Precision Measurement of $\pi \rightarrow e\nu(\gamma)$ Branching Ratio

Charles Glaser

University of Virginia

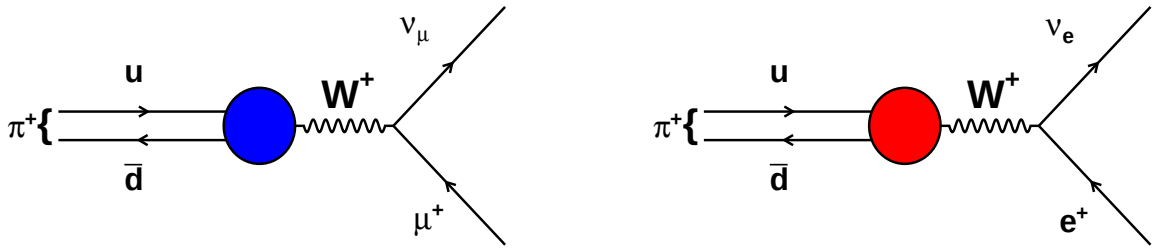
PEN Collaboration

Overview

- Theory/Motivation
- PEN Detector/Experiment
- Methods of separation
- Monte Carlo
- Radiative decays
- Event count
- Tail fraction
- Uncertainties
- 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

Theory/PEN

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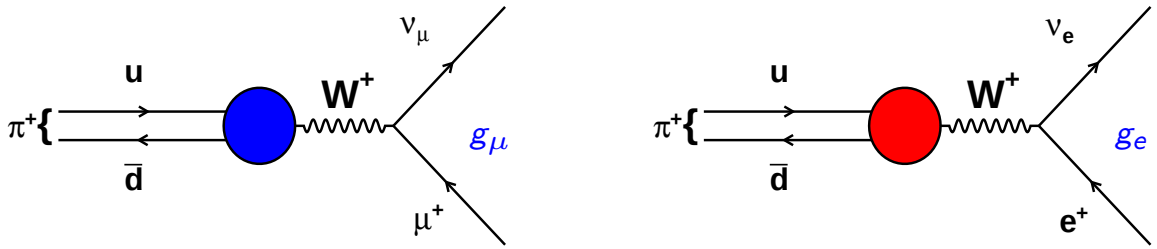

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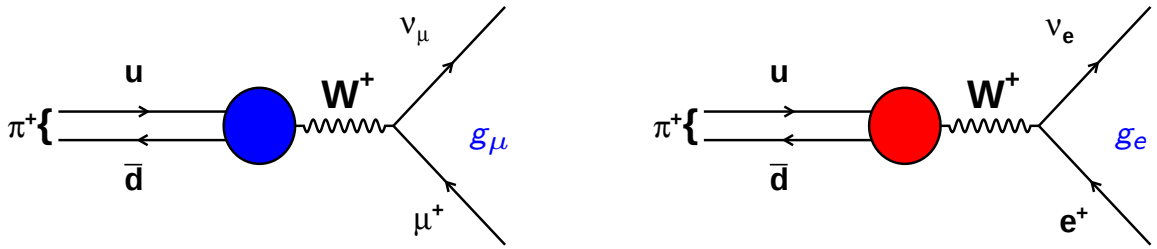

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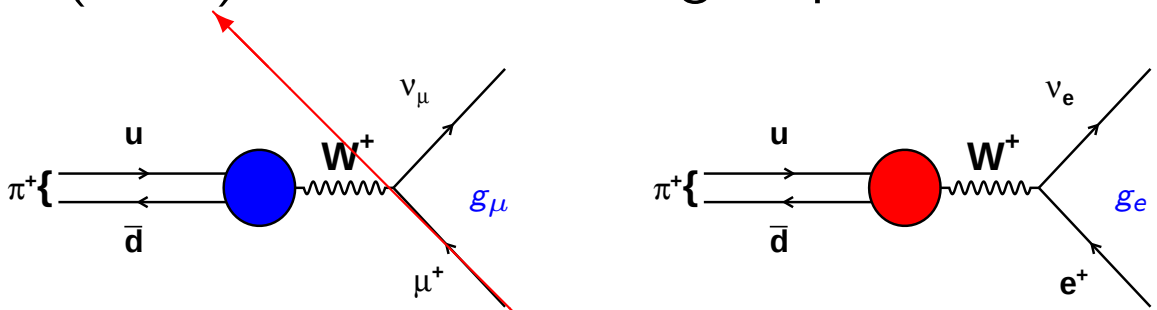

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$\sim 2.5\times 10^{-5}$

Theoretical BR: $(1.2352 \pm 0.0001)\times 10^{-4}$ Pure PS $\sim$5.4 *

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

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

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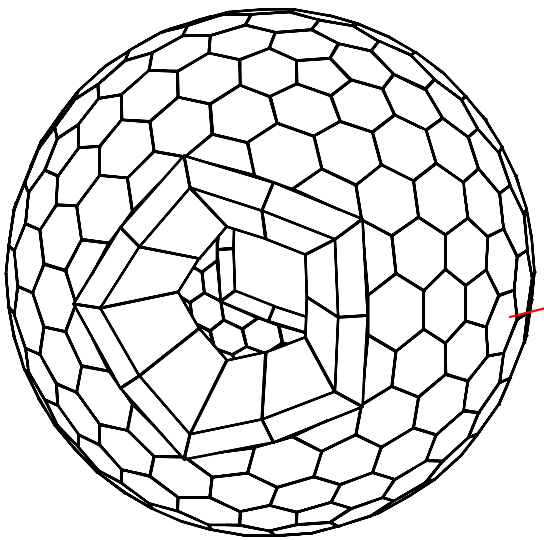
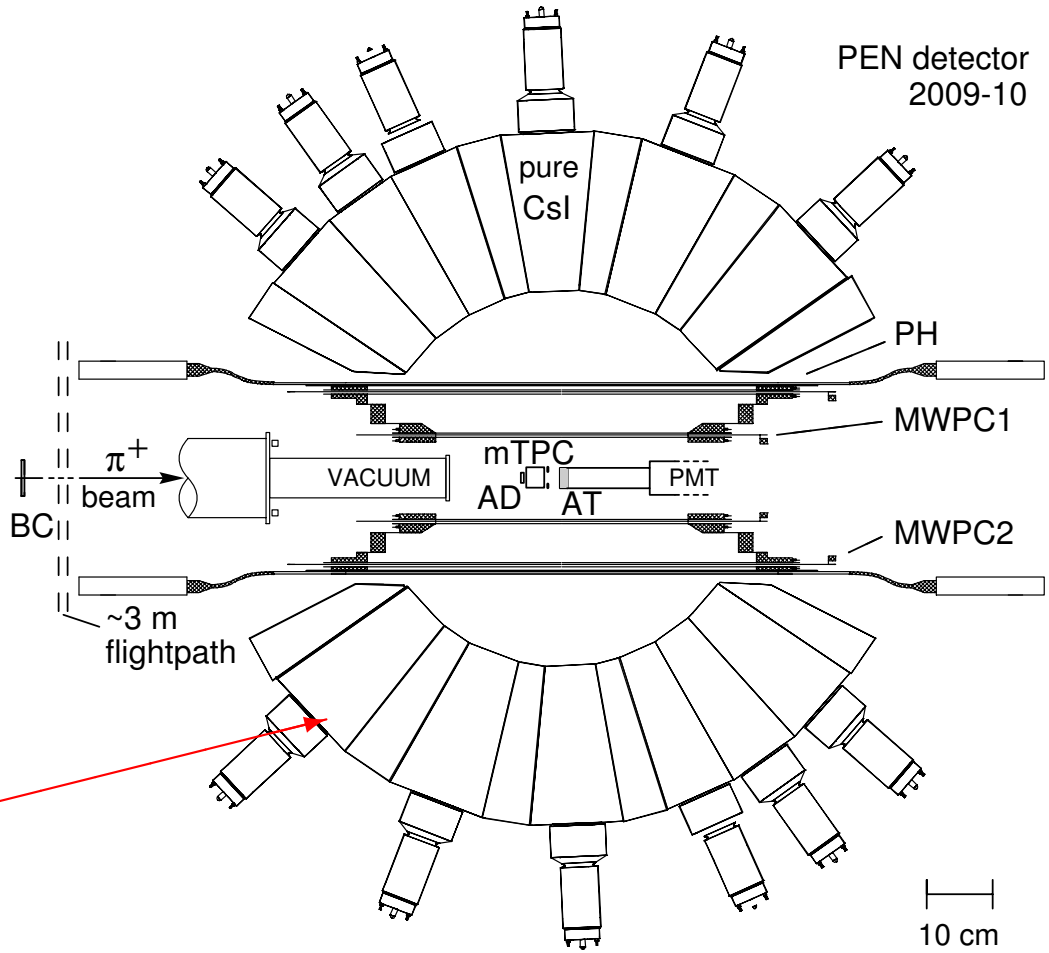
Detector Setup

- 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

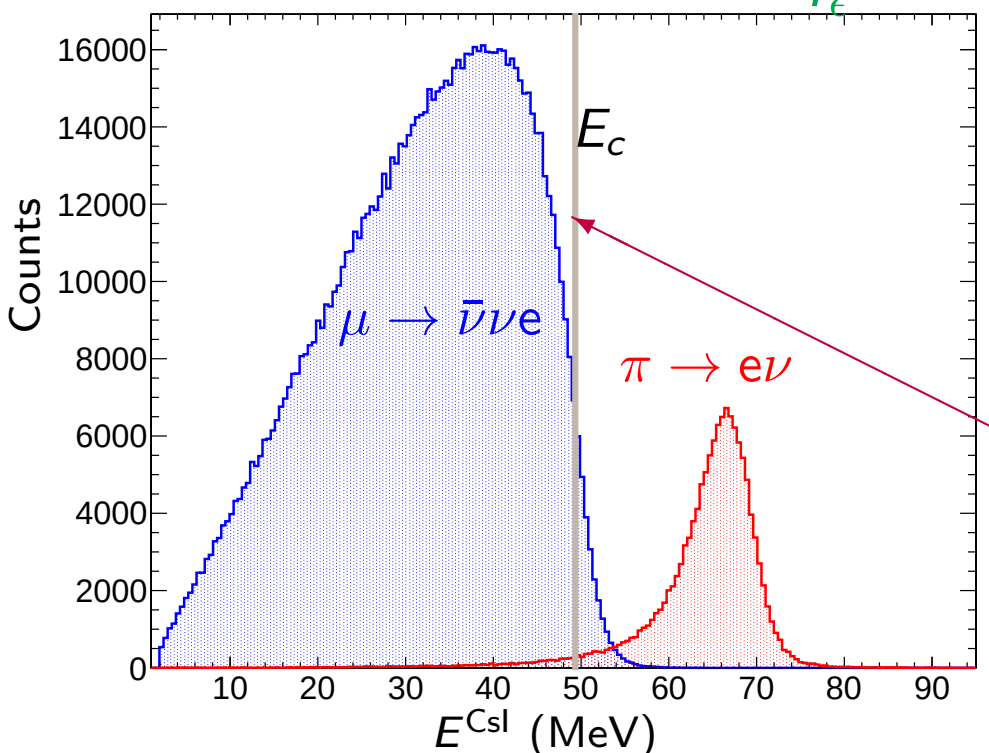
Experimental Branching Ratio (B)

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

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



E_c = cutoff energy

N = number of events

A = acceptance

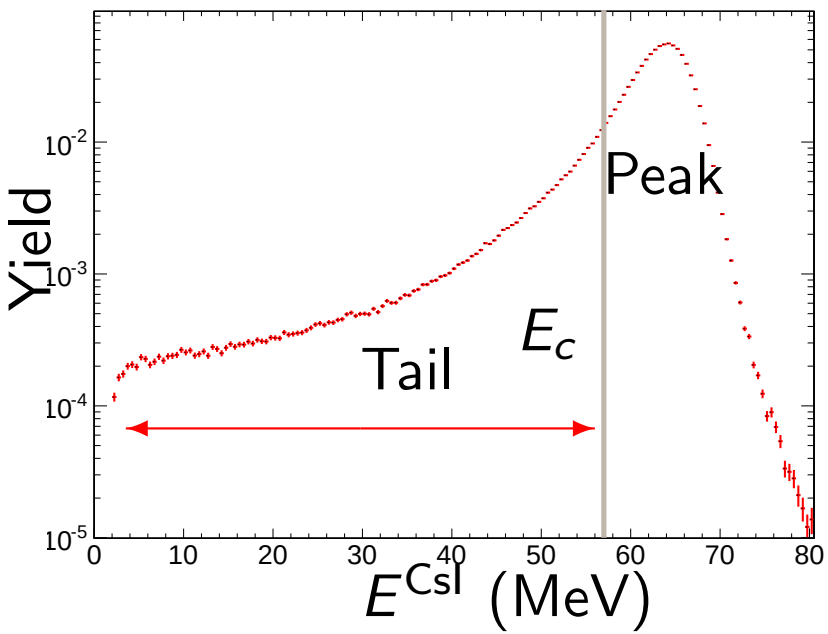
$\epsilon_{tail}(E_c)$ = tail to peak ratio

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

$f(T_e)$ = probability from time

Geant4 Monte Carlo Simulation

- particle tracking
- energy deposition
- decaying particles
- acceptances by simulating **pure processes**



Needed for N_{tail}/N_{peak}

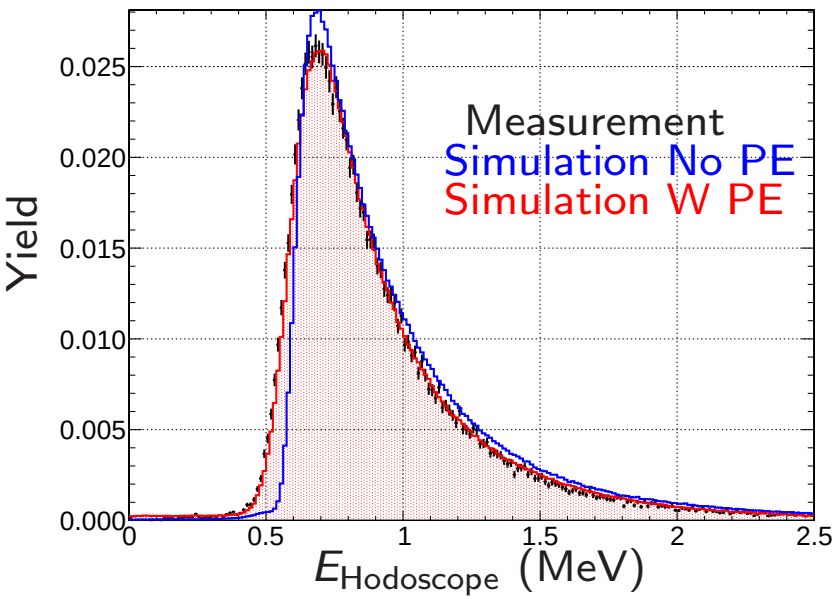
Challenges

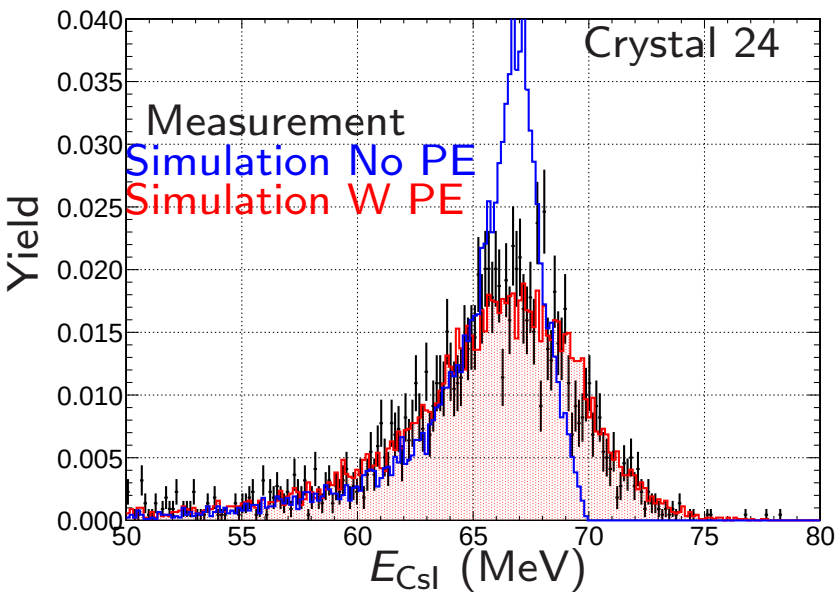
Geant gives energies, timings, and positions

Requires additional physics input to simulate full detector response

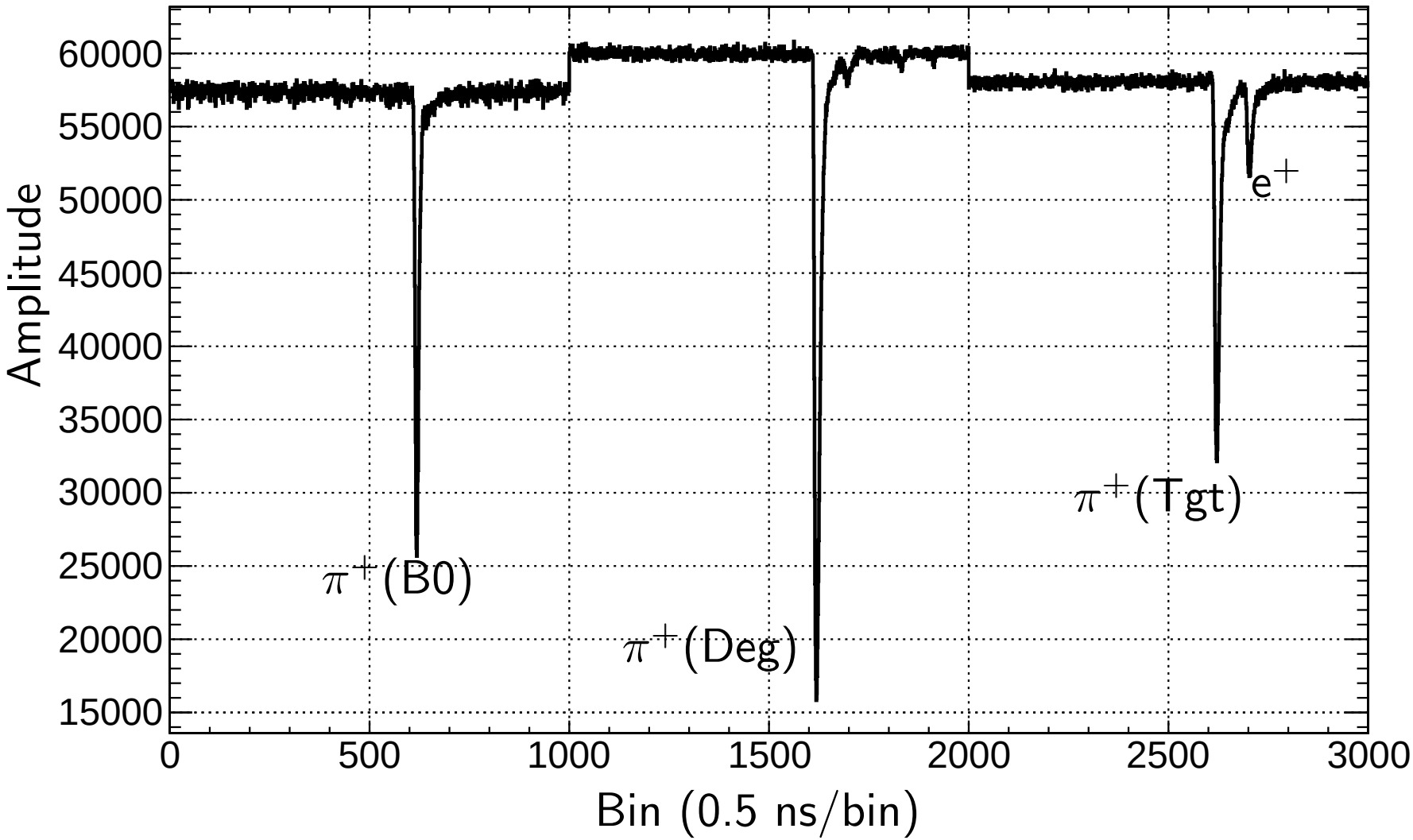
In the Experiment:

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

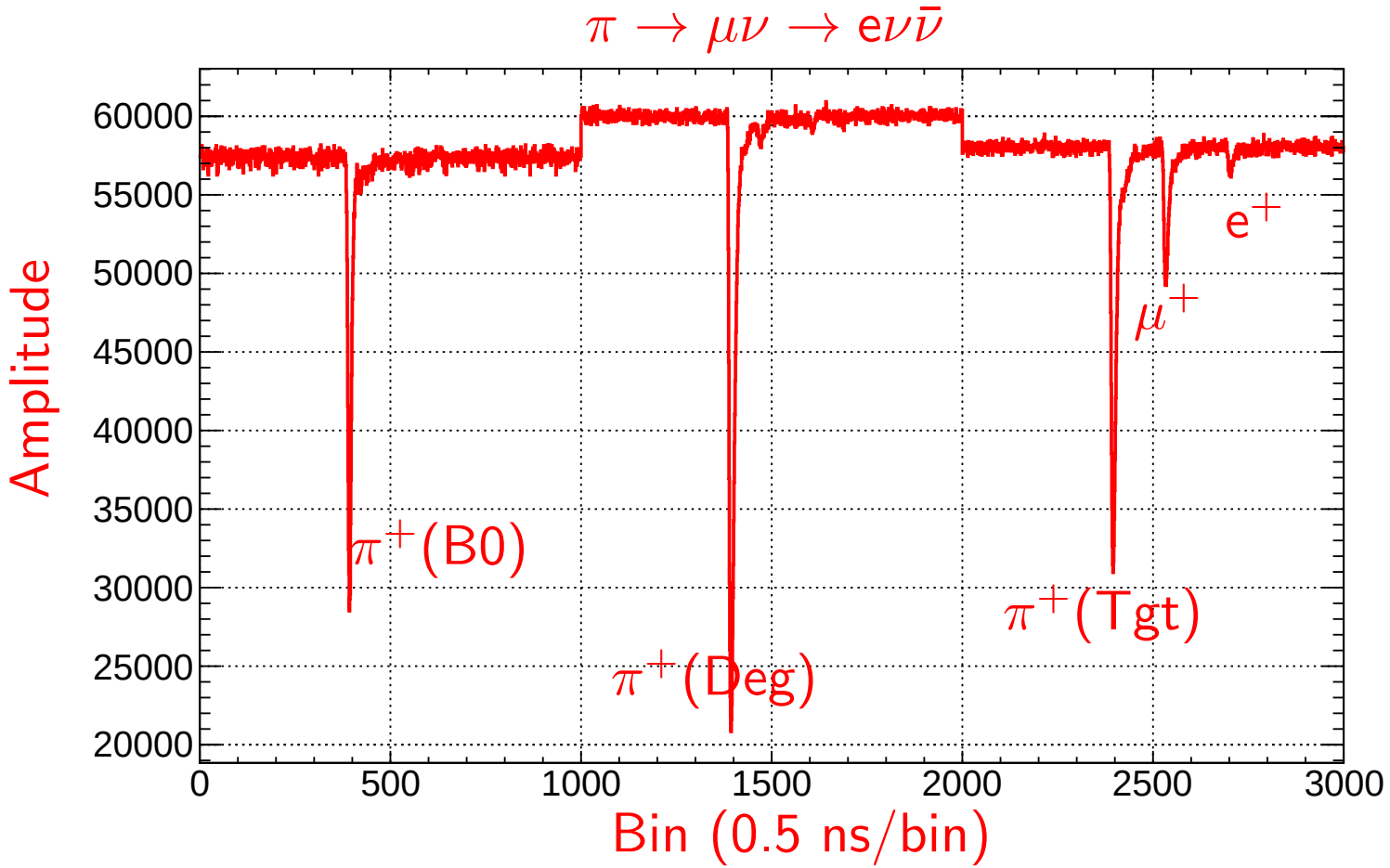




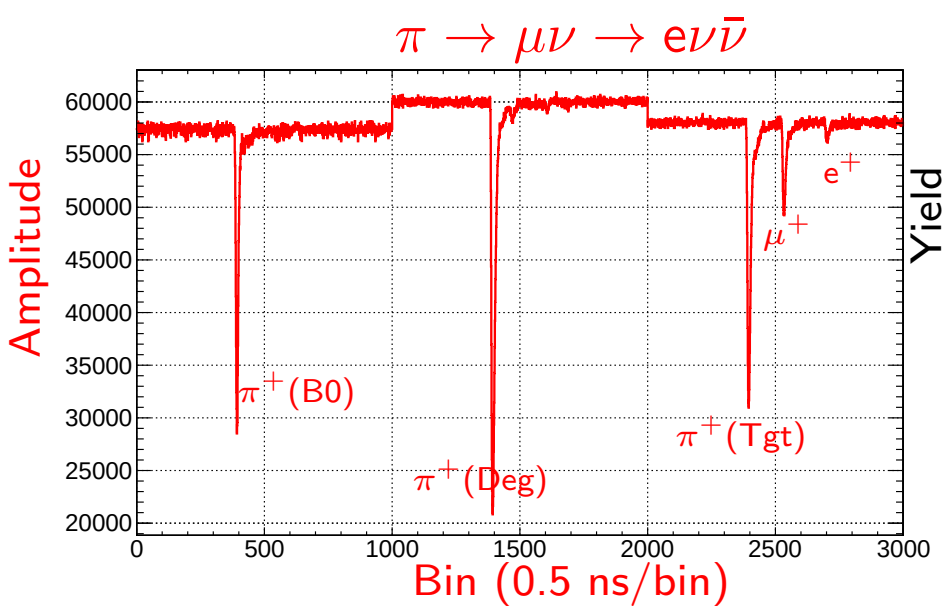
Digitizer Signals



Output


$\pi \to \mu\nu \to e\nu\bar{\nu}$
Amplitude
60000
55000
50000
45000
40000
35000
30000
25000
20000
0
500
1000
1500
2000
2500
3000
Bin (0.5 ns/bin)
π^+(B0)
π^+(Deg)
π^+(Tgt)
μ^+
e^+

Output


$\pi \rightarrow \mu\nu \rightarrow e\nu\bar{\nu}$
Amplitude
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π^+(B0)
π^+(Deg)
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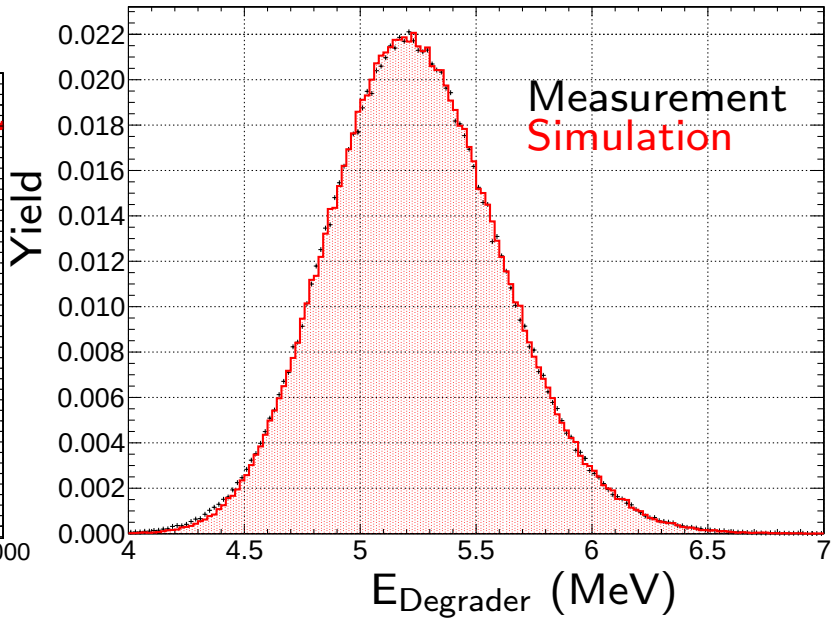
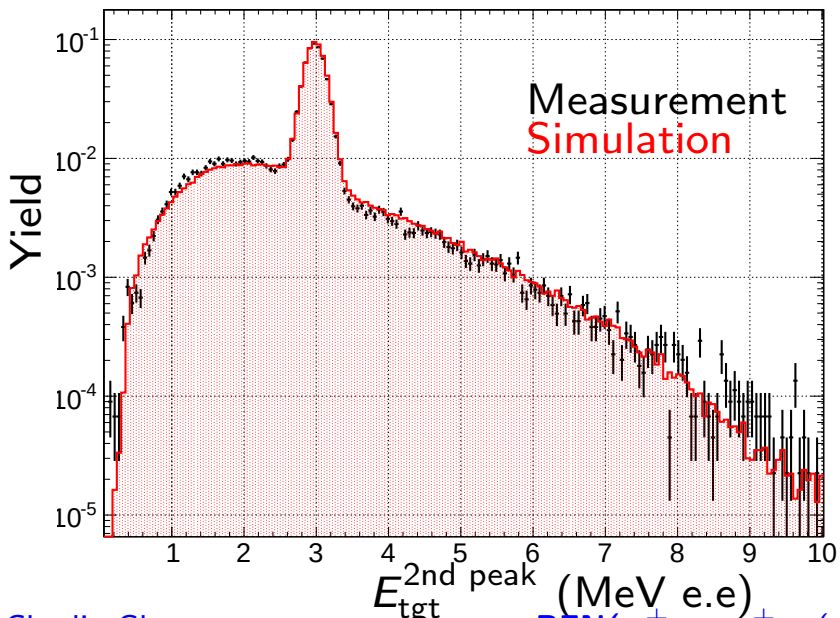
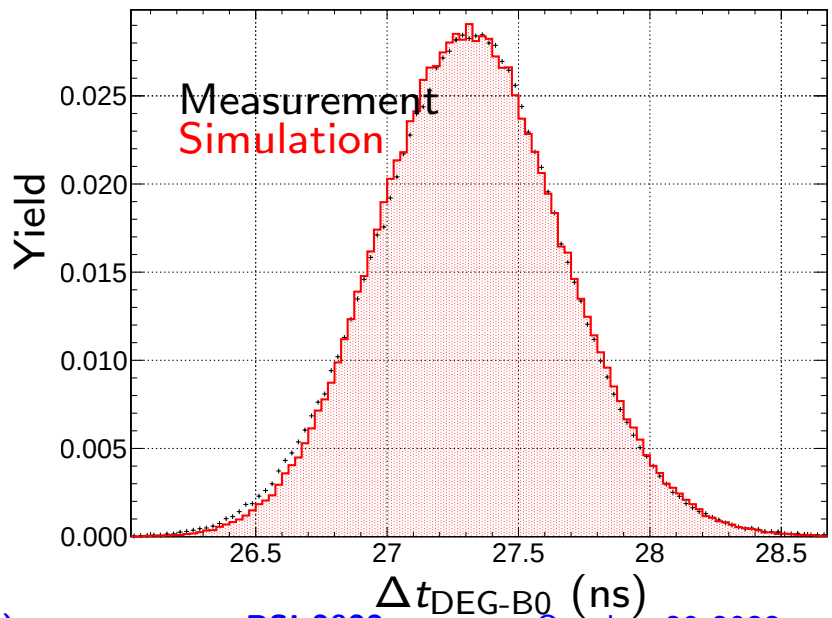
μ^+
e^+

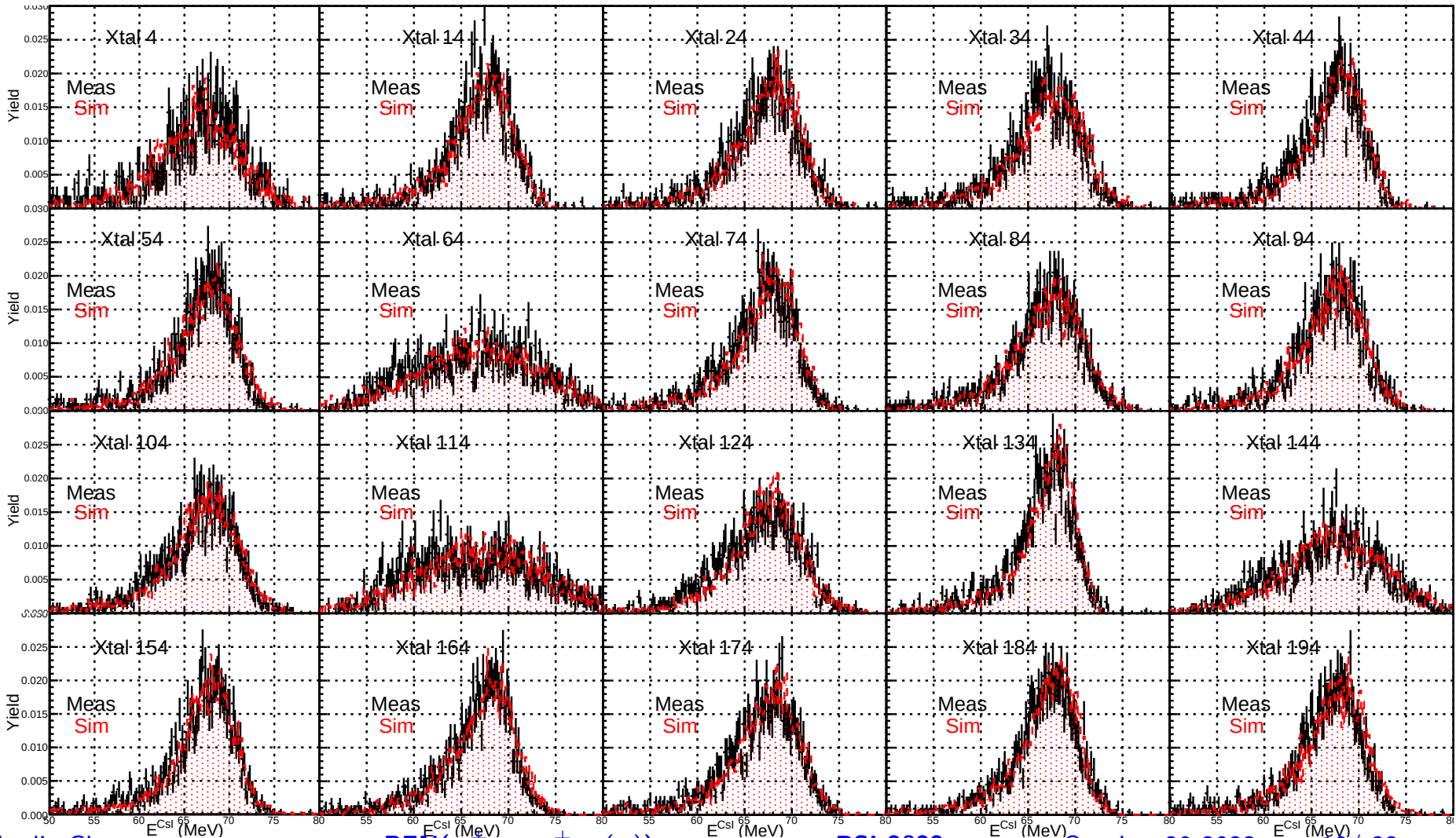

Measurement
Simulation
Yield
$E_{Degrader}$ (MeV)


Measurement
Simulation
Yield
$E_{tgt}^{2nd\ peak}$ (MeV e.e)

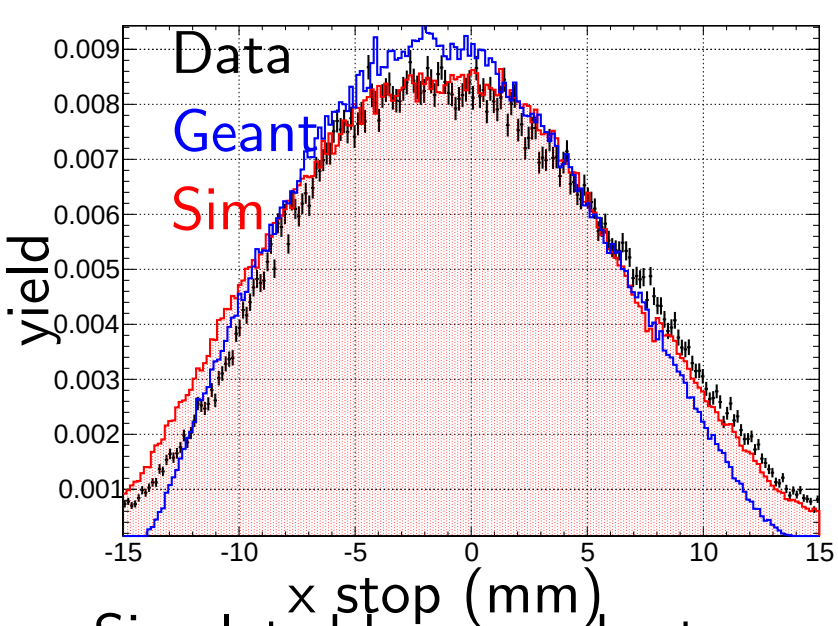

Measurement
Simulation
Yield
$\Delta t_{DEG\text{-}B0}$ (ns)

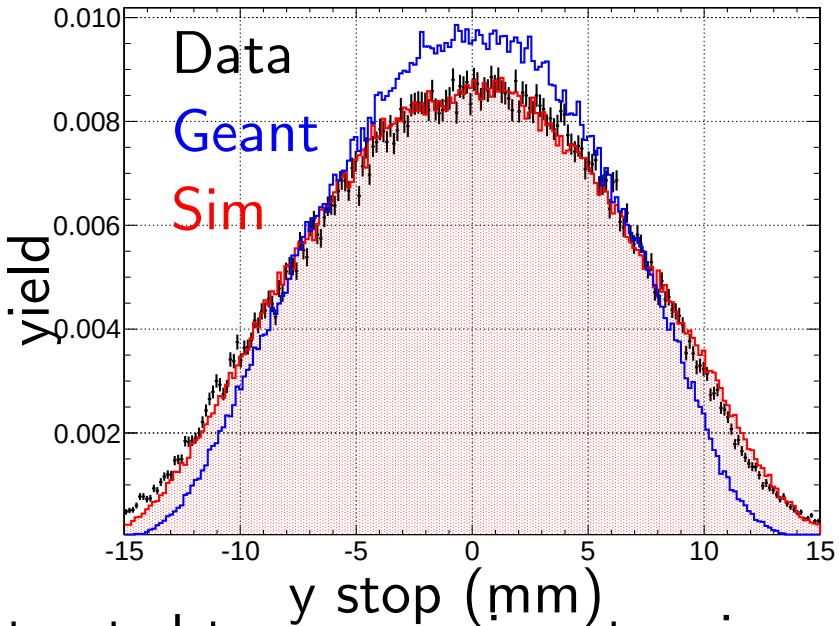
CsI Difficulties - Unique Xtals

- Optical and Response Non-uniformities, $\Delta\Omega$ Coverage
- 240 PMTs = 240 different quantum efficiencies



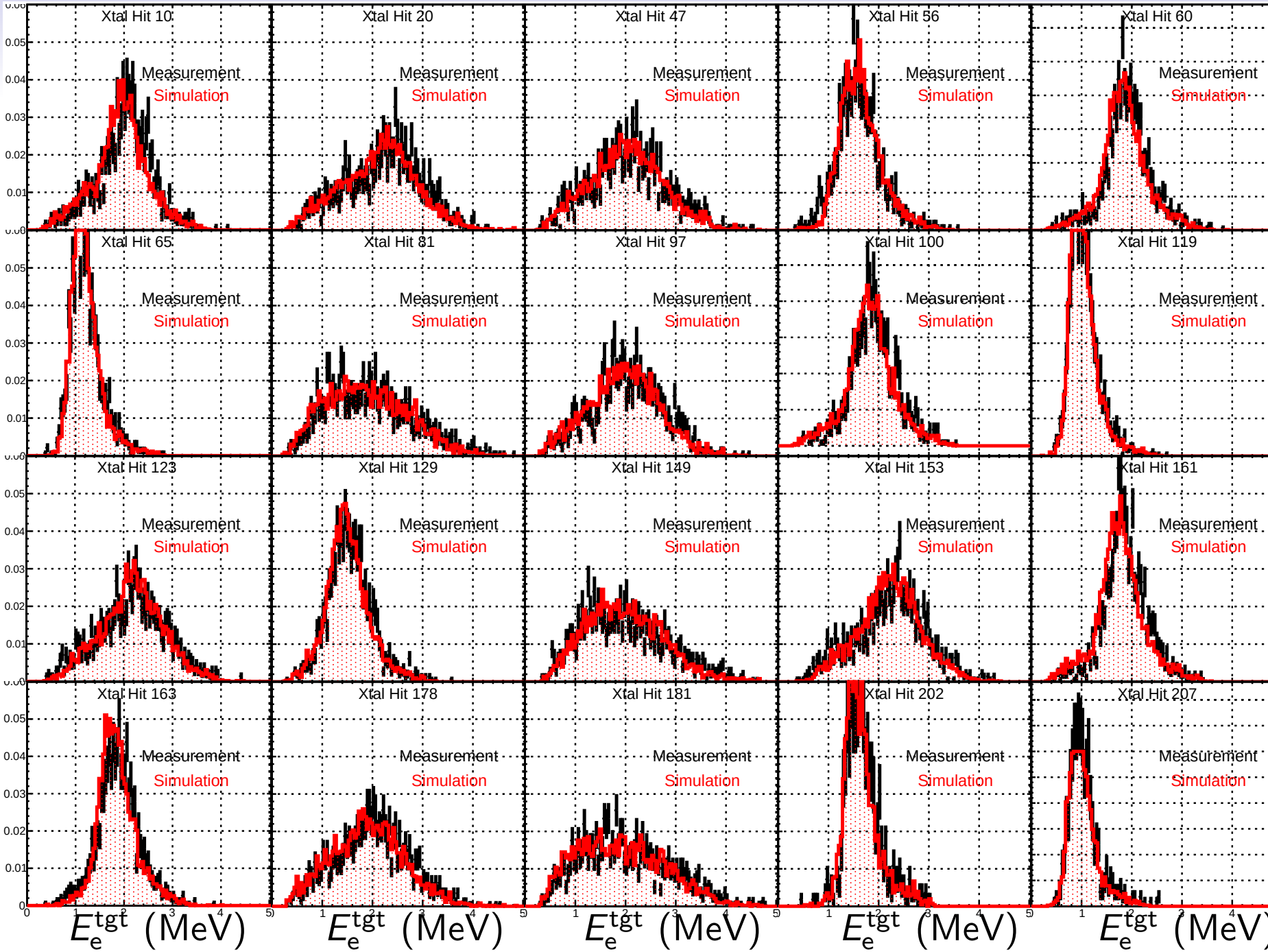
Correct stopping position



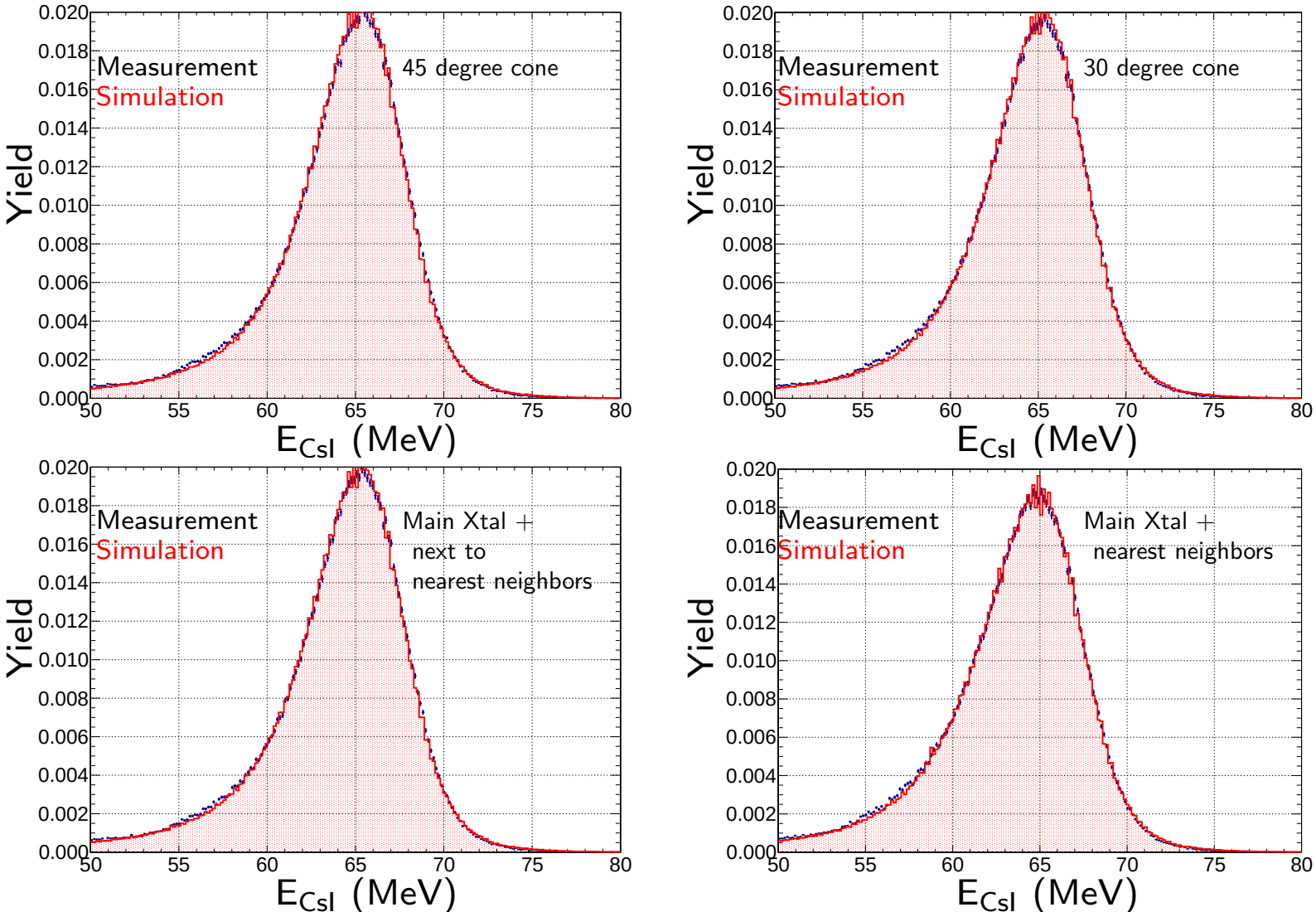


Simulated beam and mtpc constructed to ensure pion stopping positions consistent with data

Target energy deposition independent check

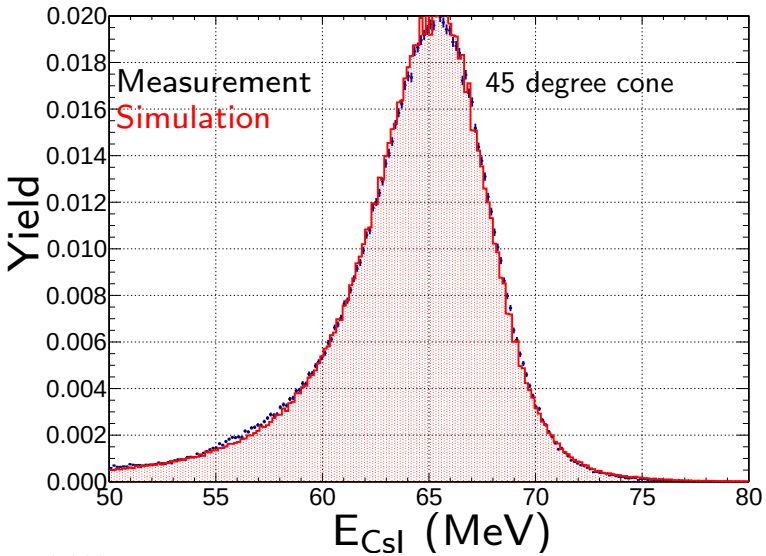

Xtal Hit 10
Xtal Hit 20
Xtal Hit 47
Xtal Hit 56
Xtal Hit 60
Xtal Hit 65
Xtal Hit 81
Xtal Hit 97
Xtal Hit 100
Xtal Hit 119
Xtal Hit 123
Xtal Hit 129
Xtal Hit 149
Xtal Hit 153
Xtal Hit 161
Xtal Hit 163
Xtal Hit 178
Xtal Hit 181
Xtal Hit 202
Xtal Hit 207
Measurement
Simulation
Yield
E_e^{tgt} (MeV)

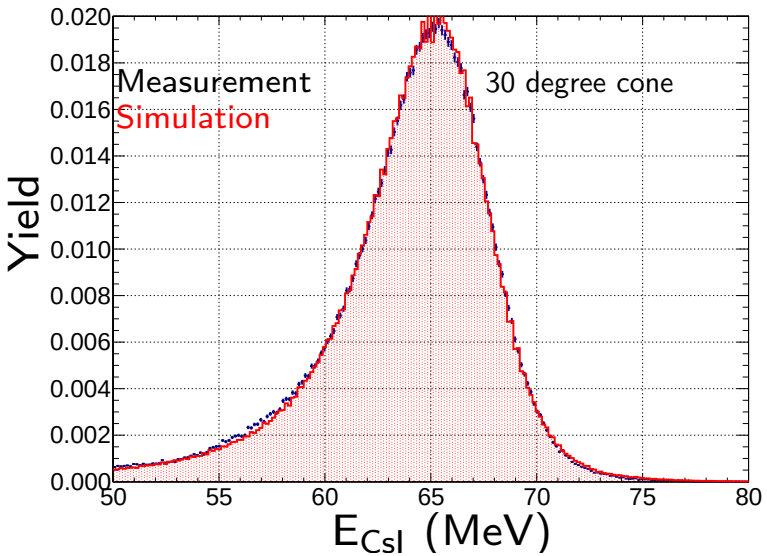
CsI

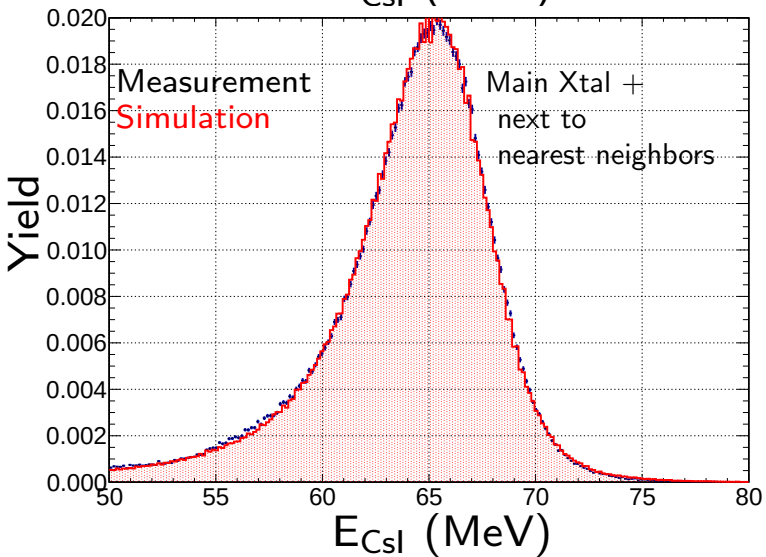


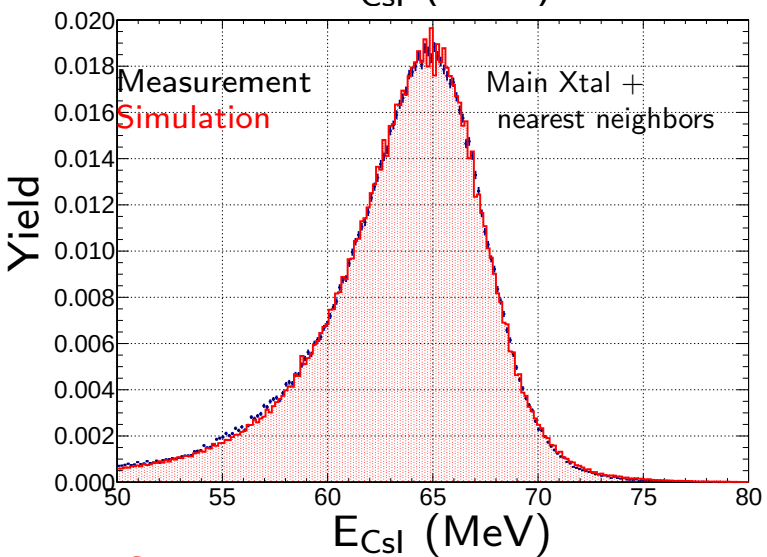
With proper inclusion of processes, such as photonuclear absorption, if all is good above 50 MeV

CsI



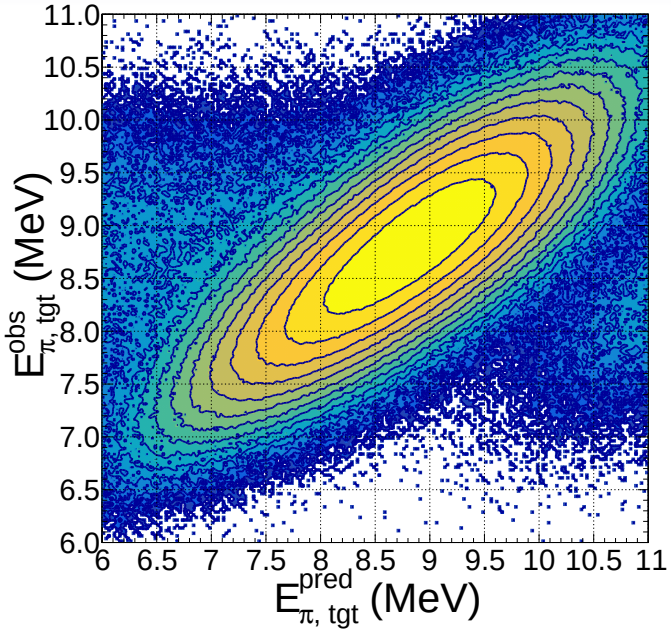


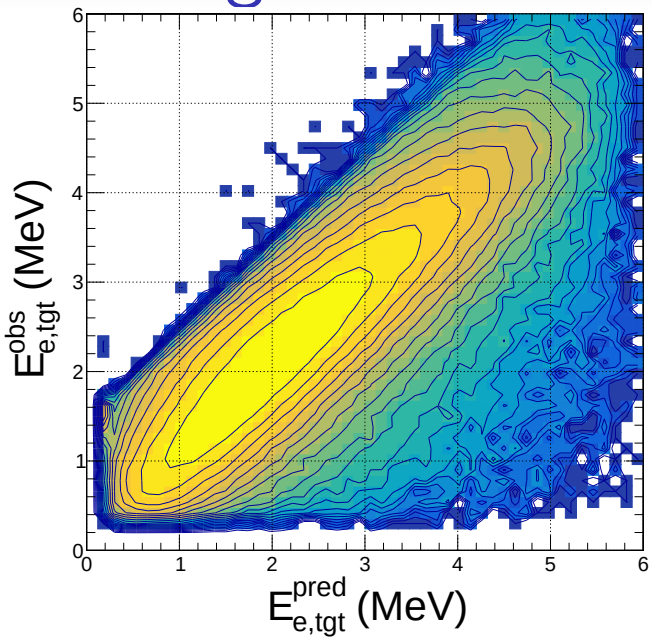


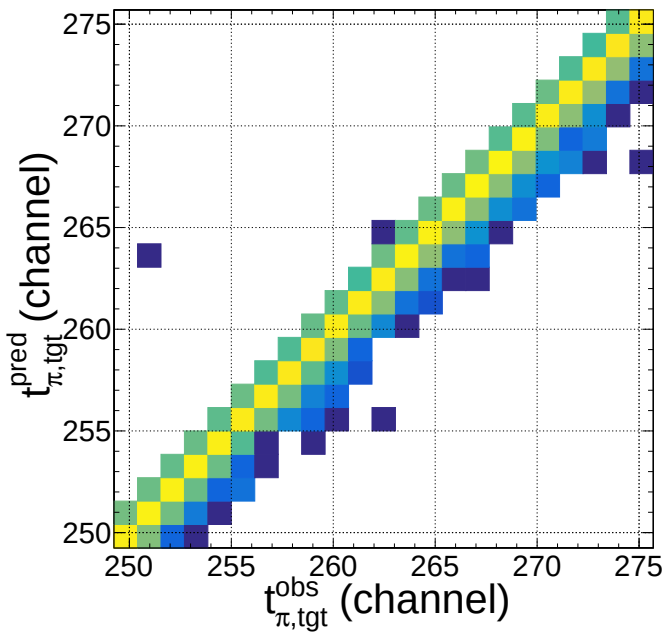


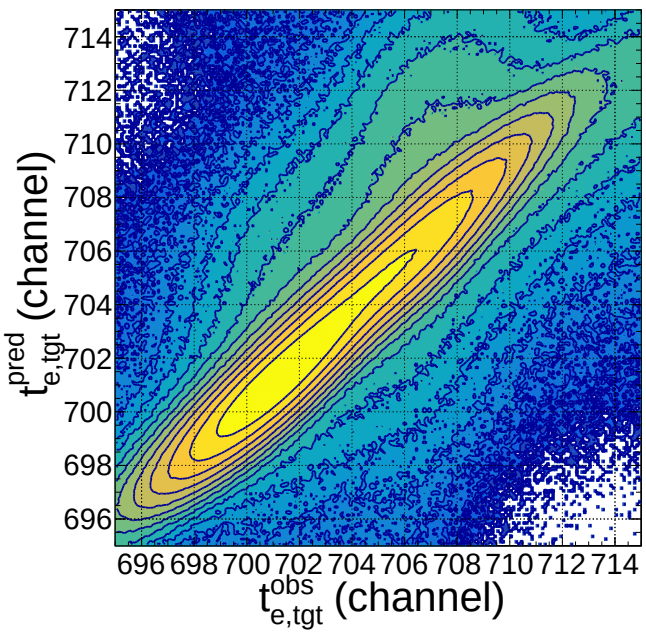
Tail-to-peak ratio falls out

Predicted and observed energies and timings







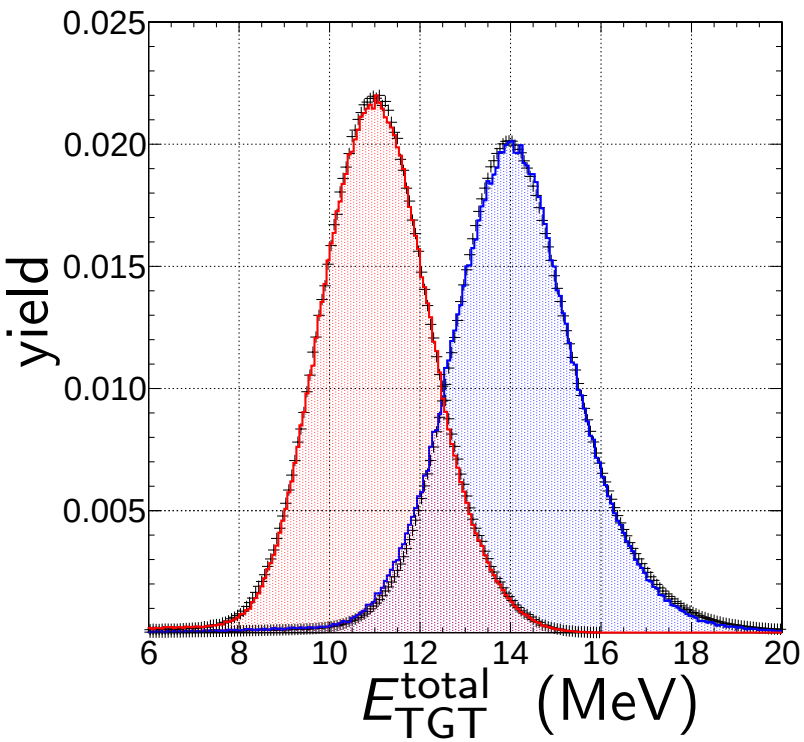


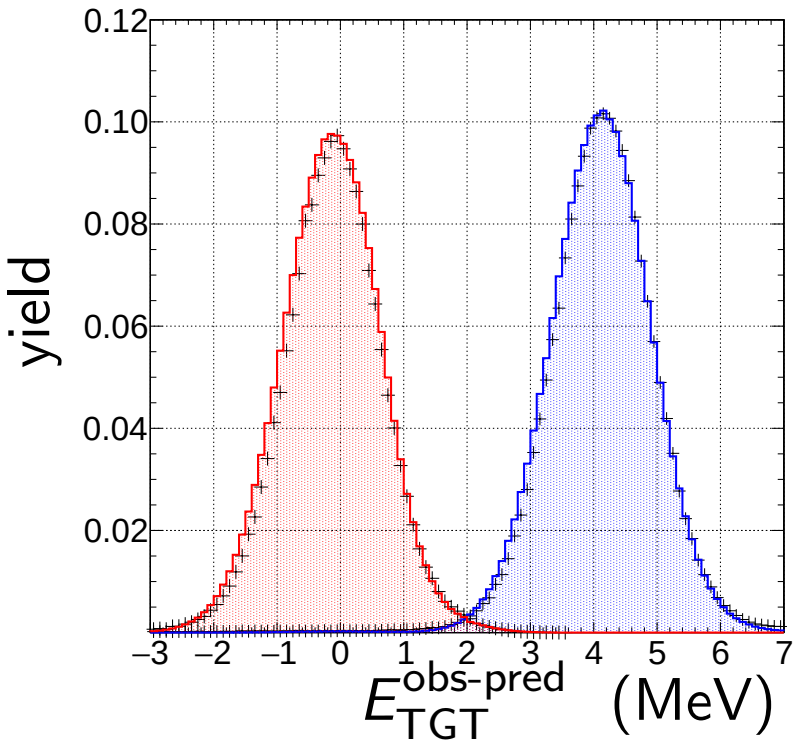
Discrimination

Measurement

$\pi \to \mu\nu(\gamma)$ Simulation

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





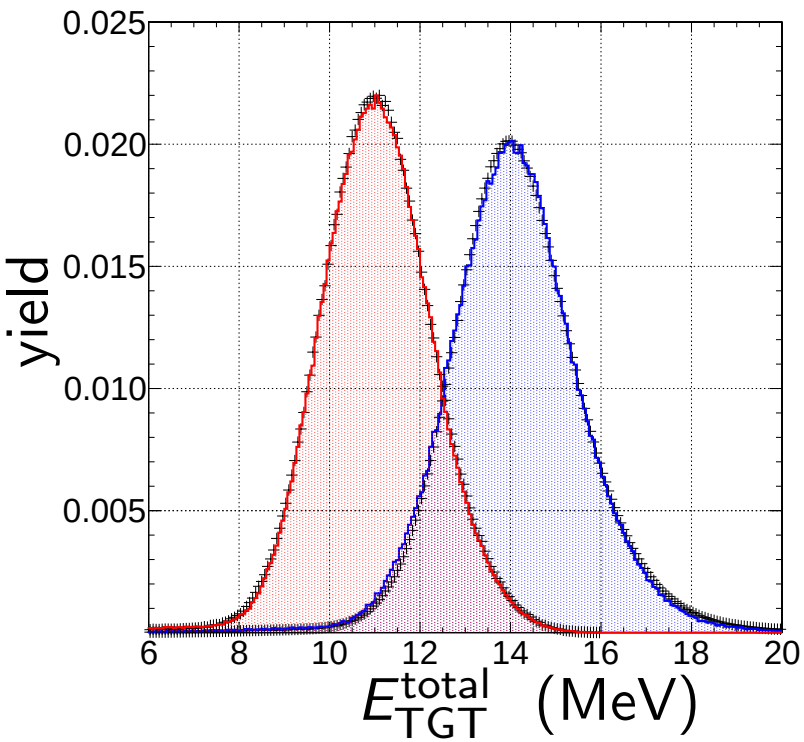
Energy predictions allow greater separation

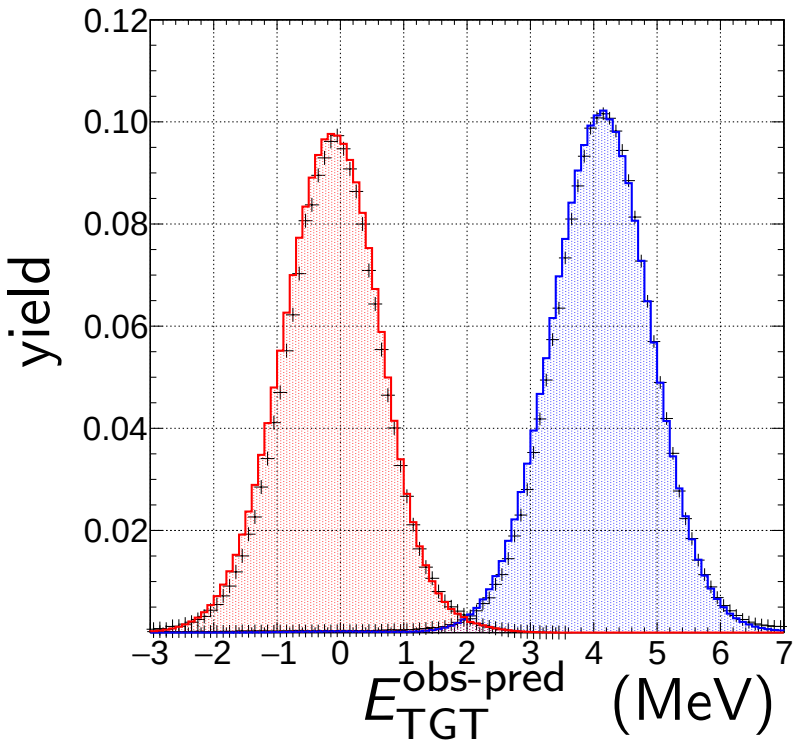
Discrimination

Measurement

$\pi \to \mu\nu(\gamma)$ Simulation

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

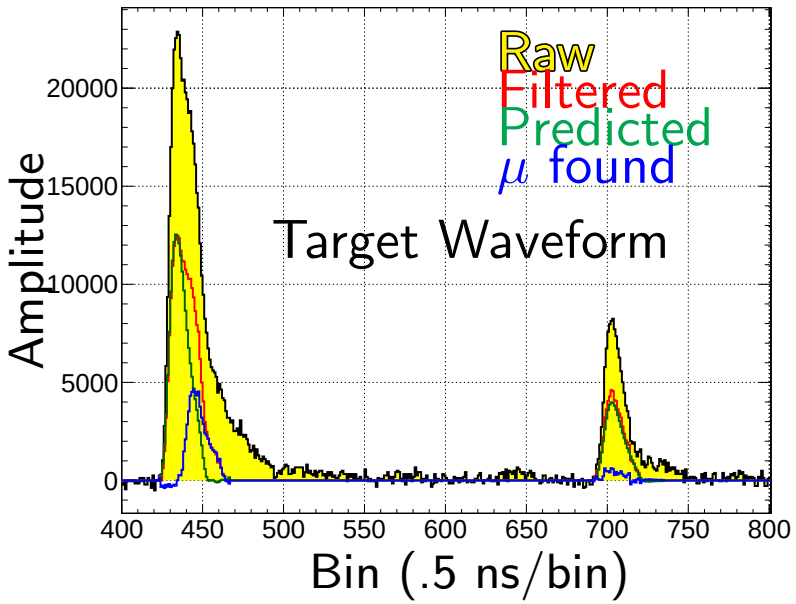


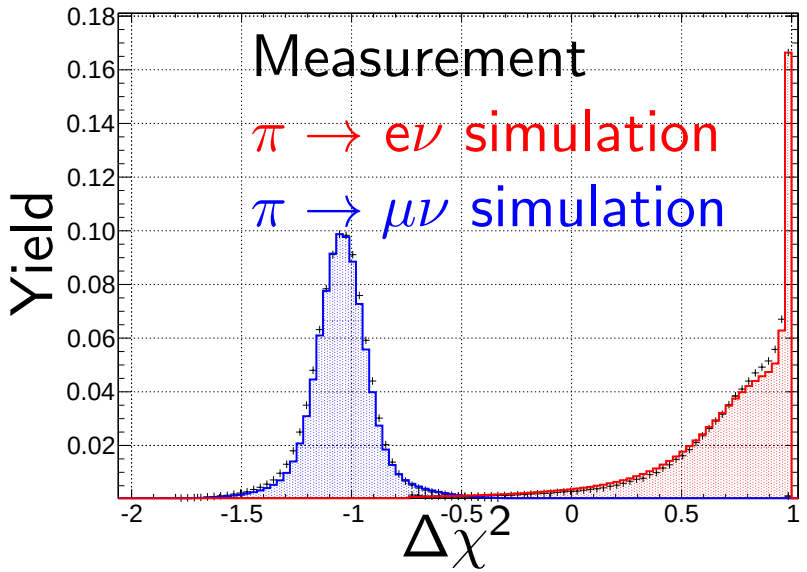


Energy predictions allow greater separation

But we can do better

Discrimination





Realistic Simulation

Higher Order Observables

Used for Acceptances and Tail

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

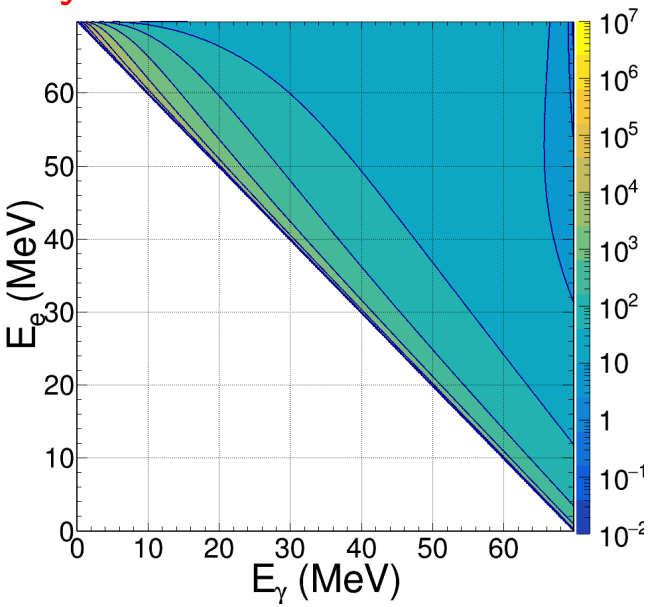
Look for 2 peak fit, take χ^2_2

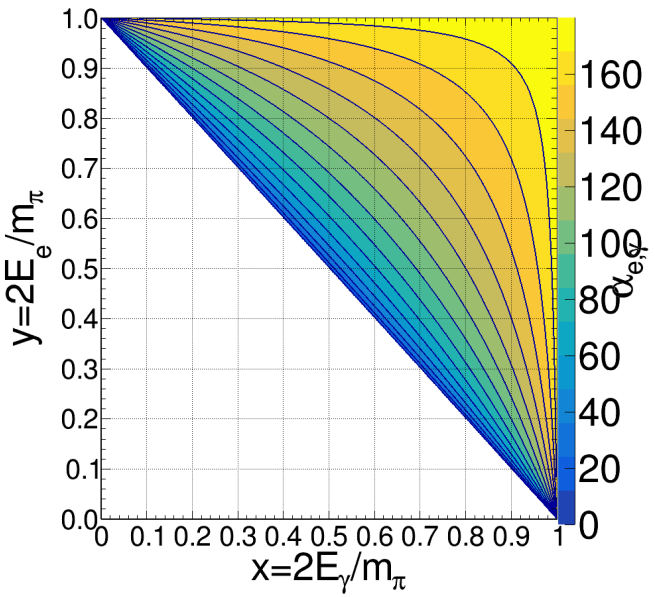
Look for 3 peak fit, takes χ^2_3

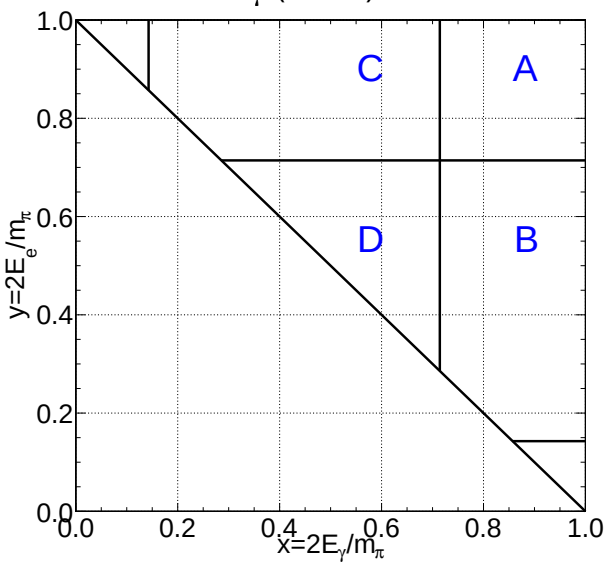
$\Delta\chi^2 = \chi^2_2 - \chi^2_3$ and Normalized

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

All decays are radiative



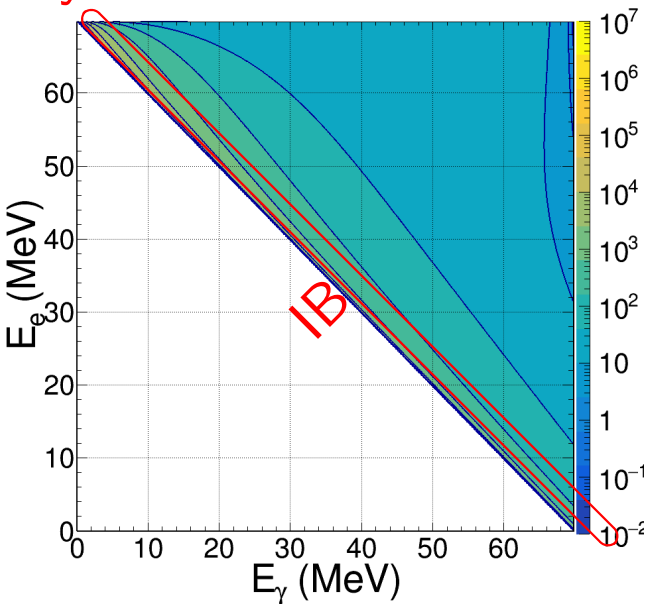


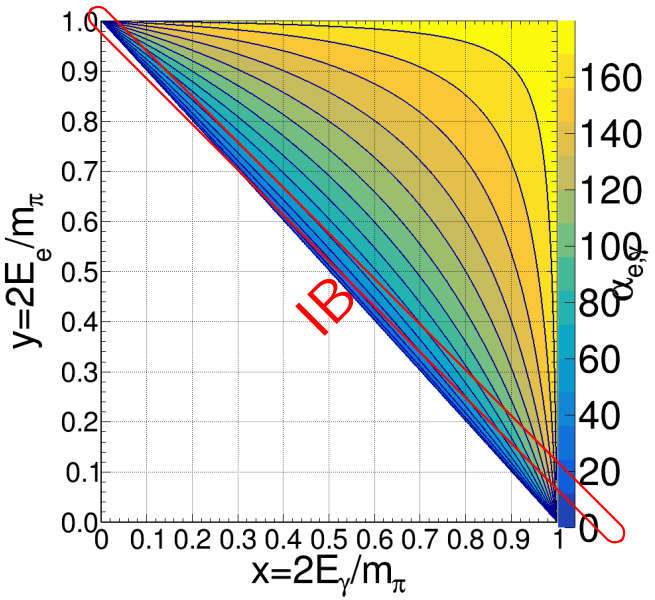


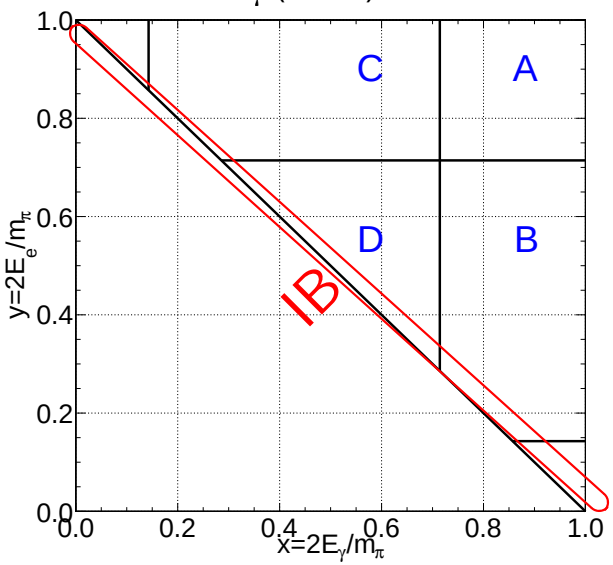
Phase space broken into regions

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

All decays are radiative



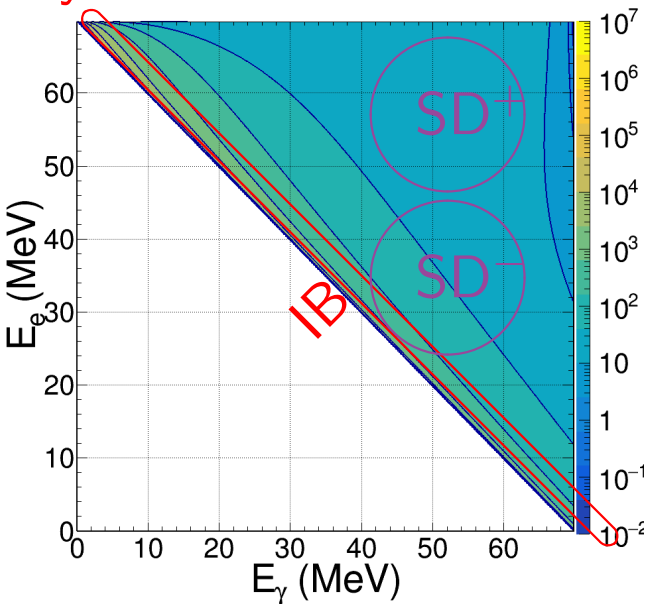


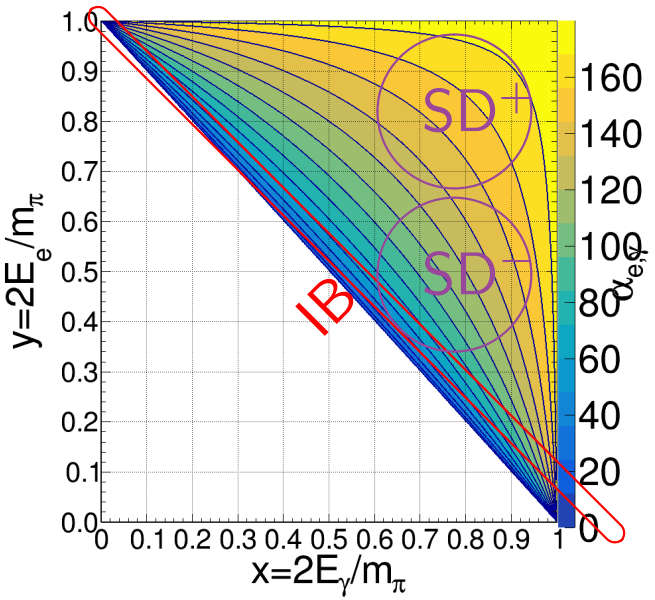


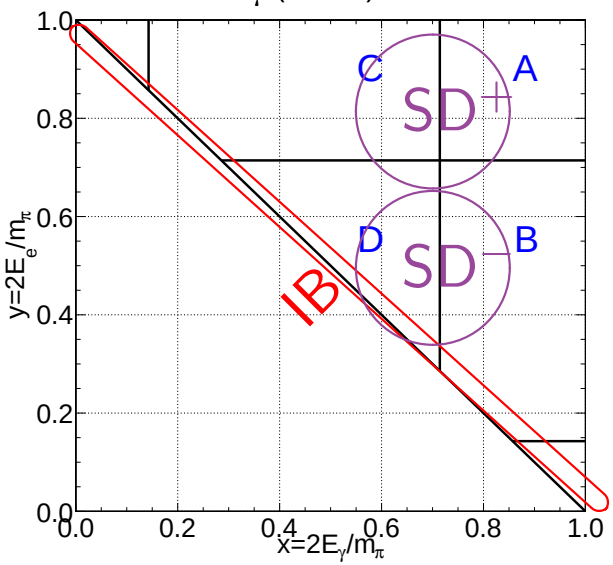
Inner Bremsstrahlung dominated

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

All decays are radiative



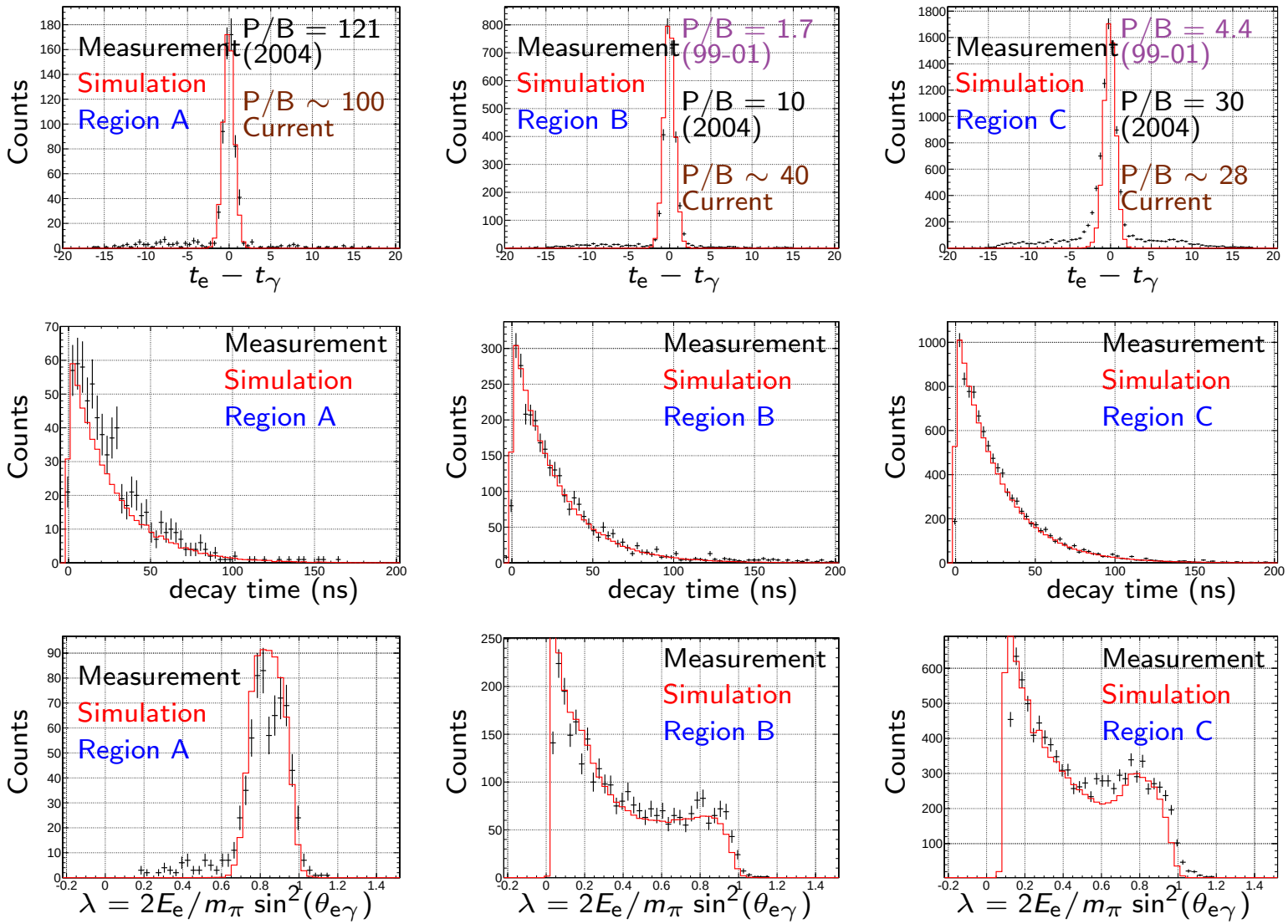




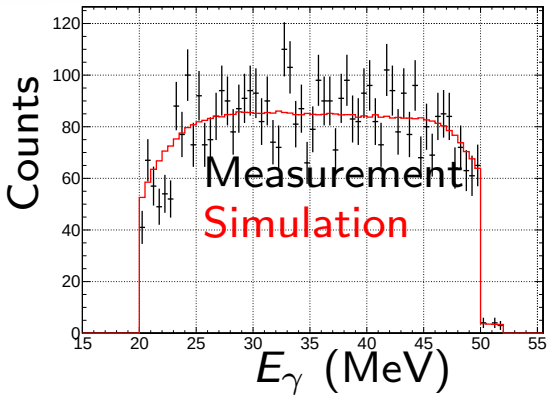
Inner Bremsstrahlung dominated

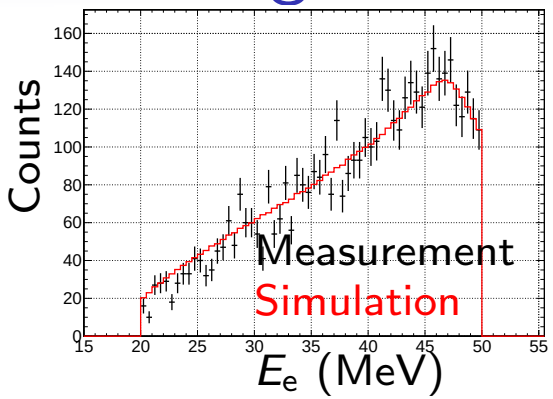
Structure Dependent
$SD^+ \sim (F_V + F_A)^2$
$SD^- \sim (F_V - F_A)^2$

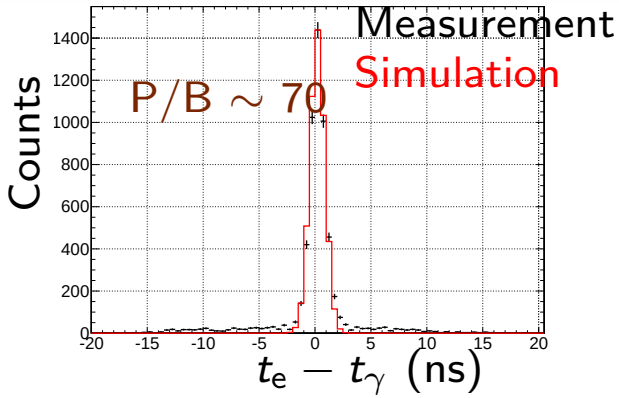
Radiative Decays $\pi \to e\nu\gamma$

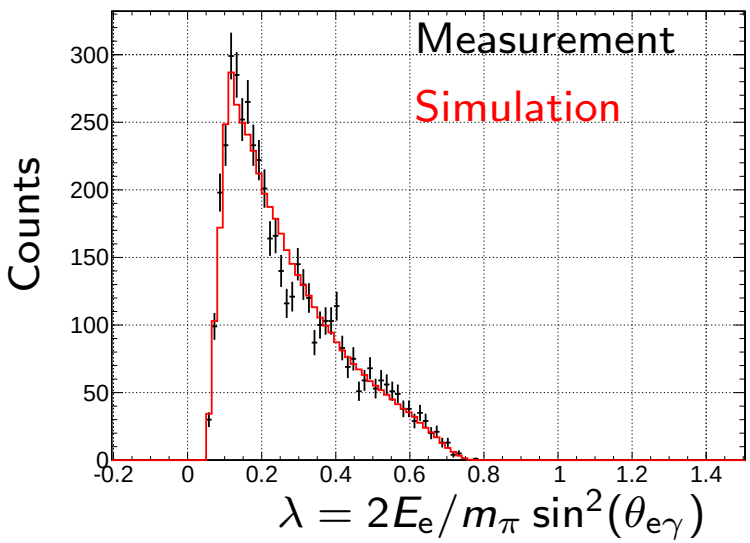


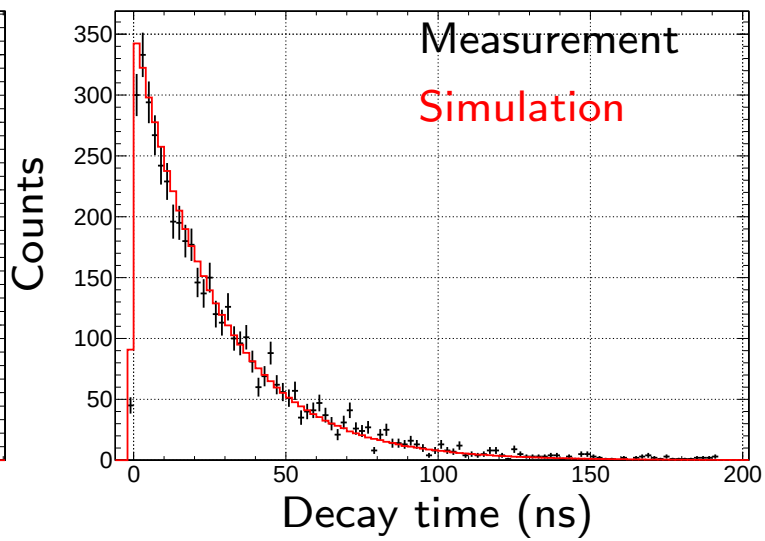
Region D





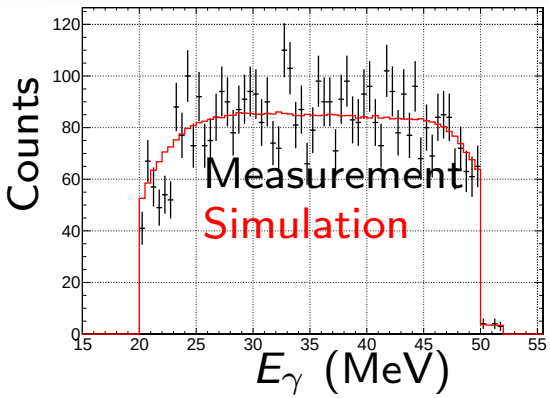


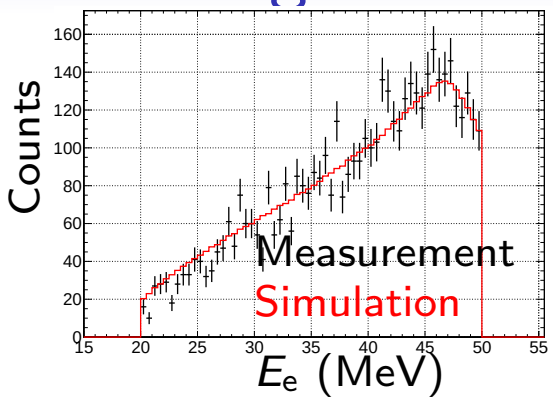


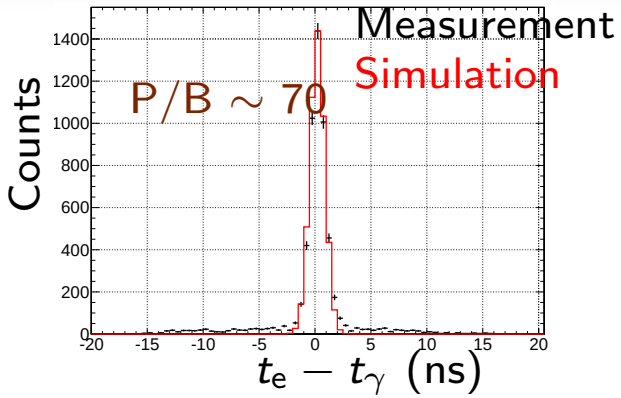


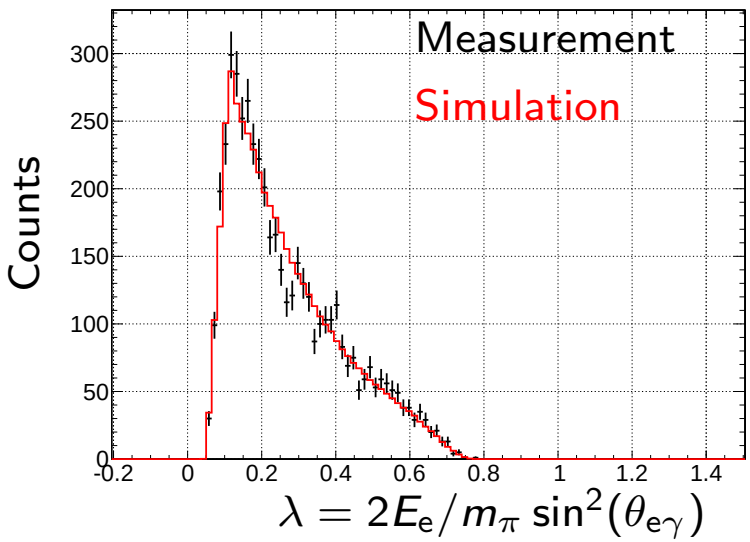
PEN is first to observe region D in detail

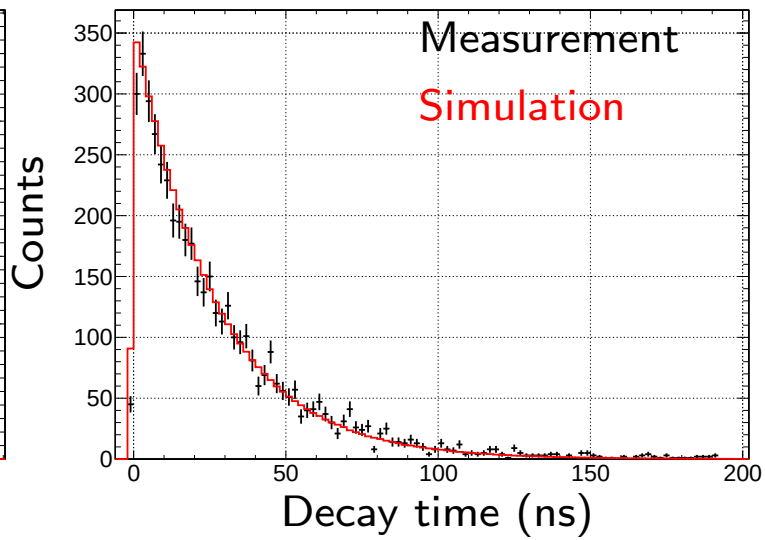
Region D





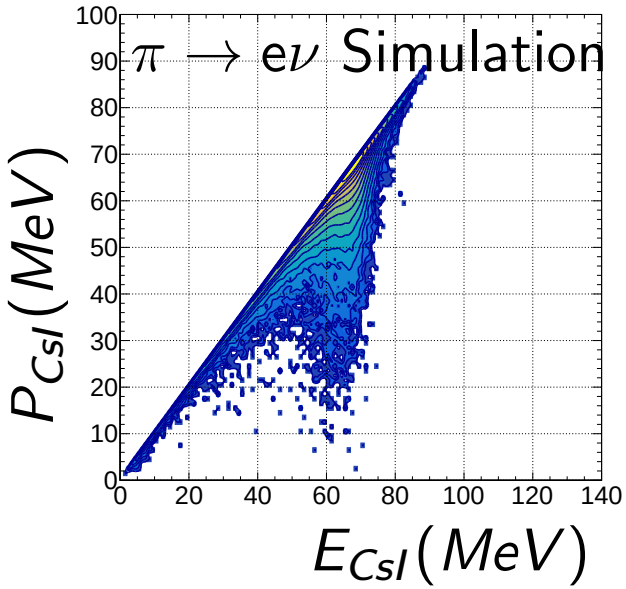






Take away: Can observe radiative decays. How to include in Branching Ratio?

Invariant Mass

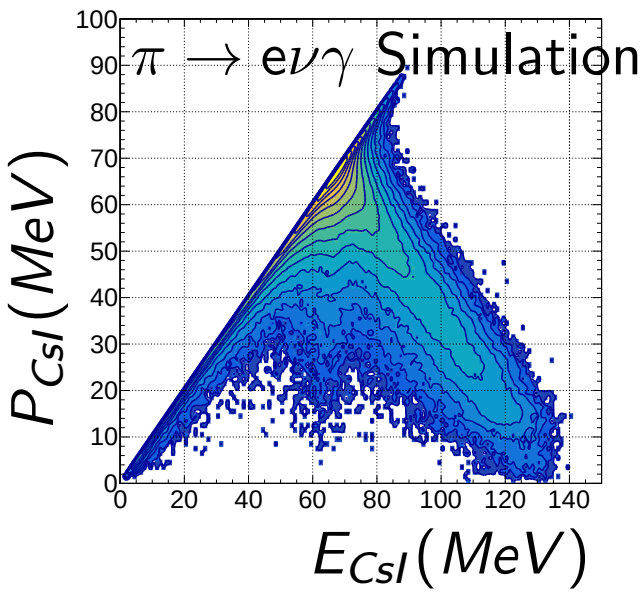


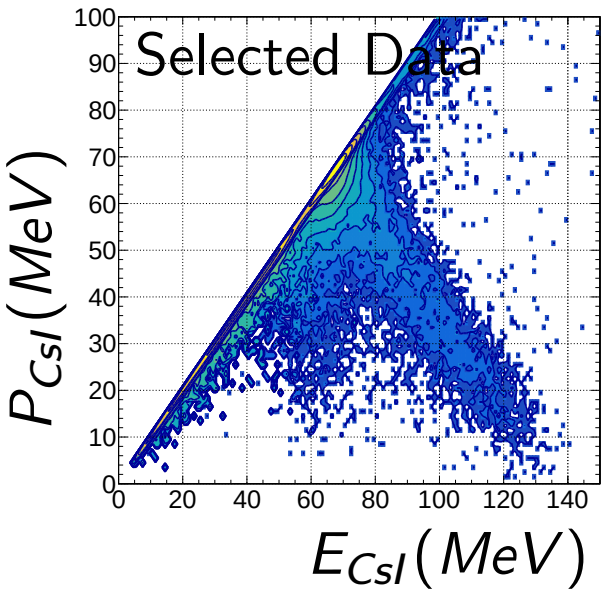
PEN indirectly measure p_ν

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

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

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





Branching ratio/uncertainties

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

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

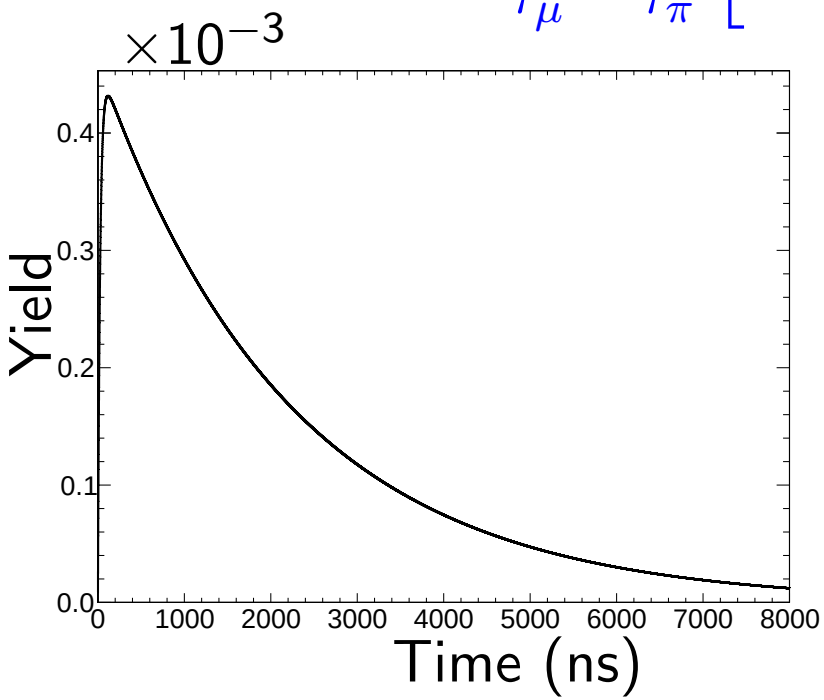
PEN goal: $\delta B/B \sim 5\times 10^{-4}$

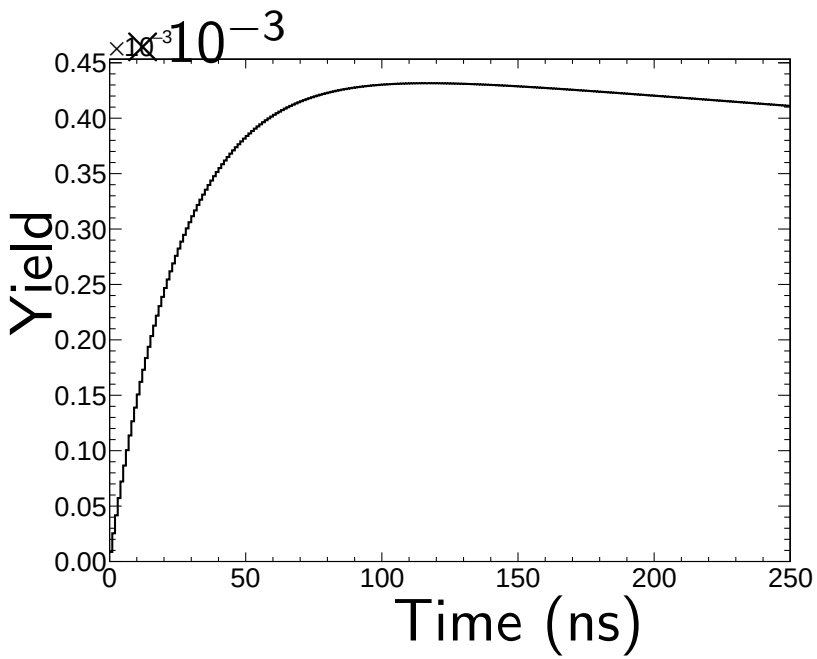
Choosing times, $f(t), \pi \to \mu \to \mathrm{e}$

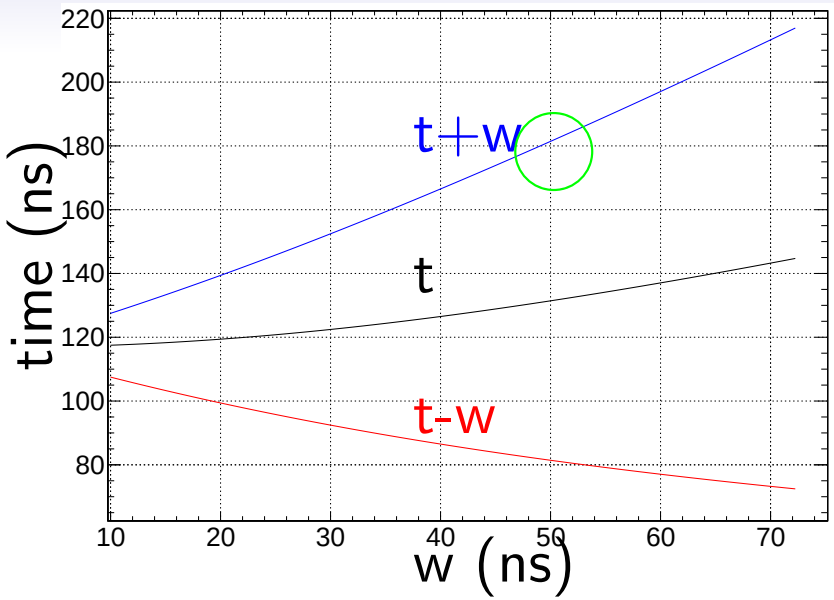
$\pi \to \mu \to \mathrm{e}$ ("Michel") timing selection: symmetric time window:

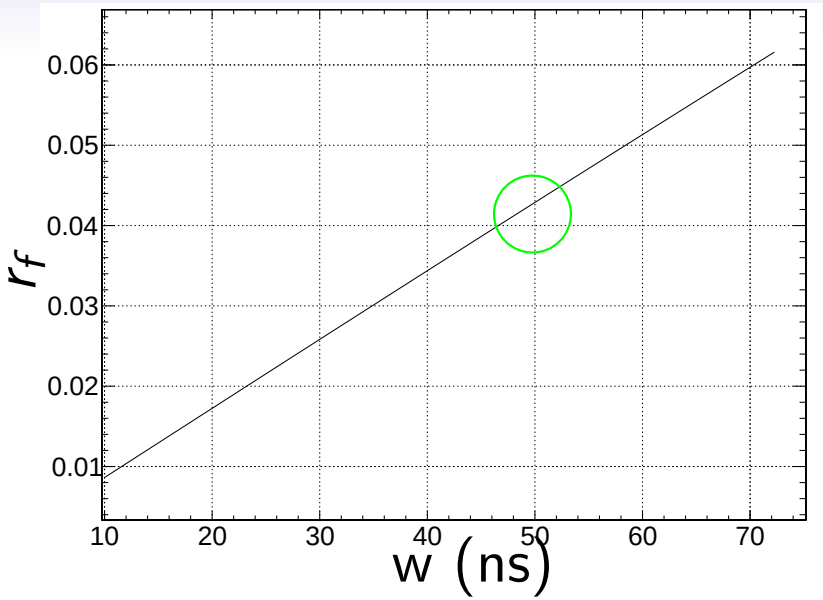
$$f_{\pi\to\mu\to\mathrm{e}} = \int_0^t f_{\pi\to\mu}(t-t')f_{\pi\to e}(t')dt' = \frac{1}{\tau_\mu - \tau_\pi}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right)$$

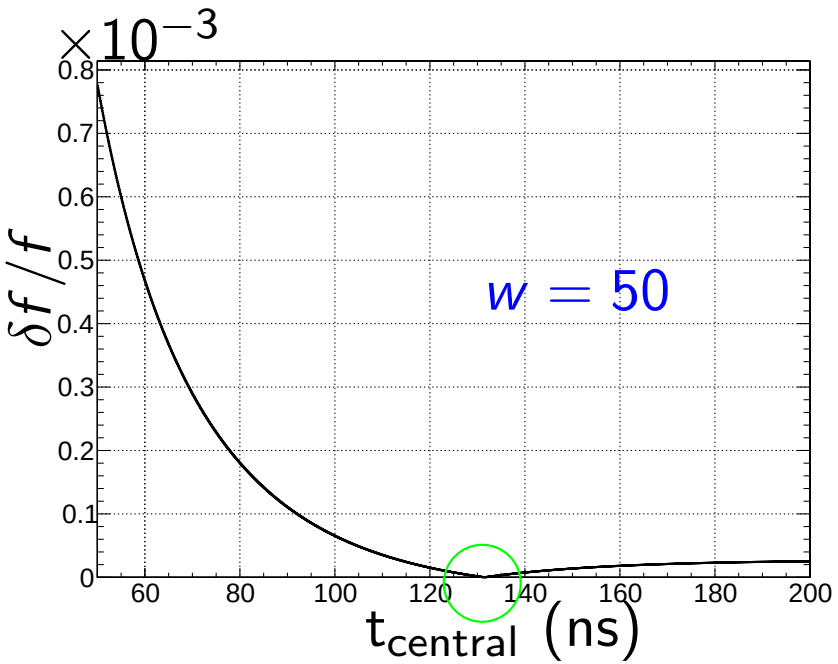
$$\left|f_{\pi\to\mu\to\mathrm{e}}\right|_{t-w}^{t+w} = \frac{2}{\tau_\mu - \tau_\pi}\left[\tau_\mu e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - \tau_\pi e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right]$$











Pen $t \sim$ -50 to 220 ns

200 ns, trigger (in)efficiencies

Large enough statistics

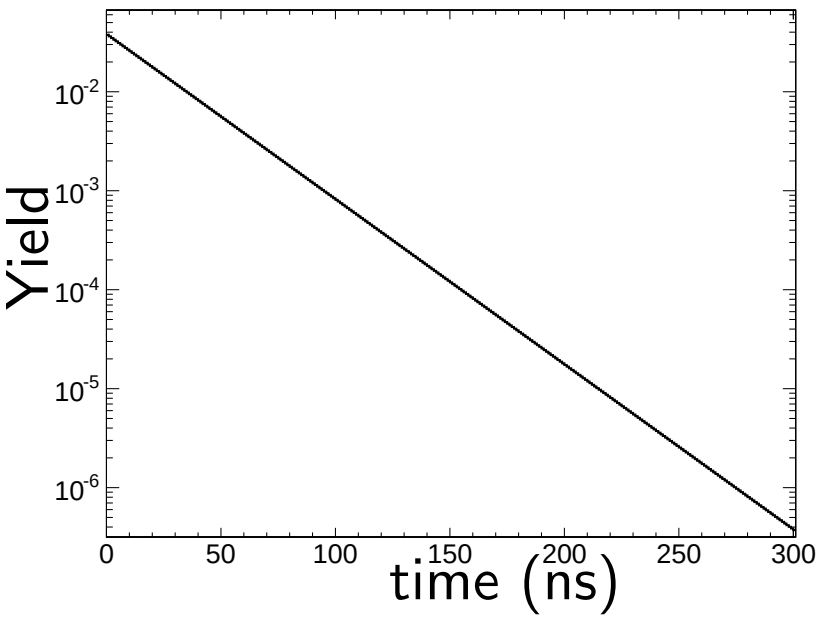
Minimize $\delta f/f$

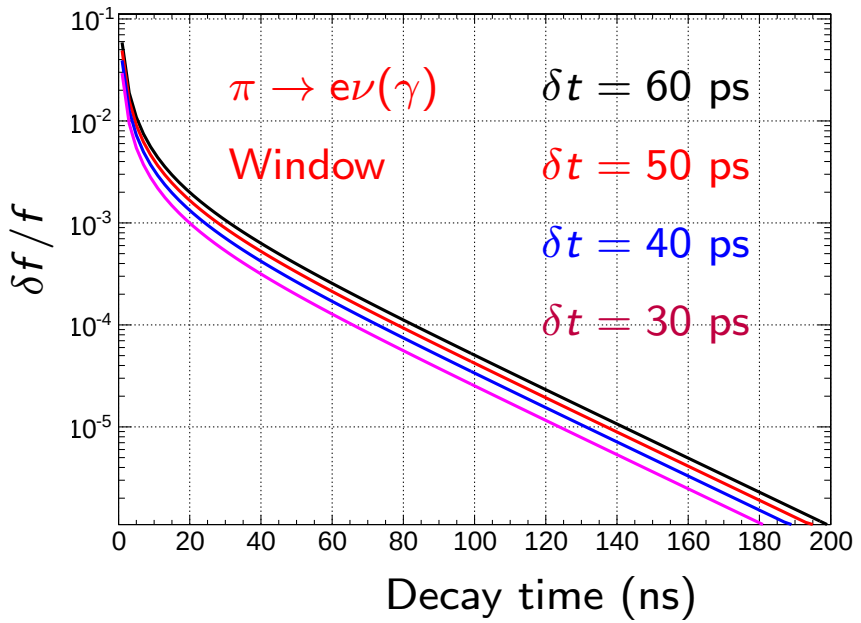
Choosing times, $f(t)$, $\pi \to e\nu(\gamma)$

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

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

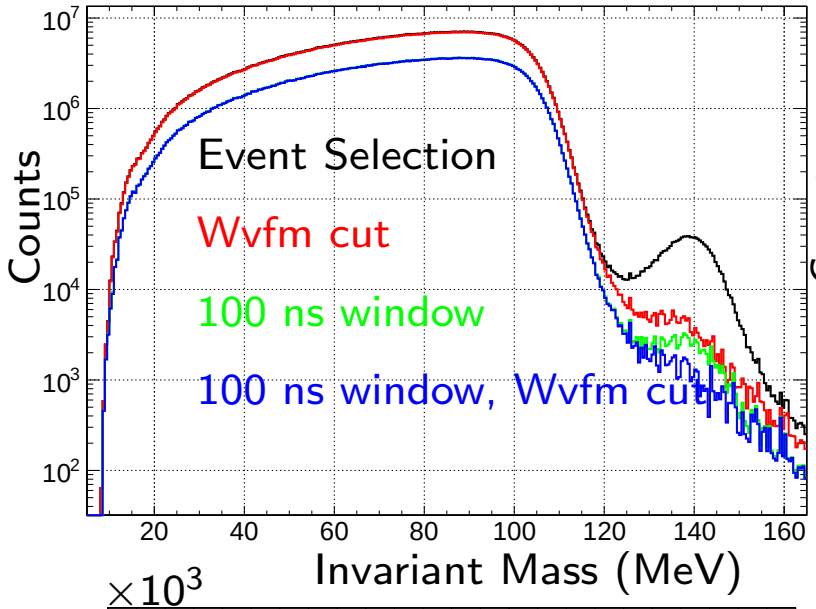
Choose $t_1 < 0$: $\delta f_{\pi\to e\nu} = \frac{\delta t}{\tau_\pi} e^{-t_2/\tau_\pi}$

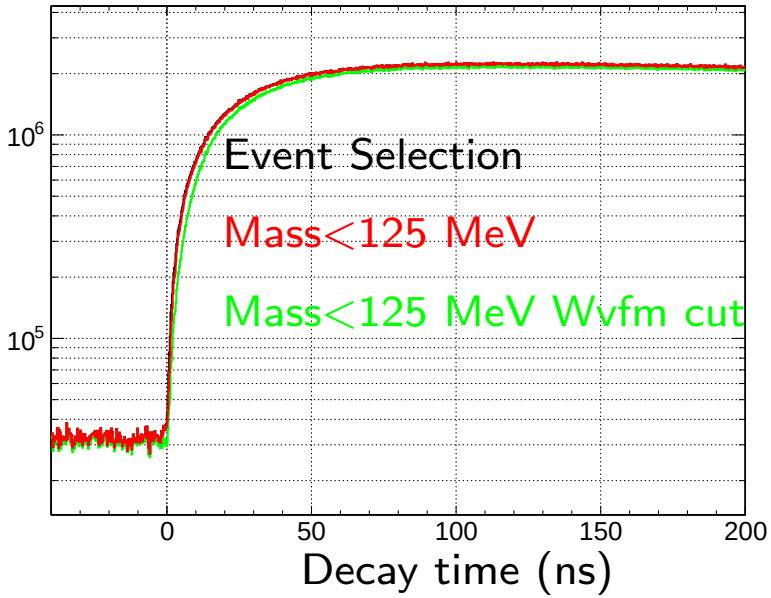


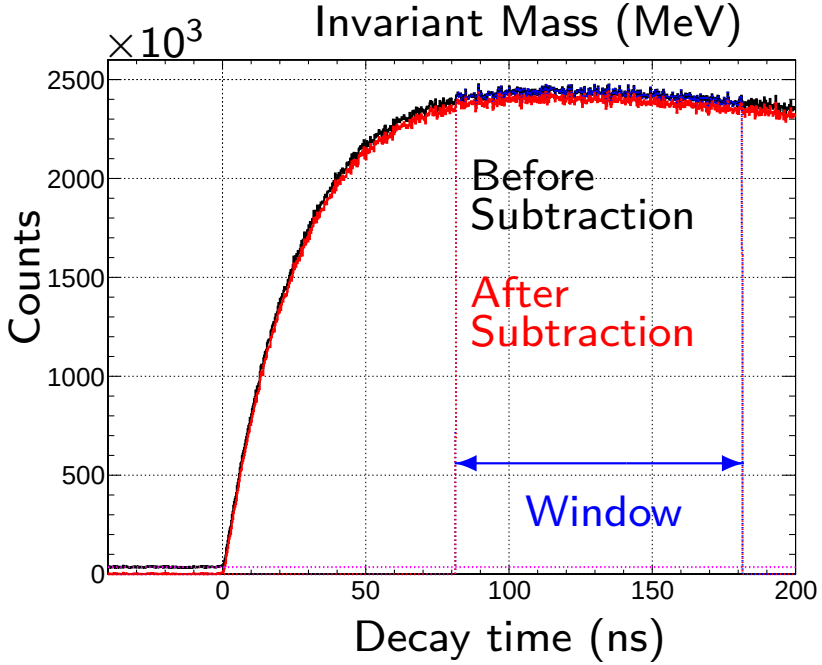


$\delta f/f$ negligible for $t_2 \geq 90$ ns

Number Michels

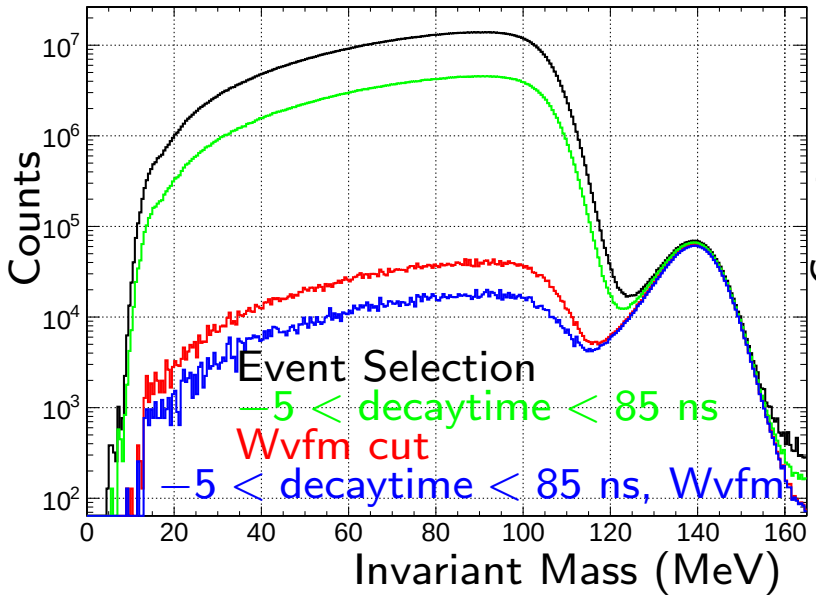


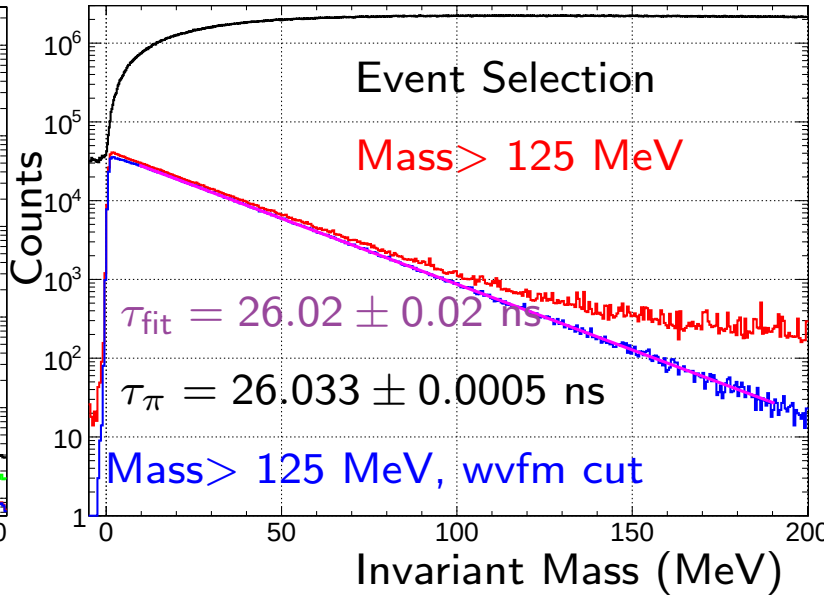




$$N_{\text{michel,run 2}} = (5225.68 \pm 0.23) \times 10^5$$
$$N_{\text{michel, run 3}} = (9545.50 \pm 0.33) \times 10^5$$
$$\delta N_{\text{michel,run 2}} / N_{\text{michel,run 2}} = 4.4 \times 10^{-5}$$
$$\delta N_{\text{michel,run 3}} / N_{\text{michel,run 3}} = 3.5 \times 10^{-5}$$

Number of $\pi \to e\nu$

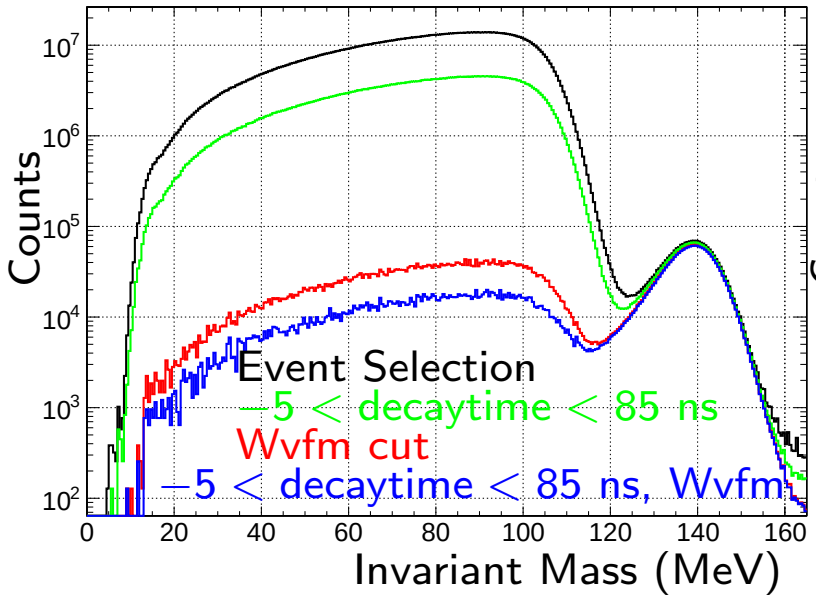


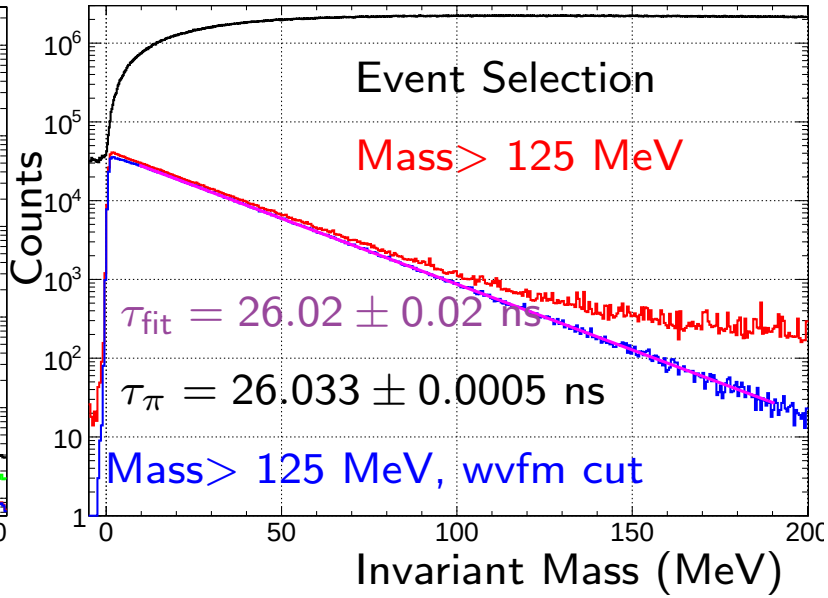


Wvfm cut is needed.

$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (1409.33 \pm 1.18) \times 10^3$$
$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (2413.81 \pm 1.63) \times 10^3$$
$$\delta N_{\pi\to e\nu(\gamma),\text{run 2}} / N_{\pi\to e\nu(\gamma),\text{run 2}} = 8.50 \times 10^{-4}$$
$$\delta N_{\pi\to e\nu(\gamma),\text{run 3}} / N_{\pi\to e\nu(\gamma),\text{run 3}} = 6.49 \times 10^{-4}$$

Number of $\pi \to e\nu$



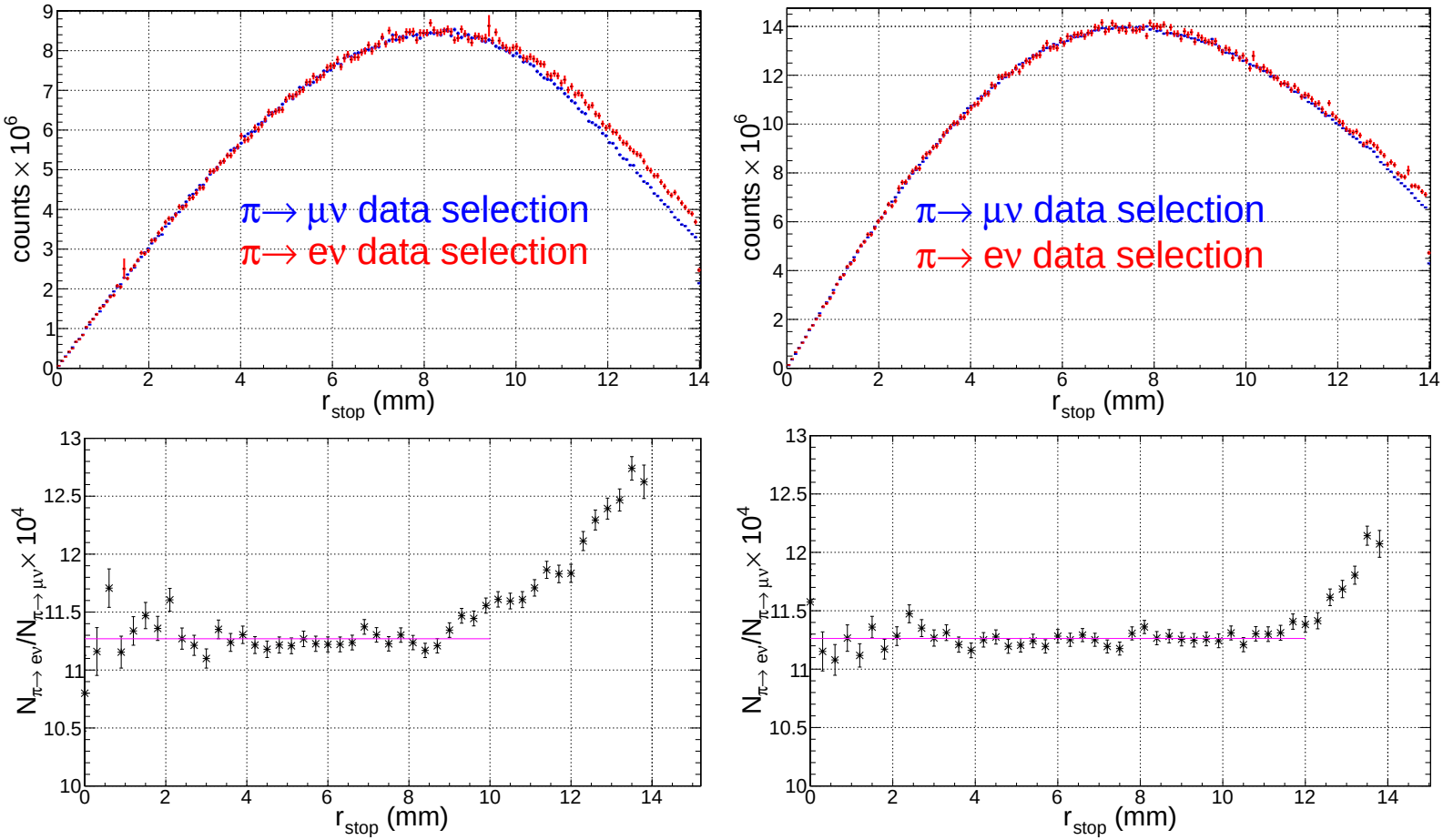


Wvfm cut is needed.

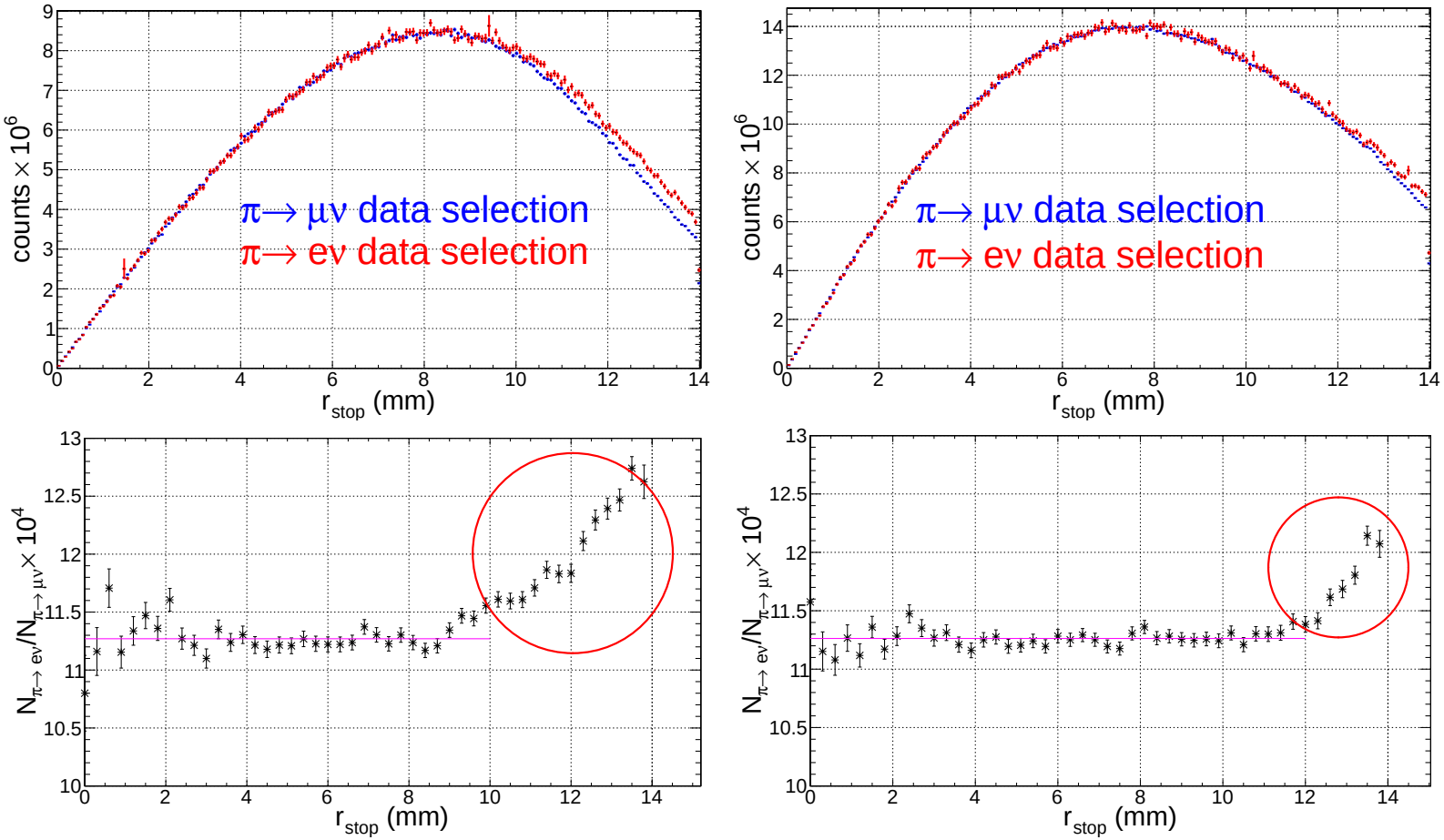
$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (1409.33 \pm 1.18) \times 10^3$$
$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (2413.81 \pm 1.63) \times 10^3$$
$$\delta N_{\pi\to e\nu(\gamma),\text{run 2}} / N_{\pi\to e\nu(\gamma),\text{run 2}} = 8.50 \times 10^{-4}$$
$$\delta N_{\pi\to e\nu(\gamma),\text{run 3}} / N_{\pi\to e\nu(\gamma),\text{run 3}} = 6.49 \times 10^{-4}$$

$$\delta N_{\pi\to e\nu(\gamma)} / N_{\pi\to e\nu(\gamma)} = 5.26 \times 10^{-4} \text{ (GOAL: } 5 \times 10^{-4})$$

Energy requirement at positron birth



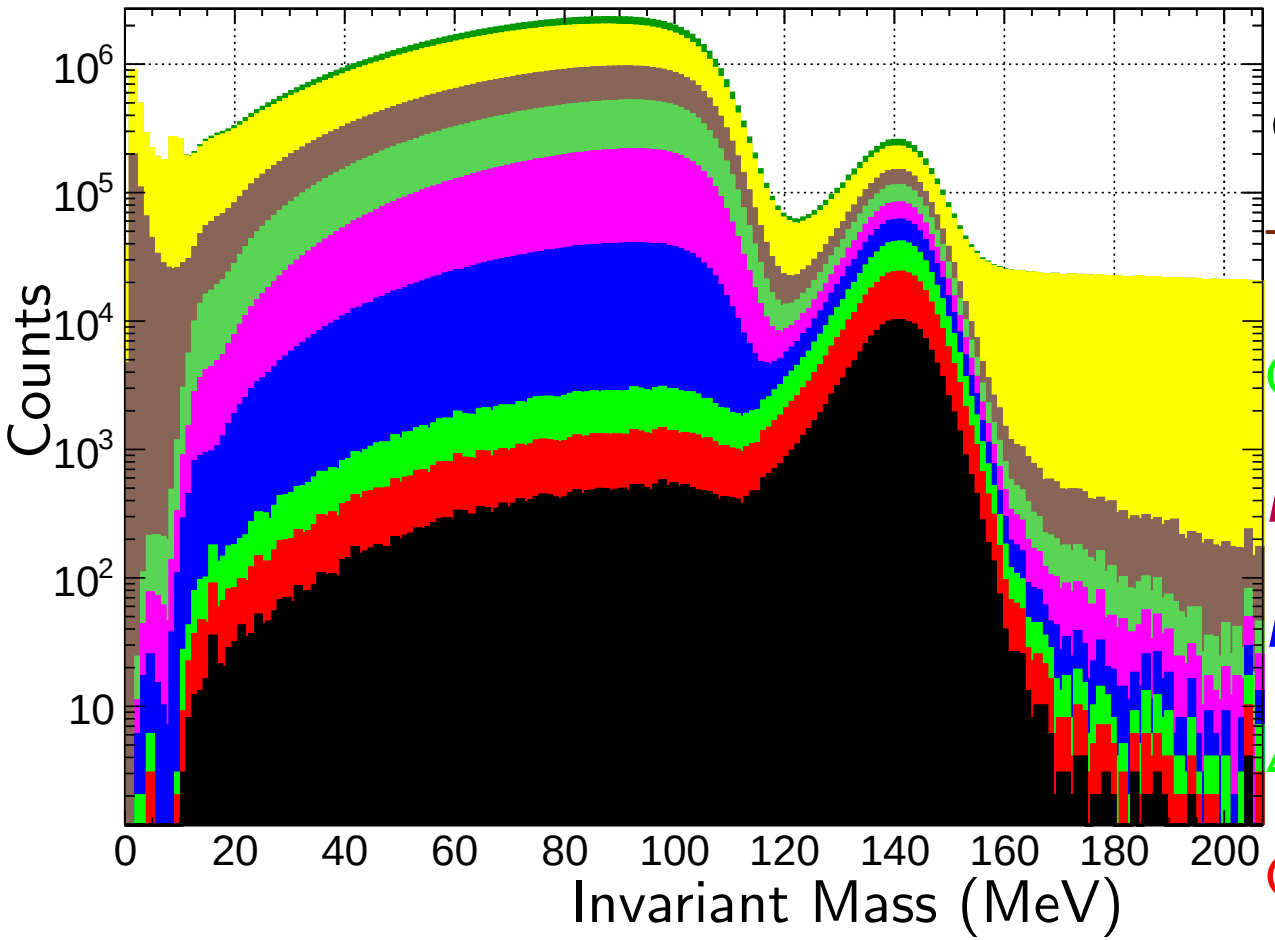
Energy requirement at positron birth



run 2 data $\sim 50\%$ run 3 data $\sim 30\%$

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

Tail Trigger



Trigger events

Good π stop

Track Constructed

Good Track

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

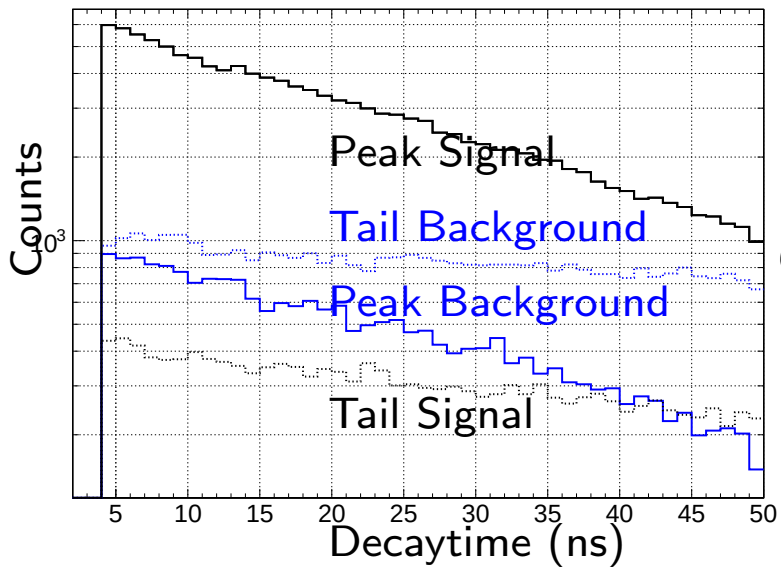
$E_{\text{tgt}}^{\text{pred-obs}} < 1$

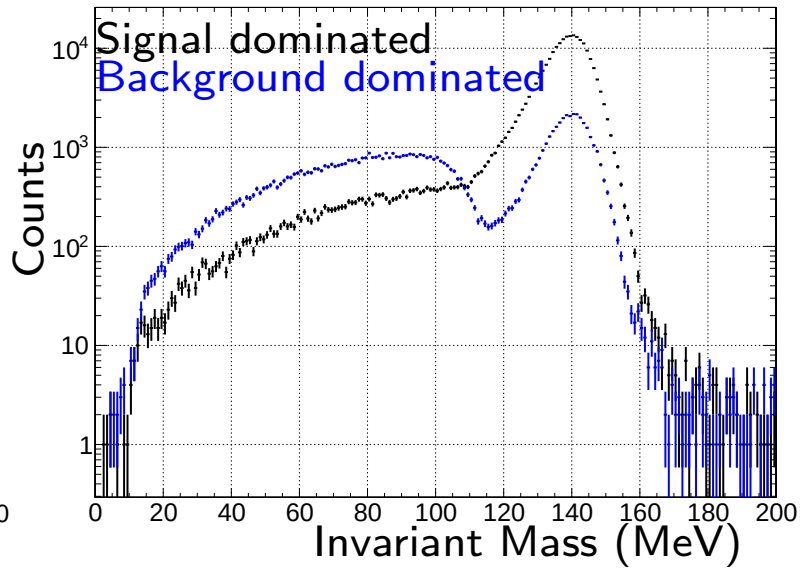
$\Delta\chi^2 > .55$

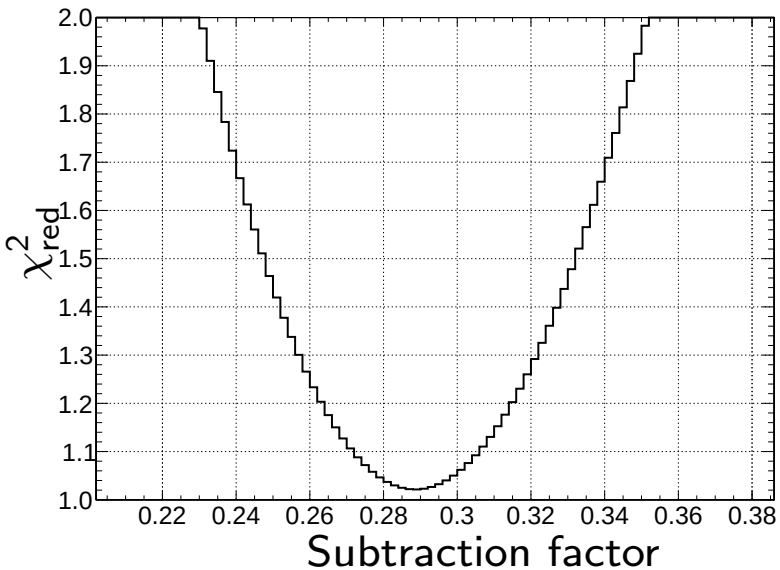
Good Vertex

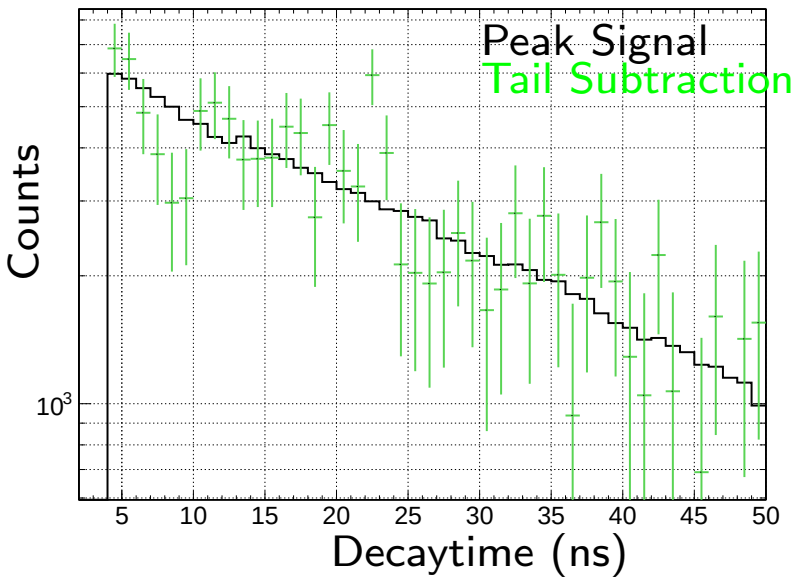
Tgt dEdx

Subtraction

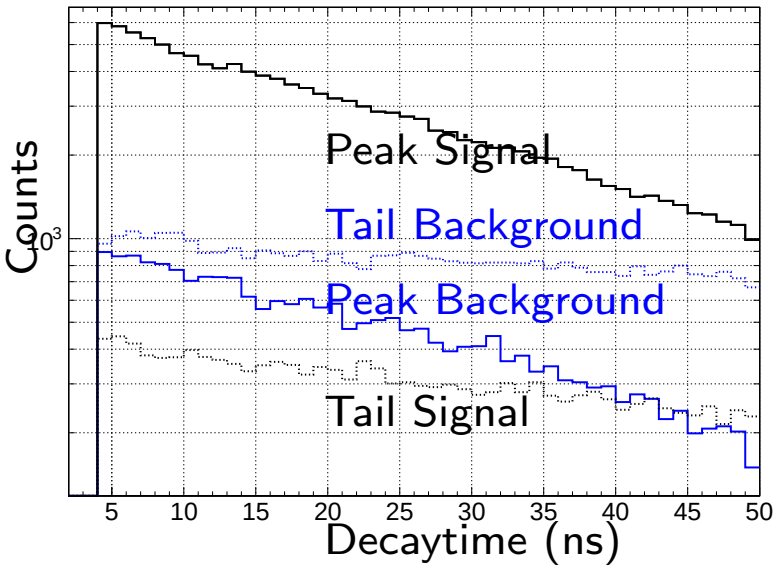


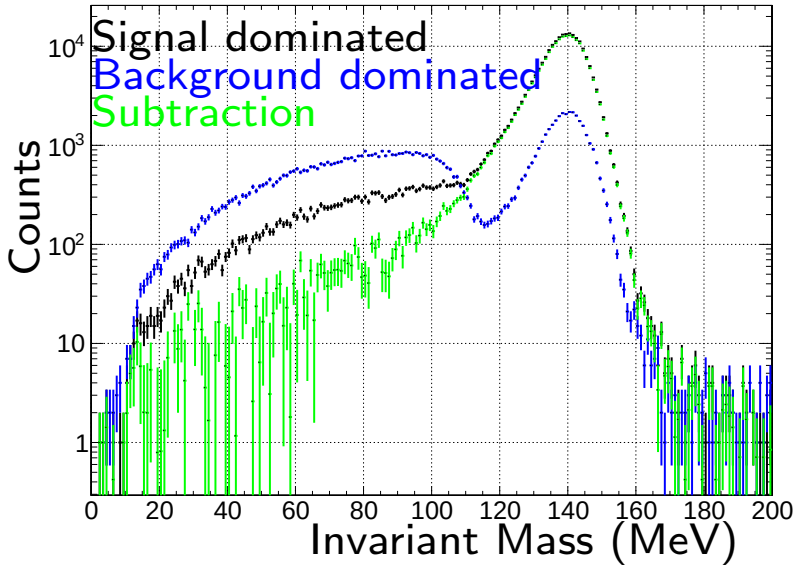


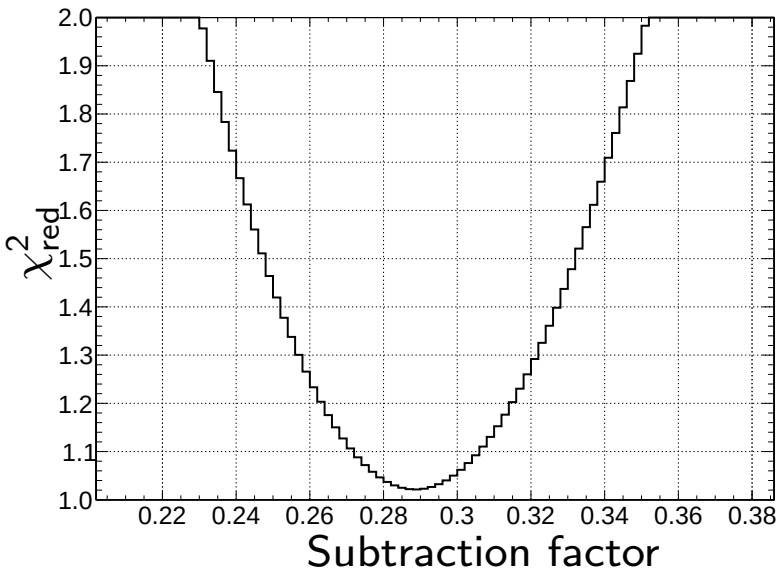


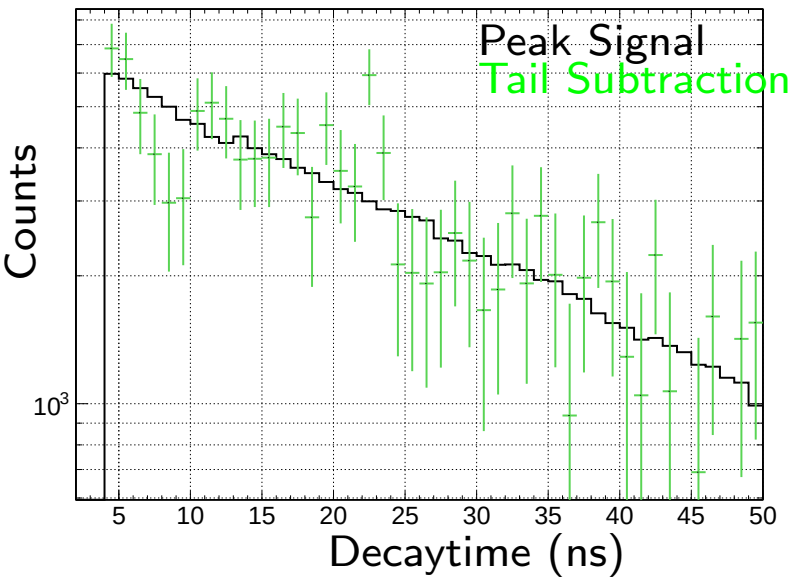


Subtraction

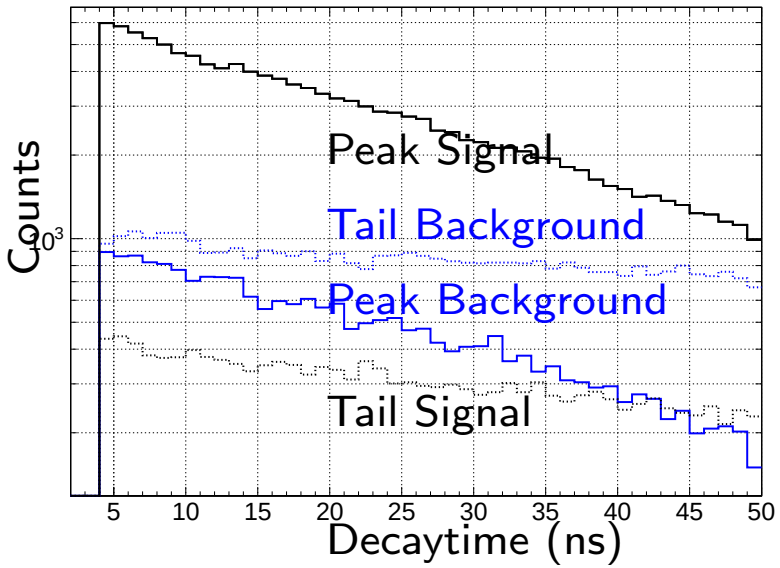


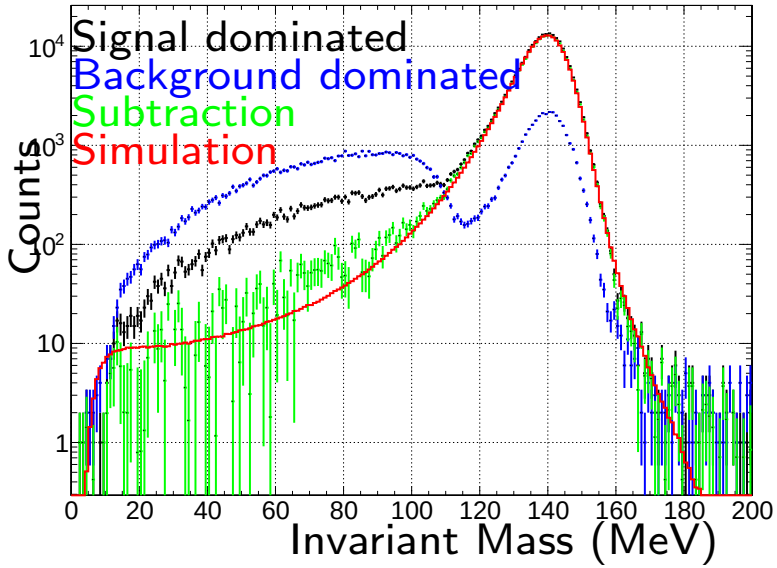


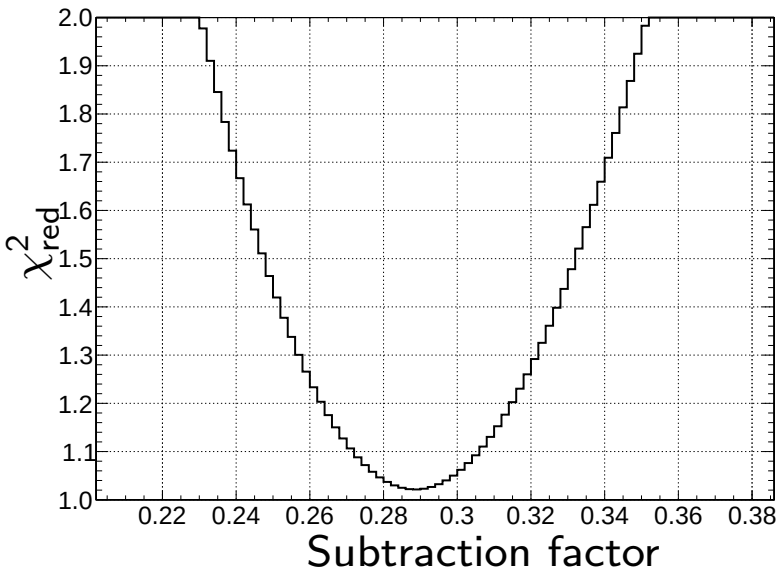


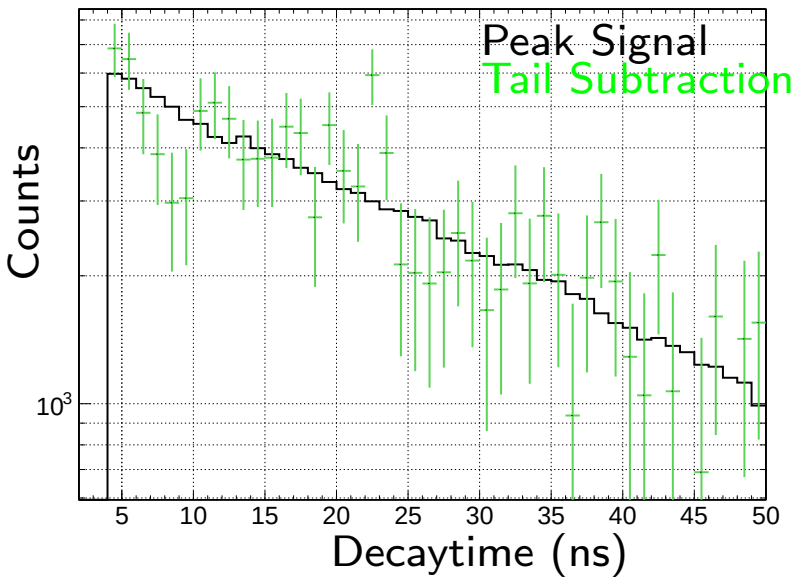


Subtraction

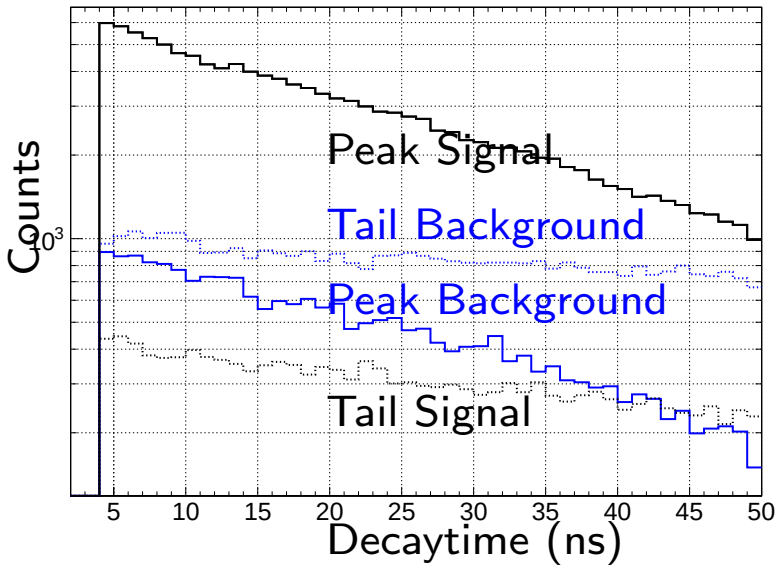


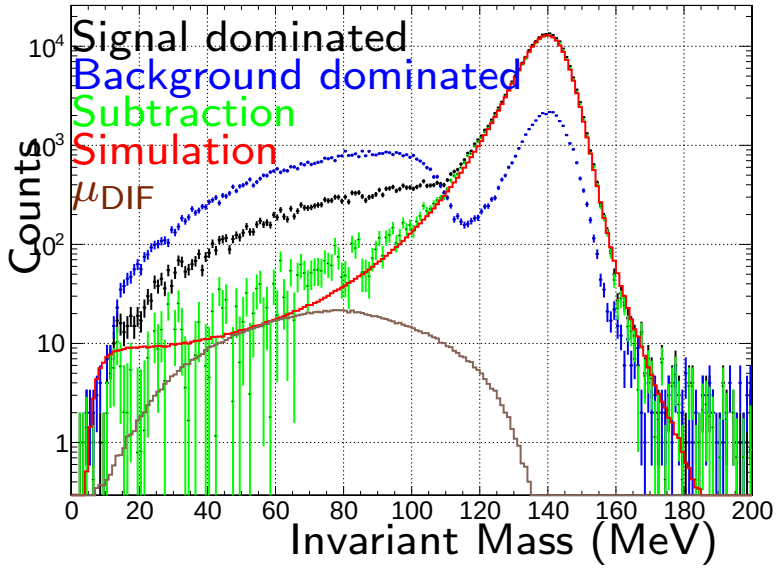


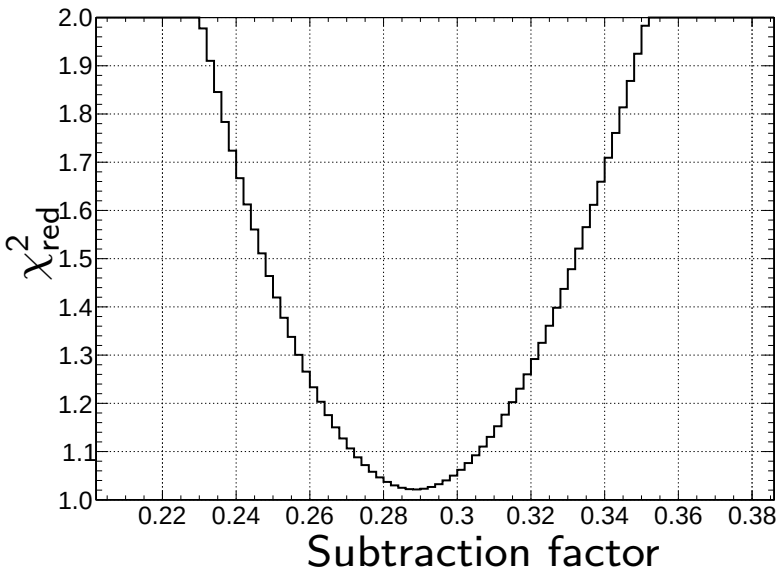


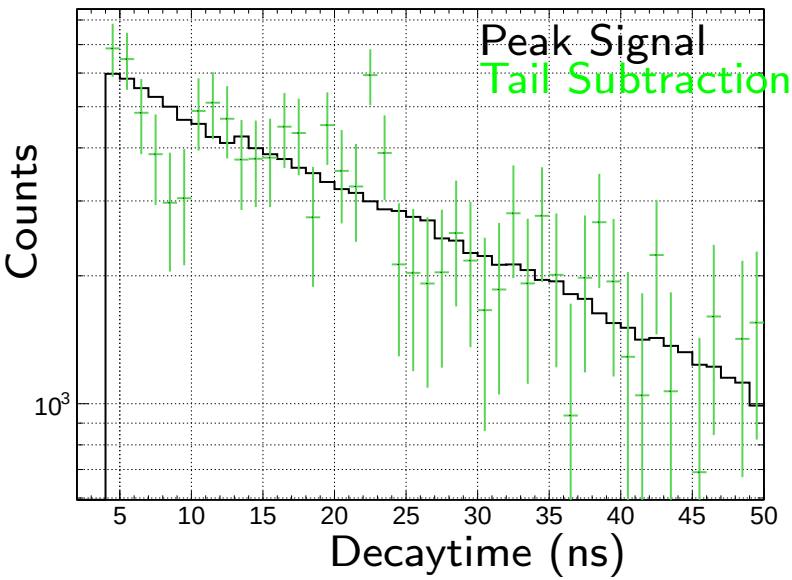


Subtraction

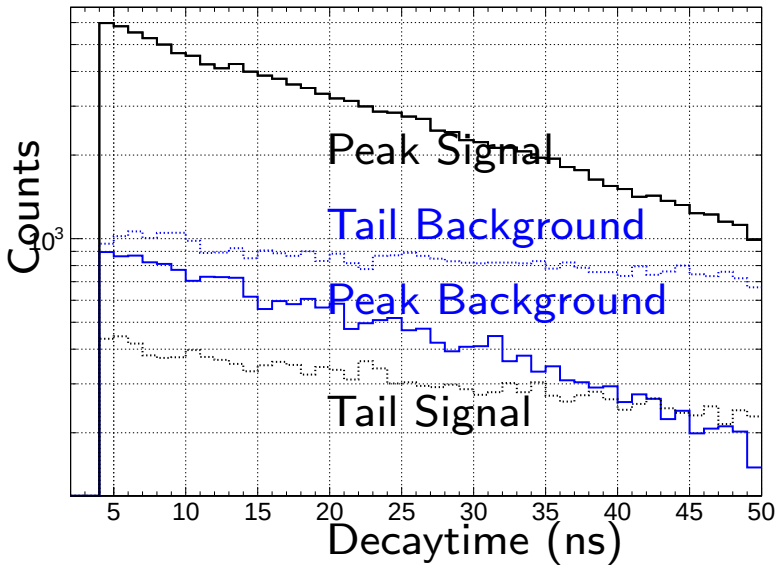


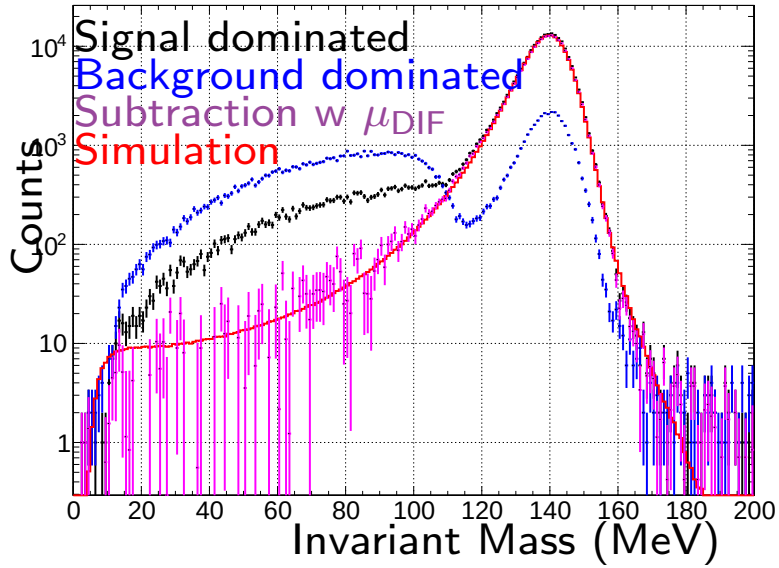


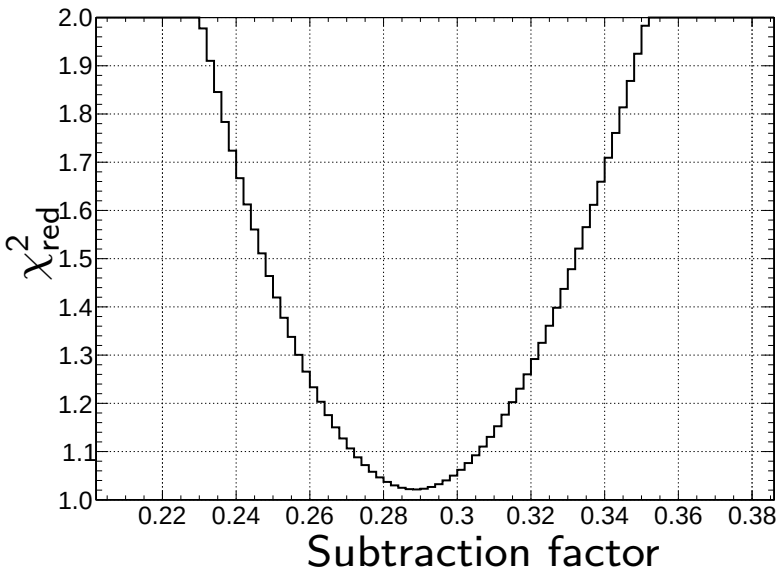


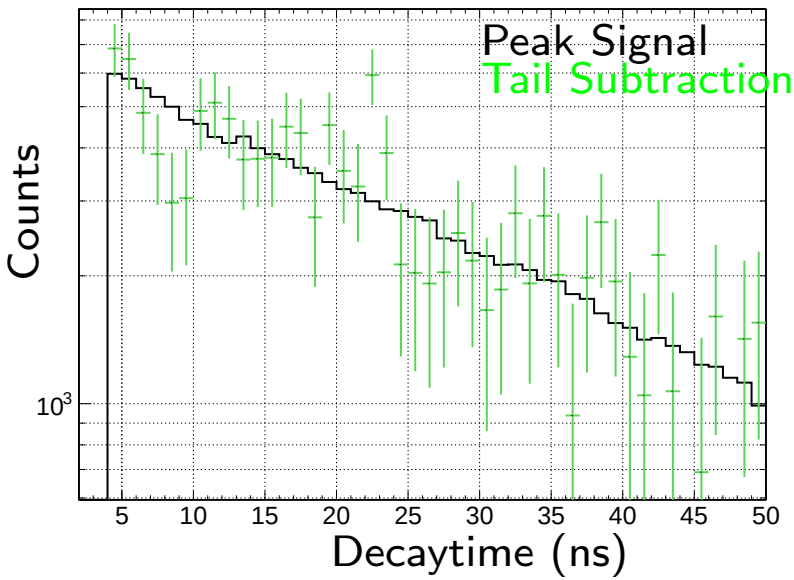


Subtraction









Photonuclear Absorption

* A. Aguilar-Arevalo *et al.*, *Nucl Instrum. Methods.* **A621**, 188 (2010)

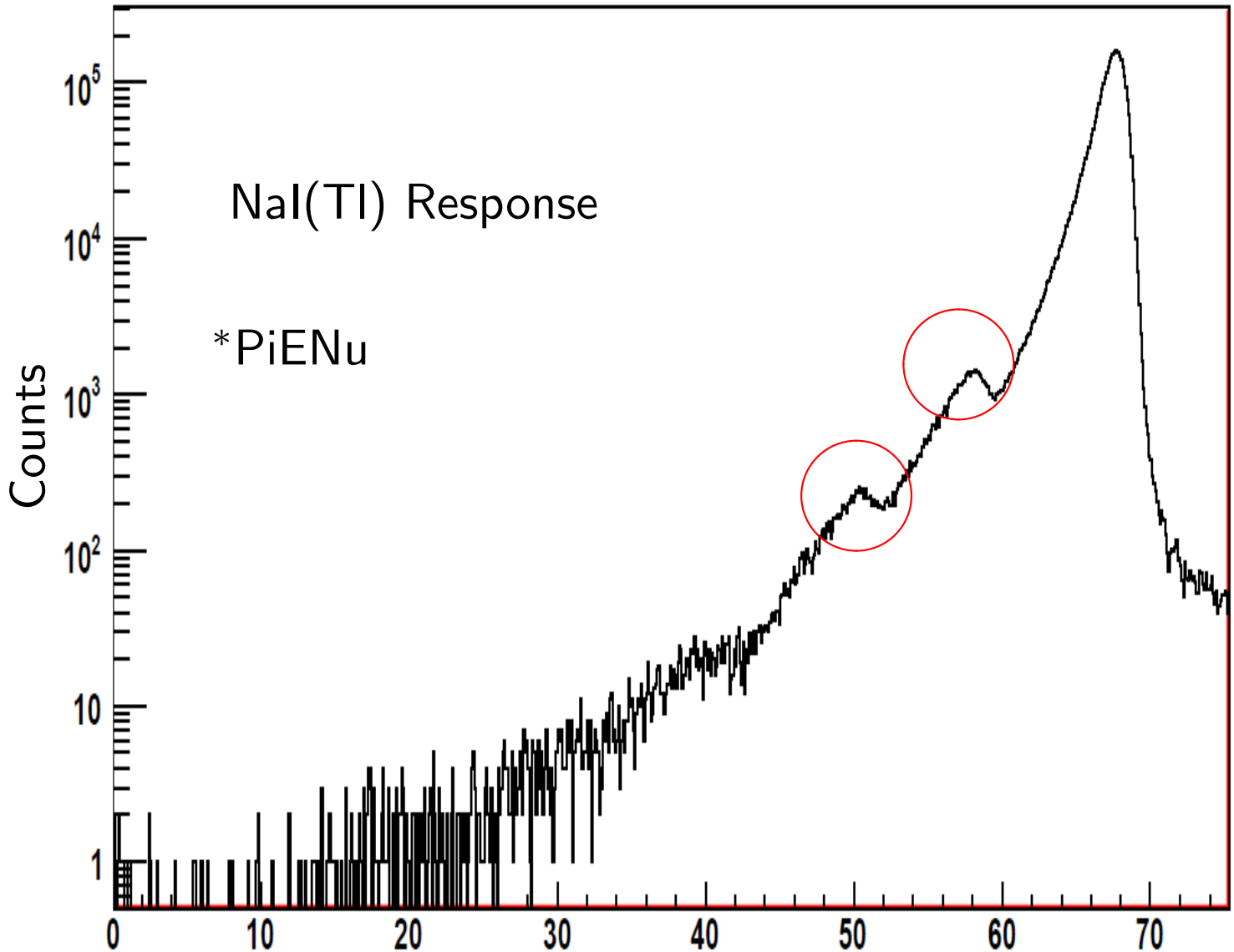
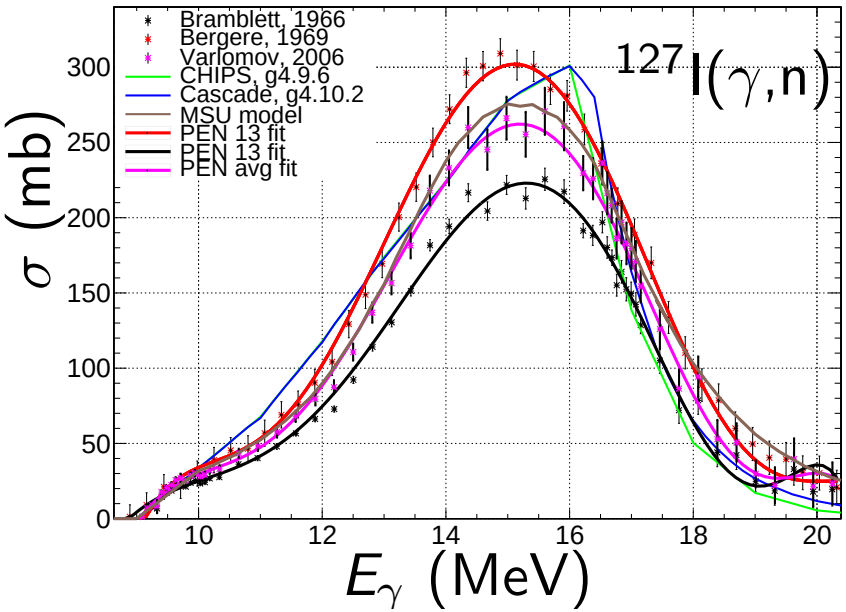
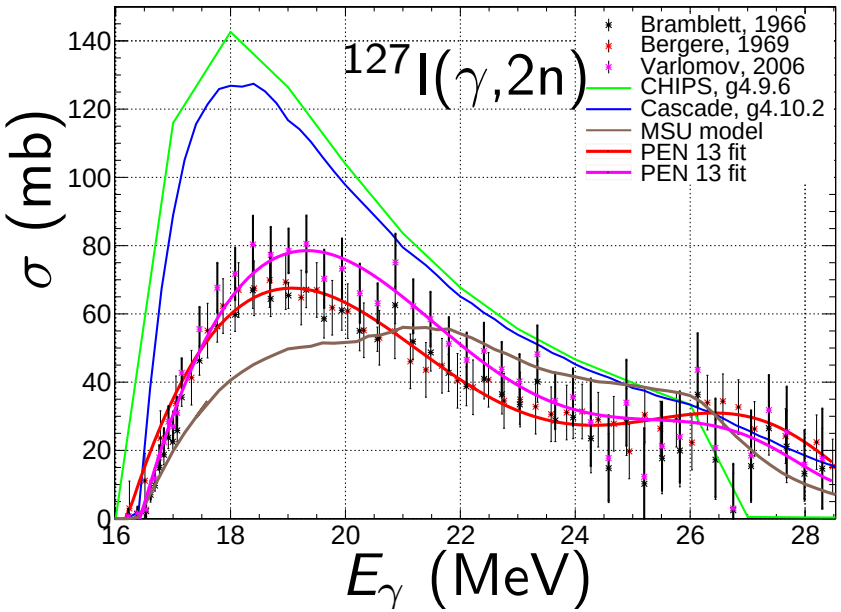
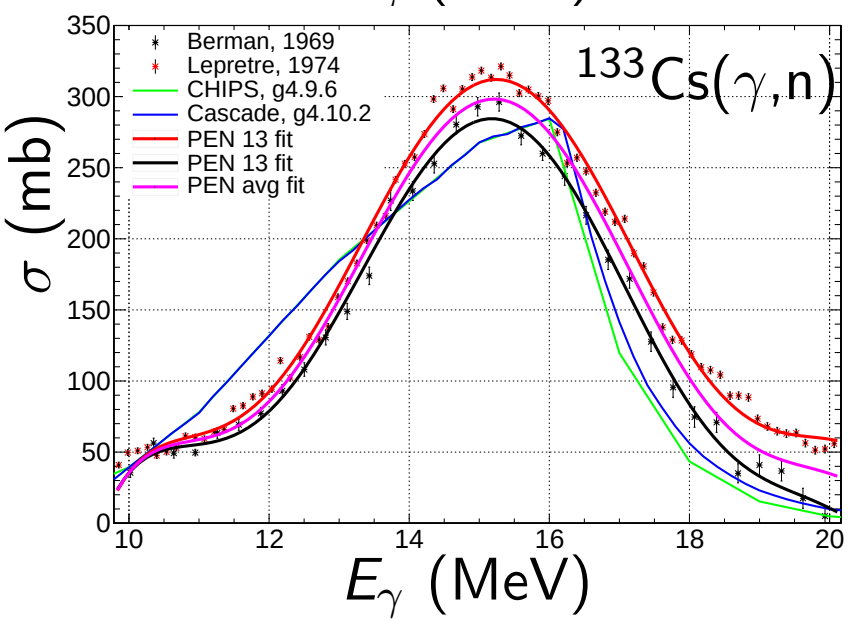
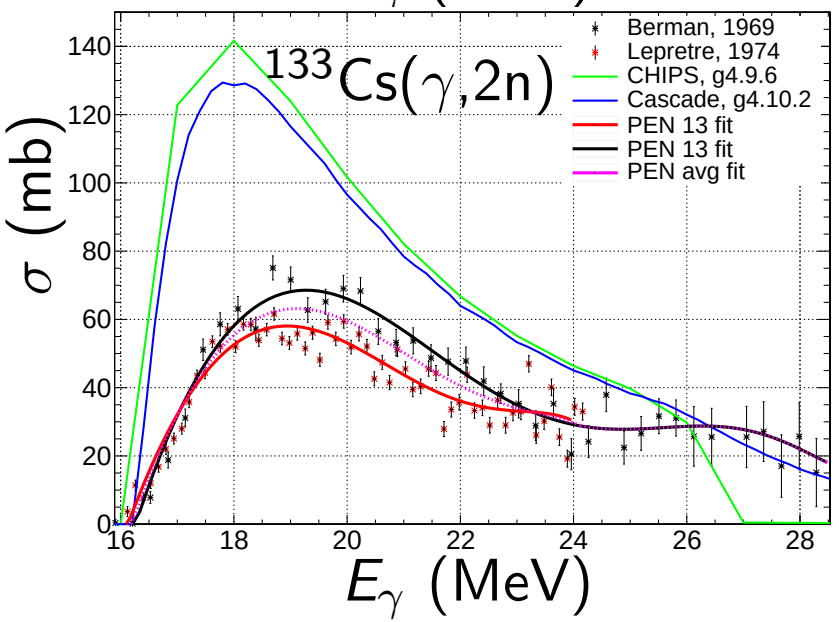


Photo nuclear X-sections

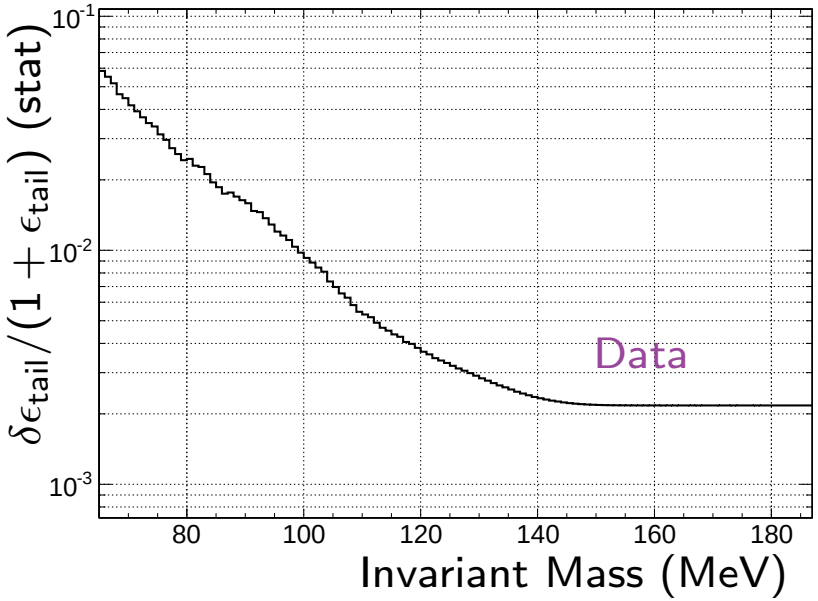








$\delta\epsilon_{\text{tail}}/(1+\epsilon_{\text{tail}})$



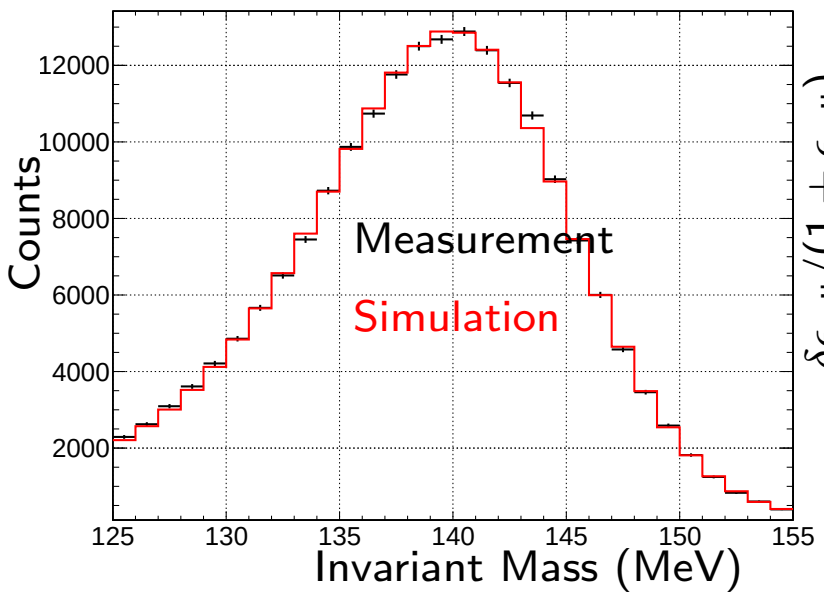
Statistical too high

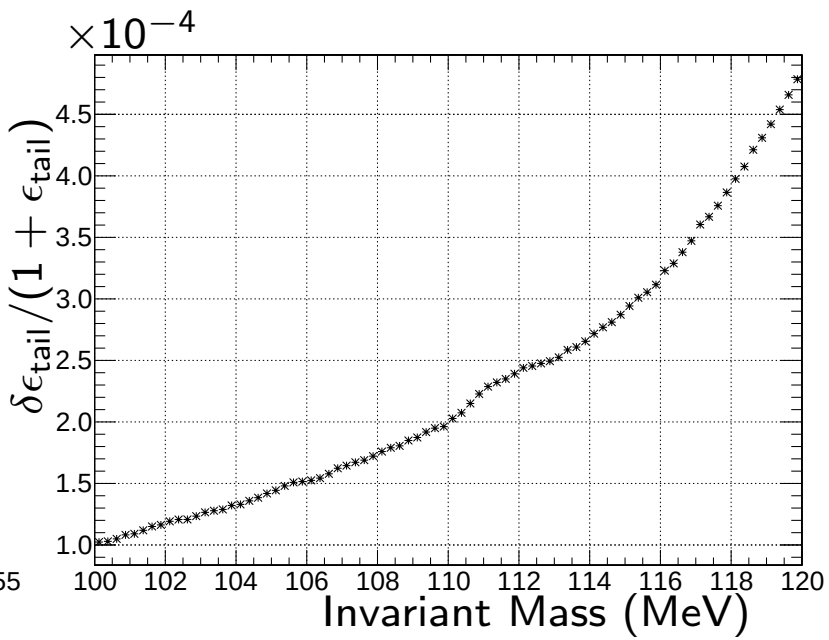
Simulation needed!

Systematics from :

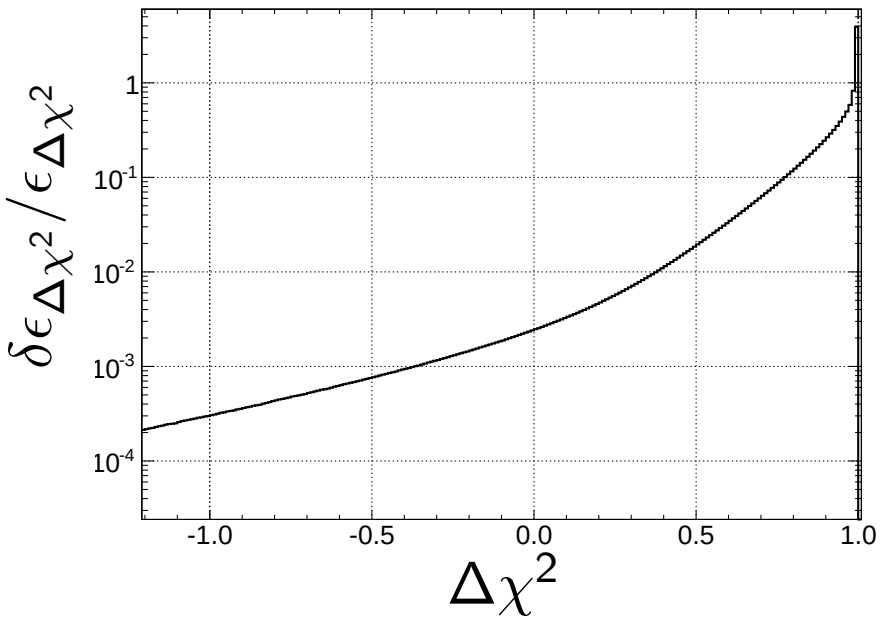
Gain Variation

Photo-nuclear physics





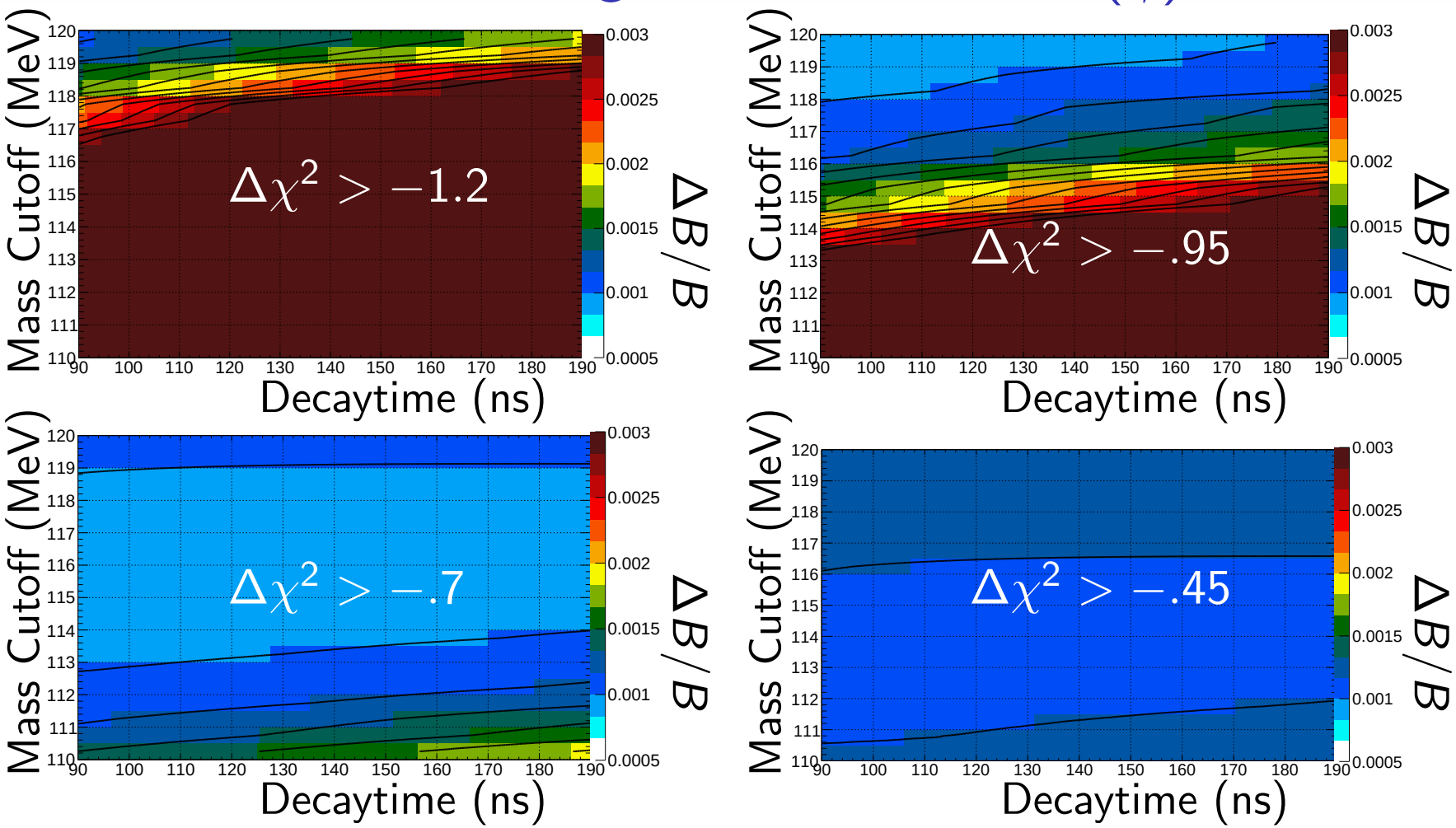
Minimizing Error for $\pi \to e\nu(\gamma)$



$\Delta\chi^2$ 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 $\pi \to e\nu(\gamma)$

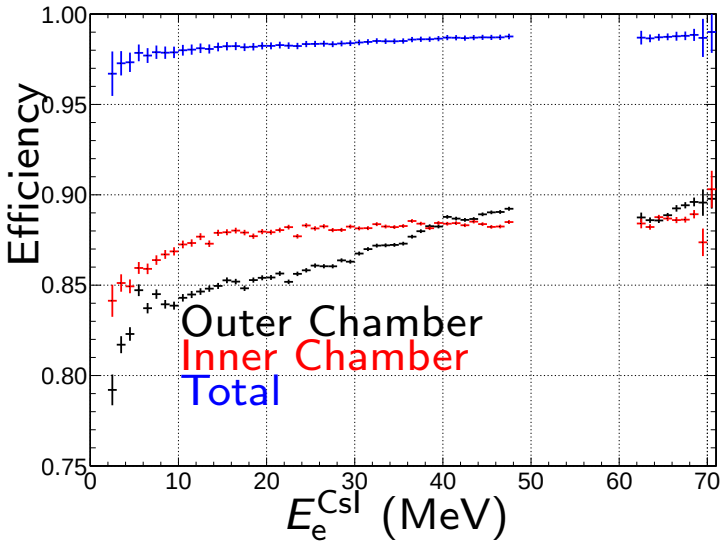


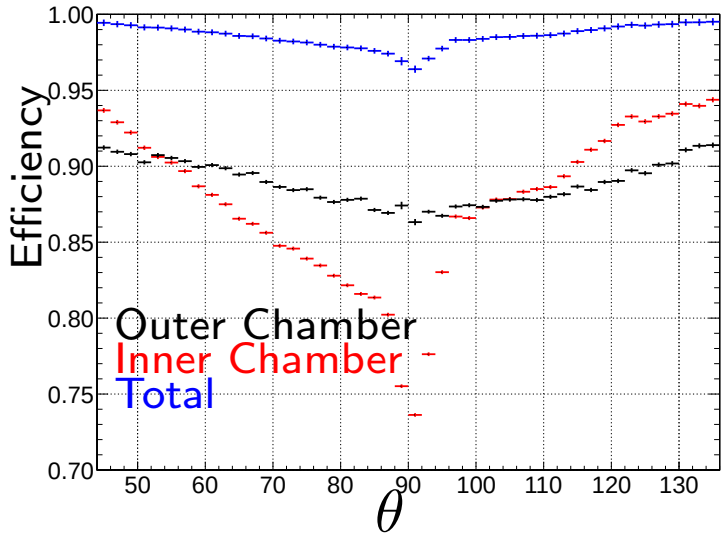
Cutoff = 117.5 MeV

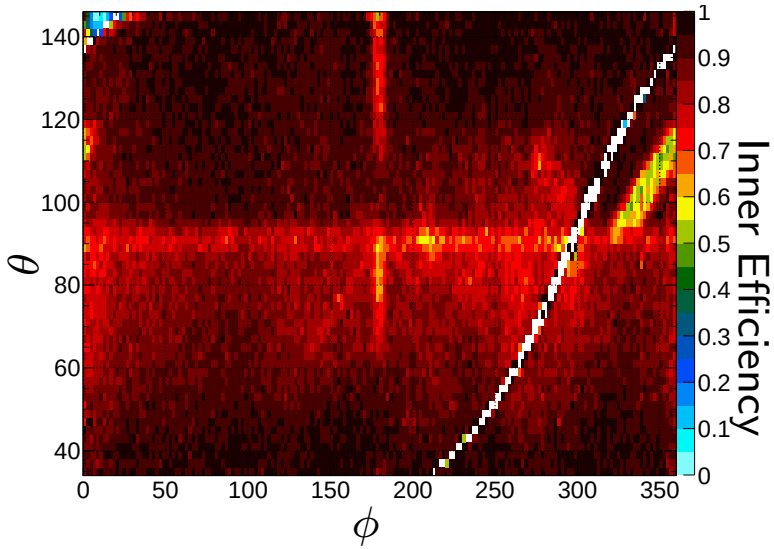
Decay time = 93.5 ns

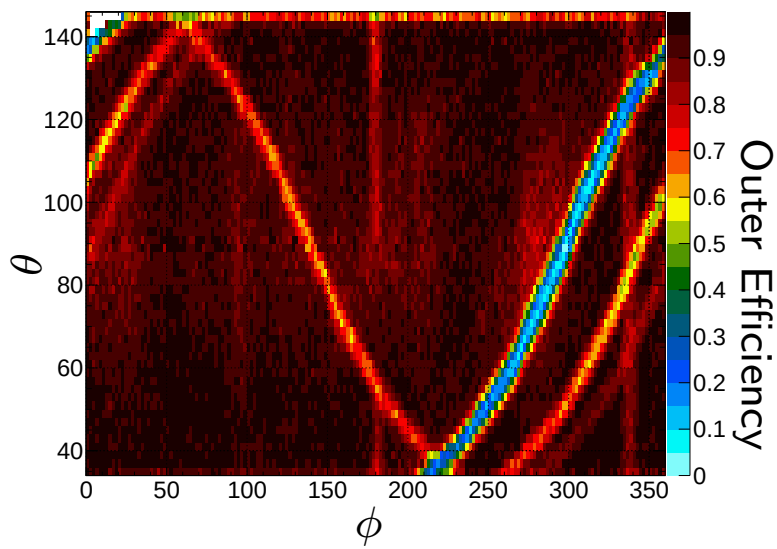
$\Delta\chi^2 > -0.8$

Chamber Efficiencies

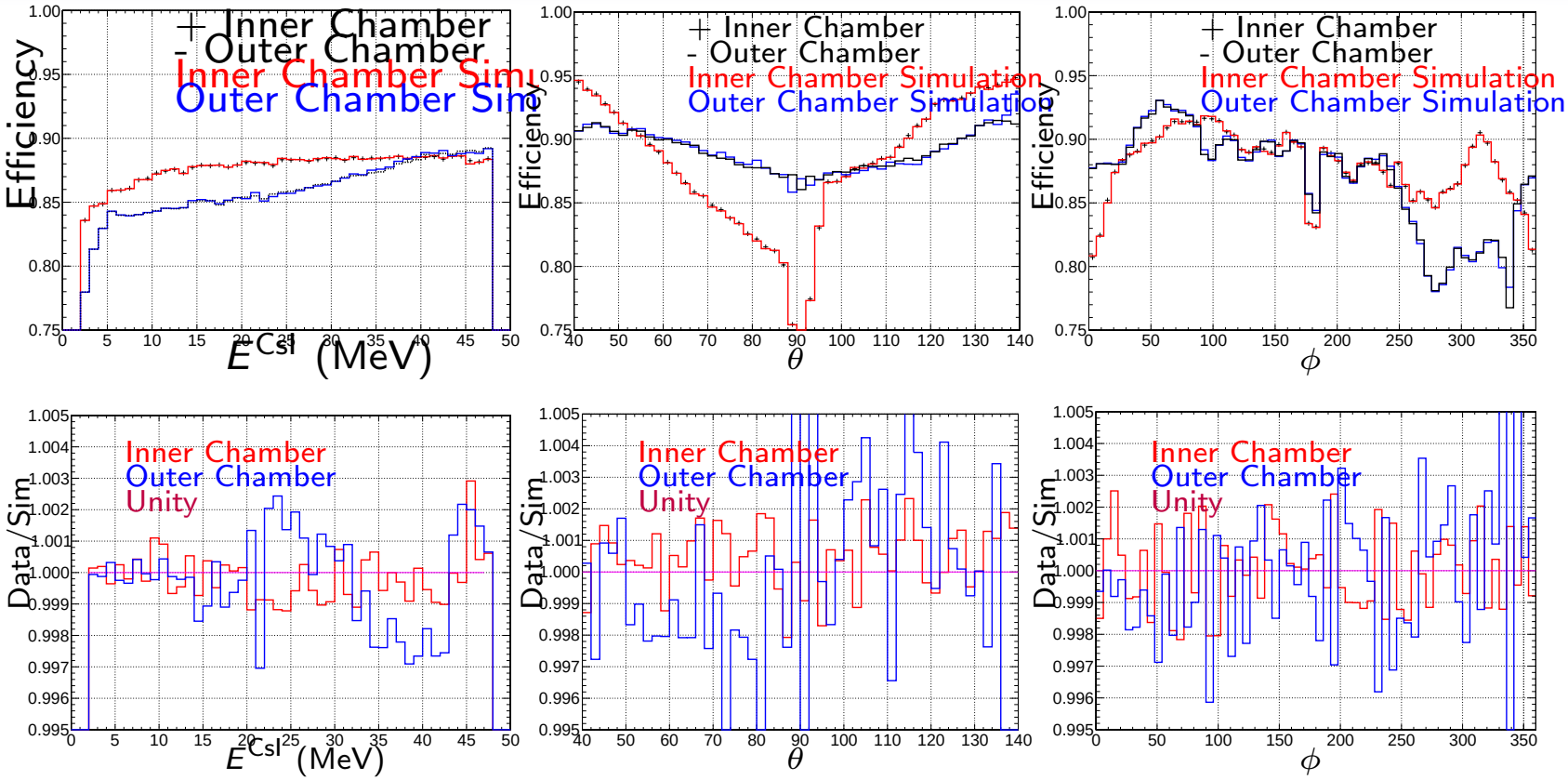








Simulation Chamber Efficiencies



dE/dx = g(E) in Chamber Gas

$\pi \rightarrow e^+\nu_e$ 70 MeV monoenergetic
$\mu \rightarrow e\nu\bar{\nu}$ 0-52.5 MeV spectrum

Monte Carlo is weighted to simulate chamber efficiencies

Absorbed into Acceptances (Blinded)

PEN is on its way to evaluate $R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$

In the process of releasing series of papers (analysis, instrumental, methods ...)

Event selection for $\pi \to e\nu(\gamma)$ decays
– Tail/Peak separation 117.5 MeV
– Decay time -5 to 93.5 ns
– $\Delta\chi^2 > -.8$

Current tasks underway:

- Systematic corrections on trigger energy
- More realistic radiative muon Monte Carlo
- Improvements on $\Delta\chi^2$
- Experimental tail
- Unblinding

Table of Uncertainties

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

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} (09/10)
	5×10^{-4} (*Goal*)	7.6×10^{-4}

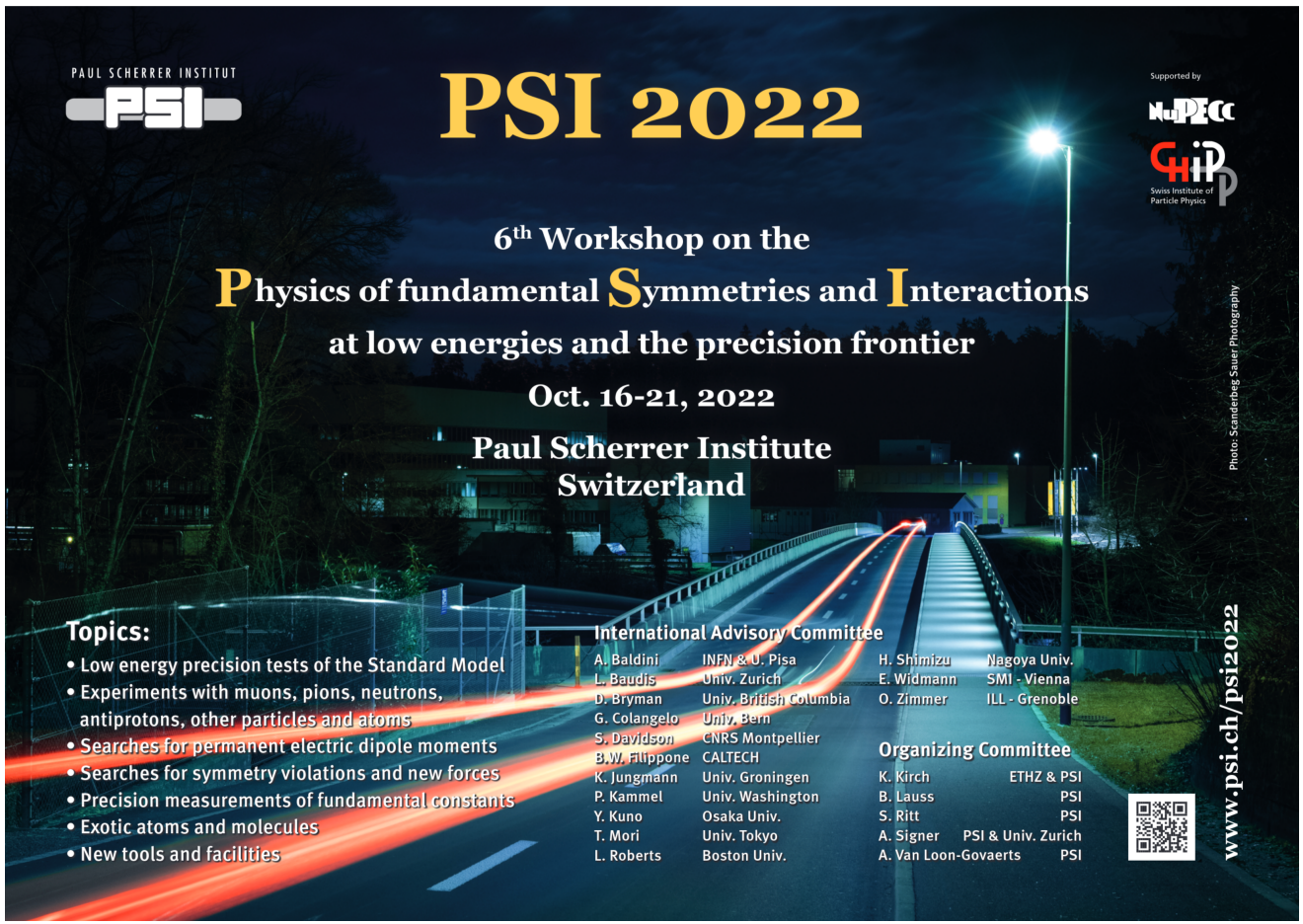
Family

Current and former PIBETA and PEN collaborators

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

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

Thanks for listening!



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

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

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

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