Searching for new physics with low-energy pions

Chloé Malbrunot

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TRIUMF

McGill University, University of British Columbia

* (non -official logo)

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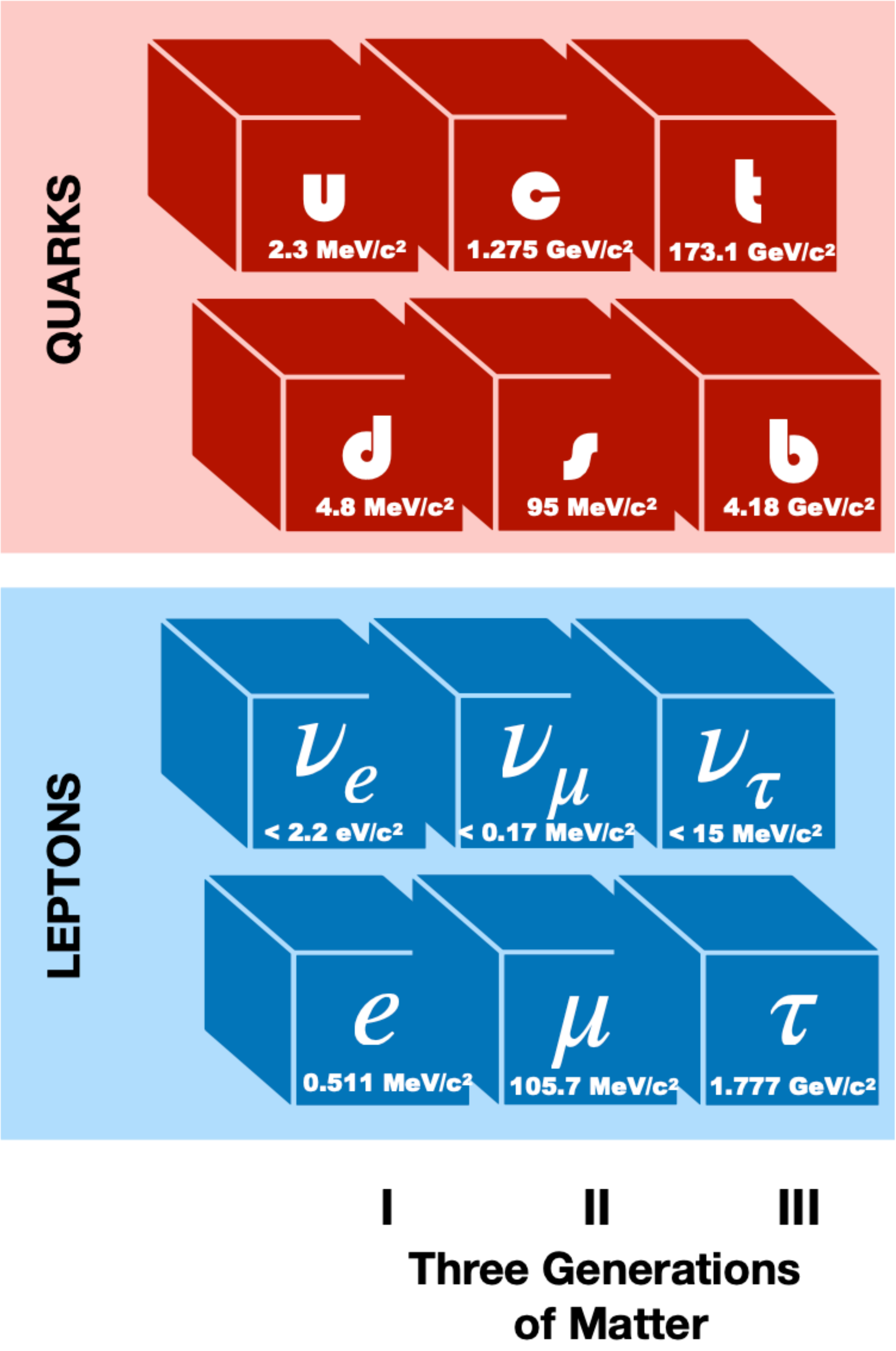
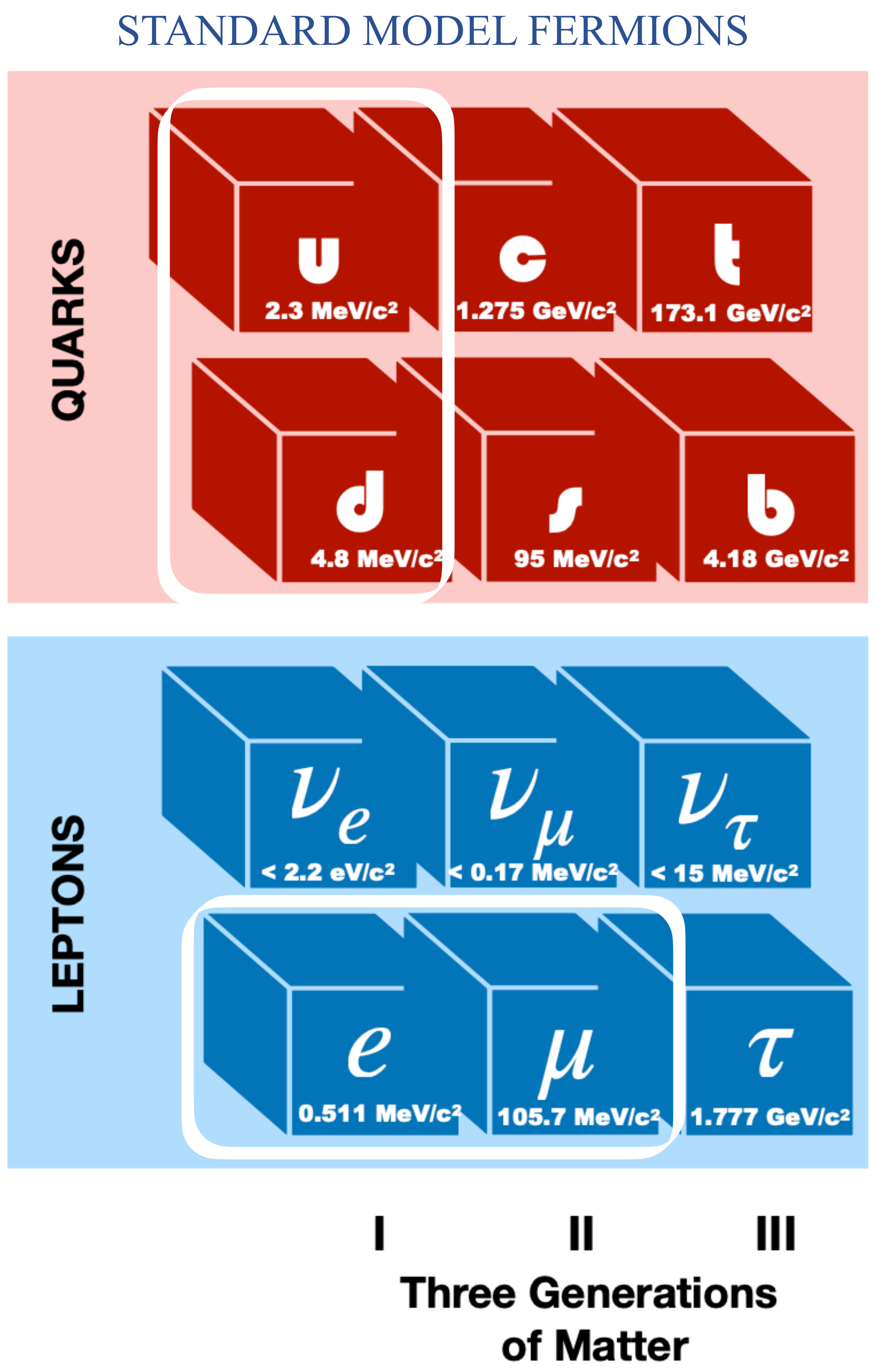
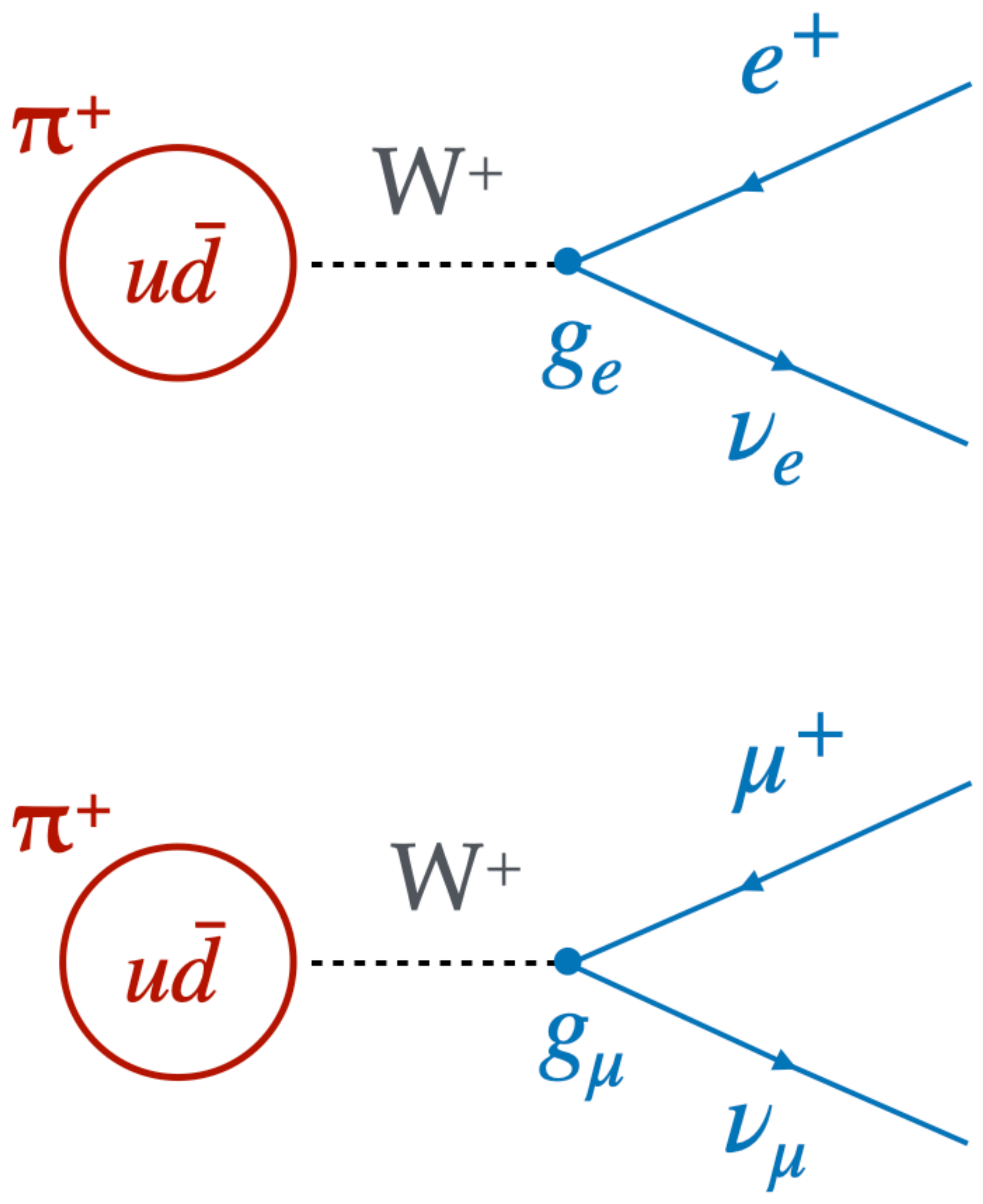
Flavour physics with pions

STANDARD MODEL FERMIONS



Flavour physics with pions





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

\

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

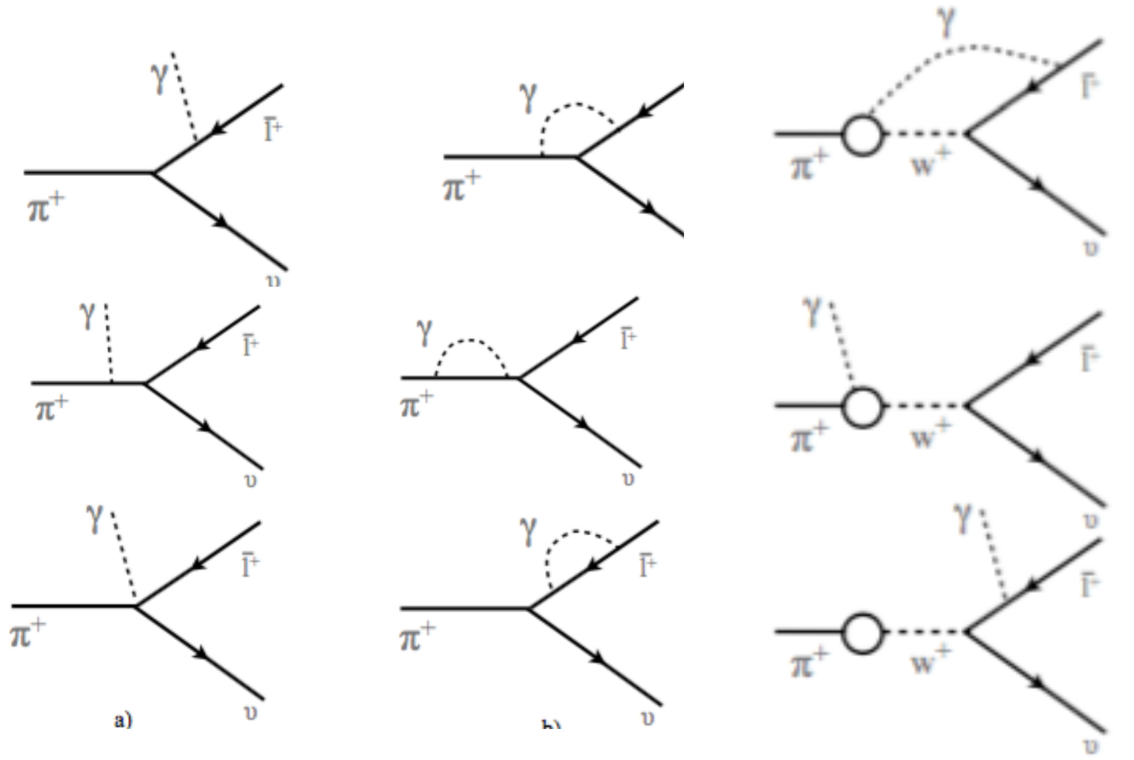
one of the most precisely known observable involving quarks in the SM

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

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

S. Berman: Phys.Rev.Lett. 1(12), 468 (1958)
T. Kinoshita: Phys.Rev.Lett. 2(11), 477 (1959)
T. Goldman, W.Wilson: Phys.Rev.D 14(9), 2428 (1976)
W. Marciano, A. Sirlin: Phys.Rev.Lett. 36(24), 1425 (1976)

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



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

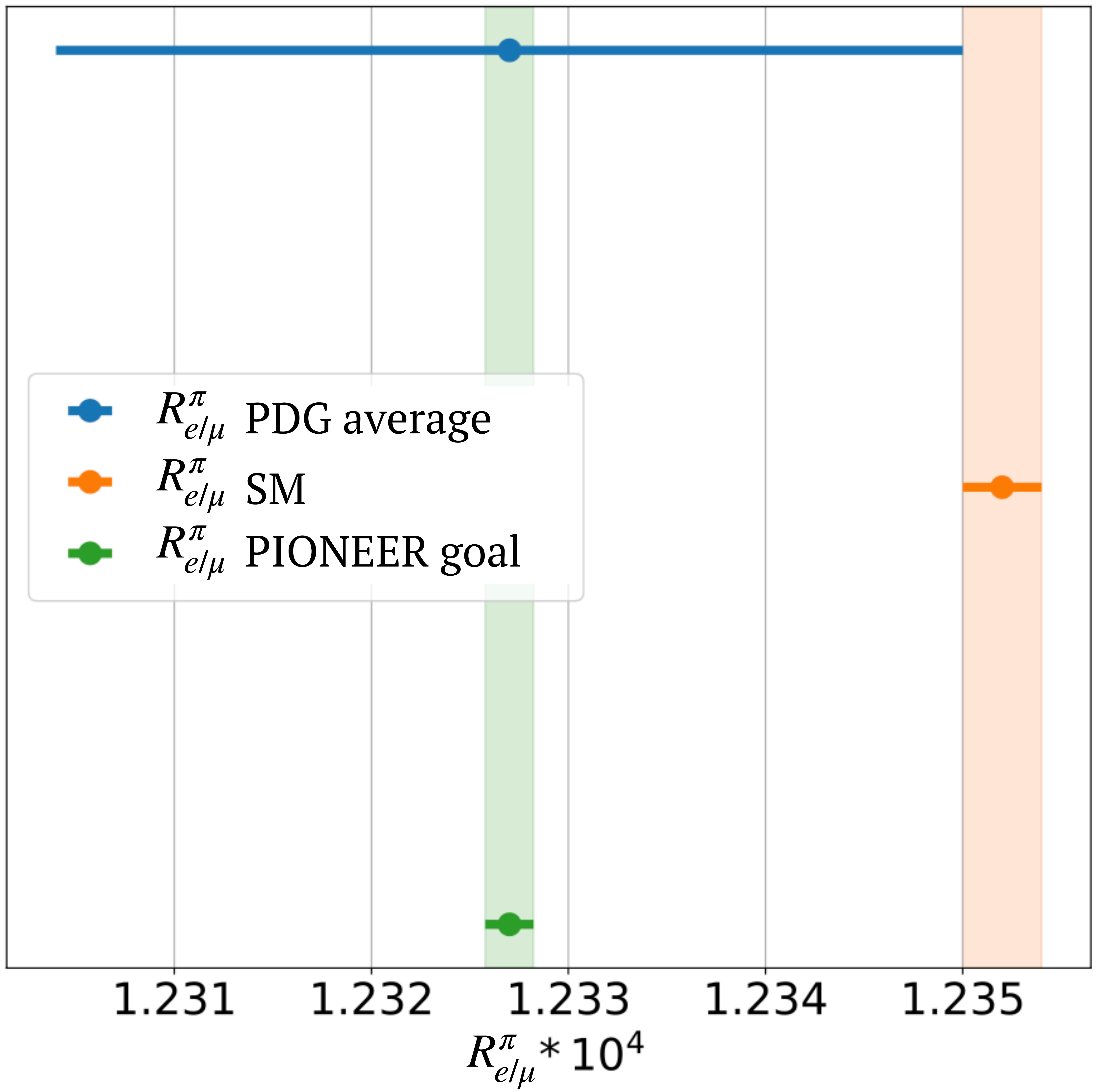
$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(exp.)}$$

x 15

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

PIONEER: closing the precision gap

PDG average dominated by the PIENU @ TRIUMF result
blind analysis based on partial data set (~10% of full statistics)



75 years of $R^{\pi}_{e/\mu}$

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 1.3 \times 10^{-4}$$

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

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

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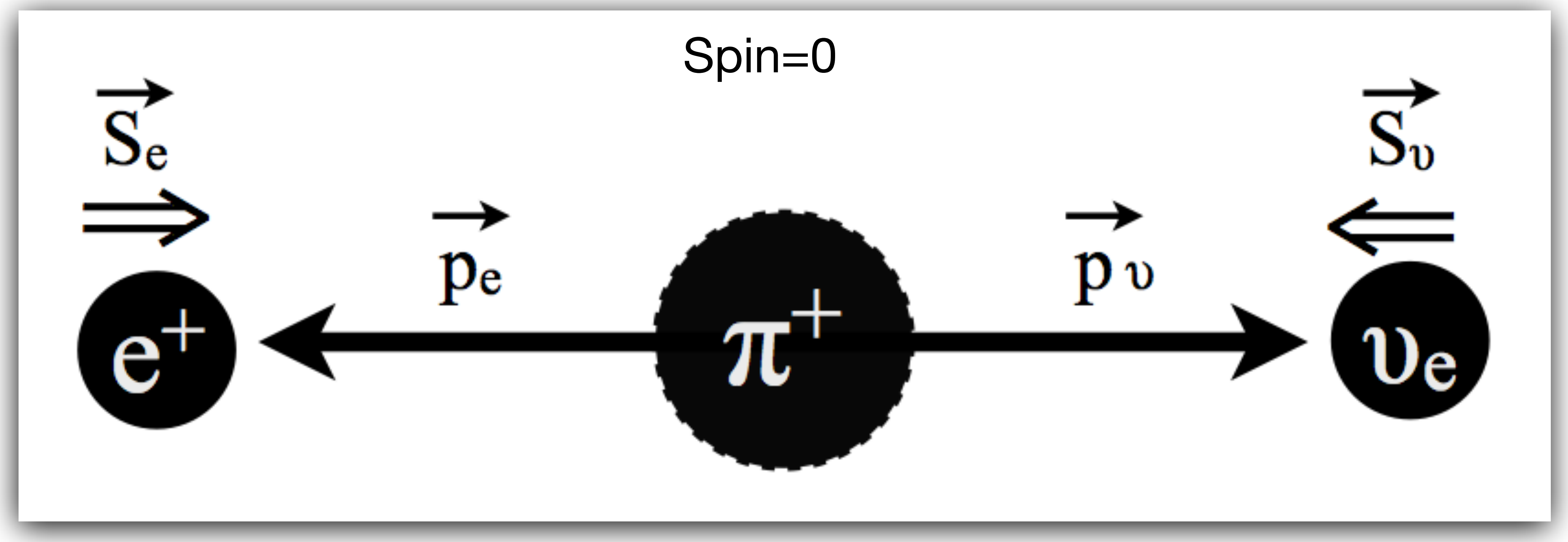

Weak Interaction

Neutrinos: left-handed helicity
= directions of spin and motion are opposite

Positron is forced into the wrong helicity

75 years of $R^{\pi}_{e/\mu}$

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'Phase space' term ~ 5.5

'Helicity suppression' term ~ 2.3×10^{-5}

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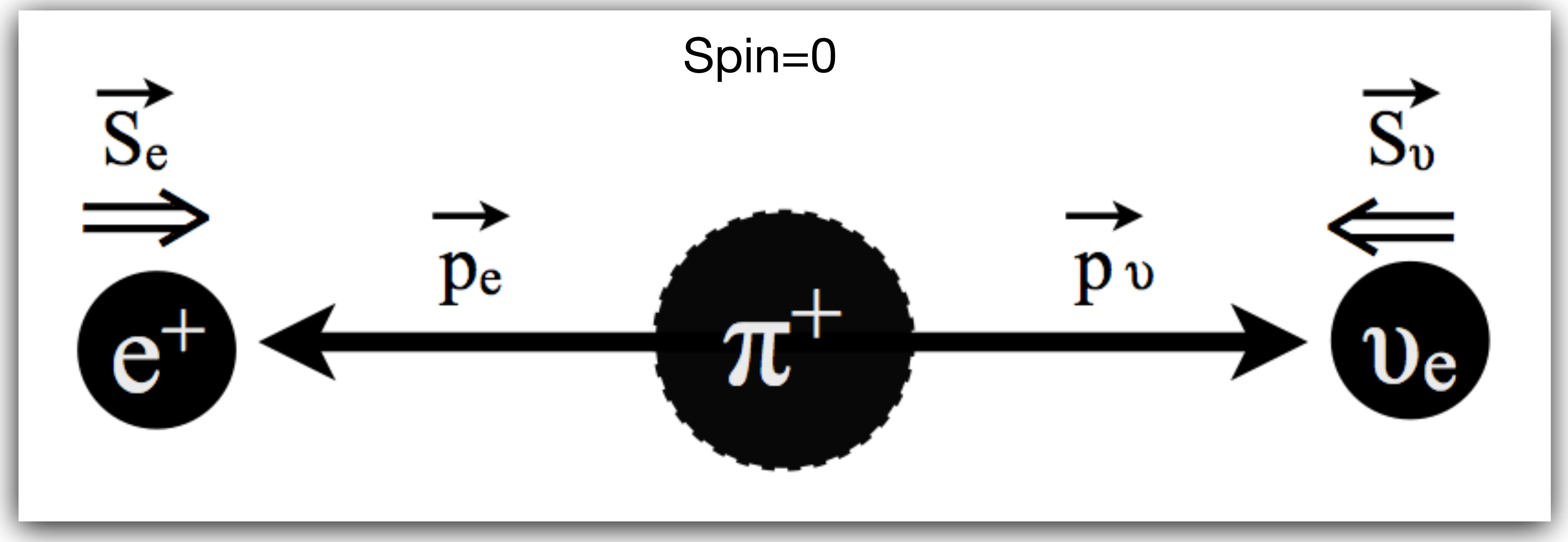

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Note on the Decay of the π-Meson

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*

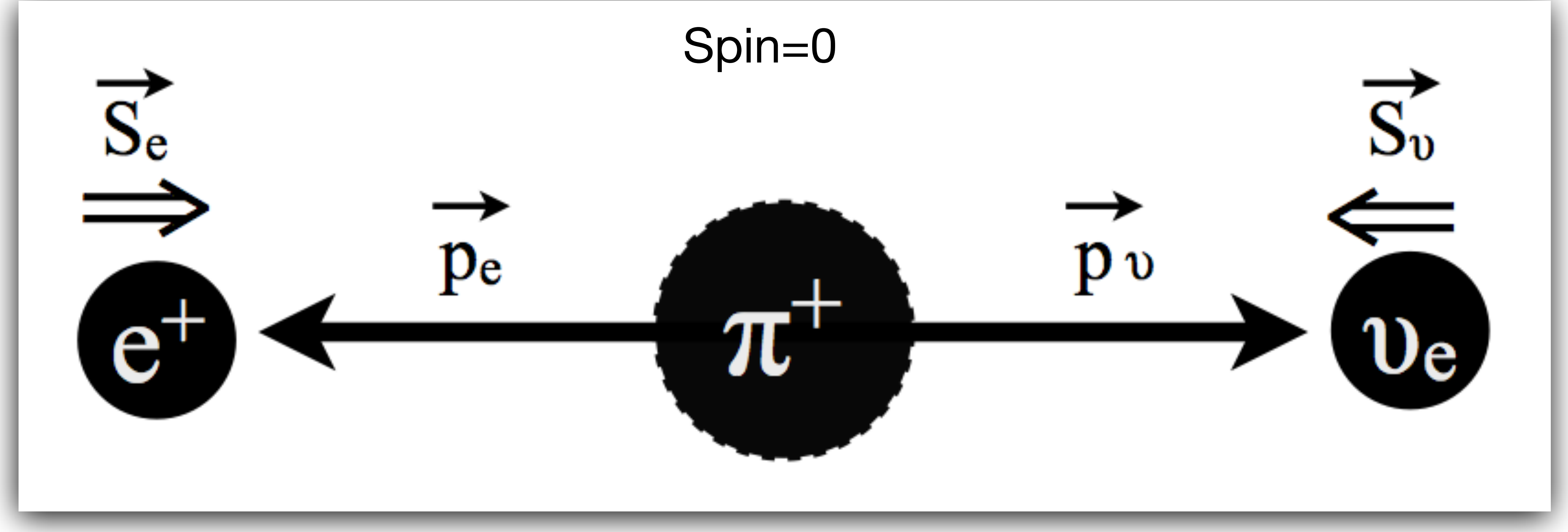
75 years of $R^{\pi}_{e/\mu}$

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{`Helicity suppression' term} \sim 2.3\times 10^{-5}} \underbrace{\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2}_{\text{`Phase space' term} \sim 5.5} \sim 1.3 \times 10^{-4}$$

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}



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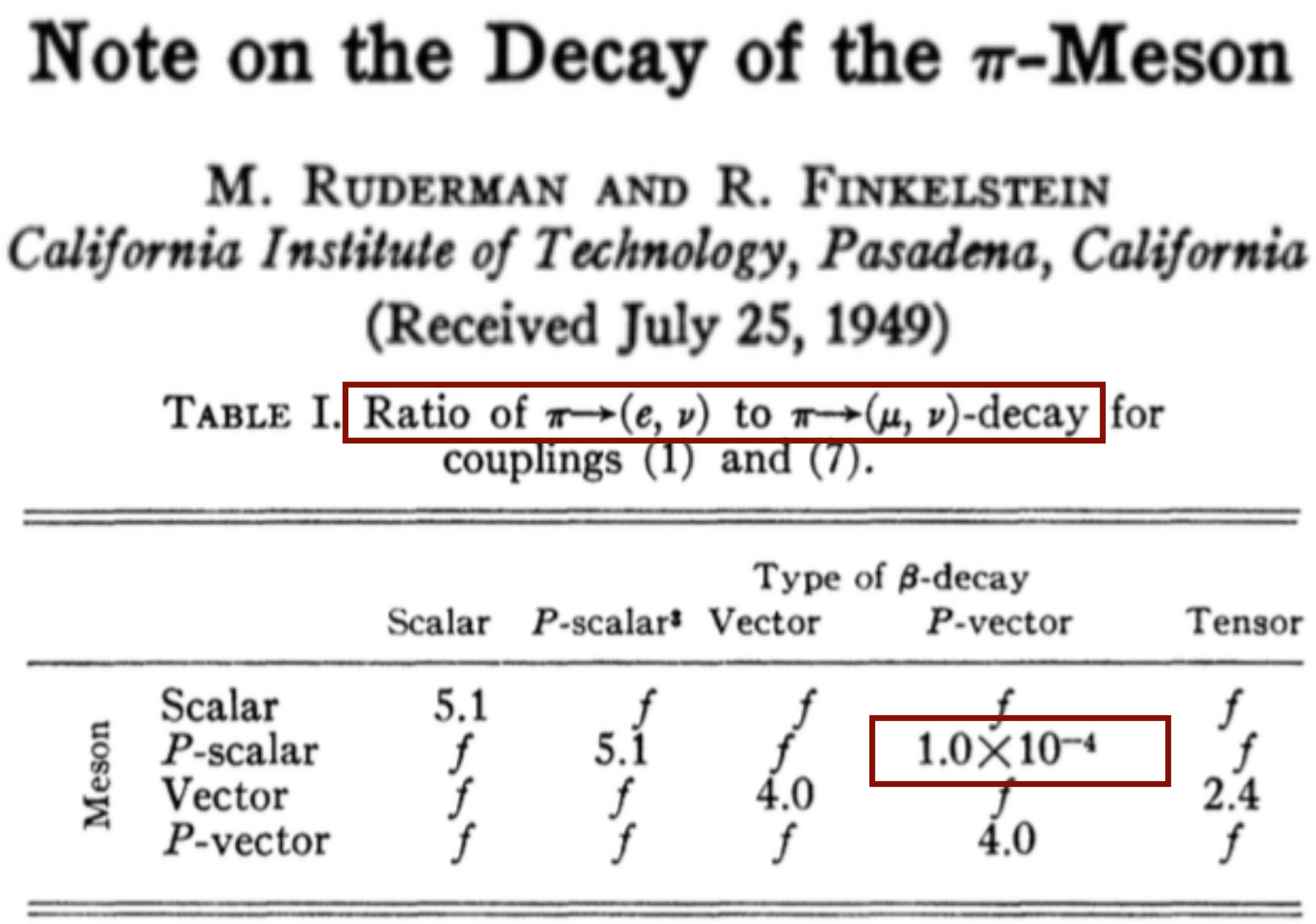

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Vector	*f*	*f*	4.0	*f*	2.4
P-vector	*f*	*f*	*f*	4.0	*f*

The $\pi \to e\nu$ puzzle …

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 1.3 \times 10^{-4}$$

SUPPLEMENTO AL VOLUME II, SERIE X
DEL NUOVO CIMENTO
N. 1, 1955
2° Semestre

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

S. LOKANATHAN and J. STEINBERGER (**)

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

$$\frac{\pi \to e}{\pi \to \mu} = f = (-.3 \pm .9) \cdot 10^{-4}\,.$$

The quoted error is the standard deviation and includes the statistical uncertainty as well as an estimate of the error in the subtraction for the inverse photomeson production.

It is therefore not likely that the actual $\pi \to e$ decay fraction is greater than $.6 \cdot 10^{-4}$ or one in 17 000. The experiment is approximately twenty

It is not likely that the $\pi \to e$ decay is greater than 0.6×10^{-4}

is coupled symmetrically to the muon.

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

The non-occurence of any kind of electronic decay of the pion is now established well below the limits set by the explanations thus far offered in

The non-occurrence of any kind of electronic decay of the pion is now established …

nucleon pair, our result implies that not only the pseudoscalar, but also the axial vector coupling must be quite small.

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

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7/6
Gloriastrasse 35

Jan. 22nd, 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 $\pi \to e + \nu$ was not occurring. 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 reflection-invariant (parity invariance. P is the violation of Oehme-Yang-Lee).

Letter of W. Pauli to V. Telegdy

The $\pi \to e\nu$ puzzle … resolved in 1958

At a small lab that opened 4 years prior
on the outskirts of Geneva, Switzerland

CERN circa 1958

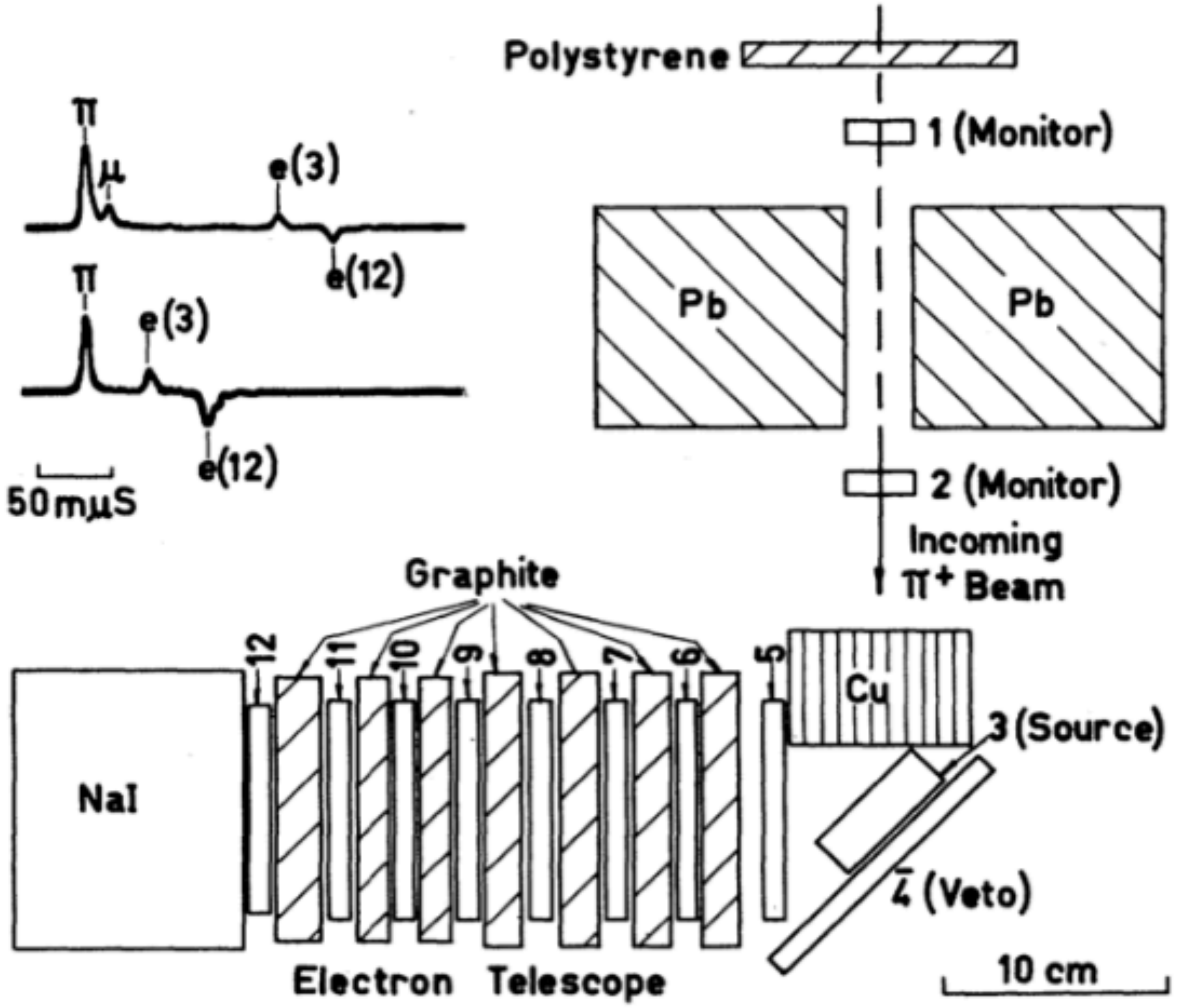

FIG. 1. Experimental layout, and (inset) typical π-μ-e and π-e pulse.

~ 40 $\pi \to e\nu$ events

https://home.cern/fr/news/series/cern70/cern70-first-discovery

"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

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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

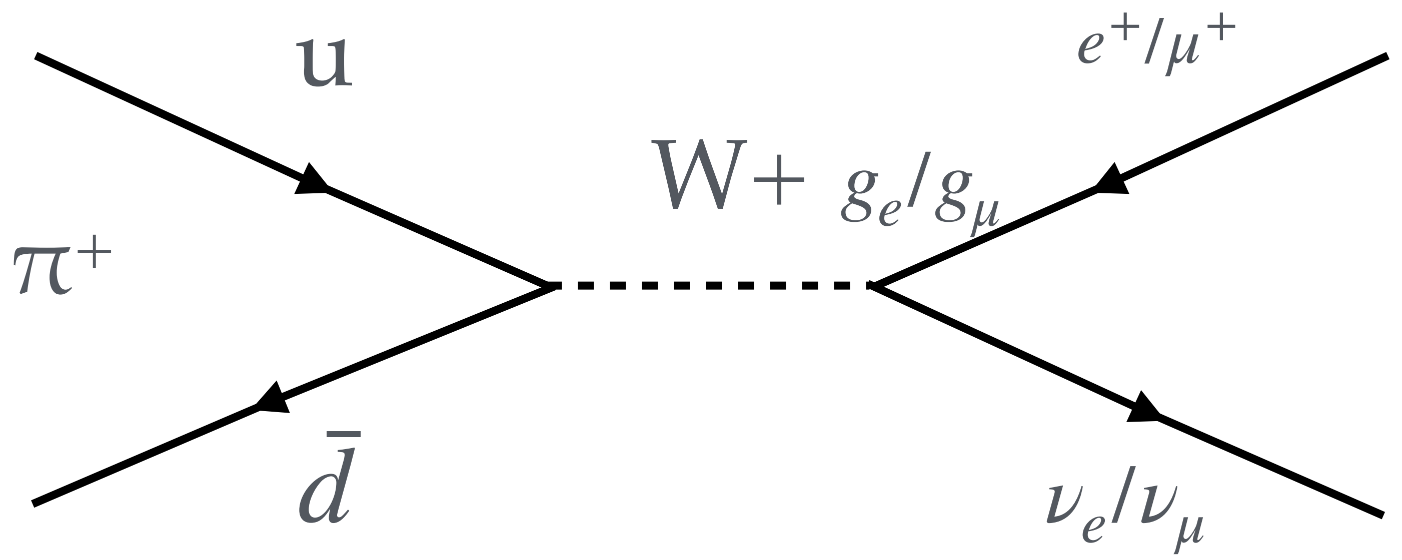
~x2

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

PIONEER | **x20**

Physics case 1: Testing $\boxed{\text{Lepton Flavor Universality}}$

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



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

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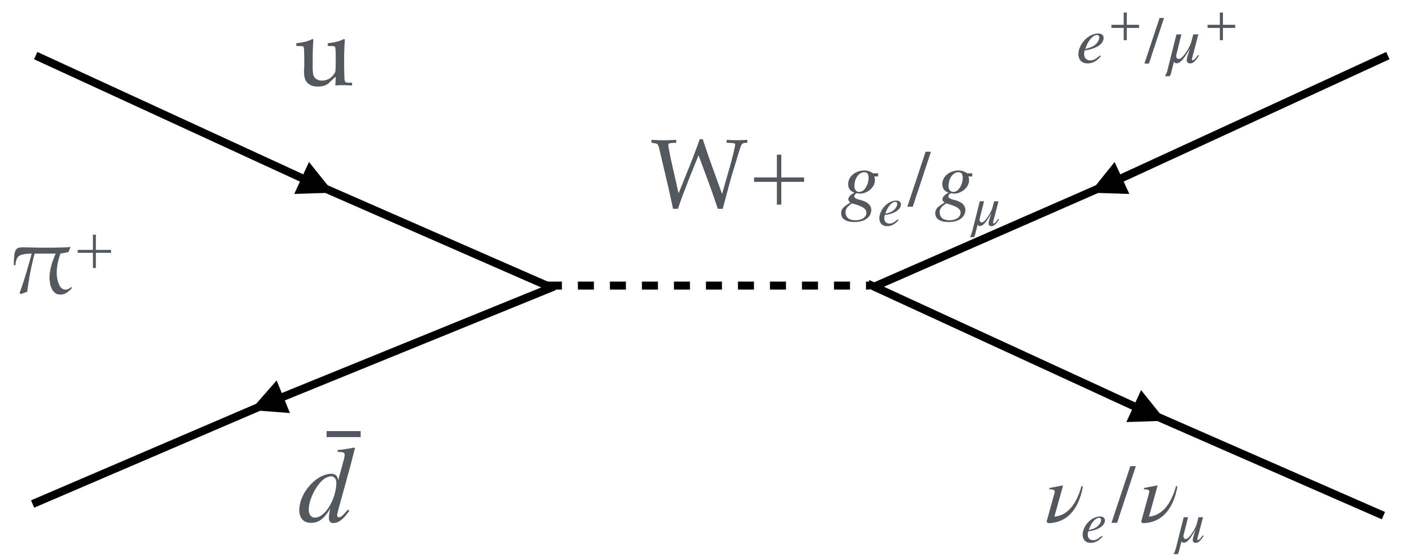


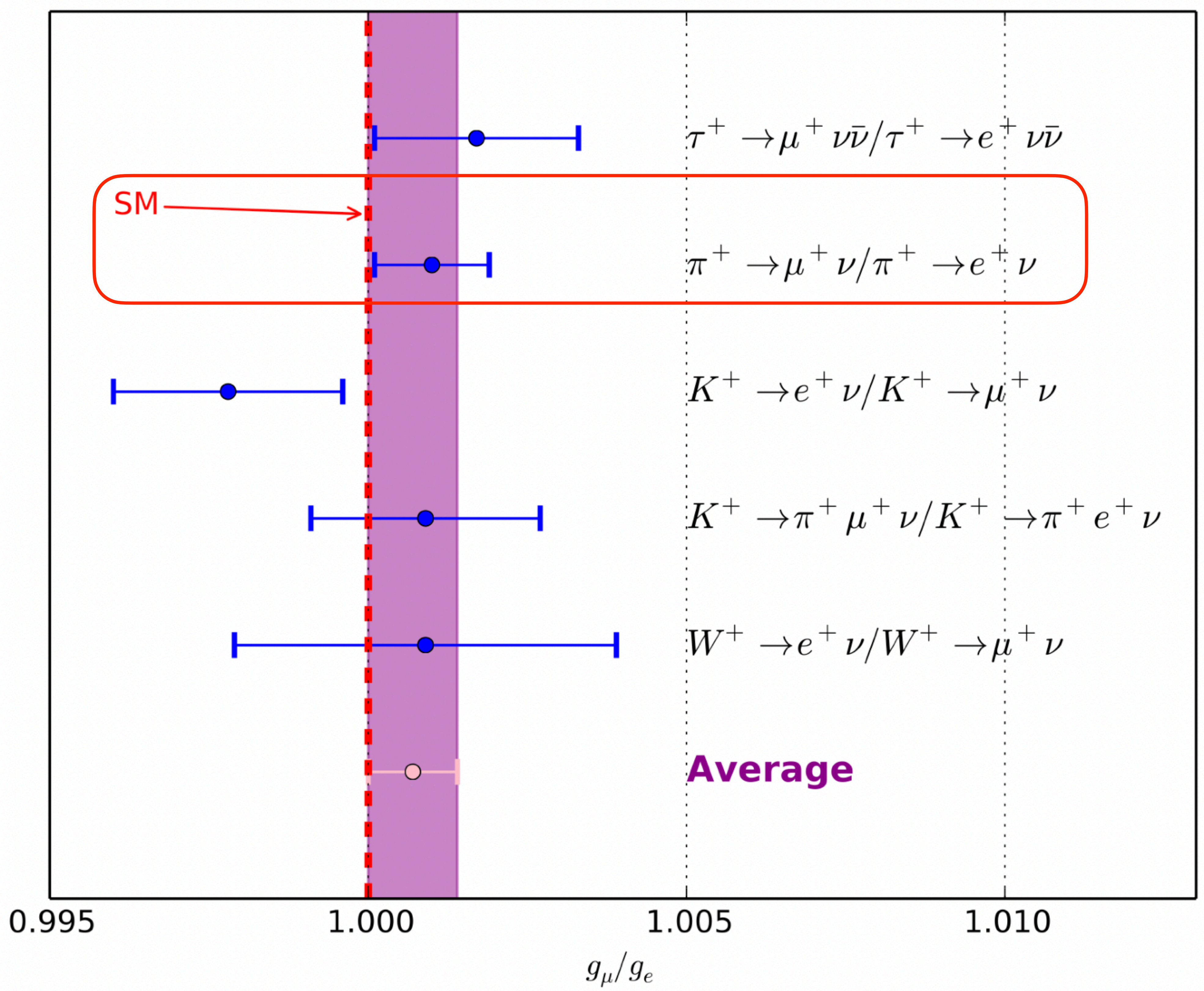
$$R^\pi = \frac{\pi^+ \rightarrow e^+\nu(\gamma)}{\pi^+ \rightarrow \mu^+\nu(\gamma)}$$

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 (@ TRIUMF)** results :

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$



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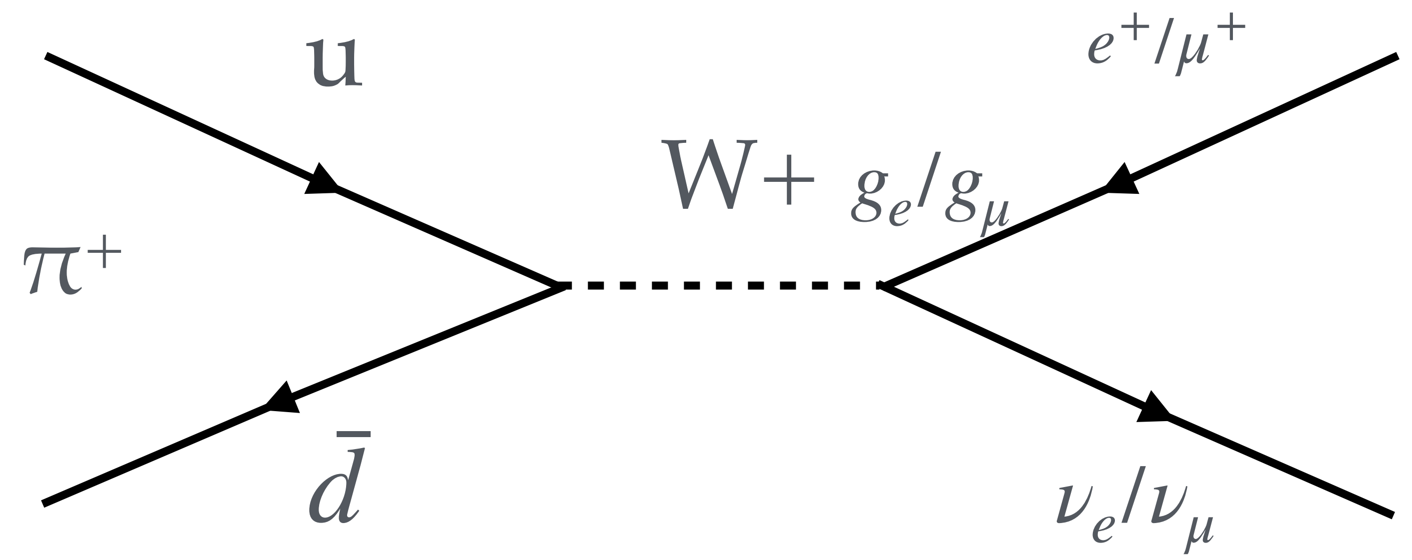

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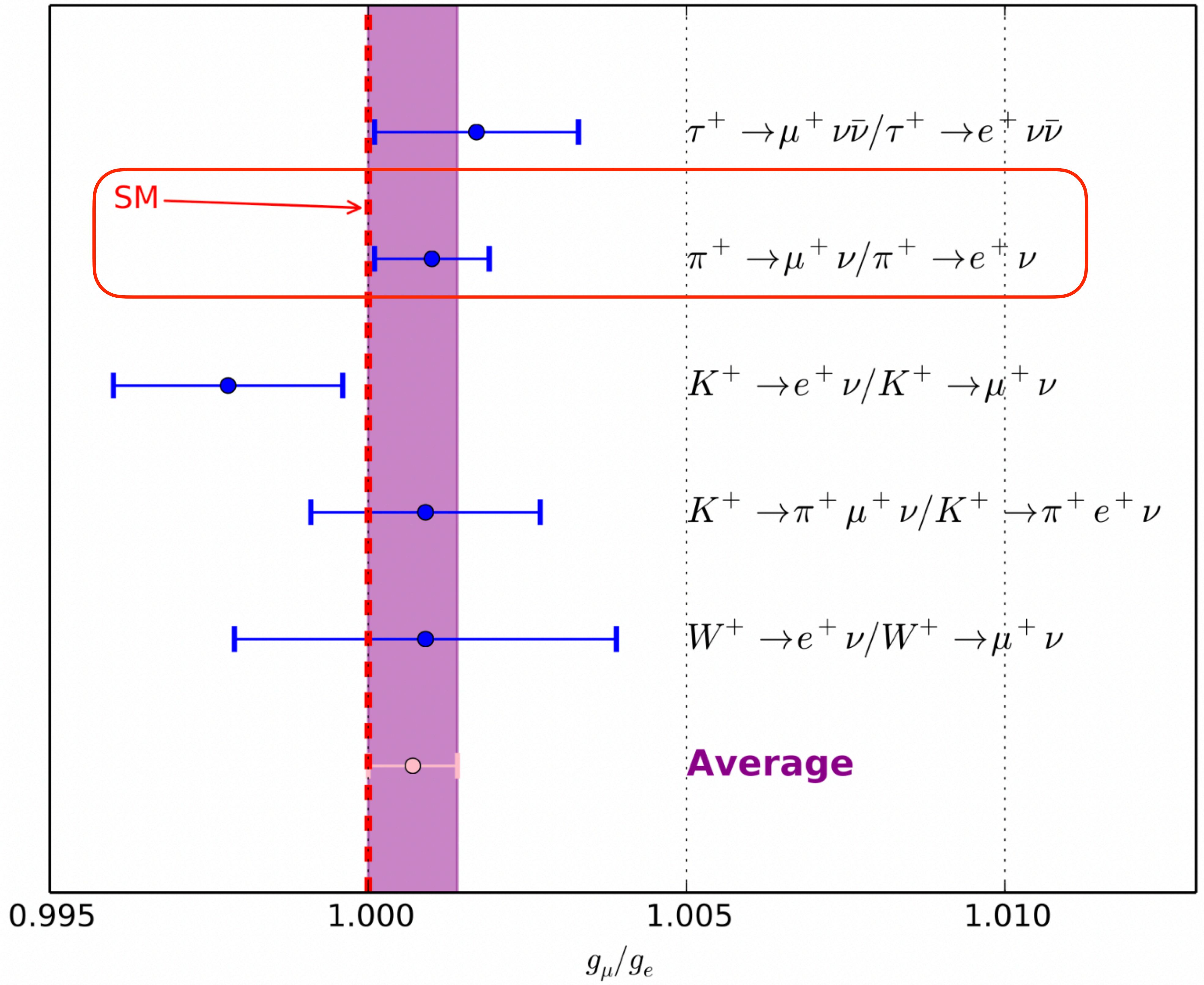


PDG value, mostly constrained by **PIENU (@ TRIUMF)** results :

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$

BUT

Several tensions in the flavour sector, potentially hinting toward LF

- 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

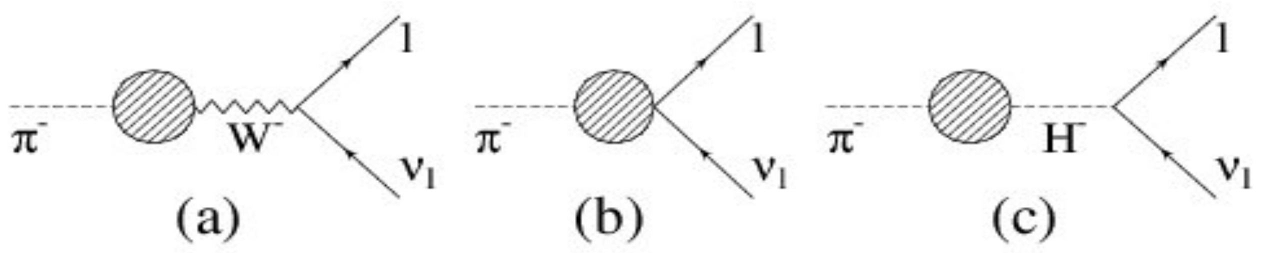
$$R^{\pi}_{SM} = \frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$

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)

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

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
  - Hidden sector
  - …

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

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ELSEVIER

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)

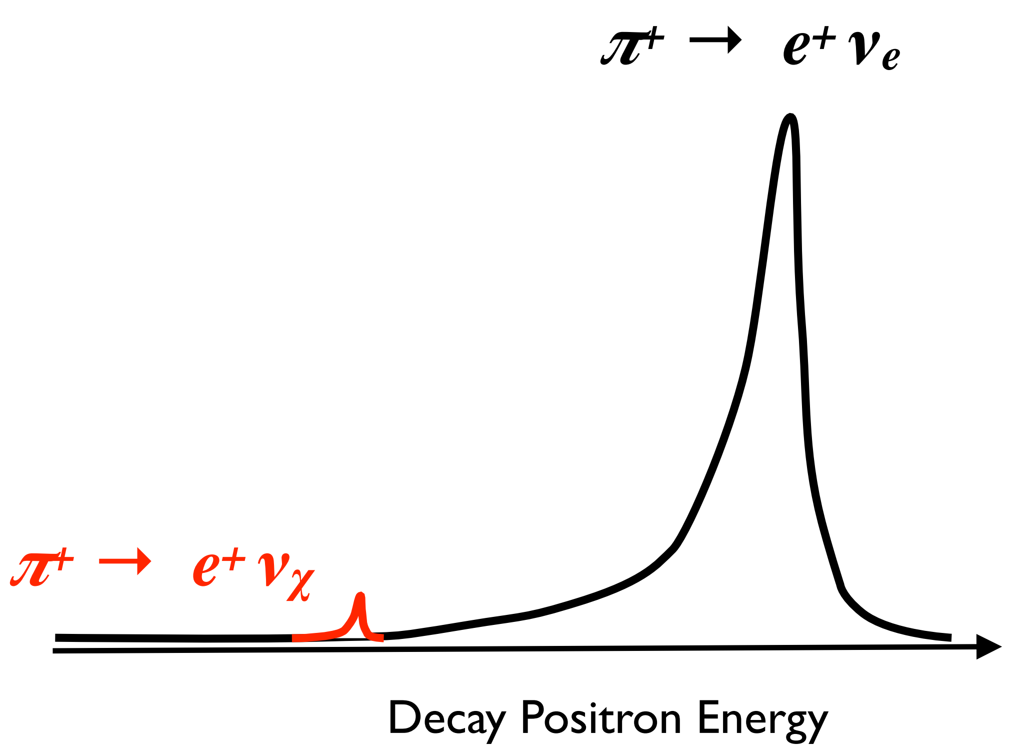
Search for three body pion decays $\pi^+ \to l^+\nu X$

recent searches performed by the **PIENU** collaboration

$\Downarrow$

PIONEER will improve on all those searches

Physics case 3: Exotics decays. Example of first sterile 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 $\pi^+ \to e^+$ spectrum

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

Heavy υ

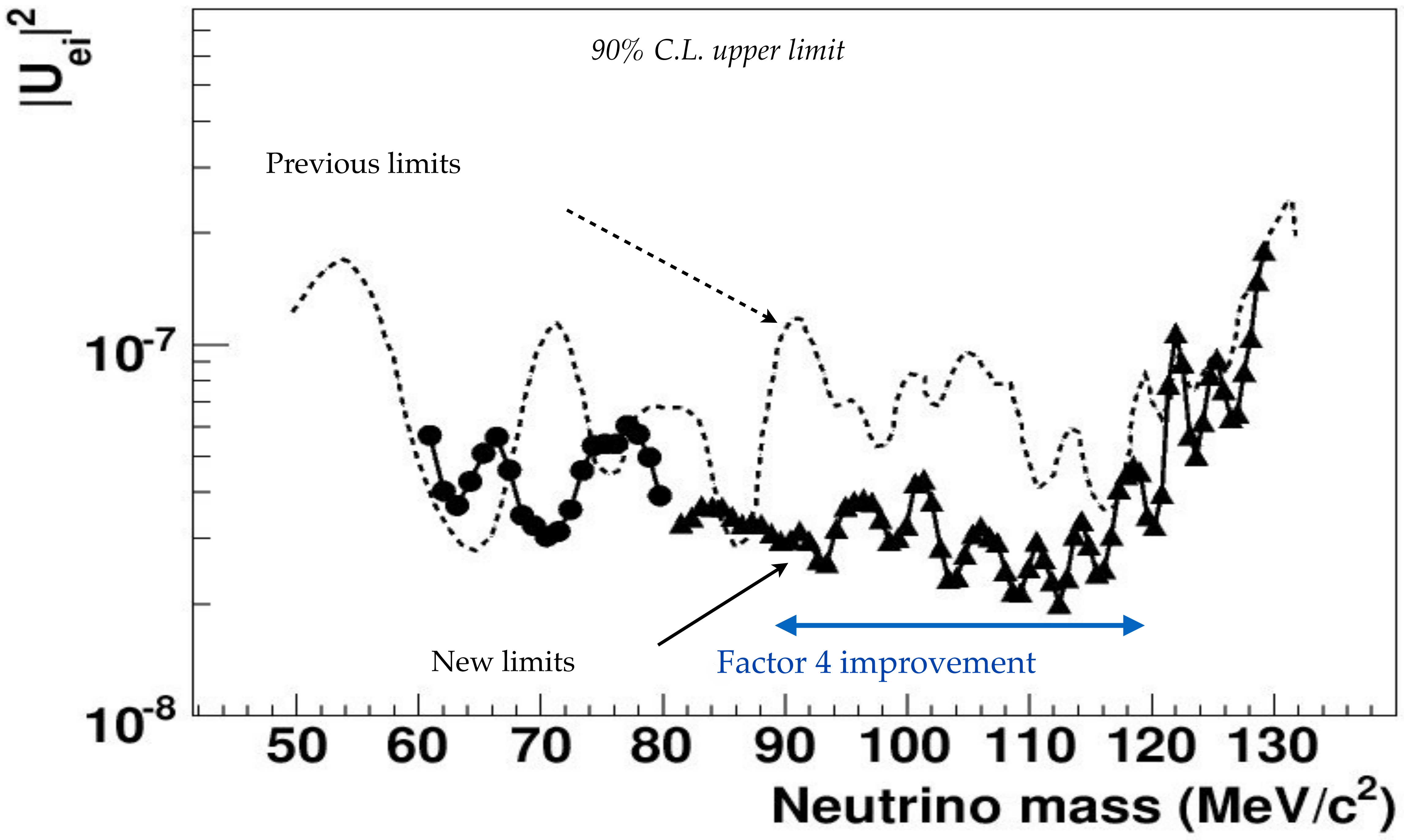
Kinematic factor

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

Conventional υ

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

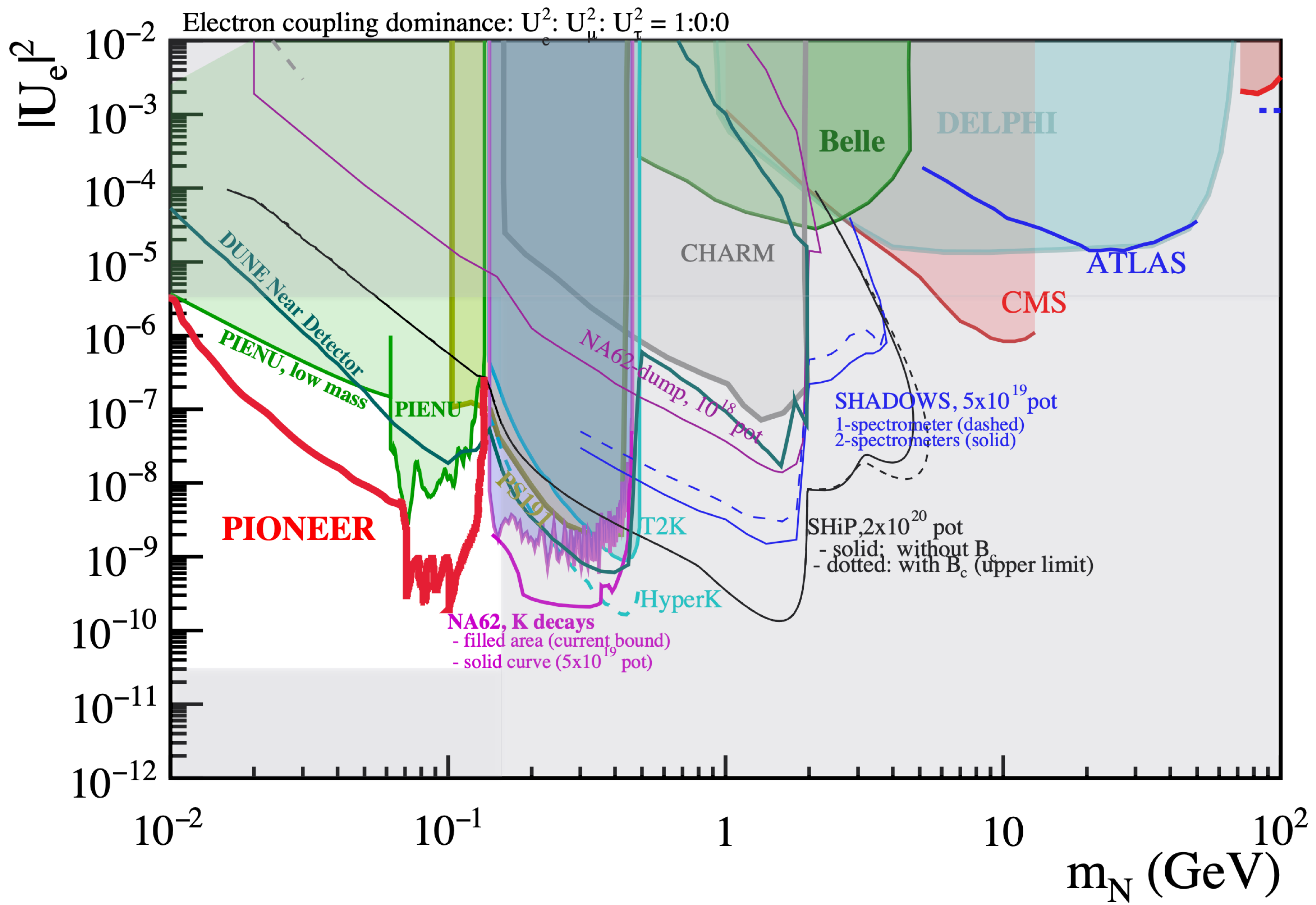
$$\ell = e, \mu, \tau, \chi_1, \chi_2 \ldots \chi_k$$



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

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

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



Asli M. Abdullahi et al. "The Present and Future Status of Heavy Neutral Leptons". *2022 Snowmass Summer Study*. Mar. 2022. arXiv: 2203.08039 [hep-ph]

Physics case 4: Testing CKM unitarity $\boxed{V_{ud}}$, $\boxed{\frac{V_{us}}{V_{ud}}}$

tested in K decays

tested in super-allowed β decays, neutron

tensions in the first row CKM unitarity test

3σ **(or even more…)**

CKM matrix : mixing of quarks of different generations through weak force

$$V_{CKM} = \begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |Vub|^2 = 1$$

Since $|V_{ub}| \ll |V_{us}|$, the third term can be neglected and the first row can be studied in a 2D plane

~3σ tension in the first-row of CKM unitarity test

Often referred to as the Cabbibo Angle Anomaly (or CAA)

Physics case 4: Testing CKM unitarity $\boxed{V_{ud}}$, $\boxed{\frac{V_{us}}{V_{ud}}}$

tested in K/π decays

tested in super-allowed β decays, neutron

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}

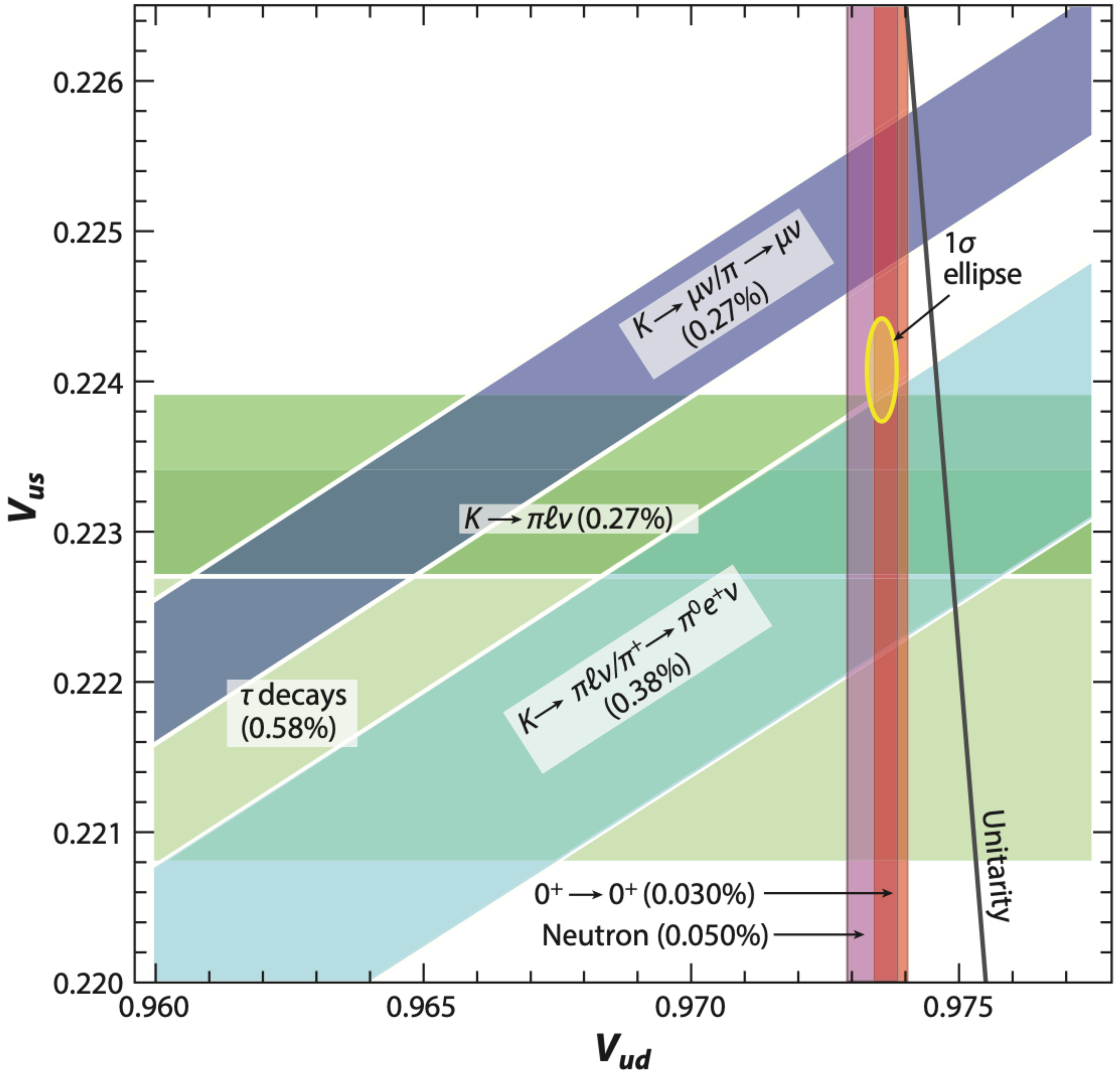
PIBETA exp. ($\pm 0.6\%$)

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

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

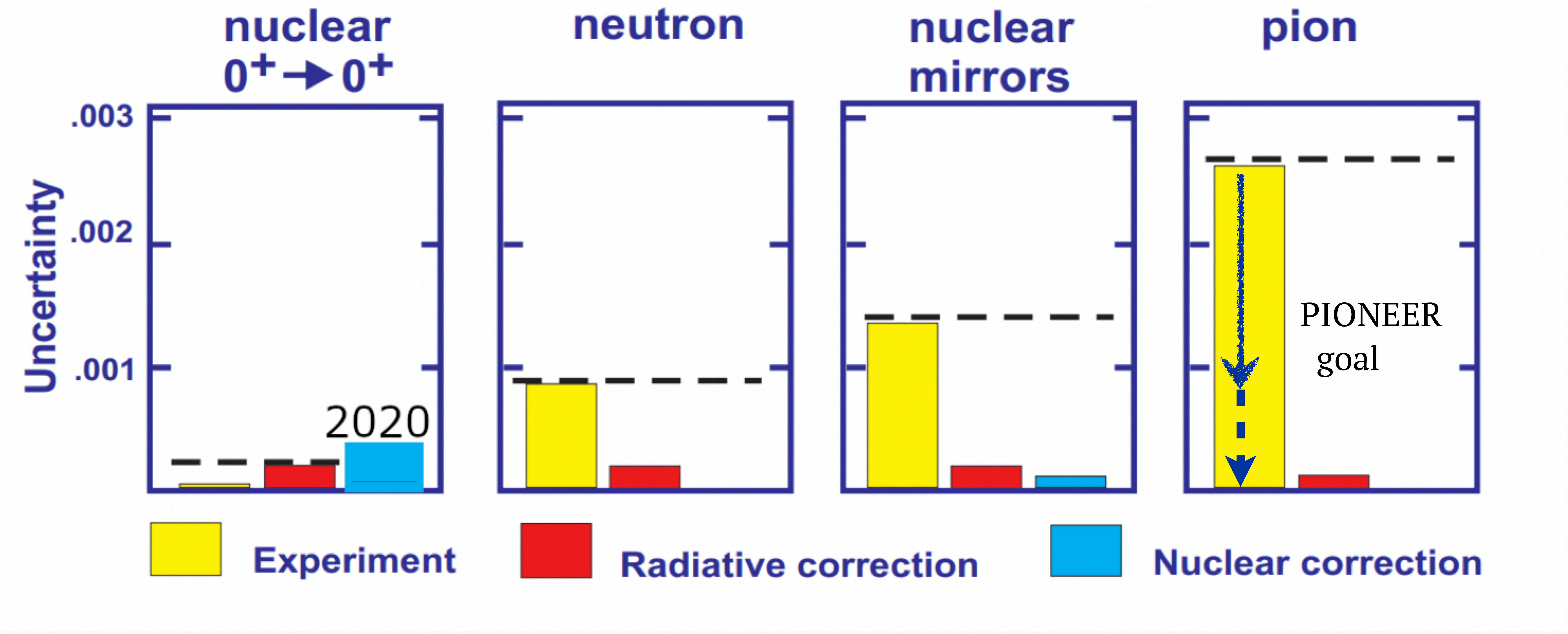
tensions in the first row CKM unitarity test

3σ (or even more…)



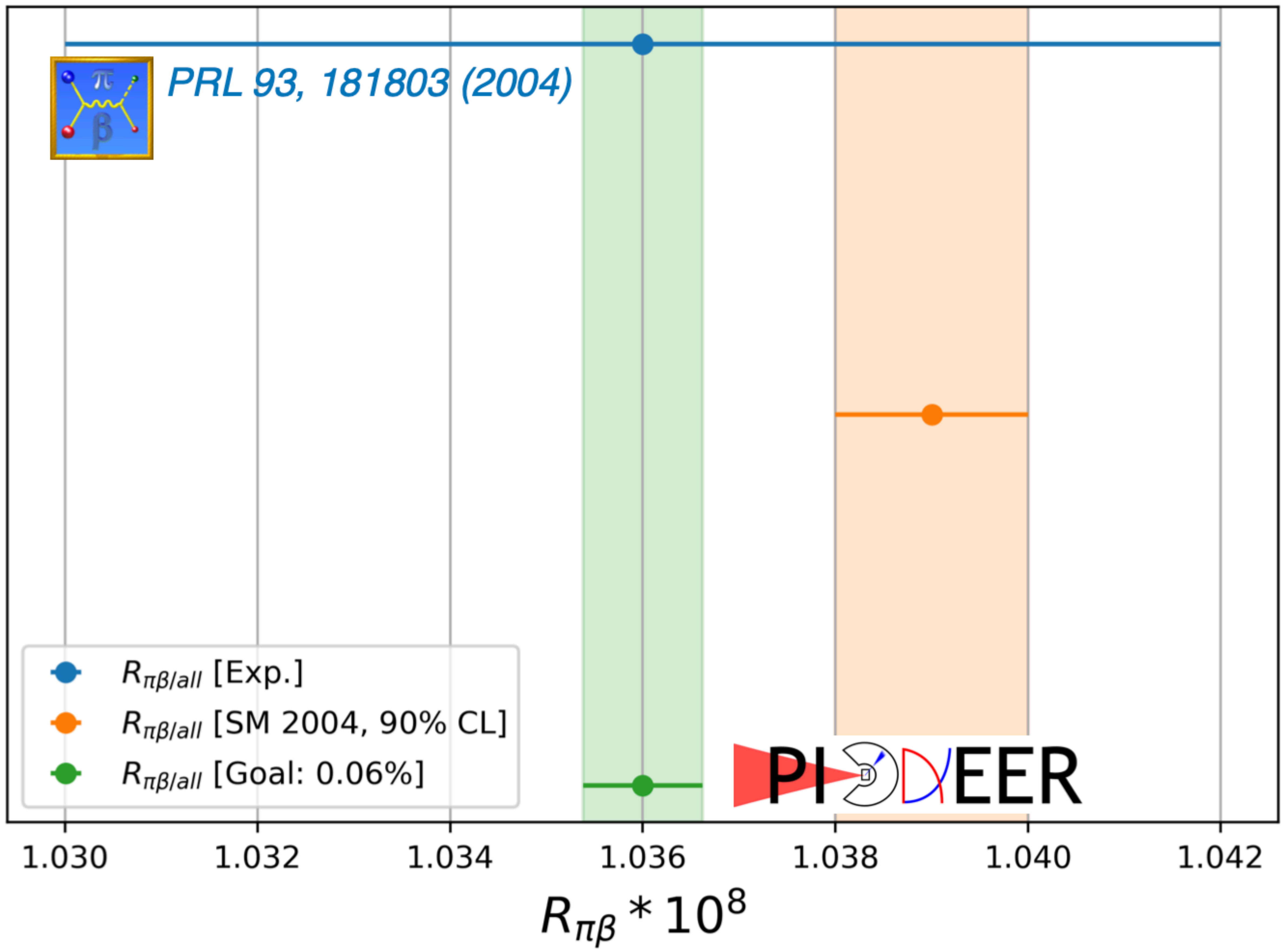
D. Bryman et al. Annu. Rev. Nucl. Part. Sci. 2022. 72:69–91

Physics case 4: Testing CKM unitarity V_{ud}



Courtesy of Leendert Hayen, talk at ELECTRO2022

Physics case 4: Testing CKM unitarity V_{ud}



Current best measurement from PIBETA at PSI

$$R_{\pi\beta}^{Exp} = 1.036(0.006) \times 10^8$$

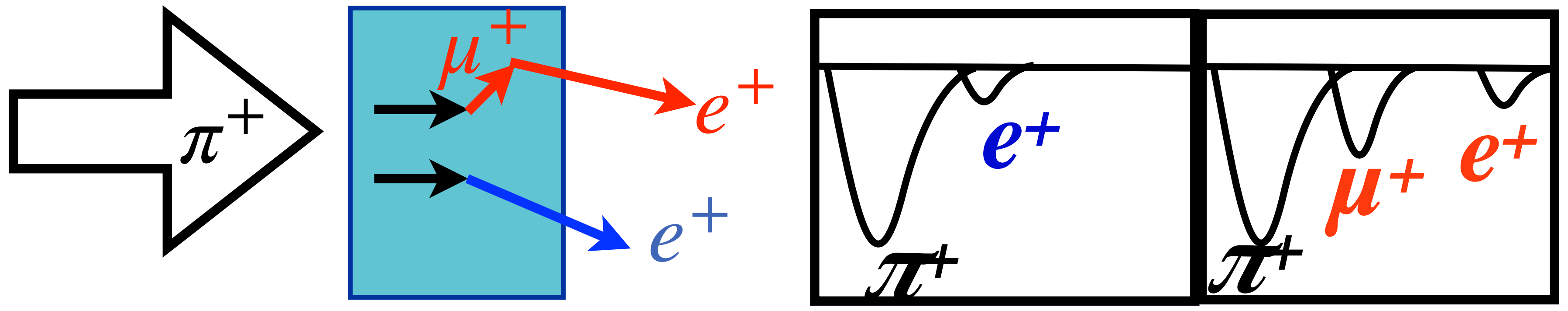
PIONEER goal is to measure $R_{\pi\beta}$ to 0.06% precision

Ten-fold improvement over current world best

Constraint on $|V_{ud}|$ comparable to super-allowed beta decay

$$R^\pi = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: 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: $B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$

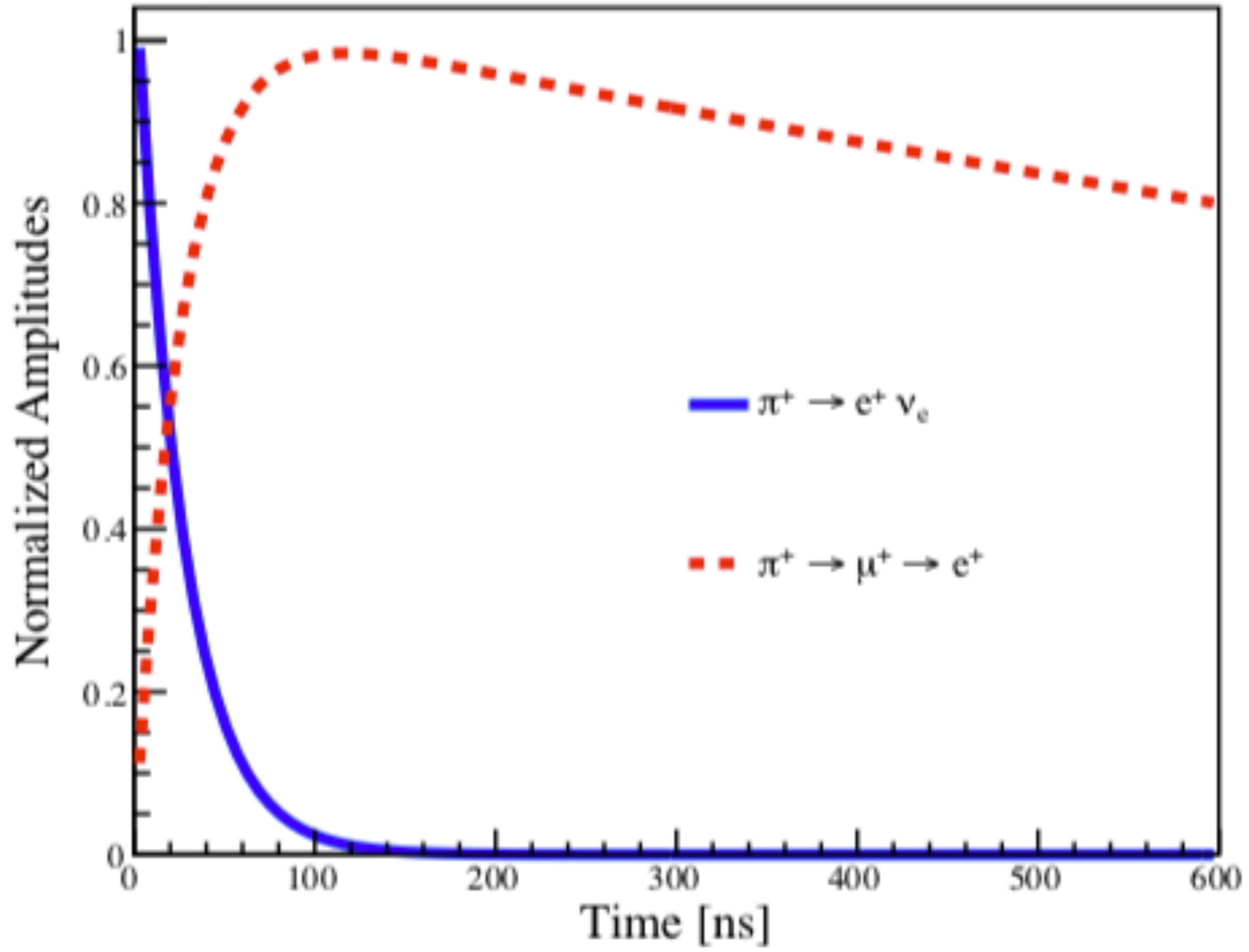
Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

Reminders:

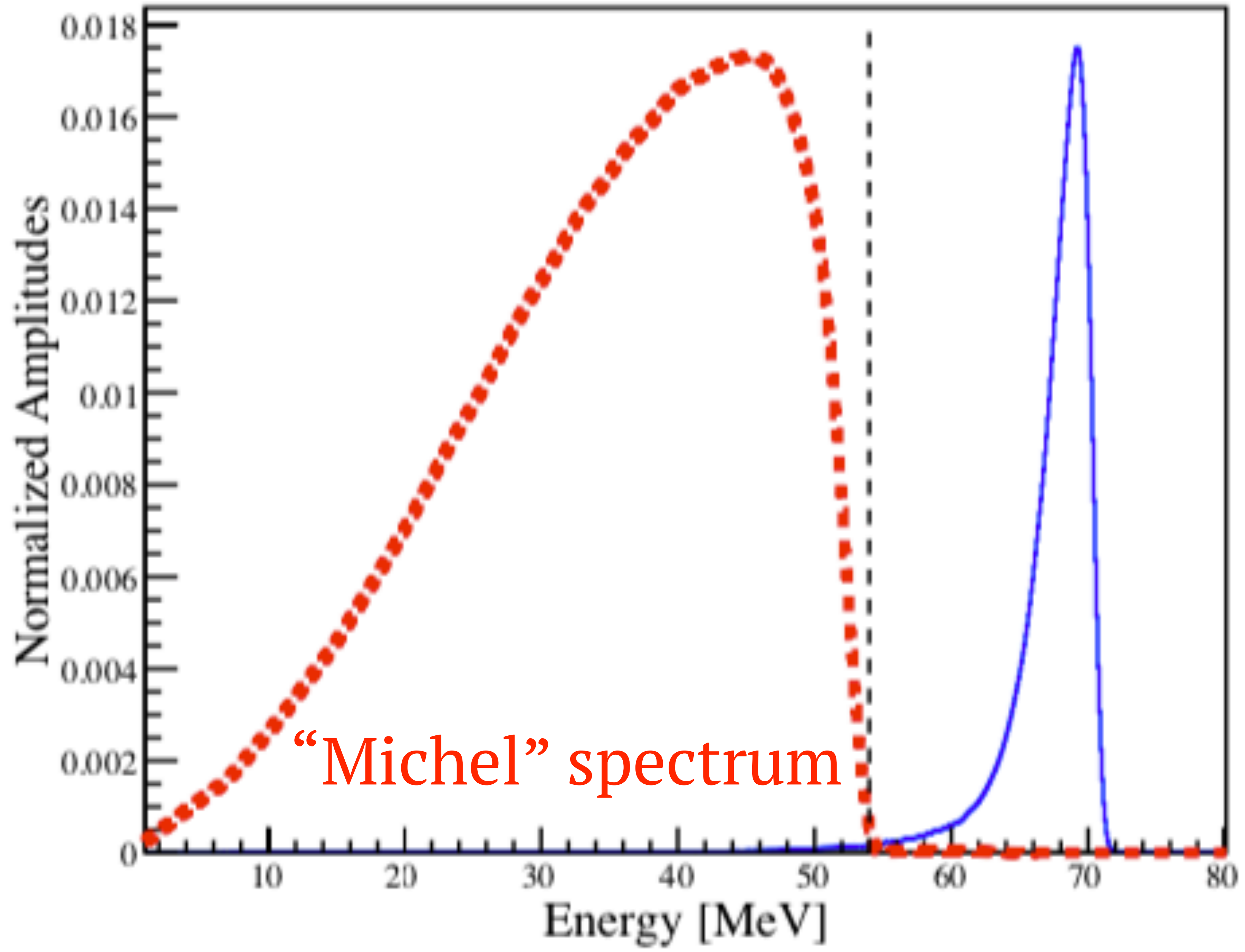
Pion lifetime:	26 ns
Muon lifetime:	2197 ns
Pion mass:	139.6 MeV
Muon mass:	105.7 MeV

Measure precisely e^+ energy spectrum and $t_{e^+} - t_{\pi^+}$

$\Longrightarrow$ different time and energy spectra - discrimination between the two decays



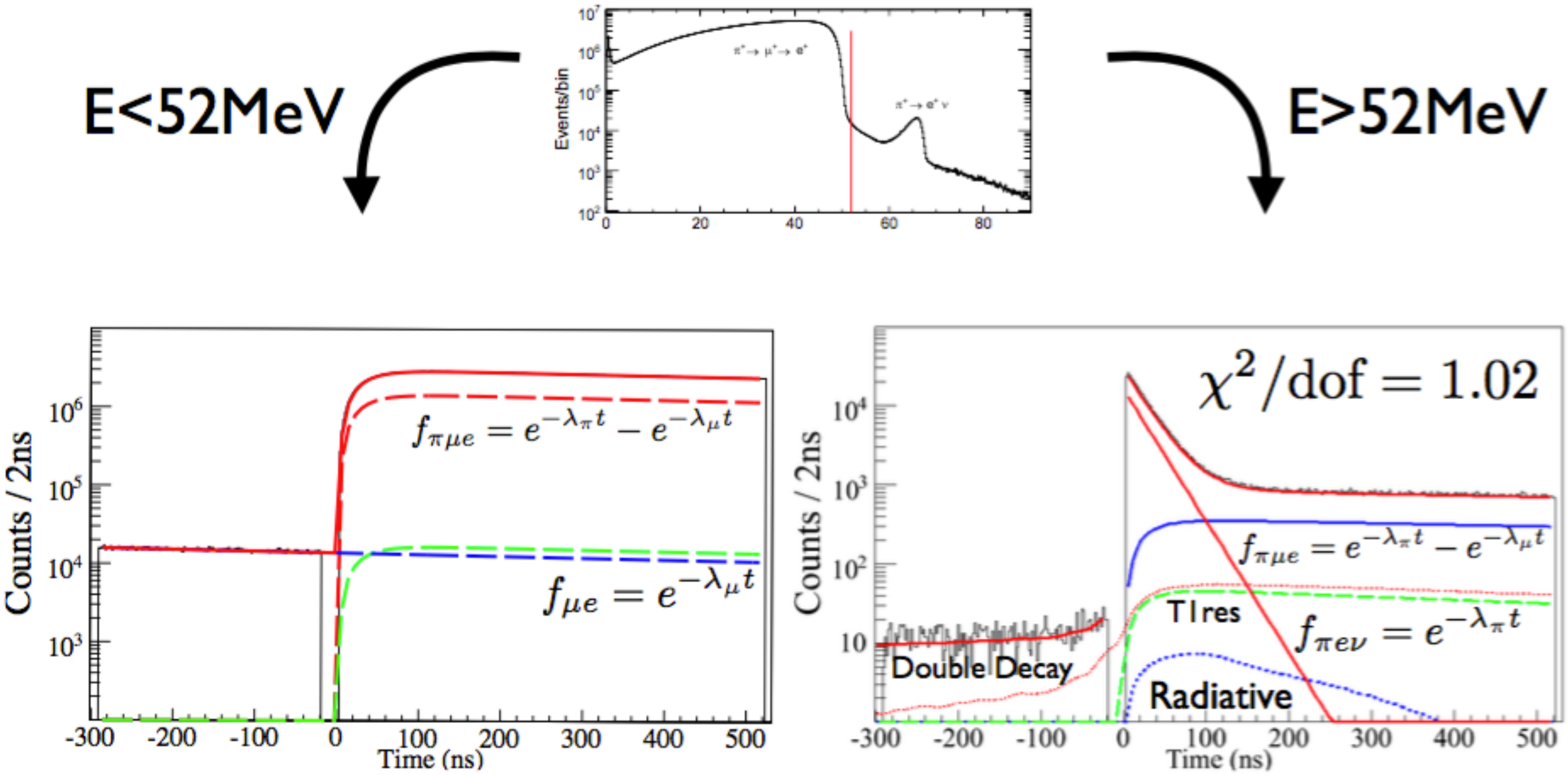
Time spectrum



e^+ energy spectrum

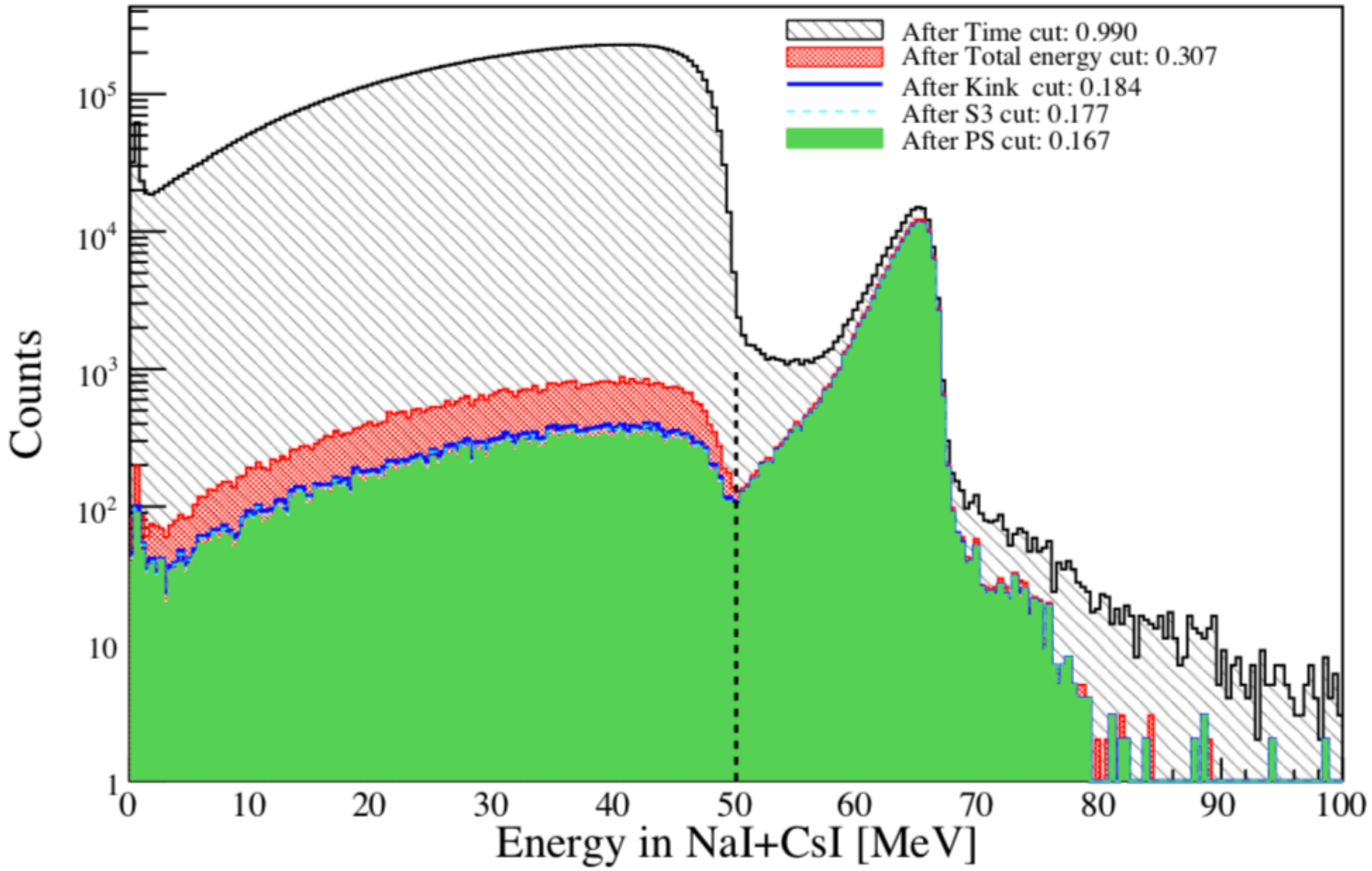
$R^{\pi} = \dfrac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$: how is it measured?

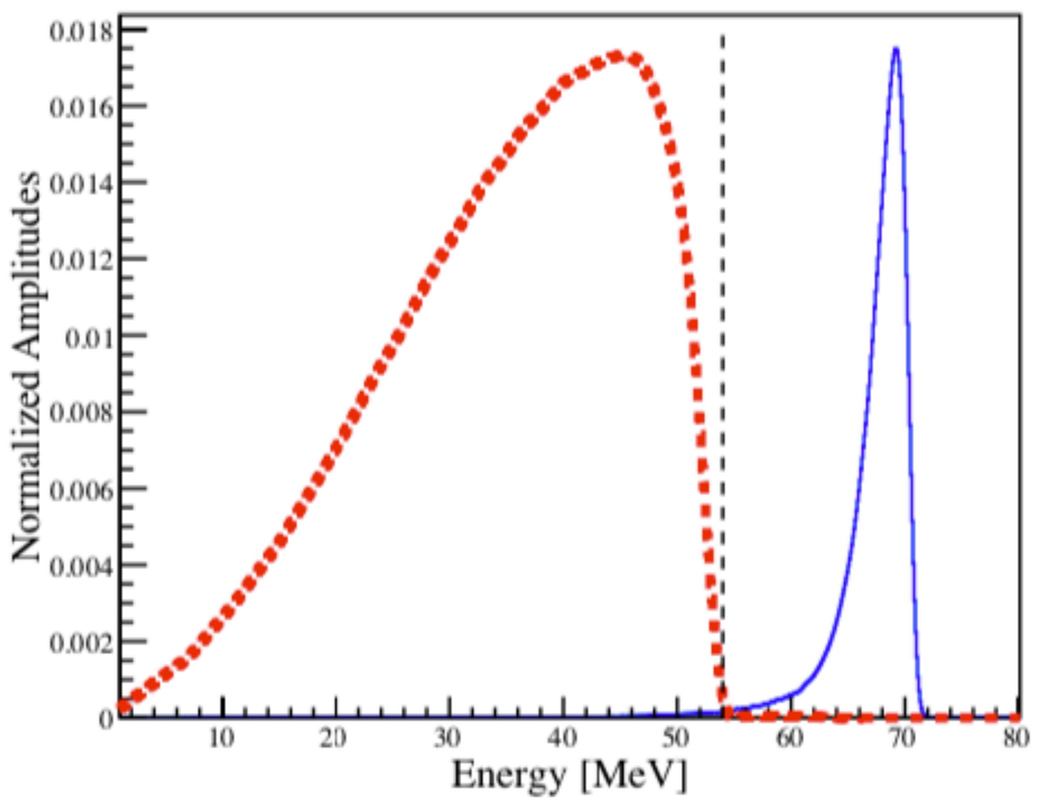
$\mu \to e\nu\bar{\nu}$

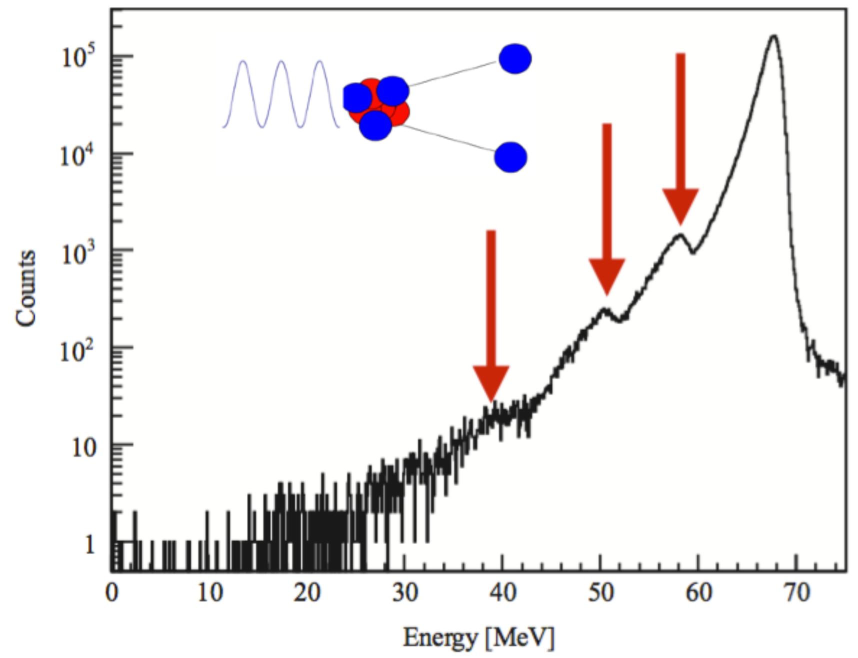


$$R^{\pi} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$: main systematic in the PIENU experiment

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



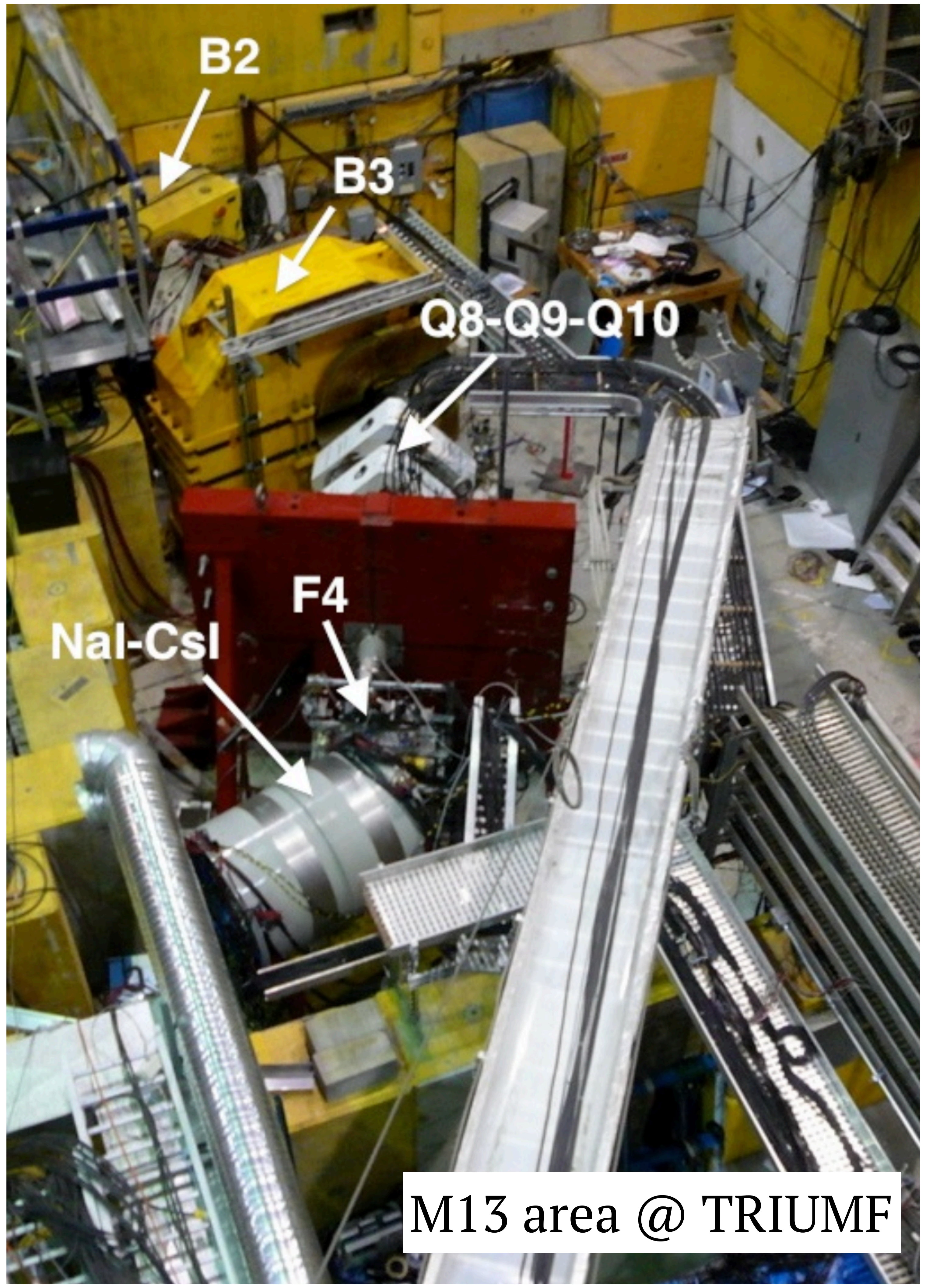


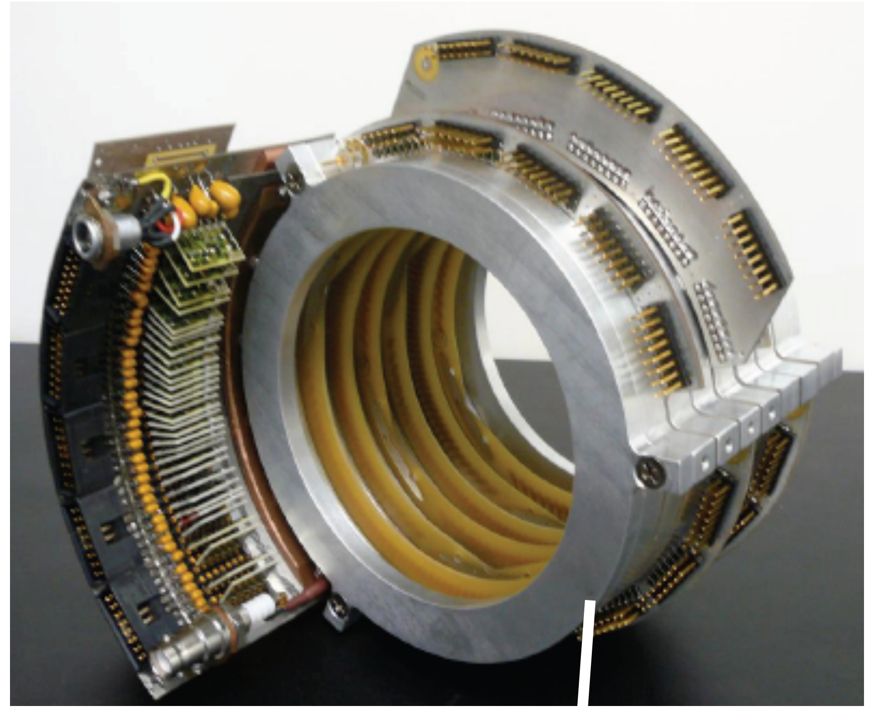


A. Aguilar-Arevalo et al., Nuclear Instruments and Methods in Physics Research A 621 (2010) 188–191

Low energy tail buried under the Michel spectrum caused by:
- finite energy resolution of the calorimeter
- photo-nuclear interactions (^{127}I(γ,n))
- shower leakage
- geometrical acceptance
- radiative decays
- etc

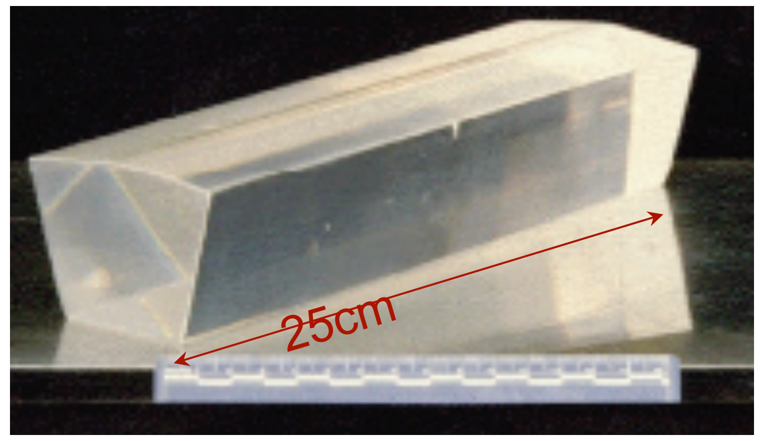
Main source of systematics : estimated using data (suppression of $\pi \to \mu \to e$ decays)


B2
B3
Q8-Q9-Q10
F4
NaI-CsI
M13 area @ TRIUMF

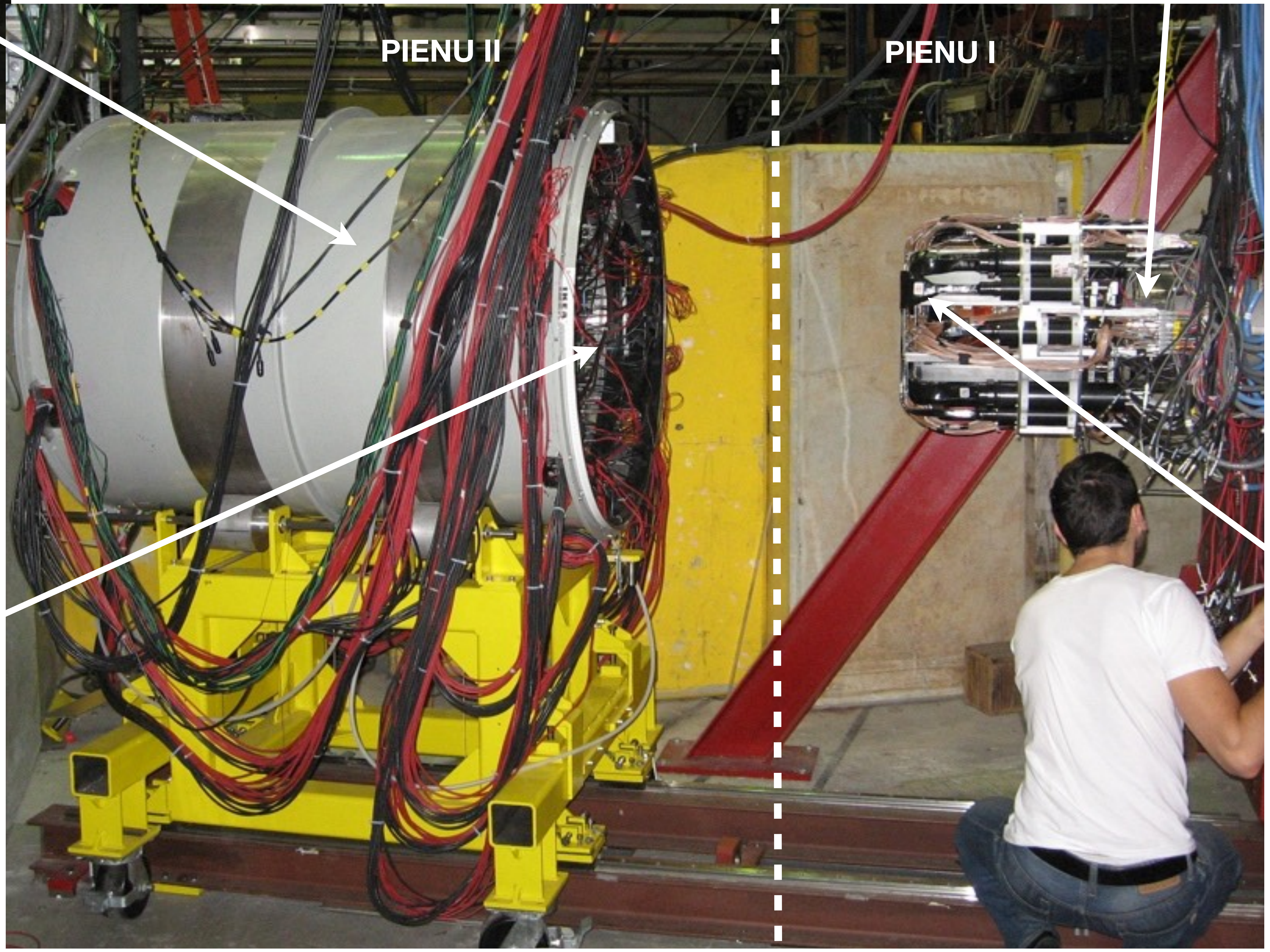


Beam Wire Chamber

Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals

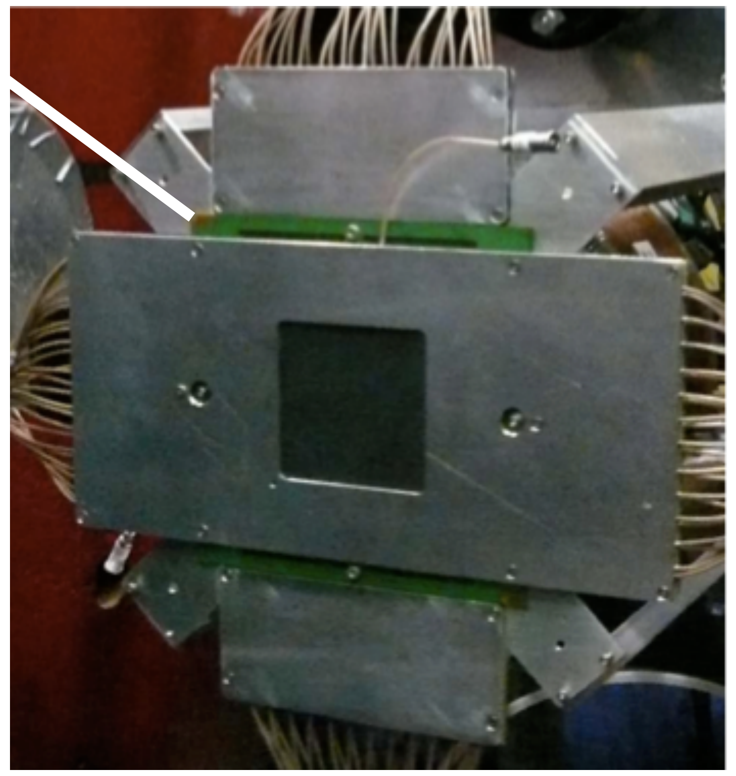


CsI crystal

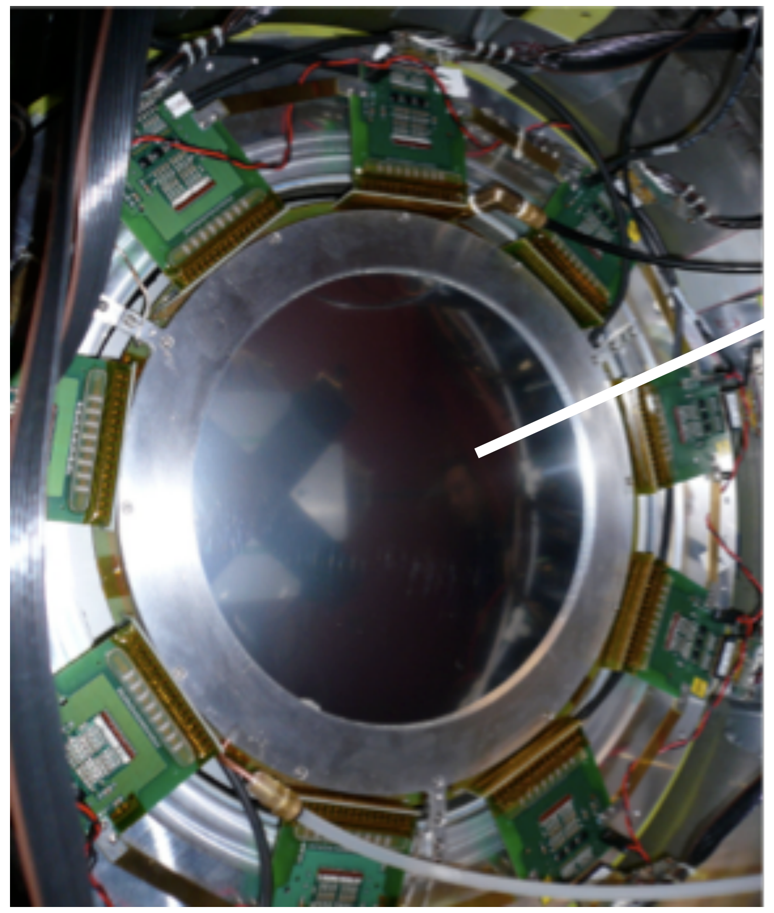


π^+

Silicon Trackers



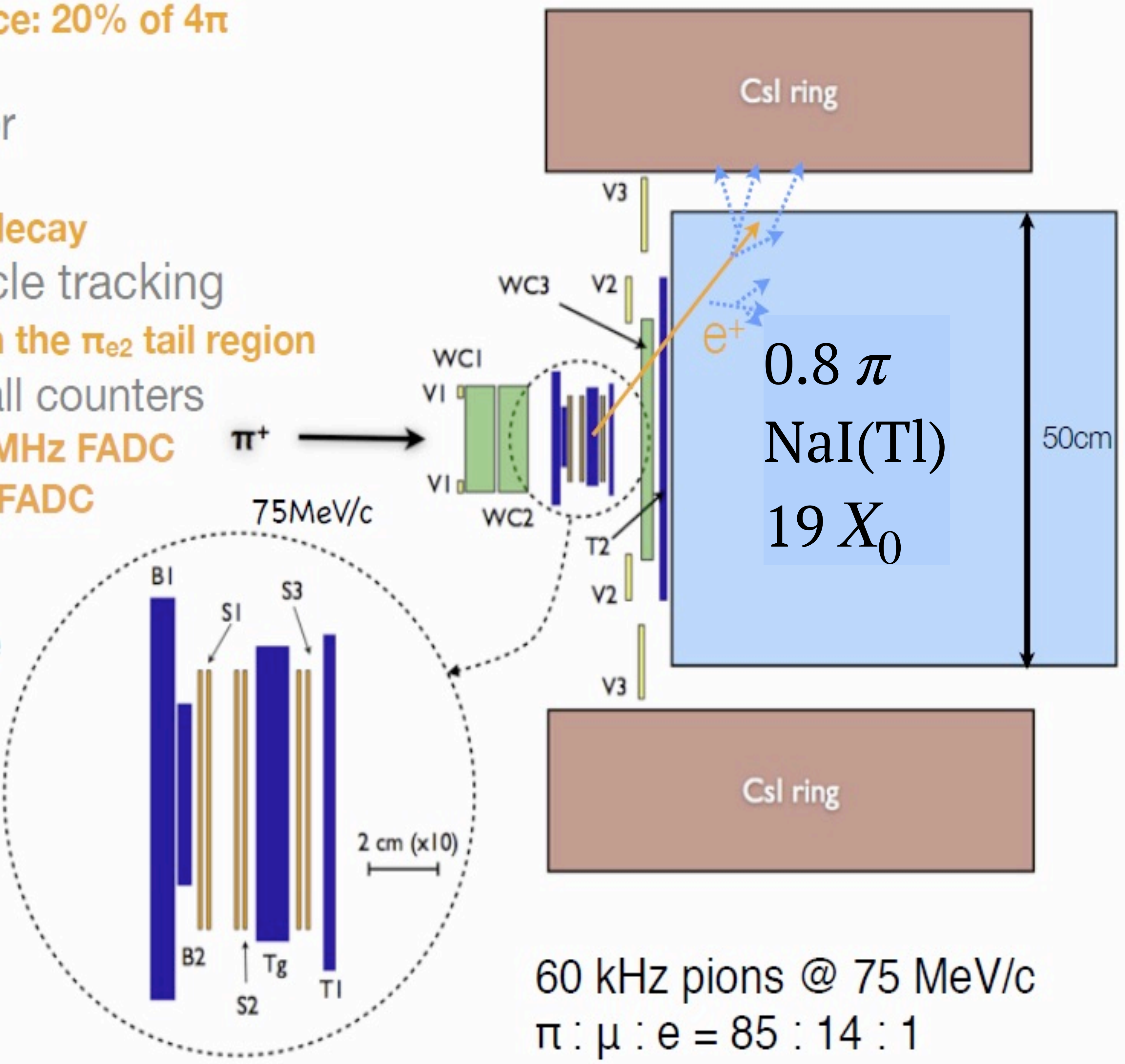
Acceptance
Wire Chamber



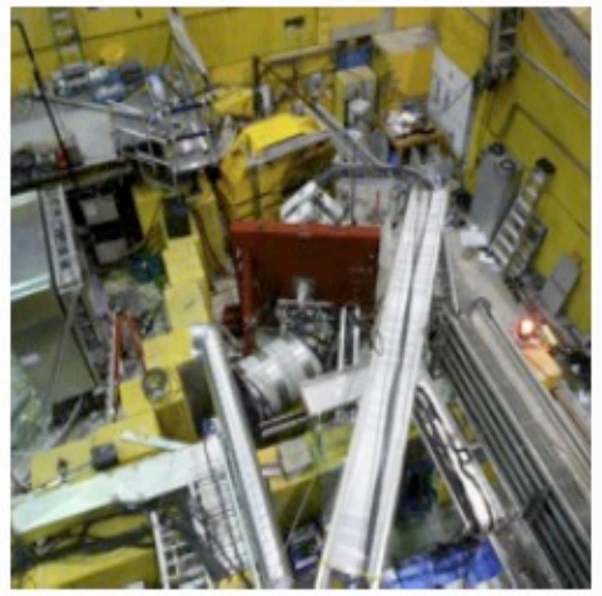
PIONEER: building on previous experiences - PIENU and PEN

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



60 kHz pions @ 75 MeV/c
π : μ : e = 85 : 14 : 1

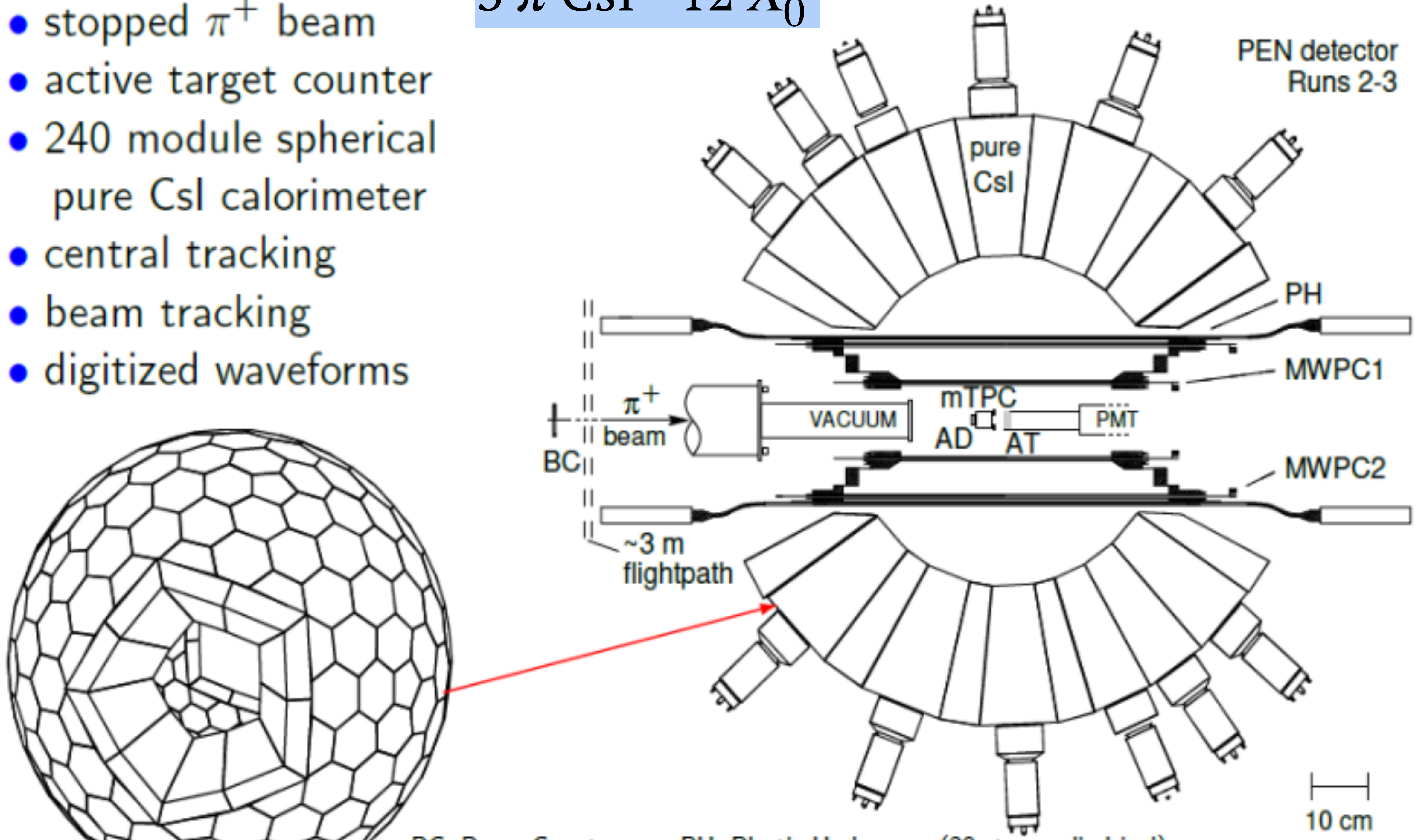
NaI slow but excellent resolution (1% σ at 70 MeV)
slow, small solid angle

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

large acceptance
calorimeter depth small, large tail

PIONEER DETECTOR CONCEPT - best of both worlds

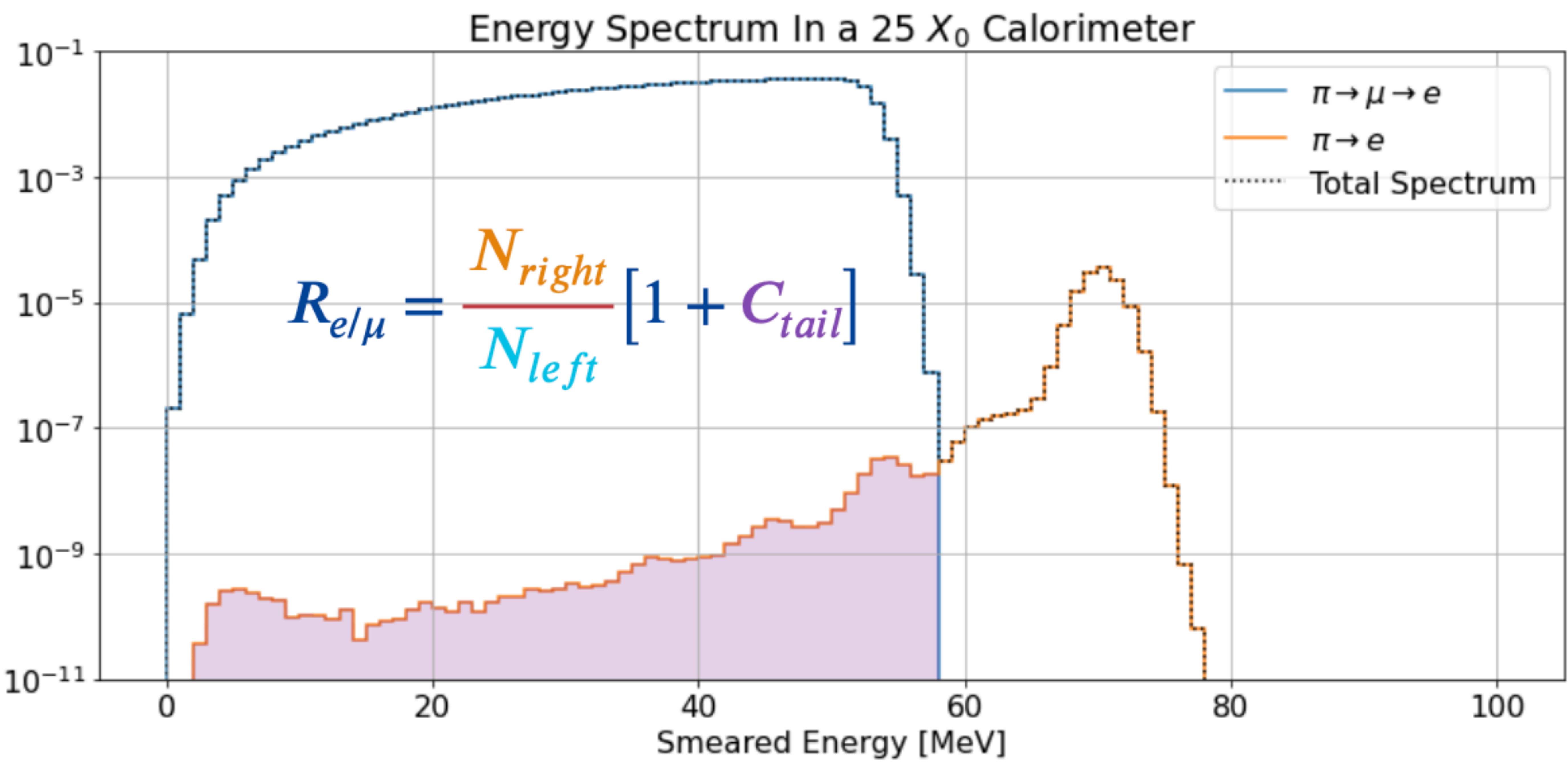
- Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)

  - Guiding principles to the design of the experiment

1. **Collect very large datasets** of rare pion decays (2e8 $\pi \to e\nu$ during Phase I)
$\to 3\pi$ sr calorimeter, intense pion beam at PSI

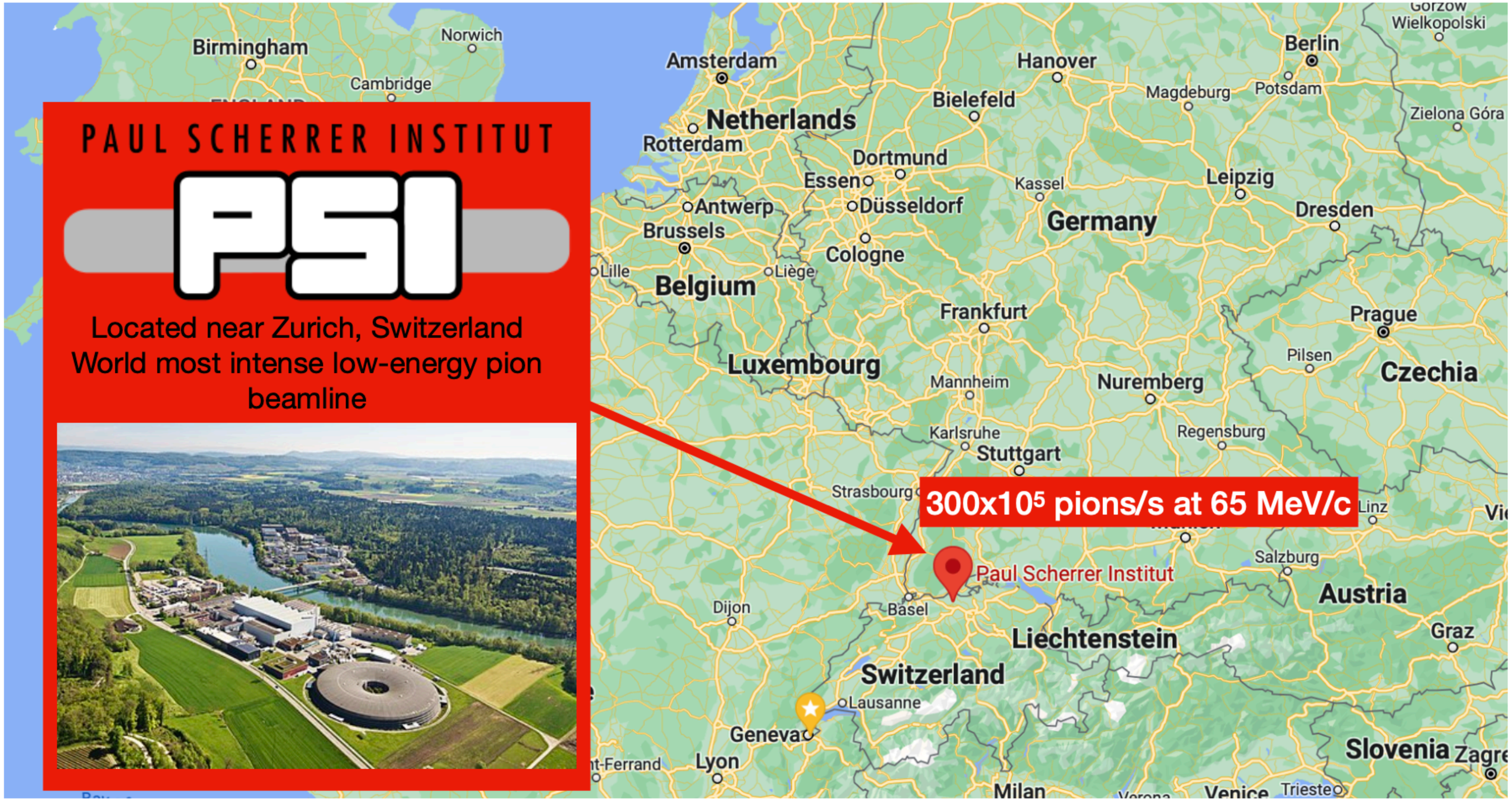
2. **Tail must be less than 1% of total signal**
$\to$ Shower containment in the calorimeter
$\to$ 25 X_0 calorimeter, high energy resolution (improve uniformity), reduce pile-up (fast detectors)

3. **Tail must be measured with a precision of 1%**
$\to$ Event identification in the active target
$\to$ highly segmented and fast target (5D detector)



Guiding principles to the design of the experiment:

1. **Collect very large datasets of rare pion decays (2e8 $\pi^+ \to e^+\nu_e$ during Phase I)**
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. Tail must be measured with a precision of 1% → Event identification in the active target



PIONEER DETECTOR CONCEPT - THE CALORIMETER

Guiding principles to the design of the experiment:

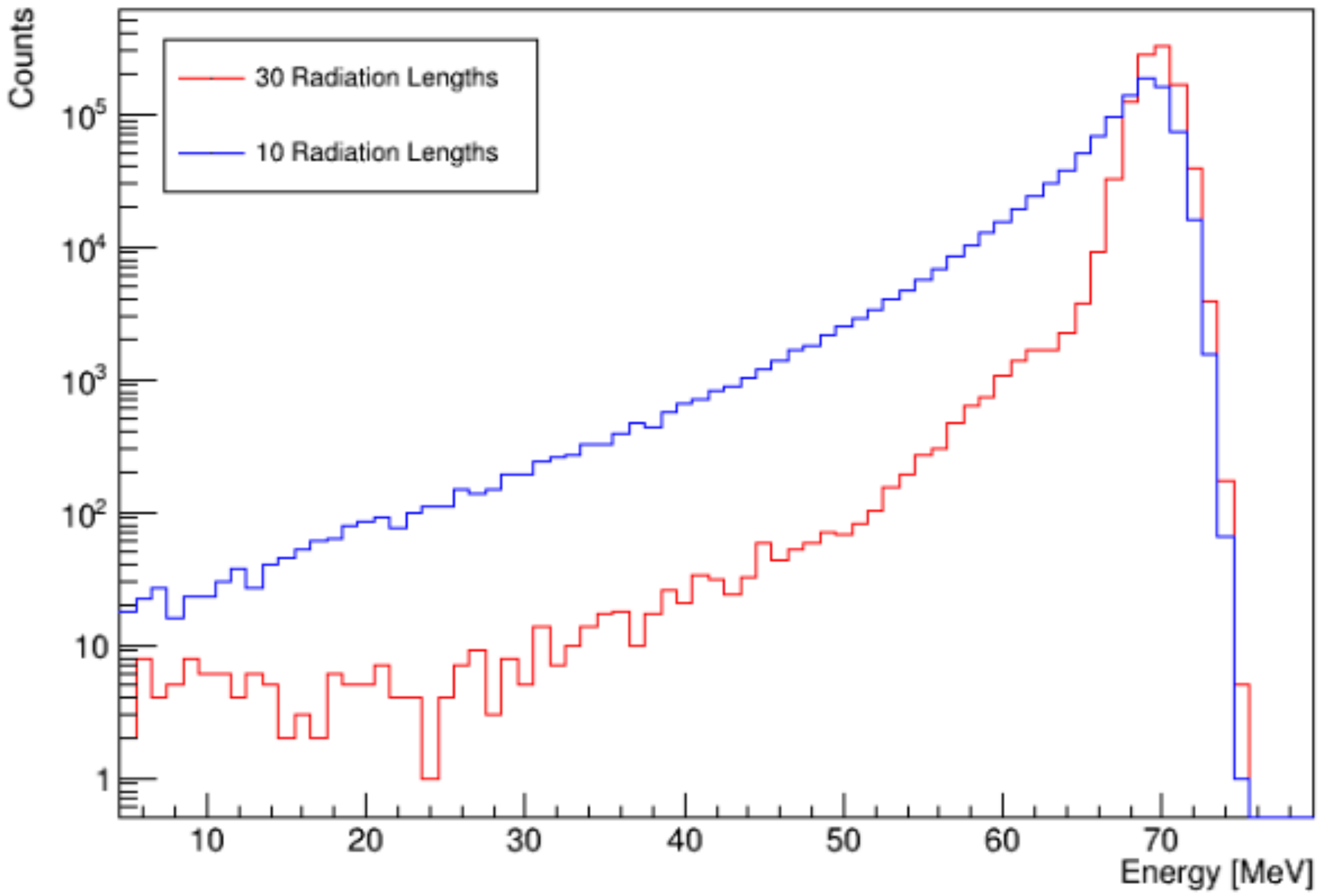
1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)
2. **Tail must be less than 1% of total signal → Shower containment in the calorimeter**
3. Tail must be measured with a precision of 1% → Event identification in the active target

Main Contender
Liquid Xenon

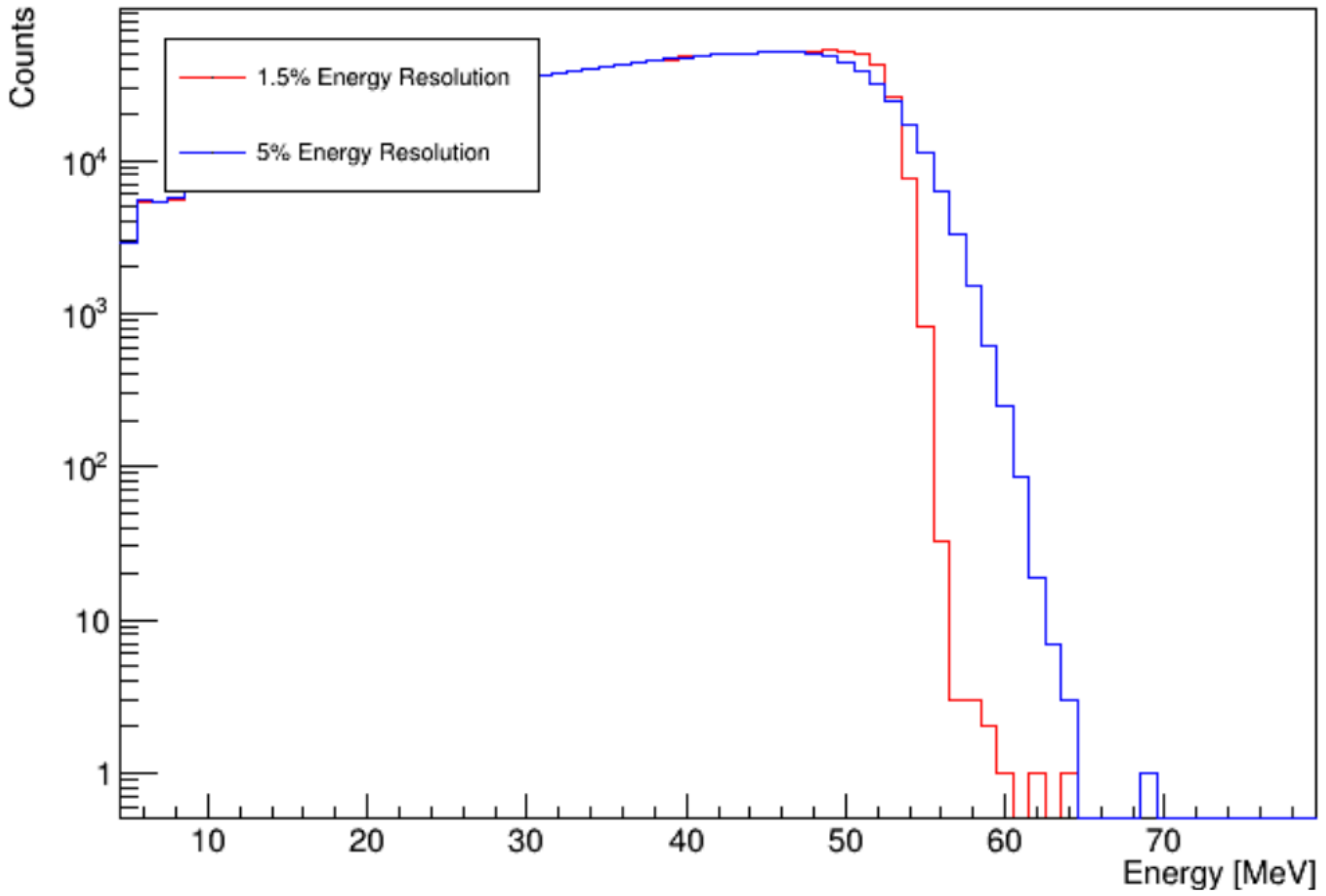
- fast response
- dense
- highly homogeneous response
- very bright
- proven high energy resolution
- Detector can be reshaped

See Ben Davis-Purcell's talk Thursday, (PPD) R1-1

$\pi \rightarrow e\nu$ signal



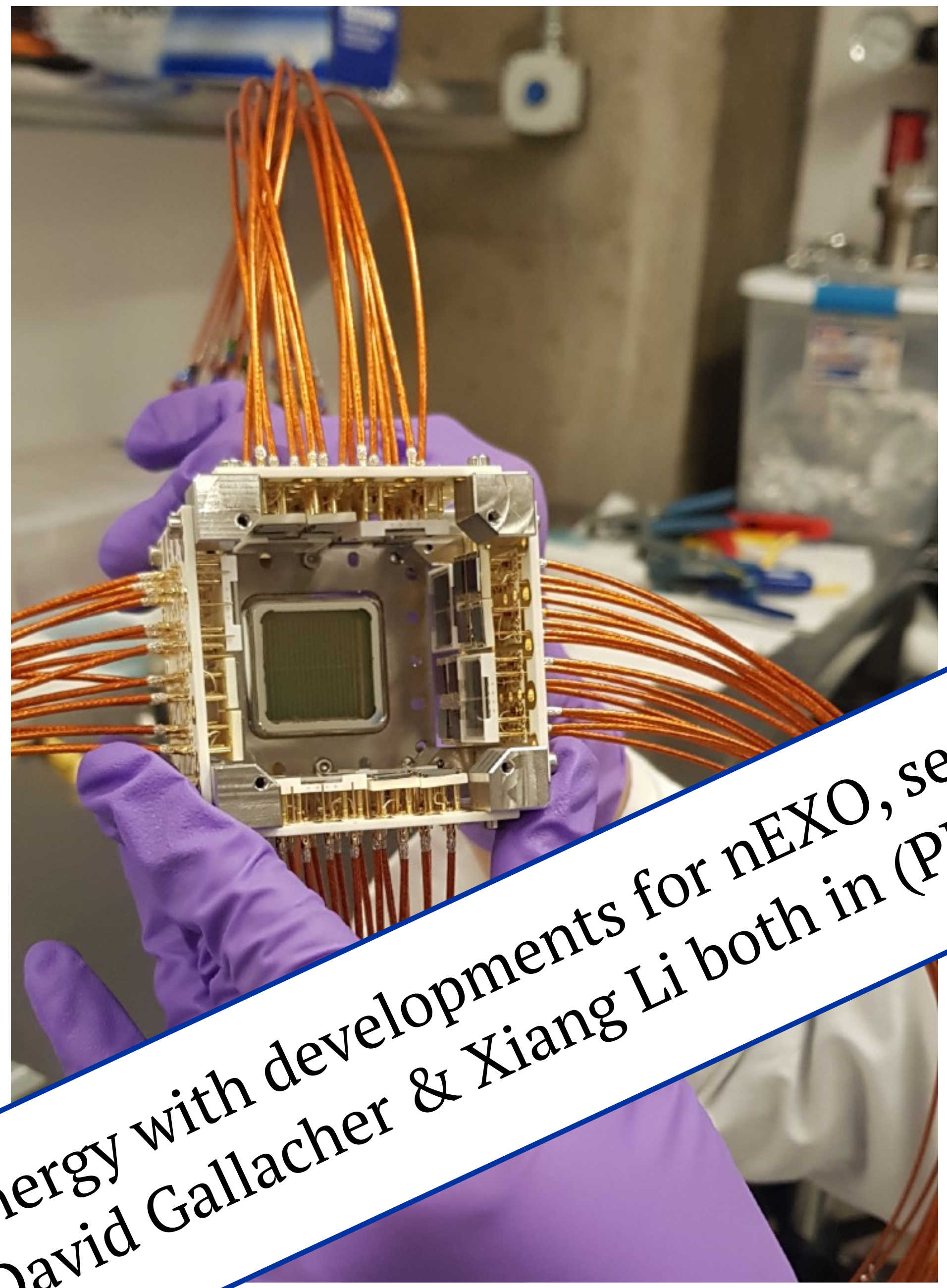
$\pi - \mu - e$ background



Target: ~25 X_0, 2% energy resolution at 70 MeV

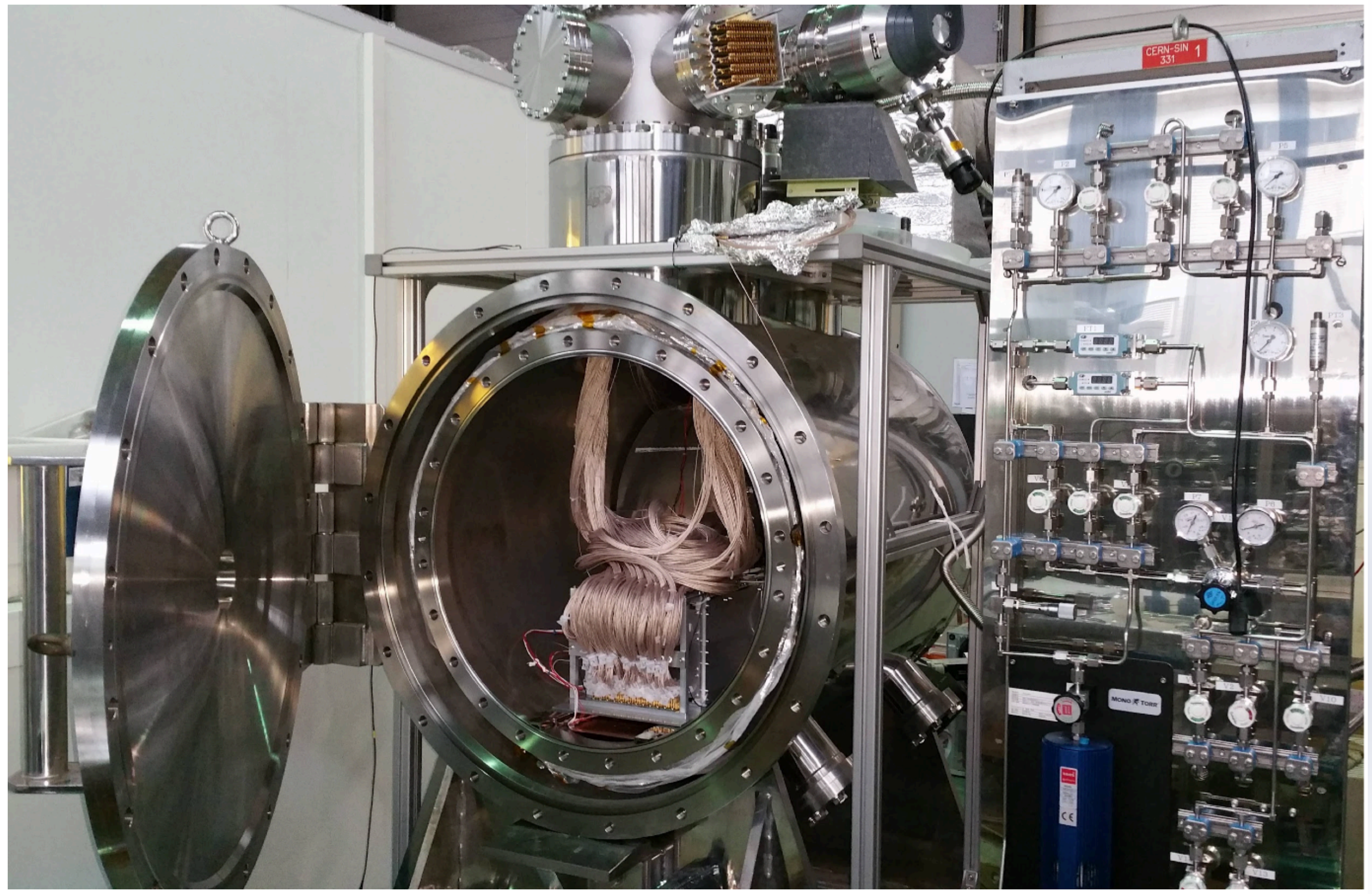
Main question:
how well can a large homogeneous LXe volume handle pile-up in a high rate environment?

LXe R&D and PROTOTYPING

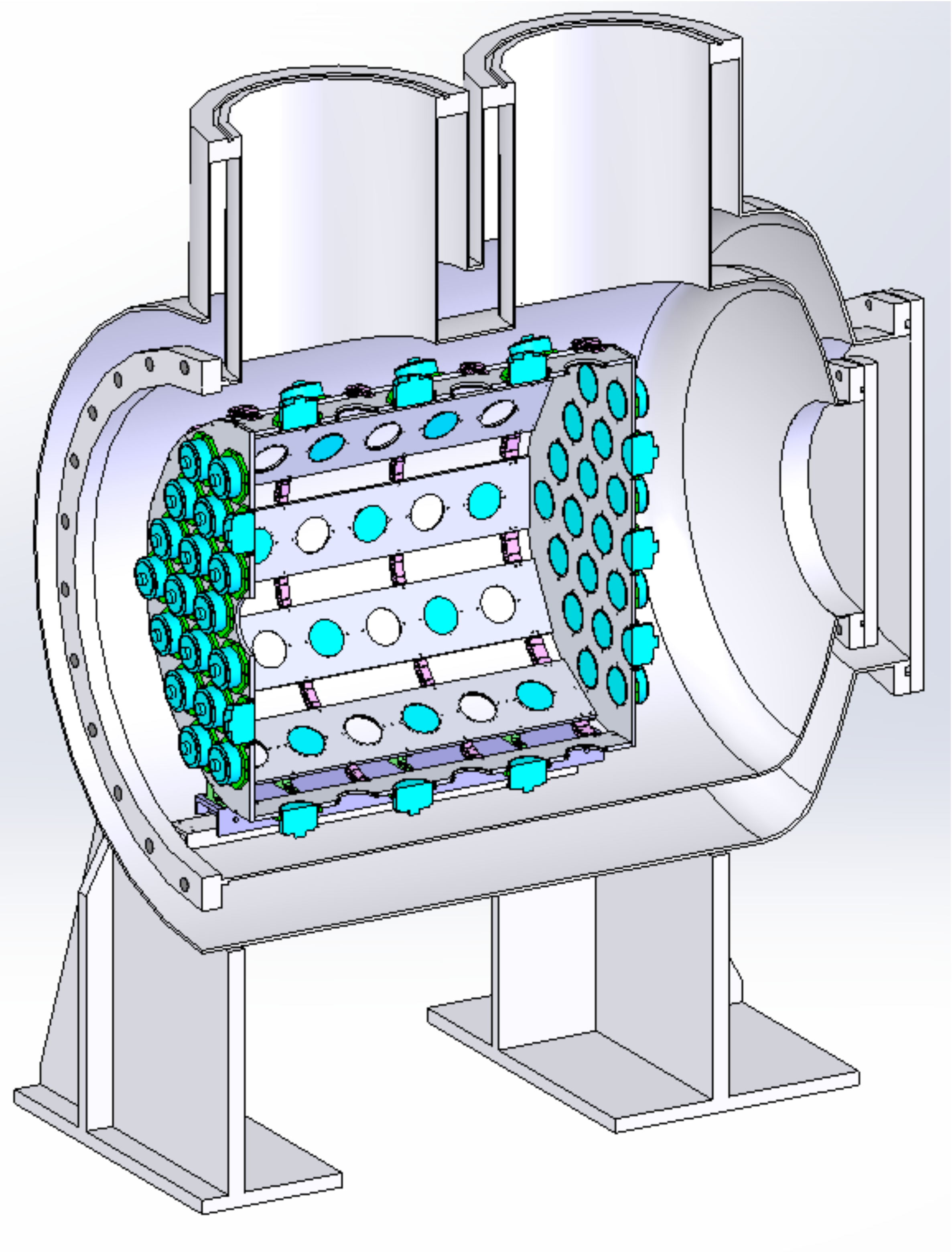


Synergy with developments for nEXO, see talks by David Gallacher & Xiang Li both in (PPD) M2-1

LoLX: 2L LXe cryostat at McGill



~100 L cryostat at PSI (former MEG large cryostat)



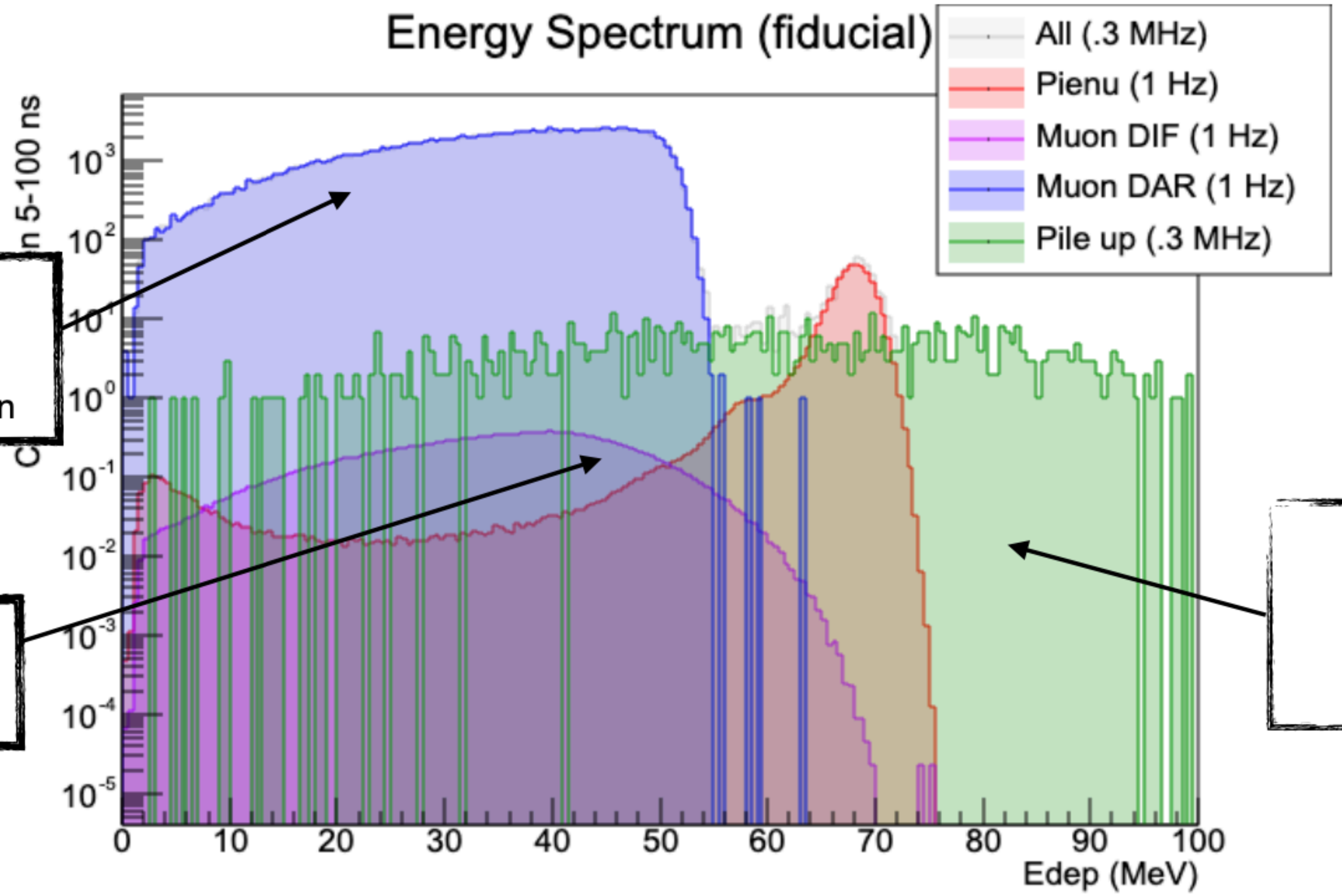
- Test and characterize photosensor technologies (PDE, response after high irradiation, stability etc)
- Benchmark simulations (G4 with and w/o NEST and optical simulations (Chroma))
- LXe scintillation properties (IR emission, Cerenkov)
- Measure energy resolution at low energies (compare to simulations)
- Data input to NEST at zero-field
- Material test (reflectivity, different coatings, WLS) etc

Benchmark/Validate simulations at PIONEER energy scales (0-70 MeV) to allow scaling to PIONEER final calorimeter.

- Measure detector lineshape including contribution of photonuclear reactions

- Measure energy resolution

PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET



Muon Decay At Rest
Excellent pulse shape separation should provide O(10-7) rejection

Muon Decay In Flight
Pion stop determination
dE/dx discrimination

Pileup
Spatial resolution in the target
Time separation from the pion stop

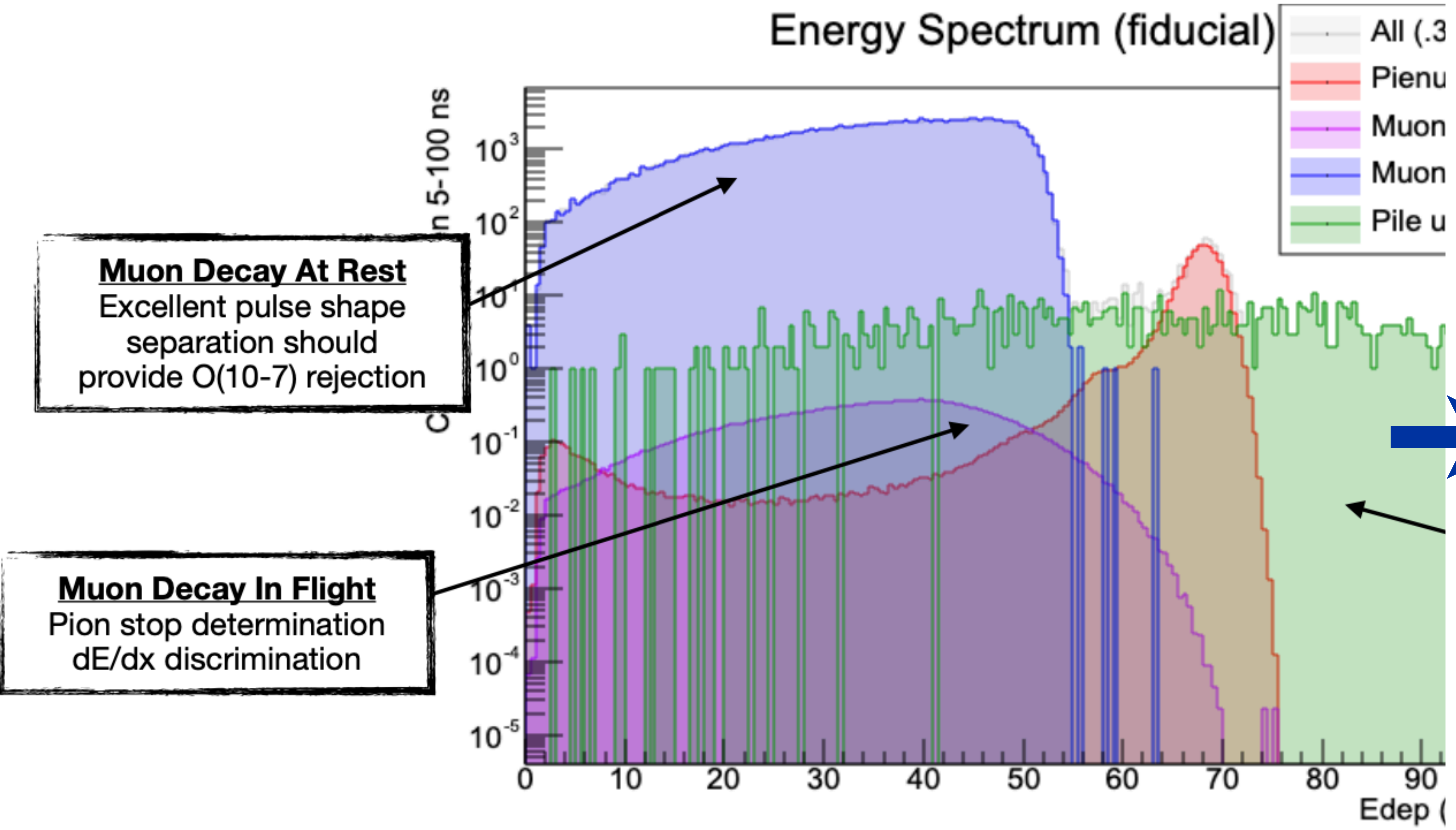
This is what real data could look like

Guiding principles to the design of the experiment:

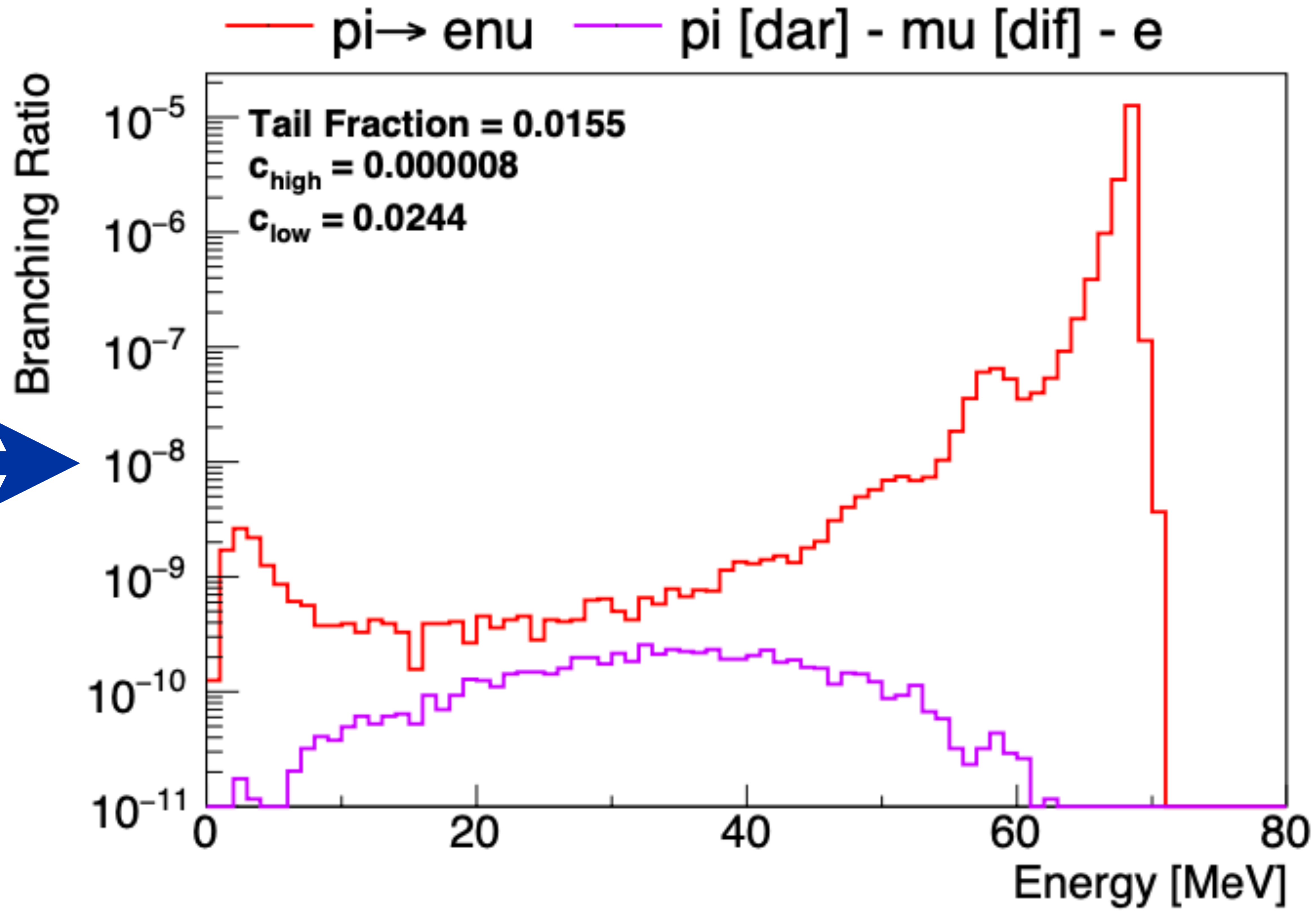
1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \to e^+\nu_e$ during Phase I)
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. **Tail must be measured with a precision of 1% → Event identification in the active target**

23

PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET



This is what real data could look like



Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \to e^+\nu_e$ during Phase I)
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. **Tail must be measured with a precision of 1% → Event identification in the active target**

23

Measuring the tail fraction

tag events with minimal bias while maintaining a decent (>1%) efficiency

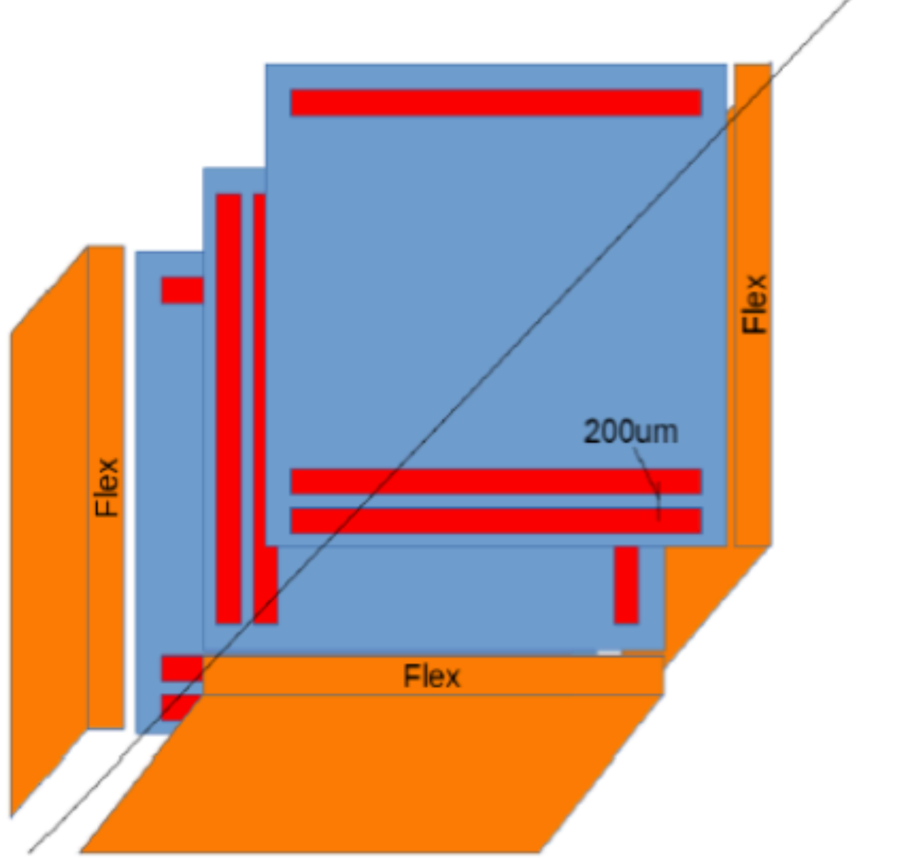
PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET

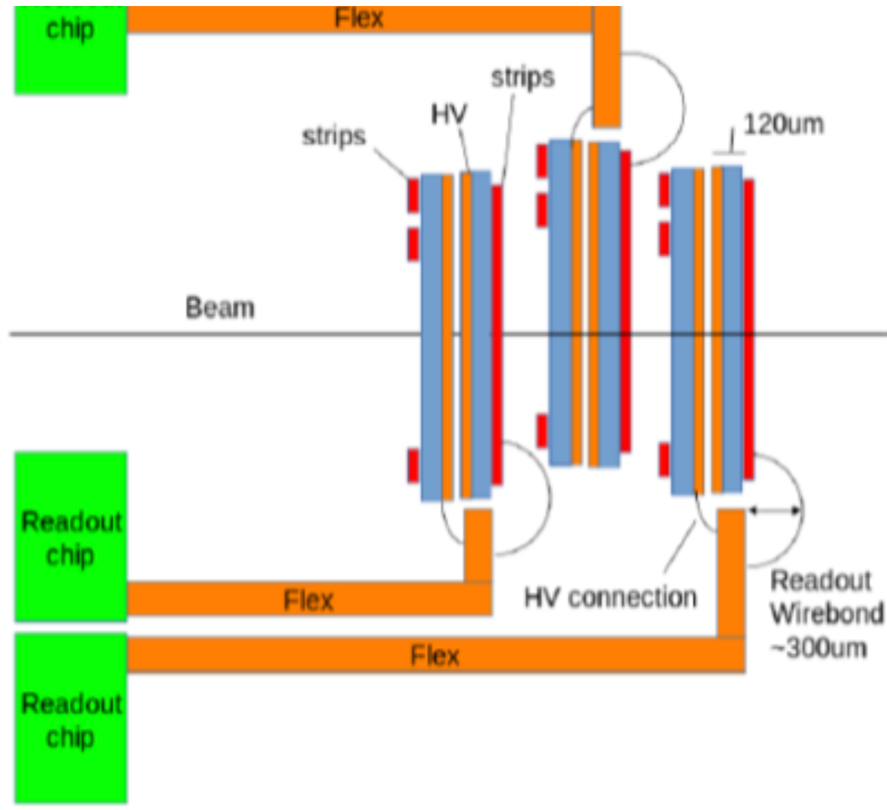
Active target ("4D - 5D!") based on low-gain avalanche diode (LGAD) technology

<u>Requirements</u>

- Different energy loss of particles through silicon -> needs to accommodate large range of energy scales

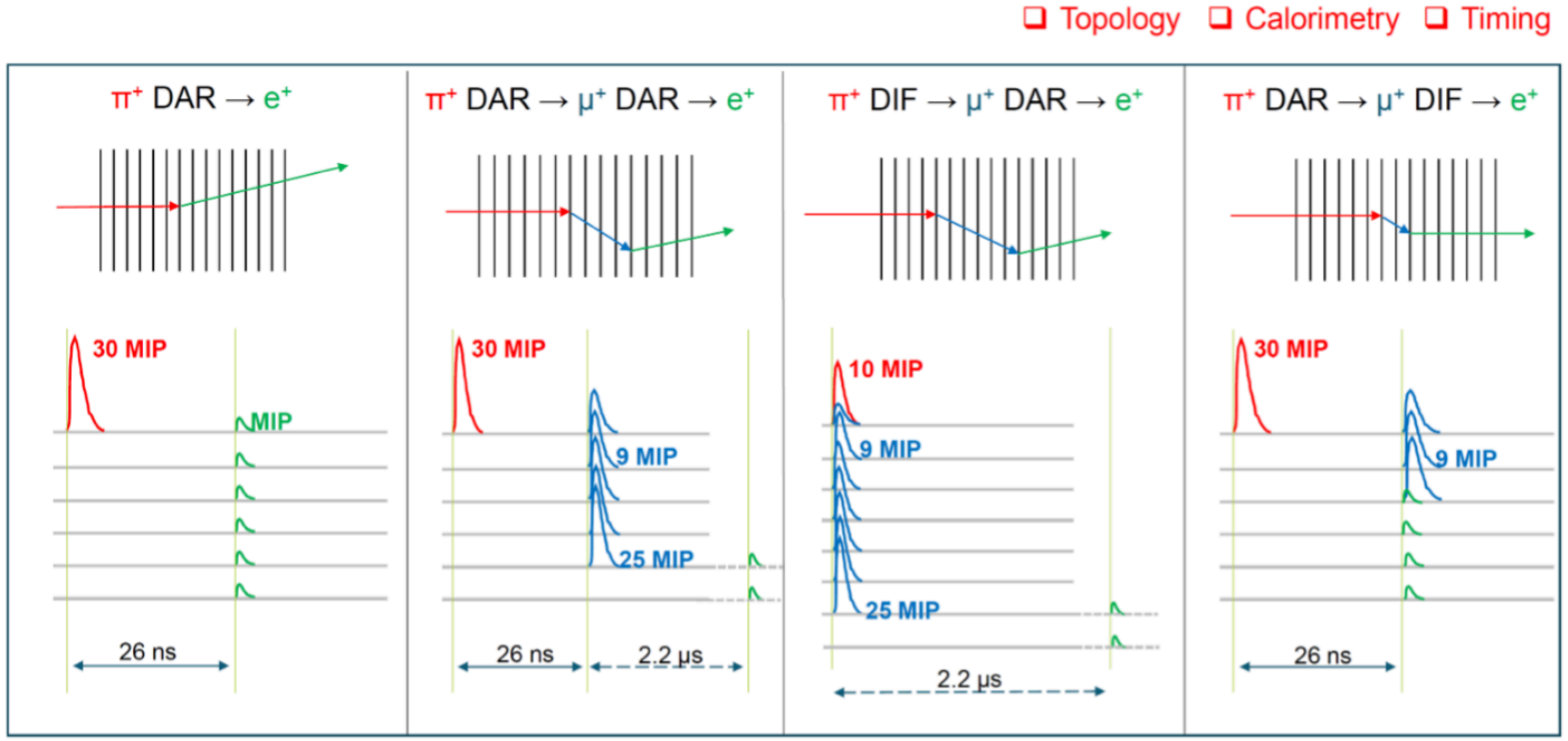
- different time properties: needs to separate signal within 1 ns apart



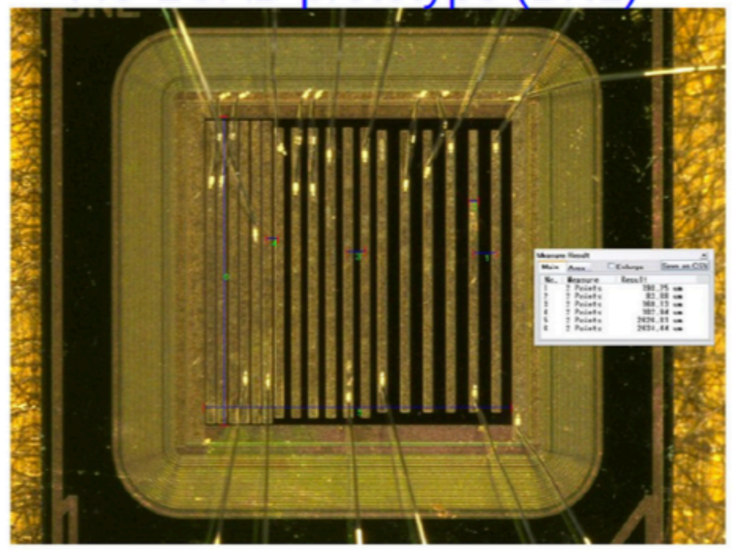


Tentative design

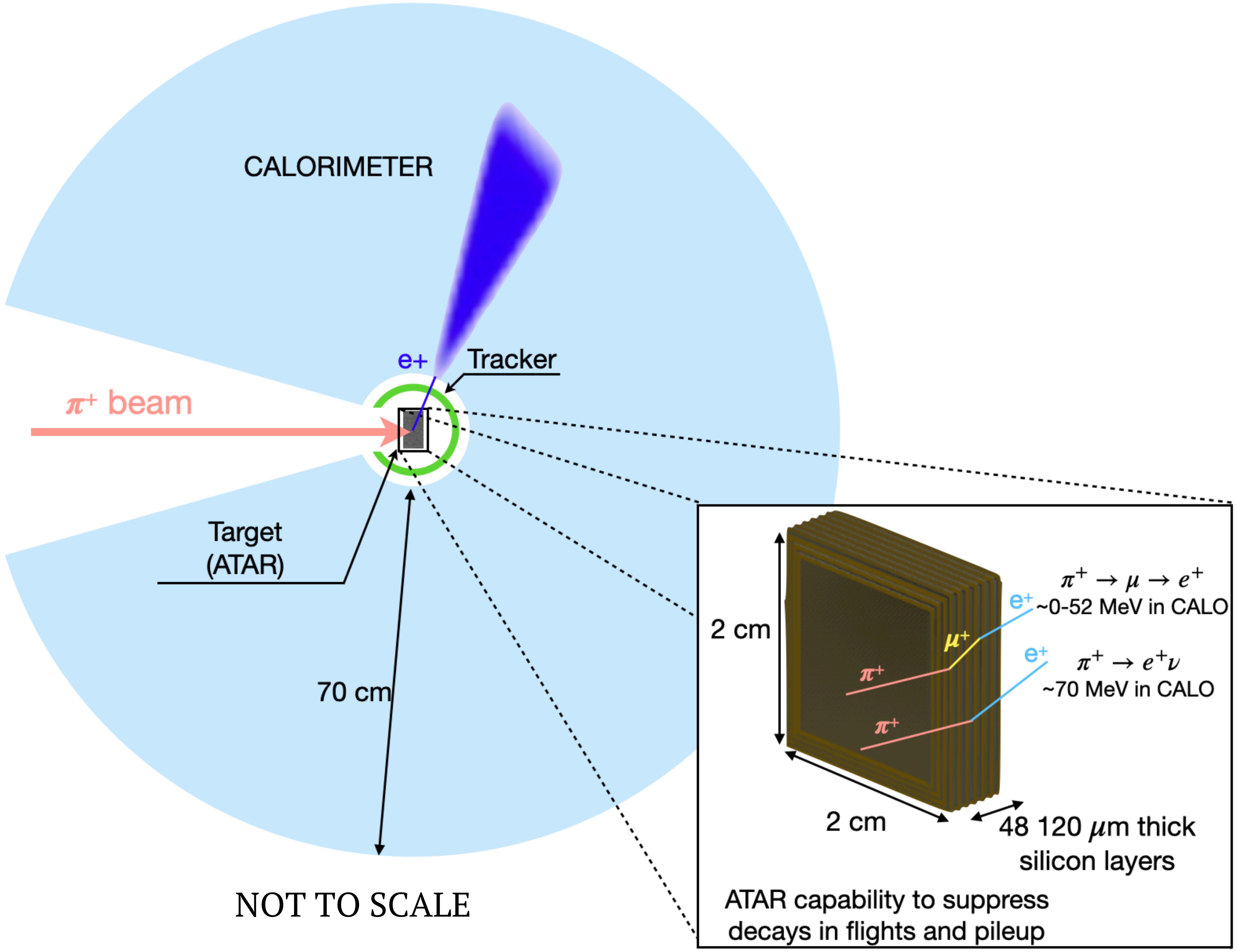
- 48 layers X/Y strips: 120 μm thick
- 100 strips with 200 μm pitch covering 2x2 cm2 area
- Sensors are packed in stack of two with facing HV side and rotate by 90 deg



AC-LGAD prototype (BNL)



80 μm-wide strips, 100, 150, 200 μm pitch; 5-15μm resolution


CALORIMETER
e+
Tracker
π^+ beam
Target
(ATAR)
70 cm
2 cm
2 cm
$\pi^+ \to \mu \to e^+$
~0-52 MeV in CALO
$\pi^+ \to e^+\nu$
~70 MeV in CALO
μ^+
π^+
π^+
e+
e+
48 120 μm thick
silicon layers
ATAR capability to suppress
decays in flights and pileup

NOT TO SCALE


CALORIMETER
e+
Tracker
π^+ beam
Target
(ATAR)
70 cm
2 cm
2 cm
π^+
μ^+
e+
$\pi^+ \to \mu \to e^+$
~0-52 MeV in CALO
$\pi^+ \to e^+\nu$
~70 MeV in CALO
48 120 μm thick
silicon layers
ATAR capability to suppress
decays in flights and pileup
1.5m

NOT TO SCALE

Conclusions and opportunities!

- High precision rare decays provide very promising windows into NP
- PIONEER : 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
- Time-scale: 10-15 years
- Approved to run at PSI. Expected start of data taking ~ 5 years timescale.
- Supported by an international collaboration: experts from previous PIENU and PEN experiments as well as a wide range of collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and theorists: **JOIN US!**

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

The PIONEER Collaboration

https://pioneer.triumf.ca

PIONEER first collaboration meeting Oct 2023, CENPA University of Washington