TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Looking for New Physics with Pion Decays

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TRIUMF

Jan 2017

Outline

- General Context
- Motivation
- Experimental Technique
- Data Analysis
- Results
- Conclusions & Outlook

PI E NU

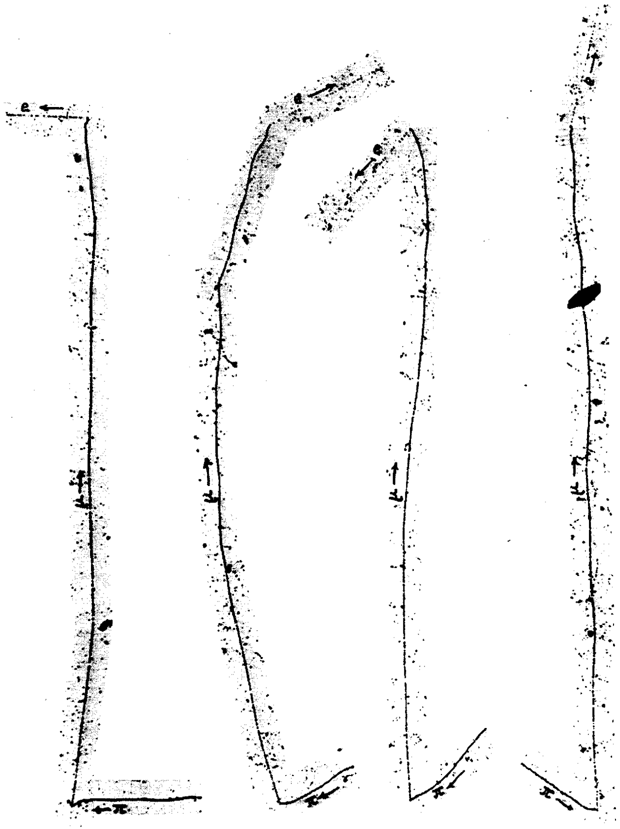
History and Physics Motivation

Early History

1935: H. Yukawa predicts a new particle

1936: Discovery of the Muon

1947: C. Powell and collaborators discover the Pion
M.Lattes, H.Muirhead, G.Occhialini, C.Powell:
Nature, 159:694-697 (1947)



1949: H.Yukawa awarded the Nobel Prize.

1950: C. Powell awarded the Nobel Prize

The Pion and the Standard Model

- Pion discovered with $\pi^+ \to \mu^+ \nu$, $\mu^+ \to e^+ \nu \bar{\nu}$

- But: $m_e = 0.511 \text{ MeV}$

$m_\mu = 105 \text{ MeV}$

- Why don't we see $\pi^+ \to e^+ \nu$?

- 1950s: Many experimental indications that the weak interactions were violating parity. "V-A" structure:

$$H_w \sim \left(\frac{g^2 V_{ud}}{8 m_W^2}\right) \bar{l} \gamma_\lambda (1-\gamma_5) \bar{\nu}_l \bar{u} \gamma^\lambda \gamma_5 d$$

The Pion and the Standard Model

PHYSICAL REVIEW VOLUME 76, NUMBER 10 NOVEMBER 15, 1949

Note on the Decay of the π-Meson

M. Ruderman and R. Finkelstein
California Institute of Technology, Pasadena, California

(Received July 25, 1949)

Assuming the symmetric coupling scheme proposed by Wheeler and Tiomno, and others, we have calculated the ratio of the decay rate π-meson→electron+neutrino to the decay rate of π-meson→μ-meson +neutrino. The electron-neutrino decay proceeds faster, in disagreement with experiment, unless the π-meson is pseudoscalar and the β-decay coupling is pseudovector. Hence if the symmetric coupling scheme is corect and no other direct couplings are introduced, the π-meson must be pseudoscalar and β-decay must be at least partially pseudovector. If symmetric coupling is not assumed, no conclusion of this kind can be drawn.

Meson	Scalar	*f*	*f*	*f*	*f*	*f*
	P-scalar	*f*	5.1	*f*	1.0×10^{-4}	*f*
	Vector	*f*	*f*	4.0	*f*	2.4
	P-vector	*f*	*f*	*f*	*f*	2.4

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Meson					
Scalar	f	f	f	f	f
P-scalar	f	5.1	f	1.0×10^{-4}	f
Vector	f	f	4.0	f	2.4
P-vector	f	f	f	f	2.4

PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

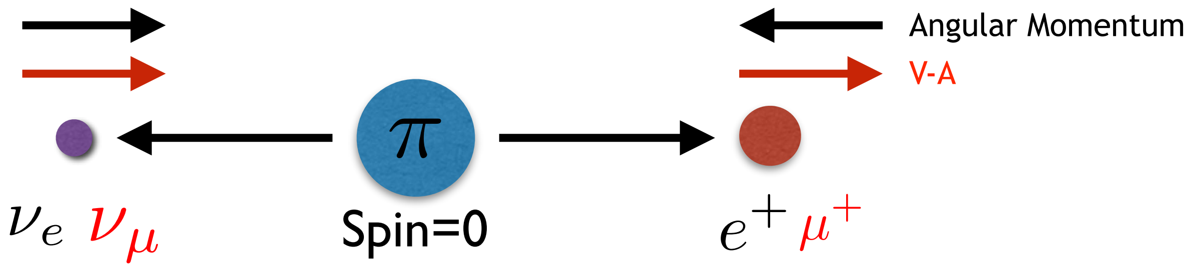
Theory of the Fermi Interaction

R. P. FEYNMAN AND M. GELL-MANN
California Institute of Technology, Pasadena, California

(Received September 16, 1957)

Experimentally[16] no $\pi\rightarrow e+\nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

Helicity Suppression



Neutrinos produced only by weak interactions:

Neutrinos: left-handed helicity

Antineutrinos: right-handed helicity

Weak interaction forces the electron into the "wrong" helicity state

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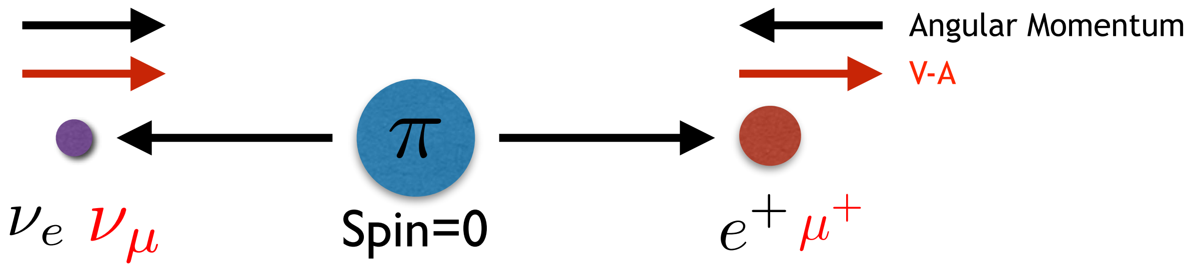

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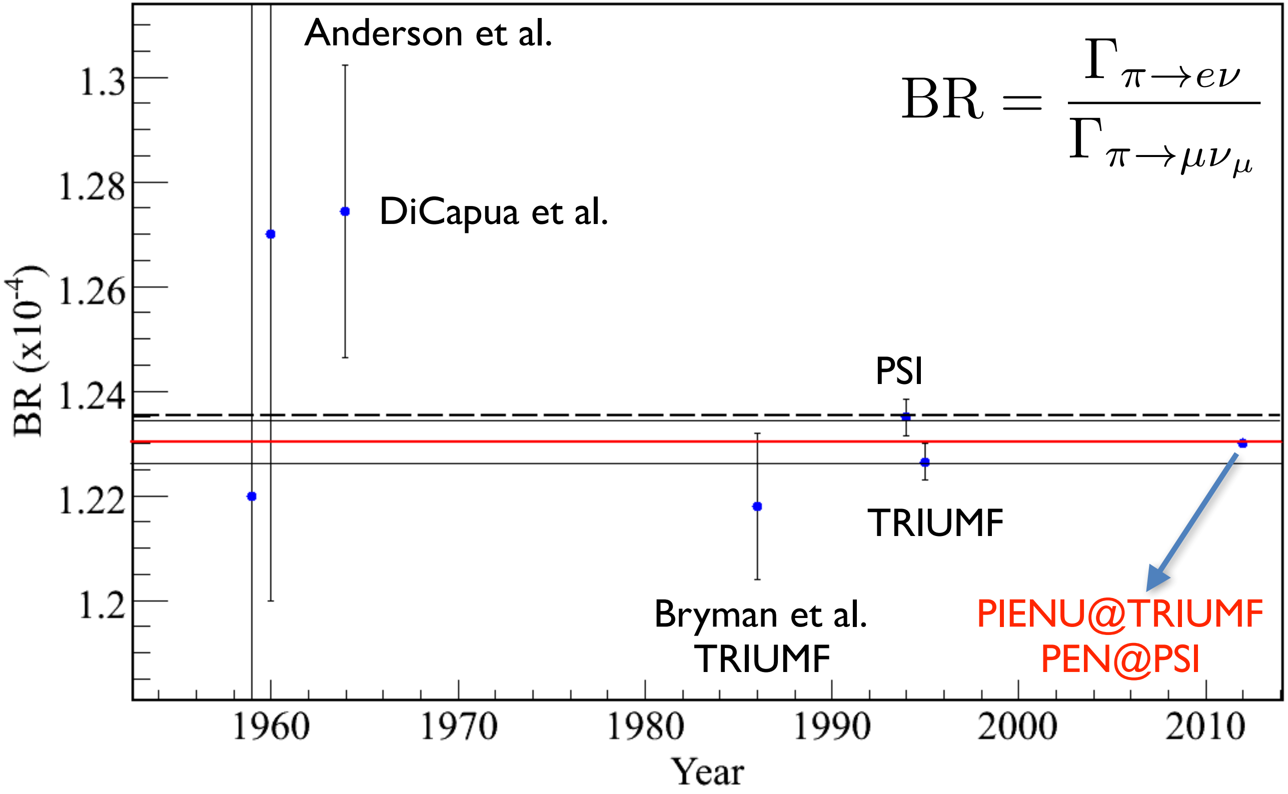
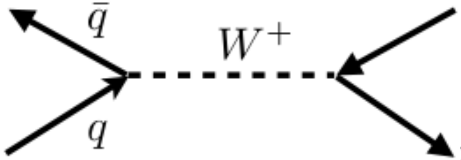
The V-A structure of the weak interactions explains why the muon decay mode is favoured!

Experimental History



$$\mathrm{BR} = \frac{\Gamma_{\pi \to e\nu}}{\Gamma_{\pi \to \mu\nu_\mu}}$$

Lepton Universality

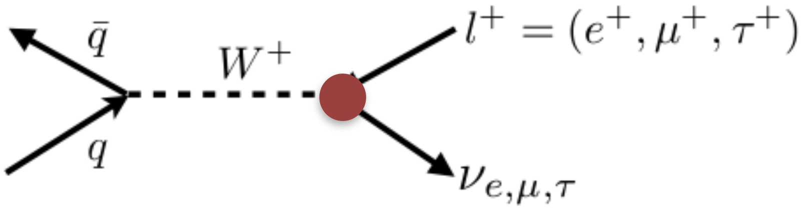


$$\Gamma_{\pi \to l \nu_l} = G^2_{e,\mu,\tau} \frac{m_\pi f_\pi^2 m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

$$R_0 = \frac{\Gamma_{\pi \to e \nu_e}}{\Gamma_{\pi \to \mu \nu_\mu}} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28336(2) \times 10^{-4}$$

Helicity Suppression

Lepton Universality



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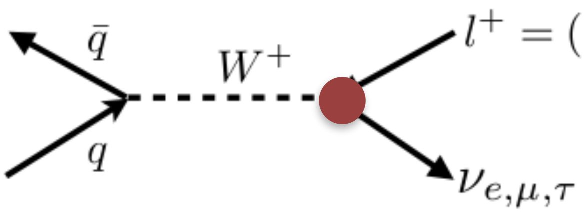

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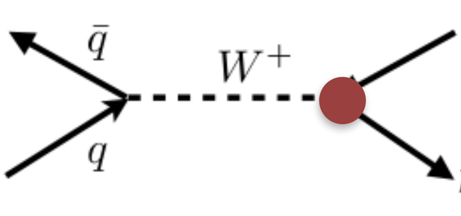

$l^+ = (e^+, \mu^+, \tau^+)$

$\nu_{e,\mu,\tau}$

$$\Gamma_{\pi\to l\nu_l} = G^2_{e,\mu,\tau} \frac{m_\pi f_\pi^2 m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

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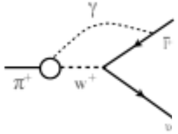
Helicity Suppression

$$R = R_0 \times \left[1 + \frac{\alpha}{\pi}\left\{F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + \frac{m_\mu^2}{m_\rho^2}\left(c_2 \ln\frac{m_\rho^2}{m_\mu^2} + c_3\right) + c_4\frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + c_5\left(\frac{\alpha}{\pi}\ln\frac{m_\mu}{m_e}\right)^2 + ..\right]$$

$(+SD_\pi)$

V.Cirigliano, I.Rosell: Phys.Rev.Lett. 99(23), 231801 (2007)

M.Terent'ev: Yad. Fiz. 18(870) (1973)



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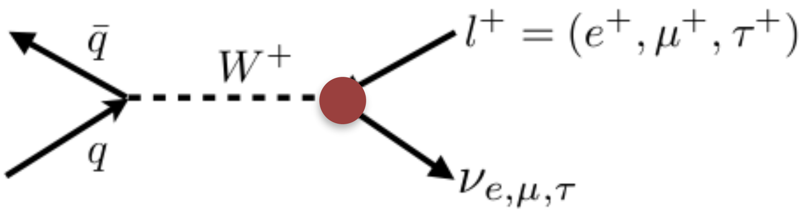
Lepton Universality



$$\Gamma_{\pi \to l \nu_l} = \underline{G^2_{e,\mu,\tau}} \frac{m_\pi f_\pi^2 m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

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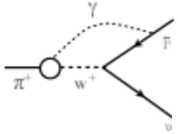

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Standard Model: $R^{SM} = 1.2353(1) \times 10^{-4}$

Experiments: $R^{exp} = 1.230 \pm 0.004 \times 10^{-4}$

TRIUMF: D.Britton et al. Phys.Rev.Lett. 68:3000-3003 (1992)
PSI: G. Czapek et al. Phys.Rev.Lett. 70:17-20 (1993)

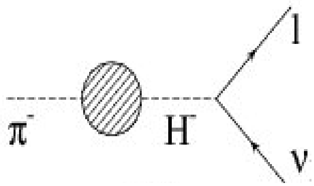
New pseudo-scalar interactions (no helicity suppression)

B.Campbell, D. Maybury: Nucl.Phys. B709, 419 (2005)

$$1-\frac{R^{exp}}{R^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu}\frac{1}{\Lambda^2}\frac{m_\pi^2}{m_e(m_d+m_u)} \sim (\frac{1\mathrm{TeV}}{\Lambda})^2 \times 10^3 \qquad \Rightarrow 1000\mathrm{TeV}$$

Charged Higgs (with non-SM couplings)

O. Shanker: Nucl.Phys. B204(3), 375 (1982)

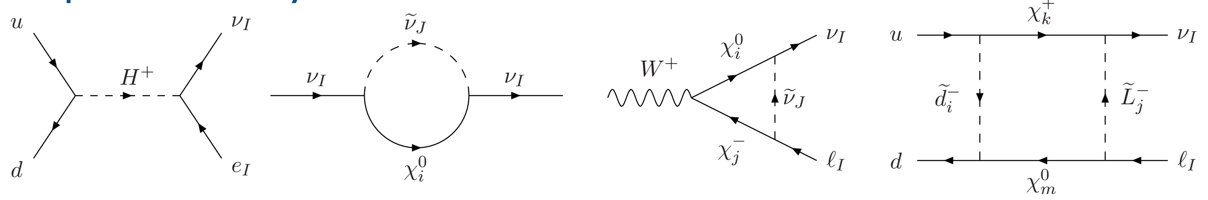


Relevant for SUSY models, Changes the BR through loop contributions

$$1-\frac{R^{exp.}}{R^{SM}} \sim \mp \frac{2m_\pi^2}{m_e(m_d+m_u)}\frac{m_W^2}{m_{H^\pm}}\lambda_{ud}(\lambda_{e\nu}-\frac{m_e}{m_\mu}\lambda_{\mu\nu}) \qquad M_H^\pm \sim 400\mathrm{GeV}$$

SUperSYmmetry

M. Ramsey-Musolf, S.Su, S.Tulin: Phys.Rev. D76, 095017 (2007)



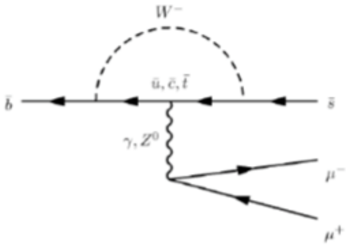
R-parity violating SUSY affects the BR already at tree-level!

And More: Leptoquarks, new scalar interactions, massive neutrinos,…

Lepton Universality Violation?

LHCb Collaboration,
R. Aaij et al., "Test of lepton universality using B+ → $K^+l^+l^-$ decays," arXiv:1406.6482.

- Previously measured by Belle and BaBar at 20-50% precision level
- R_K = 1 expected from SM
- Theoretically clean observable with small corrections
- Analysis : $1<q^2<6$ GeV^2/c^4



$$R_K = \frac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{cyst})$$

2.6σ deviation from the SM value

Feruglio, Paradisi, Pattori, Phys. Rev. Lett. 118, 011801 (2017)

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{\mathrm{exp}}/\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{\mathrm{SM}}}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})_{\mathrm{exp}}/\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})_{\mathrm{SM}}},$$

$$R^{\tau/\ell}_{D} = 1.37 \pm 0.17, \qquad R^{\tau/\ell}_{D^*} = 1.28 \pm 0.08 .$$

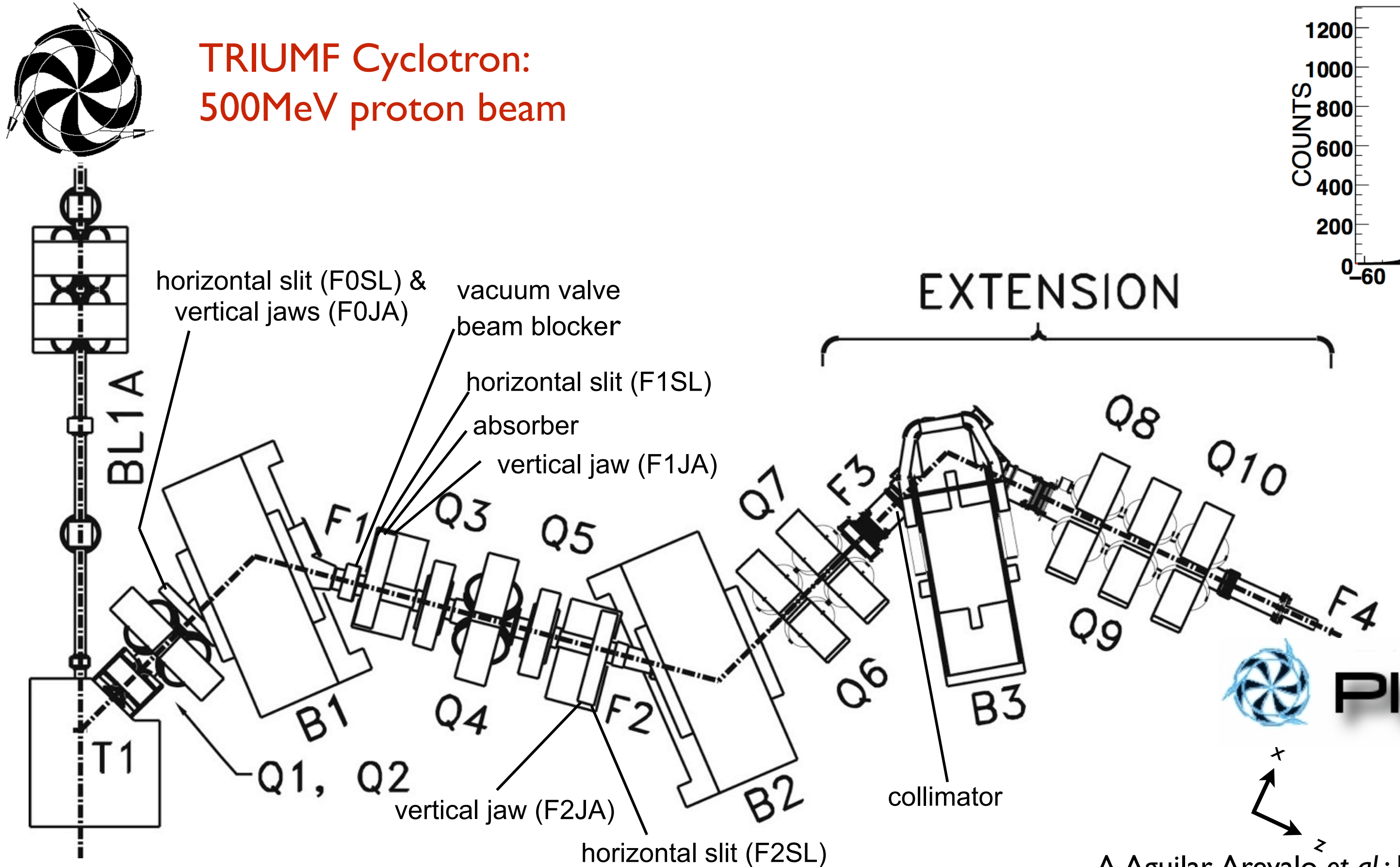
J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **88** (2013) 7, 072012 [arXiv:1303.0571].
M. Huschle *et al.* [Belle Collaboration], Phys. Rev. D **92** (2015) 7, 072014 [arXiv:1507.03233].
R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 15, 159901 [arXiv:1506.08614].

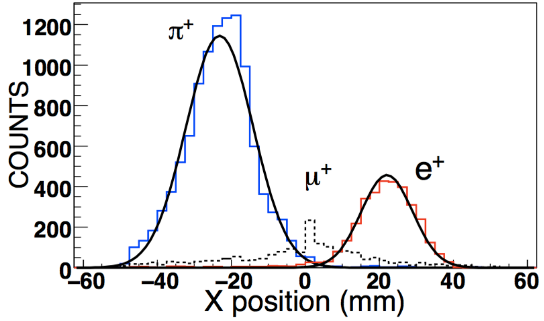
3.9σ deviation from the SM value

The PIENU Experiment at TRIUMF

The Pion Beam

TRIUMF Cyclotron:
500MeV proton beam





- 3-Dipoles Beamline
- 10 Quadrupoles
- Separation:
  Energy-loss
  Collimator
- Positron Contamination <1%
- dp/p ~ 1.5% FWHM

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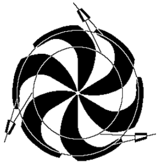
A.Aguilar-Arevalo *et al.*: Nucl. Instr. Meth. A621, 188 (2010)

The Pion Beam



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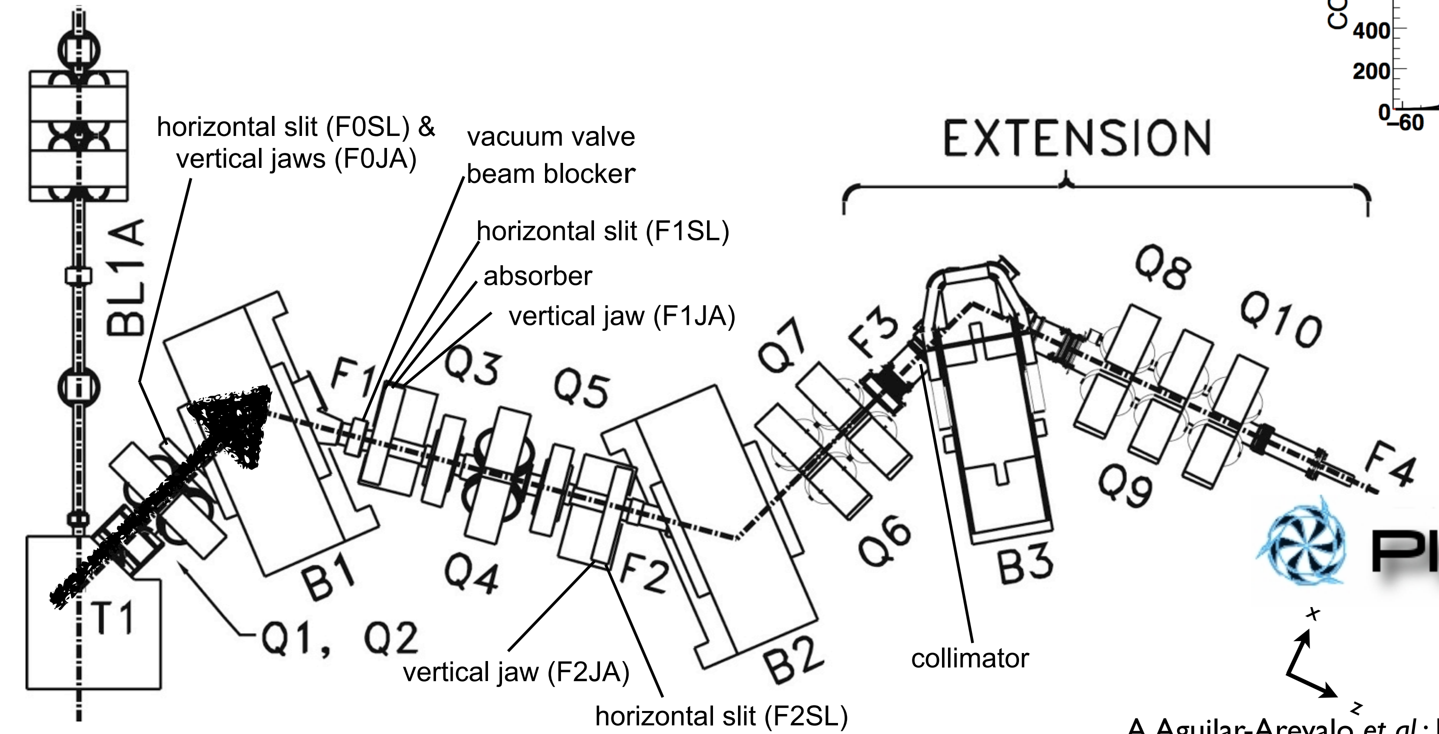

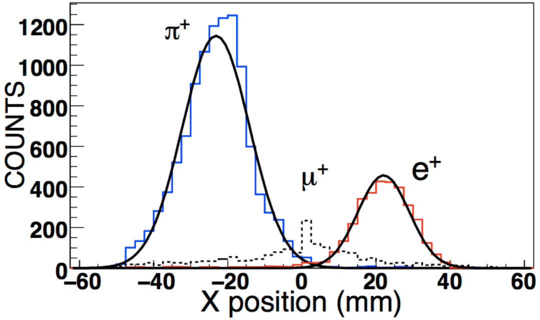

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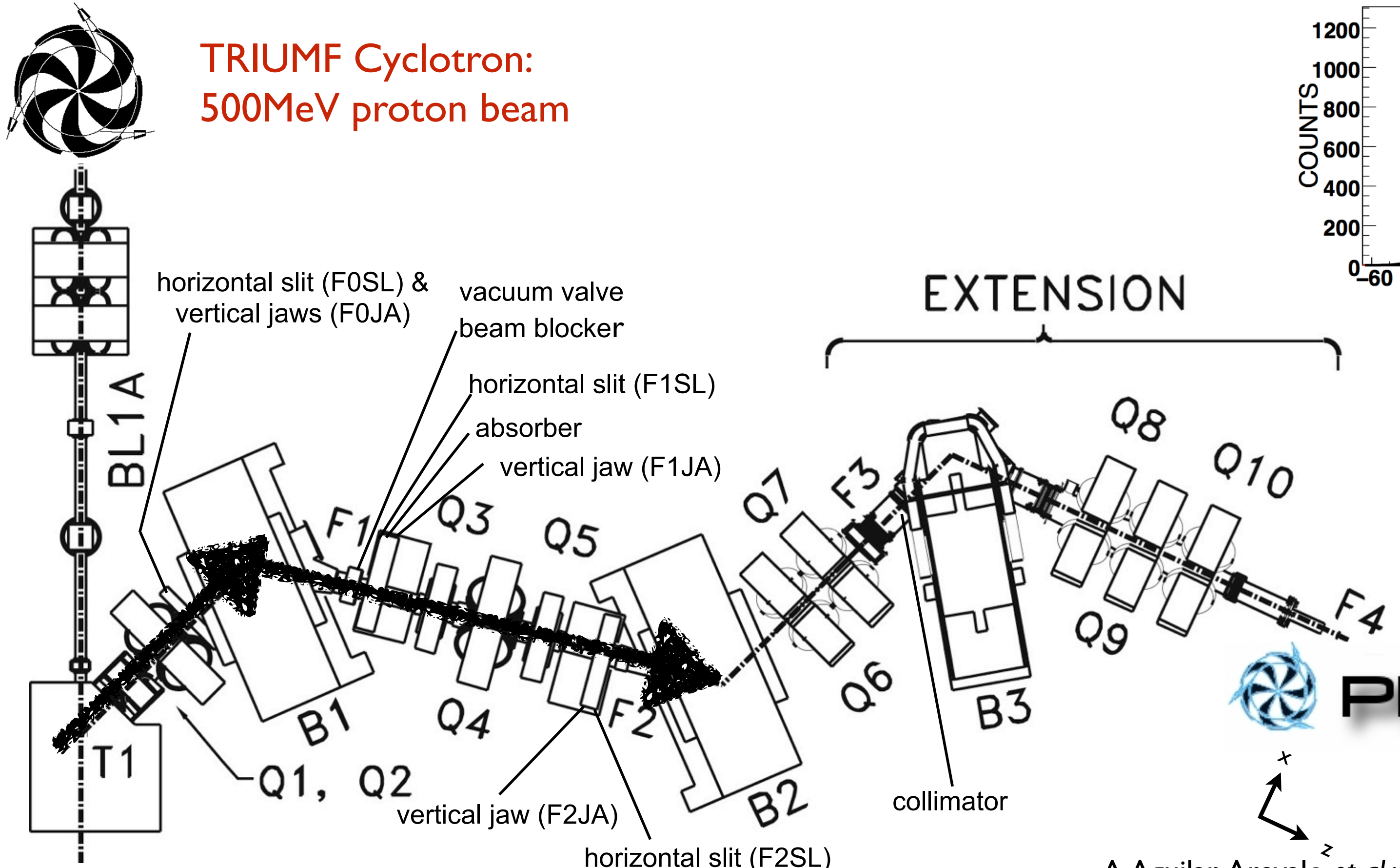

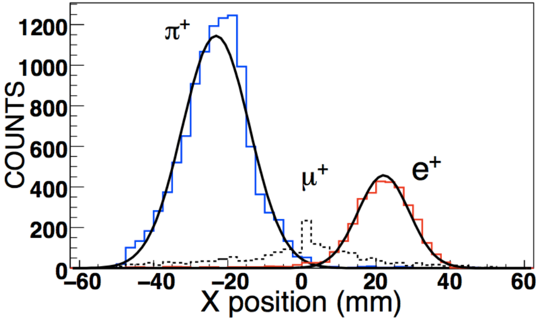

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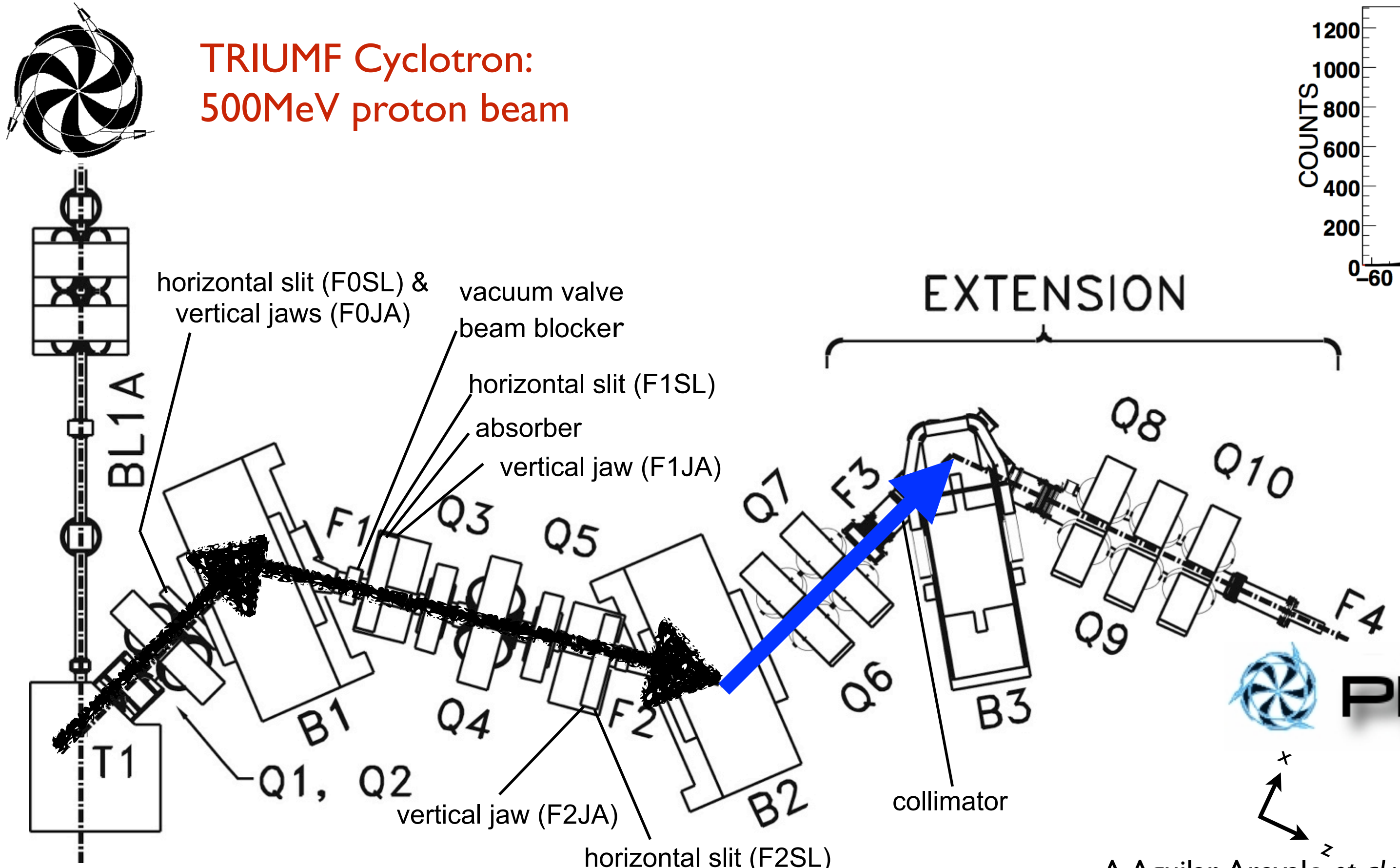

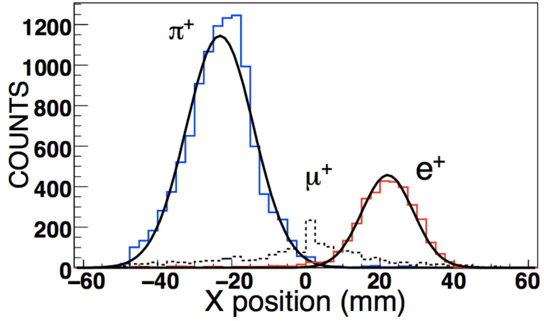

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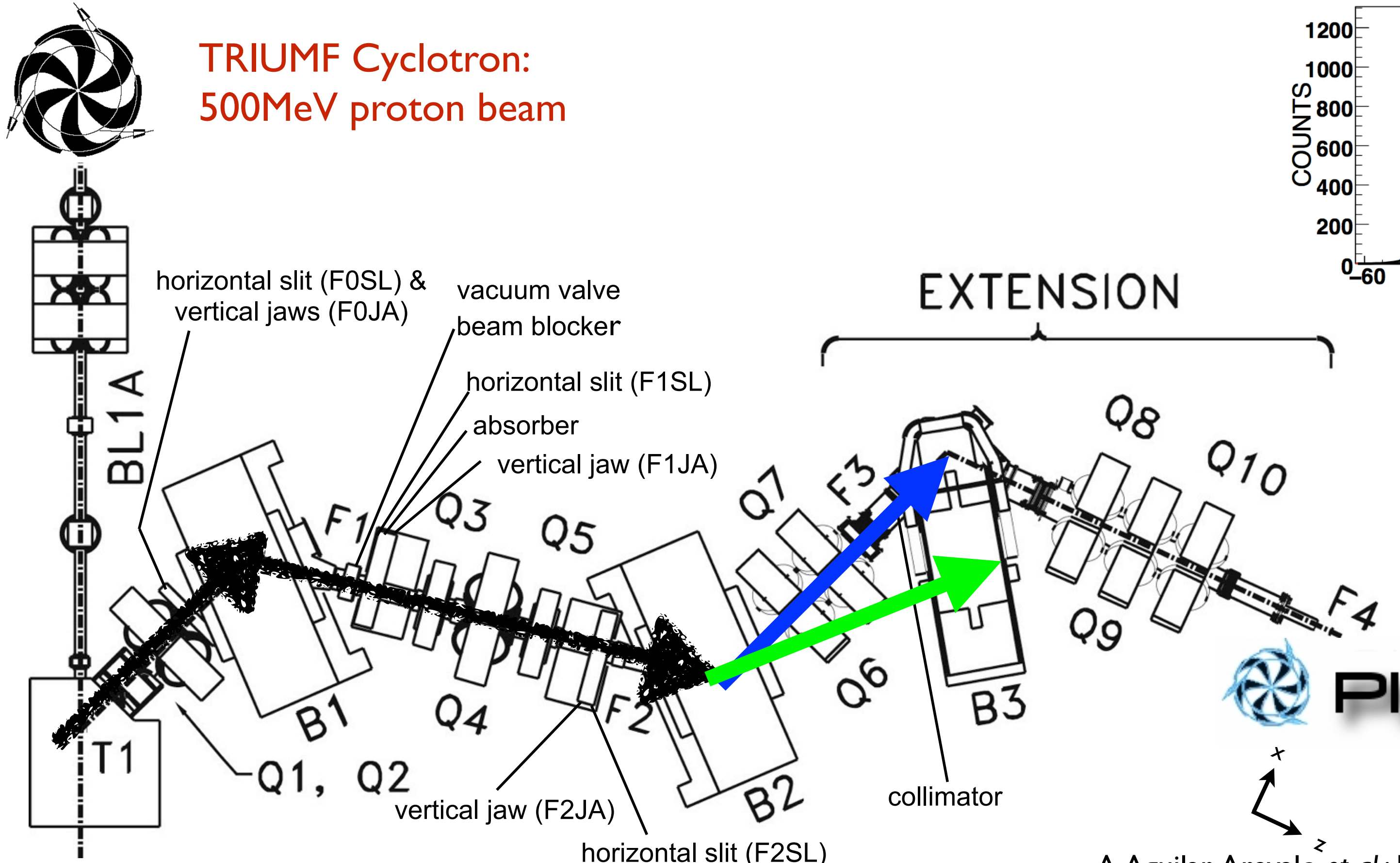

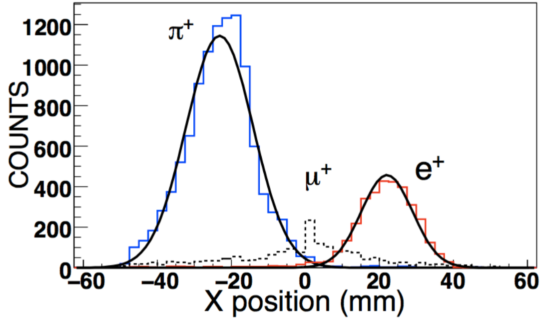

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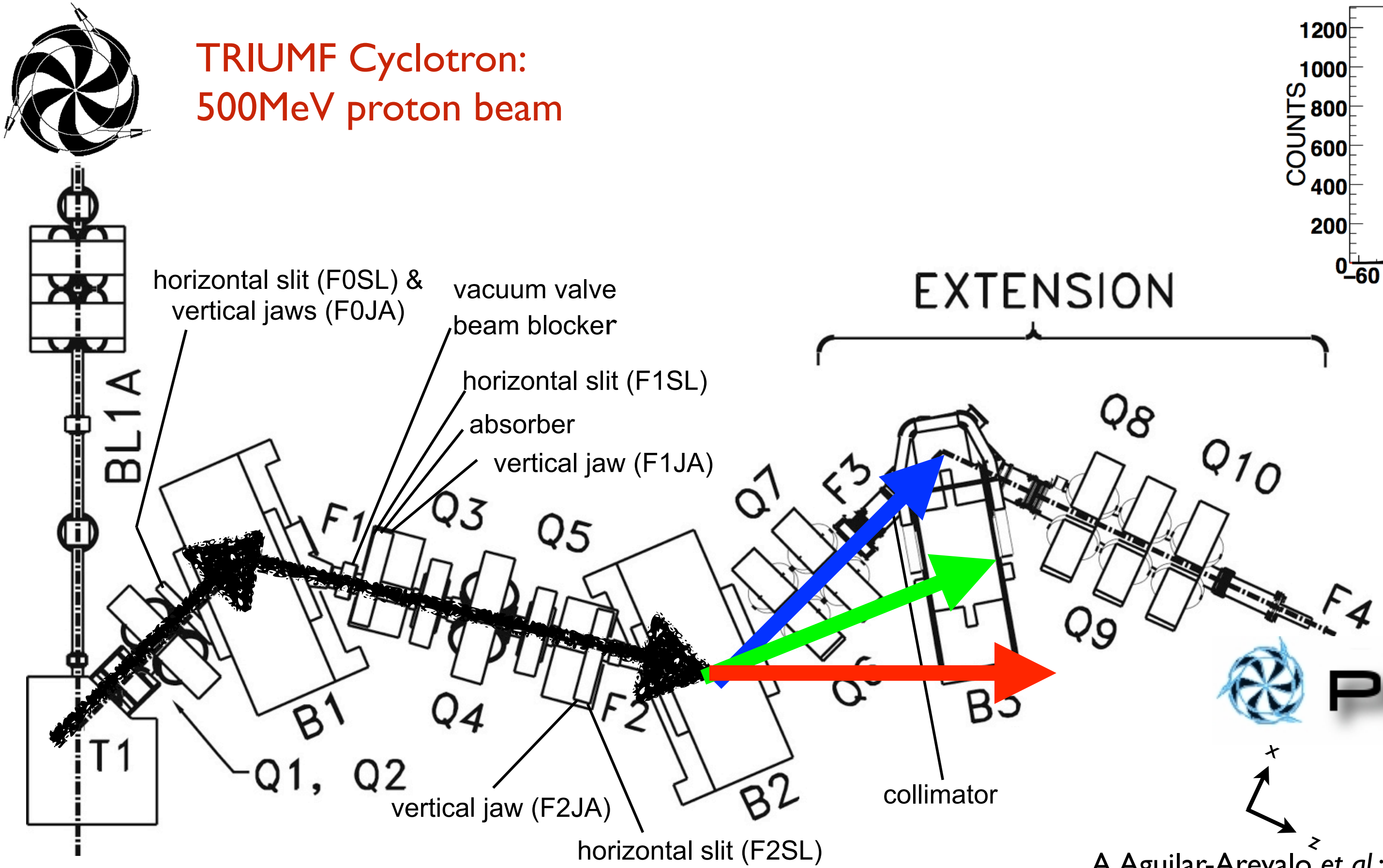

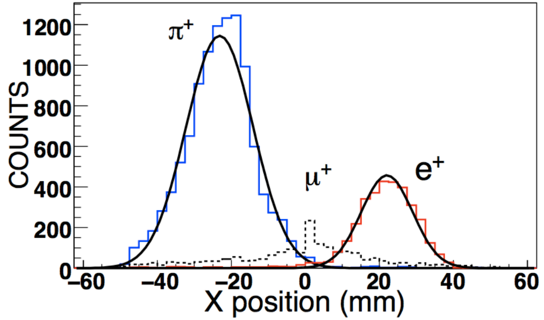

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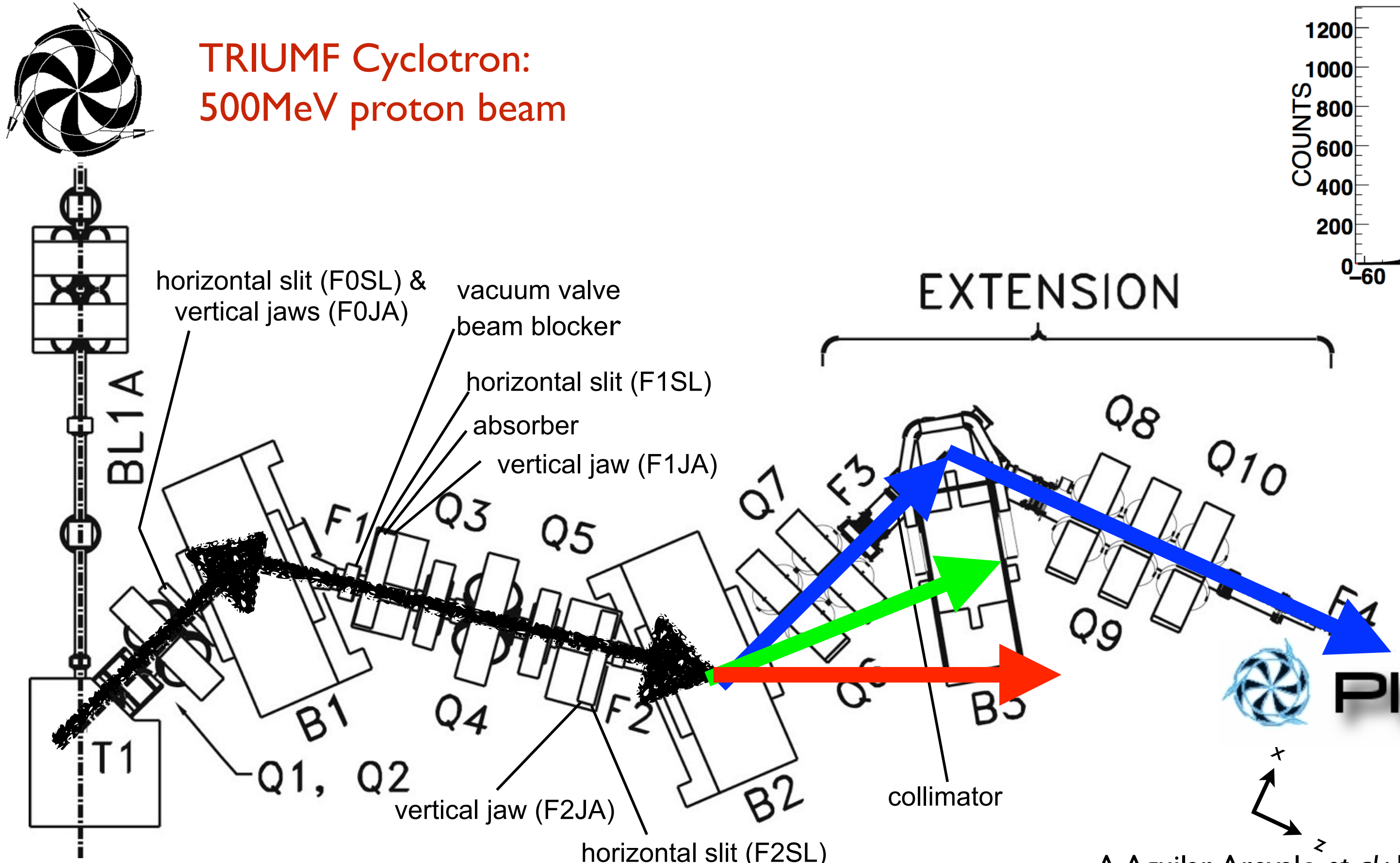

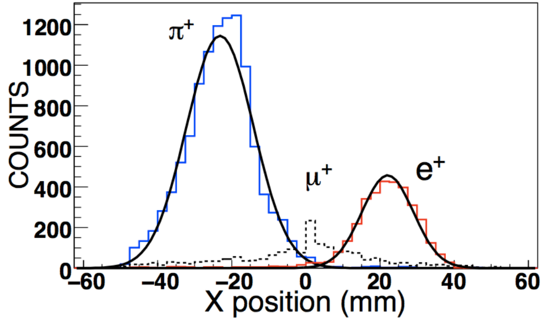

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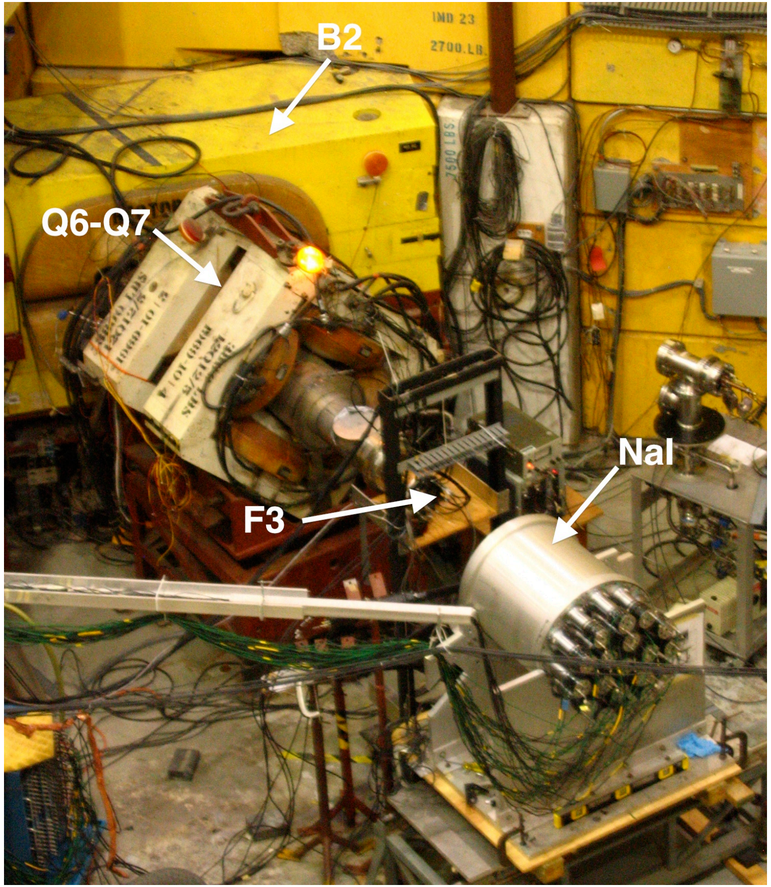
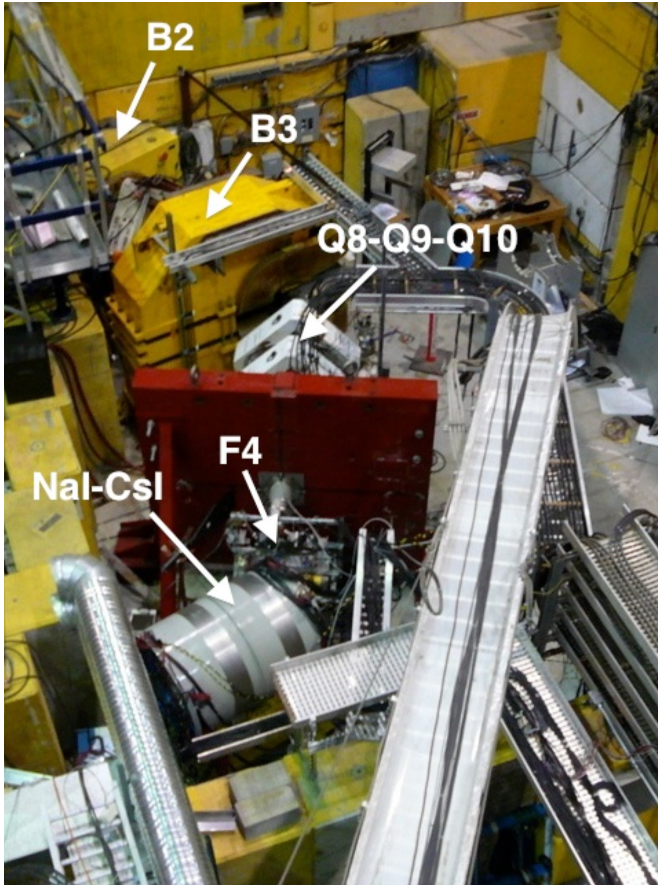




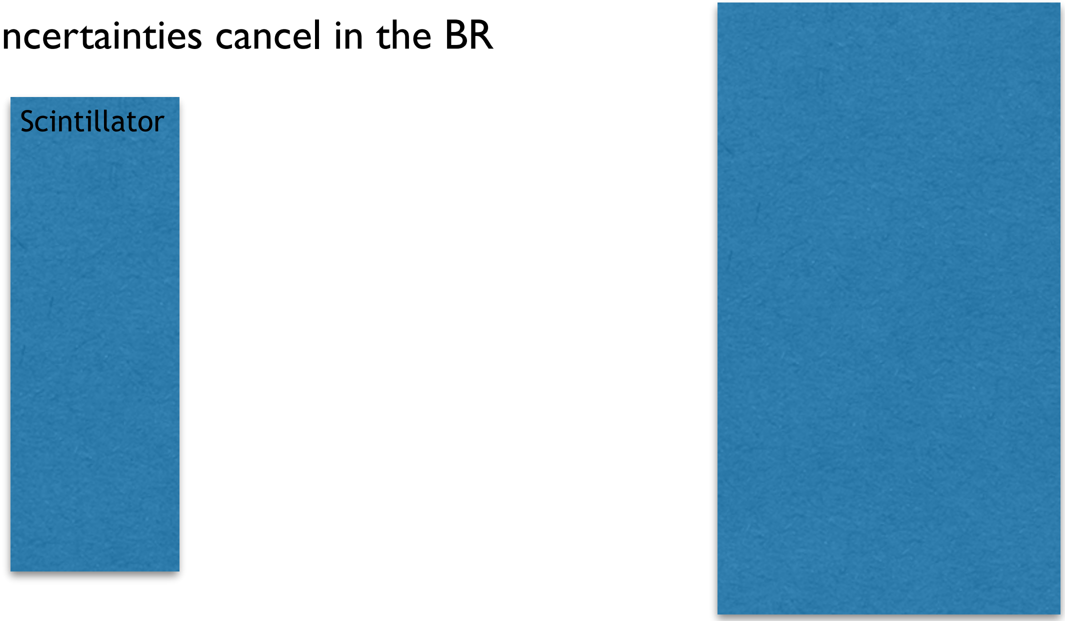
Stopped Pion Technique

Idea: Stop the pions in an active target

Measure the decay positrons from the two decays

Advantages:

- Simultaneous measurement (**energy and time**)
- Same acceptance and conditions
- Systematic uncertainties cancel in the BR



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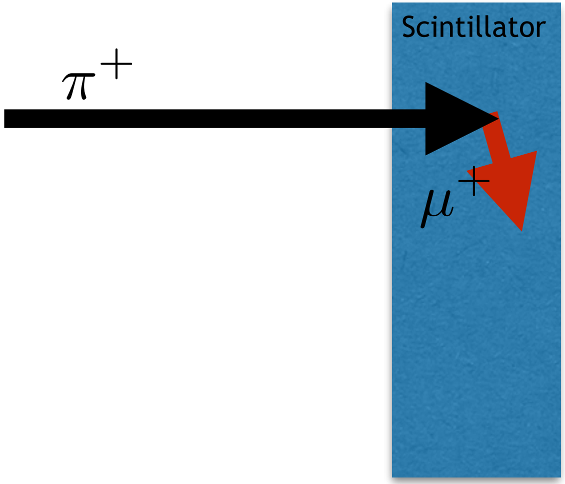

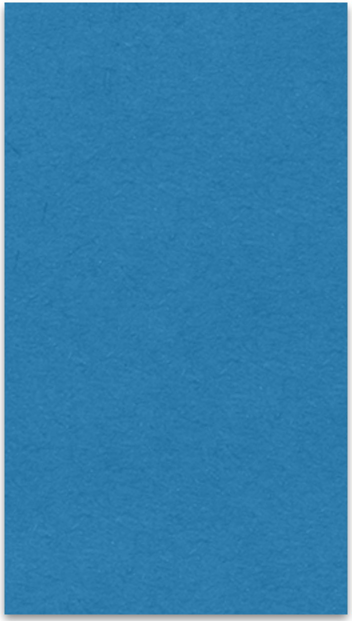

Stopped Pion Technique

Idea: Stop the pions in an active target

Measure the decay positrons from the two decays

Advantages:

- Simultaneous measurement (**energy and time**)
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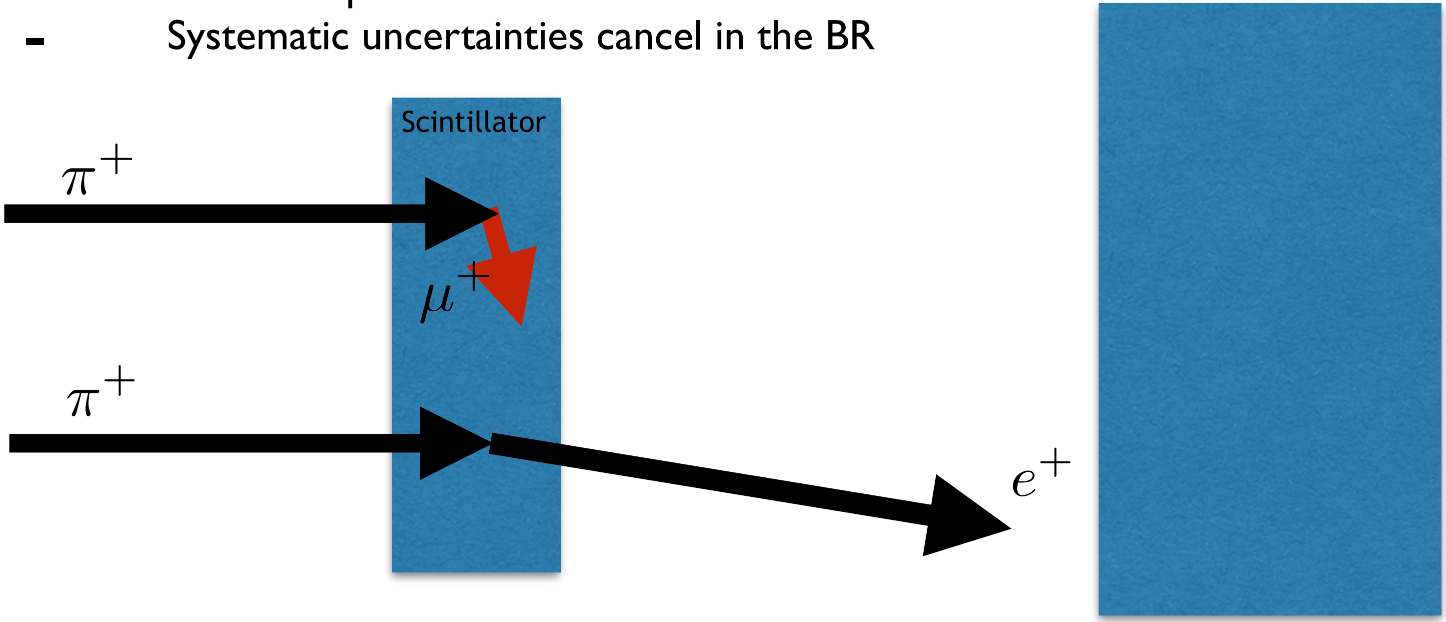

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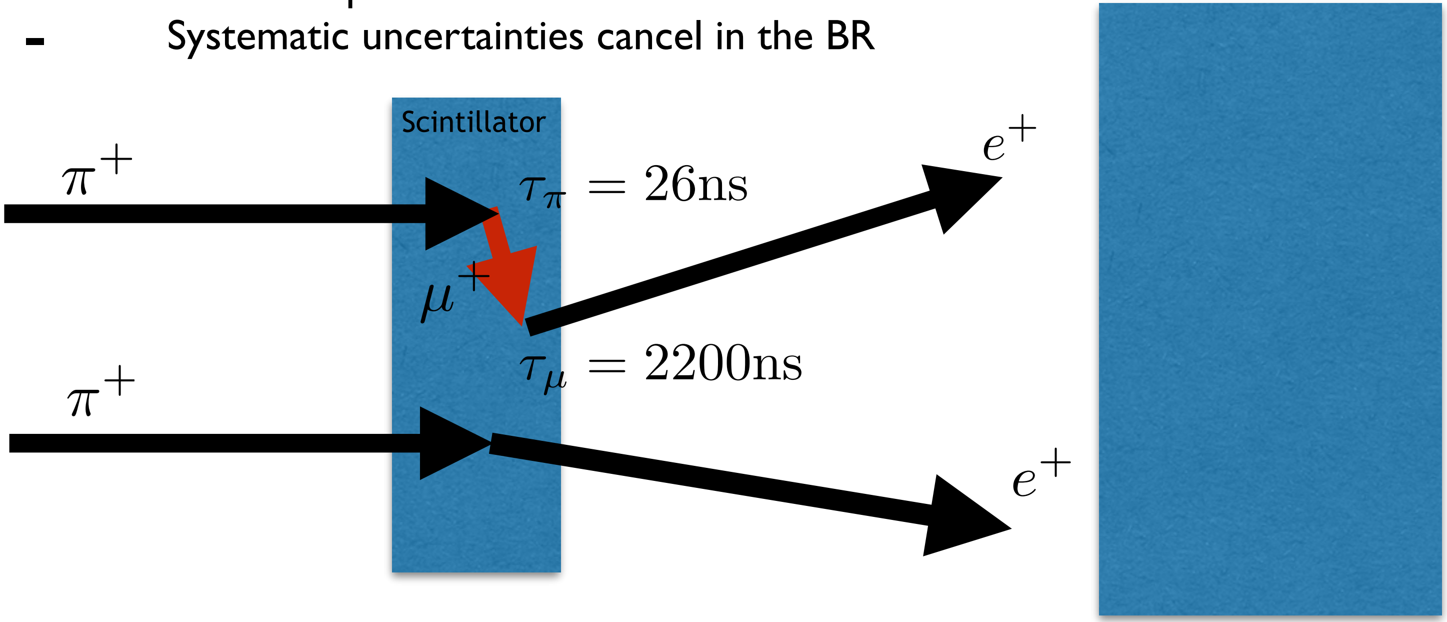

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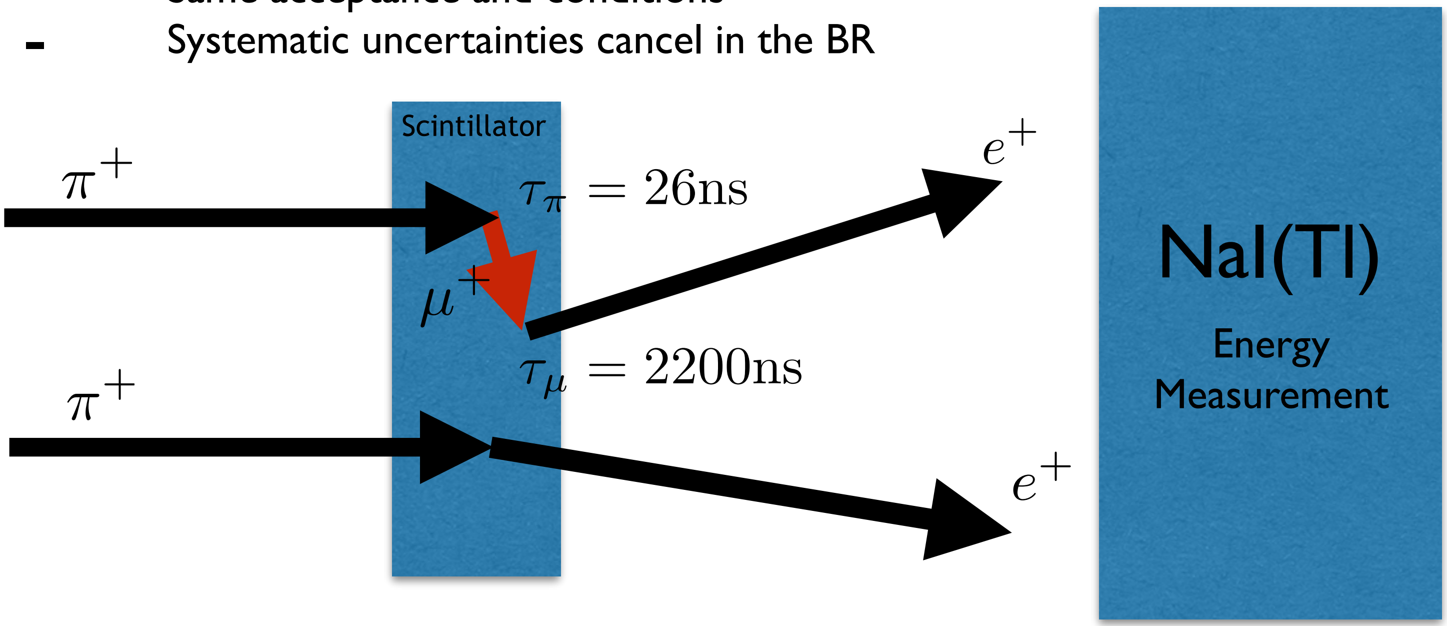

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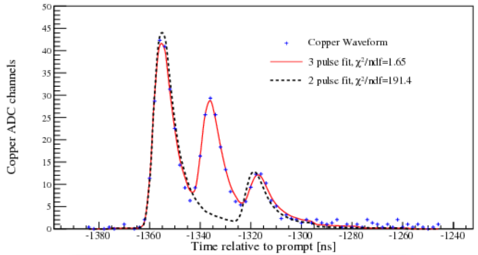

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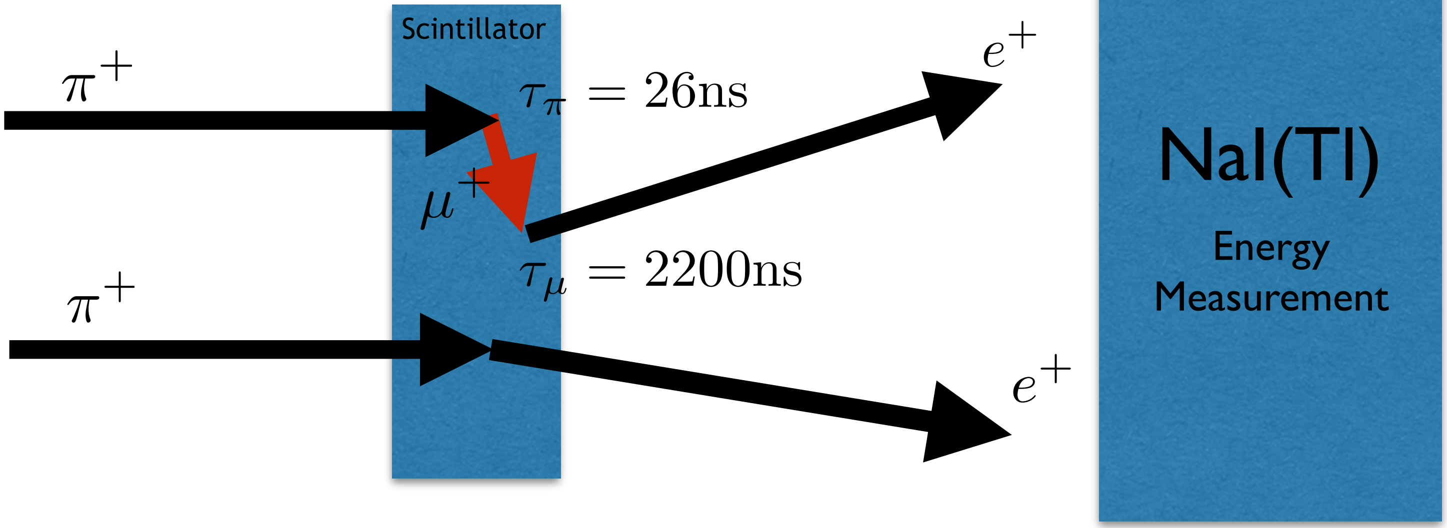

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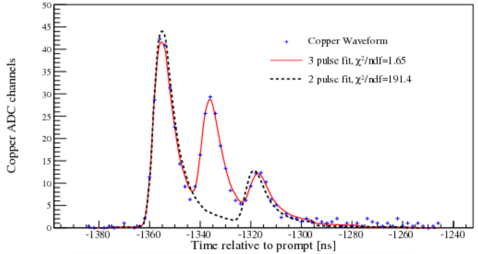
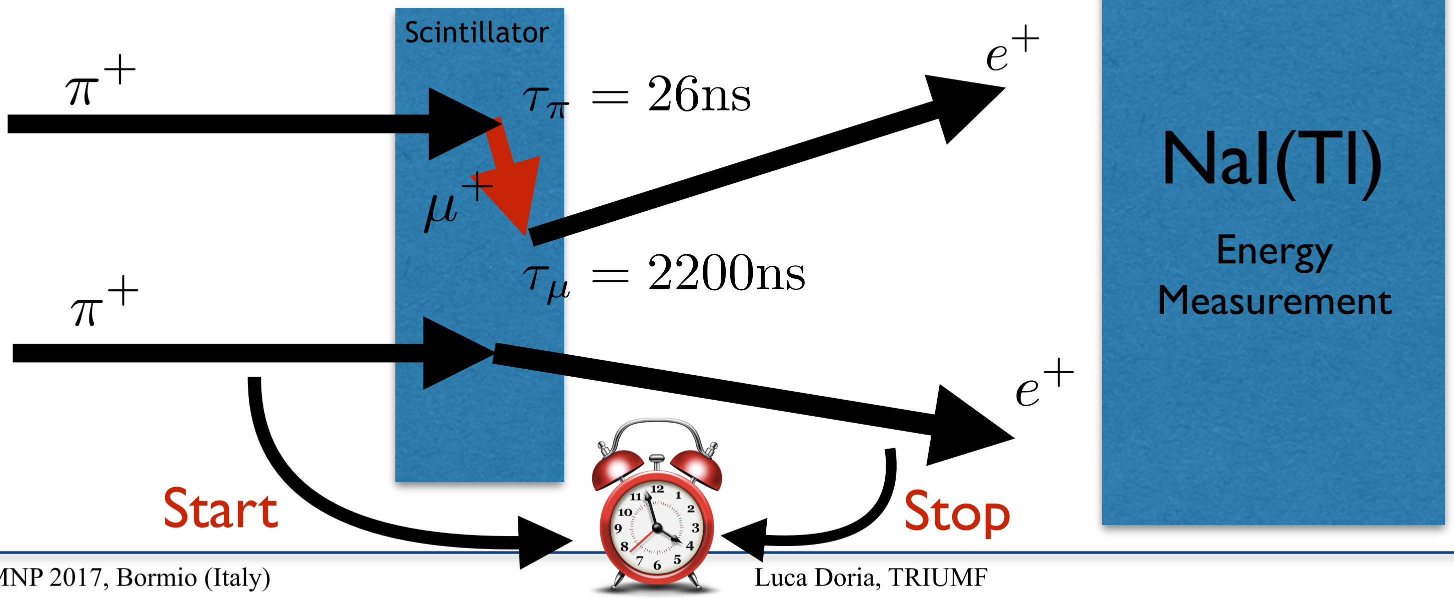




Experimental Setup

Beam:

60kHz pions @ 75 MeV/c

$$\pi : \mu : e = 85 : 14 : 1$$

Detector:

Acceptance: 20%
Plastic Scintillators
NaI(Tl) + CsI Calorimeter
Wire Chambers
Silicon Strips

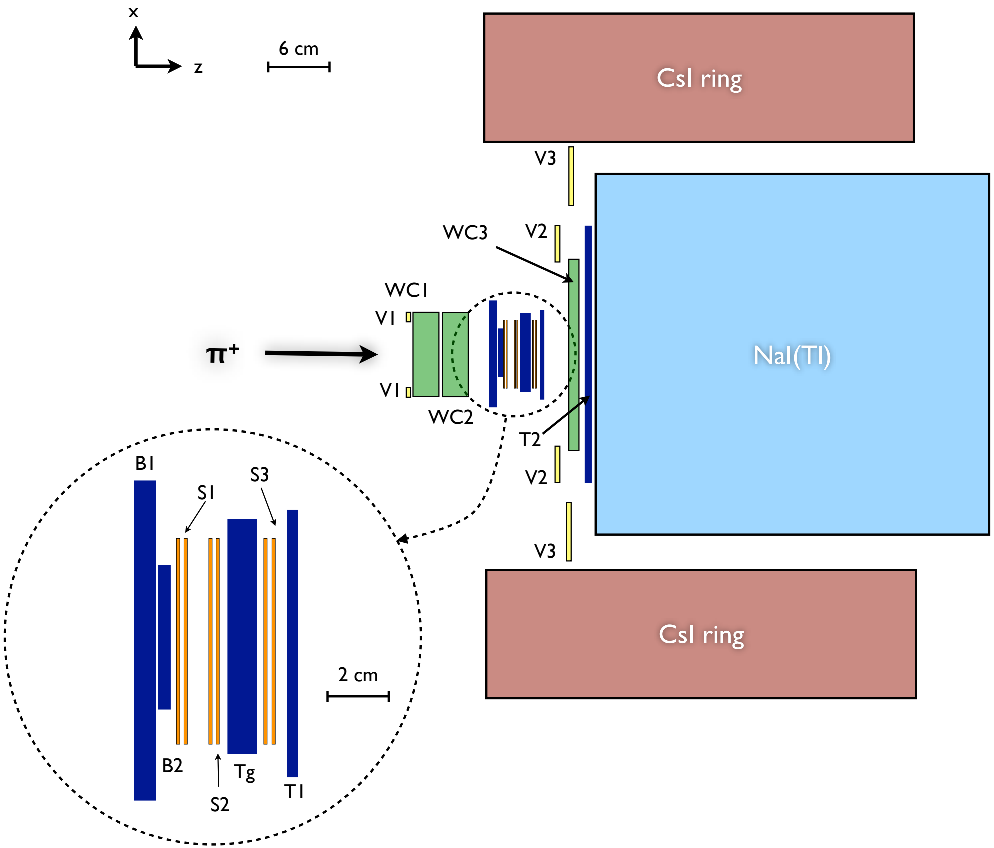
Energy resolution:

2.2% FWHM @ 70MeV

Temperature Stabilization

Data taking:

2009-2012



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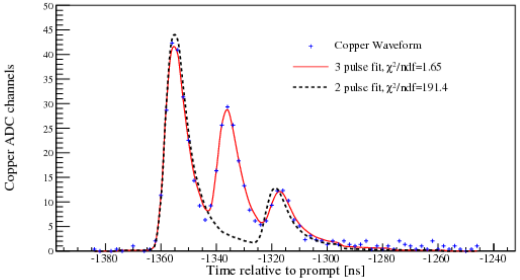
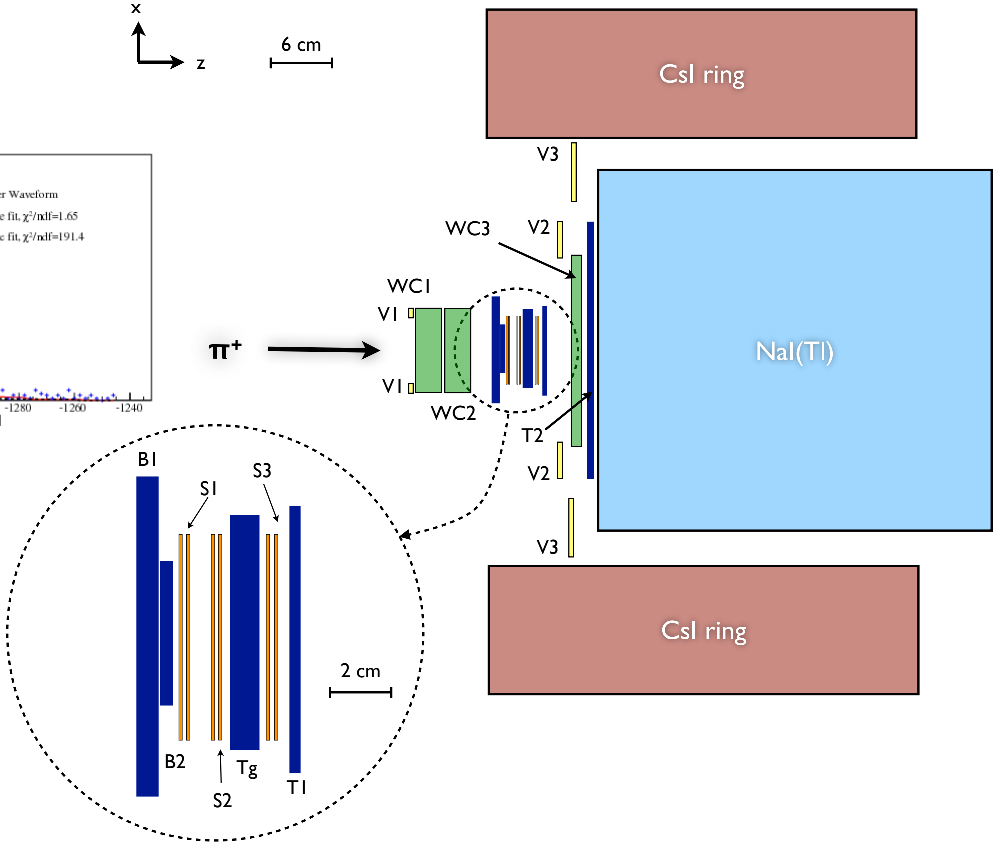
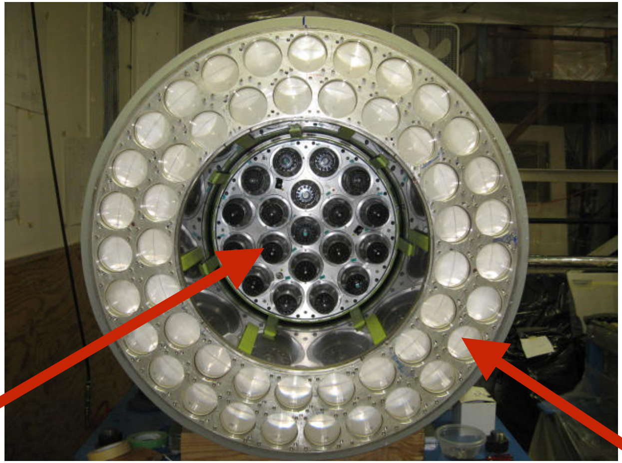
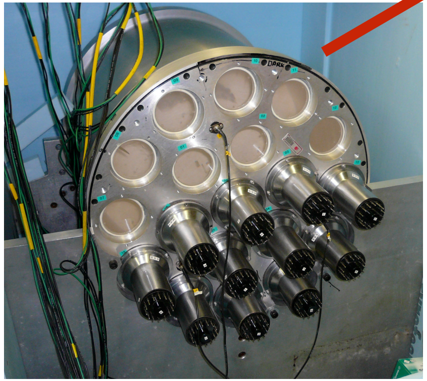


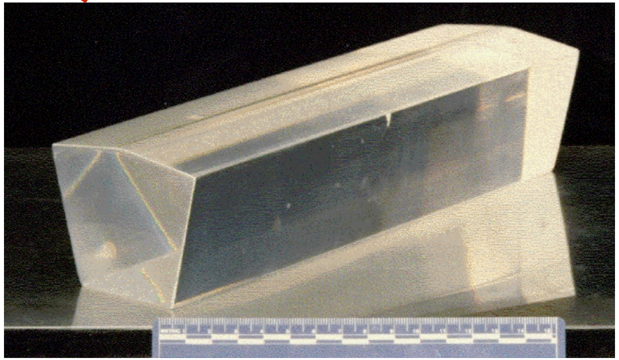


"BiNa":
Monolithic 48x48cm
NaI(Tl) crystal
19-PMTs readout

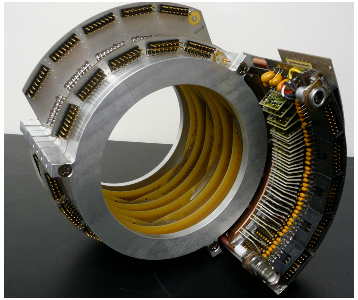


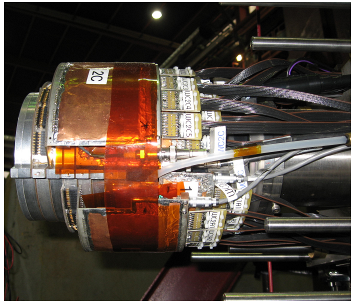


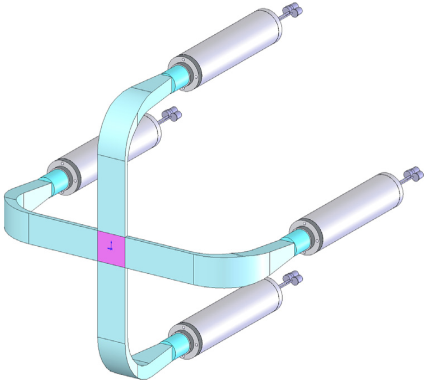
97 pure CsI crystals
single PMT readout

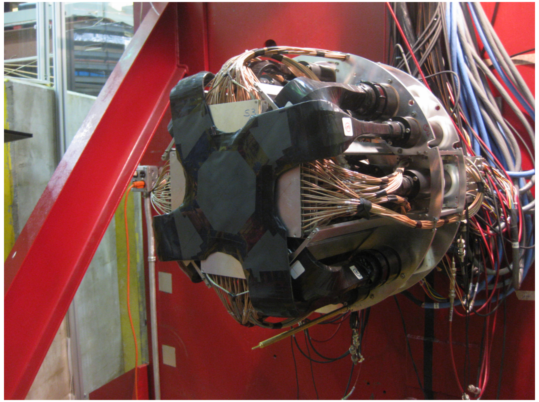


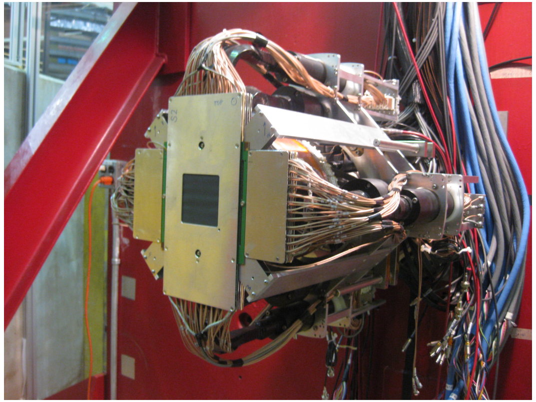
Tracking and Time/Energy Detectors

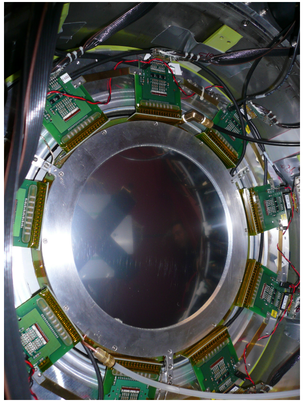












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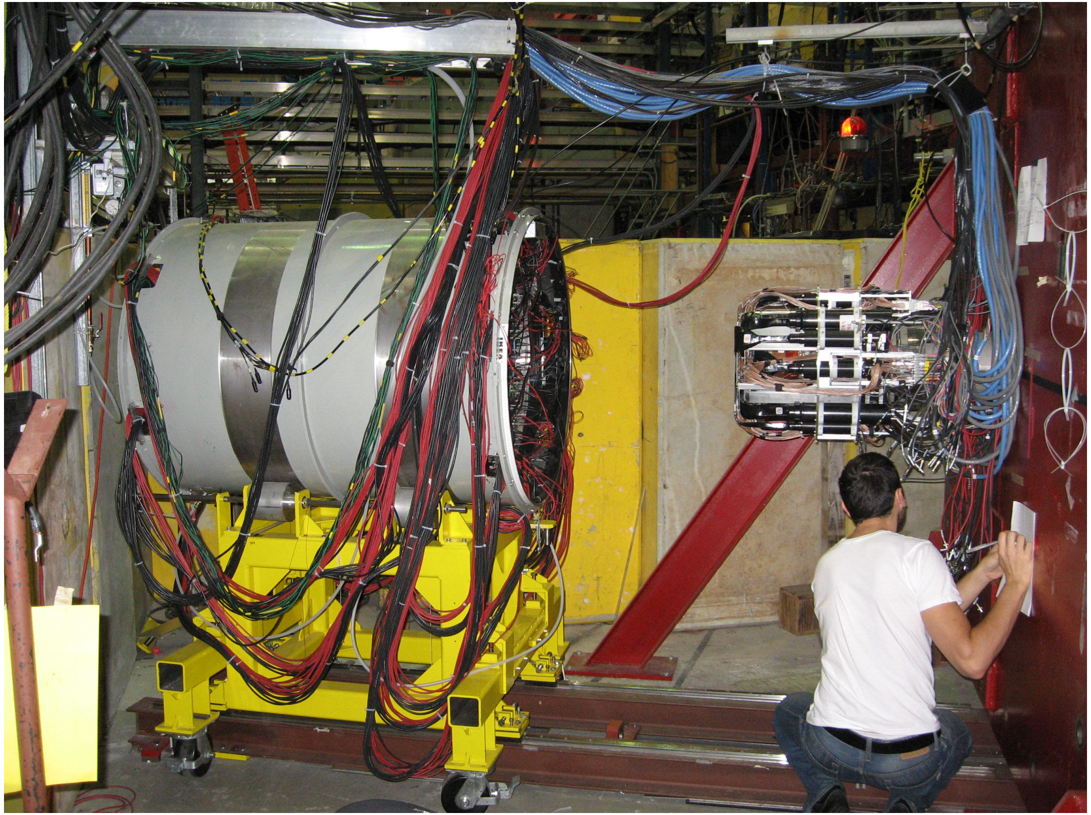


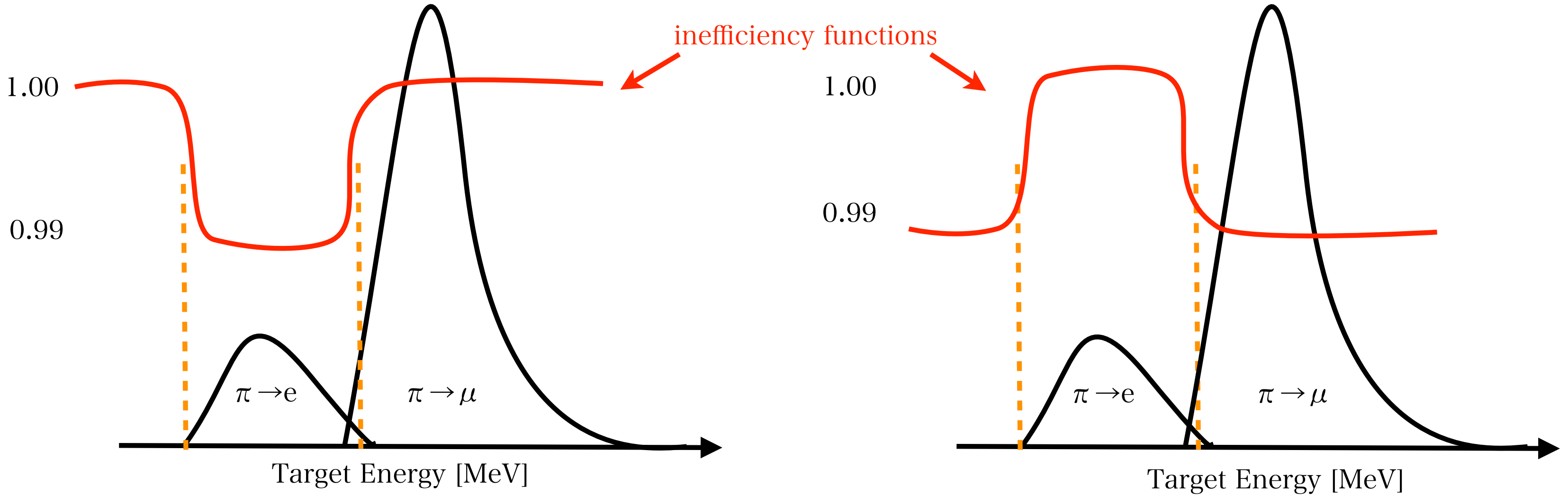
π^+ Beam

A.Aguilar-Arevalo *et al*: Nucl. Instr. Meth. A79, 38-46 (2015)

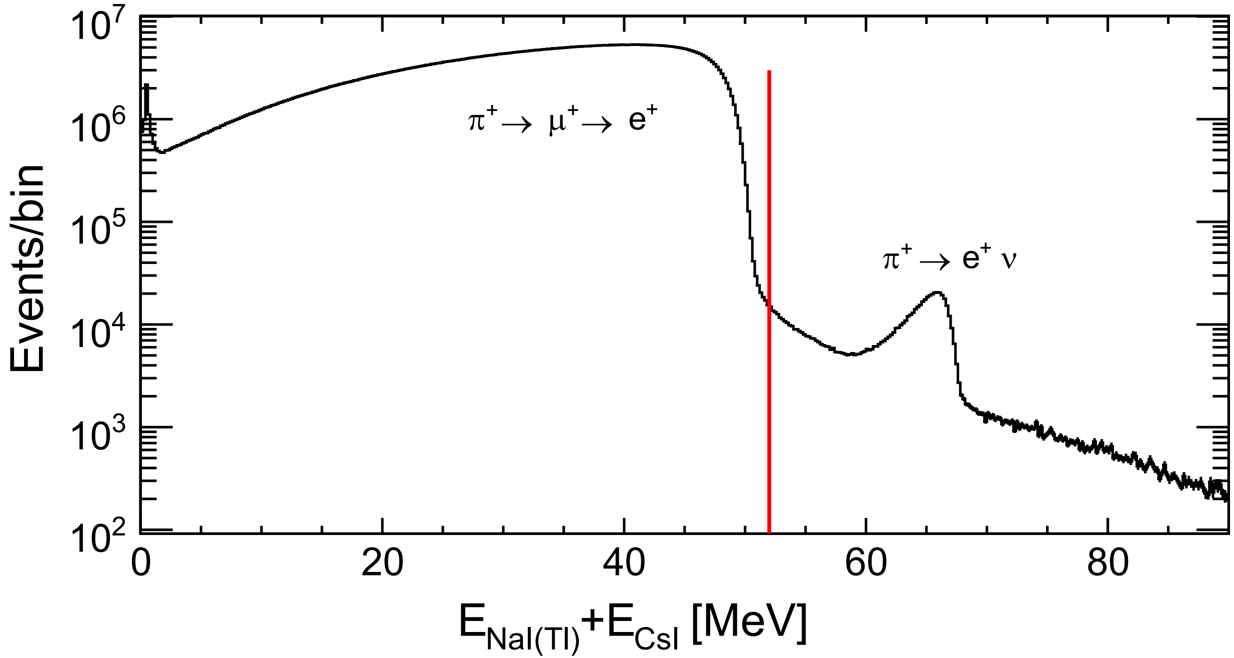
Data Analysis

Blind Analysis

- **Avoid biases in precision experiments!**
- Blinding procedure done before starting the analysis.
- One of the two decays is slightly suppressed: BR changes.
- Random and unknown inefficiency factor
- "Unblinding" only when the Collaboration agrees on the analysis procedure and systematic error estimates.

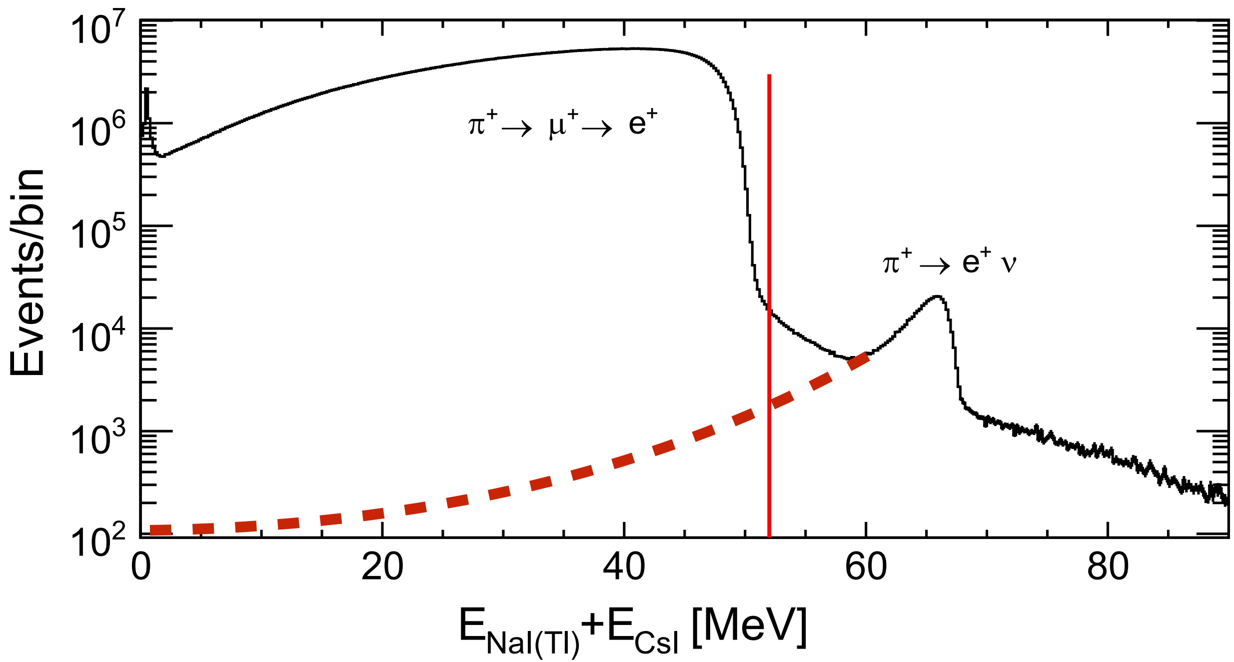


Energy Spectrum



- Low Energy Tail
- Pileup

Energy Spectrum



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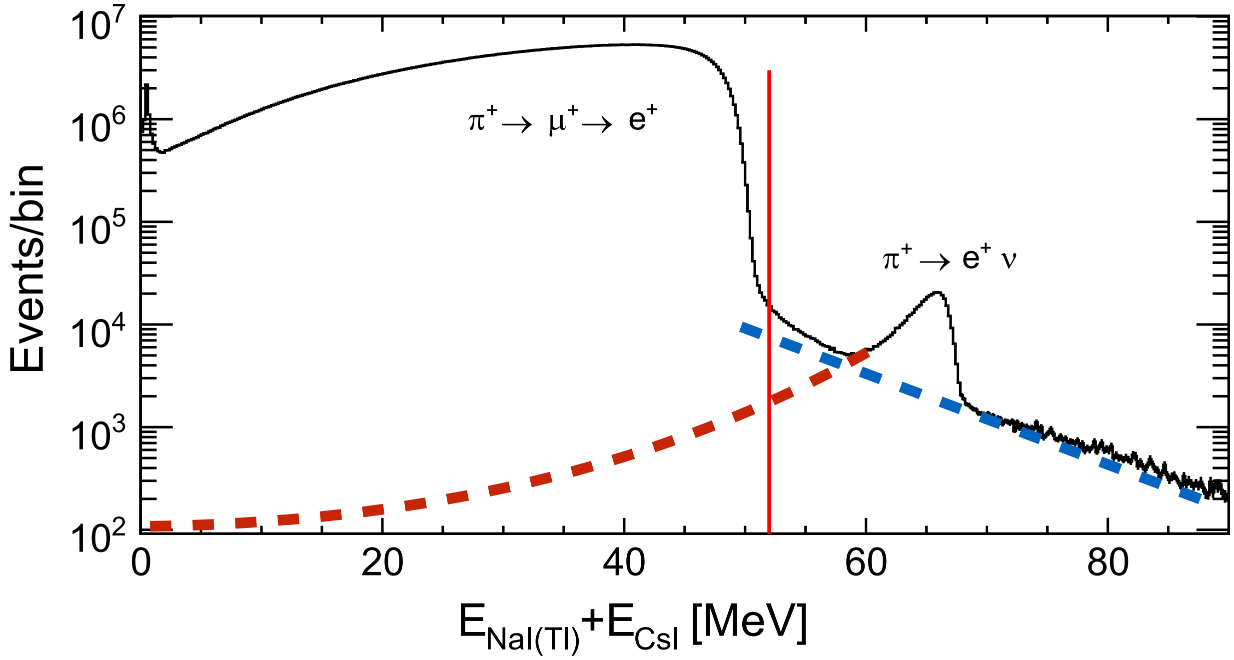

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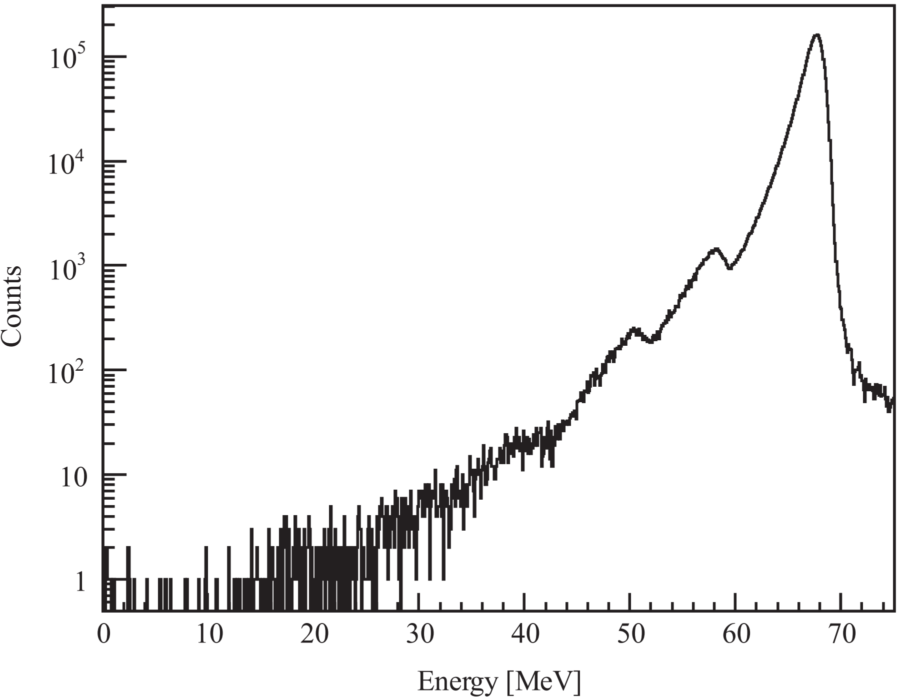
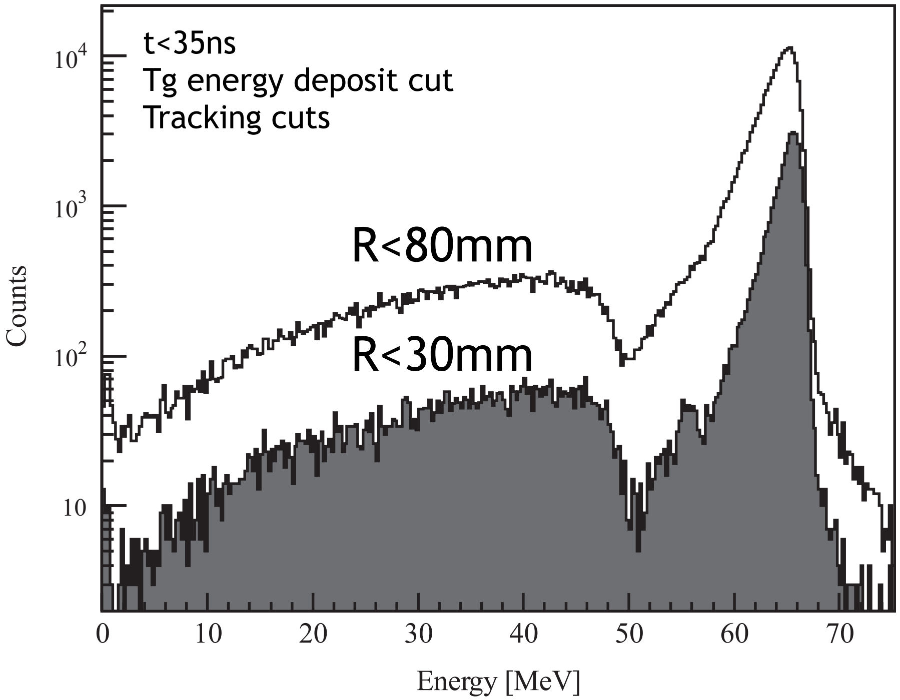


Positron Beam: Upper limit



Suppressed Spectrum: Lower Limit

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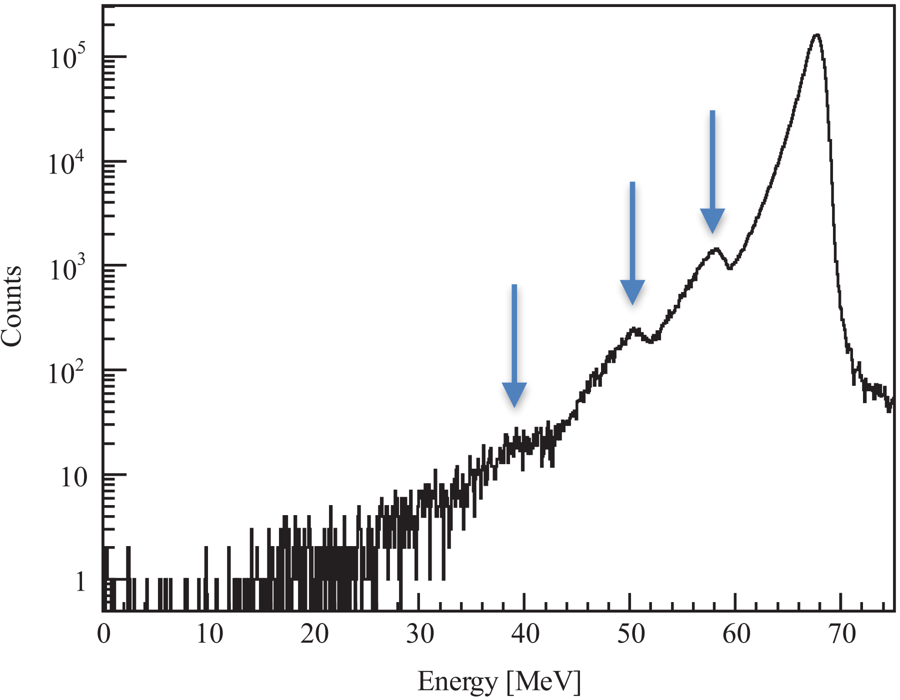

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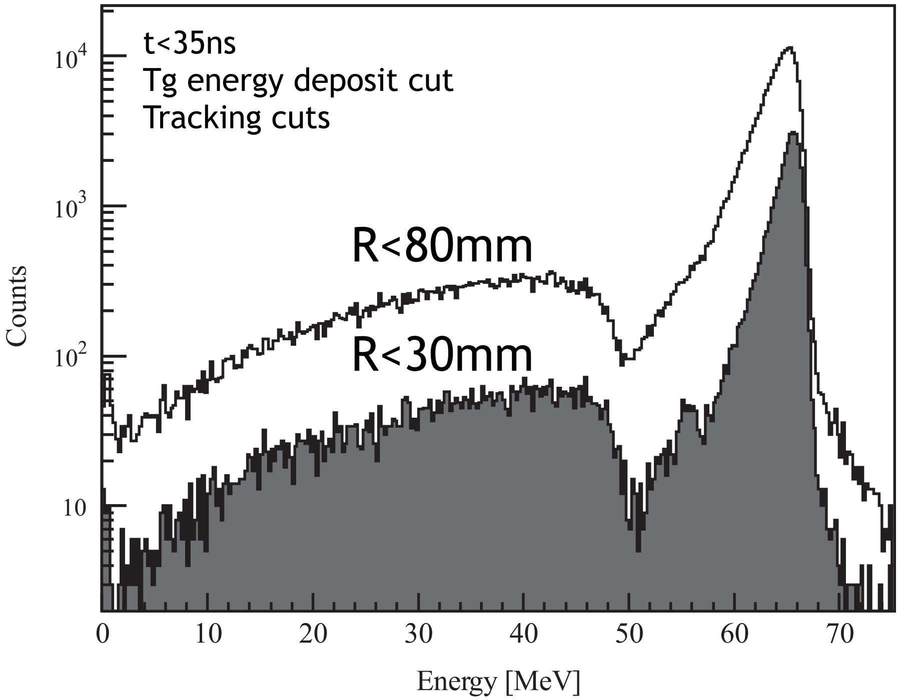

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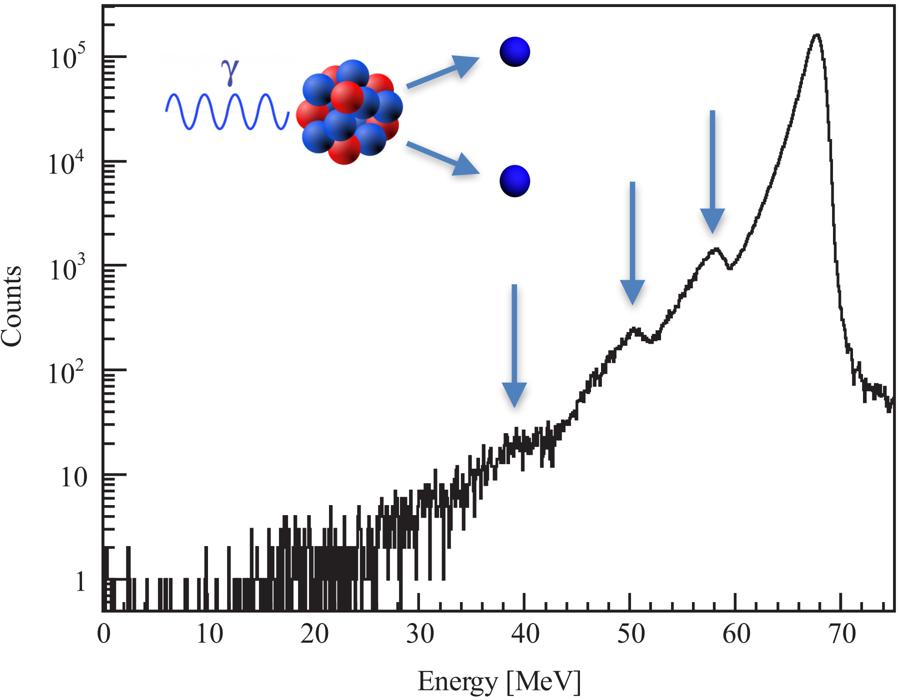

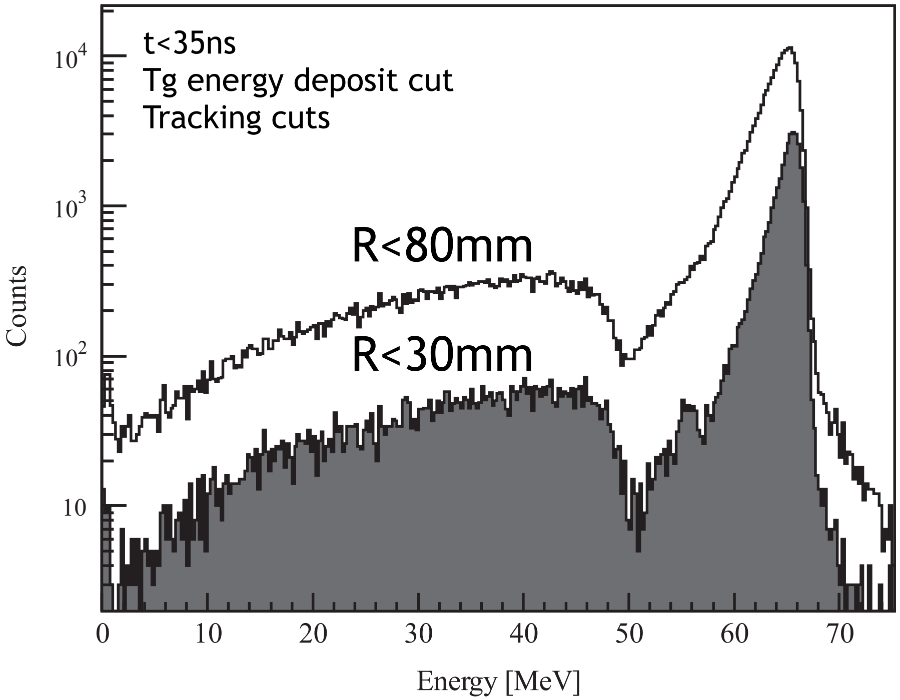

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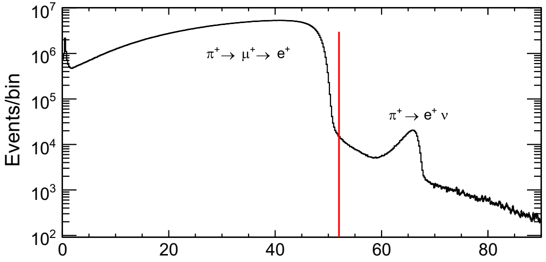
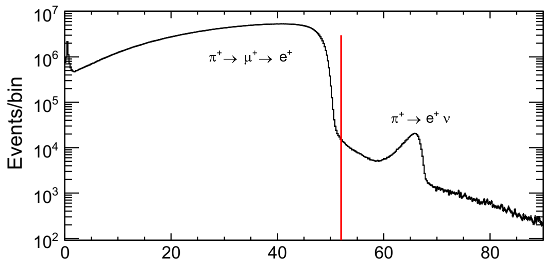
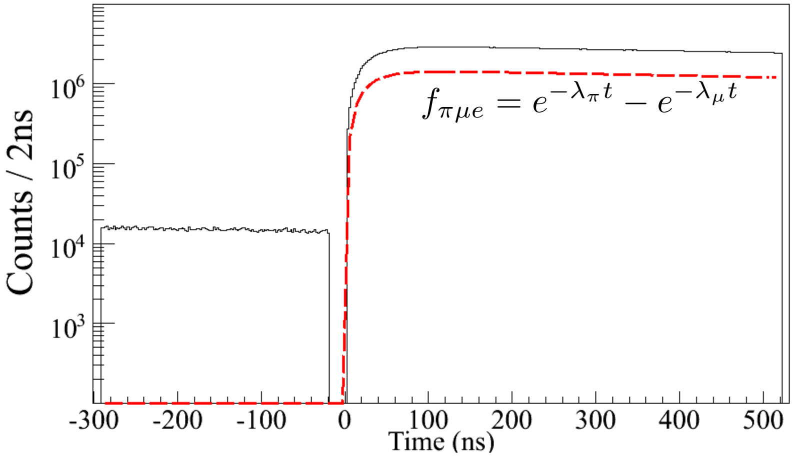

Events/bin
10^7
10^6
10^5
10^4
10^3
10^2
0
20
40
60
80
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$
$\pi^+ \rightarrow e^+ \nu$

Time Spectrum Fit



E<52MeV

E>52MeV



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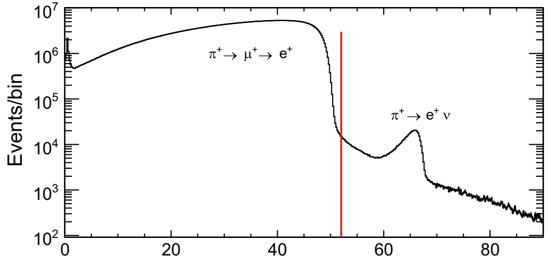

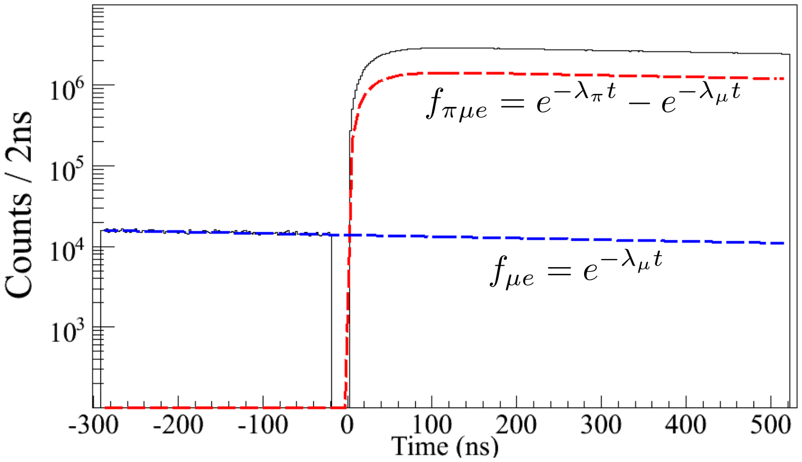

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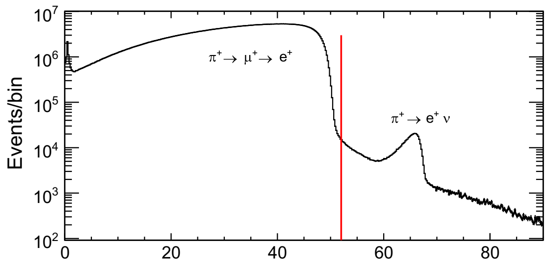

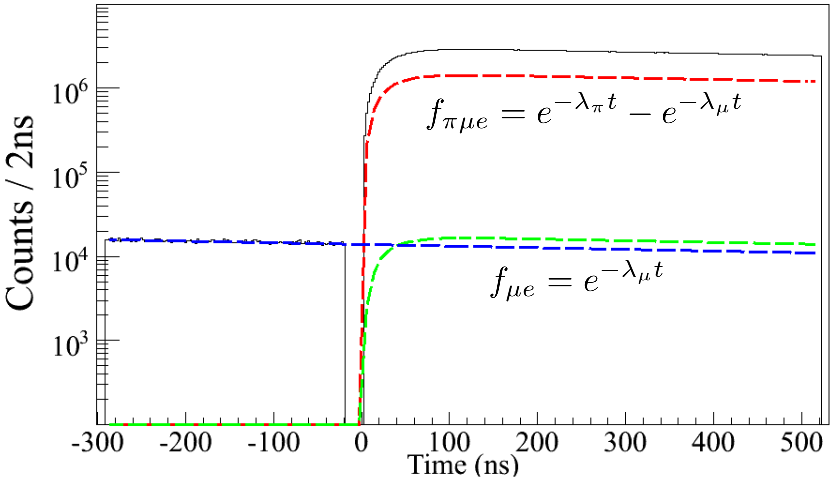

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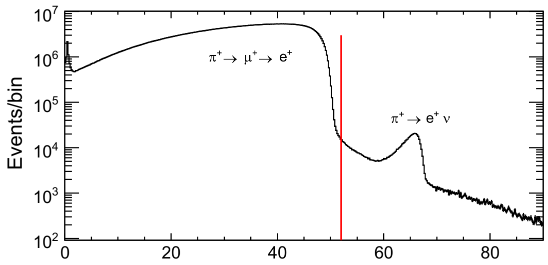

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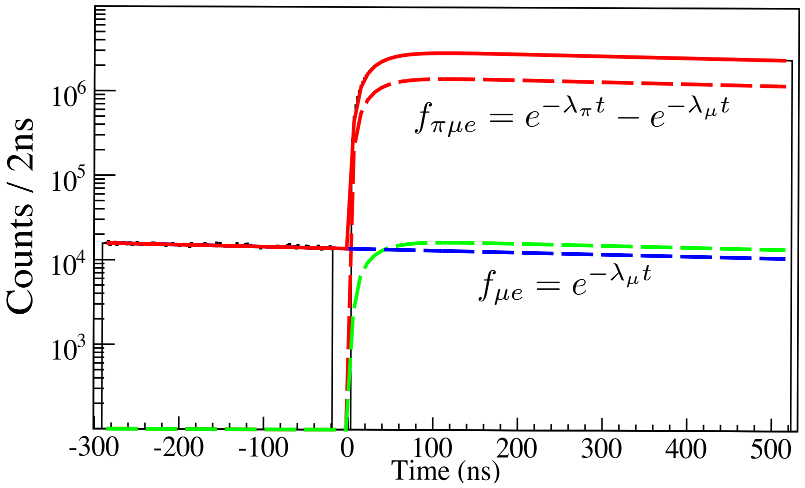

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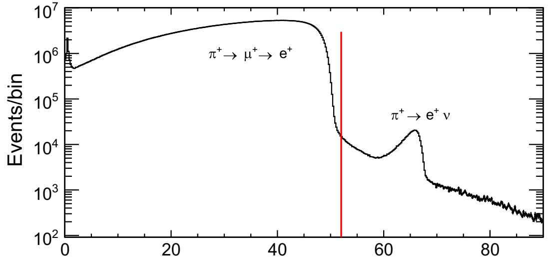

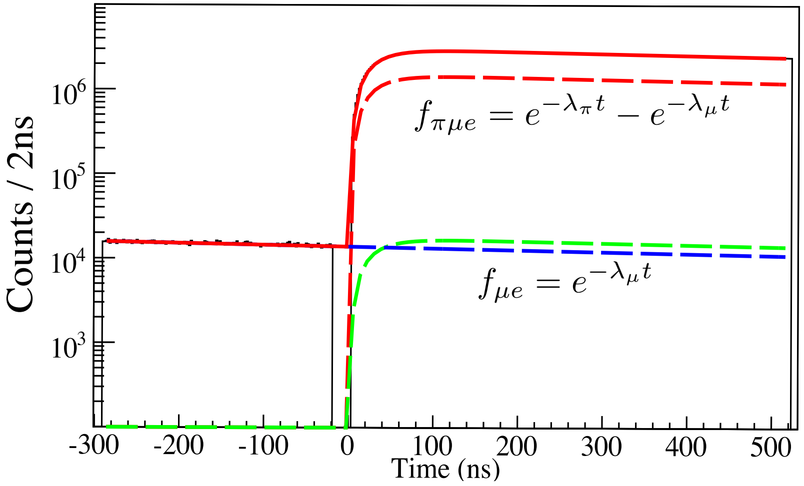

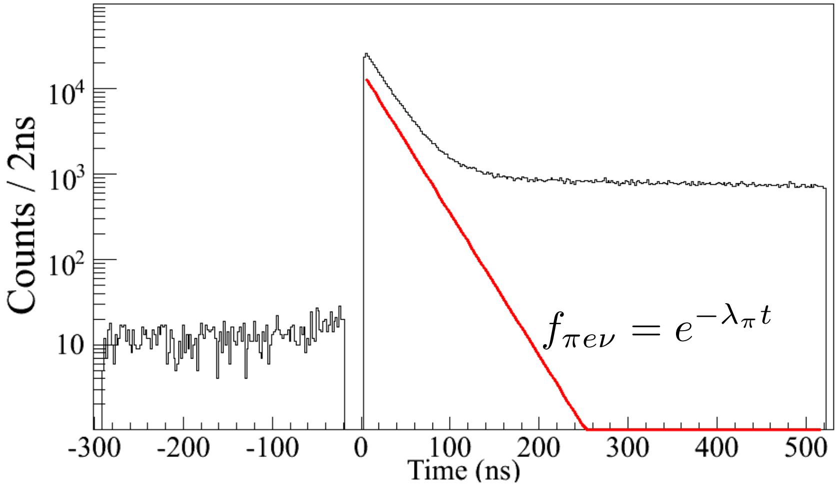

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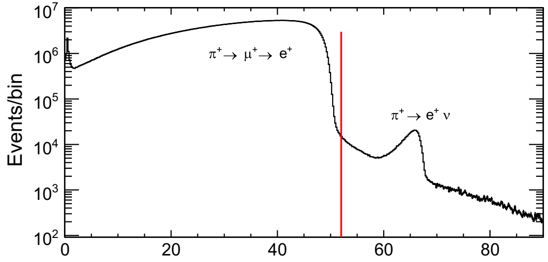

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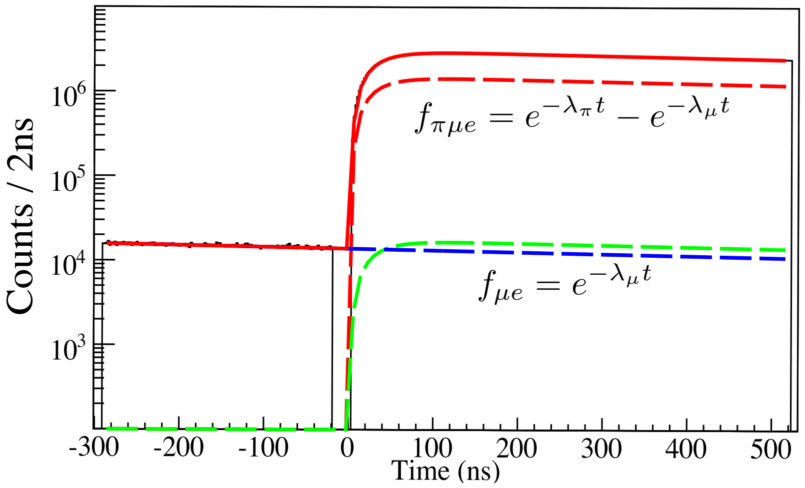

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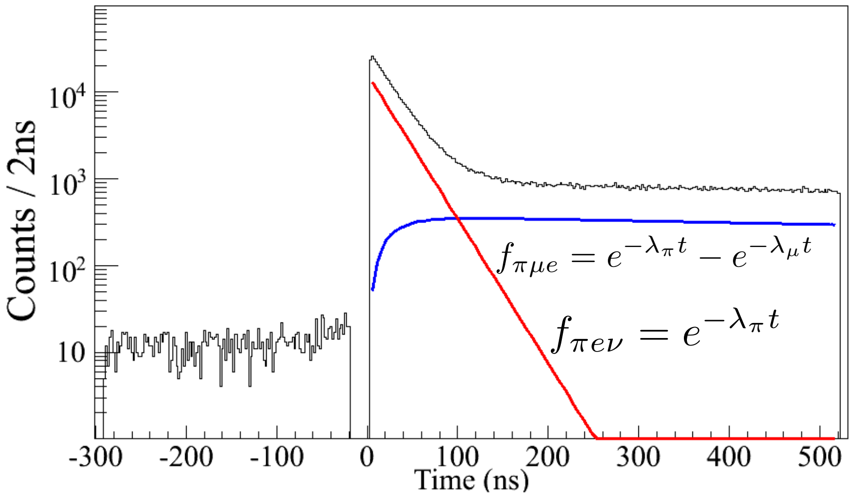

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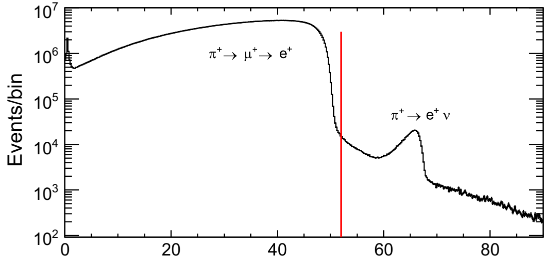

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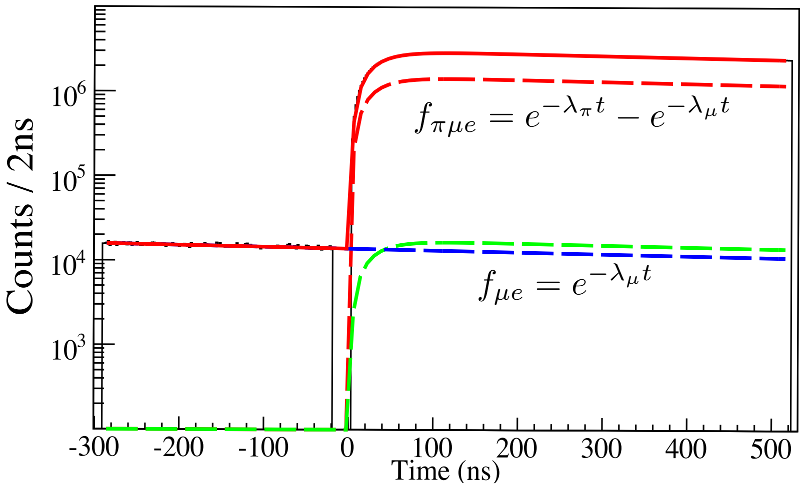

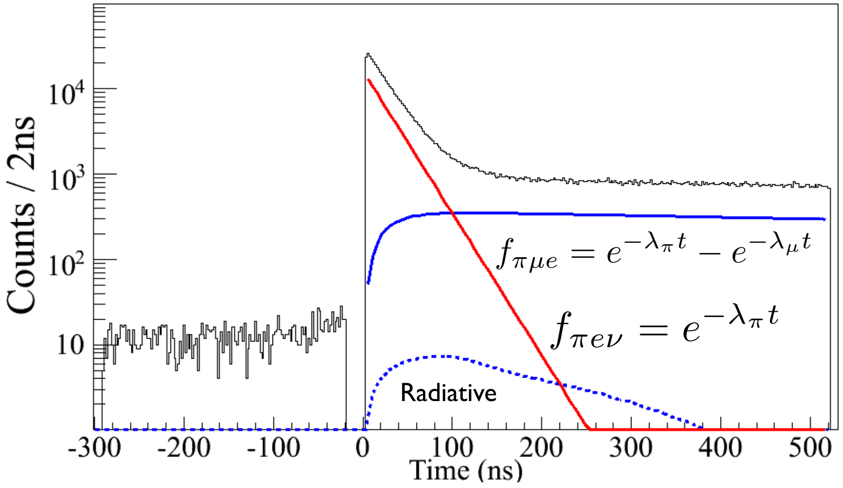

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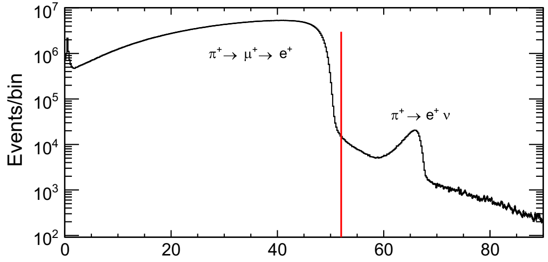

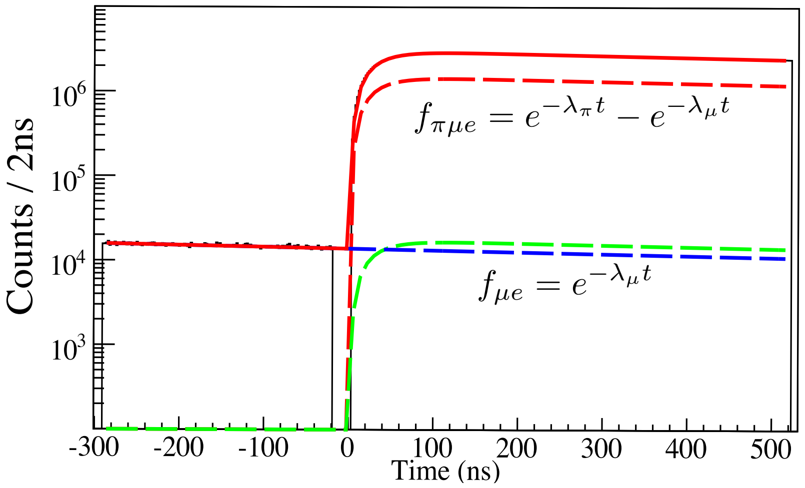

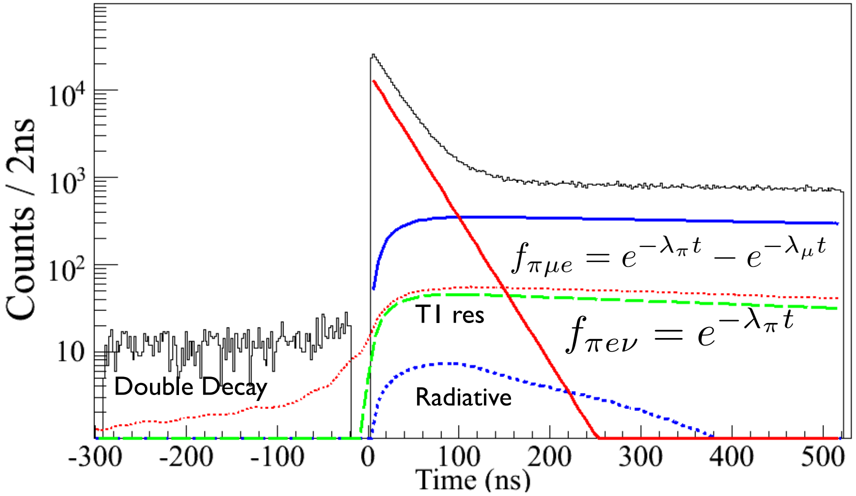

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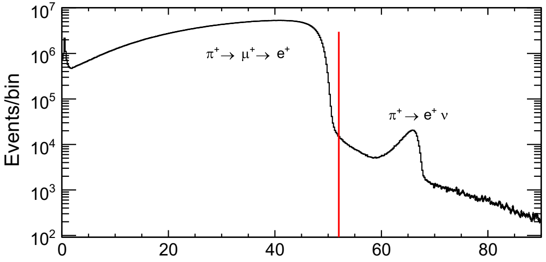
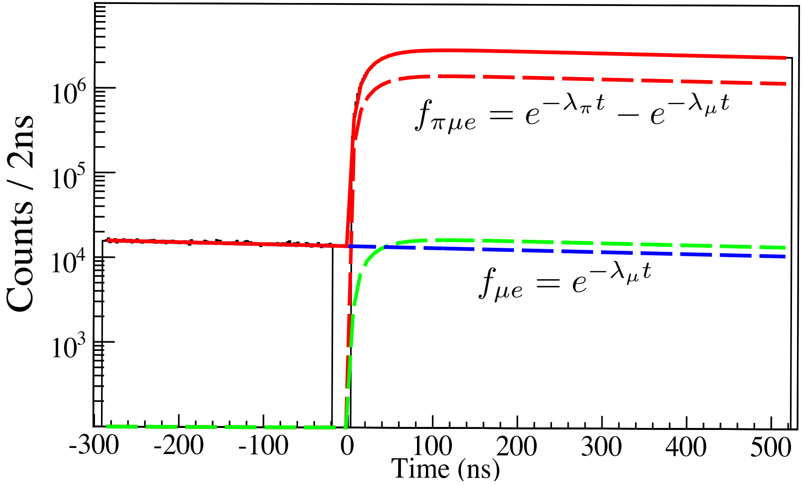
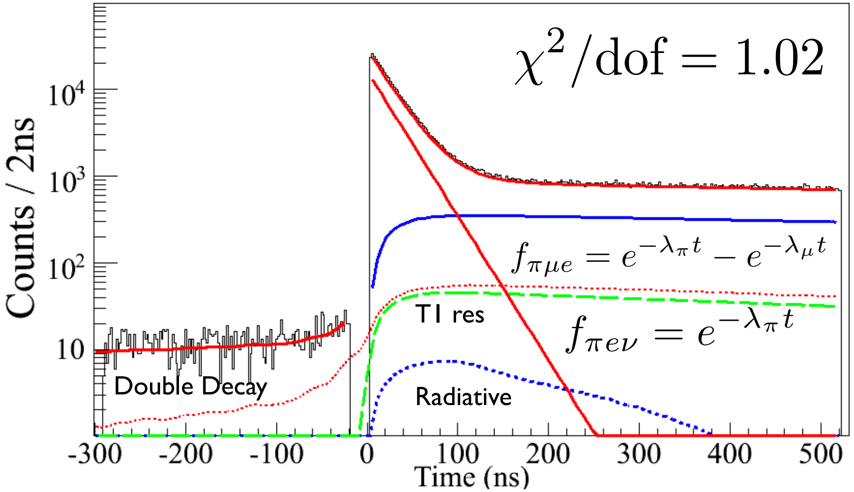






Systematic Checks

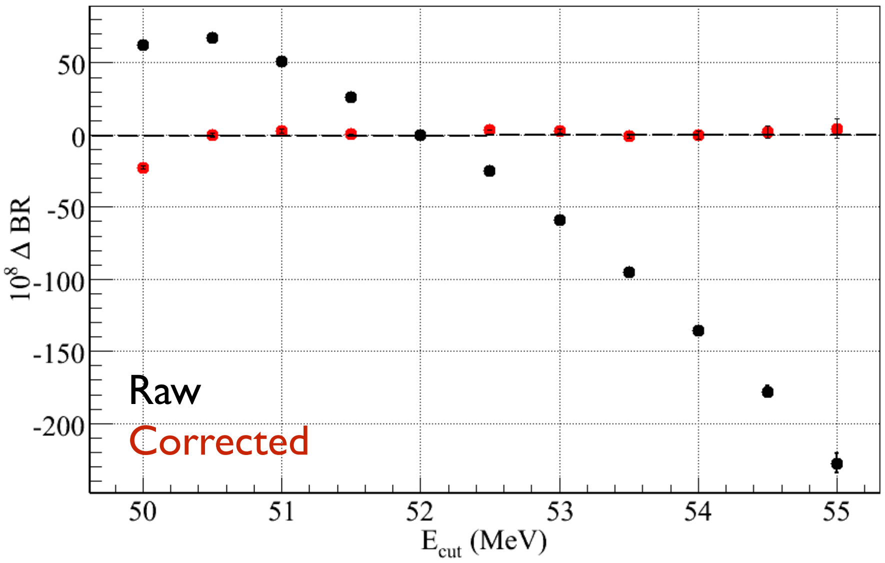
Acceptance Radius Dependence

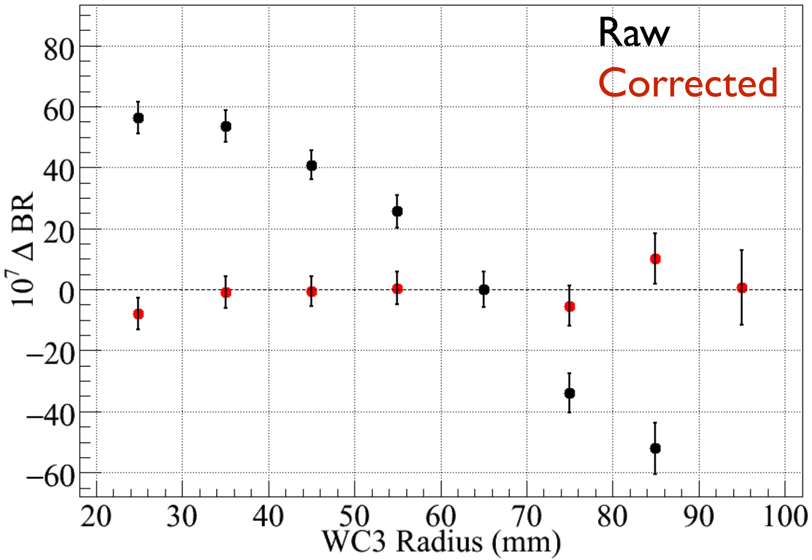
- R= 60 mm
- Errors adjusted to statistics change
- Maximum R investigated

with e^+ beam

Energy cut dependence

- Tail/muDIF corrections applied





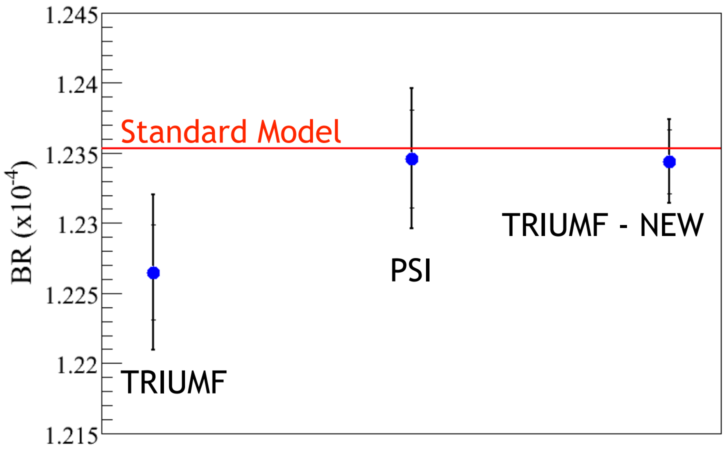
Results

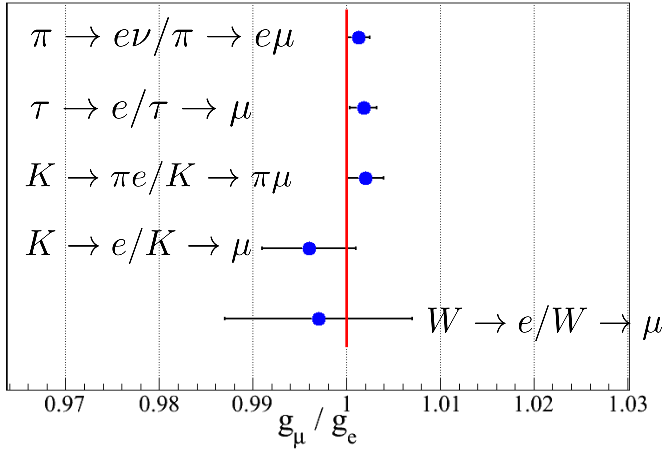
Phys. Rev. Lett. 115, 071801 (2015)

	Values	Uncertainties *Stat*	*Syst*
$R^{Raw}_{e/\mu}$ (10^{-4})	1.1972	0.0022	0.0005
π,μ lifetimes			0.0001
other parameters			0.0003
excluded components			0.0005
Corrections			
Acceptance	0.9991		0.0003
Low energy tail	1.0316		0.0012
Other	1.0004		0.0008
$R^{Exp}_{e/\mu}$ (10^{-4})	1.2344	0.0023	0.0019

$R^{Th}_{e/\mu}$ $(10^{-4}) = 1.2352(2)$

$e-\mu$ Universality: $g_e/g_\mu = 0.9996 \pm 0.0012$





Full Analysis

Dataset	BR	Status
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2011	$1.2XX \pm 0.0018 \pm 0.0013$	Completed, blind
2012	$1.2XX \pm 0.0009 \pm 0.00X$	In progress

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Final Goal: 0.1% precision

Massive Neutrino Search

$\pi \rightarrow e\nu$ is a two-body decay

The pion decays at rest

—> Kinematics fully known if e^+ is measured:

$$m_\nu = \sqrt{m_\pi^2 + m_e^2 - 2m_\pi E_e}$$

If a massive neutrino can be produced, it will show up as a peak in the energy spectrum.

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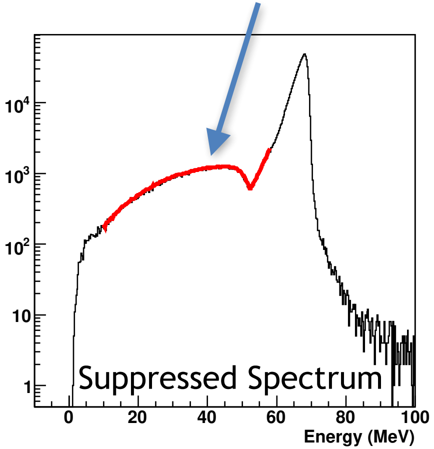
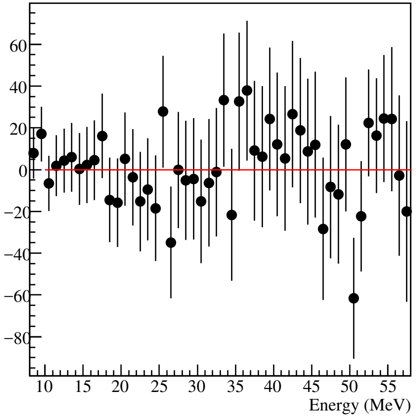




Massive Neutrino Search

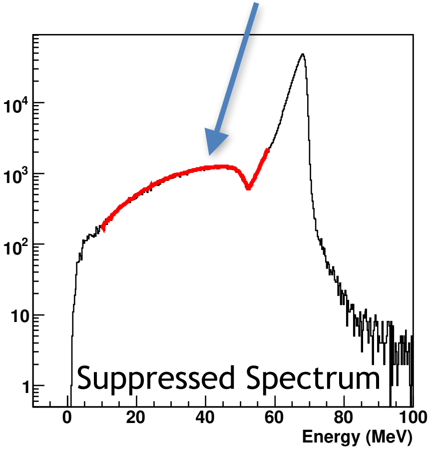
$\pi \to e\nu$ is a two-body decay

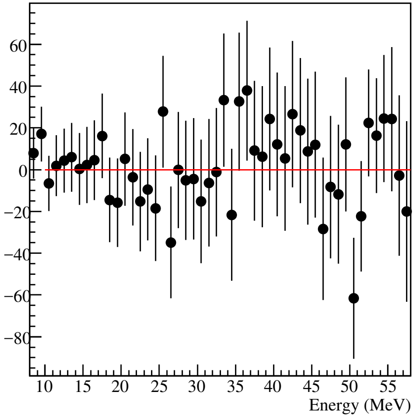
The pion decays at rest

—> Kinematics fully known if e^+ is measured:

$$m_\nu = \sqrt{m_\pi^2 + m_e^2 - 2m_\pi E_e}$$

If a massive neutrino can be produced, it will show up as a peak in the energy spectrum.



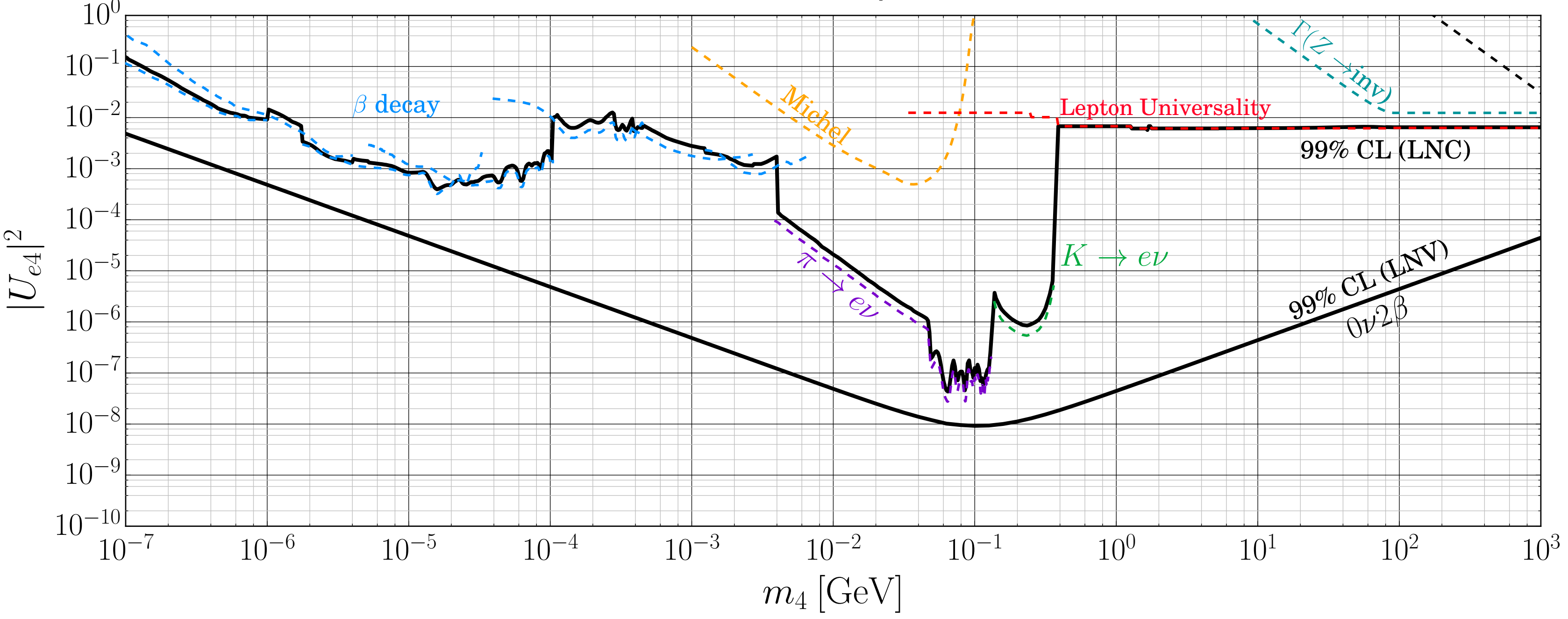


1) Consider the suppressed spectrum
2) Fit the spectrum with signal+bkg shapes:
   - $\pi \to \mu\nu \to e\nu\nu$ (data, t>150ns)
   - Muon decays in flight (MC)
   - $\pi \to e\nu$ shape (MC)
3) Set upper limits to the BR for the pion decay to massive neutrinos.

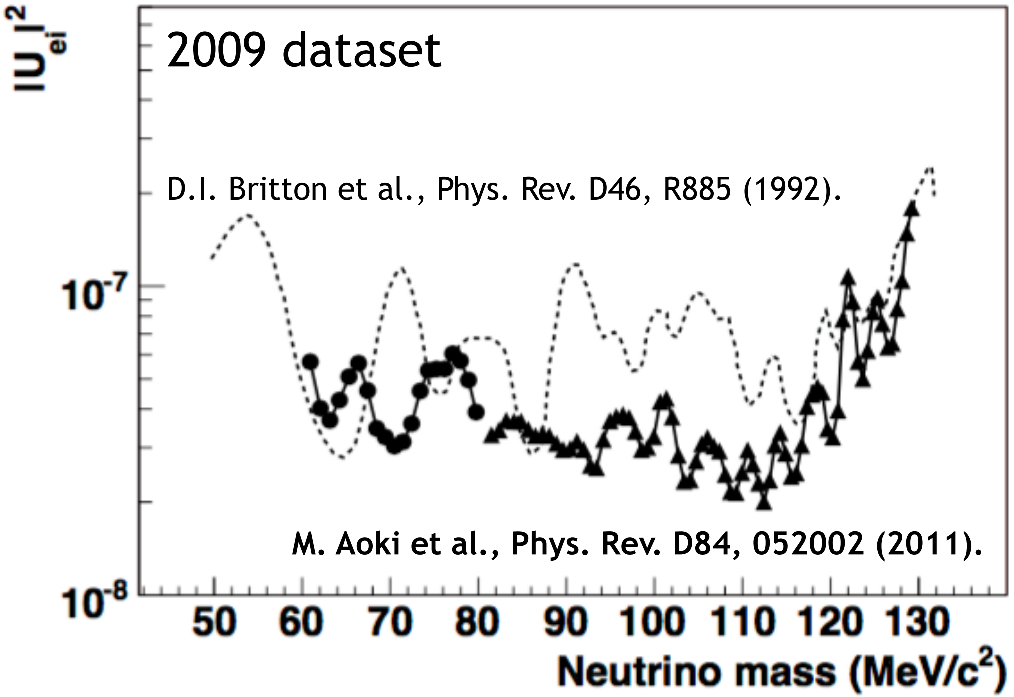
$$\frac{N(\pi \to e\nu_i)_{UL}}{N(\pi \to e\nu_l)} = |U_{ei}|^2_{UL}\rho_e$$

Present Constraints

A. de Gouvêa, A. Kobach, Phys. Rev. D 93, 033005 (2016)



(a)



Full data analysis ongoing.

Conclusions and Outlook

- Best limit on lepton universality violation established
- Work ongoing towards full dataset analysis
- Massive neutrino searches in the MeV range in pion and muon decays

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Final results coming soon: stay tuned!

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Thank you!
Merci!

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