Rare pion decays and tests of the Standard Model

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Known and measured pion and muon decays

decay		*B.R.*		physics interest
$\pi^+ \to$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(π_{e2})	⇐ ℓU, BSM (T,...)
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{e2\gamma})$	⇐ BSM (T,...), $F_A^{(\pi)}$, $F_V^{(\pi)}$,...
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	(π_{e3})	⇐ $q\ell$U (V_{ud}), BSM loops
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \to$	$\gamma\gamma$	$0.98798\,(32)$		⇐ χ anomaly
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)	
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$		
	e^+e^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \to$	$e^+\nu\bar{\nu}$	~ 1.0	(Michel)	⇐ BSM weak int. terms
	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$	(RMD)	
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

The electronic ($\pi_{\mathbf{e2}}$) decay:

$$\pi^+ \to \mathrm{e}^+\nu(\gamma)$$

$$BR \sim 10^{-4}$$

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

$$\begin{cases} 1.2352\,(5) \times 10^{-4} & \text{Marciano and Sirlin, [PRL } \mathbf{71} \text{ (1993) 3629]} \\ 1.2354\,(2) \times 10^{-4} & \text{Finkemeier, [PL B } \mathbf{387} \text{ (1996) 391]} \\ 1.2352\,(1) \times 10^{-4} & \text{Cirigliano and Rosell, [PRL } \mathbf{99} \text{ (2007) 231801]} \end{cases}$$

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- Strong SM **helicity suppression** amplifies sensitivity to PS terms ("door" for New Physics) by factor $2m_\pi/m_e(m_u + m_d) \approx 8000$.

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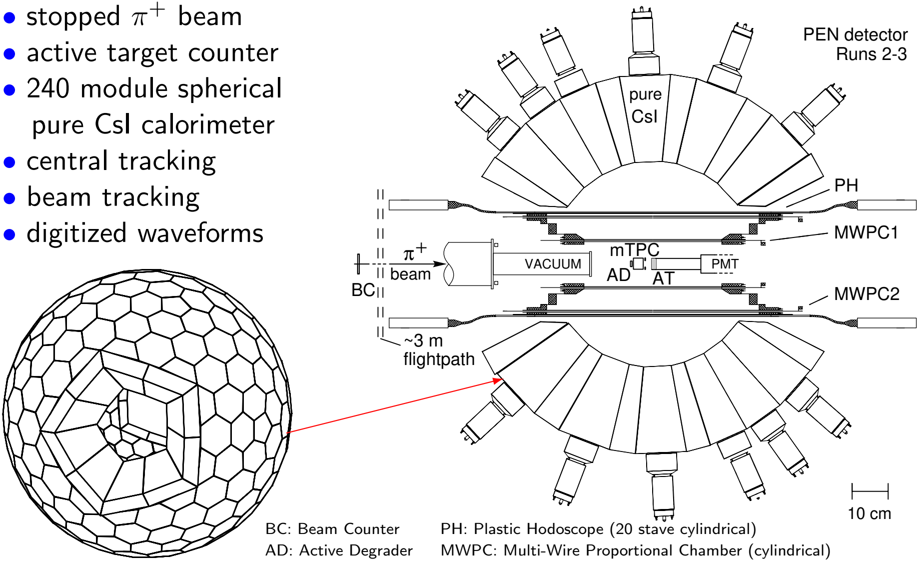
- Experimental world average is 23× less accurate than SM calculations!

  [$1.2327(23) \times 10^{-4}$]

The PEN/PIBETA apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240 module spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms



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

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

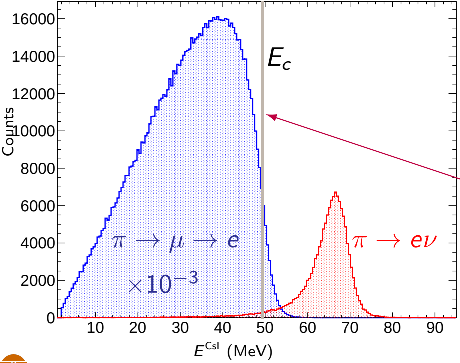
Experimental branching ratio ($R^{\pi\text{-exp}}_{e/\mu}$)

Recognizing that:

- timing gates affect the analyzed number of π_{e2} and $\pi \to \mu \to e$ events;
- MWPC efficiency depends on energy,

we have:

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



E_c = cutoff energy

N = number of events

A = acceptance

$\epsilon_{\text{tail}}(E_c)$ = tail to peak ratio

$\epsilon(E)_{\text{MWPC}}$ = efficiency of MWPC

$f(T_e)$ = decay probability during observation time window

Branching ratio/uncertainties

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

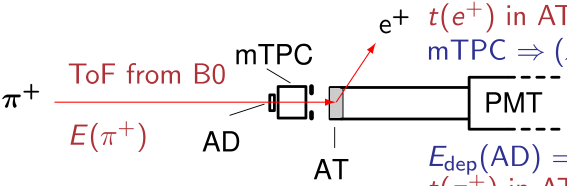
Uncertainties:

$$\frac{\delta R}{R} = \sqrt{\left(\frac{\delta r_N}{r_N}\right)^2 + \left(\frac{\delta\epsilon_{\text{tail}}}{1+\epsilon_{\text{tail}}}\right)^2 + \left(\frac{\delta r_f}{r_f}\right)^2 + \left(\frac{\delta r_\epsilon}{r_\epsilon}\right)^2 + \left(\frac{\delta r_A}{r_A}\right)^2}$$

$\epsilon_{\text{MWPC}}(E)$: chamber efficiencies. r_A: acceptances

PEN goal: $\delta R/R \simeq 5\times 10^{-4}$

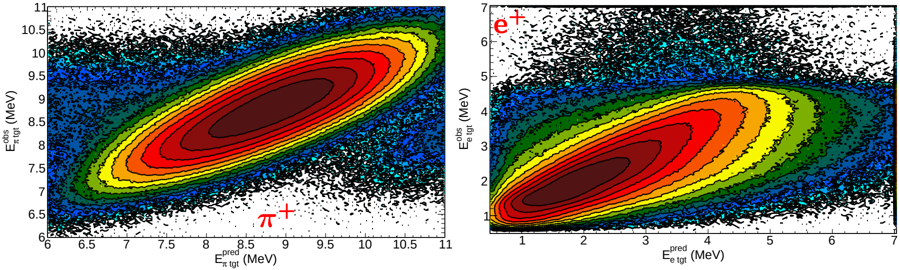
Discriminating π_{e2} and $\pi_{\mu 2}$ in TGT



$t(e^+)$ in AT predicted from t(PH)
mTPC $\Rightarrow (x, y)$ of π_{stop} in AT

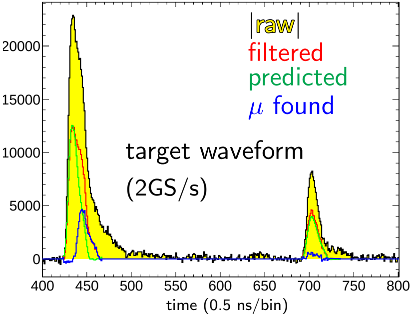
E_{dep}(AD) $\Rightarrow E_{dep}, z$ of π_{stop} in AT
$t(\pi^+)$ in AT predicted from t(AD)

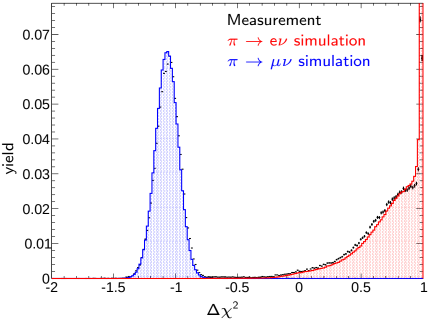
Predicted π^+ and e^+ energies agree VERY well with observations:

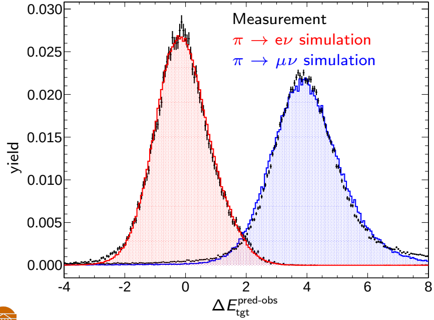


$\Rightarrow$ E and t predictions are used for $\pi_{e2}/\pi_{\mu 2}$ discrimination.

Target waveforms and event type discrimination





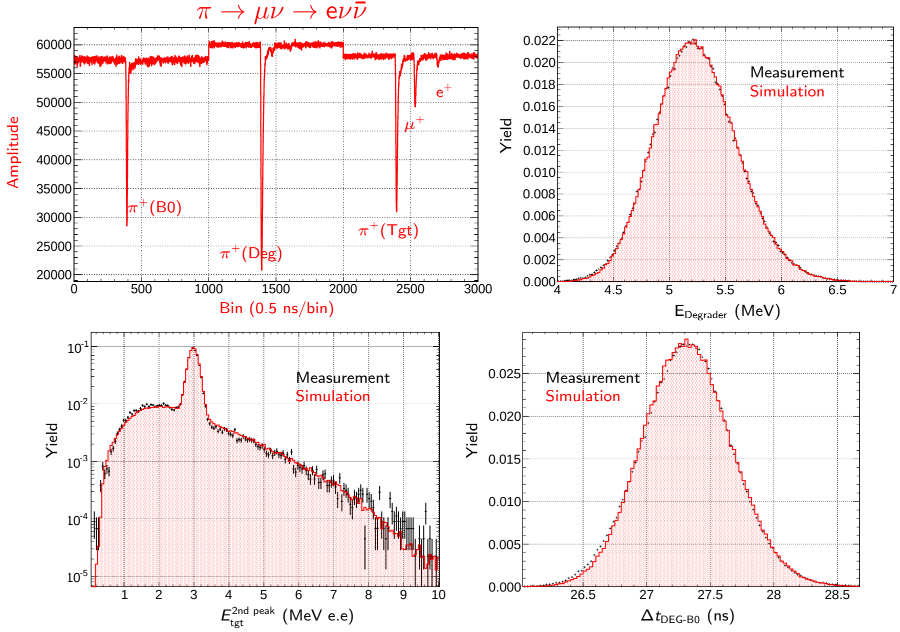


$\Delta\chi^2$ uses predicted and observed timings and energies. Steps:

1. evaluate 2 peak fit $\Rightarrow \chi_2^2$,
2. evaluate 3 peak fit $\Rightarrow \chi_3^2$,
3. find $\Delta\chi^2 = \chi_2^2 - \chi_3^2$ (normalized).

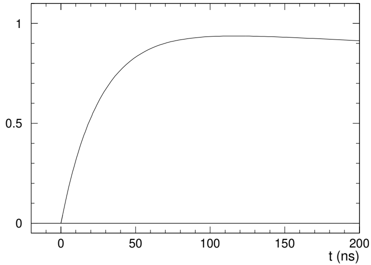
Best of $\sim$dozen similar observables at discriminating π_{e2} / $\pi_{\mu 2}$ event classes.

Realistic simulation of beam det's vs. measurement



Choice of time interval, $f(T_e)$

$\pi \to \mu \to e$ ("Michel") timing selection: symmetric time window.



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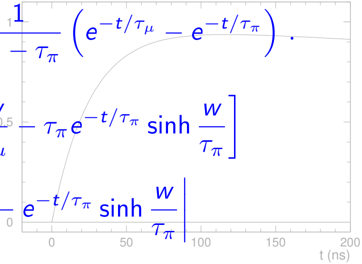
$$f_{\pi\text{-}\mu\text{-}e}(t) = \int_0^t f_{\pi\to\mu}(t-t')f_{\pi\to e}(t')dt' = \frac{1}{\tau_\mu - \tau_\pi}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right).$$

$$\left|f_{\pi\text{-}\mu\text{-}e}\right|_{t-w}^{t+w} = \frac{2}{\tau_\mu - \tau_\pi}\left[\tau_\mu e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - \tau_\pi e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right]$$

$$\delta f_{\pi\text{-}\mu\text{-}e} = \frac{2\delta t}{\tau_\mu - \tau_\pi}\left|e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right|$$



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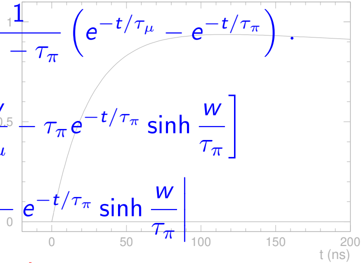

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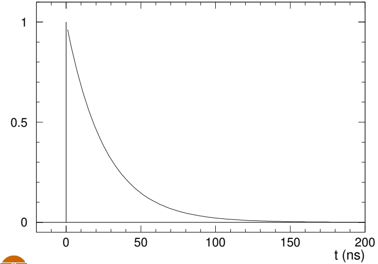
$\pi \rightarrow e\nu(\gamma)$ timing selection:



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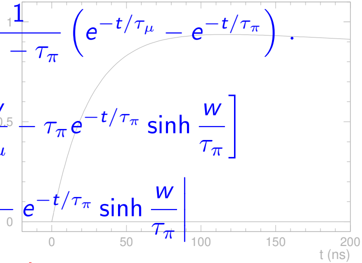

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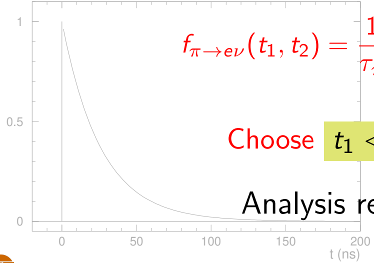
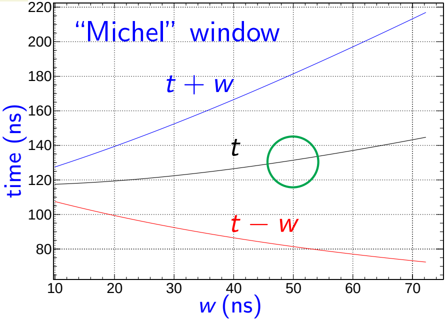
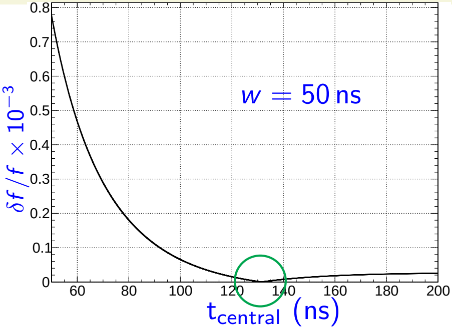


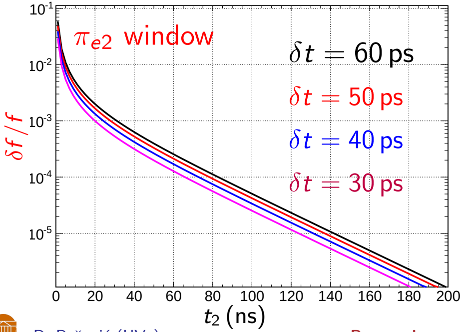
$$f_{\pi\to e\nu}(t_1, t_2) = \frac{1}{\tau_\pi}\int_{t_1}^{t_2} e^{-t/\tau_\pi} = e^{-t_1/\tau_\pi} - e^{-t_2/\tau_\pi}$$

Choose $t_1 < 0$: $\delta f_{\pi\to e\nu} = \dfrac{\delta t}{\tau_\pi}e^{-t_2/\tau_\pi}$.

Analysis requires: δt, w, t and t_2.







$\pi \to \mu\nu \to e\nu\bar{\nu}(\gamma)$

$\delta r_f / r_f$ negligible

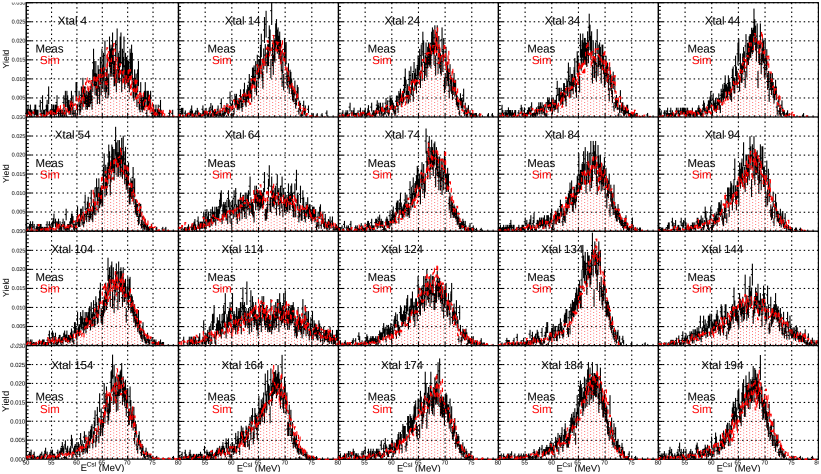
$\pi \to e\nu(\gamma)$

$\delta r_f / r_f$ negligible for $t_2 \gtrsim 90$ ns

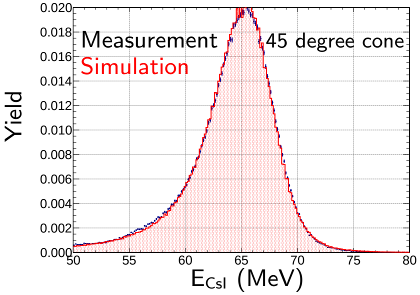
CsI EM Calorimeter: realistic simulation

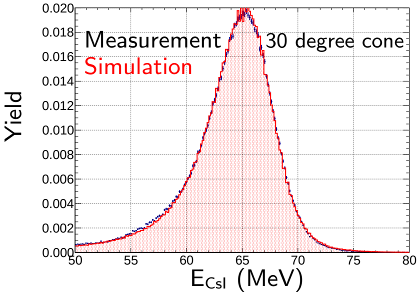
Crystals are not all the same:

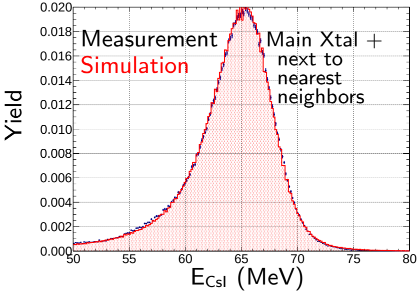
- different detector response, non-uniformities, $\Delta\Omega$ coverage;
- 240 PMTs, with slightly different properties, opt. couplings.

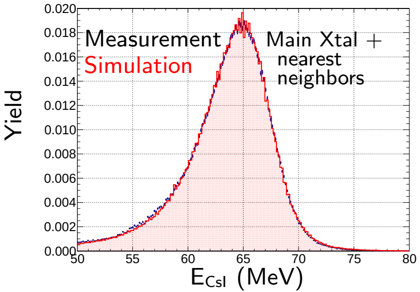


CsI simulation cont'd.

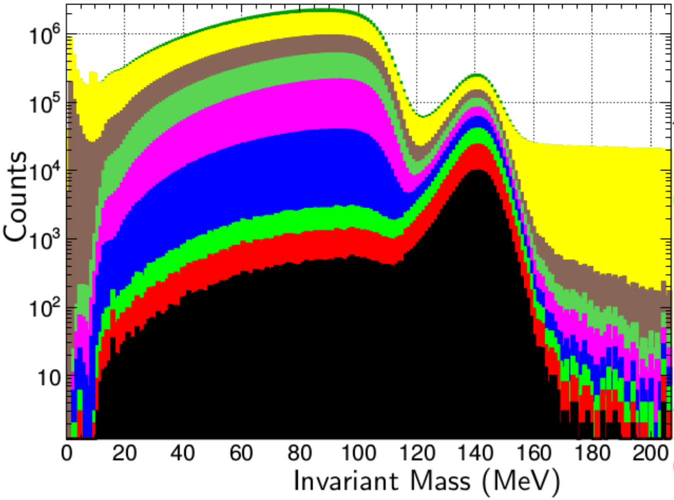








Tail trigger



Trigger events

Good π stop

Track Constructed

Good Track

$E_{tgt} < 12$ MeV

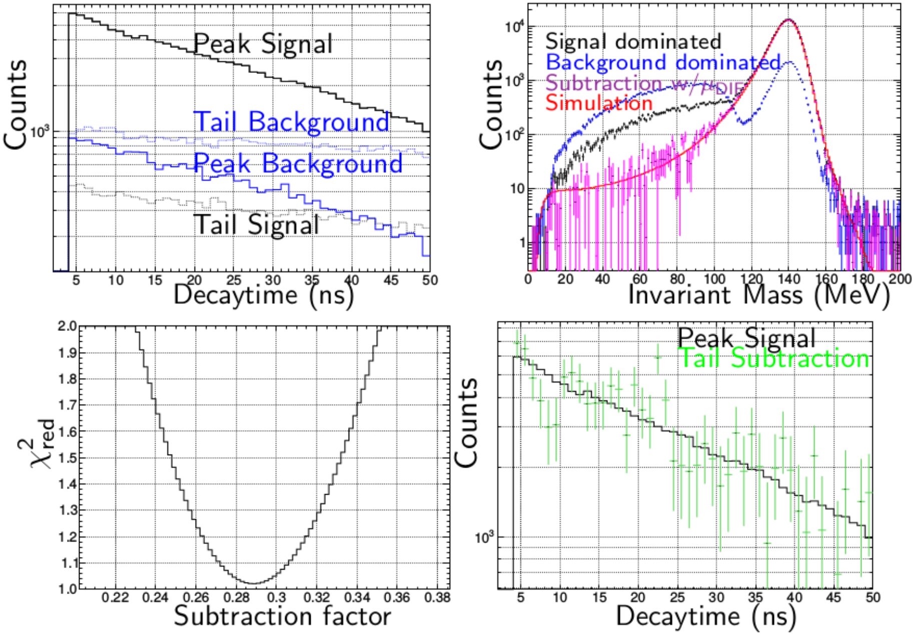
$E_{tgt}^{pred\text{-}obs} < 1$

$\Delta\chi^2 > .55$

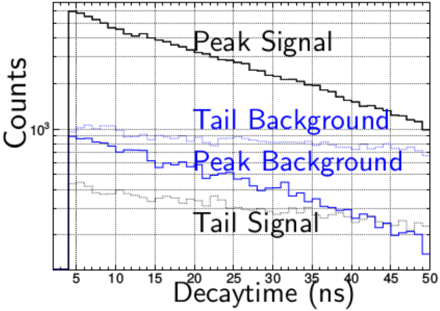
Good Vertex

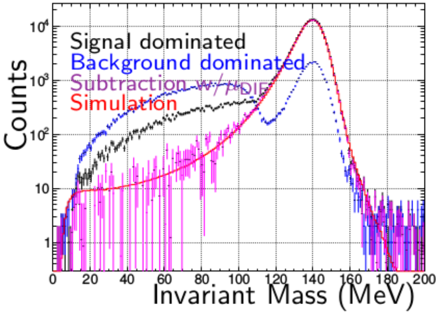
Tgt dEdx

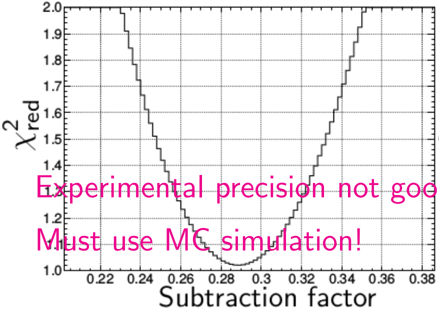
Measured “tail” after subtraction

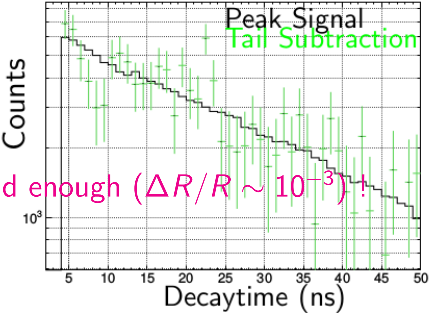


Measured "tail" after subtraction





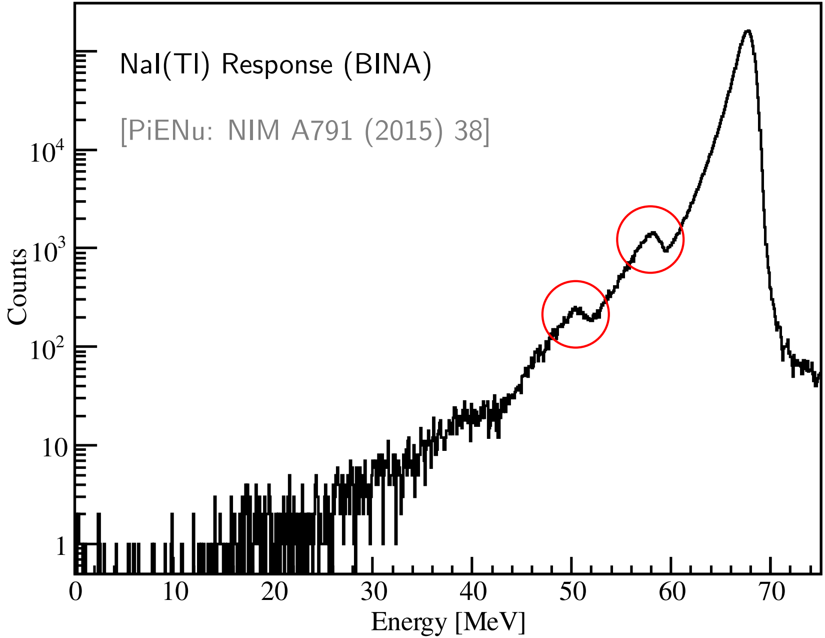




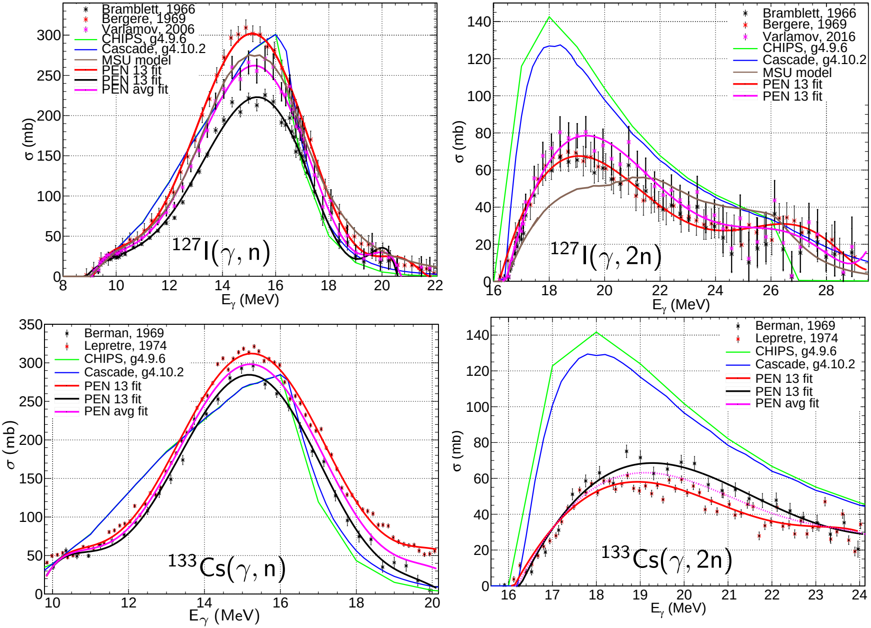
Experimental precision not good enough ($\Delta R/R \sim 10^{-3}$) !

Must use MC simulation!

$\delta\epsilon_{\mathrm{tail}}/(1+\epsilon_{\mathrm{tail}})$: photoneutron reactions



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



Radiative electronic ($\pi_{\mathbf{e2}\gamma}$) decay:

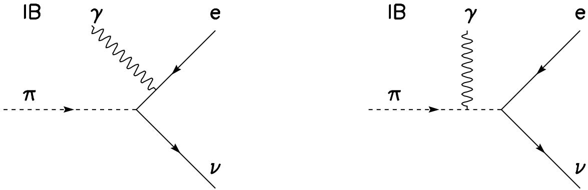
$$\pi^+ \to e^+ \nu_e \gamma$$

$$BR_{\text{non-IB}} \sim 10^{-7}$$

(Unavoidable part of $\pi \to e\nu$ decay)

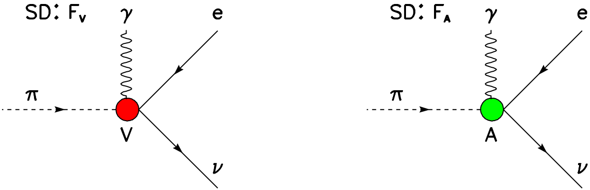
Physics of $\pi^+ \to e^+\nu\gamma$ (RPD):

QED IB terms:

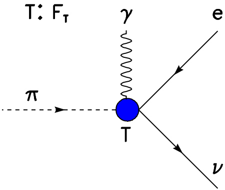


SM

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!**):

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

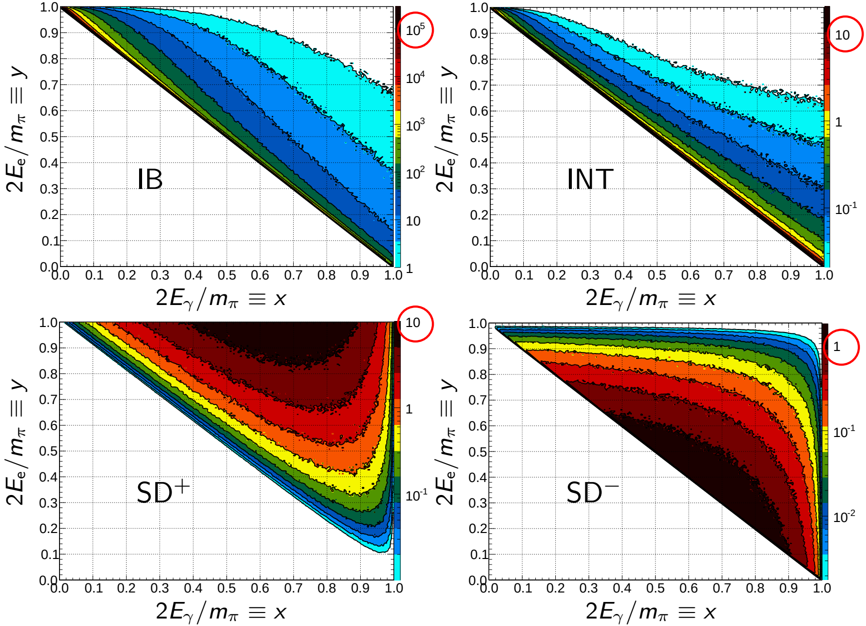
The structure-dependent amplitude (**interesting!**):

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

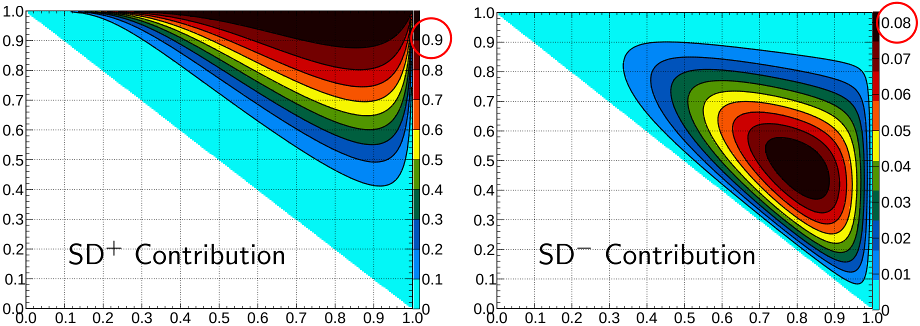
The SM branching ratio (with $x = 2E_\gamma/m_\pi$; $y = 2E_e/m_\pi$),

$$\frac{d\Gamma_{\pi e 2\gamma}}{dx\,dy} = \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Big\{ IB\,(x,y) + \left(\frac{m_\pi^2}{2f_\pi m_e}\right)^2 \times \left[(F_V+F_A)^2\, SD^+\,(x,y) + (F_V-F_A)^2\, SD^-\,(x,y) \right] + \frac{m_\pi}{f_\pi}\left[(F_V+F_A)\, S^+_{\rm int}\,(x,y) + (F_V-F_A)\, S^-_{\rm int}\,(x,y) \right] \Big\}\,.$$

Pion radiative decay regions



Best sensitivity for SD terms



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

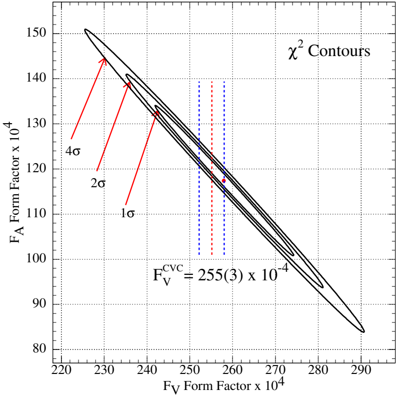
High energy track pairs occur with large opening angles.

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

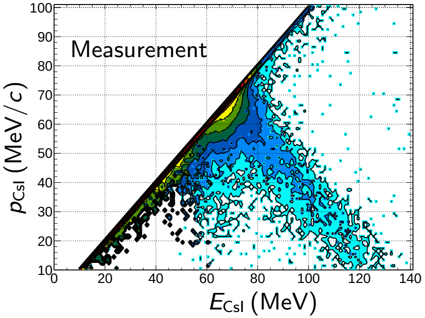
* a . . . q^2 dependence of F_V

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

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

Tight constraint on SD^+; not so tight on SD^-!

Identifying hard radiative decays in PEN

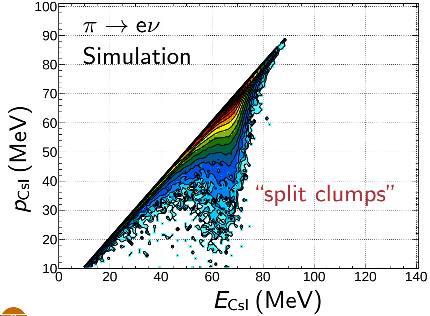


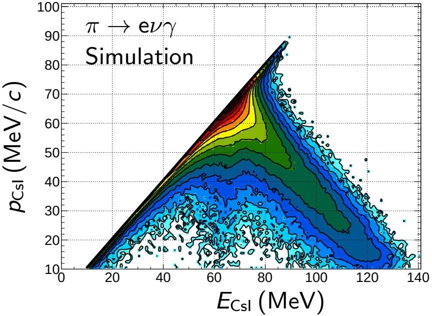
PEN indirectly measures p_ν in $\pi \to e\nu\gamma$

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

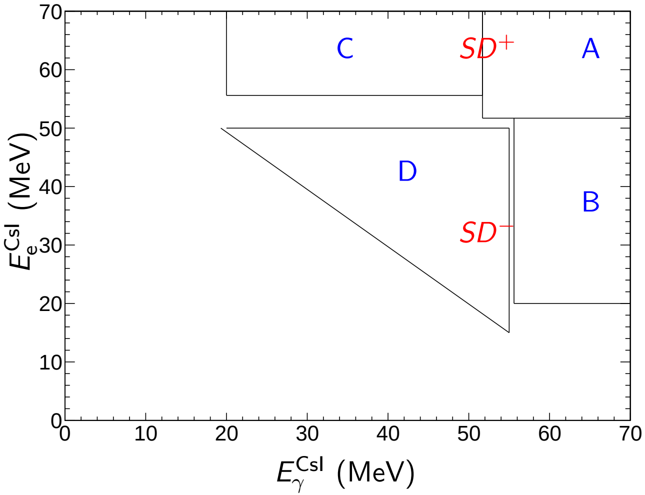
$E_e + E_\gamma \equiv E_{\rm obs}$

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

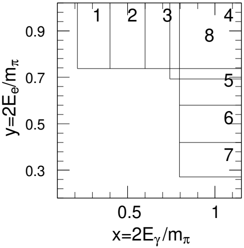




Data regions (PIBETA measurements and PEN)



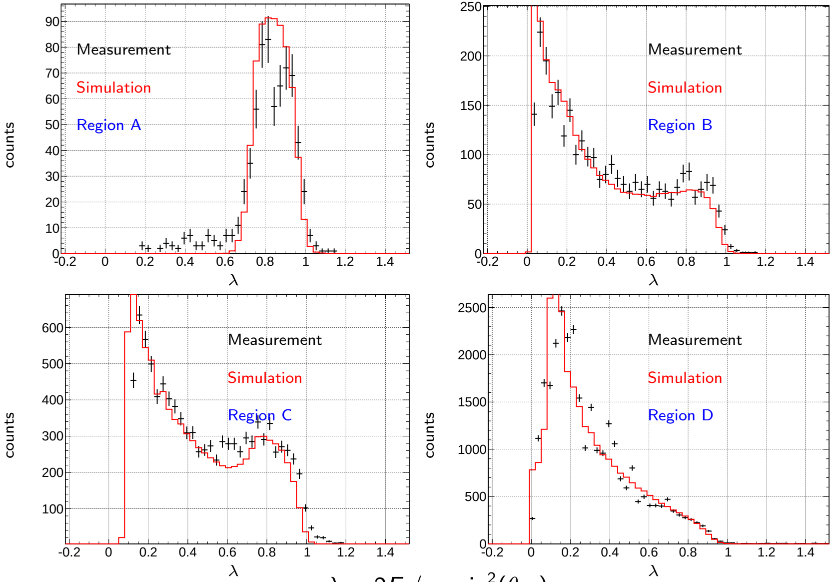
post-2004 data subdivision:



PIBETA (1999-01, 2004): regions A, B, and C.

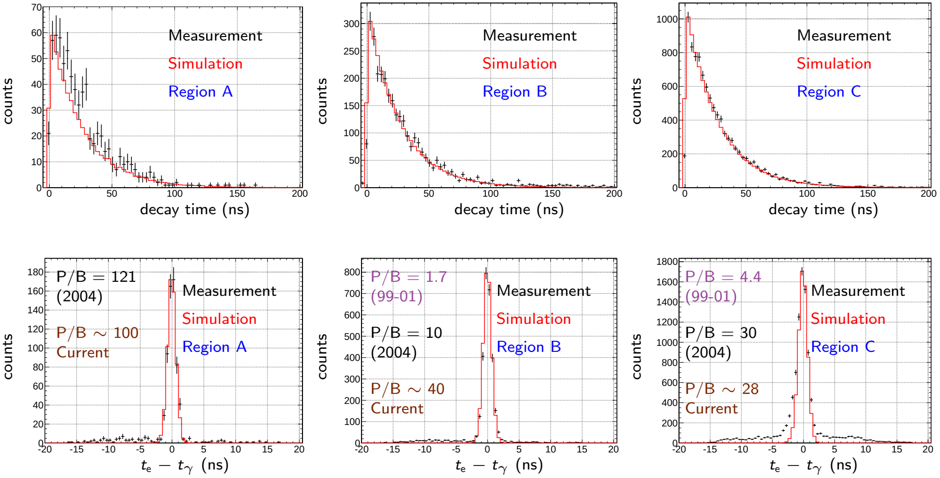
[B was problematic in 1999-01 $\Rightarrow$ resolved with 2004 data].

PEN Run 3 data



$$\lambda = 2E_e/m_\pi \sin^2(\theta_{e\gamma})$$

Timing for radiative decays



Measured spectra influenced by instrumental response and event statistics.

Region D: only in PEN

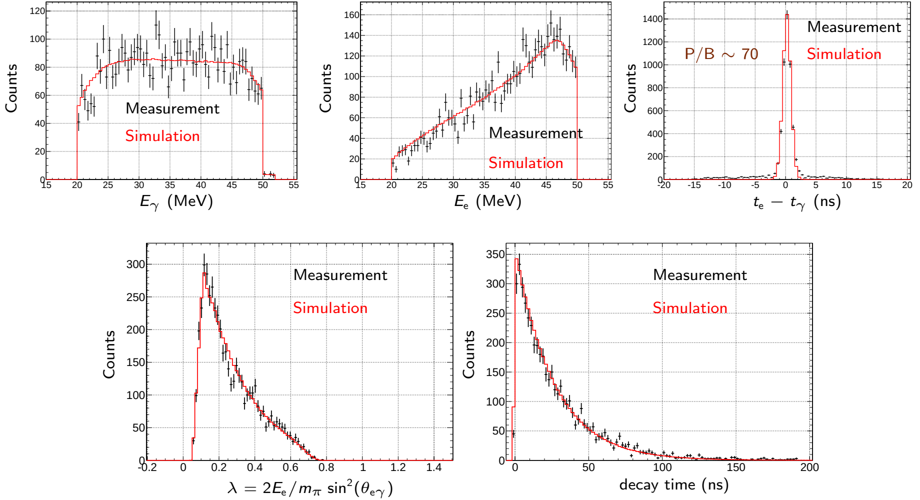


Table of uncertainties

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

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}
$^{*}r_A r_\epsilon$	$\simeq 0.98$	$\sim 3\times10^{-4}$
Statistical:		
$\Delta N_{\pi\to e\nu}/N_{\pi\to e\nu}$		5.15×10^{-4} (Runs $2^{\dagger}$&3)
Goal		5×10^{-4}

* Blinded $\qquad$ † incomplete

Summary

- PEN is on track to evaluate the experimental ratio
  $R^{\pi}_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu_\mu(\gamma))}$ with sub-10^{-3} relative precision.

- Comprehensive systematics studies have been completed; all relevant contributions are understood.

- Radiative component of the decay is well accounted for, and will enhance the existing PIBETA data set.

- Work is under way to improve the statistical uncertainty of $\Delta N/N \sim 5.1 \times 10^{-4}$.

- Unblinding will be performed once the MC acceptances and efficiencies for all beam subperiods are optimized.

- Analysis is ongoing; special recognition to Charlie Glaser.

Pion beta decay (π_{e3}):

$$\pi^+ \to \pi^0 e^+ \nu_e$$

$$BR \sim 10^{-8}$$

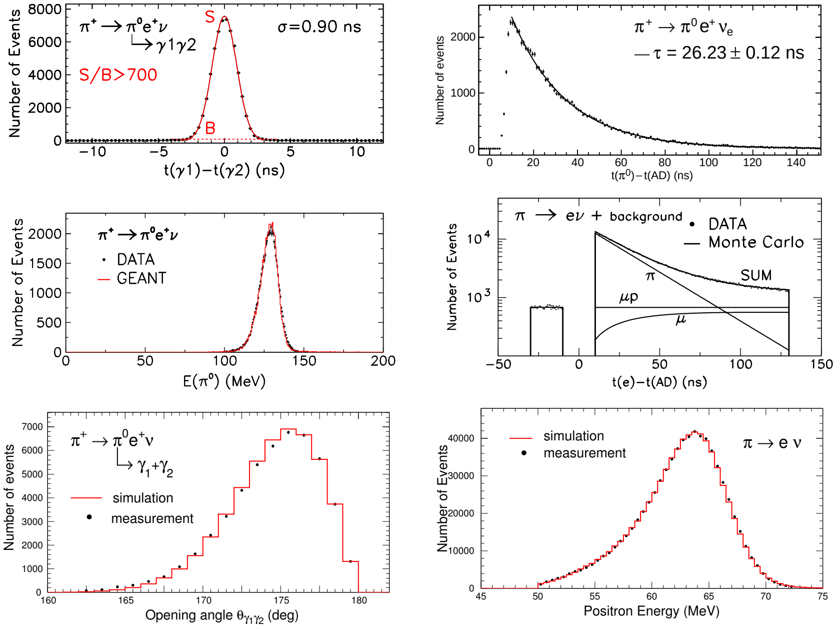
PIBETA result:

$$B.R. \equiv R^{\pi}_{e3} = 1.038\,(6) \times 10^{-8}$$

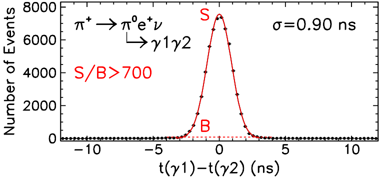
[Počanić et al., PRL **93** (2004) 181803]

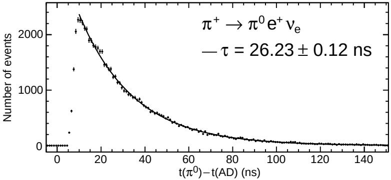
(updated for current $R^{\pi}_{e/\mu}$)

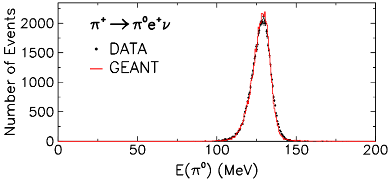
PIBETA results (2004)



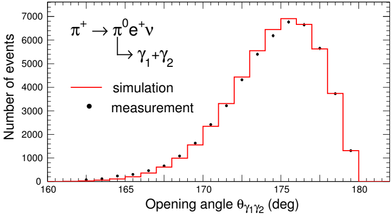
PIBETA results (2004)





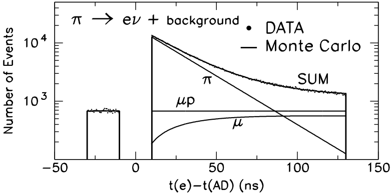


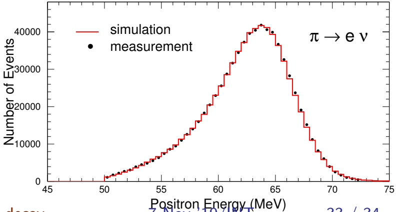
Pion beta decay observables



PIBETA results (2004)

Electronic $\pi \to e\nu$ decay observables





Concept for an improved PEN/PIBETA experiment

Goals: (a) $(\Delta R/R)^{\pi}_{e/\mu} < 10^{-4}$ (to match theoretical precision), and
(b) $(\Delta R/R)^{\pi}_{e3} \sim 2 - 3 \times 10^{-3}$ (per W. Marciano's talk).

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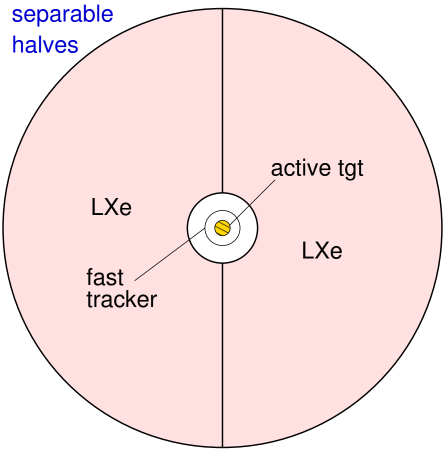
A possible setup:



- stopped pion beam in active target with central tracking,
- main detector: liquid Xe,
- $\langle r^{\pi}_{\rm stop} \rangle \sim 1.5 \times 10^6\,{\rm s}^{-1}$,
- running for $T^{\rm live}_{\rm run} \sim 3 \times 10^7$ s (> 2 years of calendar time):
- $N_{\pi^+ \to e^+\nu(\gamma)} > 5 \times 10^9$, i.e., $\left(\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu}\right)_{\rm stat} < 2 \times 10^{-5}$;
- $N_{\pi^+ \to \pi^0 e^+ \nu} \geq 4 \times 10^5$, i.e., $(\Delta R^{\pi}_{e3}/R^{\pi}_{e3})_{\rm stat} < 2 \times 10^{-3}$.

Current and former PIBETA and PEN collaborators

L. P. Alonzi[a], K. Assamagan[a], V. A. Baranov[b], W. Bertl[c], C. Broennimann[c], S. Bruch[a], M. Bychkov[a], Yu.M. Bystritsky[b], M. Daum[c], T. Flügel[c], E. Frlež[a], R. Frosch[c], C. Glaser[a], K. Keeter[a], V.A. Kalinnikov[b], N.V. Khomutov[b], J. Koglin[a], A.S. Korenchenko[b], S.M. Korenchenko[b], M. Korolija[d], T. Kozlowski[e], N.P. Kravchuk[b], N.A. Kuchinsky[b], D. Lawrence[h], W. Li[a], J. S. McCarthy[a], R. C. Minehart[a], D. Mzhavia[b,f], E. Munyangabe[a], A. Palladino[a,c], D. Počanić[a*], B. Ritchie[h], S. Ritt[a,c], P. Robmann[g], O.A. Rondon-Aramayo[a], A.M. Rozhdestvensky[b], T. Sakhelashvili[f], P.L. Slocum[a], L.C. Smith[a], R.T. Smith[a], N. Soić[d], U. Straumann[g], I. Supek[d], P. Truöl[g], Z. Tsamalaidze[f], A. van der Schaaf[g*], E.P. Velicheva[b], V.P. Volnykh[b], Y. Wang[a], C. Wigger[c], H.-P. Wirtz[c], K. Ziock[a].

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[b] *JINR, Dubna, Russia*
[c] *PSI, Switzerland*
[d] *IRB, Zagreb, Croatia*
[e] *Swierk, Poland*
[f] *IHEP, Tbilisi, Georgia*
[g] *Univ. Zürich, Switzerland*
[h] *Arizona State Univ., USA*

Home pages: http://pibeta.phys.virginia.edu
http://pen.phys.virginia.edu

Additional slides

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

$$\Gamma = \Gamma_0(1+\delta_\pi) = \frac{G_F^2 |V_{ud}|^2 \Delta^5}{30\pi^3} f(\epsilon, \Delta) \left(1 - \frac{\Delta}{2m_+}\right)^3 (1+\delta_\pi)\,,$$

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where

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

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 $\delta_\pi \sim 0.035$ is the sum of radiative/loop corrections with $\sim 0.03\%$ relative uncertainty.

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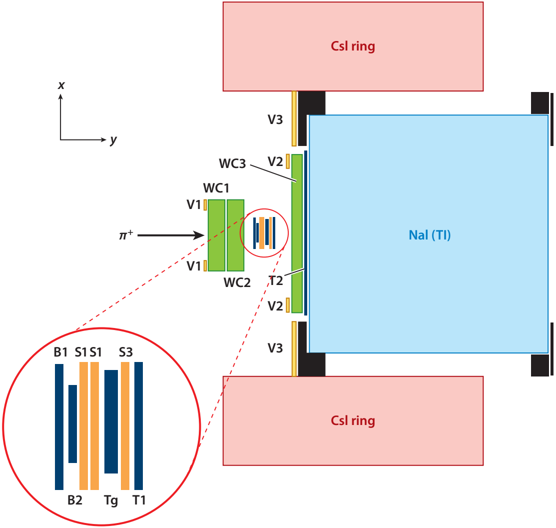
Prior to 2004, Γ and B measured with about 4 % precision.

PiENu experiment at TRIUMF



- Goal: $\Delta B/B \simeq 0.001$
- Excellent E resolution
- Very precise tracking with Si-strip detectors and MWPCs
- Data taking completed in 2012
- $\mathcal{O}(10^7)$ π_{e2} events collected
- analysis is ongoing.

First result: $1.2344(23)_{\text{stat}}(19)_{\text{syst}} \times 10^{-4}$ [Aguilar-Arevalo et al, PRL **115** (2015) 071801].

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):
$B = \quad 1.038 - 1.041 \times 10^{-8}$ (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 2018: $V_{ud} = 0.97420(21)$
PIBETA: $V_{ud} = 0.9748(25)$ or $V_{ud} = 0.9728(30)$.

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

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Reach of π_{e2} decay beyond the SM (New Physics)

$$\mathcal{L}_{NP} = \left[\pm\frac{\pi}{2\Lambda_V^2}\bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2}\bar{u}\gamma_\alpha\gamma_5 d\right]\bar{e}\gamma^\alpha(1-\gamma_5)\nu$$
$$+\left[\pm\frac{\pi}{2\Lambda_S^2}\bar{u}d \pm \frac{\pi}{2\Lambda_P^2}\bar{u}\gamma_5 d\right]\bar{e}(1-\gamma_5)\nu\,, \quad (\Lambda_i \ldots \text{scale of NP})$$

CKM unitarity and superallowed Fermi nuclear decays currently limit:

$$\Lambda_V \geq 20\,\text{TeV}, \qquad \text{and} \qquad \Lambda_S \geq 10\,\text{TeV}\,.$$

At $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} = 10^{-3}$, π_{e2} decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}}\,,$$

and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

In general multi-Higgs models with charged-Higgs couplings

$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$, at 0.1 % precision, $R^\pi_{e\mu}$ probes $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

Lepton universality (and neutrinos)

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:

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 0.9996 \pm 0.0012 \quad \text{and} \quad \left(\frac{g_\tau}{g_\mu}\right)_{\pi\tau} = 1.0030 \pm 0.0034\,.$$

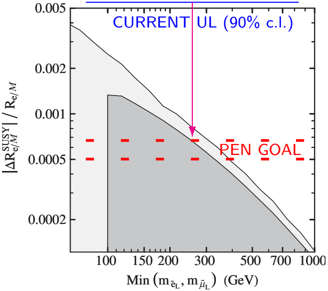
For comparison,

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

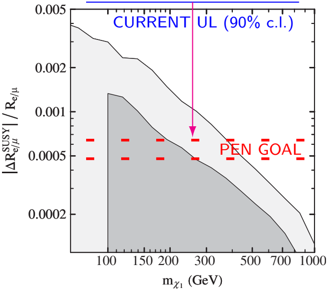
- significant consequences in the **neutrino sector**;
- interesting limits on **MSSM extension observables**.

MSSM calculations (R parity cons.) [Ramsey-Musolf et al., PR D**76** (2007) 095017]

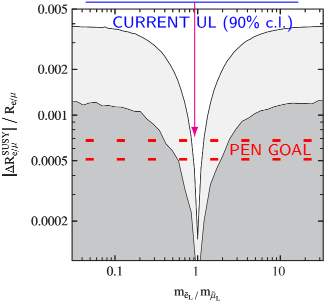
minimal selectron, smuon masses:



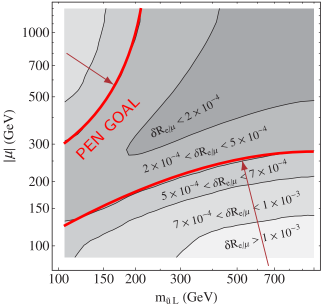
lowest mass chargino:



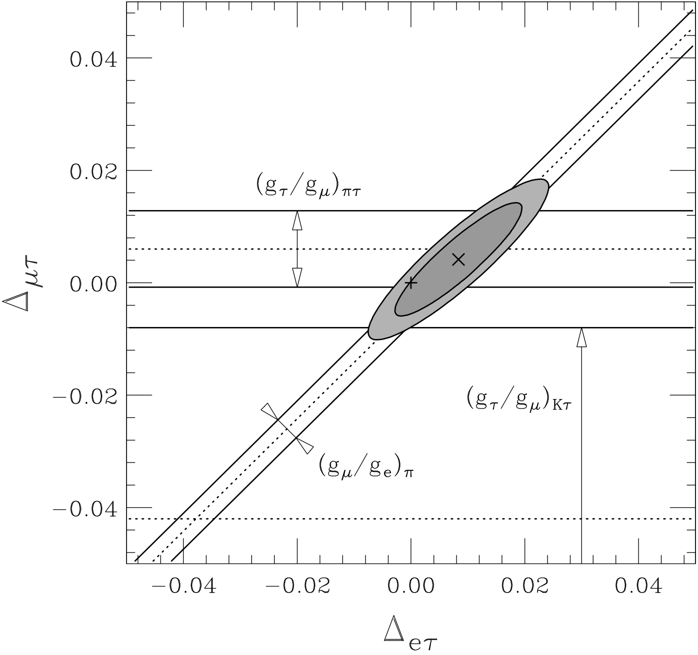
slepton mass degeneracy:



Higgsino mass param's. μ, $m_{\tilde{u}_L}$:



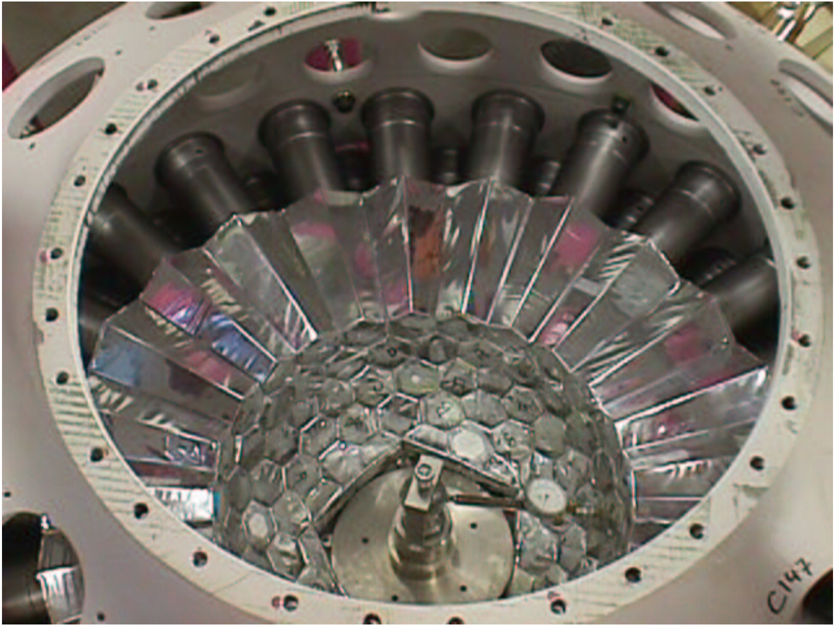
(R parity violating scenario constraints also discussed.)



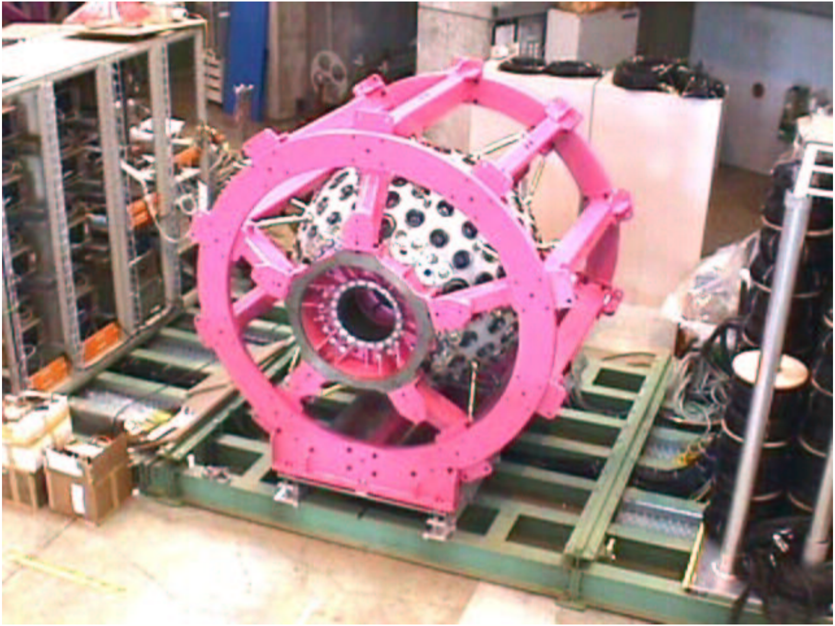
Loinaz et al., PRD **70** (2004) 113004

$$\Delta_{\ell\ell'} = 2\left(\frac{g_\ell}{g_{\ell'}} - 1\right)$$

PIBETA detector assembly



PIBETA detector on platform



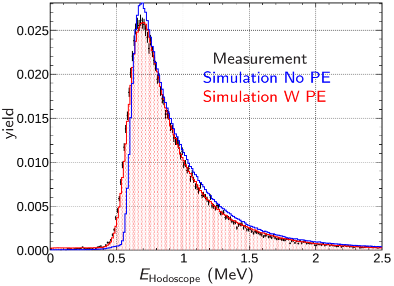
GEANT4 Monte Carlo

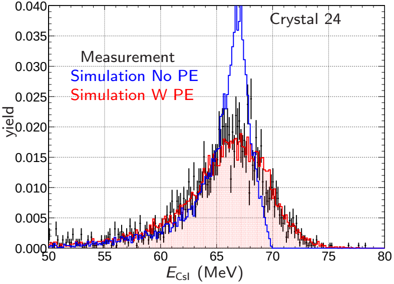
Canonical Geant gives energies, timings, and positions

Requires additional physics input to simulate full detector response

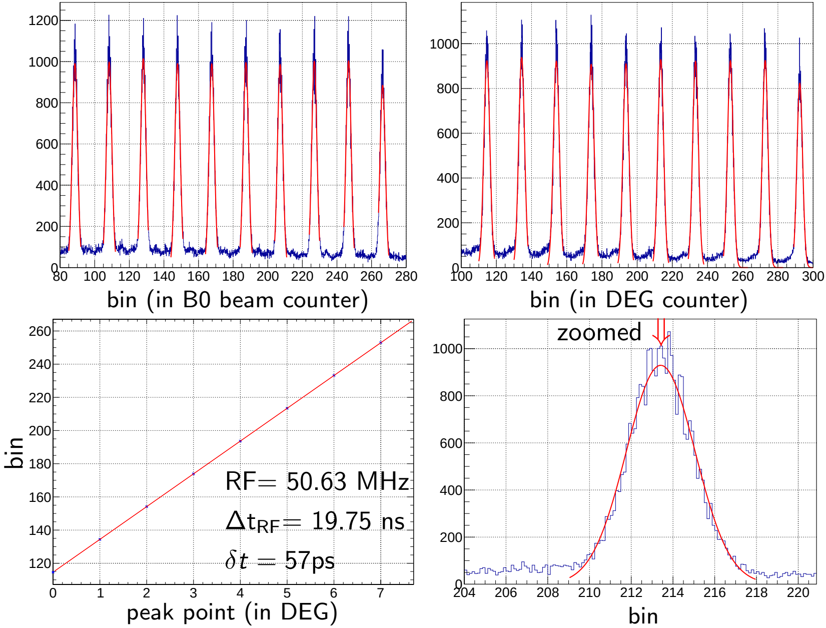
In the Experiment:

- digitized energies and timings of detector elements
- mTPC, beam counters, and target waveforms
- photoelectron statistics smear signal

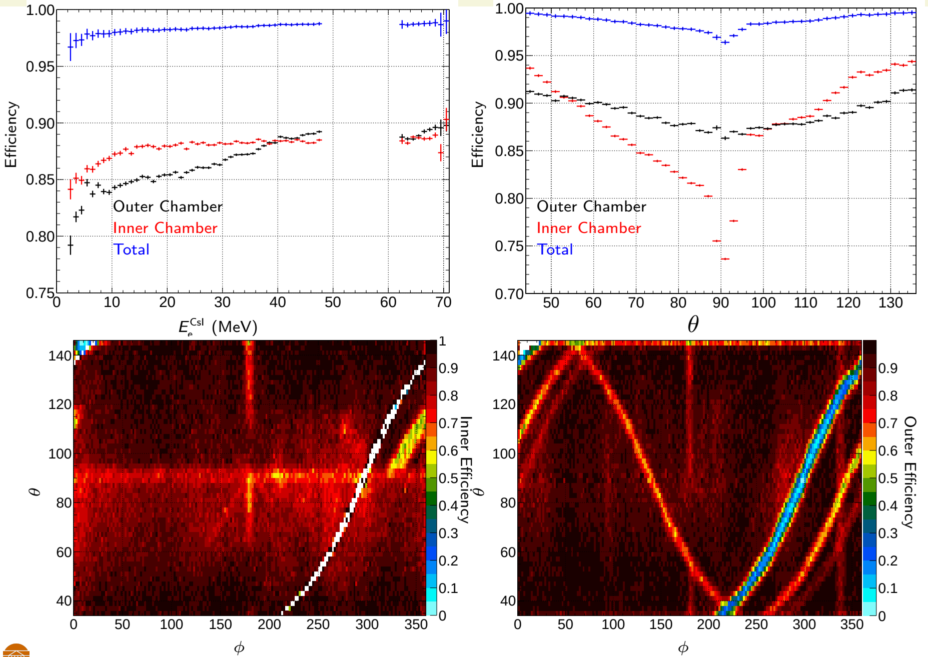




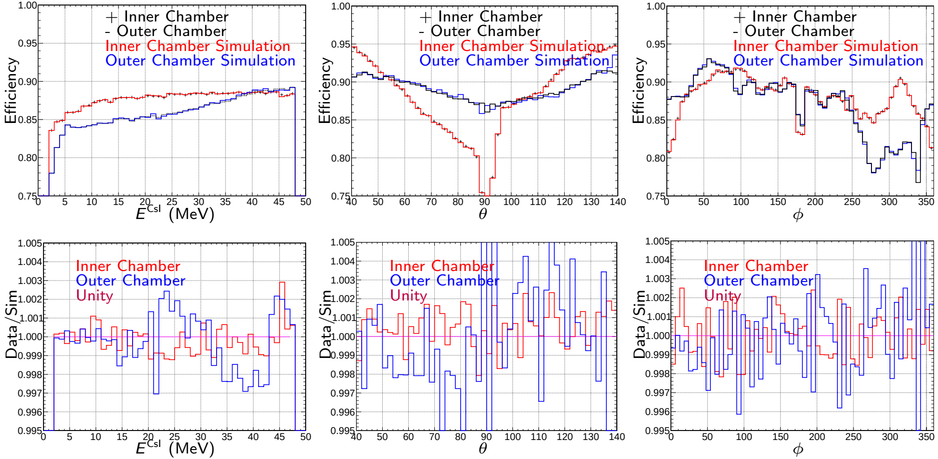
r_f: δt for beam particles



Chamber efficiencies



Chamber efficiencies: simulation



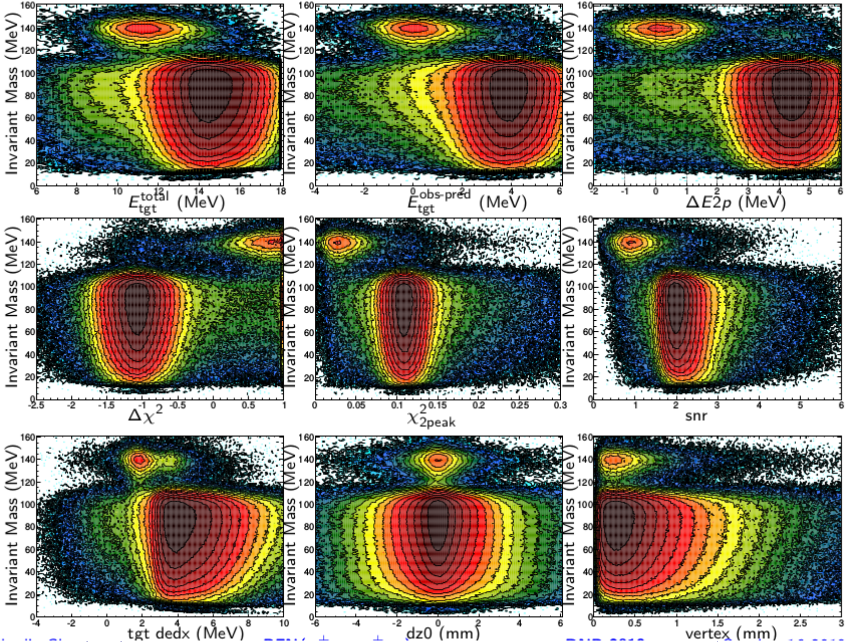
$dE/dx = g(E)$ in chamber gas $\quad \pi \to e^+\nu_e \quad$ 70 MeV monoenergetic

$\mu \to e\nu\bar{\nu} \quad 0 - 52.5$ MeV spectrum

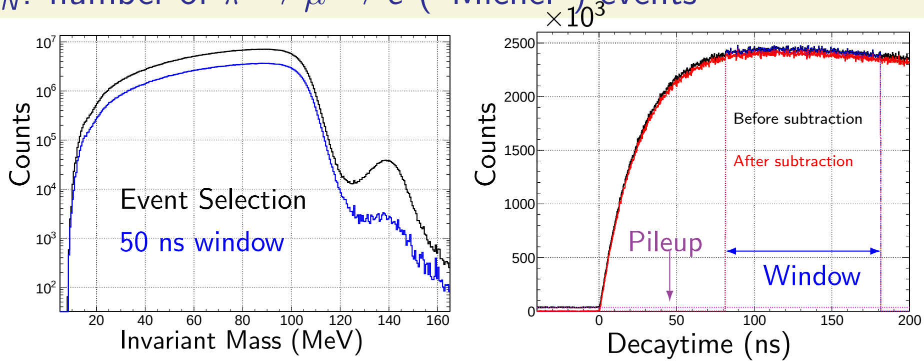
Monte Carlo is weighted to simulate chamber efficiencies

Absorbed into acceptances (blinded)

Observables to aid discrimination



r_N: number of $\pi \to \mu \to e$ ("Michel") events



$$N_{\pi\text{-}\mu\text{-e, Run 2}} = (5203.57 \pm 0.32) \times 10^5$$

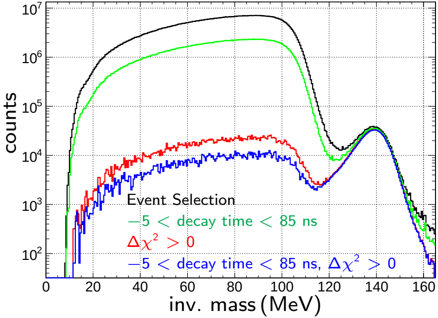
$$N_{\pi\text{-}\mu\text{-e, Run 3}} = (9545.50 \pm 0.44) \times 10^5$$

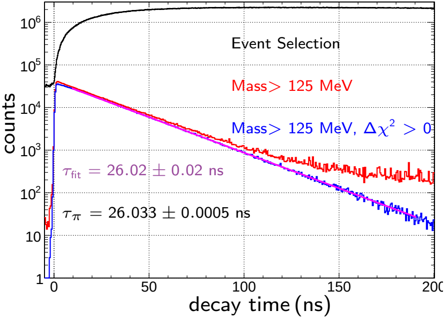
$$\delta N_{\pi\text{-}\mu\text{-e, Run 2}} / N_{\pi\text{-}\mu\text{-e, Run 2}} = 6.2 \times 10^{-5}$$

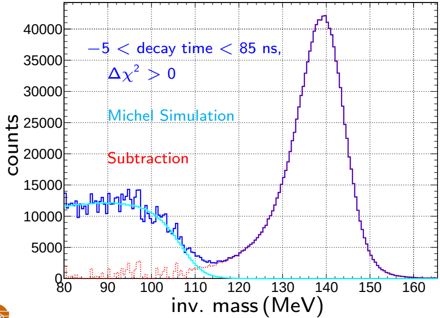
$$\delta N_{\pi\text{-}\mu\text{-e, Run 3}} / N_{\pi\text{-}\mu\text{-e, Run 3}} = 4.6 \times 10^{-5}$$

contribution to $\Delta R^{\pi}_{e/\mu} / R^{\pi}_{e/\mu}$ … not significant

r_N: number of $\pi_{e2(\gamma)}$ events







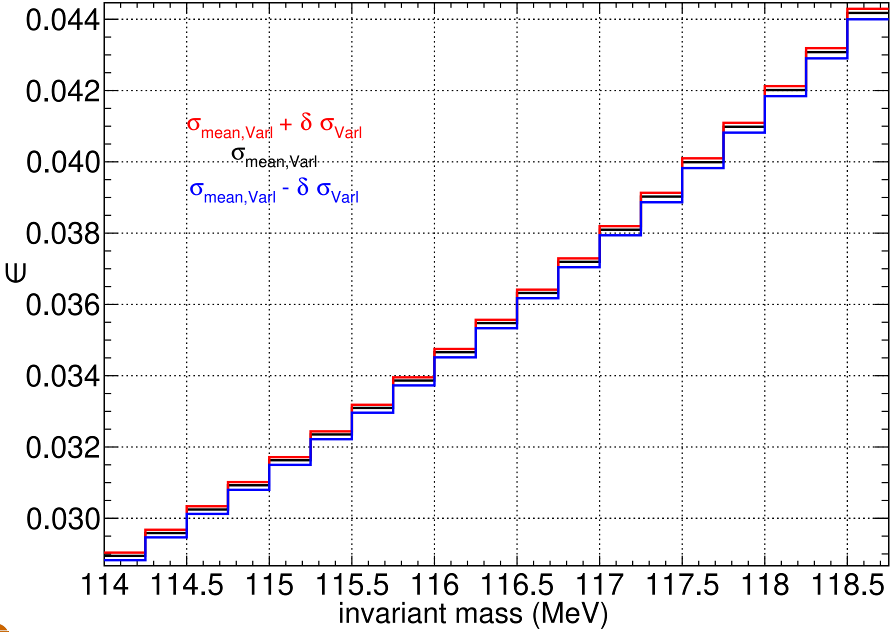
Waveform cut is needed, $\epsilon \sim 97\%$

$$N_{\pi e2(\gamma),\ \text{Run 2}} = 1387431 \pm 1179.91$$

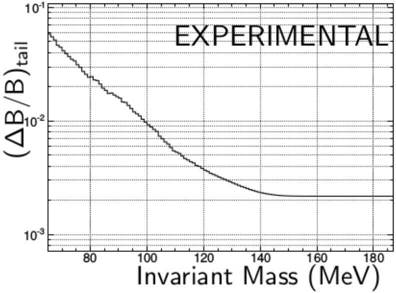
$$N_{\pi e2(\gamma),\ \text{Run 2}} = 2383805 \pm 1545.93$$

$$\frac{\delta N_{\pi e2(\gamma),\ \text{Rn 2\&3}}}{N_{\pi e2(\gamma),\ \text{Rn 2\&3}}} \simeq 5.1 \times 10^{-4}$$

π_{e2} tail including photoneutron corrections



MC simulated vs. experimental π_{e2} tail

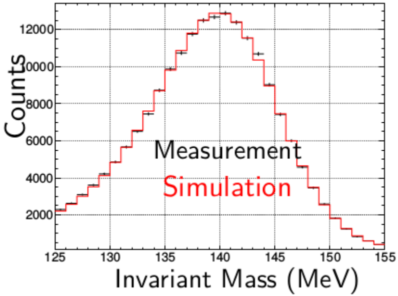


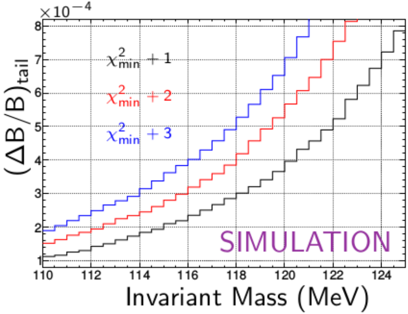
Simulation unavoidable!

Systematics from :

Gain Variation

Photo-nuclear physics





Pre-2004 data on pion form factors

$$|F_V| \stackrel{\text{CVC}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0} m_\pi}} = 0.0255(3)\ .$$

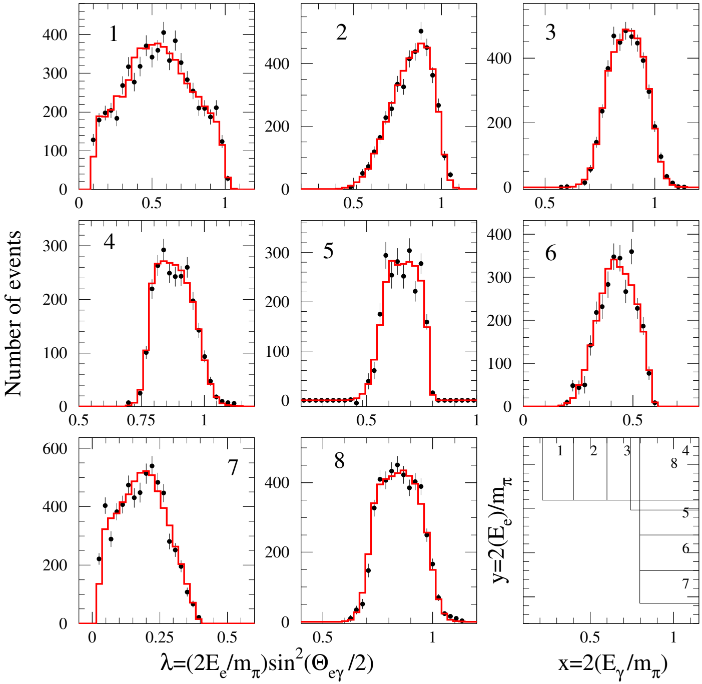
$F_A \times 10^4$	reference
106 ± 60	Bolotov et al. (1990)
135 ± 16	Bay et al. (1986)
60 ± 30	Piilonen et al. (1986)
110 ± 30	Stetz et al. (1979)
116 ± 16	world average (PDG 2004)

Pre-2004 data on pion form factors

$$|F_V| \stackrel{\text{CVC}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0} m_\pi}} = 0.0255(3)\ .$$

$F_A \times 10^4$	reference	note
106 ± 60	Bolotov et al. (1990)	$(F_T = -56 \pm 17)$
135 ± 16	Bay et al. (1986)	
60 ± 30	Piilonen et al. (1986)	
110 ± 30	Stetz et al. (1979)	
116 ± 16	world average (PDG 2004)	

PIBETA $\pi_{e2\gamma}$ differential distributions: 2009 analysis of 1999-01, 2004 data sets.

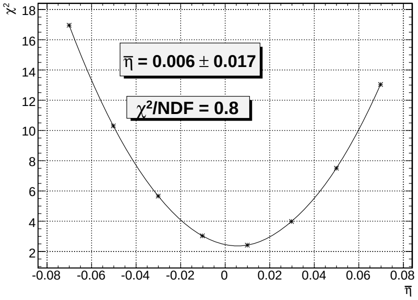


RMD preliminary results, cont'd.

Preliminary result for RMD branching ratio (thesis E. Munyangabe):

$$B_{\rm exp} = 4.365\,(9)_{\rm stat.}\,(42)_{\rm syst.} \times 10^{-3}\,, \qquad \boxed{\mathbf{29}\times}$$

$$B_{\rm SM} = 4.342\,(5)_{\rm stat\text{-}MC} \times 10^{-3} \qquad (\text{for } E_\gamma > 10\,\text{MeV},\ \theta_{e\gamma} > 30^\circ)$$



NB: preliminary results!

Analysis of PS subset:
$13\,\text{MeV} < E_\gamma < 45\,\text{MeV}$, and
$10\,\text{MeV} < E_{e^+} < 43\,\text{MeV}$, yields

$$\bar\eta = 0.006\,(17)_{\rm stat.}\,(18)_{\rm syst.}\,, \quad \text{or}$$

$$\bar\eta < 0.028 \quad (68\%\text{CL})\,.$$

$\boxed{\sim \mathbf{4}\times}$ better than best previous experiment (Eichenberger et al, 84).

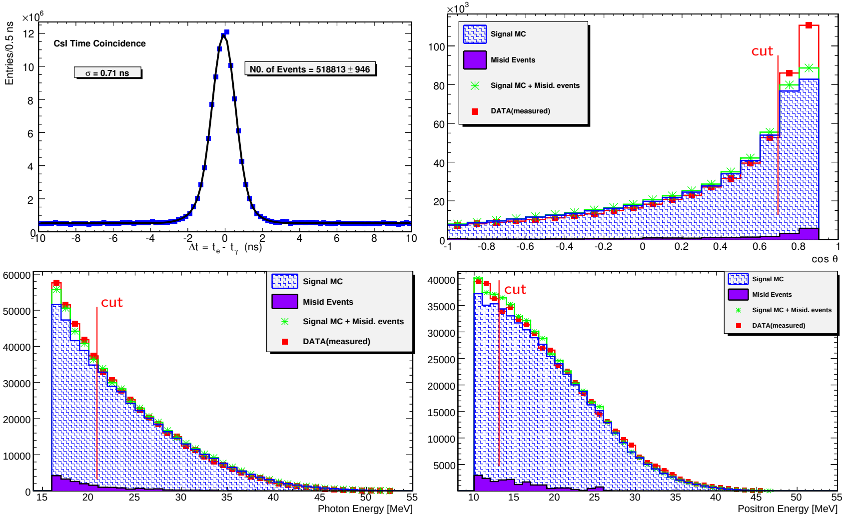
Radiative muon decay:

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$$

$BR \sim 10^{-3}$ for energetic γ's

- Sensitive to admixtures beyond $V - A$
- Limiting factor in $\mu \to e\gamma$ LFV searches

RMD: $\mu^+ \to e^+\nu\bar{\nu}\gamma$, [E. Munyangabe's analysis of 2004 PIBETA data]

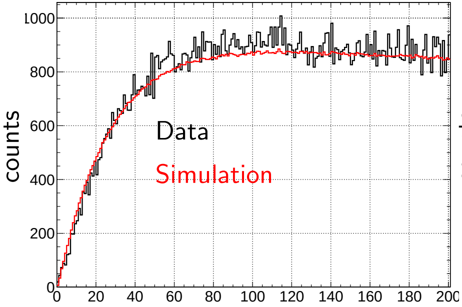


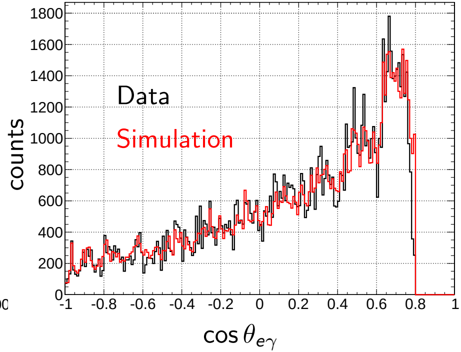
"Split clumps" very well accounted for!

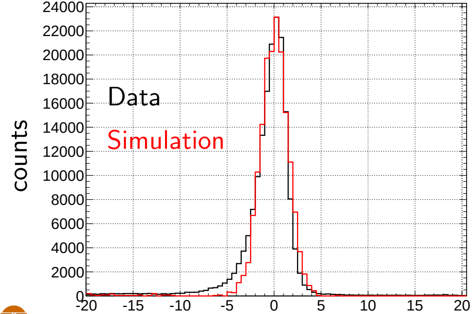
$\sim$30-fold improvement in precision of the RMD *BR*.

$\sim$4-fold improvement over best previous limit on $\bar{\eta}$ Michel parameter.

PEN RMD plots (Run 3 data set)







Simple track requirement,
Data selection using target cuts,
Adding coverage to PiBeta data set.

Ready for new BR and $\bar{\eta}$ evaluations.