Seeking New Physics with the $\pi \to e\nu$ Branching Ratio

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Overview of Light Particle Rare Decay Experiments

State of the art: single event sensitivity, 10^{-12}

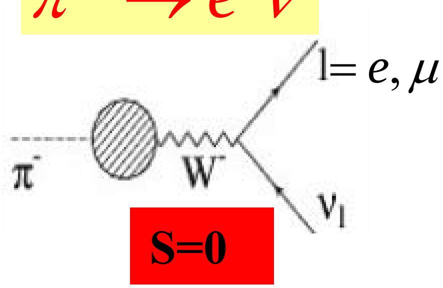
Exotic Searches ***New physics if seen; SM effects are negligible.***	$K_L^0 \to \mu\, e$ *LFV* $\mu \to e\gamma$ *LFV* $\mu^- N \to e^- N$ *LFV* $K^+ \to \pi^+ f$ *"Axions"*
SM Parameters and BSM Physics ***New physics if deviations from well-calculated SM predictions occur.***	$\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$ Universality $\pi^+ \to \pi^0 e\nu$ $\lvert V_{ud} \rvert$ $K_L^0 \to \mu^+ \mu^-$ $\lvert V_{td} \rvert$ $K^+ \to \pi^+ \nu \bar{\nu}$ $\lvert V_{td} \rvert$ $K_L^0 \to \pi^0 \nu \bar{\nu}$ CP violation
Low Energy QCD Chiral Perturbation Theory	Radiative decays $K_L^0 \to ee$

$e-\mu-\tau$ Lepton Universality

Standard Model: e, μ, τ have identical electroweak gauge interactions.

Differ only in mass and coupling to Higgs boson.

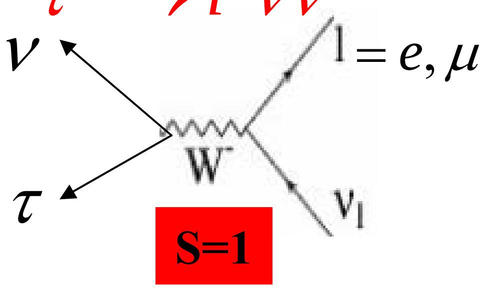
$\pi^+ \to e^+\nu$



$$R^0_{e/\mu} \equiv \frac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(\pi^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2} \frac{\left(1-\frac{m_e^2}{m_\pi^2}\right)}{\left(1-\frac{m_\mu^2}{m_\pi^2}\right)} = 1.284x10^{-4}$$

Independent of f_π, V_{ud}.

$\tau^+ \to l^+\nu\bar{\nu}$



$$R^\tau_{e/\mu} = (1-\frac{8m_\mu^2}{m_\tau^2}\ldots) = 1.0282$$

Unless... new physics does not respect universality.

Universality Tests

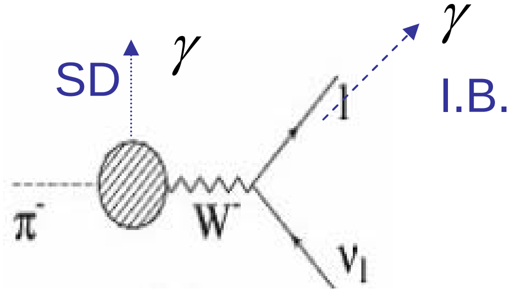
Mode	g_e/g_μ
$\pi\to e\nu/\pi\to\mu\nu$	0.9983 ± 0.0015
$K\to e\nu/K\to\mu\nu$	1.012 ± 0.010
$\tau\to e\nu\nu/\tau\to\mu\nu\nu$	0.9999 ± 0.0021
$\nu e/\nu\mu$ scattering	1.10 ± 0.05
W decays	0.999 ± 0.011
$K^{+/0}\to\pi e\nu/K^{+/0}\to\pi\mu\nu$	1.0018 ± 0.0025*

*M. Moulson, Flavinet Mini-workshop, Frascati 2007

$\pi^+ \to e^+\nu$

Kinoshita (1959), **Marciano and Sirlin** (1976, 1995), Finkemeir (1995)

Radiative Corrections; Inner Bremsstrahlung, and Structure-Dependent Radiation:



$$\Gamma(\pi \to l\bar{\nu}_l(\gamma)) = \frac{G_\mu^2 |V_{ud}|^2}{8\pi} f_\pi^2 m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2 \left[1 + \frac{2\alpha}{\pi}\ln\left(\frac{m_Z}{m_\rho}\right)\right] \quad \gamma$$

$$\times \left[1 - \frac{\alpha}{\pi}\left\{\frac{3}{2}\ln\left(\frac{m_\rho}{m_\pi}\right) + C_1 + C_2 \frac{m_l^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_l^2} + C_3 \frac{m_l^2}{m_\rho^2} + \cdots\right\}\right]\left[1 + \frac{\alpha}{\pi}F(x)\right]$$

$$\left\lfloor + \pi \;\; \text{Structure-dependent } \pi^+ \to e^+\nu\gamma \text{ terms} \right\rfloor$$

-4% for l=e

where $G_\mu = 1.16637(1)\times 10^{-5}\,GeV^{-2},\; V_{ud} = 0.9738$

But, most factors cancel in the ratio

$$R^{th}_{e/\mu} = \frac{\Gamma\left(\pi \to e\nu + \pi \to e\nu\gamma\right)}{\Gamma\left(\pi \to \mu\nu + \pi \to \mu\nu\gamma\right)}$$

$$R^{th}_{e/\mu} = R^{0}_{e/\mu}\left\{1 + \frac{\alpha}{\pi}\left[F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + C_2\frac{m_\mu^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_\mu^2} + C_3\frac{m_\mu^2}{m_\rho^2}\right]\left(+SD_\pi\right)\right.$$

$8x10^{-8}$

F : kinematic factors

C_2=3.1 (Terent'ev)

C_3 : Small but

Model dependent

Marciano : 0 ± 10

Pure Structure Dependent (SD) $\pi \to e\nu\gamma$ corrections are not helicity suppressed but are small and known for π decay:

$\pi^+ \to e^+ \nu$

$$R^{th}_{e/\mu} = \left(1.2353 \pm 0.0004\right) x10^{-4}$$

Marciano $\to \pm 0.0001$?

V. Cirigliano (TBA*)

Possibly the most accurately calculated decay process involving hadrons .

$K^+ \to e^+ \nu$

$$R^{th}_{K\to e/\mu} = \left(2.472 \pm 0.001^*\right) x10^{-5}$$

Helicity suppression 5x $\pi^+ \to e^+ \nu$

Finkemeier(1995)

Structure dependent radiation not included.

Experiments

$\pi \to e\nu$

$R_{e/\mu}^{\exp \pi}$ $(\pm 0.4\%)$

$1.2265(34)(44)x10^{-4}$ TRIUMF (1992)

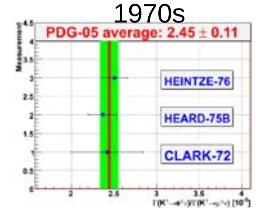
$1.2346(35)(36)x10^{-4}$ PSI (1993)

$$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 43(37)x10^{-8}$$

$K \to e\nu / K \to \mu\nu$

$R_{e/\mu}^{\exp K}$ $(\pm 2\%)$

1970s



$2.45(11)x10^{-5}$

$2.416(43)(24)x10^{-5}$ CERN(2006)

$$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 56(46)x10^{-8}$$

Two new $\pi \to e\nu$ experiments.

Goals: $\pm(5)x10^{-8}$ (0.05%)

KLOE: Stay tuned → (1-2%?);

New $K \to e\nu$ experiment at CERN.

Goal: $\pm(10)x10^{-8}$ (0.3%)

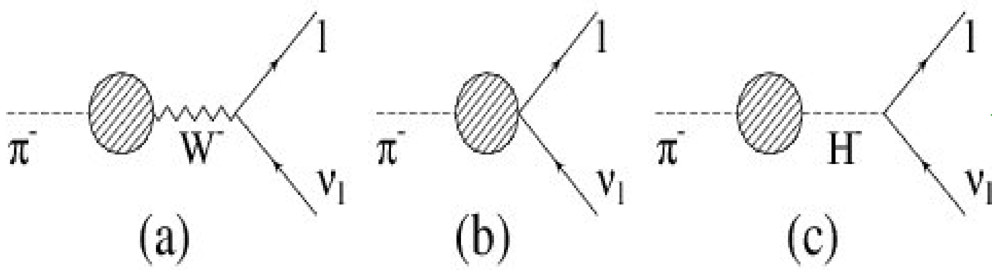
$\pi^+ \to e^+ \nu$

Beyond the Standard Model

High Sensitivity to New **Pseudoscalar** Interactions which are not helicity suppressed.

PS contribution comes as interference term with the axial-vector (dominant) term.

Effect is proportional to $1/\Lambda^2$ where Λ is the mass of the hypothetical particle.



a) – SM

b) – New four fermion interaction

c) – Charged Higgs

$$1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim \left(\frac{1TeV}{\Lambda_{eP}}\right)^2 \times 10^3$$

0.05 % Measurement $\rightarrow$ Λ_{eP}>1000 TeV

Charged Higgs mass $m_{H^\pm}$ ~200 TeV probed.

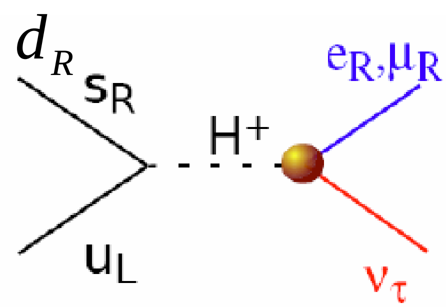
Marciano

Charged Higgs and Lepton Flavor Violation

Masiero, Paradisi, Petronzio (2006)

The unobserved neutrino involved in

$\pi^+ / K^+ \to e^+ \nu$ decay may be ν_e, ν_μ, or ν_τ



Low Energy SUSY (with R parity*); Large $\tan\beta$.

$$R^{NP}_{e/\mu} = R^{SM}_{e/\mu}\left(1 + \Delta r^{e/\mu}_{NP}\right)$$

Current (Future) Experiments:

$\left|\Delta r^{e/\mu}_{\pi}\right| < 0.004\ (0.0003)$ $\left|\Delta r^{e/\mu}_{K}\right| < 0.06\ (0.005)$

*R Parity (MSSM): $R=(-1)^{3B+L+2S}$

$i)$ FCNC $\mathrm{M} \rightarrow l\nu_l;\ \Delta r_{NP}^{e/\mu} < 10^{-6}$

$ii)$ Lepton Flavor Violation $\mathrm{M} \rightarrow l_i \nu_k; i(=e,\mu), \neq k(=\tau).$

$$\Delta r_{SUSY}^{e/\mu} = \left(\frac{m_P}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 \Delta_P^{31} \tan^6 \beta \qquad P = \pi, K$$

$$\leq O_K(0.01),\ \ O_\pi(0.0003);$$

For $\Delta_P^{31} \sim 5 10^{-4}, \tan\beta \sim 40$

Effects (optimistically!) in range of planned experiments.

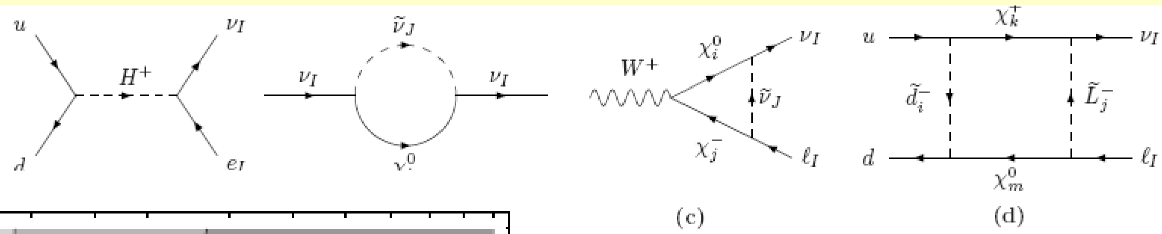
For the parameters above R($\tau \rightarrow \mu\gamma$)~$10^{-10}$;

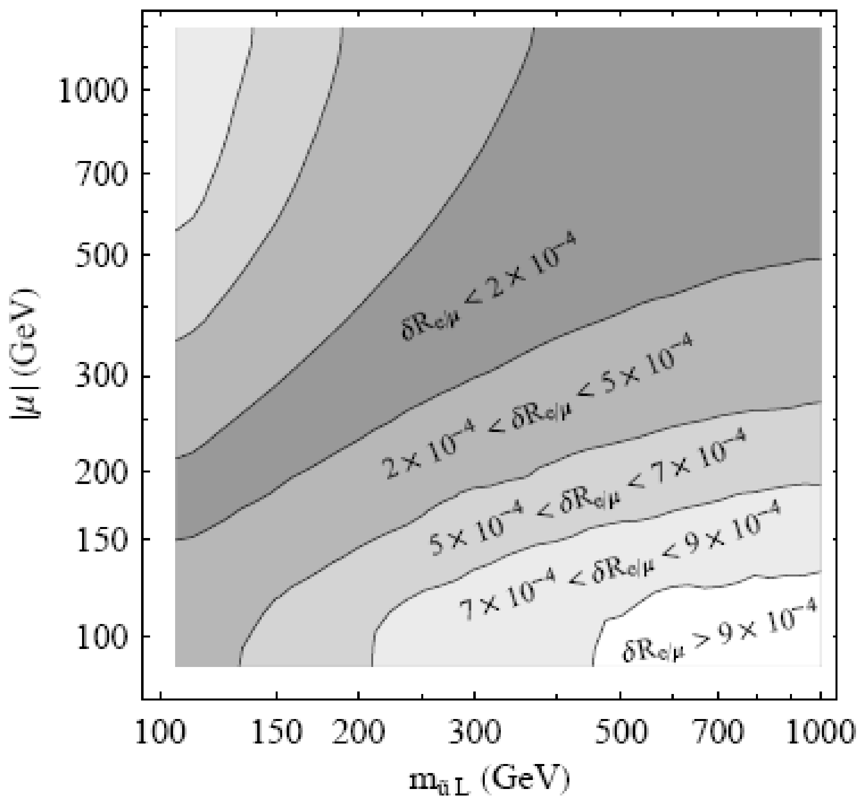
(Present experiment (Babar/Belle) R($\tau \rightarrow \mu / e \gamma$)<$10^{-7}$.)

Larger effects in B $\rightarrow$ lν, beyond reach of current experiments.

$\pi^+ \rightarrow e^+\nu$ Sensitive to R-Parity Violating MSSM

Ramsey-Musolf, Su, Tulin (2007)





μ vs. $m_{\tilde{u}_L}$

μ : Higgsino mass parameter

$m_{\tilde{u}_L}$: Mass of $\tilde{u}_L$

Campbell and Marbury (2003), Marciano

Scalar Interactions:
$\pi \to e\nu$ vs. Super-allowed β Decay

$$\left.\begin{cases} CKM \text{ Unitarity: } |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992(10) \\ R_{e/\mu} = \dfrac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(\pi^+ \to \mu^+\nu)} = 1.231(4)x10^{-4} \; (now \to < 0.1\%) \end{cases}\right\} 0.1\% \text{ Precision}$$

Constraining new Physics?

Direct Constraints

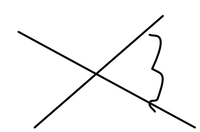
$R_{e/\mu}$: $\Lambda_A \sim 20TeV$, $\Lambda_P \sim 1000TeV\,(!)$

$SM : \frac{G_\mu}{\sqrt{2}} \sim \frac{\pi}{2\Lambda_{SM}^2};\ \Lambda_{SM} \sim 440GeV$

Unitarity: $\Lambda_V \sim 20TeV$, $\Lambda_S \sim$ 12 TeV

Induced Current Constraints

Loops



e.g. A induces V

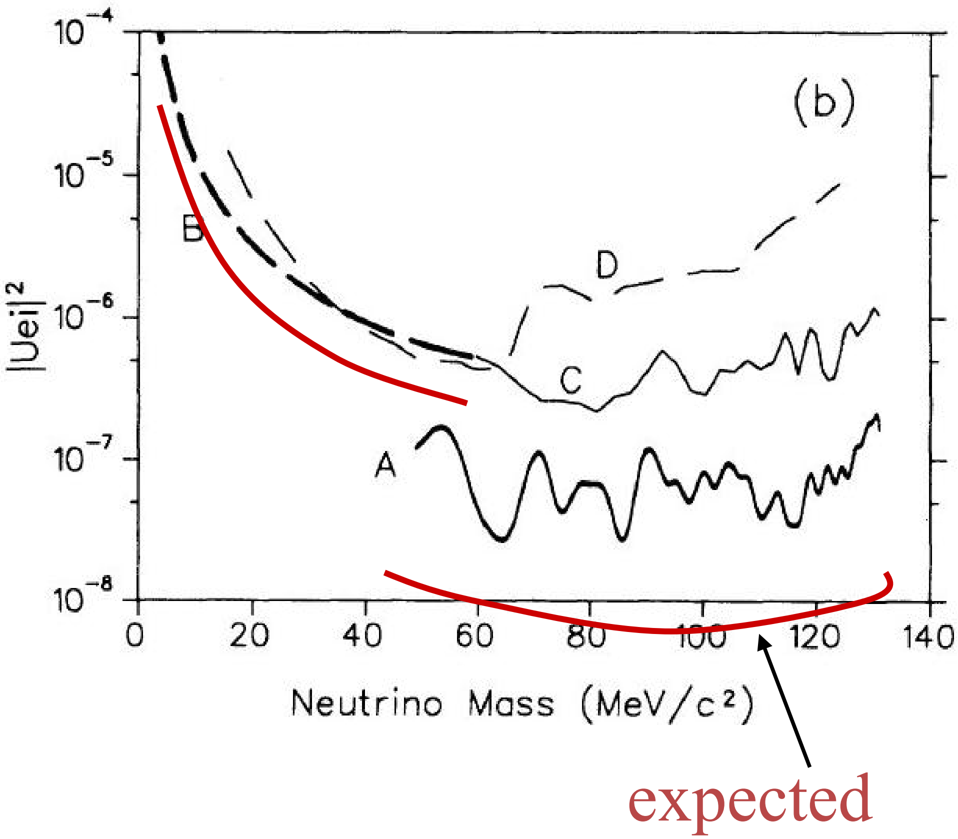
P induces S

$R_{e/\mu}$: $\Lambda_V \sim 2TeV$, $\Lambda_S \sim 60TeV\,(!)$

Unitarity: $\Lambda_A \sim 2TeV$

$\pi / K^+ \to e^+\nu$ Other BSM Physics :

Heavy ν



SM extensions:

-Leptoquarks

-Excited gauge bosons

-Compositeness

-*R-parity violating SUSY*

-Extra dimensions

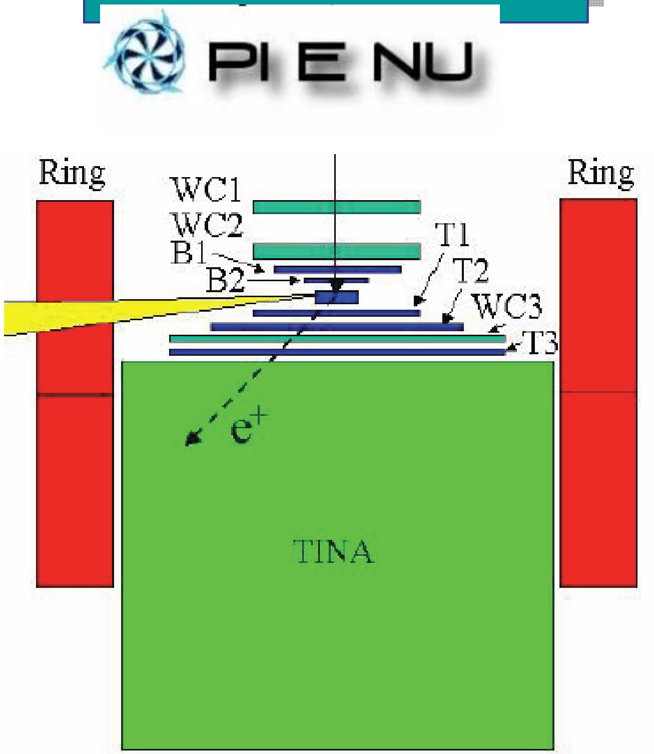
-ν Mass from QCD cond.
(Davoudias,Everett (2006))

- LFV (Isidori, Paradisi (2006)**)**

New $\pi^+ \to e^+\nu$ Experiments

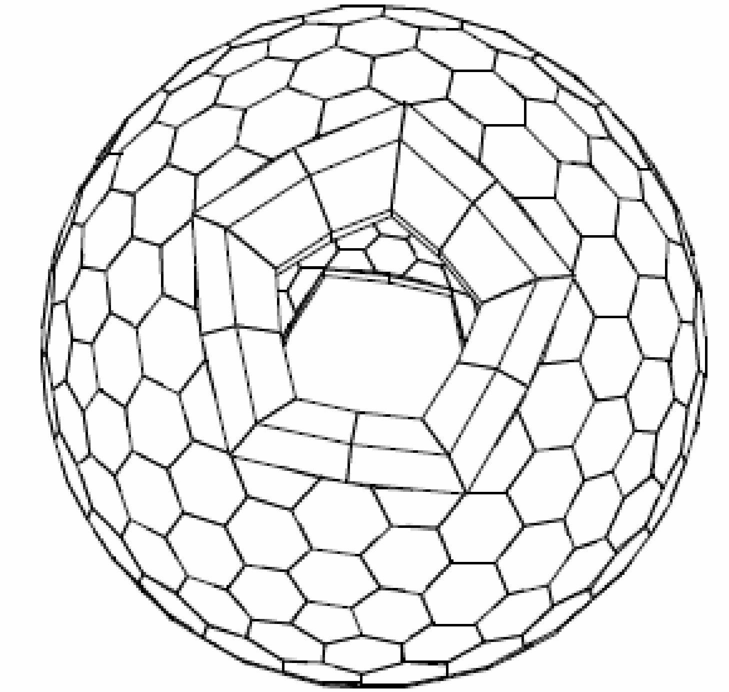
Precision Goals for $R_{e/\mu}^{\exp\pi}$: < 0.1%

TRIUMF PIENU



ASU, BNL, Osaka, TRIUMF, UBC, VPI

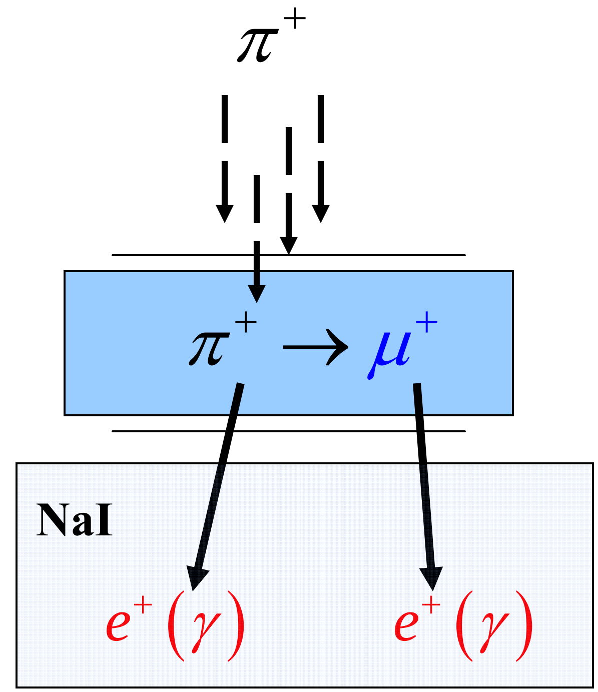
PSI PIBETA Spectrometer

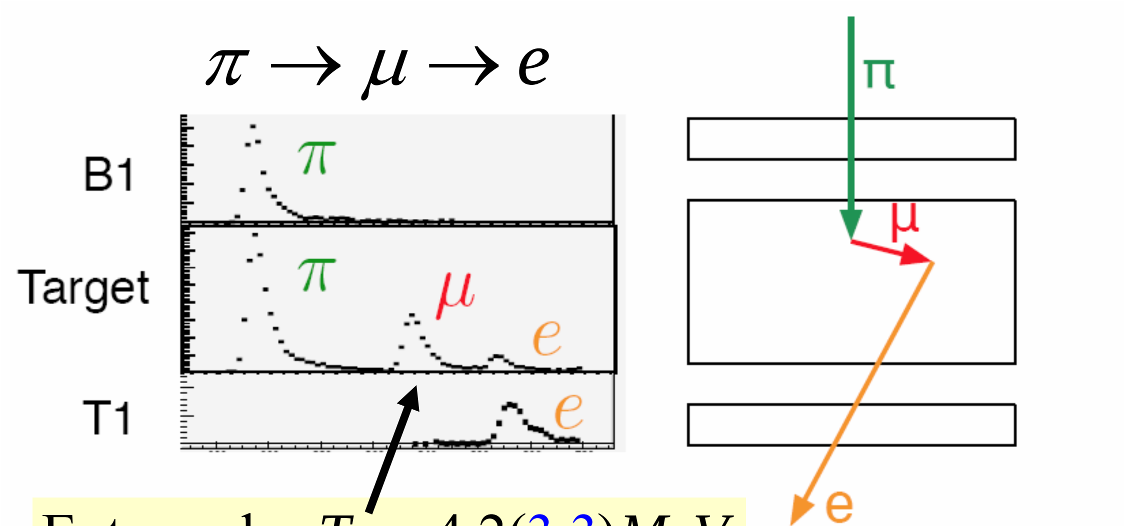


INS (Pol.), IHEP, JINR, PSI, RBI, Virginia, Zurich

Experiment Concepts

Low Momentum π Beam at p=75 MeV/c. πs lose energy and stop in a target of plastic scintillator. Scintillation detectors viewed by photo-multiplier tubes and all signals are digitized at 500 MHz.





$\tau_\pi = 26ns, \tau_\mu = 2200ns$

Extra pulse $T_\mu = 4.2(3.3)MeV$ for $\pi \rightarrow \mu \rightarrow e$ only.

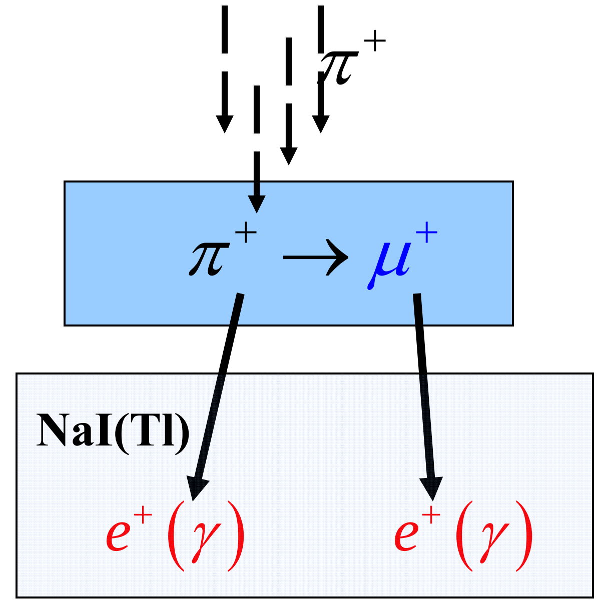
Measure positron energies in a NaI(Tl) crystal spectrometer (no magnetic field!):

$$\left[\pi^+ \to e^+ \nu\right] \qquad P_e = 70 MeV/c$$

$$\left[\pi^+ \to \mu^+ \nu\right] \quad P_\mu = 30 MeV/c$$

$$T_\mu = 4.2 MeV,\ R_\mu = 1.4 mm$$

$$\left[\mu \to e^+ \nu \bar{\nu}\right] \quad P_e = 0 - 53 MeV$$



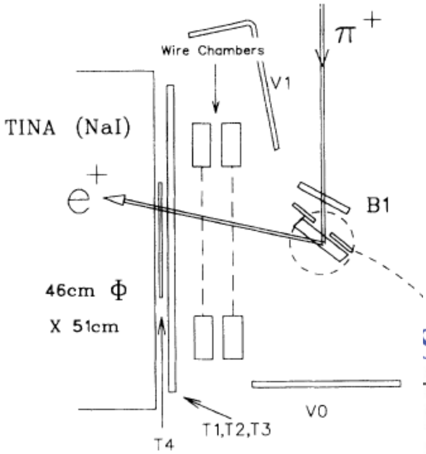
Electrons have fairly uniform interactions over the range P[1-70 MeV]:

Systematic effects cancel (to 1st order) in the ratio $\dfrac{\Gamma(\pi \to e)}{\Gamma(\pi \to \mu \to e)}$

e.g. solid angle, Multiple Coulomb Scattering, $\dfrac{dE}{dx}$, annihilation, bremsstrahlung, timing.

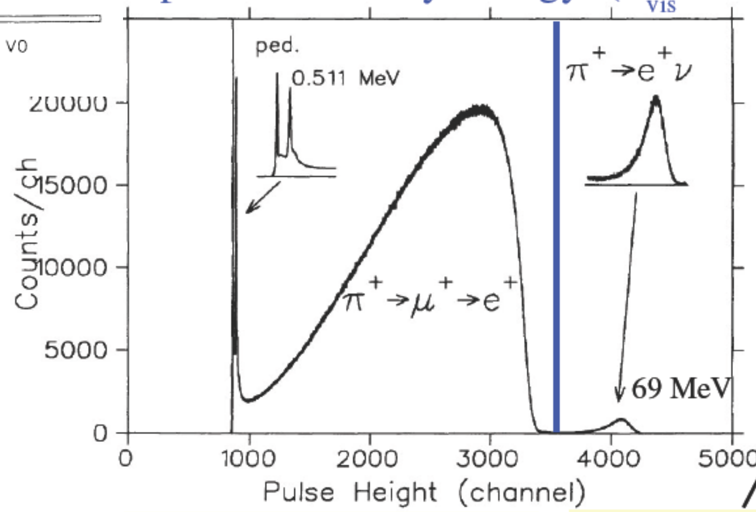
N.B.: When aiming for high precision: must rely on measurements for corrections rather than simulations whenever possible!

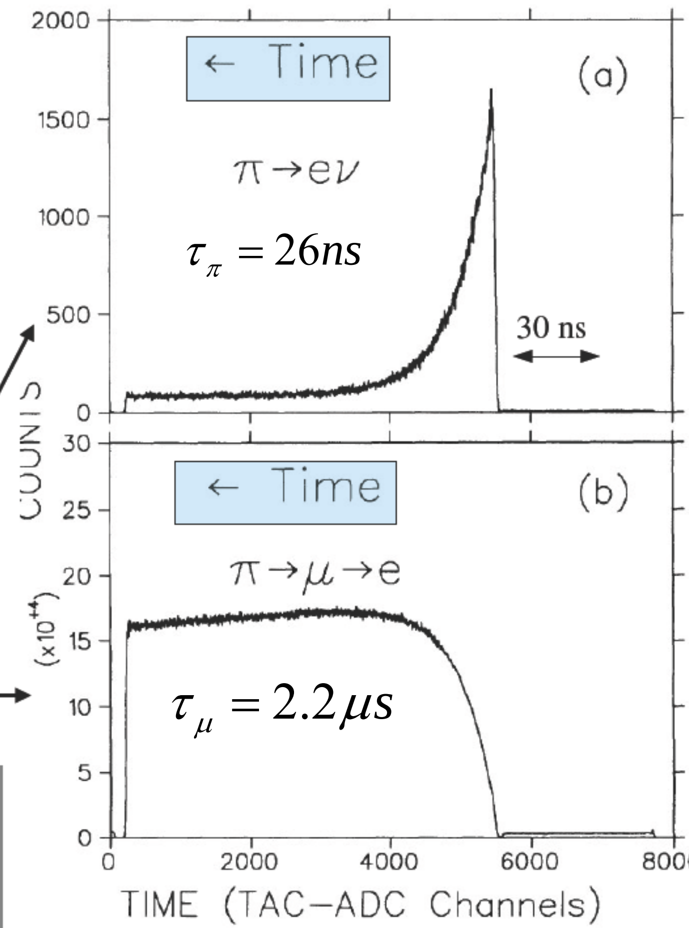
Previous TRIUMF Experiment **Britton et al. (1993)**



Energy and Time spectra

Separate events by Energy: (E_{vis} ~52 MeV)



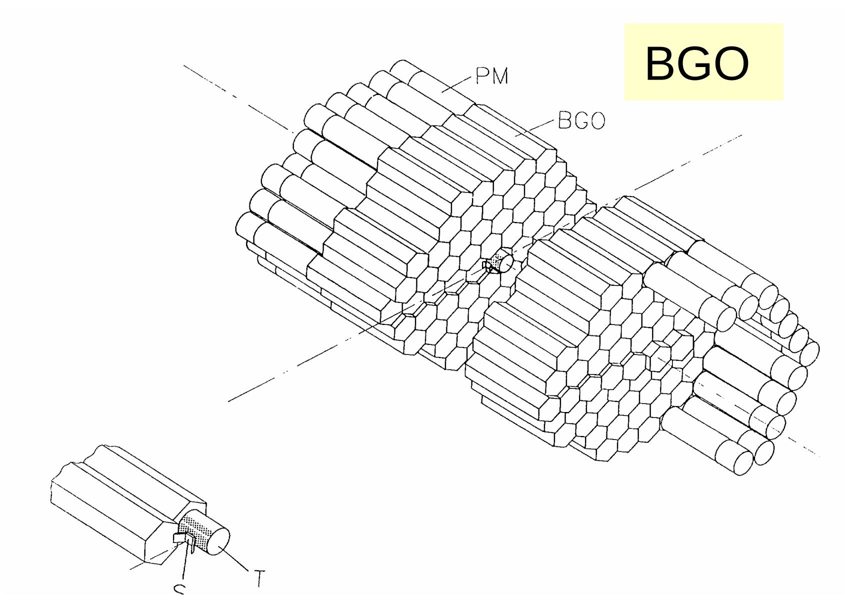


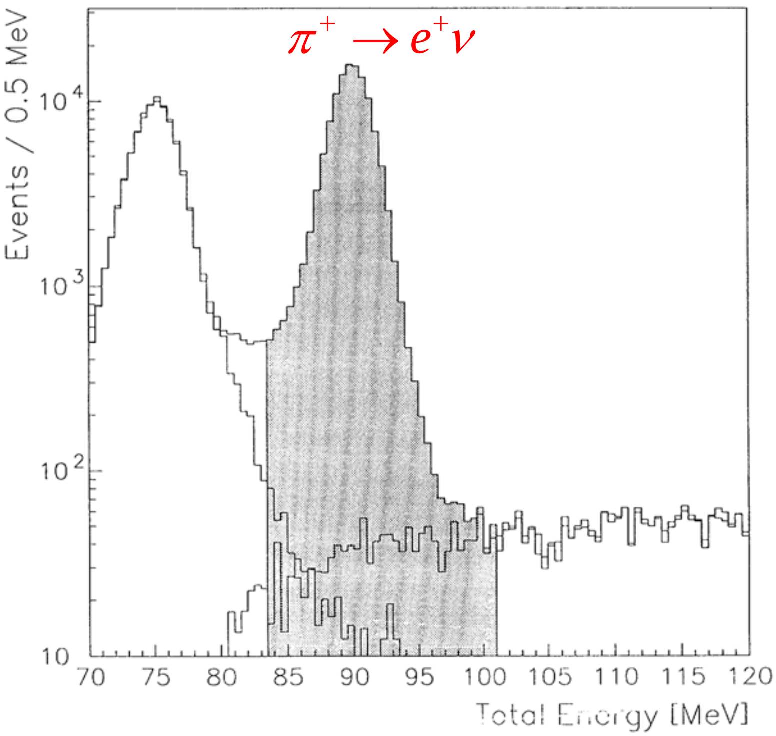
π–μ–e region

π→eν

Fit both spectra simultaneously and obtain the ratio.

Previous PSI experiment: C. Czapek et al. 1993





Energy resolution 1.7% at 90 MeV

Total Energy (including target)

Previous PSI experiment: C. Czapek et al. 1993

TABLE I. Main corrections and systematic errors of our final result for the branching ratio for the rare decay $\pi \rightarrow e\nu(\gamma)$.

Process	Correction (%)	Error (%)
Electromagnetic losses	+1.64	0.09
Photonuclear reactions	+0.95	0.19
$\pi \rightarrow e\nu\gamma$ events with $E_{\text{total}} > 101$ MeV	+0.04	0.02
Uncertainty of the energy calibration	0.0	0.08
$\pi \rightarrow e\nu$ self-veto in anticounter	+0.03	0.02
Time measurement difference for e and μ	−0.08	0.03
Pulse-shape difference for e and μ	0.0	0.03
Efficiency of e^+ detection in target	+0.15	0.01
Subtraction of radiative μ decay background	−0.45	0.17
Subtraction of pion reaction background	−1.13	0.06

PI E NU

M. Aoki, M. Blecher, D. Bryman, J. Comfort, P. Gumplinger, S. Kettell, T. Krupovnickas, Y. Kuno, L. Kurchaninov, L. Littenberg, W. Marciano, G. Marshall, T. Numao, A. Olin, R. Poutissou, M. Ramsey-Musolf, F. Retiere, A. Sher, V. Selivanov, B. Walker, K. Yamada

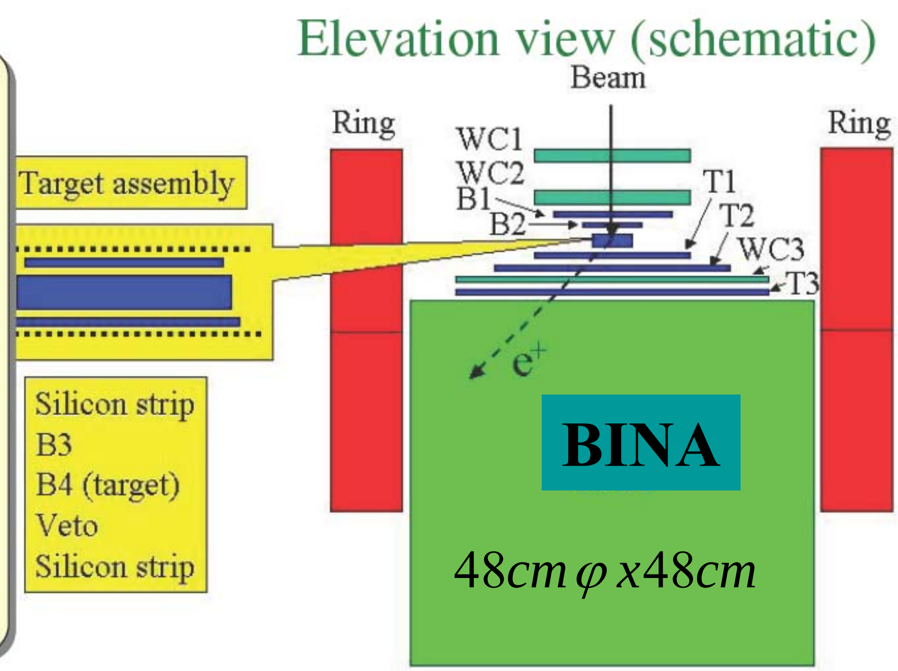
Canada-Japan-Russia-US

Arizona State University, BNL, Caltech, Kurchantov Institute, Osaka University, TRIUMF, University of BC, Virginia Polytechnic Institute and State University

TRIUMF PIENU Experiment

Precision goal: <0.05%

WC1(2,3)	Wire chambers
B1(2)	Beam counter
B3(4), Veto	Target counters
T1(2,3)	Telescope counters
TINA	NaI
	(dE/E=2% @ 66 MeV)
Ring	CsI crystals

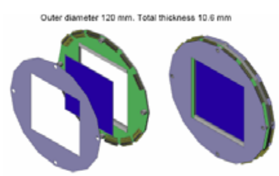


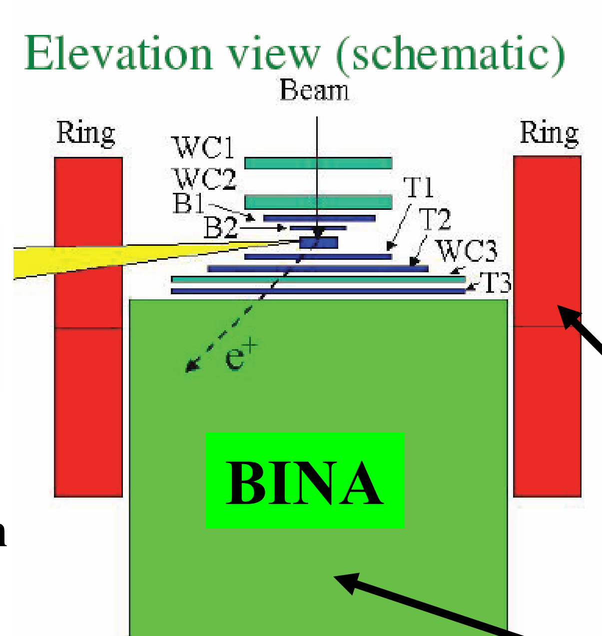
Solid angle: 25% (2.9%)
π^+ rate: ~ 70kHz (100kHz)
Tina rate: ~ 40kHz (30kHz)

Trigger rate: ~ 1kHz
Statistics: $\sim 5\times10^6$ $\pi\rightarrow e\nu$ (× 30 E248)

Equipment

- **Single crystal NaI(Tl) detector (BNL) Energy resolution <2% (RMS) at 70 MeV**
- **E949 Pure CsI crystal collar**
- **500 MHz digitizers**
- **Silicon strip and drift chamber tracking**





Pure CsI

Si Strips
300 (80) μm pitch

48 cm dia. x 48 cm ~19 X0

Britton et al. (1993)

Tail correction

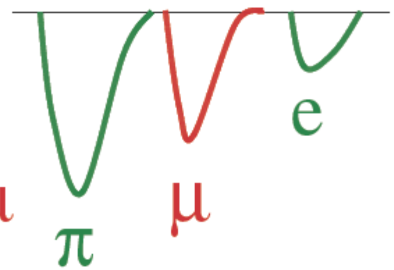
(the main source of systematics)

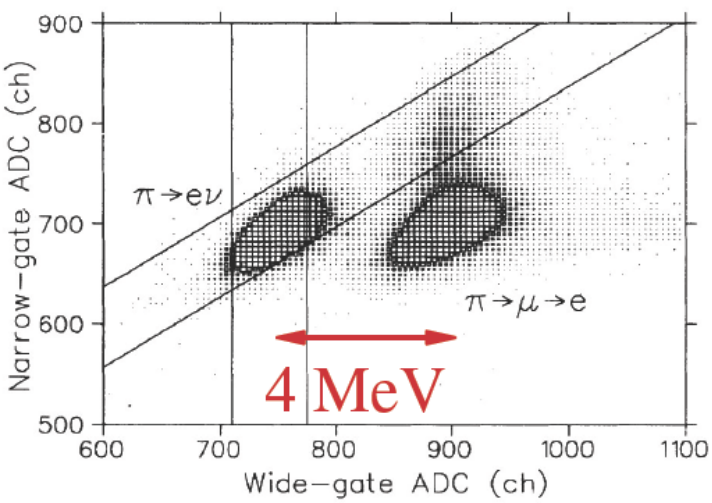
π–eν

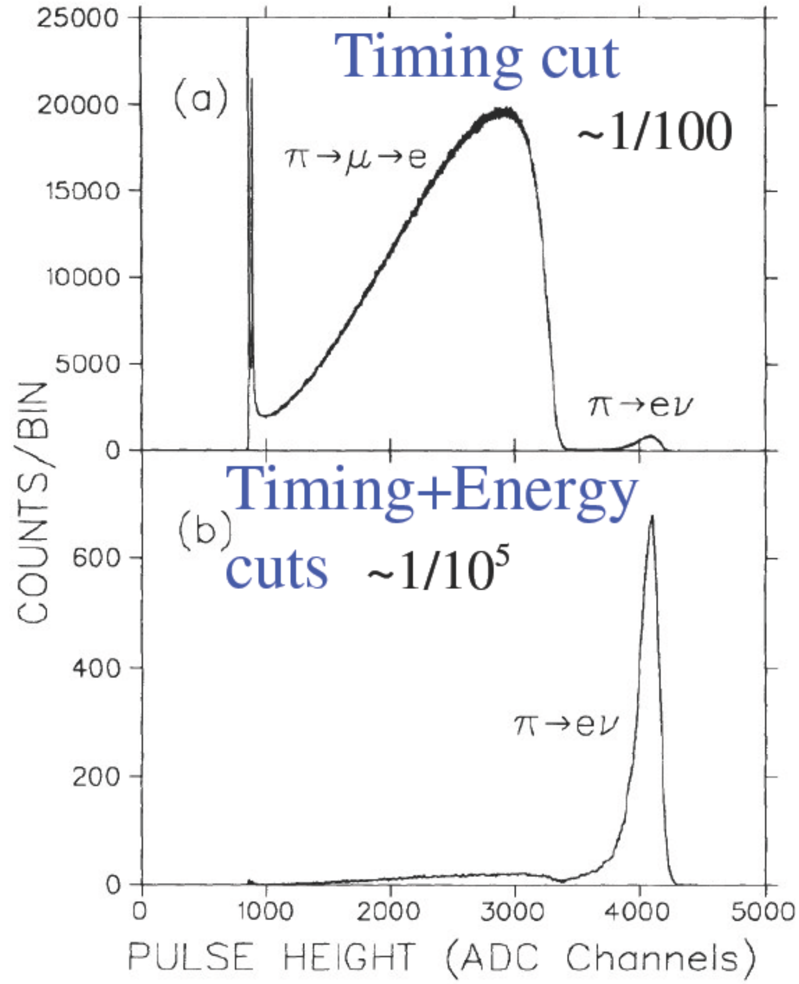
Tπ+ΔEe

π–μ–e

Tπ+ΔEe+Eμ



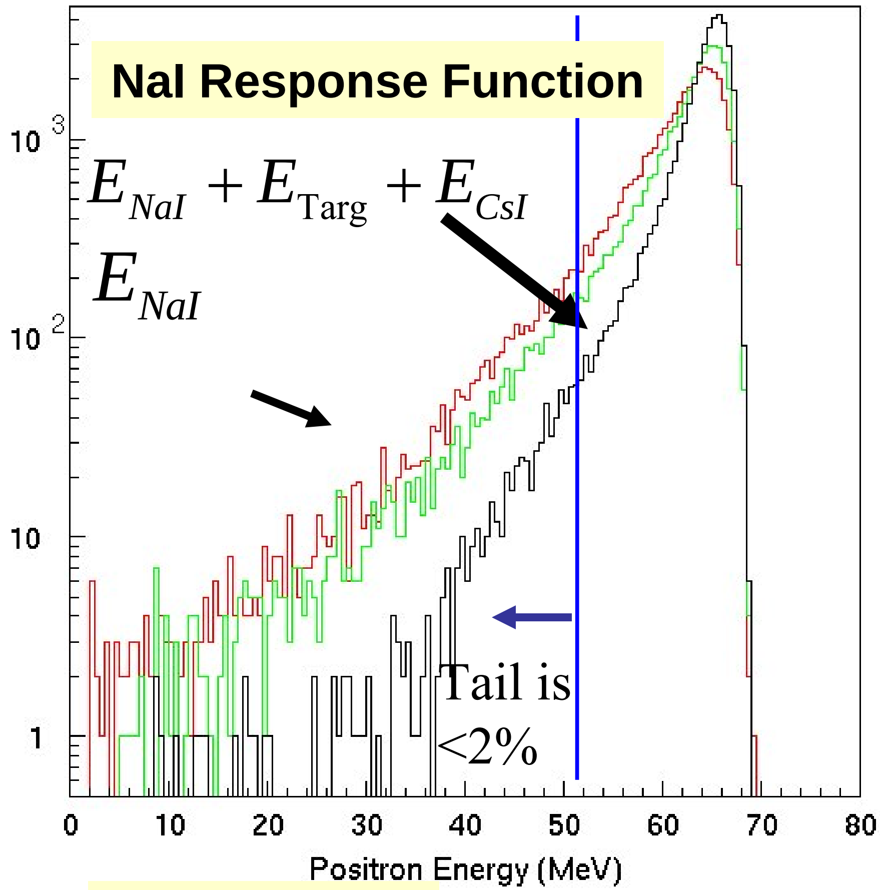




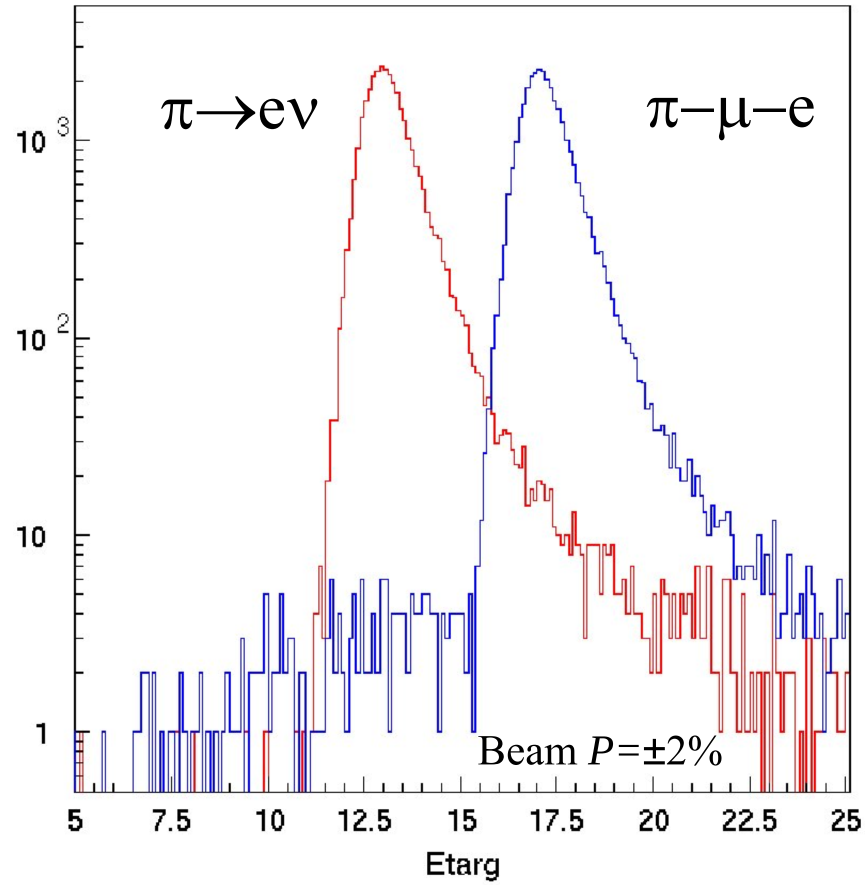
Resolution and NaI Tail

Simulations for PIENU Experiment

π→eν events



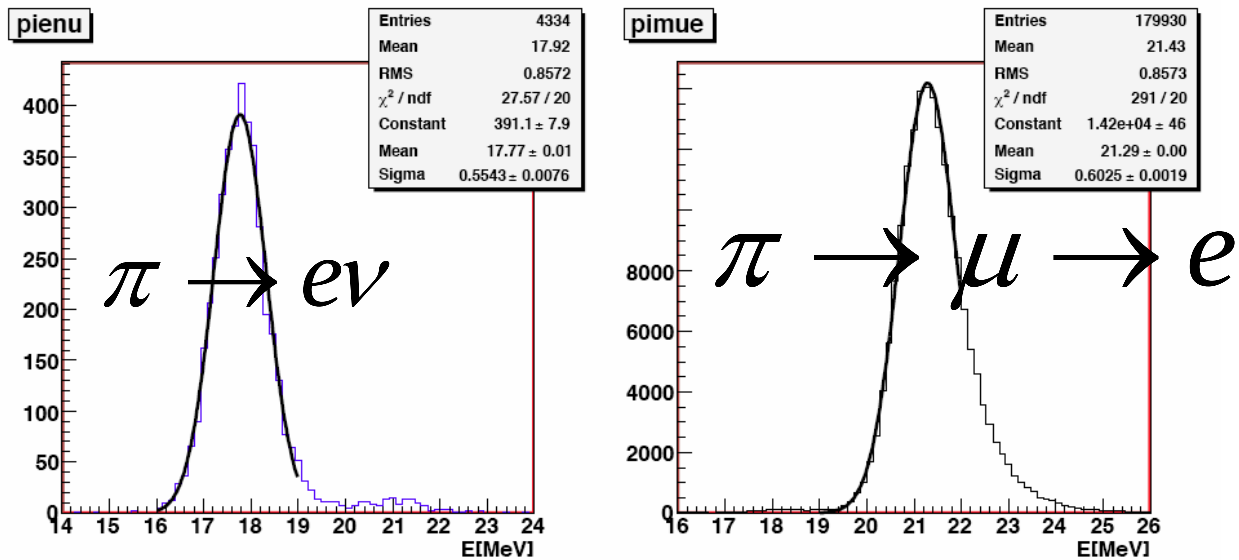
NaI(Tl) Energy



Target energy

Beam Test Data

total energy deposit in the target



Good separation in the target dE/E ~3%

Expected Uncertainties

Largest systematics come from:

Low energy tail ($\pi \rightarrow e\nu$)
0.03%

Britton et al. : 0.25%Uncertainty of the correction - limited by statistics
& contamination by in-flight pion decays

PI E NU Better dE/dx in target (x2)
and smaller statistical uncertainty (x5):

Energy dependent Acceptance difference 0.03%

PI E NU
Larger solid angle x5,geometry:

Uncertainties Summary

Sources	Britton et al. 1993	PI E NU
Statistical error	0.0028	0.0005
Low energy tail ($\pi \to e\nu$)	0.0025	0.0003
Acceptance differences	0.0011	0.0003
Pion lifetime	0.0009	0.0002
Others (time calibration, etc.)	0.0011	0.0003
Expected systematic error	0.0031	0.0006

PIENU Experiment Plan

- 2006/7: Beam Tests
- 2007: Assembly
- 2008-2009 Data runs
- 2008-10 Analysis/publications

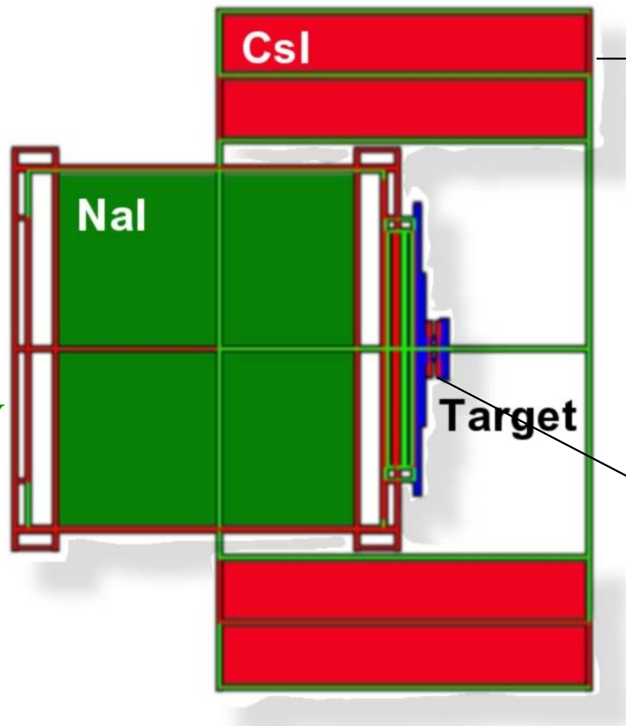
Students, Postdocs: Interested? See me later!

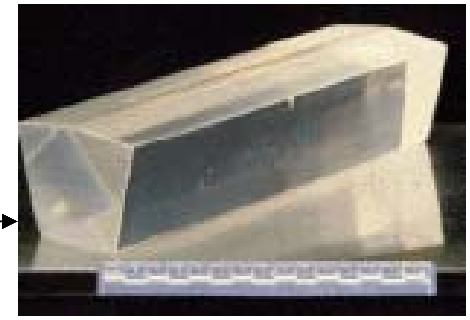
Detector build-up

Brookhaven NaI crystal (BINA)
Radius=24 cm
Length = 48 cm(19 *X0*)

Energy resolution:

~<2% (FWHM) at 70 MeV

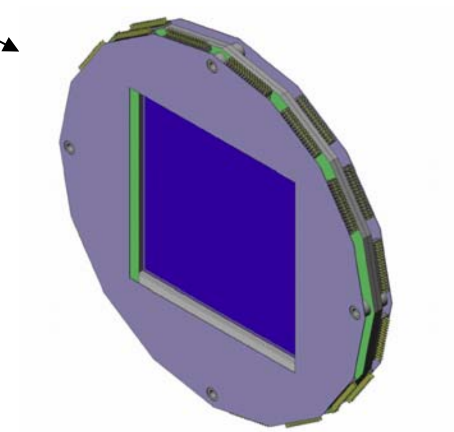




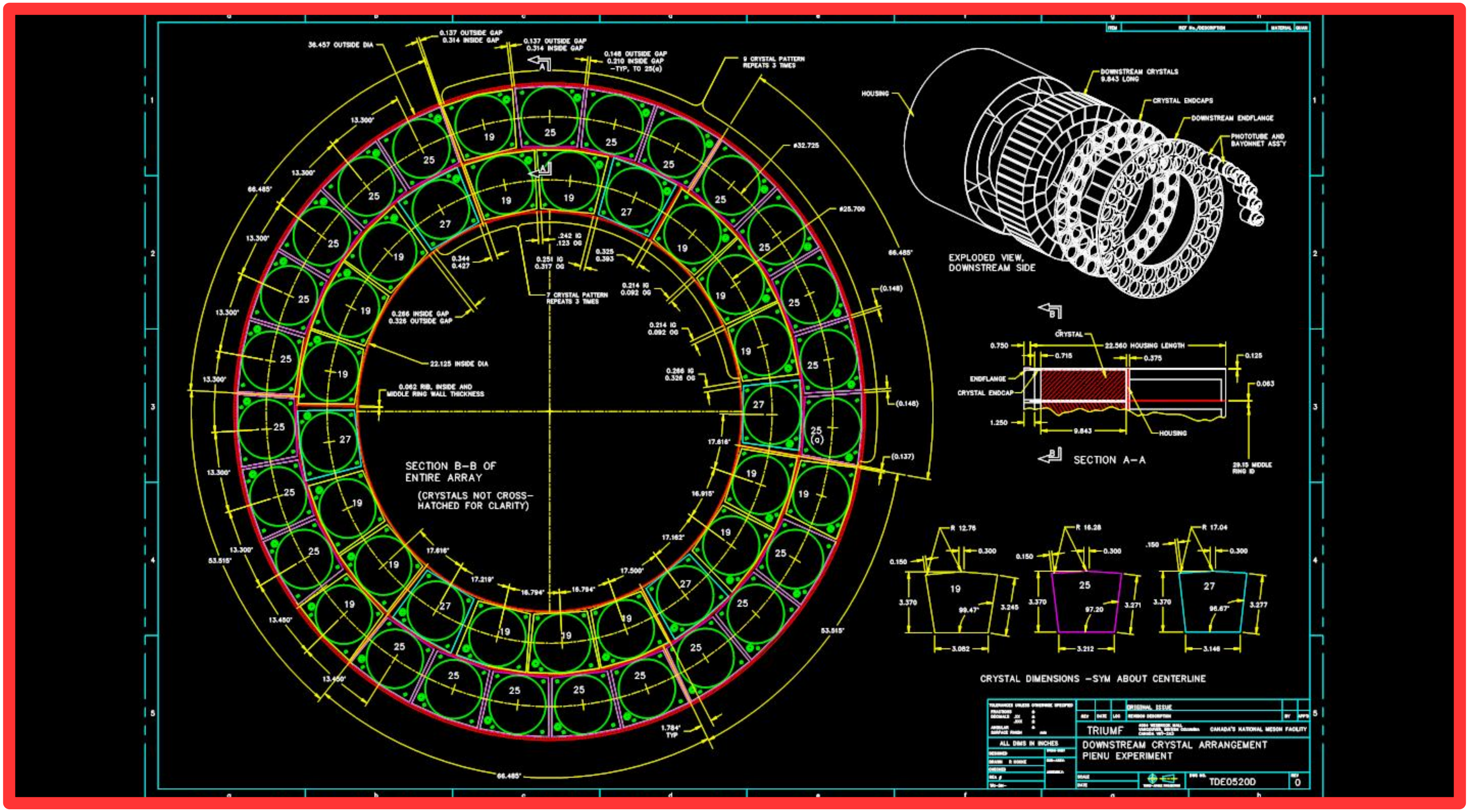
Pure CsI crystals

π **Beam**

Si Strips
300 (80) µm pitch

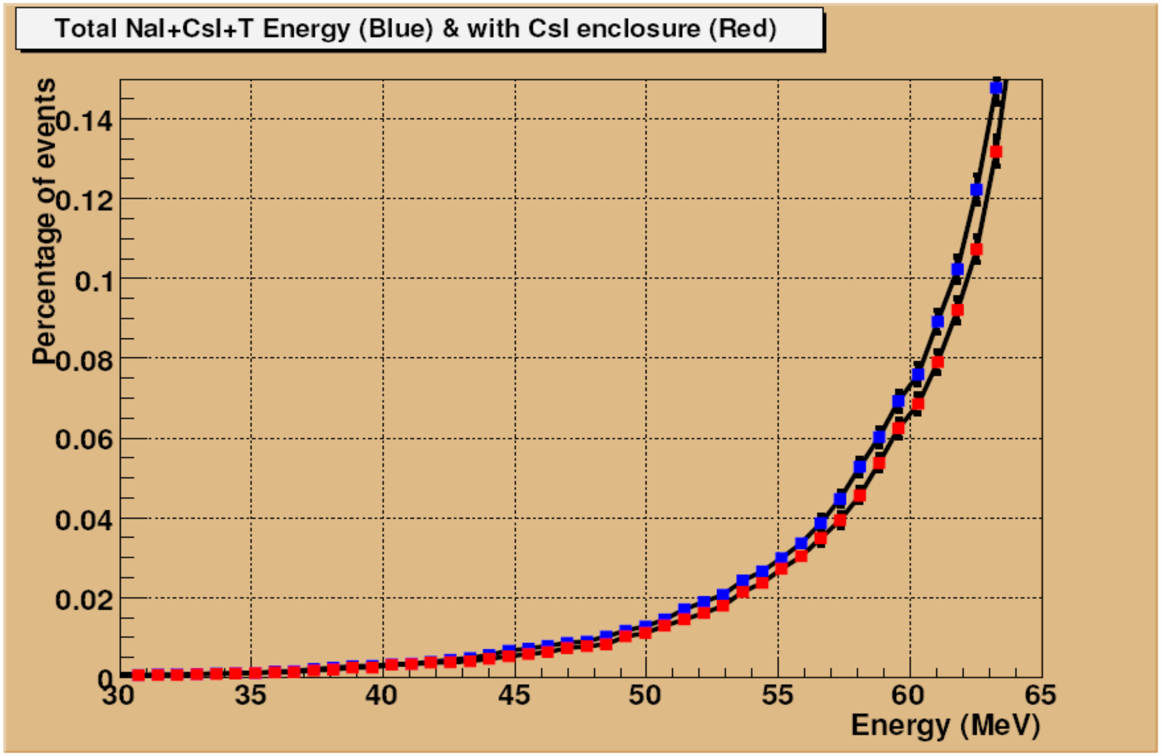


CsI enclosure



To reach 0.05% precision, everything must be studied/known to 0.01%: GEANT3 & 4 MC Studies Example:

Dead material and Gaps between crystals



Support material in gaps between crystals: <10% effect, known to <1% precision.

Beam Test data: KEK 500 MHz Digitizers

Pulse fitting

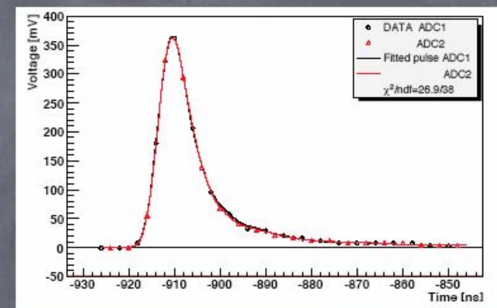
Fitting as a single pulse

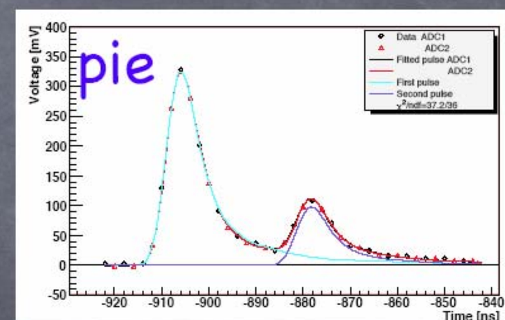
- Fitting function
  - 2 free parameters A1,T1
  - V=A1F(t+T1)
- for B1,B2,T1,T2

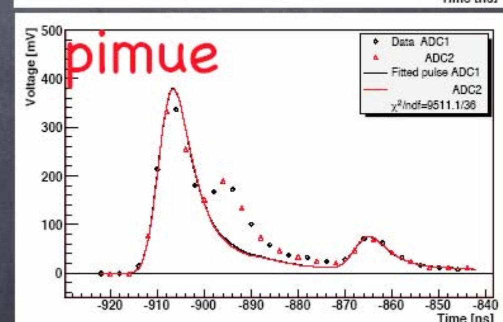
Fitting as a double pulse

- Fitting function
  - 4 free parameters Ai,Ti i=1,2
  - V=A1F(t+T1)+A2F(t+T2)
- for Target
- pie->correct assumption
- pimue->incorrect assumption

χ^2 and parameters obtained from fitting is useful for identification of the decay-mode

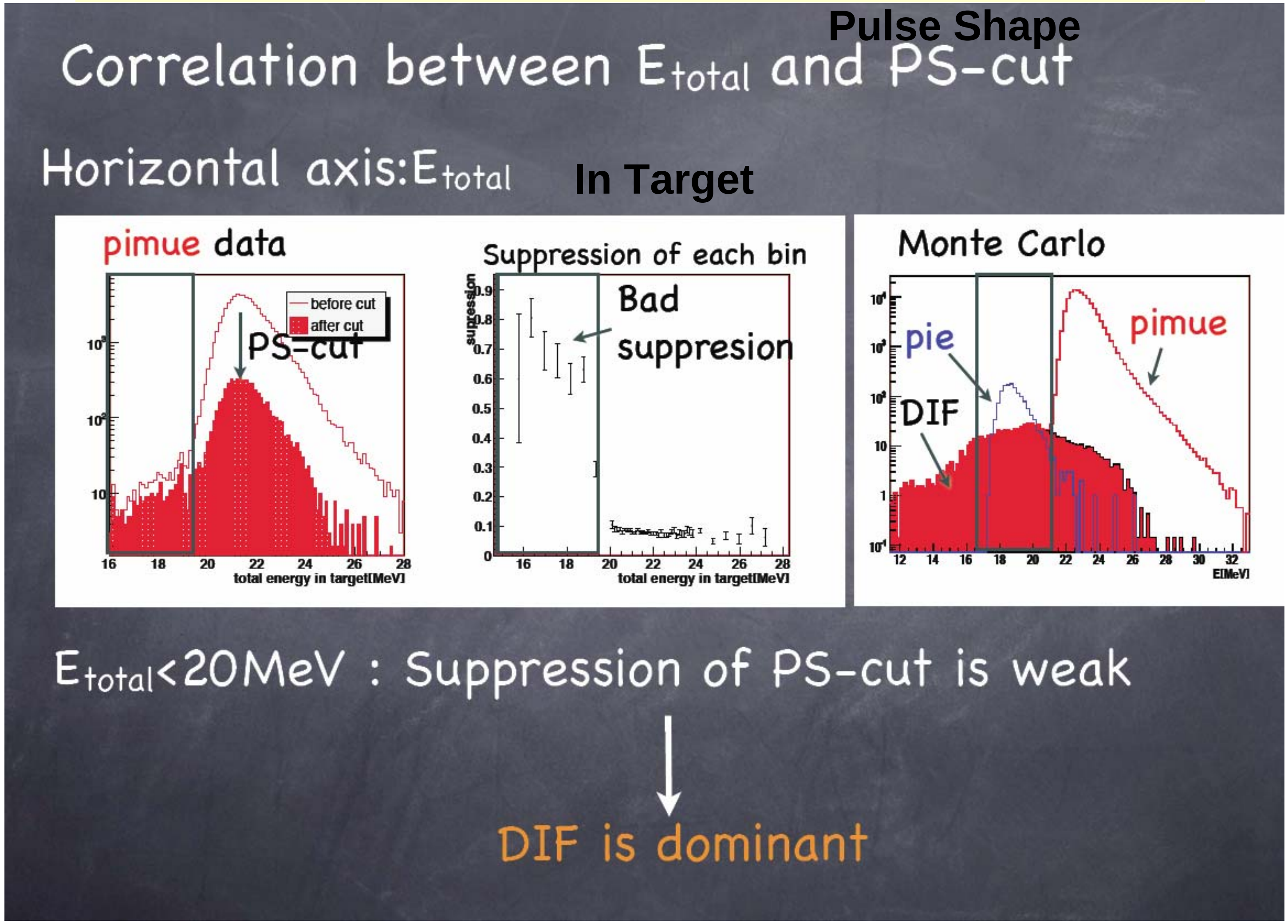




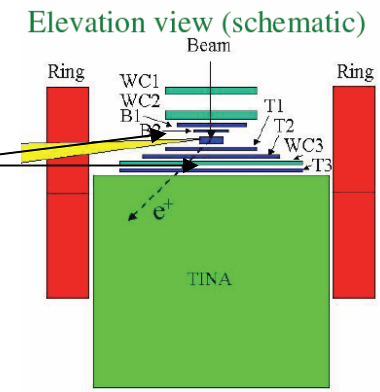


Tail Correction Background source:
π Decays-in-Flight

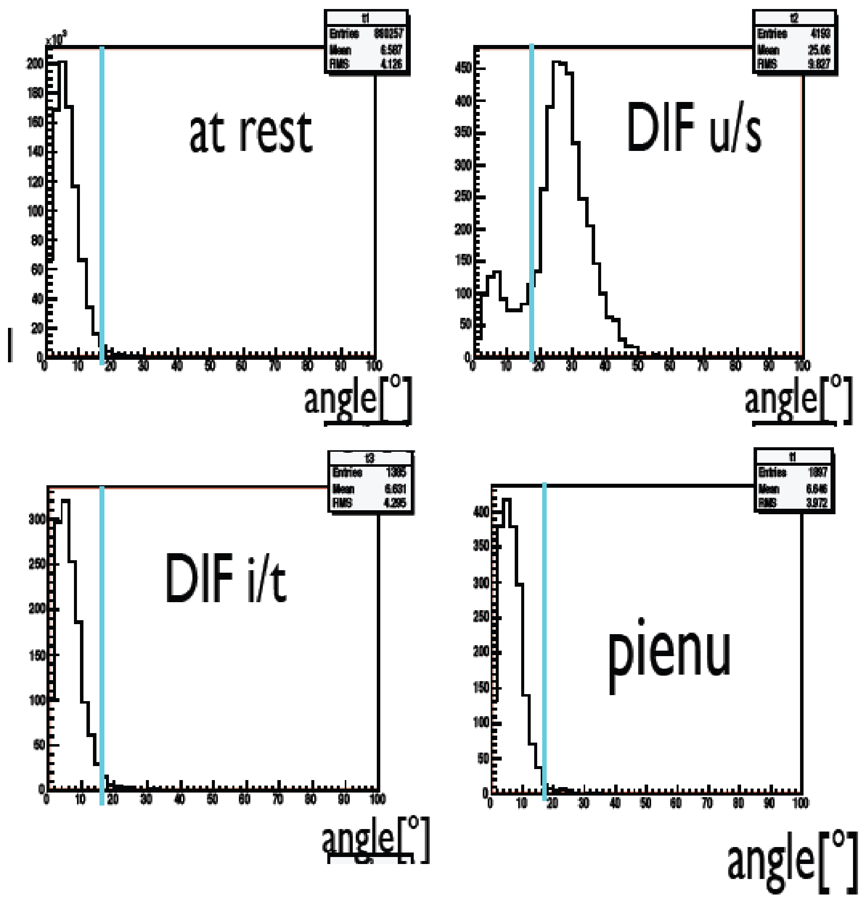
Beam Test data:



Si Strip and WC tracking suppress decays-in-flight



MC simulations

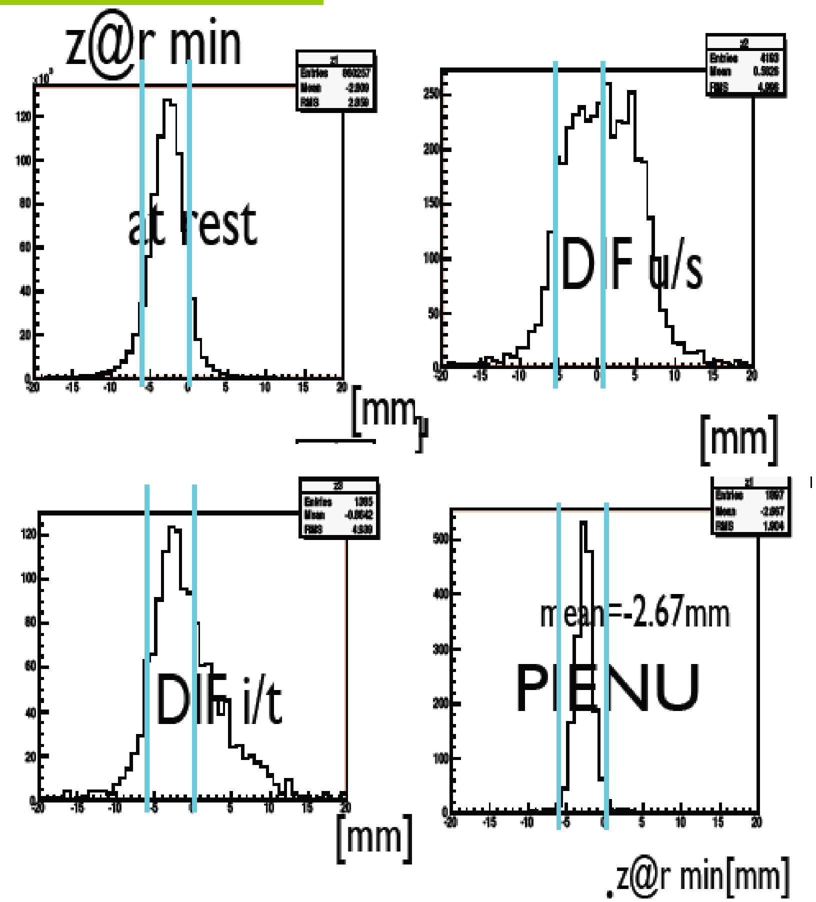


Measuring the angle between the incident beam pion (using Wire Chambers) and the charged particle entering the target (using Silicon Strip detectors) reduces decays-in-flight

(Factor ~8)

SS and WC tracking suppress decays-in-flight

MC simulations



Tracking to determine the stop/decay vertex suppresses decays-in-flight further.

Total suppression factor ~30

PEN at PSI

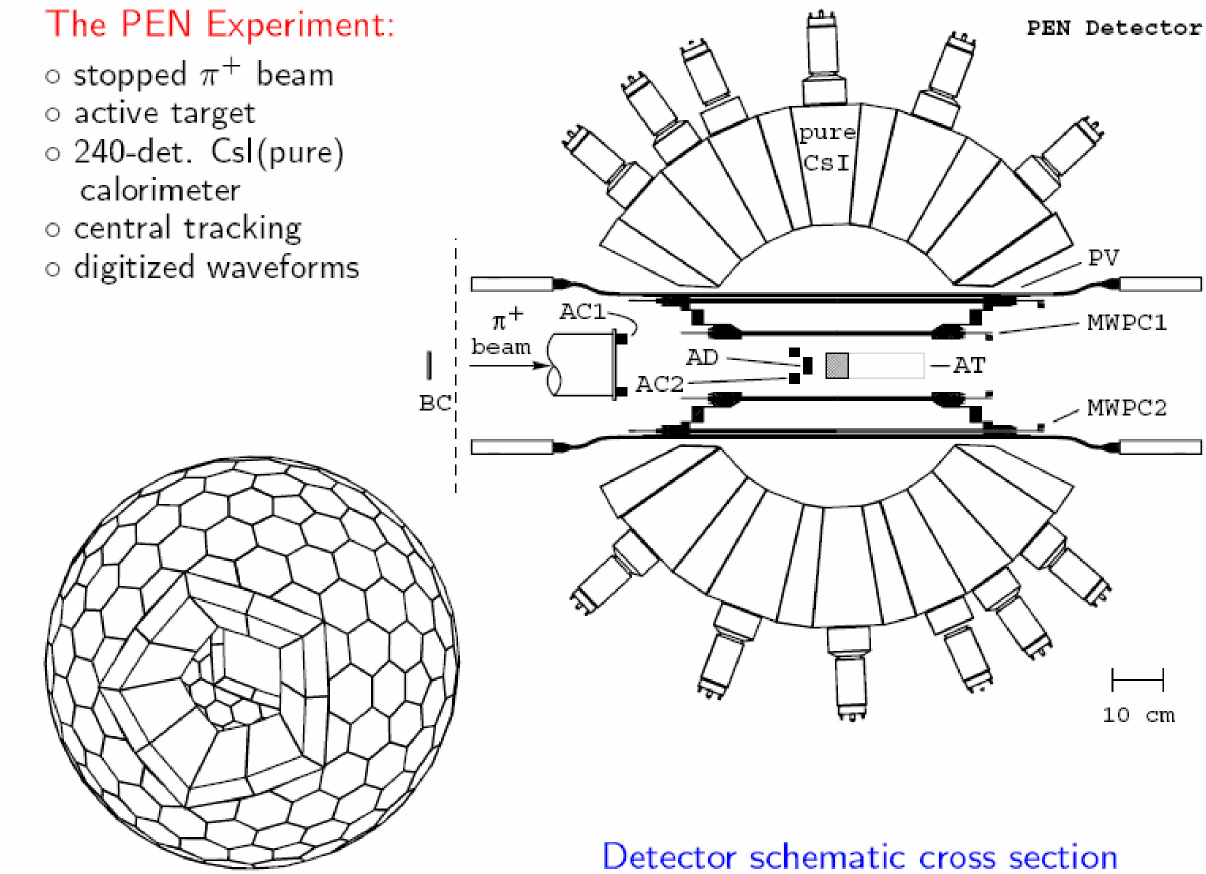
Precision Goal: 0.05%

$\pi^+ \to e^+\nu$

Previously measured

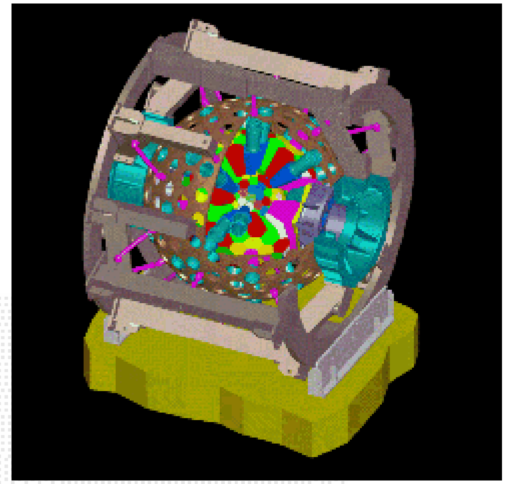
$\pi^+ \to \pi^0 e^+\nu, \pi^+ \to e^+\nu\gamma$

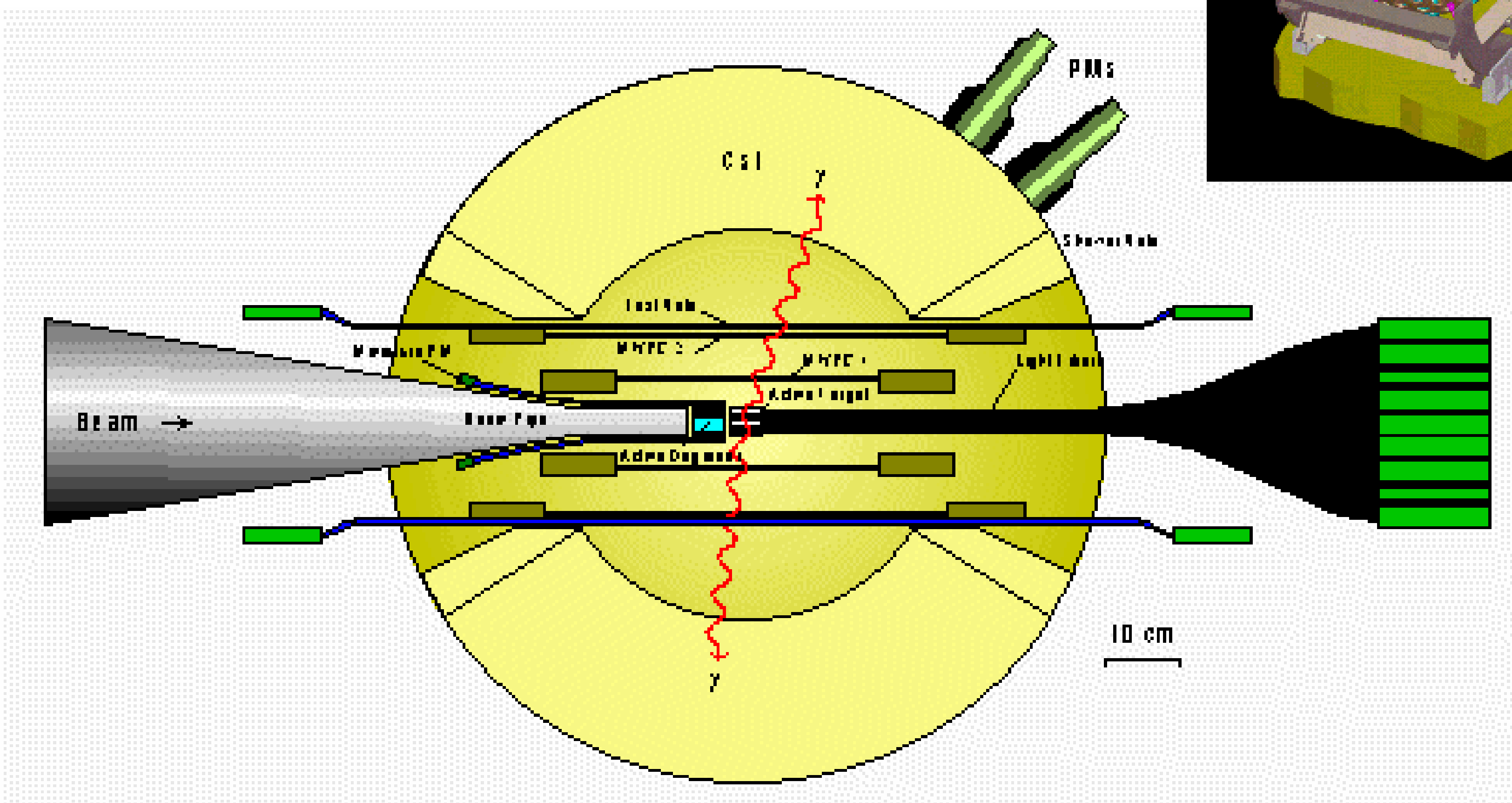
PI Beta Spectrometer: 12 X0 pure CsI



Detector schematic cross section

PSI π-β Target Arrangement

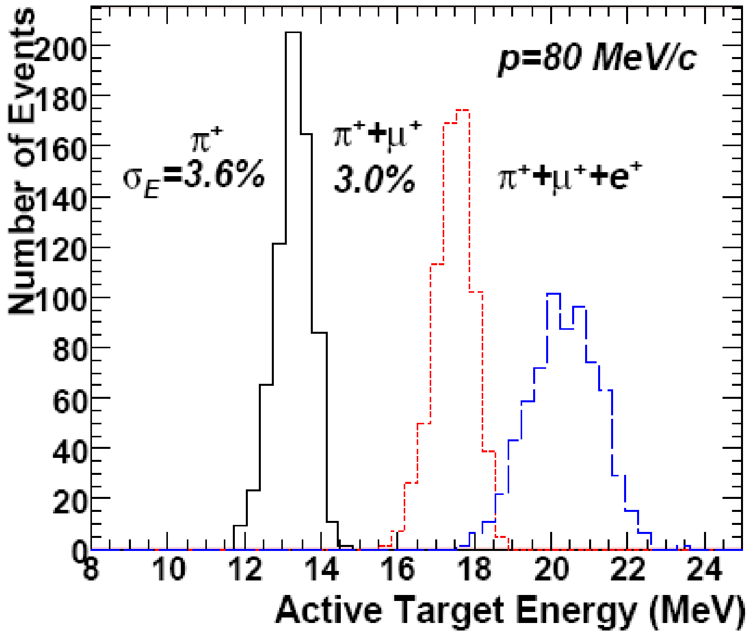




PEN Active Target detector energy resolution

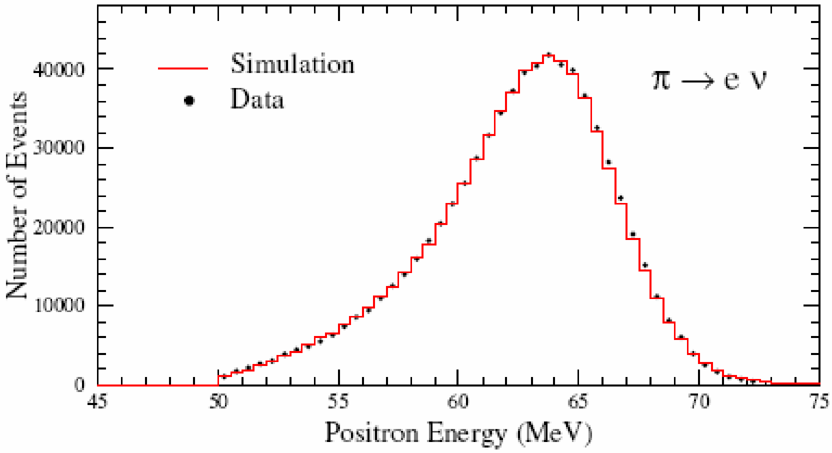
- stopped pion signal
- stopped pion with $\pi \longrightarrow \mu\nu$
- stopped pion with $\pi \longrightarrow \mu \longrightarrow e$

[From 2006 PEN test run]



Calorimeter energy resolution for $\pi^+ \longrightarrow e^+\nu$ after subtraction of late decay events.

[From 2004 PIBETA run]



12.8% FWHM at 66 MeV

Summary

High precision studies of the $\dfrac{\pi / K \to e\nu}{\pi / K \to \mu\nu}$ branching ratios offer unique, clean access to new short distance effects and high mass scales that are complementary to studies at the LHC.

New Physics Sensitvity

- $\dfrac{\pi \to e\nu}{\pi \to \mu\nu}$
- $\dfrac{K \to e\nu}{K \to \mu\nu}$

PI E NU

PSI-PEN

CERN NA48/3
KLOE

$\dfrac{1}{M_H^2}$ with $M_H \leq 1000\ TeV$