PEN Update:
A Precision Measurement of $\pi \rightarrow e\nu(\gamma)$ Branching Ratio

Charles Glaser

University of Virginia

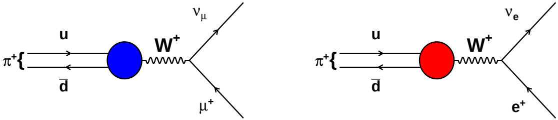
PEN Collaboration

Overview

- Theory/Motivation
- PEN Detector
- Monte Carlo Simulations
- Radiative Decays
- Statistics and Systematics
- Summary

Theory/PEN

Explore the (V−A) interaction through a precision measurement



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

Theoretical BR: $(1.2352 \pm 0.0001) \times 10^{-4}$ *

Experimental BR: $(1.2327 \pm 0.0023) \times 10^{-4}$

δ_R rad/loop corrections in SM, non V−A extensions

$(\frac{g_e}{g_\mu})^2 = 1.0021 \pm 0.0016$ (experimental)

Goal: relative uncertainty 5×10^{-4} or better

*For Review see: D.Počanić et al J. Physics G **41** 2014 11

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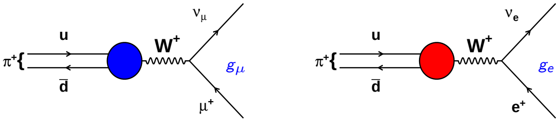

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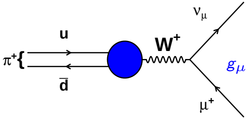

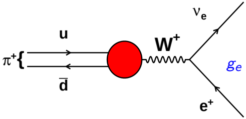

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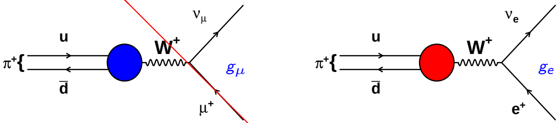

$\sim 2.5 \times 10^{-5}$

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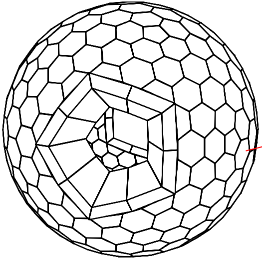
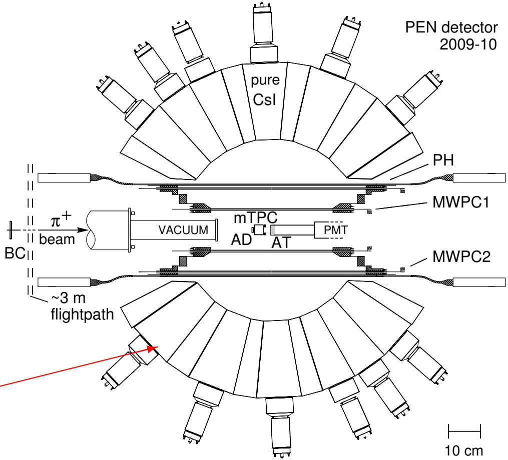
Detector Setup

- 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 (B)

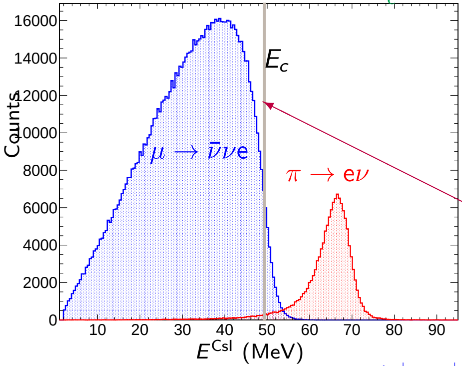
Naively, $B = \frac{N_{\pi\to e\nu} A_{\pi\to\mu\to e}}{N_{\pi\to\mu\nu} A_{\pi\to e\nu}}$ Too simplistic!

MWPC efficiency depends on energy

Timing gates affect number of observations

Monte Carlo

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



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

$f(T_e)$ = probability from time

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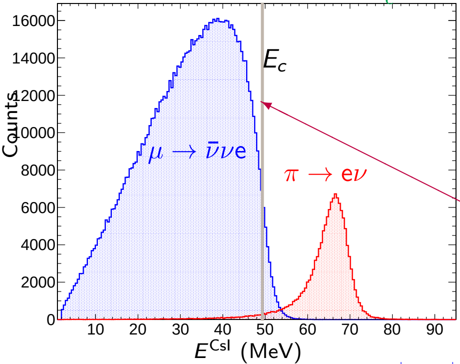

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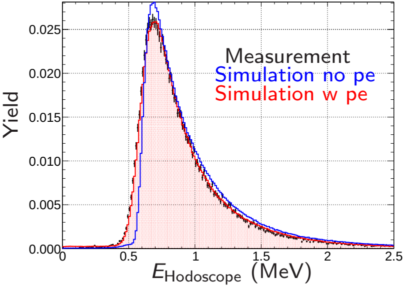
Creating realistic simulations

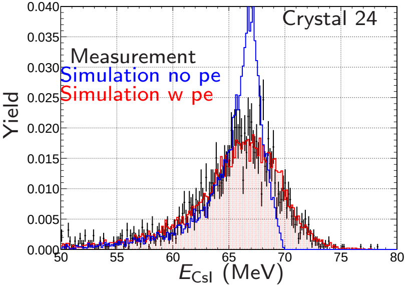
Geant gives energies, timings, and positions

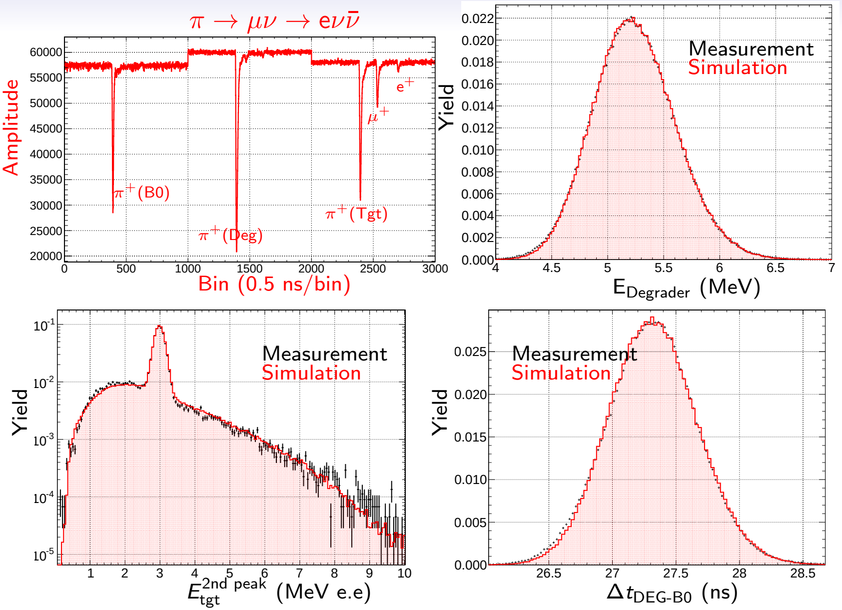
Requires additional physics input to simulate full detector response

In the Experiment:

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

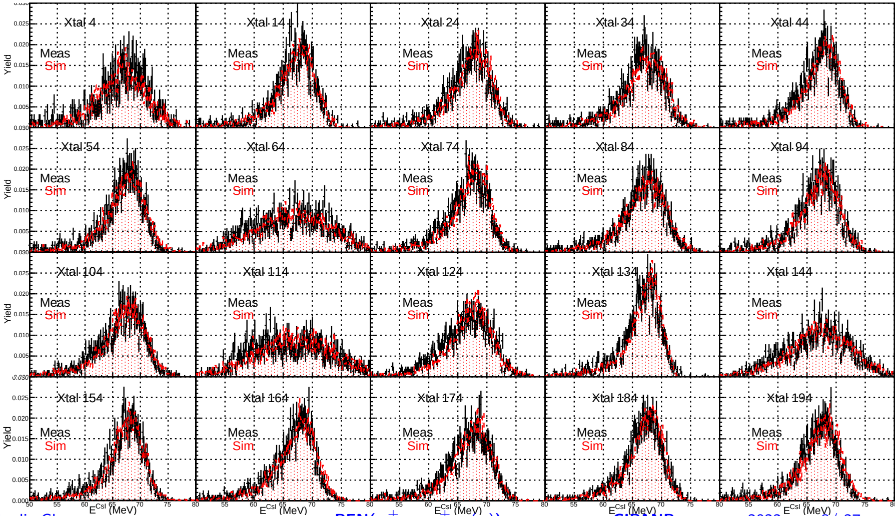





$\pi \rightarrow \mu\nu \rightarrow e\nu\bar{\nu}$
Amplitude
Bin (0.5 ns/bin)
π^+(B0)
π^+(Deg)
π^+(Tgt)
μ^+
e^+
Yield
$E_{Degrader}$ (MeV)
Measurement
Simulation
Yield
$E_{tgt}^{2nd\ peak}$ (MeV e.e)
Measurement
Simulation
Yield
$\Delta t_{DEG\text{-}B0}$ (ns)
Measurement
Simulation

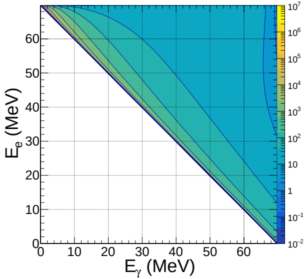
CsI challenges - unique xtals

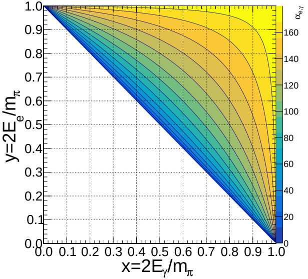
- Light collection non-uniformities, $\Delta\Omega$ Coverage
- 240 PMTs = 240 different quantum efficiencies

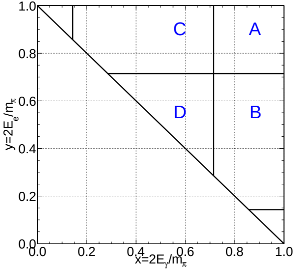


Regions of $\pi \to e\nu\gamma$

All decays are radiative







Phase space broken into regions

Regions of $\pi \to e\nu\gamma$

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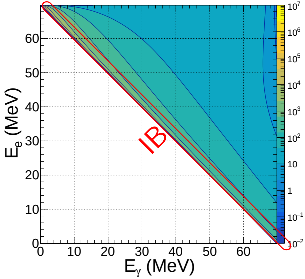

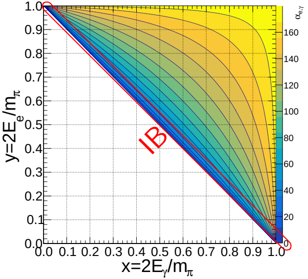

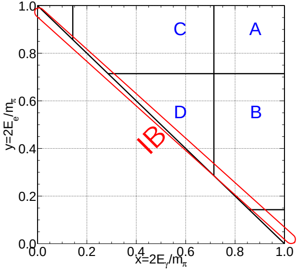

Inner Bremsstrahlung dominated

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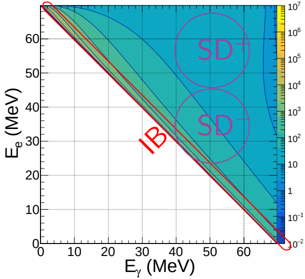
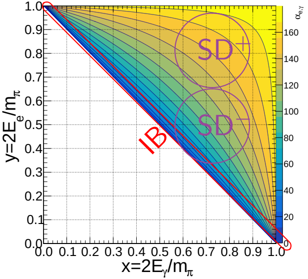
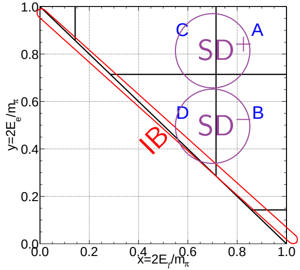






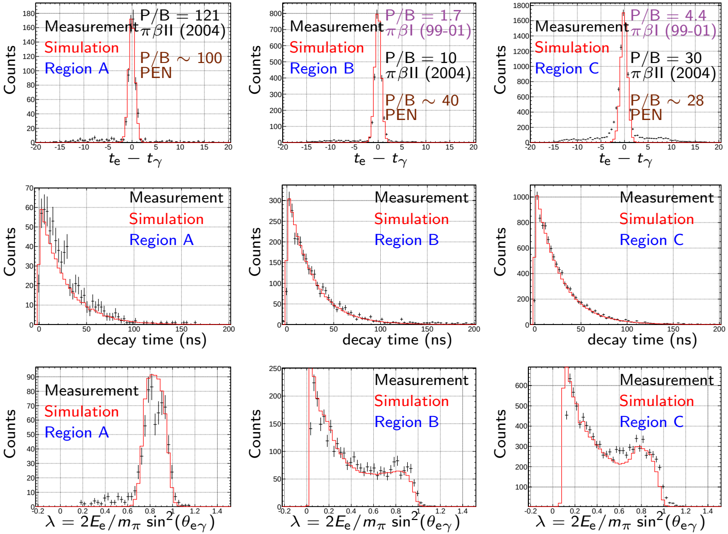
Inner Bremsstrahlung dominated

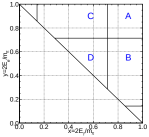
Structure Dependent

$SD^+ \sim (F_V + F_A)^2$

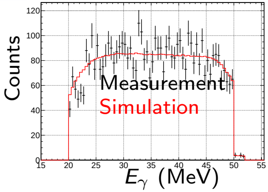
$SD^- \sim (F_V - F_A)^2$

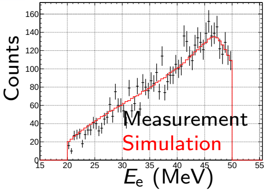
Radiative Decays $\pi \to e\nu\gamma$

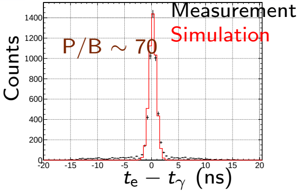


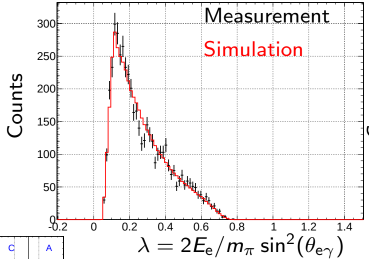


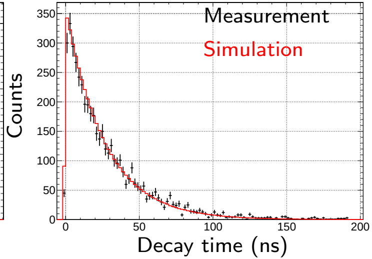
Region D

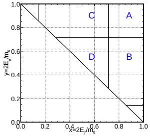






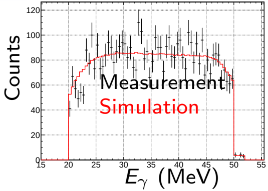


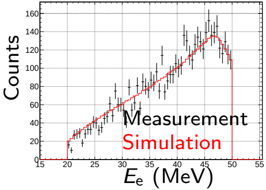


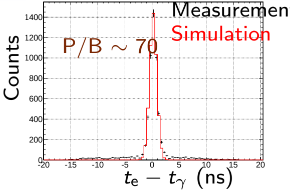


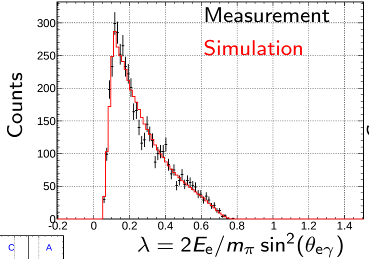
PEN: First experiment to examine Region D in detail

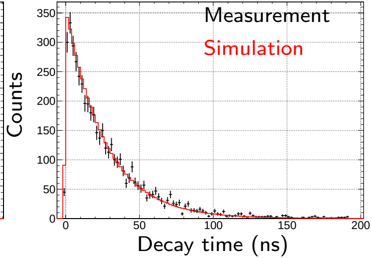
Region D

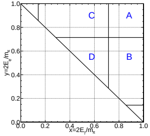






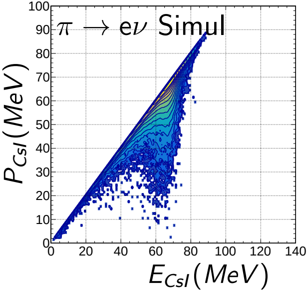






A chance to evaluate SD^- (F_V, F_A) independently

Invariant mass-inclusion of radiative decays

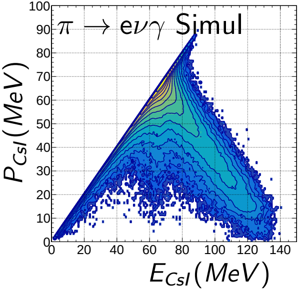


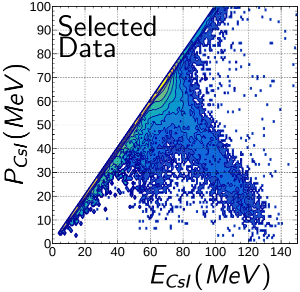
PEN indirectly measure p_ν

$$\vec{p}_e + \vec{p}_\gamma = -\vec{p}_\nu$$

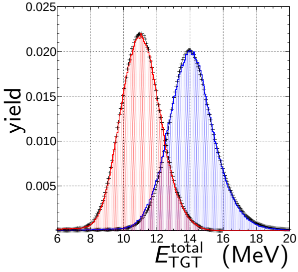
$$\underbrace{E_\gamma + E_e}_{E_{obs}} + \underbrace{E_\nu}_{p_\nu c} = m_\pi c^2$$

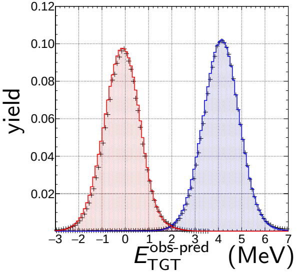
$$E_{obs} + p_\nu c = m_\pi c^2$$





Waveform selections



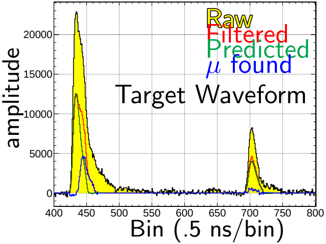


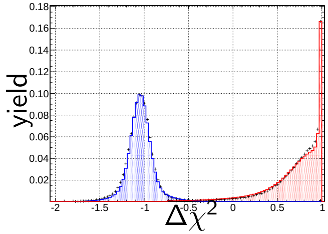
Measurement

$\pi \rightarrow \mu\nu(\gamma)$ Simul

$\pi \rightarrow e\nu(\gamma)$ Simul

Predicted energies
and
predicted timings
lead to
predicted waveforms



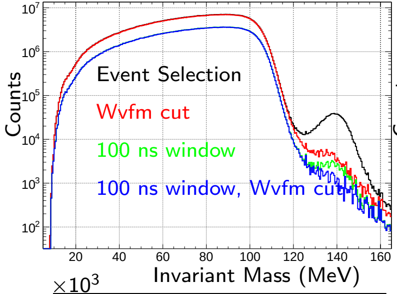


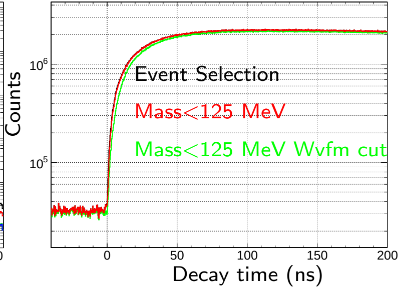
Get $\chi^2_{2\mathrm{peak}}$

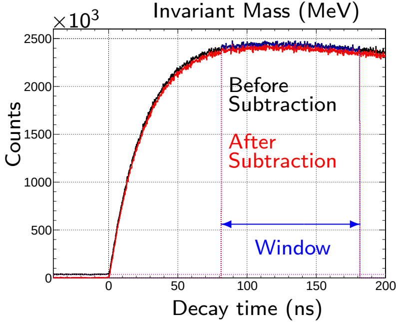
Get $\chi^2_{3\mathrm{peak}}$

$$\Delta\chi^2 = \frac{\chi^2_2 - \chi^2_3}{\text{constant}}$$

Number of $\pi \to \mu \to e$ events

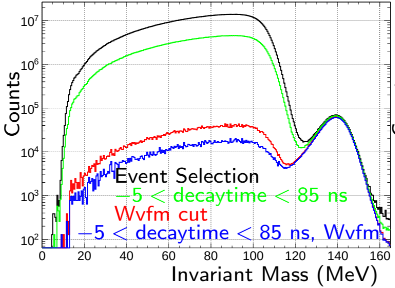


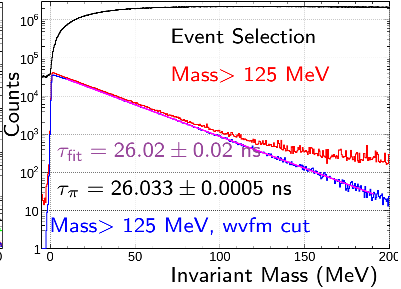


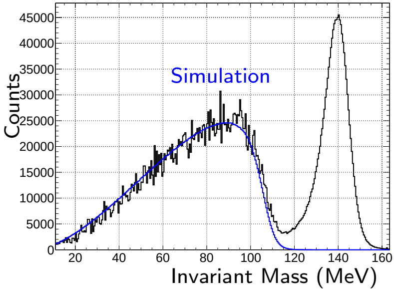


$$N_{\text{michel, run 2}} = (5225.68 \pm 0.23) \times 10^5$$
$$N_{\text{michel, run 3}} = (9545.50 \pm 0.33) \times 10^5$$
$$\delta N_{\text{michel,run 2}} / N_{\text{michel,run 2}} = 4.4 \times 10^{-5}$$
$$\delta N_{\text{michel,run 3}} / N_{\text{michel,run 3}} = 3.5 \times 10^{-5}$$

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







Wvfm cut is needed.

$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (1409.33 \pm 1.18) \times 10^3$$

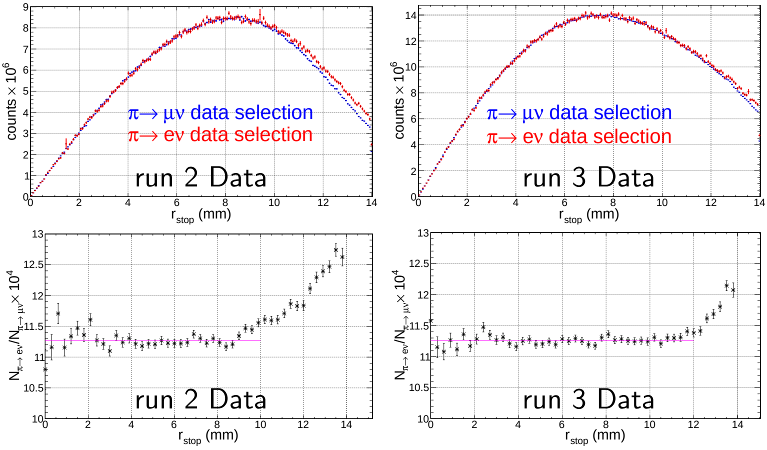
$$N_{\pi\to e\nu(\gamma),\text{run 3}} = (2413.81 \pm 1.63) \times 10^3$$

$$\delta N_{\pi\to e\nu(\gamma)}/N_{\pi\to e\nu(\gamma),\text{run 2}} = 8.50 \times 10^{-4}$$

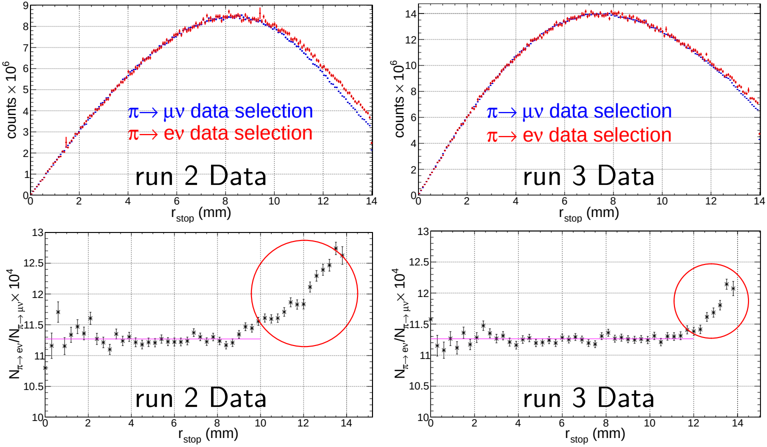
$$\delta N_{\pi\to e\nu(\gamma)}/N_{\pi\to e\nu(\gamma),\text{run 3}} = 6.49 \times 10^{-4}$$

$$\delta N_{\pi\to e\nu(\gamma)}/N_{\pi\to e\nu(\gamma)} = 5.26 \times 10^{-4}$$

Target energy requirements



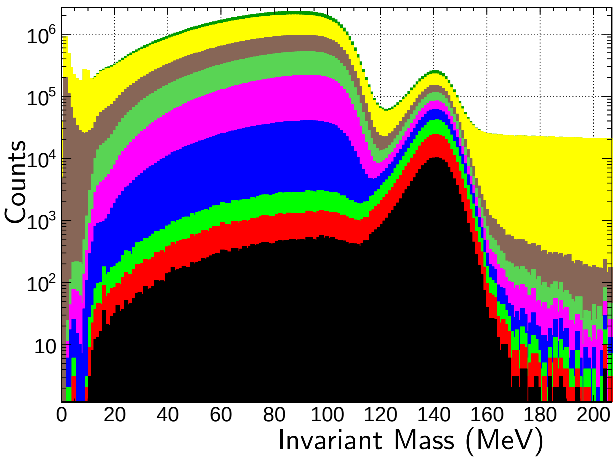
Target energy requirements



run 3 data $\sim 50\%$ run 3 data $\sim 25\%$

$\delta N/N \sim 4.13 \times 10^{-4}$

Tail trigger - studying the tail



Trigger events

Good π stop

Track Constructed

Good Track

$E_{\text{tgt}} < 12$ MeV

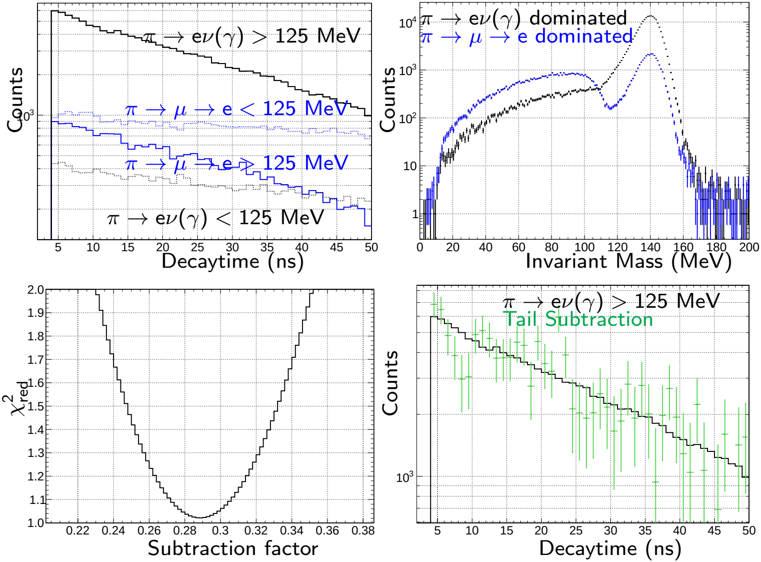
$E_{\text{tgt}}^{\text{pred-obs}} < 1$

$\Delta\chi^2 > .55$

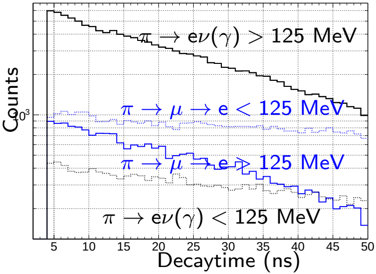
Good Vertex

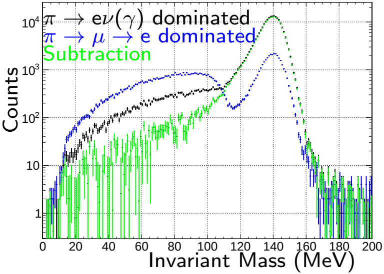
Tgt dEdx

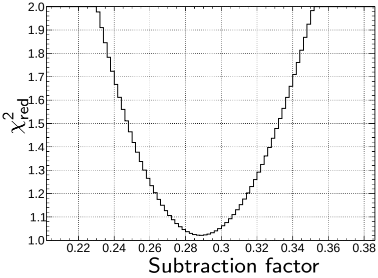
$\pi \to \mu \to$ e subtraction from tail

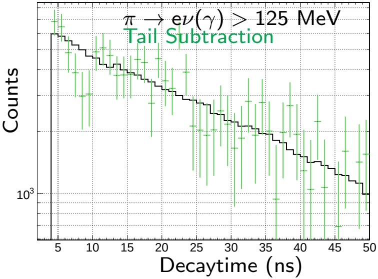


$\pi \to \mu \to$ e subtraction from tail

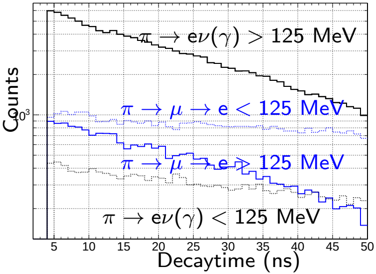


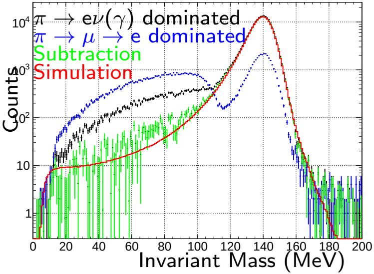


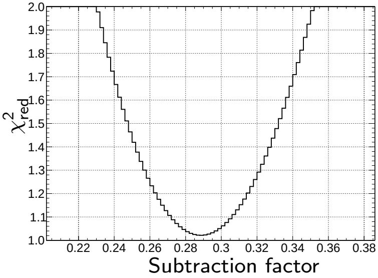


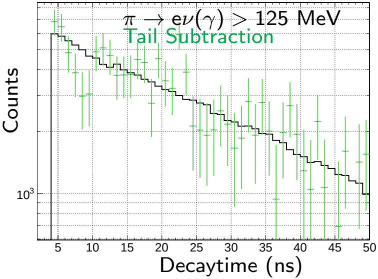


$\pi \to \mu \to$ e subtraction from tail

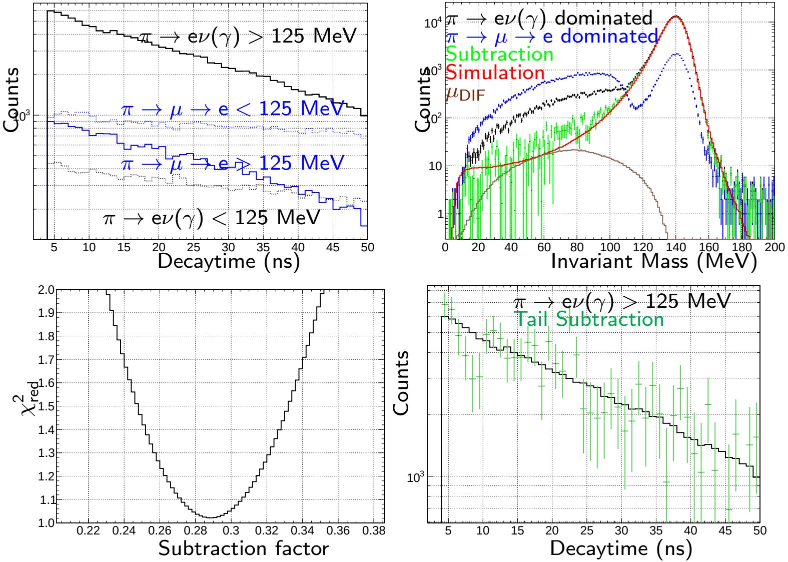




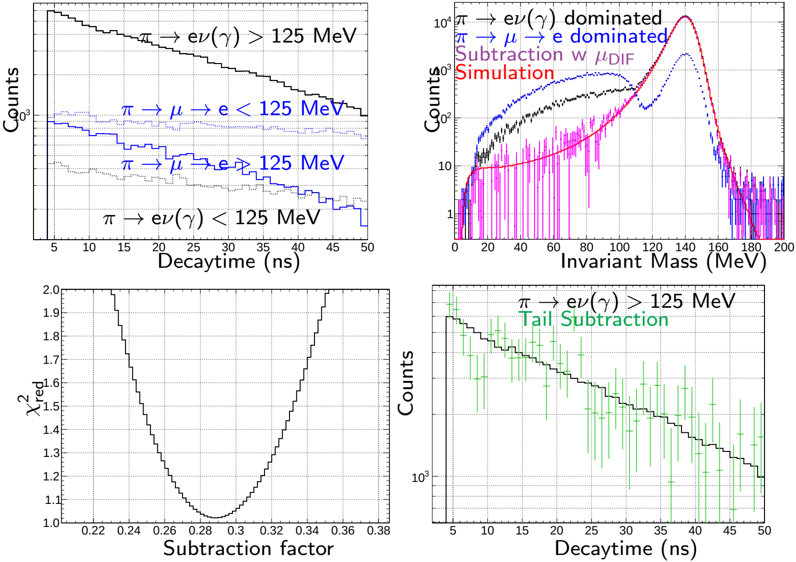




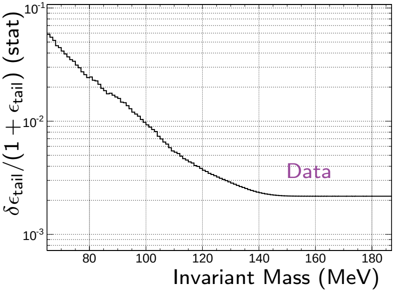
$\pi \to \mu \to$ e subtraction from tail



$\pi \to \mu \to$ e subtraction from tail



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

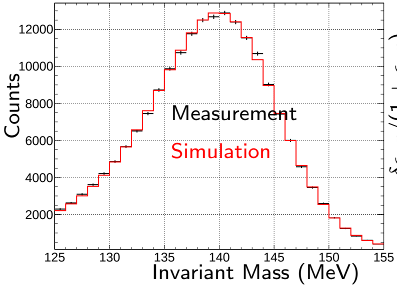


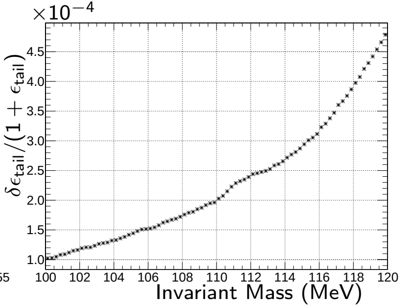
Statistical uncertainty too high

Relay on precise simulation

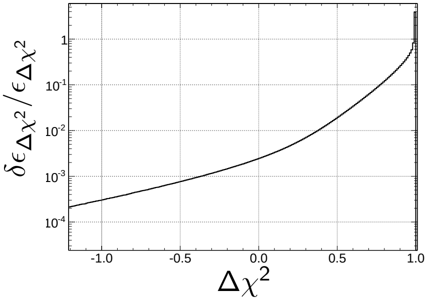
Systematics from :

- Peak positions
- Photo-nuclear physics





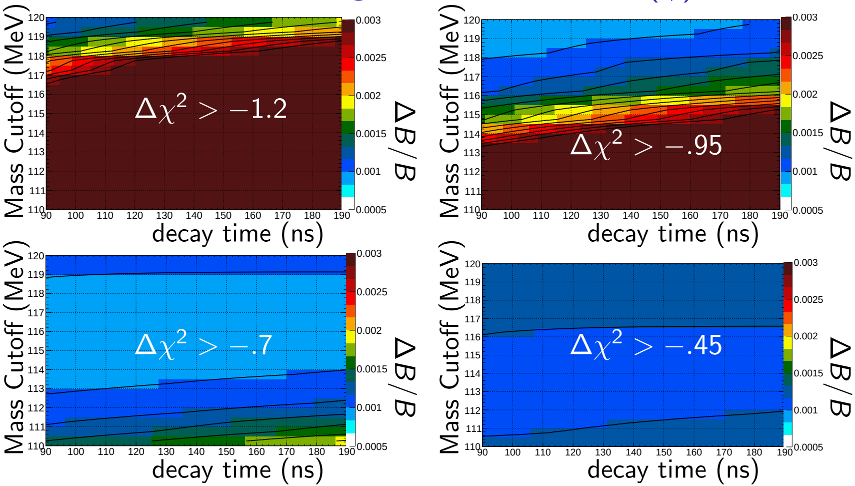
Minimizing Error for $\pi \to e\nu(\gamma)$



$\Delta\chi^2$ and decay time affect $N_{\pi\to e\nu(\gamma)}$ and $\delta N_{\pi\to e\nu(\gamma)}$

Balance between tail/peak cutoff, decay time and $\Delta\chi^2$

Minimizing Error for $\pi \to e\nu(\gamma)$

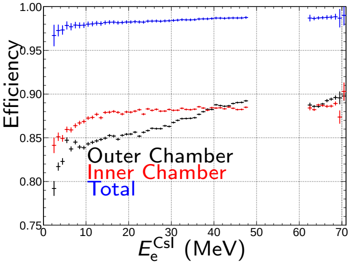


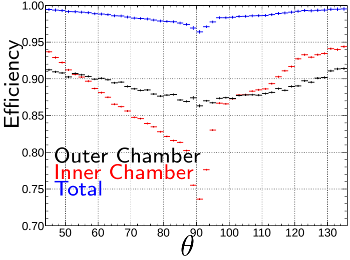
Cutoff = 117.5 MeV

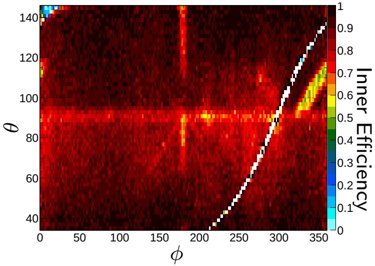
Decay time = 93.5 ns

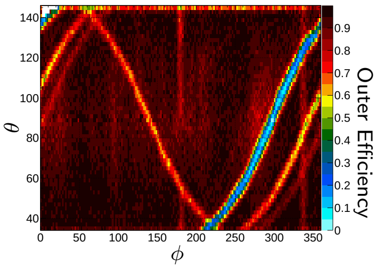
$\Delta\chi^2 > -0.8$

Chamber Efficiencies

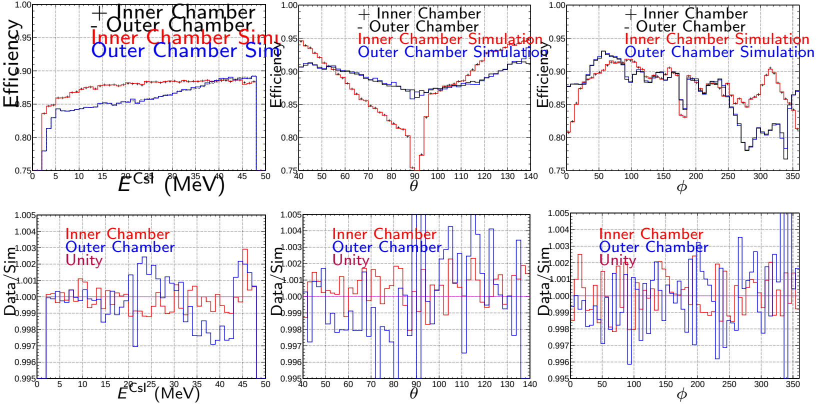








Simulation Chamber Efficiencies



dE/dx = f(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)

Table of Uncertainties

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

r_A r_ϵ r_f

Systematics	Value	$\Delta B/B$
ϵ_{tail}	$(3.804 \pm 0.040) \times 10^{-2}$	3.8×10^{-4}
r_f	0.0440926	8×10^{-5}
$^* r_A r_\epsilon$	$*$	$\simeq 10^{-4}$
Statistical:		
$N_{\pi\to\mu\nu}$	$(5225.68 \pm 0.23) \times 10^5$	4.4×10^{-5} (run 2)
	$(9545.50 \pm 0.33) \times 10^5$	3.4×10^{-5} (run 3)
$N_{\pi\to e\nu}$	$(1409.43 \pm 1.18) \times 10^3$	8.37×10^{-4} (run 2)
	$(2413.81 \pm 1.63) \times 10^3$	6.75×10^{-4} (run 3)
$\Delta N_{\pi\to e\nu}/N_{\pi\to e\nu}$	4.13×10^{-4} (possible)	5.26×10^{-4} (run 2/3)
	5×10^{-4}(*Goal*)	7.6×10^{-4}

* Blinded

Family

Current and former PIBETA and PEN collaborators

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N.V. Khomutov , J. Koglin , A.S. Korenchenko , S.M. Korenchenko ,
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H.-P. Wirtz , K. Ziock .

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

Thanks for listening!

Questions?

$\Delta\chi^2$

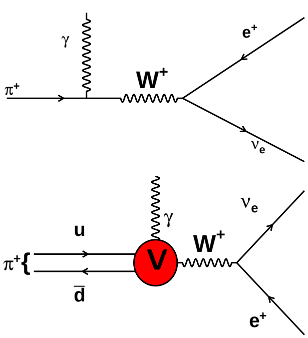
$$\chi^2_{2\text{peak}} = \Sigma(\text{observed}_i - \text{predicted}_i)^2 = \Sigma\text{netto}_i^2$$

$$\chi^2_{3\text{peak}} = \Sigma(\text{netto}_i - \text{muon}_i)^2$$

$$\Delta\chi^2 = \sum_{i=0}^{1000} \underbrace{\left((\text{netto}_i - \text{muon}_i)^2 - \text{netto}_i^2\right)}_{\chi^2_{3\ \text{peak}} - \chi^2_{2\ \text{peak}}} / \sum_{i=0}^{1000} (\text{muon}_i)^2$$

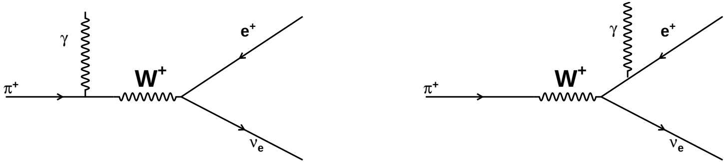
$$= 1 - 2\sum_{i=0}^{1000} \text{netto}_i \text{muon}_i / \sum_{i=0}^{1000} (\text{muon}_i)^2$$

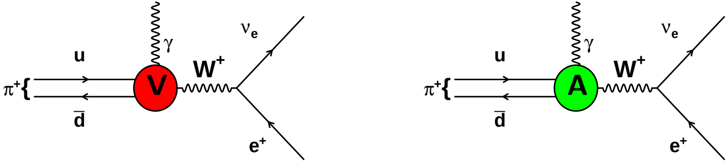
Physics of Radiative Decays



Physics of Radiative Decays

Inner Bremstrahlung (IB) (Boring)





Structure Dependent (Not Boring!)

Physics and Math of Radiative Decays

$\mathcal{M}(\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}\gamma) = \mathcal{M}_{\mathcal{IB}} + \mathcal{M}_{\mathcal{SD}}$

Parameterizing $x = 2E_\gamma/m_\pi$ and $y = 2E_\mathrm{e}/m_\pi$

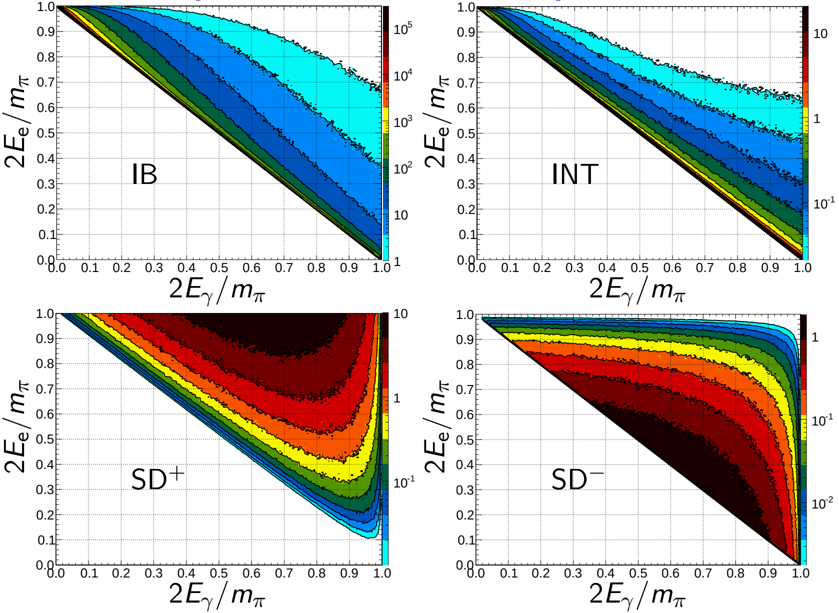
$$\frac{\Gamma_{\pi e2\gamma}}{dxdy} = \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Big\{ IB\,(x,y) + \left(\frac{m_\pi}{2f_\pi m_e}\right)^2 \times \left[(F_V + F_A)^2 SD^+\,(x,y) + (F_V - F_A)^2 SD^-\,(x,y) \right] + \left(\frac{m_\pi}{f_\pi}\right)\left[(F_V + F_A)\, S^+_{int}\,(x,y) + (F_V - F_A)\, S^-_{int}\,(x,y)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

$$IB(x,y) = \frac{(1-y)\left[(1+(1-x)^2\right]}{x^2(x+y-1)}$$

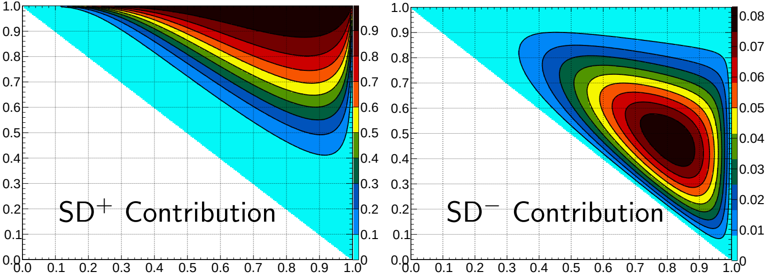
$$SD^+(x,y) = (1-x)(x+y-1)^2,\ SD^-(x,y) = (1-x)(1-y)^2$$

$$S^+_{int}(x,y) = -\frac{1}{x}(1-y)(1-x), S^-_{int}(x,y) = \frac{1}{x^2}(1-y)(1-x+\frac{x^2}{x+y+1})$$

Physics of Radiative Decays in Pictures



Best Places for SD



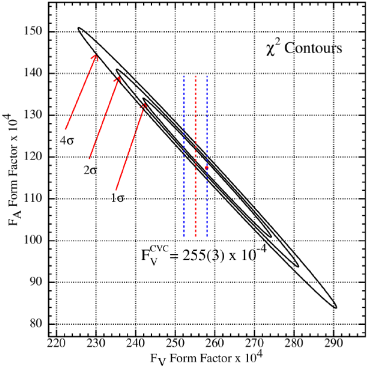
SD^+ region consists of high energy e and γ's.

These high energy particle will have big opening angle between them

Large solid angle coverage required

Pibeta results for $\pi \to e\nu\gamma$

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.
$B_{\pi_{e2\gamma}} = 73.86(54) \times 10^{-8\,\dagger}$	$(17\times)$

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

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

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

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