Measuring $\pi_{e3(\gamma)}$, the pion beta decay

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Topics discussed in this talk

PiBeta (and PEN) goals and design

Experimental method: PiBeta

- Apparatus and measurement method
- Calorimeter genesis
- Calorimeter triggers
- Active target

Detector performance and measurements

Radiative decays

- Invariant mass and pileup suppression

Photoneutron reactions

More on pileup suppression

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

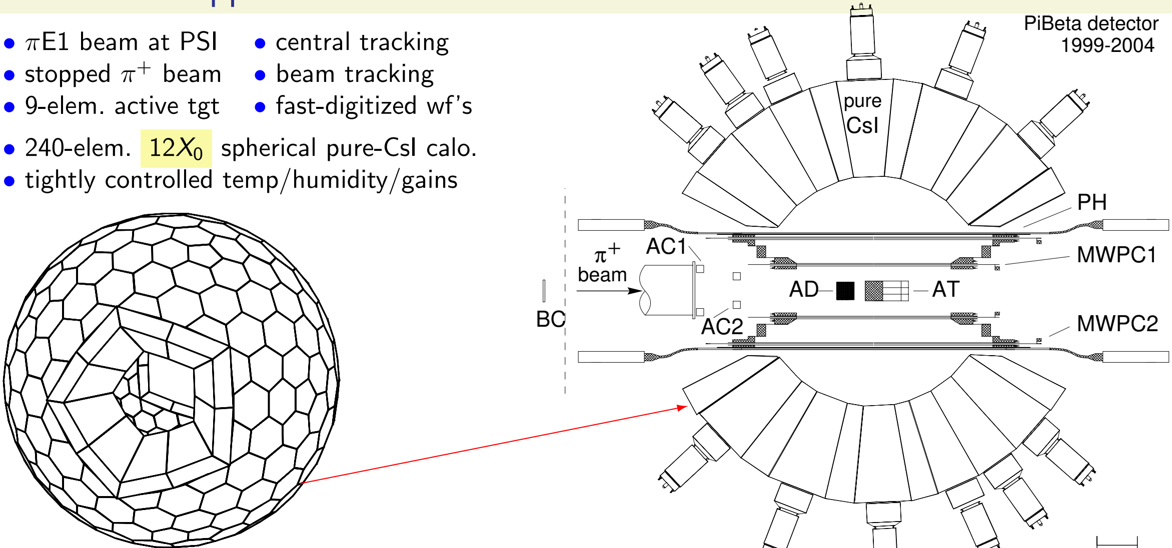
	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e3(\gamma)}$:	$\pi^+ \to \pi^0 e^+ \nu_e(\gamma)$	$R^\pi_{e3(\gamma)} \sim 10^{-8}$	$\sim 5 \times 10^{-3}$	CKM V_{ud} & related
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^\pi_{e2\gamma} \sim 10^{-7}$	$\le 1 \times 10^{-2}$	$F^\pi_A, F^\pi_V, F^\pi_T$; χPT l.e.c.
RMD:	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$	$R^\pi_{e2\gamma} \sim 10^{-3}$	$\le 1 \times 10^{-2}$	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
$\pi_{e2(\gamma)}$:	$\pi^+ \to e^+ \nu_e(\gamma)$	$R^\pi_{e2(\gamma)} \sim 10^{-4}$	$\sim 5 \times 10^{-4}$	lept. univ.; non-$V-A$, ...
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^\pi_{e2\gamma} \sim 10^{-7}$	$\sim 1 \times 10^{-2}$	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 $\bar{\eta}$

The PiBeta apparatus

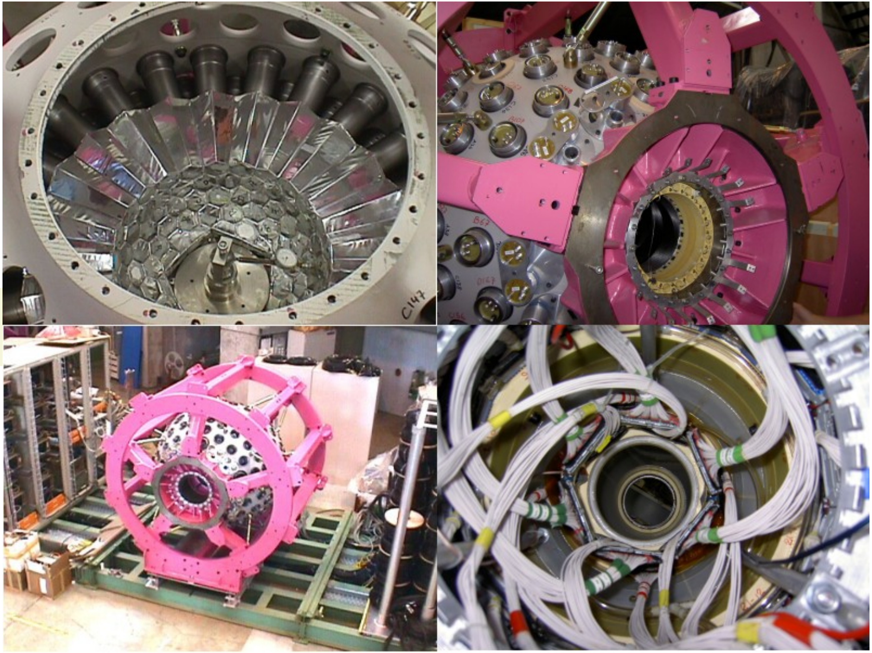
- πE1 beam at PSI
- stopped π^+ beam
- 9-elem. active tgt
- central tracking
- beam tracking
- fast-digitized wf's
- 240-elem. $12X_0$ spherical pure-CsI calo.
- tightly controlled temp/humidity/gains

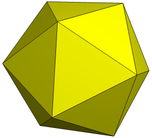


BC: Beam Counter
AD: Active Degrader
AT: Active Target

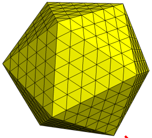
AC1,2: Active beam Collimators
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)

A few photos of the PiBeta apparatus:

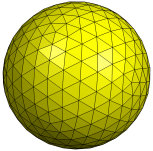




Icosahedron

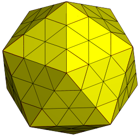


6-frequency subdivision

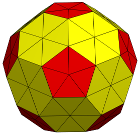


Vertices projected onto sphere

But, we don't want triangular pyramids (sharp corners ⇒ nonuniform light collection) — merge triangles into hexagons and pentagons.

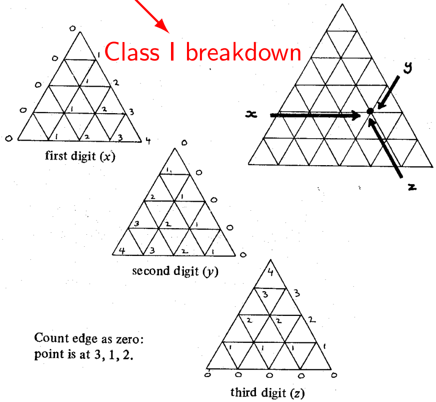


subdivided

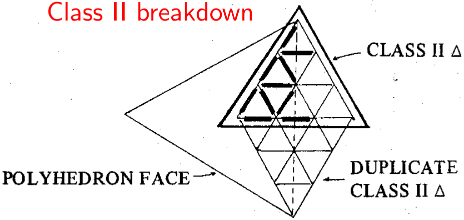


truncated icosahedron

Class I breakdown



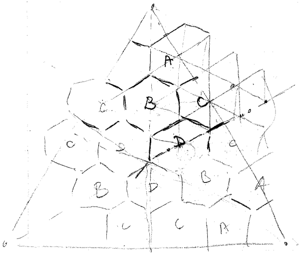
Class II breakdown



SELECTED

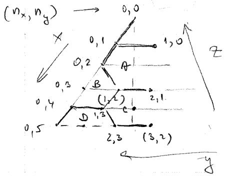
23 Nov 1990

The last option ICOSA 10 ν Class II Meth I



12 Pentagons		12
20× Hex	A ×3	60
20× Hex	B ×3	60
20× Hex	C ×3	60
20× Hex	D ×3	60
	total	252

vs. 272 for 9ν Class I



(0,1 - 1,0)	0.1366
(0,1 - 0 2)	0.1271
(0 2 - 1 2)	0.1311
(1 2 - 2 1)	0.1479
(1 2 - 1 3)	0.1410
(1 3 - 0 4)	0.1438
(0 4 - 0 5)	0.1359
(1 3 - 2 3)	0.1428
(2 3 - 3 2)	0.1523

Remove:

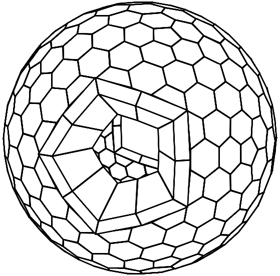
penta	×1	.00255	
A	×5	.01830	
B	×5	.01980	
C	×2.5	.02135	Σ = .051
Veto: D	10	.041	
+ C	5	.02135	Σ = .0623

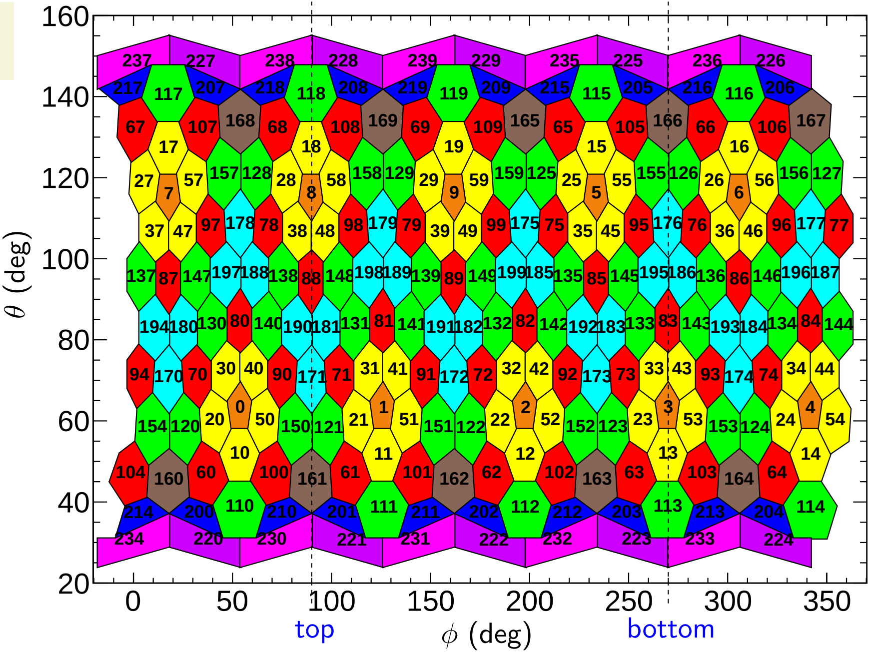
Remains 0.77 of 4π

Total # of elem: 252
− 32
220

Detector	190
Veto elem	30

PiBeta Calo map in the Mercator projection





Accepted crystals met minimum criteria for pion beta decay measurement.

CsI module calibration details posted on PiBeta website.

Pion beta decay kinematics

The $\pi^0 \to \gamma\gamma$ signal is well separated from all backgrounds;

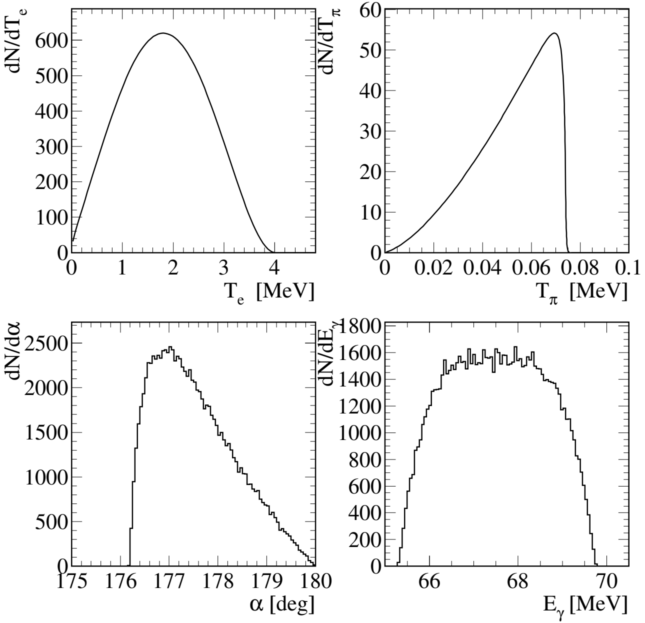
Even so, impossible to isolate without significant calo segmentation!

Challenge: detect the decay positron!

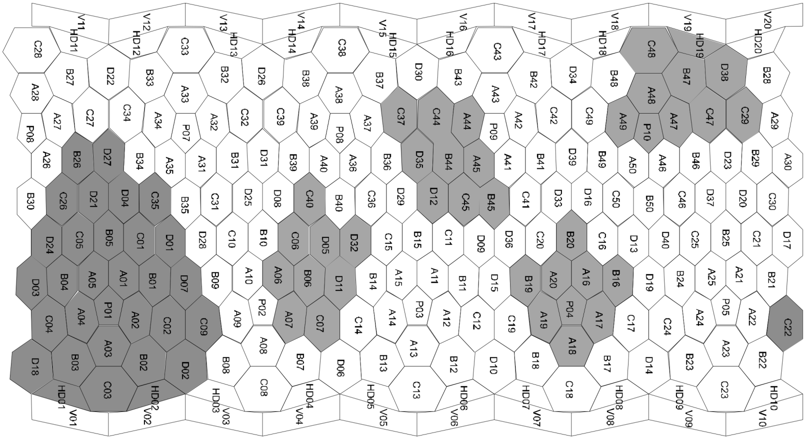
This has led to evolution in the design of PiBeta targets.

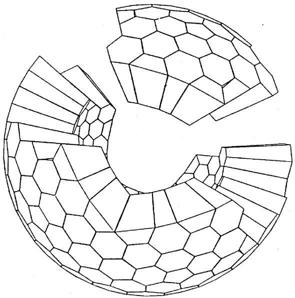
Minimize passive material!

Enlarge AT components to optimize energy resolution.

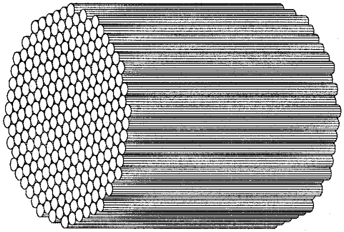


Clustering for the 2-arm HI trigger

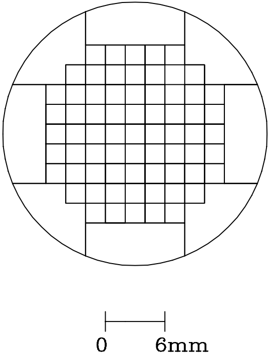




Active target evolution

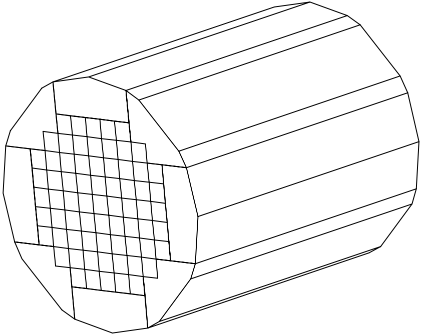


Concept 0.5



Diameter: 40 mm;

Length: 50 mm.



AT 1.0: 69 fibers 2.76 mm $\times$ 2.76 mm^2; 0.12 mm acrylic cladding

The PiBeta 9-element AT

Minimum segmentation to handle the rate.

Ultrafast ⌀ 10 mm Hamamatsu PMTs and custom made dividers at UVA (also for calo PMTs).

Radiation damaged; replaced after $\sim$3 months in beam.

Single piece in PEN:

$\sigma \simeq 4.5\%$ for 4.1 MeV μ line

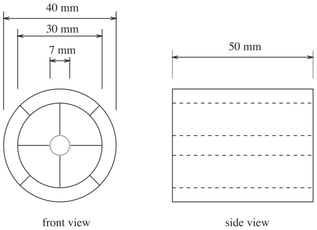


Fig. 12. A sketch of the regular PIBETA active target, composed of nine detectors. The segment sizes are chosen to balance the scaler counting rate.

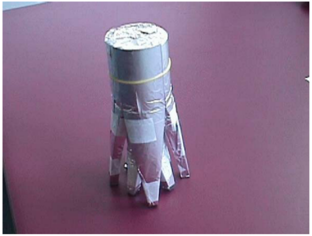


Fig. 13. A photograph of the regular PIBETA active target. Acrylic tapered light guides are glued to nine optically isolated target segments.

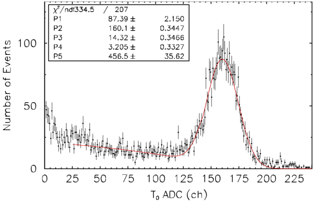


Fig. 14. The pulse-height spectrum of pions stopping in the central active target segment. The peak-to-tail area ratio depends on the beam divergence.

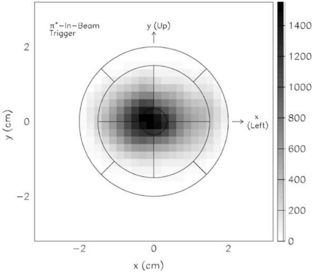
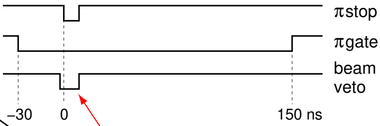
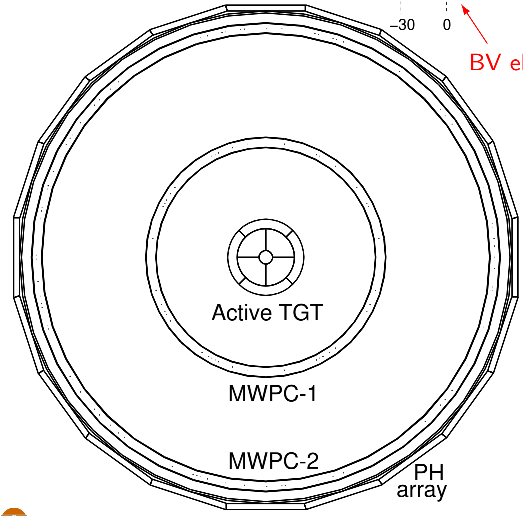


Fig. 15. Reconstructed two-dimensional shape of the π^+ beam superimposed on an outline of the segmented active target. Data for target counting rates are collected during one 48 h long series of runs.

PiBeta central detector region

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



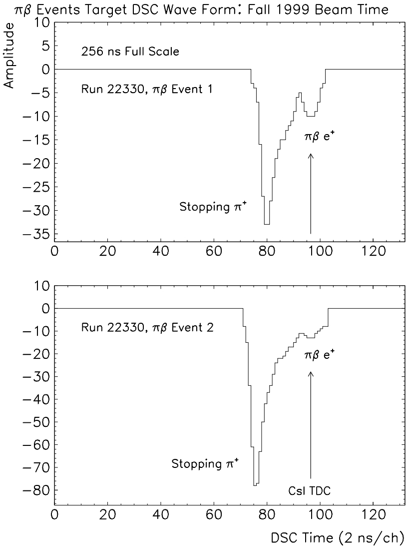


Beam $p \simeq 113\,\mathrm{MeV}/c$
(to achieve π_{stop} rate)

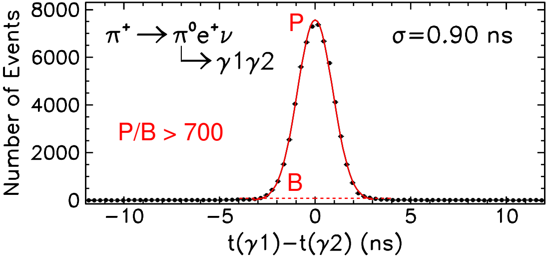
9-piece AT provides rudimentary beam stop tracking

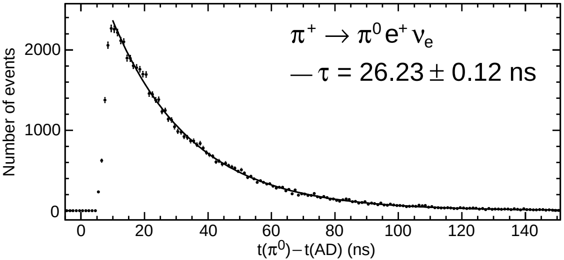
Note: AT was replaced for each annual run due to radiation damage.

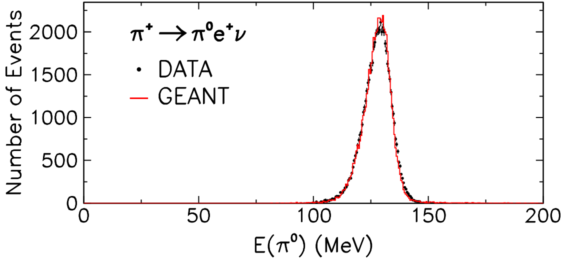
Digitized AT signal waveforms:

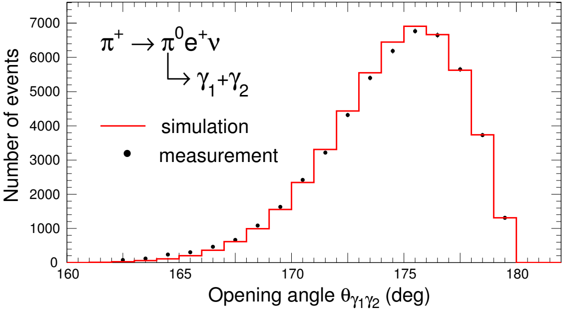


Key PiBeta spectra: π_{e3} decay (2004)

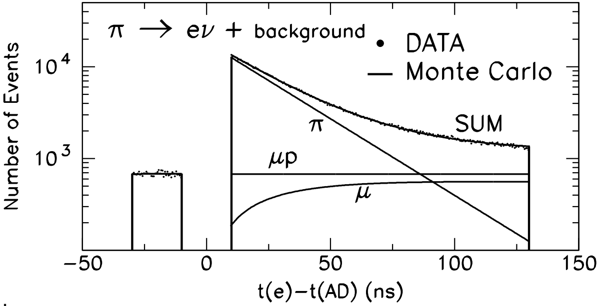


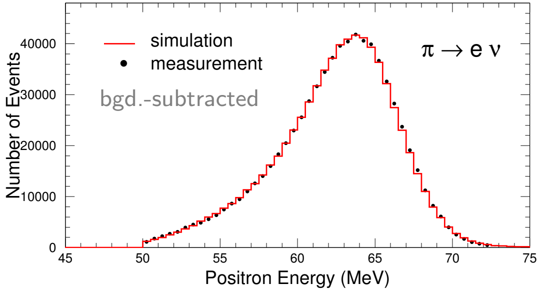






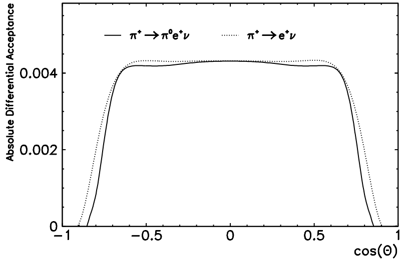
PiBeta normalization spectra: π_{e2} decay (2004)





Notes:

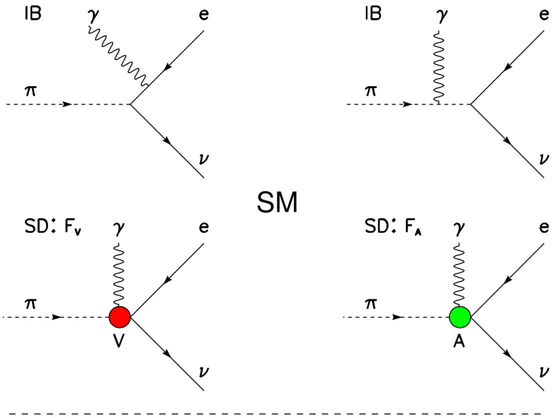
- π_{e3} signals are clean, w/low bgd. levels (previous slide);
- large background in π_{e2} from $\pi \rightarrow \mu \rightarrow e$ decay chain,
- ... also from pile-up μ's in target;
- $\sim$ 15 ns vetoed around $t = 0$ to suppress prompt hadr. bgd.;
- excellent agreement with Geant3 MC simulations;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



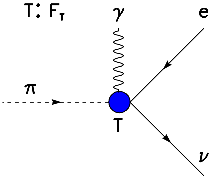
Physics of $\pi^+ \to e^+\nu\gamma$ (RPD):

QED IB terms:

and SD V, A terms:



A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

The $\pi \to e\nu\gamma$ amplitude and FF's

The IB amplitude (QED **uninteresting!**):

$$M_{\text{IB}} = -i\frac{eG_F V_{ud}}{\sqrt{2}} f_\pi m_e \epsilon^{\mu *} \bar{e} \left(\frac{k_\mu}{kq} - \frac{p_\mu}{pq} + \frac{\sigma_{\mu\nu} q^\nu}{2kq} \right) \times (1 - \gamma_5)\, \nu \, .$$

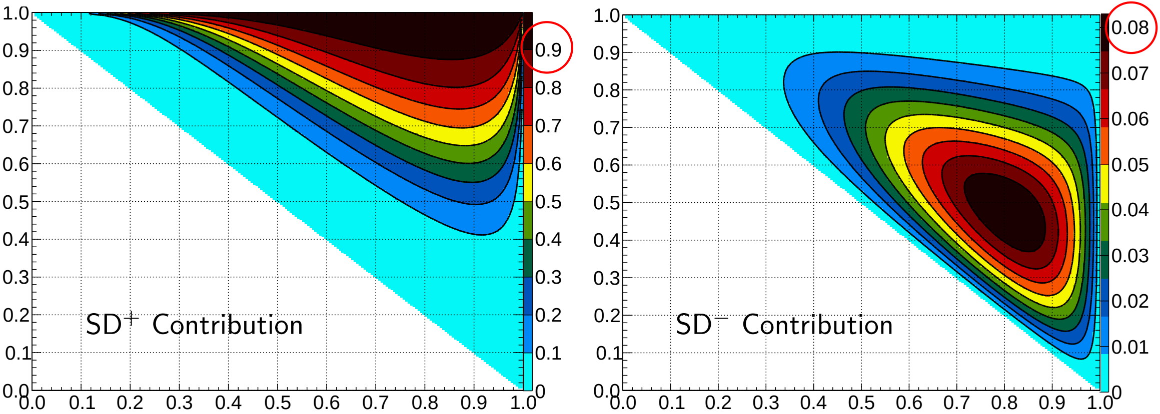
The structure-dependent amplitude (**interesting!**):

$$M_{\text{SD}} = \frac{eG_F V_{ud}}{m_\pi \sqrt{2}} \epsilon^{\nu *} \bar{e} \gamma^\mu (1 - \gamma_5) \nu \times [F_V \epsilon_{\mu\nu\sigma\tau} p^\sigma q^\tau + i F_A (g_{\mu\nu} pq - p_\nu q_\mu)] \, .$$

The SM branching ratio (with $x = 2E_\gamma / m_\pi$; $y = 2E_e / m_\pi$),

$$\frac{d\Gamma_{\pi e 2\gamma}}{dx\, dy} = \frac{\alpha}{2\pi} \Gamma_{\pi e 2} \Bigg\{ IB\,(x,y) + \left(\frac{m_\pi^2}{2 f_\pi m_e} \right)^2 \times \left[(F_V + F_A)^2\, \boldsymbol{SD^+}\,(x,y) + (F_V - F_A)^2\, SD^-\,(x,y) \right] + \frac{m_\pi}{f_\pi} \left[(F_V + F_A)\, S^+_{\text{int}}\,(x,y) + (F_V - F_A)\, S^-_{\text{int}}\,(x,y) \right] \Bigg\} \, .$$

Best sensitivity for SD terms



SD$^+$ region favors high energy e$^+$ and γ's.

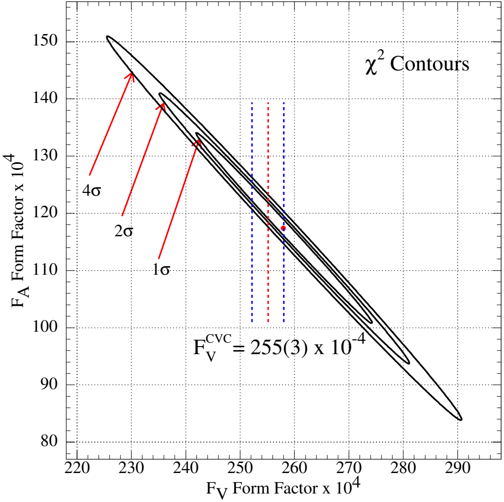
High energy track pairs occur with large opening angles.

Large solid angle coverage required $\Rightarrow$ good match to PEN!

SD$^-$ is notoriously hard to measure directly.

PIBETA results for $\pi \to e\nu\gamma$ (2009)

Pion FF values and precision improvement factors (pif) over previous work:



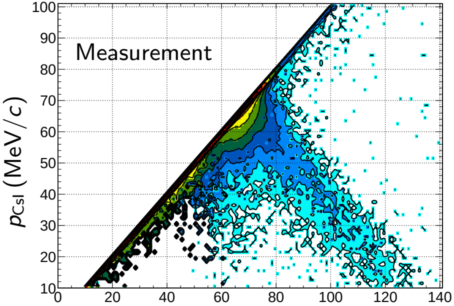
Observable	(pif)
$F_V = 0.0258(17)$	$(8\times)$
$F_A = 0.0119(1)^{\text{exp}}_{(F_V^{CVC})}$	$(16\times)$
$a = 0.10(6)\ ^*$	(∞)
$-5.2 < 10^4 \cdot F_T < 4.0$	90 % c.l.
$B_{\pi_{e2\gamma}} = 73.86(54) \times 10^{-8\,\dagger}$	$(17\times)$

* $a \ldots q^2$ dependence of F_V

† for ($E_\gamma > 10$ MeV, and $\theta_{e\gamma} > 40^\circ$)

[Bychkov et al., PRL **103**, 051802 (2009)]

Identifying hard radiative decays in PEN

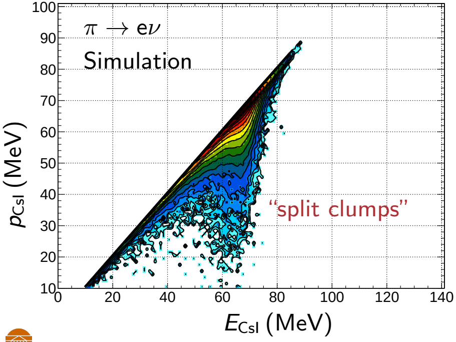


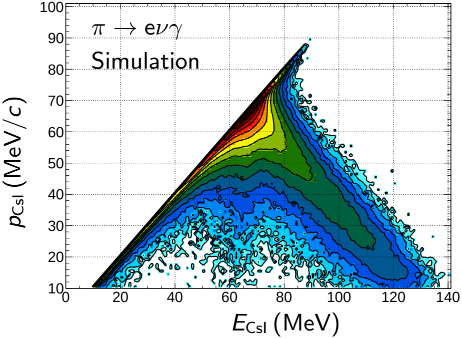
PEN indirectly measures p_ν in $\pi \to e\nu\gamma$

$\vec{p}_e + \vec{p}_\gamma = -\vec{p}_\nu \equiv \vec{p}_{obs}$; with:

$E_e + E_\gamma \equiv E_{obs}$

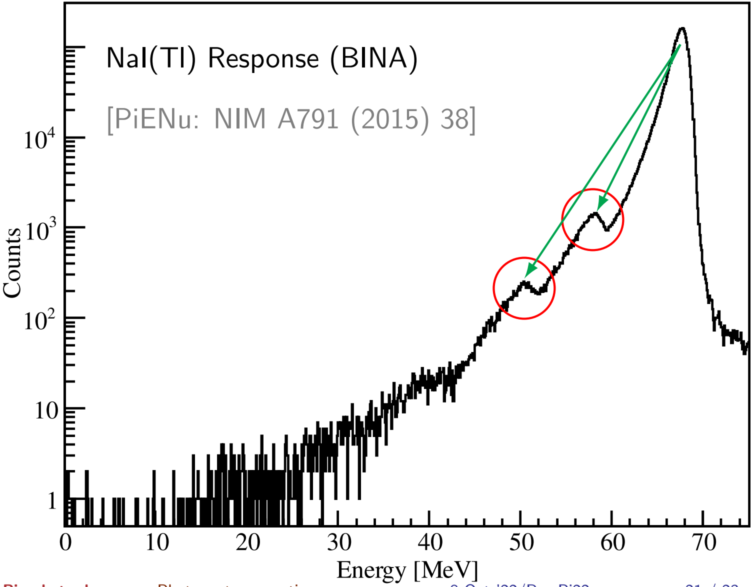
$E_{obs} + p_{obs}c = m_\pi c^2$





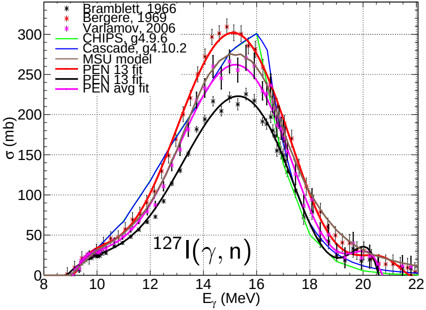
Tail fraction: photoneutron reactions

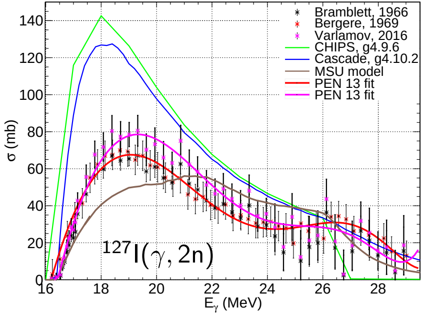
(γ, n) reactions on calorimeter nuclei, Cs and I, shift counts from the main peak to the "tail" region if the neutron is undetected.

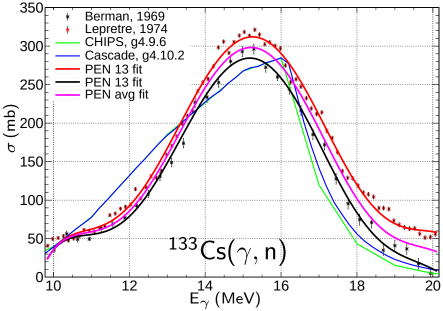


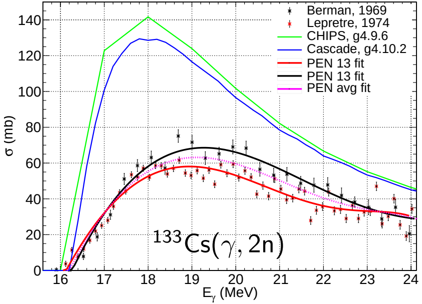
Photoneutron cross sections, $\sigma(\gamma, xn)$

- 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.









More on pileup suppression and $\pi_{e2}/\pi_{\mu2}$ discrimination

- The most potent weapon: vetoing events with prior beam pions/muons for N muon lifetimes is **not preactical in the PiBeta phase** of PiONEER!
- Meaningful review of cuts and techniques used in PEN requires a separate discussion.
- We have found that a forward beam counter (BC), active degrader (AD), central tracking (MWPC), and beam tracking (mTPC) all are essential.
- We must examine how much of this ATAR can replace, and whether or not ATAR brings new compromises.
- It is important to see how some of those functions will be replaced in the PiONEER paradigm.
- Most important of all: the pion beta phase still requires precise π_{e2} normalization!