PIONEER - a next generation pion decay experiment

Chloé Malbrunot
TRIUMF

on behalf of the PIONEER Collaboration

W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12] A. DiCanto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17] M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16] J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5] T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15] D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13] A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

[1]University of California Santa Cruz
[2]Dpt Phys. University of Washington
[3]University of Chicago
[4]University of British Columbia
[5] TRIUMF
[6]Paul Scherrer Institute
[7]Tsinghua University
[8]Institute for Nucl. Theory, University of Washington
[9]Argonne National Laboratory
[10]University of Zurich
[11]CERN
[12]Tec de Monterrey
[13]Brookhaven National Laboratory
[14]PRISMA$^+$ Cluster of Excellence, University of Mainz
[15] Fermilab
[16]Cornell University
[17]University of Virginia
[18]ETH Zurich
[19]University of Kentucky
[20]University of Bern
[21] KEK
[22]University of Tokyo
[23]University of Mainz
[24]Stony Brook University
[25]University of Victoria
[26] Inst. Div, BNL

PIONEER - a next generation pion decay experiment

Chloé Malbrunot
TRIUMF

on behalf of the PIONEER Collaboration

non official logo!

W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12] A. DiCanto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17] M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16] J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5] T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15] D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13] A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

[1]University of California Santa Cruz
[2]Dpt Phys. University of Washington
[3]University of Chicago
[4]University of British Columbia
[5] TRIUMF
[6]Paul Scherrer Institute
[7]Tsinghua University
[8]Institute for Nucl. Theory, University of Washington
[9]Argonne National Laboratory
[10]University of Zurich
[11]CERN
[12]Tec de Monterrey
[13]Brookhaven National Laboratory
[14]PRISMA$^+$ Cluster of Excellence, University of Mainz
[15] Fermilab
[16]Cornell University
[17]University of Virginia
[18]ETH Zurich
[19]University of Kentucky
[20]University of Bern
[21] KEK
[22]University of Tokyo
[23]University of Mainz
[24]Stony Brook University
[25]University of Victoria
[26] Inst. Div, BNL

PIONEER - a next generation pion decay experiment

Chloé Malbrunot
TRIUMF

on behalf of the PIONEER Collaboration

non official logo!

W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12] A. DiCanto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17] M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16] J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5] T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15] D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13] A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

[1]University of California Santa Cruz
[2]Dpt Phys. University of Washington
[3]University of Chicago
[4]University of British Columbia
[5] TRIUMF
[6]Paul Scherrer Institute
[7]Tsinghua University
[8]Institute for Nucl. Theory, University of Washington
[9]Argonne National Laboratory
[10]University of Zurich
[11]CERN
[12]Tec de Monterrey
[13]Brookhaven National Laboratory
[14]PRISMA$^+$ Cluster of Excellence, University of Mainz
[15] Fermilab
[16]Cornell University
[17]University of Virginia
[18]ETH Zurich
[19]University of Kentucky
[20]University of Bern
[21] KEK
[22]University of Tokyo
[23]University of Mainz
[24]Stony Brook University
[25]University of Victoria
[26] Inst. Div, BNL

$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

one of the most precisely known observable involving quarks in the SM

$$= (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad \text{(SM)}$$

$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(exp.)}$$

x 15

Precision low energy experiment on observables that can be very accurately calculated in the SM : highly sensitive tests of NP

OUTLINE

- Physics cases
- A bit of history
- Measurement of R^{π}
- PIONEER detector concept

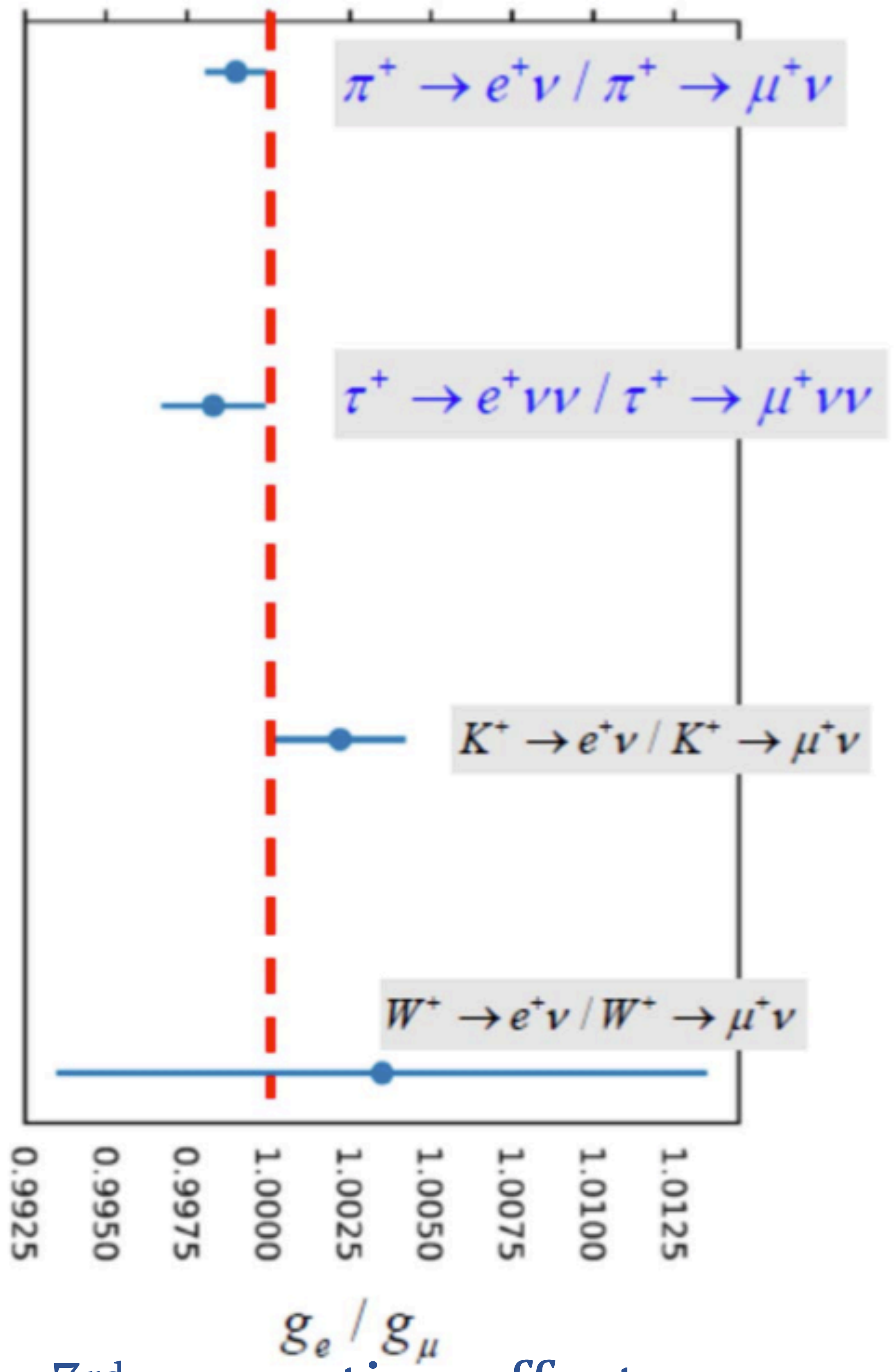
Physics case 1: Testing Lepton Flavor Universality

Weak interaction is the same for $e/\mu/\tau$ leptons

$$R^{\pi} = \frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$

provides the best test of universality in charged current weak interaction

Charged LFU tested at $\mathcal{O}(10^{-3})$



PDG value, mostly constrained by **PIENU** results : $\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$

BUT

Several new tensions in the flavour sector, potentially hinting toward LFUV

- B decays O(10%) deviations from universality.
  Both heavy quarks and leptons involved!
- Muon g-2
  Deviation (4.2 σ) from theory - new physics?
- CKM unitarity tests from β and K decays (2 - 3 σ)
  Maybe related to LFUV?

Precise measurements of 1st and 2nd generation decays could be used to distinguish between models explaining 3rd generation effects…

Physics case 2: Sensitivity to new coupling and NP at very high mass scales $\Longrightarrow$ possible interpretation of universality violation

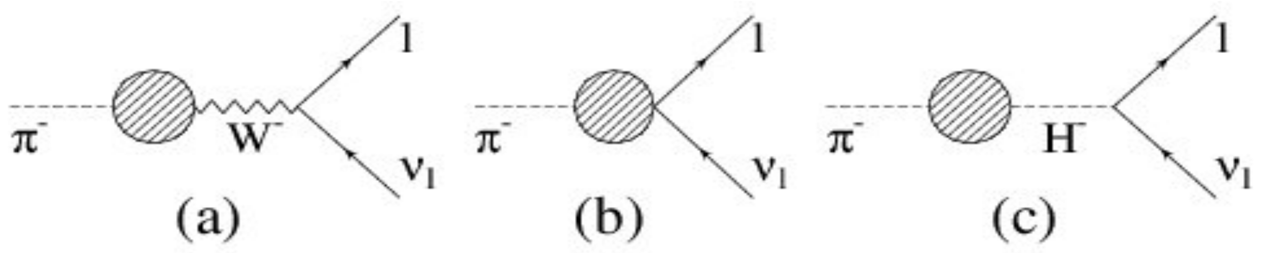
$$R^{\pi}_{SM} = \frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$

calculated at the 0.01% level

$\pi^+ \to e^+\nu$ is helicity-suppressed (V-A)

$\Rightarrow R^{\pi}$ is extremely sensitive to presence of new pseudoscalar or scalar couplings

Pseudoscalar interactions



Charged Higgs (non-SM coupling)

$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d + m_u)} \sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

Marciano…

PIONEER PHASE 1 goal:

0.01 % measurement → $\Lambda_{eP} \sim 3000$ TeV

Physics case 2: Sensitivity to new coupling and NP at very high mass scales

- Sensitive to many other new physics scenarios
  - Leptoquarks
  - Induced scalar currents
  - Excited gauge bosons
  - Compositeness
  - SU(2)xSU(2)xSU(2)xU(1)
  - Hidden sector ….

- Many exotic searches performed by the PIENU collaboration :
  e.g. sterile neutrinos
  which have implications for leptogenesis

Contents lists available at ScienceDirect
Physics Letters B
ELSEVIER
www.elsevier.com/locate/physletb

Search for heavy neutrinos in $\pi \to \mu\nu$ decay

PHYSICAL REVIEW D **97,** 072012 (2018)

Editors' Suggestion

Improved search for heavy neutrinos in the decay $\pi \to e\nu$

PHYSICAL REVIEW D **102,** 012001 (2020)

Search for the rare decays $\pi^+ \to \mu^+\nu_\mu\nu\bar{\nu}$ and $\pi^+ \to e^+\nu_e\nu\bar{\nu}$

PHYSICAL REVIEW D **101,** 052014 (2020)

Improved search for two body muon decay $\mu^+ \to e^+X_H$

PHYSICAL REVIEW D **103,** 052006 (2021)

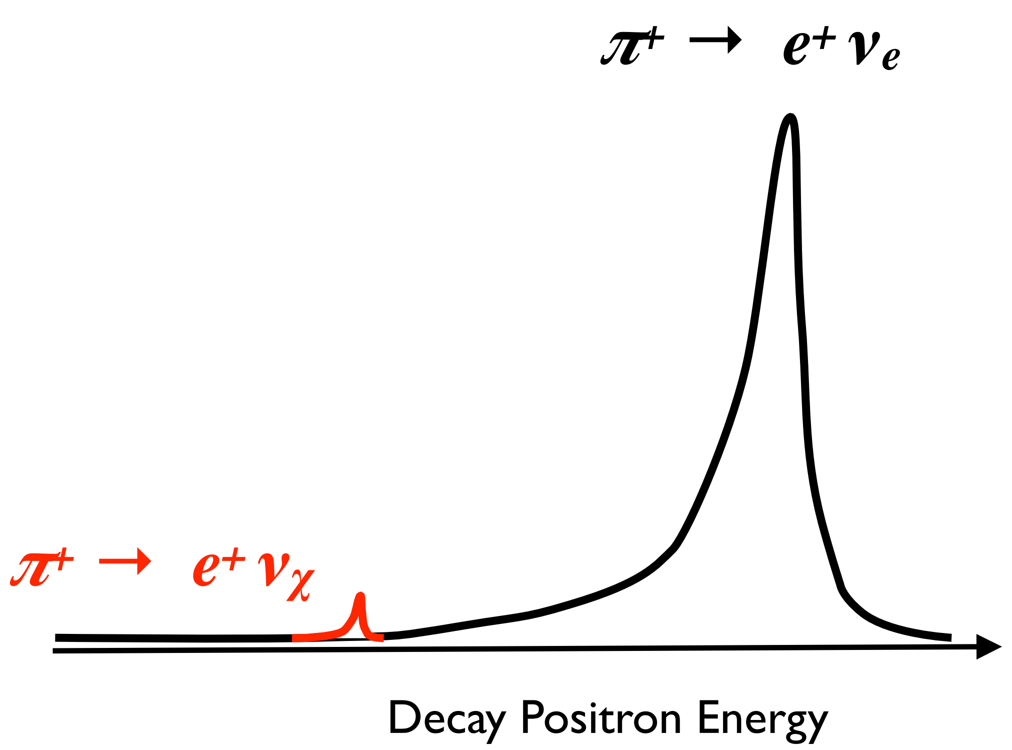
Search for three body pion decays $\pi^+ \to l^+\nu X$

recent searches performed by the **PIENU** collaboration

⇓

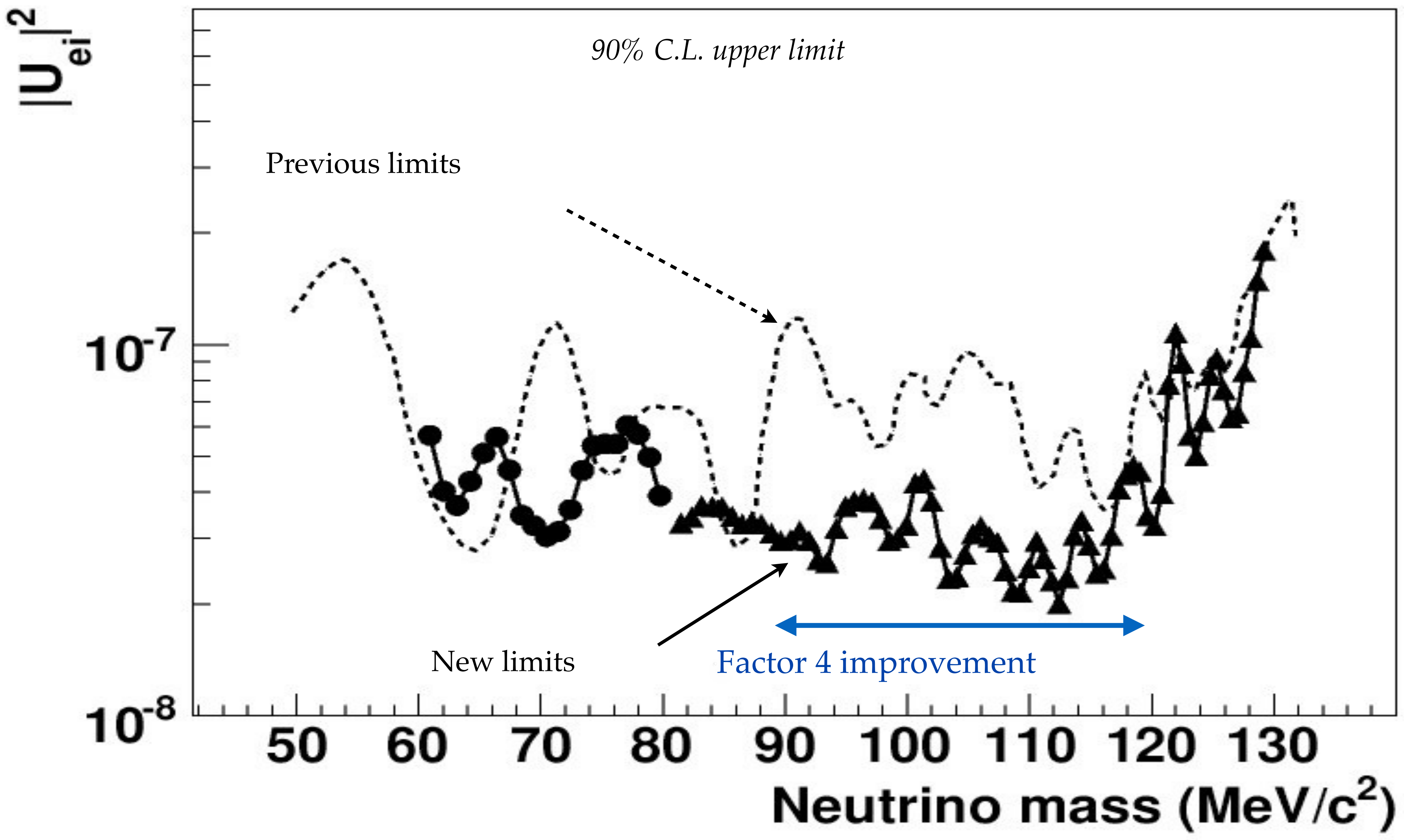
PIONEER will improve on all those searches by ~1 order of magnitude

Example (old) of first massive neutrino search



If the heavy neutrino mass is M_ν= 60~130 MeV/c^2 **additional low energy positron peak** can be detected in the $\pi^+ \rightarrow e^+$ spectrum

R.E Shrock Phys.Rev.D 24, 1232 (1981),
Phys. Lett. B 96, 159 (1980)



M.Aoki et al., Phys. Rev. D 84, 052002 (2011)

Heavy υ

Kinematic factor

$$R_{ei} = \frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to e\nu_l)} = |U_{ei}|^2 \rho_{ei}$$

Conventional υ

$$\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i} \nu_i$$

$$\ell = e, \mu, \tau, \chi_1, \chi_2 ... \chi_k$$

More recent and stronger bounds provided by PIENU :
PRD 97.072012 (2018)
PLB 798 (2019) 134980 [in $\pi \rightarrow \mu\nu$ decay]

Comprehensive constraints on sterile neutrinos in the MeV to GeV mass range
D. A. Bryman and R. Shrock, Phys. Rev. D 100, 073011

Physics case 3: Testing CKM unitarity V_{ud}, $\frac{V_{us}}{V_{ud}}$

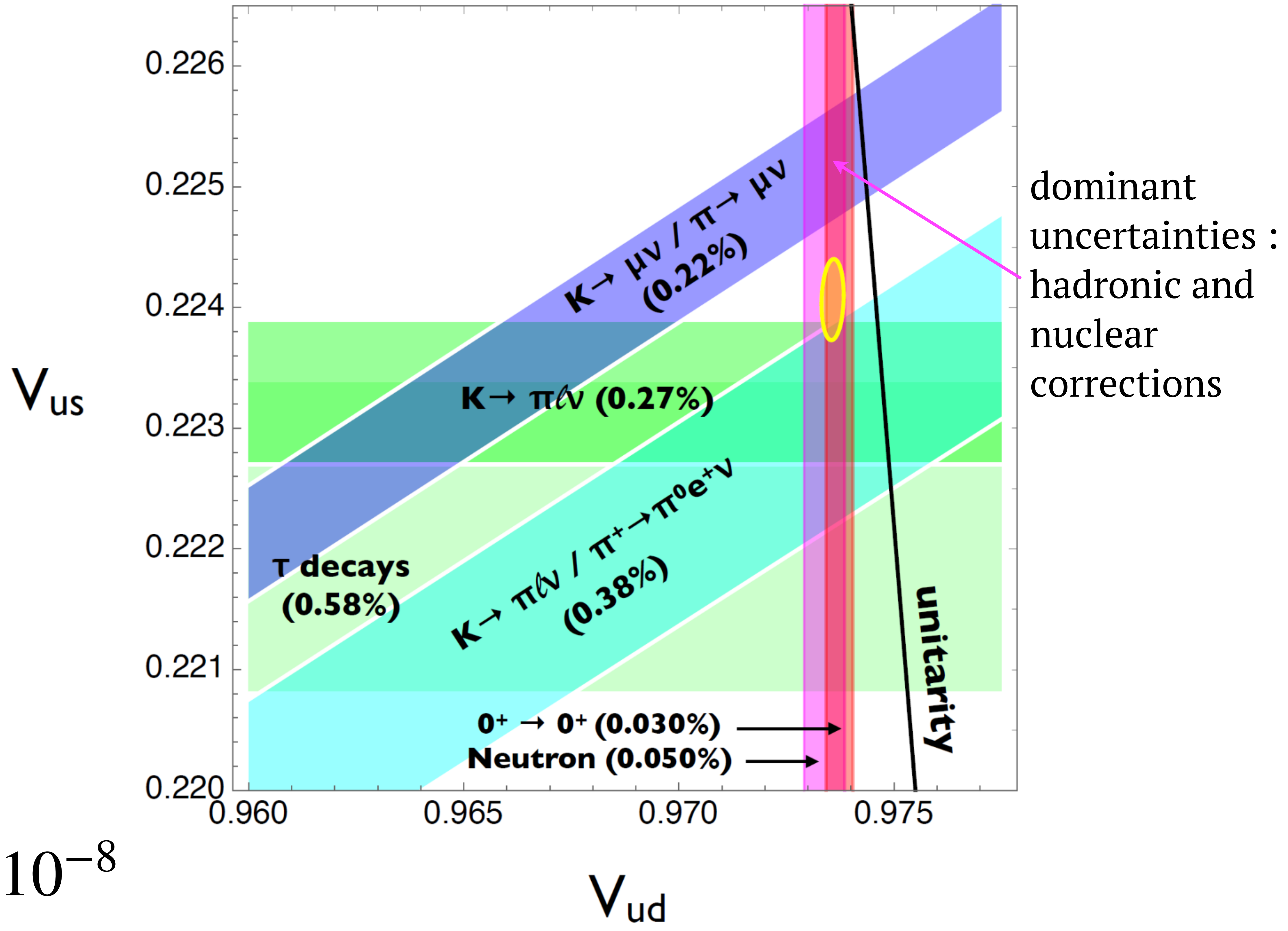
V_{ud}: tested in super-allowed β decays

$\frac{V_{us}}{V_{ud}}$: tested in Kdecays

$$\frac{B(K \to \pi l \nu)}{B(\pi^+ \to \pi^0 e^+ \nu)}$$: Theoretically clean method to obtain $\frac{V_{us}}{V_{ud}}$

tensions in the first row CKM unitarity test

3σ (or even more…)



PIONEER Phase II goal: *Phys.Rev.D* 101 (2020) 9, 091301

Improve $B(\pi^+ \to \pi^0 e^+ \nu)$ precision by >3 $\frac{V_{us}}{V_{ud}} < \pm 0.2\,\%$

Offers a new complementary constraint in the $V_{us} - V_{ud}$ plane

PIONEER Phase III goal:

Improve $B(\pi^+ \to \pi^0 e^+ \nu)$ precision by an order of magnitude

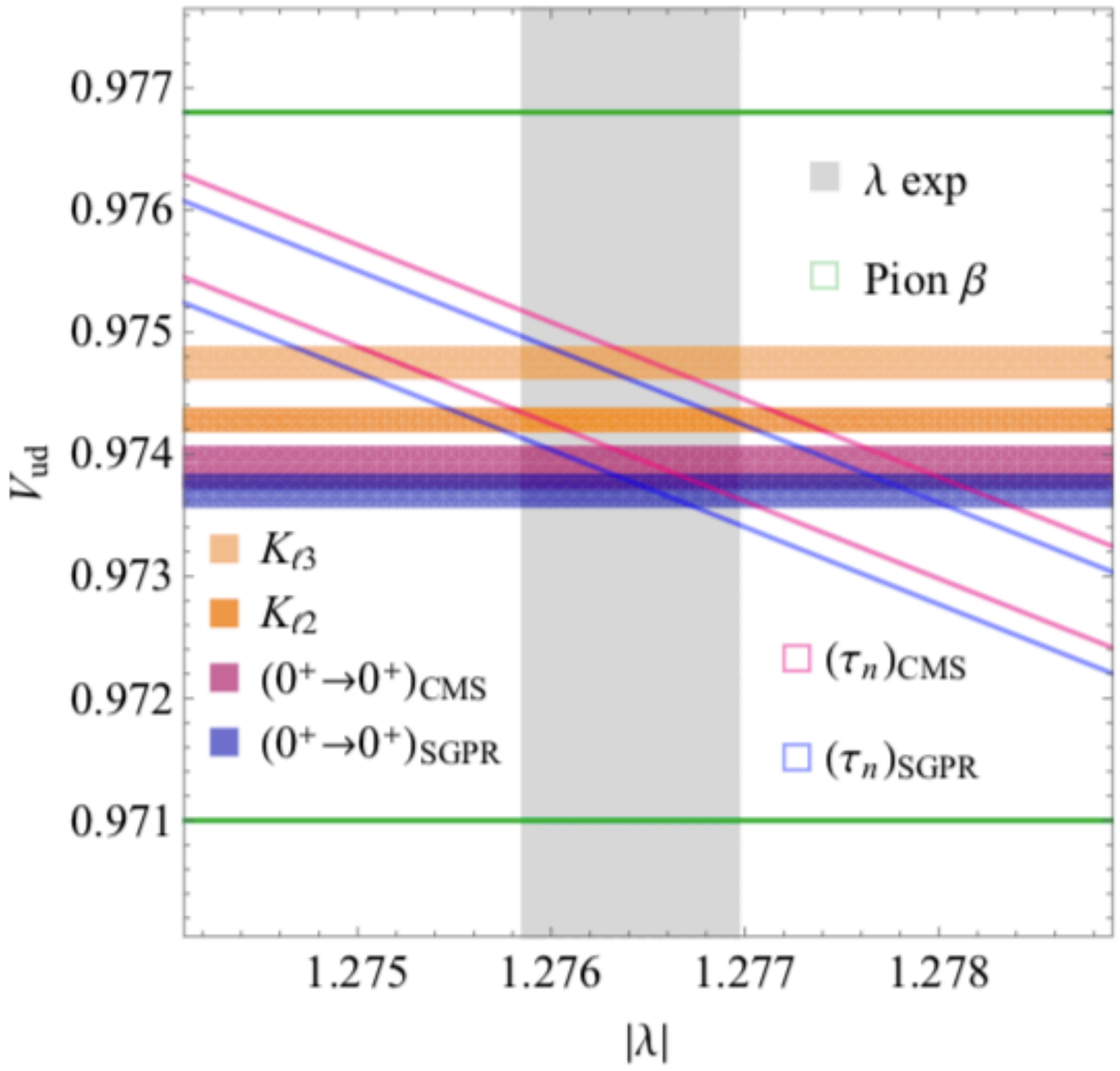
$\pi^+ \to \pi^0 e^+ \nu$ is the theoretically cleanest method to obtain V_{ud}

PIBETA exp. ($\pm 0.6\%$)

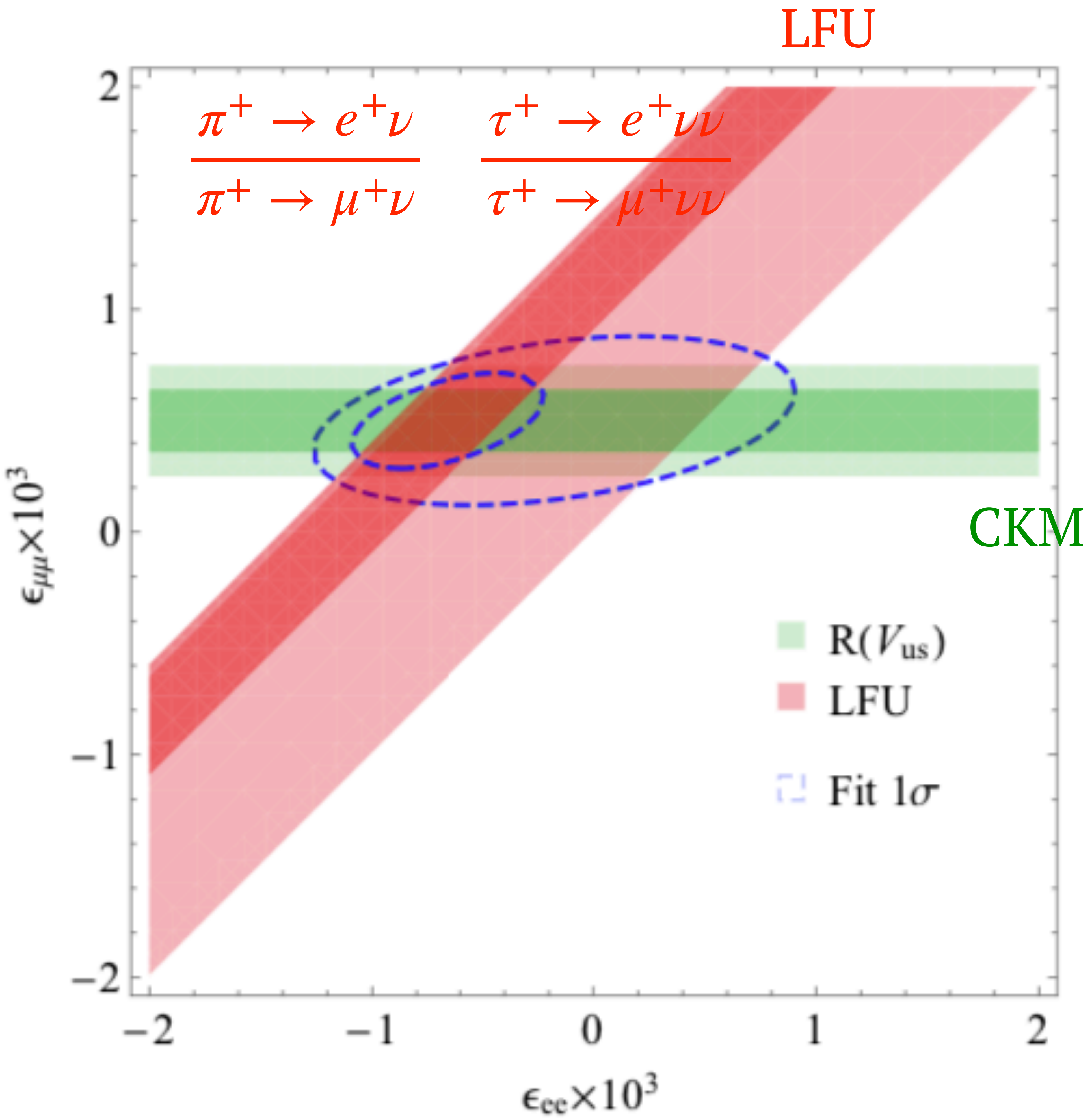
$$B(\pi^+ \to \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2}) \times 10^{-8}$$

Presently not competitive precision for V_{ud} but would be with an order of magnitude improvement (same precision as β decays)

Physics case 3bis: LFUV and CKM unitarity might be connected



if CKM first row unitarity assumed V_{ud} value obtained from kaon decays is different from super-allowed beta decay!



V_{ud} tension as a sign for LFUV?

Crivellin & Hoferichter
Phys. Rev. Lett. 125, 111801 (2020)

Modified $W l \nu$ couplings $G_F = G_F^{\mathscr{L}}(1 + \varepsilon_{ee} + \varepsilon_{\mu\mu})$

A bit of history on R^{π}

1940/50's : Development of V-A structure of weak interaction

1950's: Many experimental confirmation of the V-A theory

1956-1957: Negative experimental results BR<10^{-5}

Note on the Decay of the π-Meson

M. Ruderman and R. Finkelstein
California Institute of Technology, Pasadena, California
(Received July 25, 1949)

Table I. Ratio of $\pi\to(e,\nu)$ to $\pi\to(\mu,\nu)$-decay for couplings (1) and (7).

		Type of β-decay				
		Scalar	*P*-scalar[a]	Vector	*P*-vector	Tensor
Meson	Scalar	5.1	*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*	4.0	*f*

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 $\pi\to e+\nu$ 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.

I write this in english, for I beg you to circulate this letter next to → Oehme, Yang-Lee. Particularly to the latter with very warm regards too

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7/6
Gloriastrasse 35

Jan. 22, 1957

January 22nd 1957

Dear Telegdy,

I thank you so much for having sent to me all 3 reprints of the experimental papers. They arrived just in time (yesterday at 5 P.M.) to be used in my evening lecture on older and newer history of the neutrino (yesterday at 8[15] P.M.). I could change the end of this lecture and tell about the

2) I still don't know why the reaction $\pi \to e + \nu$ does not occur. Has anybody some new ideas about it.

I had my struggle with [illegible] violation of the energy conservation versus neutrino (after establishment of wave-mechanics). The phrase was „but we have to be prepared for surprises". He was wrong with the energy-law, but he was right that the weak interactions are a very particular field where strange things could happen, which don't happen otherwise. So I said at the end 'and now will come the surprise, which Bohr had expected'.

This time I was wrong in my expectations. But still I don't understand, why the strong interactions are reflexion-invariant (parity invariance. P is the notation of Oehme-Yang-Lee).

Letter of W. Pauli to V. Telegdy

A bit of history on R^{π}

"Particle rush"
Development of SM

Discovery of Pion

1947 — *Nature* 159:694-697

No electronic decay observed
PUZZLE!

1955 — *Supl. Nuovo cimento* 2:151

1957 — *Il Nuovo Cimento* **VI**, 6

Search for the β-Decay of the Pion. (*)

S. LOKANATHAN and J. STEINBERGER (**)

Nevis Cyclotron Laboratories, Columbia University
Department of Physics - New York

IL NUOVO CIMENTO VOL. VI, N. 6 1° Dicembre 1957

Search for the Electronic Decay of the Positive Pion (*)

H. L. ANDERSON (+)

Scuola di Perfezionamento in Fisica Nucleare dell'Università - Roma

C. M. G. LATTES (×)

Enrico Fermi Institute for Nuclear Studies
The University of Chicago - Chicago

1958

First experimental observation of the **electronic decay** at CERN **about** 65 years ago!

VOLUME 1, NUMBER 7 PHYSICAL REVIEW LETTERS OCTOBER 1, 1958

ELECTRON DECAY OF THE PION

T. Fazzini, G. Fidecaro, A. W. Merrison, H. Paul, and A. V. Tollestrup*
CERN, Geneva, Switzerland
(Received September 12, 1958)

Phys. Rev. Lett. 1, 7

… and "simultaneously" at Columbia University
Phys. Rev. Lett. 1, 249

1959

… and confirmed at Univ. of Chicago
Phys. Rev. Lett. 2, 64

x3

First precise measurement (~5%)

1964 — Di Capua et al. — *Phys. Rev.* 133(5B):B1333–B1340

~x2

"Precision area"
Search for BSM

1986 — TRIUMF by Bryman et al. — *Phys. Rev. D* 3(5):1211–1221

x2.5

1992 — TRIUMF by Britton et al. — *Phys. Rev. Lett.* 68:3000–3003

1993 — PSI by Czapek et al. — *Phys. Rev. Lett.* 70 (1) 17-20

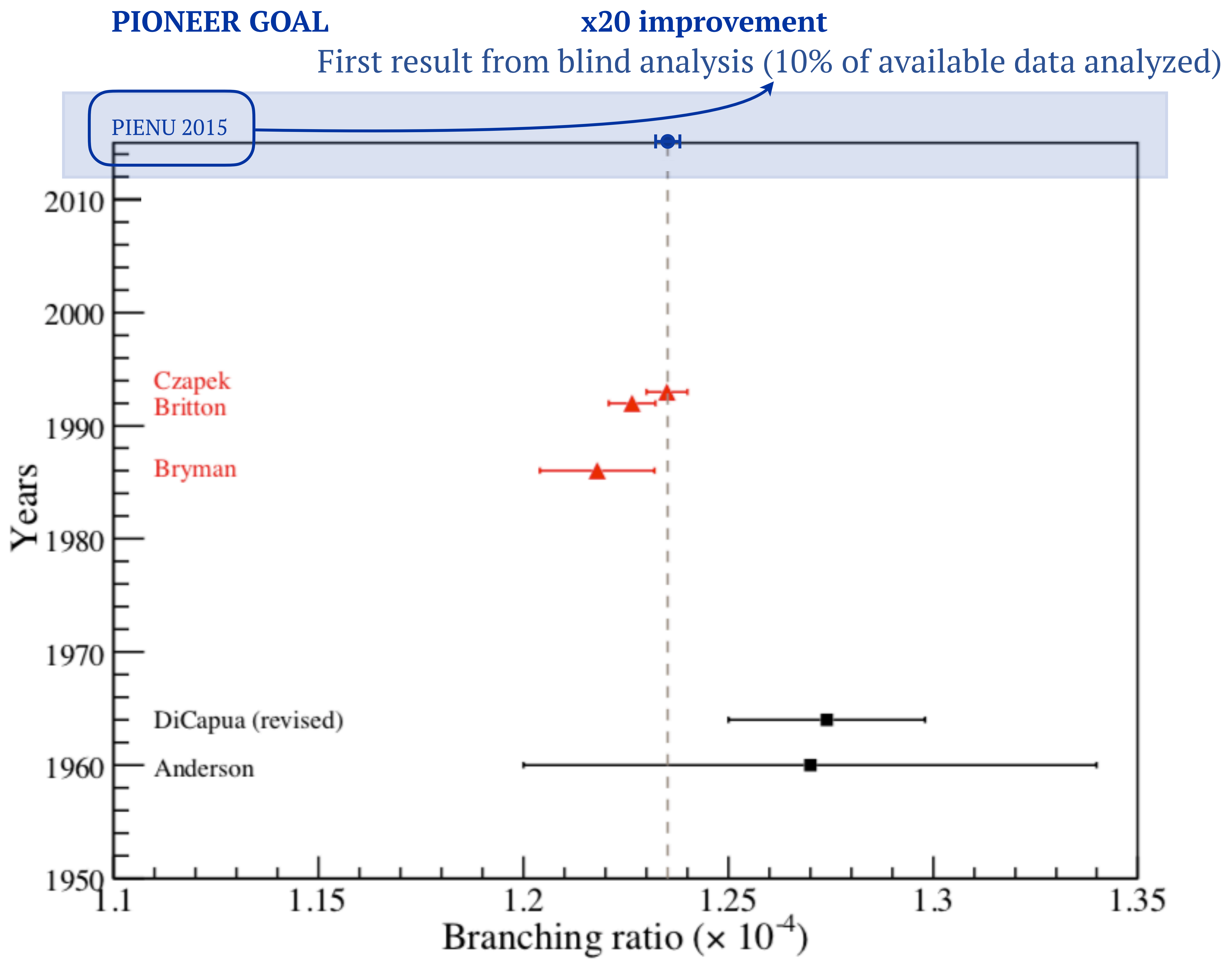
~x2

2015 — TRIUMF by Aguilar Arevalo et al. — *Phys. Rev. Lett.* 115:071801 — Most precise measurement (~0.2%)

PIONEER — ***x20***

Previous R^{π} experiments

- PIENU at TRIUMF (M13)
- PEN at PSI (same precision goal: different setup)
- several previous pion decay measurements



PDG 2018 ±0.19 %

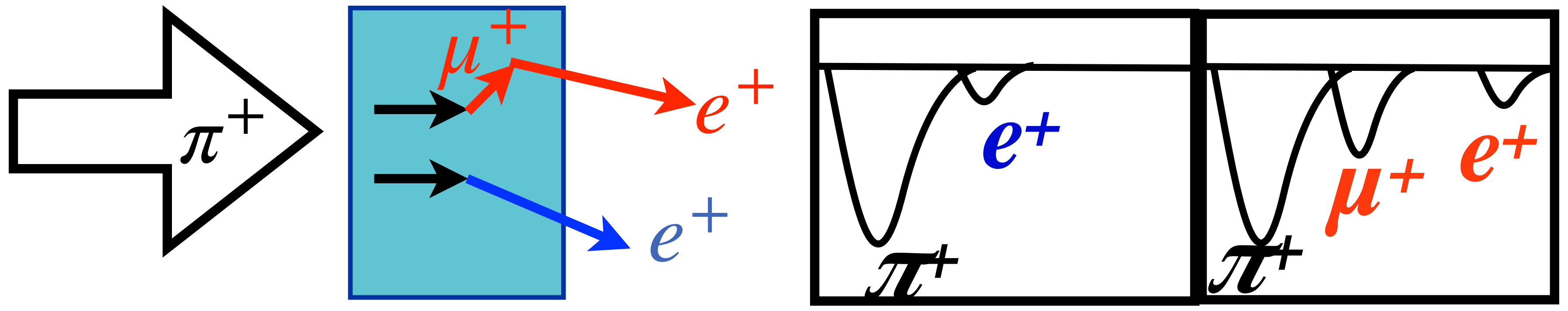
VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.2327±0.0023 OUR AVERAGE						
1.2344±0.0023±0.0019	400k	AGUILAR-AR...	15	CNTR	+	Stopping π^+
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO		Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR		Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR		Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.273 ±0.028	11k	[1] DICAPUA	64	CNTR		
1.21 ±0.07		ANDERSON	60	SPEC		

[1] DICAPUA 64 has been updated using the current mean life.

Final goal of PIENU (using full data set) and of PEN: 0.1% (factor ~2 over current precision)

$$R^\pi = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: how is it measured?

$\mu \to e\nu\bar{\nu}$

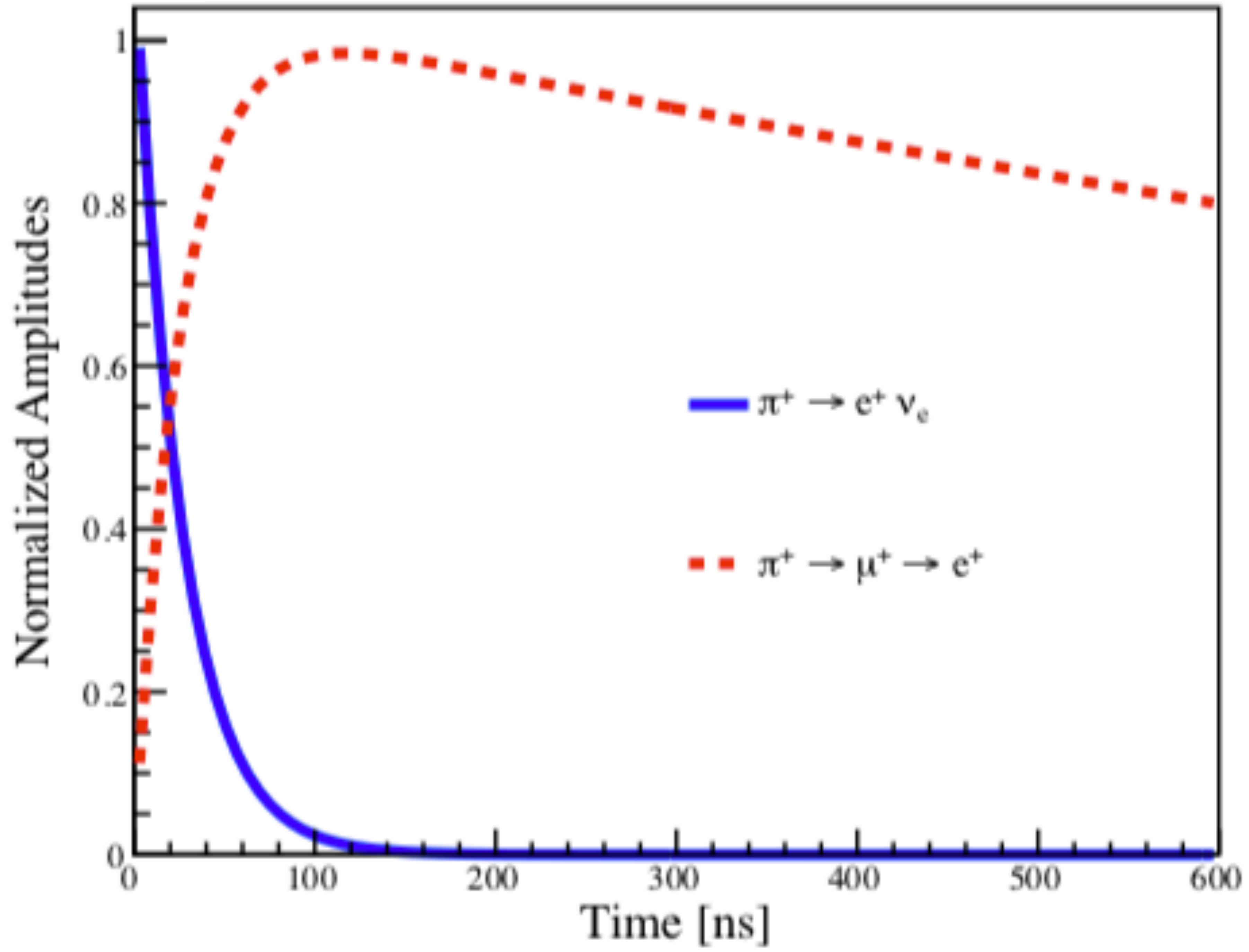


What π decay to "normally": $B(\pi^+ \to \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$
Helicity suppressed decay: $B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$
Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

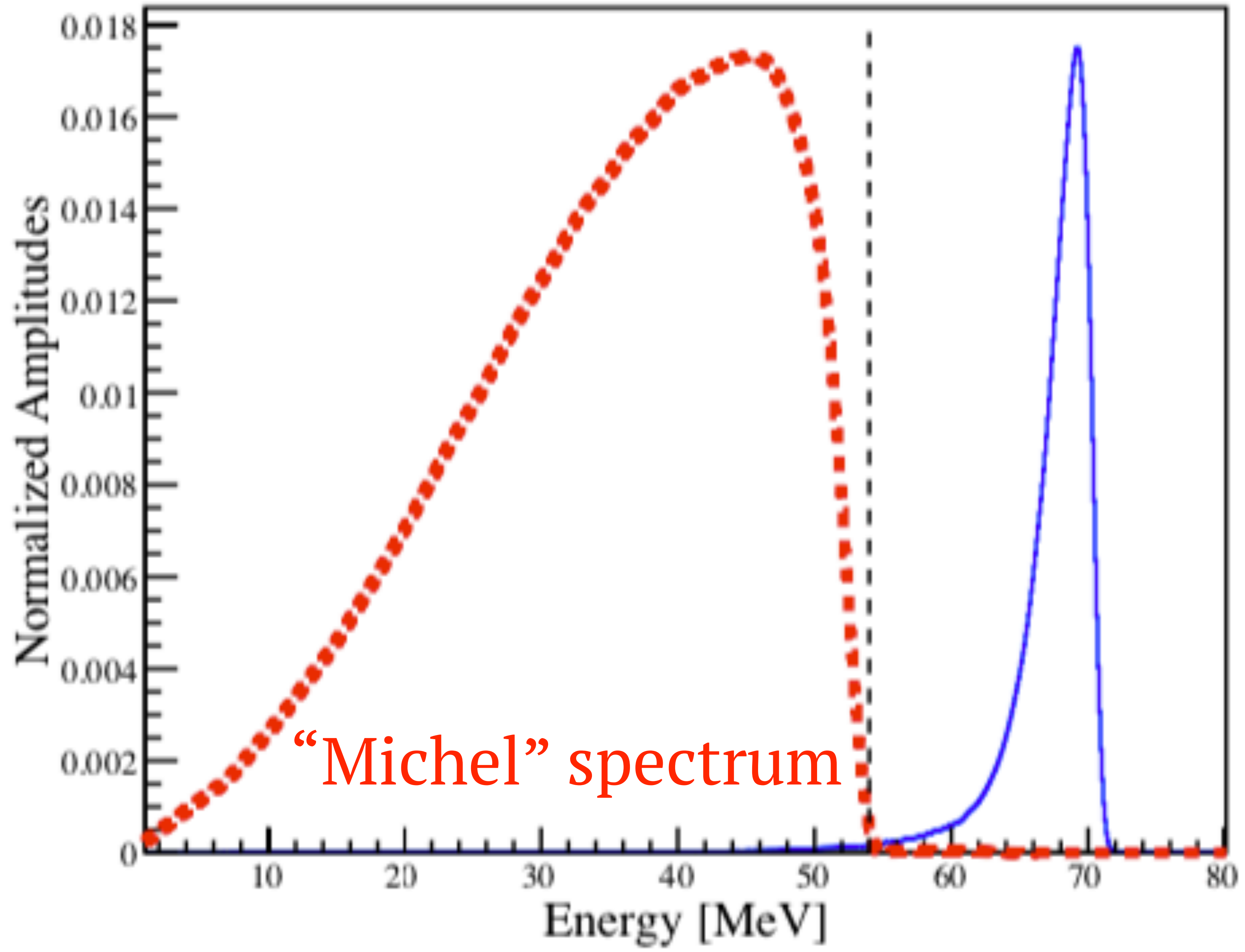
Reminders:

Pion lifetime:	26 ns
Muon lifetime:	2197 ns
Pion mass:	139.6 MeV
Muon mass:	105.7 MeV

Measure precisely e^+ energy spectrum and $t_{e^+} - t_{\pi^+}$
$\Longrightarrow$ different time and energy spectra - discrimination between the two decays



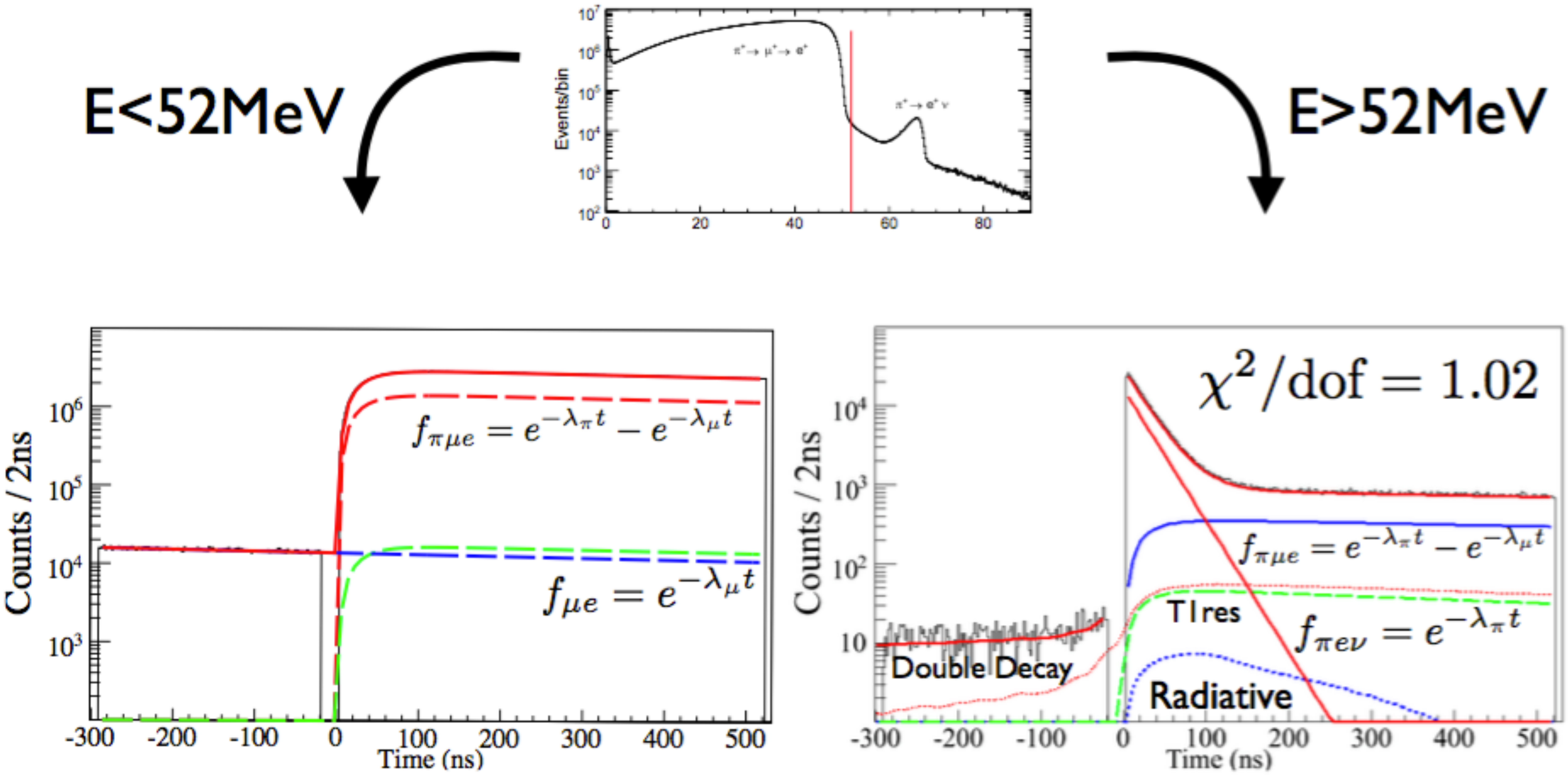
Time spectrum



e^+ energy spectrum

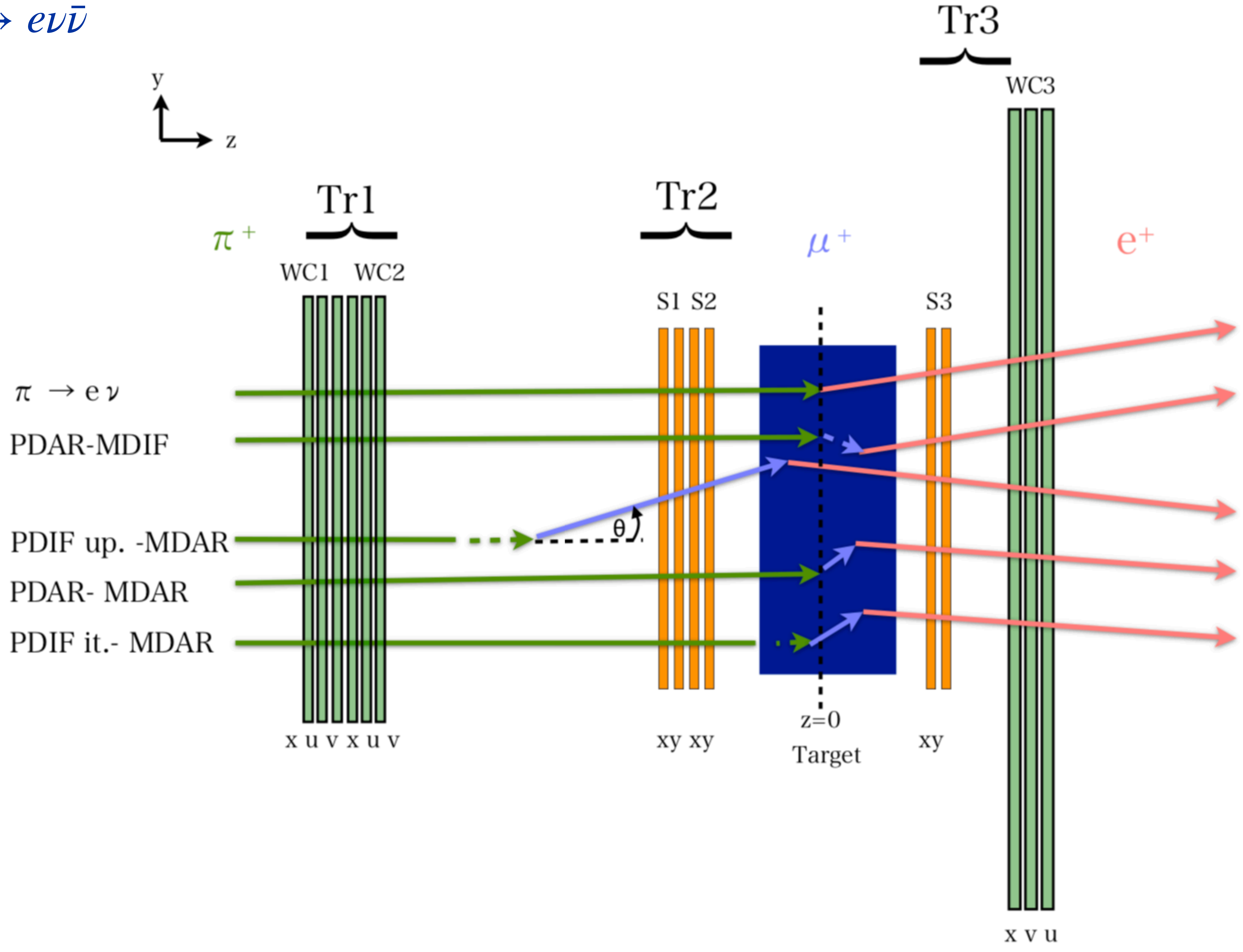
$$R^\pi = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: how is it measured?

$\mu \to e\nu\bar{\nu}$



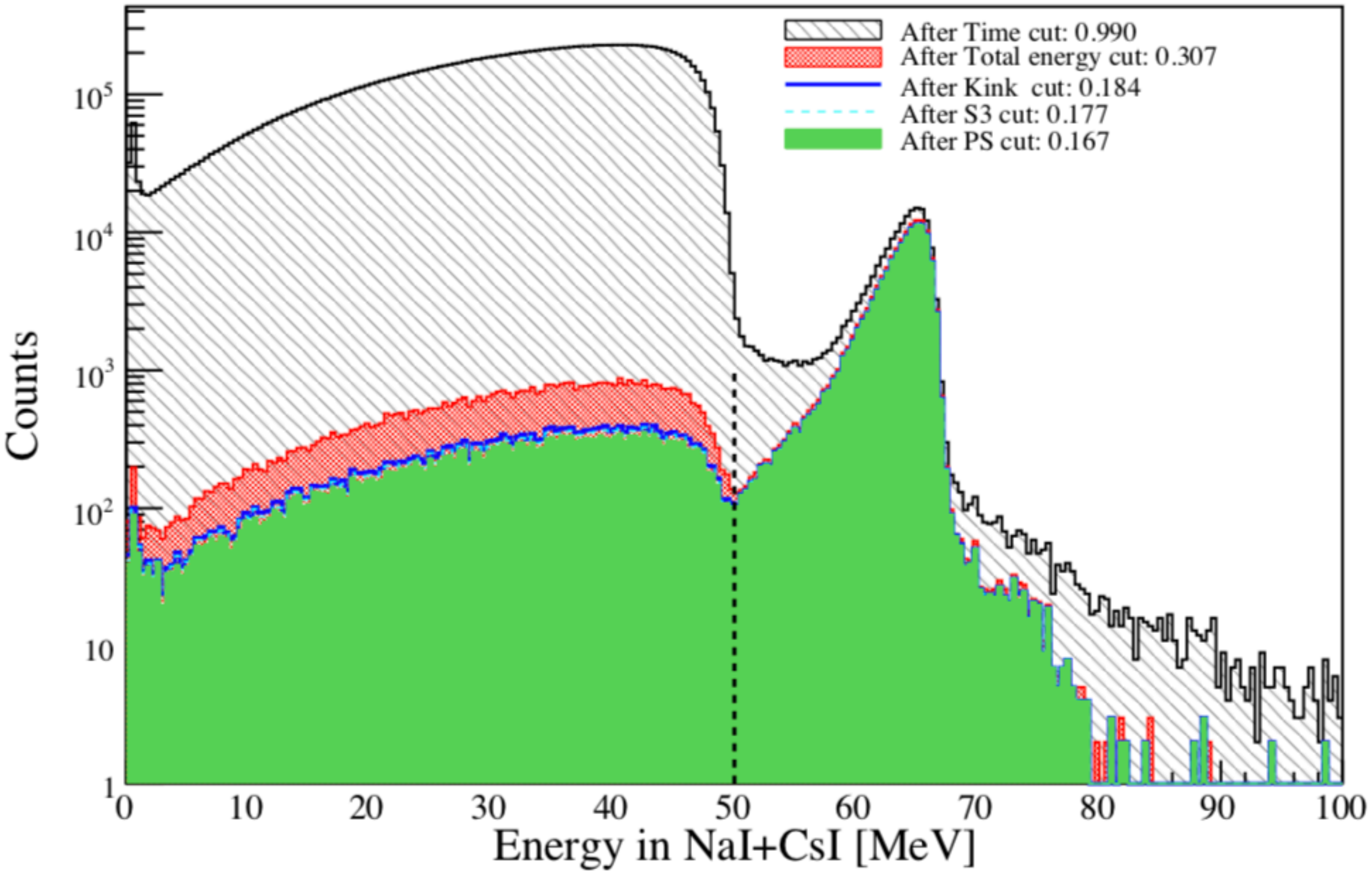
$$R^{\pi} = \frac{\pi \rightarrow e\nu(\gamma)}{\pi \rightarrow \mu\nu(\gamma)}$$: how is it measured?

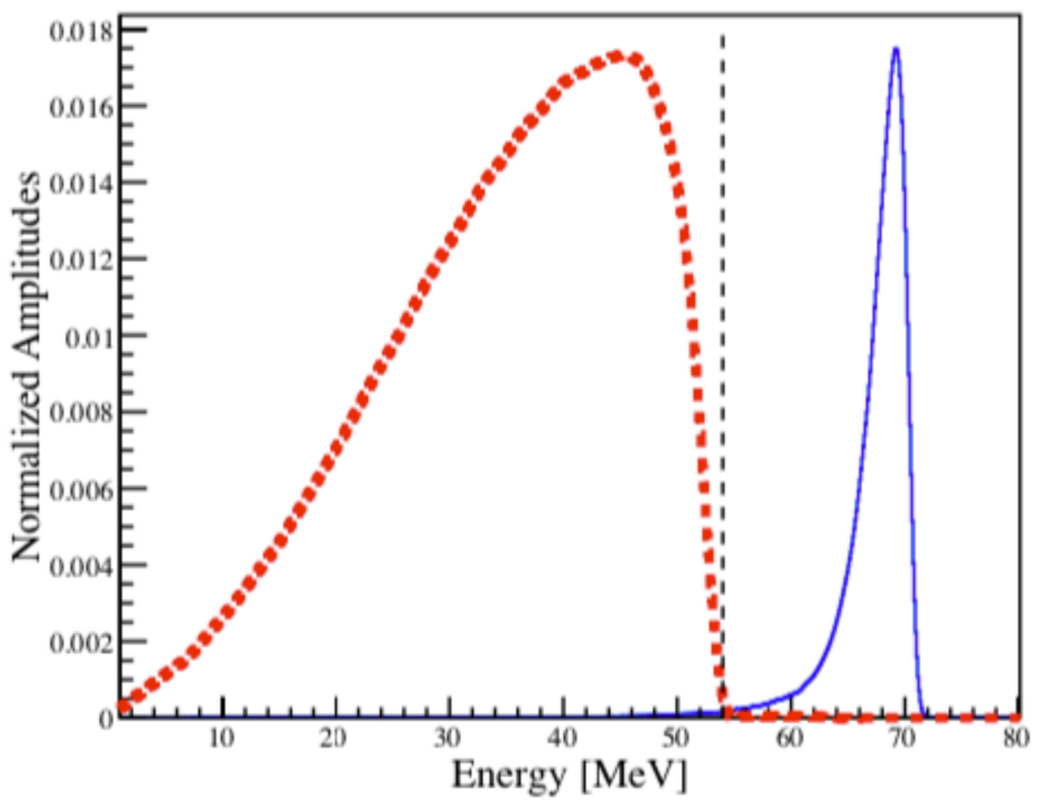
$\mu \rightarrow e\nu\bar{\nu}$

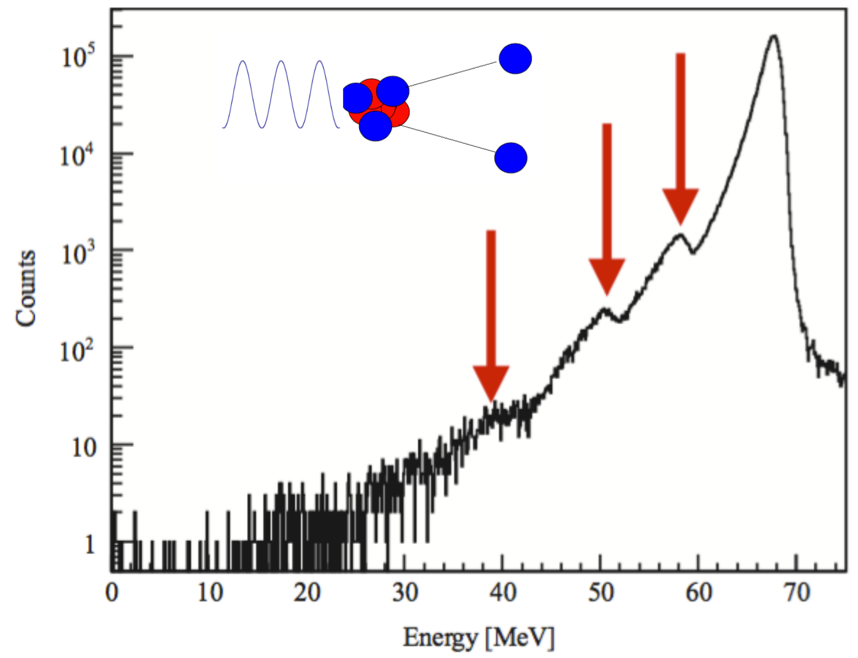


$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: main systematic in the PIENU experiment

$\mu \to e\nu\bar{\nu}$







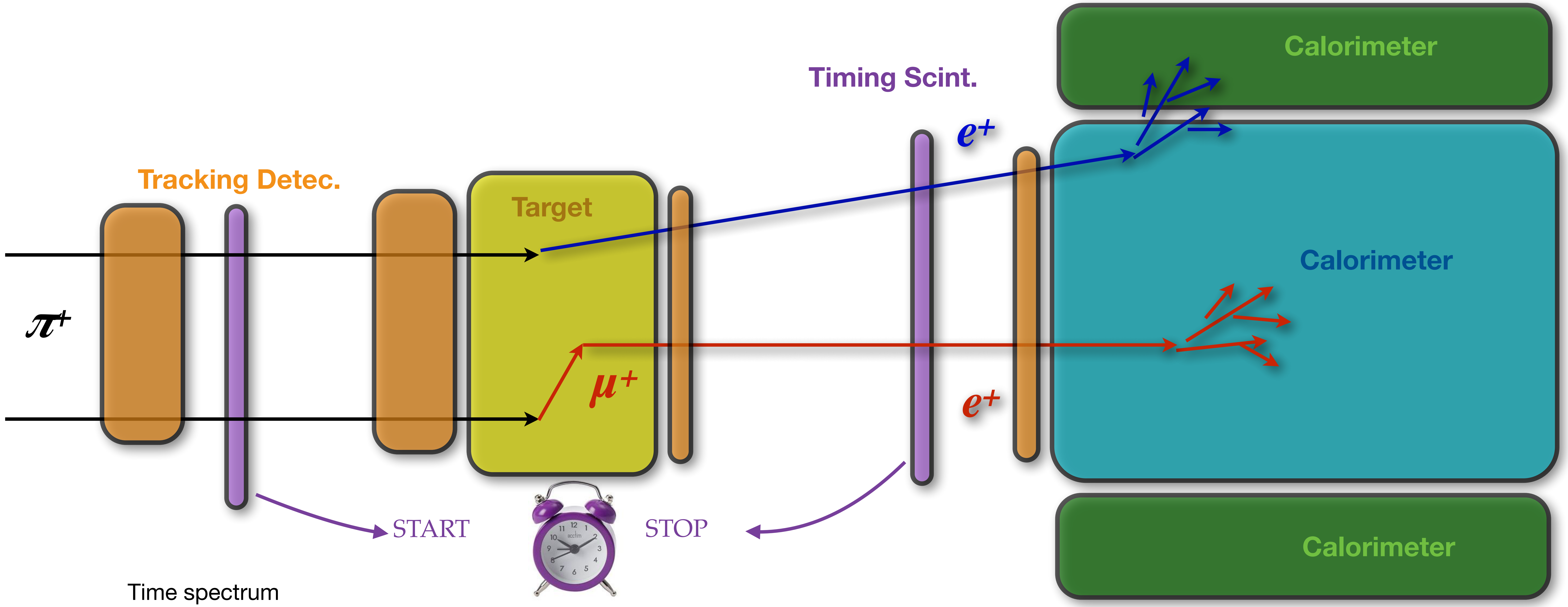
A. Aguilar-Arevalo et al., Nuclear Instruments and Methods in Physics Research A 621 (2010) 188–191

Low energy tail buried under the Michel spectrum caused by:

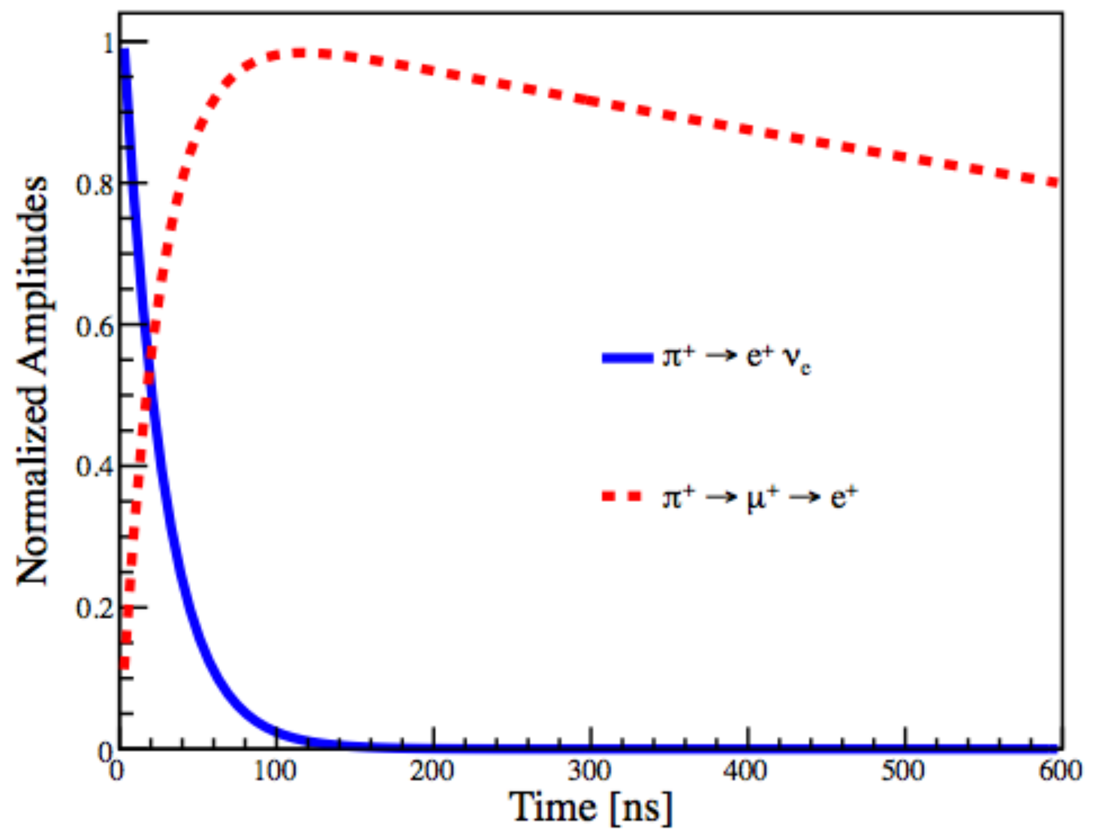
- finite energy resolution of the calorimeter
- photo-nuclear interactions (^{127}I(ɣ,n))
- shower leakage
- geometrical acceptance
- radiative decays
- etc

Main source of systematics : estimated using data (suppression of $\pi \to \mu \to e$ decays)

Schematics of the PIENU experiment



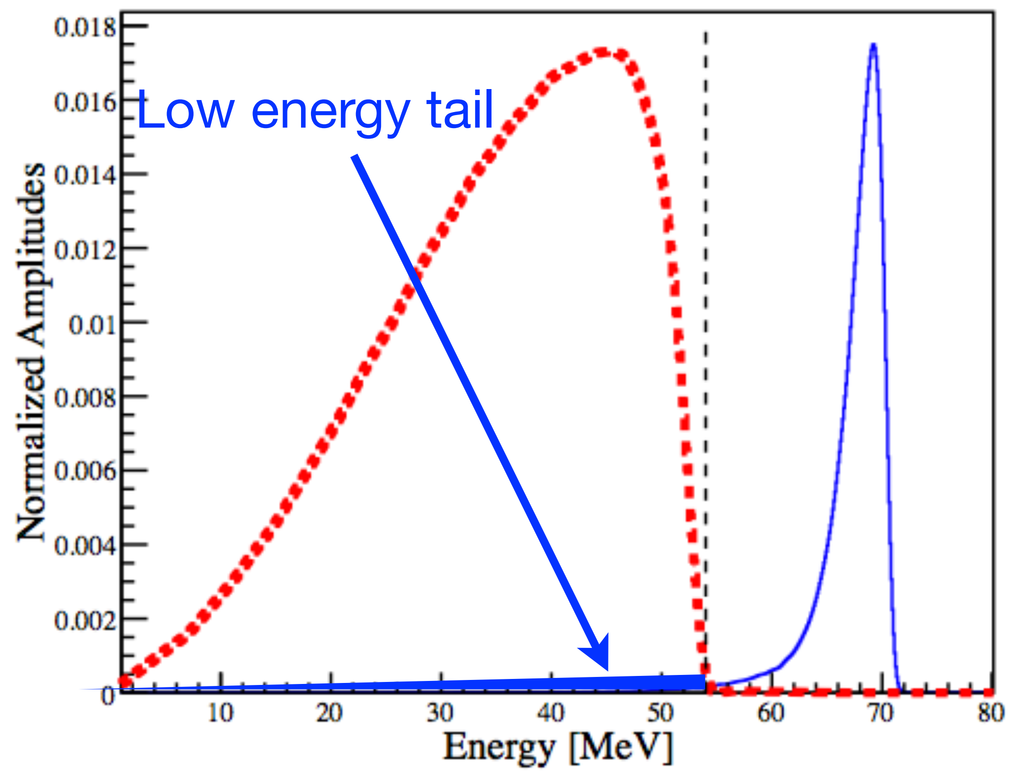
Time spectrum



Characteristics

- High purity pion beam
- Large calorimeter and excellent resolution
- High speed pulse digitization
- Good vertex reconstruction (DIF)

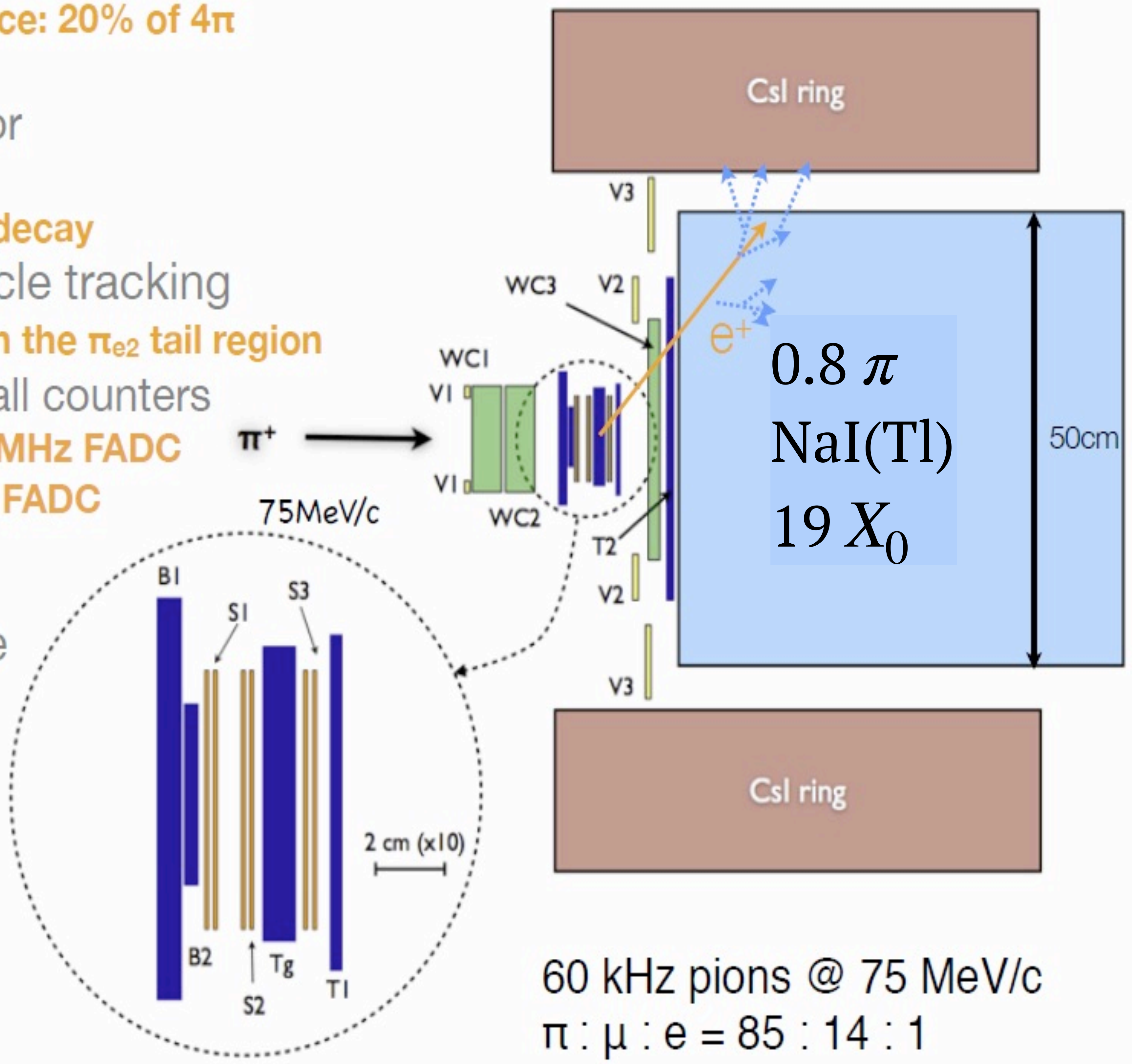
Energy spectrum



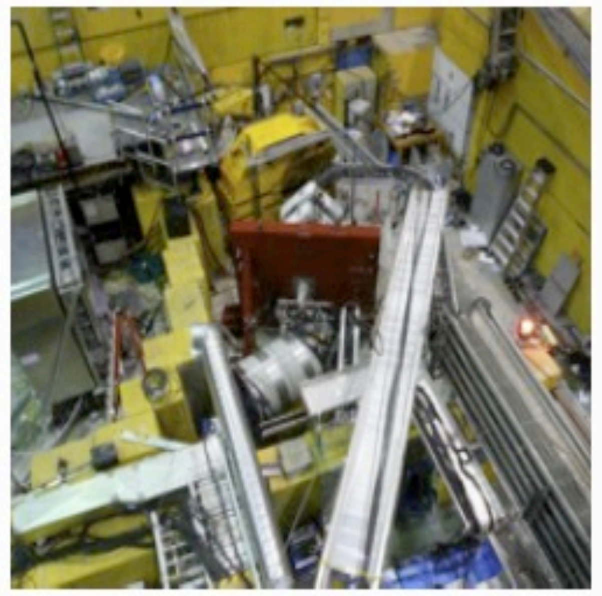
PIONEER: building on previous experiences - PIENU and PEN

PIENU @ TRIUMF

- Single crystal NaI(Tl) right behind the target
  - Geometrical Acceptance: 20% of 4π
  - ΔE = 2.2%(FWHM)
- CsI ring shower collector
  - π_{e2} tail suppression
  - gamma from radiative decay
- SSD and WC for particle tracking
  - Identify π-DIF events in the π_{e2} tail region
- Flash-ADC readout for all counters
  - Plastic Scintillator: 500MHz FADC
  - NaI(Tl) and CsI: 60MHz FADC
  - Pile-up tagging



- TRIUMF M13 beamline



NaI slow but excellent resolution (1% σ at 70 MeV)

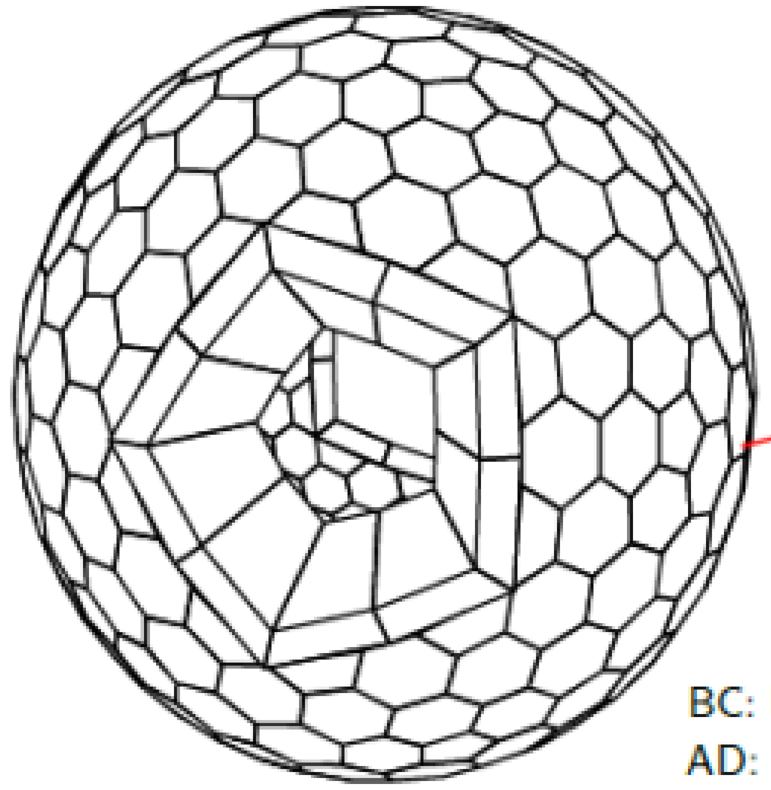
non uniformity, small solid angle

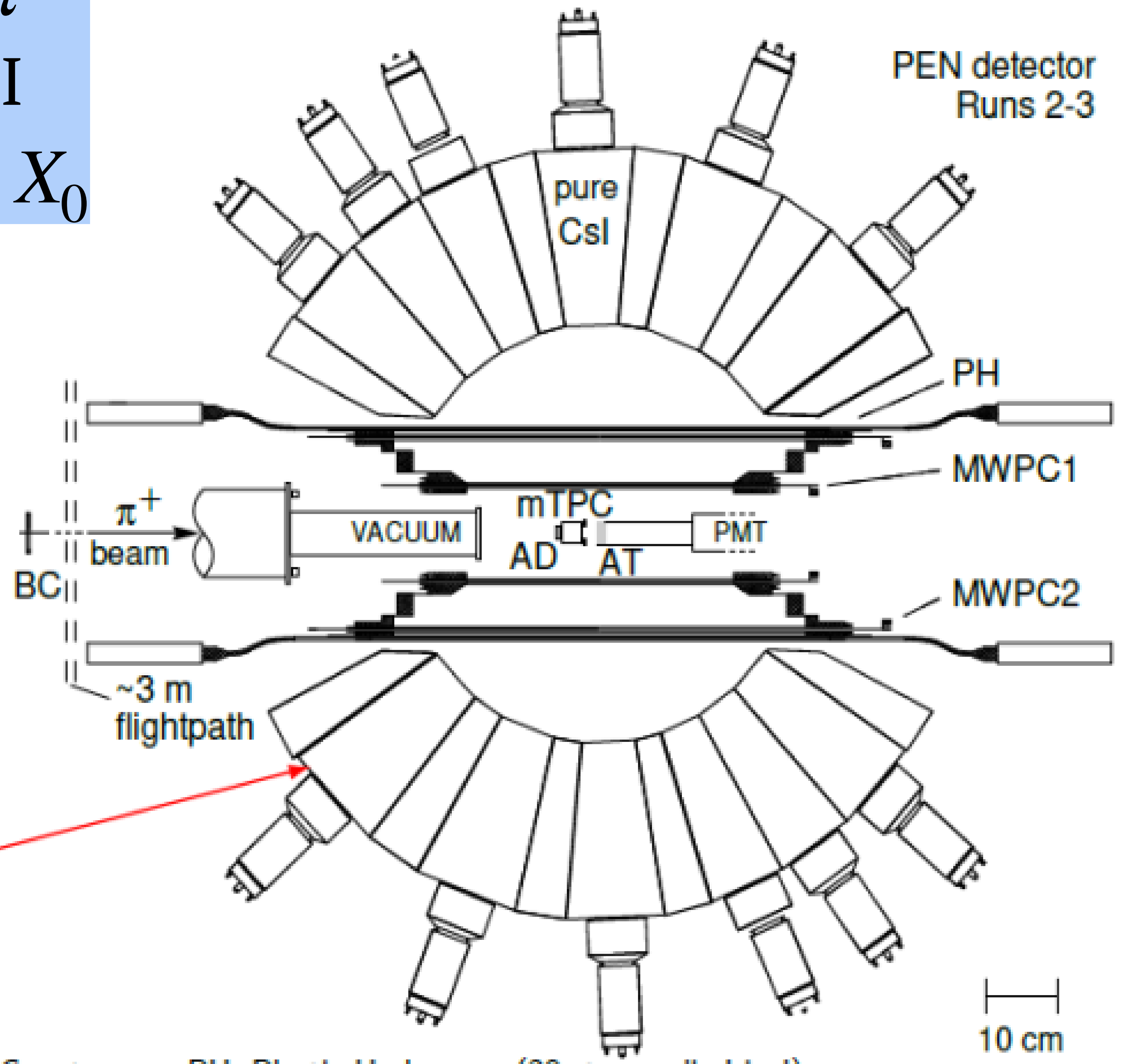
PEN @ PSI

The PEN/PIBETA apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240 module spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms

3 π
CsI
12 X_0





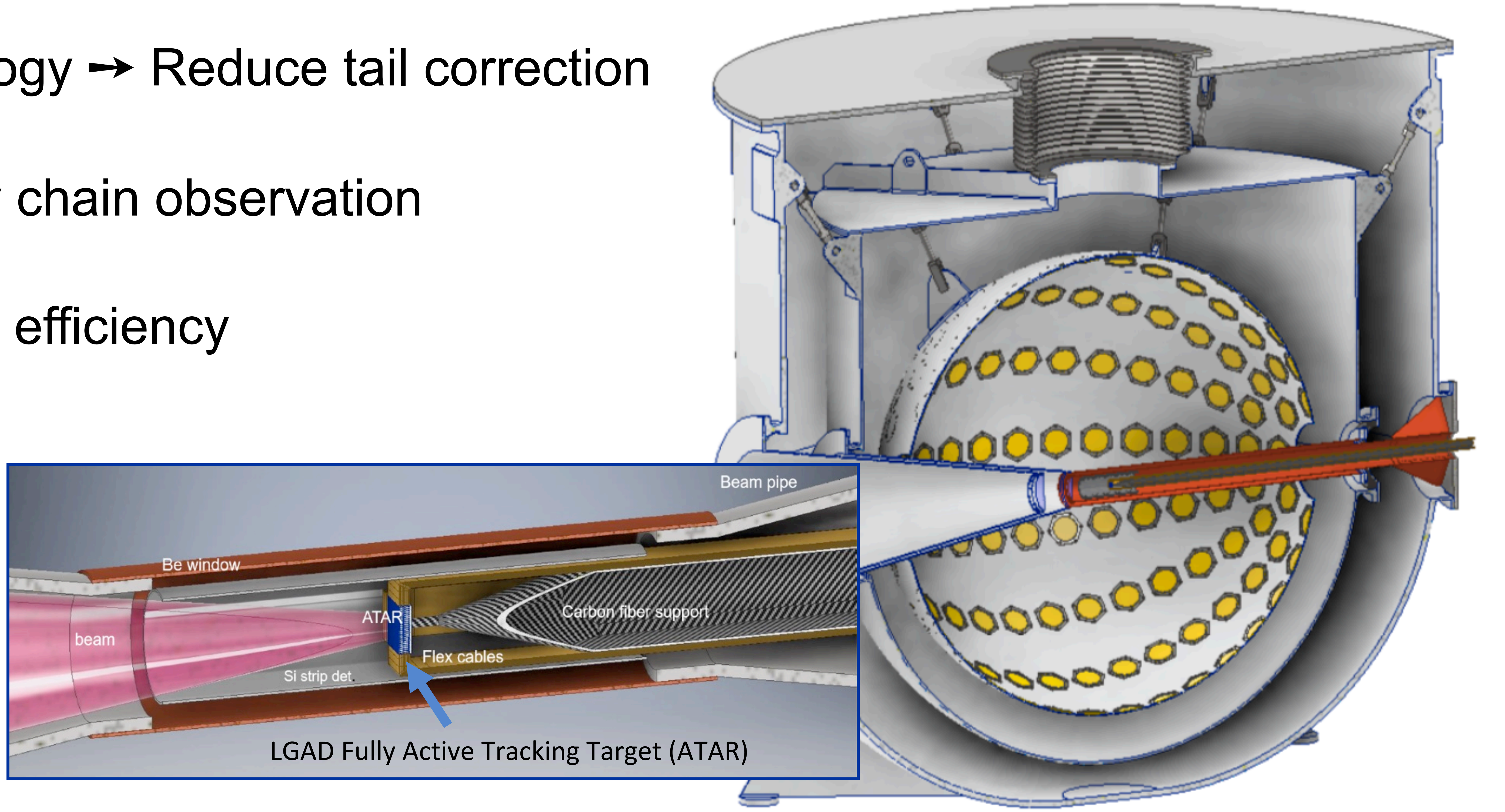
BC: Beam Counter
AD: Active Degrader
AT: Active Target

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

Good geometry but calorimeter depth too small

PIONEER DETECTOR CONCEPT - best of both worlds

- Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)
  - 25 X_0, 3π sr calorimeter ➙ Reduce tail corrections (x5) ➙ Improve uniformity (x5)
    Fast scintillator response (LXe) ➙ Reduce pile-up uncertainties (x5)
  - active target (“4D”) based on LGADs technology ➙ Reduce tail correction uncertainty (x10)
    Fast pulse shape ➙ allow $\pi \rightarrow \mu \rightarrow e$ decay chain observation
  - Fast electronics and pipeline DAQ ➙ Improve efficiency
  - Intense Pion beam at PSI

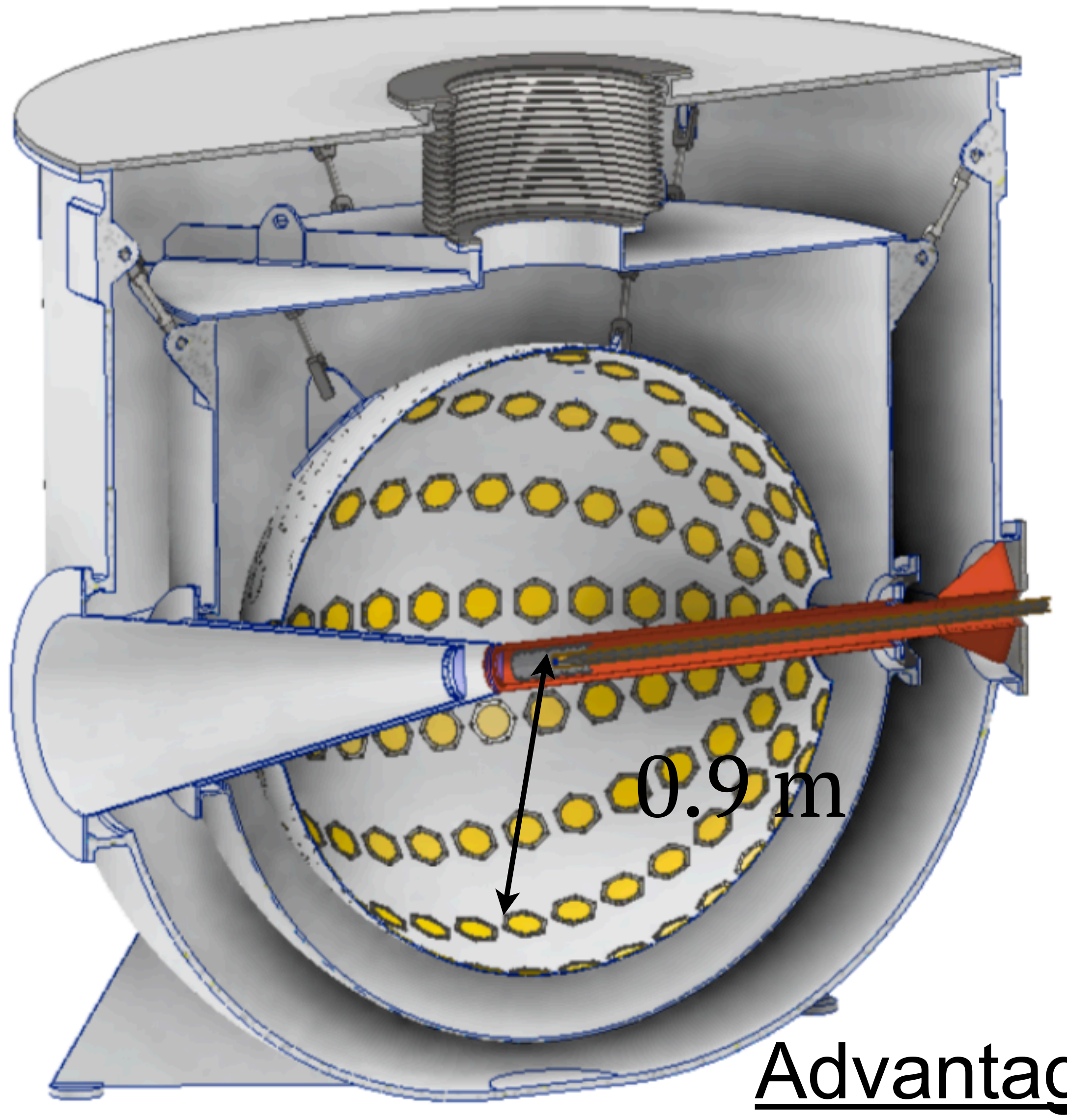


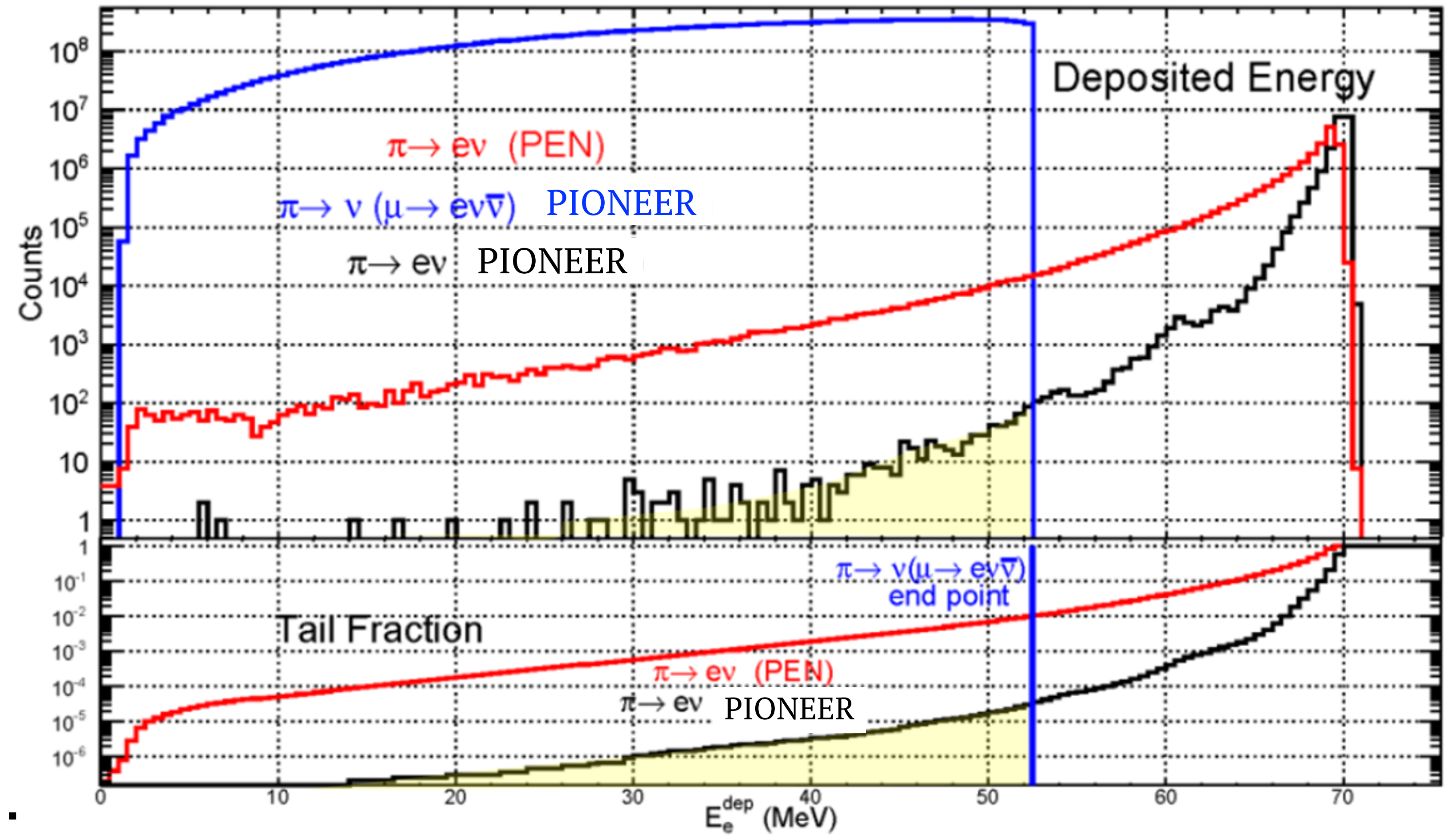
LGAD Fully Active Tracking Target (ATAR)

PIONEER DETECTOR CONCEPT : Calorimeter

- 25 X_0, 3π sr calorimeter ➙ High energy resolution, fast, symmetric ➙ Much better tail suppression

Option 1: LXe (experience from MEG)

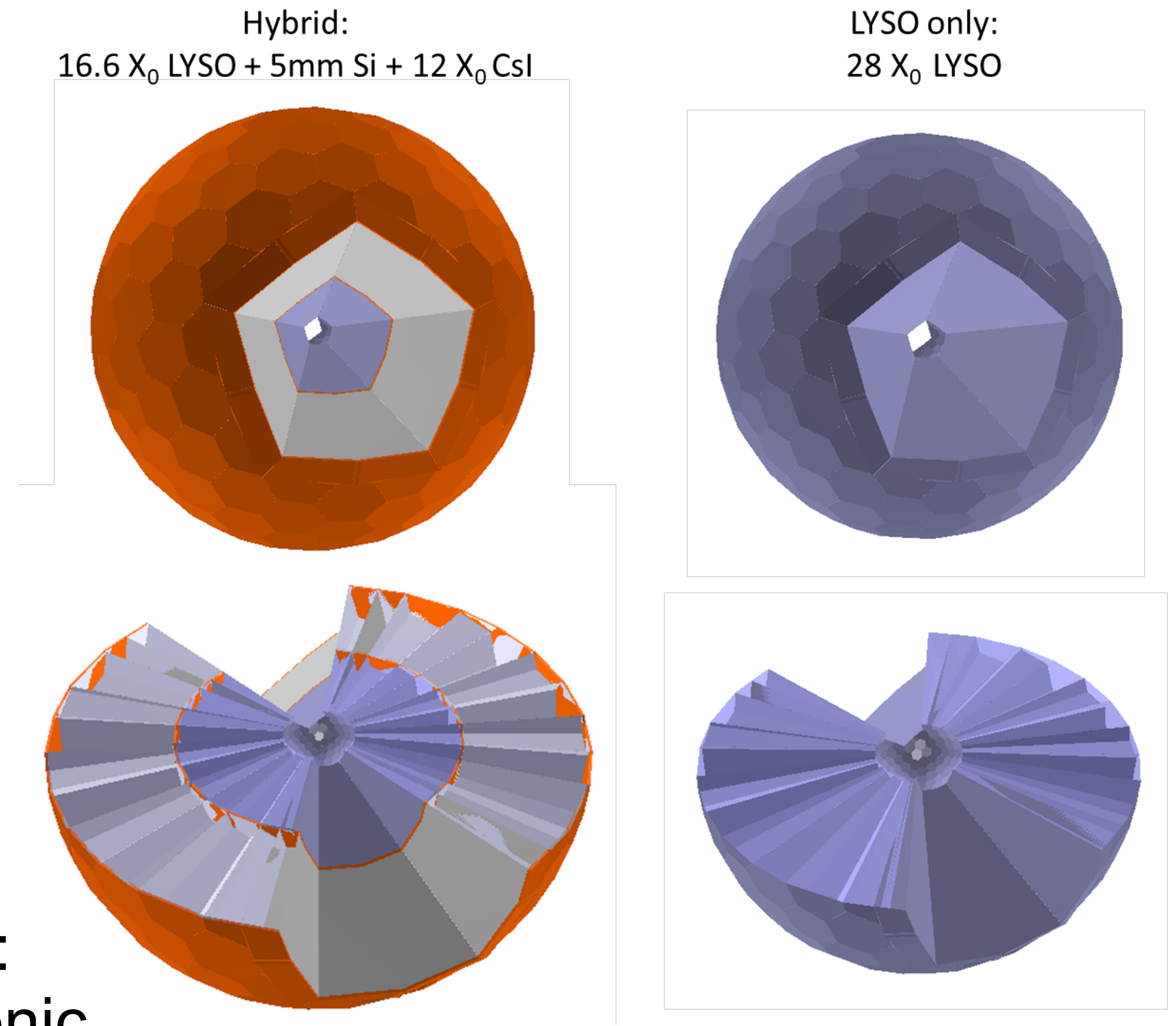




Advantages:
- uniform/homogeneous volume
- fast response
- Excellent energy resolution

Question marks
- (un)known issues with VUV SiPM
- handling pileup
- cost

Option 2: LYSO or combined LYSO/CsI using PEN crystals

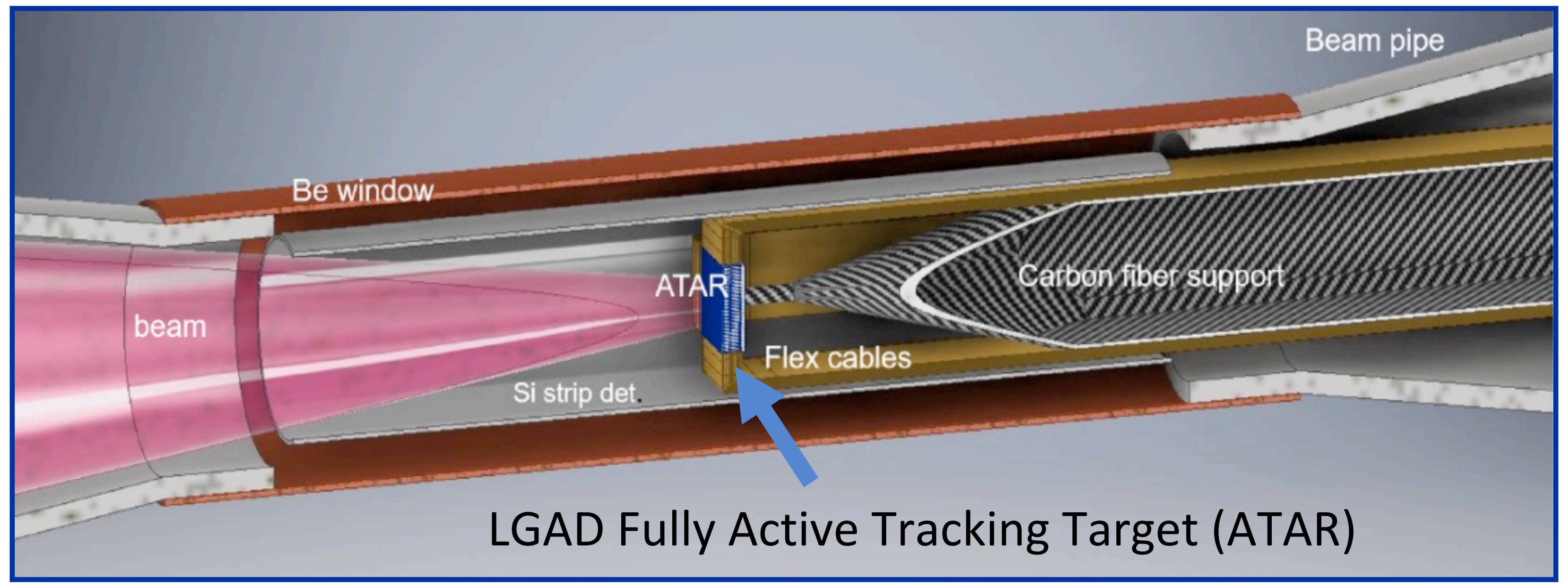


Advantages:
- Not cryogenic
- fast response
- “natural segmentation”

Question marks
- energy resolution
- possible to make long crystals?

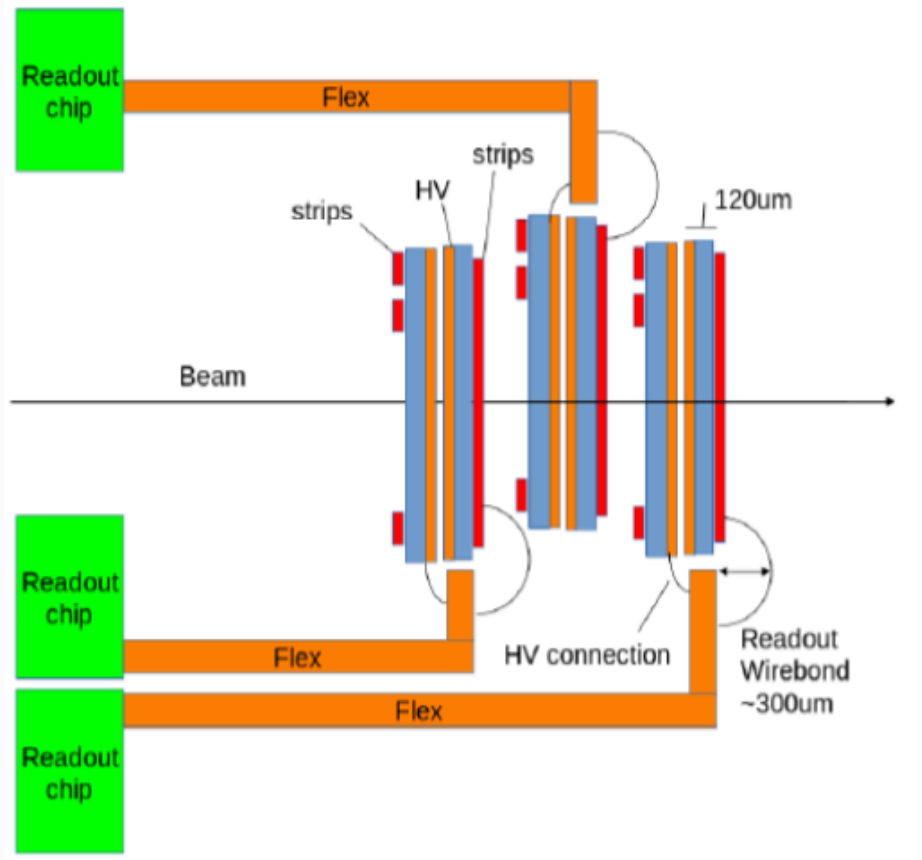
PIONEER DETECTOR CONCEPT : Active Target (ATAR)

- active target (“4D”) based on LGADs(Low gain avalanche diode) technology



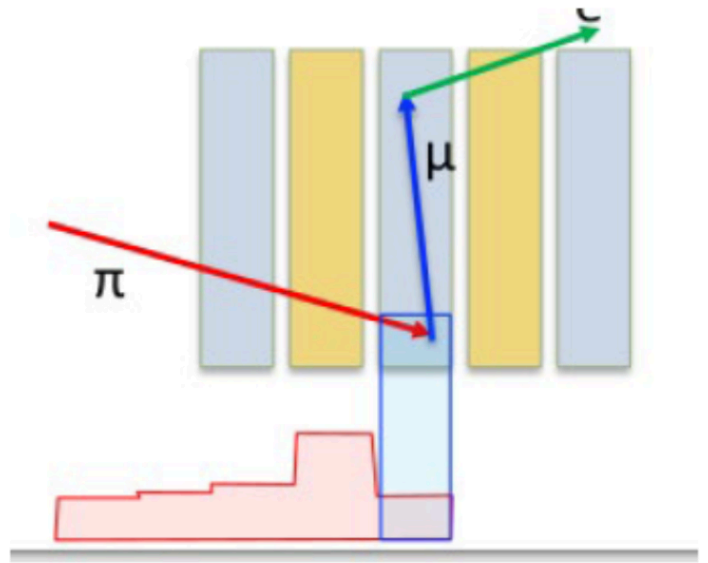
Requirements

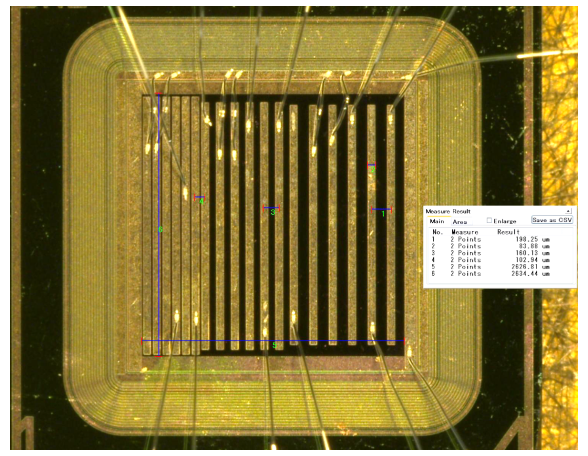
- High longitudinal segmentation: to detect the decay in flight of pions
- Compact: less dead material (including air) as possible in between planes and around ATAR
- Fast collection time: separate pulses that are close in time to reconstruct the pion decay chain
- Large Dynamic range: detect energy deposit in from positrons (MiP) and slow pions/muons (non-MiP)



Tentative initial design

- 48 layers of 120um thick silicon sensors (total of 6 mm in beam direction)
- 100 strips, 2 cm length, with 200 um pitch (2x2 cm area)
- Compromise between granularity, total active area, timing and dead material
- Sensors are packed in stack of 2 with facing HV side and rotated by 90°





Developments led by UCSC

Conclusions and opportunities!

- PIONEER is a major new experiment addressing emerging SM **anomalies in flavor physics**
- Staged goals
  - R^{π} at 0.01% matching theoretical precision
  - Pion β decay at 0.03% (in two steps) matching super-allowed β decay experiments
- Precision experiment: Sensitive to **very high energy scales**.
- Unique new information on **Lepton Flavor Universality and CKM unitary** with unprecedented precision
- Pion decay: long history of establishing and challenging the SM
- 2-body spectra very sensitive to a wide range of **exotics**
- PIONEER is employing state-of-the-art technology (**LGADs, Noble liquid calorimetry**)
- Time-scale: 10-15 years
- Approved to run at PSI. Expected start of data taking ~ 5 years timescale (first beamtime for beam characterization happened a few weeks ago)
- Supported by a large, experienced international collaboration: experts from previous PIENU and PEN experiments as well as a wide range of international collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and leading theorists: **JOIN US!**

If interested contact cmalbrunot@triumf.ca, hertzog@uw.edu, doug@triumf.ca or any other member of the collaboration

Snowmass PIONEER white paper: https://arxiv.org/abs/2203.05505
PIONEER PSI proposal: https://arxiv.org/pdf/2203.01981.pdf)

	PIENU 2015	PIONEER Estimate
Error Source	%	%
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	$\leq$ **0.01**