Study of rare pion decays in the PiBeta and PEN experiments: a look forward

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Topics discussed in the talk

Known and measured pion and muon decays

	decay	$B.R.$		physics interest
$\pi^+ \rightarrow$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(π_{e2})	$\Leftarrow$ lepton universality, beyond SM terms $(T, \ldots)$
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{e2\gamma})$	$\Leftarrow$ BSM terms $(T, \ldots)$, form fact's: $F_A^{(\pi)}, F_V^{(\pi)}, \ldots$
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	(π_{e3})	$\Leftarrow$ quark-lepton universality (V_{ud}), BSM loops
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \rightarrow$	$\gamma\gamma$	$0.98798\,(32)$		$\Leftarrow \chi$ anomaly, low energy chiral parameters
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)	
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$		
	e^+e^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \rightarrow$	$e^+\nu\bar{\nu}$	~ 1.0	(Michel)	$\Leftarrow$ beyond SM weak interaction terms
	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$	(RMD)	
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

Summary of PiBeta and PEN goals

Goals of the **PiBeta** experiment (data runs 1999-2004):

	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e3(\gamma)}$:	$\pi^+ \to \pi^0 e^+ \nu_e(\gamma)$	$R^{\pi}_{e3(\gamma)} \sim 10^{-8}$	$\sim 5 \times 10^{-3}$	(see below)
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^{\pi}_{e2\gamma} \sim 10^{-7}$	$\leq 1 \times 10^{-2}$	$F^{\pi}_A, F^{\pi}_V, F^{\pi}_T$; χPT l.e.c.
RMD:	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$	$R^{\pi}_{e2\gamma} \sim 10^{-3}$	$\leq 1 \times 10^{-2}$	Michel param.: $\bar{\eta}$

Goals of the **PEN** experiment (data runs 2008-2010):

	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e2(\gamma)}$:	$\pi^+ \to e^+ \nu_e(\gamma)$	$R^{\pi}_{e2(\gamma)} \sim 10^{-4}$	$\sim 5 \times 10^{-4}$	(see below)
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^{\pi}_{e2\gamma} \sim 10^{-7}$	$\sim 1 \times 10^{-2}$	improve F^{π}_V & limit on F^{π}_T
RMD:	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$	$R^{\pi}_{e2\gamma} \sim 10^{-6}$	$\sim 1 \times 10^{-2}$	improve $\bar{\eta}$

π_{e3} decay rate in the SM (a pure vector $0^- \to 0^-$decay)

$$\Gamma^{\pi}_{e3(\gamma)} = \Gamma_0(1+\delta_\pi) = \frac{G_F^2|V_{ud}|^2\Delta^5}{30\pi^3} f(\epsilon,\Delta)\left(1-\frac{\Delta}{2m_+}\right)^3 (1+\delta_\pi) \qquad \left[\equiv R^{\pi}_{e3(\gamma)}/\tau_\pi\right] ,$$

where

$$\Delta = m_+ - m_0 = 4.5936(5)\,\text{MeV} \qquad \text{and} \qquad \epsilon = \left(\frac{m_e}{\Delta}\right)^2 \simeq \frac{1}{81}$$

while

$$f(\epsilon,\Delta) = \sqrt{1-\epsilon}\left(1-\frac{9}{2}\epsilon-4\epsilon^2\right) + \frac{\epsilon^2}{4}\ln\left(\frac{1-\sqrt{1-\epsilon}}{\sqrt{\epsilon}}\right) - \frac{3}{7}\frac{\Delta^2}{(m_+ + m_0)^2} \simeq 0.941$$

and $\delta_\pi \sim 0.0335$ is the sum of radiative/loop corrections with $\sim 0.03\%$ relative uncertainty.

This is the theoretically cleanest way to determine CKM V_{ud}, which leads to several interesting SM tests, but is at the same time experimentally the hardest!

[Physics reach of precise measurements of $R^{\pi\text{-exp}}_{e3(\gamma)}$ and $R^{\pi\text{-exp}}_{e2(\gamma)}$ has been discussed by Hoferichter, Bryman, and Cirigliano in talks at this meeting.]

Prior to 2004, Γ^{π}_{e3} and R^{π}_{e3} measured with about 4 % precision.

π_{e2} decay: SM calculations, lepton universality

- Early evidence for $V - A$ nature of weak interaction.

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2} \frac{m_e^2}{m_\mu^2} \frac{(1 - m_e^2/m_\mu^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} \left(1 + \delta R_{e/\mu}\right)$$

- Modern SM calculations: $R^{\pi}_{e/\mu} = \left.\dfrac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\text{CALC}} =$

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- $\boldsymbol{R^{\pi}_{e/\mu}}$ tests lepton universality: in SM **e**, $\boldsymbol{\mu}$, $\boldsymbol{\tau}$ differ by Higgs couplings only; there could also be new S or PS bosons with non-universal couplings (New Physics); repercussions also in the neutrino sector, SUSY, ALPS . . .

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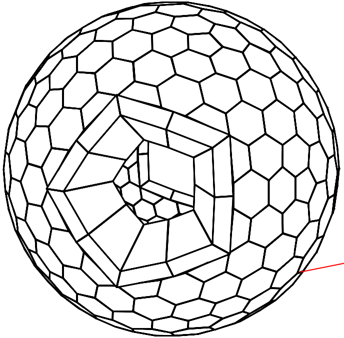
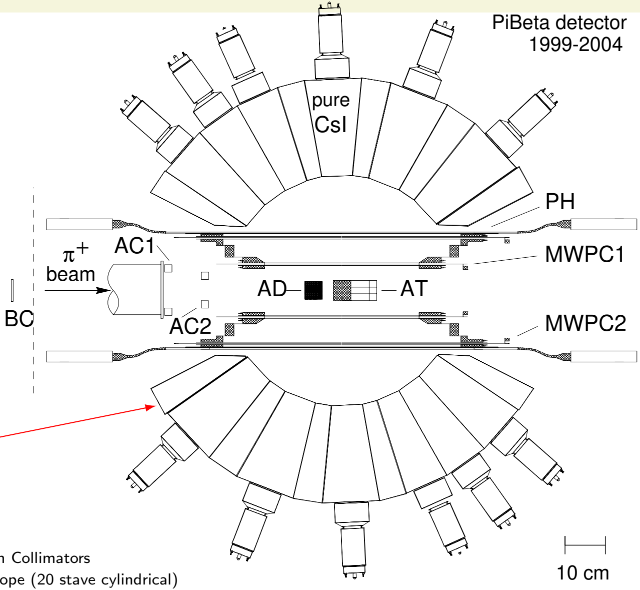
- Experimental world average is 23× less accurate than SM calculations! $[1.2327(23) \times 10^{-4}]$

The PiBeta apparatus

- πE1 beam at PSI
- stopped π^+ beam
- 9-elem. active tgt
- central tracking
- beam tracking
- fast-digitized wf's
- 240-elem. $12X_0$ spherical pure-CsI calo.
- tightly controlled temp/humidity/gains

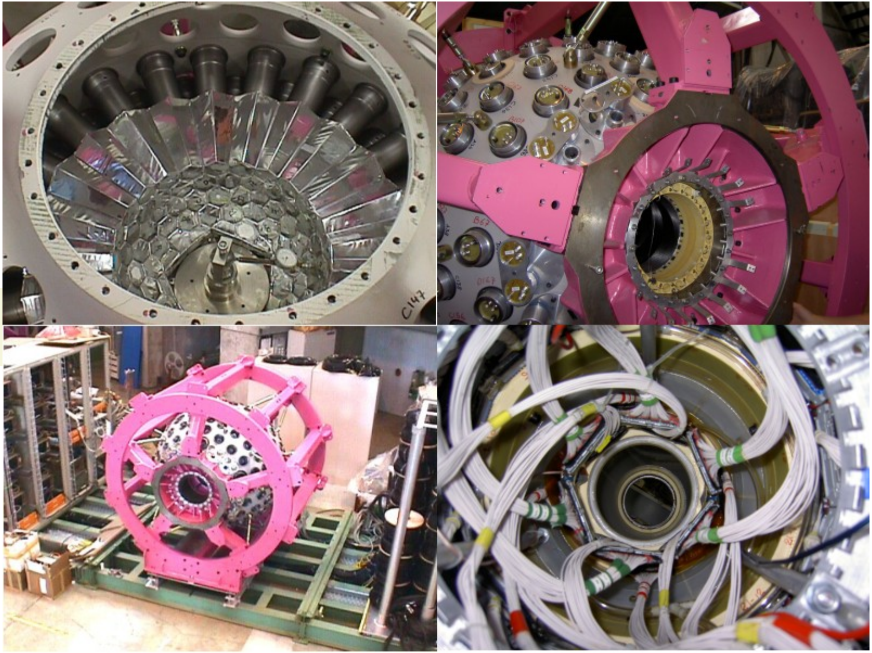




BC: Beam Counter
AD: Active Degrader
AT: Active Target

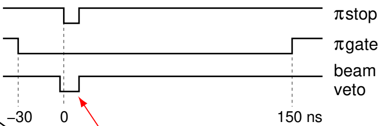
AC1,2: Active beam Collimators
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)

A few photos of the PiBeta apparatus:

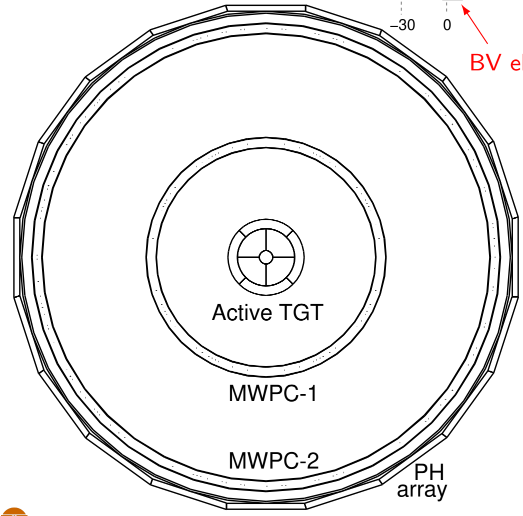


PiBeta central detector region

TGT stopping rate: $\geq 10^6\ \pi/\mathrm{s}$;
9-pc. AT: 5 inner (fiducial stop)
4 guard/tracking ring;



BV eliminated in PEN!

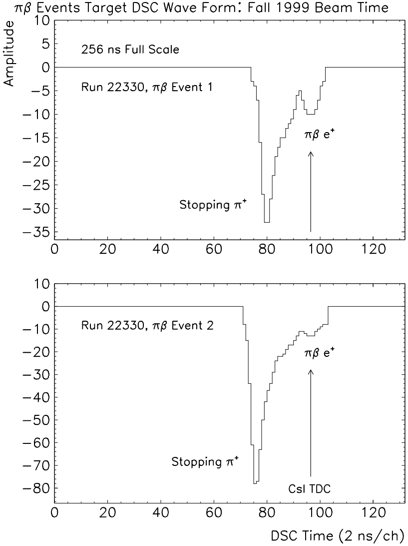


Beam $p \simeq 113\,\mathrm{MeV}/c$
(to achieve π_{stop} rate)

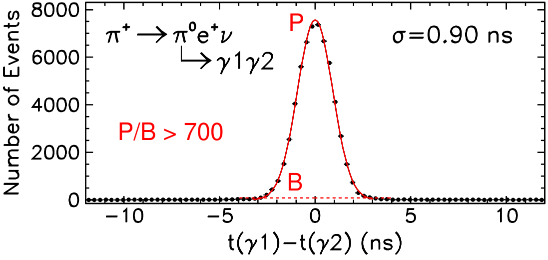
9-piece AT provides rudimentary beam stop tracking

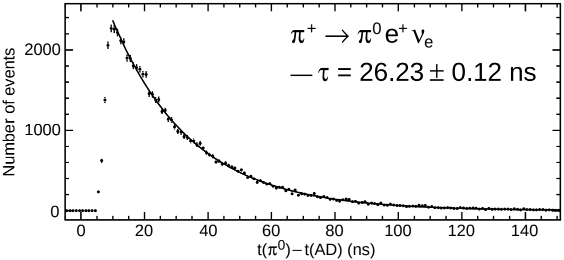
Note: AT was replaced for each annual run due to radiation damage.

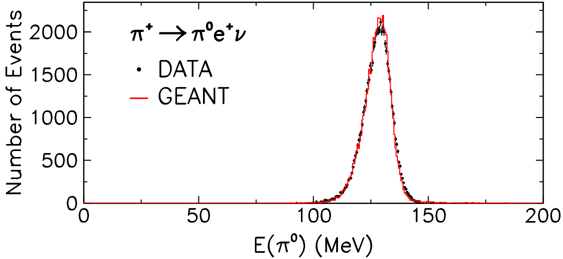
Digitized AT signal waveforms:

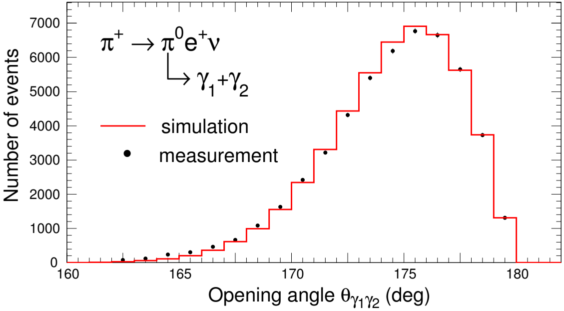


Key PiBeta spectra: π_{e3} decay (2004)

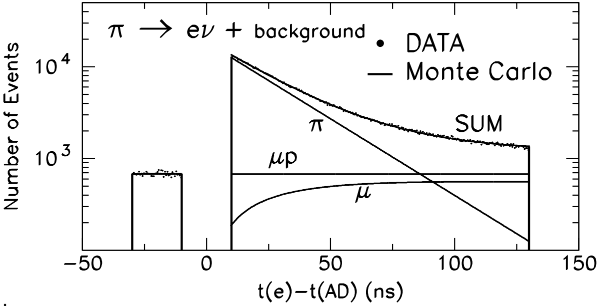


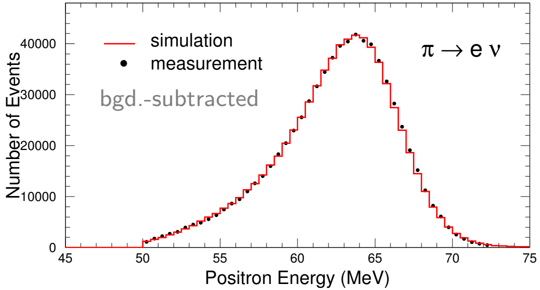






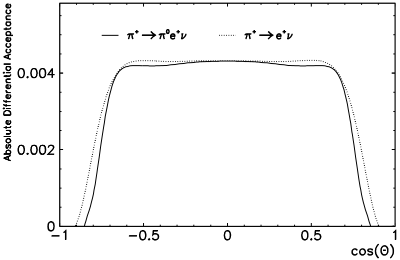
PiBeta normalization spectra: π_{e2} decay (2004)





Notes:

- π_{e3} signals are clean, w/low bgd. levels (previous slide);
- large background in π_{e2} from $\pi \to \mu \to e$ decay chain,
- . . . also from pile-up μ's in target;
- $\sim$ 15 ns vetoed around $t = 0$ to suppress prompt hadr. bgd.;
- excellent agreement with Geant3 MC simulations;
- π_{e2}: large subtraction of $\pi \to \mu \to e$ events below $\sim$ 55 MeV;
- well matched acceptances for π_{e3}, π_{e2} decays (shown);
- even closer for π_{e2} and $\pi \to \mu \to e$ channels (not shown).



PiBeta result for $\pi^+ \to \pi^0 e^+ \nu$ (π_β) decay [PRL **93**, 181803 (2004)]

Pion beta decay yield normalized to measured $\pi \to e\nu$ events:

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

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

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

SM Prediction (PDG):
$B =$ $1.038 - 1.041 \times 10^{-8}$ (90% C.L.)
$(1.005 - 1.007 \times 10^{-8}$ excl. rad. corr.)

⇒ Most sensitive test of CVC/radiative corr. in a meson to date!

PDG 2020: $V_{ud} = 0.97370(14)$
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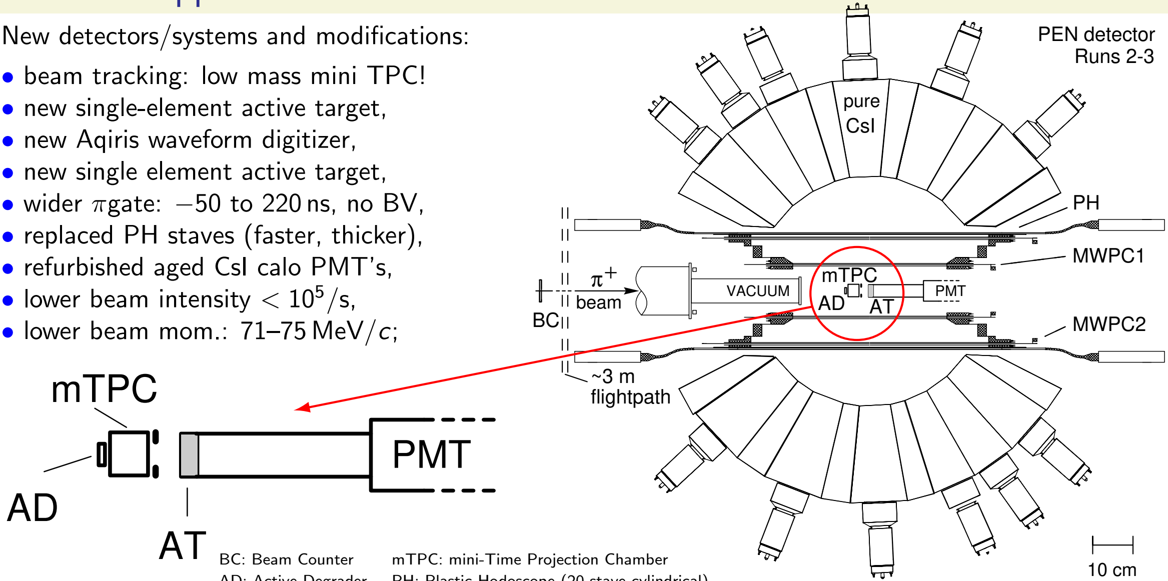
The PEN apparatus

New detectors/systems and modifications:

- beam tracking: low mass mini TPC!
- new single-element active target,
- new Aqiris waveform digitizer,
- new single element active target,
- wider πgate: -50 to 220 ns, no BV,
- replaced PH staves (faster, thicker),
- refurbished aged CsI calo PMT's,
- lower beam intensity $< 10^5$/s,
- lower beam mom.: 71–75 MeV/c;



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mTPC: mini-Time Projection Chamber
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)

PEN measurement principles for $R^{\pi}_{e/\mu}$; key challenges

Basic principle: record pion decays at rest in a beam stopping target[1] and count each:

(a) $\pi_{e2(\gamma)}$: $\pi^+ \to e^+\nu_e(\gamma)$, and (b) $\pi_{\mu2(\gamma)}$: $\pi^+ \to \mu^+\nu_\mu(\gamma)$ decay event

during an observation time window, and evaluate the yield ratio (a)/(b), applying appropriate corrections. Since (a) and (b) cannot be identified sufficiently reliably in the stopping target alone, an e-m calorimeter and tracking detectors are used, identifying (b) through the subsequent decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu(\gamma)$.

Key challenges in achieving sub-10^{-3}, or sub-10^{-4} precision are of **systematic** nature:

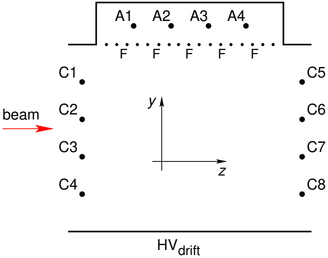
- accurately **identify** processes (weak decay, hadronic interaction, etc.) for each event,
- accurately **count** and **sort** each type of decay event (without missing/mislabeling any).

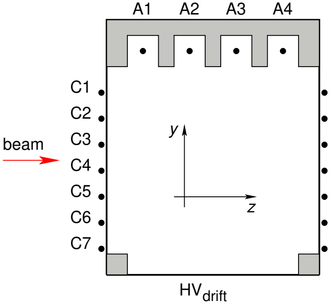
In practice this means that beam and decay particles must be tracked, and their interactions with matter detected and recorded, until the final stop of the detectable decay products in the calorimeter.

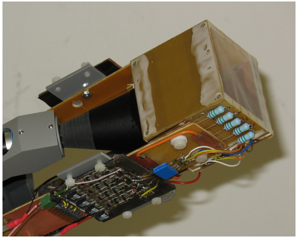
Key design requirements include minimizing mass in the particle path to target/calorimeter, while maximizing detection efficiency and resolution: E, t and spatial.

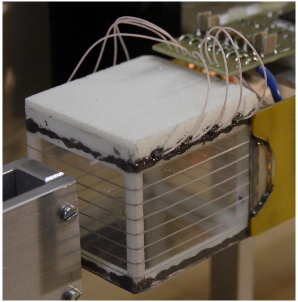
[1] Here we do not discuss decays in flight which present a wholly different set of challenges.

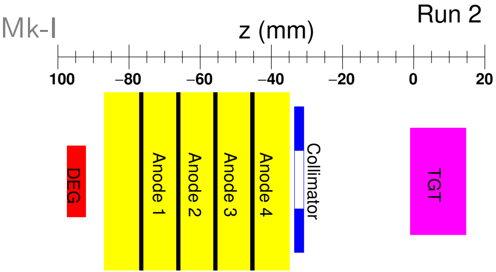
PEN beam tracking: the mini TPC's (Runs 2 and 3; JINR Dubna designed and built)

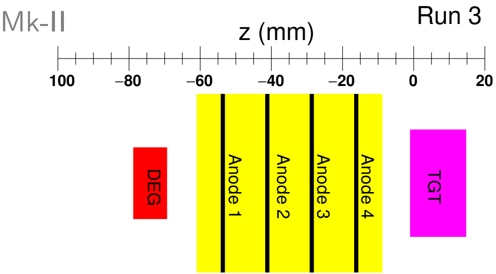






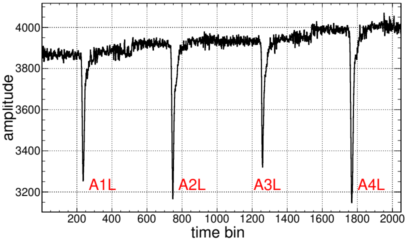


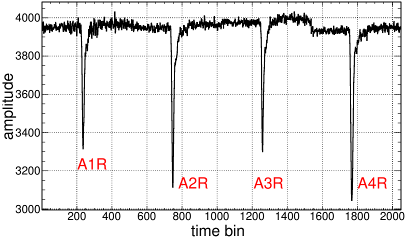




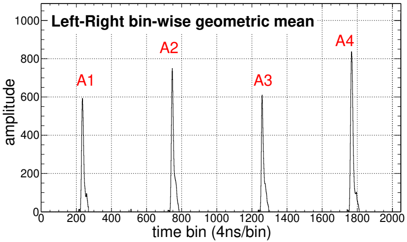
Beam tracking: x: (resistive) anode L/R amplitude asymmetry; y: anode mean time vs. AD.

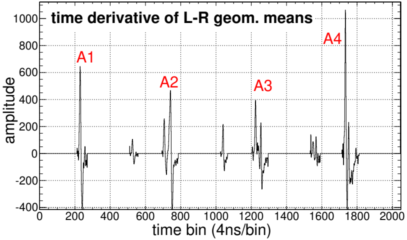
multiplexed anode waveforms:

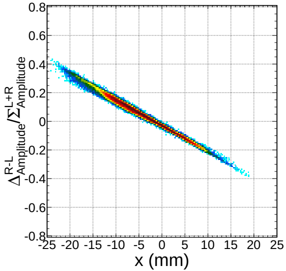


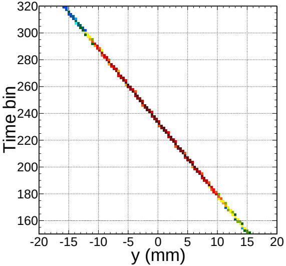


amplitude & timing data:



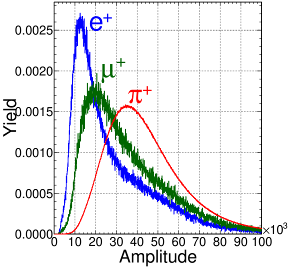


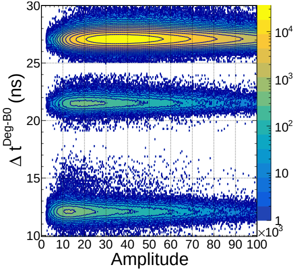




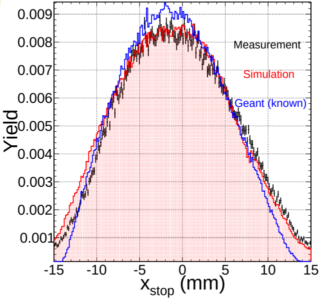
More on mTPC performance

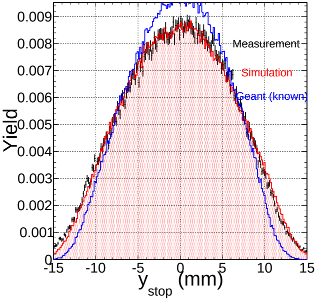
mTPC beam particle ID:



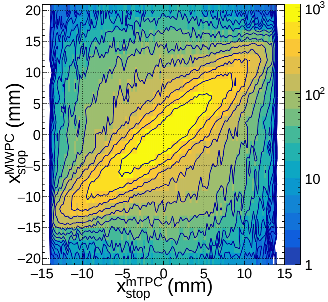


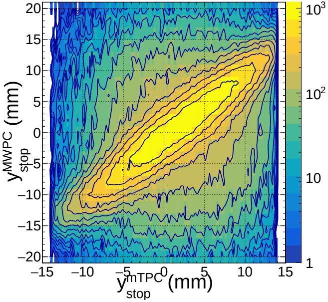
mTPC stopping distr.:



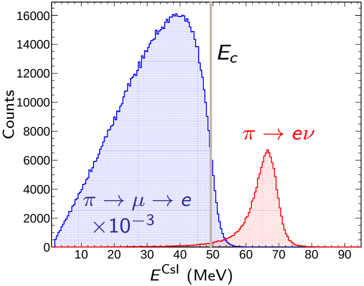


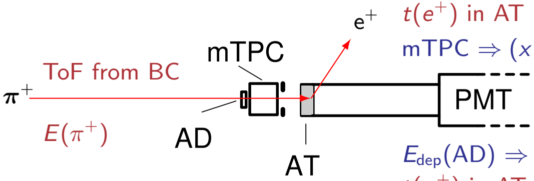
$(x, y)_{\text{stop}}$: mTPC vs. MWPC





Discriminating π_{e2} and $\pi_{\mu 2}$ in TGT



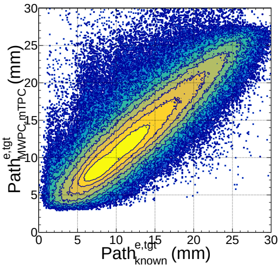


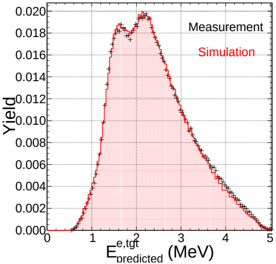
$t(e^+)$ in AT predicted from t(PH)

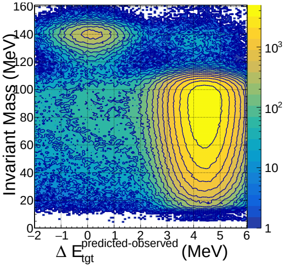
mTPC $\Rightarrow$ (x, y) of π_{stop} in AT

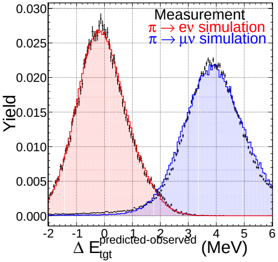
E_{dep}(AD) $\Rightarrow$ E_{dep}, z of π_{stop} in AT

$t(\pi^+)$ in AT predicted from t(AD)

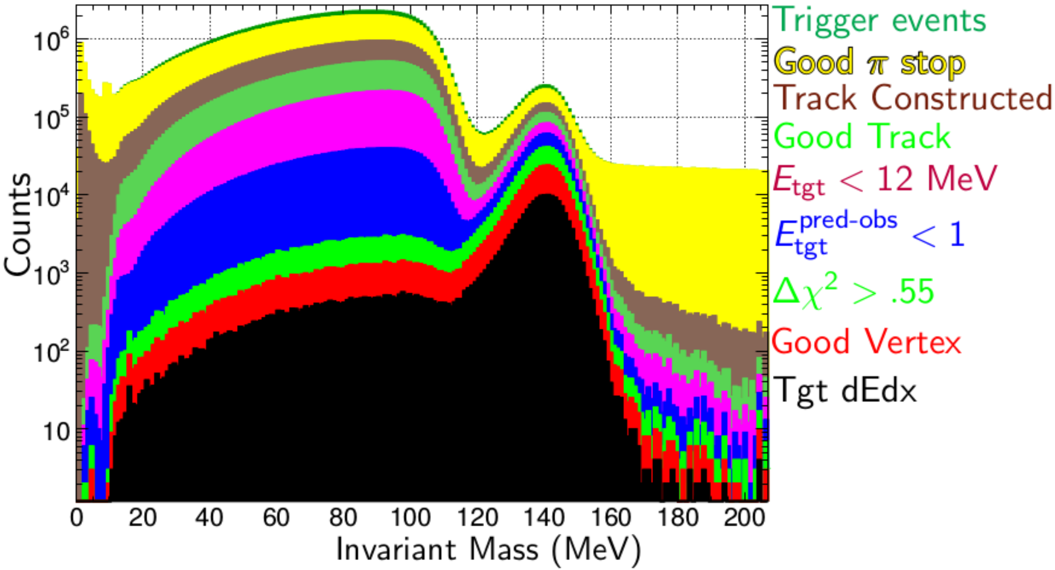




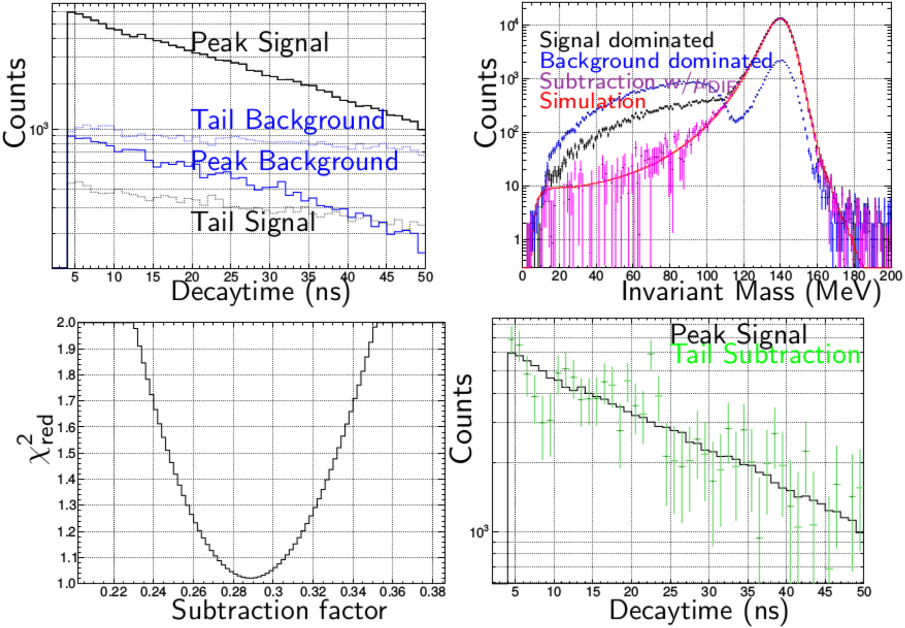




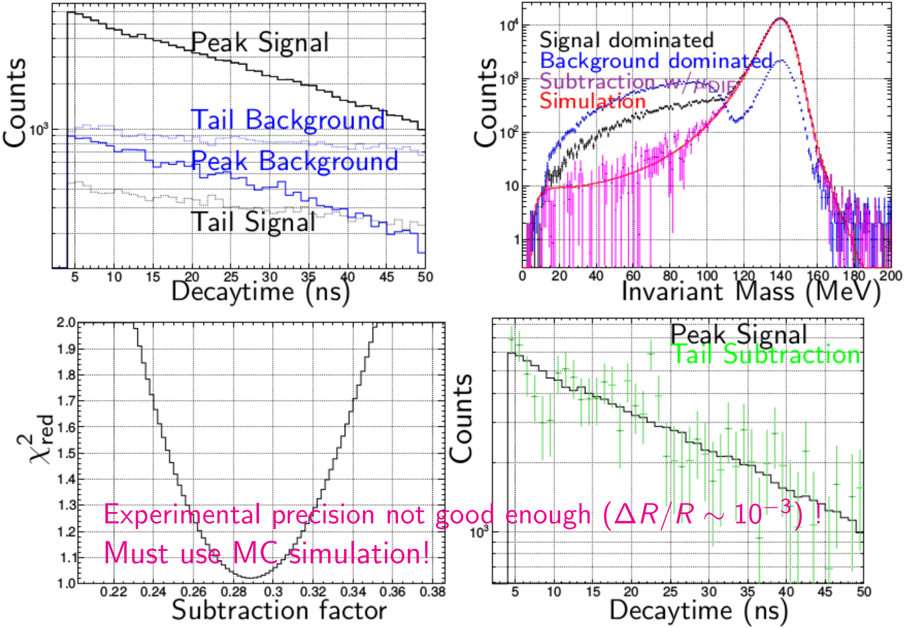
Tail trigger



Main trigger: measured 'tail' after backgd. subtraction ⇒



Main trigger: measured 'tail' after backgd. subtraction ⇒

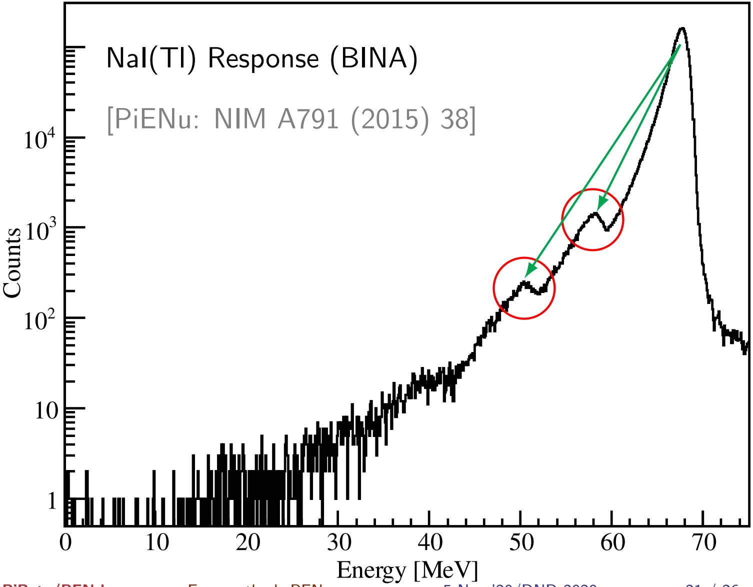


Experimental precision not good enough ($\Delta R/R \sim 10^{-3}$) !

Must use MC simulation!

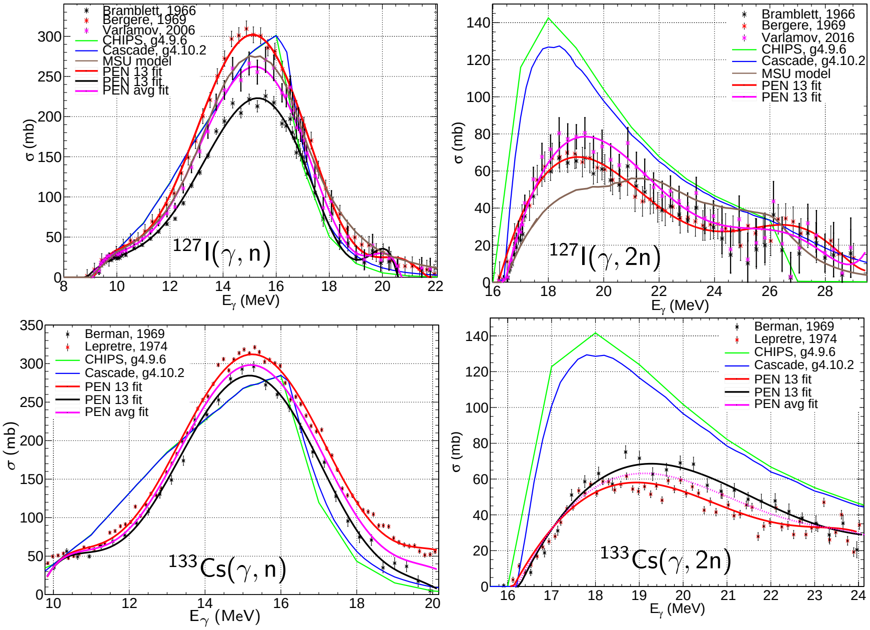
Tail fraction: photoneutron reactions

(γ, n) reactions on calorimeter nuclei, Cs and I, shift counts from the main peak to the "tail" region if the neutron is undetected.



Photoneutron cross sections, $\sigma(\gamma, xn)$

- Many inconsistencies among the data sets;
- Geant4 descriptions inadequate, often miss data by a wide margin.
- PEN was forced to implement its own parametrization in Geant4 (C. Glaser).
- This procedure works at the PEN goal precision, but would be inadequate at higher precision.



Current status of PEN analysis

$$R^{\pi}_{e/\mu} = \frac{N^{\text{peak}}_{\pi\to e\nu}}{N_{\pi\to\mu\nu}} (1 + \epsilon_{\text{tail}}) \frac{A_{\pi\text{-}\mu\text{-e}}}{A_{\pi\text{-}\mu\text{-e}}} \frac{\epsilon(E_{\mu\to e\nu\bar{\nu}})_{\text{MWPC}}}{\epsilon(E_{\pi\to e\nu})_{\text{MWPC}}} \frac{f_{\pi\text{-}\mu\text{-e}}(T_e)}{f_{\pi\text{-}\mu\text{-e}}(T_e)}$$

r_A $\quad r_\epsilon$ $\quad r_f$

Systematics	Value	$\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu}$
ϵ_{tail}	0.032	3.5×10^{-4}
r_f	0.04292034	5×10^{-6}
$^*r_A r_\epsilon$	$\simeq 0.98$	$\sim 3 \times 10^{-4}$
Statistical:		
$\Delta N_{\pi\to e\nu}/N_{\pi\to e\nu}$		5.15×10^{-4} (Runs 2†&3)
Goal		5×10^{-4}

* Blinded $\quad$ † incomplete

Work is currently ongoing on the systematic analysis of the remaining steps and checks.

Lessons for a next generation experiment

- One can never know too much about an event. **Redundancy** in the measured observables is essential.
- **Precision tracking** of beam and decay product particles is critically important.
- There is no substitute for **resolution (E, t, spatial)**, especially in the calorimeter. Calorimeter thickness, though expensive, is essential.
- Calorimeter must be **separable** so that its response can be studied directly with beam in a controlled manner.
- **Calorimeter segmentation** is critical. The PiBeta calorimeter was designed to provide sufficient angular resolution for photon-induced showers, and delivered. Calorimeter segmentation enables use of high beam stopping rates with ease.
- **Low mass** everywhere in the path of particles (beam and decay products) is essential.
- Highly realistic **simulation** of the apparatus and processes is a given.
- Handling the **high target rate** for an ultimate $R^{\pi}_{e3(\gamma)}$ measurement is a **challenge**.

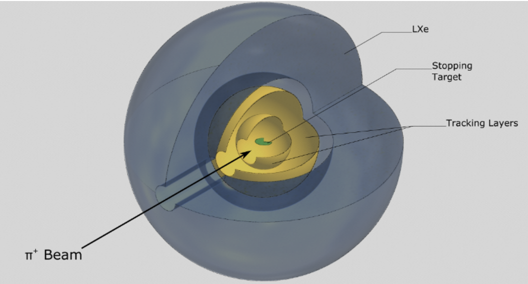
A caveat: radiative decays

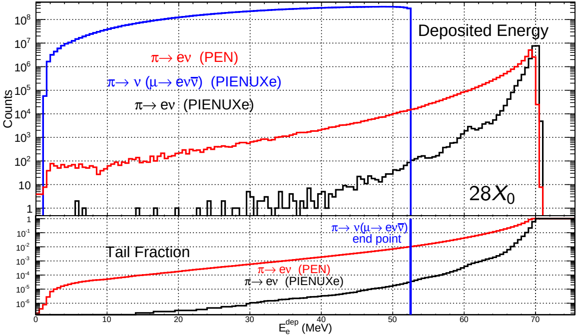
I have not discussed the study of radiative decays:

1. $\pi^+ \to e^+ \nu_e \gamma$, and
2. $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$.

These are rich in physics and interesting to study, and accessible with the apparatus discussed here.

Arguably our most impactful result to date is the high precision measurement of $R^{\pi}_{e2\gamma}$ and limit on F_T that has provided the best constraint on ϵ_T, the weak **tensor** coupling.





Concept for an improved RarePi experiment

Goals:

1. $(\Delta R/R)^{\pi}_{e/\mu} < 10^{-4}$ (to match theory),
2. $(\Delta R/R)^{\pi}_{e3} \sim 2 - 3 \times 10^{-3}$ (per W. Marciano).

A possible setup:

- stopped π^+ in active target with full tracking,
- main detector: liquid Xe,
- $\langle r^{\pi}_{\text{stop}} \rangle \sim 1.5 - 2 \times 10^6\,\text{s}^{-1}$,
- with $T^{\text{live}}_{\text{run}} \sim 3 \times 10^7\,\text{s}$ ($>$ 2 calendar years):
- $N^{\pi}_{e2(\gamma)} > 5 \times 10^9$: $\left(\Delta R^{\pi}_{e/\mu}/R\right)_{\text{stat}} < 2 \times 10^{-5}$;
- $N^{\pi}_{e3(\gamma)} \geq 4 \times 10^5$: $(\Delta R^{\pi}_{e3}/R)_{\text{stat}} < 2 \times 10^{-3}$.

Matching the theoretical precision in π_{e3} decay would require substantially higher beam stop rates and further attention to the target and central tracking detectors.

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