Rare pion decay studies in the PEN experiment

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(for the PEN Collaboration)

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Known and measured pion and muon decays

	Decay	BR	
$\pi^+ \to$	$\mu^+\nu$	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})
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	($\pi_{e2\gamma}$)
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	(π_{e3}, π_β)
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})
$\pi^0 \to$	$\gamma\gamma$	0.98798 (32)	
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(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)
	$e^+\nu\bar{\nu}\gamma$	0.014 (4)	(RMD)
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$	

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The electronic (π_{e2}) decay:

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

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

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

$1.2352\,(5) \times 10^{-4}$	Marciano and Sirlin, [PRL **71** (1993) 3629]
$1.2354\,(2) \times 10^{-4}$	Finkemeier, [PL B **387** (1996) 391]
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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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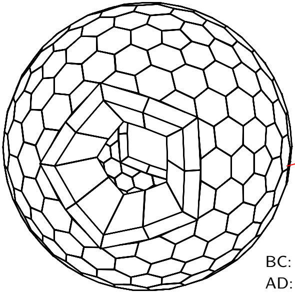
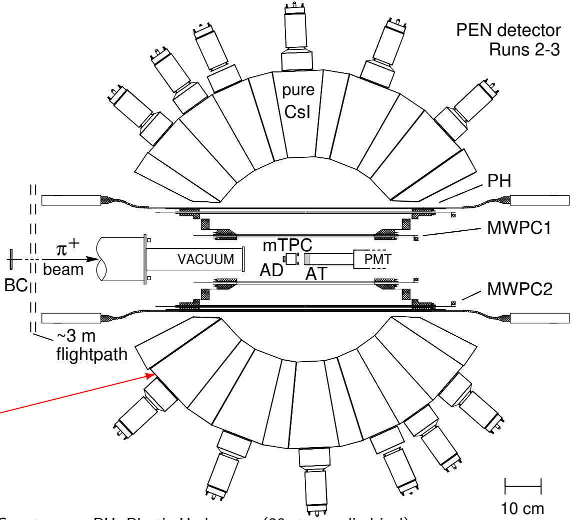
- Experimental world average is 23× less accurate than SM calculations!
  [$1.2327(23)\times 10^{-4}$]

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

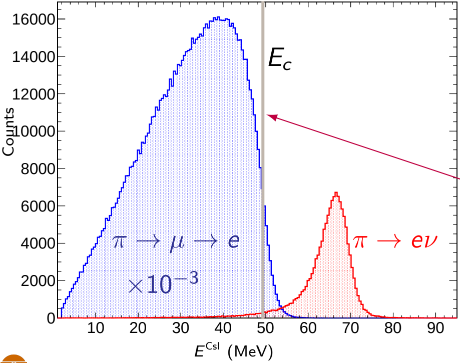
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

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

Knowing that:

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

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



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

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

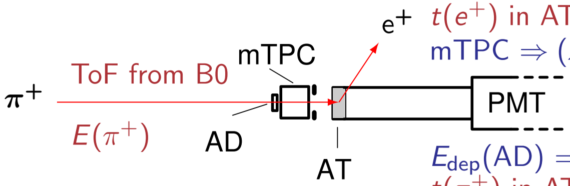
Uncertainties:

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

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

PEN goal: $\delta R/R \simeq 5\times10^{-4}$

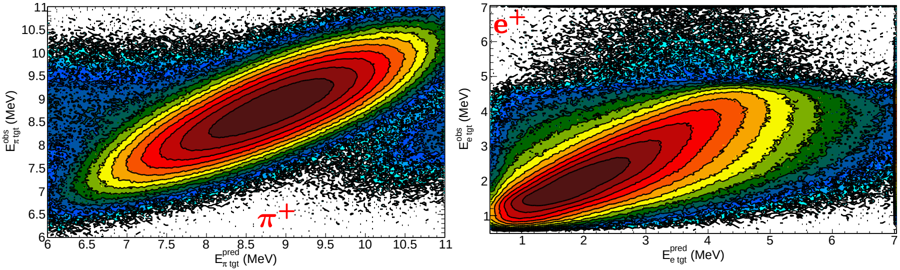
Discriminating π_{e2} and $\pi_{\mu 2}$ in TGT



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

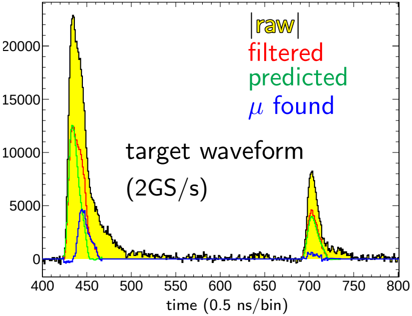
E_{dep}(AD) $\Rightarrow E_{\text{dep}}, z$ of π_{stop} in AT
$t(\pi^+)$ in AT predicted from t(AD)

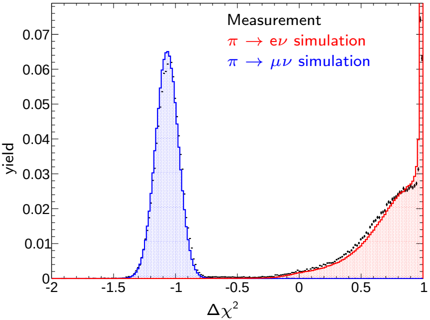
Predicted π^+ and e^+ energies agree VERY well with observations:

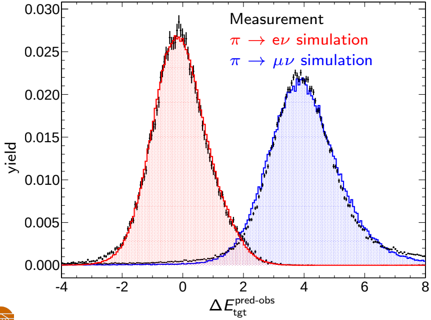


$\Rightarrow$ E and t predictions are used for $\pi_{e2}/\pi_{\mu 2}$ discrimination.

Target waveforms and event type discrimination





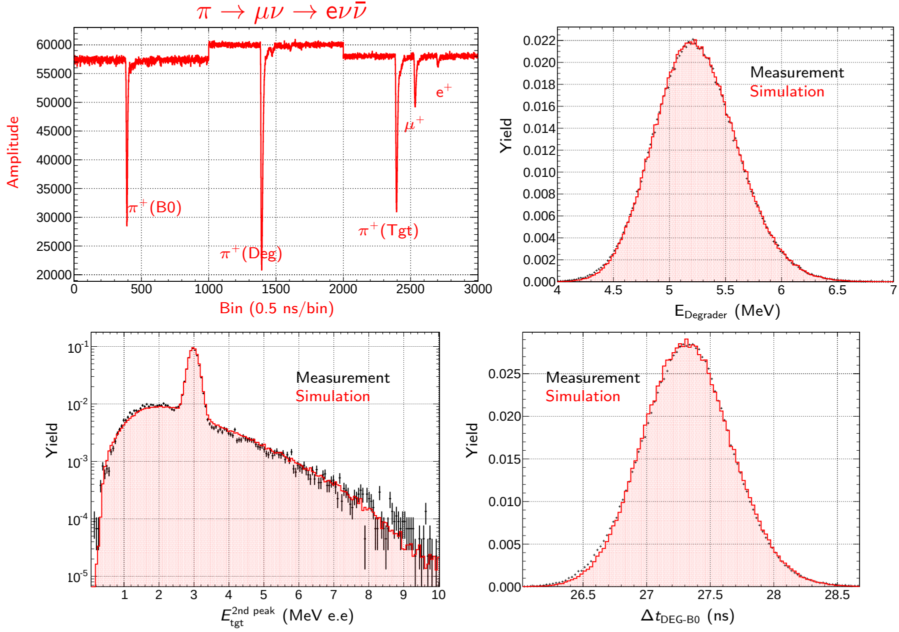


$\Delta\chi^2$ uses predicted and observed timings and energies. Steps:

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).

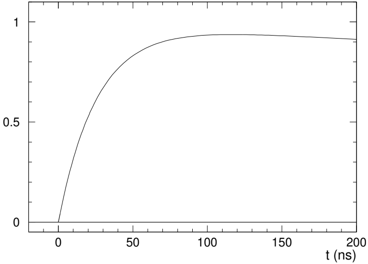
Best of $\sim$dozen similar observables at discriminating π_{e2} / $\pi_{\mu 2}$ event classes.

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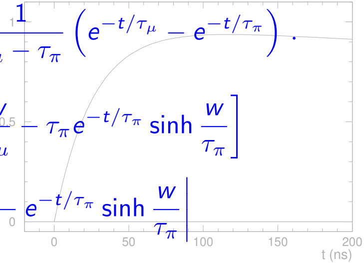
$$f_{\pi\text{-}\mu\text{-e}}(t) = \int_0^t f_{\pi\to\mu}(t-t') f_{\pi\to\text{e}}(t') dt' = \frac{1}{\tau_\mu - \tau_\pi}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right).$$

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

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



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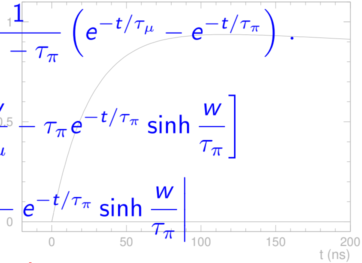
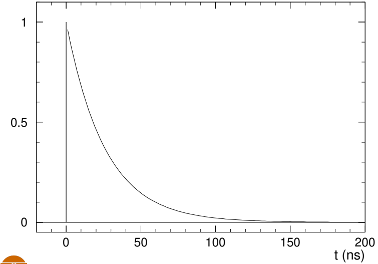


$\pi \to e\nu(\gamma)$ timing selection:



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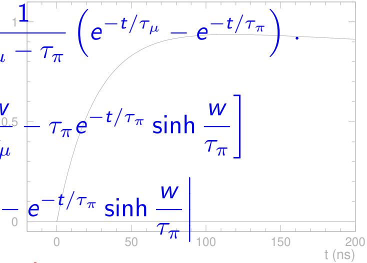

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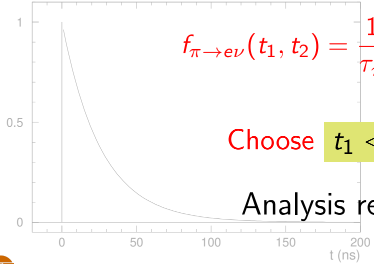
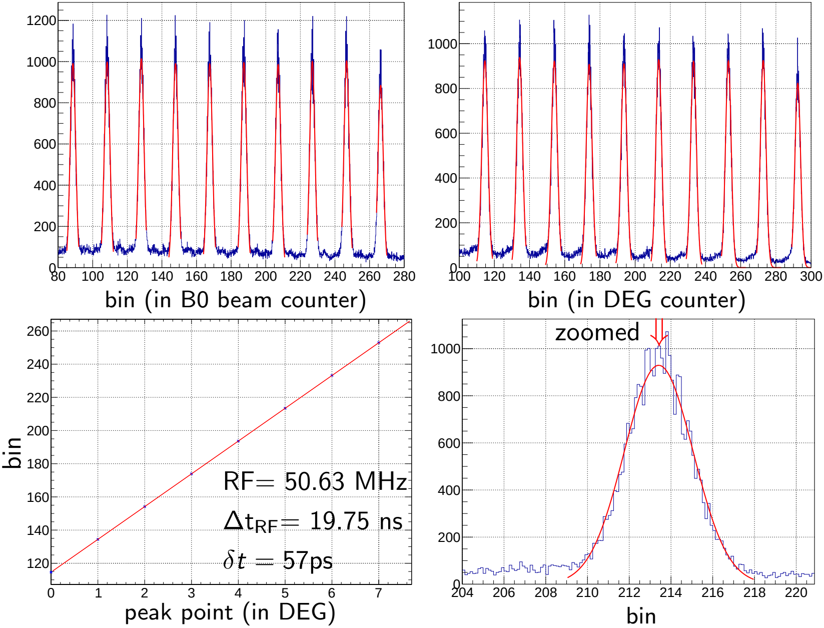


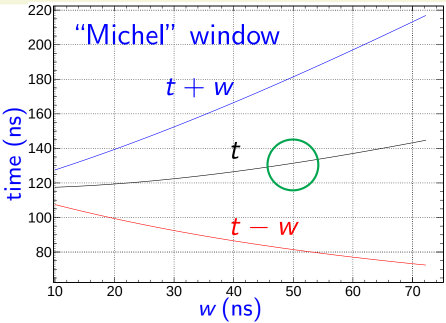
$$f_{\pi\to e\nu}(t_1, t_2) = \frac{1}{\tau_\pi}\int_{t_1}^{t_2} e^{-t/\tau_\pi} = e^{-t_1/\tau_\pi} - e^{-t_2/\tau_\pi}$$

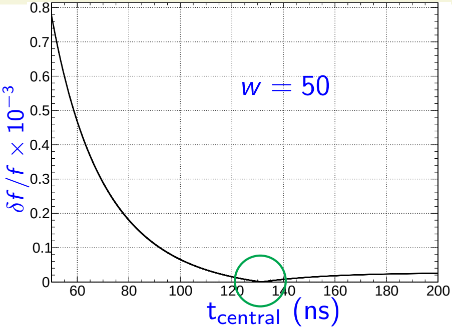
Choose $t_1 < 0$: $\delta f_{\pi\to e\nu} = \frac{\delta t}{\tau_\pi}e^{-t_2/\tau_\pi}$.

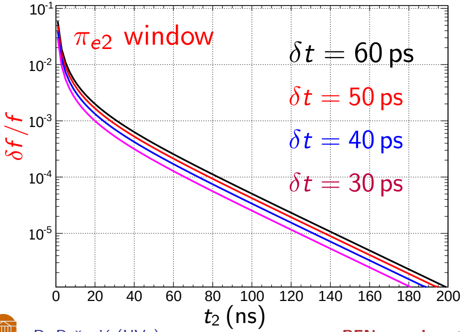
Analysis requires: δt, w, t and t_2.

r_f: δt for beam particles









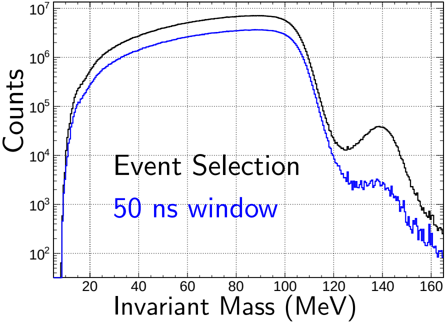
$\pi \to \mu\nu \to e\nu\bar{\nu}(\gamma)$

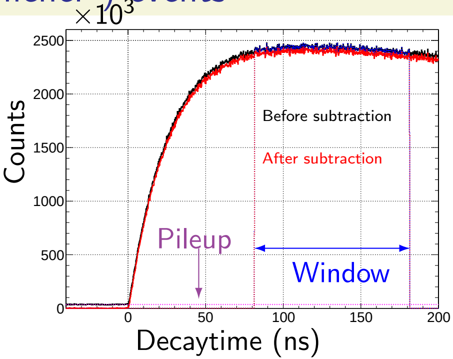
$\delta r_f/r_f$ negligible

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

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

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





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

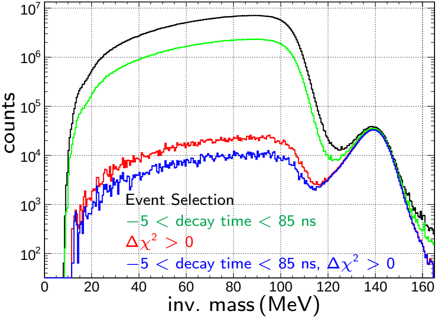
$$N_{\pi\text{-}\mu\text{-e, Run 3}} = (9545.50 \pm 0.44) \times 10^5$$

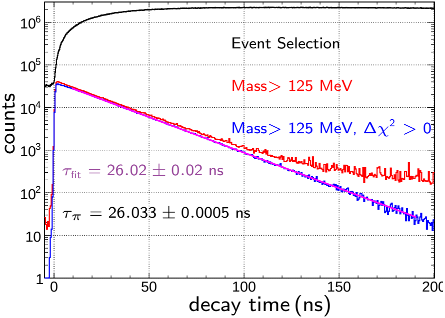
$$\delta N_{\pi\text{-}\mu\text{-e, Run 2}} / N_{\pi\text{-}\mu\text{-e, Run 2}} = 6.2 \times 10^{-5}$$

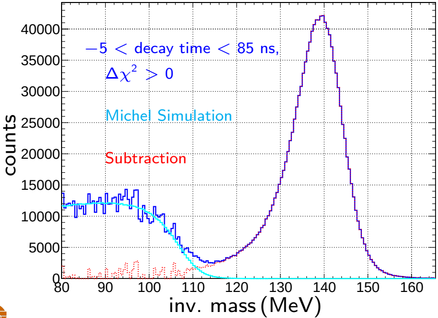
$$\delta N_{\pi\text{-}\mu\text{-e, Run 3}} / N_{\pi\text{-}\mu\text{-e, Run 3}} = 4.6 \times 10^{-5}$$

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, $\epsilon \sim 97\%$

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

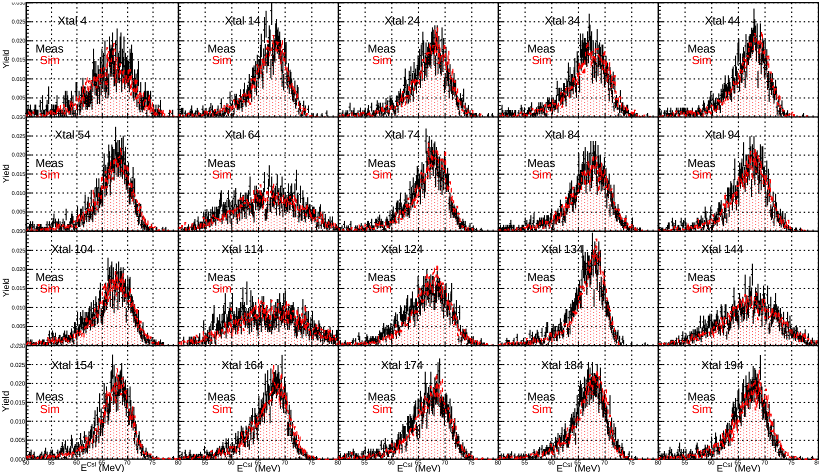
$$N_{\pi e2(\gamma),\text{ Run 2}} = 2383805 \pm 1545.93$$

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

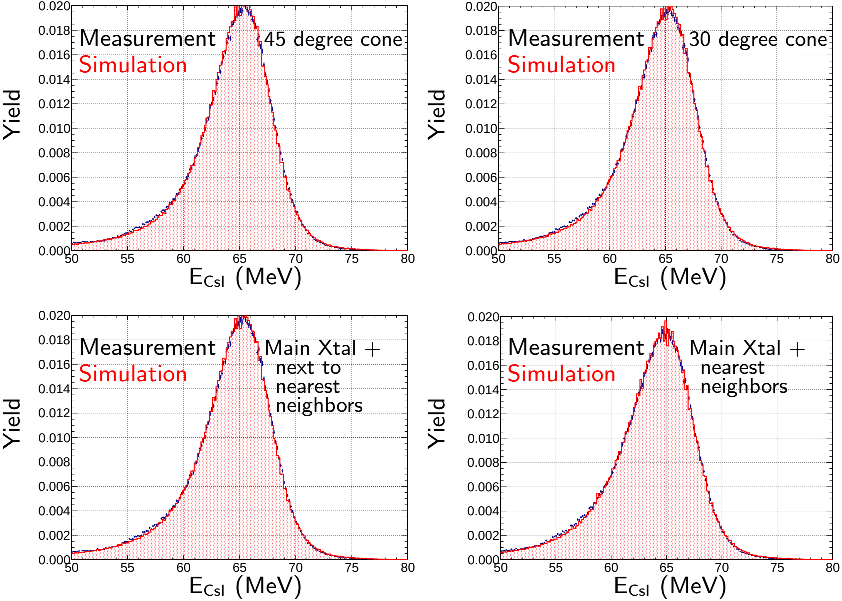
CsI EM Calorimeter: realistic simulation

Crystals are not all the same:

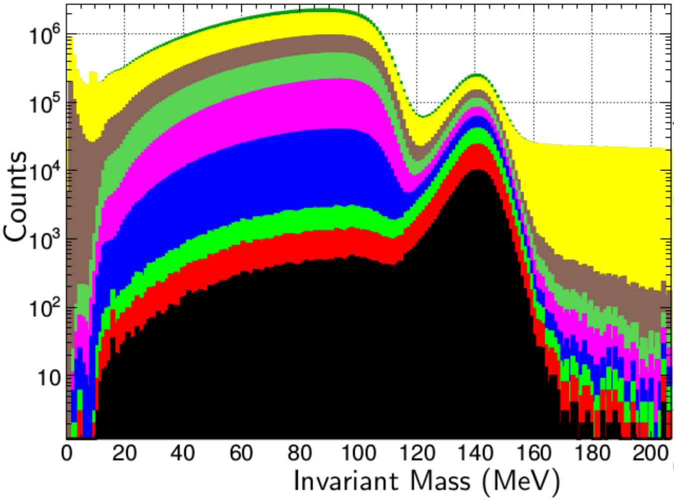
- different detector response, non-uniformities, $\Delta\Omega$ coverage;
- 240 PMTs, with slightly different properties, opt. couplings.



CsI simulation cont'd.



Tail trigger



Trigger events

Good π stop

Track Constructed

Good Track

$E_{tgt} < 12$ MeV

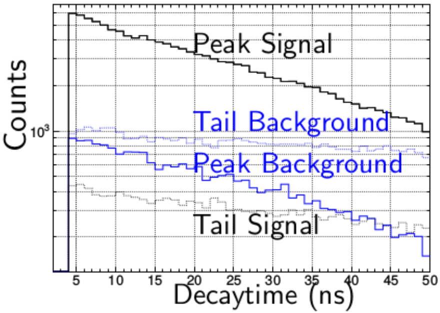
$E_{tgt}^{pred\text{-}obs} < 1$

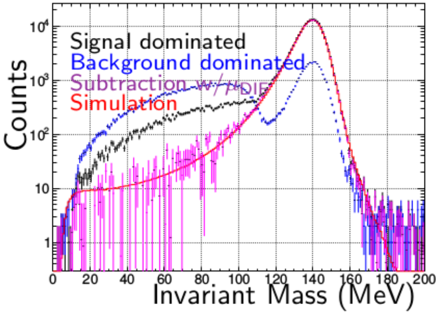
$\Delta\chi^2 > .55$

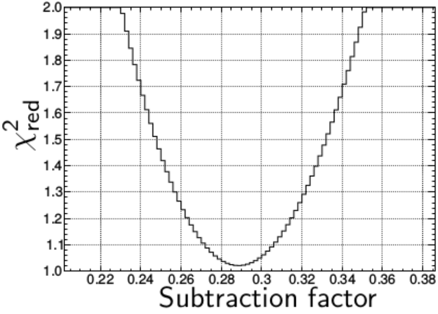
Good Vertex

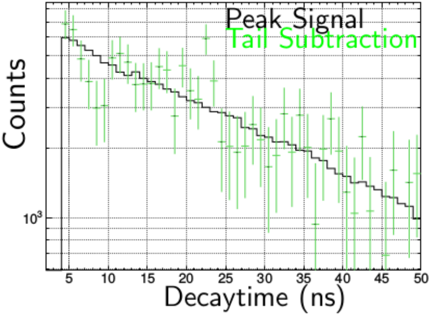
Tgt dEdx

Measured “tail” after subtraction

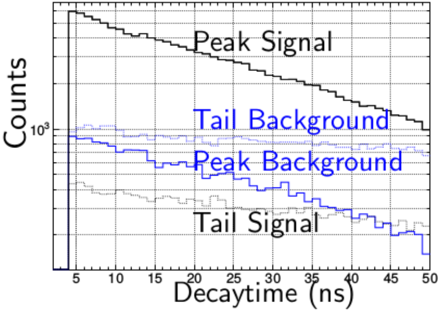


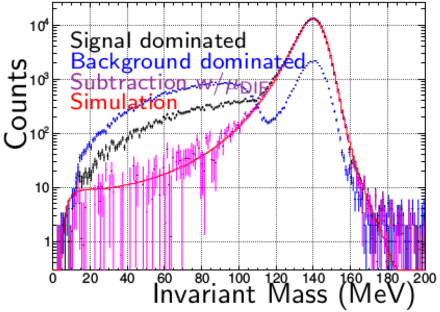


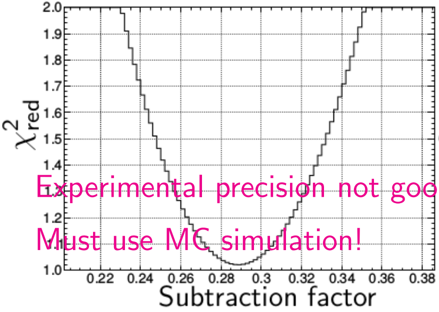


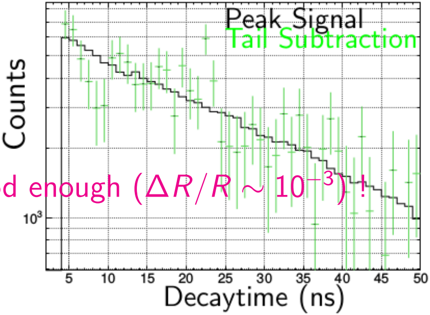


Measured "tail" after subtraction





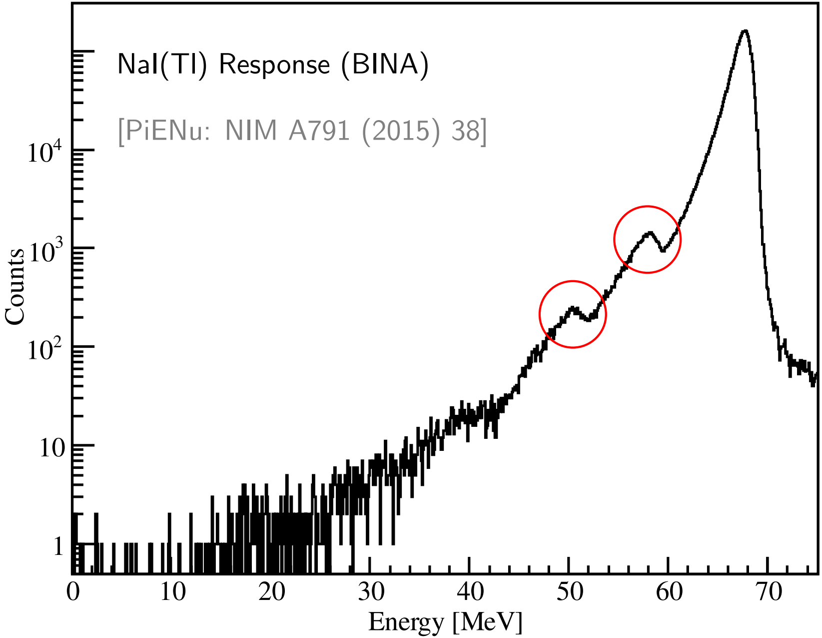




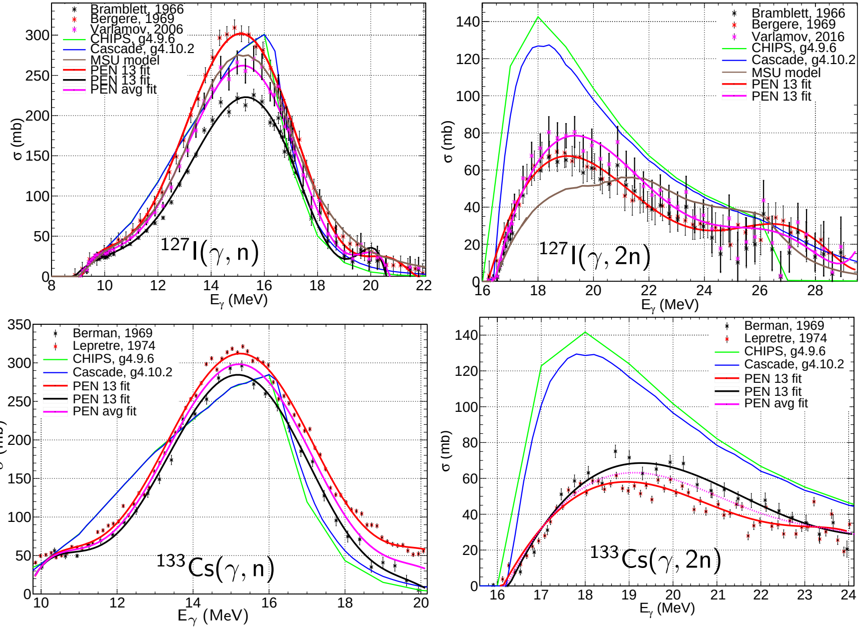
Experimental precision not good enough ($\Delta R/R \sim 10^{-3}$) !

Must use MC simulation!

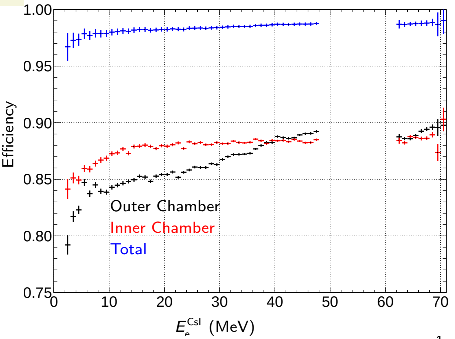
$\delta\epsilon_{\text{tail}}/(1+\epsilon_{\text{tail}})$: photoneutron reactions

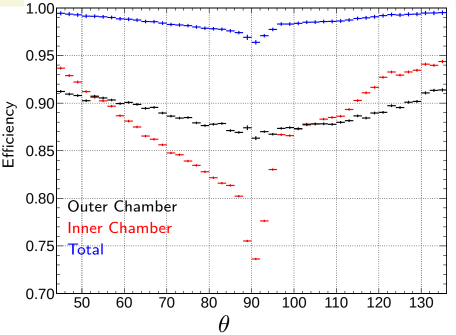


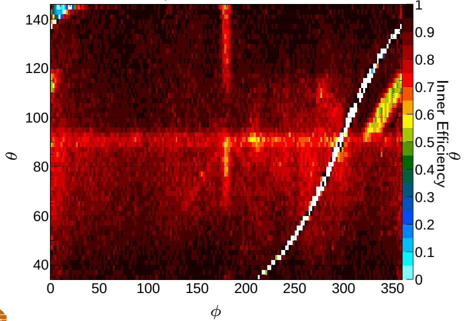
Photoneutron cross sections, $\sigma(\gamma, xn)$

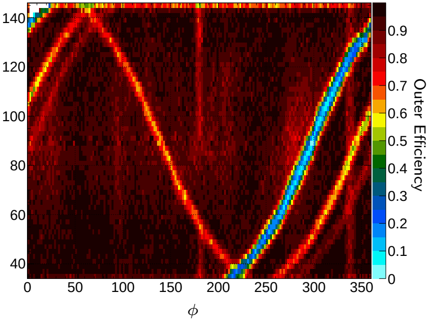


Chamber efficiencies

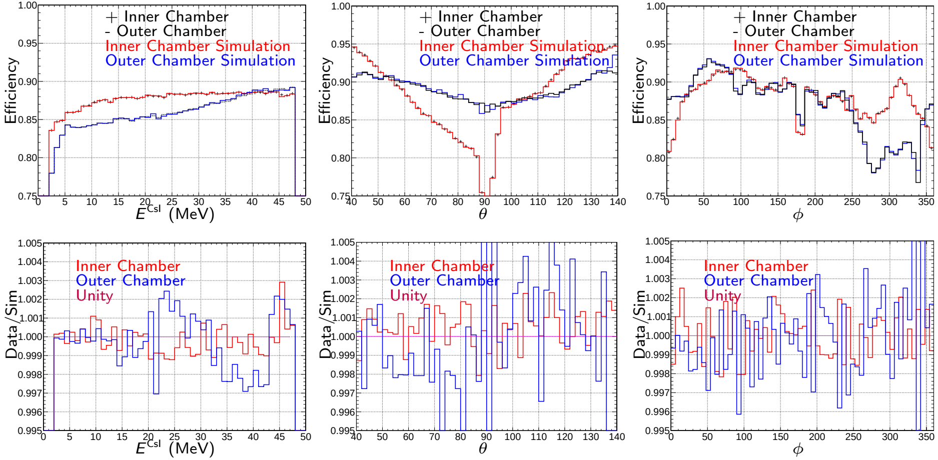








Chamber efficiencies: simulation



$\mathrm{d}E/\mathrm{d}x = g(E)$ in chamber gas

$\pi \to e^+\nu_e$ 70 MeV monoenergetic

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

Monte Carlo is weighted to simulate chamber efficiencies

Absorbed into acceptances (blinded)

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

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

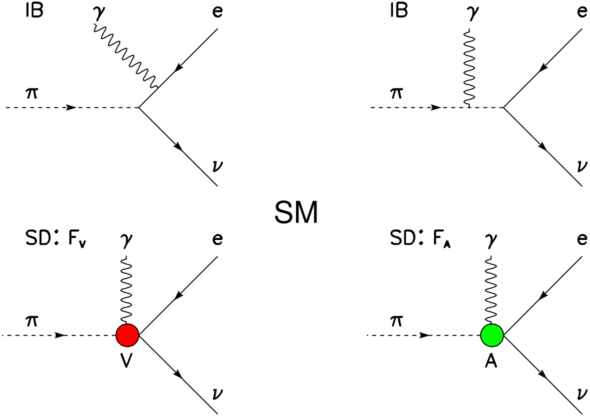
$$BR_{\text{non-IB}} \sim 10^{-7}$$

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

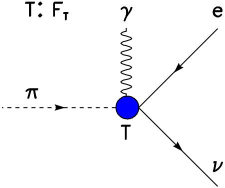
Physics of $\pi^+ \to e^+\nu\gamma$ (RPD):

QED IB terms:

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!**):

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

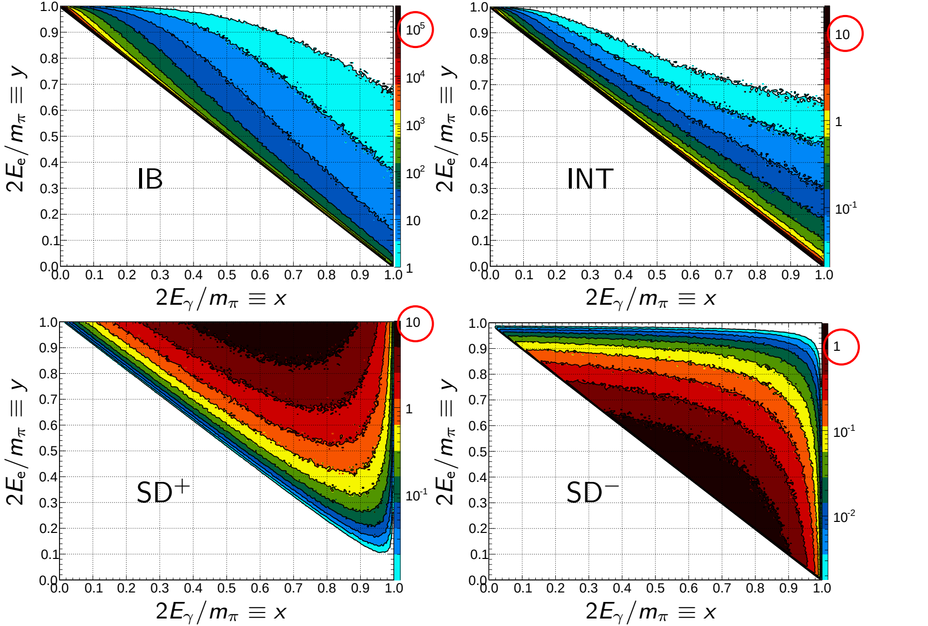
The structure-dependent amplitude (**interesting!**):

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

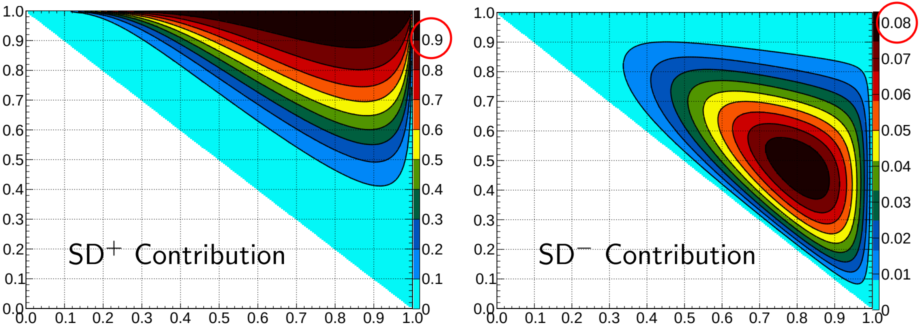
The SM branching ratio ($x = 2E_\gamma/m_\pi;\ y = 2E_e/m_\pi$),

$$\begin{aligned} \frac{\mathrm{d}\Gamma_{\pi e2\gamma}}{\mathrm{d}x\,\mathrm{d}y} = & \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Big\{ IB\,(x,y) + \left(\frac{m_\pi^2}{2f_\pi m_e}\right)^2 \\ & \times \left[(F_V+F_A)^2\, \boldsymbol{SD^+}\,(x,y) + (F_V-F_A)^2\, SD^-\,(x,y) \right] \\ & + \frac{m_\pi}{f_\pi} \left[(F_V+F_A)\, S^+_{\mathrm{int}}\,(x,y) + (F_V-F_A)\, S^-_{\mathrm{int}}\,(x,y) \right] \Big\}\,. \end{aligned}$$

Pion radiative decay regions



Best sensitivity for SD



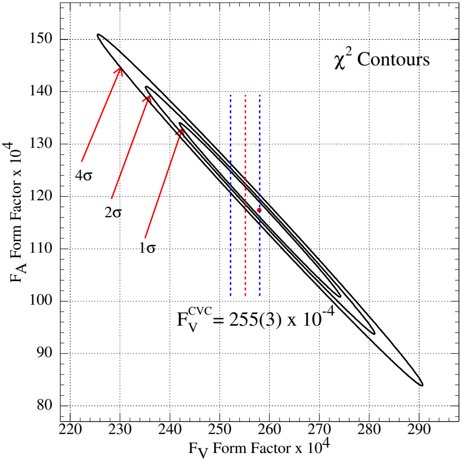
SD$^+$ region favors high energy e$^+$ and γ's.

High energy track pairs occur with large opening angles.

Large solid angle coverage required ⇒ good match to PEN!

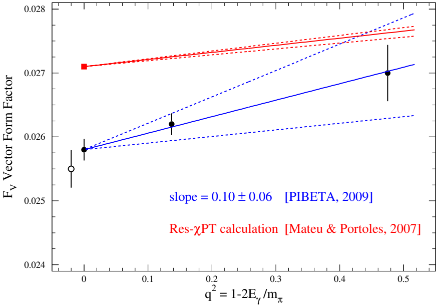
SD$^-$ notoriously hard to measure directly.

Best values of pion Form Factor Parameters:



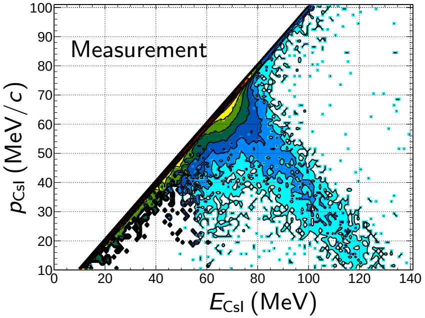
Combined analysis of all PIBETA data sets

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



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

Identifying hard radiative decays in PEN

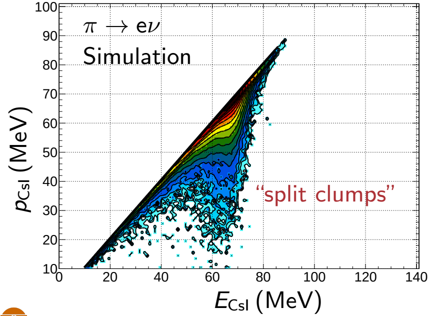


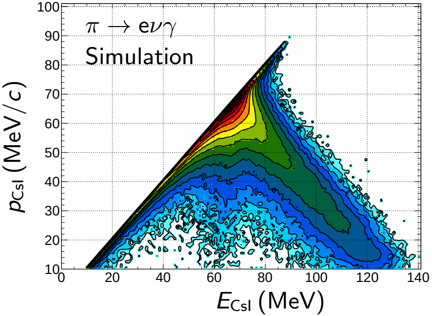
PEN indirectly measures p_ν in $\pi \to e\nu\gamma$

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

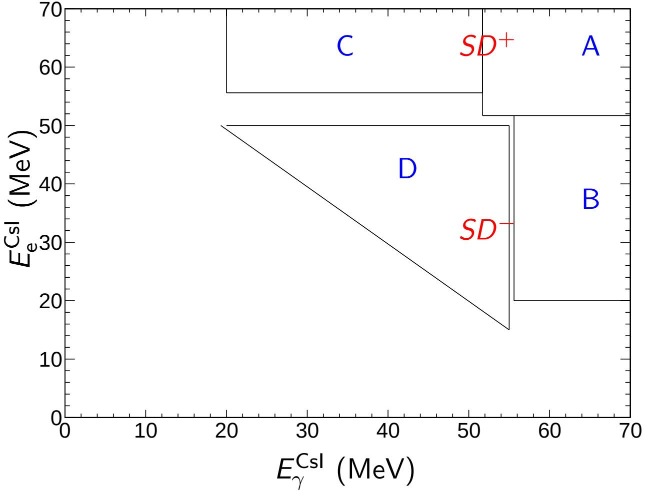
$E_e + E_\gamma \equiv E_{obs}$

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

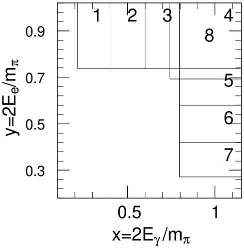




Data regions (PIBETA measurements and PEN)



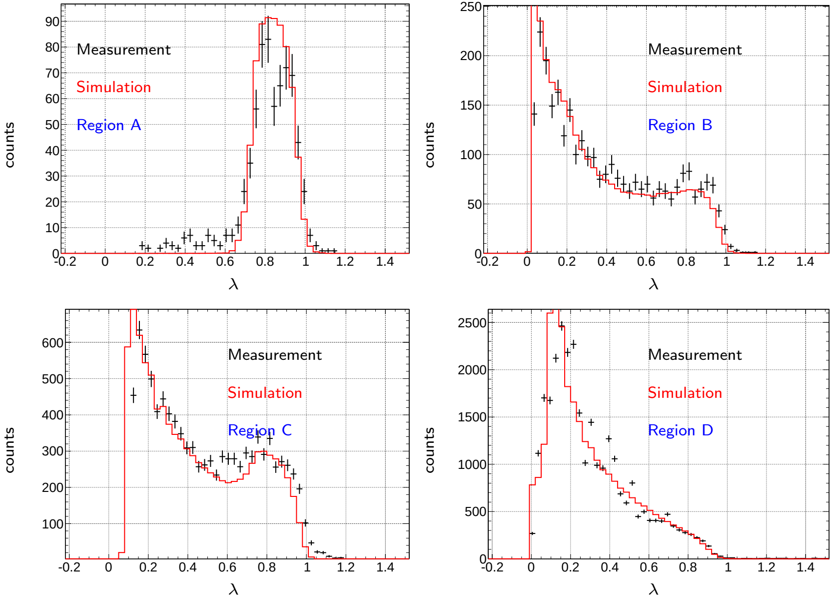
post-2004 data subdivision:



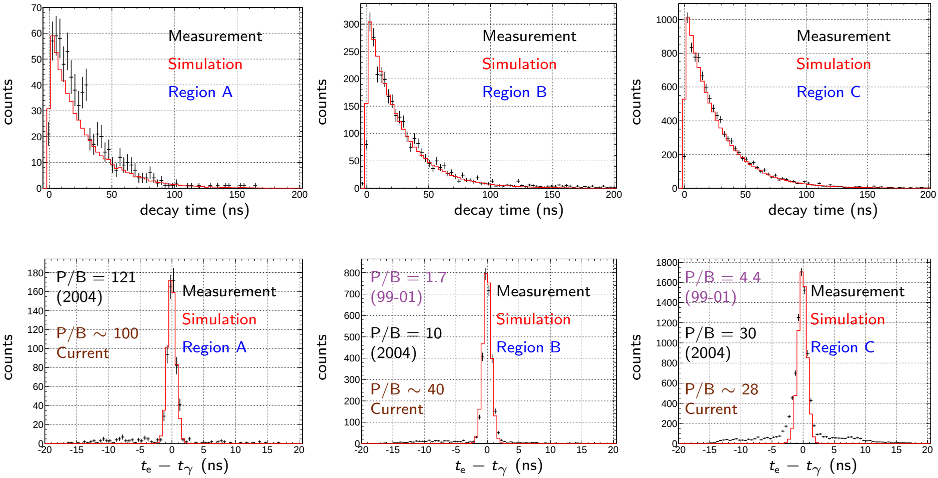
PIBETA (1999-01, 2004): regions A, B, and C.

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

Parameterizing $\lambda = 2E_e/m_\pi \sin^2(\theta_{e\gamma})$ (PEN Run 3 data)

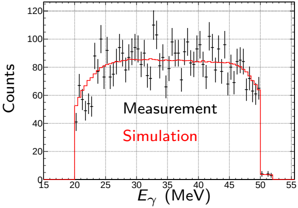


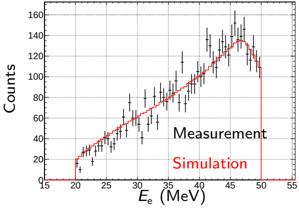
Timing for radiative decays

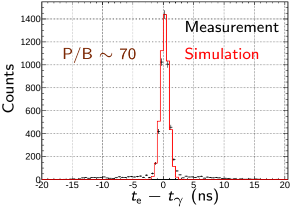


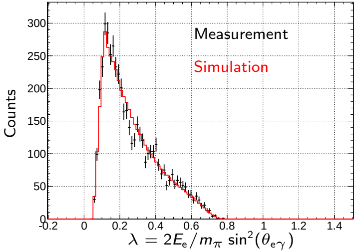
Observed spectra determined by instrumental response and event statistics.

Region D: only in PEN









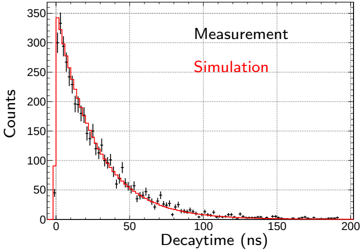


Table of uncertainties

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

r_A $\quad$ r_ϵ $\quad$ r_f

Systematics	Value	$\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu}$
$\epsilon_{\rm tail}$	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 add to 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.

Current and former PIBETA and PEN collaborators

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

Additional slides

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:

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

$$R_{\tau/\pi} = \frac{\Gamma(\tau \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_\tau^2}{g_\mu^2} \frac{m_\tau^3}{2m_\mu^2 m_\pi} \frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{\tau/\pi})$$

one can evaluate:

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

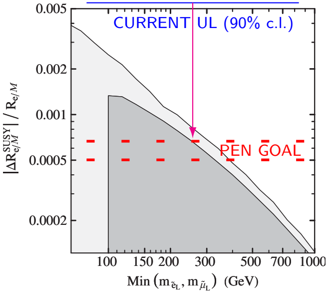
For comparison,

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

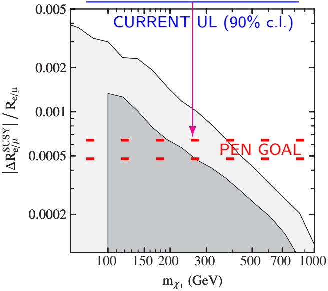
- significant consequences in the **neutrino sector**;
- interesting limits on **MSSM extension observables**.

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

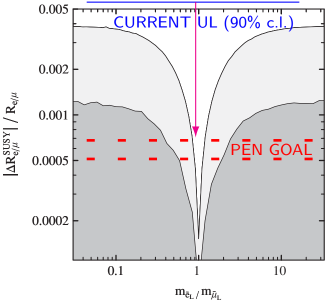
minimal selectron, smuon masses:



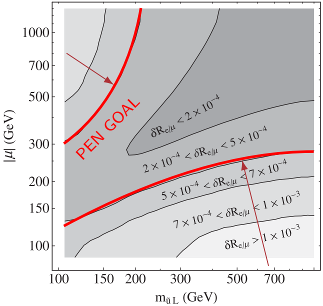
lowest mass chargino:



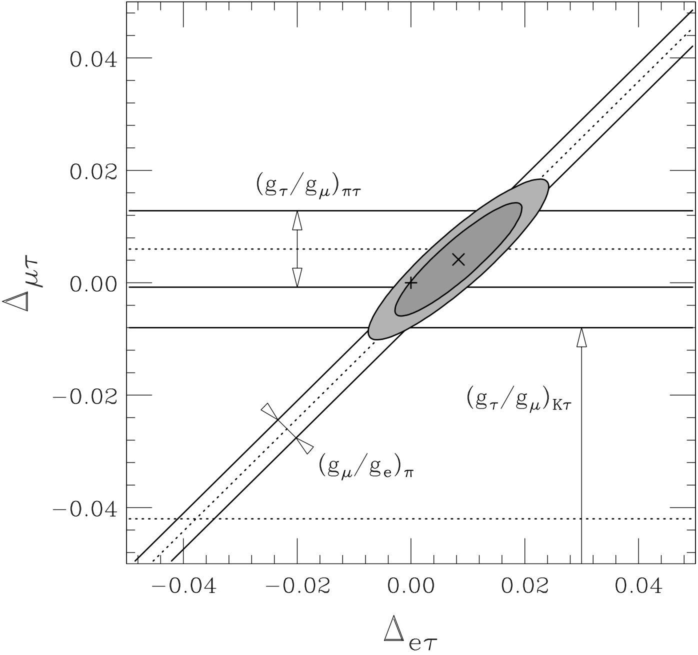
slepton mass degeneracy:



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



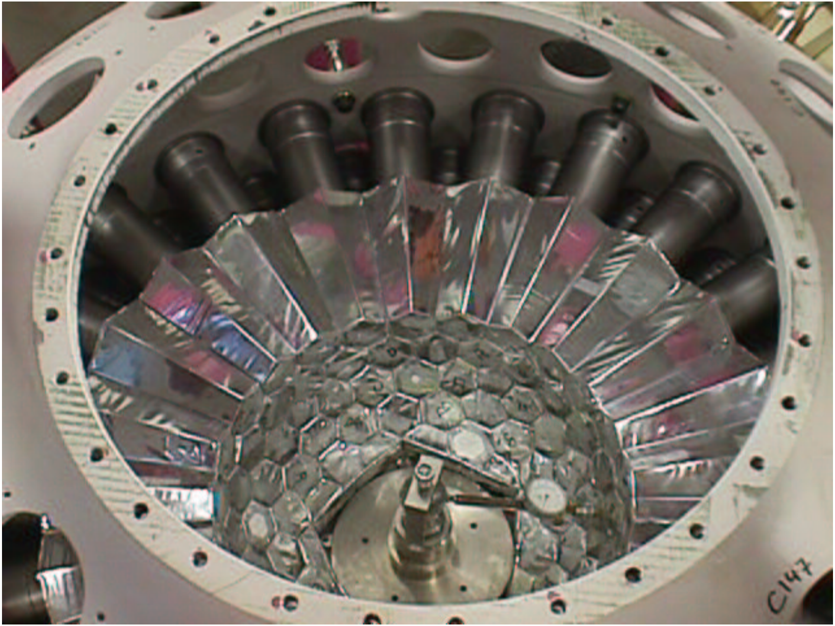
(R parity violating scenario constraints also discussed.)



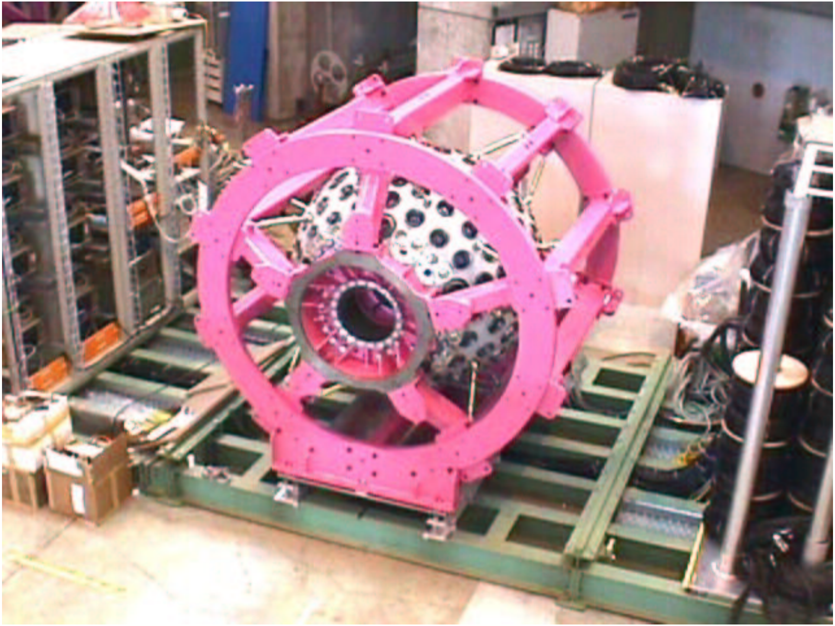
Loinaz et al., PRD **70** (2004) 113004

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

PIBETA detector assembly



PIBETA detector on platform



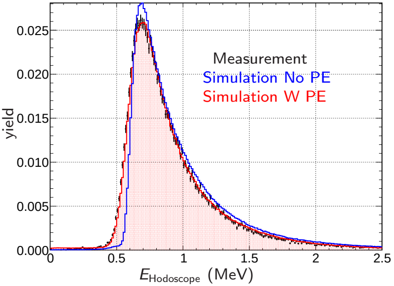
GEANT4 Monte Carlo

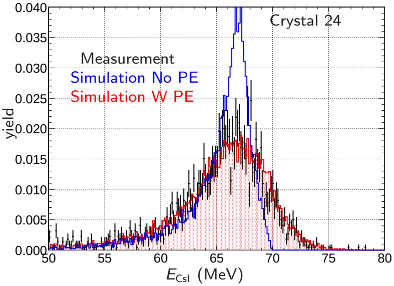
Canonical Geant gives energies, timings, and positions

Requires additional physics input to simulate full detector response

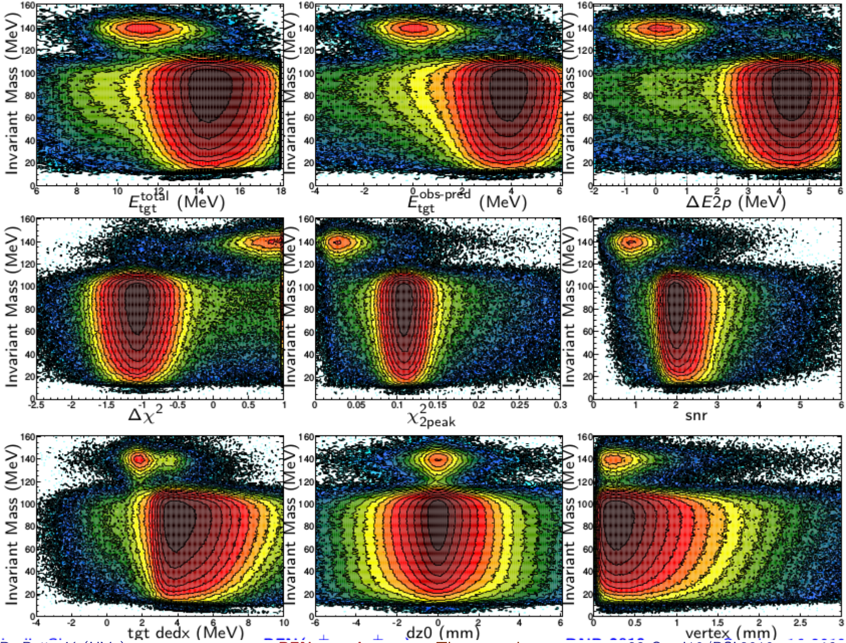
In the Experiment:

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

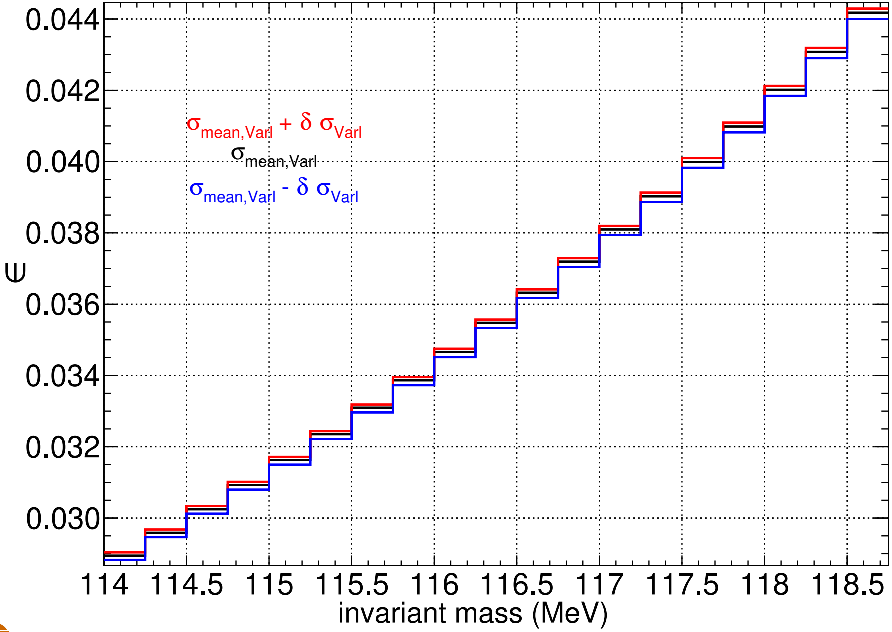




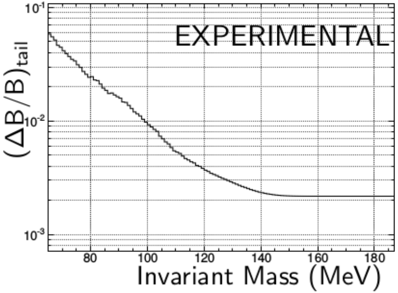
Observables to aid discrimination



π_{e2} tail including photoneutron corrections



MC simulated vs. experimental π_{e2} tail

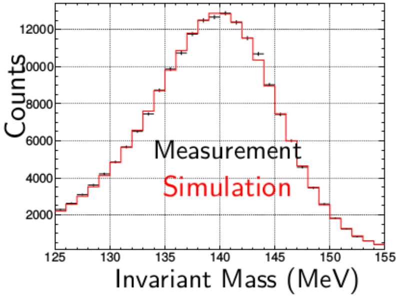


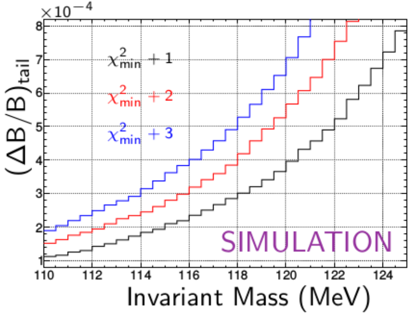
Simulation unavoidable!

Systematics from :

Gain Variation

Photo-nuclear physics





Pre-2004 data on pion form factors

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

$F_A \times 10^4$	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)

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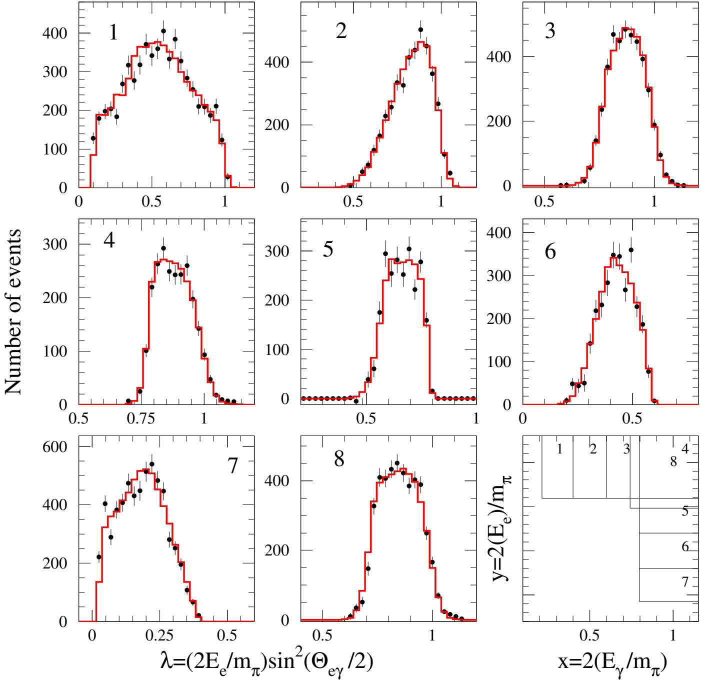
$F_A \times 10^4$	reference	note
106 ± 60	Bolotov et al. (1990)	$(F_T = -56 \pm 17)$
135 ± 16	Bay et al. (1986)	
60 ± 30	Piilonen et al. (1986)	
110 ± 30	Stetz et al. (1979)	
116 ± 16	world average (PDG 2004)	

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



$F_V = 0.0258 \pm 0.0017$	(8×)
$F_A = 0.0119 \pm 0.0001^{\mathrm{exp}}_{(F_V^{\mathrm{CVC}})}$	(16×)
$a = 0.10 \pm 0.06$ (q^2 dep of F_V)	(∞)
$-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}$	90 % C.L.

$B_{\pi_{e2\gamma}}(E_\gamma > 10\,\mathrm{MeV}, \theta_{e\gamma} > 40^\circ) = 73.86(54) \times 10^{-8}$ (17×)

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Above results will improve with the new PEN data analysis!

Summary of PIBETA results on $\pi \to e\nu\gamma$ [PRL **103**, 051802 (2009)]

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At L.O. ($l_9 + l_{10}$), F_A, F_V are related to pion polarizability and π^0 lifetime

$$\alpha_E^{\text{LO}} = -\beta_M^{\text{LO}} = (2.783 \pm 0.023_{\text{exp}}) \times 10^{-4}\ \text{fm}^3$$

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\text{s}$$

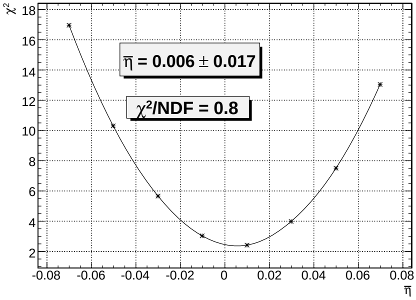
- current PDG avg: 8.52 (18)
- PrimEx PRL '11: 8.32 (22)

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).

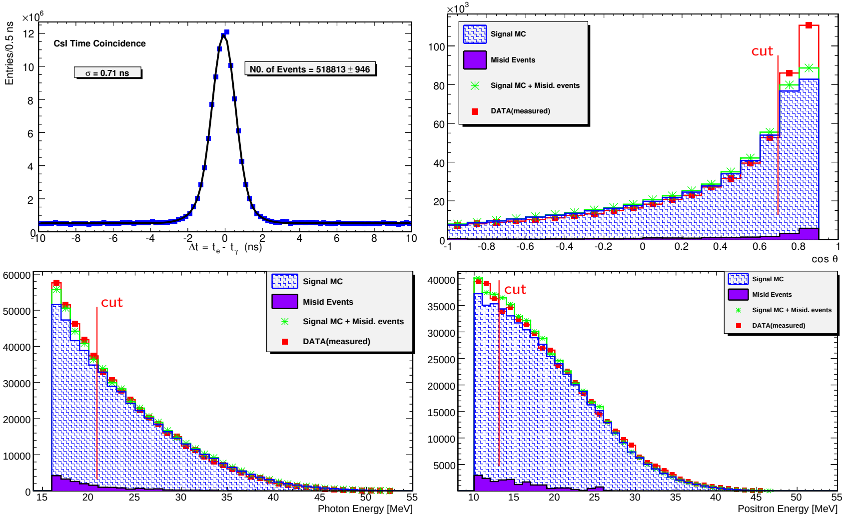
Radiative muon decay:

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

$BR \sim 10^{-3}$ 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]

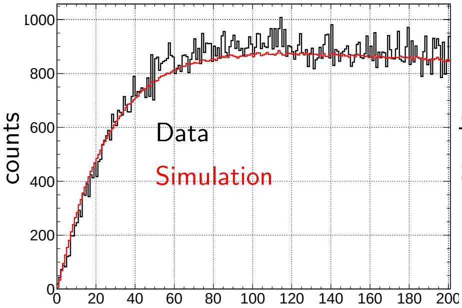


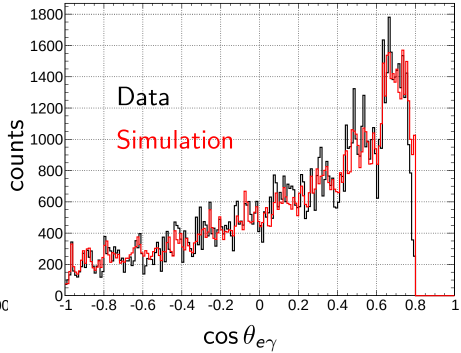
"Split clumps" very well accounted for!

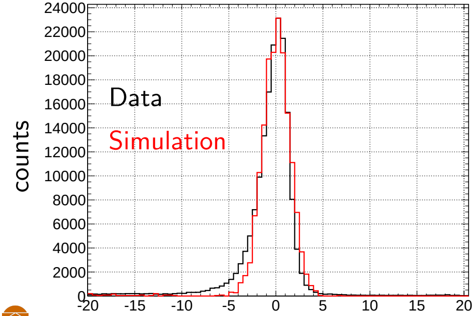
$\sim$30-fold improvement in precision of the RMD *BR*.

$\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.