resolution [see below].

- Uncertainties in the muon decay normalization
  - LT1 CsI threshold: $5 \longrightarrow \sim 1\,\mathrm{MeV}$
  - energy scale calibration: in PIBETA running we had $\Delta g/g \leq 2 \times 10^{-3}$;
  - assuming no improvement, and with a 5 MeV LT1 threshold we get $\Delta N_M/N_M = 1 \times 10^{-4}$

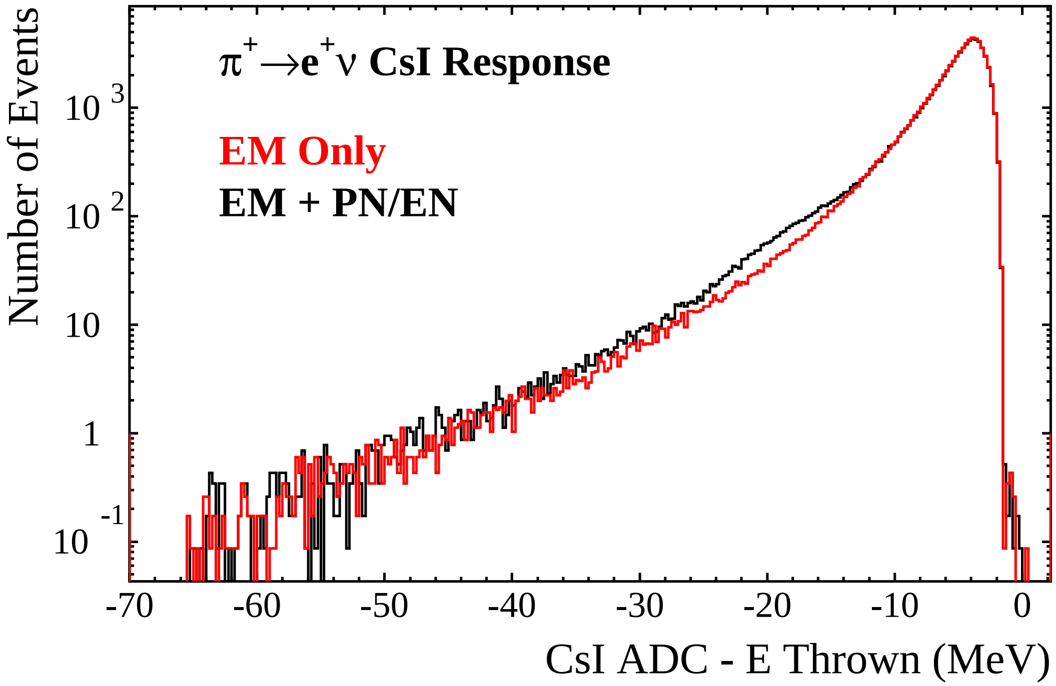
# SYSTEMATICS (cont'd)

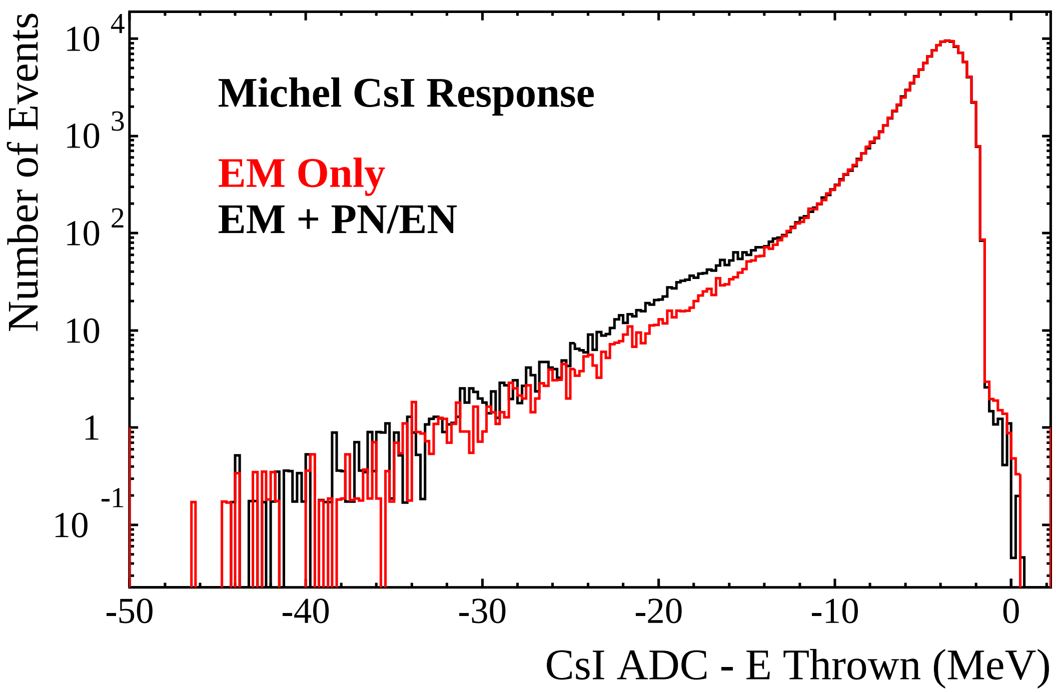
- Ratio of acceptances for $\pi_{e2}$ and Michel decay events
  - Radiative muon decay yield: we measured with $9 \times 10^{-5}$ accuracy (R-04-01).

    Dominant error external–should be reduced to $\sim 3 \times 10^{-5}$.
  - Time-zero definition and ratio $f_{\pi d}(T)/f_{sd}(T)$.

    Requires 5 ps resolution in relative offset between $\pi_{e2}$ and $\pi \rightarrow \mu \rightarrow e$ data sets; PIBETA achieved 22 ps.

    Required: faster TGT detector, fast, low-noise waveform digitization; will use $t$(three beam detectors).
  - Nuclear interactions in the detector (discussion follows)




GEANT4 Calculations including photonuclear and electronuclear interactions, compared with electromagnetic-only showers, with source $\pi \longrightarrow e\nu$ and $\mu \longrightarrow e\nu\bar{\nu}$ positrons.

# Breakdown of photo/electro-nuclear effects

We have used FLUKA, GEISHA; recently switched to latest hi-precision GEANT4 data sets G4EMLOW.3.0 ($\gamma$,e-nucl., 10 eV and up) and G4NDL.3.7 (neutron el./inel./capture 10 eV and up).

Relevant photo/electro-nuclear fractions (all will be measured)

| $E_{th}$ (MeV) | % below $E_{th}$ $\pi_{e2}$ | % below $E_{th}$ Michel |
|---|---|---|
| 54 | 0.84 (3) | n/a |
| 46 | 0.18 (3) | n/a |
| 5 | $<$0.01* | $\sim$0.02* |
| 1 | $\ll$0.01* | $<$0.01* |

* Conservative upper bounds; statistical uncertainties in simulation results still too large; we're currently running higher-statistics simulations.

# Plan of Activities and Beamtime Use

1. Spring/summer 2006: order new equipment, refurbish detector and DAQ parts.

2. Fall 2006: run with full detector, waveform digitizer (6 weeks):

   (a) shake down new equipment

   (b) determine optimal $p_{\pi}$, $R_{\pi\mathrm{stop}}$ and $f$.

3. Winter/spring 2007: analyze data, make required adjustments

   Summer/fall: 2007 run "production" for ∼4 months.

4. Repeat the same cycle in 2008; assuming no major problems, end data taking in 2008.