PEN/PIENU: is $g_e = g_\mu$?

a new round of $B_{\pi \to e\nu}$ measurements

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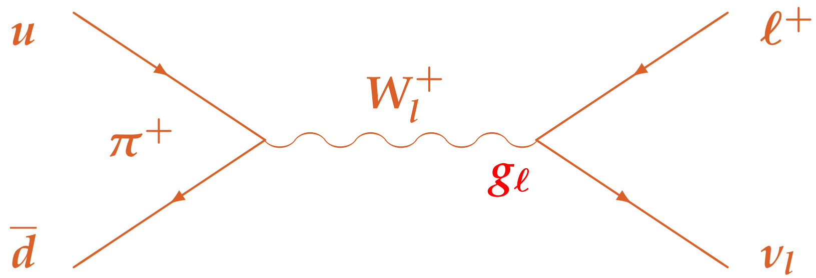
Contents

1 theoretical considerations



Most theoretical (and experimental!) uncertainties cancel when studying the branching **ratio**:

$$B \equiv \Gamma[\pi^+ \to e^+\nu_e(\gamma)]/\Gamma[\pi^+ \to \mu^+\nu_\mu(\gamma)]$$

In lowest order B is the product of a phase-space factor and a helicity factor:

$$B = (1 - \frac{m_\mu^2}{m_\pi^2})^{-2} \times \frac{m_e^2}{m_\mu^2} = 5.4869 \times 2.3390 \times 10^{-5} = 1.2834 \times 10^{-4}$$

complete calculation: 1.2353×10^{-4} [1].

SM predictions and measured values for $R^P_{e/\mu}$ $(P = \pi, K)$

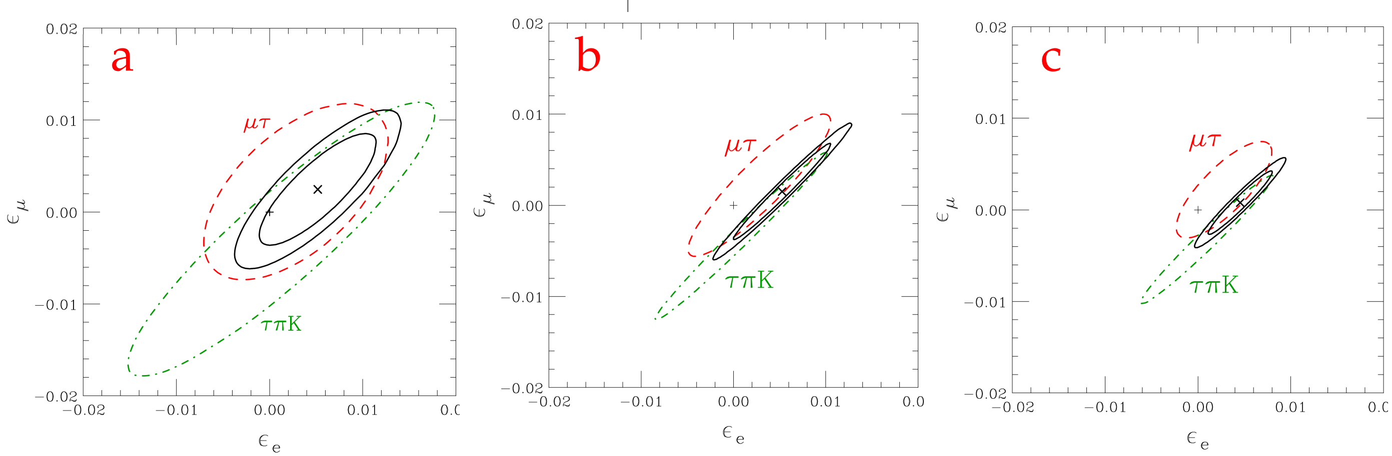
	$\Gamma_{\pi^+\to e^+\nu}/\Gamma_{\pi^+\to\mu^+\nu}$	$\Gamma_{K^+\to e^+\nu}/\Gamma_{K^+\to\mu^+\nu}$
theory	$1.2353(1) \times 10^{-4}$	$2.477(1) \times 10^{-5}$
experiment	$1.2312(37) \times 10^{-4}$	$2.488(12) \times 10^{-5}$

[1] V. Cirigliano and I. Rosell, JHEP **10** (2007) 5; Phys. Rev. Lett. **99** (2007) 231801.

Allowing for a flavour dependence of g transition probabilities should be multiplied with g_l^2.

charged lepton universality tests (τ indicates the particle or a lifetime!)

decay	g_e/g_μ	g_τ/g_μ	g_τ/g_e
$\pi^+ \to \bar{l}\nu_l$	0.9985 ± 0.0016		
$K^+ \to \bar{l}\nu_l$	1.0018 ± 0.0026		
$K^+ \to \pi\bar{l}\nu_l$	0.998 ± 0.002		
$\tau^+ \to \bar{l}\nu\bar{\nu}$	0.9998 ± 0.0020		
$W^+ \to \bar{l}\nu_l$	0.997 ± 0.010	1.039 ± 0.013	1.036 ± 0.014
$\tau \to \pi \;/\; \pi \to \mu$		0.996 ± 0.005	
$\tau \to K \;/\; K \to \mu$		0.979 ± 0.017	
$\tau \to e \times \tau_\mu/\tau_\tau$		1.0006 ± 0.0022	
$\tau \to \mu \times \tau_\mu/\tau_\tau$			1.0005 ± 0.0023



Limits on charged lepton non-universality[2]

a: present situation

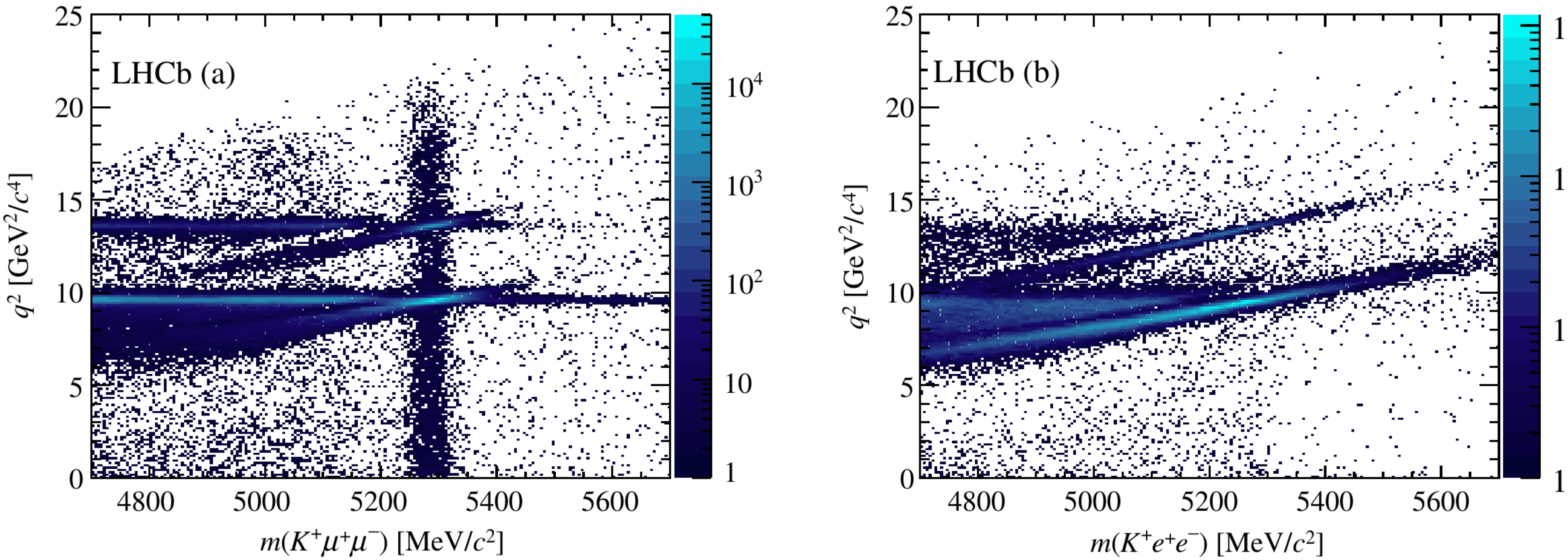
b: after improved branching ratios

c: after new lifetimes

$\epsilon_i = g_i - 1$.

[2] Tatsu Takeuchi, Melbourne Neutrino Theory Workshop, June 2, 2008.

Lots of excitement and creativity by model builders after this LHCb result[3]:



Dilepton invariant mass squared versus $K^+l^+l^-$ invariant mass

$$\Gamma(B^+ \to K^+\mu\overline{\mu})/\Gamma(B^+ \to K^+e\overline{e}) = 0.745^{+0.090}_{-0.074}(\text{stat})\pm0.036(\text{syst})$$

a 2.6σ deviation!

[3]R. Aaij *et al.*, LHCb Collaboration, Phys.Rev.Lett. **113**, 151601 (2014).

MICHAEL J. RAMSEY-MUSOLF, SHUFANG SU, AND SEAN TULIN PHYSICAL REVIEW D **76,** 095017 (2007)

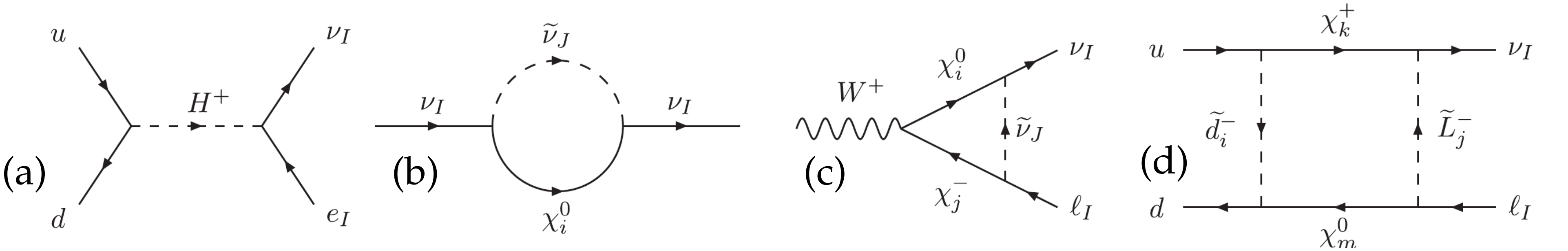


FIG. 1. Representative contributions to $\Delta R^{\mathrm{SUSY}}_{e/\mu}$: (a) tree-level charged Higgs boson exchange, (b) external leg diagrams, (c) vertex diagrams, (d) box diagrams. Graph (a) contributes to the pseudoscalar amplitude, graphs (b),(c) contribute to the axial vector amplitude, and graph (d) contributes to both amplitudes.

Minimal Supersymmetric Standard Model

Fig.1b-d contribute to l-universality violation.

A scan was made over all MSSM parameters.

Violations could be everal times larger than the next-future experimental uncertainty.

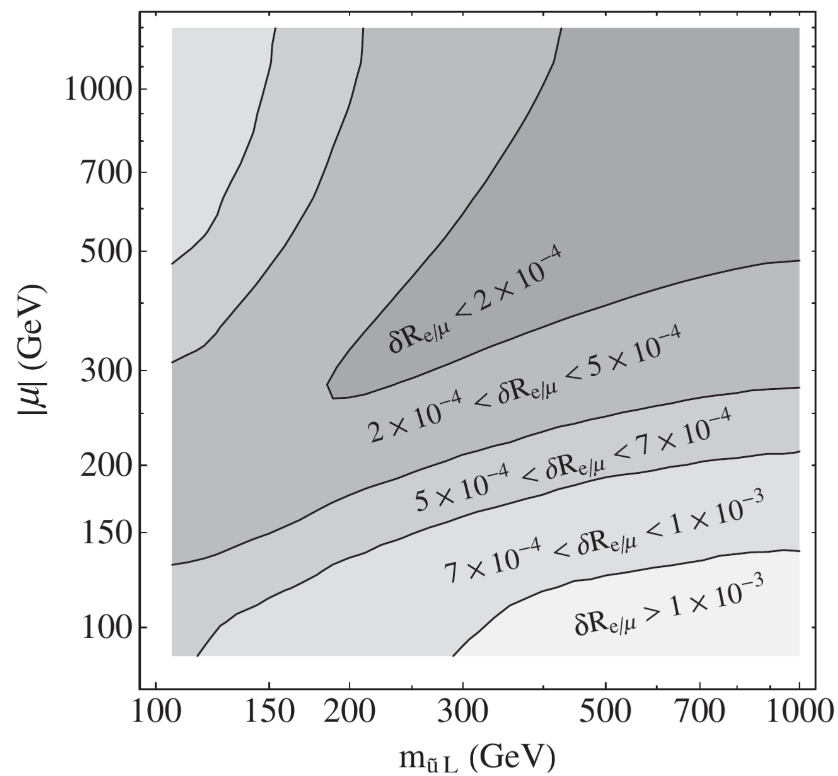
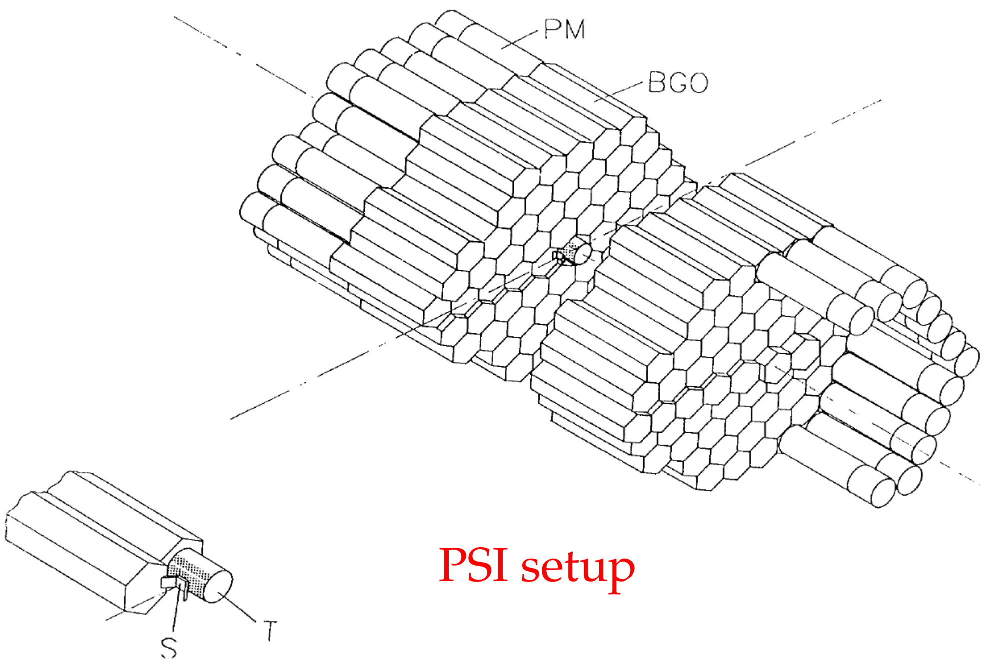
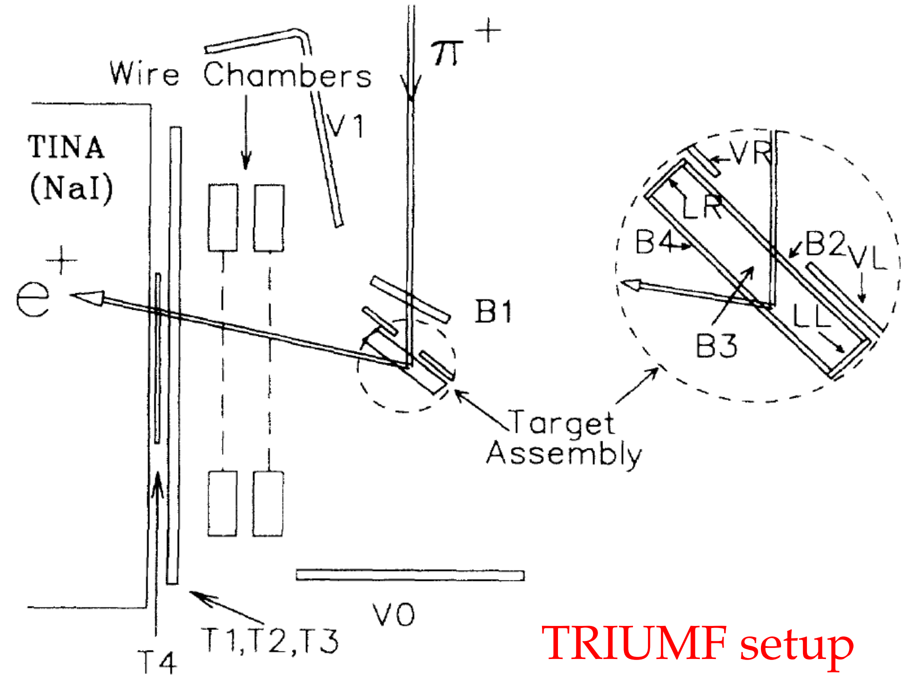


FIG. 9. Contours indicate the largest values of $\delta R^{\mathrm{SUSY}}_{e/\mu}$ obtained by our numerical parameter scan (26), as a function of $|\mu|$ and $m_{\tilde{u}_L}$. The solid shaded regions correspond to the largest values of $\delta R^{\mathrm{SUSY}}_{e/\mu}$ within the ranges indicated. All values of $\delta R^{\mathrm{SUSY}}_{e/\mu}$ correspond to parameter points which satisfy the LEP II bound.

2 the $\pi \to e\nu$ experiments



PSI setup



TRIUMF setup

S: last beam defining scintillator
T: active target
a single BGO crystal is 20 cm deep

Tina: NaI(Tl) calorimeter
B: plastic π detectors
V: plastic veto scintillators
T: plastic positron detectors

1992 TRIUMF result[4]: $B = (1.2265 \pm 0.0034(\text{stat}) \pm 0.0044(\text{syst})) \times 10^{-4}$

1993 PSI result[5]: $B = (1.2350 \pm 0.0035(\text{stat}) \pm 0.0036(\text{syst})) \times 10^{-4}$

combined: $B = (1.2312 \pm 0.0035) \times 10^{-4}$

[4] D. I. Britton *et al.*, Phys. Rev. Lett. **68** (1992) 3000.
[5] G. Czapek *et al.*, Phys. Rev. Lett. **70** (1993) 17.

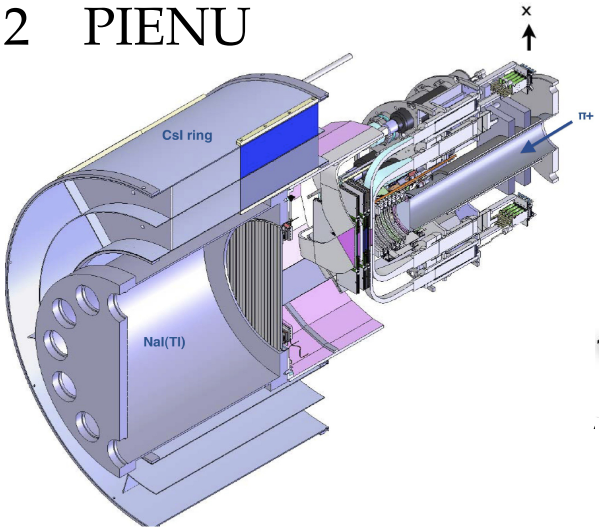
2.1 PEN[6] and PIENU[7] teams

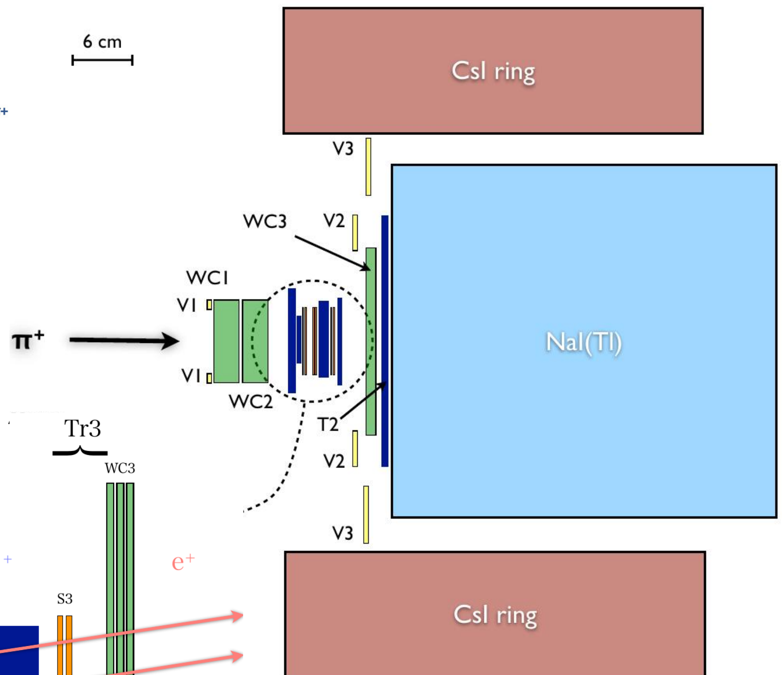
Systematic errors play a crucial role so it is very fortunate there are two experiments (like ATLAS and CMS at the LHC)

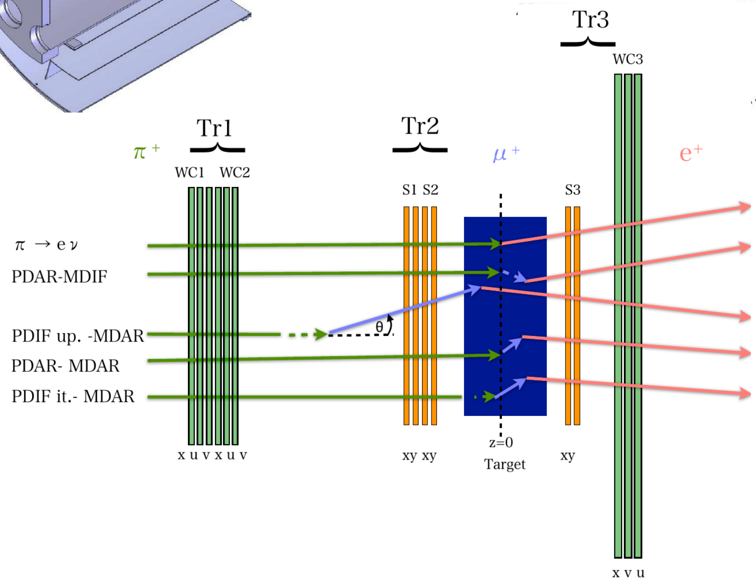
Aguilar-Arevalo Alonzi Aoki Baranov Bertl Blecher Britton vom Bruch Bryman Bychkov Bystritsky Chen Comfort Cuen-Rochin Ding Doria Frlez Glaser Gumplinger Hurst Hussein Igarashi Ito1 Ito2 Kettell Khomutov Korenchenko1 Korenchenko2 Korolija Kozlowski Kravchuk Kuchinskiy Kuno Kurchaninov Lehman Littenberg Malbrunot Mekterovic Mischke Mzhavia Numao Palladino Počanić Poutissou Robmann Rozhdestvenskiy Sandorfi van der Schaaf Sher Sidorkin Sullivan Supek Truöl Vavilov Velicheva Vitz Volnykh Yamada Yoshida

[6] PEN Collaboration, PSI experiment R-05-01 (2005), D. Počanić and A. van der Schaaf, spokespersons
[7] PIENU Collaboration, TRIUMF proposal 1072 (2006), D. Bryman and T. Numao, spokespersons.

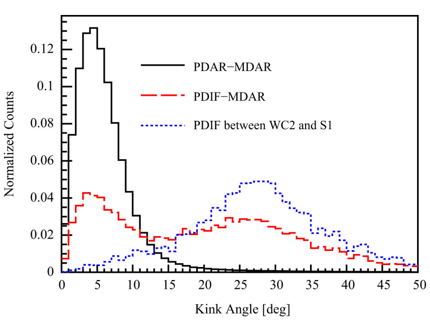
2.2 PIENU

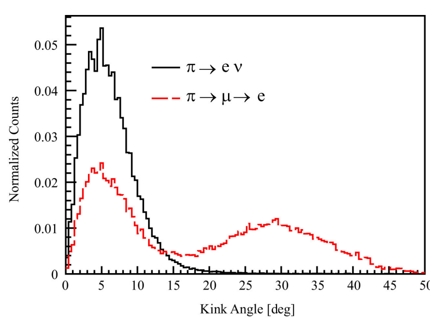


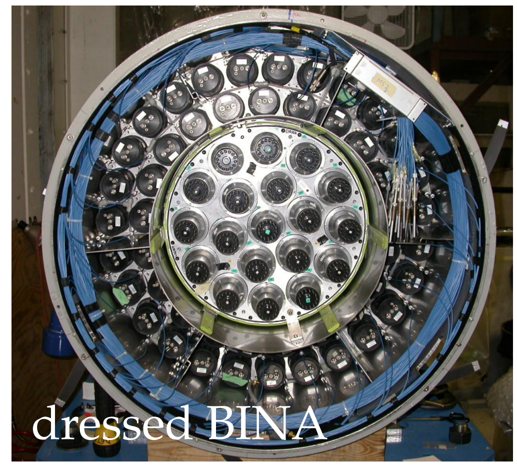


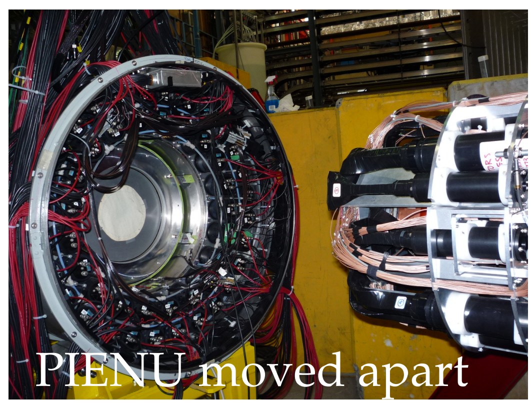


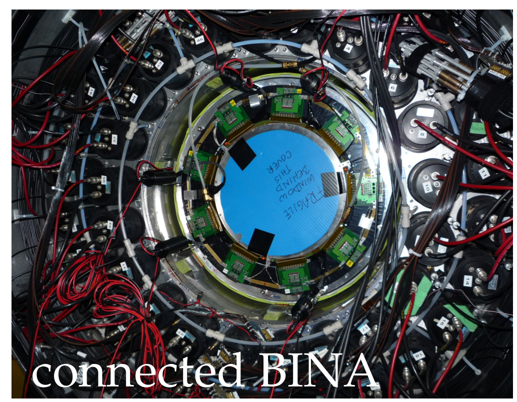
NaI(Tl) diameter and depth: 48 cm



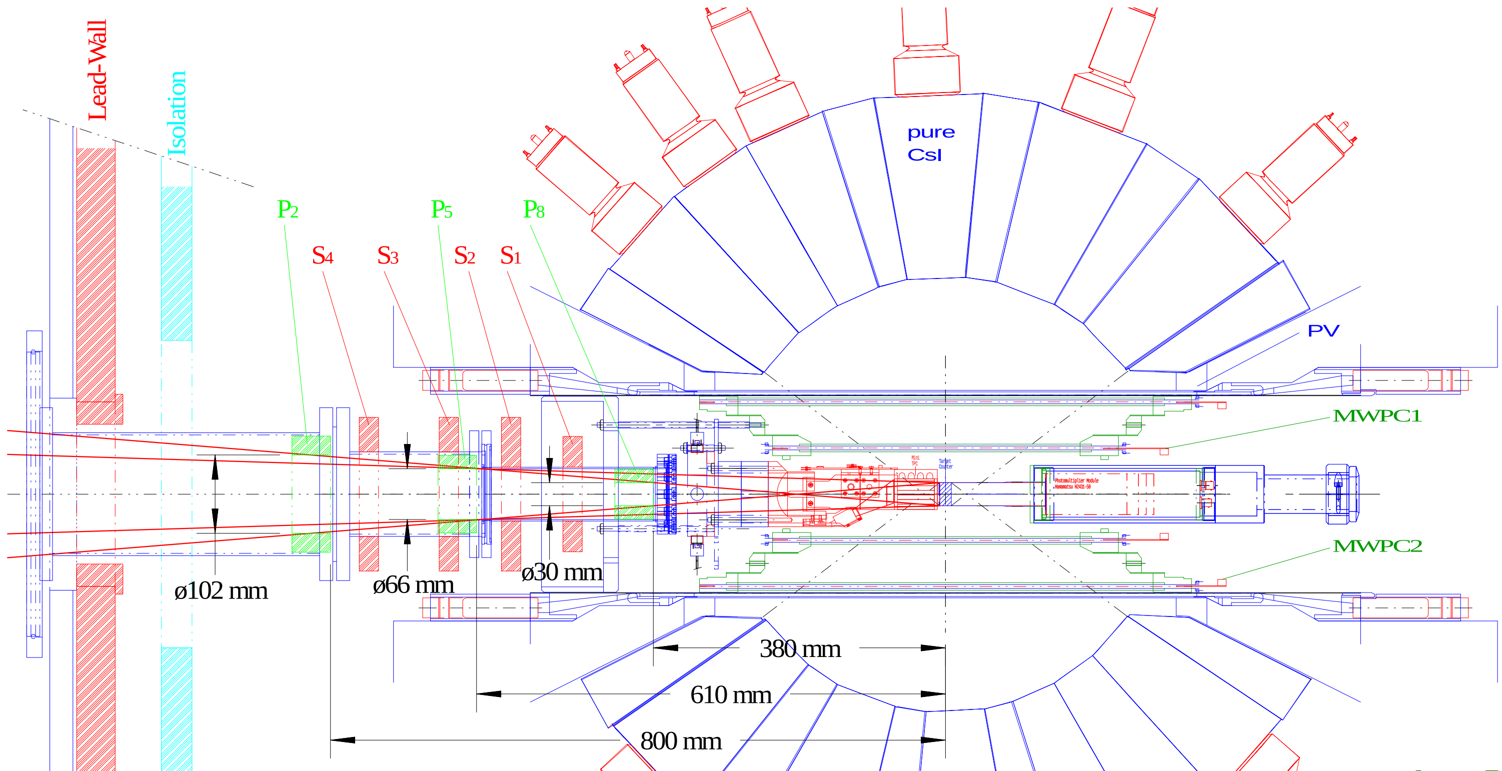




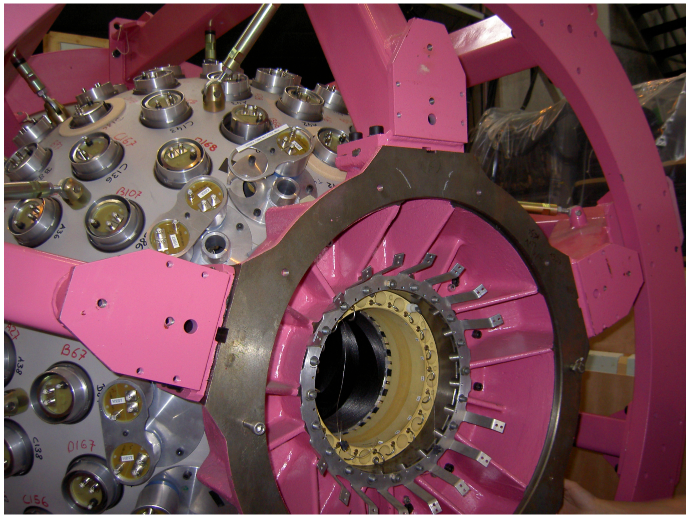


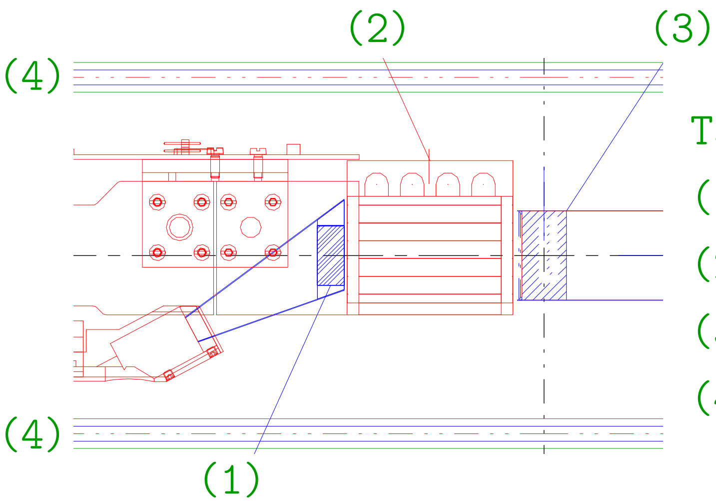


2.3 PEN



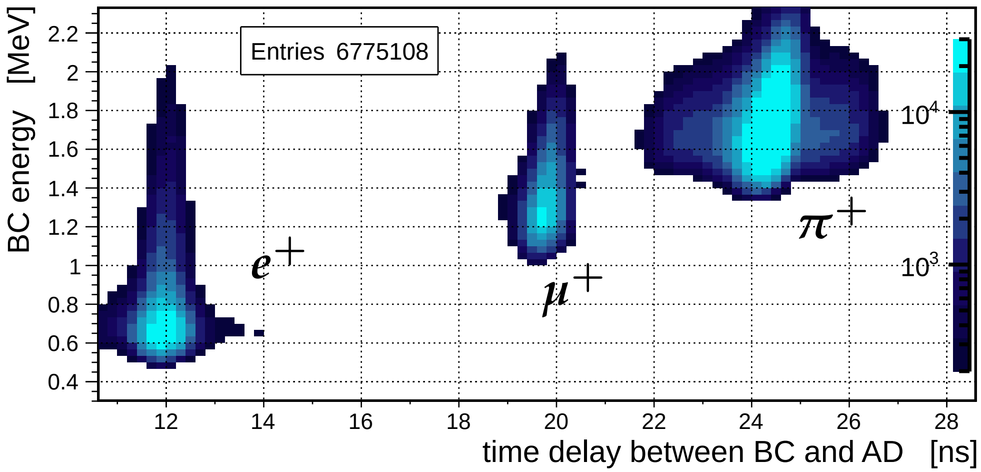
the PEN setup





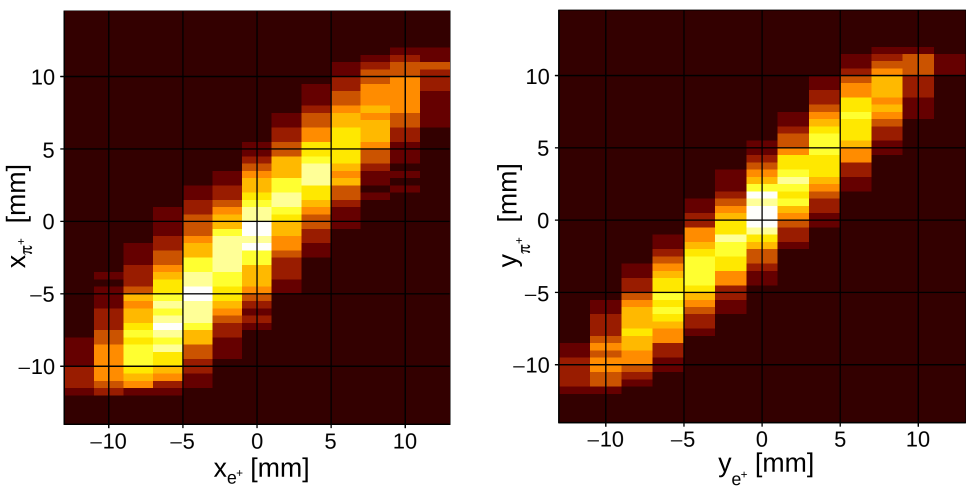
Target region
(1) degrader
(2) mini TPC
(3) target scintillator
(4) inner MWPC.

3 the pion beams



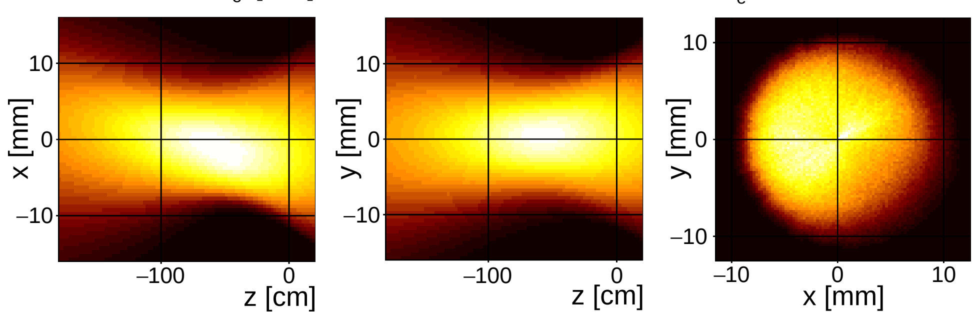
PEN results:

beam counter energy versus time of flight between beam counter and active degrader at beam momentum 75 MeV/c. Time of flight is used not only for pion selection but also for an accurate energy determination, event by event.

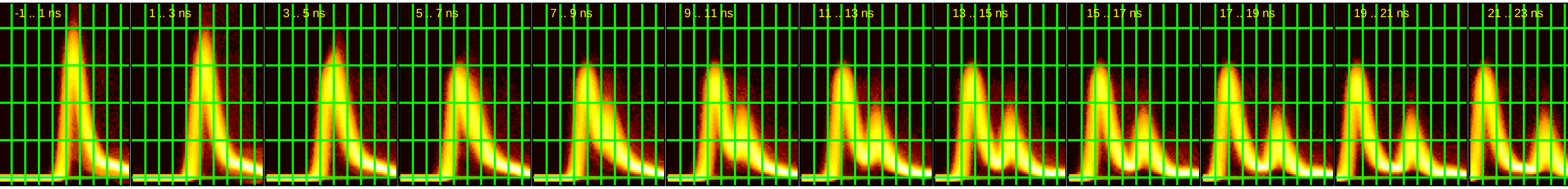


Correlations between the position coordinates of π^+ and e^+ for e^+ moving vertically (left) and horizontally (right).

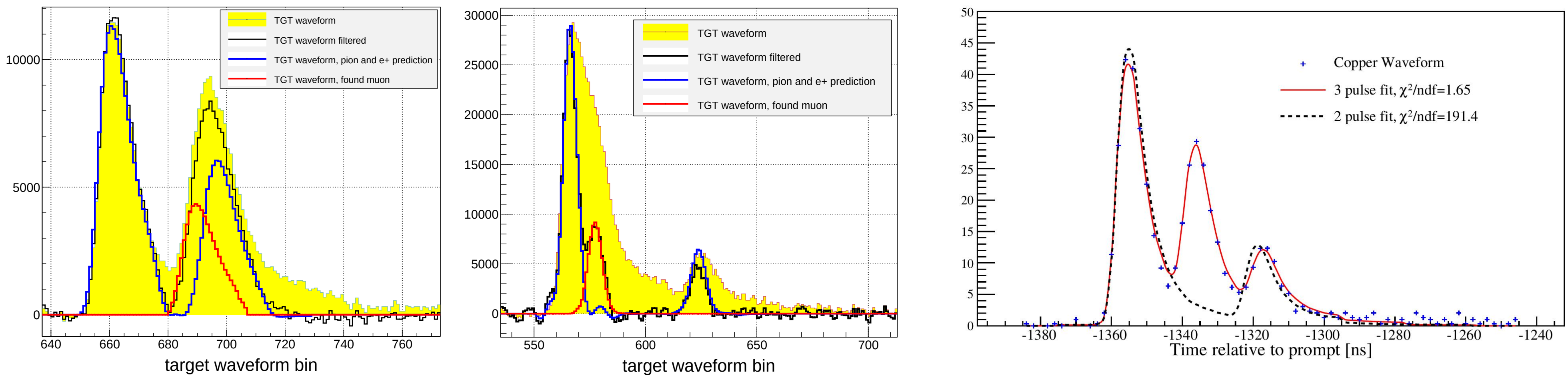
x_{π^+} is based on charge division, y_{π^+} on drift time.



Mini TPC trajectories. The beam spot, limited by a $\varnothing = 20$ mm lead collimator upstream of the target, is off-center in x for best suppression of beam e^+ situated further to the left.



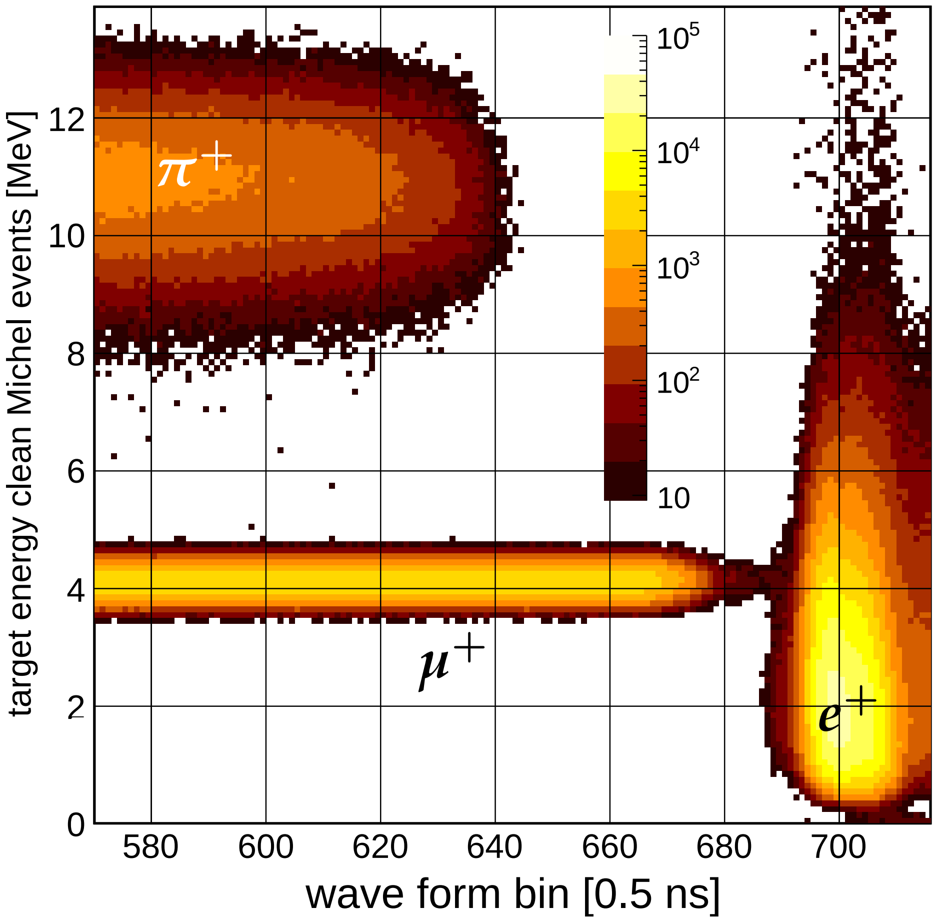
4 target waveform analysis

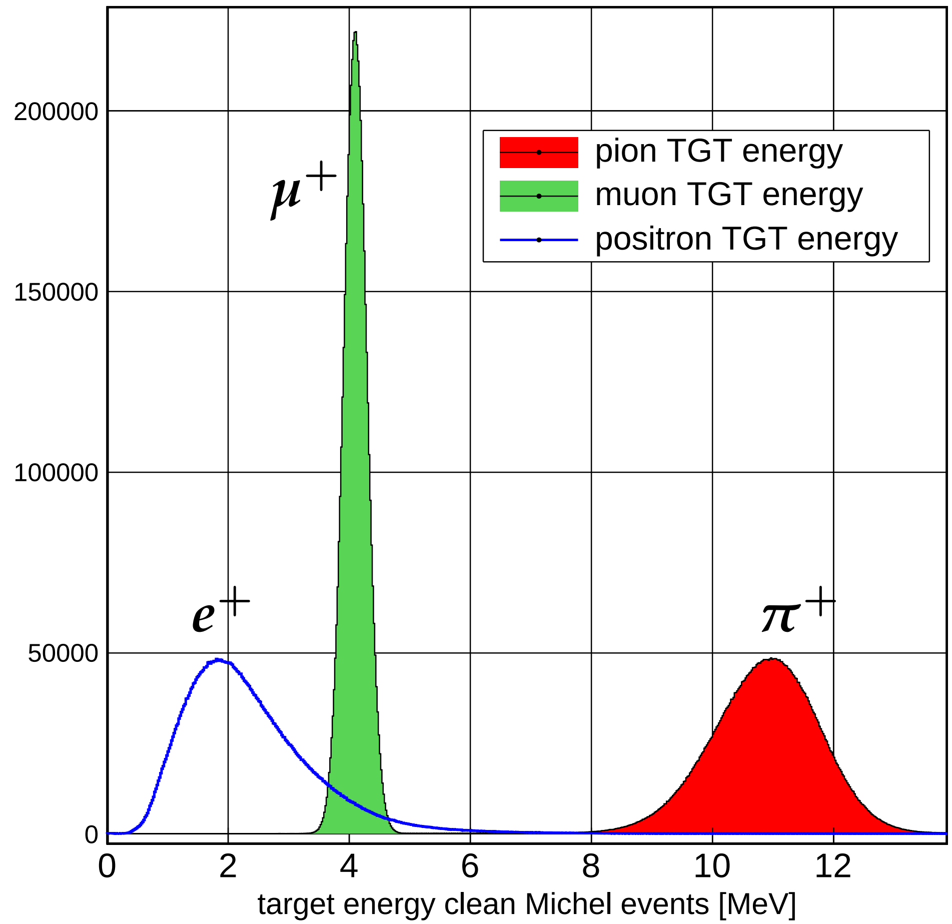


Examples of target waveforms and their analysis.

The panels on the left illustrate the novel loss-free PEN signal shaping based on vector multiplication. The π and e^+ signals are NOT adjusted but predictions based on the information of the surrounding detectors. The only free parameter is the location of the muon signal.

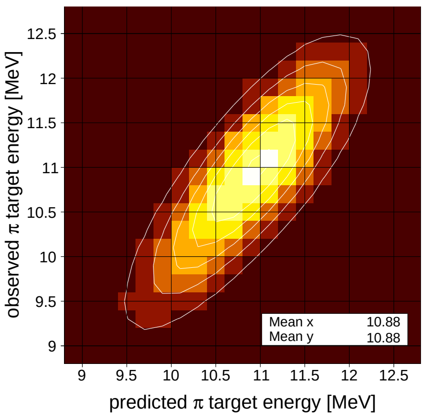
The panel on the right shows a PIENU example.



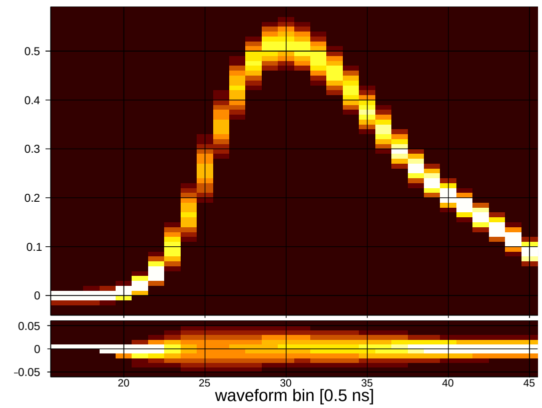


PEN results:

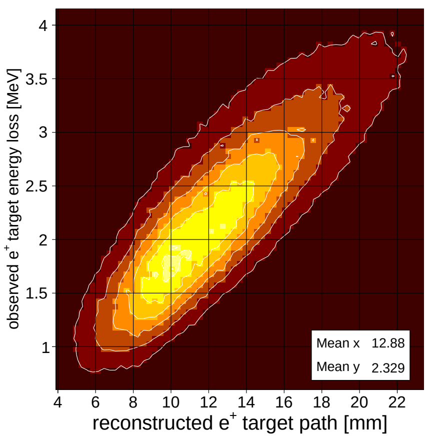
Target waveform analysis for $\pi \to \mu \to e$ decay chains in which the three signals are well-separated. Signal quenching by high ionization density has been corrected. Positrons, which timed the trigger, are situated around waveform bin 700. The muons are situated to their left and mono-energetic with $T = 4.1\,\text{MeV}$ since they originate in π decay at rest. The pions deposit typically 11 MeV.



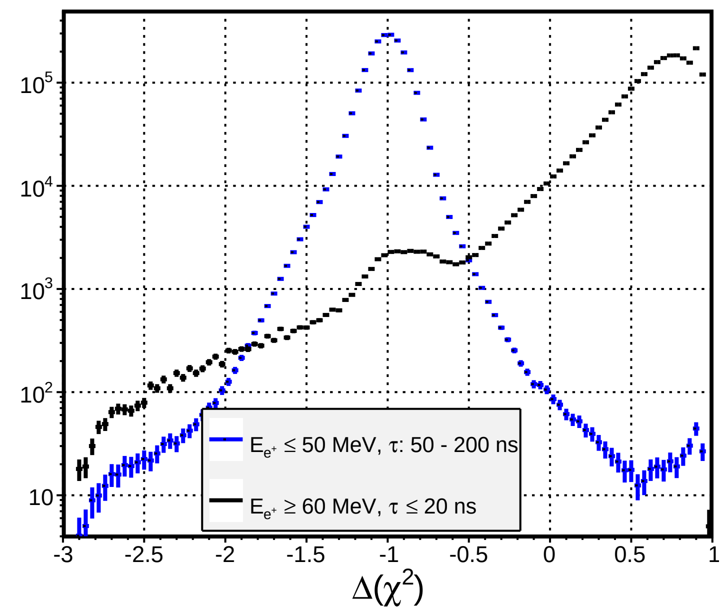
π^+ target energy versus the predicted value based on time of flight and observed degrader energy.



Pion waveforms before (upper panel) and after (lower panel) subtraction of the predicted signal.



e^+ target energy versus path length. Observed mean dE/dx is 1.81 MeV/cm, or 1.73 MeV/g.

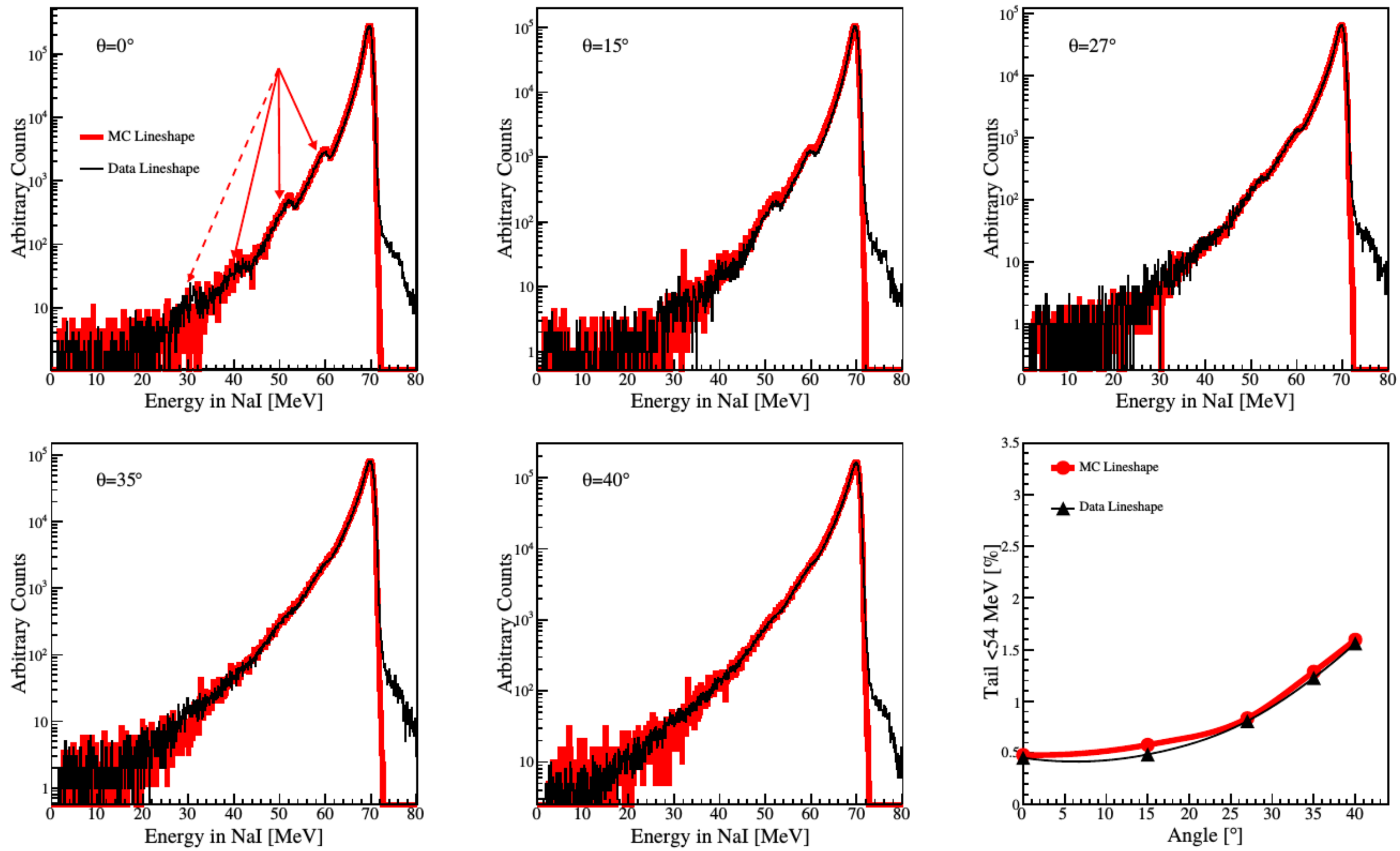


$\Delta(\chi^2)$ of the target waveform for $\pi \to e$ and for $\pi \to \mu \to e$. The algorithm always returns a value in the region shown.

PEN results

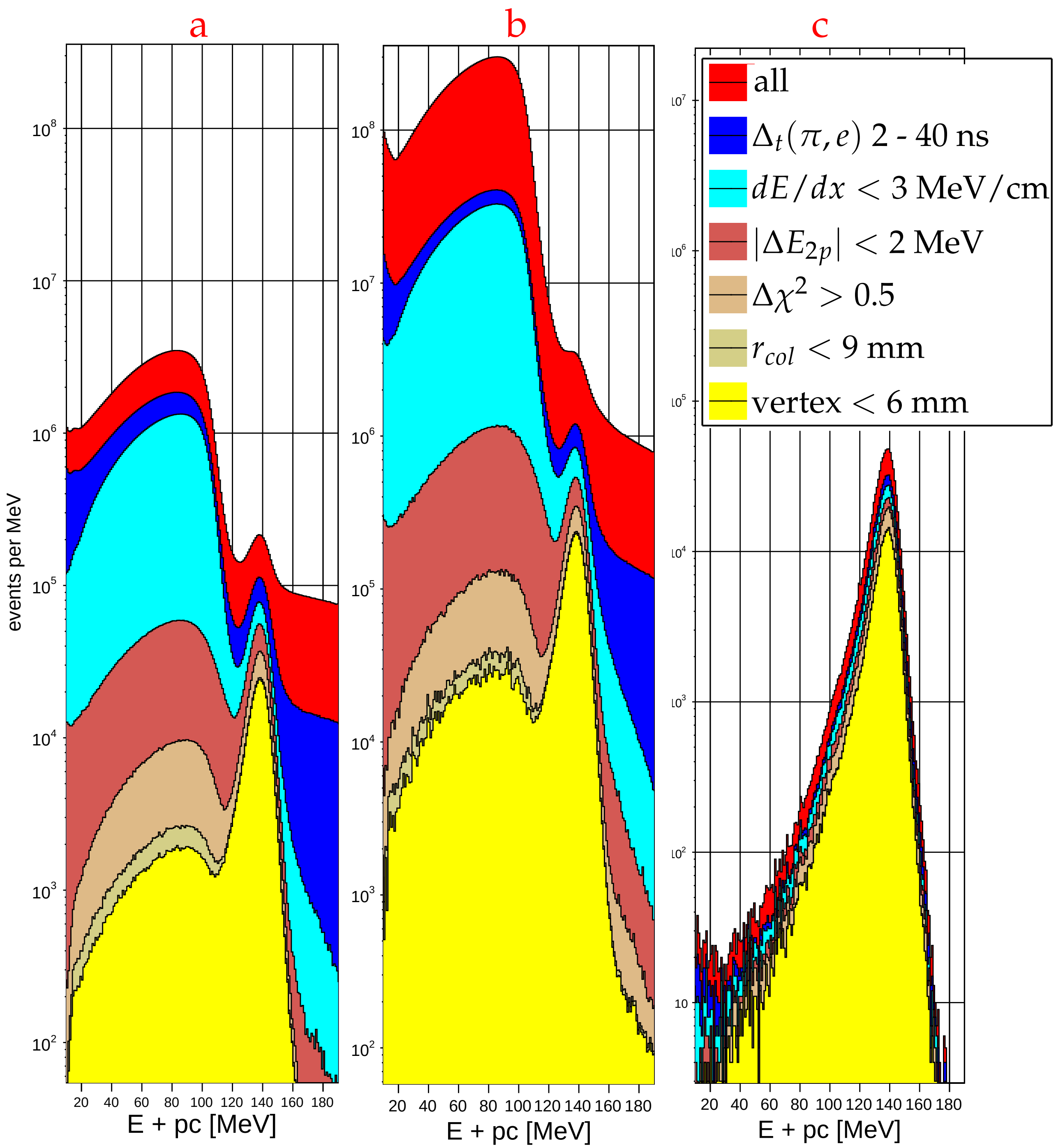
5 the key observables, e^+ energy and decaytime

5.1 low-energy tail



PIENU NaI(Tl) energy spectra with 70 MeV e^+ beam for central showers at various θ. The final plot shows the resulting fraction with energy deposit below 54 MeV. [8]

[8] A. Aguilar-Arevalo *et al.*, [PIENU Collaboration], Nucl. Instr. Meth. **A 621** (2010) 188.



PEN indirectly measures p_ν in $\pi \to e\nu\gamma$ since $\vec{p_\nu} + \vec{p_e} + \vec{p_\gamma} = 0$.

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

This moves such events out of the low-energy tail.

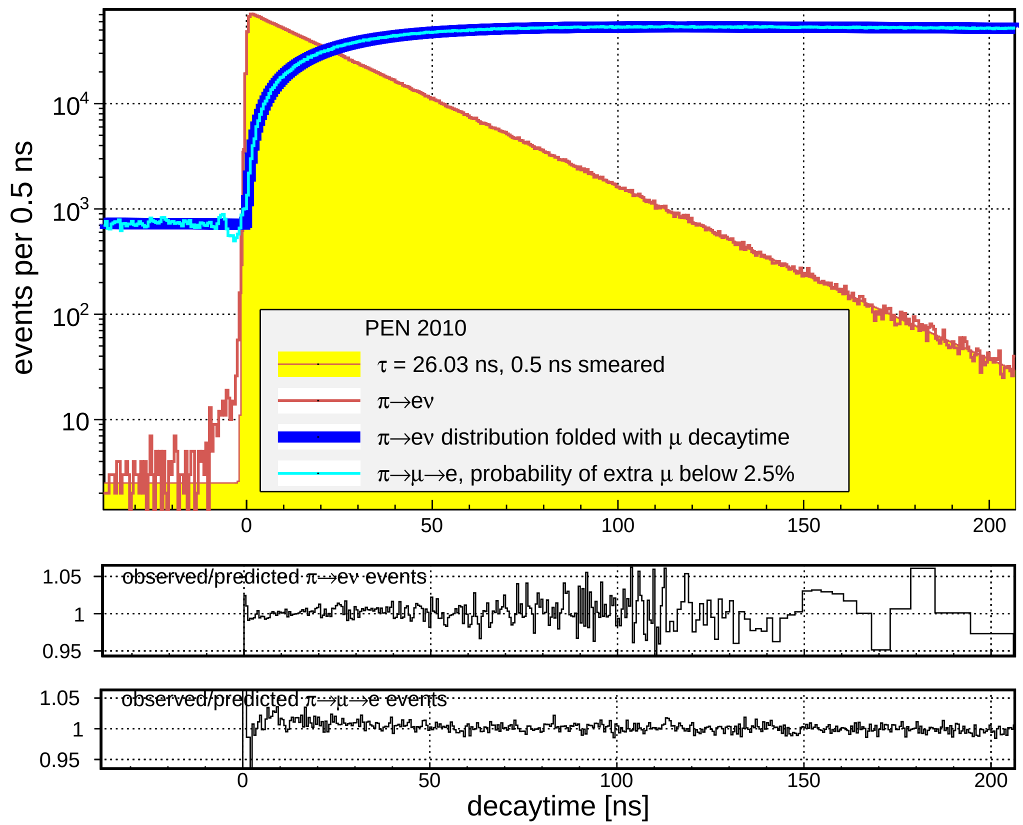
E+pc distributions for increasing number of selection conditions that suppress the $\pi \to \mu \to e$ branch:

a: Tail-trigger events, recorded irrespective of the CsI signals but pre-scaled 1:10.

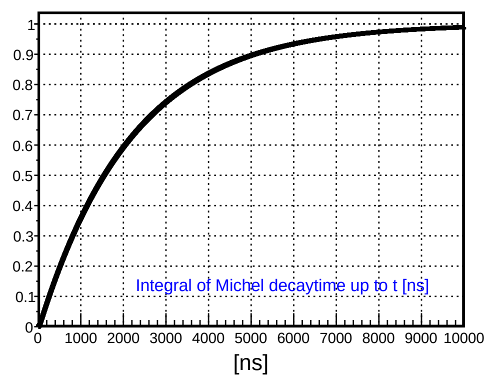
b: Main-trigger events, pre-scaled 1:64 in the tail-region.

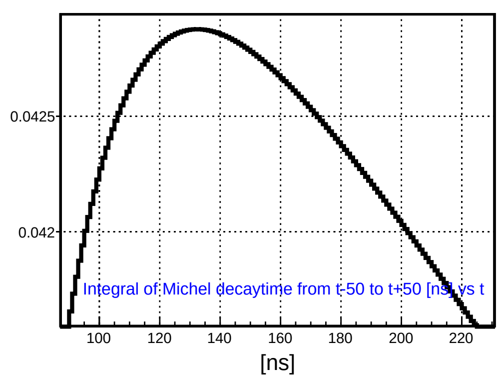
c: $\pi \to e\nu$ simulation

5.2 decay time



PEN year 2010 $\pi \to e\nu$ decaytime distribution showing an extremely low accidental background. Also shown are the $\pi \to \mu \to e$ distribution and its prediction, obtained by folding the $\pi \to e\nu$ result with τ_μ. Note the perfect agreement between observation and prediction.





Fraction of $\pi \to \mu \to e$ events with a $\pi - e^+$ time delay in a window t±50 ns, versus t.
The distribution peaks at 131.4 ns but falls less than 10^{-5} when moving 1 ns away from that value.

6 $\pi \to e\nu\gamma$

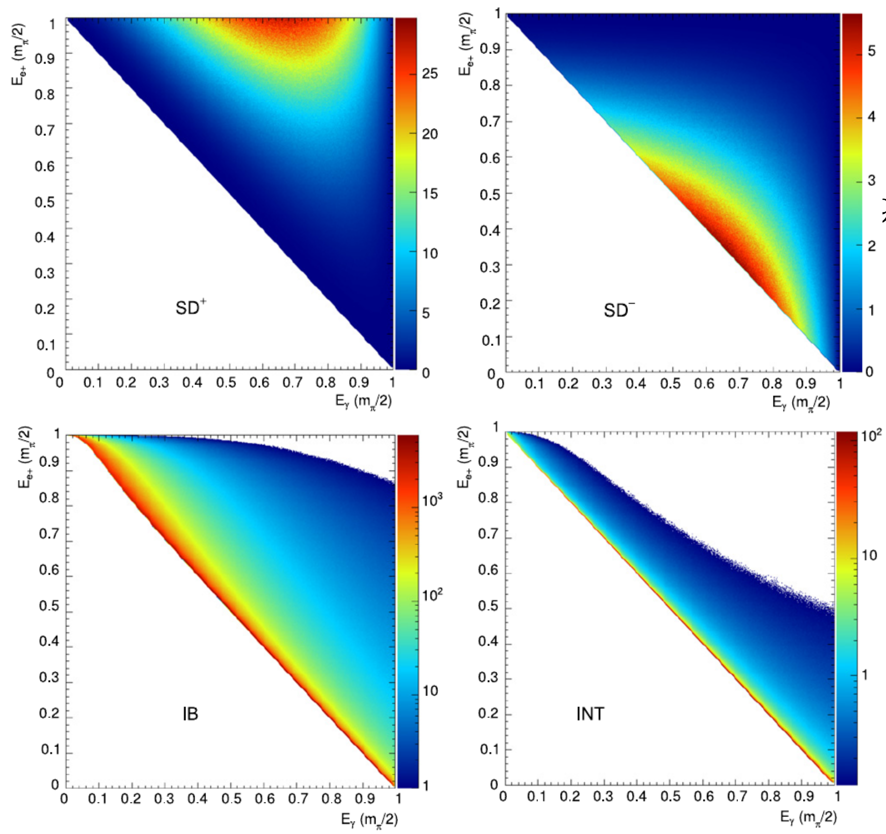
$$\frac{d^2\Gamma_{\pi\to e\nu\gamma}}{dxdy} = \frac{d^2\Gamma_{IB}}{dxdy} + \frac{d^2\Gamma_{SD}}{dxdy} + \frac{d^2\Gamma_{INT}}{dxdy}$$

The structure-dependent contribution is not helicity-suppressed
The interference term is small.

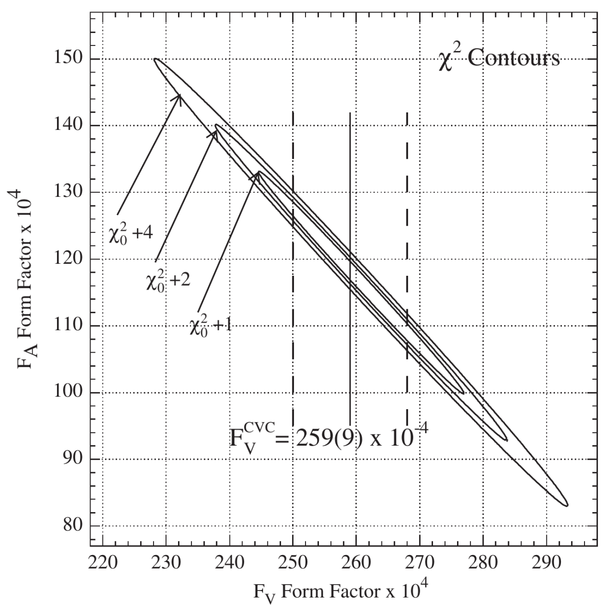
$$\frac{d^2\Gamma_{SD}}{dxdy} \propto [(F_V + F_A)^2 SD^+ + (F_V - F_A)^2 SD^-]$$

F_V and F_A are vector and axial-vector form factors.

Sofar only the region not populated by radiative muon decay (so either E_e or E_γ is above $m_\mu/2$) was studied.



PIBETA[9]:
(PEN predecessor)

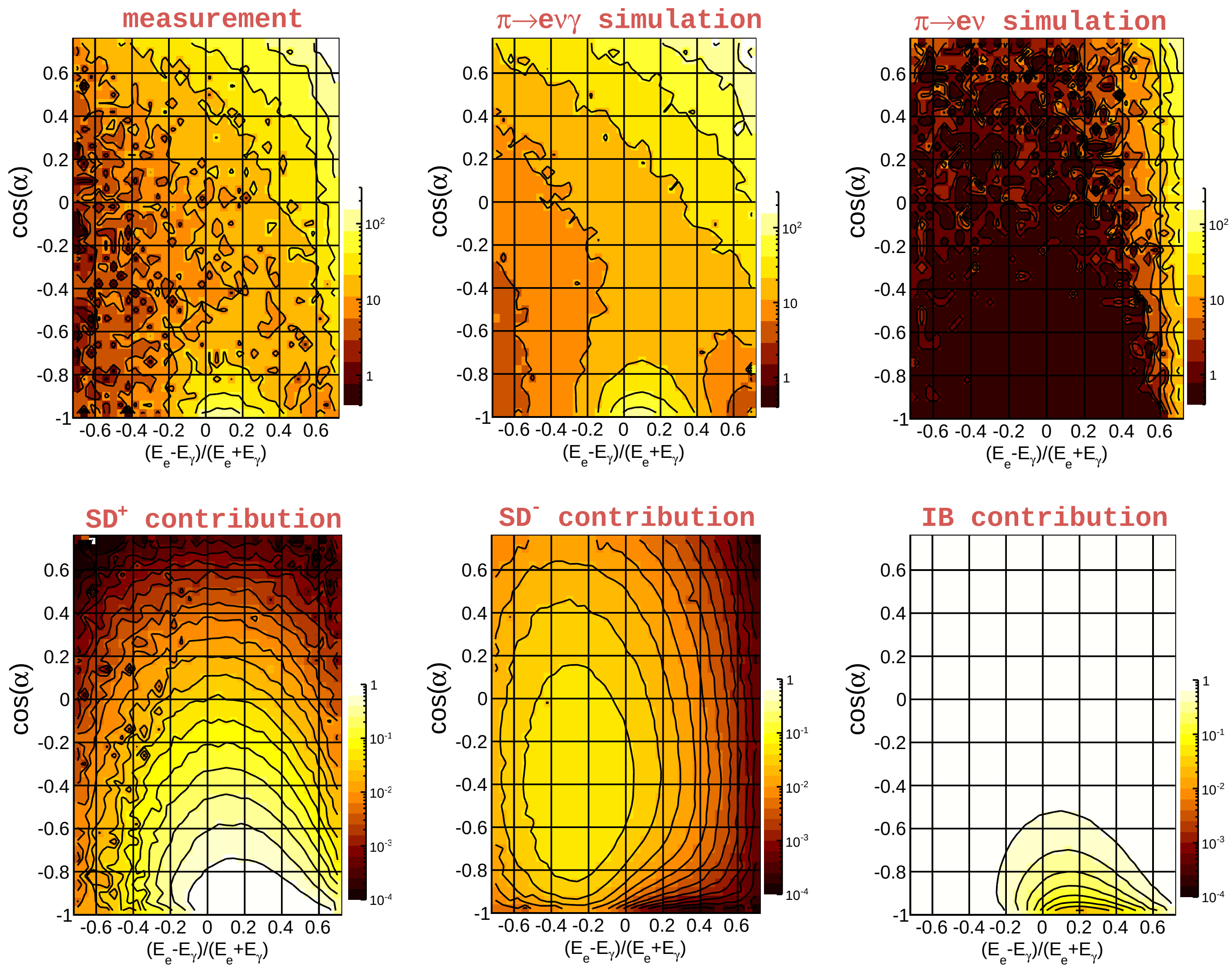


[9]M. Bychkov *et al.*. PIBETA Colalboration, Phys. Rev. Lett. 103, 051802 (2009)

Cosine $e\gamma$ opening angle versus energy sharing.

Top: PEN 2009/10 data are compared to GEANT predictions. The region shown contains 33140 measured events.

Bottom: relative contributions of the SD$^+$, SD$^-$ and IB components as known to the SIMULATOR. SD$^-$ contributes up to 6%.



These measurements require a large solid angle and a modular calorimeter to reconstruct the photon. The PIENU setup does not offer this.
Thanks to the powerfull target waveform analysis and the trigger for data readout based on the total CsI energy, PEN succeeded in measuring $\pi \to e\nu\gamma$ in full phase-space.

7 decays in flight

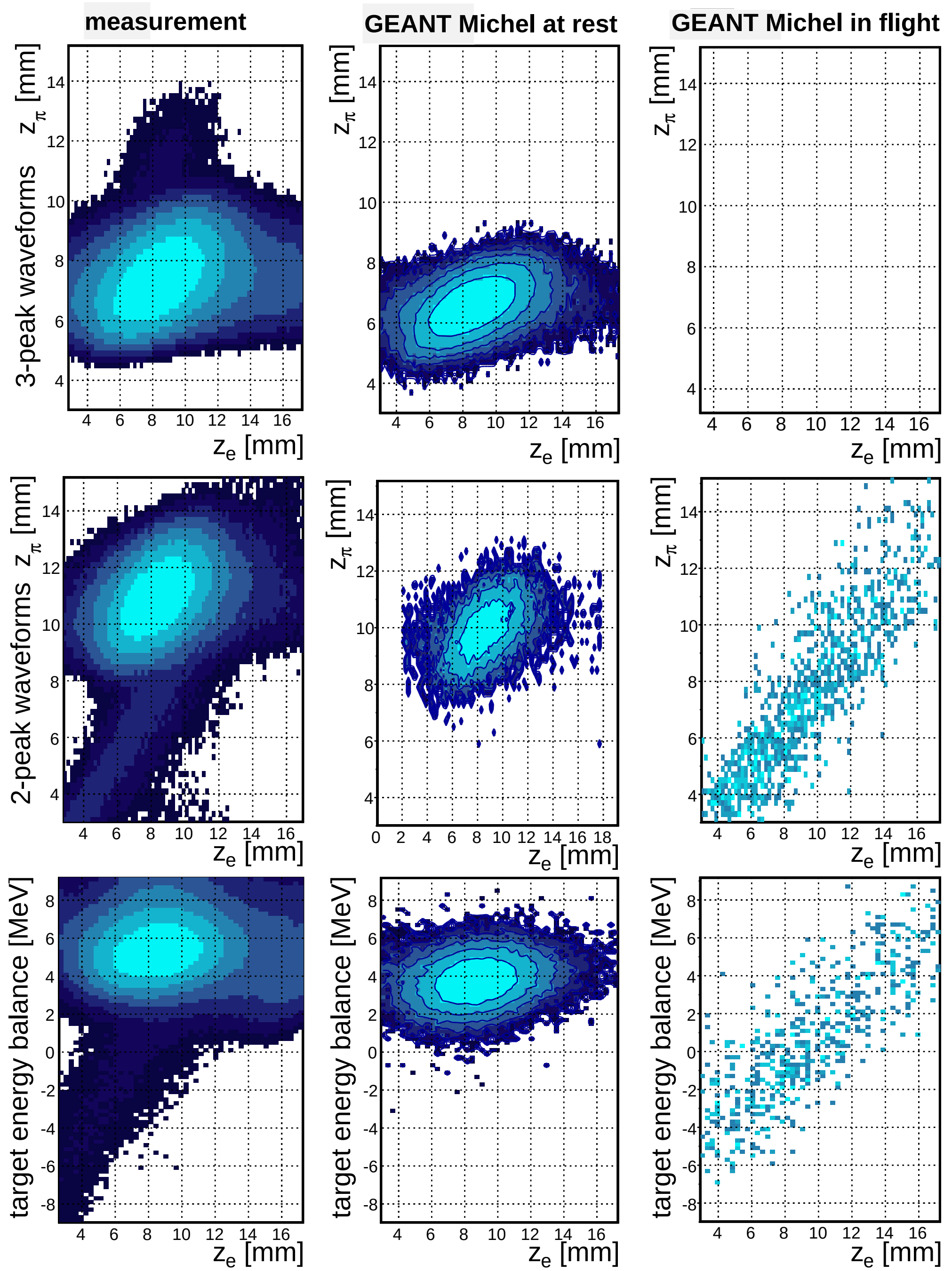
Evidence for $\pi \to \mu\bar{\nu}$ decay in flight.

Events are selected with e^+ energy between 30 and 50 MeV.
Measured distributions are compared with simulation, where the muon decayed at rest or in flight.

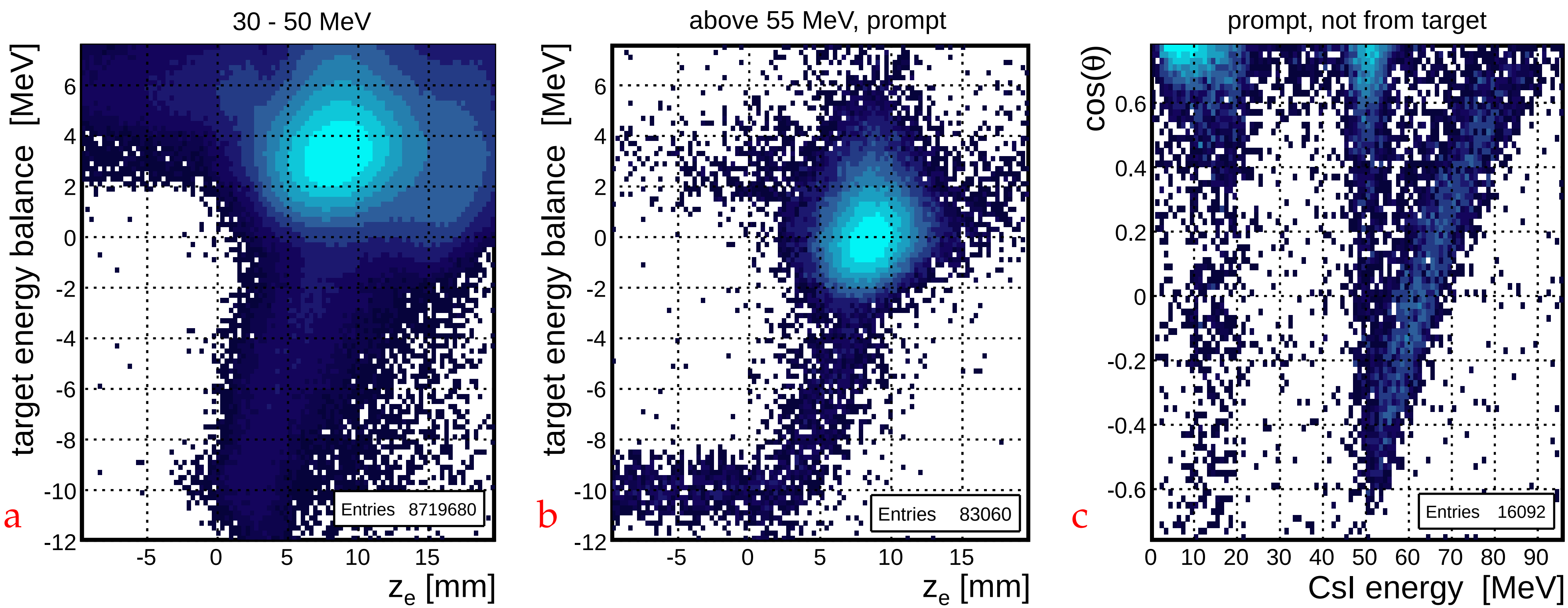
The two top rows: events with well separated target signals, either three (typical for $\pi - \mu - e$) or just two (as expected for decay in flight).

The bottom row shows all events.

z_e: starting position of the e^+ along the beam line (from MWPCs).
z_π: final position of the π^+ from the target energy.
Target energy balance: total energy minus predictions for π^+ and e^+.



Evidence for $\pi^+ \to e^+\nu$ decay in flight.



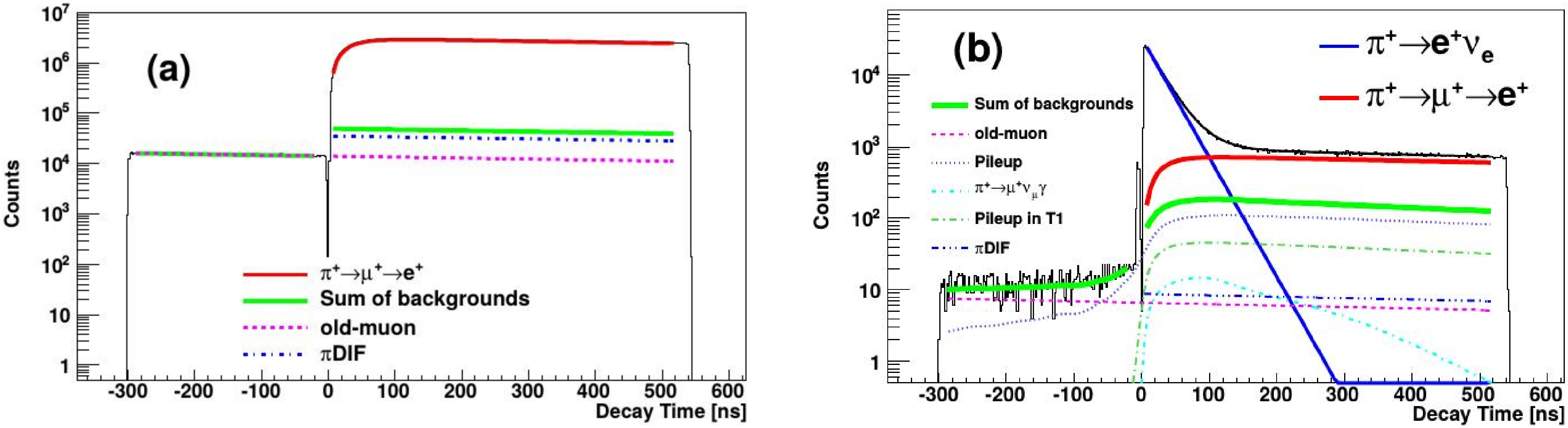
a: $\pi^+ \to \mu^+ \to e^+$ distribution

b: $\pi^+ \to e^+\nu$ in flight requires no stopping material and leads to decay vertices in front of the target without any target signal (horizontal band around -10 MeV).

c: Selection of these events.
The e^+ energy shows the θ dependence expected for Lorentz broadening.
The region below 50 MeV was pre-scaled 1:64 in the readout trigger.
Forward contributions are from scattered beam and μ^+ decays in the degrader.

8 a first result from PIENU

Based on ≈ 10% of all recorded data.
0.5×10^6 $\pi \to e\nu$ events enter the time analysis.



Decay-time analysis of events with e^+ energy below **(a)** or above **(b)** 52 MeV.
At this cut the tail-fraction amounts to $3.16 \pm 0.12\%$.

1992 TRIUMF result:	$B = (1.2265 \pm 0.0034(\text{stat}) \pm 0.0044(\text{syst})) \times 10^{-4}$
1993 PSI result:	$B = (1.2350 \pm 0.0035(\text{stat}) \pm 0.0036(\text{syst})) \times 10^{-4}$
combined:	$B = (1.2312 \pm 0.0035) \times 10^{-4}$
2015 TRIUMF result[10]:	$B = (1.2344 \pm 0.0023(\text{stat}) \pm 0.0019(\text{syst})) \times 10^{-4}$
new average:	$B = (1.2329 \pm 0.0019) \times 10^{-4}$

[10] A. Aguilar-Arevalo *et al.*, [PIENU Collaboration], Phys. Rev. Lett. **115** (2015) 071801.

9 Outlook

PEN finished data-taking five years ago and has been studying these data in great detail ever since. Energy, time and geometry calibrations are done and most features observed are understood and reproduced by simulation.

The question remains when one might expect to “open the box” and finish the project by publishing the branching ratio. Unfortunately, that question can’t be answered for sure but it should happen within the next year.

It is likely that PIENU will be finished by then as well so a significant reduction in the experimantal error of the world avarage can be anticipated.